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Contents

Editorial
by Donald Geesaman ................................................................................................................................... 3

Laboratory Portrait
ATLAS with CARIBU: A Laboratory Portrait
by Richard C. Pardo, Guy Savard, and Robert V. F. Janssens ............................................................... 5

Facilities and Methods
The CUORE Experiment: An Observatory for Neutrino-Less Double Beta Decay
by Matteo Biassoni and Oliviero Cremonesi ........................................................................................... 12

Impact and Applications
CERN@School: Forming Nationwide Collaborations for Physics Research in Schools
by T. Whyntie ............................................................................................................................................... 16
RHIC 2015: Operating More than One Order of Magnitude Above Design
by Angelika Drees and Mike Blaskiewicz ............................................................................................ 20

Meeting Reports
“Re-Writing Nuclear Physics Textbooks: 30 Years of Radioactive Ion Beam Physics”
by Angela Bonaccorso and Giovanni Casini ............................................................................................ 26
EuNPC2015: “The Future of Nuclear Physics, Today!”
by Nasser Kalantar-Nayestanaki and Johan Messchendorp ................................................................ 28
Hadron 2015: The New Excited States of QCD Generate Excitement
by Michael Pennington ................................................................................................................................... 29
The Twelfth International Topical Meeting on Nuclear Applications of Accelerators (AccApp’15)
by Phil Cole ............................................................................................................................................... 31

News and Views
The 2016 Tom W. Bonner Prize in Nuclear Physics
by Calvin R. Howell ................................................................................................................................... 33
Meeting of the Antiprotons Community in Vienna
by Paola Gianotti ....................................................................................................................................... 34
Strengthening Particle Accelerator R&D in Europe: From ESGARD to TIARA
by Roy Aleksan .......................................................................................................................................... 34

In Memoriam
In Memoriam: Janusz Wilczyński (1938–2015)
by Adam Sobieczewski .......................................................................................................................... 38
In Memoriam: Heinz Oberhummer (1941–2015)
by Walter Kutschera ................................................................................................................................... 39

Calendar ....................................................................................................................................................... 40

Cover Illustration: Photograph of the CARIBU 252Cf source, gas catcher, and beamline system on the high voltage platform—see article on page 5.

Since 1979, nuclear science research in the United States has been guided by a series of Nuclear Science Advisory Committee (NSAC) Long Range Plans. In April 2014, NSAC was once again charged by the Department of Energy Office of Science and the National Science Foundation Directorate of Mathematical and Physical Sciences to conduct a new study of the opportunities and priorities for U.S. nuclear science and to recommend a long range plan that will provide a framework for the coordinated advancement of the U.S. nuclear science program over the next decade.

The entire community actively contributed to developing the plan in a series of town meetings and white papers under the leadership of the American Physical Society Division of Nuclear Physics. Ideas and goals, new and old, were examined and community priorities were established. The long range plan working group with international observers from Europe (NuPECC) and Asia (ANPhA) gathered in Kitty Hawk, NC (the site of the Wright brothers’ first airplane flight) in April 2015 to converge on the recommendations and priorities.

The last Long Range Plan (2007) occurred after a period of several years when the community was focused on running its then-new facilities. The major recommendations of the 2007 plan focused on new challenges, including the CEBAF 12-GeV Upgrade, the Facility for Rare Isotope Beams (FRIB), a targeted program of fundamental symmetries and neutrino research, and an upgrade of RHIC.

The charge for the 2015 plan asked what resources and funding levels would be required to maintain a world-leadership position in nuclear physics and what the impacts and priorities should be if the funding available provided for a constant level of effort. It is well recognized that resources are always limited, so hard choices have been made concerning parts of the program that can not go forward in a realistic budget scenario. Considering the research opportunities in an international context was particularly important in these choices.

The 2015 Long Range Plan was developed by consensus and was unanimously accepted by NSAC on 15 October 2015. Electronic copies are available at http://science.energy.gov/~media/np/nsac/pdf/2015LRP/2015_LRPNS_091815.pdf. The exact wording of the recommendations is carefully chosen and I encourage each of you to read them verbatim. Unfortunately, space limits here prohibit me from directly quoting them.

In short, the first recommendation is to capitalize on the investments made since 2007. This includes completing the construction and carrying out the scientific programs of the CEBAF 12-GeV Upgrade and FRIB, sustaining the targeted program of fundamental symmetries and neutrino research, and utilizing the upgraded capabilities of RHIC. It also requires robust support for research at universities and national laboratories and operating our two low-energy national

The views expressed here do not represent the views and policies of NuPECC except where explicitly identified.
user facilities—ATLAS and NSCL, each with their unique capabilities and scientific instrumentation.

The United States recognizes and values the strong international contributions at these facilities as these contributions have been essential to the facilities’ successes.

The plan identifies two major scientific opportunities as new priorities. The second recommendation is to lead the development and deployment of a ton-scale neutrinoless double beta decay experiment. In budget planning, it is envisioned that construction of this experiment starts in a few years. The third recommendation is for a high-energy, high-luminosity electron ion collider as the highest priority for new facility construction following the completion of FRIB. The plan also identifies targeted initiatives in theory, including computing resources for theory, and in R&D to support the second and third recommendations. Since a workforce trained in cutting-edge nuclear science is a vital resource to any nation, the plan also proposes steps to help recruiting and educating early career nuclear scientists.

The working group carefully considered the budgetary implications of these recommendations. With careful sequencing of initiatives, an effective and efficient U.S. program can be accomplished by modest growth in Department of Energy and National Science Foundation nuclear science budgets with increases of about 1.6% in spending power above cost-of-living adjustments (inflation) each year for the ten years of the plan. At constant effort, promising opportunities will be lost. Nonetheless, a constant effort budget can fund a sustainable program for nuclear science.

The plan presents the frontiers and accomplishments in each sub-discipline of nuclear science, the facilities and tools available, issues concerning the scientific workforce, education and outreach, and the broader impacts of nuclear science on other sciences and society.

Inspired by the symbolism of the Wright brothers’ great leap forward in the winds of Kitty Hawk, the new plan, Reaching for the Horizon, offers the promise of great leaps forward in our understanding of nuclear science and new opportunities for nuclear science to serve society.

We look forward to working with our European colleagues as NuPECC and the nuclear scientists of Europe embark on their own new long range plan.

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Introduction and Evolution of ATLAS

The Argonne Tandem Linac Accelerator System (ATLAS) is the world’s first superconducting accelerator for projectiles heavier than the electron. This unique system is a U.S. Department of Energy (DOE) national user research facility open to scientists from all over the world. It is located within the Physics Division at Argonne National Laboratory and is one of five large scientific user facilities located at the laboratory.

ATLAS began as a proof-of-principle project in the early 1970s to demonstrate that a superconducting resonator’s field amplitude and phase could be controlled with sufficient precision to enable the acceleration of ions. The first demonstration of such heavy-ion acceleration was accomplished in 1978 and in 1985 ATLAS [1] was identified as a U.S. national user facility for low-energy nuclear physics research. In the 30 years since, the field has moved significantly with regard to the demands for the types of beams required to address its current research topics. In order to continue to meet these evolving requirements, ATLAS has been continuously upgraded to provide the tools necessary to remain at the forefront of nuclear science.

The facility serves a national and international user community of more than 500 registered members. ATLAS is maintained and operated by a staff of roughly 25 technicians, engineers, and scientists and a similar sized group provides support for the experimental program. On average between 40 and 50 experiments take place every year. Roughly 300–400 users come to the facility yearly to carry out their measurements. The facility operates around the clock, 7 days/week and typically provides 5,500–6,000 hours of operation for research per year.

Today, ATLAS consists of three superconducting linac sections: the Positive Ion Injector, the Booster, and the ATLAS linacs. Together, they can provide over 50 MV of accelerating voltage for all stable ions from protons through uranium. Recently, the array of beams available was expanded, by the CARIBU [2] project, and now includes neutron-rich, short-lived nuclei produced in the spontaneous fission of $^{252}\text{Cf}$. In addition, near-to-stability light radioactive ions are available

![Figure 1. Floor plan of ATLAS facility with the major components of the accelerator and the major experimental equipment identified.](image-url)
via an in-flight production technique [3] using charge exchange or few-nucleon transfer reactions with stable ion beams on a gas or foil target. The floor plan of the present ATLAS facility is shown in Figure 1.

The heart of ATLAS is the superconducting resonator (Figure 2). The first successful test of a niobium split-ring resonator occurred in November 1977. A key component in the continuing success of ATLAS has been constant improvements to the facility including the evolution of best practices in constructing and operating superconducting resonators. Those developments are seen in the different classes of resonators that have been developed at Argonne and the new techniques in superconducting RF (SRF) technology that have been applied. From the split-ring resonator, which was capable of approximately 3 MV/m accelerating field to the quarter-wave resonators used in the Positive Ion Injector section of ATLAS [4] installed in the early 1990s; and now to the fully helium immersed, pure niobium quarter-wave resonators used in an energy upgrade [5] of the facility in 2009 as well as the most recent new upgrade [6] to the center (Booster) section of ATLAS in 2014, one sees a continuing progression of state-of-the-art SRF technology now culminating in routine accelerating fields of about 9 MV/m.

In the last six years, the ATLAS accelerator has undergone a number of improvements that are aimed at addressing the current and future needs of the nuclear science community. In addition to the CARIBU project described below, which has opened a completely new class of ion species for research, three major changes to the ATLAS accelerator have provided significant performance improvements in both accelerating fields and beam transmission:

1. A new cryostat of six quarter-wave (\(\beta = 0.13\)) resonators has been installed as the last ATLAS cryostat raising the maximum beam energy to approximately 21 MeV/u for the lightest ions.

2. A new, room-temperature CW radio frequency quadrupole (RFQ) linac [7] has been installed as the first accelerating resonator in the linac. It replaces three of the original, very low-velocity, superconducting resonators of the Positive Ion Injector (PII) Linac. This project has improved the overall bunching efficiency so that approximately 80% of the DC source current can be captured into a high-quality beam for acceleration through ATLAS.

3. A second new cryostat of seven quarter-wave (\(\beta = 0.07\)) resonators has replaced three cryostats of split-ring resonators in the middle section (booster) of the ATLAS linac. These resonators are achieving world-record accelerating field performance for low-beta resonators, thereby reducing the total resonator count in the linac (from 65 to 51) while maintaining the total accelerating voltage.

It should be noted that the original injector accelerator for ATLAS—the FN tandem electrostatic accelerator—has now been retired, and the facility only has two electron cyclotron resonance (ECR) sources as injectors at the present time (Figure 1). The improvement in performance resulting from these upgrades now enables the total beam delivery to often reach 70% from the ion source to the target compared to 30–40% common in the older configuration. This improved transmission is critical for the delivery of the weak-intensity radioactive beams from CARIBU and for the maximum beam intensity available for experiments requiring high currents of stable beams.
such as the in-flight RIB program, for example.

The CARIBU Project

In 2005, it was proposed to increase the radioactive beam capabilities of ATLAS by the installation of a new source of ions to provide beams of short-lived, neutron-rich isotopes. This is the Californium Rare Ion Breeder Upgrade (CARIBU) project (http://www.phy.anl.gov/atlas/caribu/index.html). This upgrade enhances the reach of ATLAS into neutron-rich nuclei and offers world-unique capabilities for study in (N,Z) regions largely unreachable to date. In CARIBU, the neutron-rich isotopes are obtained from an approximately 1 Curie (Ci) $^{252}$Cf fission source located in a large gas catcher filled with high-purity helium which rapidly thermalizes and transports the fission fragments to a RFQ cooler. This arrangement transforms approximately 50% of the fission fragments emitted from the source into a beam of $1^+$ (or $2^+$) ions with very low transverse emittance and energy spread. The beam from the gas catcher is then accelerated to 30–50 keV and mass analyzed by a high-resolution (1 part in 20,000) isobar separator. The selected ion species is finally sent either to a low-energy experimental area for measurements using a multi-reflection time-of-flight spectrometer (MRTOF) to further purify the beam, or to an ECR ion source modified for charge breeding prior to subsequent acceleration into ATLAS. The source and gas cooler system are installed on a high-voltage platform that allows the ions to gain sufficient velocity for injection into the ATLAS linac and acceleration to energies up to $\sim$15 MeV/u. The ion extraction and beam formation steps at CARIBU are efficient and fast, 20–30 ms from fission to mass separation, for all species independently of their chemical properties. As a result, the distribution of ions available from CARIBU is essentially determined by the $^{252}$Cf fission branches. Figure 3 shows the extracted low-energy isotope distribution expected for CARIBU operating with a thin 1 Ci fission source. The $^{252}$Cf source for CARIBU must have high activity yet be thin enough to minimize self-absorption of the recoils in the source. Such a source has not yet been available for CARIBU, but the physics program has started with a very intense (initially 1.7 Ci), but very thick source that is effectively equivalent to a 70 mCi thin source for fission recoils. Therefore, the intensity of these beams is currently roughly an order of magnitude below that expected with a thin source, but the universally fast and efficient extraction for even the most refractory species is confirmed and allows CARIBU to deliver world-unique reaccelerated beams to its users. The overall CARIBU facility layout is found in Figure 4 and a picture of the CARIBU high-voltage platform is shown on the cover.

