
{jIAPS}
2015
ICPS edition

IN THIS ISSUE

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international association of physics students

EDITOR'S NOTE

Welcome to the ICPS 2015 issue of the journal of the International Association of Physics Students (jIAPS). This issue will cover a subset of the submitted articles in the academic year of 2014-2015.

This issue is loaded with several articles written by students about their research and physics which they deem interesting, articles about activities organised by IAPS and our member organisations, a bid for the next ICPS and the new member countries in the association.

The editorial team of jIAPS and the executive committee of IAPS would like to congratulate Nicholai Cumbo for winning the jIAPS article contest 2015 with his article "*Neutron Stars*" which can be found on page 26.

Hope you have a good time reading the 2015 ICPS edition of jIAPS!

Norbert Bonnici
Editor

PRESIDENT'S LETTER

The last year has been one of the most successful and active one in the history of IAPS. With new committees in Italy, Denmark and Turkey IAPS keeps growing and attracts more and more physics students from all over the globe. Two of our new committees will present themselves in this edition and one is even bidding for ICPS 2017. With our first spring programme iaps@GranSasso on particle and astro-particle physics at the GranSasso Science Institute, the Laboratori Nazionali del GranSasso and the ENEA agency in Italy, we were able to offer a new event in addition to the annual iaps2CERN trip. Several member committees of IAPS were enthusiastic in organising events as well. You can find some detailed information on the second edition of the PLANCKS competition which took place in Leiden, The Netherlands and was a fantastic follow-up of the original event. Furthermore, an article about the Balaton Summer School in Hungary, will show one of the wonderful events in the International Year of Light to whose Opening Ceremony in the UNESCO headquarters in Paris a number of IAPS members were invited to. Accompanying, you find interesting scientific articles written by IAPS members in which they explain their subject of interest or research.

With this, I want to thank everyone who contributed to our events and to this particular edition of jIAPS. All of us are looking forward to future volunteers with ideas for new events and who are full of enthusiasm and spirit to organise them!

Matthias Zimmermann
President

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Italy joins IAPS

by Michele Re Fiorentin and Lucio M. Milanese

During ICPS 2014 in Heidelberg, a group of enthusiastic young physicists founded the Italian Association of Physics Students (*Associazione Italiana Studenti di Fisica*, AISF in Italian). The idea was ambitious and the task challenging: putting together students from all corners of our *Bel Paese* to create a strong network of students from many academic and research institutions. It was definitely not easy at first, but the tireless efforts of the founding executive committee allowed to overcome the first bureaucratic hurdles and provide initial momentum for the growth of the society. Less than a year after the foundation, we can say that those efforts have paid off. Today, AISF boasts more than 160 individual members from 15 establishments of higher education, has organised the first Italian Conference of Physics Students (CISF, Turin 16th-17th May) and has also been a partner of IAPS in the organisation of the successful event at the ENEA and GranSasso National Laboratory in Italy. Several other projects and initiatives have also flourished within AISF and the five active Local Committees are now independently organising their activities.

The first CISF marked an important step for the newborn AISF. It showed that the Association, even though still very young, could brilliantly face and win challenges such as the organisation of a national event without any external help. It is also quite remarkable that nothing like this had ever taken place in Italy before: it was indeed the first time that Italian physics students could meet on a national basis. The participation of 70 students coming from all over the country shows that it was indeed quite a success. The students enjoyed two days of interesting activities, with a unique chance to create bonds and new friendships. A series of lectures held by world-class professors and researchers accompanied the first General Meeting of the Association. The participants also had the opportunity to visit the national research centre of meteorology (INRIM), which hosts several experiments on nanomaterials, quantum optics and time measurement. This conference had a very positive impact on the participants and on the Association as whole. In particular, it was the seed from which several Local Committees sprouted all around the country and new members joined the Association, on a steady wave of enthusiasm.

Among AISF's initiatives, the FERMI project is well underway in its development. The project has two important aims. On the one hand, we have created a rich and up-to-date on-line database of internships for physics students, with particular emphasis on the ones available in Italy. On the other hand, we would like to boost the culture of internships in our country, by contributing to the creation of new opportunities for students to carry out research in universities, research laboratories, and major companies.

The IAPS@GranSasso event took place last May and had a group of 40 young physicists from thirteen different countries enjoying four days of exposure to cutting-edge research within the beautiful settings of Rome and the Abruzzo region in central Italy. The participants visited the Frascati Tokamak Upgrade, a nuclear fusion research facility, and had the unique opportunity to explore the GranSasso underground laboratories - world-leaders for neutrino physics. Several presentations were held by undergraduate students, who had received a scholarship to support their participation from the GranSasso Science Institute (GSSI), a centre for advanced studies created in L'Aquila, after the terrible earthquake that severely damaged the city in 2009. The GSSI aims at attracting the brightest young minds in the domains of physics, mathematics, city planning and the social sciences. Throughout the four days of the event, the atmosphere was exceptionally stimulating, and good food oversaw daring scientific discussions and the birth of new friendships. We should very much like to catch this opportunity to thank all participants for their enthusiasm, active involvement and positive feedback. It was immensely satisfying to see that the event was inspirational and great fun at the same time for many of you. Take the chance to read more about IAPS@GranSasso in Jacopo Mazza's article on the event, published in this issue of jIAPS!

AISF has taken its first steps and is now walking firmly, constantly improving. The initiatives here presented have been core parts of our activities, which make AISF confident and, at the same time, even more eager to do better, to do more. Each event brings about a new goal, more and more ambitious. This is what AISF wants to offer to its members, and also what its members want to have from AISF. More events, more opportunities, more tools in order to build a solid network among the Italian students, that is able to enrich them with new, unique moments and to represent them at the international level. For this reason, AISF's horizon is not closed by the national borders but it extends further so that, very soon, a mature Association will not be afraid of tackling challenges at an international level.

AISF Website: *http://www.ai-sf.it/*
English version: *http://www.ai-sf.it/joomla/en/*

Let there be the year of light!

2015 is a magical year for sure, especially for scientists all over the world uniting to celebrate the International Year of Light and Light-based Technologies. IAPS is proud to be a Silver Associate sponsor of IYL 2015 and had the privilege of participating in the Opening Ceremony that took place from 19th-20th January 2015 at the UNESCO headquarters, Paris. IAPS was present with 16 volunteers from different national and local committees, including 6 EC members.

Most of the volunteers arrived in the evening of 16 January and were outside to help setting up the "Light is Here" installation created by Finnish artist Kari Kola. Meanwhile the remaining volunteers were preparing the over 1000 conference bags which, as you can imagine, also required quite a lot of time and work. At the end of that really productive day everyone felt exhausted.

In the morning, after a good night's sleep we were ready to explore Paris, The City of Light. A few of us got together and went sightseeing. We couldn't have squeezed more into one day: the Eiffel Tower, a nice walk along the Seine River and then a quick packed lunch in front of the Notre Dame. After the obligatory

was a really nice evening of good conversation, sharing thoughts and ideas, and preparing possible future collaborations. However, all good things must come to end, and quickly the evening was over. Mattias, Ana, Andreea and I decided to squeeze one more thing out of the experience and headed towards the 60 m tall ferris wheel, the Roue de Paris. We had so much fun! Afterwards it was time to go back to our accommodation, as the next day was the big day: the actual start of the Opening Ceremony.

I wouldn't say we were fresh and fit in the morning, but surely were we excited! It was the big day for IAPS

greeted by dinner made by some of the early birds. Actual preparations began next morning. It was still dark when we headed towards the UNESCO headquarters. There we met the organizers and after a short introduction came the hard work. We were split into two working groups: most of the boys were directed

souvenir shopping and chocolaterie visit we still had a little time left, so Ana, Andreea and I decided to go for a coffee in the famous Café de Flore.

In the evening the present members of the EC were invited to have dinner with the leaders of SPS. It

as well, as Danielle Harper gave a speech on behalf of IAPS and we also presented our video to the public featuring the contributions of some of our committees. The audience could get an overview on the planned activities of IAPS members contributing to the International Year of Light. The video and Danielle's speech were more than well received in the great lecture hall. Meanwhile we had set up our stand in the exhibition area along with all the other organizations who were present. It was a great feeling that IAPS was treated equally with the hibition of the organization of 1001 Inventions, promoting the work of Ibn al-Haytham. In the evening the participants had a chance to make conversation. It was really interesting to see how the mutual celebration of light can bring together to come. I hope that the collaborations and activities will be fruitful and that we, physics students, won't forget about how much we can do if we unite. So, as a last word I'll just say: let there be the year of light

leading organizations from all over the world.

During the two days keynote speakers were Noble laureates, the founders of IYL 2015 among them John Dudley, president of EPS, the leaders of UNESCO and also many other leading scientists and representatives from international non-governmental organizations. The event featured several cultural and musical interludes, such as the aforementioned beautiful installation of Kari Kola, a live musical performance by Joshua Bell and the ex- more than a thousand people with so different backgrounds. Time was passing very quickly and soon the Opening Ceremony was over. In the morning of 21 January we said farewell to each other as well as to the city: it was time to go home.

It surely was an amazing and inspiring experience. I think that all of us could gain knowledge in either the scientific way of thinking or the cultural aspects of life. Since the beginning of IYL 2015 a huge amount of events have taken place worldwide, and a lot more is expected

by Eszter Piros
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Eszter Piros started Physics BSc in 2010 at the University of Debrecen, Hungary. As a freshman she started working as a volunteer at Mafihe's Debrecen local committee, which she has been representative of since 2011 and president since 2013. She graduated in 2013 and started her Material Science master's studies.

ICPS 2017 - Turin, Italy

Every year ICPS is organised by an IAPS member in a different country. We would be glad to offer the city of Turin (Torino) in Italy, as the 2017 destination.

The Italian Association of Physics Students (AISF) is quite new in IAPS, but has already proved its members' motivation and resolution in creating events both of international and national interest. You can have a better insight in the article dedicated to AISF in this issue. Up to now, Italy has never hosted an ICPS, so we would be immensely pleased to break this record and offer all IAPS guests this new, unforgettable experience.

ICPS organisers

The Organising Committee will be composed of 12 core members and around 30-40 volunteers. To ensure the most suitable outcome, we would appoint three main officers: a project coordinator, a financial coordinator and an operations coordinator.

Dates

Arrival on 14th August 2017
Departure on 21st August 2017

Location

Italy is well known for its landscapes and history, not to mention food and wines and unorthodox Prime Ministers. Turin is a large city (roughly one million people) in the northwest of the country, close to the Alps and the border with France.

Its position is particularly smart and allows for easy trips to the mountains as well as to the sea. Turin was the first capital of the country, when it was united in a kingdom in 1861 and its royal origins are still very clear in the architecture of the city. Later on, it was one of the main industrial centres in Italy, due to the car manufacturing of FIAT (now FIAT-Chrysler). The fine baroque city centre and the dynamic passion for modernity and technology make Turin a unique place for all to enjoy and discover. Turin has a clear vocation for international and multicultural events: in 2006, for example, it hosted the XX Olympic winter games, so why not ICPS in 2017?

Politecnico di Torino

The Politecnico di Torino (Polytechnic University of Turin) was established in 1859. It is Italy's oldest technical University, devoted to engineering and architecture. It counts more than 32.000 students per year and it is listed in the top world Universities rankings. The main lectures and parallel sessions will be held here.

Accommodation

Around the "cittadella politecnica" the hall of residence Borsellino (10 minutes from the Main Hall) will

host 404 students in double and single rooms, while the Collegio Einaudi residence (15 minutes walking from Main Hall) will be able to host up to 150 more students.

