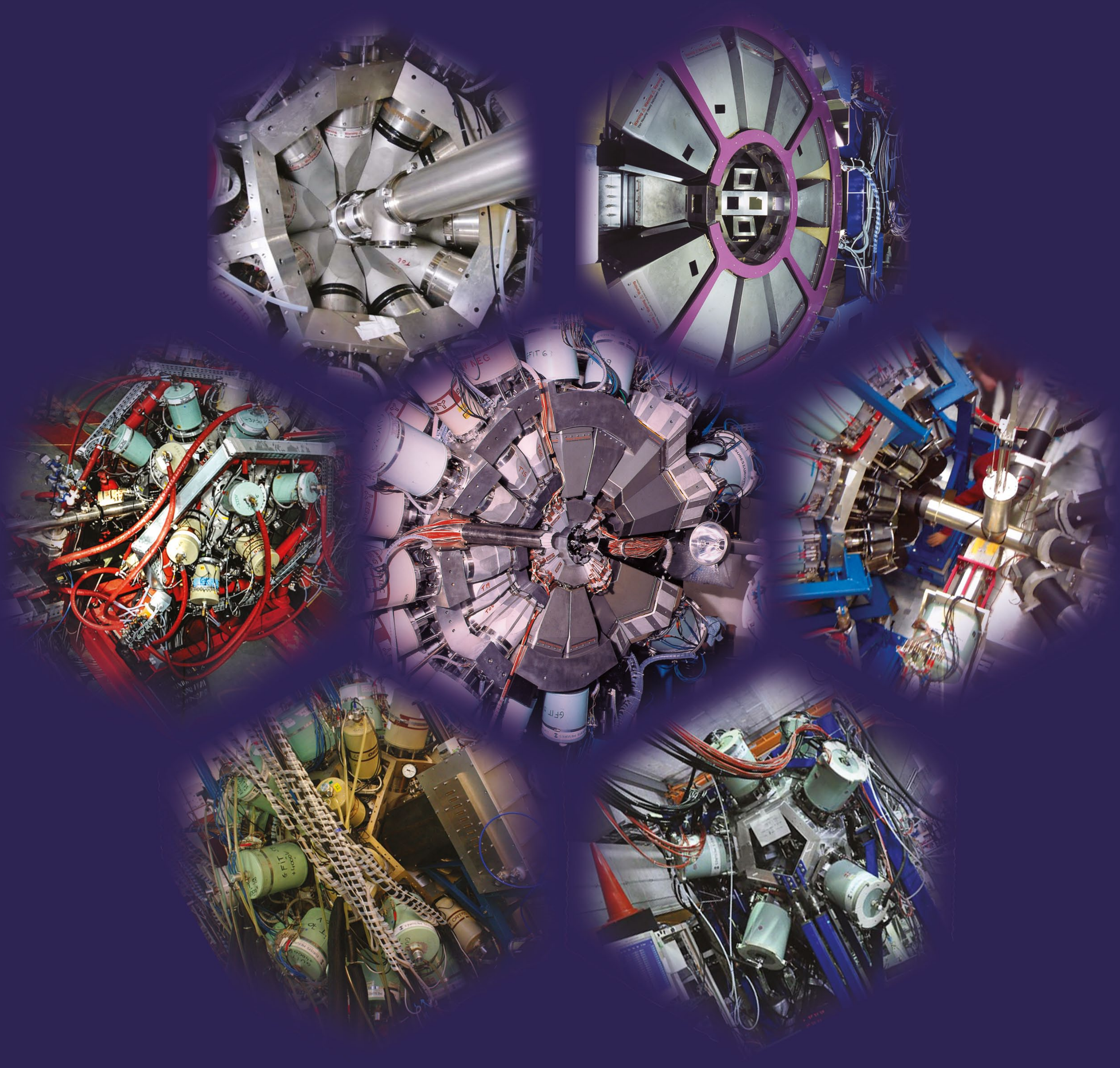
GAMMAPOOL

2003 – 2013

Celebrating the first 10 Years of the European Gamma-Ray Spectroscopy Pool



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David Cullen	UK	member
Benoit Gall	France	home base manager
Magda Gorska	Germany	member
Rolf-Dietmar Herzberg	UK	chair (since April 2008)
Arne Johnson	Sweden	vice chair
Jan Jolie	Germany	member
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Peter Lieb	Germany	(till 2006) succeeded by M. Gorska from October 2008
Santo Lunardi	Italy	succeeded by S. Lenzi from October 2003
Geirr Sletten	Denmark	succeeded by R. Julin from October 2008 (chair from March 2003 till April 2005)

Acknowledgements

The original EUROBALL detector system was designed, developed, built, and operated by a multi-national collaboration of researchers at institutions in Denmark, France, Germany, Italy, Sweden and the United Kingdom (for a detailed list see http://euroball.lnl.infn.it/ where also technical descriptions and references are given). The project was strongly supported by the research councils in these countries, the concerned institutions and various foundations as well as EU.

During the 10 years of research activities, following the EUROBALL MoU ending in 2002, and supported by The European Gamma Ray Spectroscopy Pool, EUROBALL resources have been utilized in new constellations at research laboratories in Finland, France, Germany, Italy, Japan, Poland and The United Kingdom. This research has been strongly supported by the host laboratories as well as research authorities in many contributing countries and EU via EURONS (FP6). Detailed acknowledgements are found in the individual publications. The GAMMAPOOL Steering Committee likes to acknowledge all support and the excellent handling and effective use of the resources to produce front line research and for upgrading the resources by e g developing new electronics.

Introduction

Rolf-Dietmar Herzberg, Chair GAMMAPOOL

In 2013 we celebrate the first ten years of the Gamma-Ray Spectroscopy Pool (GAMMAPOOL) – the European collaboration for γ-ray spectroscopy research. During these years the experimental resources of GAMMAPOOL have been distributed to several large-scale facilities and infrastructures to allow spectroscopy campaigns, producing a large amount of excellent physics results. This booklet is an attempt to look back on this decade of versatility and to celebrate the successful use of this unique resource for science.

In the first part of the nineties, an agreement was reached between several γ-ray spectroscopy research groups to establish a European collaboration for the construction of an ambitious γ-ray spectrometer. The EUROBALL Memorandum of Understanding (MoU) was signed by representatives from Denmark, France, Germany, Italy, Sweden, and the United Kingdom. Two early implementations were installed at the Daresbury Laboratory while detectors were added. The full EUROBALL array was operated between 1997 and 2002, first at the Laboratori Nazionali di Legnaro in Italy and later at the Institut de Recherches Subatomiques in Strasbourg, France. A report on the large scientific production of EUROBALL can be found in http://euroball.lnl.infn.it/.

Together with GAMMASPHERE in the United States, EUROBALL set new limits to γ-ray detector technology and represented a giant step forward in terms of efficiency and resolving power. EUROBALL was composed of three different types of detectors: the tapered, single crystal Ge detectors also referred to as Phase I detectors, and two different types of composite detectors, Clover and Cluster detectors. The Clovers consist of four Ge crystals sitting in a common cryostat while the Cluster detectors are composed of individually encapsulated Ge crystals in a configuration of a central capsule surrounded by six others. The power and selectivity of the EUROBALL γ-ray detector array has been enhanced substantially by coupling it to different ancillary devices.

> **“The idea was to keep the resources in a pool, the European GAMMAPOOL, making them available to the nuclear physics community for dedicated experimental campaigns at accelerator laboratories offering unique new physics opportunities”**

After the EUROBALL MoU, and hence the EUROBALL collaboration, ended officially in December 2002, the detectors could have returned to their owners. However, the γ-ray spectroscopy community decided to keep the detectors together in a common pool dedicated to pursuing scientific campaigns that would otherwise be impossible on this scale, and a new, fruitful collaboration was born, whose 10th anniversary we celebrate here. The idea was to keep the resources in a pool, the European GAMMAPOOL, making them available to the nuclear physics community for dedicated experimental campaigns at accelerator laboratories offering unique new physics opportunities. In this way GAMMAPOOL assured the optimum use of the resources in large scale campaigns, where the various γ-ray detectors could be coupled to different spectrometers and ancillary detectors for dedicated studies.

A new MoU was signed starting in January 2003 and an Owners Committee, with representatives of the countries who had contributed to the funding of the EUROBALL detectors, was created to administrate GAMMAPOOL resources. It soon became clear that a networking activity in the framework of the Integrated Infrastructure Initiative of the European Community, EURONS (FP6), would be the ideal setting to coordinate and promote the optimum use of the resources.

The GAMMAPOOL Network was active for four years from January 2005. The Steering Committee, composed of the members of the existing GAMMAPOOL Owner's Committee, met twice a year to evaluate the status and perspectives of the ongoing campaigns, to discuss the requests for prolongation of the loans and to evaluate the new proposals that could be submitted every year. In this framework, a new series of dedicated annual workshops was organized. The workshops focused on nuclear structure physics studies with γ-ray detector arrays in Europe, with particular emphasis on the presentation of the large amount of results achieved by the different campaigns and to allow the gestation of future collaborations and developments. The first workshop was held in May 2006 at the ECT* in Trento, followed by one in the Physics Department of Padua University in 2007, and a third in the IN2P3 headquarters in Paris. The GAMMAPOOL Network acted also as a forum where problems of common interest such as the maintenance and repair of the detectors were discussed, not only among the GAMMAPOOL users community, but involving other collaborations like EXOGAM (based at GANIL) and MINIBALL (based at Rex-ISOLDE).

Initially the different types of Ge detectors were assigned to three main campaigns. The Phase I detectors were used to build the JUROGAM array at Jyväskylä, in Finland, coupled to the RITU recoil separator. The Clover detectors were sent to Legnaro, Italy, where the CLARA γ-ray detector array was coupled to the magnetic spectrometer PRISMA, and the Cluster detectors at the Fragment Recoil Separator (FRS) in GSI formed the Rising array. Finally, the anti-Compton BGO shield was used at GSI and in the Physics Department of the Liverpool University to characterize the AGATA detectors. Two of the EUROBALL ancillary detectors are also administrated by GAMMAPOOL. The charged-particle detector EUCLIDES was used in Legnaro coupled to the GASP γ-ray detector array while the Neutron-Wall was operated in GANIL together with the EXOGAM γ-ray spectrometer.

The GAMMAPOOL policy of favoring large-scale campaigns assures the optimized use of the detectors and of the resources that each research community invests on the campaigns. An important requisite of the hosting infrastructures is to have a detector laboratory to keep the resources in good working conditions. There is no fee for the loans but it is requested that the detectors return to the GAMMAPOOL home base in the same condition in which they have been delivered to the campaigns. After more than 15 years of use, the detectors are in very good shape. On the other hand, the analog electronics is aging and had to be phased out. Most of the campaigns have invested heavily in digital electronics, which have greatly increased the rate capabilities of the detectors and are vital for the continued usefulness of the resource. Any newly proposed campaign will need to think carefully about the electronic instrumentation for the detectors, as the original EUROBALL electronics is no longer available.

With this brochure we celebrate this outstandingly successful endeavor. None of it would have been possible without a strong will in the community to pool resources, use them in innovative new ways in large campaigns and invite the whole community in to contribute scientifically to these campaigns. The success of GAMMAPOOL is mostly down to the user communities formed around the different campaigns, and they deserve our thanks and appreciation. May this spirit of scientific partnership continue for many more years.

Application Procedure:

The GAMMAPOOL is always open for suggestions and ideas for new campaigns with an annual call for proposals at a fixed deadline of 1 July. The overriding deciding criterion is scientific quality and uniqueness of opportunity. The proposals should be accompanied by a full technical and scientific case and will, if successful, require the establishment of a Memorandum of Understanding between the host and GAMMAPOOL. Campaigns will usually be established for an initial period of two years, with the option of annual prolongations. Full details of the available equipment and pool rules can be found on the GAMMAPOOL website: http://GAMMAPOOL.lnl.infn.it/index.htm. The website also includes a list of pool members and contact details. It has proven advantageous to contact the GAMMAPOOL chair or one of the national representatives early in the planning of an application, and Letters of Intent/ Statements of Interest are welcome at any time.

Fast Beam Rising

GSI, Darmstadt, Germany

The in-beam Rare ISotope INvestigations at GSI (RISING) project combined the former EUROBALL Ge-Cluster detectors, MINIBALL Ge detectors, HECTOR BaF_2 scintillator detectors, and the fragment separator FRS at GSI for high-resolution in-beam γ-ray spectroscopy experiments with radioactive ion beams. The in-beam RISING campaign exploited secondary unstable beams at relativistic energies up to 600 AMeV for γ-ray spectroscopy studies following relativistic Coulomb excitation or secondary fragmentation reactions. New experimental concepts had to be developed for spectroscopy at such unprecedented high relativistic energies. Physics cases focused on shell structure of unstable doubly-magic nuclei and their vicinity, symmetries along the $N=Z$ line, mixed symmetry states, shapes and shape coexistence, collective modes and *E1* strength distributions. The accomplished results of the fast beam campaign yielded 25 publications including several letters in highly ranked journals.

Compared with other fragmentation facilities in the world, most of the RISING in-beam experiments relied on fragmentation products from heavy primary beams or the high secondary beam energy, both features unique for GSI. The exotic beams were produced by fragmentation of a heavy stable primary beam or fission of a ^{238}U beam in front of the FRS. Secondary beam intensities took advantage of the high primary target thickness and large production yields for fragmentation reactions and fission.

The secondary exotic beams were used for Coulomb excitation or secondary fragmentation experiments in order to explore the nuclear structure of the projectiles or projectile-like nuclei by measuring the de-excitation photons. The complex set-up is shown in Fig. 1. The relativistic Lorentz boost implied an asymmetric set-up: The HPGe detectors were mounted up-stream of the target in three rings around the beam tube. A photopeak efficiency of 2.8% (at 1.33 MeV) and an energy resolution of 1.5% were attained. In part of the fast beam experiments MINIBALL triple detectors were added increasing the photo peak efficiency to 7.3%. Eight large volume BaF_2 detectors from the HECTOR array were mounted to measure very high energy γ-rays. Behind the target the CAlorimetric TElescope array CATE, a position sensitive ΔE-E detector, was placed to identify the scattered particles and breakup products. Publications related to the in-beam RISING spectrometer, its ancillary detectors and new analysis methods are given in the publication list, e.g. *[H.J. Wollersheim et al., Nucl. Instr. Meth. A537 (2005) 637]*

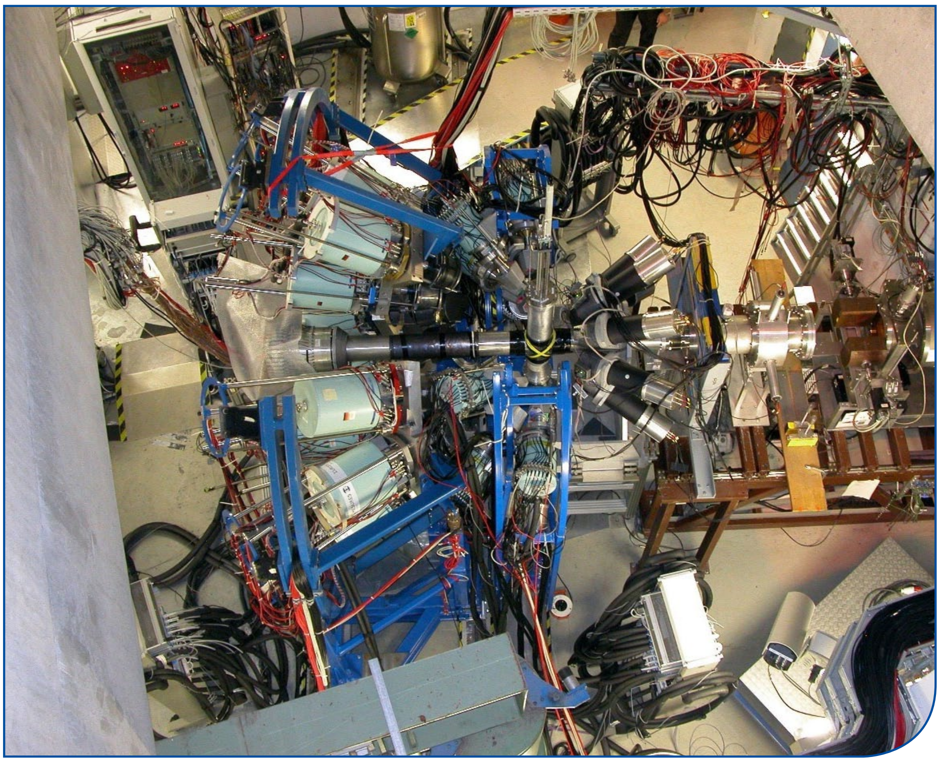

Fig. 1: RISING in-beam set-up. The beam enters the set-up from the right. After hitting the target the ions are detected in the CATE detector. The γ-rays are detected using the HECTOR array (right), the MINI-BALL detectors (middle) and the EURO-BALL Cluster detectors (left).

A total of twelve experiments were approved for this campaign by GSI's scientific Programme Advisory Committee and nine of these could be performed. A number of groundbreaking results were put forward by this pan-European effort – arising from new conceptual thinking of Ge-detector based, high-resolution in-beam γ-ray spectroscopy, i.e. combining existing expensive infrastructure and detectors using forefront detector technology and data analysis. A physics program based on Coulomb excitation and secondary fragmentation experiments was successfully performed with the RISING spectrometer, a new instrument for high-resolution γ-ray spectroscopy experiments employing secondary beams of short-lived isotopes at 100–600 AMeV energy from the SIS/FRS facility at GSI.

Fast beam -RISING	
Detectors	15 EUROBALL and 8 MINIBALL Clusters
Efficiency at 1332keV	7.3 %
Operational	October 2003 - May 2005
Number of experiments	12
Beamtime hours	1900

RISING fast beam physics program

Shell structure

Spectroscopic data on the single particle structure of unstable doubly magic nuclei and their neighbours are pivotal for theoretical description of the effective interactions in large-scale shell-model calculations. The RISING studies along the N=Z line, passing doubly-magic nuclei ^{40}Ca and ^{100}Sn, provided an excellent probe for single-particle shell structure, proton–neutron interaction and the role of correlations, normally not treated in mean field approaches. For example one of the first RISING results was the $B(E2,2^+_1 \rightarrow 0^+)$ value in semi-magic ^{108}Sn which provided a sensitive test for the $E2$ polarisability and the shape response of the magic core *[A. Banu et al., Phys. Rev. C72 061305 (2005)]*.

> **New experimental concepts had to be developed for spectroscopy at such unprecedented high relativistic energies.**

The development of new shell structure at N » Z as studied in light and medium-heavy neutron-rich nuclei around N=8, 20, 28 is generally ascribed to the weakening of the surface slope of the neutron potential due to the large neutron excess. Alternatively, the existing experimental evidence of changing shell structure can be explained in terms of the monopole part of the nucleon–nucleon residual interaction which causes large monopole shifts of neutron single particle orbits due to their missing proton partner at large neutron excess, and thus generates new shell gaps. The effect was first discussed for the sd shell and for the *fp* shell. The fast beam RISING investigations concentrated on the region of neutron-rich Ca isotopes about the most significant matrix elements, the spectroscopic factors and the magnetic moments, which are sensitive indicators of their structure. In the Ca isotopes beyond N=28 a possible (sub)shell closure at N=32, 34 is predicted. RISING results were obtained for the chain of ^{54,56,58}Cr isotopes *[A. Bürger et al., Acta Phys. Pol. B36 (2005) 1249 and Phys. Lett. B622 (2005) 29]* which show a maximum in $B(E2,2^+_1 \rightarrow 0^+)$ strength at N=32 and revealed such a change in shell structure. On the other hand within the N=34 isotones the E(2^+_1) values are increasing from Fe to Cr in contrast to the expected trend towards midshell, which supports a N=34 closure.

Symmetries

For mirror nuclei with larger values of isospin spectroscopic studies in medium-mass nuclei have been undertaken with the fast beam RISING set-up. The large proton excess for the proton-rich members of the isobaric multiplets had an increasing effect on the one-body part of the measured Coulomb energy. This includes the bulk Coulomb effect associated with the differences in radii of specific orbitals as well as the more subtle effect of the Coulomb distortion of the specific nucleon wave functions (the Thomas–Ehrman shift). The mirror pair ^{53}Ni/^{53}Mn was of particular interest, as these nuclei have a very simple $(f_{7/2})^{-3}$ structure - neutron holes in ^{53}Ni and proton holes in ^{53}Mn. This allowed for a comparison of the proton and neutron multiplets, and the CED between these gave information on the Coulomb two-body matrix elements in the upper $(f_{7/2})^{-3}$ shell. In one of the first RISING experiments even Z, T_z=−3/2 nuclei in the $f_{7/2}$-shell were produced after secondary fragmentation reactions and a spectroscopic study of the energy levels up to 3–4 MeV excitation energy was performed *[G. Hammond et al., Acta Phys. Pol B36 (2005) 1253]*

Collective excitations

Collective excitations such as the giant dipole resonance (GDR), built from a superposition of single-particle excitations are necessarily influenced by the nuclear shell structure. In exotic nuclei like $^{68-78}$Ni theoretical calculations predicted a significant change in the GDR strength distribution as one progresses towards the doubly magic ^{78}Ni. The excitation function of the isovector GDR mode is expected to fragment substantially and a redistribution of the strength towards lower excitation energies (Pygmy resonance) needed experimental proof.

The RISING experiment exploited relativistic Coulomb excitation and detected the γ-ray from the PDR $E1$ decay to the ground state. This is a direct method to study the $E1$ strength function and complementary to the virtual photon breakup method.