The individual isotopes are extracted from CARIBU as a 30 to 50 keV continuous beam. Experiments at low energies do, however, rely more and more on ion-trapping techniques, which have specific requirements for an efficient capture of the ions, namely pulsed beams at very low energy of a few keV. The low-energy beam-line configuration, in Figure 4, consists of an RFQ ion buncher used to accumulate the ions, followed by an electrostatic elevator where the energy of the beam is adapted to the experimental requirements, followed by a low-energy switch yard to distribute the ions of interest to various experiments. For typical measurements, the beam is accumulated and cooled for 50 to 100 ms after which it is extracted as a few $\mu$s long ion bunch. By changing the small acceleration potential or the potential to which the elevator electrode is pulsed, ion beams with repetition rates of 1 to 20 Hz can be obtained at variable energies $\leq$10 keV, depending on the needs of the particular experiment. These beams then pass through two electrostatic switchyards that can feed a total of five experimental stations.

For nuclear reaction studies, the ions must be accelerated in the ATLAS linacs. Since $1^+$ or $2^+$ ions emerge from the gas catcher system, the charge state needs to be increased so that the mass-over-charge (m/q) ratio for accelerated ions is $\leq$7, the ATLAS acceptance. As shown in Figure 4, until recently, this has been accomplished with an ECR ion source. The CARIBU charge breeder (ECRB) is a 10 GHz ECR ion source modified to allow multiple-frequency plasma heating, and significantly redesigned on the rear (injection) side to accept beams from CARIBU into the ECR plasma. The ions are stopped in this plasma, charge-bred and extracted in a variety of runs with both stable and radioactive ions is approximately 10% and the best performance for CARIBU beams has been 15% [8].

Early in the development of the ECRB charge breeder, it was realized that background beams from various impurities in the system could pose a problem with the delivery of very weak, radioactive beam species. This continues to be a major issue for ECR sources [8]. The inherent scrubbing action of the plasma on the walls of the vacuum chamber and other source components creates a background of
stable beam species which can have the same m/q ratio as the radioactive beam of interest. Once such contaminant species are in the plasma, they are very difficult to reject. To improve the beam purity, an Electron Beam Ion Source (EBIS) has been developed. The ions in an EBIS do not have wall interactions and, thus, the EBIS-bred beams generally have much higher purity as well as a somewhat better efficiency into the peak charge state. The EBIS operates best in a pulsed mode with a time period of the order of 10–100 ms and so requires a much more complex beam preparation system than is the case for the ECR charge breeder. Still, a factor of roughly 2 increase in breeding efficiency is expected when compared to the ECRB source, while achieving a much lower background of stable ions. The ATLAS EBIS source [9] has now been commissioned off-line and installation at CARIBU is underway. Commissioning with a CARIBU beam is planned for April 2016.

CARIBU is now fully operational and its low-energy and reaccelerated beams have been used in a number of physics campaigns over the last few years. The main instrument in the low-energy experimental area is the Canadian Penning Trap mass spectrometer which has been used to measure to high accuracy the mass of over 150 of the close to 500 neutron-rich isotopes available at the facility. This program aims at a better determination of the key nuclear inputs to r-process calculations. It is supplemented by decay spectroscopy measurements and beta-delayed neutron measurements. The CARIBU reaccelerated beam program takes advantage of the suite of instruments available at ATLAS. For the last year, ATLAS has hosted GRETINA, the national gamma-ray tracking array. As a result, the program with reaccelerated CARIBU beams has mostly focused on Coulomb excitation measurements on nuclei located near the two peaks in the distribution of fission fragments (Figure 3). Thus, this part of the ATLAS research program focused on the onset of collectivity near A = 100, the search for evidence of triaxiality in neutron-rich Zr, Mo, and Ru nuclei, and the determination of octupole strength in the Ba – La – Ce region. The combination of the unique CARIBU beams, at the optimum energy for multi-step Coulomb excitation, with the exquisite Doppler reconstruction of GRETINA proved ideal for this campaign.

While the beam intensity currently available at CARIBU is sufficient for a low-energy program over a wide range of isotopes and for reaccelerated beam experiments with beams close to the peak in the production, a broader reaccelerated beam program requires both higher intensity to extend the measurements to a wider range of

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**Figure 3.** Distribution of isotopes available from the 3% fission branch of $^{252}$Cf. The color legend provides the yields expected from a thin 1 Ci source exhibiting the wide distribution of neutron-rich isotopes characteristic of fission. Also shown in marked red squares are the isotopes thought to be located along a typical r-process path.
isotopes and improved beam purity to perform experiments which must detect beam-like particles at zero degree. This is being addressed with the new EBIS charge breeder that will come in operation in early 2016 and with the installation of a new, thinner $^{252}$Cf source that is expected on a similar time scale. This will allow for not only an extension of the ongoing programs but also for the start of new programs such as transfer reaction measurements in the region near $^{132}$Sn.

In-Flight RIB Capability at ATLAS: Present and Future

In many nuclear physics laboratories around the world, there has recently been an increased interest in experiments with light, short-lived radioactive nuclei. At ATLAS, prior to the CARIBU facility, experiments with radioactive beams have been performed for about two decades with such short-lived nuclei. For this purpose, the ATLAS accelerator provides a high-intensity stable beam accelerated onto a production target at an energy suitable to produce the radioactive species of interest through charge exchange or few nucleon transfer reactions. The reaction products are collected and separated from the un-reacted primary beam before being used for experiments. This “in-flight” production method gives access to more than 100 short-lived isotopes in the mass range up to $A \sim 60$. Over the years, this technique has been refined by making use of the unique time structure of the ATLAS accelerator to improve the energy resolution and the purity of the secondary beams. For example, to produce the short-lived isotope $^{17}$F (half-life 1.08 m), a primary $^{16}$O beam impinges on a gas cell containing deuterium. A beam intensity of $2 \times 10^6$ $^{17}$F/s was produced by the $d(^{16}$O, $^{17}$F)n reaction with a 100 pnA primary beam of $^{16}$O in a way schematically depicted in Figure 5.

Because of the kinematics of the reaction, the $^{17}$F ions of interest exit the cell in a narrow forward cone. They are then focused and collected into a beam by a 4 T superconducting solenoid, before passing through a superconducting RF cavity employed in a so-called de-bunching mode to reduce the energy spread of the ra-
A bending magnet then separates the $^{17}$F ions from the remaining $^{16}$O primary beam before it hits the target where the experiment takes place. Recently, a RF beam sweeper has been added to the system in order to remove the tail components of the primary beam which have the same magnetic rigidity as the radioactive beam of interest. Additional information on the technique and a list of beams produced in this manner is available at http://www.phy.anl.gov/atlas/facility/radioactive_beams.html.

In order to increase the in-flight RIB beam intensity and to expand the range of nuclei that can be studied via direct reactions, a new project to build a dedicated in-flight production target and a recoil separator downstream of the last accelerator cryostat has been initiated. The Argonne In-flight Radioactive Ion Separator (AIRIS) [10] will be able to take advantage of the higher primary beam intensity and beam energy that is available as a result of the recent accelerator upgrades. The future location of AIRIS is indicated in Figure 1. The modeled design of the AIRIS separator (Figure 6) consists of a focusing quadrupole doublet magnet Q1, located immediately after the production target, followed by two dipoles, D1 and D2, which bend the particles in opposite directions. This arrangement focuses the reaction products and the primary beam onto the mid-plane of the separator where the desired radioactive beam component can be selected by a slit arrangement. The second half of the separator mirrors the upstream components.

Figure 6. A schematic of the magnetic chicane now under construction for the new AIRIS in-flight facility.

Figure 7. Radioactive isotopes which have been produced with the present in-flight system are given in purple. The beams, with rates above 1000 ions/s, expected to be available from the AIRIS facility are given in blue.
The intrinsic kinematic energy spread of the radioactive beam can be partly eliminated by using superconducting de-bunching cavities further downstream of the target and AIRIS chicane. In addition, the RF sweeper mentioned above will be relocated onto the main beam-line to further improve the purity of the radioactive beams by removing primary beam tail components. An additional benefit of AIRIS compared to the previous in-flight system is that its location on the main beam-line after the last ATLAS resonator will allow these beams to be available at all targets stations past this point.

For production reactions such as (d,p) neutron-transfer for example, a liquid-film target using deuterated vacuum pump oil is being developed. This target employs the technology pioneered at Argonne to provide liquid lithium strippers for the Facility for Radioactive Ion Beams (FRIB) that is presently being built at Michigan State University. For radioactive beams that are best produced with solid targets, such as $^{12}$C and $^9$Be, the standard technology of a fast-rotating target wheel will be employed. The beams that are expected to be available from the AIRIS system are given in Figure 7.

**Summary**

ATLAS pioneered the use of superconducting RF (SRF) for low velocity beams over 35 years ago and its development team continues to play leading roles in SRF accelerator R&D and in associated technologies. Uses of these technologies are now widespread in accelerator facilities around the world. The ATLAS team continues to develop new techniques to address the current research goals of the nuclear science community, as demonstrated with the CARIBU, and accelerator upgrade projects that have just recently been completed as well as with ongoing construction projects such as the EBIS charge breeder and the AIRIS in-flight separator.

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11
The CUORE Experiment: An Observatory for Neutrino-Less Double Beta Decay

Introduction
The Standard Model (SM) of particle physics is a theory that aims at the description of every phenomenon of nature in terms of the properties and interactions of the microscopic constituents of matter: the elementary particles. Despite its great success, continuously confirmed by experimental evidences and measurements across many decades, nowadays it is clear that in a small number of cases the SM description is oversimplified, and an extension of the theory is mandatory in order to explain the most recent experimental observations. Among the elementary particles included in the model, neutrinos, the neutral "brothers" of electrons, muons and tau leptons, are definitely the most elusive. At the same time they are characterized by peculiar behaviors that can hardly be accommodated in the SM picture. Since more than one decade the neutrinos are known to have a tiny, but not vanishing, mass. This property, demonstrated by observing the oscillating behavior of their leptonic flavor, cannot be explained within the SM, where neutrinos are massless by construction. In order to include the neutrino mass, the theory has to be modified and the neutrino nature itself is put into discussion: in the SM all the fermions, that is, the particles that make up the matter (as opposed to bosons that are responsible for the interaction between fermions), are Dirac particles. Dirac particles are different from their own anti-particles (i.e., the equivalent constituents of anti-matter). For massive neutrinos, however, this is not necessarily true: they could be, unique in nature, Majorana particles, meaning that they could be identical and indistinguishable from their anti-matter counterparts. In this case, some new, unforeseen phenomena could occur outside the predictions of the Standard Model.

Neutrino-Less Double Beta Decay
Neutrino-less double beta decay is a nuclear process that is not allowed by the Standard Model theory [1]. In fact, it implies a violation of the lepton number by two units, and requires the neutrino to be a massive Majorana particle. Two-neutrinos double beta decay is a second-order transition in the weak interaction. It is therefore a rare process allowed by the Standard Model and already observed in a number of even-even nuclei. Double beta decay is the simultaneous transformation of two neutrons in the father nucleus, leading to a lighter isotope with atomic number larger by two units. During the decay, two anti-neutrinos and two electrons are emitted, carrying away the mass difference as kinetic energy. The summed energy spectrum of the two electrons is therefore continuous because a fraction of the energy is carried by the neutrinos.

Neutrino-less double beta decay is an alternative decay channel, where no neutrinos are emitted. The most direct description is that the anti-neutrino emitted in the first weak process is absorbed as a neutrino at the second vertex. Obviously, as in the final state only two electrons are emitted, the process violates the lepton number conservation and implies that neutrinos and anti-neutrinos are the same particle. For this reason, its experimental observation would be a tremendous breakthrough in the understanding of what’s beyond the standard model.

The main goal of the Cryogenic Underground Observatory for Rare Events (CUORE) experiment is the observation of the neutrino-less double beta decay, through the measurement of the energy of the two emitted electrons that should sum up to the Q-value of the decay.

Thermal Detectors
In order to measure with extreme precision the energy of the interacting particles, the CUORE experiment consists of a large array of thermal detectors (i.e., single crystals of a dielectric and diamagnetic material, whose temperature is monitored by very sensitive thermometers). An energy deposition in the crystal (called absorber) is detected as an increase in its temperature, following the very simple law

$$\Delta T = \frac{E}{C}$$

Given that the involved energies are of the order of a few MeV, an extremely small heat capacity C is needed in order to have a measurable temperature increase. This is achieved by operating the thermal detectors at very low temperatures, typically around 10–100 mK, and exploiting the strong (third power) dependence of a dielectric and diamagnetic crystal heat capacity on the temperature (Debye Law).

