The nu-ball project

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Summary

The nu-ball project is the construction and deployment of a hybrid, high efficiency gamma-ray spectrometer at the ALTO facility of the IPN Orsay. It aims to exploit unique features of the ALTO installation, such as coupling to the LICORNE high flux directional neutron source[1], to perform experiments at the forefront of research in both nuclear structure and nuclear fission. The main goals of the project are as follows: (i) To perform gamma-ray spectroscopy of the ^{238}U(n,f) and ^{232}Th(n,f) neutron induced reactions as a novel technique to gain unique information on the nuclear structure of very-neutron rich fission products at high spin; (ii) To gain a deeper understanding of the nuclear fission mechanism by measuring new fission observables such as gamma-ray total energy and multiplicity distributions correlated with individual fission fragments pairs; (iii) to push the limits of the hybrid spectrometer technique to perform lifetime measurements of excited nuclear states in the 10 ps – 10 ns range to extract information on nuclear moments; (iv) To facilitate original nuclear spectroscopy experiments at the ALTO facility for national and international users of the facility.

1. The key scientific questions

The key scientific questions addressed by the nu-ball project are as follows:

- Understanding the nuclear structure of very neutron-rich isotopes far from nuclear stability, which are only produced in nature in astrophysical environments and are the precursors of the stable nuclei here on earth.
- To gain a better understanding of the process of nuclear fission by coupling a unique spectrometer with a unique directional neutron source to study fast neutron-induced fission. In particular nu-ball addresses important questions such as understanding the origin of angular momentum in fission, the sharing of energy between fragments and understanding the configuration at fission, the fission yield distributions Y(A,Z) as a function of excitation energy and the competition between neutron and gamma emission in the de-exciting fragments.
- The extraction of nuclear moments from lifetime measurements using fast timing techniques with the $LaBr_3$ scintillator part of the spectrometer, and searching for nano-second or sub-nano second isomeric states in atomic nuclei, which have been unable to be detected at present.
- In addition, a whole host of other important physics questions were addressed during the first nu-ball campaign in experiments carried out on the device by national and international users of the ALTO facility, for example, studying the super-allowed beta-decay of ^{10}C to test the weak interaction and unitarity of the CKM matrix[2], or studying the Giant-Dipole Resonance (GDR) feeding of low-energy structures with different deformations[3], using nu-ball coupled to the PARIS array[4].

The nu-ball project can be considered state-of-the art due to the uniqueness of certain aspects of the ALTO facility such as the LICORNE neutron source, and the innovative nature of the spectrometer - coupling Ge detectors with $LaBr_3$ detectors or clusters from the PARIS array. Furthermore, the array uses state-of-the art digitization technology for all the detector signals, which permits merging of radically different detector types into the same data stream, and event-by-event calorimetry measurements. The project addresses outstanding problems in nuclear structure and nuclear fission, and is intended to provide complementary information to other facilities. For example, the big facilities RIKEN in Japan (SEASTAR project[5]) have made important advances in discovering first excited states in a whole range of very neutron-rich nuclei over the past few years. However, the high beam velocities used which allow excellent selection of the nuclei of interest have an associated severe Doppler broadening of emitted prompt gamma-rays, and this places considerable limits on the sensitivity. These discoveries then require further detailed and complementary information on excited nuclear states, which exactly what the nu-ball project can provide.

2. The nu-ball project description

The nu-ball spectrometer can be seen in figure 1 and an inner view showing the coupling to LICORNE in figure 2. The array in its standard configuration comprises of 174 separate detectors and is a hybrid spectrometer covering around 75% of 4π steradians of solid angle. The three main detector types are as follows: Germanium detectors with excellent energy resolution (~2.5 keV at 1.33 MeV); LaBr3 scintillators with excellent intrinsic time resolution (~150 – 200 ps), and Bismuth Germinate Oxide (BGO) high-density scintillators for efficient Compton suppression of scattered gamma-rays. Twenty four Compton suppressed germanium clover detectors and their corresponding BGO shields are positioned at angles near 90 degrees with respect to the beam axis with another 10 coaxial germanium detectors placed at backward angles. Twenty $LaBr_3$ detectors are placed at forward angles, since these detectors are resilient to neutron damage from elastic scattering of neutrons from the actinide target which occurs mostly at small angles. The clover detectors were been borrowed from the GammaPool[6] and the $LaBr_3$ scintillators from the FATIMA collaboration[7].

