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Cover Illustration: RIKEN Nishina Center, RIBF Building—see article on page 5.

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ENSAR, a Nuclear Science Project for European Research Area

During the period from September 2010 to December 2014, the European project European Nuclear Science and Applications Research (ENSAR) coordinated research activities of the Nuclear Physics community performing research in three major subfields: Nuclear Structure, Nuclear Astrophysics, and Nuclear Applications.

ENSAR has been an “integrated activity” funded for 8 M€ by the European Commission within the Seventh Framework Programme (FP7), meaning a project offering support for networking activities, joint research activities and transnational access to major infrastructures in Europe. Therefore, it has profited the community at large, much beyond the thirty official beneficiary institutions that actively participated in this project.

ENSAR’s top-priority objectives were:

• to ensure that the European communities of Nuclear Structure, Nuclear Astrophysics and Applications of Nuclear Science concentrate on the most essential Joint Research Activities, for further improvements and extensions of the infrastructure facilities;
• to focus on activities that are in general relevant to more than one facility;
• to benefit from the R&D potential of the European University groups, often in leading positions;
• to promote the most needed R&D, as identified by the community, using as main criterion scientific and technical promise, combined with a rather rapid applicability; and last but not least,
• to stimulate multidisciplinary and application-oriented research.

To pursue its objectives ENSAR comprised 20 work packages: 6 Networking Activities (NAs) including that of the management of the project, FISCO; 7 Joint Research Activities (JRAs); and 7 Transnational Access Activities (TNAs). Among all successful results that came out of ENSAR, we may distinguish some main features:

• ENSAR core aim was to provide access to seven of the complementary world-class large-scale facilities: GANIL (F), GSI (D), joint LNL-LNS (I), JYFL (FI), KVI (NL), CERN-ISOLDE (CH) and ALTO (F). These facilities have provided stable and radioactive ion beams of excellent qualities ranging in energies from tens of keV/u to a few GeV/u for European scientists to perform their research projects.
• A large part of the ENSAR project was dedicated to R&D in order to improve functionality of and access to the European research infrastructures: important progress has been achieved on ECR sources, actinide targets, ion-beam production, detectors, simulations, instrumentation for rare nuclear processes and theoretical models.
• Numerous workshops, schools and town meetings were organized on essential topics for the community such as physics with high-intensity stable beams—ECOS, EURISOL techniques and methods, nuclear astrophysics, gamma detectors and applications of nuclear science. Such events are especially important for young researchers.

It is also interesting to note some significant figures connected with ENSAR during its running period:

• Around 40 persons were hired specifically for ENSAR activities.
• About 1800 users were supported during their experiments at ENSAR infrastructures, which corresponds to more than 34,000 hours of beam delivered.
• More than 200 articles were published in high-impact peer-reviewed journals.
• About 100 scientific events, for scientists or civil society, were organized by the ENSAR participating institutions to present and discuss Nuclear Physics and its applications.

With all these successes, ENSAR fulfilled completely the foreseen deliverables promised in its application to the European Commission. But such a project is much more than a contract with the European Commission. It has provided important and essential support to the Nuclear Physics community, especially at a
time of tight financial budgets. For instance, ENSAR was by far the main funding for scientists from European countries with financial difficulties to perform experiments at the ENSAR research infrastructures from 2010 to 2014. ENSAR was also of great help to young researchers who could join experiments and/or propose their own, thus gaining in knowledge and experience. Some researchers from other fields, such as biology and medicine, could perform experiments with ion beams for the first time, thanks to ENSAR support.

We can conclude that ENSAR was a very important project for nuclear science and its applications in the European Research Area, through its many activities and large offer of services.

The support for the nuclear science research infrastructures and for their users’ communities with benefit to European society at large will continue in the coming four years through the recently EU-funded ENSAR2 project.

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A Dream Come True: Our 80-Plus-Year History with Nine Cyclotrons at RIKEN

Introduction: History of Cyclotrons in RIKEN

At RIKEN, there is a long and unique tradition: whenever a new cyclotron is completed, a memorial photo is taken with everybody involved with the construction project on top of it. Figures 1a–d show a part of our history. In 1931, Dr. Yoshio Nishina became a Chief Scientist of RIKEN. Our research center was named after him since he is indeed the father of nuclear physics in Japan. He was, at the same time, a theorist, an experimentalist, an accelerator-builder, and a promoter of nuclear application.

In 1937, Nishina built the first Japanese cyclotron based on the extensive knowledge learned from Ernest Lawrence. Nishina’s second cyclotron, one of the world’s largest accelerators at the time shown in Figure 1a, was completed in 1944. This cyclotron fated for a tragic end was destroyed.

Figure 1. (a) The RIKEN Cyclotron #2, completed in 1944, presently at the bottom of Tokyo Bay. Yoshio Nishina is at the center. (b) The RIKEN Cyclotron #4, completed in 1966, presently exhibited as the monument in the RIKEN Wako Campus. Hiroo Kumaagai is at the center. (c) The RIKEN cyclotron #5, in operation since 1986. Hiromichi Kamitsubo is at the center. (d) The RIKEN cyclotron #9 (SRC: Superconducting Ring Cyclotron) in operation since December 2006. Yasushige Yano is at the center.
and abandoned into Tokyo Bay by the U.S. Army, just after World War II. In 1952, RIKEN’s third cyclotron was rebuilt from the first one. The fourth cyclotron, the first heavy-ion cyclotron in Japan (Figure 1b) was built in 1966, as a symbol of the rebirth of Japanese nuclear science. These four cyclotrons are history.

Today, the RIKEN RIBF delivers the world’s strongest heavy-ion beam using 5 cyclotrons from the 5th to the 9th. The 5th (Figure 1c) and 6th were built in the 1980s. By using them as an injector, we completed the 7th, 8th, and 9th cyclotrons in 2006. Today, the heart and soul of the Nishina Center is the 9th cyclotron (Figure 1d), Super Conducting RING Cyclotron (SRC), which operates with Big-RIPS, the super conducting RI separator. These accelerators are located 23 m underground of the RIBF building. You can see from the number of people in Figure 1d how big SRC is. Weighing 8,300 tons in total, it is as heavy as the Eiffel Tower.

The RIKEN Radioactive Isotope Beam Factory (RIBF) delivers the uranium-beam with the world’s highest intensity, recording 40 pnA in April 2015. With the use of this powerful beam, many experiments are being performed by diverse groups of researchers from all over the world who are producing many new data that were just a dream only several years ago. The impossible dream of Yoshio Nishina has finally come true.

**RIBF Accelerator Complex**

The schematic view of RIBF is shown in Figure 2. A typical accelerator operation uses the four cyclotrons, RRC (5th), fRC (7th), IRC (8th), and SRC (9th) in cascade, with one of the linear accelerators (RILAC1 or RILAC2) as the injector. The RIKEN Ring Cyclotron (RRC) can accept ions either from RILAC1, RILAC2, or the AVF cyclotron (6th). While RILAC2 is specially designed to accelerate only heavy nuclei larger than xenon and AVF only light nuclei, RILAC1 is versatile. In principle, we can operate three experiments simultaneously by using RILAC1 for super-heavy-element search, RILAC2 with four cyclotrons in cascade to deliver 345 MeV/u uranium to BigRIPS, and the AVF cyclotron to deliver 5 MeV/u light ions to the CNS Radio Isotope beam (CRIB) facility.

Figure 3 shows our records of beam intensities with the bullets and the outlook with the dashed line. For lighter ions, we have almost reached our design goal of 1,000 pnA. This corresponds to 6.2 kW of beam power

![Figure 2. Bird’s eye view of the RIKEN RI Beam Factory. Two linear accelerators (RILAC and RILAC2) and five cyclotrons (AVF, RRC, fRC, IRC and SRC) are shown with the experimental facilities.](image)

**Figure 3. The history of beam intensity improvements.** For light and medium nuclei, we have almost reached the facility’s radiological limit of 1,000 pnA. For heavy nuclei such as Xe or U, the design goal is 100 pnA. Achieved beam intensities are shown with bullets and the prospects with the dashed line.
in the case of oxygen. For heavier nuclei like uranium, we faced many difficulties to crank up the intensity. For example, in order to ensure stable operation, we had to develop a gas-filled charge stripper to replace the originally planned disk-type charge stripper. In addition, we had to modify fRC to accept lower charge states, such as 65+. The present beam performances can be found in Ref. [1]. We have accelerated $^{48}$Ca with 415 pnA and $^{70}$Zn with 100 pnA. For uranium, we have achieved 40 pnA, and 342 pnA for 100 pnA. For uranium, we have $^{78}$Kr. Our goal for the uranium beam is 100 pnA, which we expect to reach in around 2020, the worldwide research capability to promote RI science will be dramatically improved by then. We at RIKEN must upgrade our facility in the next five to ten years to remain competitive. To go beyond 100 pnA of uranium beam, our plan is to change fRC to a super conducting cyclotron and to build a superconducting LINAC. The expected increase in beam intensity is almost 100 times, reaching five to ten thousands particle nano amps.

Although the RIKEN RIBF is the world’s leading RI beam facility, new facilities are currently being constructed around the world ready to become strong competitions or may even surpass the performance of RIBF. Table 1 summarizes the worldwide situation, with a list of $^{138}$Sn intensities as a typical performance measure of the facilities. In reality, there are many more details to be considered for the comparison, but a very rough comparison to the present RIBF shows that the upcoming projectile-fragmentation facility (PF) will be able to deliver RIs by a factor of ten to hundred times more, the new ISOL facilities by thousand times more, and in the next 20 or more years, the Super ISOLs by 10,000 times more.

With the facilities under construction expected to become operational around 2020, the worldwide research capability to promote RI science will be dramatically improved by then. We at RIKEN must upgrade our facility in the next five to ten years to remain competitive. To go beyond 100 pnA of uranium beam, our plan is to change fRC to a super conducting cyclotron and to build a superconducting LINAC. The expected increase in beam intensity is almost 100 times, reaching five to ten thousands particle nano amps.

Table 1. RIKEN RIBF is compared with projectile-fragmentation (PF) facilities and ISOL facilities under construction (Super ISOLs are still in the planning stage). Expected intensities of $^{138}$Sn are listed below. These values are very rough estimates calculated by the author; readers should refer to the latest status reports of these facilities.