The crystal and thermometer are linked to a heat sink through a small thermal conductance (Figure 1). The heat generated in the crystal by the interacting particle can slowly flow through the conductance, restoring the base temperature after the signal

facilities and methods
has been recorded. Capacities and conductivities are carefully matched to achieve the maximum energy resolution with a reasonable signal time-scale of a few hundreds of milliseconds.

In CUORE the absorber is a tellurium dioxide (TeO$_2$) crystal, the thermometer is a germanium Neutron Transmutation Doping (NTD) resistor whose resistance exponentially depends on the temperature at the working conditions, and the heat bath is a copper structure that simultaneously acts as a mechanical supporting element. The thermistor is mechanically and thermally coupled to the crystal by epoxy glue spots, while the thermal link between the detector and the bath is granted by PTFE supporting clamps and the signal readout golden wires.

Thermal detectors are characterized by an intrinsically high energy resolution, limited only by the statistical fluctuations of the thermal phonons that rule the thermal equilibrium of the system. The extremely small energy of these quanta (few meV) accounts for the excellent energy resolutions of the devices which, in the case of the CUORE detectors, is about 5 keV at an energy of 2.5 MeV.

**The CUORE Experimental Setup**

In CUORE, the absorber crystals act at the same time as detectors and sources of the decay under investigation. $^{130}$Te is an excellent candidate as neutrino-less double beta decay emitter [2, 3]. Indeed it has a very large natural abundance (~34%), the single beta decay to the intermediate nucleus is forbidden and the two-neutrino decay mode has a very long lifetime. Furthermore $^{130}$Te has a relatively high Q-value of 2527.5 keV, which limits the background contributions from the natural radioactivity. The experimental signature of a neutrino-less double beta decay is a monochromatic peak at the transition energy in the spectrum of events fully contained in a single crystal (the two electrons emitted during the decay release all their energy in the original crystal more than 88% of the time).

Since neutrino-less double beta decay, if existing, is expected to be extremely rare, a large number of nuclei under investigation (i.e., a very large detector) is compulsory. In CUORE, 988 cubic crystals, 5 cm side and weighing ~750 g each, are arranged in a modular array of 19 structures, called towers (Figure 2), 13 floors each, with four crystals per floor. The active mass is 741 kg, 206 kg of which are $^{130}$Te. Even with such a large amount of active material (about $10^{27}$ source nuclei), the expected signal is very weak: assuming a half lifetime of 10$^{26}$ years, only few events might be observed in the detector over a full year of data taking. In this condition, another experimental aspect becomes crucial: the background level.

Any event, produced by a phenomenon different from the double beta decay, that releases in the detector an energy close to the Q-value is considered a background event: it cannot be discriminated from the signal events and reduces therefore the sensitivity of the experiment by potentially hiding the already small double beta decay signal. For this reason any source of spurious events in the energy range of interest must be minimized, and different techniques are used to reduce the different contributing sources:

- **underground location:** CUORE is located in the Laboratori Nazionali del Gran Sasso, a very large infrastructure built in the heart of the Appennino Mountains, in Italy. The experimental hall is covered with a thick layer of rocks, corresponding to 3600 meters of water, that stops most of the cosmic rays, reducing the muons flux to $3\cdot10^{-8}$ s$^{-1}$cm$^{-2}$;
- **material selection and detector design:** all the materials used in the construction of the experimental setup have been carefully selected based on their radioactivity levels, the amount of material to be used and the distance from the detector active elements. The design of the detector itself has been optimized in order to minimize the amount of passive material, and all the elements have been constructed, cleaned, and assembled in the final setup following very stringent protocols to avoid any recontamination;
- **passive shielding:** the detectors are surrounded by a very heavy,
facilities and methods

Lead is used to stop gamma radiation and polyethylene to shield from neutrons. The inner layers of the radiation shield, amounting to about 7 tons, are located inside the cryogenic system and maintained at low temperature. They are made of ancient Roman lead, selected for its low content of radioactive $^{210}\text{Pb}$ (Figure 3, right);

- active background rejection: a fraction of the background can be actively rejected by correlating the simultaneous energy depositions in different crystals; the signal, indeed, is expected to activate a single crystal, while many background sources have a multisite signature.

Figure 2. A group of CUORE towers stored underground in the CUORE clean room.

Figure 3. General view of the CUORE cryostat (left) and cold Roman lead shield (right).
A unique feature of the CUORE experiment is the very low working temperature (10 mK) of the detectors which has to be reached and maintained in stable conditions over year-long data taking campaigns.

This is an unprecedented technological challenge that required a specially designed cryostat equipped with a powerful dilution refrigerator (Figure 3, left). A total mass of several tons have been successfully cooled down at temperatures close to the absolute zero demonstrating the effectiveness of the adopted solutions. This challenge is even more severe when the strong constraints on the choice of materials for the cryostat construction and the need for a very quiet, vibrations-free experimental environment are taken into account.

The outcome of these partially contrasting requirements is a custom-made, 3 m tall and 1 m in diameter cryostat with the largest dilution unit ever built and a complex cryogenic system to win the huge thermal inertia of the large mass of material and the power dissipated by the massive readout of the 988 electronics channels and keep the cold heart of the experiment, a cubic meter of sensitive crystals, at 10 mK.

The CUORE detectors have been assembled between 2013 and 2014. They are stored inside their protecting boxes in the CUORE clean room, while waiting to be connected to the coldest section of the cryostat.

The cryogenic system is reaching the final phase of the commissioning. It has been successfully cooled down at temperatures well below the design 10 mK in different conditions and with very different loads and is now being prepared to host the CUORE detector. In the meanwhile, a small array of thermal detectors has been installed in order to monitor and debug the system performance and noise levels.

The operation of the full CUORE detector is planned to start in early 2016.

CUORE-0: Physics and Technological Results

Between 2013 and 2015 one of the CUORE towers was cooled down and run as an independent experiment, called CUORE-0. The experiment had a twofold goal: being a proof of concept of many technological and scientific aspects of the CUORE project, and collecting data to extract a physics result on the neutrino-less double beta decay of $^{130}\text{Te}$.

By achieving an average energy resolution below 5 keV and a remarkable operational stability, CUORE-0 demonstrated that the technology of tellurium dioxide based thermal detectors with NTDs thermistors is mature to be applied to large scale experiments. Similarly, a reduction in the background level of almost an order of magnitude compared to previous experiences showed proved the effectiveness of the cleaning protocols and assembly procedures in achieving and preserving the requested level of radio-purity.

As a stand-alone experiment for the search of neutrino-less double beta decay, CUORE-0 has improved the existing results [ref. CUORICINO]. By observing a no signal with an improved background and almost 10 kg-yr of $^{130}\text{Te}$ exposure it allowed to set the most stringent limit on the half life of $^{130}\text{Te}$: $4.0 \times 10^{24}$ years at 90% C.L. [4].

References


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CERN@School: Forming Nationwide Collaborations for Physics Research in Schools

CERN@school is a program that brings CERN, the European Organisation for Nuclear Research, into the classroom. By supplying schools with cutting-edge detector technology and giving them access to the Worldwide LHC Computing Grid, students in the United Kingdom are being offered the opportunity to conduct authentic research in the field of nuclear and particle physics. Thanks to the support of the Science and Technology Facilities Council (STFC), the Royal Commission for the Exhibition of 1851, and the Institute of Physics, the program has resulted in a nationwide network of student scientists working together to conduct a number of research projects. This article looks at how CERN@school has achieved this, some of the ongoing experiments, and the potential for rolling out the approach across the world.

What is CERN@school?
CERN@school is based around technology by the Medipix2 Collaboration, led by Dr. Michael Campbell at CERN. The Timepix hybrid silicon pixel detector [1] was originally developed as a particle physics spin-out technology for medical applications, its ability to count and measure the energy of single photons offering unprecedented X-ray imaging capabilities. However, it was during a schools visit to the Medipix laboratories in 2007 that the eureka moment struck. A Timepix detector was being used to visualize not just X-ray radiation, but alphas, betas, gammas, and cosmic rays in demonstrations for the students from the Simon Langton Grammar School for Boys, led by Becky Parker. Parker and Campbell realized that the portable nature of the detector meant that they could be given to schools for classroom practical experiments by teachers and, excitingly, scientific research by students. With the help of Kent County Council and the South East Physics network (SEPnet), a pilot project in the south east of England was established and CERN@school was born.

The Timepix detector features a 300 mm silicon sensor wafer bump-bonded to the Timepix ASIC. With a sensitive area of just under 2 cm$^2$, the detector is capable of detecting, visualising and measuring ionizing radiation with a $256 \times 256$ grid of pixels. Alpha particles appear as big “blobs” of adjacent pixels, betas as curly tracks, and gammas as individual pixels. More exotic signatures, such as minimum ionizing particles (MIPs) and muons, appear as long, straight lines of pixels. These capabilities mean that the detectors can be used to demonstrate the different types and properties of radiation in the classroom, greatly enhancing what can be taught in the physics curriculum [2]. Unlike a Geiger counter, students are able to see radiation in real time—and, if suitably inspired—go on to make measurements that can form the basis of authentic research projects.

Measurements from the detectors can be viewed and analyzed locally by the user [3], but they can also be uploaded to the CERN@school Data Acquisition, Management, Analysis and Presentation (DAQMAP) system. The DAQMAP is a Ruby-on-Rails powered Web application that allows data to be shared by the Collaboration in a secure manner. The DAQMAP then interfaces with the Worldwide LHC Computing Grid thanks to the support of the GridPP Collaboration [4], which uses the computing network that found the Higgs boson to process, store, and publish CERN@school data. GridPP has committed 10% of its computing resources to non-LHC use, and the CERN@school Virtual Organisation (VO) has played a role in testing and developing software for new users to engage with the grid. With the CERN Virtual Machine (CERN VM) service, analysis software can easily be installed and used from within schools. This allows students to use and share analysis code easily, as well as inspire them to develop their computing skills. After all, physics in the real world relies on computers for data analysis—and CERN@school is no different.

However, what really makes CERN@school tick is not the detector technology, or indeed the computing power of the grid: it is the people—the support staff, the teachers, the students—and the networks they form. The Power of Networks

The original pilot project with SEPnet placed a detector with each participating physics department’s outreach officer. The officer would then act as a “network hub” for the region, deploying the detector to a local school and providing the necessary training or using the detector in schools workshops and demonstration sessions. The success of this pilot then prompted interest from the UK Institute of Physics’s (IOP’s) Physics Teacher Network (PTN). The PTN consists of a nationwide network...
impact and applications

of Physics Network Coordinators (PNCs), dedicated teachers or former teachers who work with schools in their respective regions to inspire students and fellow teachers alike. A joint funding bid from CERN@school and the IOP saw STFC fund 25 detectors and laptops to create a national network of detectors. Over 50 schools, outreach groups and national laboratories have taken part in CERN@school activities—which are managed by the local network hubs as they see fit—and this number is growing all the time. There are even networks-within-networks—for example, one PNC has distributed their detector to Northumbria University Newcastle’s Think Physics project, which will see the detector used by a local network of 30 schools in the north east of England.

Thanks to the nationwide coverage possible through the IOP Physics Teacher Network and SEPnet, a number of nationwide experiments have been started by students and teachers in schools with the aim of creating large datasets for collaboration members to explore. These include:

**Radiation Around You (RAY):**
the Simon Langton Grammar School for Boys were runners-up in the Rolls-Royce Science Prize 2013 with the RAY project. This aims to create an interactive radiation map of the United Kingdom using background radiation measurements with the CERN@school detectors. In situ measurements made with the detectors based in schools and outreach groups across the country are fed into the DAQMAP, processed using the grid, and presented using ArcGIS mapping technology.

**Solar Eclipse 2015:** the morning of Friday, 20 March 2015, saw a partial solar eclipse sweep across the United Kingdom. Victor Hess famously used a balloon ride during a solar eclipse to rule out the Sun as the source of background ionizing background radiation. However, the UK eclipse (Figure 1) provided a unique opportunity for CERN@school Collaboration members to make a simultaneous background radiation measurement with their Timepix detectors, as many schools held off-timetable events to celebrate this rare celestial phenomenon. Background radiation measurements also provide results even when it is cloudy—which was very useful with the British weather! The setup for the background radiation measurement with the Jablotron MX-10 detector can be seen in Figure 2. Data was collected from as far as Wales, Scotland—and even Svalbard—and will be used to look for deviations in radiation levels at the time of the eclipse or confirm Hess’s findings with much more up-to-date technology. The eclipse measurement will also provide a useful dataset for RAY.

**Radiation in Soil Experiment (RISE):** a group of fifteen girls

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**Figure 1.** The UK solar eclipse as seen from Northumbria University Newcastle, home of the Think Physics project. Credit: Jonathan Sanderson/Think Physics 2015.