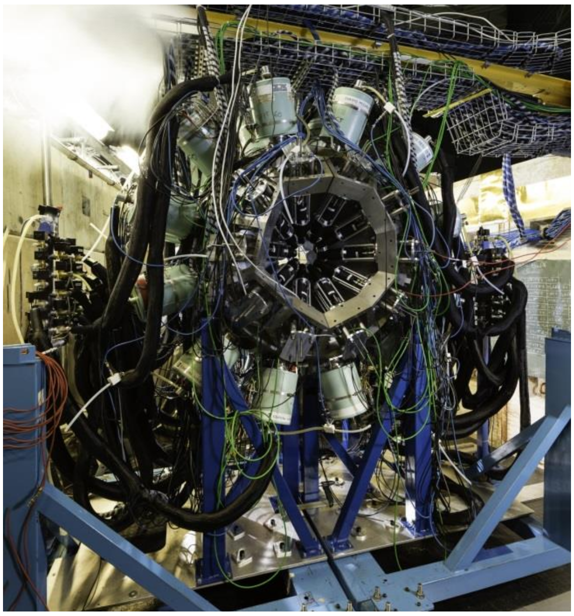
Figure 1 The nu-ball spectrometer installed at the ALTO facility of the IPN Orsay

While large gamma-ray spectrometers have been in existence since the early 1990’s[8][9] the nu-ball array has three particular innovations which make it uniquely able to respond to current scientific questions in nuclear physics research:

- A hybrid spectrometer: Combining $LaBr_3$ fast scintillator detectors with the selectivity associated with high-resolution germanium detectors allows the construction of a unique instrument. A hybrid array combines the best aspects of the two different detector types. Germanium detectors provide the required level of channel selectivity by allowing individual isotope gating on one or two discrete-energy transitions from the nuclide in question, while $LaBr_3$ coincidences can provide some additional gamma-ray energy selectivity together with the (sub-nanosecond) fast timing information[10]. Excited state lifetimes of nuclear states down to tens of picoseconds can be measured directly providing access to electromagnetic transition strengths and reduced matrix probabilities, which ultimately allow the determination of other nuclear structure observables such as nuclear moments (e.g. quadrupole deformations).

- Calorimetry: The anti-Compton shields made of BGO scintillator in nu-ball play a dual role to both veto gamma-rays escaping from the central germanium elements that have not deposited their full photo-peak energy in the Ge crystal, and to directly detect gamma-rays coming from the fission reaction. The BGO's have their heavy metal collimators removed to be directly in the line of sight of the target. The advantage is that it gives valuable information on the sum energy and multiplicity of each event which can then be used to separate fission events from unwanted background processes (e.g. inelastic neutron scattering ^{238}U(n,n'γ) , Coulomb excitation of the primary ^{7}Li beam ^{7}Li(p,p' γ), or beta decays occurring in the target). This extra selectivity comes at the price of a slightly decreased peak-to-total ratio for the array and the small possibility of fission gamma-rays being falsely vetoed by each other in the same Ge/BGO module. The latter effect occurs with typically ~3% probability because the average gamma ray multiplicity in fission is low (typically ~8).

