46th IPhO
INTERNATIONAL PHYSICS OLYMPIAD
2015 MUMBAI - INDIA

Proceedings of the
46th International Physics Olympiad
5-12 July 2015, Mumbai, India

Homi Bhabha Centre for Science Education
Tata Institute of Fundamental Research

IPhO

46th

INTERNATIONAL PHYSICS OLYMPIAD

2015 MUMBAI - INDIA

Homi Bhabha Centre for Science Education
Tata Institute of Fundamental Research

The International Physics Olympiad 2015 was supported by the Government of India thorough its Department of Atomic Energy (DAE), Department of Science and Technology (DST) and the Ministry of Human Resources Development (MHRD).

Edited by:
Manoj Nair
Sumana Amin
Shirish Pathare
Anwesh Mazumdar

July 2016

Published by:
Homi Bhabha Centre for Science Education
Tata Institute of Fundamental Research

Contents

1. Foreword ... 5

2. The Host Institution ... 9

3. The 46th IPhO Logo ... 11

4. Overview ... 13

5. The Opening Ceremony ... 17

6. People ... 19

7. Programme ... 77

8. Problems, Solutions and Marking Scheme ... 79

9. Results ... 139

10. Reflections (Newsletter) ... 151

11. IPhOrum (Software) ... 153

12. International Board ... 155

13. Statutes of IPhO ... 157

14. Syllabus of IPhO ... 171

15. Minutes of the International Board Meeting ... 179

16. Closing Ceremony 183

17. Glimpses 184

18. Acknowledgements 193

19. Afterword 195

Foreword

Jayashree Ramadas

Centre Director, HBCSE

The Homi Bhabha Centre for Science Education (HBCSE) of the Tata Institute of Fundamental Research is the country's nodal centre for the science and mathematical Olympiads. While Indian teams have competed in the mathematical Olympiads since the late eighties, our participation in the science Olympiads began with the 1998 International Physics Olympiad (IPhO) at Reykjavik, with a team selected and trained at HBCSE. Since then HBCSE's involvement as well as the national reach of the Olympiads has grown steadily, the latter in significant measure owing to the country-wide network of the Indian Association of Physics Teachers (IAPT) who conduct the first level of the selection exams for the science Olympiads.

After more than a decade of participation in IPhO and with experience gained in hosting of many other international Olympiads it was time for India to bid to host IPhO. HBCSE was able to take up this challenge on the strength of the country's dedicated and enthusiastic network of physics teachers, along with many members of India's active physics research community, who fully supported us in the mission to conduct the 46th IPhO. Intensive preparations over a year and a half and meticulous hard work of about 170 teachers, researchers and students went into the development of the academic tasks, including standardisation of 430 sets of experiments that worked flawlessly, and subsequently in the widely acknowledged perfect results of evaluation and moderation. A hundred and thirteen student volunteers and 70 staff of HBCSE ably managed the multiple and diverse aspects of this highly complex event.

It was a most rewarding experience for us to host IPhO. There was much that our students, teacher-mentors and volunteers learnt from interacting with the wonderfully rich multicultural mix of delegations from around the world. An important aim of the international Olympiads is to stimulate a global exchange of ideas leading to mutual understanding and a spirit of peace and harmony among nations. I hope and trust that the 46th IPhO has contributed to this aim.

Finally the grand scale and success of the 46th IPhO owes crucially to generous and timely financial support that we received from the Department of Atomic Energy (DAE), the Ministry of Human Resource Development (MHRD) and the Department of Science and Technology (DST) of the Government of India. I sincerely thank these agencies and ultimately the people of India for making it all possible.

Hans Jordens

President, International Physics Olympiad

For many of us the stay in India during the IPhO was like a fairytale. Buzzing Mumbai where traffic goes on day and night, where people never seem to sleep, where tuktuks come and go to any place you like to visit. Not that we had to. The Indian organizers spoiled us by providing us lodging, food and transportation to a very high standard. During the opening and closing ceremonies we got a taste of India by overwhelming shows of her highly developed colorful culture.

All that was the bonus. What we came for was the physics competition. No one could be disappointed by the problems that treated modern physics. The discovery of the double helix structure of DNA in 1952 by Rosalind Franklin done with X-ray diffraction, was transformed in an optical experiment. A second diffraction experiment dealt with surface waves in water which had to be studied with the help of a laser.

The three theoretical problems treated respectively the energy production of the sun, the use of the extremum principle in physics and the design of a nuclear reactor. Beautiful problems with a variety of levels of difficulty designed in such a way that at the end the full scale of the maximum 50 marks was used. This fortunate situation was also due to the way in which the well trained markers did their job, with an almost ideal distribution of the awards as a result. We remain most grateful to the Indian organizers for this excellent IPhO.

The Host Institution

The 46th IPhO, 2015 was held in Mumbai from 5th July, 2015 to 12th July, 2015. The event was organised by Homi Bhabha Centre for Science Education (HBCSE), a national centre of the Tata Institute of Fundamental Research, Mumbai. HBCSE aims to promote equity and excellence in science and mathematics from school to undergraduate level. The centre is involved in carrying out basic research in science education and bringing out good educational material; it also has a strong outreach programme. HBCSE is the national centre of the country for Olympiad programmes in mathematics and sciences including astronomy. It is responsible for the selection and training of the Indian delegations to the international Olympiads in six subjects, a process involving nearly 200,000 students annually. Its research programmes include mapping the structure and dynamics of knowledge, design and technology, mathematics education, visuo-spatial reasoning and alternative conceptions in different areas of science.

The 46th IPhO Logo

The logo of the 46th IPhO combines the depiction of a well-known concept in physics and a representation of the Indian flag. The bending of light due to a massive object is a prediction of classical physics as well as Einstein's general theory of relativity. This bending enables a star directly behind the Sun to be viewed during a total solar eclipse, a phenomenon which is depicted in the logo. However the angle of deflection is underestimated in a classical approach, but can be correctly obtained using the general theory of relativity. The confirmation of the exact amount of bending predicted by Einstein's theory during a total solar eclipse in 1919 was one of the most celebrated events in the history of science.

The three colours, saffron, white and green, are from the national flag of India. The top band is of saffron colour, indicating strength and courage, the white middle band symbolizes peace and truth while the green band represents fertility and growth of the nation.

Overview

Anwesh Mazumdar

Convener, 46th IPhO

The 46th International Physics Olympiad (IPhO) was held in Mumbai, India from 5 to 12 July, 2015. The event was organised by the Homi Bhabha Centre for Science Education (HBCSE), a national centre of the Tata Institute of Fundamental Research (TIFR). The event was fully funded by the Government of India through the Dept. of Atomic Energy (DAE), the Ministry of Human Resource Development (MHRD) and the Dept. of Science and Technology (DST).

The academic preparations for IPhO 2015 started in early 2014 when nearly 80 teachers and scientists from across India met and put forward a large number of ideas as proposals for problems. The academic committee evaluated these ideas and selected the final problems through a rigorous progressive procedure over several months. One of the major challenges was the development of the experiment for which 430 copies of the apparatus were assembled and tested at HBCSE. This huge task was carried out with the help of nearly 50 teachers from across the country. These teachers also joined in the final IPhO event, where they participated in the setting up of more than 400 sets of apparatus, and the administration, marking and moderation of the tests taken by the international students. For the theoretical tasks, dedicated development groups worked for months to help the main authors give shape to the final problems and their solutions. The task of evaluation of the theory answer sheets was carried out by a large team of undergraduate students, many of whom were past Olympiad medallists, under the supervision of a team of senior scientists and teachers.

The much-awaited IPhO 2015 began with the arrival of the teams from July 4 onwards. There were 382 students, 160 leaders, 80 observers and 18 visitors from 83 countries at this edition of IPhO. The students were hosted at the sprawling Hotel The Leela while the leaders, observers and visitors stayed at the Hotel Taj Lands End, enjoying the magnificent view of the Arabian Sea and the Mumbai skyline. The academic team was hosted at the latter hotel and the International Board (IB) meetings were also held there. The students were accompanied and escorted throughout their stay in India by a team of 113 student guides who were mainly undergraduate students from different institutions in and around Mumbai.

The event was inaugurated at the Homi Bhabha Auditorium of TIFR on the evening of July 5. TIFR is one of the top research institutions in India. The Chief Guest, Dr. R. K. Sinha, Chairman, Atomic Energy Commission of India, declared the Olympiad open by lighting a ceremonial lamp and raising of the IPhO flag. The opening ceremony included a colourful cultural programme.

The next day was devoted to the International Board meeting to discuss the experimental tasks. The students had a free day, visiting the Nehru Centre and Planetarium. The five-hour experimental examination was conducted on 7 July at the Bombay Exhibition and Convention Centre (BCEC) in Goregaon, Mumbai. More than 400 cubicles, each of area 3 sq. m. had been erected to house the experimental setups. The experimental test, consisting of two tasks was based on the theme of use of diffraction of light as a probe of matter. After the examination the students relaxed by actively participating in a traditional Indian acrobatics show. The leaders, observers and visitors had a tour of south Mumbai and a museum on this day.

The International Board discussed and translated the theoretical tasks on the next day in another gruelling meeting while the students were taken on a trip of south Mumbai and TIFR. In the meantime, the evaluation of the experimental examination had begun in earnest at the leaders' hotel. The team of experimental markers worked through the next two days to complete the evaluation of all the answer scripts.

The students took the theoretical examination on 9 July at the BCEC. The theoretical tasks ranged from understanding the Sun from its emitted photons and neutrinos, to the overarching extremum principles in different branches of physics, to the design of a safe nuclear reactor. While the students were facing up to these challenges, the leaders experienced a taste of the famous Mumbai monsoon while visiting the Kanheri caves and the Sanjay Gandhi National Park. In the evening the students and the leaders met over dinner at the students' hotel.

Having completed all the examinations, the students had a grand day of frolicking at the Adlabs Imagica amusement park in Khopoli on 10 July. The leaders went on a brief tour to the Godrej Locks Factory, and were occupied in marking the theoretical answer scripts of their own students. The team of Indian markers stayed up through the night to complete the marking of all the theoretical answer scripts in less than 24 hours. The marks of both the theoretical and experimental examinations were exchanged between the leaders and the hosts in the evening. The whole academic process was facilitated by a software, named IPhOrum, designed exclusively for IPhO 2015 by a team of past Indian Olympiad students.

The penultimate day, 11 July, saw the International Board meet twice. In the morning the threshold marks for the different medals were announced. The late evening meeting was devoted to discussions on the syllabus, other administrative matters and the approval of the final results. During the day the leaders met the markers in the moderation session to arrive at a consensus for the final marks. The students visited the Mahindra Vehicle Manufacturers Limited factory in Chakan to marvel at the entire process of building cars and trucks from bare pieces of metal.

Finally, on 12 July, the closing ceremony was held in the Convocation Hall of the Indian Institute of Technology Bombay (IITB), a premier institution of technical education in India. Dr. R. Chidambaram, Principal Scientific Advisor to the Govt. of India, was the chief guest. Students received their medals and certificates from the Chief Guest and other dignitaries. The award ceremony was interspersed with a show of folk dances of India. At the end, the IPhO flag was passed on to the next hosts, Switzerland and Liechtenstein. Thus the 46th IPhO came to a close, leaving behind sweet memories for the participants as well as the organisers. Onwards to IPhO 2016!

More details at IPhO 2015 website: www.ipho2015.in

Opening Ceremony

The opening ceremony of the 46th IPhO was held at the Homi Bhabha Auditorium of the Tata Institute of Fundamental Research (TIFR) on 5 July 2015 at 4 PM. The event was inaugurated by lighting a ceremonial lamp and raising the IPhO flag. The student participants from 83 countries displayed their national flags on the stage one by one and were greeted by the audience. The chief guest of the ceremony was Dr. R. K. Sinha, Chairman, Atomic Energy Commission of the Government of India. The President of IPhO, Prof. Hans Jordens welcomed the participants. Prof. Mustansir Barma, former Director, TIFR, Prof. Jayashree Ramadas, Centre Director, HBCSE and Prof. Anwesh Mazumdar, National Coordinator of Science Olympiads in India, and Convener, 46th IPhO, also addressed the gathering of students, leaders, observers, and the academic and organisational teams of the host country. Dr. Rajesh Khaparde, Coordinator, Experimental Component of IPhO 2015, proposed the vote of thanks. The ceremony included a colourful ensemble of seven different classical dance forms of India by Devendra Shelar and troupe, and a virtuoso Kathak dance performance by Nandita Puri and troupe. The whole ceremony was compered by Prof. Vijay Singh, former National Coordinator of Science Olympiads in India and a key member of the IPhO 2015 academic committee.

People

Participants

1. **Edgar Ara Vardanyan**
Contestant
edgarvardanyan1999@gmail.com

Armenia **ARM01**

2. **Ashot Harutyun Movsisyan**
Contestant
ashot.movsisyan.97@gmail.com

Armenia **ARM02**

3. **Hrant Armen Topchyan**
Contestant
hranttopchyan1@gmail.com

Armenia **ARM03**

4. **Ashot Artur Matevosyan**
Contestant
ashmat98@gmail.com

Armenia **ARM04**

5. **Ara Tigran Mambreyan**
Contestant
ara.mambreyan@yahoo.com

Armenia **ARM05**

6. **Gagik Vardan Grigoryan**
Leader
gagrig@gmail.com

Armenia **ARM11**

7. **Bilor Koryun Kurghinyan**
Leader
bilorkurghinyan@gmail.com

Armenia **ARM12**

8. **Yinuo Han**
Contestant

Australia **AUS01**

9. **Joshua Zexi Lin**
Contestant

Australia **AUS02**

10. **Sudarshan Ravi**
Contestant

Australia **AUS03**

11. **Shiye Su**
Contestant

Australia **AUS04**

12. **Janet Fan Mi Zhong**
Contestant

Australia **AUS05**

13. **Alix Laura Verdon**
Leader
alix.verdon@gmail.com

Australia **AUS11**

14. **Jake Andrew Paul Glidden**
Leader
j.glidden@uq.edu.au

Australia **AUS12**

15. Matthias Diez
Contestant
m.diez@gmx.at

Austria **AUT01**

16. Michael Pfeifer
Contestant
michael.pfeifer@hotmail.com

Austria **AUT02**

17. Jakob Bachler
Contestant
jakobbachler@gmx.at

Austria **AUT03**

18. Lukas Wimmer
Contestant
lukas.wimmer.kaprun@gmail.com

Austria **AUT04**

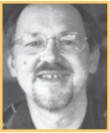
19. Julius Nicolaus Piso
Contestant
julius@piso.at

Austria **AUT05**

20. Helmuth Otto Mayr
Leader
helmuth.mayr@chello.at

Austria **AUT11**

21. Engelbert Stuetz
Leader
engelbert.stuetz@liwest.at



Austria **AUT12**

22. Sabuhi Mikayilov
Contestant

Azerbaijan **AZE01**

23. Tural Aliyev
Contestant

Azerbaijan **AZE02**

24. Farhad Allahverdiyev
Contestant

Azerbaijan **AZE03**

25. Nurlan Rzayev
Contestant

Azerbaijan **AZE04**

26. Emil Alizada
Contestant

Azerbaijan **AZE05**

27. Nagif Nabiyev
Leader
nagnew@list.ru

Azerbaijan **AZE11**

28. Rashadat Gadmaliyev
Leader
reshadqedim@gmail.com

Azerbaijan **AZE12**

29. Rashad Khamoyev
Observer

Azerbaijan AZE21

30. Arpon Paul
Contestant
arponpaul1995@gmail.com

Bangladesh BGD01

31. Avoy Datta
Contestant
avoydatta@gmail.com

Bangladesh BGD02

32. Supantho Rakshit
Contestant
sukantoraxit@gmail.com

Bangladesh BGD03

33. Mohaimenul Islam
Contestant
mohaimen_26@hotmail.com

Bangladesh BGD04

34. Dibyatanoy Bhattacharjee
Contestant
drpradipcmc@gmail.com

Bangladesh BGD05

35. M Arshad Momen
Leader
amomen@du.ac.bd

Bangladesh BGD11

36. Fayez Ahmed Jahangir Masud
Leader
jmbadsha@bdpho.org

Bangladesh BGD12

37. Bahdan Andreevich Zviazhynski
Contestant
bogdan.zvezhinskiy@mail.ru

Belarus BLR01

38. Artsiom Maksimovich Pivavarchyk
Contestant
artyompivovarchik@gmail.com

Belarus BLR02

39. Anton Igorevich Talkachov
Contestant
bloodyboy07@mail.ru

Belarus BLR03

40. Uladzislau Viktorovich Klimashonak
Contestant
klvl-1998@mail.ru

Belarus BLR04

41. Evgeni Aleksandrovich Shurygin
Contestant
zhenyavski50@gmail.com

Belarus BLR05

42. Anatoli Ivanavich Slabadzianiuk
Leader
slabadzianiuk@mail.ru

Belarus BLR11

43. Leonid Grigorjevich Markovich
Leader
markovich@bsu.by

Belarus **BLR12**

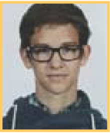
44. Florian Quatresooz
Contestant
florian.quatresooz@gmail.com