Conference fee & prices

The conference fee will be student-friendly, as in the previous editions of ICPS. We will be having an early registration and a late registration fees but for organisational reasons the late registration one needs

to be a bit more expensive than last years':

Early registration fee: 190 €
Late registration fee: 250 €

Scientific Programme

Among the main goals of the organising committee there is the attention to the educational aspects of ICPS and the will to offer an excellent scientific programme, with top quality guests.

We are already in contact with leading Italian scientists (Carlo Rubbia, Fabiola Gianotti, etc.), and we will get in touch with world famous foreign physicists.

Our main goal is to provide the widest range of topics in Physics, from theoretical to medical physics, from solid state to astrophysics. This way, virtually every participant will have the chance to find their inspiration. As usual, parallel talks will give everyone the opportunity to talk about his/her own research, as in the customary poster session.

Lab tours and excursions

There will be the possibility to visit different laboratories in research institutes and technical companies.

We have already in the programme, for instance, a visit to Thales Alenia Space, a leading company for building of spacecrafts and ISS modules; INRIM, the National Institute of Metrology, with precision experiments on nanomaterials and quantum optics; CNAO the hadrotherapy oncologic national centre, in Pavia, that carries out ground-breaking research in cancer treatment with particles radiation; the CSHR, Centre for Space Human Robotics; the Astronomic Observatory; the Italian Institute of Technology (IIT) in Genova and the Underground Modane Laboratory (LSM) - an important facility for neutrino detection and study. A softer and much relaxed side will be coupled to all tours, such as Laser park, canoeing on the Po river, a wine tasting and cellar visit, a Biopark safari, half day trip to the beach or to the mountains, visit of the city of Pavia and many others.

Nights

We will provide a full course of traditional and well-known ICPS parties, such as the Nations Party and the Costume Party, an astounding welcome party and a farewell party. There will be an "Italian Food night party" with a proper taste of Italy's finest "cucina", plus Italian music and the "That's amore party", a spicy surprise for everyone. We would like also to test your physical (in both senses) skills, by proposing again, after 6 years since its last edition in Budapest, the "Drink & derive" contest, that will be held during the free night.

Transportation

Turin has an international airport (TRN) which is 40 minutes by bus five Euros to the city centre and the accommodation facilities. The intercontinental Milan-Malpensa (MXP) airport can also be used to get to Turin, taking into account two more hours by bus to get to the city. There are two international stations, well-connected to the rest of Europe via high-speed trains. All city transport during the week will be included in the registration fee.

Backup solution

In the event that not so many participants would attend the conference, we will use the Campus Einaudi, a smaller but brand new facility (opened in 2012) for lectures and accommodations, reducing the expenses significantly.

Conclusions

As stated before, this would be the first ICPS occurring in Italy, in more than thirty editions. We would like to provide all participants with the best the city of Turin has to offer. We would be extremely glad to welcome all students in our warm, funny country and show you that the Italian physicists are indeed quite easygoing, chaotic and messy at times, but can also produce a very well organised, memorable event that will surely meet and surpass everyone's expectations.

By Andrea Celon
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Andrea Celon received a bachelor in physics in 2012. Currently is attending a master in theoretical physics at the University of Turin (Torino). He has been attending ICPS since Utrecht, The Netherlands in 2012.

Aeter - A new member of IAPS

Ever felt like visiting the Danish city of Odense but never had a proper occasion? Now you have - Odense has got its very own local committee of IAPS.

Being part of Scandinavia with Germany to the South, the UK to the West, Sweden to the East, and Norway to the North, Denmark is comfortably placed in Northern Europe. The country's shape is defined by one of the largest coastlines in the world compared to land area, with the addition of a coastal climate which keeps the weather not too cold nor too warm. The largest and mainland part of the country is Jutland with the largest island being Zeeland where the capital Copenhagen is located. It is possible to study physics in Jutland (Aalborg and Aarhus) as well as on Sealand (Copenhagen and Roskilde) but we'll focus on the central island of Funen with the city of Odense.

Æter

Æter (Danish for "ether") is the student council for physics, chemistry, and pharmacy students in Odense at the University of Southern Denmark. Run by the students, Æter works in the interest of its students and influences the politics at the university in general and in each of the study programmes. Æter has its own rooms at the university where students can come to study or have fun with the other colleagues while drinking coffee for free.

Though not obligatory, many of our members will have attended one of our Christmas and Easter lunches as it is customary to hold in Denmark. We also have a day for making Christmas decorations as well as some movie nights.

Usually around May, the grand finale is our trip where we go to a remote cabin somewhere else on the island to party and have fun for a weekend, supplying us with stories to tell until next year.

When it comes to the relationship between students and researcher, Æter has started having the aptly named Torsdagste "Thursday Tea". Every other time hosted by Æter and every other time hosted by the institute itself, it is an event where students and professors meet for tea and cake while talking about whatever they want. Often, it may be combined with a presentations on subjects such as job opportunities. Æter also backs this year's participants at ICPS, ensuring that their participation fees would be covered by the institute and the hearing support company Oticon. Though until recently forgotten, the University of Southern Denmark actually hosted ICPS in 2003.

The courses

When the students are not in Æter they are likely to be studying and the research and teaching is mainly

associated with the three research centres.

In the theoretical corner is the Centre for Cosmology and Particle Physics Phenomenology (CP^3) which does research in the area of elementary particles, dark matter, and dark energy. Their activities include conducting a winter school, workshops and cooperation with CERN among others. On a biweekly basis, they have the CP^3 Lectures where external researchers visit to give a lecture on their topic of interest. The lectures are attended by researchers and advanced students but everyone is welcome. Recently, an extra 15 minutes have been added before the lecture to give time to explain the basics which the topic of the lecture builds on. More informal, a journal club is also regularly held where researchers and sometimes students present an article for discussion; also these meetings are open. Especially for students, more basic lectures are also held.

At one point in 2012, a Ph.D. student came to talk about being a doctoral student abroad. It was during this presentation, that the current physics students were first made aware of the existence of the ICPS and IAPS leading to a continuous Danish participation since ICPS 2013.

If you are a final or semi-final year bachelor student, you can get introduced to CP^3 by participating in their brand new 2015 Physics Challenge. The challenge is designed to be a test of your skills in quantum mechanics, electrodynamics, statistical mechanics, and classical mechanics. It is also the exam of the CP^3-Genius programme which provides extra physics courses for motivated bachelor students. Apart from meeting the staff at CP^3, you get a signed certificate, and if you excel you will be announced on their website. If you think this sounds interesting, the exam takes place on-site at the university on September 3rd with the deadline for registration being August 31st.

If you are more into biophysics, you might want to consider visiting MEMPHYS - the Centre for Membrane Physics. An interdisciplinary centre, it aims to understand the mechanisms in biological membranes and the functions of their molecules. Some work is theoretical and involves computer modelling while other work takes place in the in-house lab and at research facilities outside of Odense and Denmark. They are also open to the outside so if you like computer modelling in biophysics, you might want to visit their workshop this October.

Not to be forgotten, some of the researchers also study the science and physics of food, i.e. gastrophysics, with Memphys even being a partner in the outreach project SMAGforLIVET (roughly translates to "TASTEforLIFE") which works to spread the knowledge on food and good taste.

Finally, the University of Southern Denmark also host the Centre For Life and Living Technologies (FLinT in short) which aims at creating artificial life from inanimate materials. Their work is diverse with project ranging from constructing protocells able to grow with energy from the Sun, over metabolising electronic chips, to 3D printers. Though nothing to mention at the moment of writing this, they also make external events so you might want to look out for that.

The city

When you are not at the university you can go to the city. During the day, cafés are available with two, StudieStuen and Studenterhuset, specifically targeting students ensuring a nice place to study as

well. StudieStuen (English: "the Study Living Room") was founded by students in 2010 and continuous to be run and financed exclusively through the work of students. Events like lectures, concerts and social singing happen regularly.

Studenterhuset is supported by the city's institutions for education including the university. Being the largest of cafés, it is often visited by musicians and comedians; they even have something called Science in the City where the researchers from CP³ come by for a beer and discuss physics with anyone who wants to.

For the culturally minded, the city has several museums, including one for Hans Christian Andersen, and the Brandts building complex containing a multi-story art exhibition and show venues. The cafés and additional venues make sure that public cultural, and some scientific, events are made all years round - Den Smagløse Café (English: "The Tasteless Café") has a very small museum for sausages.

The one most active scientific associations is probably UNF (English: "the Youth's Scientific Association") which arranges public events for high school students, university students, and others who are interested. They have even arranged excursions to the nuclear reactor in Barsebäck, Sweden and the particle accelerator facility DESY in Hamburg, Germany to name a few.

If you are really looking for something out of the ordinary, Odense also hosts several festivals every year with the municipality having recently invested in even more. To mention a few, the Odense International Film Festival in August is always a good way to see the newest in short films with three awards qualifying the winning films for an Academy Award nomination. The festival hosts several daily events where you can watch the participating films free of charge as well as an open air cinema with longer films.

If you, on the other hand, want to party with some music, the festival Tinderbox might be the thing for you. 2015 being its first ever year, the festival is in a small forest at the edge of the city and was celebrated this year with artists including Robbie Williams - a name fitting for a budget of around 40 million kroner or about 5.3 million Euros.

If you don't feel like paying for a festival ticket, you can also just go to the King's Garden near the city centre where free concerts are hosted every Thursday during the summer.

Interested?

Are you feeling tempted to come study here? With all master courses as well as many bachelor courses being taught in English, language should, in any case, not be a barrier. Though there are generally tuition fees for foreign students, citizens of the EU, EEA, or Switzerland are exempt from those and can study for free. Meeting some specific conditions, some even become eligible to receive the state education support which will cover some, if not all, of your monthly expenses. To see what applies to you, better sources are available online.

So from all of us to all of you: See you in Zagreb!

Find out more

If you want to get in touch with us at Æter, you are welcome to write to our e-mail: *lc-odense@iaps.info*

If you want to learn more about studying in Odense, we recommend checking out these pages:

Æter on Facebook: facebook.com/aeter.sdu
The University of Southern Denmark: *sdu.dk/english*
CP3-Origins: *CP3-origins.dk*
The Physics Challenge: *CP3-origins.dk/research/CP3-genius-program/2015-physics-challenge*
MEMPHYS: *memphys.dk*
FLinT: *flint.sdu.dk/*
Can I receive support from the state? *su.dk/English/Sider/foreign.aspx*

If you want to learn more about spare time activities and life in general, you can also check out:

Tinderbox: *tinderbox.dk*
Odense's website: *odense.dk/subsites5/english*
This Is Odense: *thisisodense.dk/en*

BY HENRIK SIBONI
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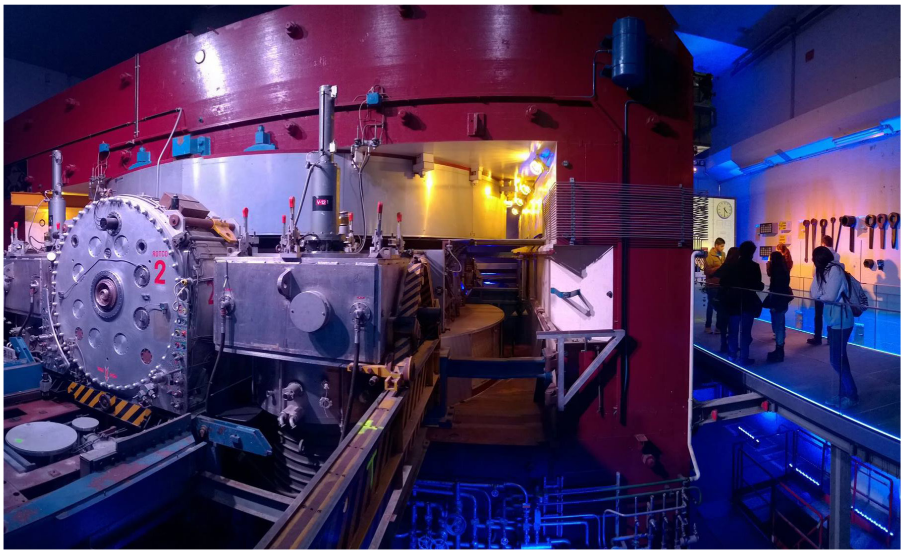
Henrik Siboni is ending his bachelor in Physics at the University of Southern Denmark and is the current IAPS representative for the LC. He has participated in and organised various academic and social activities at the University and in the city. Like most people, he is also very much looking forward to the ICPS.