<table>
<thead>
<tr>
<th>Category</th>
<th>Facility country</th>
<th>Beam</th>
<th>Power (kW)</th>
<th>Fission/s or beam current</th>
<th>Type</th>
<th>$^{138}$Sn/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF Running</td>
<td>RIBF Japan</td>
<td>$^{48}$Ca 345 MeV</td>
<td>4</td>
<td>100 pnA</td>
<td>SC cyclotron</td>
<td>$3 \times 10^8$</td>
</tr>
<tr>
<td>PF Coming</td>
<td>FRIB USA</td>
<td>$^{48}$Ca 200 MeV</td>
<td>400</td>
<td>8500 pnA</td>
<td>SC Linac</td>
<td>$10^4 \sim 10^6$</td>
</tr>
<tr>
<td></td>
<td>RISP Korea</td>
<td>$^{70}$Zn 200 MeV</td>
<td>400</td>
<td>8000 pnA</td>
<td>SC Linac</td>
<td>$10^4 \sim 10^6$</td>
</tr>
<tr>
<td></td>
<td>FAIR Germany</td>
<td>$^{48}$Ca 1500 MeV</td>
<td>10</td>
<td>500 pnA</td>
<td>Synchrotron</td>
<td>$10^3 \sim 10^5$</td>
</tr>
<tr>
<td>ISOL Coming</td>
<td>ARIEL Canada</td>
<td>$^{48}$Ca 50 MeV</td>
<td>-100</td>
<td>$1 \times 10^4$</td>
<td>SC Linac</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>HE-ISOLDE CERN</td>
<td>$^{48}$Ca 1 GeV</td>
<td>2</td>
<td>$5 \times 10^4$</td>
<td>SC Linac</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>SPIRAL2 France</td>
<td>$^{48}$Ca 40 MeV</td>
<td>200</td>
<td>$1 \times 10^4$</td>
<td>Cyclotron</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>SPEX Italy</td>
<td>$^{48}$Ca 0.2 mA</td>
<td>8</td>
<td>$1 \times 10^5$</td>
<td>Cyclotron</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>Super ISOL Future</td>
<td>EURISOL EU</td>
<td>$^{48}$Ca 5 GeV</td>
<td>4 MW</td>
<td>$1 \times 10^5$</td>
<td>SC Linac</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>CARIB China</td>
<td>$^{48}$Ca 5000 mA</td>
<td>6 MW</td>
<td>$2 \times 10^5$</td>
<td>—</td>
<td>$5 \times 10^5$</td>
</tr>
</tbody>
</table>

**RIBF Experimental Facility**

**BigRIPS (RIKEN Projectile Fragment Separator)**

The beam from SRC goes into the RII separator BigRIPS. The BigRIPS separator is composed of fourteen superconducting triplet quadrupoles with large apertures ($\pm 40$ mr horizontally and $\pm 50$ mr vertically) and six room-temperature dipoles with a bending angle of 30 degrees. The maximum magnetic rigidity of the BigRIPS separator is as large as 9.5 Tm and 8.8 Tm in the first and the second stage, respectively. The total length of the BigRIPS separator is 78.2 m. As of the summer 2014, 120 new isotopes and 43 new isomers were discovered with BigRIPS. Although many of them are yet to be published, available intensities of these isotopes are known so users can plan their experiments. Up to now, 308 isotopes have been delivered to 78 different experiments. Figure 4 shows the bird-eye view of BigRIPS and its discovery record.

RI beams purified in BigRIPS go to either of the three beam-lines, that is, Zero Degree Spectrometer line, SAMURAI multi-particle spectrometer line, or SHARAQ high resolution line, as shown in Figure 2.

**Zero Degree Spectrometer**

At the end of the Zero Degree Spectrometer, the Euroball, known as the RISING detector at GSI, is now being operated by the EURICA (Euro-Riken Cluster Array) collaboration [2]. A hundred days of beam time were approved by the RIBF Program Advisory Committee (PAC), 80% of which have been executed in the so-called EURICA campaign. Figure 5 shows the nuclei measured with EURICA at RIBF. Published results are updated in their home page [2]. The powerfulness of EURICA at RIBF can be seen in the reference [3], where the $\beta$-decay half-lives of 110 neutron-rich...
isotopes of the elements from $^{37}$Rb to $^{60}$Sn were measured. The new data have direct implications for r-process calculations and reinforce the notion that the second (A $\approx$ 130) and the rare-earth-element (A $\approx$ 160) abundance peaks may result from the freeze-out of an $(\alpha,\gamma) \leftrightarrow (\gamma,\alpha)$ equilibrium.

Another important discovery is the one highlighted by the “Nature” article describing that the neutron number 34 is a new magic number in Ca isotopes [4], which was confirmed by the measurement of the 2$^+$ states of $^{54}$Ca as shown in Figure 6. To perform further systematic measurements of 2$^+$ states in the region of the r-process path, we have started the SEASTAR project (Shell Evolution and Search for Two-plus energies At RIBF). Unlike other experiments, a single SEASTAR proposal covers a variety of nuclei in many regions of the nuclear chart, and was approved by PAC within the new framework called “Proposal for Scientific Program.” SEASTAR uses the DALI-2, NaI gamma ray detector, combined together with the MINOS setup. MINOS is a Saclay-made thick liquid hydrogen target combined with a state-of-the-art recoil tracker. Interaction points are measured with MINOS and a precise Doppler correction can be performed to the de-excited gamma rays. The SEASTAR collaboration had the first run and $^{58}$Fe excited peaks were newly observed together with many other new peaks for a variety of nuclei (Figure 7).

**SAMURAI (Superconducting Analyzer for Multi-particle from Radio Isotope Beam)**

Just next to the Zero Degree Spectrometer, the SAMURAI spectrometer is in operation. SAMURAI is characterized by its magnet with the bending power of 7 Tm. The special feature of this gigantic spectrometer is to perform kinematically complete measurements by detecting multiple particles in coincidence (i.e., to perform invariant mass spectroscopy and missing mass spectroscopy). The entire program can be seen in their collaboration page [5].

Figure 8 shows some examples of exclusive coulomb breakup of a borromean halo nucleus $^{22}$C. Using the $^{48}$C primary beam, they have done the measurements with 10 pps of $^{22}$C beam. Similar measurements were also performed for $^{26}$O. For both $^{21}$C and $^{26}$O, new excited states were found [6].

Another major interest for the SAMURAI spectrometer is “Equation of State.” When we talk about the nuclear phase diagram, it is usually done two dimensionally; temperature and density. Another important axis is isospin asymmetry $\delta$, which must be very asymmetric in a neutron star. One of the possible approaches toward the large $\delta$ region is to use neutron-rich ion beams. The SnRIT collaboration has introduced a large Time Projection Chamber in SAMURAI as shown.
in Figure 9, aiming to reach $\delta = 0.25$ (say 25% more neutrons than protons) by colliding two Sn isotopes ($^{132}$Sn on $^{124}$Sn). The EOS should change drastically even with this $\delta$.

**SHARAQ (Spectroscopy with High-resolution Analyzer and Radio Active Quantum beams) and Rare-RI Ring**

SHARAQ is a high resolution spectrometer (with an achieved resolution of 8,100) built by the Center of Nuclear Study, the University of Tokyo. Such high resolution is achieved by using a dispersion matching technique, and the spectrometer is optimized for exothermic charge exchange reactions. One of the highlights of the experiments using SHARAQ is a tetra neutron search with double-charge-exchange $^4$He ($^8$He, $^9$Be)$^4n$ reaction. The results will soon be available, so stay tuned for the update in the homepage [7].

Using the SHARAQ spectrometer as a beam-line, RIs can be transferred to the Rare RI Ring (Figures 2 and 10). This ring can be considered as a 24-sector ring cyclotron without acceleration cavities due to its most important characteristic, the isochronous operation. When an RI of interest is detected at BigRIPS, a trigger signal is transferred to the Rare RI Ring to kick the RI into the closed orbit. The ring can accept RIs with the momentum acceptance of 0.5% and the isochronicity at the level of $10^{-6}$. This enables us to provide mass measurements for $r$-process nuclei with very low production rate ($\sim 1$/day) and short life time ($\sim 50$ ms).

The ring was completed very recently and four seconds of revolution of injected particles were already observed. Real RI injection will be done within a year.

**Facilities Under Development**

**SCRIT (self-confining RI target).**

Located on the upper floor, separated from other experimental facilities sits SCRIT as shown in Figure 11. Electrons of 350 MeV stored in a race track type storage ring are used for electron scattering as well as to confine RIs. Ions are self-confined around the electron beam and in the electric mirror potential along the beam. Presently, we are preparing an ISOL driven by the same electron source and have observed isotopes of Sn and Xe successfully. We are making progress on the production rate of these isotopes to realize the first electron scattering experiment on a rare radio isotope.

**SlowRI (slowed-down RI beam).**

SlowRI provides slow and cold RI
beams for users of trap, MRTOF, β-NMR, and so on. There are two kinds of devices that slow down the produced RIs. One is called PALIS (Parasitic Laser Ion-Source) located besides the BigRIPS beam-line, and accepts unused beam fragments in the gas catcher cells. Laser ionization technique is adopted for the selection of the RIs of interest. This is the only device that can run parasitically with other experiments. The other is located at the exit of BigRIPS, with the RF carpet technology to collect and slow down RIs. Figure 12 shows the layout of SlowRI. The day-1 experiment will be performed in 2015.

RILAC (Riken Linear Accelerator) and GARIS (Gas-Filled Recoil Ion Spectrometer)

On August 12, 2012, we observed the third decay chain of element 113 [8] in the GARIS spectrometer using the RILAC beam with \(^{209}\text{B} (^{70}\text{Zn}, \text{1}_n)^{278}\text{Lv}\) reaction showing beautiful decay chain with six consecutive alpha decays (Figure 13). After the observation, we terminated the experiment to synthesize element 113, and started to prepare for hot fusion experiments. We had 10 days of beam time in December 2013 to deliver 800 \(\mu\text{A}\) of 262-MeV \(^{48}\text{Ca}\) beam on the \(^{248}\text{Cm}\) target to create compound nucleus of \(^{296}\text{Lv}\). Kosuke Morita and his team successfully observed two events of \(3\text{n}(^{293}\text{Lv})\) and three events of \(4\text{n}(^{292}\text{Lv})\) channels. Although the number of events is limited, the cross-section and the lifetime of these data are totally consistent with the previously confirmed data in FLNA.

The shift from cold fusion to hot fusion experiments enabled us to promote more chemistry experiments for super heavy elements. Very recently, the team headed by Dullman succeeded in observing the chemical property of Sg (Co)\(_6\), which has led to one to conclude that seaborgium is the Group 6 element [9]. Note that such an experiment can only be performed.

![Figure 7](image1.jpg)  
**Figure 7.** (Left) MINOS setup with the gamma detector DALI-2. (Right) Gamma ray energies before and after the Doppler correction as the function of reaction points are shown for \(^{68}\text{Fe}\) nuclei produced in \(^{69}\text{Cu}(p,2p)^{68}\text{Fe}\) reaction.

![Figure 8](image2.jpg)  
**Figure 8.** (Left) The break-up spectrum of \(^{21}\text{C}\) obtained with SAMURAI. (Middle) The quality of isotope separation for oxygen. (Right) The break-up spectrum of \(^{26}\text{O}\).
Summary

The combined operation of SRC and BigRIPS at RIKEN RI Beam Factory has been in effect since 2007. SRC has been fully operational since 2010, with the only temporary break in 2011 due to the Great East Japan earthquake. Up to now, the number of days approved for experiments by PAC is close to 500 days of which about 200 days are executed and 300 days are in the backlog. We are now aiming to deliver 100 user-beam-days per year. We also expect to have a 345 MeV/A uranium beam that will reach 100 pnA (2.5 times to go) within a year or two. Major characteristics of ~100 key unstable nuclei close to R-process path and/or vicinity of the magic numbers will be measured in order to solve the mystery of element genesis and to establish the ultimate picture of nucleus.

The RIKEN RIBF is in its harvest time, running the world’s most intense RI beam. Most of the experimental facilities are in place, with many experimental contributions from around the world. Although the current budget

Figure 9. The cross-section view of SAMURAI and TPC. A simulated event of $^{132}$Sn + $^{124}$Sn collision is also shown.

Figure 10. Rare RI Ring is often abbreviated as the R3 ring. The magnets were recycled from TURN-II at the Institute of Nuclear Study, the University of Tokyo.

Figure 11. Schematic view of SCRIT where the acronyms are as follows: RTM (racetrack microtone), eBT (electron beam transport line), IBT (ion beam transport line), ERIS (electron induced RI separator on-line), and SR2 (scrit-equipped Riken storage ring).
situation in Japan is still very tight due to the aftermath of the Great Tohoku Earthquake, we will continue to try to operate RIBF as much as we can. You will never be disappointed with the RIBF beam quality. We are ready to provide you with the world’s best RI beams.