Belgium **BEL01**

45. Cédric Philippe Nicolas Schoonen
Contestant
cedric.schoonen1@gmail.com

Belgium **BEL02**

46. Keano De Vos
Contestant
Keanodevos@gmail.com



Belgium **BEL03**

47. Jakob Declercq
Contestant
jakob.declercq@hotmail.com

Belgium **BEL04**

48. Roeland Germain J. Van Haecke
Contestant
roeland.vanhaecke@live.be

Belgium **BEL05**

49. Philippe Leonard
Leader
pleonard@ulb.ac.be

Belgium **BEL11**

50. Geert Verschoren
Leader
g_verschoren@yahoo.com

Belgium **BEL12**

51. Sophie Alix Houard
Observer
pleonard@ulb.ac.be

Belgium **BEL21**

52. Michel Roger Feys
Observer
michel.feys@gmail.com

Belgium **BEL22**

53. Richard Brandon Ortuno Davila
Contestant
richardbrandon_98@hotmail.com

Bolivia **BOL01**

54. Veronica Subieta
Leader
veronica.subieta.f@gmail.com

Bolivia **BOL11**

55. Ajdin Palavric
Contestant
ajdinnl@gmail.com

Bosnia and Herzegovina **BIH01**

56. Mustafa Grabus
Contestant
mustafagrabuss@gmail.com

Bosnia and Herzegovina **BIH02**

57. Nermedin Dzekovic
Contestant
nermedin.dzekovic@gmail.com

Bosnia and Herzegovina **BIH03**

58. Bahrudin Trbalic
Contestant
bahrudin.trbalic96@gmail.com

Bosnia and Herzegovina **BIH04**

59. Naida Dedic
Contestant
naida.d96@gmail.com

Bosnia and Herzegovina **BIH05**

60. Benjamin Fetic
Leader
benjamin.fetic@gmail.com

Bosnia and Herzegovina **BIH11**

61. Nudzeim Selimovic
Leader
nudzeims@gmail.com

Bosnia and Herzegovina **BIH12**

62. Mateus Arraes Feitosa Borges
Contestant
mateusfeitosaborges@hotmail.com

Brazil **BRA01**

63. Felipe Vieira Coimbra
Contestant
felipecoimbra97@gmail.com

Brazil **BRA02**

64. Tafnes Silva Barbosa
Contestant
tafnessilvabarbosa@hotmail.com

Brazil **BRA03**

65. Felipe De Castro Silva
Contestant
felipedecastrosilva325@hotmail.com

Brazil **BRA04**

66. Delson Barros Oliveira Filho
Contestant
dede_baros@hotmail.com

Brazil **BRA05**

67. Munemasa Machida
Leader
machida@ifi.unicamp.br

Brazil **BRA11**

68. Airton Deppman
Leader
adeppman@gmail.com

Brazil **BRA12**

69. Deric De Albuquerque Simao
Observer
leonardobruno@aridesa.com.br

Brazil **BRA21**

70. Francisco Odivaldo Teixeira Júnior
Observer
teixeira.junior@fariasbrito.com.br

Brazil **BRA22**

71. Rawlinson Medeiros Ibiapina
Observer
rawlinsonibi@gmail.com

Brazil **BRA23**

72. Mario Ueda
Observer
ueda@plasma.inpe.br

Brazil **BRA24**

73. Angel Kostov Sherletov
Contestant
sherletov.angel@gmail.com

Bulgaria **BGR01**

74. Konstantin Juliyev Karchev
Contestant
kosiokarchev@gmail.com

Bulgaria **BGR02**

75. Radostin Radostinov Dimitrov
Contestant
radostinr.dimitrov@gmail.com

Bulgaria **BGR03**

76. Hristosko Dimitrov Chaushev
Contestant

Bulgaria **BGR04**

77. Boyko Ivanov Vodenicharski
Contestant
boyko_voden@abv.bg

Bulgaria **BGR05**

78. Viktor Genchev Ivanov
Leader
vgi@phys.uni-sofia.bg

Bulgaria **BGR11**

79. Miroslav Vergilov Abrashev
Leader
mvabr@phys.uni-sofia.bg

Bulgaria **BGR12**

80. Sivhuo Prak
Contestant
praksivhuo2012@yahoo.com

Cambodia **KHM01**

81. Menghour Pech
Contestant
mengourpich7777@gmail.com

Cambodia **KHM02**

82. Soviro Heng
Contestant
hsoviro11@gmail.com

Cambodia **KHM03**

83. Kim Sor Hong
Contestant
hongkimsor987@gmail.com

Cambodia **KHM04**

84. Soriya Theang
Contestant
pheakdeytheang@gmail.com

Cambodia **KHM05**

85. Chan Oeurn Chey
Leader
ch.chey@gmail.com

Cambodia **KHM11**

86. Kimleang Khun
Leader
kimleang.khunkh17@gmail.com

Cambodia **KHM12**

87. Oliver Jin Wang
Contestant
oliverjwca@gmail.com

Canada **CAN01**

88. Stephen Liu
Contestant
stephen.sc.liu@hotmail.com

Canada **CAN02**

89. Wilson Fan Wu
Contestant
wufanwilson@gmail.com

Canada **CAN03**

90. Qingyue Wu
Contestant
qwerytiop@gmail.com

Canada **CAN04**

91. Andrew Jinwook Kim
Contestant
andrew.kim2015@utschools.ca

Canada **CAN05**

92. Andrzej Kotlicki
Leader
kotlicki@phas.ubc.ca

Canada **CAN11**

93. Run Ze Cao
Leader
caodav@hotmail.com

Canada **CAN12**

94. Chantal Louise Haussmann
Visitor
chantalh@shaw.ca

Canada **CAN31**

95. Yi-Lim Tsao
Contestant
chiact@ntnu.edu.tw

Chinese Taipei **TWN01**

96. Pei-Kai Tsai
Contestant
chiact@ntnu.edu.tw

Chinese Taipei **TWN02**

97. Yu-Chia Lin
Contestant

Chinese Taipei **TWN03**

98. Chih-Hsiang Yang
Contestant

Chinese Taipei **TWN04**

99. Chung-Yao Cheng
Contestant

Chinese Taipei **TWN05**

100. Chih-Ta Chia
Leader
chiact@ntnu.edu.tw

Chinese Taipei **TWN11**

101. Shang-Fang Tsai
Leader
sfincyc@gmail.com

Chinese Taipei **TWN12**

102. Jiun-Huei Wu
Observer
jhpw@phys.ntu.edu.tw

Chinese Taipei **TWN21**

103. Chung-Yu Mou
Observer
mou@phys.nthu.edu.tw

Chinese Taipei **TWN22**

104. Chon Saar Chu
Observer
cschu@cc.nctu.edu.tw

Chinese Taipei **TWN23**

105. Yu-Lim Chen
Observer
d00222019@ntu.edu.tw

Chinese Taipei **TWN24**

106. Chun-Tao Kao
Visitor

Chinese Taipei **TWN31**

107. Daniel Sierra Botero
Contestant
d_sierra123@hotmail.com

Colombia **COL01**

108. Samuel Hoyos Aristizabal
Contestant
Shoyos97@hotmail.com

Colombia **COL02**

109. Fernando Vega Salamanca
Leader
vega.fernando@gmail.com

Colombia **COL11**

110. Eduardo Zalamea Godoy
Leader
ezalameag@unal.edu.co

Colombia **COL12**

111. Elena Patricia Losada Falk
Observer
helencilla1978@gmail.com

Colombia **COL21**

112. Juan Carlos Badilla
Guest Contestant
juanca-simpson@hotmail.com

Costa Rica **CRI01**

113. Daniel Alejandro Ballestero
Observer
daballest@gmail.com

Costa Rica **CRI21**

114. Sandra Irene Frech
Visitor
sandrafrech@yahoo.es

Costa Rica **CRI31**

115. Martin Bajzek
Contestant

Croatia **HRV01**

116. Ivan Jercic
Contestant

Croatia **HRV02**

117. Leonardo Kokot
Contestant

Croatia **HRV03**

118. Grgur Palle
Contestant

Croatia **HRV04**

119. Matej Pavlovic
Contestant

Croatia **HRV05**

120. Kreso Zadro
Leader

Croatia **HRV11**

121. Filip Toric
Leader

Croatia **HRV12**

122. Michel Romero Rodriguez
Contestant
michelcenrr@gmail.com

Cuba **CUB01**

123. Alberto Mawad Santos
Leader

Cuba **CUB11**

124. Anastasios Irakleous
Contestant
herchristos1@cytanet.com.cy

Cyprus **CYP01**

125. Nikolas Michael
Contestant
nikolas.michael@hotmail.com

Cyprus **CYP02**

126. Antigoni Avraam
Contestant
antigoneavraam@hotmail.com

Cyprus **CYP03**

127. Andreas Georgiou
Contestant
andreasg.g3@gmail.com

Cyprus **CYP04**

128. Demetrios Philippou
Leader
phildem@cytanet.com.cy

Cyprus **CYP11**

129. Antreas Antoniou
Leader
antreas.antoniou@ymail.com

Cyprus **CYP12**

130. Vaclav Miratsky
Contestant

Czech Republic **CZE01**

131. Jakub Dolejsi
Contestant

Czech Republic **CZE02**

132. Jiri Kucera
Contestant

Czech Republic **CZE03**

133. Filip Bialas
Contestant

Czech Republic **CZE04**

134. Vaclav Rozhon
Contestant

Czech Republic **CZE05**

135. Jan Kriz
Leader

Czech Republic **CZE11**

136. Filip Studnicka
Leader
filip.studnicka@uhk.cz

Czech Republic **CZE12**

137. Asbjoern Baekgaard Lauritsen
Contestant

Denmark **DNK01**

138. Daniel Luo
Contestant

Denmark **DNK02**

139. Mads Holmark Vandborg
Contestant

Denmark **DNK03**

140. Svend Kroejer Moeller
Contestant

Denmark **DNK04**

141. Frederik Orm Hansen
Contestant

Denmark **DNK05**

142. Henrik Bruus
Leader

Denmark **DNK11**

143. Niels Erik Wegge
Leader
niels.wegge@gmail.com

Denmark **DNK12**

144. Jacob Gade Koefoed
Observer

Denmark **DNK21**

145. Markus Emil Jacobsen
Observer

Denmark **DNK22**

146. Afnan Khaled Elhamshari
Contestant
Afnan.elhamshary@stemmaadi.edu.eg

Egypt **EGY01**

147. Abdelwahab Mohamed
Contestant
abdel-wahab10010@stemegypt.edu.eg

Egypt **EGY02**

148. Mohamed Ahmed Elsharnouby
Contestant
mohamed92010@stemegypt.edu.eg

Egypt **EGY03**

149. Ahmed Hussein
Contestant
ahmed35010@stemegypt.edu.eg

Egypt **EGY04**

150. Samy Farrag
Contestant
sami135010@stemegypt.edu.eg

Egypt **EGY05**

151. Ekhlas Ahmed
Leader
ekhlas@ideasgym.com

Egypt **EGY11**

152. Salaheldin Elsabagh
Leader

Egypt **EGY12**

153. José Manuel Escalante Castro
Contestant
josem.9904@gmail.com

El Salvador **SLV01**

154. Alicia Alejandra Cortez
Contestant
aly_cortez@hotmail.com

El Salvador **SLV02**

155. Rodrigo Emilio Pérez Ortiz
Contestant
rodrigoep.ortiz@gmail.com

El Salvador **SLV03**

156. Ignacio Alfonso González Oliva
Leader
iagogonz92@gmail.com

El Salvador **SLV11**

157. Taavet Kalda
Contestant
taavet.kalda@gmail.com

Estonia **EST01**

158. Kristjan Kongas
Contestant
kongaskristjan@gmail.com

Estonia **EST02**

159. Kaarel Hänni
Contestant
kaarelh@gmail.com

Estonia **EST03**

160. Jonatan Kalmus
Contestant
jonatan.kalmus@gmail.com

Estonia **EST04**

161. Hans Daniel Kaimre
Contestant
hans.daniel15@gmail.com

Estonia **EST05**

162. Mihkel Kree
Leader
mihkel.kree@gmail.com

Estonia **EST11**

163. Siim Ainsaar
Leader
ainsaar@gmail.com

Estonia **EST12**

164. Timo Iiro Ilmari Takala
Contestant
timotakala95@gmail.com

Finland **FIN01**

165. Iiro Johannes Sallinen
Contestant
sallinen.iiro@gmail.com

Finland **FIN02**

166. Arttu Otto Benjamin Tolvanen
Contestant
arttu.tolvanen@hushmail.com

Finland **FIN03**

167. Tuomas Petteri Oikarinen
Contestant
tuomas.oikarinen@live.fi

Finland **FIN04**

168. Joonatan Bergholm
Contestant

Finland **FIN05**

169. Lasse Aatos Franti
Leader
lasse.franti@helsinki.fi

Finland **FIN11**

170. Matti Johannes Vaisanen
Leader
matti.vaisanen@jyu.fi

Finland **FIN12**

171. Moïse Jean-Baptiste Blanchard
Contestant
moise.blanchard@free.fr

France **FRA01**

172. Pierre Richard Samir Côte De Soux
Contestant
pcds@live.fr

France **FRA02**

173. Hugues Déprés
Contestant
dehug@free.fr

France **FRA03**

174. Paul Emmanuel Robin
Contestant
paul.emmanuel.robin@free.fr

France **FRA04**

175. Marine Schimel
Contestant
marine.schimel@hotmail.fr

France **FRA05**

176. Dominique Marcel Obert
Leader
dominique.obert@education.gouv.fr

France **FRA11**

177. Isabelle Claude Daumont
Leader
idaumont@msn.com

France **FRA12**

178. Nicolas Schlosser
Observer
nicolas.schlosser@louislegrand.eu

France **FRA21**

179. Arsenadze Giorgi
Contestant
g.arsenadze@gmail.com

Georgia **GEO01**

180. Bakhtadze Giorgi
Contestant
george-bakhtadze@live.com

Georgia **GEO02**

181. Sokhashvili Mikheil
Contestant
m.sokhashvili@yahoo.com

Georgia **GEO03**

182. Tsereteli Giorgi
Contestant
abcgiotsero@gmail.com

Georgia **GEO04**

183. Mdinaradze Nikoloz
Contestant
nmdi1997@gmail.com

Georgia **GEO05**

184. Vladimir Paverman
Leader
vladpav@mail.ru

Georgia **GEO11**

185. Tsimakuridze Nikoloz
Leader
n.tsimakuridze@freeuni.edu.ge

Georgia **GEO12**

186. Dalakishvili Giorgi
Observer
giorgi.dalakishvili@iliauni.edu.ge

Georgia **GEO21**

187. Georg Dieter Michael Benno Christoph Berger
Contestant
georg.berger.97@gmail.com

Germany **DEU01**

188. Vincent Peter Grande
Contestant
vincentp.grande@gmail.com

Germany **DEU02**

189. Friedrich Uwe Hübner
Contestant
huebnerfriedrich@freenet.de

Germany **DEU03**

190. Sven Jandura
Contestant
sven.jandura@gmail.com

Germany **DEU04**

191. Arne Christian Wolf
Contestant
Arne.Wolf5@web.de

Germany **DEU05**

192. Stefan Petersen
Leader
petersen@ipn.uni-kiel.de

Germany **DEU11**

193. Peter Wulff
Leader
wulff@ipn.uni-kiel.de

Germany **DEU12**

194. Zoi Tsangalidou
Contestant
zoitsangalidoy@gmail.com

Greece **GRC01**

195. Menelaos Papadopoulos
Contestant
papadopoulosmen97@gmail.com

Greece **GRC02**

196. Fotios Siammenos
Contestant
fotistg@gmail.com

Greece **GRC03**

197. Andreas Panagiotis Tzortzakakis
Contestant
andtzortzakakis@gmail.com

Greece
GRC04

198. Filippos Lymperopoulos-Bountalis
Contestant
phillybero@gmail.com

Greece
GRC05

199. Georgios Kalkanis
Leader
kalkanis@primedu.uoa.gr

Greece
GRC11

200. Panagiotis Tsakonas
Leader
ptsakon@gmail.com

Greece
GRC12

201. Gkikopoulou Ourania
Observer
gikopoulou@gmail.com

Greece
GRC21

202. Shun Leung Frankie Lam
Contestant
frankiesllam@yahoo.com

Hong Kong
HKG01

203. Ching Yin Lui
Contestant
frankiebrianlui@hgcbroadband.com

Hong Kong
HKG02

204. Wai Ting Tai
Contestant
waiting19991115@yahoo.com.hk

Hong Kong
HKG03

205. Yat Wong
Contestant
apollo@eastop.com

Hong Kong
HKG04

206. Yuk Wong
Contestant
asia@eastop.com

Hong Kong
HKG05

207. Wing Yim Tam
Leader
phtam@ust.hk

Hong Kong
HKG11

208. Kwok Yee Michael Wong
Leader
phkywong@ust.hk

Hong Kong
HKG12

209. Oi Kwan Lam
Observer
phsandy@ust.hk

Hong Kong
HKG21

210. Jun He
Observer
jheaa@ust.hk

Hong Kong
HKG22

211. Kam Tuen Law
Observer
phlaw@ust.hk

Hong Kong
HKG23

212. Yilong Han
Observer
yilong@ust.hk

Hong Kong
HKG24

213. Menyhert Balogh
Contestant
meno.balo@gmail.com

Hungary
HUN01

214. Andras Holczer
Contestant
holczerandris@gmail.com

Hungary
HUN02

215. Botond Oreg
Contestant
oregb@yahoo.com

Hungary
HUN03

216. Kristof Sal
Contestant
sal.kristof@gmail.com

Hungary
HUN04

217. Tamas Lajos Tompa
Contestant
tompatamas98@gmail.com

Hungary
HUN05

218. Peter Vanko
Leader
vanko@mono.eik.bme.hu

Hungary
HUN11

219. Mate Vigh
Leader
vighmate@gmail.com

Hungary
HUN12

220. Krisztian Szasz
Observer
szaszkri@gmail.com

Hungary
HUN21

221. Kristín Björg Bergþórsdóttir
Contestant
kristinbjorg95@gmail.com

Iceland
ISL01

222. Valtýr Kári Daníelsson
Contestant
vltrkri8@gmail.com

Iceland
ISL02

223. Matthías Baldursson Harksen
Contestant
matthias.harksen@gmail.com

Iceland
ISL03

224. Gunnlaugur Helgi Stefánsson
Contestant
ghs11@mr.is

Iceland
ISL04

225. Runar Unnsteinsson
Contestant
runar.u51@gmail.com

Iceland **ISL05**

226. Vidar Agustsson
Leader
vidaragustss@gmail.com

Iceland **ISL11**

227. Sigtryggur Hauksson
Leader
sih65@hi.is

Iceland **ISL12**

228. Thorbjorg Helga Hilmarsdottir
Visitor
helgahilmars@gmail.com

Iceland **ISL31**

229. Anuj Shripad Apte
Contestant

India **IND01**

230. Arindam Sonali Amar Bhattacharya
Contestant

India **IND02**

231. Gowtham Amrithya Neppoleon
Contestant

India **IND03**

232. Sri Eshwar Sai Prakash Reddy Pabatireddy
Contestant

India **IND04**

233. Sheshansh Agrawal
Contestant

India **IND05**

234. Subhash Chandra Samanta
Leader

India **IND11**

235. Patrick Das Gupta
Leader

India **IND12**

236. Mukund Laxman Ogalapurkar
Observer
ogalapurkar@yahoo.com

India **IND21**

237. Ravi Shankar Bhattacharjee
Observer
ravi_bhattacharjee@yahoo.co.in

India **IND22**

238. Ratnakar Madhusudan Dharkar
Observer

India **IND23**

239. Pramendra Ranjan Singh
Observer

India **IND24**

240. Deepak Chandra
Visitor

India **IND31**

241. Mita Choudhury
Visitor

India **IND32**

242. Hugo Herdianto
Contestant
hugoherdianto@yahoo.com

Indonesia **IDN01**

243. Kevin Liminta
Contestant
kl.kevinlimanta@gmail.com

Indonesia **IDN02**

244. Jaswin Jaswin
Contestant
jaswin1998@yahoo.com

Indonesia **IDN03**

245. Rhesa Edrick Tendean
Contestant
rhesa.tendean@gmail.com

Indonesia **IDN04**

246. Jason Kristiano
Contestant
jasonjk22@gmail.com

Indonesia **IDN05**

247. Mohammad Syamsu Rosid
Leader
s_rosid@yahoo.com

Indonesia **IDN11**

248. Bobby Eka Gunara
Leader
bobby@fi.itb.ac.id

Indonesia **IDN12**

249. Rinto Anugraha Nur Qomaru Zaman
Observer
rinto@ugm.ac.id

Indonesia **IDN21**

250. Eko Warisdiono
Visitor
eko_warisdiono@yahoo.com

Indonesia **IDN31**

251. Seyed Mohammad Javad Tabatabaei Yazdi
Contestant

Islamic Republic of Iran **IRN01**

252. Mohammadali Khademsohi
Contestant

Islamic Republic of Iran **IRN02**

253. Mohammadhossein Darestanifarahani
Contestant

Islamic Republic of Iran **IRN03**

254. Ali Shirali
Contestant

Islamic Republic of Iran **IRN04**

255. Ali Fathi
Contestant

Islamic Republic of Iran **IRN05**

256. Ahmad Shirzad
Leader
shirzad@mail.ipm.ir

Islamic Republic of Iran **IRN11**

257. Ayoub Esmail Pour
Leader
esmailpour@iust.ac.ir

Islamic Republic of Iran **IRN12**

258. Mehdi Saadat
Observer
mehsaa@yahoo.com

Islamic Republic of Iran **IRN21**

259. Hamidreza Mokhtarnezhadarabi
Visitor

Islamic Republic of Iran **IRN31**

260. Ilan Mitnikov
Contestant
igfgr2@gmail.com

Israel **ISR01**

261. Morane Shapira
Contestant
rani_shapira@yahoo.com

Israel **ISR02**

262. Nir Jacob Yaron
Contestant
njyaron@gmail.com

Israel **ISR03**

263. Shaked Rosenstein
Contestant
shakedrosenstein@gmail.com

Israel **ISR04**

264. Tom Segal
Contestant
tomsegal10@gmail.com

Israel **ISR05**

265. Eli Raz Somech
Leader
raz@tx.technion.ac.il

Israel **ISR11**

266. Pavel Radzivilovsky
Leader
bugpwr@gmail.com

Israel **ISR12**

267. Itamar Hason
Observer
itamarhason@gmail.com

Israel **ISR21**

268. Simone Bombari
Contestant
simone.bombari@yahoo.it

Italy **ITA01**

269. Andrea Ferrario
Contestant
andreaferrario@sec.cnnet.it

Italy **ITA02**

270. Pietro Pelliconi
Contestant
pietropelliconi@gmail.com

Italy **ITA03**

271. Giovanni Maria Tomaselli
Contestant
gimmytomas@gmail.com

Italy **ITA04**

272. Fabio Zoratti
Contestant
fabio.zoratti96@gmail.com

Italy **ITA05**

273. Dennis Luigi Censi
Leader
dl.censi@gmail.com

Italy **ITA11**

274. Franco Bocci
Leader
franco.bocci@gmail.com

Italy **ITA12**

275. Silvano Sgrignoli
Observer
SISGRI@GMAIL.COM

Italy **ITA21**

276. Hajime Ueda
Contestant
zituhabuturikennkyuubuinndesu@gmail.com

Japan **JPN01**

277. Hideharu Kashu
Contestant
hkashu98@gmail.com

Japan **JPN02**

278. Hiroto Takahashi
Contestant
hrttkhsh@gmail.com

Japan **JPN03**

279. Satoshi Yoshida
Contestant
satoshi.yoshida@gaia.eonet.ne.jp

Japan **JPN04**

280. Akihiro Watanabe
Contestant
mnaklpon@m5.kcn.ne.jp

Japan **JPN05**

281. Tadao Sugiyama
Leader
tsugi49@ybb.ne.jp

Japan **JPN11**

282. Susumu Fukatsu
Leader
cfkatz@mail.ecc.u-tokyo.ac.jp

Japan **JPN12**

283. Hiromasa Nakatsuka
Observer
hiroatpcshiyoutyu@gmail.com

Japan **JPN21**

284. Sho Higashikawa
Observer
higashikawa@cat.phys.s.u-tokyo.ac.jp

Japan **JPN22**

285. Shuhei Yoshida
Observer
yoshida@cat.phys.s.u-tokyo.ac.jp

Japan **JPN23**

286. Tsutomu Nakayashiki
Observer
nakayask@po.harenet.ne.jp

Japan **JPN24**

287. Temirlan Ulugbek Uulu
Contestant

Kyrgyzstan **KGZ01**

288. Nurbek Baizakov
Contestant

Kyrgyzstan **KGZ02**

289. Uran Maimekov
Contestant

Kyrgyzstan **KGZ03**

290. Mikhail Gubarenko
Contestant

Kyrgyzstan **KGZ04**

291. Aizada Nurdinova
Contestant

Kyrgyzstan **KGZ05**

292. Raia Sultanalieva
Leader
raia-ktu@mail.ru

Kyrgyzstan **KGZ11**

293. Ainur Konushbaeva
Leader
aikat80@mail.ru

Kyrgyzstan **KGZ12**

294. Rudolfs Treilis
Contestant
rudolfstr@gmail.com

Latvia **LVA01**

295. Helvijs Sebris
Contestant
helvijs.sebris@gmail.com

Latvia **LVA02**

296. Daniels Krimans
Contestant
danielskrimans@inbox.lv

Latvia **LVA03**

297. Valdis Mizers
Contestant
vami3@inbox.lv

Latvia **LVA04**

298. Reinis Irmejs
Contestant
reinisirmejs@gmail.com

Latvia **LVA05**

299. Vjaceslavs Kascejevs
Leader
slava@latnet.lv

Latvia **LVA11**

300. Sandris Lacis
Leader
sandris.lacis@lu.lv

Latvia **LVA12**

301. Fritz Epple
Observer
epple.fritz@lg-vaduz.li

Liechtenstein **LIE21**

302. Daniel Oehry
Observer
oehry.daniel@lg-vaduz.li

Liechtenstein **LIE22**

303. Tadas Indrele
Contestant

Lithuania **LTU01**

304. Gintautas Kamuntavicius
Contestant

Lithuania **LTU02**

305. Vytautas Strimaitis
Contestant

Lithuania **LTU03**

306. Jonas Virsilas
Contestant

Lithuania **LTU04**

307. Elvinas Ribinskas
Contestant

Lithuania **LTU05**

308. Pavelas Bogdanovicius
Leader

Lithuania **LTU11**

309. Edmundas Kuokstis
Leader

Lithuania **LTU12**

310. Liliana Rukiene
Observer

Lithuania **LTU21**

311. Lam Lam
Contestant
annabella.vcl@gmail.com

Macao-China **MAC01**

312. Kin Ian Lo
Contestant
keonlo123@gmail.com

Macao-China **MAC03**

313. Ka Seng Ng
Contestant
foreverphysical141@gmail.com

Macao-China **MAC04**

314. Iat Neng Chan
Leader

Macao-China **MAC11**

315. Chon-Fai Kam
Leader

Macao-China **MAC12**

316. Dejan Maksimovski
Contestant
dejan_maksimovski@yahoo.com

Macedonia **MKD01**

317. Dragan Trajchev
Contestant
dragan_trajchev97@yahoo.com

Macedonia **MKD02**

318. Filip Mitrovski
Contestant
mitrovskifilip@gmail.com

Macedonia **MKD03**

319. Dejan Pejchinoski
Contestant
pejchinoskidejan@yahoo.com

Macedonia **MKD04**

320. Sofija Dimoska
Contestant
sofijadimoo@yahoo.com

Macedonia **MKD05**

321. Stanisha Veljkovikj
Leader
stanisha.velkovic@ykc.edu.mk

Macedonia **MKD11**

322. Lambe Barandovski
Leader
lambe@pmf.ukim.mk

Macedonia **MKD12**

323. Ming Yi Lee
Contestant
leemingyi136@gmail.com

Malaysia **MYS01**

324. Khee Ing Marcus Leong
Contestant
marcusleong96@hotmail.com

Malaysia **MYS02**

325. Jer Yong Chan
Contestant
chanjeryong@live.com

Malaysia **MYS03**

326. Yi Jie Ong
Contestant
y.j.o@hotmail.com

Malaysia **MYS04**

327. Farish Mohd Ismail
Contestant
farish.ismail@gmail.com

Malaysia **MYS05**

328. Mai Ying Chin
Leader
cmaiying@hotmail.com

Malaysia **MYS11**

329. Wan Mohd Aimran Wan Mohd Kamil
Leader
aimran@ukm.edu.my

Malaysia **MYS12**

330. Gerardo Javier Valdez Lozano
Contestant
gera_m4a1@hotmail.com

Mexico **MEX01**

331. Jesús Alejandro González Sánchez
Contestant
zzz12300212@gmail.com

Mexico **MEX02**

332. Alfonso Santacruz García
Contestant
ponchosg96@gmail.com

Mexico **MEX03**

333. Fernando Ballesteros Flores
Contestant
ferballe98@hotmail.com

Mexico **MEX04**

334. Demian Ulises Hernández Rendón
Contestant
duhr1997@outlook.com

Mexico **MEX05**

335. Erick Leonardo Patiño Jaidar
Leader
leopj@ciencias.unam.mx

Mexico **MEX11**

336. Eleazar Neri Medina
Leader
eleazarneri@gmail.com

Mexico **MEX12**

337. Didier Omar Gamboa Angulo
Observer
didier.gamboa@gmail.com

Mexico **MEX21**

338. Alejandro Cagliostro Lara Neave
Observer
alara@fcfm.uanl.mx

Mexico **MEX22**

339. Edgar Andrés Sánchez García
Observer
edgarandres@fisica.unam.mx

Mexico **MEX23**

340. Francisco Javier Ayala Falcón
Observer
fayala@ipn.mx

Mexico **MEX24**

341. Gleb Vizitiv
Contestant
glebvizitiv@gmail.com

Moldova **MDA01**

342. Romina Dolgopol
Contestant
romina.dolgopol@yahoo.com

Moldova **MDA02**

343. Laurentiu Calancea
Contestant
calancea.laurent@gmail.com

Moldova **MDA03**

344. Alexandru Cotos
Contestant
cotosalexandru@yahoo.com

Moldova **MDA04**

345. Eugeniu Dimitriu
Contestant
eudimitriu@mail.ru

Moldova **MDA05**

346. Victor Paginu
Leader
victorpaganu@gmail.com

Moldova **MDA11**

347. Igor Evtodiev
Leader
ievtodiev@yahoo.com

Moldova **MDA12**

348. Tugsbayasgalan Manlaibaatar
Contestant
bbtgn@num.edu.mn

Mongolia **MNG01**

349. Bat-Orgil Bayar
Contestant
bbtgn@num.edu.mn

Mongolia **MNG02**

350. Banzragch Dolgormaa
Contestant
bbtgn@num.edu.mn

Mongolia **MNG03**

351. Tserenchimeg Khasgerel
Contestant
bbtgn@num.edu.mn

Mongolia **MNG04**

352. Turtsetseg Nanjid
Contestant
bbtgn@num.edu.mn

Mongolia **MNG05**

353. Ganbat Munkhuu
Leader
ganbatmunkhuu@yahoo.com

Mongolia **MNG11**

354. Bat-Otgon Bat-Ochir
Leader
bbtgn@num.edu.mn

Mongolia **MNG12**

355. Tsookhuu Khinayat
Observer
bbtgn@num.edu.mn

Mongolia **MNG21**

356. Ulam-Orgikh Duger
Observer
ulamorgikh@gmail.com

Mongolia **MNG22**

357. Andrija Rasovic
Contestant
andrijarasovic@gmail.com

Montenegro **MNE01**

358. Danilo Pejovic
Contestant
danilopejovic@rocketmail.com

Montenegro **MNE02**

359. Predrag Miranovic
Leader
pedjam@ac.me

Montenegro **MNE11**

360. Tatijana Carapic
Leader
tatijana.carapic@iccg.edu.me

Montenegro **MNE12**

361. Bibek Kumar Pandit
Contestant
bibekandpandit@outlook.com

Nepal **NPL01**

362. Prabhat Devkota
Contestant
prabhatdevkota@gmail.com

Nepal **NPL02**

363. Satish Wasti
Contestant
smartwastisatish@gmail.com

Nepal **NPL03**

364. Ayush Kumar Shah
Contestant
ayush.kumar.shah@gmail.com

Nepal **NPL04**

365. Ajay Mishra
Contestant
Ajaymshr123@gmail.com

Nepal **NPL05**

366. Jeevan Jyoti Nakarmi
Leader
nakarmijj@gmail.com

Nepal **NPL11**

367. Bablu Kant Thakur
Leader
thakurbablukant@gmail.com

Nepal **NPL12**

368. Christian Primavera
Contestant
christian.primavera@gmail.com

Netherlands **NLD01**

369. Ewoud Wempe
Contestant
ewoudwempe@hotmail.com

Netherlands **NLD02**

370. David Liu
Contestant
Davindi09@gmail.com

Netherlands **NLD03**

371. Pepijn De Maat
Contestant
Pepijn.de.maat@planet.nl

Netherlands **NLD04**

372. Ethan Van Woerkom
Contestant
ethanvanwoerkom@yahoo.com

Netherlands **NLD05**

373. Arie Mooldijk
Leader
a.h.mooldijk@uu.nl

Netherlands **NLD11**

374. Jan Enno Van Der Laan
Leader
J.E.van.der.Laan@rug.nl

Netherlands **NLD12**

375. Bamidele Andrae Ayomide
Contestant

Nigeria **NGA01**

376. Ebubechi Emmanuel Ezenwanne
Contestant
ayhan7@hotmail.com

Nigeria **NGA02**

377. Mitchell Chukwuebuka Okoli
Contestant
ayhan7@hotmail.com

Nigeria **NGA03**

378. David Bayode Oyinbo
Contestant
ayhan7@hotmail.com

Nigeria **NGA04**

379. Oghenetega Wisdom Oguns
Contestant
ayhan7@hotmail.com

Nigeria NGA05

380. Ayhan Yaman
Leader
ayhan7@hotmail.com

Nigeria NGA11

381. Lewis Obagboye
Leader
lewisgboye@yahoo.com

Nigeria NGA12

382. Okike Okorie
Observer
ayhan7@hotmail.com

Nigeria NGA21

383. Nelson Ebi Omomo
Observer
ayhan7@hotmail.com

Nigeria NGA22

384. Vincent Nwabufochukwu Egwuatu
Observer
ayhan7@hotmail.com

Nigeria NGA23

385. Peter Poleszynski Hoel
Contestant

Norway NOR01

386. Peter Erdmann Dougherty
Contestant

Norway NOR02

387. Eilif Tandberg Swensen
Contestant

Norway NOR03

388. Martin Aria Mojahed
Contestant

Norway NOR04

389. Mikal Solberg Stapnes
Contestant

Norway NOR05

390. Torbjoern Mehl
Leader
mestern@online.no

Norway NOR11

391. Thomas Fraagaat
Leader
Thomas.Fragat@jessheim.vgs.no

Norway NOR12

392. Nicole Rynning Rezende
Visitor

Norway NOR31

393. Noor Ul Huda
Contestant
noorulhuda409@yahoo.com

Pakistan PAK01

394. Talha Irfan Khawaja
Contestant
tlh.irfan@gmail.com

Pakistan PAK02

395. Tabish Saeed
Contestant
tabishsaeed255@gmail.com

Pakistan PAK03

396. Zaid Hassan Chaudhry
Contestant
zaidhassanch@gmail.com

Pakistan PAK04

397. Bushra Mansoor
Contestant
bushramansoor2010@hotmail.com

Pakistan PAK05

398. Fazal Badshah
Leader
fazal.badshah@comsats.edu.pk

Pakistan PAK11

399. Ahmer Naweed
Leader
ahmer_naweed@comsats.edu.pk

Pakistan PAK12

400. Deng Pan
Contestant
735361168@qq.com

People's Republic of China CHN01

401. Xinyu Wang
Contestant
1285443500@qq.com

People's Republic of China CHN02

402. Chenxing Zhang
Contestant
FYHHYYB@126.com

People's Republic of China CHN03

403. Jingyu Zhao
Contestant
zhaojingyu1@126.com

People's Republic of China CHN04

404. Lingbang Zhu
Contestant
1120166529@qq.com

People's Republic of China CHN05

405. Feng Song
Leader
fsong@nankai.edu.cn

People's Republic of China CHN11

406. Lisa Liu
Leader
lisaliu@nankai.edu.cn

People's Republic of China CHN12

407. Tianhao Zhang
Observer
Zhangth@nankai.edu.cn

People’s Republic of China **CHN21**

408. Yiding Sun
Observer
18802205592@139.com

People’s Republic of China **CHN22**

409. Adam Sebastian Kucz
Contestant
acalc79@gmail.com

Poland **POL01**

410. Stanislaw Pawel Kurdzialek
Contestant
kurdzialek@gmail.com

Poland **POL02**

411. Rafal Ernest Cwiek
Contestant
rav.cwiek@gmail.com

Poland **POL03**

412. Jan Krzysztof Marucha
Contestant
jkmarucha@gmail.com

Poland **POL04**

413. Piotr Krzysztof Kubala
Contestant
pkua.log@gmail.com

Poland **POL05**

414. Jan Mostowski
Leader
mosto@ifpan.edu.pl

Poland **POL11**

415. Jacek Andrzej Jasiak
Leader
Jacek.Jasiak@fuw.edu.pl

Poland **POL12**

416. André Miguel Gomes Pereira Lello De Almeida
Contestant
andre.lello@hotmail.com

Portugal **PRT01**

417. David José Simões Pereira
Contestant
davidpereira_3@hotmail.com

Portugal **PRT02**

418. José Guilherme Boura De Matos
Contestant
ze.boura@gmail.com

Portugal **PRT03**

419. João Carlos Lourenço Antunes
Contestant
j.c.l.a.3114@gmail.com

Portugal **PRT04**

420. Grégory François Xavier Laetitia Boneart
Contestant
gregory_bonaert@hotmail.com

Portugal **PRT05**

421. Fernando Nogueira
Leader
fnog@uc.pt

Portugal **PRT11**

422. Rui Davide Martins Travasso
Leader
rui@teor.fis.uc.pt

Portugal **PRT12**

423. Carlos Alberto Gonçalves De Azevedo
Observer
karlos_azevedo@netcabo.pt

Portugal **PRT21**

424. Jose Manuel Ortiz Tavarez
Contestant

Puerto Rico **PRI01**

425. Hector Jesus Jimenez
Leader

Puerto Rico **PRI11**

426. Ayan Segizbay
Contestant
daryn.intal@gmail.com

Republic of Kazakhstan **KAZ01**

427. Anton Sedletskiy
Contestant
daryn.intel@gmail.com

Republic of Kazakhstan **KAZ02**

428. Adilkhan Sarsen
Contestant
daryn.intel@gmail.com

Republic of Kazakhstan **KAZ03**

429. Khalykbek Yelshibekov
Contestant
daryn.intel@gmail.com

Republic of Kazakhstan **KAZ04**

430. Daulet Kurmantayev
Contestant
daryn.intel@gmail.com

Republic of Kazakhstan **KAZ05**

431. Yernur Rysmagambetov
Leader
daryn.intel@gmail.com

Republic of Kazakhstan **KAZ11**

432. Pavel Levchenko
Leader
daryn.intel@gmail.com

Republic of Kazakhstan **KAZ12**

433. Sol Kim
Contestant
ddwonos@naver.com

Republic of Korea **KOR01**

434. Joonhwi Kim
Contestant
aurora9836@naver.com

Republic of Korea **KOR02**

435. Taehyoung Kim
Contestant
aqweds@naver.com

Republic of Korea **KOR03**

436. Seou Choi
Contestant
jasonwj777@naver.com

Republic of Korea **KOR04**

437. Hyunsoo Ha
Contestant
cielosjr@naver.com

Republic of Korea **KOR05**

438. Dongryul Jeon
Leader
jeon@snu.ac.kr

Republic of Korea **KOR11**

439. Moohee Lee
Leader
mhlee@konkuk.ac.kr

Republic of Korea **KOR12**

440. Gunsang Jeon
Observer
gsjeon@ewha.ac.kr

Republic of Korea **KOR21**

441. Jaewan Kim
Observer
jwkim@mju.ac.kr

Republic of Korea **KOR22**

442. Dohyeong Jang
Observer
dogyya@snu.ac.kr

Republic of Korea **KOR23**

443. Seungyeon Han
Observer
fortuniche@msip.go.kr

Republic of Korea **KOR24**

444. Hyangsuk Cho
Visitor
hscho@kofac.re.kr

Republic of Korea **KOR31**

445. Darren Chua
Contestant
darrencys98@gmail.com

Republic of Singapore **SGP01**

446. Garett Tok
Contestant
garettok@hotmail.com

Republic of Singapore **SGP02**

447. Joel Tan
Contestant
joeltansq@gmail.com

Republic of Singapore **SGP03**

448. Joshua Lim
Contestant
joshuayklim@gmail.com

Republic of Singapore **SGP04**

449. Peter Yuen
Contestant
ppeetteerrsx@gmail.com

Republic of Singapore **SGP05**

450. Rajdeep Singh Rawat
Leader
rajdeep.rawat@nie.edu.sg

Republic of Singapore **SGP11**

451. Nidhi Sharma
Leader
phyns@nus.edu.sg

Republic of Singapore **SGP12**

452. Tze Kwang Leong
Observer
leongtzekwang@gmail.com

Republic of Singapore **SGP21**

453. Fabiola Bernadette Lip
Observer
fabiola_lip_ys@acjc.edu.sg

Republic of Singapore **SGP22**

454. Dan Stefan Eniceicu
Contestant
stefaneniceicu@yahoo.com

Romania **ROU01**

455. Ileana Rugina
Contestant
rugina.ileana@yahoo.com

Romania **ROU02**

456. Tudor Costel Cretu
Contestant
cretutudor97@yahoo.com

Romania **ROU03**

457. Cristian Alexandru Frunza
Contestant
christian95e@gmail.com

Romania **ROU04**

458. Razvan-Octavian Radu
Contestant
razvan_radu57@yahoo.com

Romania **ROU05**

459. Delia Constanta Davidescu
Leader
davdelia@yahoo.com

Romania **ROU11**

460. Adrian Dafinei
Leader
asdafinei@yahoo.com

Romania **ROU12**

461. Sebastian Dumitru Popescu
Observer
seba@uaic.ro

Romania **ROU21**

462. Kirill Voronin
Contestant
k251097@yandex.ru

Russia **RUS01**

463. Aleksei Krasnikov
Contestant
krasnikov138@yandex.ru

Russia **RUS02**

464. Ivan Uteshev
Contestant
uteshevia@gmail.com

Russia **RUS03**

465. Dmitrii Tatarkin
Contestant
fizika-mat@mail.ru

Russia **RUS04**

466. Georgii Korepanov
Contestant
gkorepanov.gk@gmail.com

Russia **RUS05**

467. Mikhail Osin
Leader
miosin@yandex.ru

Russia **RUS11**

468. Artem Voronov
Leader
voronov.aa@mipt.ru

Russia **RUS12**

469. Vitaly Shevchenko
Observer
shevchenkovitaly@gmail.com

Russia **RUS21**

470. Alexey Gudenko
Observer
a.v.gudenko@gmail.com

Russia **RUS22**

471. Faisal Fahad Alsaif
Contestant

Saudi Arabia **SAU01**

472. Faour Fadl Faour
Contestant

Saudi Arabia **SAU02**

473. Nawaf Turki Alotaibi
Contestant

Saudi Arabia **SAU03**

474. Mohammed Eidha Al Wazeenani
Contestant

Saudi Arabia **SAU04**

475. Abdulmalik Hesham Al Ghonaim
Contestant

Saudi Arabia **SAU05**

476. Abdullah Ibrahim Aljaafari
Leader

Saudi Arabia **SAU11**

477. Jaan Kalda Kalda
Leader

Saudi Arabia **SAU12**

478. Mohammed Saeed Barziq
Observer

Saudi Arabia **SAU21**

479. Zeidan Mahd Zeidan Zeidan Mahd Zeidan
Observer

Saudi Arabia **SAU22**

480. Adel Mohammed Alghadr
Observer

Saudi Arabia **SAU23**

481. Dusan Novicic
Contestant
dnovicic1@gmail.com

Serbia **SRB01**

482. Janko Sustersic
Contestant
janko.sustersic@gmail.com

Serbia **SRB02**

483. Marija Sindik
Contestant
masasindik@gmail.com

Serbia **SRB03**

484. Zeljko Arsic
Contestant
zeljkoarsic1996@gmail.com

Serbia **SRB04**

485. Radoica Draskic
Contestant
r.draskic@gmail.com

Serbia **SRB05**

486. Mico Mitrovic
Leader
mico@ff.bg.ac.rs

Serbia **SRB11**

487. Vladimir Markovic
Leader
vmarkovic@kg.ac.rs

Serbia **SRB12**

488. Jelena Markovic
Visitor
jelena.etsntesla@gmail.com

Serbia **SRB31**

489. David Bugar
Contestant
bugard@citromail.hu

Slovakia **SVK01**

490. Martin Gazo
Contestant
gm.martingazo@gmail.com

Slovakia **SVK02**

491. Miroslav Gasparek
Contestant
mirec95@yahoo.com

Slovakia **SVK03**

492. Filip Ayazi
Contestant
filipayazi@gmail.com

Slovakia **SVK04**

493. Jozef Bucko
Contestant
jo_bu@windowslive.com

Slovakia **SVK05**

494. Ivo Cap
Leader
ivo.cap@fel.uniza.sk

Slovakia **SVK11**

495. Lubomir Konrad
Leader
lubomir.konrad@gmail.com

Slovakia **SVK12**

496. Klara Capova
Observer
klara.capova@fel.uniza.sk

Slovakia **SVK21**

497. Tomaz Cvetko
Contestant

Slovenia **SVN01**

498. Jakob Jazbec
Contestant

Slovenia **SVN02**

499. Aleksej Jurca
Contestant

Slovenia **SVN03**

500. Blaz Karner
Contestant

Slovenia **SVN04**

501. Zan Kokalj
Contestant

Slovenia **SVN05**

502. Jurij Bajc
Leader
jurij.bajc@pef.uni-lj.si

Slovenia **SVN11**

503. Barbara Rovsek
Leader
barbara.rovsek@pef.uni-lj.si

Slovenia **SVN12**

504. Tashic Nataal
Contestant
tashicmaharaj@gmail.com

South Africa **ZAF01**

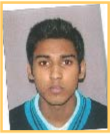
505. Damien Lawrence Naidoo
Contestant
damiennaidoo1999@gmail.com

South Africa **ZAF02**

506. Ulrik Reinhardt De Muelenaere
Contestant
ulrikdem@gmail.com

South Africa **ZAF03**

507. Darshen Bhawan
Contestant
Darshenmp6@gmail.com



South Africa **ZAF04**

508. Iliya Victorovich Matveyuk
Contestant
ksbvictor@gmail.com

South Africa **ZAF05**

509. Mervlyn Moodley
Leader
moodleym2@ukzn.ac.za

South Africa **ZAF11**

510. Jagathesan Govender
Leader
govenderj@ukzn.ac.za

South Africa **ZAF12**

511. Gabriel Sánchez Pérez
Contestant
gasape21@gmail.com

Spain **ESP01**

512. Ramón Martínez Tatay
Contestant
ramon.martinez.tatay@gmail.com

Spain **ESP02**

513. José Polo Gómez
Contestant
josepologomez@gmail.com

Spain **ESP03**

514. Jesús Arjona Martínez
Contestant
jesus.arjona.255@gmail.com

Spain **ESP04**

515. Adam Teixidó Bonfill
Contestant
adamteixido@gmail.com

Spain **ESP05**

516. Jose Francisco Romero Garcia
Leader
pepepaco@gmail.com

Spain **ESP11**

517. Antonio Guirao
Leader
guirao@um.es

Spain **ESP12**

518. Gihan Chanaka Jayatilaka
Contestant
gihanchanaka@gmail.com

Sri Lanka **LKA01**

519. Jayasuriya Kuranage Malsha Vijini Perera
Contestant
malshaperera14@gmail.com

Sri Lanka **LKA02**

520. Harshana Sumedha Weligampola
Contestant
uwillfindharshana@gmail.com

Sri Lanka **LKA03**

521. Dilshan Chameera Karunarathna
Contestant
dilkaru.825@gmail.com

Sri Lanka **LKA04**

522. Ranasinghe Arachchige Pasindu Dhanuka
Contestant
Pasindhudhanuka.pd@gmail.com

Sri Lanka **LKA05**

523. Loku Balasuriyage Don Ruwan Palitha Wijesundera
Leader
palitha@kln.ac.lk

Sri Lanka **LKA11**

524. Wasantha Jayatissa
Leader

Sri Lanka **LKA12**

525. Bharat Shaam Basropansingh
Contestant
bharatbs@live.nl

Suriname **SUR01**

526. Shivan Bissesar
Contestant
shivan_b@live.com

Suriname **SUR02**

527. Oseï Jaïr Fränkel
Contestant
ofrankel@hotmail.com

Suriname **SUR03**

528. Nazreen Sova Kromopawiro
Contestant
kromopawiro.nazreen@hotmail.com

Suriname **SUR04**

529. Randall Daniël Wijntuin
Contestant
randallwijntuin@hotmail.com

Suriname **SUR05**

530. Tjien Bing Tan
Leader
b.tan@uvs.edu

Suriname **SUR11**

531. Himankoemar Parveen Debi
Leader
himankoemar.debi@uvs.edu

Suriname **SUR12**

532. Åke Karl Olof Andersson
Contestant
akeskola@hotmail.se

Sweden **SWE01**

533. Axel Per Zacharias Ljungdahl Sundkvist
Contestant
axel@styron.se

Sweden **SWE02**

534. Christian Wing-Keith Le
Contestant
christian@familj-le.se

Sweden **SWE03**

535. Ida Kristina Svenningsson
Contestant
ida.svenningsson@gmail.com

Sweden **SWE04**

536. Peter Joakim Hallstadius
Contestant
peter@hallstadius.se

Sweden **SWE05**

537. Bo Peter William Söderberg
Leader
bo.soderberg@thep.lu.se

Sweden **SWE11**

538. Max Bengt Kesselberg
Leader
max.kesselberg@yahoo.se

Sweden **SWE12**

539. Margareta Gurli Linnéa Berg Kesselberg
Observer
margareta.kesselberg@yahoo.se

Sweden **SWE21**

540. Johan Erik Runeson
Observer
johan.runeson@gmail.com

Sweden **SWE22**

541. Anne-Sofie Mårtensson
Observer
anne-sofie.martensson@hb.se

Sweden **SWE23**

542. Anian Altherr
Contestant
anian.altherr@sunrise.ch

Switzerland **CHE01**

543. Andrea Gebek
Contestant
andrea.gebek@schlup.com

Switzerland **CHE02**

544. Linus Geiser
Contestant
linus.g@bluewin.ch

Switzerland **CHE03**

545. Mattia Humbel
Contestant
mattia.humbel@gmail.com

Switzerland **CHE04**

546. Kajo Vivian Krummenacher
Contestant
kajo.krummenacher@bluewin.ch

Switzerland **CHE05**

547. Lionel Philippoz
Leader
philippoz.lionel@gmail.com

Switzerland **CHE11**

548. Pierre Francois Duc
Leader
pfduc87@gmail.com

Switzerland **CHE12**

549. Andrea Beatrice Schneider
Observer
andrea.schneider@physik.uzh.ch

Switzerland **CHE21**

550. Simon Birrer
Observer
simon.birrer@olympiads.ch

Switzerland **CHE22**

551. Marco Gerber
Observer
marco.gerber@olympiads.unibe.ch

Switzerland **CHE23**

552. Thomas Uehlinger
Observer
thomas.uehlinger@gmail.com

Switzerland **CHE24**

553. Andreas Schilling
Visitor

Switzerland **CHE31**

554. Tony Philip Makdissy
Contestant
TONY.MAKDISSY.SY@GMAIL.COM

Syria **SYR01**

555. Jafar Abdul Aziz Badour
Contestant
JAFER.BA@GMAIL.COM

Syria **SYR02**

556. Mahmoud Saeed Monther
Contestant
MHMODMONTHER@HOTMAIL.COM

Syria **SYR03**

557. Adnan Salman Saood
Contestant
ADNAN2061998@HOTMAIL.COM

Syria **SYR05**

558. Akil Ali Salloum
Leader
akil.salloum@gmail.com

Syria **SYR11**

559. Baida Mohsen Achkar
Leader
BAIDACHKAR@GMAIL.COM

Syria **SYR12**

560. Ali Said Abou Khoder
Observer
aaboukhoder@gmaul.com

Syria **SYR21**

561. Leen Ali Skaf
Visitor
BAYDACHKAR@GMAIL.COM

Syria **SYR31**

562. Ismoil Odinaev
Contestant

Tajikistan **TJK01**

563. Murod Mirzhalilov
Contestant

Tajikistan **TJK02**

564. Zikrulloh Khuzhakulov
Contestant

Tajikistan **TJK03**

565. Ilkhomdzhon Bakhodurzoda
Contestant

Tajikistan **TJK04**

566. Azimdzhon Temurdzhonov
Contestant

Tajikistan **TJK05**

567. Dalerbek Haydarov
Leader
h.dalerbek@gmail.com

Tajikistan **TJK11**

568. Shamsiddin Kodirov
Leader

Tajikistan **TJK12**

569. Abhijatmedhi Chotrattanapituk
Contestant
c_earth@doramail.com

Thailand **THA01**

570. Sompob Shanokprasith
Contestant
sompob.s.pob@gmail.com

Thailand **THA02**

571. Watchara Sornwanee
Contestant
Sornwanee22@gmail.com

Thailand **THA03**

572. Phum Siriviboon
Contestant
btaf10@hotmail.com

Thailand **THA04**

573. Panawat Wong-Klaew
Contestant
panawat_vista@hotnmail.com

Thailand **THA05**

574. Phichet Kittara
Leader
pkittara@gmail.com

Thailand **THA11**

575. Sirapat Pratontep
Leader
kpsirapat@gmail.com

Thailand **THA12**

576. Oratai Rueangsombat
Observer
aui_oratai@hotmail.com

Thailand **THA21**

577. Kittiwit Matan
Observer
kittiwit.mat@mahidol.ac.th

Thailand **THA22**

578. Samer George Baqaeen
Contestant
samer.baqaeen@hotmail.com

The Hashemite Kingdom of Jordan **JOR01**

579. Mousa Sadik Nofal
Contestant
mousa.s.nofal@gmail.com

The Hashemite Kingdom of Jordan **JOR02**

580. Dana Iyad Marei
Contestant
danaeyad256@yahoo.com

The Hashemite Kingdom of Jordan **JOR03**

581. Anas Walid Al Shikh Khalil
Contestant
anas.khalil@outlook.com

The Hashemite Kingdom of Jordan **JOR04**

582. Wesam Maher Al Quza
Contestant
wesammaherrny@yahoo.com

The Hashemite Kingdom of Jordan **JOR05**

583. Imad Baker Jaber
Leader
ijaber@jubilee.edu.jo

The Hashemite Kingdom of Jordan **JOR11**

584. Amal Farid Sweis
Leader
amal_sweis@hotmail.com

The Hashemite Kingdom of Jordan **JOR12**

585. Ahmet Burak Catli
Contestant
ahmetburakcatli@gmail.com

Turkey **TUR01**

586. Tolga Gurcan
Contestant
tgfener@gmail.com

Turkey **TUR02**

587. Ali Veli
Contestant
aliveli1998av@gmail.com

Turkey **TUR03**

588. Mert Kayaalp
Contestant
mertkayaalp2728@hotmail.com

Turkey **TUR04**

589. Umut Eren Usturali
Contestant
erenust@gmail.com

Turkey **TUR05**

590. Coskun Kocabas
Leader
ckocabas@fen.bilkent.edu.tr

Turkey **TUR11**

591. Ahmet Levent Subasi
Leader
alsubasi@itu.edu.tr

Turkey **TUR12**

592. Menderes Iskin
Observer
menderes@gmail.com

Turkey **TUR21**

593. Harun Arslan
Observer
harun.arslan@tubitak.gov.tr

Turkey **TUR22**

594. Omargeldi Atanov
Contestant
omar.atanov@gmail.com

Turkmenistan **TKM01**

595. Dovran Amanov
Contestant
dovranovich4@gmail.com

Turkmenistan **TKM02**

596. Allamyrat Amanmadov
Contestant
allamyrat16@gmanil.com

Turkmenistan **TKM03**

597. Seyithan Rozyyev
Contestant
Rozyyev.98@mail.ru

Turkmenistan **TKM04**

598. Eziz Gulladyyev
Contestant
bairamovich45@gmail.com

Turkmenistan **TKM05**

599. Gylychmammet Orazov
Leader
tirkesh.sh@gmail.com

Turkmenistan **TKM11**

600. Rustam Durdyyev
Leader
rustam.durdyyev@yahoo.com

Turkmenistan **TKM12**

601. Taras Zhylenko
Contestant
ioa@univ.kiev.ua

Ukraine **UKR01**

602. Oleksii Mikulenko
Contestant
ioa@univ.kiev.ua

Ukraine **UKR02**

603. Mykhailo Rashkovetskyi
Contestant
ioa@univ.kiev.ua

Ukraine **UKR03**

604. Oleksandr Shumaiev
Contestant
ioa@univ.kiev.ua

Ukraine **UKR04**

605. Mark Yuhai
Contestant
ioa@univ.kiev.ua

Ukraine **UKR05**

606. Igor Anisimov
Leader
ioa@univ.kiev.ua

Ukraine **UKR11**

607. Borys Kreminskyi
Leader
ioa@univ.kiev.ua

Ukraine **UKR12**

608. Lada Kreminska
Visitor
ioa@univ.kiev.ua

Ukraine **UKR31**

609. Bianca Ana-Maria Andrei
Contestant
bianca.andrei97@yahoo.com

United Kingdom **GBR01**

610. James Alexander Bamber
Contestant
jamie14142@btinternet.com

United Kingdom **GBR02**

611. Deaglan John Bartlett
Contestant
deaglanb@btinternet.com

United Kingdom **GBR03**

612. Jared Anand Jeyaretnam
Contestant
jaredjey@gmail.com

United Kingdom **GBR04**

613. Robert Stephen Tji-Kean Swan
Contestant
08robertswan@gmail.com

United Kingdom **GBR05**

614. Robin William Hughes
Leader
rh584@cam.ac.uk

United Kingdom **GBR11**

615. Robert Paul Nicholls
Leader
rpn@merchiston.co.uk

United Kingdom **GBR12**

616. James Andrew Peter Bedford
Observer
j.a.p.bedford@gmail.com

United Kingdom **GBR21**

617. Matthew Paul Bennett
Observer
matthewb@truro-penwith.ac.uk

United Kingdom **GBR22**

618. David Richard Lovett
Observer
lovettashbury@btInternet.com

United Kingdom **GBR23**

619. Muriel Irene Hughes
Visitor
irenehughes77@hotmail.com

United Kingdom **GBR31**

620. Fiona Margaret Nicholls
Visitor
fmnicholls@gmail.com

United Kingdom **GBR32**

621. Kevin Q Li
Contestant
likevinq@gmail.com

United States of America **USA01**

622. Adam Robert Busis
Contestant
gaga64@gmail.com

United States of America **USA02**

623. Zachary Bogorad
Contestant
zachbogorad@gmail.com

United States of America **USA03**

624. Jason Lu
Contestant

United States of America **USA04**

625. Saranesh Thanika Prembabu
Contestant
saranesh.prembabu@gmail.com

United States of America **USA05**

626. Paul Elliott Stanley
Leader
stanleyp@beloit.edu

United States of America **USA11**

627. David Wiliam Fallest
Leader
dwfalles@ncsu.edu

United States of America **USA12**

628. Nam Thanh Trung Vu
Contestant
vuthanhtrungnam@yahoo.com

Vietnam **VNM01**

629. Khanh Ngoc Nguyen
Contestant

Vietnam **VNM02**

630. Thao Thi Huong Dinh
Contestant
dinhthihuongthao1998@gmail.com

Vietnam **VNM03**

631. Thanh Cong Nguyen
Contestant
foreverloveya321@gmail.com

Vietnam **VNM04**

632. Nam Quang Nguyen
Contestant
quangnamgalaxie@gmail.com

Vietnam **VNM05**

633. Khoi The Nguyen
Leader
khoint@hnue.edu.vn

Vietnam **VNM11**

634. Hoang Huy Luc
Leader
hoanglhsp@hnue.edu.vn

Vietnam **VNM12**

635. Anh Duc Le
Observer
anhld@hnue.edu.vn

Vietnam **VNM21**

636. Trung Bao Nguyen
Observer
trunghhpt@yahoo.com

Vietnam **VNM22**

637. Loi Tien Vu
Observer
loiloan@yahoo.com

Vietnam **VNM23**

638. Thanh Xuan Ha
Observer
hxthanh@moet.edu.vn

Vietnam **VNM24**

639. Tho An Thi Le
Visitor
anlam4847@gmail.com

Vietnam **VNM31**

640. Quyet Tho Tran
Visitor
ttquyetchp@gmail.com

Vietnam **VNM32**

Academic Members

Academic Committee

Chairperson

Joseph Samuel
Raman Research Institute, Bengaluru

Charudatta Kadolkar
Indian Institute of Technology Guwahati

Coordinator, Theory Component

Anwesh Mazumdar
Homi Bhabha Centre for Science Education, TIFR, Mumbai

Vijay A. Singh
Homi Bhabha Centre for Science Education, TIFR, Mumbai

Coordinator, Experimental Component

Rajesh Khaparde
Homi Bhabha Centre for Science Education, TIFR, Mumbai

Praveen Pathak
Homi Bhabha Centre for Science Education, TIFR, Mumbai

S. Annapoorni
University of Delhi, New Delhi

Shirish Pathare
Homi Bhabha Centre for Science Education, TIFR, Mumbai

Arnab Bhattacharya
Tata Institute of Fundamental Research, Mumbai

H. C. Pradhan
Homi Bhabha Centre for Science Education, TIFR, Mumbai

C. K. Desai
Bajaj Science Centre, Vardha

M. K. Raghavendra
Indian Institute of Science, Bengaluru

Amol Dighe
Tata Institute of Fundamental Research, Mumbai

Ajit Mohan Srivastava
Institute of Physics, Bhubaneswar

Manoj Harbola
Indian Institute of Technology, Kanpur

Chairperson & member till November 2015

H. S. Mani
Chennai Mathematical Institute, Chennai

Academic Development Group

Joseph Amalnathan	*Bhabha Atomic Research Centre, Mumbai*
Amar Chand Biyani	*Govt. College, Ranchi*
Ananda Dasgupta	*IISER Kolkata*
Sunil Datta	*Retd., Bhabha Atomic Research Centre, Mumbai*
Manish Kapoor	*Christ Church College, Kanpur*
Prasanta Kumar Jena	*Retd., Ravenshaw University, Cuttack*
K. G. M. Nair	*Chennai Mathematical Institute, Chennai*
Suvrat Raju	*International Centre for Theoretical Sciences, (TIFR), Bengaluru*
Arnab Ray	*Jaypee University, Guna*