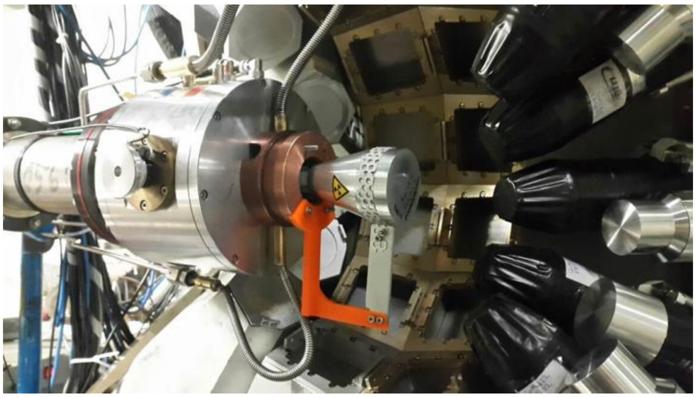

Figure 2 The nu-ball array coupled to the LICORNE neutron source. The 232Th high-mass, low-density target can be seen in the centre.

- A fully digital data acquisition system: The digital acquisition system (DAQ) for nu-ball is based on the FASTER digitizer system[11] built by our sister laboratory at LPC Caen. The DAQ can operate in both triggered or triggerless modes with each detection event given its unique 64-bit time stamp in the data stream. Various pre-programmed algorithms can be used to process the digitized signals e.g. ADC, QDC, TDC, etc. 12-bit CARAS 500 MHz digitizers are used for fast scintillator detectors and 14-bit MOSAHR 125 MHz digitzers are used for the germanium detectors. The two types of card can be combined on the same mother board and mixed in slots in the same electronics crate. Hence the FASTER system has a great flexibility for mixing very different types of detector in the same DAQ system. A common clock is provided for multiple crates, so all timestamps are synchronized in the data stream.

3. The nu-ball timeline

The nuball project began as the logical extension of a research program developed around the LICORNE directional neutron source, using state-of-the art detectors to measure prompt gamma-ray emission in fission. The LICORNE source began life in 2012 with internal financing from the IPN Orsay. The performance and available fluxes increased significantly over time and spectroscopy of neutron-induced reactions using LICORNE was evaluated positively by the scientific council of the IPN Orsay in 2015. The first coupling to a high efficiency spectrometer was a first successful experiment during the Miniball/Minorca campaign at IPN in 2016, which resulted in the publication of a Physical Review letter on Fission yield Measurements in ^{238}U(n,f)[12]. The nu-ball project began as an international Letter of Intent in 2015 signed by scientists from 14 different institutions [13]. An overview of the timeline can be seen in figure 3.

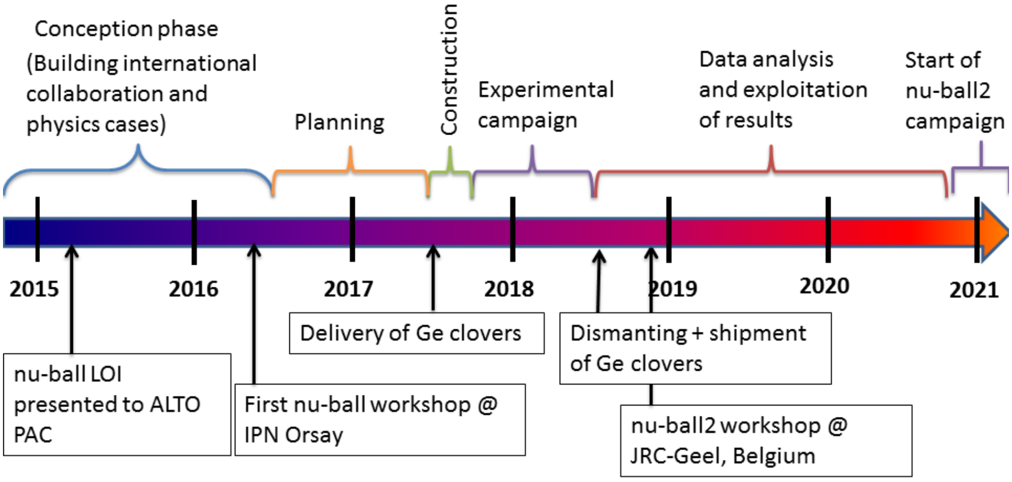

Figure 3 The nu-ball project timeline

To pave the way for the first nu-ball experimental campaign, a scientific workshop was held in May 2016 at the IPN Orsay, with over 40 international participants from the gamma spectroscopy and fast timing communities in Europe and beyond. A memorandum, of understanding (MOU) was signed with the GammaPool which provided 28 Germanium clover detectors, holding frame, some cables and some high voltage supplies for the project. A second MOU was signed between the IPN Orsay and IFJ PAN, the institute in Krakow Poland which manufactured the mechanical structures to couple nu-ball with four PARIS clusters.