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Highlights from Fast Beam Rising

The Pygmy Dipole Resonance in ^{68}Ni

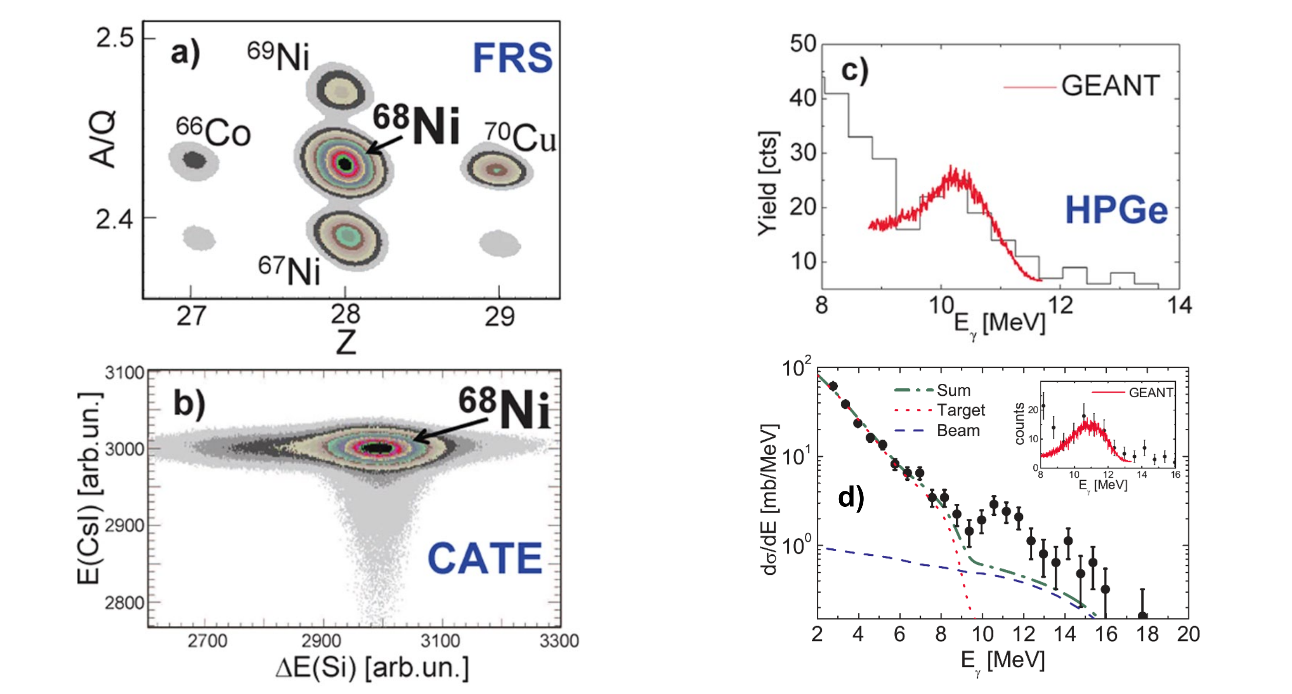


Fig. 2: (a) The fragments selected in the FRS are shown in a A/Q versus Z plot. (b) E-ΔE spectrum of the outgoing beam detected after the target in the CATE calorimeter with selection of the incoming ^{68}Ni. (c) HPGe spectrum of the Cluster detectors after the selection of incoming and outgoing ^{68}Ni and applying the Doppler correction for the projectile. The continuous red line is the result of a GEANT simulation for the in flight emission of a 11 MeV transition. (d) High-energy Doppler corrected γ-ray spectrum measured with BaF_2 detectors. The lines are the statistical model calculations for the target (dotted line) and for the beam (dashed line) nuclei. The excess yield around 11 MeV corresponds to the PDR [O. Wieland et al., PRL 102, 092502 (2009)]. In the inset the continuous line superimposed to the measured data is the result of a GEANT simulation for a gamma-transition at 11 MeV.

The nuclear collective response reveals information on the bulk properties of nuclei and nuclear matter. This response is characterized by the giant resonances of various multipolarities. Especially, the electric dipole (*E1*) response of nuclei at energies around the particle separation energy is presently attracting large attention, particularly for unstable neutron rich nuclei produced as radioactive beams. One of the very important aspects regarding the *E1* response of nuclei is the fact that the dipole strength distribution around the binding energy strongly affects the reaction rates in astrophysical scenarios where photodisintegration reactions are important, i.e. in hot stars and stellar explosions. The accumulation of *E1* strength around the particle separation energy is commonly denoted as pygmy dipole resonance (PDR) due to the minor size of its strength in comparison with the giant dipole resonance (GDR) which dominates the *E1* response. If one assumes that all the excess neutrons participate in a collective oscillation against the core within a hydrodynamical model, then one finds a correlation between Pygmy Dipole Resonance (PDR) strength and neutron excess.

The RISING collaboration measured the PDR in ^{68}Ni, using the virtual photon scattering technique at the bombarding energy of 600 MeV/nucleon and the RISING fast beam setup. The γ-rays produced at a Au target were measured with HPGe detectors at forward angles and with BaF_2 scintillators at backward angles *[O. Wieland et al., PRL 102, 092502 (2009) and references therein]*.

Evidence is found for the presence of sizeable strength energetically located below the GDR and centered around 11 MeV with approximately 5% of the energy-weighted sum rule (EWSR) strength *[O. Wieland et al., PRL 102, 092502 (2009) and references therein]*. This intensity can be explained in terms of an enhanced strength of the dipole response function (pygmy resonance). Such pygmy structure has been predicted in this unstable neutron-rich nucleus by theory and corresponds to the vibration of the neutron skin against the core.

The behavior of the nuclear symmetry energy has been investigated using correlations between the neutron skins and the percentage of EWSR exhausted by the PDR in ^{68}Ni and ^{132}Sn. A different Random Phase Approximation (RPA) model for the dipole response, based on a representative set of Skyrme effective forces plus meson-exchange effective Lagrangians has been used. Values of relevant parameters in the equation of state were derived. In particular: for L (the derivative of the symmetry energy at saturation) a value of L=64.8 ± 15.7 MeV was found; for J (the symmetry energy at saturation) the determined value is J=32.3 ± 1.3 MeV; and consequently, for the neutron skin thickness DR = 0.200 ± 0.015 fm *[G. Carbone et al., Phys. Rev. C 81 (2010) 041301(R) and references therein]*.

A test for isospin symmetry of shell gaps at the driplines

Excited states of the same total isospin, *T*, in a set of isobars have nearly degenerate values of excitation energy, with small differences attributable to Coulomb effects. These Coulomb energy differences of isobaric analogue states and especially the mirror energy difference (MED) in $T_z = \pm T$ pairs of nuclei provide a sensitive spectroscopic probe to investigate orbital radii in excited states and the reduced overlap of identical proton and neutron orbitals. Together with precise large-scale shell model calculations the latter effect allows detailed investigations of the evolution of (sub) shell gaps. The well known shell effects in the sd shell with the dramatic *N*=20 shell quenching in ^{32}Mg below the *Z*=14,16 sub shells are expected to be dominated by the monopole part of the two-body interaction. The scenario is anticipated to be symmetric in respect to the isospin projection T_z. On the other hand the proton-rich mirror *Z*=20 (Ca) nuclei are situated close to the proton dripline which may destroy the T_z symmetry. A negative MED may be anticipated by approaching the proton dripline. The quenching of the two-body interaction due to a reduced orbital overlap may cause the opposite energy shift. These competing scenarios were investigated in the *N*=20 mirror region along the light Ca (*Z*=20) isotopes.

The FRS-RISING setup was used to identify excited states in ^{36}Ca employing the two step fragmentation technique *[P. Doornenbal, et al., Phys. Lett. B 647 (2007) 237]*. A primary beam of ^{40}Ca 420 AMeV was incident upon a ^{9}Be target at the entrance of the FRS and ^{37}Ca fragments of interest were selected and identified in-flight on an event-by-event basis. At the final focus, ^{37}Ca ions impinged on a secondary ^{9}Be target at an energy of 196 AMeV. The reaction products were selected using the calorimeter telescope array CATE. The energy for the $I^{\pi} = 2^+_1$ state of ^{36}Ca, the heaviest *T*=2 nucleus with an observed γ-decay, was determined to be 3015(16) keV (see Fig. 3). The extremely large mirror energy difference relative to ^{36}S can be understood with an isospin symmetric shell model interaction using experimental proton and neutron single particle energies, which account empirically for the one-body part of Thomas-Ehrman and/or Coulomb effects. The results are consistent with a monopole driven shell structure scenario and the expectation that Ca isotopes below *N*=16 develop another "island of inversion".

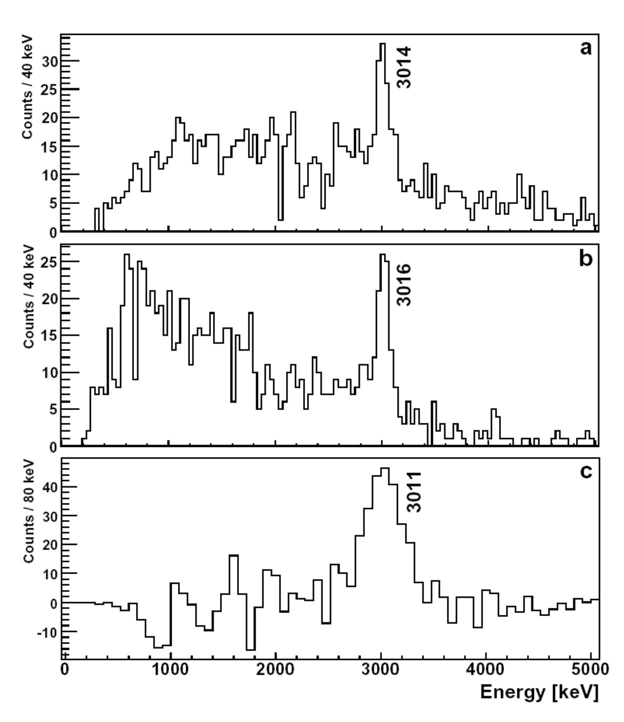


Fig. 3: Doppler corrected ^{36}Ca gated γ-ray spectra measured with the Cluster (a), MINIBALL (b) and HECTOR (c) detectors. For (c) the background was subtracted.

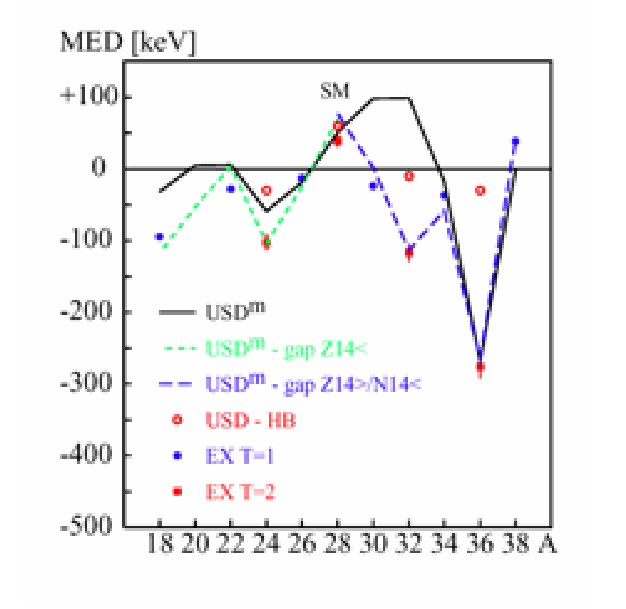


Fig. 4: Experimental mirror energy differences for the first $I^{\pi} = 2^+$ states of even-even T=1 (filled circles) and T=2 (filled squares) sd shell mirror nuclei in comparison to shell model results of Ref. [H. Herndl, et al., Phys. Rev. C 52 (1995) 1078] (open circles) and the present work (USDm) (full line). The dashed lines correspond to a reduced Z=14 gap in the lower sd shell (A ≤ 28, short dashed) and a reduced N=14 gap with a small increase of the corresponding mirror gap in the upper shell (A ≥ 28, long dashed).

From the systematics of *T*=1 and *T*=2 MED in the *sd* shell, shown in Fig. 4, a reduction of the *Z*=14 gap in the *N*=8 isotones and the *N*=14 gap in the *Z*=20 Calcium isotopes relative to their mirror gaps *N*, *Z*=14 in *Z*=8 Oxygen isotopes and *N*=20 isotones is inferred. In view of the considerable reduction of the *Z*=20 shell gap relative to the *N*=20 gap in ^{36}Ca and ^{36}S, respectively, the RISING result suggests that inversion may start as early as *N*=14 in ^{34}Ca.

PRESPEC In-Beam

GSI, Darmstadt, Germany

After the successful completion of all three RISING campaigns between 2003 and 2009, the Memorandum of Understanding of the subsequent and internationally steered PRESPEC project was signed late 2009. Based on RISING experience and results, PRESPEC was primarily established to give the European Nuclear Structure community an opportunity for a physics-driven preparation phase for the approved HISPEC and DESPEC experiments at the upcoming FAIR facility: By means of upgrades to the previous RISING set-ups, new FAIR-related detector systems were to be integrated and commissioned under realistic experimental conditions while simultaneously giving rise to frontline physics output, the latter scrutinized by both internal PRESPEC revision and the GSI programme advisory committee.

The set-up for a brief PRESPEC in-beam campaign using the existing RISING in-beam Ge-detector configuration (cf. page 6) comprising the 15 former EUROBALL Cluster detectors was installed in 2010. It was combined with the prototype of the new heavy-ion tracking and identification device, the Lund-York-Cologne CAlorimeter (LYCCA). LYCCA is an accepted FAIR-NUSTAR in-kind contribution from Sweden, Germany, and the United Kingdom *[D. Rudolph et al., LYCCA Tech. Design Report (2008)]*.

LYCCA-0 commissioning and two PRESPEC experiments were conducted in 2010, followed by a third experiment Spring 2011 along with preparation runs for additional HISPEC equipment, namely a hydrogen target *[C. Louchart et al., GSI Scientific Report 2011, PHN-NUSTAR-FRS13, GSI Report 2012-1]* for knockout and (p,p'γ) reactions as well as a plunger lifetime device *[M. Hackstein et al., GSI Scientific Report 2011, PHN-NUSTAR-FRS12, GSI Report 2012-1]*. The EUROBALL Cluster detectors were replaced by position sensitive, highly segmented AGATA Ge-detectors in 2012, which in conjunction with an upgraded LYCCA-1 defines the PRESPEC-AGATA campaign of 2012-2014. In combination with significantly enhanced primary SIS and thus secondary FRS beam intensities, the sensitivity of the PRESPEC-AGATA campaign for high-resolution γ-ray spectroscopy at relativistic energies is increased by about three orders of magnitude and thus sets new scientific standards. For this campaign, which in fact can be viewed as FAIR-HISPEC phase 0, at least 12 weeks of primary beam time were originally contracted between GSI and the AGATA collaboration. Unfortunately, only about half could be allocated because of severe overall research beam time constraints at GSI due to the preparation and construction of FAIR.

PRESPEC IN-BEAM	
Detectors	15 EUROBALL Clusters
Efficiency at 1332keV	2.8 %
Operational	September 2010 - May 2011
Number of experiments	3 (main) + 3 (commissioning)
Beam time days	18 (main) + 32 (commissioning)

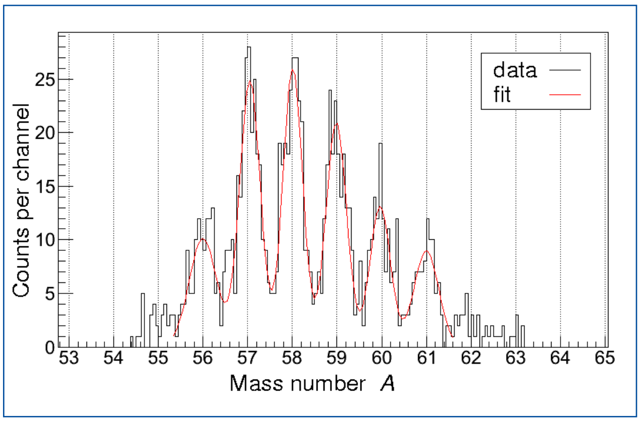


Fig. 1: LYCCA mass-identification plot for Fe fragments [P. Golubev et al., Nucl. Instr. Meth. A723, 55 (2013)].

In 2010, LYCCA-0 was successfully commissioned *[P. Golubev et al., Nucl. Instr. Meth. A723, 55 (2013), J. Taprogge, MSc thesis, Universität zu Köln (2011)]*. Figure 1 shows the mass-identification plot of Fe nuclei following the fragmentation of a ^{63}Co beam at the secondary target *[L. Scruton, PhD thesis, University of York (2013)]*. The first physics results from the 2010-2011 PRESPEC campaign are just emerging in the context of several PhD theses being finalized at the time of writing:

The reduced transition probability $B(E2;0^+\rightarrow2^+)$ has been measured for ^{104}Sn (cf. page 15). The experimental result established an anticipated downward trend of *B(E2)* strengths towards doubly-magic ^{100}Sn *[G. Guastalla PhD thesis, TU Darmstadt (2013) and Phys. Rev. Lett. 110, 172501 (2013) , D. DiJulio, PhD thesis, Lund University (2013)]*.

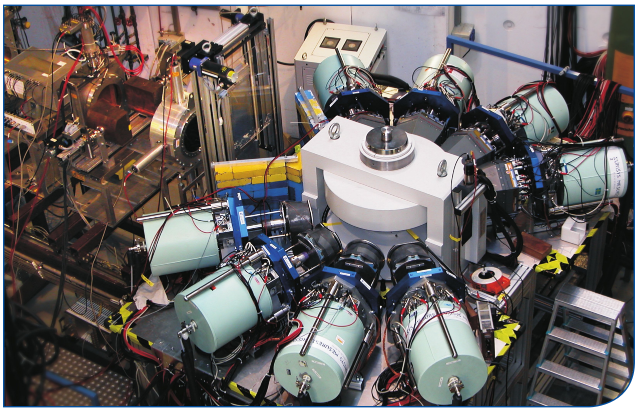
Detailed isospin symmetry breaking effects in the sd-shell (cf. page 9) were probed by measurements of transition strengths in the neutron-deficient odd-mass nucleus ^{33}Ar *[A. Wendt, PhD thesis, Universität zu Köln (2013) and submitted to Phys. Lett. B]*.

Reduced transition probabilities from the ground state to a series of excited 2^+ states in ^{88}Kr aimed at strength and effects of proton-neutron interactions in mixed symmetry states *[K. Moschner et al., GSI Scientific Report 2011, PHN-NUSTAR-FRS11, GSI Report 2012-1]*.

g-factor and stopped beam campaigns at RISING

GSI, Darmstadt, Germany

g-RISING: measurements on spin-aligned isomeric beams

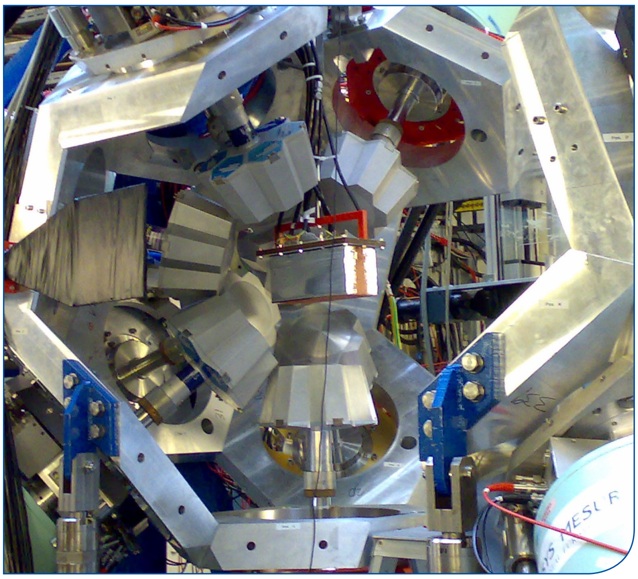


g-RISING	
Number of detectors	8 EUROBALL Clusters
Efficiency at 1332keV	3 %
Operational	2 months in 2005
Number of experiments	3 + 1 commissioning run
Beamtime hours	15 days + 1 day

The scientific goal of the g-RISING program is to obtain information about novel aspects of nuclei at extreme isospin. The tool used in g-RISING is to measure nuclear electromagnetic moments (and in particular the g-factor) of isomeric states in exotic nuclei. The aim of the g-RISING campaign was to establish the experimental techniques and methodology for such studies on isomeric relativistic beams. The nuclear g-factor (and related magnetic moment) is very sensitive to the single-particle structure in the wave function, particularly in high-spin isomeric states where configurations are usually quite pure. One novel feature is to measure, for the first time, spin-alignment in isomeric fragments produced by ^{238}U fission at relativistic energies and to use this spin-alignment to measure of the g-factor of isomeric states in neutron fission fragments. Very few other techniques and facilities exist that can measure heavy, neutron-rich nuclei.

In the g-RISING setup, the selected relativistic radioactive nuclei came to rest in a high-purity annealed Cu plate of 2 mm thickness, placed between the poles of an electromagnet providing a field of about 0.7 Tesla. Delayed isomeric gamma emissions were recorded in eight EUROBALL Ge-Cluster detectors. with the time of the ion arrival, determined by a thin plastic detector placed upstream of the set-up. For optimal sensitivity to the Zeeman precession, the γ-detectors were arranged in the horizontal plane, perpendicular to the magnetic field, four on each side of the beam axis.

STOPPED-RISING: spectroscopy with stopped beams



STOPPED RISING	
Detectors	15 EUROBALL Clusters
Efficiency at 1332keV	10 %
Operational	Years
Number of experiments	16
Beamtime hours	123 days of experiments

The g-RISING set-up was followed by a Stopped RISING experimental campaign aimed at studying the isomeric and beta delayed γ-ray spectroscopy of heavy nuclei with the most exotic proton-to-neutron ratios. These studies spanned the entire nuclear chart but focused on the structural studies of exotic nuclei centered around the doubly-magic nuclei ^{100}Sn, ^{132}Sn and ^{208}Pb. The Stopped RISING set-up of 15 Cluster detectors was complemented for some experiments with active Double-Sided Silicon Strip Detector (DSSSD) stopper detectors to provide beta-decay coincidence signals for decay studies of exotic systems.

Dissemination	
Peer reviewed publications	36
PhD thesis	19

Highlights from g-factor and stopped beam campaigns at RISING

Spin-alignment in relativistic fission and fragmentation of a ^{238}U beam

By fission of a relativistic ^{238}U beam on a thick ^{9}Be target, intense beams of neutron-rich isomers around ^{132}Sn can be produced. In spontaneous and neutron-induced fission reactions, spin alignments of the order of 30-60% have been observed if a cone of fission fragments is selected. This spin-alignment, inherent with the fission reaction process, can be used to study the nuclear moments of microsecond isomeric states. Such experiments are difficult in in-beam or spontaneous fission experiments, because of the very low isomeric γ-decay-intensity as compared to the total spontaneous decay-intensity. However, at fragment separators the isomer of interest can be separated from the other reaction products, significantly reducing the photon background.

A condition to maintain the reaction-induced spin-alignment through the fragment separation process is that a fully-stripped secondary beam survives up to the end of the fragment separator. This gets more difficult as the *Z*-value of the selected fragments increases, because electron pick-up reaction probabilities increase with *Z*. Thus also for U-fragmentation reactions producing heavy isomeric states in the Pb region, the question rises whether sufficient spin-alignment is maintained in the selected ensemble, up to the end of the beam line.

It was a goal of the g-RISING project to establish the amount of spin-alignment of selected relativistic fission fragments and projectile fragments of intermediate- and heavy-mass isotopes using the FRS fragment separator at GSI and the RISING detectors.