Academic Team : Experiments

No	Name	Affiliation
1	Bhavna Anchan	*Indian Institute of Science, Bengaluru*
2	Achutha B. S.	*VVS Sardar Patel Pu College, Bengaluru*
3	Tushima Basak	*Mithibai College, Mumbai*
4	Sonali Bhatnagar	*Dayalbagh Educational Institute, Agra*
5	Dhruva Bhattacharjee	*APPED, BARC, Mumbai*
6	Rangeet Bhattacharya	*IISER, Kolkata*
7	Vivek Vasant Bhide	*G. J. College, Ratnagiri*
8	Shyamala Prajapati Bodhane	*St. Xavier's College, Mumbai*
9	Dattaram K. Bopardikar	*Shri Ramdeobaba College, Nagpur*
10	Asit Kumar Chakrabarti	*Chakdaha College, Nadia*
11	Bhupati Chakrabarti	*Retd. From City College, Kolkata*
12	Surajit Chakrabarti	*Ramkrishna Mission Vidyamandir*
13	Birendra Nath Das	*Presidency University, Kolkata*
14	Pradip Kumar Dasgupta	*Retd. From Siddharth College,Mumbai*
15	Saswati Dasgupta	*Rammohan College, Kolkata*
16	Rekha Ghorpade	*R. J. College, Mumbai*
17	Subhankar Ghosh	*St. Xavier's College, Kolkata*
18	Makhanlal Nanda Goswami	*Midnapore College, Midnapore*
19	Anshul Gupta	*K. J. Somaiya College, Mumbai*
20	Saurabhee Huli	*HBCSE, TIFR, Mumbai*
21	Deepak Jalla	*K. J. Somaiya College, Mumbai*
22	James Joseph	*Retd. From St.Paul College, Kerala*
23	Leena Joshi	*St. Xavier's College, Mumbai*
24	Rakesh Joshi	*HBCSE, TIFR, Mumbai*
25	Prashant Kadam	*HBCSE, TIFR, Mumbai*
26	Vinayak Shripad Katdare	*D. G. Ruparel College, Mumbai*
27	Aditya Kulkarni	*HBCSE, TIFR, Mumbai*
28	Govind Diliprao Kulkarni	*Abasaheb Garware College, Pune*
29	Gayatri Vishwas Kulkarni	*Maharashtra Knowledge Foundation, Pune*
30	Vikrant Kurmude	*HBCSE, TIFR, Mumbai*
31	Rohan Dattaram Lahane	*NIO, Mumbai*
32	Swapan Majumdar	*Hindi H S School, Agartala*
33	Manmohan Singh Marwaha	*S. G. G. S. College, Chandigarh*
34	Mitaxi Mehta	*IET, Ahmedabad*

35	Amit Arvind More	*K. J. Somaiya College, Mumbai*
36	Bipul Pal	*IISER, Kolkata*
37	Tushar Chaitanya Pandya	*St. Xavier's College, Ahmedabad*
38	Arun Pravinchan Patel	*St. Xavier's College, Ahmedabad*
39	Rashmi Puranik	*HBCSE, TIFR, Mumbai*
40	Geetha R. S.	*Vijaya College, Bengaluru*
41	Keyuri Raodeo	*HBCSE, TIFR, Mumbai*
42	Shobha Devi S. N.	*BMS College for Women, Bengaluru*
43	Manoj B. Sawaikar	*H. B. Desai Govt. High School, Goa*
44	A. M. Shaker	*K. J. Somaiya College, Mumbai*
45	Sapna Sharma	*St. Bede's College, Shimla*
46	Raghunath Mandaram Shewale	*Z. B. Patil College, Dhule*
47	Vijay Vasant Soman	*S. M. Mohata College, Nagpur*
48	Manoj Kumar Srivastava	*Army Cadet College, Dehradun*
49	Debapriyo Syam	*CAPSS, Bose Institute, Kolkata*
50	Shreeman Narayan Tiwary	*St. Xavier's College, Ranchi*
51	B. P. Tyagi	*NGPE, Dehradun*
52	Manjunatha V. G.	*Indian Institute of Science, Bengaluru*
53	K. Venkataraman	*PMB Gujarati Science College, Indore*
54	Kamala Y. C.	*National Degree College, Bengaluru*

Academic Team: Theory

No	Name	Institution
1	Ravi Teja A. V.	*IIT Bombay*
2	Rishabh Agarwal	*IIT Bombay*
3	Jithendar Anumula	*IIT Bombay*
4	Kushal Babel	*IIT Bombay*
5	Aniket Bajpai	*IIT Delhi*
6	Gurkirat Singh Bajwa	*IIT Delhi*
7	Bhavya Bandaru	*IIT Delhi*
8	Uddipan Banik	*IIT Kanpur*
9	Rutvij V. Bhavsar	*IIT Kanpur*
10	Siddharth Bulia	*IIT Bombay*
11	Sai Kiran Burle	*IIT Bombay*
12	Abhisek Datta	*IIT Kharagpur*
13	Abhinav Deshpande	*IIT Kanpur*
14	Rupanshu Ganvir	*IIT Bombay*
15	Srajan Garg	*IIT Bombay*
16	Shubham Goel	*IIT Bombay*
17	Amey Gupta	*IIT Bombay*
18	Shreyan Gupta	*IIT Delhi*
19	Varun Harbola	*IIT Kanpur*
20	Pavan Hebbar	*IIT Bombay*
21	Prudhvitej Immadi	*IIT Bombay*
22	Karan Jain	*IIT Bombay*
23	Varun Jorapur	*IIT Kanpur*
24	Vidul Joshi	*IIT Kanpur*
25	Sandesh Kalantre	*IIT Bombay*
26	Kandarp S. Khandwala	*IIT Bombay*
27	Devesh Khilwani	*IIT Bombay*
28	Harshal Mahajan	*IIT Bombay*
29	Naren Manjunath	*IISc, Bengaluru*
30	Anuj Mittal	*IIT Bombay*
31	Chitraang Murdia	*IIT Bombay*
32	Aniket Murhekar	*IIT Bombay*
33	Abu Saleh Musa	*IIT Kanpur*
34	Girish Raguvir J.	*IIT Madras*

35	Pratik Rath	*IIT Kanpur*
36	Jyotirmoy Roy	*UM-DAE CBS, Mumbai*
37	Sanchar Sharma	*IIT Bombay*
38	Utkarsh Sharma	*IIT Bombay*
39	Mayank Singh	*UM-DAE CBS, Mumbai*
40	Shubham Sinha	*IISc, Bengaluru*
41	Chaitanya Tappu	*IISc, Bengaluru*
42	M. Tharun	*IIT Kharagpur*
43	Meet Udeshi	*IIT Bombay*
44	Kapil Vaidya	*IIT Bombay*
45	Bhargav Sri Venkatesh	*IIT Bombay*
46	Mohit Vyas	*IIT Bombay*
47	Aniruddha	*UM-DAE CBS, Mumbai*
48	Sumith	*IIT Bombay*

Academic Assistants

Pradeep Chaudhari	Karthik K.	Rakesh M.
Baba Dhebe	Sachin S.	Anand B.
Sadashiv Shirodkar	Rajendran K.	Sunil B.
Vikas Nadkar	Sandeep S.	Vijay M.
Varsha Sathe	Parshuram P.	Sunil P.
Shankar Kadam	Kiran K.	Anil P.
Sana Shaikh	Umesh G.	Mohin M.
Elayraju K.	Yogesh B.	
Raju D.	Iyappan D.	

Special thanks for academic help

Arvind Kumar	Sandip Ghosh	Tarun K. Barik

Organizers

Core Organizational Group

Jayashree Ramadas	*Centre Director, HBCSE - TIFR and Chair, IPhO 2015*
Anwesh Mazumdar	*HBCSE - TIFR, Convener, IPhO 2015*
Rajesh Khaparde	*HBCSE - TIFR, Mumbai*
Savita Ladage	*HBCSE - TIFR, Mumbai*
Sugra Chunawala	*HBCSE - TIFR, Mumbai*
Rekha Vartak	*HBCSE - TIFR, Mumbai*
Madhavi Gaitonde	*HBCSE - TIFR, Mumbai*

Programme Planning Group

Anwesh Mazumdar	*HBCSE - TIFR, Mumbai*
Sumana Amin	*HBCSE - TIFR, Secretary, IPhO 2015*
Manoj Nair	*HBCSE - TIFR, Mumbai*
Swapna Narvekar	*HBCSE - TIFR, Mumbai*
Praveen Pathak	*HBCSE - TIFR, Mumbai*
Shirish Pathare	*HBCSE - TIFR, Mumbai*
V. P. Raul	*HBCSE - TIFR, Mumbai*
Anupama Ronad	*HBCSE - TIFR, Mumbai*
Aniket Sule	*HBCSE - TIFR, Mumbai*

Organizational Committee Members

Abha Vaishampayan	K. S. Ghadiali	Sana Shaikh
Adithi Muralidhar	K. T. Hambir	Sandhya Rajashekar
Ajay Singh	M. B. Bamne	Sangam Sinha
Amit Jadhav	M. D. Gaitonde	Santosh Rasam
Aniket Sule	Manish S. Thakur	Sarada Bulchand
Anil Sankhwar	Manisha B. Deshmukh	Savita Ladage
Anupama Ronad	Manoj Nair	Shankar Kadam
Arijit Das	Meena Kharatmal	Shuvechha Mukherjee
Arnab Bhattacharya	Milind G. Shinde	Shweta Naik
B. L. Valvi	N. D. Deshmukh	Shweta Sakre

B. S. Bhagit	N. Y. Tribhuvan	Smita Burli
Baba Dhebe	Nivrutti K. Kadam	Sugra Chunawala
C. D. Deshmukh	P. K. Joshi	Sumana
D. D. Pednekar	Pooja Sharma	Swapna Narvekar
Devashree Prabhu	Pradip Chaudhari	Swapnila K. Desai
Devendra R. Mhapsekar	Prakash Nawale	Tilottama Shirodkar
Disha Gupta	Prithwijit De	Tushar Vaity
Gajanan V. Mestry	R. G. More	U. V. Shenoy
Gauri Tawate	Raju Ambekar	V. C. Jacob
H. H. Rane	Rashmi Shrotri	V. C. Sonawane
Hemant Mandlik	Ravindra Sawant	V. D. Lale
Indrani Das	Rekha Vartak	V. P. Ahire
J. B. Waghmare	Rupesh Nichat	V. P. Raul
J. J. Tambe	S. D. Pardeshi	Varsha Sathe
Jayashree Ramadas	Sachin S. Chavan	Vikas Nadkar
K. G. Suresh	Sadashiv Shirodkar	Vikrant Ghanekar

Student Guides

No	Name	Country
1	Amogh Pathak	*Armenia*
2	Jyoti Malvi	*Australia*
3	Pournima Jaju	*Austria*
4	Krishna Gupta	*Azerbaijan*
5	Suketu Das	*Bangladesh*
6	Parth Surve	*Belarus*
7	Mrinmayee Patki	*Belgium*
8	Shashwat Kulkarni	*Bolivia*
9	Chelsea D'souza	*Bosnia and Herzegovina*
10	Anwesh Bhattacharya	*Brazil*
11	Vishal Padwal	*Bulgaria*
12	Adhishree Neurgaonkar	*Cambodia*
13	Shruti Alekar	*Canada*
14	Harsh Bhatt	*Chinese Taipei*
15	Apurva Ganu	*Colombia and Cuba*
16	Rukmini Durge	*Croatia*
17	Pinki Gahlot	*Cyprus*
18	Niharika Singh	*Czech Republic*
19	Eliza Fernandes	*Denmark*
20	Sweety Jose	*Egypt*
21	Avani Sawant	*El Salvador and Costa rica*
22	Srinath Raja	*Estonia*
23	Sheetal Chopde	*Finland*
24	Khushboo Doshi	*France*
25	Kunal Dixit	*Georgia*
26	Madhuri Acharya	*Germany*
27	Deepali Ramane	*Greece*
28	Anirudh Pillai	*Hong Kong*
29	Shikha Jain	*Hungary*
30	Manasi Acharya	*Iceland*
31	Amish Dhandhukia	*India*
32	Shivam Negi	*Indonesia*
33	Kamran Sayed	*Islamic Republic of Iran*
34	Akshay Joshi	*Israel*
35	Lamia Varawala	*Italy*
36	Ketaki Kelkar	*Japan*
37	Aakanksha Sawant	*Kyrgyzstan*
38	Pratibha Jagtap	*Latvia*
39	Sadhana Thevar	*Lithuania*
40	Satori Pansare	*Macao-China*
41	Samidha Shinde	*Macedonia*
42	Siddharth Dhanpal	*Malaysia*
43	Samvit Mahapatra	*Mexico*
44	Geethu Gangadharan	*Moldova*
45	Ishanee Pophale	*Mongolia*
46	Anup Suralkar	*Montenegro and Puerto rico*
47	Aditya Dethe	*Nepal*
48	Isha Kakkad	*Netherlands*
49	Parth Nisar	*Nigeria*
50	Tanushri Pardeshi	*Norway*
51	Saima Nakhwa	*Pakistan*
52	Upnishad Sharma	*People's Republic of China*
53	Anuja Sahasrabuddhe	*Poland*
54	Poorva Daptardar	*Portugal*
55	Akshay Hotkar	*Republic of Kazakhstan*

56	Shruti Singh	*Republic of Korea*
57	Ishwar Atre	*Republic of Singapore*
58	Monika Bhalke	*Romania*
59	Anton Iyer	*Russia*
60	Mohd. Shahnawaz	*Saudi Arabia*
61	Amruta More	*Serbia*
62	Amish Parmar	*Slovakia*
63	Abhinav Rawat	*Slovenia*
64	Shubham Gupta	*South Africa*
65	Avni Shah	*Spain*
66	Sampada Sawant	*Sri Lanka*
67	Atharva Rawte	*Suriname*
68	Vatsala Sharma	*Sweden*
69	Asira Lele	*Switzerland*
70	Ravi Bari	*Syria*
71	Kunal Chaudhari	*Tajikistan*
72	Anuj Trivedi	*Thailand*
73	Swapnaja Patil	*The Hashemite Kingdom of Jordan*
74	Faiz Khan	*Turkey*
75	Tanmay Keluskar	*Turkmenistan*
76	Nirvan Bhawar	*Ukraine*
77	Aron G.	*United States of America*
78	Sumit Pai	*United Kingdom*
79	Jyutika Satghar	*Vietnam*

Volunteers

Nidhi Agarwal
Nilaksh Aggarwal
Ankita Athalye
Kumar Ayush
Advaiet Chadha
Amitoj Singh Chandiok
Sarthak Chandra
Sharvari Dixit
Kruti Dongrey
Rudra Gadekar
Tanuja Gumaste
Rishabh Jha
Gurpreet Kaur
Mikail Khona
Yogesh Meena
Sharad Mirani

Aditya Mutha
Neha Paranjape
Jenifer Philip
Saurabh Pinjani
Siddhant Ranade
Bandi Rajiv Reddy
Arati Saptarshi
Trupti Sawant
Priyanka Sawant
Phalguni Shah
Srushti Shah
Aanchal Sharma
Pulkit Sharma
Anuj Shetty
Shalom Sonawane
Keshav Srinivasan

Programme

Date	Students	Leaders
July 4	Arrival (Check-in after 14:00 hrs) and Registration	
July 5	Registration (08:00-12:00 hrs) and Opening ceremony (16:00-19:00 hrs)	
July 6	Excursion at Nehru Planetarium and Nehru Centre	International Board meeting - Discussion and translation of experimental problems
July 7	Experimental Exam	Excursion to South Mumbai
July 8	Excursion to South Mumbai and Tata Institute of Fundamental Research	International Board meeting - Discussion and translation of theoretical problems
July 9	Theoretical Exam	Excursion to Sanjay Gandhi National Park and Kanheri Caves
July 10	Excursion to Imagica Amusement Park	Excursion to Godrej Lock Factory
July 11	Excursion to Mahindra Car and Truck Factory	Moderation and International Board meeting
July 12	Closing Ceremony (10:00 - 13:00 hrs) and Departure	
July 13	Departure (Check-out before 12:00 hrs)	

Problems, Solutions, Marking Scheme

Joseph Samuel
Chair Academic Committee, IPhO 2015

Introduction

The IPhO 2015 was held in Mumbai and organised by the Homi Bhabha Centre for Science Education (HBCSE). The HBCSE drew on available academic expertise throughout the country to put together a physics test that is of appropriate level and interest for students at the high school level. The questions were developed in a series of Resource Generation Camps in which many possible lines of thought were explored. Only a fraction of the ideas discussed made it into the final paper. The experimental part was addressed first since this takes more time to develop, test and realise. The experiments were finalised by the hard work of the developers, criticism from the academic committee and also an enormous contribution from physics teachers across the country, who individually tested the experimental apparatus. The theory questions finally chosen range from Astrophysics, to fundamental physics to engineering physics. A major challenge was to develop a good grading scheme which would be transparent and easy to implement. All this was possible due to dedicated effort from the graders, teachers, members of the academic committee and organisational support from HBCSE. From the response from the international community, we gather that our efforts were appreciated by students and teachers alike.

Experimental Tasks

The experiments deal with light as a probe of matter. This would seem an appropriate choice in the Year of Light! When light waves are incident on objects of size similar to their wavelength, they undergo delicate diffraction effects that reveal the structure of the object being probed.

The first part of the experiment is inspired by Rosalind Franklin's study using X-ray diffraction, which revealed the double helical structure of DNA.

In the simplified student version, X-rays are replaced by light and the double helix by mechanical springs. The second part has an analogue of a crystal lattice constructed by tiny ripples on the surface of water. These ripples (also called capillary waves) are due to the surface tension of water, which provides a restoring force when the level surface of water is disturbed. You may have seen such waves when riding a bicycle through a puddle. In the experiment, the wavelength of the ripples is much smaller than the eye can see and comparable to the wavelength of light.

The diffraction of light by standing water waves is very similar to X-ray diffraction from a crystal lattice and gives us a probe for the surface tension and viscosity of water.

Theoretical Tasks

Understanding the Sun

The first task concerns our nearest star, the Sun.

The Sun puts out energy in the form of light and also some less familiar forms like neutrinos. The problem starts by using the light emitted by the Sun to learn about the temperature at the surface of the Sun.

Next we learn how to harvest the energy put out by the Sun using semiconductor physics.

Finally, we realise that the elusive neutrino permits us to look deep into the interior of the Sun, just as X-rays are used by doctors to see our bones.

This enquiry brings us abreast with current research in the Standard model of particle physics.

Extremum Principles in Physics

The second task has to do with variational principles in physics. This is an idea with a long and illustrious history, dating back to Hiero of Alexandria and traversing the centuries through Fermat, Maupertuis, Hamilton and Feynman. This is an advanced idea that threads between optics, classical mechanics and Schrodinger's wave mechanics.

Variational principles give a very economical statement of the laws of physics and are the very corner stone of research in fundamental physics.

Design of a Nuclear Reactor

The first two problems were mainly concerned with fundamental aspects of physics. The third problem is more applied, dealing with the design of nuclear reactors. For safe operation a reactor has to be designed so that energy is released in a controlled fashion.

This involves physics of a different kind, making dimensional estimates, understanding material properties, calculating numbers and finally designing a reactor which is safe in operation.

We hope you enjoy doing these problems.

Experimental Tasks

Cover Page

46th INTERNATIONAL PHYSICS OLYMPIAD
2015 MUMBAI - INDIA

Experimental Examination

July 07, 2015

General Instructions

- The experimental examination lasts for 5 hours and is worth a total of 20 marks.
- You must neither open the envelope with the problems nor touch the experimental equipment before the sound signal indicating the beginning of the competition.
- Dedicated IPhO Answer Sheets are provided for writing your answers. Enter the observations into the appropriate tables/boxes in the corresponding Answer Sheet. All graphs must be drawn only on the IPhO Graph Papers provided. Blank pages are also provided (marked **B**). If you have written something on any sheet which you do not want to be graded, cross it out.
- Fill out all the entries in the header (Contestant Code, Page number etc.).
- You are not allowed to leave your working place without permission. If you need any assistance (broken calculator, need to visit a restroom, etc), please draw the attention of the invigilator using one of the two cards (red card for help and green card for toilet).
- The beginning and end of the examination will be indicated by a sound signal. Additionally there will be sound signals every hour indicating the elapsed time. Additionally there will be a buzzer sound, fifteen minutes before the end of the examination (before the final sound signal).
- At the end of the examination you must stop writing immediately. Sort and number your Answer Sheets and Graph Papers. Put them in the envelope provided, and leave the envelope on your table. You are not allowed to take any sheet of paper out of the examination area.
- Wait at your table till your envelope is collected. Once all envelopes are collected your student guide will escort you out of the examination area.

Experimental Examination

July 07, 2015

10:00 – 15:00

2015 is being celebrated as the International Year of Light. Optical techniques play an important role in experimental physics. Diffraction is an amazingly powerful tool used across the sciences, and has helped unravel the structure of complex molecules like DNA and study the properties of matter in great detail. Today you will perform experiments using diffraction of laser light.

Experiment E-I: **Diffraction due to helical structures**	10 marks
Experiment E-II: **Diffraction due to surface tension waves**	10 marks

Experiments E-I and E-II use the same optical bench, but with different apparatus and settings. You must begin with experiment E-I and then go on to E-II.

Important Precautions

- Do not look into the laser beam directly or through any optical device.
- The experiments use low-power visible lasers. However, you are advised to wear laser goggles while performing optical alignments.
- Do not place highly reflective objects (such as rings, watches etc.) in the path of the laser beam.
- The stand on your right hand side has a pre-adjusted setup for E-II. Do not disturb it before you start working on E-II.
- The mirrors are front-coated, avoid touching the surface of the mirrors.
- Do not use the DC regulated power supply for the tablet computer.
- Avoid unnecessary movements during the experimental examination. Do not shake the walls of your cubicle. Laser experiments require stability.

Diffraction due to Helical Structure[1]

(Total marks: 10)

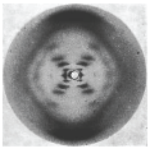


Figure 1: Photo 51

Introduction

The X-ray diffraction image of DNA (Fig. 1) taken in Rosalind Franklin's laboratory, famously known as "Photo 51", became the basis of the discovery of the double helical structure of DNA by Watson and Crick in 1952. This experiment will help you understand diffraction patterns due to helical structures using visible light.

Objective

To determine geometrical parameters of helical structures using diffraction.

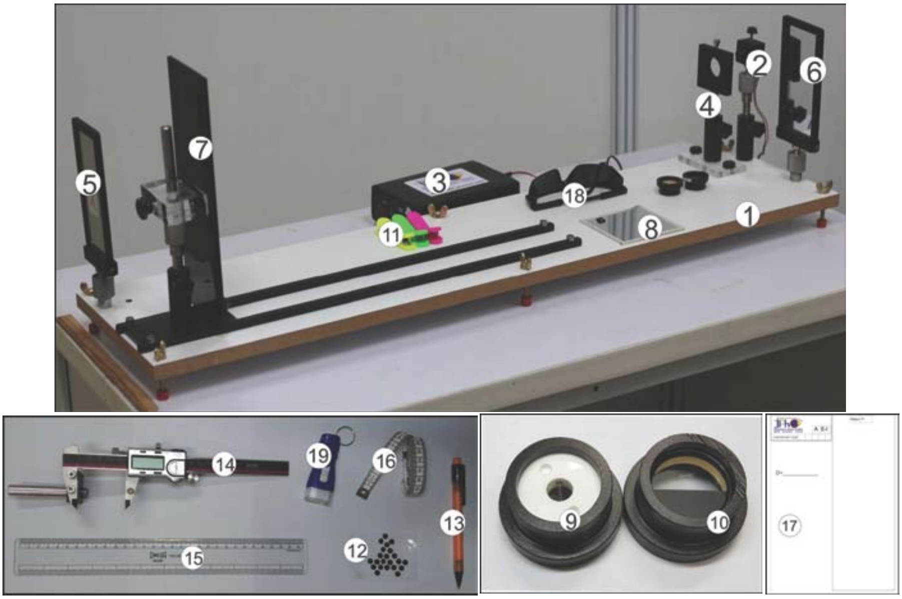


Figure 2: Apparatus for E-I

List of apparatus

[1]	Wooden platform	[11]	Plastic clips
[2]	Laser source with its mount and base	[12]	Circular black stickers
[3]	DC regulated power supply for the Laser source	[13]	Mechanical pencil
[4]	Sample holder with its base	[14]	Digital caliper with a mount
[5]	Left reflector (front coated mirror)	[15]	Plastic scale (30 cm)
[6]	Right reflector (front coated mirror)	[16]	Measuring tape (1.5 m)
[7]	Screen (10 cm x 30 cm) with its mount and base	[17]	Pattern marking sheets
[8]	Plane mirror (10 cm x 10 cm)	[18]	Laser safety goggles
[9]	Sample I (helical spring)	[19]	Battery operated flashlight
[10]	Sample II (double-helix-like pattern printed on glass plate)		

Note: Items [1], [3], [14], [15], [16] and [18] are also used in experiment E-II.

---

[1] *Praveen Pathak (HBCSE-TIFR, Mumbai), Charudatt Kadolkar (IIT, Guwahati), and Manish Kapoor (Christ Church College, Kanpur) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

Description of apparatus

Wooden platform [1]: A pair of guiding rails, laser, reflectors, screen and sample mounts are rigidly fixed on it.

Laser source with its mount and base [2]: Laser source of wavelength $\lambda = 635$ nm (1 nm $= 10^{-9}$ m) is fixed in a metallic mount clamped to the base using a ball joint ([20] in Fig. 3) allowing the adjustment in X-Y-Z directions. The laser body can be rotated and clamped using the top lock-in screw. The beam focus can be adjusted by rotating the front lens cap (red arrow in Fig. 3) to obtain a clear and sharp diffraction pattern.

DC regulated power supply [3]: The front panel has an intensity switch (high/low), socket for laser source connector and three USB sockets. The back panel has power switch and mains power socket (inset of Fig. 4).

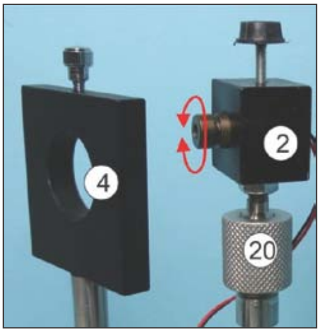


Figure 3: Laser source and sample holder. [20] Ball joint.

Figure 4: DC regulated power supply

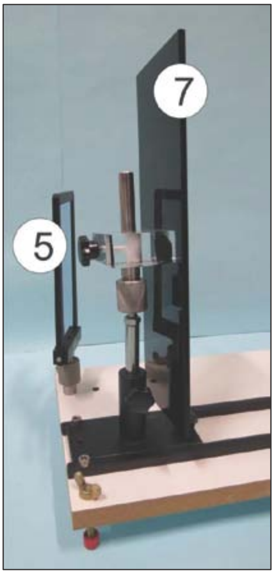


Figure 5: Left reflector and screen

Sample holder with its base [4]: Use the top locking screw to affix the samples in it (Fig. 3). The sample holder can be adjusted horizontally, vertically and rotated.

Left reflector [5]: This reflector is fixed to the platform (Fig. 5). Do not use the side marked X.

Right reflector [6]: This reflector is fixed to the platform and is removable (It will be removed in experiment E-II). Do not use the side marked X.

Screen with its mount [7]: The screen is mounted on ball joint and a base allowing rotational adjustments in all directions (Fig 5). The screen can be fixed as shown in Fig. 2 or Fig. 6 as required.

Sample I [9]: A helical spring fixed on a circular mount using white acrylic plates.

Sample II [10]: A double-helix-like pattern printed on a glass plate which is fixed on a circular mount.

Digital caliper with a mount [14]: Digital caliper is fixed to a mount (the mount is required in E-II). It has an On/Off switch, a switch to reset the reading to zero, a mm/inch selector (keep on mm), a locking screw and a knob for moving the right jaw. The digital caliper can be used to make measurements on pattern marking sheets.

Pattern marking sheets [17]: The given pattern marking sheets can be folded in half and clipped onto the screen using the plastic clips. Ensure that you mark the diffraction pattern within the rectangular box.

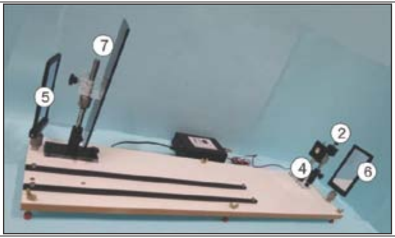


Figure 6: Alternate position of screen compared to that shown in Fig. 2

Theory

A laser beam of wavelength λ, falling normally on a cylindrical wire of diameter a, is diffracted in the direction perpendicular to the wire. The resulting intensity pattern as observed on a screen is shown in Fig. 7.

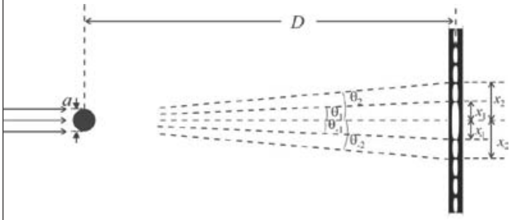


Figure 7: Schematic of the diffraction pattern due to single cylindrical wire of diameter a.

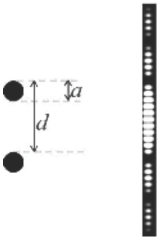


Figure 8: Schematic of diffraction pattern due to two cylindrical wires

The intensity distribution as a function of angle θ with the incident direction is given by

$$I(\theta) = I(0)\left[\frac{\sin\beta}{\beta}\right]^2 \qquad \text{where } \beta = \frac{\pi\, a \sin\theta}{\lambda}$$

The central spot is bright and for other angles, when $\sin\beta$ $(\beta \neq 0)$ is zero, the intensity vanishes. Thus the intensity distribution has n^{th}minimum at the angle θ_n, given by

$$\sin\theta_n = \pm n\frac{\lambda}{a} \qquad n = 1, 2, 3, 4, 5 \ldots.$$

Here $\pm$ refers to both sides of the central spot $(\theta = 0)$.

The diffraction pattern due to two parallel identical wires kept at a distance d from each other (Fig. 8) is a combination of two patterns (diffraction due to a single wire and interference due to two wires). The resultant intensity distribution is given by,

$$I(\theta) = I(0)\cos^2\delta\left[\frac{\sin\beta}{\beta}\right]^2$$

where $\delta = \frac{\pi\, d \sin\theta}{\lambda}$ and $\beta = \frac{\pi\, a \sin\theta}{\lambda}$

For a screen placed at a large distance D from the wire, the positions of the minima on the screen are observed at $x_{\pm n} = \pm n\frac{\lambda D}{a}$ due to diffraction and at $x_{\pm m} = \pm\left(m-\frac{1}{2}\right)\frac{\lambda D}{d}$ due to interference (where $m, n = 1, 2, 3, 4, 5$ ...). Similarly for a set of four identical wires (Fig. 9), the net intensity distribution is a combination of diffraction from each wire and interference due to pairs of wires and hence depends on a, d and s. In other words, the combination of three different intensity patterns is observed.

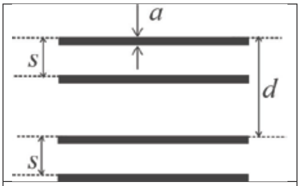


Figure 9: Set of four wires

Initial adjustments

1. Switch on the laser source and adjust both reflectors so that the laser spot falls on the screen.
2. Use the plastic scale and adjust the laser mount and reflectors such that the laser beam is parallel to the wooden platform.
3. Make sure that the laser spot falls near the centre of the screen.
4. Switch off the laser source. Clamp the pattern marking sheet on the screen.
5. Clamp the given plane mirror on the screen using plastic clips and switch on the laser again.
6. Adjust the screen so that the laser beam retraces its path back to the laser source. Remove the mirror once your alignment is completed.
7. Lights in the cubicle may be switched on/off as required.

Experiment

Part A: Determination of geometrical parameters of a helical spring[2]

Sample I is a helical spring of radius R and pitch P made of a wire of uniform thickness a_1 as shown in Fig. 10(a). When viewed at normal incidence its projection is equivalent to two sets of parallel wires of the same thickness separated by distance d_1 and angle $2\alpha_1$ between them (Fig. 10(b)).

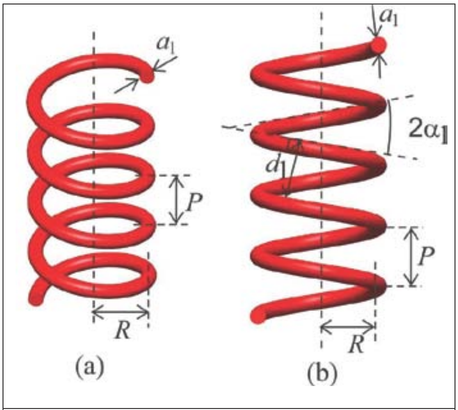


Figure 10: (a) Typical view of helical spring (b) Schematic diagram when viewed at normal incidence

---

[2] Reference: G. Braun, D. Tierney and H. Schmitzer, Phys. Teach. **49**, 140 (2011).

- Mount sample I in the sample holder ensuring that the spring is vertical.
- Obtain a clear and sharp X-shaped diffraction pattern on the pattern marking sheet.
- For this you may adjust
  - laser beam focus (rotate lens cap)
  - beam orientation (rotate the laser body so that only two turns of the spring are illuminated)
  - laser intensity (high/low switch on power supply)
  - ambient light (by switching on or off cubicle light)

If the central maximum is very bright, you may stick circular black stickers on the pattern marking sheet to reduce scattering.

Tasks	Description	Marks
A1	Mark the appropriate positions (using given pencil [13]) of the intensity minima to determine a_1 and d_1 on the both sides of the central spot on the pattern-marking sheet. Please label your pattern-marking sheets as P-1, P-2 etc.	**0.7**
A2	Measure the appropriate distances using digital calipers and record them in Table A1 for determining a_1.	**0.5**
A3	Plot a suitable graph, label it Graph A1 and from the slope, determine a_1.	**0.7**
A4	Measure the appropriate distances and record them in Table A2 for determining d_1.	**0.8**
A5	Plot a suitable graph, label it Graph A2 and from the slope, determine d_1.	**0.6**
A6	From the X-shaped pattern, determine the angle α_1.	**0.2**
A7	Express P in terms of d_1 and α_1 and calculate P.	**0.2**
A8	Express R in terms of P and α_1 and calculate R (neglect a_1).	**0.2**

Part B: Determination of geometrical parameters of double-helix-like pattern

Figure 11(a) shows two turns of a double helix. Fig. 11(b) is a two-dimensional projection of this double helix when viewed at normal incidence. Each helix of thickness a_2 has an angle $2\alpha_2$ and perpendicular distance d_2 between turns. The separation between two helices is s. Sample II is a double-helix-like pattern printed on glass plate (Fig. 12), whose diffraction pattern is similar to that of a double helix. In this part, you will determine the geometrical parameters of sample II.

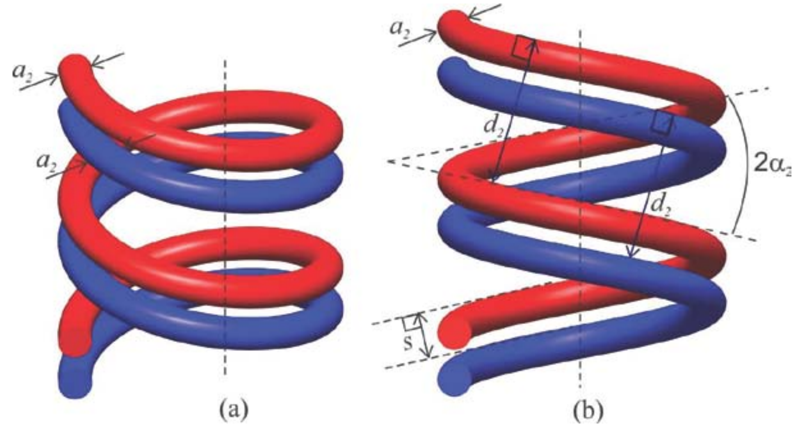


Figure 11: (a) Typical view of double-helical spring (b) Its schematic diagram when viewed at normal incidence.