**Figure 2.** The Jablotron MX-10 digital particle camera [1, 4] mounted face up in a clamp with its cover open, showing: (a) the Jablotron MX-10 digital particle camera; (b) the detector’s sensor element, exposed by opening the cover; (c) the mini-USB cable that connects the detector to the laptop; (d) the boss; (e) the clamp used to hold the detector in place; (f) the retort stand. The axes indicate the relative orientation of the detector coordinate system, although the origin should be taken as the bottom-left corner of the sensor element. Photo credit: Tom Whyntie/CERN@school.
at Ruislip High School (Ruislip, UK), is using a CERN@school detector to measure the radioactivity of different soils. Taking a different approach to RAY, the group will be asking teachers and students at the school to collect samples of soil whenever they visit somewhere and bring them back to the RISE research team for analysis. The CERN@school detector is then used to detect and characterise the different types of radiation (if any) emitted by the sample (Figure 3), which in turn can be used to create a geological radiation map of the country.

These are just a flavor of what can be done with CERN@school. As well as the research itself, it has been interesting to see how different sub-collaborations like RAY and RISE have evolved, with schools sharing data or competing with each other to establish their own take on a similar concept. Whatever happens, students have the chance to share their results and experiences at the annual CERN@school Research Symposium. In September 2014, this was held in conjunction with the 10th International Conference on Position Sensitive Detectors (PSD10) at the University of Surrey, Guildford with over 100 students and teachers from around the United Kingdom. This year the CERN@school Collaboration convened on Wednesday, 16 September 2015 at Queen Mary University of London with a series of lectures, workshops and poster sessions. As happens at regular academic conferences, participants once again had the chance to bounce ideas off each other over coffee and—importantly—cake. New projects discussed included an expedition to Greenland, placing a detector on a nautical drone with CERN@sea, and monitoring radiation levels on the International Space Station with the TimPix project.

**Outlook**

CERN@school offers students the chance to actually carry out scientific research and so directly experience what a career in science or engineering might be like. This is the philosophy of the Langton Star Centre and the recently established Institute for Research in Schools (IRIS), led by Becky Parker as part of her remit as Visiting Professor at the Schools of Physics & Astronomy at Queen Mary University of London. CERN@school is a flagship program for the IRIS as it seeks to establish research in schools as a source of inspiration for students and teachers alike.

But there could also be wider and more important impacts associated with this approach. Research commissioned by the United Kingdom’s Department for Children Schools and Families and the Institute of Physics [5] has shown that being able to directly relate a subject to potential careers and work with positive role models has a positive impact on girls’ experience with physics—and CERN@school offers such opportunities in abundance. Through Dr. Jessica Hamer (IOP), a geologist and former physics teacher, Ruislip High School is taking part in the Drayson Project, which aims to address the issue of gender imbalance in subject choice at A-level. By offering the team the chance to work with Dr. Hamer and the CERN@school Collaboration through the RISE experiment, it is hoped that the impact of the research-based approach on the uptake of physics among girls can be studied in greater detail.

To date, CERN@school has focused on the United Kingdom for the simple reason that STFC, the national funding body for nuclear and particle physics, has provided the funding for equipment and full-time staff to run the project through its public engagement team and strategy. Partners such as GridPP and the Royal Commission for the Exhibition of 1851 have then joined with match-funding for

**Figure 3.** The MX-10 particle camera being used to analyze geological samples as part of the Radiation in Soil Experiment (RISE) at Ruislip High School (UK), a nationwide CERN@school experiment. Photo credit: Dr. Jessica Hamer/IOP.
infrastructure support. Other CERN member states could easily join the program and collaborate through their national grid organizations, while the detectors themselves are supplied independently by Jablotron, a company based in the Czech Republic. The MX-10 particle camera units package the Timepix technology in a secure plastic casing with a sliding cover that protects the delicate silicon sensor when not in use. Jablotron have also developed an “EduKit” featuring a number of demonstration experiments for use in schools. Jablotron’s Vladimír Stanislav said, “We’re delighted to support the CERN@school research programme in the United Kingdom, and it’s great to see our MX-10 units helping students to learn about radiation. We’d love to hear from more teachers around the world to get Timepix technology into as many classrooms as possible!”

Indeed, with the right support from national funding bodies there is no reason CERN@school could become a truly international endeavor, conducting worldwide experiments and bringing students and teachers across the planet together to carry out new and exciting scientific research in the field of nuclear and particle physics. Readers are encouraged to contact us to discuss how they too can get involved with CERN@school!

References

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Introduction

Commissioning any large research facility such as a collider will have its troubles and pitfalls no matter how thoughtful and sophisticated the design. Only once childhood diseases are surmounted, routine operation begins. At first the focus will be on reaching the design goals. This will be followed by pushing the boundaries and reaching beyond the design capabilities. The Relativistic Heavy Ion Collider (RHIC) 15 years after its first physics run in 2000, has certainly reached this phase. The demands and expectations of the scientific user community are ever growing with each run, with the requests as diverse as the user community itself. One popular demand is the call for more and more collisions and another one the request for uneven species such as operating the accelerator with protons in one ring while circulating gold ions in the other. But what can actually be done to meet those expectations once the obvious solutions and ideas are exhausted?

RHIC Overview and History

The Relativistic Heavy Ion Collider [1], shown in Figure 1 together with its injectors, consists of two 3.8 km long rings containing approximately 1,740 super-conducting magnets. It owns six arcs interspersed with six straight sections, two of which house experimental detectors, namely STAR and PHENIX. While the clock-wise (“blue”) and counter-clock-wise (“yellow”) rings are separate for the most part, they share a total of 12 crossing dipoles (called DX magnets) on either side of the six interaction points (IP). The DX magnets are needed to simultaneously steer the incoming beam into the common beam pipe and through the interaction region and the outgoing beam away from the other beam back into its separate beam pipe and ring. Later we will come back to the question why this, the shared magnets, is of any significance.

RHIC is capable of accelerating and colliding a variety of species of particles, from polarized protons (pp) to gold (Au) and uranium. Beams collided at numerous energies starting from 3.85 GeV/u (Au) up to 255 GeV/u (pp). While for the most part symmetric species have circulated in both rings, there were several combined species runs as well. Figure 2 shows the achieved luminosities for the three different types of RHIC running: polarized protons on polarized protons, heavy ions on heavy ions, and combined species. The latter graph includes the most recent identical heavy ion runs for comparison as well.

Beam Parameters

Luminosity, the ultimate albeit not sole performance measure for a collider, defines how many collisions are available to the experiments and is thus of particular interest. It starts low in the early years and keeps increasing—provided some hurdles are overcome on the way. Assuming no crossing angles and equal beam sizes in the two rings (a.k.a. “blue” and “yellow”), instantaneous luminosity \( L \) can be calculated from beam parameters according to:

\[
L = R \times f_{rev} \times \frac{N_{blue} \times N_{yellow}}{4\pi \sigma_x \sigma_y}
\]

where \( R \) is a varying reduction factor, \( f_{rev} \) is the revolution frequency, \( N_{blue,yellow} \) are the number of particles
in the relevant ring and $\sigma^*_x, y$ are the two transverse rms beam sizes at the IP. Given that $f_{\text{rev}}$ is constrained by the speed of light and RHIC’s circumference, all one can do is change the other factors. In other words, the larger we can make the number of particles and the smaller the beam size the larger the luminosity and the better the collider performance!

The beam size for once is not constant but a function of the position along the ring, $s$, and is defined by the magnet configuration, the lattice:

$$\sigma_{x,y}(s) = \sqrt{b_{x,y}(s)e_{x,y}},$$

where $b_{x,y}(s)$ is called the betatron function and represents the focusing properties of the lattice. It does not describe a feature of the beam. The emittance $e_{x,y}$ on the other hand represents a property of the beam and is not a function of the position along the ring. It is constant, albeit not constant in time since, for hadrons, it tends to grow significantly with time spent at store. The emittance is defined as the phase space area formed by the beam particle distribution. It is measured accordingly in units of $\mu$rad. As a result the beam size changes with position as well as with time. In the case of a collider such as RHIC it is smallest at the IP, a location that is indicated by an asterisk ($\sigma^*$ and $\beta^*$). In order to “squeeze” the betatron function and with it the beam size at the IP to smaller and smaller values, RHIC employs triplets of strong focusing quadrupole magnets on either side of all IPs. In turn, the betatron function within the triplet itself grows, ultimately putting a limit on the achievable value of $\beta^*$ due to scraping and increasing losses in the triplets. Table 1 summarizes various highlights of RHIC Au-Au operation such as the first Au-Au run at top energy of 100 GeV/u (2002), the last run before stochastic cooling became fully operational (2007), the last Au-Au run before an ad-ditional dynamic $\beta^*$-squeeze (2011) and finally the most recent Au-Au run in 2014. Interjacent years, spent on combined species, polarized protons as well as more Au-Au operation in addition to upgrades of the stochastic cooling system and the injectors, are not listed here. Nevertheless, without stochastic cooling and the dynamic $\beta^*$-squeeze, RHIC could not have improved its performance as much as it did and both techniques deserve a closer look.

Since the betatron function is periodic with the circumference of RHIC, the phase advance of this oscillation increases by a constant amount with every complete revolution. The betatron tune $Q_{x,y}$, often simply called “tune,” represents the number of oscillations in the horizontal and vertical coordinate per turn. If Q is an integer, any imperfection in the magnetic fields becomes a synchronous perturbation and leads to a resonant excitation of the oscillation and hence to growth of the amplitude. Therefore the betatron tunes should not be integer or any simple low order fraction. For protons for instance the fractional parts are constrained between the 2/3 and 7/10 resonances. Control of the
fractional tune together with the tune distribution within a bunch is of utmost importance when trying to keep beam losses and emittance growth to a minimum. However, while in collisions the beam particles experience strong Coulomb forces of the other beam. Those magnetic and electric forces are coherently additive and basically form an addition to the magnetic configuration that controls the tune, thus shifting the tune. The linear beam-beam tune shift \( x \) per IP for a hadron collider is given by [3]:

\[
\frac{1}{N^2} \frac{\lambda}{\gamma} \frac{\sqrt{2}}{\sin\theta} \frac{\beta^*}{\epsilon} \frac{L}{N}
\]

where \( r_0 \) is the classical radius of the particle, \( N \) the number of particles per bunch and \( \gamma \) is Lorentz’ relativistic factor. In RHIC, the beam-beam tune shift is negligible for all species but protons and for that it is of the order of \( \frac{1}{N} \) due to the larger values of \( N \). Such a tune shift causes the tune distribution of the beam particles to come dangerously close to or cross the resonant terms (such as the low order fraction \( 7/10 \)) and the beam suffers an increased loss rate and emittance growth. Without extra measures to compensate for the unprofitable beam-beam tune shift, the achievable bunch intensity will remain limited and with it the luminosity.

Table 2 compares the first year of polarized proton operation at 100 GeV/u with the years 2012 and the most recent run in 2015. Proton operation at higher energies is not considered here. The improvements in the years between 2002 and 2012 are thanks to a variety of upgrades. Finally, compensating the beam-beam tune shift by using an e-lens allowed an impressive additional factor 2.5 on top of that which is why we will elaborate on the RHIC e-lens some more below.

**Stochastic Cooling**

In RHIC Au ions are tightly bunched by the radio frequency (rf) cavities. Therefore, owing to the high particle density the ions suffer multiple small angle Coulomb collisions referred to as intra beam scattering (IBS). The negative mass effect removes the possibility of even approximate thermodynamic equilibrium and IBS leads to uniform emittance growth in all three dimensions. The red curve in Figure 3 shows the effect of unchecked IBS on luminosity. Combating this emittance growth requires beam cooling. Stochastic cooling was originally used to increase the phase space density of anti-proton beams, allowing them to be used in a collider [4]. In essence it is a very wide band feedback system consisting of one matched pair of a pick-up and a kicker per dimension. The large system bandwidth allows us to correct the average positions and energies, which, due to the relatively small number of gold ions per bunch, is practical in RHIC [5]. By continually correcting the average the energy spread and emittance are reduced. The black curve in Figure 3 represents the current state of cooling in all three dimensions. Additionally, the initial luminosity has been increased significantly by improvements in the injectors. A rapid drop in luminosity is apparent while the cooling system turns on. Once on, the luminosity increases as the emittance shrinks. We are now at the point where virtually all beam losses are due to collisions rather than scraping at places with a large beta-tron function or small aperture!