We measured the time-dependent angular distribution of isomeric states in ^{126}Sn *[Ilie et al., Phys. Lett. B 687, 305 (2010)]*, $^{127,128}Sn$ *[Atanasova et al., Eur. Phys. Lett. 91, 42001 (2010)]* and in ^{192}Pb *[Kmiecik et al., Eur. Phys. J. A 45, 153 (2010)]*. Only 4 Euroball detectors, placed at 90 degrees to each other, had sufficient statistics to allow an *R(t)* analysis. The isomeric states were produced by the fission of a relativistic ^{238}U beam at 750 AMeV and the fragmentation of a ^{238}U beam at 1 AGeV. The reaction products were selected by the FRS fragment separator. For the fission reaction, due to the large longitudinal momentum spread of the fission fragments, only a fraction of the distribution was selected by the fragment separator, thus the condition for selecting an aligned beam is automatically fulfilled. In the case of the U-fragmentation reaction, slits in the intermediate focal plane are used to select fragments in the wing of the momentum distribution, where the highest alignment is observed (Fig. 1).

For the first time, spin-alignment was observed after relativistic fission and fragmentation. From an analysis of the amplitude in the *R(t)* spectra (Fig. 2), about 20% alignment was observed in the fission reaction experiments as well as in the fragmentation data (with error bars between 5-10%). Additionally, the oscillation period yielded information on the isomeric g factors. These results pave the way for studies on neutron-rich isomeric states produced by the super-FRS at FAIR.

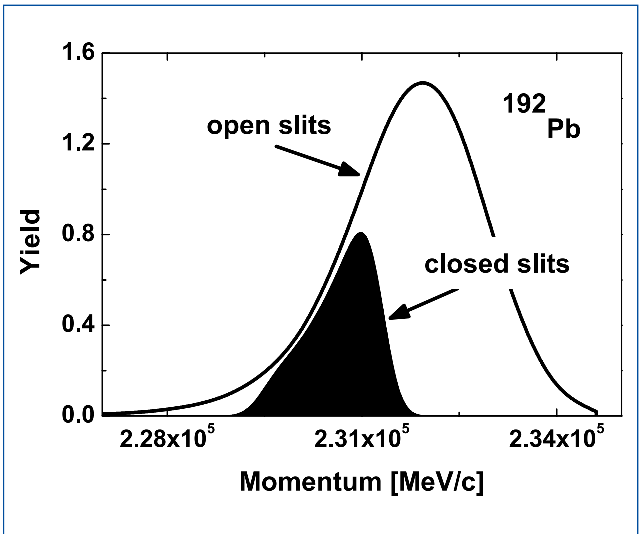


Fig. 1: Selected part of the longitudinal momentum distribution of U-fragments.

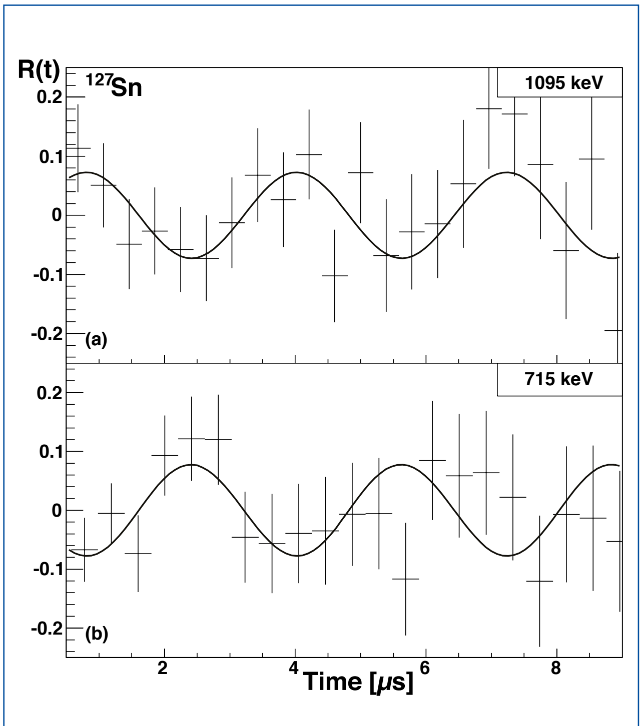


Fig. 2: R(t) spectra observed for the 10^+ isomeric decay in ^{127}Sn.

Mirror symmetry in the A=54 partners ^{54}Fe / ^{54}Ni

Decay studies of metastable states in the *A*=54 mirror pair nuclei $^{54}Ni_{26}$ and $^{54}Fe_{28}$ associated with excitations around the *N*=*Z*=28 doubly-magic closed shell nucleus ^{56}Ni were studied using RISING following the fragmentation of a ^{78}Kr primary beam.

The data identified, for the first time, the $I^{\pi}=10^{+}$ core excited isomer at E_x=6527 keV in ^{54}Ni, with three decay branches observed from this metastable state. The competing low energy *E2* and high energy core excitation *E4* decay, from the isomeric state in ^{54}Ni, were identified for the first time using RISING, together with an unexpected decay branch to excited states in ^{53}Co. This was taken as unambiguous evidence of direct proton emission from the 10^{+} isomeric state in ^{54}Ni to the $9/2^{-}$ excited state in the daughter nucleus, ^{53}Co. The state populated in the proton radioactivity suggested an *l*=5 proton transition , which implies at least some weak $h_{11/2}$ proton component in the isomeric state wave function.

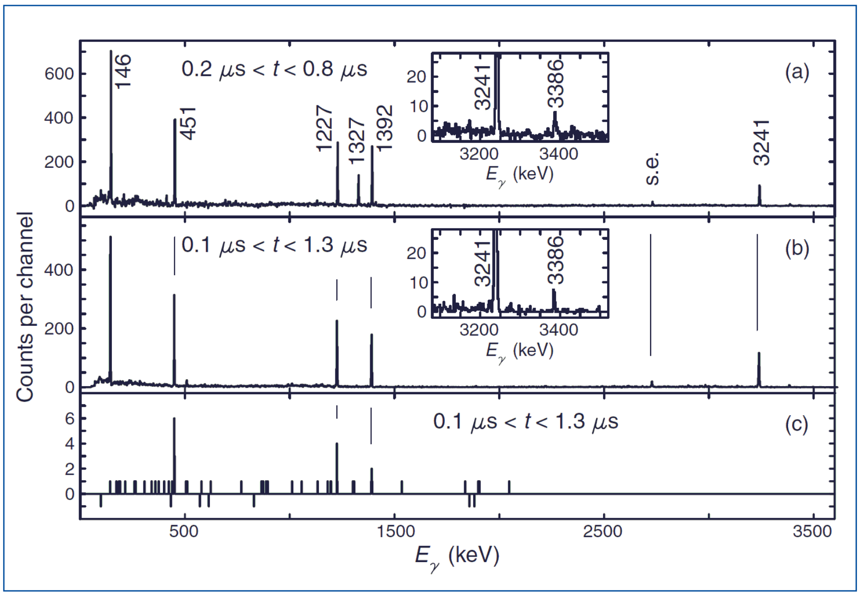


Fig. 3. Stopped RISING gamma-ray spectra showing the decay of the ^{54}Ni 10^{+} isomeric state.

Further reading

D. Rudolph et al., Isospin symmetry and proton decay: Identification of the 10^{+} isomer in ^{54}Ni, Physical Review C78, 021301 (2008)

D.Rudolph et al., Evidence for an isomeric $3/2^{-}$ state in ^{53}Co, European Physical Journal A36 (2008) 131-138.

R. Hoischen et al., Isomeric mirror states are probes for effective charges in the lower pf shell, Journal of Physics G: Nuclear and Particle Physics 38 (2011) 035104

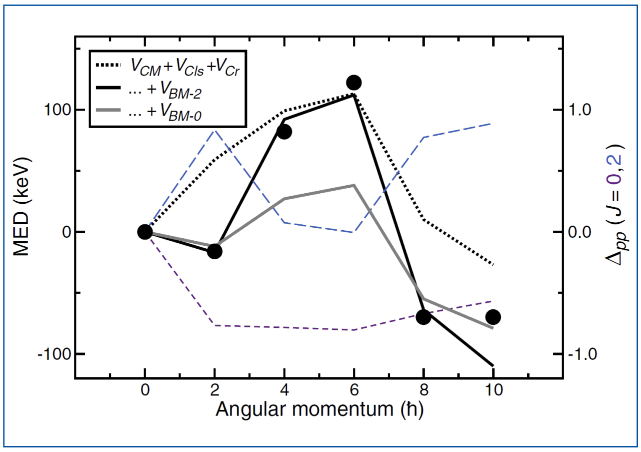


Fig. 4. Mirror energy difference, E_x (^{54}Ni) − E_x (^{54}Fe), as a function of spin. Solid circles denote the experimental values. The dotted line accounts only for Coulomb related isospin breaking terms, while the solid black and grey lines include the VBM−2 and VBM−0 terms, based on the KB3G interaction. The long- and short-dashed lines provide the difference between ^{54}Fe and ^{54}Ni of T=1 proton pairs, Δpp, coupled to either J=2 or J=0, respectively.

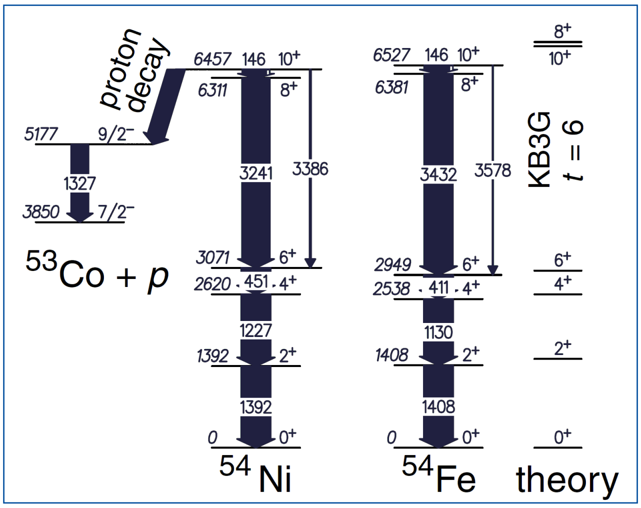


Fig. 5. Decay scheme of the 10^{+} isomer in ^{54}Ni deduced from the present work. The relevant decays of the mirror nucleus ^{54}Fe are shown for comparison. On the right-hand side, level energies from isospin-symmetric A=54, T=1 shell-model calculations are shown.

Neutron-proton pairing competition from isomeric state decays in proton drip-line *N*=*Z* nuclei ^{82}Nb and ^{86}Tc

Decays from isomeric states were identified in the *N*=*Z* nuclei ^{82}Nb and ^{86}Tc following the fragmentation of a ^{107}Ag beam. These represent the heaviest odd-odd *N*=*Z* nuclei for which internal spectroscopy had been performed to date. In both cases, the isomeric states were found to populate the isospin *T*=1 cascade, consistent with the expectation of *T*=1, $I^{\pi}=0^{+}$ ground states for these nuclei. The resulting energy level schemes for these nuclei suggest a preference for *T*=1 states over *T*=0 excitations at low energy. The lifetime and decay characteristics of the $I^{\pi}=5^{+}$ isomeric state in the deformed system ^{82}Nb are consistent with an isospin-changing *K*-isomer decay, the first of its kind to be observed in an *N*=*Z* nucleus.

In both cases, the *T*=1 ground state band remained yrast until the population of the *T*=0 isomeric states. The comparison between the density of states in these *N*=Z odd-odd nuclei and their T_z=1 odd-odd neighbours is striking, highlighting the presence of a *T*=1 pairing gap associated with odd-odd *N*=Z nuclei where the ground state is of *T*=1 character.

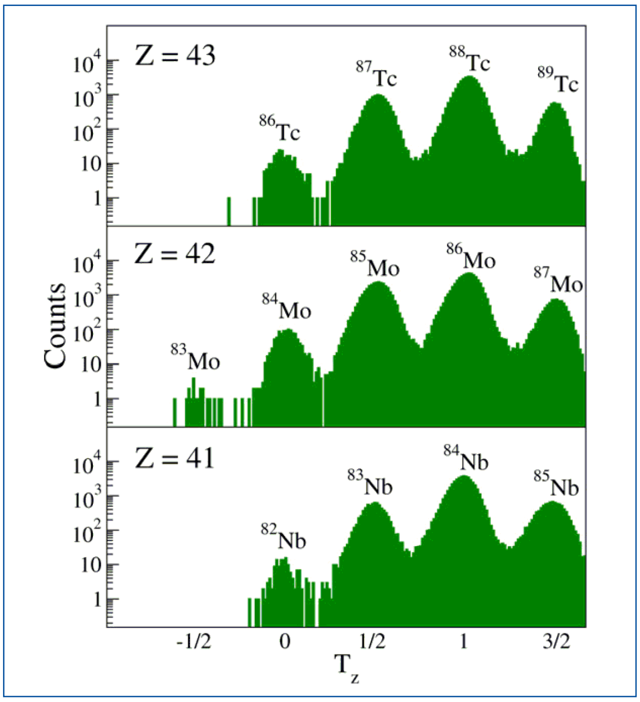


Fig. 6. Projections of the particle identification spectra from the fragmentation of a ^{107}Ag primary beam to populate isomeric states in the odd-odd N=Z proton drip-line nuclei ^{82}Nb and ^{86}Tc.

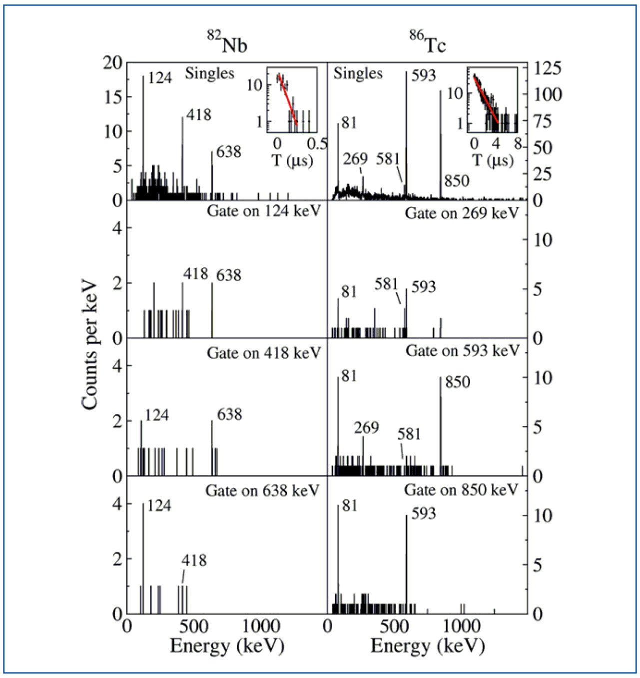


Fig. 7. Stopped RISING gamma-ray spectra showing the decays of the isomeric states in ^{82}Nb and ^{86}Tc, including gamma-gamma coincidence spectra between these transitions.

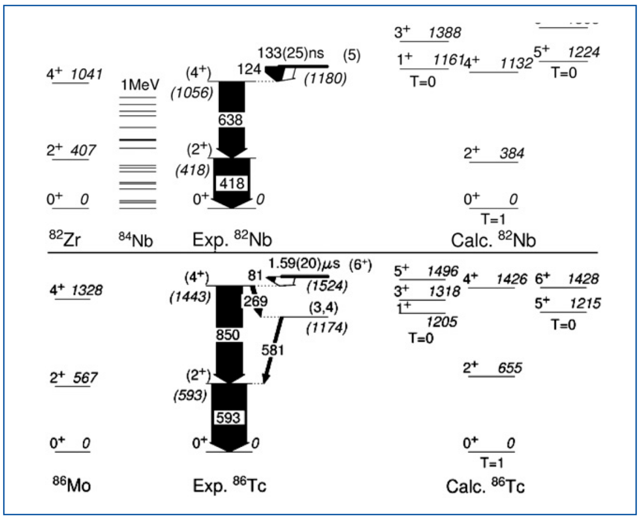


Fig. 8. Comparison of projected shell model calculations including T=0 and T=1 pairing for ^{82}Nb and ^{86}Tc with the experimental results from RISING.

Further reading

A.B. Garnsworthy et al., Neutron-proton paring competition in *N*=Z nuclei: Metastable state decays in the proton dripline nuclei ^{82}Nb and ^{86}Tc, Physics Letters B660 (2008) 326-330

A.B. Garnsworthy et al., Isomeric states in neutron deficient *A*~80-90 nuclei populated in the fragmentation of ^{107}Ag, Physical Review C80 (2009) 064303.

Studies of nuclei approaching and reaching ^{100}Sn

Two major experimental studies using a ^{124}Xe beam were carried out to study decays from well defined isomeric states in Pd, Ag and Cd nuclei formed from single-particle couplings approaching the doubly-magic nucleus ^{100}Sn. Decays from 'high-spin' core-excited isomeric states were identified in ^{94}Pd and ^{96}Ag for the first time. In ^{96}Cd, direct beta decay from the long predicted I^{π}=16^{+} yrast state which arises from the maximum angular momentum coupling between the proton and neutron $g_{9/2}$ 2-hole states in the ^{100}Sn core was identified, and transitions in the daughter nucleus ^{96}Ag clearly observed following its decay. High-energy (>4 MeV) *E4* transitions from core excited states in ^{96}Ag, ^{94}Pd and ^{98}Cd were identified for the first time using RISING, allowing detailed tests of the nuclear shell model in this region which include cross-shell excitations.

The data suggested that a full model space including excitations from the $g_{9/2}$ holes to proton and neutron particle states above the ^{100}Sn core was necessary to explain the identification of high-spin 17^{+} and 19^{+} states (in ^{96}Ag). RISING was also utilised to measure the gamma-ray transitions following the beta decay of the heaviest, *N*=Z doubly-magic nucleus, ^{100}Sn. RISING allowed the identification of decays between the excited states in the daughter nucleus, ^{100}In which showed that the majority of the Gamow-Teller beta decay strength from the decay in ^{100}Sn originated from a near-pure $\pi g_{9/2} \rightarrow \nu g_{7/2}$ spin-flip transition. The resulting measured beta decay strength implies a near perfect shell model description of this beta decay.

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B.S. Nara Singh et al., 16^{+} Spin-Gap isomer in ^{96}Cd, Physical Review Letters, 107, 172502 (2011)

P. Boutachkov et al.,High-spin isomers in ^{96}Ag: Excitations across the Z=38 and Z=50, N=50 closed shells, Physical Review C84, 044311 (2011)

T.S. Brock et al., Observation of a new high-spin isomer in ^{94}Pd, Physical Review C, 061309 (R) (2010);

C.B.Hinke et al., Superallowed Gamow-Teller decay of the doubly magic nucleus ^{100}Sn, Nature, vol. 486 (2012), 341-345

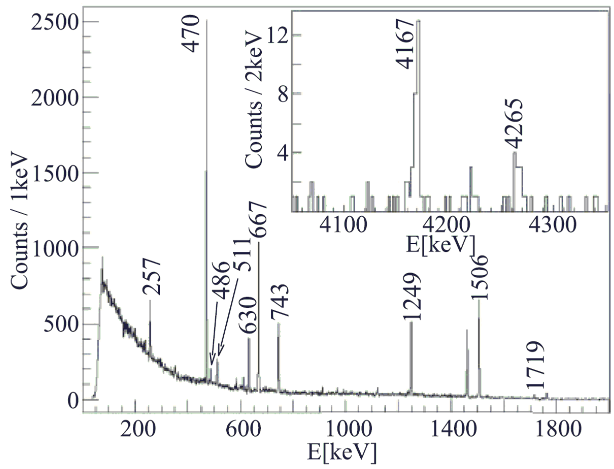

Fig. 9. A γ-ray spectrum observed with RISING from 0.075 to 90 μs after implantation of ^{96}Ag. The inset highlights the region around 4 MeV.

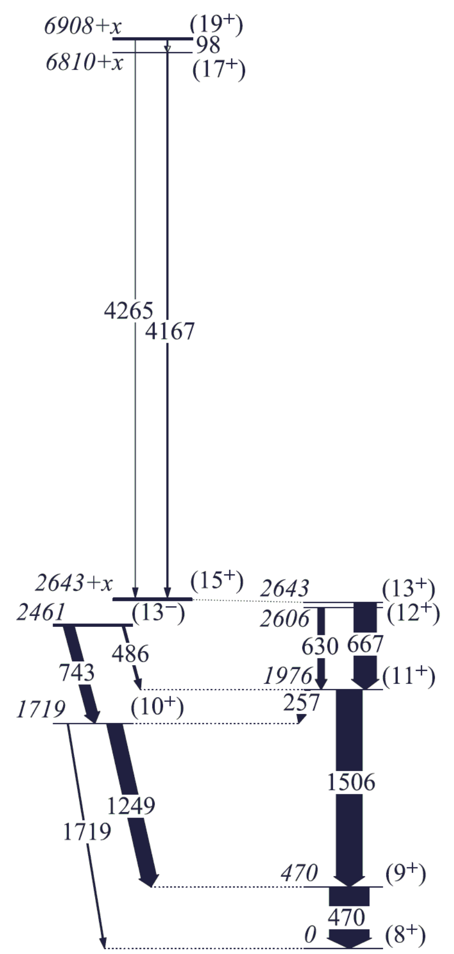

Fig. 10. Proposed level scheme of ^{96}Ag. The isomeric states identified in this experiment are drawn in bold.

Proton-hole isomers 'south' of ^{132}Sn

Decays from isomeric states associated with proton-hole configurations in the doubly-magic closed shell nucleus $^{132}_{50}Sn_{82}$ were studied in detail using RISING. The 2-proton-hole nucleus, ^{130}Cd was studied using both projectile fragmentation of a ^{136}Xe primary beam and also, separately following the projectile fission of a ^{238}U beam. This nuclear system is of particular interest as a possible 'waiting point' for the proposed rapid-neutron capture process in explosive nucleosynthesis. The Stopped RISING data revealed decays from a maximally coupled $(\pi g_{9/2})^{-2}$ $I^{\pi}=8^{+}$ state in ^{130}Cd which de-excited via a simple *E2* cascade of 4 mutually coincident transitions to the ground state of ^{130}Cd. These data were consistent with a simple, shell model description of this nucleus and were in contradiction to previous studies of this nucleus which suggested a possible break-down of the usual single particle ordering and associated magic numbers at ^{130}Cd.

The same experiment also provided the first information on core excitations associated with the 1 proton hole magic nucleus $^{131}In_{82}$.

Additional related studies include the identification of a proton-core excitation in the *N*=82 isotone ^{131}In and isomer decay studies of the 2-proton-2-neutron hole nucleus ^{128}Cd, which allowed a detailed comparison with contemporary shell model descriptions.