References

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A New Experiment to Search for Neutron–Antineutron Oscillations at the European Spallation Source

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Introduction
The discovery of neutron–antineutron ($n\bar{n}$) oscillations could answer crucial questions of particle physics and cosmology. Why do we observe more matter than antimatter in the Universe? At what energy scales do new phenomena occur? Another related intriguing subject potentially accessible with this process concerns the mechanism responsible for neutrino mass generation. The construction of the European Spallation Source (ESS) offers a remarkable opportunity to perform a sensitive experiment dedicated to the search of such oscillations. Indeed, the high neutron flux expected at this facility, combined with the important progress made in neutron optics, will enable this experiment to gather all the necessary conditions for establishing possible new physics coming from energy scales beyond the reach of colliders that can have a strong impact on our understanding of the Universe.

The European Spallation Source
The ESS [1] is a new research center under construction to be based on the world’s most powerful pulsed neutron source. ESS represents the largest pan-European research project today, gathering at least 17 partner countries. The total construction budget is estimated at 1.8 G€ with half coming directly from Sweden, Denmark, and Norway.

The facility is now under construction in Lund, Sweden. According to the current project plans, first neutrons will be available in 2019. ESS will start its user program with six instruments in 2023. In 2025, ESS construction will be complete with 22 operational instruments.

At ESS neutrons will be created by spallation. A 5 MW superconducting linac will accelerate proton beam, produced by an ion source, to an energy of 2 GeV. These protons will hit a rotating tungsten target giving high-energy neutrons. The high level parameters of the ESS accelerator are presented in Table 1 [2]. The last two steps are to slow down these neutrons with a moderator-reflector system surrounding the target, and deliver the thermal and cold neutrons produced to the different instruments.

The main characteristics of ESS are its long neutron pulse of 2.86 ms, its low repetition rate of 14 Hz and its high peak flux comparing to today’s leading neutron research centers, as shown on Figure 1. A schematic view of the ESS facility is shown in Figure 2.

<p>| Table 1. The ESS high level parameters [2, 3]. |</p>
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average beam power</td>
<td>MW</td>
<td>5</td>
</tr>
<tr>
<td>Power during pulse</td>
<td>MW</td>
<td>125</td>
</tr>
<tr>
<td>Nb of target station</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Nb of instruments in construction budget</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>Nb of beam ports</td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>Nb of moderators</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Proton kinetic energy</td>
<td>GeV</td>
<td>2</td>
</tr>
<tr>
<td>Average pulse current</td>
<td>mA</td>
<td>62.5</td>
</tr>
<tr>
<td>Pulse length</td>
<td>ms</td>
<td>2.86</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>Hz</td>
<td>14</td>
</tr>
<tr>
<td>Linac length</td>
<td>m</td>
<td>482.5</td>
</tr>
<tr>
<td>Annual operating period</td>
<td>h</td>
<td>5000</td>
</tr>
<tr>
<td>Reliability</td>
<td>%</td>
<td>95</td>
</tr>
</tbody>
</table>

The discovery of neutron–antineutron ($n\bar{n}$) oscillations could answer crucial questions of particle physics and cosmology. Why do we observe more matter than antimatter in the Universe? At what energy scales do new phenomena occur? Another related intriguing subject potentially accessible with this process concerns the mechanism responsible for neutrino mass generation. The construction of the European Spallation Source (ESS) offers a remarkable opportunity to perform a sensitive experiment dedicated to the search of such oscillations. Indeed, the high neutron flux expected at this facility, combined with the important progress made in neutron optics, will enable this experiment to gather all the necessary conditions for establishing possible new physics coming from energy scales beyond the reach of colliders that can have a strong impact on our understanding of the Universe.

The main characteristics of ESS are its long neutron pulse of 2.86 ms, its low repetition rate of 14 Hz and its high peak flux comparing to today’s leading neutron research centers, as shown on Figure 1. A schematic view of the ESS facility is shown in Figure 2.
Neutrons are a unique tool for science. With ESS, the scientific community can exploit new research opportunities in neutron scattering and also in fundamental physics.

**Precision Studies of Fundamental Physics at ESS**

Fundamental physics stands at a crossroads between particle and nuclear physics, astrophysics and cosmology. Its main purpose is to improve our knowledge of the Universe and understand its fundamental laws and evolution.

At ESS, the high neutron flux will permit neutron experiments to continue to advance the precision frontier [4] that consists in investigating low energy processes that can be precisely predicted by theory. Deviations from expectations in such processes would prove the existence of new physics. In the precision frontier, new particles are not created in the final state. The idea is to detect the footprints they leave. These traces are sought at energies below the production threshold of new particles. The energy frontier is based on measurements of particle interactions in collision of highest energy possible aiming at the production of new heavy elementary particles. These scientific paths are complementary. A good example illustrating this complementarity is the discovery of the Higgs boson. Indeed, precision measurements performed at the Large Electron-Positron collider (LEP) and other facilities allowed to constrain its mass [5]. The information extracted during these experiments was very useful for its discovery at the Large Hadron Collider (LHC) at CERN [6, 7].

The established theory describing weak, strong, and electromagnetic interactions of all known particles is the Standard Model (SM) of particle physics. However, it seems to not be the complete theory. Actually, there are some strong experimental evidences and theoretical arguments to prove it. For instance, this model does not include gravitation. It cannot explain the existence of dark matter or dark energy, which contribute as much as 25% and 70% [8], respectively, to the energy content of the Universe. Currently, the SM is able to describe less than 5% of the content of the Universe [8]. For many physicists, it is crucial to test the validity of the SM by measuring its different parameters. In this respect, precision experiments with neutrons can contribute to the understanding of the SM itself [9–12].

**Why Study Neutron–Antineutron Oscillations?**

The baryon asymmetry of the Universe (BAU) is one of the most important questions to solve in cosmology. Sakharov has proposed a set of three necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates [13]. These requirements are:

- Baryon number violation.
- Charge and charge and parity conjugation symmetry violation.
- Interactions out of thermal equilibrium during the expansion of the Universe.

Baryon number violation appears naturally in many theories that unify quarks and leptons, such as Grand Unified Theories (GUT). The difference between the baryon number $B$ and the lepton number $L$ is required for the SM to be renormalizable [14]. $B$ violation in SM occurs through nonperturbative electroweak processes, but at a rate which is strongly suppressed at low temperatures [15].

To study baryon number violation, two types of experiments have been pursued:

- Proton decay, which violates $B$ by one unit. Observation close to the current limits would imply new physics at high energy scales $\sim10^{15}$ GeV [16]. To probe this, a 100–1,000 kton detectors are needed.
- Neutron–antineutron oscillations. To observe a neutron spontaneously converting into an antineutron, $B$ has to be violated by two units with no change in lepton number. In case of discovery close to the current limits, inferring the new physics is somewhat more complex, but it could be as low as $\sim10^4$ GeV [17].

For the case of $nn$ oscillations, this topic opens other fields of exploration for the physicists:

- For instance, the possibility to test extensions to the Standard Model that allow violating either $B$ or $L$ and...
may result in B violation by two units without changing L (e.g., theoretical concepts working with extra-dimensions, or models for baryogenesis around the electroweak symmetry-breaking scale) [18].

- The selection rule ΔB = 2 relates neutron–antineutron oscillation to Majorana neutrino mass via (B-L). This link could be used to discover the origin and the nature of neutrino masses. A simple way to understand the small neutrino masses is by the seesaw mechanism [19]. Here the neutrino is a Majorana fermion, which means lepton number is broken by two units. As the Standard Model has a global (B-L) symmetry, if ΔL = 2 violating (B-L), it seems natural that B can be broken by two units as well. Indeed, theoretical concepts like quark-lepton unified theories predict Majorana neutrinos as well as neutron–antineutron oscillations. The search for these oscillations represents a direct test for these theories. Finally, this experiment may also indicate that the small neutrino mass is not a signal of physics at high-energy scales but rather at the intermediate scales.

**Phenomenology**

In the presence of $\bar{n}n$ oscillations, the Schrödinger equation describing this system is:

$$<n> \frac{\partial \Psi}{\partial t} = \left( \frac{E_n - \alpha}{E_{\bar{n}}} \right) \Psi$$  \hspace{1cm} (1)

with:

- $\Psi$: Neutron–antineutron state vector,
- $E_n$: Neutron energy,
- $E_{\bar{n}}$: Antineutron energy,
- $\alpha$: Mixing parameter as predicted by physics Beyond the Standard Model.

The transition probability to generate antineutrons from a state which was initially composed only of neutrons in the presence of magnetic and/or nuclear fields is [20]:

$$P_{n \rightarrow \bar{n}} = \frac{\alpha^2}{\alpha^2 + V^2} \times \sin^2 \left( \frac{\sqrt{\alpha^2 + V^2}}{\hbar} \times t \right)$$  \hspace{1cm} (2)

With $V$, the difference of (magnetic or nuclear) potential for neutrons and antineutrons:

$$V = \frac{1}{2} \times (E_n - E_{\bar{n}})$$  \hspace{1cm} (3)

and $t$ is an observation time.

For the following conditions:

- $(\alpha/\hbar) \times t \ll 1$;
- $(V/\hbar) \times t \ll 1$: the quasi-free condition (i.e., in vacuum and in the absence of external fields),

the probability of $n\bar{n}$ transformation becomes:

$$P_{n \rightarrow \bar{n}} = \left( \frac{\alpha}{\hbar} \times t \right)^2 = \left( \frac{2}{\tau_{n\rightarrow\bar{n}}} \right)^2$$  \hspace{1cm} (4)

with $\tau_{n\rightarrow\bar{n}} = \hbar/\alpha$, the free oscillation time.

**Previous $n\bar{n}$ Searches**

Transformations of neutrons to antineutrons have been already sought in two categories of experiments:

- experiments with neutrons bound inside nuclei, and
- experiments using free neutrons.

For the case of intranuclear transformation, the transition probability is strongly suppressed by the large nuclear potential difference $V$ as can be seen from Eq. (2). Oscillation term then is averaged down to $\frac{1}{2}$ and the transformation probability doesn’t depend on time resulting in a suppressed usual exponential lifetime of nuclei. The corresponding suppression factor (called R below) is calculated using nuclear models [21–22]. Knowing the factor $R$ and the free oscillation time it is possible to determine the intranuclear oscillation time:

$$\tau_{\text{int}} = R \times \tau_{\text{free}}^2$$  \hspace{1cm} (5)

Experiments using neutrons bound inside nuclei are limited so far by atmospheric neutrino backgrounds. The best result comes from the Super-Kamiokande experiment (yet unpublished) [23]. They found 24 neutron–antineutron oscillation candidates with an estimated atmospheric neutrino background of 24.1 events. The lower limit on the lifetime for neutrons bound in $^{16}$O deduced by this experiment is $1.89 \times 10^{32}$ years at the 90% CL [23]. The corresponding free oscillation time was extracted by using Eq. (5) and the $R$ value from Ref. [21]. The result obtained is $\tau_{\text{free}} = 2.44 \times 10^{8}$s.

Another possibility to search for neutron–antineutron oscillations consists in using free neutrons. Compared to the intranuclear case, this approach can have a much better background rejection. Moreover, if effect will be observed, it is possible to check if a signal is real as the oscillation amplitude can be suppressed by a small magnetic field. This is a unique feature of $n\bar{n}$ search with free neutrons.