**Dynamic Beta Squeeze**

While stochastic cooling deals with a beam property, the emittance, to de-
crease the beam size, the dynamic $\beta^*$-squeeze is a scheme to reduce the beam size via a lattice property, namely the betatron function. As mentioned above, scraping and increasing losses in the triplet area put a limit on the achievable $\beta^*$ value that is actually lower than the engineering limit coming from the triplet power supplies themselves. That engineering limit would correspond to approximately $\beta^* = 0.55$ m. In 2011 an attempt to reduce $\beta^*$ in the machine during a dedicated test resulted in a value of 0.58 m [6]. However, the method relied not only on the triplet power supplies in the IP where we strained to reduce $\beta^*$ but also on a specific lattice that has since been abandoned. A different method was needed.

The dynamic $\beta^*$-squeeze is based on the achromatic telescopic squeeze (ATS) generated at CERN for future LHC upgrades [7]. In this scheme the $\beta^*$ reduction at a given IP is achieved by creating a controlled and confined beta-wave using the quadrupole magnets of a preceding and a subsequent interaction region. This is done in such a way that the superposition of the beta-wave and the unperturbed (or “linear”) betatron function will have a local minimum at the desired location i.e. the IP of question. On top of reducing the deviation of the linear lattice from the model down to 10% from an original 40%, modifying the ATS scheme for RHIC specific machine constraints was another necessary prerequisite for the successful implementation of the ATS scheme at RHIC [8]. Equally as important was the efficient operation of stochastic cooling used to reduce the transverse beam size to a value that can be tolerated in the triplet quadrupoles where the betatron function has its maxima. Once all this was done it was possible to squeeze the $\beta^*$ values from 0.7 m down to 0.5 m. This happened typically several hours into a physics store [8], a time in a store by which stochastic cooling had had ample opportunity to reduce the beam sizes. Figure 4 shows 90 minutes of luminosity at one of the two detectors (STAR). The dynamic $\beta^*$ squeeze is executed at 14:10, resulting in a 15% increase in instantaneous luminosity. The dynamic $\beta^*$ squeeze became part of the routine operation in the second half of the 2014 run. Thus, together with stochastic cooling, it was leading to an average store luminosity of $5 \times 10^{26}$ cm$^{-2}$s$^{-1}$ and the integrated luminosity of the 2014 run actually exceeds the sum of all previous Au-Au runs combined!

**Beam-Beam Tune Shift Compensation**

RHIC currently has two IPs (STAR and PHENIX) with head-on collisions while the beams are separated vertically in all other interaction regions. In order to increase the bunch intensity above and beyond the 1.8 x 10$^{11}$ achieved in 2012 while keeping the emittance small, there is not enough tune space between the 2/3 and 7/10 resonances to hold the beam-beam generated tune spread. Consequently, strong emittance growth was observed in the last run without beam-beam tune shift compensation (2012). The measured emittances were equivalent to a beam-beam tune shift $\xi/\text{IP}$ of 0.006. In an effort to reduce the tune spread and to increase the tune shift limit, two electron lenses were installed and commissioned in the run of 2015 [9, 10]. An electron lens consists of a low energy electron beam that creates an amplitude dependent transverse force of the same size but opposite sign as the proton beam. For this purpose the electron and proton beam profiles are matched and the e-lens is installed in another interaction region between the two DX magnets. A RHIC e-lens consists of a DC electron gun, a solenoid in which the interaction with the proton beam occurs, a beam transport from the gun to the solenoid and from the solenoid to an electron collector. When the proton beams pass through the e-Lens solenoid, they collide head-on with the electrons just as the two proton beams collide with each other in the experimental IP. In order to compensate the beam-beam tune shift of one IP two lenses, one in each ring, were used in 2015 in conjunction with a favorable phase advance that has to be respected between the e-lens and the IP. Figure 5 demonstrates the effect of operating with (2015) and without (2012) an e-lens albeit other
significant improvements such as in lattice design are also significant contributing factors for the difference between the two years. While the 2012 peak luminosity stalled at a value of 46 $10^{30}$ cm$^{-2}$s$^{-1}$ the run in 2015 saw a factor 2.5 improvement and reached an unprecedented 120 $10^{30}$ cm$^{-2}$s$^{-1}$ for a few stores!

**Combined Species: pAu Operation**

As indicated earlier, the fact that both beams share the same crossing (DX) magnets causes some complication in cases when the beams consist of different species, in particular if protons make up one of them. The DX magnets are bending magnets. Particles traversing a dipole experience a deflection depending on their magnetic rigidity $B_r$ which in turn depends on the particles momentum and charge ratio. If the beam energies are about the same, this comes down to the mass-charge ratio $m/e$, specifically 1 in the case of a proton and 197/79 = 2.5 in the case of a gold nucleus. With other words: protons will be deflected much more than the Au ions, leading to an angle through the interaction point of approximately 4 mrad. However, in order to provide optimal luminosity, a zero crossing angle between the two beams is required and the Au beam has to assume the reverse trajectory of the proton beam. As a result, even though the DX magnet vacuum chamber has a radius of about 68 mm and is thus almost 30 mm larger than most of the RHIC beam pipes, it is too small for both beams to pass given such a slanted trajectory through the IP. This applies in particular if one considers not just the center of the beam but its size of at least $+3\sigma$ and a minimum distance of the beam edge to the vacuum chamber wall of 2 mm. This constraint excludes the p-Au operation, unless the entire DX magnet chamber is moved towards the beam that comes closer to the pipe wall, the Au beam. It turns out that a 20 mm lateral movement of the DX magnets is required for p-Au operation [11]. Fortunately, combined species operation with protons and heavy ions was anticipated already at the RHIC design stage [1]. Therefore, all DX magnets are installed such that they are movable and were moved successfully for the first time this year, making the first p-Au combined species run possible.

**Summary**

The list of issues and solutions promoted in this article is far from complete and many more species, energies, upgrades, solutions, improvements, and newly developed methods are not mentioned here. And, clearly, RHIC exceeds its early years by a lot. But, as indicated, we should see how RHIC is doing compared to the design values stated in 1999 [1]. This comparison is done in Table 3.

The peak luminosity in the Au-Au case exceeds the design by a factor 9 and in the pp case even by a factor 23. However, one might argue that the peak luminosity decays very fast and what really matters is the aver-

![Figure 5. Luminosity (peak and average) as a function of bunch intensity for the 2012 and 2015 pp runs. The dashed blue lines correspond to constant rms emittances of 2, 3, and 4 μmrad, respectively (from Ref. [10]).](image)

**Table 3. Beam and lattice properties with resulting predicted (“d.” design) and achieved (“a.”) luminosities from the RHIC design manual in 1999 [1] and the most recent runs (2014 and 2015) [2].**

<table>
<thead>
<tr>
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<th>$\beta^*$</th>
<th>$\varepsilon$ [μmrad]</th>
<th>$I_B$ [$10^9$]</th>
<th>$\text{NoB}$</th>
<th>$L_{\text{peak}}$ [cm$^{-2}$s$^{-1}$]</th>
<th>$L_{\text{avg}}$ [cm$^{-2}$s$^{-1}$]</th>
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<td>3.3</td>
<td>100</td>
<td>56</td>
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</table>
average luminosity per store. In 2014, the average store Au-Au luminosity outperformed the design by a factor 25 and the average pp luminosity in 2015 outdid its counterpart by a factor 16. Let’s see if there is still room for more development in the upcoming years!

References
2. www.agsrhichome.bnl.gov/RHIC/Runs
“Re-Writing Nuclear Physics Textbooks: 30 Years of Radioactive Ion Beam Physics”

The school “Re-writing Nuclear Physics textbooks: 30 years of radioactive ion beam physics” was organized by the Department of Physics of the University of Pisa and the Pisa and Florence branches of INFN—along with another eleven INFN branches and Physics Departments around Italy—to celebrate the 30th anniversary of nuclear structure and reaction studies with radioactive beams. Many people attended the lectures, including those of Isao Tanihata and Björn Jonson, pioneers of this field of research: most of them were students of the third and fourth year of the university course, 90 in all, of which two-thirds were Italian, while the rest were PhDs and senior colleagues, for a total of 145 participants, happily smiling in Figure 1. The contents of the lectures will be published in the *European Physical Journal Plus* (EPJ+) thanks to the collaboration with Nicolas Alamans and Eugenio Nappi.

One of the goals of the school, targeting students taking their university courses before the degree, was to attract promising young people into the radioactive ion beam (RIB) research field. From this point of view the school was a great success, as for the number of participants, the scientific level of lectures, the originality of format and content and especially the daily tutorials divided into language groups that were highly appreciated by the students. These characteristics enabled the school to be inserted in the circuit of summer schools of the University of Pisa and, through the latter, in that of the European Summer Schools.

The school started Monday, 20 July with some introductory “parallel” classes in different languages, given by the following tutors:

- China
  Baohua Sun *(Beijing)*
- Belgium/France
  Pierre Descouvemont *(Bruxelles)*
  Stéphane Grévy *(Bordeaux)*
- Canada/Finland/Germany/Japan/UK
  Andrei Andreyev *(York)*
  Stefan Typel *(GSI)*
- Italy
  Gianluca Colò *(Milano)*
  Alessia Di Pietro *(INFN - LNS)*
  Lorenzo Fortunato *(Padova)*
  José Javier Valiente Dobon *(INFN - LNL)*
- Spain
  Antonio Moro *(Sevilla)*
  Dolores Cortina-Gil *(Santiago de Compostela)*

The goal of such lectures was to get the young students accustomed with the differences between the standard Nuclear Physics described in textbooks and the new concepts which have emerged in the last thirty years from studies of nuclei with extreme N/Z ratios.

Then Isao Tanihata made an excursionus on how and why RIBs were produced at Brookhaven in the early 1980s and on the first measurements and interpretations of reaction cross-sections. It was a lot of fun, and actually moving for most of us, to see the original hand drawings of some, by now, “legendary” figures, such as that showing the nuclear radius as a function of the atomic number of some light nuclei. The figure was the first evidence of the existence of “halo” nuclei. On the other hand, the final lecture was given by Björn Jonson, another pioneer of the field, together with the late Gregers Hansen. Björn showed how RIBs physics evolved from the seminal experiments made in Copenhagen and then at CERN-Isolde and concluded by presenting future challenges.

The students were eager to learn about the wonders of the new physics.
Those were explained during eleven lectures, each of them two hours long, given by some of the youngest and most promising leaders in our field, namely:

Magda Kowalska (CERN, Geneva)
Global properties of atomic nuclei: masses, radii and modern methods to measure them.

Riccardo Raabe (Leuven)
Making radioactive ion beams, detecting reaction products.

Giovanna Benzoni (Milano)
Strong, weak and electromagnetic forces at work in atomic nuclei, decay properties.

Sonia Bacca (TRIUMF, Vancouver)
Structure models: from shell model to ab initio methods.

Stefan Typel (GSI)
Reaction theory.

Robert J. Charity (St Louis)
Resonance phenomena: from compound nucleus decay to proton radioactivity.

Tomohiro Uesaka (RIKEN)
Experimental methods and measured observables with polarized proton targets: understanding spin-orbit.

Alexandre Obertelli (Saclay)
Probing nuclear structure with direct reactions: observables, methods and recent progress with rare isotopes.

Andrea Jungclaus (Madrid)
Single particle versus collectivity, shapes of exotic nuclei.

Lucio Gialanella (Napoli)
Radioactive ion beams in experimental nuclear astrophysics.

Ulli Koester (ILL-Grenoble)
Applications of physics of unstable nuclei to energy, medicine, material science.

Each day ended with about one hour of parallel tutorials, in different languages, during which the lectures of the day were revised and discussed. Often the lecturers participated as well, moving from one group to another. These activities were very successful because they allowed the students to get a deeper insight into the new problems, thus improving also their standard Nuclear Physics knowledge. There were also presentations and posters about the possibilities offered by different countries to foreign students to pursue a Ph.D. thesis.

Finally, on Thursday, 23 July, late afternoon, there was a plenary discussion after the Björn Jonson lecture, during which the students expressed their interests for further work in the field. The evening ended with a nice garden party and dinner at the “Le Benedettine” University residence.

The school ended on Friday, 24 July, with a visit to the INFN-Laboratori Nazionali di Legnaro. We visited in particular the SPES area where the new Italian RIB facility is under construction,

We believe that this event and similar ones in the future can help spread the new physics on to young generations and thus ensure a bright future for our field.

Acknowledgments

The success of the school was due to the joint effort of many individuals. We thank in particular the members of the National and International Coordination Committees for helping setting the program and sending their students; indeed, besides Italy, students came from Belgium, Canada, China, Finland, France, Germany, Japan, Spain, and the United Kingdom. We also thank the INFN-Pisa and Department of Physics administration and technical staff; the University of Pisa Summer Schools and DAS staff for helping solving a large number of practical problems; the director Giovanni Fiorentini and the colleagues of the INFN-LNL for their hospitality and the full financial support to our visit. This report is dedicated to the memory of Lavinia Mazzanti.