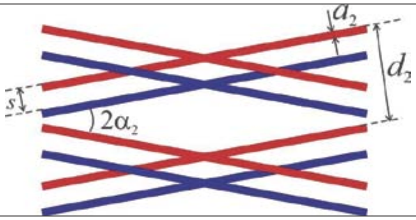


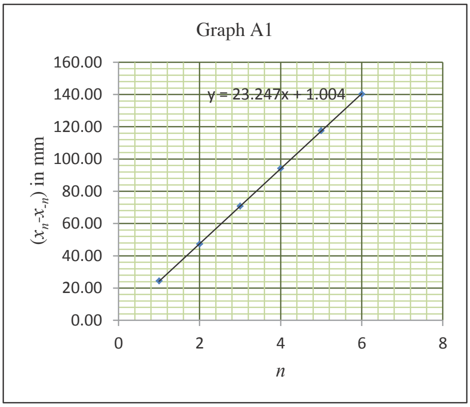
Figure 12: Double-helix-like pattern of sample II

- Mount the sample II in sample holder.
- Attach a new pattern-marking sheet on the screen.
- Obtain clear and sharp X-shaped diffraction pattern on the screen.

Tasks	Description	Marks
B1	Mark the appropriate positions of the minima on either side of the central spot to determine a_2, s and d_2. You can use more than one pattern marking sheets.	**1.1**
B2	Measure the appropriate distances and record them in Table B1 for determining a_2	**0.5**
B3	Plot suitable graph, label it Graph B1 and from the slope, determine a_2.	**0.5**
B4	Measure the appropriate distances and record them in Table B2 for determining s.	**1.2**
B5	Plot suitable graph, label it Graph B2 and from the slope determine s.	**0.5**
B6	Measure the appropriate distances and record them in Table B3 for determining d_2	**1.6**
B7	Plot suitable graph, label it Graph B3 and from the slope, determine d_2.	**0.5**
B8	From the X-shaped pattern, determine the angle α_2.	**0.2**

Diffraction due to Helical Structure[1]

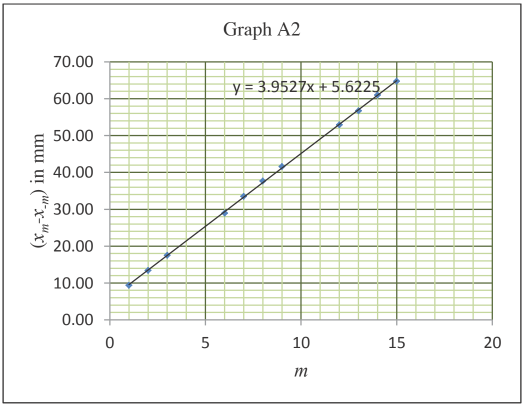
Part A: Determination of geometrical parameters of a helical spring

<table>
<tr><th>Tasks</th><th>Description</th><th>Marks</th></tr>
<tr><td>A1</td><td>Number of attached pattern marking sheet(s) for Part A: 2 with label(s): P1, P2 (patterns on page 7)</td><td>0.7</td></tr>
<tr><td>A2</td><td>Table A1: Observations from pattern P1
<table>
<tr><th>Sr. No.</th><th>Order (n)</th><th>$(x_n - x_{-n})$ in mm</th></tr>
<tr><td>1</td><td>1</td><td>24.40</td></tr>
<tr><td>2</td><td>2</td><td>47.24</td></tr>
<tr><td>3</td><td>3</td><td>70.69</td></tr>
<tr><td>4</td><td>4</td><td>94.08</td></tr>
<tr><td>5</td><td>5</td><td>117.53</td></tr>
<tr><td>6</td><td>6</td><td>140.28</td></tr>
</table></td><td>0.5</td></tr>
<tr><td>A3</td><td>

Graph A1 for determination of a_1: n versus $(x_n - x_{-n})$
Slope of the graph A1 = 23.25 mm
Calculation of a_1:
$a_1 = 2 \times \lambda \times \frac{D}{\text{Slope}} = 2 \times \lambda \times \frac{2770}{23.25}$
$a_1 = 0.151$ mm</td><td>0.7</td></tr>
</table>

---

[1] *Praveen Pathak (HBCSE-TIFR, Mumbai), Charudatt Kadolkar (IIT, Guwahati), and Manish Kapoor (Christ Church College, Kanpur) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

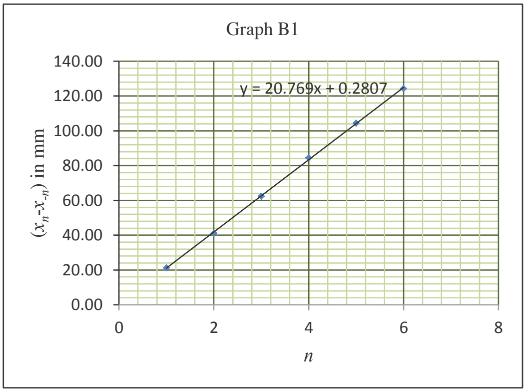
<table>
<tr>
<td>A4</td>
<td>
Table A2: Observations from pattern P1
<table>
<tr><th>Sr. No.</th><th>m</th><th>$(x_m - x_{-m})$ in mm</th></tr>
<tr><td>1</td><td>1</td><td>9.39</td></tr>
<tr><td>2</td><td>2</td><td>13.43</td></tr>
<tr><td>3</td><td>3</td><td>17.53</td></tr>
<tr><td>4</td><td>6</td><td>28.98</td></tr>
<tr><td>5</td><td>7</td><td>33.53</td></tr>
<tr><td>6</td><td>8</td><td>37.66</td></tr>
<tr><td>7</td><td>9</td><td>41.61</td></tr>
<tr><td>8</td><td>12</td><td>52.93</td></tr>
<tr><td>9</td><td>13</td><td>56.76</td></tr>
<tr><td>10</td><td>14</td><td>61.03</td></tr>
<tr><td>11</td><td>15</td><td>64.74</td></tr>
</table>
</td>
<td>0.8</td>
</tr>
<tr>
<td>A5</td>
<td>


Graph A2 for determination of d_1: m versus $(x_m - x_{-m})$
Slope of the graph A2 = 3.95 mm
Calculation of d_1:
$d_1 = 2 \times \lambda \times \frac{D}{\text{Slope}} = 2 \times 0.000635 \times \frac{2770}{3.95}$
$d_1 = 0.89\ mm$
</td>
<td>0.6</td>
</tr>
<tr>
<td>A6</td>
<td>$\alpha_1 = 10.96°$</td>
<td>0.2</td>
</tr>
<tr>
<td>A7</td>
<td>Expression of P in terms of d_1 and α_1:</td>
<td>0.2</td>
</tr>
</table>

	$P = \dfrac{d_1}{\cos\alpha_1} = \dfrac{0.89}{\cos 10.96}$ $P = 0.91$ mm	

A8	Expression of R in terms of P and α_1: $\tan\alpha_1 = \dfrac{P}{2\pi R}$ $R = \dfrac{P}{2\times\pi\times\tan\alpha_1} = \dfrac{0.91}{2\times\pi\times\tan 10.96}$ $R = 0.75$ mm	**0.2**
	Total	**3.9**

Part B: Determination of geometrical parameters of double-helix-like pattern

<table>
<tr><th>Tasks</th><th>Description</th><th>Marks</th></tr>
<tr><td>B1</td><td>Attached pattern marking sheet number(s): 2 with label(s): P3, P4 (patterns on page 7)</td><td>1.1</td></tr>
<tr><td>B2</td><td>Table B1: Observations from pattern P3
<table>
<tr><th>Sr. No.</th><th>Order (n)</th><th>$(x_n - x_{-n})$ in mm</th></tr>
<tr><td>1</td><td>1</td><td>21.24</td></tr>
<tr><td>2</td><td>2</td><td>41.12</td></tr>
<tr><td>3</td><td>3</td><td>62.41</td></tr>
<tr><td>4</td><td>4</td><td>84.40</td></tr>
<tr><td>5</td><td>5</td><td>104.41</td></tr>
<tr><td>6</td><td>6</td><td>124.25</td></tr>
</table></td><td>0.5</td></tr>
<tr><td>B3</td><td>

Graph B1 for determination of a_2: n versus $(x_n - x_{-n})$</td><td>0.5</td></tr>
</table>

Slope of the graph B1 = 20.8 mm

Calculation of a_2: $a_2 = 2 \times \lambda \times \frac{D}{\text{Slope}} = 2 \times 0.000635 \times \frac{795}{20.8}$

$a_2 = 0.049$ mm

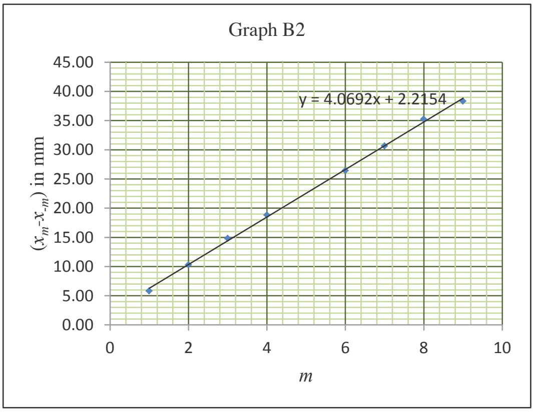
B4

Table B2: Observations from pattern P3

Sr. No.	m	$(x_m - x_{-m})$ in mm
1	1	5.84
2	2	10.29
3	3	14.83
4	4	18.84
5	6	26.44
6	7	30.65
7	8	35.26
8	9	38.34

1.2

B5



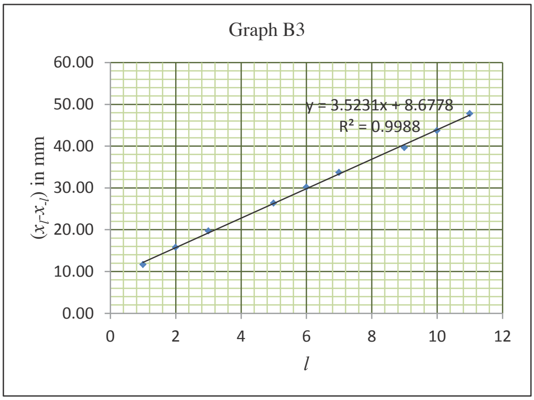
Graph B2 for determination of s: m versus $(x_m - x_{-m})$

Slope of the graph B2 = 4.07 mm

Calculation of s: $s = 2 \times \lambda \times \frac{D}{\text{Slope}} = 2 \times 0.000635 \times \frac{795}{4.07}$

$s = 0.248$ mm

0.5

<table>
<tr>
<td>B6</td>
<td>Table B3 Observations from pattern P4
<table>
<tr><th>Sr. No.</th><th>Order (l)</th><th>($x_l - x_{-l}$) in mm</th></tr>
<tr><td>1</td><td>1</td><td>11.64</td></tr>
<tr><td>2</td><td>2</td><td>15.77</td></tr>
<tr><td>3</td><td>3</td><td>19.71</td></tr>
<tr><td>4</td><td>5</td><td>26.33</td></tr>
<tr><td>5</td><td>6</td><td>30.14</td></tr>
<tr><td>6</td><td>7</td><td>33.69</td></tr>
<tr><td>7</td><td>9</td><td>39.62</td></tr>
<tr><td>8</td><td>10</td><td>43.70</td></tr>
<tr><td>9</td><td>11</td><td>47.75</td></tr>
</table>
</td>
<td>1.6</td>
</tr>
<tr>
<td>B7</td>
<td>

Graph B3 for determination of d_2: l versus ($x_l - x_{-l}$)
Slope of the graph B3 = 3.52 mm
Calculation of d_2: $d_2 = 2 \times \frac{\lambda \times D}{\text{Slope}} = 2 \times 0.000635 \times \frac{2770}{3.52}$
$d_2 = 1.00$ mm</td>
<td>0.5</td>
</tr>
<tr>
<td>B8</td>
<td>$\alpha_2 = 9.88°$</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>6.1</td>
</tr>
</table>

Reference for Part A : G. Braun, D. Tierney and H. Schmitzer, Phys. Teach. **49**, 140 (2011).

	$\tan 2\alpha_1 = \frac{42.43}{105.40}$ $\alpha_1 = 10.96\,°$ 
Pattern P1 ($D = 2770$ mm)	Pattern P2
$\tan 2\alpha_2 = \frac{36.67}{102.04}$ $\alpha_2 = 9.88°$ 	
Pattern P3 ($D = 795$ mm)	Pattern P4 ($D = 2770$ mm)

Diffraction due to surface tension waves on water[1]

Introduction

Formation and propagation of waves on a liquid surface are important and well-studied phenomena. For such waves, the restoring force on the oscillating liquid is partly due to gravity and partly due to surface tension. For wavelengths much smaller than a critical wavelength, λ_c, the effect of gravity is negligible and only surface tension effects need be considered ($\lambda_c = 2\pi\sqrt{\frac{\sigma}{\rho g}}$, where σ is the surface tension, ρ is the density of the liquid and g is the acceleration due to gravity).

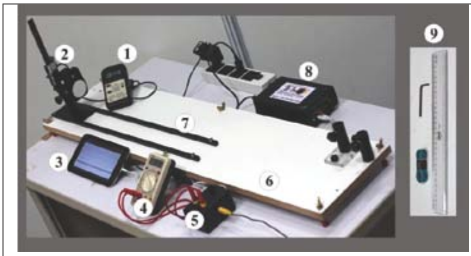
In this part, you will study surface tension waves on the surface of a liquid, which have wavelengths smaller than λ_c. Surface tension is a property of liquids due to which the liquid surface behaves like a stretched membrane. When the liquid surface is disturbed, the disturbance propagates as a wave just as on a membrane. An electrically-driven vibrator is used to produce waves on the water surface. When a laser beam is incident at a glancing angle on these surface waves, they act as a reflection grating, producing a well-defined diffraction pattern.

Surface tension waves are damped (their amplitude gradually decreases) as they propagate. This damping is due to the viscosity of the liquid, a property where adjacent layers of a liquid oppose relative motion between them.

Objective

To use diffraction from surface tension waves on water to determine surface tension and viscosity of the given water sample.

List of apparatus

	[1]	Light meter (connected to light sensor assembly)
	[2]	Light sensor assembly mounted on vernier caliper placed on a screen base
	[3]	Tablet computer (used as sine wave generator)
	[4]	Digital multimeter
	[5]	Vibrator control box
	[6]	Wooden platform
	[7]	Track for moving light sensor assembly
	[8]	DC regulated power supply
	[9]	Hex key, measuring tape and plastic scale
Figure 1: Wooden platform unit		
	[10]	Scale and rider with vibrator position marker
	[11]	Vibrator assembly
	[12]	Water tray
	[13]	Plastic cover
	[14]	Assembly for adjusting vibrator height
	[15]	Laser source 2 (Wavelength, $\lambda_L = 635$ nm, 1nm = 10^{-9} m)

---

[1] *Shirish Pathare (HBCSE, Mumbai) and K G M Nair (CMI, Chennai) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

	[16]	Water sample for the experiment
	[17]	500 ml measuring cylinder

Figure 2: Vibrator/laser source unit

Description of apparatus

a) Tablet computer as sine wave generator

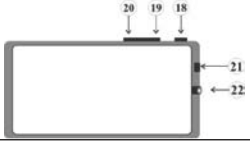
	[18]: Power Switch
	[19]: Volume up
	[20]: Volume down
	[21]: Charging port
	[22]: Socket for Audio connector pin of cable coming from vibrator control box[5]

Figure 3: Switches and sockets of the tablet

Note
- Keep the tablet always charging.
- Gently press the power switch *once* to display initial screen.
- Keep the output volume at maximum using the "Volume up" button[19].

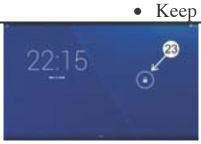
	Touch and slide the icon[23] to unlock		Tap the icon [24] to start the sine wave generator

Figure 4: Initial screens of the tablet

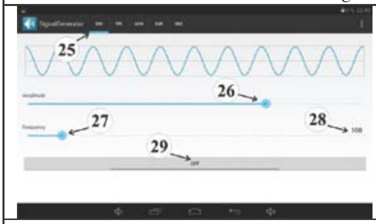
	[25]: Waveform selector (always keep at "SIN")
	[26]: Amplitude slider
	[27]: Frequency slider
	[28]: Frequency value field [Hz]
	[29]: Application status indicator/switch "OFF" - the sine wave generator is OFF "ON" - the sine wave generator is ON

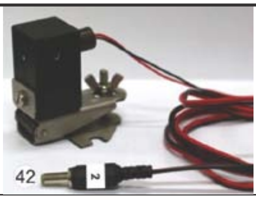
Figure 5: The sine wave generator application

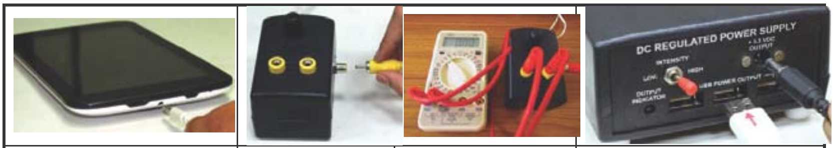
	*To vary frequency* • Tap frequency value field [28] (Fig. 5) to reveal number pad • Use backspace button [30] to erase frequency value • Enter the required frequency, and press "Finished" button[31]

Figure 6: Screen showing number pad to enter frequency value

To vary amplitude
- Use amplitude slider [26] on tablet screen or the variable knob [33] on vibrator control box [5] to vary output amplitude.

b) Vibrator control box, digital multimeter, DC regulated power supply and their connections

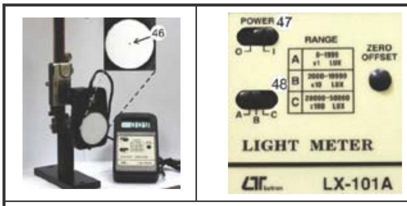
		
[32]: Sockets to connect cables from multimeter	[37]: Vibrator strip	Figure 10: Laser source 2 [15] (mounted on a metal block) with connector [42]
[33]: Knob for varying amplitude of the sine wave	[38]: Pin of the cable from vibrator assembly	
[34]: Socket for pin of the cable from the vibrator assembly	Figure 8: Vibrator assembly[11]	
[35]: USB pin to be connected to DC regulated power supply	 [39]: AC/DC selector switch	[43]: Intensity switch (keep on "High" position)
[36]: Audio pin to be connected to the tablet	[40]: Range selector knob	[44]: USB socket for USB pin from vibrator control box
	[41]: Input sockets	[45]: Socket for connector from laser source 2
Figure 7: Vibrator control box[5]	Figure 9: Digital multimeter[4]	Figure 11: DC regulated power supply[8]



[36]→[22]	[38]→[34]	[41]↔[32]	[35]→[44] and [42]→[45]

Figure 12: Connections between tablet, vibrator control box and DC regulated power supply

c) Light sensor assembly and light meter



[46]: Circular aperture on the light sensor
[47]: Power switch of the light meter
[48]: A, B, C – Sensitivity ranges of the light meter

Figure 13: Light sensor assembly and light meter

One jaw of the vernier caliper fits into a slot at the back of the light sensor

Tighten the screw using the hex key

Figure 14: Attaching light sensor assembly

Initial Adjustments

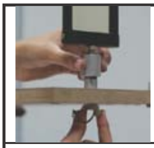


Figure 15: Removing the right reflector

Figure 16: Base screws touching the wooden strip

Figure 17: Correct position of the vibrator strip and black knob for height adjustment

1. Disconnect the laser 1 connector and insert the laser 2 connector into the socket of the DC regulated power supply. Note: Laser 2 has been already adjusted for a specific angle of incidence. Do not touch the laser source!

2. Remove the right reflector used in E-I by turning the bolt under the wooden platform (Fig. 15).

3. Remove the screen used in E-I and insert the light sensor assembly into the screen base. Place the screen base between the guiding rails of the track.

4. Position the wooden platform [6] with its base screws touching the wooden strip attached to the working table (Fig. 16).

5. Raise the side flap of the plastic cover on the vibrator/laser source unit. Pour exactly 500 ml of the water sample into the tray [12] using the measuring cylinder [17].

6. Switch on the laser. Locate the reflected laser spot on the light sensor. As you move the light sensor assembly back and forth along the track, the laser spot should move vertically and not at an angle to the vertical. Minor lateral adjustment of the wooden platform and vertical movement of light sensor assembly will allow you to get the laser spot exactly on the aperture. The intensity shown by the light meter will be maximum, if the centre of the laser spot coincides with the centre of the aperture,.

7. The vibrator strip has already been arranged in the correct vertical position. Do NOT change the black knob of the height adjustment assembly [14] (Fig. 17).

8. The vibrator assembly can be moved back and forth horizontally. Vibrator position marker indicates the position of the assembly on the scale [10].

9. While recording data, keep the flap of the plastic cover lowered in order to protect the water surface from air currents.

Experiment

Part C: Measurement of angle θ between the laser beam and the water surface

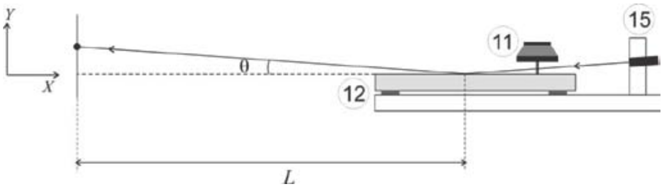


Figure 18: Measurement of angle θ

Tasks	Description	Marks
C1	Move the light sensor assembly in suitable steps along the track. Note down the X–displacement of the assembly and the corresponding Y-displacement of the laser spot. Record your readings in Table C1. (Select appropriate range in the light meter.)	**1.0**
C2	Plot a suitable graph (label it Graph C1) and determine the angle θ in degrees from its slope.	**0.6**

Part D: Determination of surface tension σ of the given water sample

From diffraction theory it can be shown that

$$k = \frac{2\pi}{\lambda_L} sin\theta \; sin\gamma \qquad (1)$$

where, $k = {}^{2\pi}/_{\lambda_w}$ is the wave number of the surface tension waves,

λ_w and λ_L being the wavelengths of the surface tension waves and the laser respectively.

The angle γ is the angular distance between the central maximum and the first-order maximum (Fig. 19).

The vibration frequency (f) of the waves is related to the wave number k by

$$\omega = \sqrt{\frac{\sigma}{\rho} k^q} \qquad (2)$$

where, $\omega = 2\pi f$, ρ is the density of the water and q is an integer.

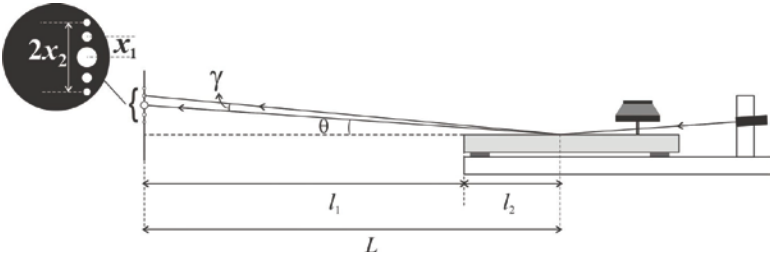


Figure 19: Schematic diagram of the apparatus

1. Fix the light sensor assembly (using the tightening bolt at the screen base) at the position shown in Fig. 1. Select the appropriate range on the light meter.

Task	Description	Marks
D1	Measure the length l_1 between the light sensor aperture and outer edge of the water tray. You will see a line where the laser strikes the water surface. The centre of this line is the point of incidence of the laser. Measure l_2, the distance of this point from the edge. Obtain L. Record it on your answersheet.	**0.3**

2. Set the vibrator position marker at 7.0 cm mark on the horizontal scale [10].
3. Set the sine wave frequency to 60 Hz and adjust its amplitude such that the first- and second-order maxima of the diffraction pattern are clearly visible (Fig. 19 inset).

Tasks	Description	Marks
D2	Measure the distance between the second-order maximum above and below the central maximum. Hence calculate x_1. Record your observations in Table D1. Repeat this by increasing the frequencies in appropriate steps.	**2.8**
D3	Identify the appropriate variables for a suitable graph whose slope would give the value of q. Enter the variable values in Table D2. Plot the graph to find q (label it Graph D1). Write down equation 2 with the appropriate integer value of q.	**0.9**
D4	From the equation 2, identify the appropriate variables for a suitable graph whose slope would give the value of σ. Enter the variable values in Table D3. Plot the graph to determine σ (label it Graph D2). (ρ=1000 kg.m^{-3}).	**1.2**

Part E: Determination of the attenuation constant, δ and the viscosity of the liquid, η

The surface tension waves are damped due to the viscosity of water. The wave amplitude, h, decreases exponentially with the distance, s, measured from the vibrator,

$$h = h_0 e^{-\delta s} \tag{3}$$

where, h_0 is the amplitude at the vibrator position and δ is the attenuation constant.

Experimentally, amplitude h_0 can be related to the voltage (V_{rms}) applied to the vibrator assembly as,

$$h_0 \propto (V_{rms})^{0.4} \tag{4}$$

The attenuation constant is related to the viscosity of the liquid as

$$\delta = \frac{8}{3}\frac{\pi\eta f}{\sigma} \tag{5}$$

where, η is the viscosity of the liquid.

1. Set the vibrator position marker at 8.0 cm.
2. Adjust the frequency to 100 Hz.
3. Adjust the light sensor using the vernier caliper such that the first-order maximum of the diffraction pattern falls on the aperture.
4. Adjust the amplitude of sine wave (V_{rms}) such that the reading in the light meter is 100 on range A. Note down V_{rms} corresponding to the light meter reading.
5. Move the vibrator away from the point of incidence of the laser in steps of 0.5 cm and adjust V_{rms} to get the light meter reading 100. Note down corresponding V_{rms}.

Tasks	Description	Marks
E1	Record your data for every step in Table E1.	**1.9**
E2	Plot a suitable graph (label it Graph E1) and determine the attenuation constant δ from its slope.	**1.0**
E3	Calculate the viscosity η of the given water sample.	**0.3**

Experiment 2 Solutions

Diffraction due to surface tension waves on water[1]

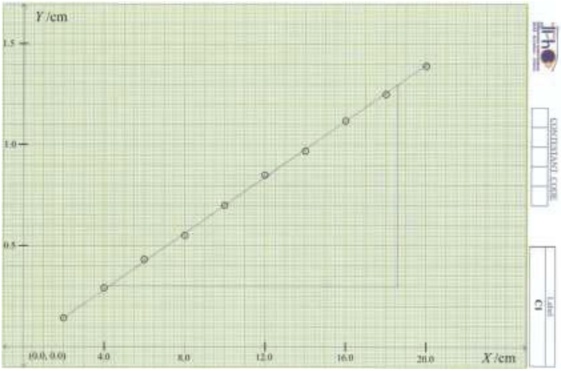
Part C: Measurement of angle, θ

[C1] **Table C1**

Obs. no.	X /cm	Y /cm
1	2.0	0.136
2	4.0	0.285
3	6.0	0.425
4	8.0	0.549
5	10.0	0.703
6	12.0	0.846
7	14.0	0.965
8	16.0	1.124
9	18.0	1.251
10	20.0	1.390

[C2]

Graph C1 for determination of θ: X versus Y



Slope = 0.0699

$$\boxed{\theta = 4.0°}$$

---

[1] *Shirish Pathare (HBCSE, Mumbai)and K G M Nair (CMI, Chennai) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

Part D: Determination of the surface tension of the liquid

[D1]:

$l_1 = 98.5$ cm

$l_2 = 5.5$ cm

$L = 1.04$ m

[D2]:

Table D1

Obs. no.	f /Hz	$2x_2$ /cm	x_1 /cm	x_1 /m
1	60	0.782	0.196	0.00196
2	70	0.880	0.220	0.00220
3	80	0.966	0.242	0.00242
4	90	1.030	0.258	0.00258
5	100	1.096	0.274	0.00274
6	110	1.184	0.296	0.00296
7	120	1.253	0.313	0.00313
8	130	1.336	0.334	0.00334
9	140	1.415	0.354	0.00354
10	150	1.489	0.372	0.00372
11	160	1.545	0.386	0.00386

[D3]:

$$\omega^2 = \frac{\sigma}{\rho} k^q$$

$$f^2 = \frac{1}{4\pi^2} \frac{\sigma}{\rho} \left(\frac{2\pi}{\lambda} \frac{\sin\theta}{L} \right)^q (x_1)^q$$

$$\ln f = \frac{1}{2} \ln \left[\frac{1}{4\pi^2} \frac{\sigma}{\rho} \left(\frac{2\pi}{\lambda} \frac{\sin\theta}{L} \right)^q \right] + \frac{q}{2} \ln x_1$$

Graph for determination of q: ln(f) versus ln(x_1)

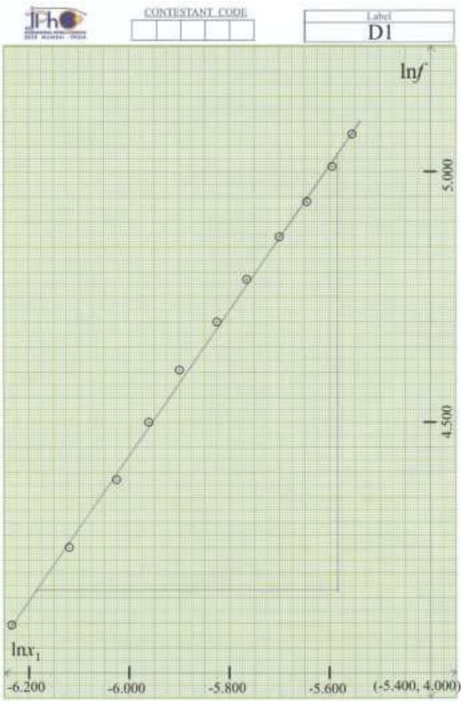


Table D2		
Obs. No.	**ln x_1**	**ln f**
1	-6.235	4.094
2	-6.119	4.248
3	-6.024	4.382
4	-5.960	4.500
5	-5.900	4.605
6	-5.823	4.700
7	-5.767	4.787
8	-5.702	4.868
9	-5.644	4.942
10	-5.594	5.011
11	-5.557	5.075

Slope = 1.45

q = 2.90

Determination of surface tension:

Equation 2:

$$\omega^2 = \frac{\sigma}{\rho} k^3$$

[D4]:

Graph for determination of σ: f^2 versus x_1^3

Table D3

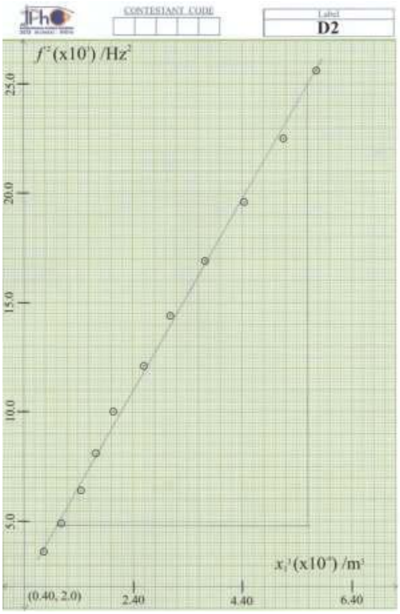
Obs. No.	f^2(×10^3) /Hz^2	x_1^3(×10^{-8}) /m^3
1	3.6	0.75
2	4.9	1.07
3	6.4	1.42
4	8.1	1.72
5	10.0	2.06
6	12.1	2.59
7	14.4	3.07
8	16.9	3.73
9	19.6	4.44
10	22.5	5.15
11	25.6	5.75

Surface Tension:

$$\omega^2 = \frac{\sigma}{\rho} k^3$$

$$f^2 = \frac{\sigma}{\rho} \frac{2\pi}{\lambda^3} \frac{\sin^3\theta}{L^3} (x_1)^3$$

Calculations:



Slope = 4.39 × 10^{11} Hz^2/m^3

$$\therefore \text{ Slope } = \frac{\sigma}{\rho} \frac{2\pi}{\lambda^3} \frac{\sin^3\theta}{L^3} = \frac{\sigma}{1000} \times \frac{2 \times 3.14}{\left(635 \times 10^{-9}\right)^3} \times \frac{(0.0698)^3}{(1.04)^3}$$

$$\boxed{\therefore \sigma = 59.2 \text{ mN/m}}$$

Part E: Determination of the viscosity of the water sample

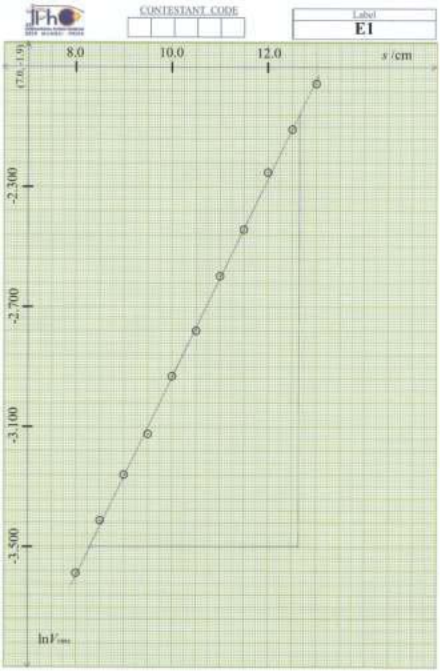
[E1]: Frequency of the signal generator = **100 Hz**

Table E1

Obs. No.	s /cm	V_{rms} /V	$\ln(V_{rms})$
1	8.0	0.0276	-3.590
2	8.5	0.0330	-3.411
3	9.0	0.0385	-3.257
4	9.5	0.0441	-3.121
5	10.0	0.0534	-2.930
6	10.5	0.0622	-2.777
7	11.0	0.0745	-2.597
8	11.5	0.0870	-2.442
9	12.0	0.1050	-2.254
10	12.5	0.1215	-2.108
11	13.0	0.1412	-1.958

[E2]:

Graph for determination of δ: ln (V_{rms}) versus s



Slope = 0.331 cm^{-1}

$\therefore \delta = 0.4 \times 0.3310 = 0.1324$ cm^{-1}

$$\boxed{\delta = 13.2 \text{ m}^{-1}}$$

[E3]:

Determination of viscosity, η:

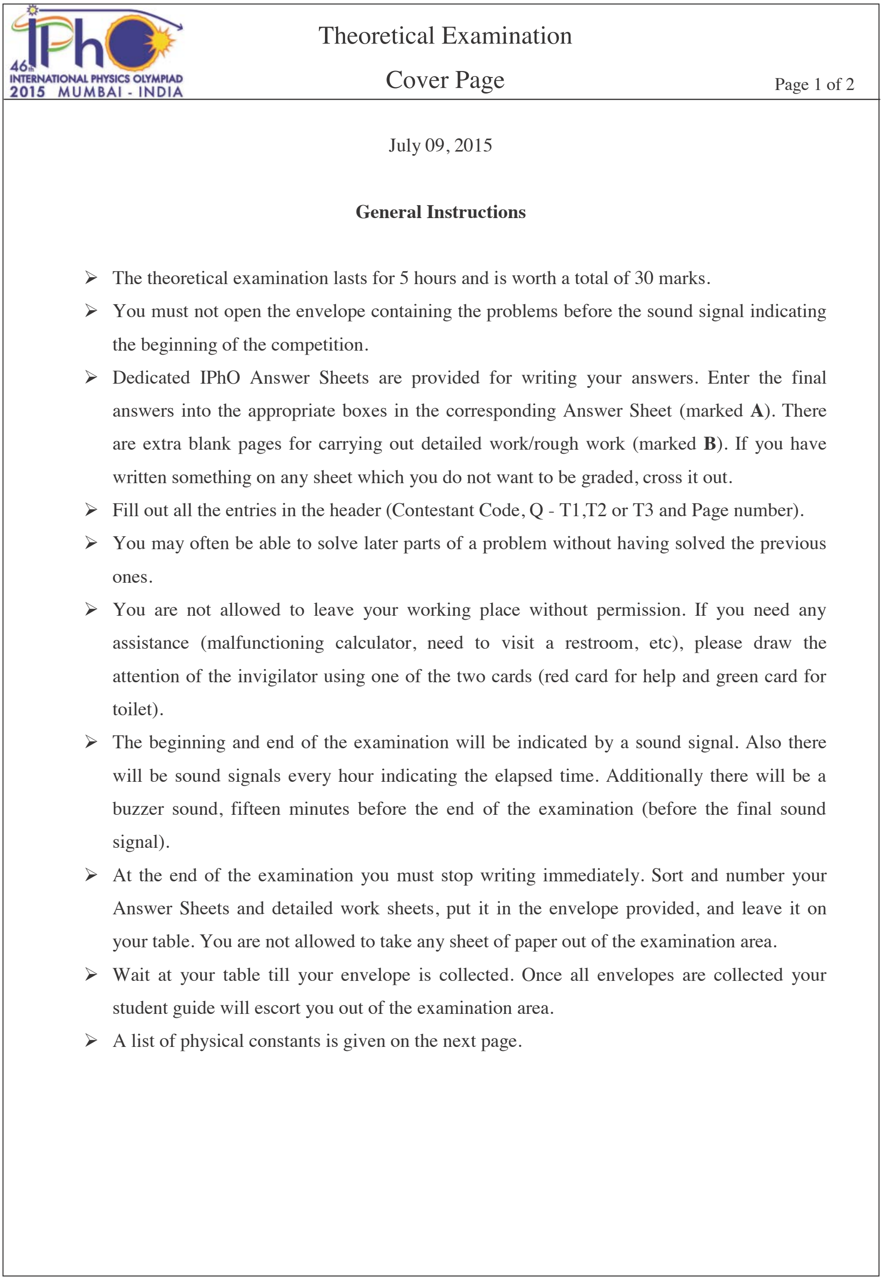
$$\delta = \frac{8}{3}\frac{\pi\eta f}{\sigma}$$

$$\eta = \frac{3}{8}\frac{\delta\sigma}{\pi f} = \frac{3}{8} \times \frac{13.2 \times 59.2 \times 10^{-3}}{3.14 \times 100} 0.933 \text{ mPa} \cdot \text{s}$$

$$\boxed{\eta = 0.93 \text{ mPa·s}}$$

Theoretical Tasks

Cover Page



46th INTERNATIONAL PHYSICS OLYMPIAD
2015 MUMBAI - INDIA

Theoretical Examination

Cover Page

Page 1 of 2

July 09, 2015

General Instructions

- The theoretical examination lasts for 5 hours and is worth a total of 30 marks.
- You must not open the envelope containing the problems before the sound signal indicating the beginning of the competition.
- Dedicated IPhO Answer Sheets are provided for writing your answers. Enter the final answers into the appropriate boxes in the corresponding Answer Sheet (marked **A**). There are extra blank pages for carrying out detailed work/rough work (marked **B**). If you have written something on any sheet which you do not want to be graded, cross it out.
- Fill out all the entries in the header (Contestant Code, Q - T1,T2 or T3 and Page number).
- You may often be able to solve later parts of a problem without having solved the previous ones.
- You are not allowed to leave your working place without permission. If you need any assistance (malfunctioning calculator, need to visit a restroom, etc), please draw the attention of the invigilator using one of the two cards (red card for help and green card for toilet).
- The beginning and end of the examination will be indicated by a sound signal. Also there will be sound signals every hour indicating the elapsed time. Additionally there will be a buzzer sound, fifteen minutes before the end of the examination (before the final sound signal).
- At the end of the examination you must stop writing immediately. Sort and number your Answer Sheets and detailed work sheets, put it in the envelope provided, and leave it on your table. You are not allowed to take any sheet of paper out of the examination area.
- Wait at your table till your envelope is collected. Once all envelopes are collected your student guide will escort you out of the examination area.
- A list of physical constants is given on the next page.