Many proposals were evaluated by the IPN program advisory committee in early 2017 and the first nu-ball campaign ran from November 2017 until June 2018. Ten experiments were performed in total and over 3200 hours of beam time delivered. In total 153 scientists from 37 national and international institutions participated in the campaign, showing a strong interest in the ALTO facility and nu-ball device in particular from the international community. A total of 80 Ph.D students participated in the campaign.

The expected scientific production is a series of high-impact publications from the majority of experiments which succeeded during the campaign. In addition, nu-ball data will be used directly in several Ph.D. theses. The experimental campaign also recently featured in the December 2018 issue of Nuclear Physics News, the journal of Nupecc, the European Nuclear Physics collaboration committee [14]. A second nu-ball experimental campaign is being planned for the beginning of 2021, provided the necessary resources to run it are made available.

4. State-of-the-art

Both in-flight an ISOL facilities aim to achieve excellent selectivity of very exotic nuclei, either by using either high-velocity beams in the case of in-flight or chemical/mass separation of

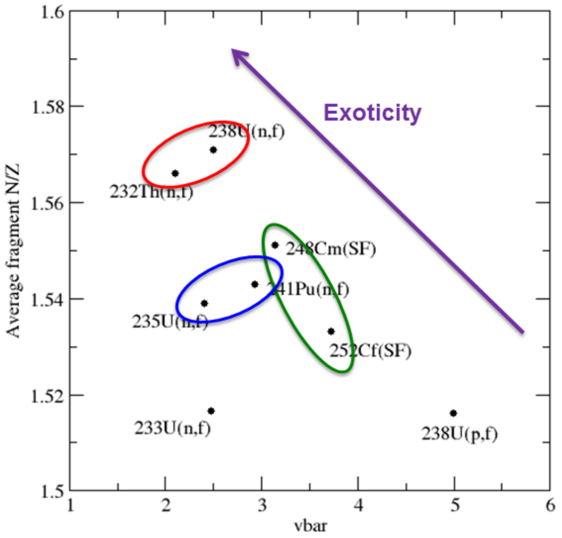

Figure 4 Available fission reaction mechanisms for producing and studying neutron-rich nuclei. The spontaneous fission sources are circled in green. The reactions studied with EXILL/FIPPS are circled in blue and the reactions that are uniquely currently available for study with nu-ball @ALTO are circled in red.

beams to study beta-decay daughters in the case of ISOL. With both techniques, the possibility to observe excited states of exotic nuclei at higher spins is limited due to either extreme Doppler broadening in the case of in-flight, or population of only low-spin states in the case of ISOL/beta-decay.

On the neutron rich side of the nuclear chart, spectroscopy of higher spin states was initially performed using spontaneous fission sources of ^{248}Cm and ^{252}Cf inside spectrometers such as Gammasphere and Euroball. However, these experiments have now reached the limit of their potential sensitivity (10^{-5} of the total SF reaction cross section). To investigate lighter fission fragments a first campaign to study the ^{235}U(n,f) reaction using thermal neutrons to induce fission at the ILL reactor in Grenoble was initiated. This campaign, called EXILL (the Exogam spectrometer at ILL), eventually grew into the FIPPS project[15], where a high efficiency Ge spectrometer has recently been constructed permanently at the ILL. However, these new reaction mechanisms are not the best available. Figure 4 shows that ^{238}U(n,f) and ^{232}Th(n,f) can reach more exotic nuclear species, however, these reactions have a threshold of around 1.2 MeV, and thus require fast neutrons. The technical problems on how to run these reactions inside a spectrometer with a high-flux neutron source without hitting the detectors with source neutrons have now been technical solved with the development of LICORNE@ALTO (directional high-flux source) and the use of high-mass low-density actinide targets, also developed at the IPN Orsay. In particular, the use of ^{232}Th(n,f) facilitates access to a whole region of unexplored territory just above the doubly magic nucleus ^{78}Ni.