IAPS@CERN 2015: A POSTMORTEM

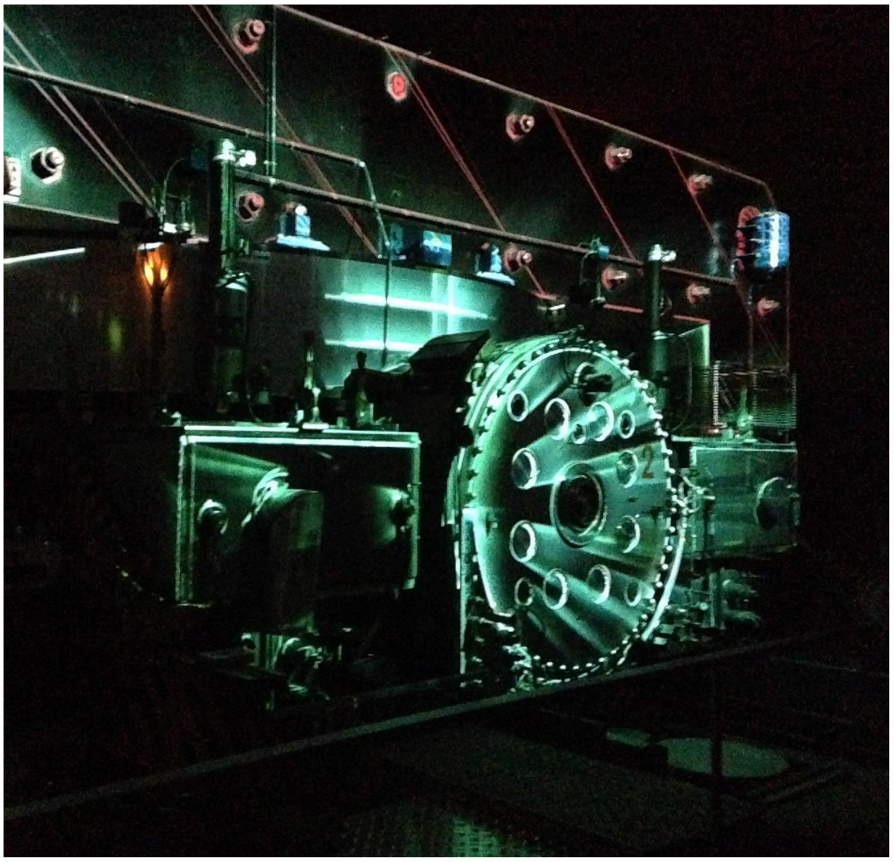


The European Organisation of Nuclear Research (CERN) is the place to be for particle physics, and with 45 participants from all around the world the annual IAPS visit took place from the 20th to the 23rd of April 2015. As one of the volunteers organising the trip, and de-facto leader during the trip I would like to both summarise the trip and share some of my impressions; for the benefit of all those who where there, and for those who were not - there is always another chance next year.

First of all, the trip was a full success. The participants were of course fantastic, and the programme organised for us by CERN was amazing - even as someone who was there a few times before the visit was full of nice surprises.

During the whole trip we had absolutely perfect weather - sunny enough to get me thoroughly sunburnt. Every now and again Mont Blanc was visible on the horizon. The weather allowed very pleasant nightly sightseeing in Geneva, with many participants enjoying the nice parks as the tight physics schedule meant spending most of the first two days at CERN. In addition we had the rare opportunity to watch a CERN amateur football game with a BBQ in the evening of our first day. A social evening of chess, checkers and card games in Geneva's main park also helped ensure that the social part of the trip did not fall short.

The physics highlights were - as probably expected - the visits to CMS, AMS, the SM18 and the Synchrocyclotron. Due to LHC run 2 the CMS experimental cavern was sadly off limits, but the CMS service cavern and overground facilities were interesting in their own right. At its rival, ATLAS, we only had access to the visitor centre and a very nice view into the ATLAS control centre. CMS and ATLAS are of course the two competing general purpose detectors at CERN, responsible among other things for the discovery of the Standard Model Higgs Boson in 2012.



AMS2 was again unfortunately off limits, as it is inconveniently attached to the ISS. However, we visited the AMS control centre and found out many interesting things about the only general purpose detector in space - everything is better in space. At SM18, the Magnet Test Facility, we were treated to an up close encounter with prototype LHC magnets, allowing detailed insights into the CERN accelerator chain, which was further explained at the tour of the CERN control centre.

As a great contrast we also saw an experiment from a different century: the Synchrocyclotron. One of the first experiments at CERN, it is immensely important as the machine that helped discover the V-A nature of the weak interaction. Nowadays it has been converted to a very modern exhibition about the beginnings of CERN and includes a spectacular light-show (as you can see in the pictures).

In addition to the tours we enjoyed several very interesting talks: An Introduction to Particle Physics by ATLAS physicist Emma Kuwertz ensured that everybody would leave Geneva with a good understanding of what they had seen, and what it meant in the big picture of fundamental physics. Manjit Dosanjh, the only Biologist at CERN and CERN Life Science Advisor, gave a fascinating presentation on the medical applications of particle physics, a topic most participants found very interesting -- even many of those who usually prefer fundamental research to applications.

Finally a Question and Answer session with ATLAS physicist Michael Hauschild was the final event of the physics programme. This session took much longer than planned, as the participants came up with question after question, and the entertaining and enlightening answers kept coming.

To roundup the trip, we also visited the United Nations in Geneva, seeing both the historic Palais des Nations and the more modern annex which hosts the Human Rights Council and many other UN meetings. Visiting CERN and the UN shows quite strikingly what amazing things humans can achieve when they manage to work together. To contrast the cutting edge research at CERN we also visited the beautiful History of Science Museum in Geneva, which is situated just off the Lac Leman. In the small but fascinating museum we could see scientific instruments dating back centuries, including ancient Egyptian steam vehicles, one of the first batteries and many more fascinating artefacts.

On a personal note, the trip was certainly a weird one, as I got to know IAPS as a participant in the 2013 iaps2CERN tour. Having switched sides now, I can appreciate the effort that goes into such a trip, and hope that everyone enjoyed the trip as much as I enjoyed my first visit to CERN. Organising this trip was a lot of work and very stressful - especially when simultaneously working on a master thesis - but also a lot of fun. I highly recommend that you get involved with IAPS, if you are not already. Maybe you could help with the existing trips, or if you have an idea why not try to start up a new IAPS excursion?

BY OLIVER LANTWIN
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Oliver is about to start a PhD in experimental particle physics at Imperial College London. He took part in ICPS in Heidelberg and will be joining the conference again this year!

Balaton Summer School in Physics 2015

The Hungarian Association of Physics Students (Mafihe, NC Hungary) was founded in 1988 in Budapest, one year after the formation of IAPS. The first Summer School was organized in 1993 and continued from that time. After some years of omission we were happy to organise a Summer School again in the name of celebrating the International Year of Light at Lake Balaton from 20th-26th July, 2015. We invited speakers in all the hot topics in physics which are related to light. The topics included spectroscopy, photonics, quantum optics, astrophysics and laser physics.

The School has also acted as the Hungarian part of the jDPG-Mafihe Exchange Program. However, it was open for every IAPS member.

Keeping to the old traditions in Mafihe we decided to put the School next to Lake Balaton (hence the name Balaton Summer School in Physics). Lake Balaton is a popular holiday region because of its sandy beaches and shallow waters. The surrounding countryside consists mainly of fertile plains dotted with old villages. Balatonalmádi is one of the most popular holiday towns in the area. It is easily accessible by train from Budapest and absolutely able to host a summer school since everything in the centre is reachable in 15 minutes.

Our accommodation was in a dormitory of a high school. There were 4-bedded rooms and we tried to create as much national diversity in the rooms as possible. The lectures were in the conference room of the Ramada Hotel. We ate in a restaurant near to the hotel and the beach was also about five minute walk from there.

At the opening ceremony I presented Mafihe then Professor Norbert Kroó spoke about the International Year of Light. After that I gave some other general information about the BSS. The original number of participants was 65 students from 13 countries. Unfortunately, there were some of them who could not come due to visa issues.

There were 3 plenary lectures and 18 parallel lectures at the School. The first plenary lecture was given by Professor Norbert Kroó who spoke about surface plasmons. His presentation consisted of two parts. In the first one, some of the basic features of nano-science and nano-technology were presented. In the second part, plasmonics, the fast growing new branch of optics was discussed as the most promising branch of nano-optics. Then Professor Lajos Diósi presented a way to decide the Schrödinger's cat state of a macroscopic object and explained some parts of the Diósi-Penrose Theory. He showed us the new field of Quantum Optomechanics. In Quantum Optomechanics, a quantized oscillator weighing nano grams or even grams is coupled to photons for double purpose: preparation and detection of controlled quantum state of the massive oscillator. The last plenary lecture was given by Professor Dezső Horváth who spoke about the spectroscopy and properties of antimatter. He presented the recent results from experiments from CERN and at the end of his talk he showed an overview of the real, possible and impossible practical applications of antimatter from medical diagnosis through dream to fantasy.

I would like to emphasize some of

the most popular parallel lectures. There was an astrophysics lecture about Digital sky surveys: building up the 3D picture of the Universe by Professor László L. Kiss from the Konkoly Observatory. He discussed both the most spectacular recent results and the planned future projects of the 2020s. Professor Péter Raffai gave us an overview on gravitational wave measurements. In the Quantum Optics Section, Dávid Nagy and Gábor Kónya introduced a complete course on Cavity Quantum Electrodynamics. Professor Péter Dombi showed the Phsyics of Attosecond Nano-Optics which play a fundamental role in many nanotechnology applications including photovoltaics, sensorics and biomedicine.

Besides professional programs, we placed great emphasis on cultural and community programs in order to create a cohesive community among physics students.

On the first night, we had a "getting acquainted" party. The members of the Italian delegation found a piano and started to play it which immediately cheered the party up. We spend the second night on the shore of Lake Balaton with some moonlight, in order to bring closer the people from different delegations to each other. The third night was the Hungarian night - we cooked goulash in a stew-pot on an

open fire, tasted some palinka and sang the Physicist March together. After the Excursion day we had a cocktail party and some of us played the Physicist's Activity at which you were supposed to mimic the Ricci tensor… We spent the last night with swimming in the Lake at night and playing some games at the shore.

Of course we were able to enjoy the summer on the beach at daylight, too.

Regarding the food, we showed all of the specialties of the Hungarian kitchen like having soup every day or having salty things for breakfast and sweet things as a main course for lunch. There was a coffee break between the lecture with sweet bakery products and also scones.