CSN IV (INFN national theory group); Department of Physics, Pisa and University of Pisa; INFN, Commissione Conferenze and Sezioni INFN of Firenze and Pisa; all others INFN branches where students came from (Catania, LNS, Napoli, Perugia, Romal, Bologna, Ferrara, Padova, Milano, Genova) and the Departments of Physics of Catania, Lecce, and Padova, Infri, CEA/Saclay, France.

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EuNPC2015: “The Future of Nuclear Physics, Today!”

The KVI-Center for Advanced Radiation Technology (KVI-CART), as part of the University of Groningen, was the host of the 3rd European Nuclear Physics Conference (EuNPC2015) that was held from 31 August until 4 September 2015, in the city of Groningen, the Netherlands. The conference, initiated by the Nuclear Physics division of the European Physical Society, was the successor of earlier events held in Bochum, Germany, in 2009 and in Bucharest, Romania, in 2012. In the same spirit as the earlier editions, EuNPC2015 was the showcase for the most recent developments in the field of nuclear physics covering a wide range of topics from fundamental aspects to instrumentation and applications. This year’s edition was particularly tuned toward the talented young scientists. In this spirit, the invited speakers of the plenary sessions were selected based on their age, talent, impact, and with a right balance in gender by a scientific program committee on the basis of recommendations of an international advisory committee. This resulted in 28 plenary speakers, of which more than half were at young age and about 30% female.

EuNPC2015 was the first conference in the series that started with a one-day master class prior to the conference and dedicated to students and postdocs who are at the start of their scientific career. The lectures (Figure 1) were organized by two role-model physicists in the field of QCD theory, Sinead Ryan, and precision experimental techniques, Klaus Blaum, who both were plenary speakers during the conference as well.

The conference counted more than 200 participants from 37 countries (Figure 2) with about 200 contributions in the form of (invited) oral or poster presentations with a broad spectrum of topics in the field of nuclear and hadron structure and dynamics, nuclear astrophysics, relativistic heavy-ion collisions and QCD phases, fundamental symmetries and interactions, accelerators, and instrumentation, few-body systems, and nuclear physics applications. The event was attended by a large number of researchers at the start of their scientific career together with well-established senior scientists. Such a diversity in experience, nationality, and research expertise made EuNPC2015 an ideal platform for cross fertilization between the disciplines, stimulating new ideas and scientific networks.

The highlights of the scientific part of the conference came from various invited keynote presentations given each morning throughout the week by the most talented physicists predominantly from within the European countries. The most recent developments, results, and future perspectives in the different research areas were presented and discussed creating a lively atmosphere, intriguing researchers outside the field of expertise as well. The afternoons were devoted to parallel and topic-specific sessions oriented toward experts in the respective fields and providing the opportunity for graduate students and young postdocs to present their work. A dedicated session was organized for the “Young Minds” boosting the creativity of students and postdoctoral researchers.

An evening lecture was organized to introduce the medical aspects of proton-therapy in general and the building of the first centers in the Netherlands, one in the city of Groningen, ready for operation in 2017.

The conference closed with an awards ceremony for the best poster presentations, the IBA prize, and dissertation awards. The 2015 IBA Prize for Applied Nuclear Science and Nuclear Methods in Medicine was awarded to Professor Mehran Salehpour in recog-
nition of the considerable impact he has made in the field of biomedical Accelerator Mass Spectrometry by facilitating routine analysis of ultra-small DNA samples in the microgram range. The 2012–2014 Dissertation Awards in Nuclear Physics were given to Christopher Walz, Liam Paul Gaffney, and Jose Manuel Alarcon. The best poster presentation of EuNPC2015 was awarded to Andre Jose Neves Marques de Ornelas.

Acknowledgments
This conference could not have been organized without the generous support of several sponsors from the academic arena to industrial partners. These are, in alphabetic order, Canberra, European Physical Society, Europhysics Letters, Stichting voor Fundamenteel Onderzoek der Materie (FOM), Groningen University Fund (GUF), GSI Helmholtzzentrum fuer Schwerionenforschung GmbH, Institut de Physique Nucleaire (IPN) Orsay, Koninklijke Nederlandse Akademie van Wetenschappen (KNAW), KVI—Center for Advanced Radiation Technology (KVI-CART), NIKHEF, Stichting Physica, and Wiener.

Figure 2. Participants of EuNPC2015.

Hadron 2015: The New Excited States of QCD Generate Excitement

At the conference “Hadron 2015” held in Newport News, Virginia in September 2015 all the talk was about the surprises of the last few years. The new XYZ states, the $P_c$ states, the behavior of transition form-factors, the spectacular progress in calculating scattering “on the lattice,” were among the many new results discussed and reviewed. This diversity displays the richness of the strong interaction exposed by experiment and amplified by theory.

To start at the beginning, hadrons, the particles that experience the strong force, fall into two families: baryons, like the proton, that are fermions, and mesons, like the pion, that are bosons. Many of their static properties reflect their underlying quark degrees of freedom with most baryons pictured as made of three quarks and mesons of a quark and an antiquark. These quarks come in different flavors, six of them in number: up, down, strange, charm, bottom, and top. The discoveries reported at Hadron 2015 lie among the first 5 flavors of quark, the masses of which range from 3 to 5,000 MeV/c².

The strong interaction that binds these quarks is governed by Quantum Chromodynamics (QCD), a theory based on Quantum Electrodynamics, but with three different charges (called colors) and a fundamental invariance under rotations in this color space. The six flavors of current quarks couple universally to gluons, the carriers of the strong force. From this seemingly simple theory, all the remarkable phenomena of the nuclear world emerge: the spectrum, structure, and dynamics of hadrons, and their binding to make nuclei. These properties, not evident in
the Lagrangian, arise from the strong coupling of QCD over distance scales of $10^{-15}$ of a meter. For instance, the near massless $u$ and $d$ current quarks are dressed by gluons to become constituent quarks that have a mass a third of that of a proton. Thus the mass of you and I, and 98% of the visible Universe, is generated by QCD interactions. It is the strength of this coupling over a femtometer that ensures color confinement (the fact that free quarks do not exist, only color neutral hadrons can reach a detector). All of this was reviewed and updated at Hadron 2015.

The biennial Hadron series of conferences started 30 years ago at the University of Maryland. In 2015 the conference returned to the United States with 170 participants coming together at the Marriott Conference Center in Newport News, VA. This is the city that is home to the Thomas Jefferson National Accelerator Facility (JLab), the heart of which is an electron machine just upgraded to 12 GeV. JLab has now started on a decade of study of the structure and spectrum of hadrons, and their strong and electroweak dynamics, in finer detail and with greater precision than ever possible before. It was therefore fitting that the $XVI^{th}$ International Conference on Hadron Spectroscopy, as Hadron 2015 is formally called, took place in Newport News. Indeed, the first physics results from just a few hours of running with the new GlueX detector were presented there.

One-hundred and thirty-five presentations, 20% plenary and 80% in parallel, covered developments across hadron physics. The advances in spectroscopy have been particularly dramatic over the past decade with a wealth of new data. Experiments with polarized beams on polarized targets are filling in critical missing pieces of the jigsaw puzzle of the light flavored hadron spectrum, especially in the excited baryon sector, with results from MAMI@Mainz, ELSA@Bonn, and CLAS6@JLab. But the big surprise is the discovery of an increasing number of puzzling new effects, known collectively as the $XYZ$ states, among the hidden heavy flavor hadrons, from Belle@KEK, BaBar@SLAC, BES in Beijing, and LHCb@CERN. Charm-anticharm mesons seemed all under control. First described by a non-relativistic confining potential, and then with greater sophistication by Effective Field Theory modeling, the spectrum of states below the threshold for producing free charmed mesons looked well understood. But then ten years ago the $X(3872)$ was found by Belle, and confirmed at Fermilab and since in many other experiments. It has a mass well above the threshold for producing ground state charmed and anticharmed mesons, yet the $X(3872)$ lives at least 100 times longer than expected in its decay to $J/\psi$ (the first discovered state of charm-anticharm) and a $\pi\pi$ pair. Indeed, the $X(3872)$ sits almost exactly at the threshold for a ground state charmed meson and an excited anticharmed meson, $D\bar{D}^*$ or $D\bar{D}$*. Is this an accident or dynamics?

Since then more than a dozen unusual states have been found in the charmonium and bottomonium sectors. Are these examples of extraordinary hadrons as described by Robert Jaffe (MIT) in the opening talk at the conference, with more than the minimal number of quarks? The discovery of charged states, like the $Z_c^+$, that decay to the $J/\psi\pi^\pm$ is only possible if the $Z_c$ contains at least four quarks. Indeed no one model, whether multiquark meson, di-hadron molecule, hadroquarkonium or hybrid (of quarks and glue), describes all the extra states. Experiment reveals that some are connected by pion and electromagnetic transitions, but more results will be required to discern the underlying pattern. Indeed, parallel session talks covered how this may need to wait for PANDA@FAIR to map out their higher spin partners, to discriminate models.

The conference hall was packed to hear the $XYZ$s reviewed as well as the latest LHCb results from CERN on $\Lambda_b$ decays to $K^-J/\psi\pi^\pm$. The discovery of a narrow highly excited nucleon, the $P_c(4450)$, in the $J/\psi\bar{p}$ channel points to an underlying pentaquark structure. As presently analyzed its interference with the cross-channel $\bar{K}N$ system of $A$-hyperons requires a broader state, the $P_c(4380)$ too. Are these new states the baryonic analogues of the $XYZ$ mesons? More discoveries surely await, perhaps in each flavor sector.

A path to understanding these structures directly from QCD is provided by lattice calculations. The construct of a 4-dimensional lattice has for a long time made the calculation of hadronic observables feasible. These computations have now reached a maturity so that not just an idealized spectrum of static (everlasting) states can be calculated, but something much closer to the real dynamics of short-lived resonances can be determined from results on scattering in a finite box. The remarkable progress made was reviewed in several inspiring talks. Over the next few years the properties of extraordinary hadrons, $XYZ$, $P_c$ and more, will come into focus. We will then learn what their dominant underlying degrees of freedom are among combinations of quarks and gluons, and color neutral hadrons and which states are generated by coupled channel dynamics. What more states are to be discovered? These questions define the future experimental programs at KEK, BEPC, CERN, FAIR, JLab, and J-PARC too.
Studies of hadron structure are advancing in parallel. An ambitious program at JLab12 and COMPASS will provide multidimensional images of the proton that over the next decade should reveal how quarks and gluons share the momentum, angular momentum, and flavor properties of a proton. Such deeper insights into the workings of QCD will have to wait for Hadron 2017 in Salamanca, and conferences beyond.

Michael Pennington
Associate Director for Theoretical and Computational Physics, Jefferson Lab, Organizer of Hadron 2015

The Twelfth International Topical Meeting on Nuclear Applications of Accelerators (AccApp’15)

AccApp’15 (http://accapp15.org/) convened in Washington, DC on 10–13 November 2015 and was the twelfth in a series of biennial international topical meetings. This nuclear applications conference was organized by the Accelerator Applications Division of the American Nuclear Society (ANS) and was cosponsored by the International Atomic Energy Agency (IAEA). The Topical Meeting was embedded in the 2015 ANS Winter Meeting, which afforded a broader profile for AccApp’15.

The purpose of these topical AccApp meetings is to present a world stage for discussing the multitudinous and multifaceted applications of particle accelerators in nuclear science. These meetings are focused on the production and utilization of accelerator-produced neutrons, photons, electrons, and other particles for scientific and industrial purposes; production or destruction of radionuclides significant for energy, medicine, defense, or other endeavors; homeland security applications; as well as medical imaging, diagnostics, and therapeutic treatment.

One of the great strengths of the AccApp set of meetings is providing an international forum for disseminating knowledge on the nuclear applications of accelerators. The conference provides a platform where nuclear engineers, nuclear physicists, and accelerator physicists can meet and discuss their research. Further, the AccApp meeting series provides a great opportunity for international experts to discuss the latest research and to form collaborations to solve common problems across disciplines.

Applications of particle accelerators cover a broad range of areas, from strategic and applied research, safety and security, environmental and medical applications, materials research and analytical sciences, to radiisotope production and radiation processing. Accelerator-based radiation sources are increasingly important in the understanding of irradiation effects in materials for nuclear reactor technologies and for fusion applications. Neutrons from accelerator-driven systems coupled to subcritical assemblies, moreover, may well be the next source of reliable and safe nuclear energy.

The Topical Meeting featured 11 distinguished plenary speakers and over 125 oral presentations on a wide variety of technical topics in the 26 parallel sessions of this 4-day conference. Supplementing the oral presentations were 33 poster presentations during the evening session. We especially thank Niowave Inc., Muons Inc., and Phoenix Nuclear Labs for covering the refreshments for the Thursday evening get-together and making it altogether even more fun.

The conference spanned three areas: accelerator applications, accelerator technology, and nuclear data analysis techniques and experimental results. The topics [associated Topic Organizers] and subtopics included:

1. Accelerator Facilities (Andrew Hutton [JLab] and Boris...
Sharkov [FAIR]): (1) planned facilities & future possibilities at present facilities, (2) progress at facilities under construction, and (c) management strategies for accelerator facilities.