The state-of-the art detection system for fission calorimetry studies is the DANCE array[16] at Los Alamos. However, while the calorimeter performance exceeds that of nu-ball, the array consists entirely of BaF_2 gamma detectors with very poor resolution. Thus no correlations between individual fission fragment pairs and fission observables can be studied with DANCE. In addition, the $LaBr_3$ detectors in nu-ball can be used to also detect neutrons by using time-of-flight techniques relative to the neutron beam pulsation. For $LaBr_3$ the flight path is a distance of 10-20 cm and for the Ge/BGO detectors it is 25 – 40 cm. For nu-ball $LaBr_3$ detectors perfect neutron/gamma separation is achieved due to their extremely good timing properties. For the Ge and BGO detectors, the separation is reasonable and reduces the neutron component of the fission calorimetry to less than 5% of the total. Hence, correlations between gamma multiplicities, neutron multiplicities and fission fragment pairs can also be studied with nu-ball. This is something that is impossible with any other current state-of-the art device.

The state-of-the-art for mixd hybrid Ge/$LaBr_3$ spectrometers for nuclear structure studies is the Rhosphere array in Bucharest[17]. However, nu-ball outperforms this device significantly due to the much higher gamma efficiency (6.7 % at 1 MeV as compared to 2% for Rhosphere). In addition nu-ball has a much higher granularity than rhosphere.

5. The nu-ball project resources

The nu-ball project was financed by the in2p3 between 2017 and 2019 with an average annual budget of around 60 k euro per year, the major costs being purchase of the digital data acquisition system (DAQ), and Ge detector maintenance. The DAQ, however, is a long-term investment in state-of-the art equipment, not just for nu-ball, but for the entire ATLO facility. The previous obsolete DAQ system, which was put into service in 1990, was in urgent need of renewal. Stripping out the DAQ costs, which were intended as an investment for the facility as a whole, the nu-ball average budget was 27 k euro per year over three years, in our view, a very reasonable cost for a device with such a high physics output potential.
The human resources deployed before, during and after the experimental campaign were considerable. In terms of CNRS full time equivalent this is estimated as 6 person-years FTE. The core team list is given in the following table and a photograph shown in figure 5:

Scientific Jonathan Wilson – DR2 (Responsable) Matthieu Lebois – MdC (Responsable) Nikola Jovancevic – Postdoc CNRS Liqiang Qi - Thesard Damien Thisse – Thesard Guillaume Mavilla – Technican Rhiann Canavan (Surrey, UK) – Thesard Matthias Rudigier (Surrey,UK) - Postdoc Rosa-belle Gerst (Köln, DE) - Thesard Joseph Nemer – Stagiaire IPNO Yannick Popovitch – Stagiaire IPNO ***Informatics*** Vincent Lafage (Responsible) Patrick Lejeannic	***Technical staff*** Bernard Genolini – IR1 (Responsable) Mechanics Christine Legalliard – IR1 (Responsable) Ge Detector Maintenance Gabriel Charles – IR2 (Responsable) Nourredine Hammoudi – AI ***ALTO technical staff*** Abdelhakim Said (Responsable ALTO) Robert Leplat Alain Semsoum ***Administration*** Pascale Pichot Celine Gaubert

However, this does not take into account all the help we directly received from the nu-ball collaborators both nationally and internationally who contributed significant help to set up and commission the device, help run the campaign and subsequently analyze experimental data. These contributions are difficult to estimate but certainly account for several extra person-years of FTE. The UK (Surrey) and Germany (Köln) in particular, provided postdocs and thesis students for long periods of time to help with the workload.