General Data Sheet

Acceleration due to gravity on Earth	g	$9.807\ \mathrm{m\ s^{-2}}$
Atmospheric pressure	P_{atm}	1.013×10^5 Pa
Avogadro number	N_{A}	$6.022 \times 10^{23}\ \mathrm{mol^{-1}}$
Boltzmann Constant	k_{B}	$1.381 \times 10^{-23}\ \mathrm{J\ K^{-1}}$
Binding energy of hydrogen atom	–	13.606 eV
Magnitude of electron charge	e	1.602×10^{-19} C
Mass of the electron	m_{e}	9.109×10^{-31} kg
Mass of the proton	m_{p}	1.673×10^{-27} kg
Mass of the neutron	m_{n}	1.675×10^{-27} kg
Permeability of free space	μ_0	$1.257 \times 10^{-6}\ \mathrm{H\ m^{-1}}$
Permittivity of free space	ϵ_0	$8.854 \times 10^{-12}\ \mathrm{F\ m^{-1}}$
Planck's constant	h	6.626×10^{-34} J s
Speed of sound in air (at room temperature)	c_{s}	$3.403 \times 10^{2}\ \mathrm{m\ s^{-1}}$
Speed of light in vacuum	c	$2.998 \times 10^{8}\ \mathrm{m\ s^{-1}}$
Stefan-Boltzmann constant	σ	$5.670 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$
Universal constant of Gravitation	G	$6.674 \times 10^{-11}\mathrm{N\ m^2\ kg^{-2}}$
Universal gas constant	R	$8.315\ \mathrm{J\ mol^{-1}\ K^{-1}}$

Theory 1 Questions

Q T-1

Page 1 of 2

Particles from the Sun[1] (Total Marks: 10)

Photons from the surface of the Sun and neutrinos from its core can tell us about solar temperatures and also confirm that the Sun shines because of nuclear reactions.

Throughout this problem, take the mass of the Sun to be $M_\odot = 2.00 \times 10^{30}$ kg, its radius, $R_\odot = 7.00 \times 10^{8}$ m, its luminosity (radiation energy emitted per unit time), $L_\odot = 3.85 \times 10^{26}$ W, and the Earth-Sun distance, $d_\odot = 1.50 \times 10^{11}$ m.

Note:

(i) $\int x e^{ax} dx = \left(\frac{x}{a} - \frac{1}{a^2}\right) e^{ax} +$ constant

(ii) $\int x^2 e^{ax} dx = \left(\frac{x^2}{a} - \frac{2x}{a^2} + \frac{2}{a^3}\right) e^{ax} +$ constant

(iii) $\int x^3 e^{ax} dx = \left(\frac{x^3}{a} - \frac{3x^2}{a^2} + \frac{6x}{a^3} - \frac{6}{a^4}\right) e^{ax} +$ constant

A Radiation from the sun :

A1	Assume that the Sun radiates like a perfect blackbody. Use this fact to calculate the temperature, T_s, of the solar surface.	**0.3**

The spectrum of solar radiation can be approximated well by the Wien distribution law. Accordingly, the solar energy incident on any surface on the Earth per unit time per unit frequency interval, $u(\nu)$, is given by

$$u(\nu) = A \frac{R_\odot^2}{d_\odot^2} \frac{2\pi h}{c^2} \nu^3 \exp(-h\nu / k_B T_s),$$

where ν is the frequency and A is the area of the surface normal to the direction of the incident radiation.

Now, consider a solar cell which consists of a thin disc of semiconducting material of area, A, placed perpendicular to the direction of the Sun's rays.

A2	Using the Wien approximation, express the total radiated solar power, P_{in}, incident on the surface of the solar cell, in terms of A, $R_\odot$, $d_\odot$, T_s and the fundamental constants c, h, k_B.	**0.3**
A3	Express the number of photons, $n_\gamma(\nu)$, per unit time per unit frequency interval incident on the surface of the solar cell in terms of A, $R_\odot$, $d_\odot$, T_s, ν and the fundamental constants c, h, k_B.	**0.2**

The semiconducting material of the solar cell has a "band gap" of energy, E_g. We assume the following model. Every photon of energy $E \geq E_g$ excites an electron across the band gap. This electron contributes an energy, E_g, as the useful output energy, and any extra energy is dissipated as heat (not converted to useful energy).

A4	Define $x_g = h\nu_g / k_B T_s$ where $E_g = h\nu_g$. Express the useful output power of the cell, P_{out}, in terms of x_g, A, $R_\odot$, $d_\odot$, T_s and the fundamental constants c, h, k_B.	**1.0**
A5	Express the efficiency, η, of this solar cell in terms of x_g.	**0.2**
A6	Make a qualitative sketch of η versus x_g. The values at $x_g = 0$ and $x_g \to \infty$ should be clearly shown. What is the slope of $\eta(x_g)$ at $x_g = 0$ and $x_g \to \infty$?	**1.0**
A7	Let x_0 be the value of x_g for which η is maximum. Obtain the cubic equation that gives x_0. Estimate the value of x_0 within an accuracy of ± 0.25. Hence calculate $\eta(x_0)$.	**1.0**
A8	The band gap of pure silicon is $E_g = 1.11$ eV. Calculate the efficiency, η_{Si}, of a silicon solar cell using this value.	**0.2**

---

[1] *Amol Dighe (TIFR), Anwesh Mazumdar (HBCSE-TIFR) and Vijay A. Singh (ex-National Coordinator, Science Olympiads) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

In the late nineteenth century, Kelvin and Helmholtz (KH) proposed a hypothesis to explain how the Sun shines. They postulated that starting as a very large cloud of matter of mass, $M_{\odot}$, and negligible density, the Sun has been shrinking continuously. The shining of the Sun would then be due to the release of gravitational potential energy through this slow contraction.

A9	Let us assume that the density of matter is uniform inside the Sun. Find the total gravitational potential energy, Ω, of the Sun at present, in terms of G, $M_{\odot}$ and $R_{\odot}$.	**0.3**
A10	Estimate the maximum possible time, τ_{KH} (in years), for which the Sun could have been shining, according to the KH hypothesis. Assume that the luminosity of the Sun has been constant throughout this period.	**0.5**

The τ_{KH} calculated above does not match the age of the solar system estimated from studies of meteorites. This shows that the energy source of the Sun cannot be purely gravitational.

B Neutrinos from the Sun :

In 1938, Hans Bethe proposed that nuclear fusion of hydrogen into helium in the core of the Sun is the source of its energy. The net nuclear reaction is:

$$4\ {}^{1}\mathrm{H} \longrightarrow {}^{4}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}}$$

The “electron neutrinos”, ν_{e}, produced in this reaction may be taken to be massless. They escape the Sun and their detection on the Earth confirms the occurrence of nuclear reactions inside the Sun. Energy carried away by the neutrinos can be neglected in this problem.

B1	Calculate the flux density, Φ_{ν}, of the number of neutrinos arriving at the Earth, in units of $\mathrm{m}^{-2}\mathrm{s}^{-1}$. The energy released in the above reaction is $\Delta E = 4.0 \times 10^{-12}\mathrm{J}$. Assume that the energy radiated by the Sun is entirely due to this reaction.	**0.6**

Travelling from the core of the Sun to the Earth, some of the electron neutrinos, ν_{e}, are converted to other types of neutrinos, ν_{x}. The efficiency of the detector for detecting ν_{x} is 1/6 of its efficiency for detecting ν_{e}. If there is no neutrino conversion, we expect to detect an average of N_1 neutrinos in a year. However, due to the conversion, an average of N_2 neutrinos (ν_{e} and ν_{x} combined) are actually detected per year.

B2	In terms of N_1 and N_2, calculate what fraction, f, of ν_{e} is converted to ν_{x}.	**0.4**

In order to detect neutrinos, large detectors filled with water are constructed. Although the interactions of neutrinos with matter are very rare, occasionally they knock out electrons from water molecules in the detector. These energetic electrons move through water at high speeds, emitting electromagnetic radiation in the process. As long as the speed of such an electron is greater than the speed of light in water (refractive index, n), this radiation, called Cherenkov radiation, is emitted in the shape of a cone.

B3	Assume that an electron knocked out by a neutrino loses energy at a constant rate of α per unit time, while it travels through water. If this electron emits Cherenkov radiation for a time, Δt, determine the energy imparted to this electron (E_{imparted}) by the neutrino, in terms of α, Δt, n, m_{e} and c. (Assume the electron to be at rest before its interaction with the neutrino.)	**2.0**

The fusion of H into He inside the Sun takes place in several steps. Nucleus of ${}^{7}\mathrm{Be}$ (rest mass, m_{Be}) is produced in one of these intermediate steps. Subsequently, it can absorb an electron, producing a ${}^{7}\mathrm{Li}$ nucleus (rest mass, $m_{\mathrm{Li}} < m_{\mathrm{Be}}$) and emitting a ν_{e}. The corresponding nuclear reaction is:

$${}^{7}\mathrm{Be} + \mathrm{e}^{-} \longrightarrow {}^{7}\mathrm{Li} + \nu_{\mathrm{e}}$$

When a Be nucleus ($m_{\mathrm{Be}} = 11.65 \times 10^{-27}$ kg) is at rest and absorbs an electron also at rest, the emitted neutrino has energy $E_{\nu} = 1.44 \times 10^{-13}$ J. However, the Be nuclei are in random thermal motion due to the temperature T_{c} at the core of the Sun, and act as moving neutrino sources. As a result, the energy of emitted neutrinos fluctuates with a root mean square (rms) value ΔE_{rms}.

B4	If ΔE_{rms}=5.54×10^{-17}J, calculate the rms speed of the Be nuclei, V_{Be}, and hence estimate T_{c}. (Hint: ΔE_{rms} depends on the rms value of the component of velocity along the line of sight).	**2.0**

Theory 1 Solutions

Particles from the Sun[1]

Photons from the surface of the Sun and neutrinos from its core can tell us about solar temperatures and also confirm that the Sun shines because of nuclear reactions.

Throughout this problem, take the mass of the Sun to be $M_\odot = 2.00 \times 10^{30}$ kg, its radius, $R_\odot = 7.00 \times 10^8$ m, its luminosity (radiation energy emitted per unit time), $L_\odot = 3.85 \times 10^{26}$ W, and the Earth-Sun distance, $d_\odot = 1.50 \times 10^{11}$ m.

Note:

(i) $\int x e^{ax} dx = \left(\frac{x}{a} - \frac{1}{a^2}\right) e^{ax} + \text{constant}$

(ii) $\int x^2 e^{ax} dx = \left(\frac{x^2}{a} - \frac{2x}{a^2} + \frac{2}{a^3}\right) e^{ax} + \text{constant}$

(iii) $\int x^3 e^{ax} dx = \left(\frac{x^3}{a} - \frac{3x^2}{a^2} + \frac{6x}{a^3} - \frac{6}{a^4}\right) e^{ax} + \text{constant}$

A. Radiation from the Sun :

(A1) Assume that the Sun radiates like a perfect blackbody. Use this fact to calculate the temperature, T_s , of the solar surface. [0.3]

Solution:

Stefan's law: $L_\odot = (4\pi R_\odot^2)(\sigma T_\text{s}^4)$

$$T_\text{s} = \left(\frac{L_\odot}{4\pi R_\odot^2 \sigma}\right)^{1/4} = 5.76 \times 10^3 \text{ K}$$

The spectrum of solar radiation can be approximated well by the Wien distribution law. Accordingly, the solar energy incident on any surface on the Earth per unit time per unit frequency interval, $u(\nu)$, is given by

$$u(\nu) = A \frac{R_\odot^2}{d_\odot^2} \frac{2\pi h}{c^2} \nu^3 \exp(-h\nu/k_\text{B}T_\text{s}),$$

where A is the area of the surface normal to the direction of the incident radiation.

Now, consider a solar cell which consists of a thin disc of semiconducting material of area, A, placed perpendicular to the direction of the Sun's rays.

(A2) Using the Wien approximation, express the total power, P_in, incident on the surface of the solar cell, in terms of A, $R_\odot$, $d_\odot$, T_s and the fundamental constants c, h, k_B. [0.3]

---

[1] *Amol Dighe (TIFR), Anwesh Mazumdar (HBCSE-TIFR) and Vijay A. Singh (ex-National Coordinator, Science Olympiads) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

Solution:

$$P_{\text{in}} = \int_0^\infty u(\nu)d\nu = \int_0^\infty A\,\frac{R_\odot^2}{d_\odot^2}\,\frac{2\pi h}{c^2}\,\nu^3\exp(-h\nu/k_{\text{B}}T_{\text{s}})d\nu$$

Let $x = \dfrac{h\nu}{k_{\text{B}}T_{\text{s}}}$. Then, $\nu = \dfrac{k_{\text{B}}T_{\text{s}}}{h}x \qquad d\nu = \dfrac{k_{\text{B}}T_{\text{s}}}{h}dx.$

$$P_{\text{in}} = \frac{2\pi hAR_\odot^2}{c^2d_\odot^2}\,\frac{(k_{\text{B}}T_{\text{s}})^4}{h^4}\int_0^\infty x^3e^{-x}dx = \frac{2\pi k_{\text{B}}^4}{c^2h^3}\,{T_{\text{s}}}^4\,A\,\frac{R_\odot^2}{d_\odot^2}\cdot 6 = \frac{12\pi k_{\text{B}}^4}{c^2h^3}\,{T_{\text{s}}}^4\,A\,\frac{R_\odot^2}{d_\odot^2}$$

(A3) Express the number of photons, $n_\gamma(\nu)$, per unit time per unit frequency interval incident on the surface of the solar cell in terms of A, $R_\odot$, $d_\odot$, T_{s} ν and the fundamental constants c, h, k_{B}. [0.2]

Solution:

$$\begin{aligned} n_\gamma(\nu) &= \frac{u(\nu)}{h\nu} \\ &= A\,\frac{R_\odot^2}{d_\odot^2}\,\frac{2\pi}{c^2}\,\nu^2\exp(-h\nu/k_{\text{B}}T_{\text{s}}) \end{aligned}$$

The semiconducting material of the solar cell has a “band gap” of energy, E_{g}. We assume the following model. Every photon of energy $E \geq E_{\text{g}}$ excites an electron across the band gap. This electron contributes an energy, E_{g} , as the useful output energy, and any extra energy is dissipated as heat (not converted to useful energy).

(A4) Define $x_{\text{g}} = h\nu_{\text{g}}/k_{\text{B}}T_{\text{s}}$ where $E_{\text{g}} = h\nu_{\text{g}}$. Express the useful output power of the cell, P_{out}, in terms of x_{g}, A, $R_\odot$, $d_\odot$, T_{s} and the fundamental constants c, h, k_{B}. [1.0]

Solution:

The useful power output is the useful energy quantum per photon, $E_{\text{g}} \equiv h\nu_{\text{g}}$, multiplied by the number of photons with energy, $E \geq E_{\text{g}}$.

$$\begin{aligned} P_{\text{out}} &= h\nu_{\text{g}}\int_{\nu_{\text{g}}}^\infty n_\gamma(\nu)d\nu \\ &= h\nu_{\text{g}}\,A\,\frac{R_\odot^2}{d_\odot^2}\,\frac{2\pi}{c^2}\int_{\nu_{\text{g}}}^\infty \nu^2\exp(-h\nu/k_{\text{B}}T_{\text{s}})d\nu \\ &= k_{\text{B}}T_{\text{s}}x_{\text{g}}\,A\,\frac{R_\odot^2}{d_\odot^2}\,\frac{2\pi}{c^2}\left(\frac{k_{\text{B}}T_{\text{s}}}{h}\right)^3\int_{x_{\text{g}}}^\infty x^2e^{-x}dx \\ &= \frac{2\pi k_{\text{B}}^4}{c^2h^3}\,{T_{\text{s}}}^4\,A\,\frac{R_\odot^2}{d_\odot^2}\,x_{\text{g}}(x_{\text{g}}^2+2x_{\text{g}}+2)e^{-x_{\text{g}}} \end{aligned}$$

(A5) Express the efficiency, η, of this solar cell in terms of x_{g}. [0.2]

Solution:

Efficiency $\eta = \dfrac{P_{\text{out}}}{P_{\text{in}}} = \dfrac{x_{\text{g}}}{6}\,(x_{\text{g}}^2 + 2x_{\text{g}} + 2)e^{-x_{\text{g}}}$

(A6) Make a qualitative sketch of η versus x_{g}. The values at $x_{\text{g}} = 0$ and $x_{\text{g}} \to \infty$ should be clearly shown. What is the slope of $\eta(x_{\text{g}})$ at $x_{\text{g}} = 0$ and $x_{\text{g}} \to \infty$? [1.0]

Solution:

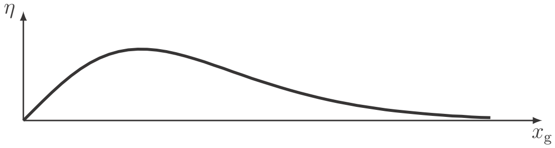
$$\eta = \frac{1}{6}\,(x_{\text{g}}^3 + 2x_{\text{g}}^2 + 2x_{\text{g}})e^{-x_{\text{g}}}$$

Put limiting values, $\eta(0) = 0 \qquad \eta(\infty) = 0$.

Since the polynomial has all positive coefficients, it increases monotonically; the exponential function decreases monotonically. Therefore, η has only one maximum.

$$\frac{\mathrm{d}\eta}{\mathrm{d}x_{\text{g}}} = \frac{1}{6}(-x_{\text{g}}^3 + x_{\text{g}}^2 + 2x_{\text{g}} + 2)e^{-x_{\text{g}}}$$

$$\left.\frac{\mathrm{d}\eta}{\mathrm{d}x_{\text{g}}}\right|_{x_{\text{g}}=0} = \frac{1}{3} \qquad \left.\frac{\mathrm{d}\eta}{\mathrm{d}x_{\text{g}}}\right|_{x_{\text{g}}\to\infty} = 0$$



(A7) Let x_0 be the value of x_{g} for which η is maximum. Obtain the cubic equation that gives x_0. Estimate the value of x_0 within an accuracy of ± 0.25. Hence calculate $\eta(x_0)$. [1.0]

Solution:

The maximum will be for $\dfrac{\mathrm{d}\eta}{\mathrm{d}x_{\text{g}}} = \dfrac{1}{6}(-x_{\text{g}}^3 + x_{\text{g}}^2 + 2x_{\text{g}} + 2)e^{-x_{\text{g}}} = 0$

$$\Rightarrow p(x_{\text{g}}) \equiv x_{\text{g}}^3 - x_{\text{g}}^2 - 2x_{\text{g}} - 2 = 0$$

A Numerical Solution by the Bisection Method:

Now,

$$\begin{aligned}
p(0) &= -2 \\
p(1) &= -4 \\
p(2) &= -2 \\
p(3) &= 10 & \Rightarrow\quad & 2 < x_0 < 3 \\
p(2.5) &= 2.375 & \Rightarrow\quad & 2 < x_0 < 2.5 \\
p(2.25) &= -0.171 & \Rightarrow\quad & 2.25 < x_0 < 2.5
\end{aligned}$$

The approximate value of x_{g} where η is maximum is $x_0 = 2.27$.

Alternative methods leading to the same result are acceptable.

$\eta(2.27) = 0.457$

(A8) The band gap of pure silicon is $E_{\text{g}} = 1.11\,\text{eV}$. Calculate the efficiency, η_{Si}, of a silicon solar cell using this value. [0.2]

Solution:

$$x_{\text{g}} = \frac{1.11 \times 1.60 \times 10^{-19}}{1.38 \times 10^{-23} \times 5763} = 2.23$$

$$\eta_{\text{Si}} = \frac{x_{\text{g}}}{6}(x_{\text{g}}^2 + 2x_{\text{g}} + 2)e^{-x_{\text{g}}} = 0.457$$

In the late nineteenth century, Kelvin and Helmholtz (KH) proposed a hypothesis to explain how the Sun shines. They postulated that starting as a very large cloud of matter of mass, $M_\odot$, and negligible density, the Sun has been shrinking continuously. The shining of the Sun would then be due to the release of gravitational energy through this slow contraction.

(A9) Let us assume that the density of matter is uniform inside the Sun. Find the total gravitational potential energy, Ω, of the Sun at present, in terms of G, $M_\odot$and $R_\odot$. [0.3]

Solution:

The total gravitational potential energy of the Sun: $\Omega = -\displaystyle\int_0^{M_\odot} \frac{Gm\,\text{d}m}{r}$

For constant density, $\rho = \dfrac{3M_\odot}{4\pi R_\odot^3}$ $\quad m = \dfrac{4}{3}\pi r^3 \rho \quad$ $\text{d}m = 4\pi r^2 \rho \text{d}r$

$$\Omega = -\int_0^{R_\odot} G\left(\frac{4}{3}\pi r^3 \rho\right)\left(4\pi r^2 \rho\right)\frac{\text{d}r}{r} = -\frac{16\pi^2 G\rho^2}{3}\frac{R_\odot^5}{5} = -\frac{3}{5}\frac{GM_\odot^2}{R_\odot}$$

(A10) Estimate the maximum possible time τ_{KH} (in years), for which the Sun could have been shining, according to the KH hypothesis. Assume that the luminosity of the Sun has been constant throughout this period. [0.5]

Solution:

$$\tau_{\text{KH}} = \frac{-\Omega}{L_\odot}$$

$$\tau_{\text{KH}} = \frac{3GM_\odot^2}{5R_\odot L_\odot} = 1.88 \times 10^7 \text{years}$$

The τ_{KH} calculated above does not match the age of the solar system estimated from studies of meteorites. This shows that the energy source of the Sun cannot be purely gravitational.

B. Neutrinos from the Sun:

In 1938, Hans Bethe proposed that nuclear fusion of hydrogen into helium in the core of the Sun is the source of its energy. The net nuclear reaction is:

$$4\,{}^{1}\mathrm{H} \longrightarrow {}^{4}\mathrm{He} + 2\mathrm{e}^{+} + 2\nu_{\mathrm{e}}$$

The "electron neutrinos", ν_{e}, produced in this reaction may be taken to be massless. They escape the Sun and their detection on Earth confirms the occurrence of nuclear reactions inside the Sun. Energy carried away by the neutrinos can be neglected in this problem.

(B1) Calculate the flux density, Φ_ν, of the number of neutrinos arriving at the Earth, in units of $\mathrm{m}^{-2}\,\mathrm{s}^{-1}$. The energy released in the above reaction is $\Delta E = 4.0 \times 10^{-12}$ J. Assume that the energy radiated by the Sun is almost entirely due to this reaction. [0.6]

Solution:

$$4.0 \times 10^{-12}\ \mathrm{J} \leftrightarrow 2\nu$$

$$\Rightarrow \Phi_\nu = \frac{L_\odot}{4\pi d_\odot^2\, \delta E} \times 2 = \frac{3.85 \times 10^{26}}{4\pi \times (1.50 \times 10^{11})^2 \times 4.0 \times 10^{-12}} \times 2 = 6.8 \times 10^{14}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}.$$

Travelling from the core of the Sun to the Earth, some of the electron neutrinos, ν_{e}, are converted to other types of neutrinos, ν_{x}. The efficiency of the detector for detecting ν_{x} is 1/6th of its efficiency for detecting ν_{e}. If there is no neutrino conversion, we expect to detect an average of N_1 neutrinos in a year. However, due to the conversion, an average of N_2 neutrinos (ν_{e} and ν_{x} combined) are actually detected per year.

(B2) In terms of N_1 and N_2, calculate what fraction, f, of ν_{e} is converted to ν_{x}. [0.4]

Solution:

$$\begin{aligned} N_1 &= \epsilon N_0 \\ N_e &= \epsilon N_0 (1-f) \\ N_x &= \epsilon N_0 f/6 \\ N_2 &= N_e + N_x \end{aligned}$$

OR

$$(1-f)N_1 + \frac{f}{6}N_1 = N_2$$

$$\Rightarrow f = \frac{6}{5}\left(1 - \frac{N_2}{N_1}\right)$$

In order to detect neutrinos, large detectors filled with water are constructed. Although the interactions of neutrinos with matter are very rare, occasionally they knock out electrons from water molecules in the detector. These energetic electrons move through water at high speeds, emitting electromagnetic radiation in the process. As long as the speed of such an electron is greater than the speed of light in water (refractive index, n), this radiation, called Cherenkov radiation, is emitted in the shape of a cone.

(B3) Assume that an electron knocked out by a neutrino loses energy at a constant rate of α per unit time, while it travels through water. If this electron emits Cherenkov radiation for a time Δt, determine the energy imparted to this electron (E_{imparted}) by the neutrino, in terms of $\alpha, \Delta t, n, m_{\text{e}}, c$. (Assume the electron to be at rest before its interaction with the neutrino.) [2.0]

Solution:

When the electron stops emitting Cherenkov radiation, its speed has reduced to $v_{\text{stop}} = c/n$.

Its total energy at this time is

$$E_{\text{stop}} = \frac{m_{\text{e}}c^2}{\sqrt{1 - v_{\text{stop}}^2/c^2}} = \frac{nm_{\text{e}}c^2}{\sqrt{n^2-1}}$$

The energy of the electron when it was knocked out is

$$E_{\text{start}} = \alpha\Delta t + \frac{nm_{\text{e}}c^2}{\sqrt{n^2-1}}$$

Before interacting, the energy of the electron was equal to $m_{\text{e}}c^2$.

Thus, the energy imparted by the neutrino is

$$E_{\text{imparted}} = E_{\text{start}} - m_{\text{e}}c^2 = \alpha\Delta t + \left(\frac{n}{\sqrt{n^2-1}} - 1\right) m_{\text{e}}c^2$$

The fusion of H into He inside the Sun takes place in several steps. Nucleus of ^{7}Be (rest mass, m_{Be}) is produced in one of these intermediate steps. Subsequently, it can absorb an electron, producing a ^{7}Li nucleus (rest mass $m_{\text{Li}} < m_{\text{Be}}$) and emitting a ν_{e}. The corresponding nuclear reaction is:

$$^7\text{Be} + \text{e}^- \longrightarrow {}^7\text{Li} + \nu_{\text{e}} \ .$$

When a Be nucleus ($m_{\text{Be}} = 11.65 \times 10^{-27}$ kg) is at rest and absorbs an electron also at rest, the emitted neutrino has energy $E_\nu = 1.44 \times 10^{-13}$ J. However, the Be nuclei are in random thermal motion due to the temperature T_{c} at the core of the Sun, and act as moving neutrino sources. As a result, the energy of emitted neutrinos fluctuates with a root mean square value ΔE_{rms}.

(B4) If $\Delta E_{\text{rms}} = 5.54 \times 10^{-17}$ J, calculate the rms speed of the Be nuclei, V_{Be} and hence estimate T_{c}. (Hint: ΔE_{rms} depends on the rms value of the component of velocity along the line of sight.)

[2.0]

Solution:

Moving ^{7}Be nuclei give rise to Doppler effect for neutrinos. Since the fractional change in energy ($\Delta E_{\rm rms}/E_\nu \sim 10^{-4}$) is small, the Doppler shift may be considered in the non-relativistic limit (a relativistic treatment gives almost same answer). Taking the line of sight along the z-direction,

$$\begin{aligned}\frac{\Delta E_{\rm rms}}{E_\nu} &= \frac{v_{z,rms}}{c}\\ &= 3.85 \times 10^{-4}\end{aligned}$$

$$= \frac{1}{\sqrt{3}}\frac{V_{\rm Be}}{c}$$

$\Rightarrow V_{\rm Be} = \sqrt{3} \times 3.85 \times 10^{-4} \times 3.00 \times 10^8\ \mathrm{m\,s^{-1}} = 2.01 \times 10^5\ \mathrm{m\,s^{-1}}$.

The average temperature is obtained by equating the average kinetic energy to the thermal energy.

$$\frac{1}{2}m_{\rm Be}V_{\rm Be}^2 = \frac{3}{2}k_{\rm B}T_{\rm c}$$

$$\Rightarrow \qquad T_{\rm c} = 1.13 \times 10^7\ \mathrm{K}$$

Theory 2 Questions

The Extremum Principle[1]

(Total Marks: 10)

A The Extremum Principle in Mechanics

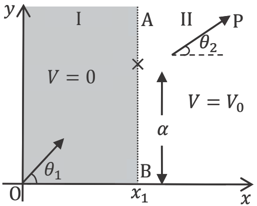


Figure 1

Consider a horizontal frictionless $x - y$ plane shown in Fig. 1. It is divided into two regions, I and II, by a line AB satisfying the equation $x = x_1$. The potential energy of a point particle of mass m in region I is $V = 0$ while it is $V = V_0$ in region II. The particle is sent from the origin O with speed v_1 along a line making an angle θ_1 with the x-axis. It reaches point P in region II traveling with speed v_2 along a line that makes an angle θ_2 with the x-axis. Ignore gravity and relativistic effects in this entire task T-2 (all parts).

A1	Obtain an expression for v_2 in terms of m, v_1 and V_0.	**0.2**
A2	Express v_2 in terms of v_1, θ_1 and θ_2.	**0.3**

We define a quantity called action $A = m \int v(s)ds$, where ds is the infinitesimal length along the trajectory of a particle of mass m moving with speed $v(s)$. The integral is taken over the path. As an example, for a particle moving with constant speed v on a circular path of radius R, the action A for one revolution will be $2\pi mRv$. For a particle with constant energy E, it can be shown that of all the possible trajectories between two fixed points, the actual trajectory is the one on which A defined above is an extremum (minimum or maximum). Historically this is known as the Principle of Least Action (PLA).

A3	PLA implies that the trajectory of a particle moving between two fixed points in a region of constant potential will be a straight line. Let the two fixed points O and P in Fig. 1 have coordinates $(0,0)$ and (x_0, y_0) respectively and the boundary point where the particle transits from region I to region II have coordinates (x_1, α). Note that x_1 is fixed and the action depends on the coordinate α only. State the expression for the action $A(\alpha)$. Use PLA to obtain the relationship between v_1/v_2 and these coordinates.	**1.0**

B The Extremum Principle in Optics

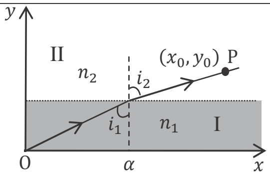


Figure 2

A light ray travels from medium I to medium II with refractive indices n_1 and n_2 respectively. The two media are separated by a line parallel to the x-axis. The light ray makes an angle i_1 with the y-axis in medium I and i_2 in medium II (see Fig. 2). To obtain the trajectory of the ray, we make use of another extremum (minimum or maximum) principle known as Fermat's principle of least time.

B1	The principle states that between two fixed points, a light ray moves along a path such that time taken between the two points is an extremum. Derive the relation between sin i_1 and sin i_2 on the basis of Fermat's principle.	**0.5**

Shown in Fig. 3 is a schematic sketch of the path of a laser beam incident horizontally on a solution of sugar in which the concentration of sugar decreases with height. As a consequence, the refractive index of the solution also decreases with height.

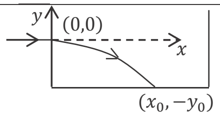


Figure 3: Tank of Sugar Solution

B2	Assume that the refractive index $n(y)$ depends only on y. Use the equation obtained in B1 to obtain the expression for the slope dy/dx of the beam's path in terms of refractive index n_0 at $y = 0$ and $n(y)$.	**1.5**
B3	The laser beam is directed horizontally from the origin $(0,0)$ into the sugar solution at a height y_0 from the bottom of the tank as shown in figure 3. Take $n(y) = n_0 - ky$ where n_0 and k are positive constants. Obtain an expression for x in terms of y and related quantities for the actual trajectory of the laser beam.	**1.2**

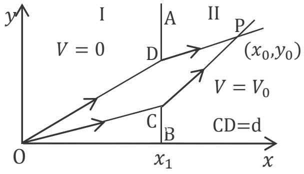
---

[1] *Manoj Harbola (IIT-Kanpur) and Vijay A. Singh (ex-National Coordinator, Science Olympiads) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

	You may use: $\int \sec\theta d\theta = \ln(\sec\theta + \tan\theta) + \text{constant}$, where $\sec\theta = 1/\cos\theta$ or $\int \frac{dx}{\sqrt{x^2-1}} = \ln\left(x + \sqrt{x^2-1}\right) + \text{constant}$	
B4	Obtain the value of x_0, the point where the beam meets the bottom of the tank. Take $y_0 = 10.0$ cm, $n_0 = 1.50$, $k = 0.050\ \text{cm}^{-1}$ (1 cm = 10^{-2} m).	**0.8**

C The Extremum Principle and the Wave Nature of Matter

We now explore the connection between the PLA and the wave nature of a moving particle. For this we assume that a particle moving from O to P can take all possible trajectories and we will seek a trajectory that depends on the constructive interference of de Broglie waves.

C1	As the particle moves along its trajectory by an infinitesimal distance Δs, relate the change $\Delta\varphi$ in the phase of its de Broglie wave to the change ΔA in the action and the Planck constant.	**0.6**
C2	Recall the problem from part A where the particle traverses from O to P (see Fig. 4). Let an opaque partition be placed at the boundary AB between the two regions. There is a small opening CD of width d in AB such that $d \ll (x_0 - x_1)$ and $d \ll x_1$. Consider two extreme paths OCP and ODP such that OCP lies on the classical trajectory discussed in part A. Obtain the phase difference $\Delta\varphi_{\text{CD}}$ between the two paths to first order.  **Figure 4**	**1.2**

D Matter Wave Interference

Consider an electron gun at O which directs a collimated beam of electrons to a narrow slit at F in the opaque partition A_1B_1 at $x = x_1$ such that OFP is a straight line. P is a point on the screen at $x = x_0$ (see Fig. 5). The speed in I is $v_1 = 2.0000 \times 10^7\ \text{m s}^{-1}$ and $\theta = 10.0000^\circ$. The potential in II is such that speed $v_2 = 1.9900 \times 10^7\ \text{m s}^{-1}$. The distance $x_0 - x_1$ is 250.00 mm (1mm = 10^{-3}m). Ignore electron-electron interaction.

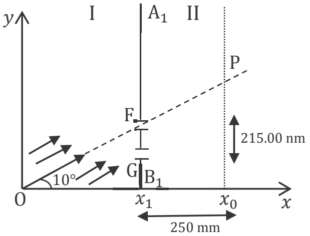


Figure 5

D1	If the electrons at O have been accelerated from rest, calculate the accelerating potential U_1.	**0.3**
D2	Another identical slit G is made in the partition A_1B_1 at a distance of 215.00 nm (1nm = 10^{-9}m) below slit F (Fig. 5). If the phase difference between de Broglie waves arriving at P through the slits F and G is $2\pi\beta$, calculate β.	**0.8**
D3	What is the smallest distance Δy from P at which null (zero) electron detection maybe expected on the screen? [Note: you may find the approximation $\sin(\theta + \Delta\theta) \approx \sin\theta + \Delta\theta\cos\theta$ useful]	**1.2**
D4	The beam has a square cross section of 500nm × 500nm and the setup is 2 m long. What should be the minimum flux density I_{min} (number of electrons per unit normal area per unit time) if, on an average, there is at least one electron in the setup at a given time?	**0.4**

The Extremum Principle[1]

A. The Extremum Principle in Mechanics

Consider a horizontal frictionless x-y plane shown in Fig. 1. It is divided into two regions, I and II, by a line AB satisfying the equation $x = x_1$. The potential energy of a point particle of mass m in region I is $V = 0$ while it is $V = V_0$ in region II. The particle is sent from the origin O with speed v_1 along a line making an angle θ_1 with the x-axis. It reaches point P in region II traveling with speed v_2 along a line that makes an angle θ_2 with the $x-$axis. Ignore gravity and relativistic effects in this entire task T-2 (all parts).

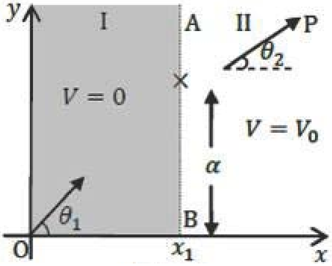


Figure 1

(A1) Obtain an expression for v_2 in terms of m, v_1 and V_0 . [0.2]

Solution:

From the principle of Conservation of Mechanical Energy

$$\frac{1}{2}mv_1^2 = \frac{1}{2}mv_2^2 + V_0$$

$$v_2 = (v_1^2 - \frac{2V_0}{m})^{1/2}$$

(A2) Express v_2 in terms of v_1, θ_1 and θ_2. [0.3]

Solution:

At the boundary there is an impulsive force ($\propto dV/dx$) in the $-x$ direction. Hence only the velocity component in the $x-$direction v_{1x} suffers change . The component in the $y-$direction remains unchanged. Therefore

$v_{1y} = v_{2y}$

$v_1 \sin\theta_1 = v_2 \sin\theta_2$

We define a quantity called action $A = m\int v(s)\, ds$, where ds is the infinitesimal length along the trajectory of a particle of mass m moving with speed $v(s)$. The integral is taken over the path. As an example. for a particle moving with constant speed v on a circular path of radius R, the action A for one revolution will be $2\pi mRv$. For a particle with constant energy E, it can be shown that of all the possible trajectories between two fixed points, the actual trajectory is the one on which A defined above is an extremum (minimum or maximum). Historically this is known as the Principle of Least Action (PLA).

---

[1] *Manoj Harbola (IIT-Kanpur) and Vijay A. Singh (ex-National Coordinator, Science Olympiads) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

(A3) PLA implies that the trajectory of a particle moving between two fixed points in a region of constant potential will be a straight line. Let the two fixed points O and P in Fig. 1 have coordinates (0,0) and (x_0,y_0) respectively and the boundary point where the particle transits from region I to region II have coordinates (x_1,α). Note x_1 is fixed and the action depends on the coordinate α only. State the expression for the action $A(\alpha)$. Use PLA to obtain the the relationship between v_1/v_2 and these coordinates. [1.0]

Solution:

By definition $A(\alpha)$ from O to P is

$$A(\alpha) = mv_1\sqrt{x_1^2+\alpha^2} + mv_2\sqrt{(x_0-x_1)^2+(y_0-\alpha)^2}$$

Differentiating w.r.t. α and setting the derivative of $A(\alpha)$ to zero

$$\frac{v_1\alpha}{(x_1^2+\alpha^2)^{1/2}} - \frac{v_2(y_0-\alpha)}{[(x_0-x_1)^2+(y_0-\alpha)^2]^{1/2}} = 0$$

$$\therefore \frac{v_1}{v_2} = \frac{(y_0-\alpha)\,(x_1^2+\alpha^2)^{1/2}}{\alpha\,[(x_0-x_1)^2+(y_0-\alpha)^2]^{1/2}}$$

Note this is the same as A2, namely $v_1\sin\theta_1 = v_2\sin\theta_2$.

B. The Extremum Principle in Optics

A light ray travels from medium I to medium II with refractive indices n_1 and n_2 respectively. The two media are separated by a line parallel to the x-axis. The light ray makes an angle i_1 with the y-axis in medium I and i_2 in medium II (see Fig. 2). To obtain the trajectory of the ray, we make use of another extremum (minimum or maximum) principle known as Fermat's principle of least time.