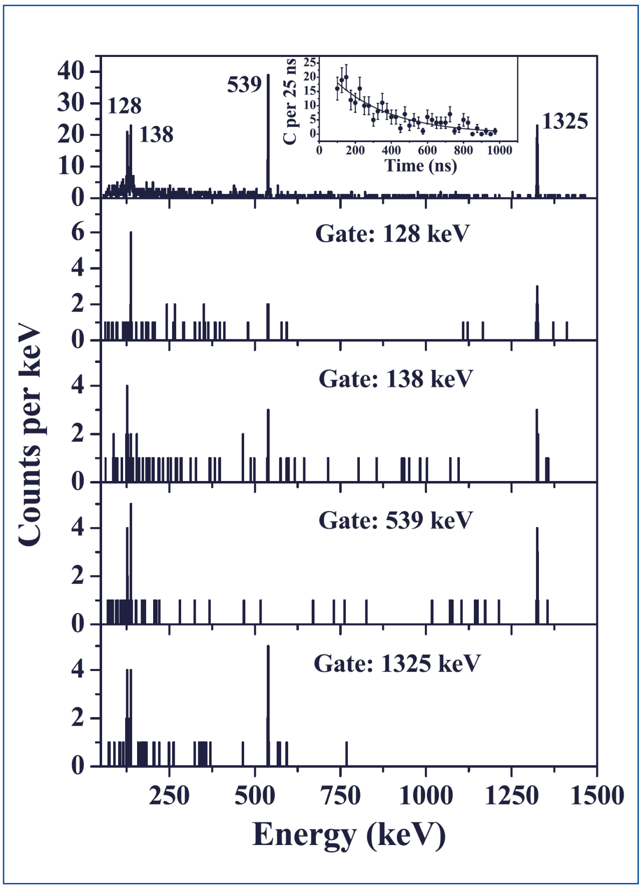

Fig. 11. Stopped RISING gamma-ray spectra showing the decay of the proposed spin/parity 8⁺ in the 2-proton hole, r-process path nucleus, ^{130}Cd.

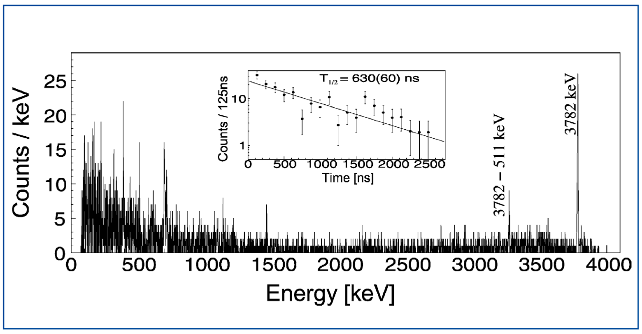

Fig. 12. Gamma-ray energy spectrum of the isomeric decay associated with a core-breaking excitation in the one proton-hole nucleus ^{131}In.

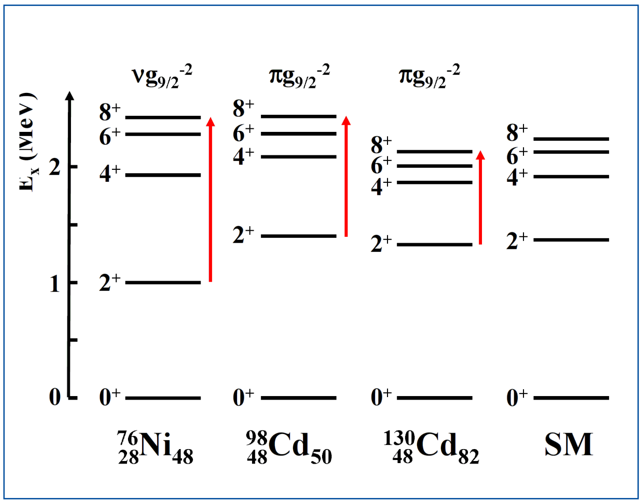

Fig.13. Comparison of seniority isomer decays in the 2-hole nuclei ^{76}Ni, ^{98}Cd and ^{130}Cd.

Further reading

A. Jungclaus et al., Observation of isomeric decays in the r-process waiting-point nucleus, $^{130}Cd_{82}$, Physical Review Letters 99, 132501 (2007)

M. Górska et al., Evolution of the *N*=82 shell gap below ^{132}Sn inferred from core excited states in ^{131}In, Physics Letters B672 (2009) 313-316

L.Caceres et al., Spherical proton-neutron structure of isomeric states in ^{128}Cd, Physical Review C79, 011301 (R) (2009)

Triaxiality in Os/Pt/W nuclei

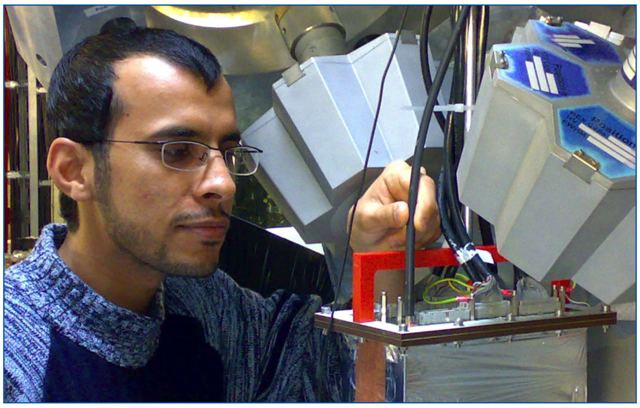

Fig. 14. The Stopped RISING 'active stopper' which allowed beta-delayed gamma-ray coincidence measurements to be performed in a range of exotic nuclei.

The RISING active stopper allowed coincidence measurements between high-energy implantations of secondary radioactive ions and their subsequent beta-decay in the same or neighboring pixel. Beta-delayed gamma-ray spectroscopy could then be performed in a range of previously unreachable isotopes of the elements tungsten and osmium following the beta-decay of their respective tantalum and rhenium parent nuclei.

The Stopped RISING data provided information on the energy spectra of the low-lying excited states in ^{188}W, ^{190}W and ^{192}W, which highlighted the change in nuclear shape at ^{190}W compared with that of lighter, axially symmetric, prolate deformed tungsten isotopes. This evolution of ground-state structure along the W isotopic chain is discussed as evidence for a possible proton subshell effect for the *A*~190 region and is consistent with maximization of the γ–softness of the nuclear potential around *N*~116.

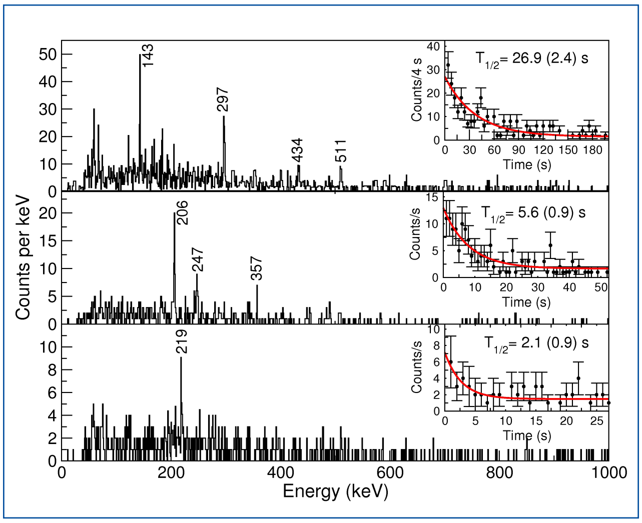

Fig. 15. Beta-delayed, Stopped RISING gamma-ray spectra showing the decays of ^{188,190,192}Ta into excited state of ^{188,190,192}W.

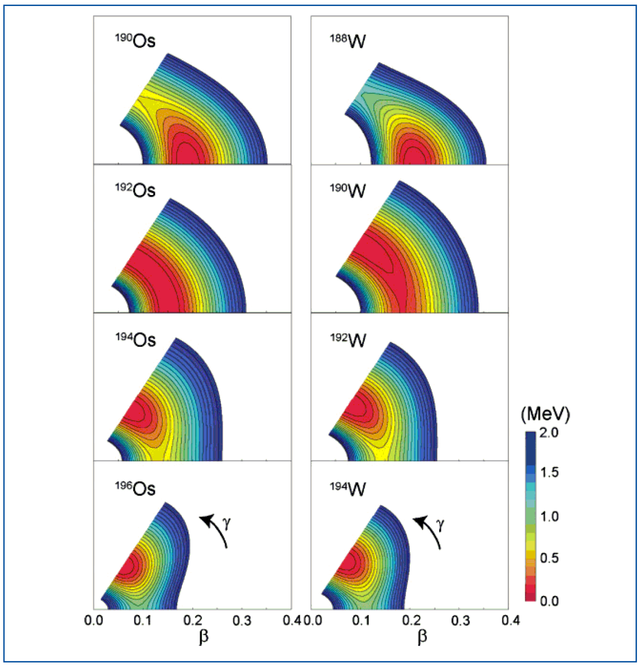

Fig. 16. Potential energy surface calculations by Nomura et al., showing the predicted evolution of ground state deformation from axially symmetric prolate in ^{186}W to oblate in ^{194}W.

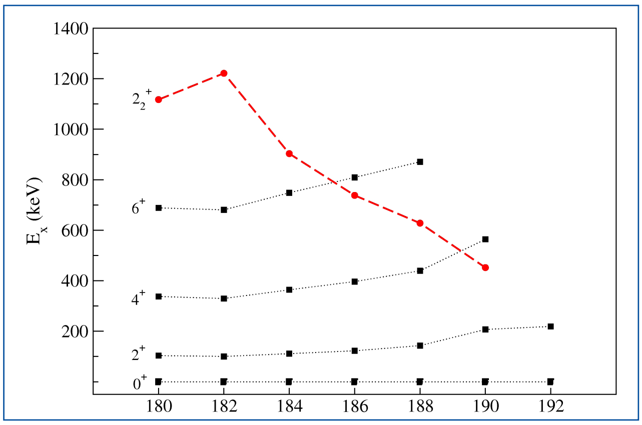

Fig. 17. Excitation systematics of W isotopes following the additional data for states in ^{190,192}W from the Stopped RISING Campaign. The evolution of the first and second 2⁺ states is consistent with the predicted evolution towards a triaxlally, gamma-soft nuclear ground state shape around N~114-116.

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K. Nomura et al., Spectroscopic calculations of the low-lying structure in exotic Os and W isotopes, Physical Review C83, 054303 (2011)

N.Al-Dahan et al., Multiple β⁻ decaying states in ^{194}Re:Shape evolution in neutron-rich osmium isotopes, Physical Review C85, 034301 (2012)

New single-particle studies around ^{208}Pb

Knowledge of the properties of heavy neutron-rich nuclei at or near the *N*=126 shell was rather limited prior to the Stopped RISING experimental campaign, in particular for nuclei with *Z*<82 and *N*>126 in which excited states were reported in only two nuclei, namely ^{208}Tl and ^{209}Tl.

An internal decay with a transition energy of 907(5) keV and a half-life of $T_{1/2}$ = 6(2)s was identified in the 3-proton hole nucleus ^{205}Au for the first time through the observation of the corresponding *K* and *L* internal conversion electron lines using the Stopped RISING Active stopper following the cold fragmentation of a primary ^{208}Pb beam. The 907 keV energy level corresponds to the $\pi h^{-1}_{11/2}$ proton–hole state and decays both internally into the $\pi d^{-1}_{3/2}$ ground-state and via β decay into ^{205}Hg.

The obtained data provides information on the evolution of single-proton hole energies which are vital inputs of shell model descriptions for nuclei around the $^{208}_{82}$Pb$_{126}$ doubly-magic core. In addition, shell model description of proton-hole states in the ^{208}Pb doubly-magic core were provided by the first determination of excited states in the 4 proton-hole nucleus ^{204}Pt, also populated in the cold fragmentation of a ^{208}Pb beam. New information on proton-hole-neutron particle residual interactions were made available following the measurement of metastable states in the *N*=128 isotones ^{208}Hg and ^{209}Tl, which were identified following the fragmentation of a ^{238}U primary beam. Delayed γ-ray transitions are interpreted as arising from the decay of I^{π}=(8$^+$) and (17/2$^+$) isomers, respectively. The data allow the most comprehensive verification of the shell-model approach in the region determined by magic numbers *Z* < 82 and *N* >126 to date.

The internal structure in neutron-rich nuclei magic Pb nuclei were extended with the observation of seniority style 8$^+$($h_{9/2}$)^2 seniority isomers observed in ^{212,214,216}Pb for the first time, providing new tests of the efficacy of the shell model description of heavy, neutron-rich nuclei.

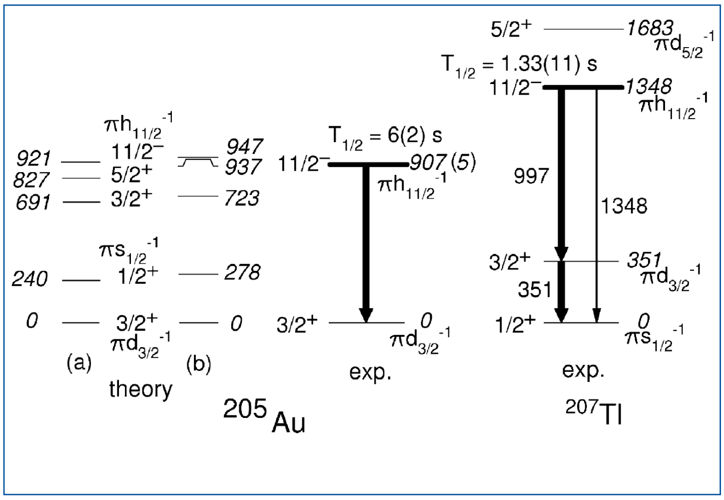

Figure 18: Calculated and experimental level schemes of ^{205}Au. For comparison the partial level scheme of ^{207}Tl is also given.

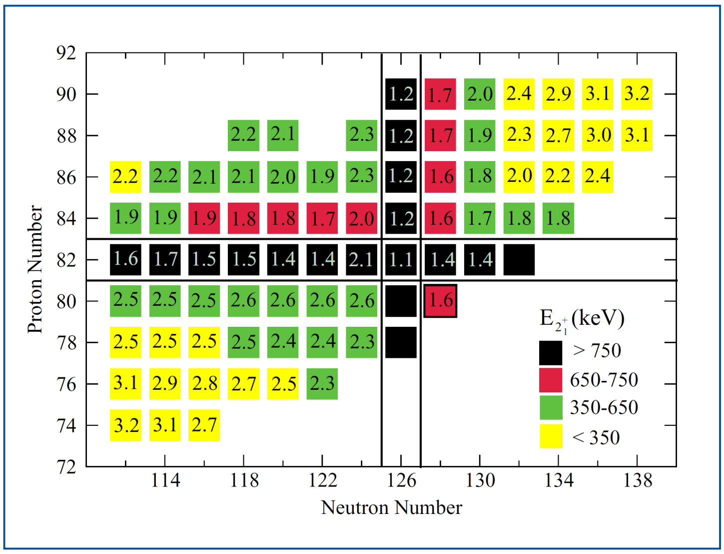

Figure 19: Energy ratios of 4$^+$ and 2$^+$ yrast states in even-even nuclei around ^{208}Pb. Following the RISING campaign, the first data point in the 'South-East' (proton-hole, neutron-particle) quadrant were obtained.

Further reading

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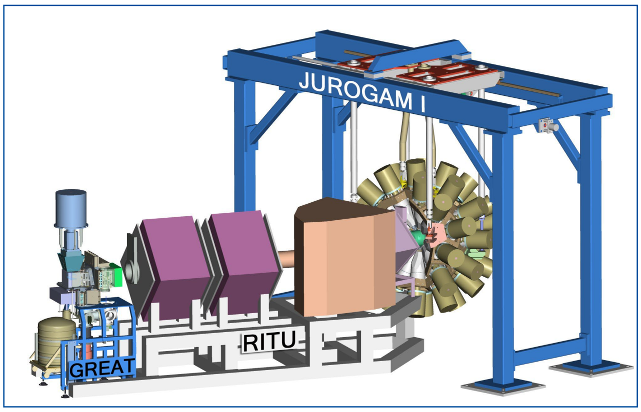
A. Gottardo et al., New isomers sin the full seniority scheme of Neutron-rich lead isotopes: The role of effective three=body forces, Physical Review Letters 109, 162502 (2012)

JUROGAM I and II

JYFL, Jyväskylä,Finland



The JUROGAM arrays at the Accelerator Laboratory of the Department of Physics of the University of Jyväskylä (JYFL), Finland, have been in operation since 2003. The JUROGAM I array consisted of 43 Phase I-type Ge detectors from the GAMMAPOOL and the UK-France Loan Pool. In 2008, the array was upgraded to JUROGAM II, consisting of 24 Clover detectors and 15 Phase I-type detectors entirely from the GAMMAPOOL resources. Since 2009, the JUROGAM II array has been fully instrumented with digital electronics, enabling experiments with high counting rates. For the most part, the detectors have been employed in Recoil-Decay-Tagging (RDT) measurements at the RITU gas-filled recoil separator with the associated focal plane spectrometer system (GREAT) and the triggerless Total-Data-Readout (TDR) data acquisition system.

Continual instrument developments have led to the construction of various complementary detector systems and exploitation of new techniques. The new instrumentation available includes the SAGE combined conversion electron and γ-ray spectrometer, the LISA spectrometer to detect light-charged particles at the target position and the DPUNS plunger device. The campaigns have also seen the birth of the recoil-beta tagging technique and extensive exploitation of a 'calorimetric' tagging technique used to delineate the decay and configurations of high-*K* states in very heavy nuclei.

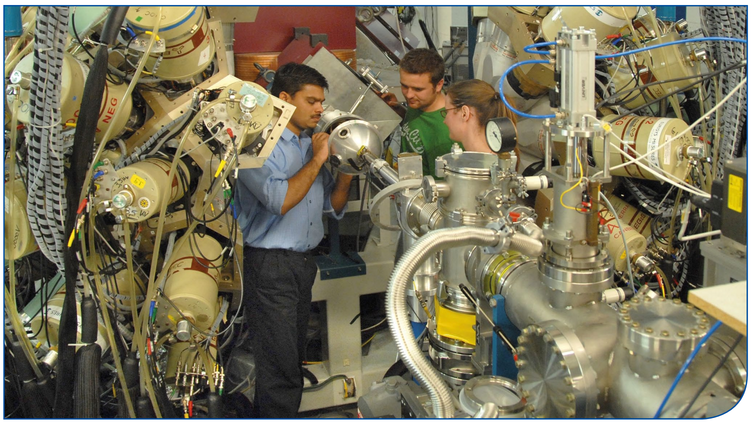
The Nuclear Spectroscopy group at JYFL has demonstrated that, by employing the JUROGAM arrays in RDT measurements, the structure of proton-drip line and superheavy nuclei can be probed in reactions with stable-ion beams down to a production level of less than 10 nb. Many of these nuclei are, and will remain, beyond the reach of future RIB facilities. Excited states in over 60 proton-rich and heavy nuclei have been observed for the first time.

The discoveries cover a broad landscape in the chart of nuclei ranging from the ^{100}Sn region all the way up to superheavy elements like ^{256}Rf.

Scientific themes and objectives of JUROGAM campaigns can be summarized as:

- Provide solid configuration assignments in odd-mass transfermium nuclei using combined electron-γ-ray spectroscopy
- Confirm existence of three different shapes in the same nucleus and relate collective phenomena to emerging data on radii and masses
- Study short-lived proton unbound states at the proton dripline
- Study the structure of nuclei on the island of alpha (and proton) decaying nuclei just above ^{100}Sn, relevant for the astrophysical rp-process
- Extend studies of physics at the N=Z line towards heavier nuclei (np-pairing, Coulomb energy differences, super-deformation at $N \approx Z \approx 40$)

The JUROGAM array with ancillary instrumentation has been operated in close collaboration with foreign institutes: University of Liverpool, STFC Daresbury, University of Manchester, IPHC Strasbourg, University of York, University of Köln.

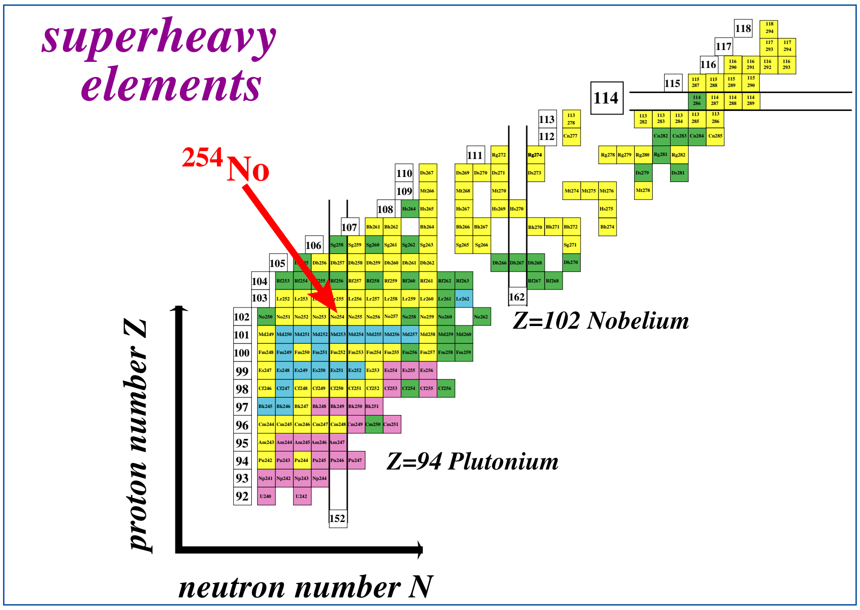


Dissemination	
Peer reviewed publications	93
PhD thesis	42

	JUROGAM I	JUROGAM II
Detectors	43 Eurogam Phase1	15 Eurogam Phase1 24 Eurogam Clover
Efficiency at 1332keV	4.3%	5.1%
Peak-to-total	48%	43%
Operational	Years 2003-2008	Years 2008-2013
Number of experiments	85	72
Beamtime hours	13700	12900

Highlights from JUROGAM I and II

Nuclear structure studies of heavy elements



The JUROGAM+RITU+GREAT system has been the foremost facility worldwide for in-beam and focal plane spectroscopy of heavy nuclei providing stringent tests of contemporary nuclear structure theories.

The power and sensitivity of the equipment has been demonstrated through a large number of experiments carried out in the region of ^{254}No. In 2005, it was possible to extend the rotational band of ^{254}No up to a spin of 24ħ and to observe non-yrast structure for the first time *[S. Eeckhaudt et al., EPJA 26, 227 (2005)]*.

In-beam investigations have also proved invaluable in providing confirmation of the configuration of band-head states inferred from complementary decay studies. Particular examples are ^{251}Md and ^{255}Lr, for which decoupled rotational bands based on the $\frac{1}{2}^-$[521] proton orbital were observed *[A. Chatillon et al., PRL 98, 132503 (2007) and S. Ketelhut et al., PRL 102, 212501 (2009)]*. This orbital stems from the $f_{5/2}$ orbital at sphericity, which along with the $f_{7/2}$ spin-orbit partner, plays an important role in determining the size of the possible shell gap at Z=114.