2. **Accelerator Design & Technology** (Stuart Henderson [ANL] and Paul Collier [CERN]): (1) codes and models, (3) radiation shielding and dosimetry and residual activation, (3) reliability analyses, and (4) prototyping.

3. **Material Research with Accelerators** (Victor Inozemtsev [IAEA] and James Stubbins [UIUC]): (1) new structural materials for fission and fusion reactors, (2) effect of fast heavy ions on materials, (3) investigations of materials for microelectronics with fast particles, and (4) structural and chemical analysis by low-energy nuclear methods at accelerators.

4. **Accelerators in Life Sciences** (Stéphane Lucas [UNamur] and Carol Johnstone [FNAL]): (1) Hadron therapy, (2) radiobiology, (3) BNCT (Boron Neutron Capture Therapy), and (4) biology with synchrotron radiation.

5. **Accelerators for Accelerator-Driven Systems** (Sama Bilbao y Leon [VCU] and Maud Baylac [CNRS-LPSC]): (1) drivers of an experiment, (2) large-scale demonstrators, and (3) industrial types and applications.

6. **High-Power Accelerators and High Power-Spallation Targets** (Eric Pitcher [ESS] and John Galambos [ORNL]): (1) window and beam dump technologies and (2) neutron spallation sources.

7. **Accelerators for Monitoring the Environment** (Aliz Simon [IAEA] and Dick Lanza [MIT]): (1) physical and chemical properties of the environment, (2) history and art, and (3) safety and security.

8. **Industrial Applications** (Bob Hamm [R&M Tech. Enterprise] and Sotirios Charisopoulos [INP]): (1) electron irradiation, (2) X-ray conversion, (3) sterilization, and (4) wear analysis.

9. **Nuclear Data** (Arjan Plompen [EC–JRC] and Mark Chadwick [LANL]): (1) fission and fusion applications, (2) photonuclear cross-sections, (3) nuclear models and applications, and (4) simulating nuclear reactions for calculations.

10. **Accelerator Production of Radioisotopes** (Lia Merminga [TRIUMF] and Dan Dale [ISU]): (1) medical applications and (2) geoscience applications.

We ended the conference with an open forum to discuss the following questions:

1. What did we learn from this conference?
2. What kinds of collaborations can we establish?
3. What science and engineering objectives are crucial in the short term? In the long term?
4. What data do we need to collect towards pursuing these science and engineering objectives?
5. What commercial/clinical objectives are crucial in the short term? In the long term?
6. What experiments, theoretical calculations, and clinical studies are needed in the short term? In the long term?
7. What kinds of funding can we seek toward pursuing the science and engineering objectives covered in the topics?
8. What business partnerships can be established in terms of, for example, Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs?
9. Where do we go from here?

We posed these questions with the purpose of leveraging the multitudinous and multifaceted talents intrinsic to the broad-ranging community of nuclear physicists, nuclear engineers, and accelerator scientists and, further, with the objective of bettering the synergies and opportunities attendant in accelerator applications of nuclear science and engineering.

AccApp’17 will return to the format of a stand-alone topical meeting and will convene in Quebec City, Quebec, Canada from 31 July to 4 August 2017. The general chair will once again be Philip Cole and the general co-chair will be Adriaan Buijs of McMaster University. Should the reader have any questions for this next nuclear science accelerator applications topical meeting, the organizers can be contacted by writing to either colephil@isu.edu or buija@mcmaster.ca.

**Phil Cole**  
*Idaho State University*
The 2016 Tom W. Bonner Prize in Nuclear Physics

The Tom W. Bonner Prize is given each year by the American Physical Society (APS) in recognition of outstanding experimental research in nuclear physics, including the development of methods, techniques, or devices that significantly contribute to the advancement of the field. This year the Prize was awarded to I. Yang Lee of Lawrence Berkeley National Laboratory (LBNL). The citation reads “For seminal contributions to the field of nuclear structure through the development of advanced gamma-ray detectors as realized in the Gammasphere device, and for his pioneering work on gamma-ray energy tracking detectors demonstrated by the Gamma-ray Energy Tracking Array (GRETINA).”

I-Yang Lee received his bachelor’s degree in physics from the National Taiwan University in 1968. He obtained a PhD degree in 1974 from the University of Pittsburgh and was a postdoc at LBNL studying nuclear high-spin properties until 1978 when he moved to Oak Ridge National Laboratory as a research scientist. In 1992 he joined the research staff at LBNL. He has made seminal contributions to nuclear structure through his development of advanced gamma-ray detector systems and his pioneering studies of high-spin phenomena in nuclei. The advanced high-resolution germanium detector arrays developed by Lee have had enormous worldwide impact on nuclear structure, nuclear astrophysics, fundamental symmetry studies and applications in national security and medicine for more than two decades and will provide capabilities at the frontiers of these fields for years to come. The systems with the highest impact in nuclear physics for which Lee provided scientific and technical leadership in the development of enabling technologies and construction are the Gammasphere and GRETINA gamma-ray spectrometers. Supporters of Lee’s nomination for the Bonner Prize credit much of the success of the U.S. program in nuclear structure over the last two decades to the invention and application of these two gamma-ray detector arrays.

By most assessment criteria, Gammasphere is the most successful high-resolution gamma-ray detector array ever built. Its impact on nuclear physics has been incredible, collecting data for over 125 PhD dissertation projects and more than 700 peer-reviewed papers to date. With the recent update to the electronics, Gammasphere will continue to be a powerful instrument in nuclear structure studies in the coming decade. Gamma-ray tracking was the next step beyond Gammasphere in Lee’s vision for advancing gamma-ray spectroscopy. Around 2000 he demonstrated the feasibility of using gamma-ray tracking in highly segmented germanium detectors for high-resolution gamma-ray spectroscopy. This technique and the enabling new technologies were game changing and led to the U.S. funding of GRETINA, which is a smaller version of the 4π gamma-ray energy tracking array (GREATA) envisaged by Lee. GRETINA is fully operational and has already been used in campaigns at both the National Superconducting Cyclotron Laboratory at Michigan State University and ATLAS at Argonne National Laboratory. The scientific results from its initial deployments are now coming out. The early results illustrate the unique capabilities of GRETINA and demonstrate its superior sensitivity in gamma-ray spectroscopy over traditional Compton-suppressed detector arrays.

In summary, I-Yang Lee has led major advances in gamma-ray spectroscopy for over a quarter of a century. His work has enabled a generation of researchers to conduct forefront experiments, and his impact will continue well into the next decade when research at the Facility for Rare Isotope Beams is underway.

Acknowledgment

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Calvin R. Howell
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Meeting of the Antiprotons Community in Vienna

The antiproton physics community of the FAIR project met at the Austrian Academy of Science in Vienna from 30 November–4 December 2015. During these five days, a critical evaluation of the possibilities offered by the FAIR Modularized Start Version (MSV) setup has been made. In the MSV approach, the PANDA (antiproton Annihilation at Darmstadt) collaboration is expecting a reduced luminosity ($\sim 10^{31}$ cm$^{-2}$ s$^{-1}$) at the High Energy Storage Ring (HESR). This is due to the fact that the realization of some components of the full facility has been postponed to a future stage.

All of the international groups that are presently involved in the design and construction of the PANDA sub-detectors gave reports showing the work status and presenting an updated timeline for the realization of their components. Particular care has been put into identifying the elements that are absolutely necessary to obtain outstanding results already in the first two years of the data taking.

This meeting has been following another one, held last June in Uppsala, where the scientific program of the experiment has been deeply evaluated in the light of the competition with the present and future experiments of the hadronic physics sector. Experts from all over the world, both from the experimental and the theoretical sides, gave their contributions to define a series of measurements that would be unique for the PANDA experiment.

In the past, all over the world, antiproton’s facilities demonstrated their capabilities to produce remarkable results. The discovery of the vector bosons mediating the weak interaction, the finding of the top-quark and more recently the production of anti-hydrogen atoms are only few of the cornerstone results obtained by using beams of antiprotons. Starting from the next decade, FAIR will be the unique facility providing antiprotons in a momentum range from 1.5 to 15 GeV/c.

The community of the antiproton users is wide and alive. At present more than 500 researchers from 18 different countries are participating in the project. At the Vienna meeting two new groups have been admitted to the collaboration. They are coming from the Novosibirsk State University and from the Charles University and the Czech Technical University of Prague. This is a clear sign that the interest toward the field is alive and growing.

2015 was crucial for the FAIR project. Due to a cost increase and an unexpected delay in the civil construction, a redefinition of priorities has been asked for. Therefore, all the scientific communities involved have checked their programs in the new framework. A deep analysis of scientific and technical aspects has been performed by the international collaborations in order to refine the objectives and timelines. This phase now is nearing completion and a prompt restart of the FAIR construction will follow shortly.

Paola Gianotti
INFN Laboratori Nazionali di Frascati, Italy

Strengthening Particle Accelerator R&D in Europe: From ESGARD to TIARA

Introduction

Particle accelerators are vital state-of-art instruments both for fundamental and applied research in several areas such as particle physics, nuclear physics, and the generation of intense synchrotron radiation and neutron beams, for the largest ones. They are also widely used for many other purposes, in particular for medical and industrial applications. Altogether, the direct “accelerator market” is very large (more than 4 B€ per year) and has a steadily increasing yearly rate. Thus, it is fair to state that the Research and Development in the field of accelerator sciences and technologies and its applications often leads to in-
novations with strong socioeconomic impacts [1].

This was acknowledged long ago within several research communities [2] but coordinated strategy was missing. Therefore ESGARD (European Steering Group for Accelerator R&D) was set up in 2002 with the mandate to develop a coherent strategy, the main objective of which is to optimize and enhance the outcome of the research and technical developments in the field of Accelerator Science and Technology in Europe. The strategy was developed and implemented with the incentive of the EC Framework Programs FP6, FP7 and now Horizon2020 and several projects have been launched [3]. Altogether, these projects represent a very substantial European effort with a total cost of about 266 M€ with about 82 M€ coming from EC.

From ESGARD to TIARA

However, even though very successful, the experience of ESGARD led to the conclusion that a stronger and wider as well as more formal effort was needed. Indeed,

- The variety of technologies (high and low temperature superconductivity, high vacuum, high power radiofrequency, high precision mechanics, high capacity cryogenics, sophisticated control electronics, fast computing, etc.), which is needed to advance further the field of novel accelerator development, is large and the requirements are diverse in terms of the size and the variety of the technical facilities needed on the one hand and of the skills and experience of the personnel required to operate these facilities on the other hand;
- The realization of particle accelerators has now reached a high level of technological complexity. To enable further advancement of the activity it has therefore become important to organize an effective European network of accelerator development laboratories and facilities, where the equipment and skills taken together provide access to the capacity needed;
- The pioneering ESGARD effort paved the way toward the proposal to establish a European consortium, which will encompass the ESGARD functions and further extend its activities. In particular, it will facilitate and support the exchange of expertise, the setting-up of joint R&D programs, education and training activities in the field of Accelerator Science and Technology in Europe as well as innovation projects jointly with industry.

In 2011, a Preparatory Phase 4-year project, TIARA (Test Infrastructure and Accelerator Research Area), was approved and co-funded by the European Commission. The project investigated and studied many aspects covering both organizational and technical issues. Concerning the technical aspects, four showcase infrastructures were targeted and the following achievements (among others) were carried out:

- Achievement of ultralow (world record) vertical emittance at the Swiss Light Source,
- Construction of multi-MegaWatt RF systems for the Ionisation Cooling Test Facility to enable the infrastructure to operate for the MICE experiment,
- Construction of new C-band structures at SPARC to boost the energy of the infrastructure,
- Design of innovative Multi MW Irradiation Facility for complex target testing as well as the design of a versatile test cryostat for testing fully equipped low beta superconducting cavities.

For the organizational aspects, several developments were made. Among those, some are highlighted below.

- Development of a database of accelerator test infrastructures in Europe followed by the Infrastructure Need and Resource Comparison.
- A plan for the development of a collaborative R&D Program.
- Development of an education and training resource database, a survey of market needs for trained personnel, and recommendations for promoting accelerator science and technology.
- A proposal for establishing T라이 with the aim to develop further particle accelerator science and technology in a sustainable way.

More details concerning TIARA achievements can be found at the website www.eu-tiara.eu.

TIARA Implementation

As mentioned above, the overall aim of TIARA is to facilitate and optimize the R&D effort in the field of accelerator science and technology in Europe in a sustainable manner. This endeavor involves a large number of partners in many European countries, including universities as well as national and international organizations managing large research centers. It also requires getting access to large accelerator R&D infrastructures. The
implementation of a coordination structure formalized by a Memorandum of Understanding (MoU) was deemed useful.