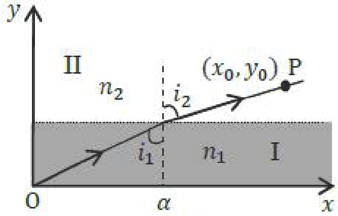


Figure 2

(B1) The principle states that between two fixed points, a light ray moves along a path such that the time taken between the two points is an extremum. Derive the relation between $\sin i_1$ and $\sin i_2$ on the basis of Fermat's principle. [0.5]

Solution:

The speed of light in medium I is c/n_1 and in medium II is c/n_2, where c is the speed of light in vacuum. Let the two media be separated by the fixed line $y = y_1$. Then time $T(\alpha)$ for light to travel from origin (0,0) and (x_0,y_0) is

$$T(\alpha) = n_1(\sqrt{y_1^2+\alpha^2})/c + n_2(\sqrt{(x_0-\alpha)^2+(y_0-y_1)^2})/c$$

Differentiating w.r.t. α and setting the derivative of $T(\alpha)$ to zero

$$\frac{n_1\alpha}{(y_1^2+\alpha^2)^{1/2}} - \frac{n_2(y_0-\alpha)}{[(x_0-\alpha)^2+(y_0-y_1)^2]^{1/2}} = 0$$

$$\therefore \quad n_1 \sin i_1 = n_2 \sin i_2$$

[Note: Derivation is similar to A3. This is Snell's law.]

Shown in Fig. 3 is a schematic sketch of the path of a laser beam incident horizontally on a solution of sugar in which the concentration of sugar decreases with height. As a consequence, the refractive index of the solution also decreases with height.

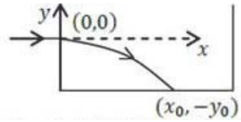


Figure 3

(B2) Assume that the refractive index n(y) depends only on y. Use the equation obtained in B1 to obtain the expresssion for the slope dy/dx of the beam's path in terms of n_0 at $y=0$ and $n(y)$. [1.5]

Solution:

From Snell's law $n_0 \sin i_0 = n(y)\sin i$

Then, $\dfrac{dy}{dx} = -\cot i$

$$n_0 \sin i_0 = \frac{n(y)}{\sqrt{1+(\frac{dy}{dx})^2}}$$

$$\frac{dy}{dx} = -\sqrt{\left(\frac{n(y)}{n_0 \sin i_0}\right)^2 - 1}$$

(B3) The laser beam is directed horizontally from the origin (0,0) into the sugar solution at a height y_0 from the bottom of the tank as shown. Take $n(y) = n_0 - ky$ where n_0 and k are positive constants. Obtain an expression for x in terms of y and related quantities. You may use: $\int \sec\theta d\theta = \ln(\sec\theta + \tan\theta)$ + constant $\sec\theta = 1/\cos\theta$ or $\int \frac{dx}{\sqrt{x^2-1}} = \ln(x+\sqrt{x^2-1})$ + constant. [1.2]

Solution:

$$\int \frac{dy}{\sqrt{(\frac{n_0-ky}{n_0 \sin\ i_0})^2-1}} = -\int dx$$

Note $i_0 = 90^o$ so $\sin i_0 = 1$.

Method I We employ the substitution

$$\xi = \frac{n_0 - ky}{n_0}$$

$$\int \frac{d\xi(-\frac{n_0}{k})}{\sqrt{\xi^2 - 1}} = -\int dx$$

Let $\xi = \sec\theta$. Then

$$\frac{n_0}{k}\ln(\sec\theta + \tan\theta) = x + c$$

Or METHOD II

We employ the substitution

$$\xi = \frac{n_0 - ky}{n_0}$$

$$\int \frac{d\xi(-\frac{n_0}{k})}{\sqrt{\xi^2 - 1}} = -\int dx$$

$$-\frac{n_0}{k}\ln\left(\frac{n_0 - ky}{n_0} + \sqrt{(\frac{n_0 - ky}{n_0})^2 - 1}\right) = -x + c$$

Now continuing

Considering the substitutions and boundary condition, $x = 0$ for $y = 0$ we obtain that the constant $c = 0$.
Hence we obtain the following trajectory:

$$x = \frac{n_0}{k}\ln\left(\frac{n_0 - ky}{n_0} + \sqrt{(\frac{n_0 - ky}{n_0})^2 - 1}\right)$$

(B4) Obtain the value of x_0, the point where the beam meets the bottom of the tank. Take y_0 = 10.0 cm, $n_0 = 1.50$, $k = 0.050$ cm^{-1} (1 cm = 10^{-2} m). [0.8]

Solution:

Given $y_0 = 10.0$ cm. $n_0 = 1.50$ $k = 0.050$ cm^{-1}
From (B3)

$$x_0 = \frac{n_0}{k}\ln\left[\left(\frac{n_0 - ky}{n_0}\right) + \left(\left(\frac{n_0 - ky}{n_0}\right)^2 - 1\right)^{1/2}\right]$$

Here $y = -y_0$

$$x_0 = \frac{n_0}{k}\ln\left[\frac{(n_0+ky_0)}{n_0} + \left(\frac{(n_0+ky_0)^2}{n_0^2} - 1\right)^{1/2}\right]$$

$$= 30\ln\left[\frac{2}{1.5} + \left(\left(\frac{2}{1.5}\right)^2 - 1\right)^{1/2}\right]$$

$$= 30\ln\left[\frac{4}{3} + \left(\frac{7}{9}\right)^{1/2}\right]$$

$$= 30\ln\left[\frac{4}{3} + 0.88\right]$$

$$= 24.0 \text{ cm}$$

C. The Extremum Principle and the Wave Nature of Matter

We now explore between the PLA and the wave nature of a moving particle. For this we assume that a particle moving from O to P can take all possible trajectories and we will seek a trajectory that depends on the constructive interference of de Broglie waves.

(C1) As the particle moves along its trajectory by an infinitesimal distance Δs, relate the change $\Delta\phi$ in the phase of its de Broglie wave to the change ΔA in the action and the Planck constant. [0.6]

Solution:

From the de Broglie hypothesis

$$\lambda \to \lambda_{dB} = h/mv$$

where λ is the de Broglie wavelength and the other symbols have their usual meaning

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta s$$

$$= \frac{2\pi}{h}mv\Delta s$$

$$= \frac{2\pi\Delta A}{h}$$

(C2) Recall the problem from part A where the particle traverses from O to P (see Fig. 4). Let an opaque partition be placed at the boundary AB between the two regions. There is a small opening CD of width d in AB such that $d \ll (x_0 - x_1)$ and $d \ll x_1$.
Consider two extreme paths OCP and ODP such that OCP lies on the classical trajectory discussed in part A. Obtain the phase difference $\Delta\phi_{CD}$ between the two paths to first order. [1.2]

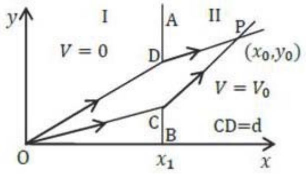
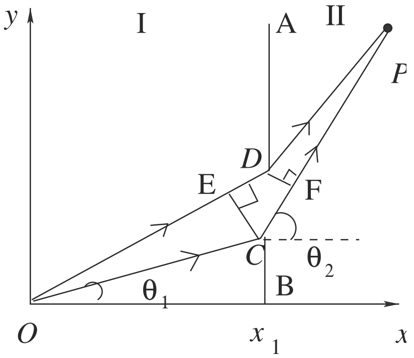


Figure 4

Solution:



Consider the extreme trajectories OCP and ODP of (C1)
The geometrical path difference is ED in region I and CF in region II.
This implies (note: $d \ll (x_0 - x_1)$ and $d \ll x_1$)

$$\Delta\phi_{CD} = \frac{2\pi d \sin\theta_1}{\lambda_1} - \frac{2\pi d \sin\theta_2}{\lambda_2}$$

$$\begin{aligned}\Delta\phi_{CD} &= \frac{2\pi m v_1 d \sin\theta_1}{h} - \frac{2\pi m v_2 d \sin\theta_2}{h} \\ &= 2\pi\frac{md}{h}(v_1 \sin\theta_1 - v_2 \sin\theta_2) \\ &= 0 \qquad \text{(from A2 or B1)}\end{aligned}$$

Thus near the clasical path there is invariably constructive interference.

D. Matter Wave Interference

Consider an electron gun at O which directs a collimated beam of electrons to a narrow slit at F in the opaque partition A_1B_1 at $x = x_1$ such that OFP is a straight line. P is a point on the screen at $x = x_0$ (see Fig. 5). The speed in I is $v_1 = 2.0000 \times 10^7\ \mathrm{m\,s^{-1}}$ and $\theta = 10.0000°$. The potential in region II is such that the speed $v_2 = 1.9900 \times 10^7\ \mathrm{m\,s^{-1}}$. The distance $x_0 - x_1$ is 250.00 mm (1 mm = 10^{-3} m). Ignore electron-electron interaction.

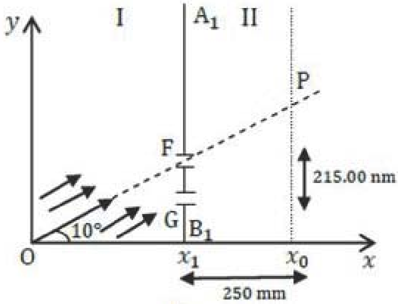


Figure 5

(D1) If the electrons at O have been accelerated from rest, calculate the accelerating potential U_1. [0.3]

Solution:

$$qU_1 = \frac{1}{2}\, mv^2$$

$$= \frac{9.11 \times 10^{-31} \times 4 \times 10^{14}}{2} J$$

$$= 2 \times 9.11 \times 10^{-17} J$$

$$= \frac{2 \times 9.11 \times 10^{-17}}{1.6 \times 10^{-19}}\ eV$$

$$= 1.139 \times 10^3\ eV \quad (\simeq 1100\ eV)$$

$$U_1 \ = 1.139 \times 10^3\ V$$

(D2) Another identical slit G is made in the partition A_1B_1 at a distance of 215.00 nm (1 nm = 10^{-9} m) below slit F (Fig. 5). If the phase difference between de Broglie waves ariving at P from F and G is $2\,\pi\,\beta$, calculate β. [0.8]

Solution: Phase difference at P is

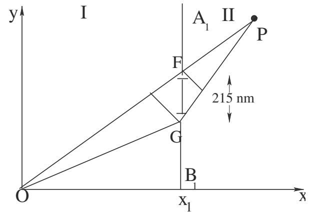
$$\Delta\phi_P \ = \ \frac{2\pi d \sin\theta}{\lambda_1} - \frac{2\pi d \sin\theta}{\lambda_2}$$

$$= 2\pi(v_1 - v_2)\frac{md}{h}\sin 10° = 2\pi\beta$$

$$\beta = 5.13$$

(D3) What is is the smallest distance Δy from P at which null (zero) electron detection maybe expected on the screen? [Note: you may find the approximation $\sin(\theta + \Delta\theta) \approx \sin\theta + \Delta\theta\cos\theta$ useful] [1.2]

Solution:



From previous part for null (zero) electron detection $\Delta\phi = 5.5 \times 2\pi$

$$\therefore mv_1\frac{d\sin\theta}{h} - \frac{mv_2 d\sin(\theta+\Delta\theta)}{h} = 5.5$$

$$\begin{aligned}
sin(\theta+\Delta\theta) &= \frac{\dfrac{mv_1 d\sin\theta}{h} - 5.5}{\dfrac{mv_2 d}{h}} \\
&= \frac{v_1}{v_2}\sin\theta - \frac{h}{m}\frac{5.5}{v_2 d} \\
&= \frac{2}{1.99}\sin 10^\circ - \frac{5.5}{1374.78 \times 1.99 \times 10^7 \times \times 2.15 \times 10^{-7}} \\
&= 0.174521 - 0.000935
\end{aligned}$$

This yields $\Delta\theta = -0.0036^\circ$

The closest distance to P is

$$\begin{aligned}
\Delta y &= (x_0 - x_1)(\tan(\theta+\Delta\theta) - \tan\theta) \\
&= 250(\tan 9.9964 - \tan 10) \\
&= -0.0162mm \\
&= -16.2\mu\,\mathrm{m}
\end{aligned}$$

The negative sign means that the closest minimum is below P.

Approximate Calculation for θ and Δy
Using the approximation $\sin(\theta+\Delta\theta) \approx \sin\theta + \Delta\theta\cos\theta$
The phase difference of $5.5 \times 2\pi$ gives

$$mv_1\frac{d\sin 10^\circ}{h} - mv_2\frac{d(\sin 10^\circ + \Delta\theta\cos 10^\circ)}{h} = 5.5$$

From solution of the previous part

$$mv_1\frac{d\sin 10^\circ}{h} - mv_2\frac{dsin10^\circ}{h} = 5.13$$

Therefore

$$mv_2\frac{d\Delta\theta\cos 10^\circ}{h} = 0.3700$$

This yields $\Delta\theta \approx 0.0036^\circ$

$\Delta y = -0.0162\,\text{mm} = -16.2\mu\text{m}$ as before

(D4) The electron beam has a square cross section of 500 nm × 500 nm and the setup is 2 m long. What should be the minimum beam flux density I_{min} (number of electrons per unit normal area per unit time) if, on an average, there is at least one electron in the setup at a given time? [0.4]

Solution: The product of the speed of the electrons and number of electron per unit volume on an average yields the intensity.

Thus $N = 1 =$ Intensity × Area × Length/ Electron Speed

$= I_{min} \times 0.25 \times 10^{-12} \times 2/2 \times 10^7$

This gives $I_{min} = 4\times\ 10^{19}\ \text{m}^{-2}\ \text{s}^{-1}$

R. Bach, D. Pope, Sy-H Liou and H. Batelaan, New J. of Physics Vol. 15, 033018 (2013).

Theory 3 Questions

The Design of a Nuclear Reactor[1]

(Total Marks: 10)

Uranium occurs in nature as UO_2 with only 0.720% of the uranium atoms being ^{235}U. Neutron induced fission occurs readily in ^{235}U with the emission of 2-3 fission neutrons having high kinetic energy. This fission probability will increase if the neutrons inducing fission have low kinetic energy. So by reducing the kinetic energy of the fission neutrons, one can induce a chain of fissions in other ^{235}U nuclei. This forms the basis of the power generating nuclear reactor (NR).

A typical NR consists of a cylindrical tank of height H and radius R filled with a material called moderator. Cylindrical tubes, called fuel channels, each containing a cluster of cylindrical fuel pins of natural UO_2 in solid form of height H, are kept axially in a square array. Fission neutrons, coming outward from a fuel channel, collide with the moderator, losing energy and reach the surrounding fuel channels with low enough energy to cause fission (Figs I-III). Heat generated from fission in the pin is transmitted to a coolant fluid flowing along its length. In the current problem we shall study some of the physics behind the (A) Fuel Pin, (B) Moderator and (C) NR of cylindrical geometry.

Fig-I

Fig-II

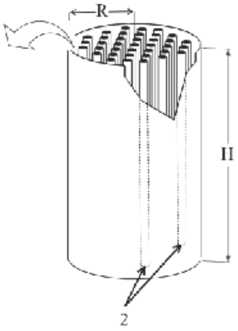
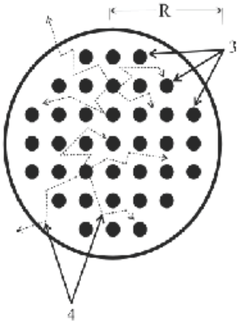


Fig-III



Schematic sketch of the Nuclear Reactor (NR)
Fig-I: Enlarged view of a fuel channel (1-*Fuel Pins*)
Fig-II: A view of the NR (2-*Fuel Channels*)
Fig-III: Top view of NR (3-*Square Arrangement of Fuel Channels* and 4-*Typical Neutron Paths*).
Only components relevant to the problem are shown (e.g. control rods and coolant are not shown).

A Fuel Pin

Data for UO_2	1. Molecular weight $M_w = 0.270$ kg mol^{-1}	2. Density $\rho = 1.060\times10^4$ kg m^{-3}
	3. Melting point $T_m = 3.138\times10^3$ K	4. Thermal conductivity $\lambda = 3.280$ W m^{-1} K^{-1}

A1	Consider the following fission reaction of a stationary ^{235}U after it absorbs a neutron of negligible kinetic energy. $$^{235}\mathrm{U} + {}^{1}\mathrm{n} \;\rightarrow\; {}^{94}\mathrm{Zr} + {}^{140}\mathrm{Ce} + 2\,{}^{1}\mathrm{n} + \Delta E$$ Estimate ΔE (in MeV) the total fission energy released. The nuclear masses are: $m(^{235}\mathrm{U}) = 235.044$ u; $m(^{94}\mathrm{Zr}) = 93.9063$ u; $m(^{140}\mathrm{Ce}) = 139.905$ u; $m(^{1}\mathrm{n}) = 1.00867$ u and 1 u = 931.502 MeV c^{-2}. Ignore charge imbalance.	**0.8**
A2	Estimate N the number of ^{235}U atoms per unit volume in natural UO_2.	**0.5**
A3	Assume that the neutron flux density, $\varphi = 2.000\times10^{18}$ m^{-2} s^{-1} on the fuel is uniform. The fission cross-section (effective area of the target nucleus) of a ^{235}U nucleus is $\sigma_f = 5.400\times10^{-26}$ m^2. If 80.00% of the fission energy is available as heat, estimate Q (in W m^{-3}), the rate of heat production in the pin per unit volume. 1MeV = 1.602×10^{-13} J	**1.2**
A4	The steady-state temperature difference between the center (T_c) and the surface (T_s) of the pin can be expressed as $T_c - T_s = k\,F(Q,a,\lambda)$, where $k = 1/4$ is a dimensionless constant and a is the radius of the pin. Obtain $F(Q,a,\lambda)$ by dimensional analysis. Note that λ is the thermal conductivity of UO_2.	**0.5**

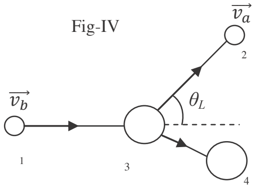
---

[1] *Joseph Amal Nathan (BARC) and Vijay A. Singh (ex-National Coordinator, Science Olympiads) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

A5	The desired temperature of the coolant is 5.770×10^2 K. Estimate the upper limit a_u on the radius a of the pin.	**1.0**

B The Moderator

Consider the two dimensional elastic collision between a neutron of mass 1 u and a moderator atom of mass A u. Before collision all the moderator atoms are considered at rest in the laboratory frame (LF). Let $\overrightarrow{v_b}$ and $\overrightarrow{v_a}$ be the velocities of the neutron before and after collision respectively in the LF. Let $\overrightarrow{v_m}$ be the velocity of the center of mass (CM) frame relative to LF and θ be the neutron scattering angle in the CM frame. All the particles involved in collisions are moving at nonrelativistic speeds.

B1	The collision in LF is shown schematically, where θ_L is the scattering angle (Fig-IV). Sketch the collision schematically in CM frame. Label the particle velocities for 1, 2 and 3 in terms of $\overrightarrow{v_b}$, $\overrightarrow{v_a}$ and $\overrightarrow{v_m}$. Indicate the scattering angle θ. Fig-IV  *Collision in the Laboratory Frame* 1-*Neutron* before collision 2-*Neutron* after collision 3-*Moderator Atom* before collision 4-*Moderator Atom* after collision	**1.0**
B2	Obtain v and V, the speeds of the neutron and moderator atom in the CM frame after collision, in terms of A and v_b.	**1.0**
B3	Derive an expression for $G(\alpha, \theta) = E_a/E_b$, where E_b and E_a are the kinetic energies of the neutron, in the LF, before and after the collision respectively and $\alpha \equiv [(A-1)\ /\ (A+1)]^2$.	**1.0**
B4	Assume that the above expression holds for D_2O molecule. Calculate the maximum possible fractional energy loss $f_l \equiv \frac{E_b - E_a}{E_b}$ of the neutron for the D_2O (20 u) moderator.	**0.5**

C The Nuclear Reactor

To operate the NR at any constant neutron flux ψ (steady state), the leakage of neutrons has to be compensated by an excess production of neutrons in the reactor. For a reactor in cylindrical geometry the leakage rate is $k_1\,[(2.405/R)^2 + (\pi/H)^2]\,\psi$ and the excess production rate is $k_2\,\psi$. The constants k_1 and k_2 depend on the material properties of the NR.

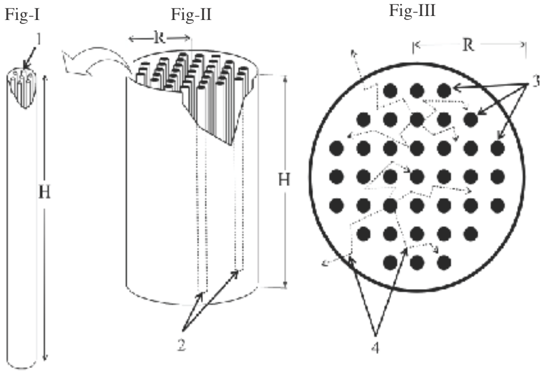
C1	Consider a NR with $k_1 = 1.021\times10^{-2}$ m and $k_2 = 8.787\times10^{-3}$ m^{-1}. Noting that for a fixed volume the leakage rate is to be minimized for efficient fuel utilization, obtain the dimensions of the NR in the steady state.	**1.5**
C2	The fuel channels are in a square arrangement (Fig-III) with the nearest neighbour distance 0.286 m. The effective radius of a fuel channel (if it were solid) is 3.617×10^{-2} m. Estimate the number of fuel channels F_n in the reactor and the mass M of UO_2 required to operate the NR in steady state.	**1.0**

Theory 3 Solutions

The Design of a Nuclear Reactor[1]

Uranium occurs in nature as UO_2 with only 0.720% of the uranium atoms being ^{235}U. Neutron induced fission occurs readily in ^{235}U with the emission of 2-3 fission neutrons having high kinetic energy. This fission probability will increase if the neutrons inducing fission have low kinetic energy. So by reducing the kinetic energy of the fission neutrons, one can induce a chain of fissions in other ^{235}U nuclei. This forms the basis of the power generating nuclear reactor (NR).

A typical NR consists of a cylindrical tank of height H and radius R filled with a material called moderator. Cylindrical tubes, called fuel channels, each containing a cluster of cylindrical fuel pins of natural UO_2 in solid form of height H, are kept axially in a square array. Fission neutrons, coming outward from a fuel channel, collide with the moderator, losing energy, and reach the surrounding fuel channels with low enough energy to cause fission (Figs I-III). Heat generated from fission in the pin is transmitted to a coolant fluid flowing along its length. In the current problem we shall study some of the physics behind the (A) Fuel Pin, (B) Moderator and (C) NR of cylindrical geometry.



Schematic sketch of the Nuclear Reactor (NR)
Fig-I: Enlarged view of a fuel channel (1-*Fuel Pins*)
Fig-II: A view of the NR (2-*Fuel Channels*)
Fig-III: Top view of NR (3-*Square Arrangement of Fuel Channels* and 4-*Typical Neutron Paths*).
Only components relevant to the problem are shown (e.g. control rods and coolant are not shown).

A. Fuel Pin

Data for UO_2

1. Molecular weight M_w=0.270 kg mol^{-1}
2. Density ρ=1.060×10^4 kg m^{-3}
3. Melting point T_m=3.138×10^3 K
4. Thermal conductivity λ=3.280 W m^{-1} K^{-1}

A1 Consider the following fission reaction of a stationary ^{235}U after it absorbs a neutron of negligible kinetic energy.

$$^{235}\mathrm{U} + ^{1}\mathrm{n} \longrightarrow ^{94}\mathrm{Zr} + ^{140}\mathrm{Ce} + 2\,^{1}\mathrm{n} + \Delta E$$

---

[1] *Joseph Amal Nathan (BARC) and Vijay A. Singh (ex-National Coordinator, Science Olympiads) were the principal authors of this problem. The contributions of the Academic Committee, Academic Development Group and the International Board are gratefully acknowledged.*

Estimate ΔE (in MeV) the total fission energy released. The nuclear masses are: $m(^{235}\mathrm{U})$ = 235.044 u; $m(^{94}\mathrm{Zr})$ = 93.9063 u; $m(^{140}\mathrm{Ce})$ = 139.905 u; $m(^{1}\mathrm{n})$ = 1.00867 u and 1 u = 931.502 MeV c^{-2}. Ignore charge imbalance. [0.8]

Solution: $\Delta E = 208.684$ MeV

Detailed solution: The energy released during the transformation is

$$\Delta E = [m(^{235}\mathrm{U}) + m(^{1}\mathrm{n}) - m(^{94}\mathrm{Zr}) - m(^{140}\mathrm{Ce}) - 2m(^{1}\mathrm{n})]\mathrm{c}^2$$

Since the data is supplied in terms of unified atomic masses (u), we have

$$\Delta E = [m(^{235}\mathrm{U}) - m(^{94}\mathrm{Zr}) - m(^{140}\mathrm{Ce}) - m(^{1}\mathrm{n})]\mathrm{c}^2$$

$= 208.684$ MeV [***Acceptable Range*** **(208.000 to 209.000)**]
from the given data.

A2 Estimate N the number of ^{235}U atoms per unit volume in natural $\mathrm{UO_2}$. [0.5]

Solution: $N = 1.702 \times 10^{26}\ \mathrm{m^{-3}}$

Detailed solution: The number of $\mathrm{UO_2}$ molecules per $\mathrm{m^3}$ of the fuel N_1 is given in the terms of its density ρ, the Avogadro number N_A and the average molecular weight M_w as

$$N_1 = \frac{\rho N_A}{M_w}$$
$$= \frac{10600 \times 6.022 \times 10^{23}}{0.270} = 2.364 \times 10^{28}\ \mathrm{m^{-3}}$$

Each molecule of $\mathrm{UO_2}$ contains one uranium atom. Since only 0.72% of these are ^{235}U,

$N = 0.0072 \times\ N_1$
$\quad = 1.702 \times 10^{26}\ \mathrm{m^{-3}}$ [***Acceptable Range*** **(1.650 to 1.750)**]

A3 Assume that the neutron flux $\phi = 2.000 \times 10^{18}\ \mathrm{m^{-2}\ s^{-1}}$ on the fuel is uniform. The fission cross-section (effective area of the target nucleus) of a ^{235}U nucleus is $\sigma_f = 5.400 \times 10^{-26}$ $\mathrm{m^2}$. If 80.00% of the fission energy is available as heat, estimate Q (in $\mathrm{W\ m^{-3}}$) the rate of heat production in the pin per unit volume. 1MeV = 1.602×10^{-13} J. [1.2]

Solution: $Q = 4.917 \times 10^8\ \mathrm{W/m^3}$

Detailed solution: It is given that 80% of the fission energy is available as heat thus the heat energy available per fission E_f is from a-(i)

$E_f = 0.8 \times 208.7$ MeV
$\quad = 166.96$ MeV
$\quad = 2.675 \times 10^{-11}$ J

The total cross-section per unit volume is $N \times \sigma_f$. Thus the heat produced per unit

volume per unit time Q is
$Q = N \times \sigma_f \times \phi \times E_f$
$= (1.702 \times 10^{26}) \times (5.4 \times 10^{-26}) \times (2 \times 10^{18}) \times (2.675 \times 10^{-11})$ W/m^3
$= 4.917 \times 10^8$ W/m^3 [***Acceptable Range* (4.800 to 5.000)**]

A4 The steady-state temperature difference between the center (T_c) and the surface (T_s) of the pin can be expressed as $T_c - T_s = kF(Q, a, \lambda)$ where $k = 1/4$ is a dimensionless constant and a is the radius of the pin. Obtain $F(Q, a, \lambda)$ by dimensional analysis. [0.5]

Solution: $T_c - T_s = \dfrac{Qa^2}{4\lambda}$.

Detailed solution: The dimensions of $T_c - T_s$ is temperature. We write this as $T_c - T_s = [K]$. Once can similarly write down the dimensions of Q, a and λ. Equating the temperature to powers of Q, a and λ, one could state the following dimensional equation:
$K = Q^\alpha a^\beta \lambda^\gamma$
$= [ML^{-1}T^{-3}]\ ^\alpha\ [L]\ ^\beta\ [ML^1T^{-3}K^{-1}]\ ^\gamma$
This yields the following algebraic equations
γ = -1 equating powers of temperature
$\alpha + \gamma = 0$ equating powers of mass or time. From the previous equation we get $\alpha = 1$
Next $-\alpha + \beta + \gamma = 0$ equating powers of length. This yields $\beta = 2$.
Thus we obtain $T_c - T_s = \dfrac{Qa^2}{4\lambda}$ where we insert the dimensionless factor 1/4 as suggested in the problem. ***No penalty if the factor 1/4 is not written.***

Note: Same credit for alternate ways of obtaining α, β, γ.

A5 The desired temperature of the coolant is 5.770 $\times 10^2$ K. Estimate the upper limit a_u on the radius a of the pin. [1.0]

Solution: $a_u = 8.267 \times 10^{-3}$ m.

Detailed solution: The melting point of UO$_2$ is 3138 K and the maximum temperature of the coolant is 577 K. This sets a limit on the maximum permissible temperature $(T_c - T_s)$ to be less than (3138 - 577 = 2561 K) to avoid “meltdown”. Thus one may take a maximum of $(T_c - T_s) = 2561$ K.
Noting that $\lambda = 3.28$ W/m - K, we have

$$a_u^2 = \frac{2561 \times 4 \times 3.28}{4.917 \times 10^8}$$

Where we have used the value of Q from A2. This yields $a_u \backsimeq 8.267 \times 10^{-3}$ m. So $a_u = 8.267 \times 10^{-3}$ m constitutes an upper limit on the radius of the fuel pin.

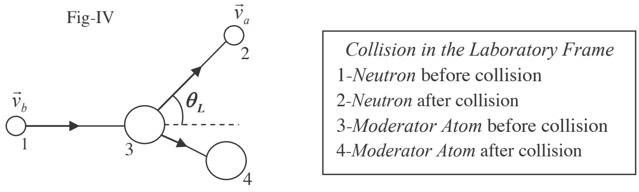
Note: The Tarapur 3 & 4 NR in Western India has a fuel pin radius of 6.090×10^{-3} m.

B. The Moderator

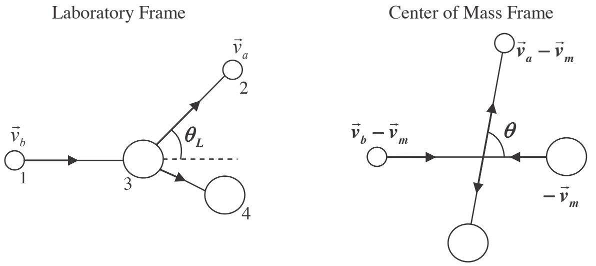
Consider the two dimensional elastic collision between a neutron of mass 1 u and a moderator atom of mass A u. Before collision all the moderator atoms are considered at rest in the laboratory frame (LF). Let $\overrightarrow{v_b}$ and $\overrightarrow{v_a}$ be the velocities of the neutron before and after collision respectively in the LF. Let $\overrightarrow{v_m}$ be the velocity of the center of mass (CM) frame relative to LF and θ be the neutron scattering angle in the CM frame. All the particles involved in collisions are moving at non-relativistic speeds

B1 The collision in LF is shown schematically with θ_L as the scattering angle (Fig-IV). Sketch the collision schematically in CM frame. Label the particle velocities for 1, 2 and 3 in terms of $\overrightarrow{v_b}$, $\overrightarrow{v_a}$ and $\overrightarrow{v_m}$. Indicate the scattering angle θ. [1.0]

Fig-IV



Solution:



B2 Obtain v and V, the speeds of the neutron and the moderator atom in the CM frame after the collision, in terms of A and v_b. [1.0]

Solution: ***Detailed solution***: Before the collision in the CM frame $(v_b - v_m)$ and v_m will be magnitude of the velocities of the neutron and moderator atom respectively. From momentum conservation in the CM frame, $v_b - v_m = Av_m$ gives $v_m = \frac{v_b}{A+1}$.

After the collision, let v and V be magnitude of the velocities of neutron and moderator atom respectively in the CM frame. From conservation laws,

$$v = AV \qquad \text{and} \qquad \frac{1}{2}(v_b - v_m)^2 + \frac{1}{2}Av_m^2 = \frac{1}{2}v^2 + \frac{1}{2}AV^2 .(\rightarrow [0.2 + 0.2])$$

Solving gives $v = \frac{Av_b}{A+1}$ and $V = \frac{v_b}{A+1}$. **(OR)** From definition of center of mass frame $v_m = \frac{v_b}{A+1}$. Before the collision in the CM frame $v_b - v_m = \frac{Av_b}{A+1}$ and v_m will be magnitude of the velocities of the neutron and moderator atom respectively. In elastic collision the particles are scattered in the opposite direction in the CM frame and so the speeds remain same $v = \frac{Av_b}{A+1}$ and $V = \frac{v_b}{A+1}$ ($\rightarrow$ [0.2 + 0.1]).

Note: Alternative solutions are worked out in the end and will get appropriate weightage.

B3 Derive an expression for $G(\alpha, \theta) = E_a/E_b$, where E_b and E_a are the kinetic energies of the neutron, in the LF, before and after the collision respectively, and $\alpha \equiv [(A-1)/(A+1)]^2$, [1.0]

Solution:

$$G(\alpha, \theta) = \frac{E_a}{E_b} = \frac{A^2 + 2A\cos\theta + 1}{(A+1)^2} = \frac{1}{2}\left[(1+\alpha) + (1-\alpha)\cos\theta\right].$$

***<u>Detailed solution</u>*:** Since $\overrightarrow{v_a} = \overrightarrow{v} + \overrightarrow{v_m}$, $v_a^2 = v^2 + v_m^2 + 2vv_m\cos\theta$ ($\rightarrow$ [0.3]). Substituting the values of v and v_m, $v_a^2 = \frac{A^2v_b^2}{(A+1)^2} + \frac{v_b^2}{(A+1)^2} + \frac{2Av_b^2}{(A+1)^2}\cos\theta$ ($\rightarrow$ [0.2]), so

$$\frac{v_a^2}{v_b^2} = \frac{E_a}{E_b} = \frac{A^2 + 2A\cos\theta + 1}{(A+1)^2}.$$

$$G(\alpha, \theta) = \frac{A^2+1}{(A+1)^2} + \frac{2A}{(A+1)^2}\cos\theta = \frac{1}{2}\left[(1+\alpha) + (1-\alpha)\cos\theta\right].$$

Alternate form

$$= 1 - \frac{(1-\alpha)(1-\cos\theta)}{2}.$$

Note: Alternative solutions are worked out in the end and will get appropriate weightage.

B4 Assume that the above expression holds for D_2O molecule. Calculate the maximum possible fractional energy loss $f_l \equiv \frac{E_b - E_a}{E_b}$ of the neutron for the D_2O (20 u) moderator. [0.5]

Solution: $f_l = 0.181$

***<u>Detailed solution</u>*:** The maximum energy loss will be when the collision is head on ie., E_a will be minimum for the scattering angle $\theta = \pi$.

So $E_a = E_{min} = \alpha E_b$.

For D_2O, $\alpha = 0.819$ and maximum fractional loss $\left(\frac{E_b - E_{min}}{E_b}\right) = 1 - \alpha = 0.181$. [***Acceptable Range*** **(0.170 to 0.190)**]

C. The Nuclear Reactor

To operate the NR at any constant neutron flux Ψ (steady state), the leakage of neutrons has to be compensated by an excess production of neutrons in the reactor. For a reactor in cylindrical geometry the leakage rate is $k_1\left[\left(\frac{2.405}{R}\right)^2+\left(\frac{\pi}{H}\right)^2\right]\Psi$ and the excess production rate is $k_2\Psi$. The constants k_1 and k_2 depend on the material properties of the NR.

C1 Consider a NR with $k_1 = 1.021\times10^{-2}$ m and $k_2 = 8.787\times10^{-3}$ m^{-1}. Noting that for a fixed volume the leakage rate is to be minimized for efficient fuel utilisation obtain the dimensions of the NR in the steady state. [1.5]

Solution: $R = 3.175$ m, $H = 5.866$ m.

Detailed solution: For constant volume $V = \pi R^2 H$,

$$\frac{d}{dH}\left[\left(\frac{2.405}{R}\right)^2+\left(\frac{\pi}{H}\right)^2\right]=0,$$

$$\frac{d}{dH}\left[\frac{2.405^2\pi H}{V}+\frac{\pi^2}{H^2}\right]=\frac{2.405^2\pi}{V}-2\frac{\pi^2}{H^3}=0,$$

gives $\left(\frac{2.405}{R}\right)^2=2\left(\frac{\pi}{H}\right)^2$.

For steady state,

$$1.021\times10^{-2}\left[\left(\frac{2.405}{R}\right)^2+\left(\frac{\pi}{H}\right)^2\right]\Psi=8.787\times10^{-3}\ \Psi.$$

Hence $H = 5.866$ m [***Acceptable Range* (5.870 to 5.890)**]
$R = 3.175$ m [***Acceptable Range* (3.170 to 3.180)**].

Alternative Non-Calculus Method to Optimize

Minimisation of the expression $\left(\frac{2.405}{R}\right)^2+\left(\frac{\pi}{H}\right)^2$, for a fixed volume $V = \pi R^2 H$:

Substituting for R^2 in terms of $V,\ H$ we get $\dfrac{2.405^2\pi H}{V}+\dfrac{\pi^2}{H^2}$,

which can be written as, $\dfrac{2.405^2\pi H}{2V}+\dfrac{2.405^2\pi H}{2V}+\dfrac{\pi^2}{H^2}$.

Since all the terms are positive applying AMGM inequality for three positive terms we get

$$\frac{\frac{2.405^2\pi H}{2V}+\frac{2.405^2\pi H}{2V}+\frac{\pi^2}{H^2}}{3}\geq\sqrt[3]{\frac{2.405^2\pi H}{2V}\times\frac{2.405^2\pi H}{2V}\times\frac{\pi^2}{H^2}}=\sqrt[3]{\frac{2.405^4\pi^4}{4V^2}}.$$

The RHS is a constant. The LHS is always greater or equal to this constant implies that this is the minimum value the LHS can achieve. The minimum is achieved when all the three positive terms are equal, which gives the condition $\frac{2.405^2\pi H}{2V} = \frac{\pi^2}{H^2} \Rightarrow \left(\frac{2.405}{R}\right)^2 = 2\left(\frac{\pi}{H}\right)^2$.

For steady state,

$$1.021 \times 10^{-2}\left[\left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{H}\right)^2\right]\Psi = 8.787 \times 10^{-3}\ \Psi.$$

Hence $H = 5.866$ m [***Acceptable Range* (5.870 to 5.890)**]
$R = 3.175$ m [***Acceptable Range* (3.170 to 3.180)**].