6. Technical details

Major technical work went into the mechanical structure to hold the 3 tons of nu-ball detectors and the design and manufacture of the ^{238}U and ^{232}Th low-density, high-mass actinide targets. Most of the work was performed by the IPN Orsay design office, with the out-contracting of manufacturing work to outside companies. Furthermore, modifications were necessary to the LICORNE source to facilitate the coupling and an entirely new target chamber complete with internal camera and rotating target wheel was manufactured using recycled equipment from earlier versions of LICORNE to minimize costs. Where possible equipment was borrowed rather than bought. Costs were deemed too high to buy any of the 1600 cables necessary to run the project, so we had to rely heavily on other laboratories for key pieces of equipment (e.g. cables, power supplies, etc.). The liquid nitrogen autofill system was a modified version of existing equipment at ALTO, dating back to the year 2000, which allowed automatic filling of the 34 Ge detector dewars, again to minimize costs. However, remote monitoring of the temperatures of these fragile and sensitive detectors would be highly desirable in future versions of nu-ball to signal problems and prevent detector damage.

7. SWOT Analysis

Strengths:

- The nu-ball project offers some excellent new scientific opportunities, since it relies on features which are unique (worldwide) to the ALTO facility such as the LICORNE directional neutron source.
- The nu-ball project offers extremely good value for money in terms of the potential for high impact scientific production and the relative low cost.
- The project is exactly the right dimension for the ALTO facility, making it very attractive, which is proven by the large number of international visitors supporting the project. The ALTO facility has relatively large quantities of beam time to devote to the project compared to other facilities. The project has excellent technical support both from IPN Orsay and from the LPC Caen team who built the fully digital DAQ.

Weaknesses.

- Poor local informatics infrastructure (data transfer bandwidth, local data storage, etc.). The technology deployed is lagging significantly behind the current needs. The informatics support for longer-term data storage at the centre de calcul in Lyon is practically inexistent.
- The nu-ball project has far too much dependence on mutualized resources (e.g. Gamma Pool detectors) that maximizes the amount of work (for IPNO) and minimizes the availability of the device.

Opportunities:

- The nu-ball device coupled to the LICORNE directional neutron source presents clear and unique to perform precision in-beam spectroscopy of fast neutron-induced reactions. When nu-ball, and the techniques it deploys, is fully optimized it can (or has already) become a world-beating device in two separate domains: research into new fission process observables and correlations, and the study of the nuclear structure of very neutron-rich nuclei at high spin.

Threats:

- The heavy dependence of the project on mutualized, internationally-used, resources gives an inherent lack of predictability about the future development of the project, and introduces extra unnecessary and preventable risks to the project timeline.

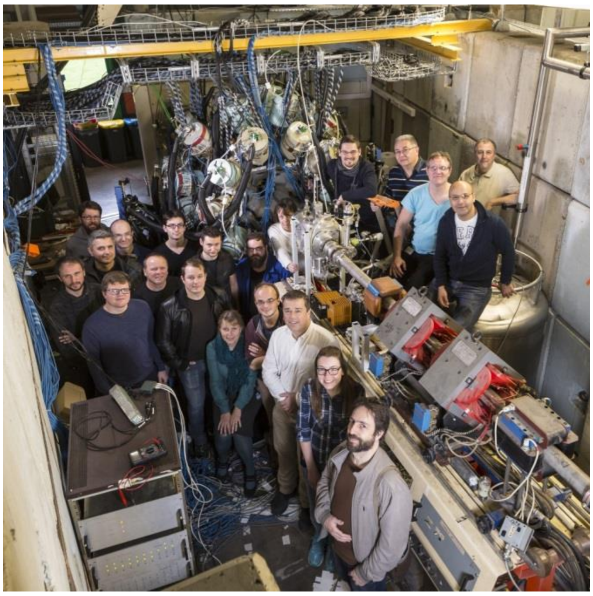

Figure 5 photograph of the core nu-ball team

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