We offered two options as excursion at the free day.

The Tihany tour begun with a boat trip meanwhile we admired the Lake Balaton. After we arrived to Tihany, we walked to Benedictine Abbey which was established in the Kingdom of Hungary in 1055. Then we went back to the centre of the village where we made unforgettable memories.

The Badacsony tour also offered a spectacular view over Lake Balaton. However, reaching the top was much more exhausting than the other tour. On the other hand it was a wonderful feeling to hike in the forest surrounded by many-thousand year old stones. After the hiking the best Hungarian wines helped us to recover at a local winery's wine tasting and have some rest in this beautiful place.

We hope that this Summer School provided a good opportunity to learn, not just about Physics but also about the cultures of other people.

BY TAMÁS ÁLMOS VÁMI

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Tamás studies Physics at the Eötvös Loránd University, Budapest. He was elected as the President of the Hungarian Association of Physics Students (Mafihe, NC Hungary) two years ago. He experienced being in the leadership of an association, as he was the Head of the Scientific Department and in the following year the Coordinator of Hungarian Student Research Association (KutDiák). At this KutDiák Association and his years of being the President of Mafihe he skilled the challenging tasks of organising conferences and the beauty of dealing with many people. It was his pleasure to organise an international event like the the Balaton Summer School 2015.

PLANCKS 2015

From 22nd to 24th May 2015, the second edition of PLANCKS (Physics League Across Numerous Countries for Kick-ass Students) was held. The event started on Friday with a very successful opening symposium, which hosted over 300 people.

The main event was of course the Physics Olympiad organised on Saturday. A total of 28 teams from 18 different countries took up the challenge, but only the best could be praised with the title of "Best Physics Students of the World", and winning the grand prize of € 2109.14

In the remaining part of the weekend, we focused on the most important goal of the whole event: bringing together physics students from all over the world. The competitors enjoyed one of the several excursions that we organised and a barbecue. As a grand finale, the closing ceremony was held in museum Boerhaave, the Leiden Museum of the History of Science.

We, as the organizing committee, are grateful for a great weekend and think that PLANCKS 2015 was a huge success!

Symposium

On Friday May 22nd, 2015 the PLANCKS symposium was held. It started in the early afternoon when the speakers and visitors arrived. The participants stored their luggage and after everyone had grabbed their coffee they went to the lecture hall. Irene Haasnoot, president of PLANCKS 2015, opened the symposium and welcomed our guests. She then introduced the scientific director of the Leiden Institute of Physics, Dr. Prof. Eric Eliel, who welcomed all and gave an introductory talk about the Leiden Institute of Physics and its history. He told stories about the research of Kamerlingh Onnes, Albert Einstein and Hendrik Lorentz. The structure of the institute was presented so that our international visitors would get an idea of how a Dutch physics institute is organised. He then thanked everyone for their presence and interest and introduced the first speaker of the day: Dr. Carlo Beenakker.

Dr. Carlo Beenakker spoke about quantum computing. He focused mainly on the conceptual part of this wildly complicated topic so that listeners would get a basic working understanding of what quantum computing is, what the main ideas are and why we need it. This talk was greatly complemented by the next talk by Dr. Leo Kouwenhoven, who spoke of the practical problems of building a quantum computer and went into detail about where in this long process we currently are. In this he talked about his own research at the Technical University of Delft, The Netherlands.

After Dr. Kouwenhoven's lecture there was time for a short coffee break. During the break the visitors engaged the speakers with questions.

After this short break, John Ellis, professor of King's College London, lectured on his speciality: particle physics. He talked about the institute CERN, where it is and its physical layout. He discussed the standard model and how experimental results about it can be obtained and verified. The talk was interspersed with anecdotes of his own time at CERN, where he was head of the theoretical physics department for several years. He then gave way for Dr. John Pendry from Imperial College London. Dr. John Pendry holds the Lorentz chair for 2015 and was asked by the theoretical physics department of the Leiden Institute of Physics to work and live in the city for several months to lecture to and collaborate with Leiden researchers. He lectured on optics

and metamaterials, specifically his own work on invisibility cloaks. The concepts of cloaking were revealed and the tests with which cloaks can be verified to work explained. Our host, Dr. Eric Eliel, then announced that the dinner was next up on the program.

The guests went to their respective dinner locations: students to the students' barbecue, organised by the Leiden Student Association "De Leidsche Flesch". Most other guests had dinner in the canteen of the Gorlaeus Laboratory, where a buffet was served. The guests enjoyed their dinners and the speakers discussed their careers and fields of research. When the dinner was over all guests walked back to the main lecture hall where Dr. Erik Verlinde lectured on his theoretical research into a new theory of gravity.

Dr. Verlinde's talk was mixed with a wide range of physics topics to tell of a new perspective of widely known phenomena. The theory that he's working on is all about gravity and how it can be explained by different means than general relativity. He told the audience about the theory and about how it was formed. Many questions from the audience ensued and when they were done, the visitors were thanked and went home.

Many of the visitors gave very positive feedback and the speakers enjoyed their day. The lectures were engaging and diverse, whilst being conceptual yet innovative.

Competition

Saturday morning the contestants arrived at the Leiden University physics building for the main event of the weekend: the competition. After a short briefing the teams were brought to their rooms where they had 4 hours to crack 10 problems ranging from scattering of subatomic particles to the drift of

iceberg on open sea. The problems were carefully selected from the submissions we received from professors all over the Netherlands. During the competition one of the jury members was present to answer any question the contestants might have about the problems. When 4 hours had passed the contestants were picked up and handed in their solutions. While the contestants were enjoying the rest of the program, the correctors were spending their Saturday afternoon correcting all the problems handed in. At the end of the afternoon all the problems were corrected and the results were in.

Excursions, barbecue and party

After the lunch on Saturday the contestants had the option to join one of three possible excursions. After working hard on solving the problems in the contest some people chose to relax in a boat tour through the canals of Leiden, while the others chose to expand their knowledge in a lab tour through the Leiden physics faculty or have a guided tour through the historical museum Boerhaave. The people who chose the lab tour were greeted by the science historian Dirk van Delft, who gave a talk about the history of physics in Leiden. After his talk they saw the different subjects that scientists in Leiden are studying like quantum cavities, metamaterials and surface physics. In the Boerhaave museum a tour guide showed the historical

artefacts collected there, like the first Leyden jar and the set-up that Kamerlingh Onnes used to liquefy helium. After the tour they were free to look around in the museum themselves. The people from the boat tour were shown Leiden in the best possible way, through a tour of the canals. Fortunately they weren't shown typical Dutch weather because it was actually quite nice!

After an either informative or cultural excursion it was time to do absolutely nothing but unwind.

The FooBar is always open for students who want to do just that, and so specially for PLANCKS the bar officially opened in the weekend for the first time in years. The barbecues were already set up by our wonderful crew, and if this all wasn't enough, the drinks were free as well.

Even though the line for the barbecue was a bit long sometimes, the sun was shining, there was enough bread with sauce and salad and the people were all socializing. After the group photo was taken everyone went to the party location. Student association SSR, where the party was located, was a very suitable place for our party. People could still talk in the bar area and when the evening progressed, more and more people would join the real party on the dance floor, where committee, crew and participants merged together in one group of friends.

Closing ceremony

On Sunday the weekend was closed with a ceremony at museum Boerhaave. During this ceremony, various people took the stage. The first was Andreea Munteanu, the president of the PLANCKS committee 2016, who told us about their plans for next year. Jan van Ruitenbeek, the chairman of the Dutch physical society (NNV), spoke about the problem he had contributed to the contest and the way he encountered it during research. Willem Tromp, the committee member responsible for the contest, showed us some statistics about the contest, and awarded some fun awards for remarkable results of the contest, such as a creativity award for an ingenious but wrong answer, and an efficiency award for the team that had managed the best points per page ratio.

Then Jan van Ruitenbeek took the stage again to award the main prizes. The first prize, an amount of $€\frac{h}{\pi}\cdot 10^{37}$ = €2109.14, went to the Dutch team Strength in Unitarity, who had scored a total of 88.5 points out of 120. The second prize was won by the Dutch team Tena, the third place went to Czech team Charles' Angels.

After the ceremony, there was a lunch provided by the Boerhaave museum, and there was the possibility of visiting the museum itself for those who hadn't seen it on Saturday or who wanted to see it again. When everyone had eaten, there was an optional excursion organised to Amsterdam, for those teams that wanted to see the city.

BY THE PLANCKS 2015 COMMITTEE
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What is a Photon?

Introduction

A photon is an elementary particle describing the quantum nature of light and all other forms of electromagnetic radiation. It is the force carrier for the electromagnetic force. The effects of this force are easily observed at both the microscopic, and macroscopic level resulting from the fact that the photon has zero rest mass; allowing for long distance interactions. Photons are best explained through quantum mechanics like all other elementary particles that exhibit wave–particle duality.

Albert Einstein was the first to develop the modern concept of a photon through experimental observations. This new concept did not agree with the classical wave model of light. In contrast with the wave theory of light, the photon model accounted for the frequency dependence of light's energy, and explained the ability of matter and radiation to be in thermal equilibrium with each other. The new photon model also accounted for anomalous observations, such as black-body radiation, a phenomenon that other physicists, such as Max Planck, had sought to explain using semiclassical models. The "Compton scattering experiment" of single photons by electrons, first carried out in 1923, validated Einstein's hypothesis that light itself is quantised.

In the Standard Model of particle physics, photons are described as a necessary consequence of physical laws having a certain symmetry at every point in spacetime. This gauge symmetry allows us to determine the intrinsic properties of photons, such as charge, mass and spin. Moreover, the photon concept has led to various advances in experimental and theoretical physics, such as lasers, Bose-Einstein condensation, quantum field theory, and the probabilistic interpretation of quantum mechanics. As we shall see later on, photons are also being applied in photochemistry, high-resolution microscopy, and measurements of molecular distances. Recently, photons have been studied as elements of quantum computers and for applications in optical imaging and optical communication such as quantum cryptography.

What are the basic physical properties of a photon?

A photon has zero mass, no electric charge [1] and has two possible polarisation states. In quantum field theory the momentum representation is preferred. This representation shall be used to derive said properties about photons. In this representation, a photon is described by its wave vector, which determines its wavelength λ and its direction of propagation. A photon's wave vector may not be zero and can be represented either as a spatial three-vector or as a (relativistic) four-vector usually represented by the light cone shown in Figure 1.