The most sensitive previous search for free neutron oscillation was performed in the early 1990s at the high flux reactor at the Institute Laue-Langevin (ILL) in Grenoble, France [24]. The average neutron flight time was ~0.1 s and
the average velocity of the cold neutrons was \( \sim 700 \) m/s. The quasi free condition was maintained with a vacuum of \( P \approx 2 \times 10^{-4} \) Pa and the Earth magnetic field shielded down to \( B < 10 \) nT. Antineutron appearance would be detected through annihilation in a thin carbon target. Carbon has a high annihilation cross section (~4 kb) and a low neutron capture cross-section (~4 mb). The annihilation reaction on the carbon target would have produced on average 5 pions. The target was surrounded by a detector consisting of tracking detectors, a time-of-flight system and a calorimeter to reconstruct the \( \sim 1.8 \) GeV invariant mass of the multi-pion system. The experiment was background free. After one year of running, no antineutron was detected and no background events were recorded. For this experiment, a limit of \( 0.86 \times 10^9 \) s was set on the free oscillation time.

**Sensitivity**

For experiments using free neutrons, the figure of merit (FoM or sensitivity) is:

\[
FoM = N \times \langle r^2 \rangle.
\]

Here

- \( N \) is the free neutron flux reaching the annihilation target and
- \( \langle r^2 \rangle \) is the square of the observation time.

The sensitivity reached by the ILL experiment was \( 1.5 \times 10^9 \) n/s [24].

The next generation experiment proposed at ESS promises a much-improved sensitivity and a considerable discovery potential. Combined with the specific advantages of ESS, it is expected to exploit recent progress in both neutron optics and detector technologies to push the figure of merit to the oscillation probability by approximately three orders of magnitude [25].

If no oscillation is seen, the expected gain in the exclusion limit would provide guidance for models aiming to explain the baryon asymmetry of the Universe. It will also set a limit on the stability of nuclear matter at the level (at \( \Lambda = 2 \) mode) \( > 10^{35} \) years.

**Requirements for a New Experiment at the ESS**

The goal of the experiment is to have neutrons traveling in free space for the maximum time possible without wall collisions. By a single reflection, the neutrons have to reach the annihilation target surrounded by the detector. If a transition to an antineutron takes place, the annihilation event needs to be detected at the end of the flight path with high efficiency.

In order to increase the sensitivity, the following factors are exploited:

- increase the free flight time of neutrons;
- increase the number of neutrons;
- keep the experiment background free;
- detector size can be possibly increased.

The first three aspects are discussed more in detail below.

**Increase the Free Flight Time of Neutrons**

*(Observation Time)*

In the new experiment at ESS, the cold neutron beam will propagate in a region with high vacuum and low magnetic field to satisfy the quasi-free condition. Equation (4) may then be used for the transformation probability. This means the vacuum should be better than \( \sim 10^{-5} \) Pa and the magnetic field must be suppressed to the few nT level at least in the whole free flight volume.

A lower limit on the neutron velocity is imposed by Earth’s gravity since very cold and ultra-cold neutrons cannot be transported over significant distance without many interactions with the mirrors. Indeed, each interaction resets the oscillation clock [26]. To increase the number of neutrons a large elliptical focusing reflector will be used [27] to direct neutrons within large solid angle to the annihilation target. Cold neutrons are particularly useful due to their low velocity and a long flight path (>200 m) will be used to increase the observation time.

**Increase the Number of Neutrons**

A high flux of cold neutrons is expected at ESS. A large beam port allowing the biggest possible view of the ESS moderator surface is necessary to obtain a maximum part of this flux. The elliptical geometry chosen for the reflector increases the phase space acceptance for cold neutrons within fixed solid angle. The cold neutron source and the annihilation target will be located in the focal planes of the ellipsoid. To increase the beam acceptance, a larger target of \( \sim 2 \) m meters diameter is required. Progress made in neutron optics represents an important opportunity to reach a higher sensitivity in the experiment. Even if the reflection of the super-mirrors decreases with velocity transverse to the reflector the range of reflected transverse velocities has been increased over Ni reflectors by a factor \( m \) thanks to Bragg scattering from multilayer coating of these mirrors. Nowadays, \( m = 4 \) mirrors are industrial standard and \( m = 7 \) can be industrially produced [28]. One final way to increase the number of neutrons is to have a longer running time comparing to the ILL experiment, which ran for one year.
Background Free Experiment

The experiment’s sensitivity is maximized if the detection of antineutrons is background free. The fast neutrons produced by the spallation process at ESS can be suppressed by using the time structure of the beam. Precise tracking and excellent timing resolution are needed to limit events to the annihilation target. Muon veto detectors are required to reject cosmic background. MeV gammas produced by neutron capture will be suppressed by the trigger system.

Figure 3 presents a schematic view of the experimental set-up for a neutron–antineutron experiment at ESS.

The nn Collaboration

In order to establish a collaboration for this experiment, a first workshop took place at CERN in June 2014 [29]. At this occasion, five working groups were identified:

- Physics: evaluation of the scientific value and identification of possible new theoretical applications as well as additional physics processes that can be studied with the experiment.
- Neutronics: design/optimization of the extraction optics, the vacuum tube, the radiation shielding, and the annihilation target. This group works on beam characterization and monitoring as well.
- Magnetics: design/optimization of the magnetic shielding and magnetometry.
- Detector: design of the detector system, tracker, calorimeter, trigger, time of flight, cosmic veto, and data acquisition system.
- Software & Computing: simulation support, data management, analysis tools, computing infrastructure.

In February 2015, at ESS, a second workshop was organized and held around these five working groups [30]. The first accomplishment of the collaboration will be the submission of an expression of interest to ESS in April 2015. At this stage, the collaboration is still forming and would be very happy to welcome new partners and/or institutions to work on the topics proposed by the different working groups [31].

Outlook

Neutrons oscillating into antineutrons could offer a unique probe for crucial questions in fundamental physics, such as the mechanisms responsible for baryon number violation and neutrino mass generation. The observation of this process would be a discovery of primary importance because of its incontestable evidence for new physics beyond the Standard Model. The construction of ESS in Lund, together with technological progress, offers a major opportunity to conduct a new search for this process with at least three orders of magnitude increase in sensitivity to the oscillation probability compared to the ILL experiment. The required technologies exist and detailed simulations to optimize the design and the technical choices are being developed by a growing collaboration. Subject to funding, the aim is to complete a technical design report in approximately two years, in time to allow the experiment to take data not long after ESS starts the production of its first cold neutrons as expected in 2019.

References

1. European Spallation Source, www.esss.se
29. First workshop on neutron antineutron oscillation at ESS, CERN, Switzerland, June 2014. www.nnbar-at-ess.org
31. www.nnbar-at-ess.org
The High Intensity γ-Ray Source (HIγS), operated by the Triangle Universities Nuclear Laboratory and located on the campus of Duke University, is presently able to provide nearly mono-energetic polarized gamma ray beams with energies ranging from 1 to 100 MeV. These beams are produced by Compton backscattering photons produced by a free-electron laser (FEL) from the same relativistic electron beam that powers the FEL inside of an electron storage ring. The maximum total intensity of these γ-ray beams produced in the vicinity of 10 MeV is approximately $3 \times 10^{10}$ γ/s, making HIγS the most intense Compton γ-ray source ever built and operated [1].

After presenting a brief description of the HIγS facility and a few of the most exciting discoveries made using this facility, some of the future plans that could lead to even more fascinating results will be described.

The HIγS facility is unique in two major ways: it uses a high-intensity intra-cavity FEL beam as its photon source [1], and it takes advantage of the low emittance and large energy acceptance of a modern storage ring. There are two different FEL systems at HIγS: the first of these consists of two planar arrays of electromagnetic wigglers produced by a free-electron laser (FEL) from the same relativistic electron beam that powers the FEL inside of an electron storage ring. The length is crucial since the round trip time of photons in the cavity is equal to the time it takes an electron
bunch to complete a revolution around the storage ring. This allows the electron bunch to interact with the photon pulse built-up by radiation of the same bunch in previous revolutions. The gain of this system can be greatly enhanced by means of a buncher magnet located between the two planar arrays. This system, called the OK-4 FEL system, produces linearly polarized γ-ray beams with the plane of polarization in the horizontal direction and is used for γ-ray production up to 60 MeV. The second FEL system consists of two 4 m long arrays of helical electromagnetic wigglers and is used primarily to produce circularly polarized γ-ray beams. Two additional helical wiggler magnetic arrays are available, and a recent upgrade provides for “switchyard,” making it possible to exchange the two OK-4 linear arrays with these two additional helical arrays. Recently, a new mode of operating using two OK-5 helical arrays has been developed to produce linearly polarized γ-ray beams with an arbitrary (switchable) plane of polarization. This opens up new opportunities to users, as will be described below. The helical arrays are used for producing γ-ray beams at energies up to 100 MeV, which can be either circularly or linearly polarized (<20 MeV). The layout of the facility and the beam production mechanism are shown in Figure 1.

The Nuclear Physics Program at HfS
The nuclear physics program at the HfS facility is very diverse and covers a number of different areas of nuclear physics. This brief report can only feature a few examples to illustrate the novel experiments which HfS has enabled in the areas of Nuclear Structure and Nuclear Astrophysics.

Nuclear Resonance Fluorescence
One of the most successful programs at HfS has been in the area of Nuclear Resonance Fluorescence (NRF) [2]. Significant results have been published on studies of various collective modes in nuclei including the Pygmy Dipole Resonance, the Giant M1 strength in nuclei, collective quadrupole–octupole coupled states, states of mixed symmetry, and others. As an example of the unique capabilities of HfS, we will describe a very recent study that used the NRF technique to determine the energy splitting of the (J,T) = (1,1) parity doublet in $^{20}$Ne in the vicinity of 11.26 MeV [3].

The parity doublet in $^{20}$Ne was previously assigned energies of 11262.3(19) keV for the 1+ state and 11270(5) keV for the 1− states. These two states are too close in energy to be resolved with an HPGe detector having a resolution of ~7.5 keV at these energies. Therefore, only the summed peaks are observed. In the case of a...
linearly polarized beam, however, the \(1^-\) state will show up mostly in the direction perpendicular to the plane of polarization, while the \(1^+\) state will be seen mostly in the parallel direction. The trick, therefore, is to take spectra in the two planes using both linearly and circularly polarized beams. The energy difference between the two states is then determined from the small energy shift between the linear and circularly polarized cases. In the present case, this shift is seen in the perpendicular plane, indicating that the \(1^-\) state lies lower in energy than the \(1^+\) state, as can be seen in Figure 2.

The peak centroids and their respective peak areas from all four spectra allow for the determination of the excitation energies of the parity doublet, their energy difference, and the ratio of their integrated cross-sections. The results of this work are presented in Table 1, which includes the value of the so-called parity violating effective nuclear enhancement factor \(F_e\). As seen in Table 1, the new results revise the energetic ordering of the two states, reduce the energy difference by a factor of about 2, and enhance the value of \(F_e\) by a factor of 2. These results make this parity doublet in \(^{20}\text{Ne}\) an intriguing candidate for the study of parity violation in nuclear excitations.