A further example in this vane was the study of high-K isomerism in ^{250}Fm, which enabled the configuration of the K=8$^-$ isomer to be determined for the first time *[P.T. Greenlees et al., PRC 78, 021303(R) (2008)]*. By using a variation of the isomer tagging technique, it was possible to extract the set of gamma rays feeding the isomeric state and to construct the level scheme of the K=8 band. Along with decay studies at the focal plane of recoil separators, experiments such as this have been able to reveal details of the location and ordering of states around the deformed shell gaps at Z=100 and N=152.

Most recently, the full digital read-out of the germanium detectors in JUROGAM has enabled data to be taken at unprecedented rates and, in turn, with much higher beam intensities. This first resulted in a successful measurement of the yrast structure of ^{246}Fm at the level of just 11nb *[J. Piot et al., PRC 85, 041301(R) (2012)]*. The ^{246}Fm experiment was followed up with a long-awaited investigation of the Z=104 nucleus ^{256}Rf, at the gateway to the superheavy elements *[P.T. Greenlees et al., Phys. Rev. Lett. 109, 012501 (2012)]*. After 450 hours of irradiation it was possible to exploit the spontaneous fission of ^{256}Rf to tag the γ rays of interest and delineate the rotational band up to a spin of 20ħ. The production cross section in this case was 17nb.

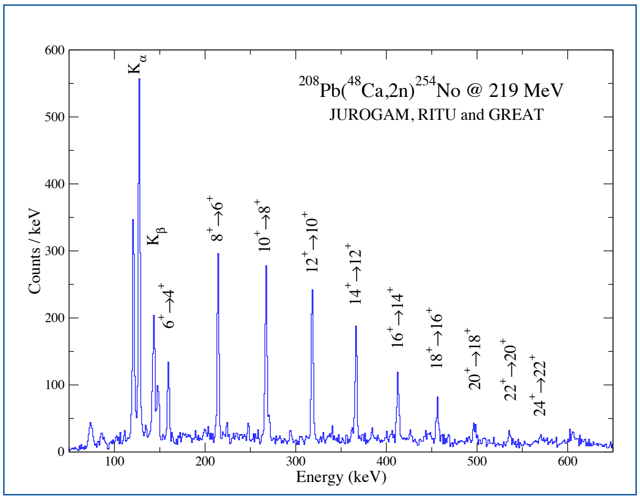


Fig1. Recoil-gated spectrum of γ-rays from ^{254}No

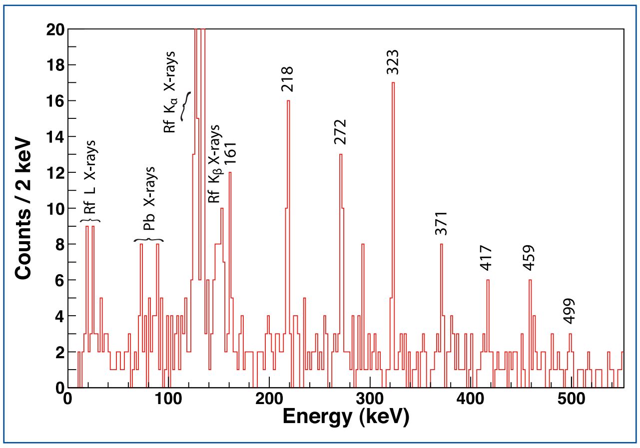


Fig 2. Fission-tagged gamma-ray singles spectrum of ^{256}Rf

Shape coexistence in light Pb isotopes

Shape coexistence in neutron-deficient Hg, Pb and Po nuclei near the *N*=104 midshell is thought to be well established. However, the spectroscopic facts to confirm the existence of different shapes are still scarce.

Verification of prolate shape

To verify that the yrast line of even-even Pb isotopes near the *N*=104 midshell represents a prolate shape, the coupling of the $i_{13/2}$ quasineutron to the even-even core was studied in $^{185}Pb_{103}$. JUROGAM I at RITU and the $^{106}Pd(^{82}Kr,3n)^{185}Pb$ reaction were employed, to observe its excited states, for the first time,. The resulting strongly coupled level pattern reveals that the core coupled with the $i_{13/2}$ quasineutron has a prolate shape *[J. Pakarinen et al., Phys. Rev. C 80, 031303(R) (2009)]*.

Prolate and oblate bands in ^{186}Pb

The triple-shape coexistence is generally associated with the low-lying 0^+ states in ^{186}Pb fed in the alpha-decay of ^{190}Po. However, only one collective band structure assigned to the prolate shape has been seen. The high efficiency of JUROGAM and RITU enabled to collect high-quality α-tagged γγ-coincidence data from ^{106}Pd + ^{83}Kr reactions, necessary to identify a new low-lying side band. The observed strong $I \rightarrow I$ and weak $I \rightarrow I-2$ interband transitions to the prolate yrast band reveal that this band is based on oblate shape of ^{186}Pb. *[J. Pakarinen et al., Phys.Rev. C 72 (2005) 011304 and C 75, 014302 (2007)]*.

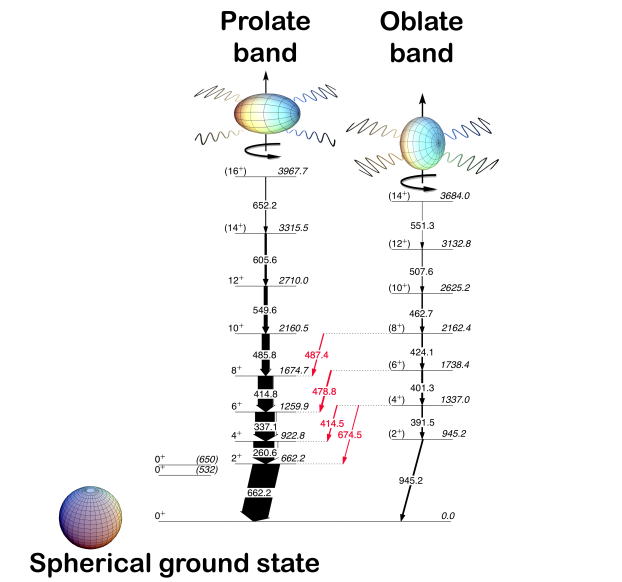


Fig. 3. Prolate and oblate bands in ^{186}Pb.

Proton unbound excited states in ^{180}Pb

Survival of shape coexistence when approaching the proton-drip line is an interesting question. Selectivity of the RDT technique with JUROGAM and RITU made it possible to observe, for the first time, prompt rays from proton-unbound states of $^{180}Pb_{98}$ *[P. Rahkila et al., Phys. Rev. C82, 011303(R) (2010)]*.

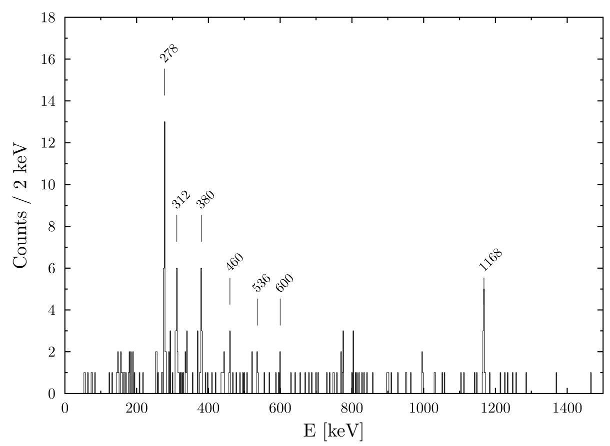


Fig. 4. Singles γ-ray energy spectrum tagged by genetic correlations of the ^{180}Pb decay chains. The measured production cross-section of ^{180}Pb via the cold $^{92}Mo(^{90}Zr,2n)$ channel was only 10nb, which represents a world record in in-beam γ-ray spectroscopy.

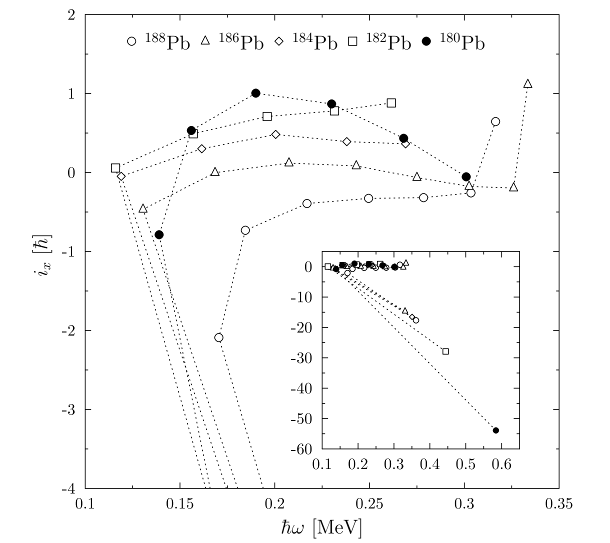


Fig. 5. Aligned angular momentum for the yrast bands in $^{180\text{-}188}Pb$. Whether the behaviour of the observed band structure is due to a mixture of two shapes or due to the unbound character of all the excited states in ^{180}Pb is still an open question.

Nuclear structure studies at the *N*~*Z* line

In the Recoil-Beta Tagging (RBT) method, developed at JYFL in collaboration with the University of York, recoils are identified by tagging on their β decay. Obvious difficulties arise from the long decay half-lives compared to α- or proton decay. Continuous energy distributions of β particles originating from various reaction channels overlap each other making clean selection of a single evaporation channel impossible. However, the Fermi super-allowed β decays of odd-odd *N*=Z and even-even *N*=Z-2 nuclei with a 0^+ ground state, are relatively fast (τ~100 ms) and have high Q values, providing a characteristic tag. Identification of high-energy β particles is carried out employing a planar germanium or plastic scintillator detector behind the DSSD at the RITU focal plane to obtain the full-energy and energy-loss information of emitted β particles (see Fig. 6).

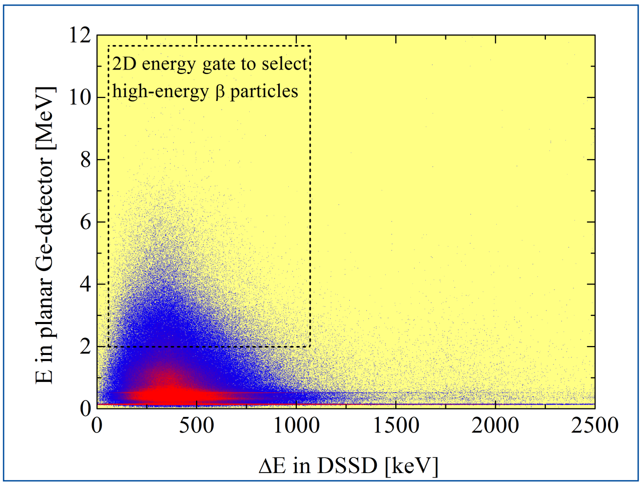


Fig. 6. Identification of high-energy β particles from a ΔE-E spectrum of the focal-plane DSSD and planar Ge-detector.

To date, ^{78}Y, ^{74}Sr, ^{74}Rb, ^{70}Br, ^{66}As and ^{66}Se nuclei have been successfully studied with RBT at JYFL utilising RITU, GREAT and JUROGAM I/II set-up.

To enhance the sensitivity of the RBT technique, a charged-particle veto detector consisting of 96 CsI(Tl)-crystals was installed around the JUROGAM II target position. This allows the studies of exotic neutron deficient nuclei produced via pure neutron emission channels. Recently, RBT method in conjunction with the charged-particle veto permitted the identification of three excited states in ^{66}Se (see Fig. 7(c)). These results, together with the recent observation of *T*=1 states up to spin 6^+ in ^{66}As, allowed the investigation of the triplet energy differences (TED) across the full *A*=66 triplet for the first time (see Fig. 8).

The TED can be used to probe the strength of the isospin non-conserving (INC) interactions such as the Coulomb force. The newly obtained TED data for the *A*=66 triplet follows the negative trend observed previously in the $f_{7/2}$ shell (see Fig. 8(a)). The origin of this behavior can be explained by Coulomb multipole (CM) effects associated with recoupling the angular momenta of pairs of particles. However, recent shell-model predictions show that the CM term alone is not sufficient to reproduce the experimentally observed TED magnitude (see Fig. 8(b)). Therefore, an additional INC interaction has to be employed in these calculations, but its fundamental origin is an open question.

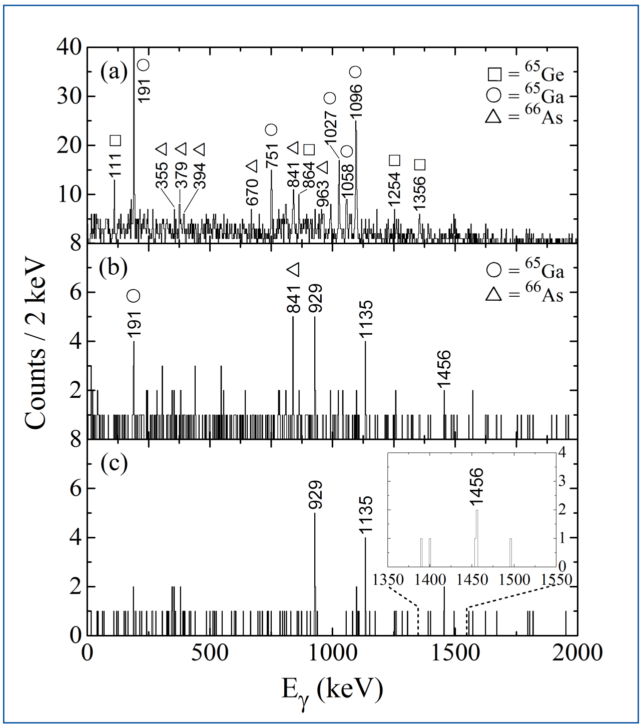


Fig. 7. (a) Recoil-β tagged JUROGAM II singles γ-ray spectrum. (b) Same as (a) but with charged-particle suppression. (c) Same as (b) but with an additional delayed γ-ray veto condition.

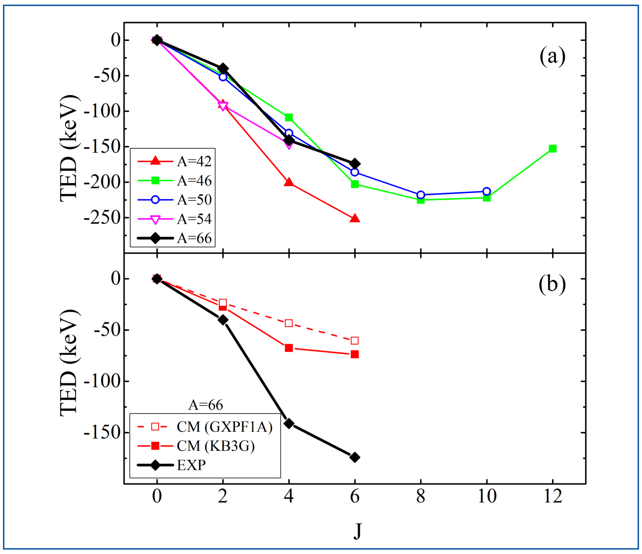


Fig. 8. (a)The experimental TED for the nuclei in A=42-66 region. (b) The shell-model predicted (red) and experimental (black) TED for the A=66 triplet.

Evidence for enhanced collectivity above the doubly magic nucleus ^{100}Sn

The evolution of collective- versus single-particle modes of excitations with changing neutron and proton number remains an important aspect for understanding the structure of nuclei far from stability. The area in the nuclear chart above the doubly magic ^{100}Sn nucleus offers a favourable situation to study this interplay as the valence space only contains a limited amount of nucleons outside a closed shell, but at the same time there are a sufficient number of particles for collective phenomena to emerge. Furthermore, the area coincides with the *N*=Z line where valence neutrons and protons occupy identical orbitals. Hence, new types of correlations such as isoscalar (*T*=0) n-p pairing interaction are expected to become important for low-lying collective motions.

A particular case, and one of the highlights of the JUROGAM I campaign, was the study of ^{110}Xe *[M. Sandzelius et al., Phys. Rev. Lett. 99, 022501 (2007)]*. Sitting four protons and six neutrons away from ^{100}Sn it serves as a perfect 'laboratory' for observing these exotic modes of excitations.

Fig. 9 depicts the performance of the JUROGAM array in conjunction with the selective power of the recoil-decay tagging technique. The recoil gated γ-ray spectrum is contrasted with the recoil-decay tagged spectrum of ^{110}Xe. The clean tag enables an identification of γ-ray transitions to be made, and hence provide an unambiguous assignment of the low-lying excited states in ^{110}Xe. The selectivity is in the order of one in several tens of millions. The unique capability of the JUROGAM array coupled with the RITU/GREAT set-up has proven it possible, even in the mass 100 region employing quite symmetric reactions, to perform in-beam γ-ray spectroscopy at a few tens of a nano barn.

“The unique capability of the JUROGAM array coupled with the RITU/GREAT set-up has proven it possible to perform in-beam γ-ray spectroscopy at a few tens of a nano barn.”

Fig. 10 shows the enhanced collective nature of the low-lying excited states in ^{110}Xe as seen through the 2^+ and 4^+ level energies. The broken trend of increasing 2^+ level energy from the neutron midshell as the *N*=50 closed shell is approached, is taken as evidence of an increase in collectivity. It is well known that the 2^+ level in an even-even nucleus is a good indicator of the degree of collectivity.

A low value will point to a high degree of collectivity whereas the opposite would indicate a single-particle like behaviour. It is expected that the maximum 2^+ level energy would occur near, or at, a closed shell for a spherical nucleus, thus exhibiting purely single-particle degree of freedom. The findings in ^{110}Xe, and in several other nuclei in this area, reveal a clear break from 'common wisdom', and the experimental results indicate a higher degree of collectivity than expected as the *N*=Z line is approached near *N*=*Z*=50.

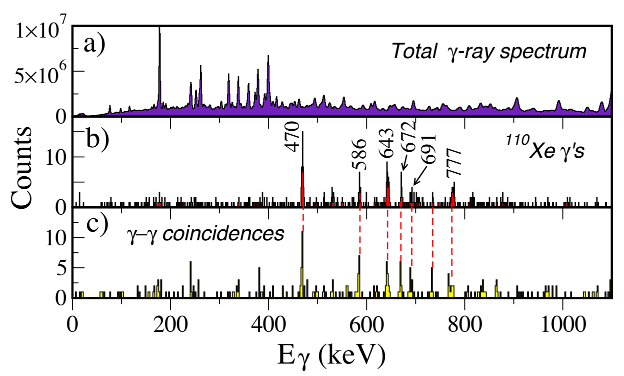


Fig. 9. (a) Total γ-ray spectrum correlated with any fusion-evaporation channel open in the experiment. (b) γ rays identified in ^{110}Xe by means of 'mother-daughter' alpha-decay tagging. (c) A γ-γ coincidence spectrum from a sum of gates on the strongest transitions. The staggering selectivity allows access to excited states in ^{110}Xe at a ~50 nb reaction cross-section.

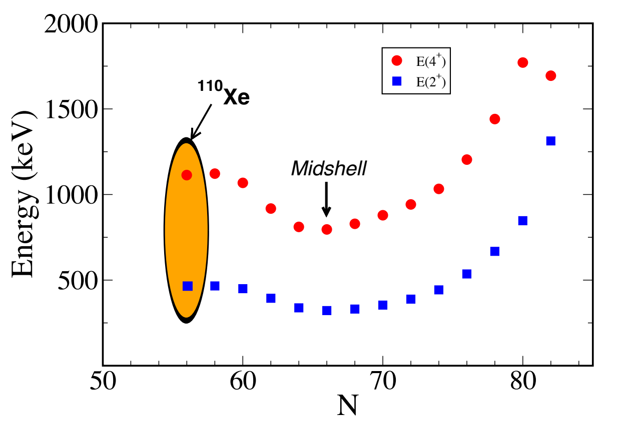


Fig. 10. Broken trend of increasing 2^+ and 4^+ level energies for the neutron deficient Xe isotopes. An enhancement in collectivity can be inferred as the N=Z is approached.

RDT-RDDS measurements with JUROGAM I & II

A variant of recoil distance Doppler-shift technique (RDDS) was developed by combining the JUROGAM I and later JUROGAM II γ-ray spectrometers with the RITU gas-filled recoil separator and the sophisticated focal plane detector system GREAT for the recoil-decay tagging experiments. A stopper foil of the plunger device used in the standard RDDS measurements was replaced by a degrader foil in order to allow recoiling evaporation residues to enter RITU. This is illustrated in Fig. 12. Additional difficulties, such as the increased background counting rate of Ge detectors and reduction of RITU transmission efficiency, are consequently introduced. These limitations combine to limit what is achievable with this technique in terms of cross section down to ~50 µb.

To date, RDDS technique has been applied in 21 experiments and typically a campaign is carried out annually. A few highlights are presented below.

Collectivity and configuration mixing of coexisting structures

First measurements of transition rates in Hg nuclei *[T. Grahn et al., Phys. Rev. C 80, 014324 (2009)]*, Pb and Po *[T. Grahn et al., Phys. Rev. Lett. 97, 062501 (2006)]*, which addressed collectivity and configuration mixing between the coexisting structures, pioneered the tagging techniques in lifetime measurements. Consequently, a large body of data has been gathered that, in turn, has provided stringent constraints of contemporary theory development *[T. Grahn et al., Nucl. Phys. A 801, 83 (2008)]*. In Fig. 11, the values of $|Q_t|/Z$, extracted from level lifetimes measured with JUROGAM, have been plotted as a function of *Z* for the prolate and oblate structures. Surprisingly increase of collectivity as a function of *Z* is observed. This is not suggested by the similar moments of inertia and therefore warrants further investigations to understand nuclear structure of coexisting shapes.

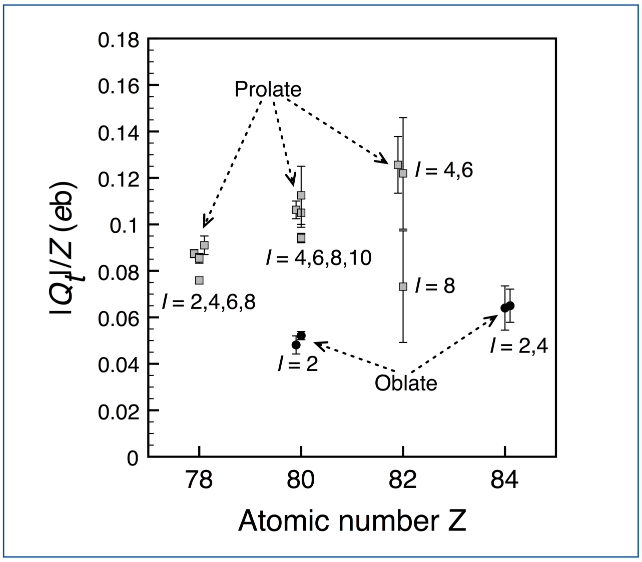


Figure 11. Experimental transition quadrupole moments normalised by the atomic number Z for the transitions between prolate (grey squares) and oblate (black circles) states in ^{182}Pt, ^{182}Hg, ^{186}Pb and 194Po nuclei in the vicinity of the neutron mid shell. The initial spin I ranges for the selected states are indicated.