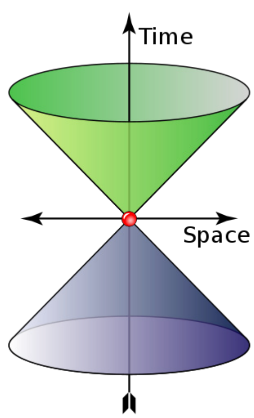

Figure 1. The cone shows possible values of wave 4-vector of a photon. The "time" axis gives the angular frequency (rad. s^{-1}) and the "space" axes represent the angular wavenumber (rad.s^{-1}). Green and indigo represent left and right polarisation. [29]

Photons are emitted in many naturally occurring radiative processes. During a molecular, atomic or nuclear transition to a lower energy level, photons of various energy are emitted. These range from radio waves to gamma rays. A photon can also be emitted when a particle and its corresponding antiparticle are annihilated. In deriving equations for the energy of a photon and other particles such as electrons, concepts from quantum mechanics and special relativity are used. Special relativity is useful since it predicts the momentum **p** and wavelength λ of the "particle". Together with quantum mechanics these statistics yield the general equations given below where m is the rest mass and E the total energy. [2] It is important to note for now that photons have zero rest mass. The reason for this shall be explained later on. In empty space, the photon moves at c (the speed of light) and its energy and momentum are related by $E = pc$, where p is the magnitude of the momentum vector **p**. This derives from the following relativistic relation, with $m = 0$ [3]:

$$E^2 = p^2c^2 + m^2c^4$$

Moreover the energy and momentum of a photon depend only on its frequency ν, or inversely, its wavelength λ.

$$E = \hbar\omega = h\nu = \frac{hc}{\lambda}$$

$$\mathbf{p} = \hbar\mathbf{k}$$

where **k** is the wavenumber and

$\hbar = \frac{h}{2\pi}$ is the reduced Planck constant. [4] Since **p** points in the direction of the photon's propagation, the magnitude of the momentum is

$$p = \hbar k = \frac{h\nu}{c} = \frac{h}{\lambda}$$

The photon also carries spin angular momentum that does not depend on its frequency. [5] The magnitude of its spin is $\sqrt{2}\hbar$ and the component measured along its direction of motion, its helicity (a combination of the spin and the linear motion of a subatomic particle), must be $\pm\hbar$ [6]

The photon as a gauge boson

In particle physics, a gauge boson is a force carrier, a bosonic particle that carries any of the fundamental interactions of nature.

The Standard Model of particle physics recognises four kinds of gauge bosons: photons, which carry the electromagnetic interaction; W and Z bosons, which carry the weak interaction; and gluons, which carry the strong interaction (refer to Figure 2). These elementary particles, whose interactions are described by a gauge theory, interact with each other by the exchange of gauge bosons. In a quantised gauge theory, gauge bosons are quanta of the gauge fields. Consequently, there are as many gauge bosons as there are generators of the gauge field.

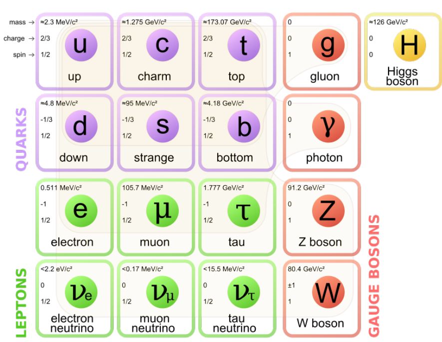

Figure 2. The Standard Model of elementary particles, with the gauge bosons in the fourth column in red. [30]

The electromagnetic field can be understood as a gauge field, a field that results from requiring that gauge symmetry holds independently at every position in spacetime. In quantum electrodynamics, the gauge group is the Abelian U(1) symmetry group of a complex number which reflects the ability to vary the phase of a complex number without affecting observables or real valued functions made from it, such as the energy or the Lagrangian. The only gauge boson in this field is the photon. For technical reasons involving gauge invariance, gauge bosons are required to be massless particles. The other gauge bosons on the other hand have mass, owing to a mechanism that breaks their SU(2) gauge symmetry. [7, 8, 9] From this we deduce that all other quantum numbers of the photon such as lepton number, baryon number, flavour quantum numbers as well as charge take on zero values. The only quantum number to have integer values is spin, having values of ± 1. From spin we can further derive the helicity of the photon which is found to take on values of $\pm\hbar$. These two spin components correspond to the classical concepts of right-handed and left-handed circularly polarised light. However, the transient virtual photons of quantum electrodynamics may also adopt unphysical polarisation states. [10]

Wave–particle duality and uncertainty principles

Photons, like all quantum objects, exhibit both wave-like and particle-like properties. The photon displays clearly wave-like phenomena such as diffraction and interference on the length scale of its wavelength. Young's double slit experiment is clear evidence of this. To account for the particle interpretation we make use of probability distribution functions which behave in accordance to Maxwell's equations. [11]

Experiments have shown that the photon is not a short pulse of electromagnetic radiation since it does not spread out as it propagates, nor does it divide once it encounters a beam splitter. [12] On the other hand, the photon seems to be a point-like particle since it is absorbed or emitted as a whole by arbitrarily small systems, having relatively very large wavelengths. Such systems include the atomic nucleus which is approximately ~10^{-15} m across and even the point-like electron.

Nevertheless, the photon is not a point-like particle whose trajectory is shaped probabilistically by the electromagnetic field. The important distinction between particles such as electrons and photons is that electrons obey Fermi-Dirac statistics, whereas photons obey Bose-Einstein statistics. A consequence of Fermi-Dirac statistics is that no two electrons in the same interacting system can be in the same state, that is, have precisely the same physical properties. Bose-Einstein statistics impose no such prohibition, hence identical photons with the same energy, momentum, and polarisation can occur together in large numbers as they do for example in a laser cavity.

Does the photon have mass?

Photons are said to be massless but the mass of the photon is set to zero in order to satisfy conditions of special relativity as we shall see in this section. Consider an isolated system of one particle which is being accelerated to some velocity **v**. Using Newtonian mechanics we get that the particle's momentum **p** must be proportional to **v** where the proportionality constant is simply the particle's mass *m*, such that **p** = *m***v**. [13, 14]

In special relativity, it turns out that although **p** and **v** still point in the same direction, these two vectors are no longer proportional. To solve this, the best alternate way to define p is through the particle's "relativistic mass" m_{rel}. This yields:

$$\mathbf{p} = m_{rel}\mathbf{v}$$

which tells us that when the particle is at rest, its relativistic mass has a minimum value called the "rest mass", m_{rest}. As the particle is then accelerated to higher speeds, its relativistic mass increases indefinitely. It also turns out that in special relativity, we are able to define the concept of energy *E* such that it has simple and well-defined properties similar to those used in Newtonian mechanics. [13] [14] In fact, when a particle is accelerated such that it has some momentum **p** (the length of the vector p and relativistic mass m_{rel}, then its energy *E* is,

$$E = m_{rel}c^2$$
$$E^2 = p^2c^2 + m_{rest}^2c^4$$

There are two interesting cases resulting from the last equation (which is just a slightly different equation to the one given in the previous section).

- If the particle is at rest, then $p = 0$, and $E = m_{rest}c^2$.
- If we set the rest mass equal to zero (regardless of whether or not that's a reasonable thing to do), then $E = pc$ so that there is no distinction between a photon's total energy and its kinetic energy. [12]

In reality photons cannot be brought to rest, so the idea of rest mass doesn't really apply to them. We can thus bring these "particles" of light into the fold of equation (1) by considering them to have no rest mass. By so doing, equation (1) gives the correct expression for light, $E = pc$, and it can now be used as a fully general equation. [13] [14]

The big question is whether we can verify the rest mass of a photon to be zero through experiment. The truth is that such an experiment is unattainable. The best we can do is to place limits on the maximum value of the rest mass of a photon. A non-zero rest mass would introduce a small damping factor in the inverse square Coulomb law of electrostatic forces. That means the electrostatic force would be weaker over very large distances. [13][14]

Heisenberg's thought Experiment

A key element of quantum mechanics is Heisenberg's uncertainty principle, which forbids the simultaneous measurement of the position and momentum of a particle along the same direction. Remarkably, the uncertainty principle for charged, material particles requires the quantisation of light into photons and even the frequency dependence of the photon's energy and momentum. [15] Heisenberg's thought experiment goes as follows: the position of the electron can be determined to within the resolving power of the microscope, which is given by a formula from classical optics

$$\Delta x \sim \frac{\lambda}{\sin\theta}$$

where θ is the aperture angle of the microscope. Thus, the position uncertainty Δx can be made arbitrarily small by reducing the wavelength λ. The momentum of the electron is uncertain, since it received a "kick" Δp from the light scattering from it into the microscope. If light were not quantised into photons, the uncertainty Δp could be made arbitrarily small by reducing the light's intensity. In that case, since the wavelength and intensity of light can be varied independently, one could simultaneously determine the position and momentum to arbitrarily high accuracy - a violation of the uncertainty principle. By contrast, Einstein's formula for photon momentum preserves the uncertainty principle; since the photon is scattered anywhere within the aperture, the uncertainty of momentum transferred equals

$$\Delta p \sim p_{\text{photon}} \sin\theta = \frac{h}{\lambda}\sin\theta$$

giving the product $\Delta x \Delta p \sim h$ which is Heisenberg's uncertainty principle. Within the same analogy, the uncertainty principle for locating a photon forbids the simultaneous measurement of the number of photons in an electromagnetic wave and the phase ϕ of that wave such that

$$\Delta n \Delta\phi > 1$$

Both photons and material particles such as electrons create analogous interference patterns when passing through a double-slit experiment. For photons, this corresponds to the interference of a Maxwell light wave whereas, for material particles, this corresponds to the interference of the Schrödinger wave equation. Although this similarity might suggest that Maxwell's equations are simply Schrödinger's equation for photons, most physicists do not agree. [16, 17] For one thing, they are mathematically different. Schrödinger's one equation solves for a complex field, whereas Maxwell's four equations solve for real fields. More generally, the normal concept of a Schrödinger probability wave function cannot be applied to photons. [18] Being massless, they cannot be localised without being destroyed. Technically, photons cannot have a position eigenstate |*r*> and, thus, the normal Heisenberg uncertainty principle $\Delta x \Delta p > \frac{h}{2}$ does not pertain to photons.

Bose Einstein model of a photon gas

Max Planck (1858-1947), in a paper presented on December 14, 1900, discovered that the observed spectrum of the radiation emitted from a black-body could not be explained in terms of classical electromagnetic theory. It was not a minor problem: Classical theory predicted an infinite energy of radiation, a disagreement so gross it was called the "ultraviolet catastrophe". [19] This led to the new definition of a "black-body". A black-body is a body which absorbs all types of radiation incident on it. This discovery marked the very beginning of quantum mechanics.

The most common example of black-body radiation is a photon gas, whereby the energy distribution is established by the interaction of photons with matter, usually with the walls of the container. In such a system the photons and the container are in thermal equilibrium with each other. [20] A Bose-Einstein condensate (BEC) is a state of matter in which separate atoms or subatomic particles, cooled to near absolute zero, coalesce into a single quantum mechanical entity which can be described by a wave function on a near-macroscopic scale. [21] This form of matter was predicted in 1924 by Albert Einstein and seen for the first time at room temperature for photons trapped in a dye between mirrors in 2010. [20]

Photons in matter

Any "explanation" of how photons travel through matter has to take into account why different arrangements of matter are transparent or opaque at different wavelengths and why individual photons behave in the same way as large groups. Explanations that invoke "absorption" and "re-emission" have to provide an answer for the directionality of the photons (diffraction, reflection) and further illustrate how entangled photon pairs can travel through matter without their quantum state collapsing.