**Compton Scattering and the Isovector Giant Quadrupole Resonance in Nuclei**

Nuclei are known to exhibit giant electromagnetic resonance, the dominant ones being the electric dipole and the electric quadrupole modes. The Isovector Giant Quadrupole Resonance (IVGQR) is especially interesting because the restoring force between the oscillating neutrons and protons that determine its properties is a result of the symmetry energy. This term appears in the Nuclear Equation of State, which describes the macroscopic behavior of nuclear matter, and plays a dominant role in nuclear matter as the neutron excess increases. A knowledge of its strength and its density dependence is crucial to our understanding of exotic nuclear matter including neutron stars. The parameters of the IVGQR have been poorly determined, until now [4]. The intense polarized \(\gamma\)-ray beams of the HI\(\gamma\)S facility, along with the realization that the sign of the interference terms between the IVGQR and the dominant electric dipole background could be flipped by measuring the ratio of the linearly polarized Compton scattered \(\gamma\)-rays perpendicular and parallel to the polarization plane \((\sigma_{\text{perp}}/\sigma_{\text{par}})\) at a backward versus a forward angle. The results for the case of \(^{124}\text{Sn}\) are shown in Figure 3. Averaging the two results shown here provides an unambiguous determination of the background term and leads to values of the energy, width (\(\Gamma\)) and strength \((\text{IVQ-EWSR})\) of the IVGQR almost an order of magnitude better than previously possible (Figure 3).

**Table 1. Results and comparison to literature for the deduced level energies of the \(1^+\) and \(1^-\) states, their energy splitting \(\Delta E\), and their nuclear enhancement factor \(F_e\).**

<table>
<thead>
<tr>
<th>Observable</th>
<th>This work [3]</th>
<th>Previous results</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E(1^+)) (keV)</td>
<td>11258.6 (2)</td>
<td>11262.3 (19)</td>
</tr>
<tr>
<td>(E(1^-)) (keV)</td>
<td>11255.4 (±0.7) stat (+1.2 – 0.6) sys</td>
<td>11270 (5)</td>
</tr>
<tr>
<td>(\Delta E) (keV)</td>
<td>–3.2 (±0.7) stat (+0.6 – 1.2) sys</td>
<td>7.7 ± 5.5</td>
</tr>
<tr>
<td>(F_e) (keV(^{-1}))</td>
<td>1.4 (±0.3) stat (±0.2) sys</td>
<td>0.67 ± 0.70</td>
</tr>
</tbody>
</table>

**Figure 3. The ratio of the Compton scattered \(\gamma\)-rays measured perpendicular versus parallel to the polarization plane from a target of \(^{124}\text{Sn}\) as a function of \(E_\gamma\) for detectors at 55° and 125°, respectively. The cross-over point leads to a precise value of the energy of the IVGQR.**
measurement of the complete angular distributions needed to extract the E1 and E2 amplitudes and their relative phase, confirming the $2^+$ nature of the state near 10 MeV. The separated E1 and E2 cross-sections were fit using Breit-Wigner resonance line shapes. A preliminary report [5] of this work presented resonance parameters that were incorrect due to a sign error in the level shift parameter contained in the Breit-Wigner formula. Once this error was corrected, it was observed that the cross-section data in the vicinity of the $2^+$ resonance could not be fit using a standard Breit-Wigner line shape with energy dependent widths and the level-shift included using typical values of the R-matrix parameter $r_0$ (between 1.3 and 1.5 fm). However, as pointed out by Fynbo and Gai [6], converged solutions were obtained for larger values of $r_0$ (ranging from about 1.5 to 1.8 fm), although the formal width had a strong dependence on the value chosen for $r_0$. Therefore, two analyses were performed: (1) a single-level Breit-Wigner fit was performed that ignored the level-shift in order to obtain the “observed” level parameters [7] and (2) fits were performed including the level-shift using large values of the $r_0$ parameter to obtain the formal level parameters. The resulting resonance parameters for both cases are presented in Table 2, where two cases are given for the larger values of $r_0$ to illustrate the dependence of the formal parameters on its value. A formal width of around 1.62 MeV is preferred since the value of the

<table>
<thead>
<tr>
<th>$r_0$ (fm)</th>
<th>E (MeV)</th>
<th>$\Gamma_\gamma$ (keV)</th>
<th>$\Gamma_\gamma$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4 (w/o level-shifts)</td>
<td>10.13 ± 0.06</td>
<td>2080 ± 330 (observed)</td>
<td>135 ± 16 (observed)</td>
</tr>
<tr>
<td>1.6 (w/level-shifts)</td>
<td>10.00 ± 0.03</td>
<td>3360 ± 45 (formal)</td>
<td>226 ± 22 (formal)</td>
</tr>
<tr>
<td>1.8 (w/level-shifts)</td>
<td>10.06 ± 0.03</td>
<td>1620 ± 130 (formal)</td>
<td>111 ± 5 (formal)</td>
</tr>
</tbody>
</table>

Figure 4. Measured E2 and E1 cross-sections and the E1–E2 phase differences as a function of incident beam energy. The results shown are averaged over the $\gamma$-ray beam energy distribution, measured to be close to a Gaussian distribution with a width of 350(40) keV. The error bars include both statistical and systematic uncertainties. The solid lines for the $2^+$ resonance represent fits to the data used to determine the “observed” resonance parameters averaged over the beam width (convolved). The dashed lines are results corrected for the beam energy spread (unfolded). Similar results are shown for the well-known $1^-$ state at 10.9 MeV.
width tends to converge at this value as the value of \( r_0 \) increases above 1.8 fm. Such a large \( r_0 \) value is not unprecedented, the R-matrix analysis of the Hoyle state by Barker and Treacy [8] required a large radius parameter (close to 1.8 fm) to reproduce the width of the Hoyle state. The current analysis suggests that both the Hoyle state and the \( 2^+_2 \) are extended objects.

A comprehensive multi-level R-Matrix theory fit to the data has been recently performed by Gerry Hale [9]. This fit to the data indicates that this newly observed \( 2^+ \) state is a Shadow Pole comprised mostly (~75%) of the 4.4 MeV \( 2^+ \) state in \(^{12}\text{C}\). The \( 2^+_2 \) state is found to have an energy of 9.7 MeV and a formal width of 1.2 MeV.

The measured cross-sections and the E1–E2 phase differences are shown in Figure 4 along with the two-level fit to the data (with \( r_0 \) of 1.4 fm). It is interesting to note that the alpha-decay width of the new \( 2^+ \) state at 10.13 MeV exhausts 157(15)% of the Wigner limit. This strongly suggests that, like the Hoyle state, this \( 2^+ \) state is an \( \alpha \)-cluster state, consistent with it being an excitation of the Hoyle state. Finally, it is interesting to note that the predictions of the Bose-Einstein Condensate (BEC) model [10] are in reasonable agreement with the present experimental results for the \( 2^+_2 \) state. This model predicts a \( 2^+_2 \) state at 9.7 MeV with a reduced \( \alpha \)-decay width of 1,200 keV, which is in rather good agreement with the observed experimental value of 1,470 +160/–120 keV. This model also predicts a B(E2) value of 1.57 e²fm⁴ (\( \Gamma_x = 135 \) meV), in remarkably good agreement with the results of this experiment.

**Future Prospects**

One of the major efforts presently underway at the HIGS facility is the commissioning of a recently installed Frozen Spin Polarized Target, intended to provide polarized proton and polarized deuteron targets. This target is presently undergoing commissioning tests and calibrations, with data-taking scheduled to begin in mid-2016.

The first scheduled experiment will be aimed at measuring the Gerasimov-Drell-Hearn (GDH) Sum Rule integrand for the deuteron below pion threshold. First results on the value of this integrand up to 20 MeV are expected in the next year or so [12]. Additional work on the photodisintegration of \(^3\text{He} \) [13] will extend our study of the GDH integrand for \(^3\text{He} \) to higher energies in both the 2- and 3-body channels.

An experimental program to produce accurate values of the electric and magnetic polarizabilities of the proton and the neutron is also scheduled for the near future. The use of polarized beams will make it possible to determine these quantities without invoking any constraints, such as those given by the Baldin Sum Rule. Once these measurements are completed for the proton and the neutron, our attention will turn to measurements of the spin-polarizabilities via Compton scattering from an upgraded (scintillating) polarized deuterium target.

Beyond the next three to five years, we plan to commission a program on near threshold photopion production from the proton in order to perform precision tests of the predictions of fundamental physics, the HIGS facility has proven to be a very valuable tool for many applied physics problems. One example of this has been the search for new means to measure the enrichment of various actinides, a problem that is of great concern to the Department of Homeland Security. Studies at the HIGS facility have shown that a measurement of the ratio of fission neutrons in the plane to those perpendicular to the plane of polarization that are produced when a 6.1 MeV \( \gamma \)-ray beam impinges on a sample consisting of an admixture of \(^{235}\text{U} \) and \(^{238}\text{U} \) can be used to determine the enrichment of the sample [11]. This is illustrated in Figure 5, which shows the huge variation in the polarization asymmetry as a function of the enrichment, making it easy to distinguish weapons-grade from reactor-grade uranium.

**Applications**

In addition to confronting outstanding problems in fundamental physics, the HIGS facility has proven to be a very valuable tool for many
the low-energy theorems of quantum chromodynamics calculated using chiral perturbation theory (ChPT), which is based on the spontaneous breaking of chiral symmetry as well as explicit breaking due to the finite quark masses [14].

The future of photonuclear physics at the Hijing facility looks very bright, indeed.

Acknowledgments
The basic and applied nuclear physics research is supported by the grants from the U.S. Department of Energy, DOE (DE-FG02-97ER41033, DE-SC0005367) and U.S. Department of Homeland Security, Domestic Nuclear Detection Office (2010-DN-077-ARI046-04).

References
The γ-Ray Beam-Line at NewSUBARU

NewSUBARU and Laser Compton-Scattering γ-Ray Beams

The synchrotron radiation facility NewSUBARU with nine beam-lines is operated by the Laboratory of Advanced Science and Technology for Industry, University of Hyogo, Japan. Gamma-ray beams are produced in the beam-line BL01 by laser Compton scattering (LCS) from 0.5–1.5 GeV electron beams in the NewSUBARU storage ring [1]. Lasers with different wavelengths are used to produce the LCS photon beam in the energy range from 0.5 MeV to 76 MeV: a Nd:YVO₄ laser ($λ = 1064$ and 532 nm), a CO₂ laser ($λ = 10.59 \text{ mm}$), and an Er fiber laser ($λ = 1540$ nm). A new experimental hutch, GACKO (Gamma Collaboration Hutch of Konan University), was installed in the BL01 in March 2012.

Figure 1 shows a bird-eye view of the NewSUBARU facility along with SPring-8 (8 GeV synchrotron radiation facility) and SACLA (X-ray free electron laser facility). Figure 2 depicts the γ-ray production beam-line BL01 and experimental hutch GACKO. The typical parameters of the gamma-ray source are listed in Table 1.

Electron Beams

In addition to the laser systems, electron beams play an important role to produce LCS photon beams. An electron beam is injected at 974 MeV in nominal energy from the SPring-8 linear accelerator (linac) [2] to the NewSUBARU storage ring whose RF frequency is 500 MHz. The electron beam involves 198 bunches along the 120 m circumference that circulate at the revolution frequency 2.53 MHz. Electrons from the linac can be injected into selected addresses. An arbitrary filling from single bunch to full-filling is feasible. After the electron beam injection at 974 MeV, the beam energy can be either accelerated up to 1.5 GeV or decelerated down to ~0.5 GeV. At 974 MeV, the top-up operation that keeps the beam current constant is possible as shown in Figure 3. At other beam energies, the stored current decays in time according to beam lifetime. The beam lifetime is determined by both scattering with gas molecules in the vacuum chamber and intra-beam scattering due to the space-charge effect (Touschek effect). The lifetime at 1.5 GeV is about 13 hours with an initial current 300 mA.