Note: Putting the condition in the RHS gives the minimum as $\frac{\pi^2}{H^2}$. From the condition we get $\frac{\pi^3}{H^3} = \frac{2.405^2\pi^2}{2V} \Rightarrow \frac{\pi^2}{H^2} = \sqrt[3]{\frac{2.405^4\pi^4}{4V^2}}$.

Note: The radius and height of the Tarapur 3 & 4 NR in Western India is 3.192 m and 5.940 m respectively.

C2 The fuel channels are in a square arrangement (Fig-III) with nearest neighbour distance 0.286 m. The effective radius of a fuel channel (if it were solid) is 3.617×10^{-2} m. Estimate the number of fuel channels F_n in the reactor and the mass M of UO_2 required to operate the NR in steady state. [1.0]

Solution: $F_n = 387$ and $M = 9.892 \times 10^4$kg.

***Detailed solution*:** Since the fuel channels are in square pitch of 0.286 m, the effective area per channel is 0.286^2 m^2 $= 8.180 \times 10^{-2}$ m^2.

The cross-sectional area of the core is $\pi R^2 = 3.142 \times (3.175)^2 = 31.67$ m^2, so the maximum number of fuel channels that can be accommodated in the cylinder is the integer part of $\frac{31.67}{0.0818} = 387$.

Mass of the fuel=387×Volume of the rod×density
$= 387 \times (\pi \times 0.03617^2 \times 5.866) \times 10600 = 9.892 \times 10^4$kg.
$F_n = 387$ [***Acceptable Range* (380 to 394)**]
$M = 9.892 \times 10^4$kg [***Acceptable Range* (9.000 to 10.00)**]

Note 1: (Not part of grading) The total volume of the fuel is $387 \times (\pi \times 0.03617^2 \times 5.866) = 9.332$ m^3. If the reactor works at 12.5 % efficieny then using the result of a-(iii) we have that the power output of the reactor is $9.332 \times 4.917 \times 10^8 \times 0.125 =$

573 MW.

Note 2: The Tarapur 3 & 4 NR in Western India has 392 channels and the mass of the fuel in it is 10.15 $\times 10^4$ kg. It produces 540 MW of power.

Alternative Solutions to sub-parts B2 and B3: Let σ be the scattering angle of the Moderator atom in the LF, taken clockwise with respect to the initial direction of the neutron before collision. Let U be the speed of the Moderator atom, in the LF, after collision. From momentum and kinetic conservation in LF we have

$$\begin{aligned} v_b &= v_a\cos\theta_L + AU\cos\sigma, && (1)\\ 0 &= v_a\sin\theta_L - AU\sin\sigma, && (2)\\ \frac{1}{2}v_b^2 &= \frac{1}{2}AU^2 + \frac{1}{2}v_a^2. && (3) \end{aligned}$$

Squaring and adding eq(1) and (2) to eliminate σ and from eq(3) we get

$$\begin{aligned} A^2U^2 &= v_a^2 + v_b^2 - 2v_av_b\cos\theta_L, \\ A^2U^2 &= Av_b^2 - Av_a^2, && (4) \end{aligned}$$

which gives

$$2v_av_b\cos\theta_L = (A+1)v_a^2 - (A-1)v_b^2. \qquad (5)$$

(ii) Let v be the speed of the neutron after collision in the COMF. From definition of center of mass frame $v_m = \dfrac{v_b}{A+1}$.

$v_a\sin\theta_L$ and $v_a\cos\theta_L$ are the perpendicular and parallel components of v_a, in the LF, resolved along the initial direction of the neutron before collision. Transforming these to the COMF gives $v_a\sin\theta_L$ and $v_a\cos\theta_L - v_m$ as the perpendicular and parallel components of v. Substituting for v_m and for $2v_av_b\cos\theta_L$ from eq(5) in $v = \sqrt{v_a^2\sin^2\theta_L + v_a^2\cos^2\theta_L + v_m^2 - 2v_av_m\cos\theta_L}$ and simplifying gives $v = \dfrac{Av_b}{A+1}$. Squaring the components of v to eliminate θ_L gives $v_a^2 = v^2 + v_m^2 + 2vv_m\cos\theta$. Substituting for v and v_m and simplifying gives,

$$\frac{v_a^2}{v_b^2} = \frac{E_a}{E_b} = \frac{A^2 + 2A\cos\theta + 1}{(A+1)^2}.$$

$$G(\alpha,\theta) = \frac{E_a}{E_b} = \frac{A^2+1}{(A+1)^2} + \frac{2A}{(A+1)^2}\cos\theta = \frac{1}{2}\left[(1+\alpha) + (1-\alpha)\cos\theta\right].$$

(OR)

(iii) From definition of center of mass frame $v_m = \dfrac{v_b}{A+1}$. After the collision, let v and V be magnitude of the velocities of neutron and moderator atom respectively in the COMF. From conservation laws in the COMF,

$$v = AV \qquad \text{and} \qquad \frac{1}{2}(v_b - v_m)^2 + \frac{1}{2}Av_m^2 = \frac{1}{2}v^2 + \frac{1}{2}AV^2.$$

Solving gives $v = \frac{Av_b}{A+1}$ and $V = \frac{v_b}{A+1}$. We also have $v\cos\theta = v_a\cos\theta_L - v_m$, substituting for v_m and for $v_a\cos\theta_L$ from eq(5) and simplifying gives

$$\frac{v_a^2}{v_b^2} = \frac{E_a}{E_b} = \frac{A^2 + 2A\cos\theta + 1}{(A+1)^2}.$$

$$G(\alpha,\theta)=\frac{E_a}{E_b}=\frac{A^2+1}{(A+1)^2}+\frac{2A}{(A+1)^2}\cos\theta=\frac{1}{2}\left[(1+\alpha)+(1-\alpha)\cos\theta\right].$$

(OR)

(iv) From definition of center of mass frame $v_m=\dfrac{v_b}{A+1}$. After the collision, let v and V be magnitude of the velocities of neutron and moderator atom respectively in the CM frame. From conservation laws in the CM frame,

$$v=AV \qquad \text{and} \qquad \frac{1}{2}(v_b-v_m)^2+\frac{1}{2}Av_m^2=\frac{1}{2}v^2+\frac{1}{2}AV^2.$$

Solving gives $v=\frac{Av_b}{A+1}$ and $V=\frac{v_b}{A+1}$. $U\sin\sigma$ and $U\cos\sigma$ are the perpendicular and parallel components of U, in the LF, resolved along the initial direction of the neutron before collision. Transforming these to the COMF gives $U\sin\sigma$ and $-U\cos\sigma+v_m$ as the perpendicular and parallel components of V. So we get $U^2=V^2\sin^2\theta+V^2\cos^2\theta+v_m^2-2Vv_m\cos\theta$. Since $V=v_m$ we get $U^2=2v_m^2(1-\cos\theta)$. Substituting for U from eq(4) and simplifying gives

$$\frac{v_a^2}{v_b^2}=\frac{E_a}{E_b}=\frac{A^2+2A\cos\theta+1}{(A+1)^2}.$$

$$G(\alpha,\theta)=\frac{E_a}{E_b}=\frac{A^2+1}{(A+1)^2}+\frac{2A}{(A+1)^2}\cos\theta=\frac{1}{2}\left[(1+\alpha)+(1-\alpha)\cos\theta\right].$$

Note: We have $v_a=\dfrac{\sqrt{A^2+2A\cos\theta+1}}{A+1}v_b$. Substituting for $v_a,\ v,\ v_m$ in $v\cos\theta=v_a\cos\theta_L-v_m$ gives the relation between θ_L and θ,

$$\cos\theta_L=\frac{A\cos\theta+1}{\sqrt{A^2+2A\cos\theta+1}}.$$

Treating the above equation as quadratic in $\cos\theta$ gives,

$$\cos\theta=\frac{-\sin^2\theta_L\pm\cos\theta_L\sqrt{A^2-\sin^2\theta_L}}{A}.$$

For $\theta_L=0°$ the root with the negative sign gives $\theta=180°$ which is not correct so,

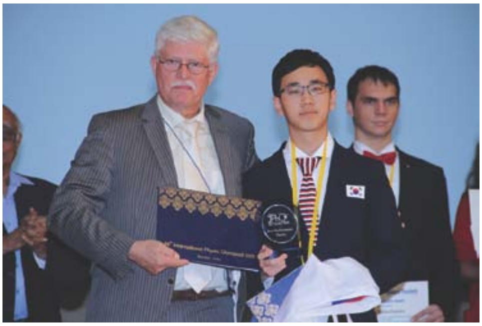
$$\cos\theta=\frac{\cos\theta_L\sqrt{A^2-\sin^2\theta_L}-\sin^2\theta_L}{A}.$$

Substituting the above expression for $\cos\theta$ in the expression for $\dfrac{v_a^2}{v_b^2}$ gives an expression in terms of $\cos\theta_L$

$$\frac{v_a^2}{v_b^2}=\frac{E_a}{E_b}=\frac{A^2+2\cos\theta_L\sqrt{A^2-\sin^2\theta_L}+\cos2\theta_L}{(A+1)^2}.$$

Results

Special Prizes



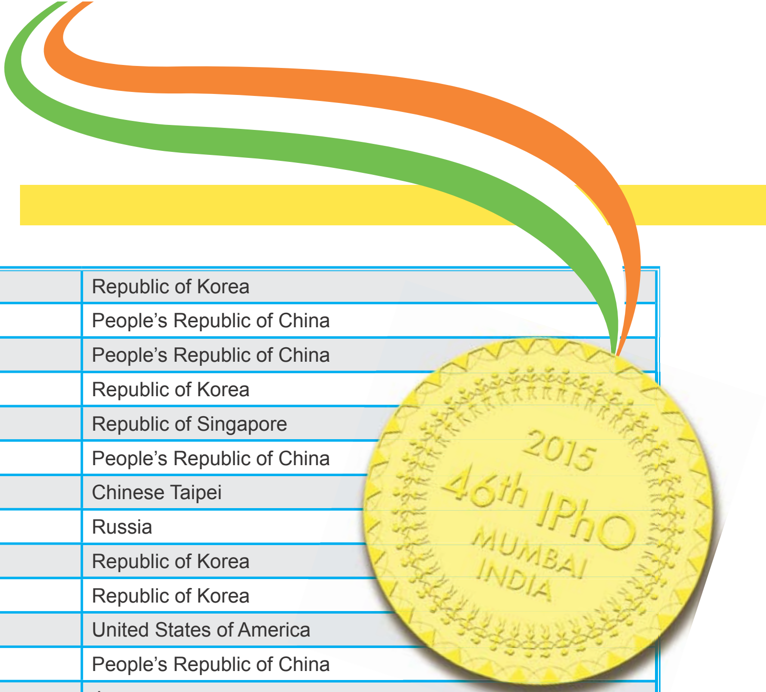
Best Performance in Theory
Taehyoung Kim, Republic of Korea

Best Performance in Experiment
Sol Kim, Republic of Korea

Best Female Participant
Thao Thi Huong Dinh, Vietnam

Overall Winner
Taehyoung Kim, Republic of Korea

Gold Medallists



Taehyoung Kim	Republic of Korea
Jingyu Zhao	People’s Republic of China
Deng Pan	People’s Republic of China
Sol Kim	Republic of Korea
Chua Yee Shuen Darren	Republic of Singapore
Chenxing Zhang	People’s Republic of China
Chung-Yao Cheng	Chinese Taipei
Aleksei Krasnikov	Russia
Hyunsoo Ha	Republic of Korea
Joonhwi Kim	Republic of Korea
Adam Robert Busis	United States of America
Xinyu Wang	People’s Republic of China
Akihiro Watanabe	Japan
Nam Thanh Trung Vu	Vietnam
Zachary Bogorad	United States of America
Yu-Chia Lin	Chinese Taipei
Mohammadhossein Darestanifarahani	Islamic Republic of Iran
Dan Stefan Eniceicu	Romania
Lingbang Zhu	People’s Republic of China
Yi-Lin Tsao	Chinese Taipei
Pei-Kai Tsai	Chinese Taipei
Yat Wong	Hong Kong
Phum Siriviboon	Thailand
Ali Shirali	Islamic Republic of Iran
Georgii Korepanov	Russia
Adam Sebastian Kucz	Poland
Dmitrii Tatarkin	Russia
Ching Yin Lui	Hong Kong
Thanh Cong Nguyen	Vietnam
Shun Leung Frankie Lam	Hong Kong
Daulet Kurmantayev	Republic of Kazakhstan
Tudor Costel Cretu	Romania
Thao Thi Huong Dinh	Vietnam
Anton Igorevich Talkachov	Belarus
Saranesh Thanika Prembabu	United States of America
Taavet Kalda	Estonia
Kirill Voronin	Russia
Kevin Q Li	United States of America

Silver Medallists

Jason Lu	United States of America
Botond Oreg	Hungary
Ivan Uteshev	Russia
Chih-Hsiang Yang	Chinese Taipei
Yuk Wong	Hong Kong
Garett Tok Em Liang	Republic of Singapore
Peter Yuen	Republic of Singapore
Joel Tan	Republic of Singapore
Gowtham Amirthya Neppoleon	India
Seou Choi	Republic of Korea
Qingyue Wu	Canada
Oleksii Mikulenko	Ukraine
Khanh Ngoc Nguyen	Vietnam
Ali Fathi	Islamic Republic of Iran
Wai Ting Tai	Hong Kong
Cristian Alexandru Frunza	Romania
Seyed Mohammad Javad Tabatabaei Yazdi	Islamic Republic of Iran
Watchara Sornwanee	Thailand
Vincent Peter Grande	Germany
Mohammadali Khademsohi	Islamic Republic of Iran
Hugo Herdianto	Indonesia
Abhijatmedhi Chotrattanapituk	Thailand
Andras Holczer	Hungary
Hrant Armen Topchyan	Armenia
Sri Eswar Sai Prakash Reddy Pabatireddy	India
Joshua Lim	Republic of Singapore
Oleksandr Shumaiev	Ukraine
Sheshansh Agrawal	India
Edgar Ara Vardanyan	Armenia
Sompob Shanokprasith	Thailand
Kevin Limanta	Indonesia
Kristof Sal	Hungary
Panawat Wong-Klaew	Thailand
Jared Anand Jeyaretnam	United Kingdom
Satoshi Yoshida	Japan
Razvan-Octavian Radu	Romania

Bahrudin Trbalic	Bosnia and Herzegovina
Bahdan Andreevich Zviazhynski	Belarus
Nam Quang Nguyen	Vietnam
Tom Segal	Israel
Nir Jacob Yaron	Israel
Fabio Zoratti	Italy
James Alexander Bamber	United Kingdom
Filip Bialas	Czech Republic
Vaclav Rozhon	Czech Republic
Simone Bombari	Italy
Jiri Kucera	Czech Republic
Hideharu Kashu	Japan
Rhesa Edrick Tendean	Indonesia
Marine Schimel	France
Menyhert Balogh	Hungary
Martin Gazo	Slovakia
Friedrich Uwe Hübner	Germany
Konstantin Juliyev Karchev	Bulgaria
Taras Zhylenko	Ukraine
Sven Jandura	Germany
Umut Eren Usturali	Turkey
Shaked Rosenstein	Israel
Tolga Gurcan	Turkey
Angel Kostov Sherletov	Bulgaria
Anuj Shripad Apte	India
Ahmet Burak Catli	Turkey
Gintautas Kamuntavicius	Lithuania
Paul Emmanuel Robin	France

Bronze Medallists

Joshua Zexi Lin	Australia
Kristjan Kongas	Estonia
Morane Shapira	Israel
Jaswin Jaswin	Indonesia
Pierre Richard Samir Côte De Soux	France
Jan Krzysztof Marucha	Poland
Georg Dieter Michael Benno Christoph Berger	Germany
Ashot Harutyun Movsisyan	Armenia
Arttu Otto Benjamin Tolvanen	Finland
Matej Pavlovic	Croatia
Asbjoern Baekgaard Lauritsen	Denmark
Ileana Rugina	Romania
Janko Sustersic	Serbia
Radostin Radostinov Dimitrov	Bulgaria
Andrea Ferrario	Italy
Tamas Lajos Tompa	Hungary
Robert Stephen Tji-Kean Swan	United Kingdom
Felipe Vieira Coimbra	Brazil
Mert Kayaalp	Turkey
Boyko Ivanov Vodenicharski	Bulgaria
Moïse Jean-Baptiste Blanchard	France
Mykhailo Rashkovetskyi	Ukraine
Ara Tigran Mambreyan	Armenia
Arne Christian Wolf	Germany
Nermedin Dzekovic	Bosnia and Herzegovina
Hristosko Dimitrov Chaushev	Bulgaria
Aleksej Jurca	Slovenia
Timo Iiro Ilmari Takala	Finland
Jakob Jazbec	Slovenia
Evgeni Aleksandrovich Shurygin	Belarus
Sudarshan Ravi	Australia
Stanislaw Pawel Kurdzialek	Poland
Piotr Krzysztof Kubala	Poland
Yinuo Han	Australia
Ayan Segizbay	Republic of Kazakhstan

Rudolfs Treilis	Latvia
Arindam Sonali Amar Bhattacharya	India
Tural Aliyev	Azerbaijan
Michel Romero Rodriguez	Cuba
Jason Kristiano	Indonesia
Filip Ayazi	Slovakia
Pietro Pelliconi	Italy
Hiroto Takahashi	Japan
Vytautas Strimaitis	Lithuania
Laurentiu Calancea	Moldova
Jakub Dolejsi	Czech Republic
Gleb Vizitiv	Moldova
Artsiom Maksimovich Pivavarchyk	Belarus
Ali Veli	Turkey
Mark Yuhai	Ukraine
Vaclav Miratsky	Czech Republic
Jesús Alejandro González Sánchez	Mexico
Åke Andersson	Sweden
Deaglan John Bartlett	United Kingdom
José Polo Gómez	Spain
Martin Bajzek	Croatia
Tuomas Petteri Oikarinen	Finland
Ashot Artur Matevosyan	Armenia
Bianca Ana-Maria Andrei	United Kingdom
Stephen Liu	Canada
Oliver Jin Wang	Canada
Grgur Palle	Croatia
Matthias Diez	Austria
Lukas Wimmer	Austria
Hugues Déprés	France
Talha Irfan Khawaja	Pakistan
Jozef Bucko	Slovakia
Ilan Mitnikov	Israel
Shiye Su	Australia
Harshana Sumedha Weligampola	Sri Lanka
David Bugar	Slovakia
Felipe De Castro Silva	Brazil
Joonatan Bergholm	Finland
Zeljko Arsic	Serbia
Tomaz Cvetko	Slovenia
Zan Kokalj	Slovenia
Linus Geiser	Switzerland
Soviro Heng	Cambodia

Blaz Karner	Slovenia
Grégory François Xavier Laetitia Boneart	Portugal
Roeland Germain J. Van Haecke	Belgium
Marija Sindik	Serbia
Uladzislau Viktorovich Klimashonak	Belarus
Kin Ian Lo	Macao-China
Pepijn De Maat	Netherlands
Hajime Ueda	Japan
Adam Teixidó Bonfill	Spain
Dibyatanoy Bhattacharjee	Bangladesh
Mattia Humbel	Switzerland
Tafnes Silva Barbosa	Brazil
Daniels Krimans	Latvia
Alfonso Santacruz García	Mexico
Dovran Amanov	Turkmenistan

Honourable Mention

Giovanni Maria Tomaselli	Italy
Jesús Arjona Martínez	Spain
Tserenchimeg Khasgerel	Mongolia
Ewoud Wempe	Netherlands
Anian Altherr	Switzerland
Kaarel Hänni	Estonia
Jakob Declercq	Belgium
Christian Primavera	Netherlands
Anton Sedletskiy	Republic of Kazakhstan
Gabriel Sánchez Pérez	Spain
Alexandru Cotos	Moldova
Khalykbek Yelshibekov	Republic of Kazakhstan
Ismoil Odinaev	Tajikistan
Peter Hallstadius	Sweden
Dejan Maksimovski	Macedonia
Radoica Draskic	Serbia
Tugsbayasgalan Manlaibaatar	Mongolia
Andrew Jinwook Kim	Canada
Ajdin Palavric	Bosnia and Herzegovina
Zoi Tsangalidou	Greece
Elvinas Ribinskas	Lithuania
Mohammed Eidha Al Wazeenani	Saudi Arabia
Dusan Novicic	Serbia
Miroslav Gasparek	Slovakia
Jafar Abdul Aziz Badour	Syria
Bakhtadze Giorgi	Georgia
Florian Quatresooz	Belgium
Jonatan Kalmus	Estonia
Delson Barros Oliveira Filho	Brazil
Bamidele Andrae Ayomide	Nigeria
Faisal Fahad Alsaif	Saudi Arabia
Allamyrat Amanmadov	Turkmenistan
Jer Yong Chan	Malaysia
Noor Ul Huda	Pakistan
Michael Pfeifer	Austria
David Liu	Netherlands
Ivan Jercic	Croatia
Jose Manuel Ortiz Tavarez	Puerto Rico
Naida Dedic	Bosnia and Herzegovina
André Miguel Gomes Pereira Lello De Almeida	Portugal

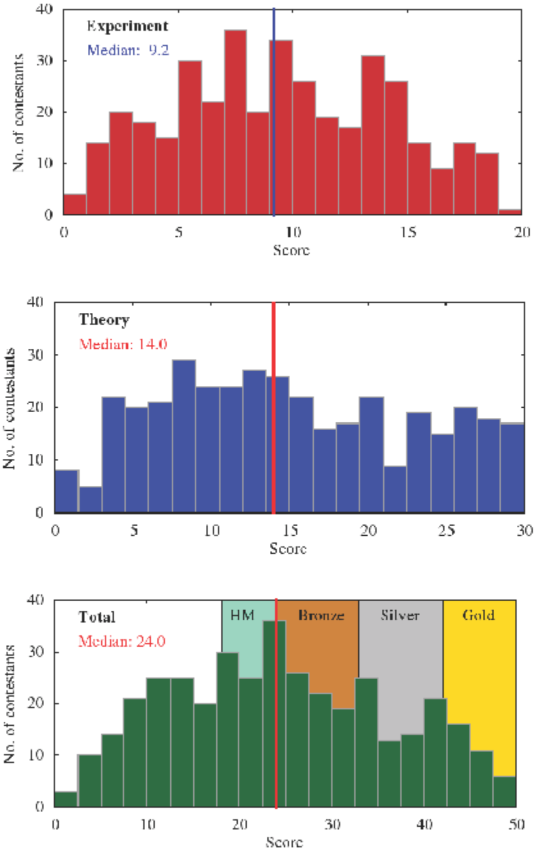
Cédric Philippe Nicolas Schoonen	Belgium
Wilson Fan Wu	Canada
Azimdzhon Temurdzhonov	Tajikistan
Ka Seng Ng	Macao-China
Ida Svenningsson	Sweden
Kristín Björg Bergþórsdóttir	Iceland
Sokhashvili Mikheil	Georgia
Andrea Gebek	Switzerland
Arsenadze Giorgi	Georgia
Janet Fan Mi Zhong	Australia
Kajo Vivian Krummenacher	Switzerland
Svend Kroejer Moeller	Denmark
Tadas Indrele	Lithuania
Abdulmalik Hesham Al Ghonaim	Saudi Arabia
Ulrik Reinhardt De Muelenaere	South Africa
Avoy Datta	Bangladesh
Faour Fadl Faour	Saudi Arabia
Temirlan Ulugbek Uulu	Kyrgyzstan
Lam Lam	Macao-China
Rafal Ernest Cwiek	Poland
José Guilherme Boura De Matos	Portugal
Bibek Kumar Pandit	Nepal
Ethan Van Woerkom	Netherlands
João Carlos Lourenço Antunes	Portugal
Bat-Orgil Bayar	Mongolia
Mateus Arraes Feitosa Borges	Brazil
Sivhuo Prak	Cambodia
Omargeldi Atanov	Turkmenistan

Analysis of the Results

Summary of Scores

Taskwise and overall summary of scores in IPhO 2015. In each task, as well as overall, the scores spanned the full range of marks from zero to maximum credit.

Marks	**E-I**	**E-II**	**Experiment**	**T-1**	**T-2**	**T-3**	**Theory**	**Total**
Full	10.0	10.0	20.0	10.0	10.0	10.0	30.0	50.0
Median	6.1	4.2	9.2	5.4	4.3	5.2	14.0	24.0
Maximum	10.0	9.6	19.0	10.0	10.0	10.0	30.0	48.3
Minimum	0.0	0.0	0.2	0.0	0.0	0.0	0.0	1.0



Distribution of scores in Experimental component, Theoretical component and in aggregate. The median scores are shown in each. The median scores show that the academic tasks met the criterion laid out in the statutes of IPhO: *"The standard of problems should attempt to ensure that approximately half the students obtain over half marks."*

Effect of Moderation

The effect of moderation of the scores was minimal in IPhO 2015, as can be seen in the summary below. The number of gold medals increased by 7, while the total number of medals and honourable mentions inflated only by 2.7%.

Change in marks post-moderation	Theory				Experiment			Grand Total
	T-1 Total	T-2 Total	T-3 Total	Total	E-I Total	E-II Total	Total	
Mean change per contestant	0.05	0.07	0.08	0.2	0.06	0.04	0.09	0.29
Maximum change in one contestant	1.0	2.0	1.5	2.6	4.8	1.3	4.8	4.8
No. of contestants with NO change	326	320	313	255	334	335	306	226

Type of award	No. of awards BEFORE moderation	No. of awards AFTER moderation
Gold Medal	31	38
Silver Medal	65	64
Bronze Medal	95	93
Honourable Mention	65	68
Total no. of awards	256	263

Newsletter Editorial Board

Sugra Chunawala	*HBCSE-TIFR, Mumbai*
Disha Gupta	*HBCSE-TIFR, Mumbai*
Adithi Muralidhar	*HBCSE-TIFR, Mumbai*
Manoj Nair	*HBCSE-TIFR, Mumbai*
Devashree Prabhu	*HBCSE-TIFR, Mumbai*
Pooja Sharma	*HBCSE-TIFR, Mumbai*
Susneha Ayare	*HBCSE-TIFR, Mumbai*

Reflections

The 46th IPhO Newsletter

Issue 1 (July 5)

Issue 2 (July 6)

Issue 3 (July 7)

Issue 4 (July 8)

Issue 5 (July 9)

Issue 6 (July 10)

Issue 7 (July 11)

Issue 8 (July 12)

Issue 9 (July 12)

IPhorum Sofware Team

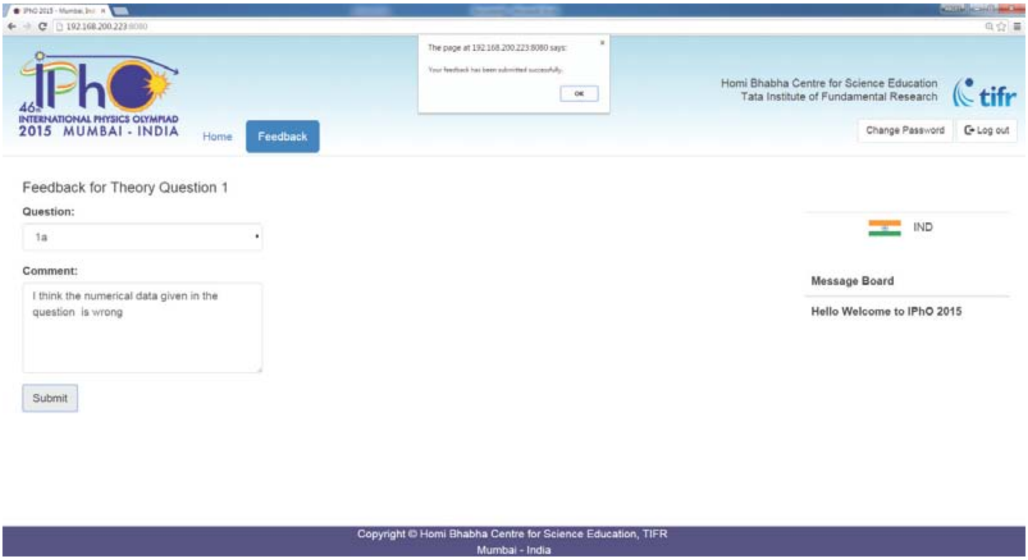
Kumar Ayush	*IIT Bombay*
Sandesh Kalantre	*IIT Bombay*
Sharad Mirani	*IIT Bombay*
Arijit Das	*HBCSE - TIFR, Mumbai*
Advisors:	
Aniket Sule	*HBCSE - TIFR, Mumbai*
Anwesh Mazumdar	*HBCSE - TIFR, Mumbai*

IPhOrum

The web interface for academic deliberations

A customised computer software, named IPhOrum, was created to facilitate the academic process of IPhO 2015. It was a browser-based application made available to all leaders on the laptops provided for the International Board meetings. The leaders used it for the downloading, uploading and printing the question papers and their translated versions during the IB meetings. They were able to post their comments on the questions as well as see the feedback from the others. The voting during the IB meetings was carried out entirely on this application. Further, the exchange of marks between the leaders and the Indian markers was also done on IPhOrum. The use of this software played a major role in the smooth conduct of the entire academic process.

The main authors of IPhOrum were undergraduate students who were Indian medal winners in past International Astronomy and Junior Science Olympiads.



The page at 192.168.200.223:8080 says:

Your feedback has been submitted successfully.

Feedback for Theory Question 1

Question: 1a

Comment: I think the numerical data given in the question is wrong

Message Board

Hello Welcome to IPhO 2015

Copyright © Homi Bhabha Centre for Science Education, TIFR
Mumbai - India

International Board

Secretariat

President

Hans Jordens
(h.jordens@rug.nl)

Secretary

Matthew Verdon
(matt.verdon@gmail.com)

Treasurer

Yernur Rysmagambetov

Statutes of IPhO

§1

In recognition of the growing significance of physics in all fields of science and technology, and in the general education of young people, and with the aim of enhancing the development of international contacts in the field of school education in physics, an annual physics competition has been organized for secondary school students. The competition is called the International Physics Olympiad and is a competition between individuals.

§2

The competition is organized by the Ministry of Education, the Physical Society or another appropriate institution of one of the participating countries on whose territory the competition is to be conducted. The organizing country is obliged to ensure equal participation of all the delegations, and to invite teams from all those countries that participated during the last three years. Additionally, it has the right to invite other countries. The list of such new countries must be presented to Secretariat of the IPhOs (§ 8) at least six months prior to the competition. Within two months the Secretariat has the right to remove, after consultations with the Advisory Committee (# 8), from the suggested list the teams that in opinion of Secretariat or Advisory Committee do not meet the criteria of participation in the IPhOs. The new countries not accepted by the Secretariat or Advisory Committee may, however, participate as "guest teams" but such participation does not create any commitments with respect to inviting these countries to the next competition(s).

No country may have its team excluded from participation on any political reasons resulting from political tensions, lack of diplomatic relations, lack of recognition of some country by the government of the organizing country, imposed embargoes and similar reasons. When difficulties preclude formal invitation of the team representing a country, students from such a country should be invited to participate as individuals.

The competition is conducted in the friendly atmosphere designed to promote future collaborations and to encourage the formation of friendship in the scientific community. Therefore all possible political tensions between the participants should not be reflected in any activity during the competition. Any political activity directed against any individuals or countries is strictly prohibited.

§3

Each participating country shall send a delegation, normally consisting of five students (contestants) and two accompanying persons (delegation leaders) at most.

The contestants shall be students of general or technical secondary schools i.e. schools which cannot be considered technical colleges. Students who have finished their school examinations in the year of the competition can be members of the team as long as they have not commenced their university studies. The age of the contestants should not exceed twenty years on June 30th of the year of the competition.

The delegation leaders must be specialists in physics or physics teachers, capable of solving the problems of the competition competently. Each of them should be able to speak English.

§4

The Organizers of the Olympiad determine in accordance to the program the day of arrival and the day of departure as well as the place in their country from which the delegations are supposed to arrive and depart. The costs for each delegation as a result of activities connected to the Olympiad from the day of arrival till the day of departure are covered by the Organizing Committee.

§5

The competition shall be conducted over two days, one for the theoretical examination and one for the experimental examination. There will be at least one full day of rest between the examinations.

The theoretical examination shall consist of three theoretical problems and shall be of five hours total duration.

The experimental examination shall consist of one or two problems and shall be of five hours total duration.

Contestants may bring into the examination drawing instruments and approved calculators. No other aids may be brought into the examination.

The theoretical problems should involve at least four areas of physics taught at secondary school level, (see Syllabus). Secondary school students should be able to solve the competition problems with standard high school mathematics and without extensive numerical calculation.

The competition tasks are chosen and prepared by the host country and have to be accepted by the International Board (§ 7).

The host country has to prepare at least one spare problem, which will be presented to the International Board if one of the first three theoretical problems is rejected by two thirds of members of the International Board. The rejected problem cannot be considered again.

§6

The total number of marks awarded for the theoretical examination shall be 30 and for the experimental examination 20. The competition organizer shall determine how the marks are allocated within the examinations.

After preliminary grading (prior to discussion of the grading with the delegation leaders) the organizers establish minima (expressed in points) for Gold Medals, Silver Medals, Bronze Medals, and Honorable Mentions according to the following rules:

(a) Gold Medals should be awarded to 8% of the contestants (rounded up the nearest integer).

(b) Gold or Silver Medals should be awarded to 25% of the contestants (rounded up the nearest integer).

(c) Gold, Silver or Bronze Medals should be awarded to 50% of the contestants (rounded up the nearest integer).

(d) An Olympic Medal or Honorable Mention should be awarded to 67% of the contestants (rounded up the nearest integer).

The minima corresponding to the above percentages should be expressed without rounding. The suggested minima shall be considered carried if one half or more of the number of the Members of the International Board cast their vote in the affirmative.

Results of those candidates who only receive a certificate of participation should strictly remain to the knowledge of the Members of the International Board and persons allowed to attend its meetings.

§7

The governing body of the IPhO is the International Board, which consists of the delegation leaders from each country attending the IPhO.

The chairman of the International Board shall be a representative of the organizing country when tasks, solutions and evaluation guidelines are discussed and the President of the IPhO in all other topics.

A proposal placed to the International Board, except Statutes, Regulations and Syllabus (see § 10), shall be considered carried if more than 50% of all delegation leaders present at the meeting vote in the affirmative. Each delegation leader is entitled to one vote. In the case of equal number of votes for and against, the chairman has the casting vote. The quorum for a meeting of the International Board shall be one half of those eligible to vote.

The International Board has the following responsibilities:

(a) to direct the competition and supervise that it is conducted according to the regulations;

(b) to ascertain, after the arrival of the competing teams, that all their members meet the requirements of the competition in all aspects. The Board will disqualify those contestants who do not meet the stipulated conditions;

(c) to discuss the Organizers' choice of tasks, their solutions and the suggested evaluation guidelines before each part of the competition. The Board is authorized to change or reject suggested tasks but not to propose new ones. Changes may not affect experimental equipment. There will be a final decision on the formulation of tasks and on the evaluation guidelines. The participants in the meeting of the International Board are bound to preserve secrecy concerning the tasks and to be of no assistance to any of the participants;

(d) to ensure correct and just classification of the students. All grading has to be accepted by the International Board;

(e) to establish the winners of the competition and make a decision concerning presentation of the medals and honorable mentions. The decision of the International Board is final;

(f) to review the results of the competition;

(g) to select the countries which will be assigned the organization of future competitions;

(h) to elect the members of the Secretariat of the IPhO.

§8

The long-term work involved in organizing the Olympiads is coordinated by a Secretariat for the International Physics Olympiads. This Secretariat consists of the President, the Secretary and the Treasurer. They are elected by the International Board for a period of five years when the chairs become vacant.

The members of the Secretariat of the IPhO should be invited to the Olympiads as the members and heads of the International Board; their relevant expenses should be paid by the organizers of the competition. The members of the Secretariat should not be leaders of any national team.

There shall be an Advisory Committee convened by the President of the IPhOs. The Advisory Committee consists of:

1. The President,
2. The Secretary,
3. The Treasurer,
4. The host of the past Olympiad,
5. The hosts of the next two Olympiads,
6. Such other persons appointed by the President.

§9

The working language of the IPhO is English.

The competition problems should be presented to the International Board in English, Russian, German, French and Spanish.

The solutions to the problems should be presented in English.

It is the responsibility of the delegation leaders to translate the problems into languages required by their students.

These statutes and other IPhO-documents shall be written in English.

Meetings of the International Board shall be held in English.

§10

These statutes are supplemented by

Regulations concerning the details of the organization

the Syllabus mentioned in § 5.

Proposals for amendment to these Statutes and the supplementing documents may be submitted to the president or his nominee no later than December 15th prior to consideration.

The President shall circulate, no later than March 15th, all such proposals together with the recommendation of the President's Advisory Committee, to the last recorded address of each delegation leader who attended at the last IPhO.

Such proposals shall be considered by a meeting of the International Board at the next IPhO and shall be considered carried if

> in case of Statutes and Syllabus two thirds or more and
>
> in case of Regulations more than one half

of the number of the members of the International Board present at the meeting cast their vote in the affirmative. Such changes shall take effect from the end of the current IPhO and cannot affect the operation of the competition in progress. The vote can only take place if at least 2/3 of the all leaders are present at the meeting.

§11

Participation in an International Physics Olympiad signifies acceptance of the present Statutes by the Ministry of Education or other institution responsible for sending the delegation.

Regulations Associated with the Statutes of the International Physics Olympiads

Regulations to §2

The Ministry of Education, or the institution organizing the competition, allots the task of preparation and execution of the Competition to an appropriate body.

Official invitations to the participating countries should be sent at least six months before the Olympiad. They normally are sent to the national institution that sent the delegation to the previous Olympiad. Copies of the invitation are also sent to the previous years' delegation leaders. The invitation should specify the place and time of the Competition plus the address of the organizing secretariat.

Countries wishing to attend the current IPhO must reply to the invitation before March 15, nominating a contact person. Each participating country must in addition supply the host country with the contestants' personal data (surname, given name, sex, address, date of birth and address of school) by May 15 or as soon as possible.

The host country is only obliged to invite delegations from countries that participated in one of the last three competitions. It may refuse

> applications for participation from any other country
>
> applications from participating countries not belonging to the delegation as defined in §3 (observers, guests).

Each country should, within five years of entry, declare its intention to host for a future Olympiad, suggesting possible years. A country that is unable to organize the competition may be prevented from participating in IPhOs by decision of the International Board.

Regulations to §3

The accompanying persons are considered by the organizers of the next Olympiad and by the Secretariat of the IPhOs (§ 8) as contact persons until the next Olympiad (unless new accompanying persons or other contact persons are nominated by the participating country).

Each participating country must ensure that the contestants are all secondary school pupils when they announce the names of the members of their delegations. In addition to the delegations, teams may be accompanied by observers and guests.

Observers may attend all Olympiad meetings, including the meetings of the International Board. However they may not vote or take part in the discussions. Guests do not attend the meetings of the International Board.

If possible, the host country should accept as observers any of the following persons:

the organizer(s), or nominee(s), from the host country in the subsequent three years

a representative of any country expressing an intention to participate in the following IPhO.