The simplest explanation is that light traveling through transparent matter does so at a speed lower than *c*, the speed of light in a vacuum. In addition, light can also undergo scattering and absorption. The factor by which the speed of light is decreased in a material is called the refractive index of the material. Photons may be viewed as always traveling at *c*, even in matter, but they have their phase shifted (delayed or advanced) upon interaction with atomic scatters. This modifies their wavelength and momentum, but not their frequency. Photons can also be absorbed by nuclei, atoms or molecules, provoking transitions between their energy levels. It is important to note though that since photons are electrically neutral, they do not steadily lose energy via Coulombic interactions with atomic electrons as charged particles do. [26]

Technological applications and recent research

Photons have many applications in technology. One of the most well-known if these is the laser. There are various methods one can use to detect individual photons. For example, the classic photomultiplier tube exploits the photoelectric effect in order to detect photons. The charge-coupled device chips use a similar effect in semiconductors: an incident photon generates a charge on a microscopic capacitor that can be detected. Other detectors such as Geiger counters use the ability of photons to ionise gas molecules, causing a detectable change in conductivity. [27]

Much research has been devoted to applications of photons in the field of quantum optics. Photons seem well-suited to be elements of an extremely fast quantum computer and the quantum entanglement of photons is a current focus of research. The study of nonlinear optical processes is also another active research area. Photons are also essential in some aspects of optical communication, especially for quantum cryptography. [28]

Conclusion

Although the nature of a photon has been the subject of much debate throughout the past, the photon is now thought of as an elementary particle describing the quantum nature of light and all other forms of electromagnetic radiation moving at a constant speed of $c = 2.998 \times 10^8\ ms^{-1}$. It has been deduced that the photon has zero mass and zero rest energy in order to confirm with laws of special relativity. It also has no electric charge and carries spin angular momentum that does not depend on its frequency. Nowadays photons have many applications in technology and are used extensively in research.

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Daphne Anne Pollacco is 21 years old and a fourth-year B.Sc Maths and Physics student at the University of Malta. She is also a student representative. In the near future she hopes to specialize in Microwave Medical Applications. She likes travelling in Europe, painting and photography as well as playing the flute.

IAPS@GranSasso

Me, walking into a sunny courtyard, then entering a narrow corridor; at its end, a hall, and a blue T-shirt already flying to my face from Leon's hands. This is the first memory I have of *iaps@GranSasso*, the very first event organised in Italy by IAPS, alongside the newborn and fast-growing AISF - its Italian national committee.

Forty students, from all over Europe and beyond, took part in this five-day event deep within the heart of central Italy. Main theme: astroparticles - but much more was in plan.

We gathered on the first day, May 5th, at a cosy hostel in the centre of Rome, many already knowing each other, thanks to different IAPS events such as CERN visits or ICPSs; and a few newcomers including myself, thrilled to jump in the blue of this new experience. After a little walk to explore the surroundings, we all moved to a nearby pizzeria (i.e. place where they make pizza) to taste some local specialities (and a lot of French fries), everything being paid for by our sponsors, then moved back to the hostel: we knew the following day was to be an intense one.

Frascati

On May 6th, first full day of our tour, we left early in the morning for Frascati, a small centre in the outskirts of Rome. There, a series of blocks host some of the most important labs of the National Institute for Nuclear Physics (INFN), the Italian agency responsible for coordinating research in many fields of fundamental physics. Right in front of those, our destination: ENEA laboratories.

ENEA is the Italian National Agency for New Technologies, Energy and Sustainable Economic Development. It leads cutting-edge research in several topics, which stand out for their great public interest: one of the most intriguing is certainly nuclear fusion.

The basic idea is pretty simple: when light atomic nuclei get very close to each other, they may fuse to give new species of higher atomic number; when the colliding elements come before iron in the period table, a mass defect exists between reactants and products, and the reaction is exothermic. Yet, in order for the reaction to have a large enough cross section - that is, to happen with sufficiently high likelihood - reactants must be strongly energetic.

In Frascati two different research paths are explored, both involving deuterium and tritium (D-T) as reactants.

In the first one, called inertial confinement, a pellet target containing D-T is hit by a powerful laser beam: when the surface of the target evaporates, the rest of the pellet gets compressed and heated; thus a sufficiently dense plasma may form, though for a short time. In our visit we had the chance to see the ABC Laser facility, which investigates this method using a room-long laser beam and impressive diagnostics.

The second technique, on the other hand, guarantees longer confinement times despite being more elaborate. In the case of magnetic confinement a D-T plasma is kept in place and heated by means of varying magnetic fields and EM waves. The machine hosting the vacuum chamber, in which the plasma moves, has the shape of a torus and is technically called Tokamak: when we got there we found it not functioning, hence we could walk around and under it freely. Such a machine requires parts with peculiar electromagnetic properties, for instance superconducting ones. ENEA researches and develops many of the components it needs, thus we had the chance to see the cryogenic equipments kept in dedicated labs.

After lunch in the labs canteen, alongside the researchers who guided us through the visit, we took a great group photo in the lawn in front of the centre, then hopped on the coach heading to L'Aquila - second step of our tour.

GranSasso National Laboratory

The beautiful and historical city of L'Aquila lies at the bottom of a wide valley surrounded by snowcapped mountains; in 2009 it was almost destroyed by a disastrous earthquake which caused more than 300 victims. It only takes a few minutes to get from its still crumbling monuments to one of the most important research centres for astroparticles and neutrino physics: the GranSasso National Laboratory (LNGS). The labs, whose construction begun in the late 80s, take their name after the mountain under which they are built, literally meaning "Big Stone" - that is pretty much what it is: 1400 m of solid rock providing a perfect shielding from cosmic rays.

We started on May 7th with a series of talks to introduce us to the main research areas covered at LNGS and describe in detail some of the experiments we would have seen underground.

Dark Matter Hunt

The great shielding offered by rock - equivalent to more than 3 km of water at GranSasso - allows experiments to work at very low level of background noise, which puts LNGS and other underground facilities in the front run for the search of very rare events, such as Dark Matter (DM) particles detection. Indeed, as most physics students will know, there has been growing evidence that the amount of matter we see in the Universe is not sufficient to account for the entire gravitational interaction we measure. Therefore, there must exit some kind of "dark", meaning not light emitting, matter; furthermore, we know that DM cannot be baryonic and none of the Standard Model's particles can do the job.

Many theoretical proposals have been put forward, but no direct observation has yet been done and very little is overall known about this subject. For this reason any clue regarding DM's behaviour is of great interest: such hint came, for instance, from the DAMA experiment at LNGS, which found an annual cosine-like modulation in DM flux - a particularly relevant result for it did not require any model dependent assumption regarding the phenomenology of its interactions.

Meanwhile, a whole set of experiments at LNGS aims at directly detecting DM candidates in the form of Weakly Interacting Massive Particles (WIMPs), via their low-energy interactions with ordinary matter: different targets are being used to explore many possible WIMPs mass regions. Stay tuned for further news.

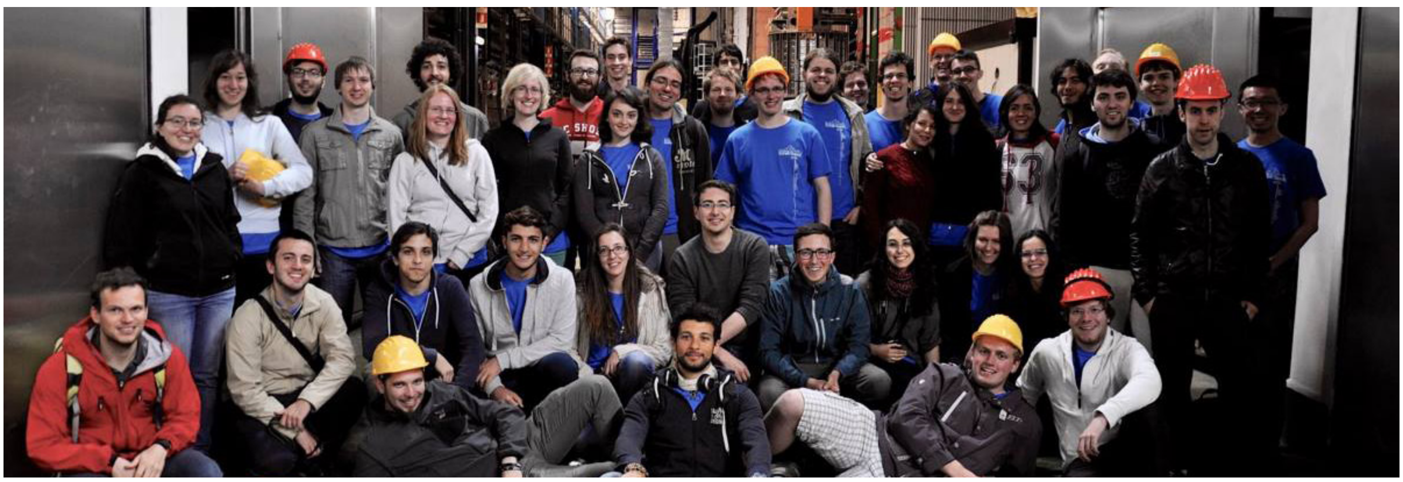
Neutrinos

Low backgrounds offer as well a great chance to perform very fine measurements on highly elusive, though more easily detectable, particles, namely neutrinos: electrically neutral elementary particles, assumed to be massless within the Standard Model.

Since their electrical charge is zero, one may well wonder whether neutrinos and antineutrinos are indeed the same particles. The question turns out to be all but trivial and may be rephrased as follows: is the neutrino a Dirac $\nu \neq \bar{\nu}$ or a Majorana $\nu = \bar{\nu}$ particle? In the latter case, one should be able to observe a particular double β decay, though a neutrinoless one, thus violating lepton number conservation: indeed the standard version of this decay, which is ordinarily detected, results in two β particles and two neutrinos[1].

Many experiments at LNGS aim at detecting such decay. One of those I'd like to mention, because of a minor detail that nonetheless surprised me: CUORE. Its inner shield, built to ensure a further protection from spurious radioactivity, is made of true Roman lead, 2000 years old, taken some years ago from a sunk ship in the Mediterranean Sea. Not exactly something you'd find at a hardware store.

We said neutrinos are assumed to be massless, yet a peculiar phenomenon has been observed which proves that they do have mass. Like leptons (electrons, muons and taus), also neutrinos come in three species, or flavours: electronic, muonic and tau. Unlike leptons, neutrinos have a certain probability to "oscillate" between different flavours. This means that a neutrino which is born, say, electronic, after traveling for some time, may end up being detected as muonic. The existence of this phenomenon, labelled neutrino oscillation, guarantees that the mass difference between flavours is non-zero[2]. Neutrino oscillations have been studied at LNGS by OPERA, an experimental set-up now in



the dismantling phase designed to measure neutrinos shot from CERN to GranSasso: just a few days ago, on June 16th, the OPERA spokesperson announced in a press conference the detection of the fifth ever tau neutrino in that beam, thus reaching a 5σ confidence level for $\nu_\mu \to \nu_\tau$ transitions [1] in fact, $\nu_e \to \nu_\mu$ transitions had already been confirmed.

In the late afternoon we moved to the underground facilities, by coach: the whole area can be easily reached from the nearby highway tunnel, a distinctive and very useful feature of the GranSasso labs. We were guided to see all the experiments mentioned above an many more. Overall a very impressive visit.

The following day we were hosted by the GranSasso Science Institute (GSSI), a newly founded multidisciplinary PhD school based in L'Aquila. We found a truly warm welcome there, and the commitment its funder show towards the city is certainly admirable. Indeed their activities seem really interesting: I strongly suggest to take a look at their website [2].

After a few interesting talks by experts of the Institute, the floor was given to the members of our students' group: first with a poster session, then with a few specific talks about the respective research interest. Although my opinion may not be of great relevance, I have to say I really got interested by each and every talk or poster alike. Moreover, many researchers there wanted to congratulate with the students for the high quality of their work - something really to be proud of!

That was the last day of our tour: the day after we moved back to Rome. We spent the last hours sightseeing around the city together, waiting for everyone to set off.

Conclusions and thoughts

The scientific program of this event was extremely interesting: all the talks were technical yet tailored to our possibilities, the language was precise yet not still a lingo; we truly had the chance to learn about the different aspects of hard core physics we encountered. Also, researchers effectively evoked the feeling of being at the edge of sound scientific knowledge and inspired in us the will to get a few steps further.