The spatial profile of an electron beam is characterized by Gaussian functions in the horizontal and vertical directions. The standard deviations $s_x, s_y$ vary along the circumference of the ring as described by $s_x = \sqrt{\epsilon_x \beta_x}, s_y = \sqrt{\epsilon_y \beta_y}$, where $\epsilon_x, \epsilon_y$ are horizontal and vertical emittances, $\beta_x, \beta_y$ betatron functions, $D_x$ horizontal dispersion function and $\Delta E/E_0$ energy spread of electron beams. The betatron functions calculated with the MAD-X code [3] are shown in Figure 4 along the half of the ring circumference starting from the center of the straight section for the BL01, $s = 0$. Individual electrons oscillate around a closed orbit in both horizontal and vertical directions. The number of oscillations per betatron turn is 6.28 horizontally and 2.23 vertically.

The natural emittance $\epsilon_0$ at 974 MeV is 40 [nm-rad], This value determined by magnet placement in the ring is a conserved quantity at a given energy and is proportional to the square of the energy. Ideally, a finite emittance arises only horizontally (natural emittance) and zero vertically. But, in reality, a small part of the horizontal emittance is coupled to the...
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Figure 2. The beam-line BL01 for γ-ray production and the experimental hutch GACKO at NewSUBARU.

Table 1. List of energies and yields of LCS gamma-ray source at NewSUBARU.

<table>
<thead>
<tr>
<th>Parameter/Lasers</th>
<th>Nd(ω)</th>
<th>Nd(2ω)</th>
<th>Er</th>
<th>CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength λ</td>
<td>1064 nm</td>
<td>532 nm</td>
<td>1540 nm</td>
<td>10.59 mm</td>
</tr>
<tr>
<td>Laser power (max) PL</td>
<td>35 W</td>
<td>20 W</td>
<td>4 W</td>
<td>7.5 W</td>
</tr>
<tr>
<td>Gamma-ray energy (no collimator)</td>
<td>Ee = 974 MeV</td>
<td>Ee = 1470 MeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5–16.7 MeV</td>
<td>8–37.6 MeV</td>
<td>10–33.4 MeV</td>
<td>15–73 MeV</td>
<td></td>
</tr>
<tr>
<td>Yield (no collimator)</td>
<td>Ee = 974 MeV</td>
<td>6000 γ/s/mA/W</td>
<td>3000 γ/s/mA/W</td>
<td></td>
</tr>
<tr>
<td>Gamma-ray energy (3 mm φ collimator)</td>
<td>Ee = 974 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.4–16.7 MeV</td>
<td>30.5–33.3 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield (3 mm φ collimator)</td>
<td>Ee = 974 MeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I = 300 mA</td>
<td>2 × 10^6 γ/s</td>
<td>6 × 10^5 γ/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

vertical one. This factor, XY coupling k, is usually less than 1%. Thus, the nominal horizontal and vertical emittances are given by \( \varepsilon_x = \varepsilon_0/(1 + \kappa) = 39.6 \text{ [nm-rad]} \), \( \varepsilon_y = \varepsilon_0 K/(1 + \kappa) = 0.4 \text{ [nm-rad]} \).

A unique feature of the NewSUBARU is that the vertical beam size is intentionally enlarged to improve the Touschek lifetime during the ordinary beam time. To enlarge the beam size, we use a kicker called RF shaker that is composed of four strip-line electrodes on which RF power resonating with betatron motions is applied. As a result, the measured vertical beam size is a few times larger than that without RF shaker.

Characteristics of LCS γ-Ray Beams
It is important to understand characteristics of laser Compton scattering γ-ray beams in the measurement of photonuclear reaction cross-sections: (1) the absolute energy, (2) the energy distribution, and (3) the flux.

Figure 3. Variation of the electron beam current as a function of time in the top-up operation.
For the determination of the absolute energy, electron beam energies of the NewSUBARU storage ring were calibrated with high accuracy of the order of 10^-5 [4]. The energy distribution is determined by a Monte Carlo analysis of response functions of a large-volume LaBr3(Ce) detector to LCS γ-rays [5], while the flux determination for pulsed γ-ray beams is based on a Poisson fitting analysis [6] of pile-up spectra measured with a large-volume NaI(Tl) detector with 100% detection efficiency.

The energy calibration of γ-rays is not a straightforward issue in the region of a few tens of MeV for a lack of proper calibration sources. A high-resolution germanium detector may be used for calibration. However, the standard γ-ray sources can cover only low energies so that a linear extrapolation to high energies may cause uncertainties of ~50 keV around 10 MeV. Furthermore, a large-volume Ge detector is needed to detect a high-energy edge corresponding to the full-energy peak for 10 MeV γ-rays if it may fail to isolate a peak.

Energies of LCS γ-rays follow the kinematics of the Compton scattering of laser photons from relativistic electrons. LCS γ-rays form a high-energy edge by Lorentz-boosting laser photons that are Compton-scattered at 180° in the rest frame of electrons. Since the wavelength of laser photons is fixed with high precision, the edge energy is sensitive only to the electron beam energy.

To calibrate electron beams of the NewSUBARU storage ring, a few MeV LCS γ-ray beams were produced with a CO2 laser. As shown in Figure 2, the beam-line BL01 has two collimators; one (C1) in the storage ring vault and the other (C2) in Hutch 1. Both collimators are made of 10 cm thick Pb. In the calibration experiment, we used the C1 collimator with an aperture of 6 mm diameter. The C2 collimator with an aperture of 2 mm diameter defined scattering angle for laser Compton backscattering.

An electron beam was injected from the linear accelerator into the NewSUBARU storage ring at the nominal energy 974 MeV. A grating-fixed CO2 laser (INFRARED INSTRUMENTS, IR-10-WS-GF-VP) oscillated at a single line of the strongest master transition P(20). The central wavelength of the P(20) transition is known (λ = 10.5915 μm ± 3 Å) [7] with the bandwidth 1.3 Å in the full width at half maximum FWHM [8]. Including the bandwidth, the accuracy of the wavelength of CO2 laser is 4.1 × 10^-5. A coaxial HPGe detector (64 mm in diameter × 60 mm in length) was used to measure the low-energy LCS γ-rays. The HPGe detector was calibrated with the standard γ-ray sources, 60Co including the sum peak, 133Ba, 137Cs, and 152Eu and a natural radioactivity 40K. After the injection of 974 MeV electrons into the NewSUBARU storage ring, the electron beam was either decelerated to the nominal energy 550 MeV or accelerated to 1460 MeV followed by a production of the LCS γ-ray beam and a measurement with the HPGe detector at every energy.

The response function of a HPGe detector to low-energy LCS γ-ray beams is characterized by a full-energy peak with a sloped high-energy edge reflecting the energy resolutions of the electron beam and the HPGe detector. The edge energy was determined by means of Monte Carlo simulation. The EGS4/PRESTA code [9], which simulates laser-Compton backscattering and interactions of γ-rays with detector materials, was used. Figure 5 shows an example of the dependence of the Monte Carlo simulation on the electron beam energy. The best fit to an experimental spectrum with the electron beam energy $E_e = 860.72$ MeV is shown in comparison with $E_e = 860.72 ± 0.50$ MeV and $E_e = 860.72 ± 1.00$ MeV. Thus, the electron beam energy was calibrated with accuracy of the order of 10^-5 in the nominal energy ranges 974–550 MeV [4] and 974–1460 MeV [10], which offers a standard for the energy calibration of LCS γ-ray beams produced with a Nd:YVO4 laser (λ = 1064 nm in the fundamental mode and 512 nm
in the second harmonics) in the energy region of a few to several tens of MeV. We remark that the electron beam energy is excellently reproduced in every routine of injection of an electron beam at 974 MeV followed by deceleration and acceleration.

The energy profile of quasi-monochromatic LCS γ-ray beams is determined by a Monte Carlo analysis of the response function of a 3.5" × 4.0" LaBr₃(Ce) detector. For this purpose, the effect of the electron beam emittance in the kinematics of inverse Compton scattering of laser photons from relativistic electrons was incorporated into the GEANT4 code in conjunction with the ELI-NP project [11]. Figure 6 shows typical spectra of LCS γ-ray beams (dark solid line) recorded with the LaBr₃(Ce) detector along with the GEANT4 simulations of the detector response function (red dotted lines) and the incident γ-ray beam (gray lines) [5]. Note that the energy of the response function is calibrated by the electron energy in the Monte Carlo simulation. The response functions are well reproduced by the GEANT4 simulation. Energy spreads of 1.2%, 1.4%, and 1.6% in the full width at half maximum (FWHM) were obtained for the three incident γ-ray beams of 6.5, 10.0, and 13.0 MeV maximum energy, respectively. Thus a large-size LaBr₃(Ce) detector serves as a profile monitor for the LCS γ-ray beams.

The flux of LCS γ-ray beams is currently monitored with a 8" × 12" NaI(Tl) detector to ensure 100% detection efficiency for high-energy γ-rays above several MeV. The electron beam bunches have a time structure of 2 ns interval (500 MHz) and 60 ps width. Both CW and Q-switch lasers are used to produce continuous and pulsed LCS γ-ray beams. The flux of a continuous γ-ray beam is determined by direct counting of individual photons.

Pulsed LCS γ-rays are generated in bunches at the frequency of the Q-switch laser. The number of LCS γ-rays per bunch is given by a Poisson distribution [12] with a mean that depends on the probability of interaction between the laser photons and the relativistic electrons. The number of recorded photons is obtained with an empirical formula of the “pile-up method” [6] based on the Poisson fitting [12, 13]. The uncertainty of the Poisson fitting is estimated to be 3%, which is attributed to the fitting and the energy linearity of the γ-ray detector in its response to multiphotons. A typical example of the experimental pile-up energy spectrum is shown in Figure 7 along with the single-photon spectrum.
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Figure 7. A pileup spectrum of a pulsed beam of LCS \(\gamma\)-rays measured with a 6\(^{\circ}\) × 5\(^{\circ}\) NaI(Tl) detector and a single photon spectrum.

Summary
The fundamental characteristics of LCS \(\gamma\)-ray beams produced at the NewSUBARU facility are examined and established well. Quasi-monochromatic \(\gamma\)-ray beams with energy spreads of 1–2\% in FWHM are produced with intensity of the order of 10\(^5\) cps. One can gain higher intensity at the cost of the monochromaticity by choosing a larger collimator. First measurements of \((\gamma,n)\) cross-sections were carried out for Nd [14] and Sm [5] isotopes. The LCS \(\gamma\)-ray beam is applicable to basic and industrial science and technology from nuclosynthesis, photonuclear data, gamma radiograph, to nuclear security.

References
11th International Spring Seminar on Nuclear Physics—Shell Model and Nuclear Structure: Achievements of the Past Two Decades

The 11th International Seminar on Nuclear Physics was held in Ischia from 12 May to 16 May 2014. It was dedicated to Aldo Covello, who has been the promoter of this series of Seminars, which started in Sorrento in 1986 and continued with meetings held every two or three years in the Naples area.

The main aim of these meetings was to offer to both theorists and experimentalists the opportunity to discuss their points of view on current achievements and future developments of nuclear structure in a lively and informal way.

We may read, in fact, as one of the motivations for Aldo’s election as Fellow of the American Physical Society in 2008 “... for his outstanding contributions to the international nuclear physics community by providing, for over two decades, a venue for theorists and experimentalists to share their latest ideas” (ASP Fellowship, http://www.aps.org/units/fip/fellowship/index.cfm).

The 11th Seminar, organized by Aldo’s former students and with the benefit of his suggestions, has maintained this tradition. The title “Shell model and nuclear structure: achievements of the past two decades” recalls that of the 2nd International Spring Seminar “Shell Model and Nuclear Structure: where do we stand?” (1989). Its scope has been, in fact, to discuss the changes of the past two decades on our view of nuclei in terms of shell structure as well as the perspectives of the shell model, which has been one of the key points in Aldo’s research. This facet is well accounted for by the Opening Speech of Igal Talmi, one of the fathers of the shell model.