Transition probabilities at the proton drip line

The studies of transition probabilities in ^{109}I *[M. G. Procter et al., Phys. Lett. B 704, 118 (2011)]* and ^{108}Te *[T. Bäck et al., Phys. Rev. C 84, 041306(R) (2011)]* provided information of transitions matrix elements in neutron-deficient nuclei above *Z*=50. The lifetime measurements in ^{109}I represent a forefront of selectivity, being the first ever proton-tagged plunger lifetime measurement. These experiments shed more light on the interplay of collectivity and single-particle regime in this region when approaching the *N*=50 shell closure.

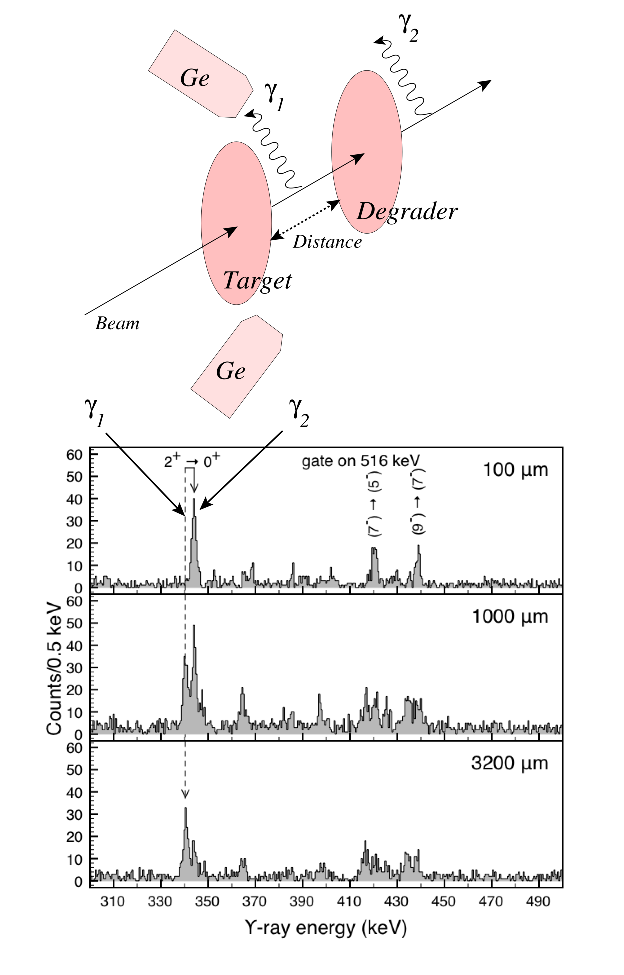


Figure 12. The principle of the RDDS technique with degrader foil.

The SAGE spectrometer

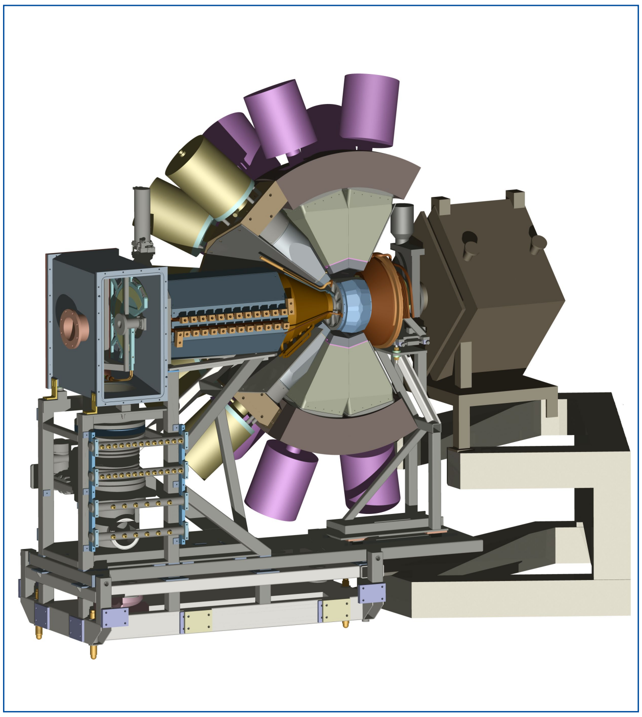


Fig. 13. Schematic design of the SAGE spectrometer coupled to RITU. [J.Pakarinen et al., EPJA (2014) 50: 53]

The SAGE spectrometer combines in-beam γ-ray and conversion-electron spectroscopy with an unprecedented level of efficiency. It is aimed to the study of superheavy nuclei (where internal conversion strongly competes with γ-ray emission) and shape coexistence (where different shapes are connected via E0 transitions).

SAGE employs the JUROGAM II array (24 Clover and 10 EUROGAM Phase-I type Compton-suppressed germanium detectors) for the detection of γ rays and a 90-fold segmented silicon detector for the detection of conversion electrons. A solenoidal magnetic field transports the electrons from the highly radioactive target region to the silicon detector. Compton suppression of the germanium detectors is not affected by the magnetic field because of magnetic shielding used around the solenoid coils. SAGE is coupled to the RITU gas filled recoil separator and the GREAT focal plane spectrometer allowing the use of various tagging techniques.

The detector is centred on the solenoidal magnetic field axis which forms a 176.8° angle with the incoming beam, thus minimising the doppler broadening of the emitted electrons and the amount of δ electrons that are transported to the silicon detector. To further reduce the δ-electron flux, an electric field gradient induced by a high-voltage barrier is placed in the region between the target and the silicon detector. A carbon-foil unit separates the high-vacuum region of the barrier from the helium-filled target chamber. Helium in the target region allows for target cooling and the use of higher intensity beams.

The transmission and detection efficiency of the electron part of SAGE depends on the configuration of the magnetic and electric fields. From source measurements and simulations for standard running mode settings, the efficiency is 4-6% for 100-300 keV electrons and decreases at higher energies.

SAGE uses a fully digital TDR data acquisition system. The combination of digital electronics with the high silicon detector segmentation and high-voltage barrier opens the way to in-beam conversion-electron experiments with higher intensity beams than ever used before.

SAGE offers the possibility to extract information concerning previously unseen highly-converted transitions. A highlight from the first SAGE campaign was the ^{184,186}Hg experiment. The conversion coefficient of the 216 keV 2_2^+ to 2_1^+ transition in ^{186}Hg extracted from the γ-ray gated electron spectrum of Fig. 14, reveals a strong *E0* component in this transition.

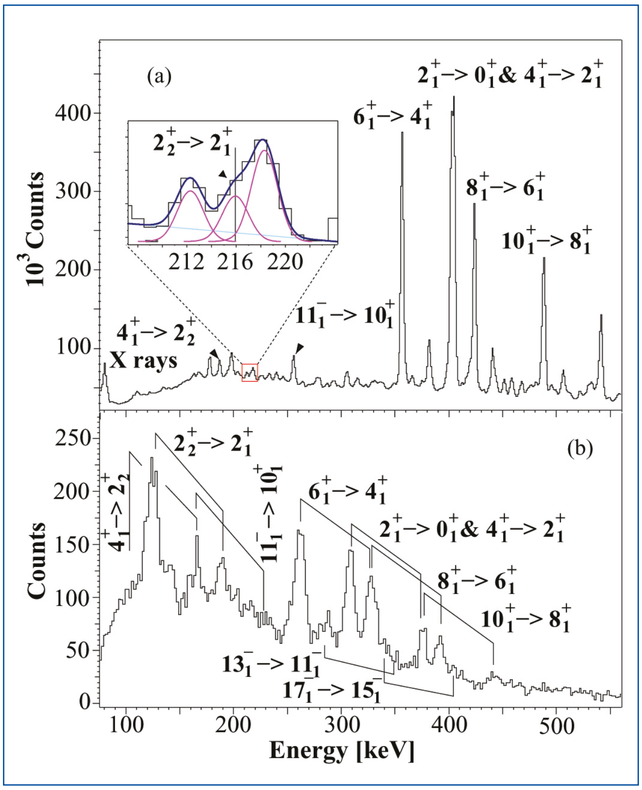


Fig. 14. Two spectra of ^{186}Hg simultaneously recorded with the SAGE spectrometer. (a) Projection of the γγ matrix. The inset shows the γ -ray peak of the 216-keV $2_2^+ \rightarrow 2_1^+$ transition. This peak forms a multiplet with the 212 keV peak (^{185}Au) and the 218 keV peak, the latter stemming from a transition of a K=8 band. The deconvoluted peaks are shown below the fitted curve. (b) The e− spectrum created by gating on the 187, 357, 403, 405, 424, 489, and 542 keV γ transitions of the γ-e− matrix. K- and L-electron peaks of one given transition are connected with brackets. [M. Scheck et al, PRC83,037303 (2011)]

Changing structure towards and beyond the proton drip line

The identification of excited states in atomic nuclei spanning complete shells is crucial to determining the evolution of nuclear structure from both empirical and theoretical perspectives. The sub-lead nuclei currently represent the best opportunity to probe the evolution of nuclear structure across the 82 ≤ N ≤ 126 neutron shell. Considerable progress has been made towards identifying excited states for the first time in the W-Os-Pt-Hg nuclei approaching the closed neutron shell at N=82. The JUROGAM γ-ray spectrometer, used in conjunction with the highly selective recoil-decay tagging technique, has been used to identify γ-ray transitions in nuclei that are over 20 neutrons lighter than their lightest stable isotopes such as ^{159}W *[P.J. Sapple et al., Phys. Rev. C84, 054303 (2011)]*, ^{162}Os *[D.T. Joss et al., Phys. Rev. C70, 017302 (2004)]*, ^{168}Pt *[M.B.G.Hornillos et al., Phys. Rev. C79, 064314 (2009).]* and ^{173}Hg *[D. O'Donnell et al., Phys. Rev. C85, 054315 (2012)]*. The excitation level schemes across the shell reveal a distinct evolution between the single-particle and collective regimes as a function of neutron number.

“The JUROGAM gamma-ray spectrometer, used in conjunction with the highly selective recoil-decay tagging technique, has been used to identify γ-ray transitions in nuclei that are over 20 neutrons lighter than their lightest stable isotopes”

The JUROGAM spectrometer has also allowed the structure of high-spin states to be determined beyond the proton drip line. A comprehensive excitation level scheme for the proton-unbound nucleus ^{161}Ta comprising five strongly coupled bands has been determined in a recoil-tagged γ-ray coincidence analysis *[K. Lagergren et al., Phys. Rev. C83, 014313 (2011)]*. Configuration assignments for all the new bands have been proposed based on the variation of the aligned angular momenta as a function of rotational frequency (see Fig. 15.) and ratios of reduced transition probabilities. Comparisons of rotational alignments with the heavier isotope ^{163}Ta (also observed for the first time using JUROGAM *[M. Sandzelius et al., Phys. Rev. C80, 054316 (2009)]*) suggest that the lower average deformation in ^{161}Ta favours the alignment of $h_{9/2}$ neutrons over the $i_{13/2}$ neutron pair alignment observed in the heavier isotopes. Features such as large signature splitting suggest that γ-soft triaxial shapes persist after the rotational alignment of the $h_{9/2}$ neutrons in ^{161}Ta. This is markedly different to the high-spin structures in the heavier isotopes where aligning an $i_{13/2}$ pair results in minimal signature splitting, consistent with an axial prolate shape. Thus additional information regarding the core polarizing character of the underlying orbital configurations is revealed.

It has been possible to probe further beyond the drip line using proton radioactivity as a selective tag, see Fig. 16. *[K. Lagergren et al., Phys. Rev. C74, 024316 (2006)]*. Similar correlations with the $d_{3/2}$ ground-state proton decay in ^{160}Re have revealed excited states in ^{160}Re that have been interpreted in terms of $\pi h_{11/2} \nu h_{9/2} (f_{7/2})^2$ excitations as observed in the lighter N=85 isotones *[P.J. Sapple et al., Phys. Rev. C84, 054303 (2011)]*. This result is consistent with complementary studies made with the GREAT spectrometer that suggest that the convergence of the $h_{9/2}$ and $f_{7/2}$ neutron levels in this region could open up a γ-decay path from the high-spin isomer to the low-spin ground state of ^{160}Re *[I.G. Darby et al., Phys. Lett. B695, 78 (2011)]*. This high-spin isomer is unique since it only decays by γ decay and not by proton or alpha-particle emission as is the case in every other proton emitter between Z=64 and Z=80.

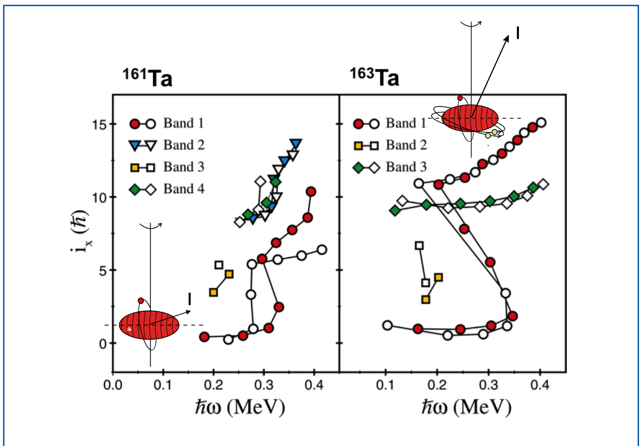


Figure 15. Rotational alignments in ^{161}Ta and ^{163}Ta showing single and three-quasiparticle bands.

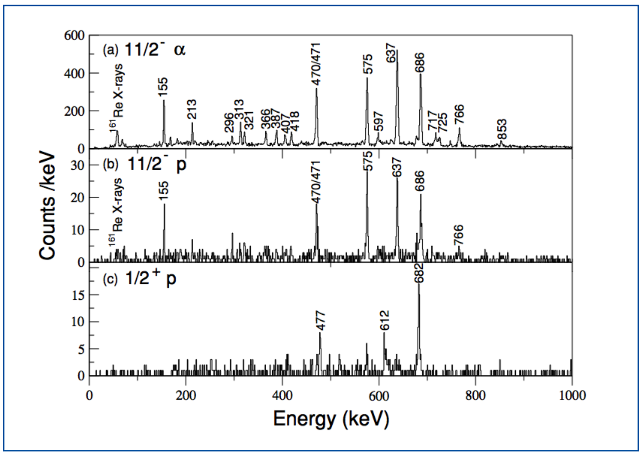
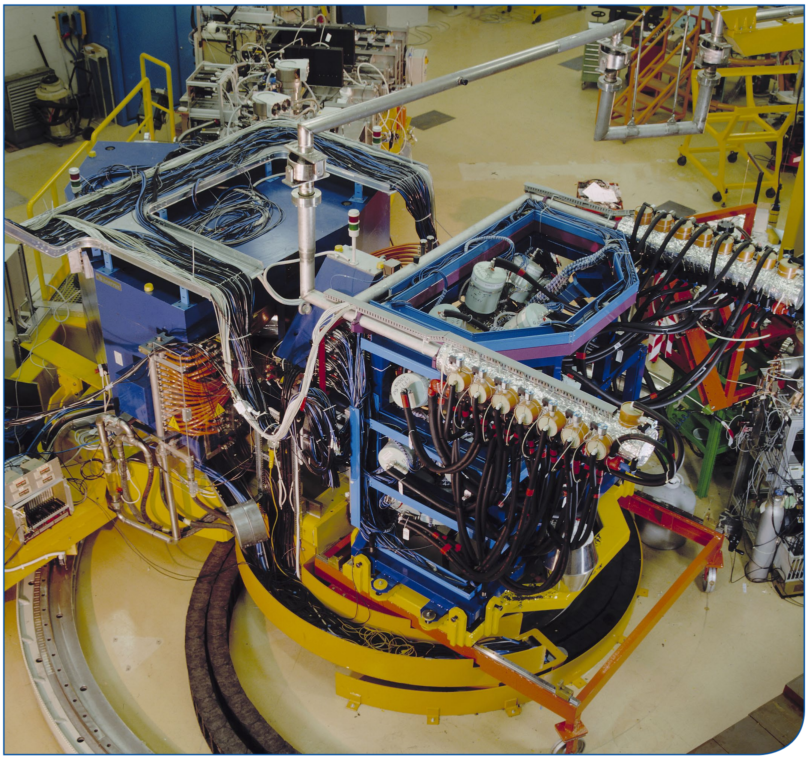


Figure 16. Gamma rays selected by recoil-decay correlations with the alpha and proton decays from the 1/2⁺ and 11/2⁻ states in the proton emitter, ^{161}Re [K. Lagergren et al., Phys.Rev. C 74, 024316 (2006)].

CLARA

LNL, Legnaro, Italy



The physics case addressed with the CLARA-PRISMA combined setup is the study of the structure of moderately neutron-rich nuclei. The structure of these nuclei has attracted considerable interest in recent years since experimental findings showed that, although 'magic numbers' are considered one of the firmest paradigms when it comes to our knowledge of the nucleus, this concept is far from being universal; the energetic gaps which occur in the shell structure at particular nucleon numbers for nuclei close to stability (the so-called magic numbers) can close while others open up when nuclei are far from stability and new magic numbers can appear. High-resolution spectroscopy of neutron-rich nuclear species plays a mayor role on the understanding of this phenomenon, and of other open questions such as the evolution of the nuclear effective interactions in the monopole and multipole terms, affecting our capability to provide a theoretical description of the nuclear structure, the evolution of the nuclear collectivity (including shape phase transitions) and the onset of exotic shapes.

The CLARA array was in operation at the Laboratori Nazionali di Legnaro (LNL), Italy, from 2004 to 2008. It was composed of 25 Clover detectors, with Compton-suppression shield, from GAMMAPOOL resources. Such a combination provided a photopeak efficiency ≈ 3%, and a peak/total ratio ≈ 45% for 1.33 MeV photons. CLARA was installed at the target position of the PRISMA magnetic tracking spectrometer of the LNL. This device has a very simple optical design consisting of a quadrupole singlet and a dipole. No further optical elements are used to correct for aberrations, rather the trajectory of each ion is software reconstructed starting from the information provided by position-sensitive start and focal plane detectors. This way, a large solid angle (approximately 80 msr) is obtained, combined with mass resolution up to $\Delta A/A \approx 1/200$ and Z resolution $\Delta Z/Z \approx 1/60$. Within the limitation of the Z and mass resolutions, PRISMA allows for the unambiguous identification of the reaction products as well as for the full vector velocity of each ion. The combination of the information provided by the germanium detectors of CLARA and by the spectrometer, makes it possible in most cases to unequivocally assign the observed transitions to a particular nucleus. This is of extreme interest for the identification of transitions from previously unobserved isotopes. Exploiting the excellent event-by-event definition of the recoil velocity provided by PRISMA, as well as the granularity of the Clover detectors, it was possible to obtain an effective energy resolution ≈ 0.6% for v/c = 10% (which was the typical recoil velocity in multinucleon transfer reactions).

Some examples of the scientific themes addressed during the CLARA-PRISMA campaign:

- study of the region close to the doubly-magic nucleus ^{48}Ca;
- persistence of the N=50 shell gap in neutron-rich nuclei;
- onset of collectivity close to N=40;
- pair transfer effects;
- particle-phonon couplings;
- molecular states.

CLARA was built thanks to the collaboration of several European institutes, including INFN, IreS Strasbourg (France), GANIL (France), the Universities of Manchester, Surrey and Paisley (UK), Daresbury Laboratory (UK), HMI Berlin (Germany), GSI Darmstadt (Germany), Universidad de Salamanca (Spain), NIPNE Bucharest (Romania).

CLARA	
Detectors	25 EUROBALL Clovers
Efficiency at 1332keV	3%
Operational	Years 2004-2008
Number of experiments	24
Beamtime hours	1600+

Highlights from CLARA

Particle–phonon coupling in ^{49}Ca with γ spectroscopy and heavy-ion transfer reactions

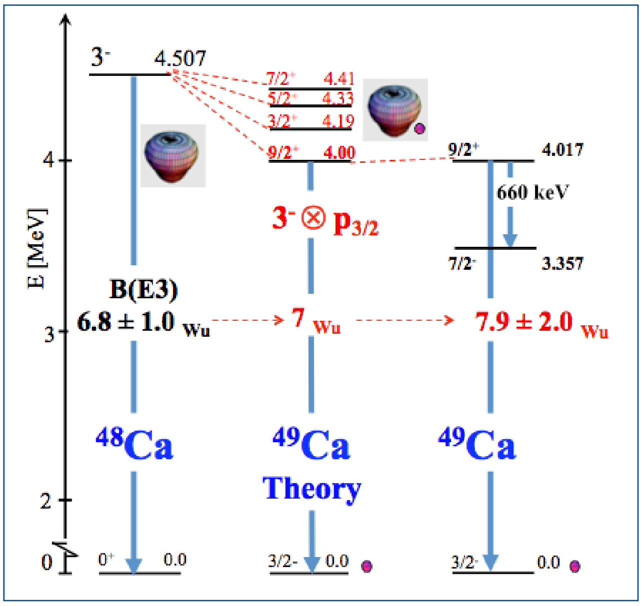


Fig. 1: Experimental level scheme of ^{49}Ca, with the 9/2$^+$ state as the lowest member of the $3^- \otimes p_{3/2}$ multiplet, arising by coupling one neutron $p_{3/2}$ to the collective 3$^-$ phonon of ^{48}Ca. Predictions are obtained by a weak-coupling model using the SkX Skyrme interaction.

The coupling of a single particle to vibrational motion is a basic phenomenon in fermionic many-body interacting systems, being a key process at the origin of anharmonicities of vibrational spectra. In nuclear physics, particle-phonon coupled states are responsible for the damping of collective excitations (as giant resonances), effective masses and the quenching of spectroscopic factors *[A. Bohr, B.R. Mottelson, Nuclear Structure, Vols. I and II, W.A. Benjamin, 1975; P.F. Bortignon, A. Bracco and R.A. Broglia, Giant Resonances: Nuclear Structure at Finite Temperature, Harwood Academic Publishers, New York (1998)]*.

Experimental indications have been found for particle-phonon states in medium-heavy nuclei, but it is an open question whether this can be considered a general nuclear property, down to the region of medium-light systems with reduced collectivity. Interesting cases are nuclei one nucleon away from the doubly magic ^{48}Ca core, since the 3$^-$ state of ^{48}Ca has a sizable, although rather reduced, *B(E3)* strength, of the order of 7 W.u.