Yet, I have to admit my fairly limited preparation, that of a second year bachelor student, did not allow my comprehension to be deepened as much as I wished. What really struck me, instead, were my group mates: their passion, along with their competence and professionalism, deeply stimulated me and boosted my determination to deepen my studies.

The same eagerness seemed to be fully shared by our hosting institutions: not only they welcomed us warmly, but sponsored our stay too. Anyone who ever tried to organise such a complex event will understand how important this contribution may be.

For my part, I invite everyone to join the second edition of this event, which many (including myself) hope will take place next year. Should you be interested in the scientific activity of the institutions that hosted us, you will find the links to their web pages among the references; also, you can find all the event materials, both by researchers and students, online at [5] - I made great use of them for writing this article. Lastly, I would like to draw your attention to their thesis and PhD proposals: they are willing to welcome students from all countries and backgrounds, to share an investigation which may bring us back to the Big Bang and forward to a brilliant future of advances in Physics.

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1. The nuclear reaction is of the kind $(A, Z) \to (A, Z+2) + 2\beta + 2\nu$
2. The amplitude of the oscillation depends on Δm^2.

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Neutron Stars

What is a Neutron Star?

A neutron star is a compact star composed mainly of neutrons. Its size is relatively small with a radius of around 10 to 20 km. However, the mass of a neutron star is about 1.4 to 2 times more than that of the Solar Mass (the mass of the Sun M_o) with the largest mass observed recorded at 2.01 M_o. This leads to high densities ranging from about 2.4 to 9.1 x 10^{17} kg m^{-3}. The density distribution is lowest at the outer most part of the crust starting from about 1 x 10^9 kg m^{-3}. It then increases with depth to more than 6 x 10^{17} kg m^{-3} deep inside the core. The closest comparison to this density is the approximate density of an atomic nucleus of 3 x 10^{17} kg m^{-3}. Compared to the sun, a neutron star is of order 10^{24} times more dense. The surface temperature is typically around 6 x 10^5 K. To put things into perspective, "a single teaspoon of neutron star material would weigh a billion tons — assuming you somehow managed to snag a sample without being captured by the body's strong gravitational pull." [1,2,3]

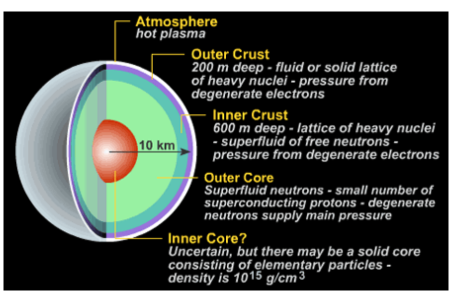

Figure 1: Structure of Neutron Star [11]

The Formation of Neutron Stars

In ancient times, it was believed that the stars were ever-lasting. As time passed, this belief was proven false. A star is created, and goes through a long process. It spends its lifetime fusing matter together until its 'fuel' runs out. At this point fusion stops and the massive star collapses towards its centre of mass due to the overwhelming influence of its own gravity. This process is called gravitational collapse, and is the heart of structure formation in the universe. [1,4]

A new star is formed through the gradual gravitational collapse of a cloud of interstellar matter. The collapse causes compression which raises the temperature until nuclear fuel ignites in the centre of the star. This produces a thermal pressure outwards, which balances the gravitational forces and brings about dynamic equilibrium to the star. When the fuel runs out again, the same process is repeated until a new equilibrium state is reached. However, this process can not go on indefinitely, and so at some point the star will reach its death. The type of death the star experiences depends mostly on its mass. [1,4]

Typically, small stars end their life as white dwarfs, glowing compact stars with mass up to 1.39 M_o cooling over billions of years. The mass of a white dwarf is restricted by the Chandrasekhar limit which gives the maximum mass of a stable white dwarf star. This is the same ending that awaits our sun. For stars that exceed 10 M_o, the neutron degeneracy pressure is overcome. The force of gravity of the star is so large that it breaks down the particles. The resulting matter and everything else within its reach is compressed and a black hole is formed. The force of gravity of a black hole is so strong that anything that gets close enough is sucked inside including light. The smallest observed mass of a black hole is recorded at 3.8 M_o [1,5]

In between the white dwarf and the black hole, compact stars having mass ranging from 1.40 to 3 M_o typically form neutron stars. To understand how neutron stars form, we must first understand how neutrons form. In 1920 Ernest Rutherford predicted the existence of neutrons and a few years later it was observed by James Chedwick. Soon after, astronomers Walter Baade and Fritz Zwichy predicted that a supernova could produce a neutron star and in 1967 a pulsating neutron star was first discovered. Apart from the neutrons found in the nucleus of atoms, these can also be produced through a process called electron capture. With enough force, an electron in an atom's inner shell is drawn into the nucleus where it combines with a proton to form a neutron and a neutrino. Neutrinos, having mass considered to be negligible even when compared to subatomic particles, are extremely fast and elusive, so they escape from the atom while the neutrons stay behind. [1,6]

Figure 2: Ernest Rutherford [14]

Figure 3: James Chedwick[14]

Figure 4: Walter Baade [14]

Figure 5: Fritz Zwichy [14]

The process of electron capture can be related to how neutron stars form. The star's gravity is strong enough to combine the electrons and protons together to form neutrons and neutrinos. The neutrinos escape into space leaving behind a large sphere of neutrons. These neutrons are compressed together due to the large force of gravity. However, these stars are supported against further collapse by the quantum degeneracy pressure due to the Pauli Exclusion principle. This states that no two neutrons can occupy the same place and quantum state simultaneously. The result is a neutron star. [1,6]

PARTICLE REACTION
FOR ELECTRON CAPTURE

$$ {}^{0}_{-1}e + {}^{1}_{1}p \longrightarrow {}^{1}_{0}n + \nu $$

Figure 6: Electron Capture Equation [13]

Between the neutron star and black holes, hypothetical intermediate-mass stars such as quark stars and electroweak stars have been proposed, however none have been shown to exist.

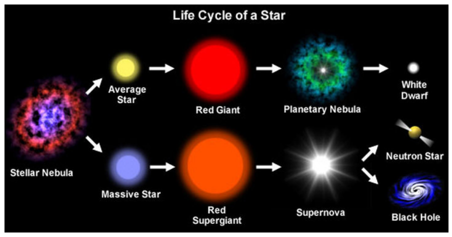

Figure 7: Life Cycle of a Star [12]

Detecting Neutron Stars

Neutron stars are not composed entirely of neutrons. A number of protons and electrons are still present within the star. Some neutron stars rotate very rapidly (up to 716 times per second), and since the star contains charged particles a massive magnetic field is created. This magnetic field does not have to line up with the axis of rotation. Due to this magnetic field, beams of electromagnetic radiation are emitted as pulsars, like a stellar lighthouse. Neutron stars are sometimes called pulsars because of the pulsing signal. Another way of detecting neutron stars is through gammarays. When rapidly rotating, high-mass stars collapse to form a neutron star, bursts of gammarays are sometimes produced. [4,7]

In the Milky-way galaxy there are approximately an order of 10^8 neutron stars. However, they are only detectable in certain instances, as if they are a pulsar of a binary system. Non-rotating and non-accreting Neutron Stars are virtually undetectable, however the Hubble Space Telescope has observed one thermally radiating Neutron Star within the Corona Australis constellation. [4,7]

The Equation of State

Neutron stars contain matter with the highest densities in the observable universe. Thus they make ideal testing grounds to unleash the full power of theoretical physics, and further the study of dense matter. However, constructing a model of a neutron star's crust requires atomic and plasma physics, as well as the theory of condensed matter, the physics of matter in strong magnetic fields, the theory of nuclear structure, nuclear reactions, the nuclear many-body problem, superfluidity, physical kinetics, hydrodynamics, the physics of liquid crystals, and the theory of elasticity. Furthermore, "theories must be applied under extreme physical conditions, very far from the domains where they were originally developed and tested." [1]

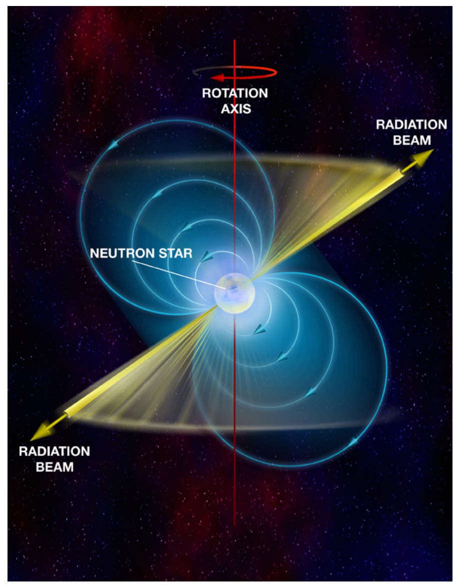

Figure 8: Radiation Emission [15]

For a model to be constructed the equation of state (EoS) is also required. This is determined by the interactions between the particles making up the neutron star. It is a relation between the pressure P, and the density ρ which can be translated to a mass-radius relation. The EoS for the core of the neutron star is problematic as the structure of the matter is not known, therefore the EoS cannot be found. [1,8]

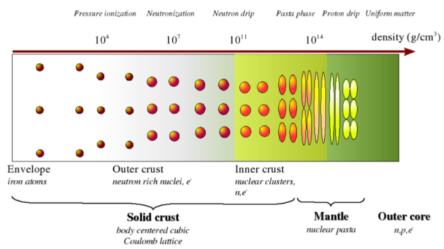

Figure 9: Particle Behaviour [16]

On the other hand, the structure of the crust should be less complicated to obtain. Since the density varies with depth, the density of the crust is much less than the average density of the star. At the outer part of the crust the density is of order 10^9, which allows this part of the crust to be composed of neutrons, protons and electrons, just like the matter around us. The density here is "sub-nuclear" and so nuclear physics methods which have been developed and successfully applied on terrestrial planets can be applied to this section of the neutron star crusts. However, the physical conditions are extreme and far from terrestrial ones. At lower levels in the crust, compression of matter increases by gravity. This causes the process of electron capture and the protons and electrons in the crust neutralise. This creates an 'excess' of neutrons, which produces conditions alien to terrestrial planets. For densities approaching 10^{14} g cm^{-3}, around 90% of nucleons (subatomic particles) are neutrons. At densities over 10^{14} g cm^{-3} nuclei can no longer exist. They collapse into a uniform plasma of nearly-pure neutron matter, with a few percent admixture of protons and electrons. This is the bottom of the crust. [1,9]

The crust contains only a small percentage of a neutron's star mass. This is crucial for many astrophysical phenomena involving neutron stars. Since the matter it contains is at sub-nuclear density, the interactions are known, and many-body theory techniques can be used. This led theoretical physicists to derive EoS. The two cases typically considered for the EoS of the crust are for cold catalysed matter (ground state crust), and accreted crust matter. The ground state approximation at the outer crust is well established, so that the pressure at any given density is determined within a few percent of accuracy. However, only theoretical models can be formed for the inner crust since the nuclei are influenced by a gas of dripped neutrons. This leads the EoS to be much more uncertain for the inner crust. The accreted crust EoS was calculated by Haensel and Zdunik, using a compressible liquid drop model with a "single nucleus" scenario. This model related closely to cold catalysed model for the lowest and highest values, but predicts different values in the midrange. [1,9]

Conclusion

The extreme conditions inside the crusts of neutron stars are already far beyond anything that can be recreated in terrestrial laboratories. The dense core of the neutron star is even more extreme. The matter in neutron star crusts experiences high pressures, and also a huge magnetic field. Neutron star branches many different fields of physics together. However, they remain a fascinating test-bed for all extreme physics and studying the details of their interior is still an active area of research.