The program of the meeting consisted of general talks and more specialized seminars, going through four main topics: (1) From nuclear forces to nuclear structure; (2) Exploring nuclear structure toward the drip line; (3) Role of the shell model in the study of exotic nuclei; (4) Nuclear structure aspects outside the shell model. Focal points of current developments in the study of nuclear structure and future challenges have been highlighted from the experimental and theoretical point of view. Several talks have shown how the advent of radioactive beams has substantially improved our knowledge of nuclear structure and how the next generation facilities will open the way to new perspectives. On the theory front, the discussion focused on the...
progress made toward a microscopic theory capable of describing the properties of nuclei and nuclear reactions, with particular attention on our understanding of nuclear forces and on the new/improved methods to perform microscopic calculations. The role of symmetries in nuclear physics was also emphasized.

A session was dedicated to special topics as, for instance, the nuclear astrophysical frontier and that of the neutrino physics, while the main conclusions of the meeting were drawn in two final keynotes talks given by Amand Faessler and Franco Iachello.

The meeting has greatly benefited from the expertise of scientists who have significantly contributed to the advancement of nuclear physics research as well as from the large international participation. In fact, the conference had about 90 participants from some 20 countries. This is well in line with the tradition of these meetings, as is the fact that more than 50% of the present participants attended one or more of the previous Seminars.


The Seminar took place in a pleasant thermal hotel located in Ischia, a volcanic island in Gulf of Naples, and was sponsored by the University and the Department of Physics of Naples, and the Italian Institute for Nuclear Physics.

Acknowledgments
This report is written in Honor of Aldo Covello.

ANGELO GARGANO
INFN, Sezione di Napoli, Italy

Figure 3. Aldo Covello at the conference dinner.

Figure 4. Group photo from the 11th International Spring Seminar on Nuclear Physics, May 2014.
TRIUMF was honored to host the 15th international conference on Nuclear Structure (NS2014) which was held from 20–25 July 2014 on the campus of the University of British Columbia (UBC) in Vancouver, Canada (Figure 1). This biennial conference series has evolved to cover the latest results on experimental and theoretical research into the structure of nuclei at the extremes of isospin, excitation energy, mass, and angular momentum. Special emphasis was given to the physics and techniques associated with gamma-ray spectroscopy; however, atomic, mass, and charged-particle spectroscopy were also represented. This series is organized by North American national laboratories, and returned to Canada for the first time since 1992.

Of the 180 abstracts contributed, based on the recommendations of the International Advisory Committee, 44 were selected to complement the 21 invited speakers. An additional 70 contributions were presented as posters. During the poster session an international ad-hoc committee selected the best student presentations with the top three students receiving cash prizes and diplomas.

The conference began with invited talks on experimental and theoretical investigations of the role of three-nucleon forces in medium-mass nuclei. The measured and predicted structure of neutron-rich nuclei were strongly represented in the program. There were also selected sessions devoted to topics such as octupole and quadrupole collectivity, mirror or nearly mirror nuclei, nuclear tests of fundamental forces and symmetries, and superheavy nuclei. A session on high-$K$ isomers was dedicated to the late Professor George D. Dracoulis, a pioneer in this field and a regular participant in this conference series, who passed away in June 2014 at age 69. Although it is difficult to select highlights from this comprehensive program, some of the more intriguing experimental results included decay spectroscopy of the Element 115 daughters, the influence of new beta-decay measurements with EURICA on $r$-process nucleosynthesis, and direct evidence for a strong prolate deformation in the self-conjugate nucleus $^{72}$Kr. The conference concluded with updates on major gamma-ray detector arrays around the world and nuclear physics research facilities in North America. Electronic versions of the oral presentations can be freely accessed through the website http://ns2014.triumf.ca.

Outside of the lecture hall, the delegates had the chance to visit some of

Figure 1. Attendees of the 15th International Conference on Nuclear Structure (NS2014).
UBC’s and Vancouver’s attractions, including a tour of TRIUMF, an excursion to Grouse Mountain or a boat cruise up the Indian Arm, and a visit including the conference dinner at the UBC Museum of Anthropology.

Representatives of the current and prior organizing committees selected Oak Ridge National Laboratory as the host of the next conference in this series in 2016.

Following the conference, about 25 participants joined the 1.5 day “3rd North American Workshop on Beta-Delayed Neutron Emission.” This year’s workshop celebrated the 75th anniversary of the discovery of beta-delayed neutron emission in 1939 with 12 talks dedicated to the ongoing and future projects in many radioactive-beam facilities around the world, including TRIUMF’s ISAC and future ARIEL facility.

The organizing committee thanks the International Advisory Committee for their wise guidance, and thankfully acknowledges generous funding from our sponsors: Canberra, the Canadian Institute for Nuclear Physics, the Division of Nuclear Physics of the Canadian Association of Physicists, Simon Fraser University, University of British Columbia, AAPS, Nordion, and TRIUMF.
The project Extreme Light Infrastructure–Nuclear Physics (ELI–NP) [1], to build in Romania a European research center to study ultraintense lasers interaction with matter and nuclear science using gamma and laser beams, ends in December 2014 the second year of its implementation. The new research center will be located in Magurele, a town a few kilometers away from Bucharest, Romania. The project is implemented by “Horia Hulubei” National Institute for Physics and Nuclear Engineering (IFIN-HH). ELI–NP will host two 10 PW lasers and a gamma beam system producing gamma beams with parameters beyond those available at the present state of the art machines. At ELI–NP two well-established scientific communities, high-power lasers and nuclear physics, have joined their efforts to build a new interdisciplinary facility and to define its research program [2–4]. As a result of this collaboration the scientific interest of ELI–NP is covering a broad range of key topics in frontier fundamental physics and nuclear physics. The total cost of the facility will be 300 million euro, without value-added tax (VAT). In September 2012, the project was approved by the European Commission and the first phase was financed with 180 million euro, with 83% financial support from the existing Structural Funds cycle, which ends in 2015 and 17% from the Romanian National Budget. The second phase of financing will be granted in the next Structural Funds cycle which will start in 2015. The entire facility will be operational in 2018.

ELI–NP Buildings Complex and Major Equipment

The ELI–NP main buildings complex, covering more than 15,000 m², is dedicated to the experimental activities and it will host the main research equipment, the experimental areas, laboratories and workshops, control rooms, and user area. The high spatial accuracy of the laser and gamma beam is a special design of the concrete base plate of the building to prevent vibrations. The state of the art equipment will require special clean-room, temperature, and humidity conditions. The architect’s vision of the main buildings complex is shown in Figure 1. Other buildings under construction are the office building, a guest house and a canteen. The construction of the building complex started in May 2013 and will be completed in 2015. Figure 2 shows the status of the construction in December of 2014.

ELI–NP hosts two major research equipment with beyond state-of-the-art characteristics: a high-power laser system (HPLS), with two arms—reaching up to 10 PW for each arm—and a gamma-beam system (GBS) that will provide very intense and narrowband gamma-rays with energies up to 19 MeV.

The high-power laser system of ELI–NP consists of two 10 PW lasers based on Optical Parametric Chirped Pulse Amplification (OPCPA) [5, 6] at about 820 nm central wavelength, with a dual front-end architecture with two parallel amplification arms. Each of the two parallel chains includes Ti: Sapphire amplifiers to bring the final output energy to the level of a few hundreds of Joule. Subsequently, the pulses are compressed to around a 20 fs pulse duration that implies a peak power of 10 PW at a repetition rate of 1 shot per min for each of the two arms [7]. Along the two amplifi-
cation chains, additional outputs with corresponding optical compressors will be installed. Their corresponding power levels are 0.1 PW and 1 PW at repetition rates of 10 Hz and 1 Hz, respectively. For the two 10 PW outputs an unprecedented level of intensity of about $10^{23}$–$10^{24}$ W/cm$^2$ will be achieved. Out of the six possible outputs on the two arms, two of them, one from each arm, can be provided simultaneously for experiments, combined in the same experimental setup or to be used independently in two different setups. The HPLS is being built by Thales Optronique France and Thales Romania (Figure 3).

The Gamma Beam System (GBS) for ELI–NP was designed to provide a very intense and brilliant gamma beam with tunable energy based on the incoherent inverse Compton scattering of a high repetition pulsed laser beam on a high intensity, low emittance, relativistic electron beam. The electron accelerator will be a warm linac, with two acceleration stages of 360 MeV each [8, 9]. The gamma beam up to 19 MeV will have a bandwidth smaller than 0.5%. The very low cross-section for Compton scattering will be compensated in obtaining high brilliance gamma beam by very intense high repetition rate photon beam, very intense low emittance electron beam and a very small and precise interaction volume. The ELI–NP GBS is being constructed by EuroGammaS [8], a European Consortium of academic and research institutions and industrial partners with expertise in the field of electron accelerators and laser technology from 8 European countries, consortium led by INFN Italy. A layout of the Gamma Beam system is displayed in Figure 4.

The ELI–NP Scientific Program

The scientific case for ELI–NP was elaborated by an international collaboration of more than 100 scientists from 30 countries and published as the ELI–NP White Book [10]. It is based on the unique features of the high–power laser and gamma beams. The main research topics of interest are: laser driven nuclear physics experiments, characterization of the laser–target interaction by the means of nuclear physics methods, photonuclear reactions, exotic nuclear physics and astrophysics. In addition to fundamental themes, applications of HPLS and GBS are under study. Accelerated particles produced by laser-matter interaction radiation-induced damage, and gamma beams–induced nuclear reactions are major active research areas in nuclear physics and engineering. Their applications extend from the nuclear power plants to medicine and from space science to material science.

The ELI–NP team, together with their collaborators from the international scientific community, shaped the future scientific program of ELI–NP in a series of workshops and de-
fined ten development directions for the facility. The Technical Design Reports (TDRs) are being finalized and in the first part of 2015 will be approved by the scientific community and by the ELI–NP International Scientific Advisory Board.

Eight experimental areas will be available for performing experiments using the laser beams, the gamma beams or combined.

**Laser-Driven Nuclear Physics Experiments**

One of the most exciting driving forces behind the studies of the high-intensity laser interaction with matter is the perspective of obtaining laser-driven particles beams with characteristics similar to those obtained with conventional accelerators but, potentially, much less expensive. The present energy frontier of high energy physics is several TeV, but colliders capable of reaching this regime are very costly to build. Relatively expensive are also the accelerators used for science, hadron-therapy, or synchrotrons for material studies. Virtually all of today’s accelerators are using the electric field generated between conducting electrodes or electromagnetic cavities. In this approach electrical breakdown limits the maximum field to less than 100 MV/m. Laser-based accelerators have the potential to deliver accelerating gradients more than 1,000 times higher than in conventional accelerator technology, reducing the required accelerator length by the same factor. This large increase in accelerating gradient for laser technology is the key to reducing the size up to a tabletop scale and reducing associated cost over conventional accelerators. It is expected that the compact, high repetition rate, tabletop laser will define the future for laser-driven nuclear and particle phenomena [11].

The observation of high brilliance beams of multi-MeV protons from solid targets has stimulated an enormous amount of studies. However, the laser-driven beams have yet to achieve the quality of conventional accelerator beams and, consequently, systematic studies should be performed in order to obtain mono-energetic particle beams. This novel technology must be followed by the development of diagnostics and suitable detectors for such beams with \(10^8–10^{12}\) particles in 1 ps pulse at 1–200 Hz repetition rate. For this purpose, typical nuclear physics studies, with specific methods and tools, are extremely important for the development of this new field.