The multi-nucleon transfer reaction ^{48}Ca on ^{64}Ni at 6 MeV/A was employed at PRISMA-CLARA to populate neutron rich nuclei around ^{48}Ca. Evidence is found for a large spin alignment, allowing to use angular distributions and polarizations of γ rays to firmly establish, for the first time, spin and parities of several excited states. In the one neutron transfer channel ^{49}Ca, the level at 4017 keV is established as 9/2$^+$ with a lifetime τ=8.5(2.0) ps, as measured by a differential plunger technique. This gives a reduced transition probability *B(E3)* = 7.9 ± 2.0 W.u., similar to the 3$^-$ phonon strength of ^{48}Ca. The 9/2$^+$ state is therefore interpreted, within the weak-coupling model, as the lowest member of the $3^- \otimes p_{3/2}$ multiplet, arising by coupling the unpaired $p_{3/2}$ neutron to the collective 3$^-$ phonon of the core nucleus ^{48}Ca *[D.Montanari, S. Leoni et al. Phys. Lett. B697, 288(2011)]*. Similar type of states are also observed in ^{47}Ca *[D.Montanari, S. Leoni et al. Phys. Rev. C85, 044301(2012)]*, showing the robustness of nuclear collectivity in rather light systems.

The work demonstrates the feasibility of complete γ-ray spectroscopy with heavy-ion transfer reactions, offering a method to be further exploited with heavy targets and radioactive beams.

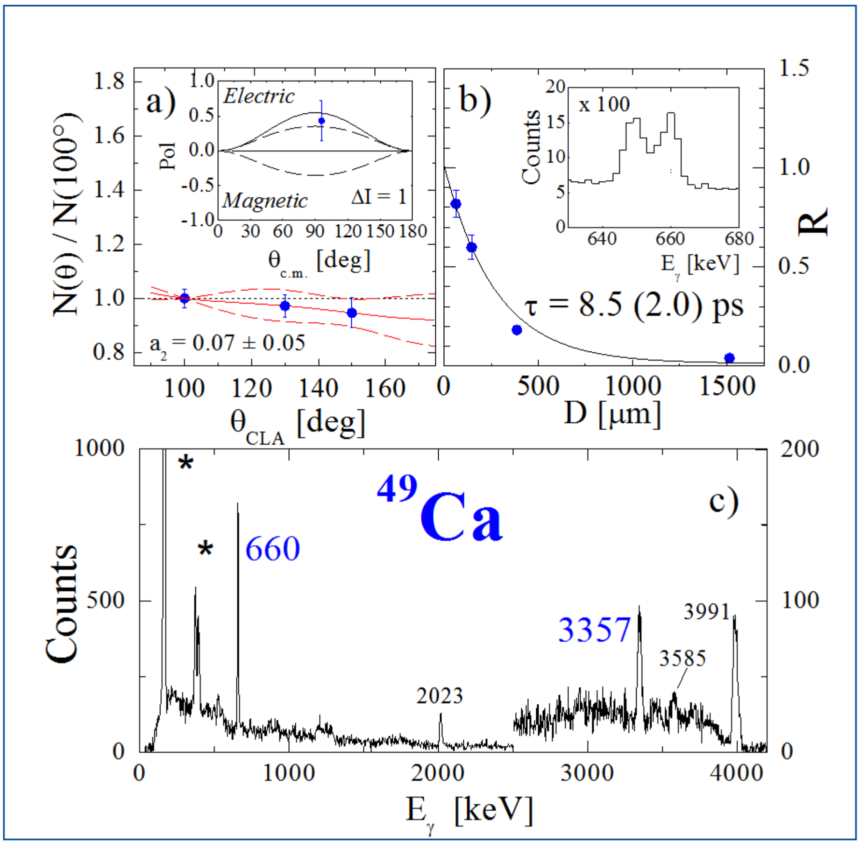
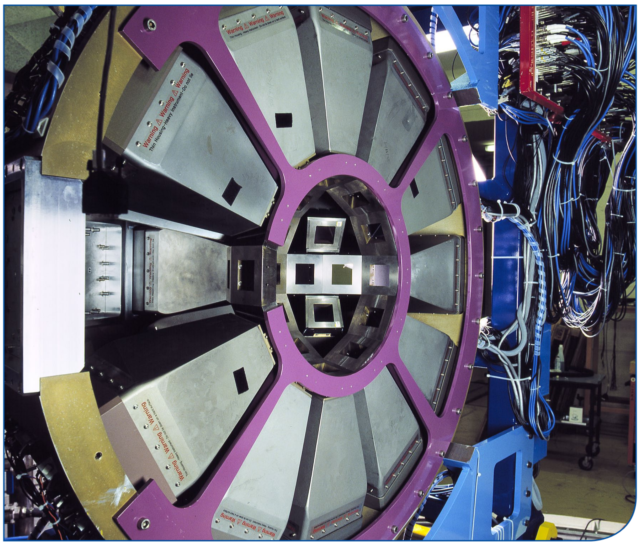


Fig. 2: Angular distribution, polarization and lifetime analysis (a) and b)) of the 660-keV transition depopulating the 9/2$^+$ state of ^{49}Ca [D.Montanari, S. Leoni et al. Phys. Lett. B697, 288(2011)].

Shape evolution in neutron-rich nuclei around *N*=40: a new island of inversion



Unexpected modifications to the shell structure have been already encountered far from the valley of stability in light and medium light nuclei. There is clear evidence that new magic numbers appear in neutron-rich nuclei far from stability and new regions of deformation develop at neutron numbers that are 'magic' near stability. The observed changes help to shed light on specific terms of the effective nucleon-nucleon interaction and to improve our knowledge of the nuclear structure evolution towards the drip lines. These changes manifest clearly in the nuclear shape and structure along isotopic chains.

Neutron-rich isotopes can be populated at relatively high spin by means of deep-inelastic and multinucleon transfer reactions using the most neutron-rich stable heavy ions. These experiments have been done at LNL using the Ge-detector array CLARA, coupled to the PRISMA magnetic spectrometer. Beams of ^{64}Ni and ^{70}Zn were used to bombard targets of ^{238}U and, for the first time, excited states could be identified in several neutron-rich nuclei of mass A~60 south of the 'doubly magic' ^{68}Ni. Very rapid changes in the shape and in collectivity of V, Ti, Cr, Mn, Fe and Co isotopes have been observed. In particular, the Cr isotopes pass from spherical shapes at the new magic number N=32 to very deformed shapes approaching N=40.

The isotope ^{58}Cr has been proposed as a candidate for the critical point shape phase transition at N=34 *[N. Marginean et al., Phys. Lett. B633 (2006) 696]*. While this nucleus can be described in the fp shell model space, the Mn isotopes also identified in these experiments show that, approaching N=40, the contribution of the $g_{9/2}$ orbital becomes important *[J.J. Valiente et al., Phys. Rev. C 78, 024302 (2008).]* This is more evident in the Fe and Co isotopes that have been observed up to N=40-42. The new data on Fe isotopes *[S. Lunardi et al., Phys. Rev. C 76, 034303 (2007) and S.M. Lenzi et al., LNL Annual Report 222 (2007) 15]* proves that the removal of two $f_{7/2}$ protons from the spherical ^{68}Ni drives the N=40 nucleus ^{66}Fe into a prolate shape generates a new region of deformation at N=40. Theoretical investigations have explained this phenomenon in terms of the shell model, where the neutron $d_{5/2}$ orbital plays an important role together with the $g_{9/2}$ orbital *[LNPS interaction, S.M. Lenzi et al., Phys. Rev. C 82, 054301 (2010)]*. The Co nuclei, lying between Ni and Fe, show the coexistence of spherical and well deformed structures at low excitation energy, which is particularly evident in ^{67}Co with one proton hole in ^{68}Ni *[F. Recchia et al., Phys.Rev. C 85, 064305 (2012)]*. These rapid changes of shape, along isotopic and isotonic chains, are the result of the shell evolution far from stability and constitute a very good laboratory to investigate and understand the effective nuclear interaction.

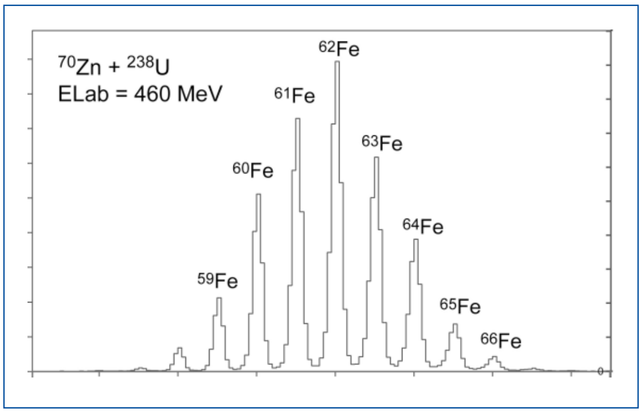


Fig 3 : Mass distribution of Fe isotopes.

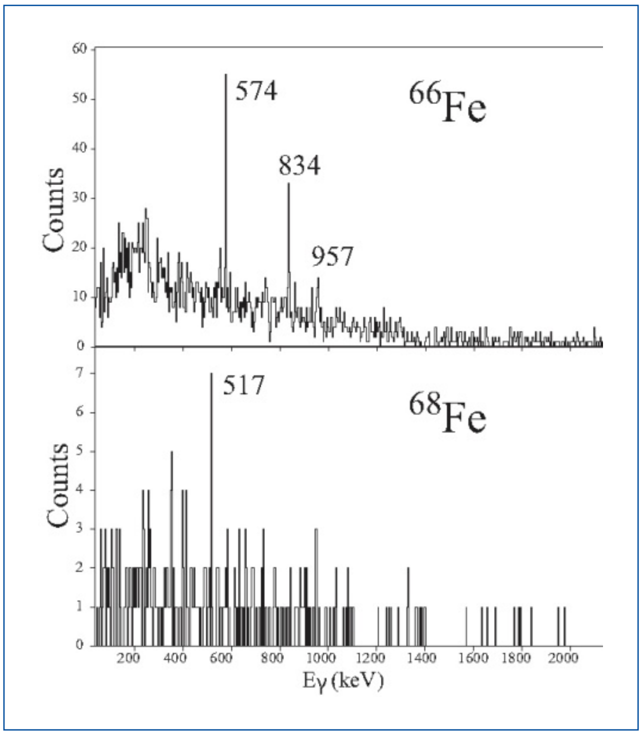


Fig 4: γ spectrum in CLARA in coincidence with ^{66,68}Fe.

Lifetime measurements of the neutron-rich *N*=30 isotones ^{50}Ca and ^{51}Sc: Orbital dependence of effective charges in the fp shell

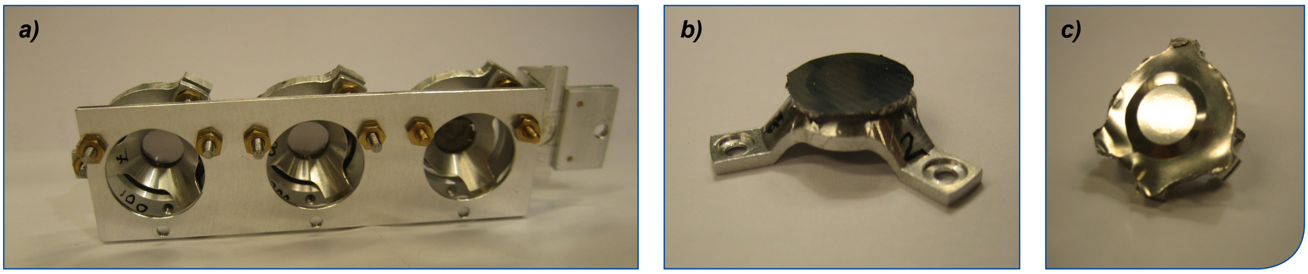


Fig. 5. a) A ladder holding three different target-to-degrader distances, b) the target and c) the degrader.

Structural changes have been verified in the magic character of *N*=32 in Ca, Ti and Cr isotopes *[B. Fornal et al., Phys. Rev. C77, 014304 (2008)]* and in the possible quenching of the *N*=28 shell closure, yet spectroscopic information is scarce due to the difficulty in populating such neutron-rich nuclei. Therefore, an experiment was performed at LNL, using the CLARA-PRISMA set-up *[A. Gadea et al., Eur. Phys. J. A20, 193 (2004), A. Stefanini et al., Nucl. Phys. A701, 217c (2002) and D. Montanari et al., Eur. Phys. J. A 47, 4 (2011)]* in combination with a novel version of the RDDS method *[D.Mengoni et al., Eur. Phys. J. A42, 387(2009)]*. A ^{48}Ca beam of 310 MeV from the LNL Tandem-ALPI accelerator complex was focused on a target consisting of 1.0 mg/cm^2 of enriched ^{208}Pb evaporated onto a 1.0 mg/cm^2 Ta support to accomplish the stretching of the target. A 4 mg/cm^2 Mg foil was used as an energy degrader. The target-to-degrader distances ranged from 20 µm to 3000 µm. The target-degrader system was placed at the center of the CLARA array *[J.J. Valiente Dobon at al., Phys. Rev. Lett. 102, 242502 (2009)]*.

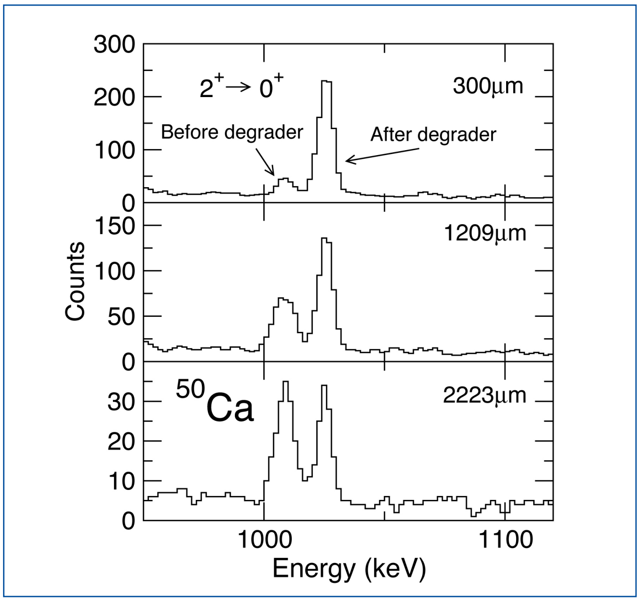


Fig. 6: Doppler-corrected γ-ray spectra showing the 2⁺→0⁺ 1027-keV and transitions in ^{50}Ca for different target-to-degrader distances. The higher-energy and lower-energy peaks correspond to the decays after and before the degrader, respectively.

Figures 6 and 7 outline the results on the precise measurements on the *B(E2)* values on Ca isotopes, that enabled study of the isoscalar/isovector quadrupole excitation contribution of the core, and highlight an important advantage of the RDDS method coupled to a magnetic spectrometer in terms of the feeding control, which is one of the problems of the singles RDDS method.

Fig. 6 shows the 1027 keV $2^+ \rightarrow 0^+$ γ-ray transition in the ^{50}Ca nucleus as a function of the target-to-degrader distance. The lifetime of the state can be deduced when the recoil velocity before the degrader is provided and the intensity from the upper feeders properly taken into account.

The recoil velocity is calculated considering that the Doppler shift, between the shifted and unshifted peaks, for each angle, is a function of the velocity. Where statistics are sufficiently high, feeding is taken into account using the total kinetic energy loss. The Q-value of the reaction is used to select an entry-point in the excitation mechanism in the case of ^{46}Ca. See Fig. 7.

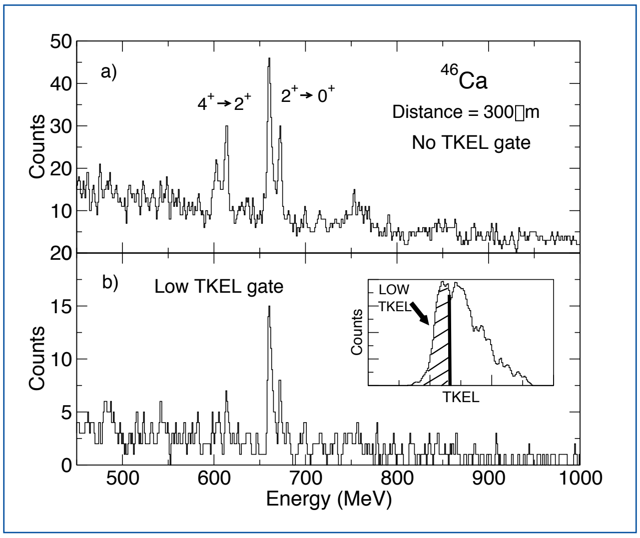


Fig. 7: Doppler-corrected γ-ray spectra corresponding to the $2^+ \rightarrow 0^+$ 1346 keV and 4+→2+ 1229-keV transitions in ^{46}Ca for different TKEL cuts, a) gate on low TKEL and b) gate on high TKEL.

Evolution of collectivity close to the N_pN_n valence maximum

The importance of the number of proton-neutron interactions, which is equal to the product of valence nucleons N_pN_n, for quadrupole collectivity, is well known. In particular, the energy, E(2⁺) and the reduced transition probability, *B(E2)* of the first 2⁺ state, as well as the energy ratio E(4⁺)/E(2⁺), are quantities that have a smooth dependence on this quantity. Neglecting any potential sub-shell closures, the nucleus with the largest number of valence particles with *A*<208 is ^{170}Dy. Accordingly, it should be one of the most collective of all nuclei in its ground state *[P. H. Regan et al., Phys. Rev. C65(2002)037302]*.

Looking how E(2⁺) changes in Fig. 8, the dysprosium isotopes appear to become more collective, that is, have lower E(2⁺) values, with increasing neutron numbers from ^{160}Dy up to ^{164}Dy. At ^{166}Dy, however, E(2⁺) increases again, suggesting that the maximum collectivity is found in ^{166}Dy. There is no theoretical consensus regarding the cause of this effect, but one theoretical prediction in particular suggests the appearance of a new deformed sub-shell closure at *N*=100 in the Sm region *[S.K. Ghorui et al., Phys. Rev. C85(2012)064327.]*.

The experiment reported here was carried out using multinucleon transfer reactions between ^{82}Se and ^{170}Er. The beam delivered by the accelerator complex at LNL was ^{82}Se at an energy of 460 MeV and an intensity of ~25 enA (~2 pnA). This beam was incident on a 500 μg/cm² thick self-supporting ^{170}Er target. Beamlike fragments were identified using the PRISMA magnetic spectrometer.

An irregularity in the energy systematics of the yrast 2⁺ and 4⁺ states exists at *N*=98 for *Z*=64 (gadolinium) and *Z*=66 (dysprosium). Extending the systematics to higher spin, shows that this irregularity also appears further up in the yrast band of *Z*=66, showing that this is a systematic effect and not only a small fluctuation at low energies (see Fig. 8). This irregularity also appears in elements with larger *Z* at higher spin. According to existing data, the energy minimum at *N*=104 is clear at low spins and stays quite stable up to 12⁺. However, for *Z*=68 (Er) the energy levels of the isotopes with *N*=102 and *N*=104 increase relative to *N*=98, even above the corresponding energy levels in *Z*=70 (Yb), causing *N*=98 to become a new global minimum. The data on ^{168}Dy presented by Söderström et al *[P.-A. Söderström et al., Phys. Rev. C81(2010)034310.]* show no such increase relative to ^{164}Dy.

The interpretation that the irregularity is an effect in ^{166}Dy and not in neighboring isotopes is strengthened by the tentative identification of the 4⁺→2⁺ transition at 163 keV in ^{170}Dy. The energy systematic of the yrast band of ^{168}Dy as well as the tentative identification of the 4⁺ → 2⁺ transition at 163 keV in ^{170}Dy further suggests that maximum collectivity in dysprosium isotopes occur at *N*=104, as expected, but with a weak influence of the possible *N*=100 deformed sub-shell closure.

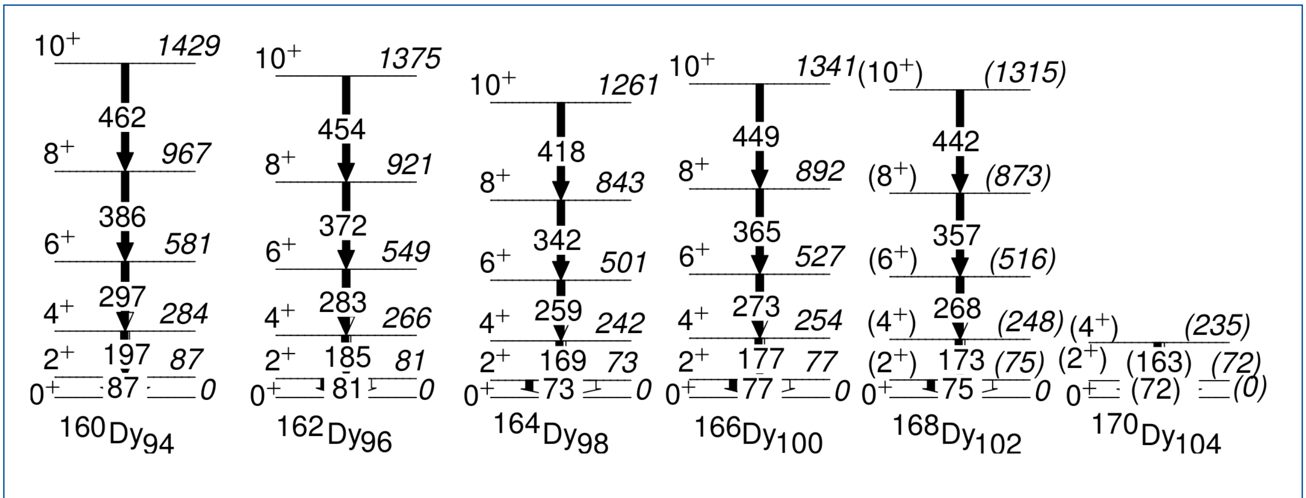


Fig. 8: Ground state rotational bands for dysprosium isotopes with N=94-104. The 6⁺–10⁺ transitions in ^{168}Dy and the 4⁺ → 2⁺ transition in ^{170}Dy are from [P.-A. Söderström et al., Phys. Rev. C81(2010)034310] and the 2⁺ → 0⁺ transition in ^{170}Dy is from the calculations in [W.-H. Zou and J.-Z. Gu. Chin. Phys. Lett 27(2010)012101]

Molecular Resonances and Jacobi Shape Transitions in ^{48}Cr studied in the ^{24}Mg + ^{24}Mg reaction

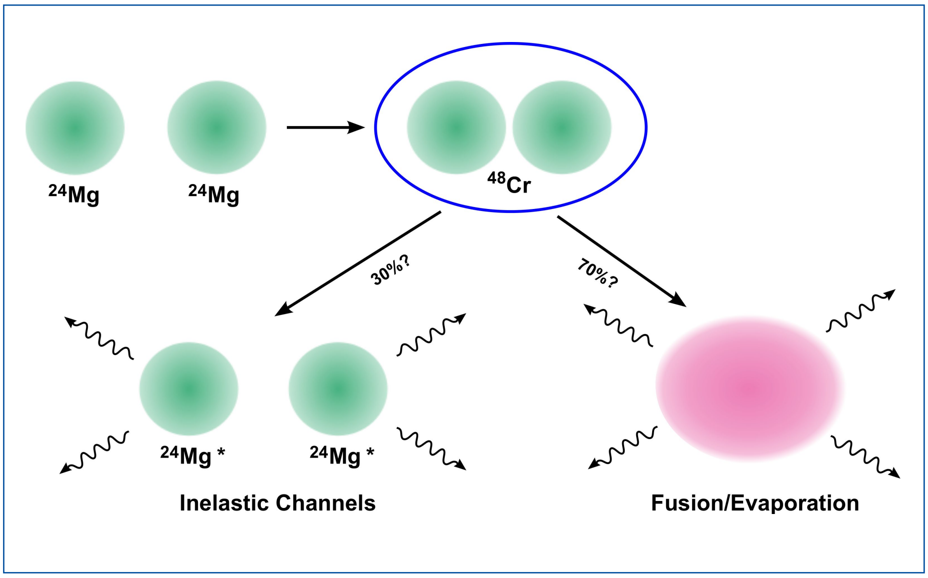


Fig. 9: Schematics of the two experiments performed in Legnaro to study the ^{24}Mg + ^{24}Mg reaction.