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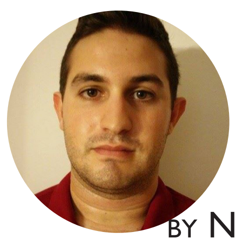

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I am in the final year of the Bachelor degree in Mathematics and Physics. Although I find most of the fields in physics very interesting, I would like to specialise in plasma physics. More specifically in nuclear fusion, the main reason being that it could lead to cleaner energy. I am also fascinated by astronomical phenomena and so I spend most of my free time reading about them. I also love to travel, to explore different cultures, and discuss varies topics while having a beer or two.

Laser Cooling by the Doppler effect

The ability to cool and manipulate atoms using laser beams has allowed a relatively new, rapid expanding field to emerge. Current research focus primarily on how existing cooling techniques can be improved. The applications of cold atoms can vary from atomic clocks to studies of quantum degeneracy. This paper explains the basic mechanisms used in laser cooling and illustrates the development of the field by describing a selection of key experiments.

Introduction

By laser cooling, one can prepare a sample of atoms with an RMS velocity <1ms^{-1} and with a temperature on the order of a few $100\mu K$. On absorbing and emitting light, an atom recoils since the photon imparts some momentum, albeit a tiny amount, to the atom. This causes the atom to be either accelerated or decelerated depending on whether it is moving towards or away from the light source. Doppler cooling involves light whose frequency is red-detuned to just below the resonance frequency of the atoms. Now, atoms moving towards the light are blue-shifted into resonance and are more likely to absorb the light whilst those moving away from the light are red-shifted further away from resonance and are less likely to absorb the light. The atoms absorb more photons if they move towards the light source due to the Doppler effect and hence this leads to preferential absorption towards the light source. As this is the direction of motion, the atoms are decelerated or slowed. Following absorption, atoms re-emit spontaneously and the recoil is in a random direction. However, on repeating this process many times, the mean velocity and thus the kinetic energy of the atom will be reduced. As a result atoms are slowed down and since temperature is the measure of random internal kinetic energy, the atoms are cooled.

Deceleration and cooling of atomic beams

The cooling process of atoms in free space can be done in various ways including the cavity Doppler cooling method. This method could be done either with a single transverse mode or by using degenerate transverse modes. We will see, in some detail, how does the former method works.

Cooling with a single transverse mode

Consider an atom of mass *m* with momentum **p**=*m*/**v** and kinetic energy $W = \mathbf{p}^2/2m$ that is illuminated by a plane electromagnetic wave of wave vector $\mathbf{k}_i$. In order for the coherent scattering peak to dominate the spectrum of scattered light, we assume that the light is detuned by more than one linewidth from any atomic transition and that its intensity is insufficient to saturate the transitions at the given detuning. Incident light falling on a fixed (in space) atom would be monochromatic and scattered at the incident frequency, while for a free particle the recoil may be taken into consideration. By the conservation of momentum, in scattering, the atom would have a momentum equivalent to $\mathbf{p'} = \mathbf{p} + \hbar\mathbf{k}_i - \hbar\mathbf{k}_s$ and a kinetic energy of $W' = W - \hbar\nabla$ (1) where $\mathbf{k}_s$ is the photon's wave vector.

$$\nabla = -(\mathbf{k}_i - \mathbf{k}_s).\mathbf{v} - \frac{\hbar(\mathbf{k}_i - \mathbf{k}_s)^2}{2m} \quad (2)$$

By conservation of energy the frequency of the scattered photon is $ck_s = ck_i + \nabla$ which is determined by the two-photon Doppler effect along the transferred momentum $\hbar(\mathbf{k}_i - \mathbf{k}_s)^2$. During scattering, recoil takes place and results as heat as shown in Eq. (2). If the scattered photon is blue detuned relative to the incident photon, the atom's kinetic energy is reduced. Conventional Doppler cooling fails to work for atoms with multilevel internal structure.

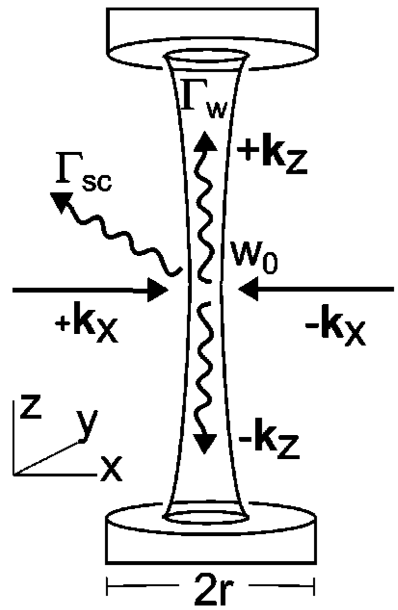

Fig. 1: Schematic diagram of 2D or 3D cavity Doppler cooling using multiple beams and a single cavity. For 2D cooling a pair of counter propagating beams along the x axis and polarized along y is used, while for 3D cooling and added pair of beams are introduced propagating along +/- y and polarized along the x.

In contrast, cavity Doppler cooling relies on a negative two-photon Doppler effect $<(\mathbf{k}_i - \mathbf{k}_s).\mathbf{v}>$.This method depends on the frequency of the incident and scattered light, so internal structures can be cooled at a rate which is proportional to the coherent scattering rate. Since,in this method, the force is dissipated in the same direction as the transferred momentum, it is possible to conduct two-dimensional or three-dimensional cooling by the use of multiple incident beams and a single optical cavity as shown in Fig. 1 above. The force f due to coherent scattering is

$$\mathbf{f} = \Gamma_w[\hbar(\mathbf{k}_x - \mathbf{k}_z)L(\delta_{++}) + \hbar(\mathbf{k}_x + \mathbf{k}_z)L(\delta_{+-}) + \hbar(-\mathbf{k}_x - \mathbf{k}_z)L(\delta_{-+}) + \hbar(-\mathbf{k}_x + \mathbf{k}_z)L(\delta_{--})] \quad (3)$$

Γ_w is the rate of scattering, from one beam, of the cavity mode without the cavity enhancement and $L(\delta_{\pm\pm})$ is the frequency-dependent intensity-enhancement factor of the cavity at the detuning of the scattered light. Γ_w can be found by decomposing the directional dependence of the strength of the waves from the source into Gaussian transverse modes.

The force due to scattering in the cavity is found by:

$$\mathbf{t} = \hbar(\mathbf{k}_x - \mathbf{k}_z)\Gamma_{sc}\eta_0 \frac{4\delta_i^{`}\gamma_c^2(\mathbf{k}_x - \mathbf{k}_z).\mathbf{v}}{(\gamma_c^2+\delta_{++}^2)(\gamma_c^2+\delta_{--}^2)} + \hbar(\mathbf{k}_x + \mathbf{k}_z)\Gamma_{sc}\eta_0 \frac{4\delta_i^{`}\gamma_c^2(\mathbf{k}_x + \mathbf{k}_z).\mathbf{v}}{(\gamma_c^2+\delta_{+-}^2)(\gamma_c^2+\delta_{-+}^2)} \quad (4)$$

Where Γ_{sc} is the free space scattering rate for a single incident beam and η_0 is the ratio of power scattering into a single direction of the cavity to the power scattered into free space. The maximum scattering rate is achieved when the Doppler effect $(\pm\mathbf{k}_x \mp \mathbf{k}_z).\mathbf{v}$ is equal to $\delta_i^{`}$, such that the denominator of equation (4) is reduced to its minimum value. The maximum force is achieved on the resonating scattering rate into the cavity which is represented by $\Gamma_{sc}\eta_0$ at which the two-photon recoil momentum $\hbar(\mathbf{k}_x \mp \mathbf{k}_z)$ is transferred onto the atom. (Refer to Fig. 2)

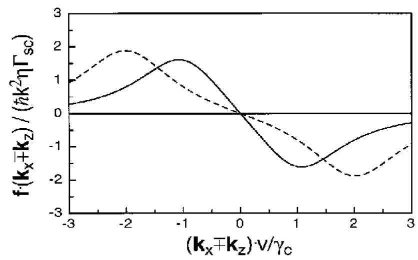

Fig. 2: Cavity Doppler force along a diagonal direction as a function of Doppler effect. The detuning of the incident light relative to the cavity resonance is $\delta_i = -\gamma_c - 2E_{rec}/\hbar$ (solid line) and $\delta_i = -2\gamma_c - 2E_{rec}/\hbar$

Doppler cooling limit

In laser cooling, when a photon is absorbed by the respective atom with two red-detuned beams, it is expected to spontaneously emit a photon in a random direction. Since these emissions are non-directional, over time the combined momentum averages out. The time taken for an atom to emit a photon depends on the natural line width, γ, of the excited state of the atom and this factor sets the lower limit to the temperature of the atoms after cooling, which is:

$$T_{Doppler} = \frac{h\gamma}{2k_B}$$

where k_B is the Boltzmann's constant and h is the Planck's constant.

Apart from the Doppler cooling limit there is also the recoil limit which is a fundamental limit of the atom. The recoil velocity an atom gains when it emits a single photon corresponds to a temperature termed the recoil limit.

To calculate the 3D cooling limit due to recoil heating in the setup with four incident beams along +/- *x* and +/- *y* we separate the heat due to scattering into free space and into the cavity mode. The scattering into free space is unaffected only if the cavity mode occupies a very small solid angle.

For a dipole pattern the average free space heating parallel to the dipole is 1/5 E_{rec} and that along the direction of the beam is 7/5 E_{rec}. If the cavity line width $2\gamma_c > \frac{E_{rec}}{\hbar}$ the detuning that minimizes the temperature will be given by $\delta_i^{`} = -\gamma_c$. Thus if the cooling rate is equal to the heating rate, the resulting kinetic temperature $T_{\alpha,min}$ along direction α is:

$$k_B T_{\alpha,min} = \frac{\hbar\gamma_c}{2}\left(1 + \frac{C_\alpha}{\eta_0 D_\alpha}\right)$$

When the scattering rate into the resonator mode is bigger than the scattering rate into free space, the latter stops limiting the final temperature. Also, a large cavity linewidth leads to a large velocity capture range, while a narrow linewidth allows one to achieve a low final temperature.

The power coupling strength between atom and cavity is given by the intensity profile of the cavity mode. Therefore Eq. 4 remains valid for the position-dependent force if the cavity-to-free-space ratio η_0 is replaced by its position dependent value:

$$\eta(\rho, z) = \eta_0 \frac{w_0^2}{w^2(z)} exp\left[-\frac{2\rho^2}{w^2(z)}\right]$$

where $w^2(z) = w_0^2[1 + (\frac{z}{z_R})^2]$ and $z_R = \frac{\pi w_0^2}{\lambda}$ is the Rayleigh range of the cavity mode.

Conclusion

Laser cooling has become a routine tool in many laboratories and especially in atomic and molecular physics. It is widely used for the investigation of cold quantum gases and trapping of atoms with optical fields. Laser cooling techniques also has applications for quantum information processing, for time and frequency standards and for highly accurate spectroscopy.

Apart from the laser cooling mechanism studied in this paper, there are more laser cooling mechanisms in which you can cool by laser polarisation gradients and work at low laser power. These are much more efficient than usual Doppler cooling, and they could be responsible for the low temperatures recently observed in 3D molasses, where polarisation gradients are certainly always present.

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