The purpose of the MoU is the establishment of the “Test Infrastructure and Accelerator Research Area (TIARA),” a Consortium of European Research Institutions operating significant R&D Infrastructures in the European Particle Accelerator Research Area, so as to create a dedicated structure to exchange expertise and to facilitate and support the setting-up of joint R&D programs and education and training activities in the field of Accelerator Science and Technology in Europe.

TIARA will carry out activities with the goal of developing and strengthening state-of-the-art research, competitiveness, and innovation in a sustainable way in the field of Accelerator Science and Technologies in Europe. These Activities include but are not limited to the following:

- Provision of scientific and technical guidance and advice for cooperative R&D toward future Accelerator Science and Technology;
- Promotion and facilitation of cooperation concerning accelerator R&D activities for the benefit of the accelerator developers and the accelerator-user communities, so as to contribute to the development of innovation and the state of the art;
- Provision of support to the scientific communities, including those within industry, for accessing equipment, facilities, and accelerator systems at accelerator R&D facilities at a European level;
- Facilitation of the upgrading of existing accelerator R&D facilities and the development of new accelerator R&D infrastructures by the Parties with a view to the efficient realization of joint R&D projects;
- Facilitation of applications by the Parties for grants or external funding from the European Commission and other international organizations.

Organization

TIARA’s management bodies are the Collaboration Council and the Executive Office led by the TIARA coordinator. The Collaboration Council represents the Consortium Partners, and has elected José-Manuel Perez, from CIEMAT, as its chair. The Executive Office ensures the execution of the overall TIARA activities as decided by the Collaboration Council and is led by Roy Aleksan, from CEA. Following the signature of the MoU by all its members, TIARA has been officially established as of 1 July 2015.

TIARA Founding Members at the Collaboration Council

The consortium includes 11 participants embracing 11 countries:

- Commissariat à l’Energie Atomique et aux Energies Alternatives (CEA), France, represented by Pierre Vedrine.
- European Organization for Nuclear Research (CERN), International Organization, represented by Frederick Bordry.
- Centre National de la Recherche Scientifique (CNRS), France, represented by Bernard Launé.
- Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain, represented by José-Manuel Perez.
- Stiftung Deutsches Elektronen-Synchrotron (DESY), Germany, represented by Reinhard Brinkmann.
- Helmholtzzentrum für Schwerionenforschung GmbH (GSI), Germany, represented by Oliver Kester.
- Istituto Nazionale di Fisica Nucleare (INFN), Italy, represented by Eugenio Nappi.
- Paul Scherrer Institut Villigen (PSI), Switzerland, represented by Leonid Rivkin.
- Science and Technology Facilities Council (STFC), United Kingdom, represented by Graham Blair.
- Uppsala Universitet (UU), Sweden, represented by Tord Ekelof, (also representing Universities of Aarhus (AU) in Denmark, Helsinki (HU) and Jyväskylä (JYU) in Finland, Oslo (UIO) in Norway, and Lund (LU) and Stockholm (SU) in Sweden).
- The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences (IFJ PAN), Poland, represented by Marek Jezabek, (also representing the University of Science and Technology (AGH) in Krakow, the Cracow University of Technology (CUT), the Technical University of Lodz (TUL), the Andrzej Soltan Institute (IPJ) in Swierk, the Warsaw University of Technology (WUT) and the Wroclaw University of Technology (PWR)).

One should note that the TIARA membership may be enlarged and procedures have been defined for including new members or observers.
For more information on TIARA, the TIARA coordinator Roy Aleksan or the chair of the Collaboration Council José-Manuel Perez may be contacted.

References
1. See, for example, the site Accelerator for Society at http://www.accelerators-for-society.org/index.php
3. These projects were in FP6 (CARE, EuroTeV, Eurisol, and Euroleap), in FP7 (EuCARD, EuCARD2, EUROnu, HiLumi, SLHC-PP, ILC-Higrade, and TIARA) and in H2020 (EuroCirCol and EuPRAXIA).

ROY ALEKSAN
CEA/Saclay, DSM/DRF/IRFU, Gif sur Yvette, France

Filler
In Memoriam: Janusz Wilczyński (1938–2015)

Born on 27 August 1938 in Gniezno (an old Polish town, the first capital of Poland), Janusz graduated in 1961 from the Mathematics, Physics and Chemistry Department of the Jagiellonian University in Kraków. The topic of his diploma was experimental nuclear physics. Directly after this, he started work in the same department of the university under the leadership of Professors Henryk Niewodniczański and Adam Strzałkowski.

The years 1963–1966 and 1967–1972 he spent at the Laboratory of Nuclear Reactions (in the group of Professor V. V. Volkov) of the Joint Institute of Nuclear Research (JINR) in Dubna. These were the years of early, pioneering work on heavy-ion reactions. Janusz enthusiastically joined these studies.

Very characteristic of him was hard, ambitious, original, and ingenious work on the interpretation of the results obtained in experiments. This quite often resulted in interesting and important discoveries. For example, analyzing the limitations on the cross-section of the compound nucleus, he introduced the notion of the “contact force,” that is, the attractive nuclear force when two nuclei come into contact via their surfaces. The value of this force, estimated by him with the use of the liquid-drop model, gave very good results for the critical angular momentum. The notion of the contact force was generalized by W. J. Świątecki and co-workers in Berkeley to the proximity force, which is still used in nuclear physics.

Also very original and ingenious was his interpretation of deep inelastic reactions with the use of the classical deflection function. Here, the two-dimensional plot, known in the literature as “Wilczyński’s plot,” proved to be very useful.

In 1966 he started to work at the Institute of Nuclear Physics in Kraków. A year later, in 1967, Janusz defended his PhD work at the Jagiellonian University. In the same year he married Krystyna Siwek-Diament. In 1973, Krystyna changed the topic of her scientific interests and joined Janusz in his work. In 1980, Janusz moved from Kraków to Warsaw, to work in the Sołtan Institute for Nuclear Studies in Świerk.

Throughout his scientific life, Janusz often visited institutes where experiments on heavy-ion reactions were carried out, participated in these experiments and worked on the interpretation of the results, mostly after his return home. He participated in experiments at JINR-Dubna (Russia), at the Niels Bohr Institute in Copenhagen (Denmark), at the Institut de Physique Nucleaire in Orsay (France), at the Kernphysich Versneller Instituut in Groningen (Holland), at the National Superconducting Cyclotron Laboratory in East Lansing (USA), at the Lawrence Berkeley National Laboratory (USA) and at the INFN di Catania (Italy; Figure 1, taken in 2010).

During these visits he participated in the discovery of deep inelastic reactions and applied, together with his co-workers, these reactions to produce about 30 new exotic nuclides (around argon) with large neutron excess. He also participated in the discovery of the non-complete fusion reaction, in systematic studies of this reaction and the formulation of the quantitative model of the two-body heavy-ion reaction (the so-called sum-rule model) as well as other studies.

Janusz Wilczyński received a number of awards and honors, among them: the individual Award of the Polish Physical Society (1976), individual 2nd Class Award of the Polish State Council for the Use of Nuclear Energy (1978), Golden Cross of Merit (1989), and the Knight’s Cross of the Order Polonia Restituta (2015).

He passed away on 22 October 2015 in Warsaw. Up to the last days he preserved a skilful mind and was working together with his wife Krystyna and his PhD student on their last publication.

Janusz Wilczyński

AdAm Sobiczewski
National Centre for Nuclear Research, Warsaw, Poland
Heinz Oberhummer was an Austrian nuclear physicist with extraordinary interests. As a child he grew up in a remote mountainous area not far from Salzburg. There he gazed at the stars at night and hoped to receive a star map as a Christmas present. When he did not get it, he was very disappointed. At the age of 14 he went by boat to New York, hitchhiked about 8,000 km to San Francisco, and spent two years at the High School in Los Gatos, Santa Clara County. After the Californian experience he returned to Austria and finished Gymnasium in Salzburg. Then he studied Physics and Mathematics at the University of Graz, where he received his PhD in 1970. Shortly thereafter he joined the Atominstitut of the University of Technology in Vienna (TU Wien), where he became a professor of Theoretical Physics. Remembering his admiration of the starry sky during his childhood, Oberhummer’s main research focused on nuclear astrophysics. In 1990 he organized the first International Symposium on Nuclei in the Cosmos in the historic spa town of Baden near Vienna. This symposium developed into a bi-annual meeting of nuclear astrophysicists around the world, and continues till today. The 14th International Symposium on Nuclei in the Cosmos will take place in Niigata, Japan, 19–24 June 2016.

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His deep interest in the basics of stellar nucleosynthesis led Oberhummer to a unique investigation about the production of $^{12}$C in red giant stars. He found that a minimal variation of the underlying forces could have reduced the triple-alpha process and thus the stellar production of $^{12}$C to a level where no carbon-based life in the universe is possible [Science 289 (2000) 88]. As a consequence of this seminal work he was invited in 2001 to a special gathering of astrophysicists and cosmologists at the University of Cambridge, with Stephen Hawking as one of the participants (Figure 1).

Besides his research in nuclear astrophysics, Oberhummer had a keen interest in communicating science to the public. In 2007, after his retirement as a professor of Theoretical Physics, he formed a comedy show together with an experimental physicist. This highly successful show, called “Science Busters,” was moderated by a professional comedian and entertained people with humorous discussions about physical problems. The group appeared on stage and TV, and published several popular books on science.

Heinz Oberhummer passed away on 24 November 2015, after a brief bout with pneumonia. As a true humanist, he believed that service to mankind is more important than service to a church. He decided that his body will be used for science after his death.

Walter Kutschera
Faculty of Physics, University of Vienna

Figure 1. With Stephen Hawking in Cambridge, 2001.
2016

March 6–11
Kanazawa, Japan. 12th International Conference on Low Energy Antiproton Physics (LEAP2016)
http://leap2016.riken.jp/

March 21–23
GANIL Caen, France. Workshop EMILIE
https://indico.in2p3.fr/event/12466/overview

April 28–30
Hatay, Turkey. International Conference on Theoretical and Experimental Studies in Nuclear Applications and Technology (TENAT 2016)
http://www.tesnat.org/

May 8–13
Busan, Korea. International Particle Accelerator Conference, IPAC’16
http://www.ipac16.org/

May 9–12
GANIL Caen, France. IWM-EC 2016 “International Workshop on Multi facets of EoS and Clustering”
http://pro.ganil-spiral2.eu/events/workshops/iwm/2016

May 23–27
Napoli, Italy. 11th International Conference on Clustering Aspects of Nuclear Reactions and Dynamics
https://agenda.infn.it/conferenceDisplay.py?ovw=True&confId=9919

May 23–27
Niš, Serbia. Fourth International Conference on Radiation and Applications in Various Fields of Research (RAD 2016)
http://www.rad-conference.org/

May 28–29
Istanbul, Turkey. International Workshop on Theoretical and Applied Physics
http://conf-scoop.org/science/iwtap/

June 2–7
Kraków, Poland. 14th International Workshop on Meson Production, Properties and Interaction
MESON2016
http://meson.if.uj.edu.pl/

June 19–24
Niigata, Japan. 14th International Symposium on Nuclei in the Cosmos (NIC-XIV)
http://nic2016.jp/

June 26–July 2
Rila, Bulgaria. 35th International Workshop on Nuclear Theory
IWTN’35
http://ntl.inrne.bas.bg/workshop/2016/

July 3–8
Malmö, Sweden. 57th Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams HB2016
https://hb2016.esss.se/

July 11–15
Halifax, Canada. DREB 2016
http://conferences.triumf.ca/DREB2016/index.html

July 24–29
Knoxville, TN, USA. Nuclear Structure 2016 (NS2016)
https://public.ornl.gov/conferences/ns2016/

August 8–12
Aarhus, Denmark. 23rd European Conference on Few-Body Problems in Physics
http://owww.phys.au.dk/~fedorov/EFB23/

August 28–September 4
Zakopane, Poland. Zakopane Conference on Nuclear Physics 2016
http://zakopane2016.ifj.edu.pl/

August 29–September 2
Helsinki, Finland. 9th International Conference on Nuclear and Radiochemistry (NRC9)
http://nrc9.it.helsinki.fi/

September 4–10
Kazan, Russia. VIII International Symposium on Exotic Nuclei EXON2016
http://exon2016.jinr.ru/

September 11–16

September 11–16

September 11–16
Bruges, Belgium. International Conference on Nuclear Data for Science and Technology ND2016
http://www.nd2016.eu/

September 11–16
Zürich, Switzerland. 21st International Conference on Cyclotrons and their Applications
http://www.cyc2016.ch/

October 30–November 4
Fort Worth, Texas, USA. 24th Conference on the Application of Accelerators in Research and Industry CAARI 2016
http://www.caari.com/

2017

January 11–13
GSI Darmstadt, Germany. NuPECC Long Range Plan Town Meeting
http://www.nupecc.org/index.php?display=misc/meetings

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