As a leading facility in laser-driven nuclear physics, ELI–NP will take advantage of the high intensity laser beams. Acceleration of ions with high-power lasers offers unique features such as production of beams with solid target densities and large acceleration over very short distances. Laser acceleration of heavy ions will be investigated and the possibility to use it for nuclear reactions.

The flagship experiment involves production of neutron rich isotopes using fission of Th and subsequent fusion process [12], to shed light on the formation of heavy elements (beyond Fe) in the universe. The needed data for the formation of heavy elements in the region of lead (Z = 82) and beyond are those related to very neutron-rich isotopes. The fusion cross-section even with secondary beams of radio-isotopes is so low that in practice these key measurements are not within reach today. Using HPLS with a CD\(_2\) production target and a very thin Th target, one may reach fusion of two very neutron-rich isotopes originating from the fission of Th (e.g., fusion of Z = 35) leading to this unknown mass region. First circular polarized laser beam incident on production target produces, through Radiation Pressure Acceleration (RPA) mechanism, a high density bunch of \(^{232}\)Th, \(^{12}\)C, and D ions. Then fission reactions will take place. \(^{232}\)Th ion bunches interacts with \(^{12}\)C (or \(^1\)H) in the 1st layer and \(^{12}\)C and D nuclei interacts with \(^{232}\)Th in the 2nd layer of reaction target. Following their production, the two light fission fragments fuse in the reaction target and neutron rich nuclei (close to \(N = 126\)) are produced. Such experiments require significant experimental development in the field of laser-driven ion acceleration in order to produce intense heavy-ion bunches in the 5–10 MeV/u energy range relevant for fission and fusion reactions.

Experiments related to strong-field quantum electrodynamics are also planned. The tightly focused beams up to \(10^{23}\) W/cm\(^2\) on solid targets will
be used for electron positron pair creation studies. The pair production can be enhanced by combining the laser and gamma beams.

The high-repetition rate 0.1 PW and 1 PW beams, where laser pulses produce relatively broadband spectrum of secondary radiation (electrons, gamma, protons, neutrons and positrons), are proposed to study the material behavior under extreme conditions of radiation.

**Nuclear Science and Applications with High Brilliance Low-Energy Gamma Beams**

The ELI–NP gamma beam experimental program will explore new territory in the field of Nuclear Resonance Fluorescence (NRF) [13] and experiments above the particle separation threshold such as studies of giant resonances, nuclear astrophysics reactions, and photo-fission experiments. The narrow bandwidth beam excites a single excited state, whose decay is studied in the experiment. The excited state can be below or above the particle separation energy. In the former case, the NRF method is applied and, in the latter case, induced reactions, such as $(\gamma, n)$, $(\gamma, p)$, are proposed to study the material behavior under extreme conditions of radiation.

An intense and high-energy resolving $\gamma$-ray beam from ELI–NP will open up new horizons for the investigation of the nuclear photo-response at and above the separation threshold. Both the GDR and the PDR can be covered within the energy range of the ELI–NP beams. In the experiments the excitation functions for elastic and inelastic scattering will be measured, revealing possible fine-structures/splitting of the Giant Dipole Resonance (GDR) and the Pigmy Dipole Resonance (PDR). The excitation function with high resolution for $(\gamma, n)$ and $(\gamma, \text{charged-particle})$ channels, allows the determination of the branching ratios for various decay channels. The polarized beam will also allow the determination of the $E1$ or $M1$ type of excitation for the observed structures.

Photo-fission is also a topic where ELI–NP gamma beam will bring significant advances. So far bremsstrahlung was used to induce fission of actinide nuclei. Two classes of experiments have been identified: investigations of the fission potential barrier and the high efficiency production of neutron rich nuclei through photo-fission of $^{238}\text{U}$ nuclei. High-resolution photo-fission of the second and third potential minima in actinide nuclei, angular and mass distribution, cross-sections, studies of rare photo-fission events, such as triple fission and highly asymmetric fission will be investigated.

Gamma beams of 15 MeV are highly efficient for producing short-lived and refractory elements in thin $^{238}\text{U}$ targets using a gas-cell catcher (IGISOL technique). After their separation, the nuclei of interest can be transported to different measurement stations.

The ELI–NP facility provides unique opportunities for nuclear astrophysics research. Gamma-induced nuclear reactions of astrophysical interest still represent a challenge due to their very low cross-sections as the reactions occur deep below the Coulomb barrier. The study of these reactions will benefit from the use of the high intensity gamma beams at ELI–NP. Laboratory astrophysics experiments aiming at explaining the nucleosynthesis processes will be possible, through direct or inverse reactions. To advance the explanation of the formation of a large part of the known elements in the Universe, reactions relevant for the $p$- and $r$-processes will be investigated. All $p$-nuclei can be synthesized from the destruction of pre-existing nuclei of the $s$- and $r$-type by a combination of $(p, \gamma)$ captures and $(\gamma, n)$, $(\gamma, p)$ or $(\gamma, a)$ photo-reactions [14]. In particu-
lar, charged-particle detector systems, needed to measure nuclear reaction cross-sections of the proton and alpha burning processes and—most importantly—the $^{12}$C$(\alpha, \gamma)$ reaction cross-section relevant for stellar helium burning, will be investigated.

In order to carry out the scientific program discussed above, a number of different state-of-the-art instruments are being considered. These include: a high-resolution spectrometer of (segmented) large HPGe (clover) detectors, combined with good timing, for example, LaBr$_3$ detectors, a spectrometer with medium resolution of large LaBr$_3$ detectors and a neutron detector array, a tape station and a close-geometry spectrometer for high-resolution decay studies, a 4π charged-particle array of segmented DSSSD detectors and a TPC gas cell for astrophysics reaction measurements.

In addition, a variety of applied research experiments are proposed using low-energy brilliant intense gamma, neutron, and positron beams, which will open new fields in materials science and life sciences. The new production schemes of medical isotopes [15] (e.g., $^{99}$Mo currently used in therapies, $^{195}$Ir for nuclear imaging to determine efficiency of chemotherapy, and $^{117}$In, an emitter of low-energy Auger electrons for tumor therapy) via $(\gamma, n)$ processes may also reach socioeconomical relevance. Computed tomography with gamma-ray beams for non-destructive inspection of objects will also benefit from high-energy quasi-monochromatic and high beam intensity to shorten the scanning time. The gamma beams will also be used to produce positrons in a converter foil via the $(\gamma, e^-e^+)$ process. After moderation, the positrons will be used for material science, as probes for defect spectroscopy to depths up to several 100 nm.

Conclusions

The ELI–NP facility combines two major research equipment with beyond state-of-the-art parameters, namely a high power laser system with two amplification arms to deliver 10 PW and intensities on the target in the range of $10^{23}$ W/cm$^2$ at least every minute and, a gamma beam system to deliver up to 19 MeV photons with extremely good brilliance and bandwidth. Their outstanding performances will allow the exploration of new frontiers in nuclear physics. Benefiting from the support of a large number of specialists across the globe, the ELI–NP facility is on track with TDR and construction of the experimental areas. Commissioning is expected to take place in 2018.

Acknowledgments

The ELI–NP project is the result of an international collaborative effort of more than 100 scientists from 20 countries and their contribution to the definition and implementation of the project scientific program is gratefully acknowledged. The tremendous work of the ELI–NP scientific team and the essential contribution of my enthusiastic and tenacious colleagues from the Management team in the implementation of the project are also deeply acknowledged.

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References

1. www.eli-np.ro
9. C. Ur et al., Zakopane Conference on Nuclear Physics, 2014, Poland.

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Be sure to check the Calendar for upcoming events of interest to nuclear scientists.
IUPAP Young Scientist Prize in Nuclear Physics

This prize was established by IUPAP in 2005 at the time of the General Assembly in Capetown, South Africa. The purpose of this prize, which consists of 1,000€, a medal, and a certificate citing the recipient’s contributions, is:

To recognize and encourage very promising experimental or theoretical research in nuclear physics, including the advancement of a method, a procedure, a technique, or a device that contributes in a significant way to nuclear physics research. Candidates for the prize must have a maximum of eight years of research experience (excluding career interruptions) following the Ph.D. (or equivalent) degree.

Nominations by one or two nominators (and distinct from the nominee) are open to all experimental and theoretical nuclear physicists. The nomination package should contain, other than the nomination letter, at least two additional letters of support, the curriculum vitae of the nominee containing also the list of publications. Three prizes will ordinarily be awarded at the time of the tri-annual International Nuclear Physics Conference.

Nominations are due 1 December 2015 and are valid only until then. The additional letters supporting the nomination should detail the expected significance of the contributions of the nominee to nuclear physics. To underline this, additional material such as published articles can be added to the nomination package. Especially information that allows the selection committee to evaluate the nominee’s contribution to and its direct impact on the field.

Nominations for prizes to be awarded at the next International Nuclear Physics Conference, 11–16 September 2016, in Adelaide, Australia, are to be sent by e-mail by 1 December 2015 to the Chair of the IUPAP Commission of Nuclear Physics (C12): Professor Alinka Lépine-Szily, Institut of Physics, University of São Paulo, alinka@if.usp.br, subject “IUPAP prize nomination.”

Alinka Lépine-Szily
Institut of Physics, University of São Paulo, São Paulo, Brazil

2015 - 2016 Free Event Listings

Conferences  Workshops  Schools

If you are planning a future event, ensure that the nuclear physics community is aware of it by sending the dates, location and contact details as soon as they are available to:

sissy.koerner@ph.tum.de
2015

September 27–October 3
Kobe, Japan. Quark Matter 2015
http://qm2015.riken.jp/

October 1–3
Osaka, Japan. “Frontiers of gamma-ray spectroscopy” (Gamma 15)
http://www.rcnp.osaka-u.ac.jp/index/event/829/

October 4–11
Kemer (Antalya), Turkey. Fifth International Conference on Nuclear Fragmentation NUFRA2015
http://fias.uni-frankfurt.de/historical/nufra2015/

October 8–10
Sofia, Bulgaria. Shapes and Dynamics of Atomic Nuclei: Contemporary Aspects SDANCA-15
http://ntl.inrne.bas.bg/events/sdanca15/

October 12–16
Shanghai, China. 12th International Computational Accelerator Physics Conference, ICAP’15
http://icap2015.csp.esience.cn/dct/page/1

October 17–23
Melbourne, Australia. 15th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 2015)
http://www.icalepcs2015.org/

October 19–23
Tokyo, Japan. Fifth International Workshop on Compound-Nuclear Reactions and Related Topics, CNR*15
http://www.nr.titech.ac.jp/~chiba/CNR15/index.html

November 1–7
Paphos, Cyprus. Electromagnetic Interactions with Nucleons and Nuclei (EINN)
http://www.cyprusconferences.org/einn2015/

November 10–13
Washington, DC, USA. 12th International Topical Meeting on Nuclear Applications of Accelerators (AccApp’15)
http://aad.ans.org/meetings.html

November 12–13
Caserta, Italy. Workshop on Nuclear Astrophysics at SPES
https://agenda.infn.it/conferenceDisplay.py?confId=9725

December 1–5
Medellin, Colombia. The XI Latin American Symposium on Nuclear Physics and Applications
http://www.gfnum.umal.edu.co/LASNPAXI/

December 15–20
Honolulu, HI, USA. International Chemical Congress of Pacific Basin Societies, PACIFICHEM 2015
http://www.pacificchem.org/

2016

February 22–28
Bormio, Italy. Third Topical Workshop on Modern Aspects in Nuclear Structure
https://sites.google.com/site/wsbornomi2016/

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

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/

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

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

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/

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