Regulations to §4

The host country must pay for organization of IPhO, food, lodging, transport and excursions of the delegations plus prizes.

However it is not responsible for medical costs and sundry expenses of the participants. Observers and guests may be asked to pay the full cost of their stay plus an attendance fee.

The host country may ask the delegations for a contribution to the obligatory costs. Delegations with economic difficulties may ask waving this fee by sending a motivated appeal to the Secretariat of the IPhO.

Regulations to §5

It is recommended that the Competition should last 10 days (including arrival and departure days).

The host country is obliged to ensure that the Competition is conducted according to the Statutes. It should provide full information for participating countries, prior to their arrival, concerning venue, dates, accommodation, transport from airports, ports and railway stations. The addresses, telephone, fax, e-mail of all IPhO officers should be provided, together with information concerning relevant laws and customs of the host country.

A program of events during the IPhO should be prepared for the leaders and contestants. It should be sent to the participating countries, prior to the Olympiad.

The organizers of the IPhO are responsible for devising all the problems. They must be presented in English and the other official languages of the Olympiad as indicated in § 9. The examination topics should require creative thinking and knowledge contained within the Syllabus. Factual knowledge from outside the Syllabus may be introduced provided it is explained using concepts within the Syllabus.

Everyone participating in the preparation of the competition problems must not divulge their content.

The standard of problems should attempt to ensure that approximately half the students obtain over half marks.

All problems should be presented simultaneously and the board should have at least one hour (exact time to be determined by the organizers) to read them carefully and suggest changes. Changes should be suggested to the organizers during this period. Changes accepted by the organizers will not require a vote: they will form a new text of the problems. After this period, the organizers will present the modified problem set. The International Board shall be given time to consider the examination papers. It may change, or reject, problems. IB Members should not be allowed to suggest the cuts in the problems unless the part contains wrong or poor physics. They can suggest that the whole set of problems is too long and ask for a vote on this. If accepted, it will be up to the organisers to suggest the cuts. The next vote can decide if the cuts are sufficient or not and this procedure acan be repeated until the IB decides that the length of the problems is correct.

If a problem is rejected, the alternative problem must be accepted. The host country will be responsible for grading the examination papers. The delegation leaders shall have an opportunity to discuss with the examiners the grading of their students' papers. If an agreement, between graders and leaders, to the final marks cannot be reached, the International Board has to decide.

A calculator shall be an approved calculator if it is not a graphical calculator, its display has no more than three lines, and if its user memory is completely cleared immediately prior to each examination.

The host country may provide calculators to students which are approved calculators. If the country chooses to do this then the team leaders of the countries attending IPhO must be advised of the exact model at least two months in advance of the competition. Students who bring their own approved calculators shall be permitted to use them.

The organizers shall provide the delegation leaders with copies of their students' scripts and allow at least 12 hours for them to mark the scripts.

The host country shall provide medals and certificates in accordance with the Statutes. They must also produce a list of all contestants receiving awards with their marks and associated award. The awards are presented at the Closing Ceremony.

The host country is obliged to publish the Proceedings of the Competition electronically, in English, within the subsequent year.

Regulations to §6

Special prizes may be awarded. The participant who obtains the highest score should receive a special prize.

Regulations to §7

During the meeting of the graders where the final and most detailed version of the grading scheme is set, 3 members of the International Board will be present. They have the right to give advice to the group of graders in order to keep the grading scheme within the tradition of the IPhOs.

If it is found that leaders, observers or students from a country have been in collusion to cheat in one of the International Olympiad examinations, the students concerned should be disqualified from that Olympiad. In addition, the leaders, observers and students involved should not be allowed to return to any future Olympiad. Appropriate decisions are taken by the International Board.

Regulations to §8

Election of the members of the Secretariat

All members of the Secretariat have to have been for the five years prior to the nomination

- a member of the International Board for at least three of these years,
- or an observer or member of the International Board, who has attended all these five IPhOs.

All members of the Secretariat will hold office for a period of five years commencing at the conclusion of the final meeting of the International Board at which the concerned person has been chosen.

The members of the Secretariat must be appointed at different IPhOs. If this is the case, however, the period of the Secretary and/or the Treasurer will have to be shortened in such a way that the elections can be held at different IPhOs.

The members of the Secretariat must come from different delegations.

If the term of one of the members of the Secretariat comes to an end, the International Board has to be informed one year in advance that there will be the ballots of a new member of the Secretariat during the following IPhO. In addition to that, the Secretariat is responsible to send a letter to all leaders of the last three IPhOs with this information and with the question if any leader will be ready to run for these positions for the coming period by 31st January. This is normally done by e-mail.

If someone is willing to be a candidate for the ballot, he or she will have to tell this to the current Secretary by 31st March, normally by e-mail. A nominee has to send his/her curriculum vitae up to 31st March. A nomination may not be made by a person from the same country as one of the current members of the Secretariat who holds chair on another position than the one that becomes vacant.

The Secretariat is responsible to collect all these answers and has to make a list with all the names.

If the current members of the Secretariat are willing to continue his/her term, he or she has to enter his/her name in this list and has to follow the same rules as all the other candidates.

If the current secretary is willing to continue his/her activity as secretary, he or she has to enter his/her name in this list and has to follow the same rules as all the other candidates.

The list with the candidates for the new member of the Secretariat has to be published on the IPhO-home-page and the home page of the IPhO during which the ballot will be held.

If there is just one candidate for the vacant position of the Secretariat, the current Secretary has to inform the current President about that. In that case this candidate is accepted as the elected one.

The Secretariat and the organizers of the IPhO during which the election will be held are responsible for a democratic, secret ballot of the member of the Secretariat during the last meeting of the International Board:

If the current member of the Secretariat resigns or becomes incapable of continuing his/her work, the remaining members of the Secretariat shall appoint a replacement to act as provisional President, Secretary or Treasurer up to the next IPhO. The ballot of the new one has to be made as soon as possible.

Appendices to the Statutes of the International Physics Olympiads

Accepted in 2011 in Bangkok, Thailand

Appendix I : Voting rules

(The following voting rules are the same as those stated in the Statutes, but are summarized in the appendix for convenient purpose.)

1.1 Subjects:	The suggested minima for awards (Statutes §6)
	Classification of the students (Statutes §7)
	To establish the winners (Statutes §7)
	Medals and honourable mentions (Statutes §7)

Quorum: one half of those eligible to vote (Statutes §7)

A proposal is carried: more than one half of the members of the International Board present at the meeting cast their vote in the affirmative; in the case of equal number of votes for and against, the chairman has the casting vote

1.2 Subjects: Changes in the text of a problem (Statutes §7)

Quorum: one half of those eligible to vote (Statutes §7)

A proposal is carried: more than one half of the members of the International Board participating in the vote cast their vote in the affirmative; in the case of equal number of votes for and against, the chairman has the casting vote

1.3 Subjects: Rejection of one of the first three theoretical problems (Statutes §5)

Selection of future organisers (Statutes §7)

Election of the president (Statutes §8)

Election of the secretary (Statutes & Regulations §8)

A country unable to organise the competition may be prevented from participating (Regulations §8)

Disqualification of participants, leaders, teams in collusion to cheat (Regulations §7)

Quorum: one half of those eligible to vote (Statutes §7)

A proposal is carried: two thirds or more of the number of the members of the International Board present at the meeting cast their vote in the affirmative

1.4 Subjects: Change in the Regulations (Statutes §10)

Quorum: 2/3 of those eligible to vote

A proposal is carried: more than one half of the members of the International Board present at the meeting cast their vote in the affirmative; in the case of equal number of votes for and against, the chairman has the casting vote

1.5 Subjects: Change in the Statutes (Statutes §10)

Change in the Syllabus (Statutes §10)

Quorum: 2/3 of those eligible to vote

A proposal is carried: two thirds or more of the number of the members of the International Board present at the meeting cast their vote in the affirmative

Appendix II: Marking Rules

1. Establishing the Marks

1.1 In §6 of the Statutes it is stated that: ”The total number of marks awarded for the theoretical examination shall be 30 and for the experimental examination 20. The competition organiser shall determine how the marks are allocated within the examinations. ”

1.2. During the meeting of the International Board (IB) of the IPhO where the problems are discussed, a detailed marking scheme has to be provided which will be approved by the IB, if more than 50% of all delegation leaders present at the meeting vote in the affirmative.

1.3. The number of marks should reflect the required performance of the contestant. This performance can have different features:

- a. knowledge and physical understanding
- b. algebraic evaluation (mathematical formulation)
- c. numerical evaluation and units
- d. problem solving strategy and knowledge on how to draw conclusions
- e. collecting data (from measurements)
- f. representing data (plotting data curve)
- g. data analysis and uncertainty (error) estimation

1.3. In the detailed marking scheme it is indicated which of the above is required.

2. Detailed requirements

2.1. All results per (sub)question need to be presented with it's correct unit. Within a numerical or algebraic evaluation units are not demanded unless this is specifically asked for.

2.2. Drawings need to be completed with the necessary labels (i.e. numbers, letters, titles, …)

2.3. Tables need to indicate:

- a title or number
- per column the quantity
- the unit of the quantity
- the uncertainty (error) of the quantity (by measurement or by calculated uncertainty (error) estimation. (remark: numerical values of single data without an uncertainty are always useless since no comparison with other measurements or theoretical predictions can be made, unless the data are part of a series from which, by using statistics, an error estimation (or spread) can be calculated.)

2.4. Graphs need to fulfil:

- a title, a number or a name of the graph
- minimum sizes (i.e. at least half A4) and proper aspect ratio
- axes with the quantity and unit
- visible dots representing the coordinates of the data
- error bars when asked for in the question
- quality of the curve

2.5 Unless specified otherwise in the question, the student needs to state how they derived their uncertainty (error) estimations, equally acceptable either by graphical or theoretical methods.

3. The marking

3.1. The leading principle to mark is to award the contestant in accordance to the extent in which the required performance is met. Therefore marks will be added for every correct intermediate or final result; this in contrast to a system in which marks are subtracted for every error.

3.2. Per (sub)question the maximum of marks allotted has to be in accordance with the marking scheme.

3.3. The allotted marks will reflect to what extent the contestant has fulfilled the task.

3.4. Partial marks (0 – maximum) will be given when the performance is incomplete. This includes evaluations where for instance the final result is incorrect.

3.5. In case an error propagates in subsequent results, full marks will be given per intermediate and final result when no extra errors are made, unless the error clearly simplifies the calculations or the algebraic manipulations. In the latter case the degree of simplification should be reflected in the marks allotted.

3.6. At any stage the contestant should – if possible - reflect on the physical meaning of a(n) (intermediate) result. In case of wrong results only partial marks, if any, will be given. The reflection will regard:

> the unit of a quantity,
>
> the order of magnitude of a numerical result in accordance with the unit used,
>
> when in the case of error propagation the student remarks that the order (with respect to the unit) is wrong or that the unit is wrong, but when the student is unable to correct the error, no more than 2/3 of the marks should be allotted.

4. The Moderation

4.1 In the Regulation to §5 of the Statutes it is stated that: "The organisers shall provide the delegation leaders with copies of their students' scripts and allow at least 12 hours for them to mark the scripts." The time allotted for the preliminary marking should be long enough to achieve a high quality of grading. This benefits the moderations, assures more fair results and increases the predictability of the number of awards.

4.2. The markers in the moderation should have excellent knowledge on the problem they moderate. It is preferred that these markers are the same as the ones that marked the papers of the contestants who are discussed with the team leaders.

4.3. The markers master English to the extent that a quick discussion on their marking is assured. In case the markers need translations the time for the moderation will be doubled.

4.4. In §3 of the Statutes it is stated that: "The delegation leaders must be specialists in physics or physics teachers, capable of solving the problems of the competition competently. Each of them should be able to speak English." When the moderation is slowed down due to the fact that the delegation leaders do not meet these requirements, there will be no extra time allotted for the moderation.

4.5. In the Regulations to §7 of the Statutes it is stated that: "During the meeting of the graders where the final and most detailed version of the grading scheme is set, 3 members of the International Board will be present. They have the right to give advice to the group of graders in order to keep the grading scheme within the tradition of the IPhOs." Since these members are elected by the International Board, which is the governing body of the Olympiad (see §7 of the Statutes), their advise is decisive.

4.6. After the leaders and graders accept the moderation results, the marks of the concerned contestants should be final. If there is any special reason for changing the grades, it has to obtain consent from the three representatives of the International Board.

(Remark: This is to avoid unnecessary competing by some leaders for the highest grade.)

Syllabus of IPhO

1. Introduction

1.1 Purpose of this syllabus

This syllabus lists topics which may be used for the IPhO. Guidance about the level of each topic within the syllabus is to be found from past IPhO questions.

1.2 Character of the problems

Problems should focus on testing creativity and understanding of physics rather than testing mathematical virtuosity or speed of working. The proportion of marks allocated for mathematical manipulations should be kept small. In the case of mathematically challenging tasks, alternative approximate solutions should receive partial credit. Problem texts should be concise; the theoretical and the experimental examination texts should each contain fewer than 12000 characters (including white spaces ,but excluding cover sheets and answer sheets).

1.3 Exceptions

Questions may contain concepts and phenomena not mentioned in the Syllabus providing that sufficient information is given in the problem text so that students without previous knowledge of these topics would not be at a noticeable disadvantage. Such new concepts must be closely related to the topics included in the syllabus. Such new concepts should be explained in terms of topics in the Syllabus.

1.4 Units

Numerical values are to be given using SI units, or units officially accepted for use with the SI.

It is assumed that the contestants are familiar with the phenomena, concepts, and methods listed below, and are able to apply their knowledge creatively.

2. Theoretical skills

2.1 General

The ability to make appropriate approximations, while modelling real life problems. Recognition of and ability to exploit symmetry in problems.

2.2 Mechanics

2.2.1 Kinematics

Velocity and acceleration of a point particle as the derivatives of its displacement vector. Linear speed; centripetal and tangential acceleration. Motion of a point particle with a constant acceleration. Addition of velocities and angular velocities; addition of accelerations without the Coriolis term; recognition of the cases when the Coriolis acceleration is zero. Motion of a rigid body as a rotation around an instantaneous center of rotation; velocities and accelerations of the material points of rigid rotating bodies.

2.2.2 Statics

Finding the center of mass of a system via summation or via integration. Equilibrium conditions: force balance (vectorially or in terms of projections), and torque balance (only for one-and two-dimensional geometry). Normal force, tension force, static and kinetic friction force; Hooke's law, stress, strain, and Young modulus. Stable and unstable equilibria.

2.2.3 Dynamics

Newton's second law (in vector form and via projections (components)); kinetic energy for translational and rotational motions. Potential energy for simple force fields (also as a line integral of the force field). Momentum, angular momentum, energy and their conservation laws. Mechanical work and power; dissipation due to friction. Inertial and non-inertial frames of reference: inertial force, centrifugal force, potential energy in a rotating frame. Moment of inertia for simple bodies (ring, disk, sphere, hollow sphere, rod), parallel axis theorem; finding a moment of inertia via integration.

2.2.4 Celestial mechanics

Law of gravity, gravitational potential, Kepler's laws (no derivation needed for first and third law). Energy of a point mass on an elliptical orbit.

2.2.5 Hydrodynamics

Pressure, buoyancy, continuity law. the Bernoulli equation. Surface tension and the associated energy, capillary pressure.

2.3 Electromagnetic fields

2.3.1 Basic concepts

Concepts of charge and current; charge conservation and Kirchhoff's current law. Coulomb force; electrostatic field as a potential field; Kirchhoff's voltage law. Magnetic B-field; Lorentz force; Ampère's force; Biot-Savart law and B-field on the axis of a circular current loop and for simple symmetric systems like straight wire, circular loop and long solenoid.

2.3.2 Integral forms of Maxwell’s equations

Gauss’law (for E-and B-fields); Ampère’s law; Faraday’s law; using these laws for the calculation of fields when the integrand is almost piece-wise constant. Boundary conditions for the electric field (or electrostatic potential) at the surface of conductors and at infinity; concept of grounded conductors. Superposition principle for electric and magnetic fields.

2.3.3 Interaction of matter with electric and magnetic fields

Resistivity and conductivity; differential form of Ohm’s law. Dielectric and magnetic permeability; relative permittivity and permeability of electric and magnetic materials; energy density of electric and magnetic fields; ferromagnetic materials; hysteresis and dissipation; eddy currents; Lenz’s law. Charges in magnetic field: helicoidal motion, cyclotron frequency, drift in crossed E-and B-fields. Energy of a magnetic dipole in a magnetic field; dipole moment of a current loop.

2.3.4 Circuits

Linear resistors and Ohm’s law; Joule’s law; work done by an electromotive force; ideal and non-ideal batteries, constant current sources, ammeters, voltmeters and ohmmeters. Nonlinear elements of given V -I characteristic. Capacitors and capacitance(also for a single electrode with respect to infinity); self-induction and inductance; energy of capacitors and inductors; mutual inductance; time constants for RL and RC circuits. AC circuits: complex amplitude; impedance of resistors, inductors, capacitors, and combination circuits; phasor diagrams; current and voltage resonance; active power.

2.4 Oscillations and waves

2.4.1 Single oscillator

Harmonic oscillations: equation of motion, frequency, angular frequency and period. Physical pendulum and its reduced length. Behavior near unstable equilibria. Exponential decay of damped oscillations; resonance of sinusoidally forced oscillators: amplitude and phase shift of steady state oscillations. Free oscillations of LC-circuits; mechanic-electrical analogy; positive feedback as a source of instability; generation of sine waves by feed back in a LC-resonator.

2.4.3 Waves

Propagation of harmonic waves: phase as a linear function of space and time; wave length, wave vector, phase and group velocities; exponential decay for waves propagating in dissipative media; transverse and longitudinal waves; the classical Doppler effect. Waves in inhomogeneous media: Fermat’s principle, Snell’s law. Sound waves: speed as a function of pressure (Young’s or bulk modulus) and density, Mach cone. Energy carried by waves: proportionality to the square of the amplitude, continuity of the energy flux.

2.4.4 Interference and diffraction

Superposition of waves: coherence, beats, standing waves, Huygens' principle, interference due to thin films (conditions for intensity minima and maxima only). Diffraction from one and two slits, diffraction grating, Bragg reflection.

2.4.5 Interaction of electromagnetic waves with matter

Dependence of electric permittivity on frequency (qualitatively); refractive index; dispersion and dissipation of electromagnetic waves in transparent and opaque materials. Linear polarization; Brewster angle; polarizers; Malus' law.

2.4.6 Geometrical optics and photometry

Approximation of geometrical optics: rays and optical images; a partial shadow and full shadow. Thin lens approximation; construction of images created by ideal thin lenses; thin lens equation Luminous flux and its continuity; illuminance; luminous intensity.

2.4.7 Optical devices

Telescopes and microscopes: magnification and resolving power; diffraction grating and its resolving power; interferometers.

2.5 Relativity

Principle of relativity and Lorentz transformations for the time and spatial coordinate, and for the energy and momentum; mass-energy equivalence; invariance of the space time interval and of the rest mass. Addition of parallel velocities; time dilation; length contraction; relativity of simultaneity; energy and momentum of photons and relativistic Doppler effect; relativistic equation of motion; conservation of energy and momentum for elastic and non-elastic interaction of particles.

2.6 Quantum Physics

2.6.1 Probability waves

Particles as waves: relationship between the frequency and energy, and between the wave vector and momentum. Energy levels of hydrogen-like atoms (circular orbits only) and of parabolic potentials; quantization of angular momentum. Uncertainty principle for the conjugate pairs of time and energy, and of coordinate and momentum(as a theorem, and as a tool for estimates).

2.6.2 Structure of matter

Emission and absorption spectra for hydrogen-like atoms (for other atoms —qualitatively), and for molecules due to molecular oscillations; spectral width and lifetime of excited states. Pauli exclusion principle for Fermi particles. Particles (knowledge of charge and spin): electrons, electron neutrinos, protons, neutrons, photons; Compton scattering. Protons and neutrons as compound particles. Atomic nuclei, energy levels of nuclei (qualitatively); alpha-, beta-and gamma-decays; fission, fusion and neutron capture; mass defect; half-life and exponential decay. Photoelectric effect.

2.7 Thermodynamics and statistical physics

2.7.1 Classical thermodynamics

Concepts of thermal equilibrium and reversible processes; internal energy, work and heat; Kelvin's temperature scale; entropy; open, closed, isolated systems; first and second laws of thermodynamics. Kinetic theory of ideal gases: Avogadro number, Boltzmann factor and gas constant; translational motion of molecules and pressure; ideal gas law; translational, rotational and oscillatory degrees of freedom; equipartition theorem; internal energy of ideal gases; root-mean-square speed of molecules. Isothermal, isobaric, isochoric, and adiabatic processes; specific heat for isobaric and isochoric processes; forward and reverse Carnot cycle on ideal gas and its efficiency; efficiency of non-ideal heat engines.

2.7.2 Heat transfer and phase transitions

Phase transitions (boiling, evaporation, melting, sublimation) and latent heat; saturated vapor pressure, relative humidity; boiling; Dalton's law; concept of heat conductivity; continuity of heat flux.

2.7.3 Statistical physics

Planck's law (explained qualitatively, does not need to be remembered), Wien's displacement law;the Stefan-Boltzmann law.

3. Experimental skills

3.1 Introduction

The theoretical knowledge required for carrying out the experiments must be covered by Section 2 of this Syllabus.

The experimental problems should contain at least some tasks for which the experimental procedure (setup, the list of all the quantities subject to direct measurements, and formulae to be used for calculations) is not described in full detail.

The experimental problems may contain implicit theoretical tasks (deriving formulae necessary for calculations); there should be no explicit theoretical tasks unless these tasks test the understanding of the operation principles of the given experimental setup or of the physics of the phenomena to be studied, and do not involve long mathematical calculations.

The expected number of direct measurements and the volume of numerical calculations should not be so large as to consume a major part of the allotted time: the exam should test experimental creativity, rather than the speed with which the students can perform technical tasks.

The students should have the following skills.

3.2 Safety

Knowing standard safety rules in laboratory work. Nevertheless, if the experimental set-up contains any safety hazards, the appropriate warnings should be included in the text of the problem. Experiments with major safety hazards should be avoided.

3.3 Measurement techniques and apparatus

Being familiar with the most common experimental techniques for measuring physical quantities mentioned in the theoretical part.

Knowing commonly used simple laboratory instruments and digital and analog versions of simple devices, such as calipers, the Vernier scale, stopwatches, thermometers, multimeters (including ohmmeters and AC/DC voltmeters and ammeters), potentiometers, diodes, transistors, lenses, prisms, optical stands, calorimeters, and so on.

Sophisticated practical equipment likely to be unfamiliar to the students should not dominate a problem. In the case of moderately sophisticated equipment (such as oscilloscopes, counters, rate meters, signal and function generators, photo gates, etc), instructions must be given to the students.

3.4 Accuracy

Being aware that instruments may affect the outcome of experiments.

Being familiar with basic techniques for increasing experimental accuracy (e.g. measuring many periods instead of a single one, minimizing the influence of noise, etc).

Knowing that if a functional dependence of a physical quantity is to be determined, the density of taken data points should correspond to the local characteristic scale of that functional dependence.

Expressing the final results and experimental uncertainties with a reasonable number of significant digits, and rounding off correctly.

3.5 Experimental uncertainty analysis

Identification of dominant error sources, and reasonable estimation of the magnitudes of the experimental uncertainties of direct measurements (using rules from documentation, if provided).

Distinguishing between random and systematic errors; being able to estimate and reduce the former via repeated measurements.

Finding absolute and relative uncertainties of a quantity determined as a function of measured quantities using any reasonable method (such as linear approximation, addition by modulus or Pythagorean addition).

3.6 Data analysis

Transformation of a dependence to a linear form by appropriate choice of variables and fitting a straight line to experimental points. Finding the linear regression parameters (gradient, intercept and uncertainty estimate) either graphically, or using the statistical functions of a calculator (either method acceptable).

Selecting optimal scales for graphs and plotting data points with error bars.

4. Mathematics

4.1 Algebra

Simplification of formulae by factorization and expansion. Solving linear systems of equations. Solving equations and systems of equations leading to quadratic and biquadratic equations; selection of physically meaningful solutions. Summation of arithmetic and geometric series.

4.2 Functions

Basic properties of trigonometric, inverse-trigonometric, exponential and logarithmic functions and polynomials.

This includes formulae regarding trigonometric functions of a sum of angles. Solving simple equations involving trigonometric, inverse-trigonometric, logarithmic and exponential functions.

4.3 Geometry and stereometry

Degrees and radians as alternative measures of angles. Equality of alternate interior and exterior angles, equality of corresponding angles. Recognition of similar triangles. Areas of triangles, trapezoids, circles and ellipses; surface areas of spheres, cylinders and cones; volumes of spheres, cones, cylinders and prisms. Sine and cosine rules, property of inscribed and central angles, Thales' theorem. Medians and centroid of a triangle. Students are expected to be familiar with the properties of conic sections including circles, ellipses, parabolae and hyperbolae.

4.4 Vectors

Basic properties of vectorial sums, dot and cross products. Double cross product and scalar triple product. Geometrical interpretation of a time derivative of a vector quantity.

4.5 Complex numbers

Summation, multiplication and division of complex numbers; separation of real and imaginary parts. Conversion between algebraic, trigonometric, and exponential representations of a complex number. Complex roots of quadratic equations and their physical interpretation.

4.6 Statistics

Calculation of probabilitiesas the ratio of the number of objects or event occurrence frequencies. Calculation of mean values, standard deviations, and standard deviation of group means.

4.7 Calculus

Finding derivatives of elementary functions, their sums, products, quotients, and nested functions. Integration as the inverse procedure to differentiation. Finding definite and indefinite integrals in simple cases: elementary functions, sums of functions, and using the substitution rule for a linearly dependent argument. Making definite integrals dimensionless by substitution. Geometric interpretation of derivatives and integrals. Finding constants of integration using initial conditions. Concept of gradient vectors (partial derivative formalism is not needed).

4.8 Approximate and numerical methods

Using linear and polynomial approximations based on Taylor series. Linearization of equations and expressions. Perturbation method: calculation of corrections based on unperturbed solutions. Numerical integration using the trapezoidal rule or adding rectangles.

Minutes of the International Board - IPhO 2015

1. A total of 382 students from the following countries participated in the 2015 IPhO: Armenia, Australia, Austria, Azerbaijan, Bangladesh, Be larus, Belgium, Bolivia, Bosnia and Herzegovina Brazil, Bulgaria, Cambodia, Canada, Chinese Taipei, Colombia, Costa Rica (observer), Croatia, Cuba, Cyprus, Czech Republic, Denmark, Ecuador, Egypt, El Salvador, Estonia, Finland, France, Georgia, Germany, Greece, Hong Kong, Hungary, Iceland, India, Indonesia, Islamic Republic of Iran, Israel, Italy, Japan, Kyrgyzstan, Latvia, Liechtenstein, Lithuania, Macao-China, Macedonia, Malaysia, Mexico, Moldova, Mongolia, Montenegro, Nepal, Netherlands, Nigeria, Norway, Pakistan, People's Republic of China, Poland, Portugal, Puerto Rico, Republic of Kazakhstan, Republic of Korea, Re- public of Singapore, Romania, Russia, Saudi Arabia, Serbia, Slovakia, Slovenia, South Africa, Spain, Sri Lanka, Suriname, Sweden, Switzerland, Syria, Tajikistan, Thailand, The Hashemite Kingdom of Jordan, Turkey, Turkmenistan, Ukraine, United Kingdom, United States of America, Uzbekistan, Vietnam.

2. 142 Members of the International Board were present at the final meeting.

3. The President of the IPhO reported the process and results of the election of the new position of IPhO Treasurer. Since there was only one candidate, Yernur Rysmagambetov (Kazakhstan), for the position of Treasurer, according to the IPhO Statutes the President officially announced that Yernur Rysmagambetov is to be the IPhO Treasurer for the five year term from 2015 to 2020. The new Treasurer's experience with the IPhO and with finance were presented to the International Board and he was congratulated on his appointment.

4. The President reported on the state of the IPhO Foundation, which has continued its role in supporting countries to attend the IPhO through assistance with the cost of travel. The foundation has remaining around 3400 euro, and the Treasurer plans to work to attract new funding for the foundation.

5. The future IPhO hosts were discussed. Switzerland and Liechtenstein are well on the way for preparations to host the next IPhO in 2016. Moldova had to withdraw their hosting for 2017. Singapore wished to help but was unable due to government restrictions. Surya University in Indonesia expressed the willingness and ability to organise the IPhO in 2017, and Singapore suggested that they could explore hosting the IPhO in 2021. The International Board approved this with thanks by a vote of 138-3.

6. Ecuador had previously expressed an intention to host the 2026 IPhO, but Hungary wishes to host that year. So approval from the International Board was sought and obtained to switch Ecuador to the year 2028 and allow Hungary to organise the 2026 IPhO. The International Board approved this by a vote of 139-1.

7. Bangladesh suggested that they could host the IPhO in 2041. The International Board agreed with a vote of 135-1.

8. Representatives from Switzerland and Liechtenstein presented the International Board with information about the 2016 IPhO. The organising committee was presented and outlined the state of the preparations. The budget for the IPhO was stated as 3.7 million CHF. The organisers graciously invited all delegations to attend the 2016 IPhO in Zurich, Switzerland, from 10th to 18th July, 2016.

9. The International Board discussed a proposal submitted by Denmark to amend the Regulations to §5 to allow the IPhO host countries to publish the Proceedings of the IPhO electronically. The International Board voted in favour of the proposal, which required a simple majority, by 121 votes to 18.

10. The International Board discussed a three part proposal submitted by Canada to amend the Statutes and Regulations regarding the conduct of the International Board meetings. The first part of the proposal, to amend the Statutes §7 to change the chair of the meetings of the IB, was rejected by the International Board by a vote of 80 to 61. This vote required a 2/3 majority which was not achieved. The second part of the proposal, to amend the Regulations to §5 to require IPhO host countries to present all three theoretical problems at once rather than one by one, was carried by the International Board by a vote of 83 to 61. This vote required only a simple majority. The third part of the proposal, to amend the Regulations to §5 to introduce a procedure for suggesting cuts to the problems, was carried by the International Board by a vote of 85 to 62. This vote required only a simple majority.

11. The International Board discussed a proposal submitted by the Netherlands to amend the Regulations to §5 to create a committee of three who would see the problems of the IPhO in advance. The International Board rejected this proposal by a vote of 8 in favour to 124 against.

12. The Syllabus Committee from the previous IPhO, consisting of Dr. Lasse Franti (Finland), Dr. Helmuth Mayr (Austria), Dr. Stefan Petersen (Germany), Dr. Matthew Verdon (Australia), Dr. Andrzej Kotlicki (Canada), Dr. Jaan Kalda (Estonia) and Dr. Robin Hughes (Great Britain), put together a revised proposal dealing with many of the Syllabus changes suggested at the 2015 IPhO. The proposal was to amend the new format syllabus by adding many separate items. The items were divided into three groups, and due to the number of individual items, voting was conducted using paper forms counted by the Secretariat. Items which obtained a simple majority were accepted. The President presented the results of the votes, which were:

- Group 1: All suggestions were accepted by the International Board except for sections 11, 13 and 16.
- Group 2: All suggestions were accepted by the International Board except for sections 5,6,7,8,11, 14 and 18.
- Group 3: All suggestions were rejected by the International Board.

13. The President asked the International Board members to check the names of the leaders listed on the website and to submit pictures of each leader, to keep the website up to date.

14. A vote of thanks was made to Prof. Anwesh Mazumdar, for his excellent work in organising the 2015 IPhO. Prof. Mazumdar gave many thanks to his whole team, including organisers, staff, volunteers, sponsors and the Government.

15. The Final Results of the 2015 IPhO were presented to the International Board, which voted to approve the results by a vote of 135 to 1. The thresholds for awards were 42.2 for a Gold Medal, 33.0 for a Silver Medal, 24.0 for a Bronze Medal and 18.0 for an Honourable Mention. There were 38 Gold Medals, 64 Silver Medals, 93 Bronze Medals and 68 Honourable Mentions awarded.

16. The following Special Prizes were awarded:

- Individual winner: Taehyoung Kim (Republic of Korea)
- Best performance in theory: Taehyoung Kim (Republic of Korea)
- Best performance in experiment: Sol Kim (Republic of Korea)
- Best female participant: Thao Thi Huong Dinh (Vietnam)

Closing Ceremony

The closing ceremony of the 46th IPhO was held at the Convocation Hall of the Indian Institute of Technology Bombay (IIT-B) on 12 July at 10 AM. The audience were shown a video “Glimpses from 46th IPhO”, showing the highlights of the week-long event. The President, IPhO, Prof. Hans Jordens spoke about the event and thanked the organisers. Prof. Joseph Samuel, Chairperson of the Academic Committee, described the academic tasks of the competition. The chief guest, Dr. R. Chidambaram, Principal Scientific Advisor to the Govt. of India, spoke on the importance of the Olympiads for the development of science and society. The medal winners of the 46th IPhO were awarded their medals and certificates by a number of dignitaries from the IPhO Secretariat (Prof. Jordens, Prof. Matthew Verdon and Dr. Yernur Rysmagambetov) and the Academic Committee (Prof. Samuel, Prof. Vijay Singh, Prof. H. C. Pradhan, Prof. Arvind Kumar and Prof. Jayashree Ramadas). The gold medals and the special prizes were given away by the chief guest. The medal ceremony was interspersed with a jamboree of traditional folk and popular dances from different part of India, presented by Devendra Shelar and troupe. Prof. Anwesh Mazumdar, Convener, 46th IPhO, presented the vote of thanks. The whole ceremony was compered by Prof. Arnab Bhattacharya, a member of the Academic Committee. At the end, the next hosts, Switzerland and Liechtenstein welcomed participants to the next IPhO in Zurich with a video presentation. The IPhO flag was passed on to the next hosts by the Indian students, signalling the end of a memorable event.

Glimpses


RAJASAURUS
RIVER ADVENTURE

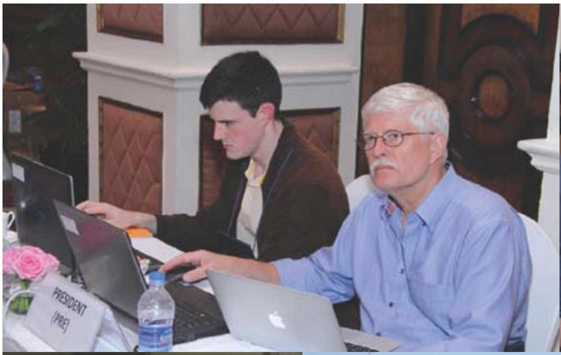

RAJASAURUS


NO ENTRY


B2


1897


NAUTICAL
98


PRESIDENT
(PRE)


2015 MUMBAI - INDIA
omi Bhabha Centre for Scienc ucation
Ta stitute of F mental Res h


SWITZERLAND
(CHE)


INDIA


Zoi Tsangalidou (GRC)
Elvinas Ribin LTU)
Mohammed Al
Wazeenani

Acknowledgements

Funding agencies

- Department of Atomic Energy, Govt. of India
- Department of Science and Technology, Govt. of India
- Ministry of Human Resource Development, Govt. of India

Accommodation

- Taj Lands End
- The Leela, Mumbai

Tours and Transport

- Science Popularisation and Public Outreach Committee, TIFR
- Discovery of India, Nehru Centre
- Nehru Planetarium
- Chhatrapati Shivaji Vaastu Sangrahalay
- Archaeological Survey of India
- M/s Godrej Industries Pvt. Ltd
- M/s Mahindra Vehicle Manufacturers Ltd
- M/s Travel Logs
- M/s Le Passage to India

Exam Venue

- Bombay Convention and Exhibition Centre, Goregaon
- M/s RMB Events

Opening and closing ceremonies

- Auditorium Services, TIFR
- Indian Institute of Technology Bombay
- Nandita Puri and troupe
- Devendra Shelar and troupe

Video and still photography

- M/s Argora Films & Media Inc, Dinesh Lakhanpal
- Deepak Gawda

Computers

- M/s SNA Infotech

Afterword

Anwesh Mazumdar

Convener, 46th IPhO

When the responsibility of hosting an IPhO was bestowed upon India by the International Board nearly eight years ago, we had felt greatly honoured, although perhaps we did not fully realize the magnitude of the task at that time. When the time came to really prepare for it, we slowly became aware of the organisational complexities of this busy event. But in the course of the preparation and the event itself, we all went through an exceptional and fulfilling experience.

At the heart of IPhO is a challenging competition. The tasks would have to be difficult enough to stretch the powers of the best students of the world. At the same time, nearly every participant should be able to make some headway in each problem. The tasks should not merely be instruments of a competition, but should also fire a strong interest in physics among the students and perhaps inspire them to embark on a lifelong pursuit of learning and research in physics.

The preparations started in early 2014 and over the next one and half years, the academic team worked hard to prepare the final tasks that we believed would meet the above goals. It appears that we were able to achieve this at least in some measure, considering the final distribution of scores and the overall feedback from the students and leaders about the quality of the tasks. This indeed makes us very happy. In the course of this preparation, we were able to mobilise a large number of teachers and researchers from across our vast country, which is indeed a massive gain for the national Olympiad movement. I thank all the resource persons who contributed to the thoroughly enjoyable and lively academic discourse in the numerous discussion meetings and the experimental workshops. They were also responsible for the evaluation and moderation of the tasks. We thank the International Board for the valuable inputs provided during IPhO which helped to improve the tasks.

Hosting an international event of the scale of IPhO is a huge organisational challenge. The planning for the event also began more than a year in advance, with several teams being formed to plan and implement the various tasks such as registration, accommodation, transportation, food, etc. Almost the entire administrative staff of HBCSE, numbering about 50, were involved in the organisation. Student guides and volunteers were selected from among undergraduate students in colleges in Mumbai and Pune, and were briefed in orientation sessions. I thank all these people who worked tirelessly over several months, and especially during the event, to make it a success. Special thanks are due to the core organisers, the Programme Planning Group, especially Sumana, Manoj and Aniket.

We thank the IPhO Secretariat, particularly, the president Prof. Hans Jordens for his valuable guidance and support in shaping the academic programme as well as in practical preparations. The hosting of IPhO 2015 was only possible due to the generous funds that we received from the Government of India, through the Department of Atomic Energy, Ministry of Human Resource Development, and the Department of Science and Technology. We thank the government and the people of India for this crucial help.

Personally, it was an immensely enjoyable experience for me. Throughout the phase of preparation, we had an excellent spirit in the whole team, both academic and practical components. It was a greatly enriching experience to discuss physics with so many teachers and researchers from within India and abroad. Apart from the science, for ten days Mumbai became a great melting pot of cultures of more than eighty nations and it was a wonderful experience to interact with so many people from such far away lands. I apologise for any inconvenience caused by some shortcoming of our organisation. Finally, I thank the young students from all over the world who converged in our city to take part in IPhO 2015. I hope they will remember this event for a long time, just as IPhO 2015 will be a sweet memory for us to cherish forever.

www.ipho2015.in