A fast rotating ^{48}Cr is predicted to be highly prolate and deformed after a Jacobi shape transition and just before fission. It has been proposed that a narrow and high-spin ^{24}Mg + ^{24}Mg resonance corresponds to the formation of this exotic ^{48}Cr. Despite the very high excitation energy of 60 MeV in the ^{48}Cr composite system, this resonance has a narrow total width of 170 keV. This value corresponds, using the Heisenberg principle, to a lifetime of 4×10^{-21} s, which is 10 times longer than a typical nuclear reaction time and relates to a rotation of about 2 turns of the composite system, giving credit to the possible formation of a ^{48}Cr di-nucleus in the resonance process.

To establish the connection between the resonance and a molecular state of ^{48}Cr, the decay of the resonance into the inelastic and fusion-evaporation channels has been investigated. The ON and OFF resonance decay yields have been measured in two complementary experiments at INFN-LNL, using the CLARA-PRISMA setup for the inelastic channels, and the Si array EUCLIDES installed in the LNL GASP array for the fusion-evaporation channels, The schematics of the two experiments are presented in Fig. 9.

The first experiment aimed to study the decay of ^{48}Cr in the inelastic channels, where two excited ^{24}Mg are detected in the exit channel of the reaction. PRISMA enabled identification of the ^{24}Mg fragments whereas CLARA detected the γ-rays emitted by the excited ^{24}Mg. The results are shown in Fig. 10. Two strong lines at 1.36 MeV and 2.75 MeV can be observed in the γ spectra. This implies that we have a selective feeding of the 0^+, 2^+ and 4^+ states of the $K^\pi = 0^+$ band in this reaction. Comparing this result with theoretical calculations we conclude that there is a selective feeding of a deformed composite nucleus.

As only 30% of the decay was observed in these inelastic channels, the second experiment was performed to look at the fusion-evaporation channels. In this process, several residues are formed. The light charged particles emitted by the compound nucleus were recorded in EUCLIDES and the γ-rays from the residues were observed in GASP. For this reaction, eight residues close to ^{48}Cr were identified, but no clear proof of a real selective feeding of deformed states in the residues were found.

From the results obtained in these complementary experiments, it is obvious that there is still some missing flux. A more detailed presentation and discussion of this work can be found in *[M.-D. Salsac et al.,Nucl. Phys. A801 (2008) 1]*.

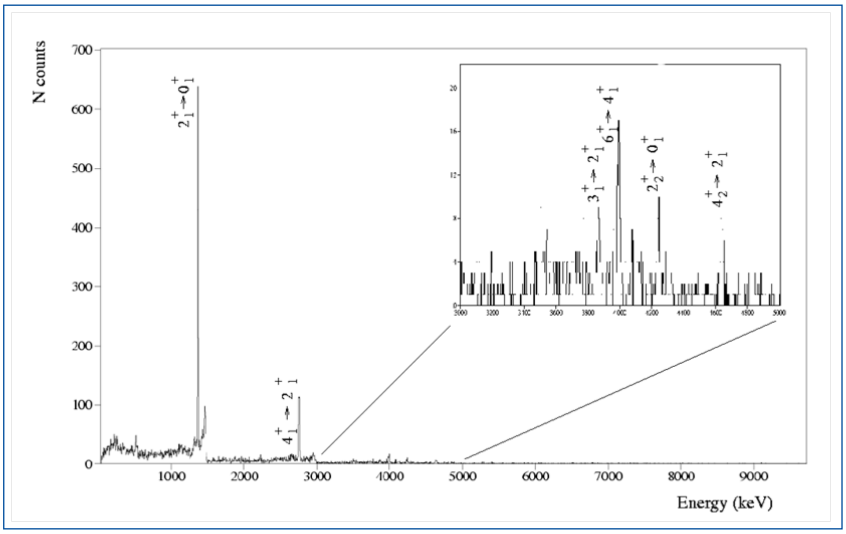


Fig. 10: Spectra obtained from the CLARA-PRISMA experiment.

NEUTRON WALL

GANIL, Caen, France

Fig. 1. Neutron Wall and EXOGAM at GANIL.

The Neutron Wall is a neutron detector array consisting of 50 closely packed liquid scintillator detectors. It covers a solid angle of about 25% of 4π and can be placed in the forward hemisphere of a gamma-ray spectrometer, for example EUROBALL, EXOGAM (see Fig. 1) or AGATA. Together with a light charged particle detector array, such as EUCLIDES or DIAMANT, the Neutron Wall and the gamma-ray spectrometer form a very efficient experimental setup for studies of the structure of exotic proton-rich nuclei. The task of the Neutron Wall is to select and identify very weakly populated reaction channels associated with neutron emission, by efficiently detecting the neutrons from the fusion-evaporation reactions, induced by stable or radioactive heavy-ion beams.

The Neutron Wall has 15 hexagonal detectors (3 segments each) and one pentagonal detector (5 segments). The total liquid scintillator volume is about 150 litres. The distance from the target to the front of the neutron detectors is 51 cm and the distance from the front edge to the back edge of the liquid in the detector segments is 15 cm.

The neutron-gamma discrimination is done by combining pulse-shape analysis, based on the zero-cross-over (ZCO) time method, and the difference between the time-of-flight (TOF) of gamma rays and neutrons from the target to the detectors, as illustrated in Fig. 3. Fast analog and logic 'multiplicity' signals, with information on the number of detected neutrons and gamma rays per event, can be generated and used for triggering purposes.

In a fusion-evaporation reaction with roughly equal mass numbers of the target and projectile nuclei, the one neutron (1n) detection efficiency of the Neutron Wall is 20-25%. After discrimination of scattered neutrons, the efficiency to detect two neutrons is 1-3%.

NEUTRON WALL	
Detectors	50 liquid scintillator detectors
Operational period	2005-2012
Number of experiments	8
Beamtime hours	1552

Experimental campaigns and physics of interest

The experiments with the Neutron Wall are usually organised as campaigns of several consecutive experimental runs. The very first campaign, in which the Neutron Wall was used together with EUROBALL, took place at Laboratori Nazionali di Legnaro LNL-INFN in 1998,. The physics of interest has mainly been the structure of proton-rich nuclei along the N=Z line with mass numbers from about A=30 to A=100.

Current activity

Since 2005, the Neutron Wall has been located at the G2 beam line at GANIL (see Fig. 1). It has been used there in eight experiments; seven of these were performed together with the EXOGAM gamma-ray spectrometer and one was done without EXOGAM, but instead with additional neutron detectors from the EDEN setup. Six of the experiments were run with the DIAMANT charged particle detector array and two with a Si CD detector system. Six experiments used stable heavy-ion beams and fusion-evaporation reactions, while two used radioactive beams of ^{6}He and ^{8}He for studies of neutron correlations in these halo nuclei.

Future plans

The Neutron Wall will be used in one experiment at GANIL in 2014. After this, the array will be shipped to LNL-INFN for experiments with GALILEO. The present plan is to use the Neutron Wall at LNL-INFN for 1-2 years, then ship it back to GANIL for the AGATA@GANIL campaign. A development of the new neutron detector array (NEDA) is ongoing. As part of this development, new digital electronics, based on the EXOGAM2 digitiser card NUMEX02, is being built for the Neutron Wall. The aim is to start using the new electronics in the Galileo campaign.

Dissemination (2005-2012)	
Peer-reviewed publications	5
PhD theses	3

Highlights from Neutron Wall

Evidence for a spin-aligned neutron-proton coupling scheme in ^{92}Pd

Shell structure and magic numbers in atomic nuclei are generally explained as being due to a strong spin-orbit interaction of the nucleons. Our knowledge of the nuclear forces and the mechanisms governing the structure of nuclei is still incomplete, especially for nuclides far from stability. In nuclides with equal number of neutrons and protons (*N*=Z), enhanced correlations arise between these two distinct types of fermions that occupy orbitals with the same quantum numbers. Such correlations have been predicted to favour an unusual type of nuclear superfluidity, termed isoscalar neutron-proton pairing, in addition to normal isovector pairing. Despite many experimental efforts, these predictions have not been confirmed.

“The EXOGAM + Neutron Wall + DIAMANT setup was used to identify gamma-rays emitted by excited states in the *N*=*Z*=46 nucleus ^{92}Pd following the ^{58}Ni(^{36}Ar,2n)^{92}Pd fusion-evaporation reaction”

The EXOGAM + Neutron Wall + DIAMANT setup was used to identify gamma-rays emitted by excited states in the *N*=*Z*=46 nucleus ^{92}Pd following the ^{58}Ni(^{36}Ar,2n)^{92}Pd fusion-evaporation reaction (Fig. 2).

The results reveal evidence for a spin-aligned, isoscalar neutron–proton coupling scheme, different from the previous prediction (Fig. 4). It is suggested that this coupling scheme replaces normal superfluidity (characterised by seniority coupling) in the ground and low-lying excited states of the heaviest *N*=Z nuclei. Such strong, isoscalar proton-neutron correlations may have a considerable impact on the nuclear level structure and might influence the dynamics of rapid-proton capture in stellar nucleosynthesis.

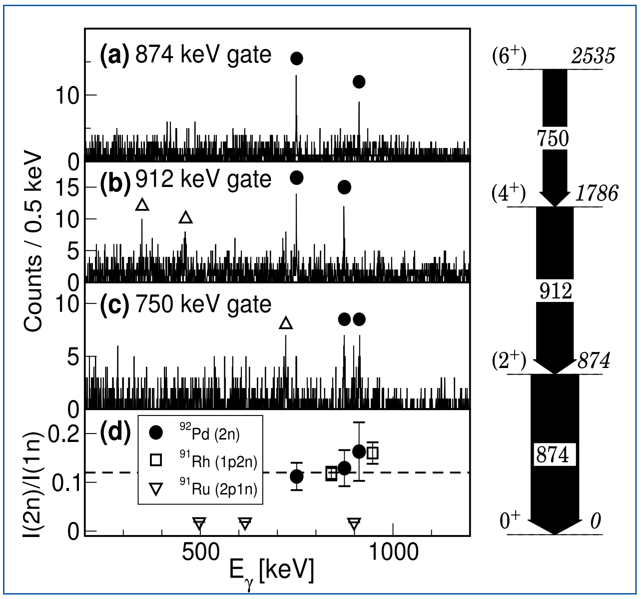


Fig. 2. Identification of γ-ray transitions in ^{92}Pd. The γ rays are in coincidence with two neutrons but not in coincidence with any charged particles. [B. Cederwall et al., Nature 469 (2011) 68].

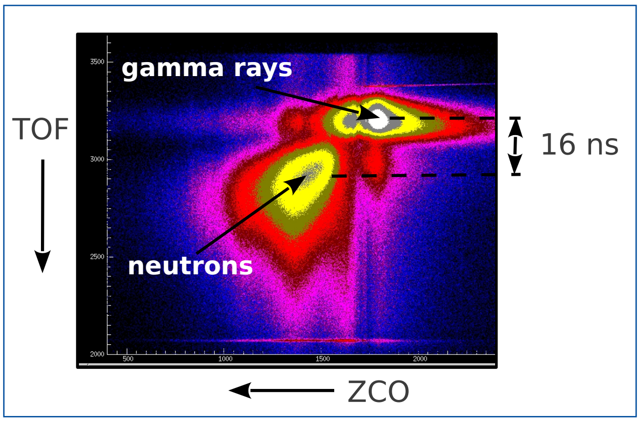


Fig. 3. Zero-Crossover Time (ZCO) versus Time-of-Flight (TOF) measured by one of the Neutron Wall detectors.

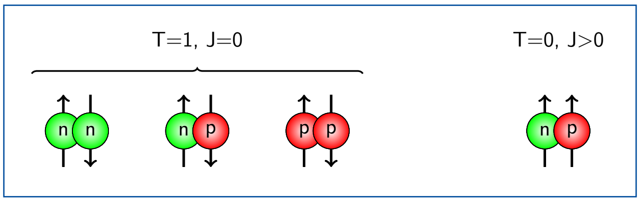


Fig. 4.

a) The normal isospin T=1 triplet. The two like-particle pairing components are responsible for most known effects of nuclear superfluidity. Within a given shell these isovector components are restricted to spin zero owing to the Pauli principle.

b) Isoscalar T=0 proton-neutron pairing. Here the Pauli principle allows only nonzero components of angular momentum. [B. Cederwall et al., Nature 469 (2011) 68].

1n and 2n transfer with the Borromean nuclei $^{6,8}He$ near the Coulomb barrier

The first Neutron Wall experiments with radioactive beams concerned studies of neutron transfer reactions using beams of ^{6}He at 22.6 MeV and ^{8}He at 19.9 and 30.6 MeV on a ^{65}Cu target. The experimental setup consisted of an annular Si ΔE-E telescope, the Neutron Wall and EXOGAM (see Fig. 5).

In the ^{6}He experiment, triple coincidences were measured between charged particles, neutrons and gamma rays from the target-like residues (see Fig. 6). This technique made it possible to separate for the first time the contributions arising from 1n and 2n transfer. The differential cross sections for these channels, elastic scattering, and fusion were analysed using a coupled reaction channels approach. A large value of the measured ratio of the 2n to 1n transfer cross section and the strong influence of 2n transfer on other reaction channels, indicate that the di-neutron configuration of ^{6}He plays a dominant role in the reaction mechanism.

The study of the ^{8}He+^{65}Cu system and a comparison with the results obtained with ^{6}He provided the first experimental information regarding the role of pair and single neutron transfer in reactions involving the most neutron-rich nucleus at energies around the Coulomb barrier.

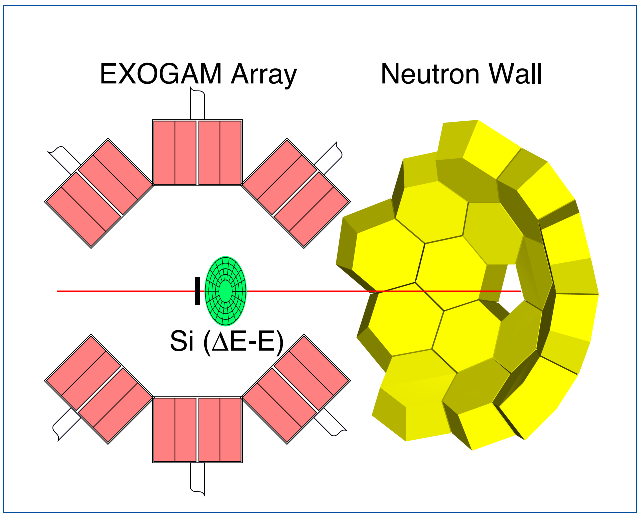


Fig. 5. Experimental setup in the $^{6,8}He$+^{65}Cu experiments. [A. Chatterjee et al., Phys. Rev. Lett. 101 (2008) 032701].

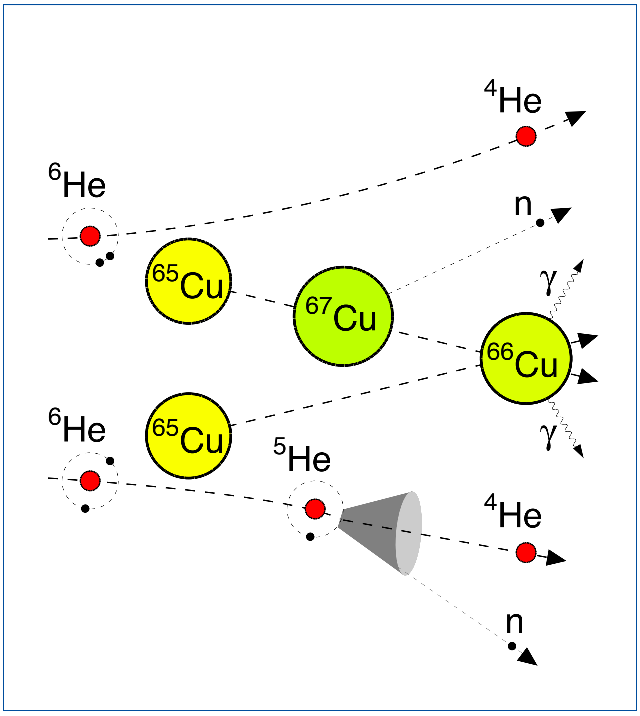
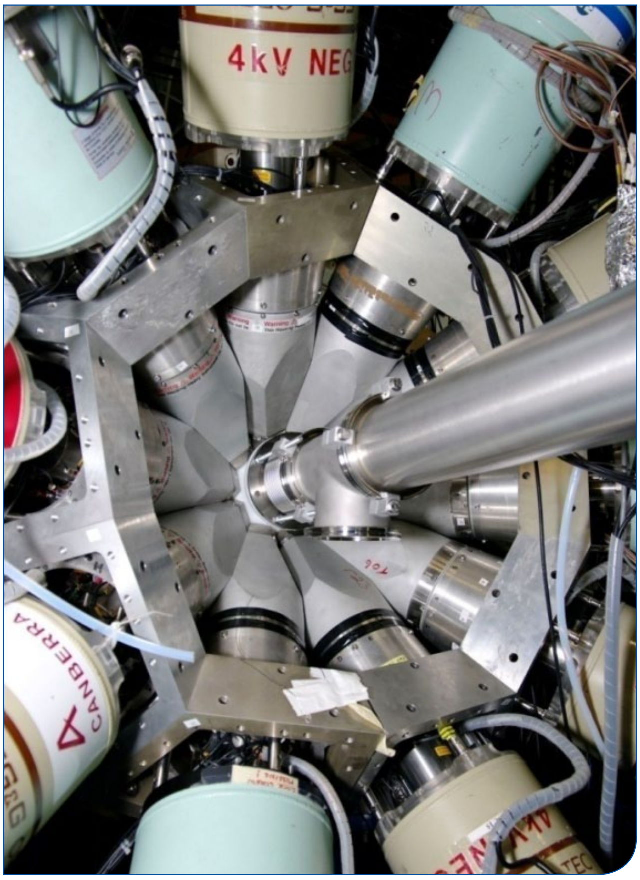


Fig. 6. Illustration of the reaction mechanism for 2n and 1n transfer in the reaction ^{6}He+^{65}Cu at the Coulomb barrier. [A. Chatterjee et al., Phys. Rev. Lett. 101 (2008) 032701] .

ORGAM – The ORsay GAMma array

IPN, Orsay, France



The Orsay Gamma Array (ORGAM) has been installed and running at IPN Orsay/France since 2009. It is dedicated to gamma ray spectroscopy using stable beams accelerated by a 15 MV MP-Tandem Accelerator.

The array is composed of 45 EUROGAM frames and can host up to 45 Compton Suppressed Ge detectors. It is permanently installed in IPN's room 420 where stable beams can be provided. We use Phase 1 Ge detectors and their AC shields loaned from both GammaPool and the French-UK Loan Pool. In this geometry, the efficiency per detector at 1 MeV is about 0.1 %.

A large amount of beam time has been devoted to ORGAM campaigns from 2009 to end 2012, with about 4 experiments per campaign. Experiments are accepted by an international PAC that meets during the first trimester of each year. The proximity of the Germanium Laboratory installed in IPN since 2007 helps with maintenance of the detectors used.

Ancillary detectors can be used in conjunction with the ORGAM array. This is the case for LaBr3:Ce scintillators used for fast timing measurements, Si-ball (CNS, University of Tokyo, Japan) for channel selection in fusion-evaporation reactions and the OUPS IPN/CSNSM Plunger for lifetime measurements (see highlights).

Most of the physics cases covered by the 4 ORGAM campaigns from 2009 to 2012 can be classified in the following research axes:

- Gamma-ray spectroscopy for deep inelastic collisions at forward angles to investigate the possibility of producing exotic species by quasi-fusion. This allows the study of the possible weakening of N=40 and 50 and Z=28 gaps in neutron-rich nuclei.
- Lifetime measurements using RDDS, DSAM, Fast timing techniques covering from fs to ns lifetime range. The physics addressed here is the search for different types of symmetries (X(5), E(5)) and phase transition nuclei, shape coexistence and competition between collective and single particle states in different regions of the nuclear chart.
- Nuclear Moment Measurements of long or short lived nuclear states.
- Search for tetrahedral symmetry in nuclei in the framework of TETRANUC collaboration.

Part of the experiment is still under analysis. Two PhDs have been completed and results have been published for 3 experiments.

In 2013, we plan the commissioning of the ORGAM2 project, consisting of 15 CS Phase 1 Ge detectors coupled with the Split Pole Spectrometer available in IPN Orsay.

ORGAM	
Detectors	Can host up to 45 Eurogam Phase 1 Ge detectors
Efficiency at 1.3 MeV	0.1% per detector
Peak-to-total	~50%
Operational	2009 – 2012
Number of experiments	16
Beam time (hours)	~2000

Dissemination	
Peer reviewed articles	3
PhD Thesis	4

Highlights from ORGAM

Quadrupole moment of the 6^- isomeric state in ^{66}Cu: Interplay between different nuclear deformation driving forces

Nickel is the only element in nature that has three known isotopes that are doubly magic nuclei (^{48}Ni, ^{56}Ni and ^{78}Ni). The common understanding is that a gradual change of the shape of these nuclei appears between each two magic shells. Recently, the nuclei in the vicinity of ^{68}Ni were studied extensively since they yield important information about the shell structure away from stability and the onset of deformation, based on experimental evidence from the 2^+_1 excitation energies and their *B(E2)* transition rates *[O. Sorlin et al., Eur. Phys. J. A 16(2003) 55, S. Raman, C.W. Nestor-JR, P. Tikkanen, At. Data Nucl. Data Tables 78 (2001) 1]*.

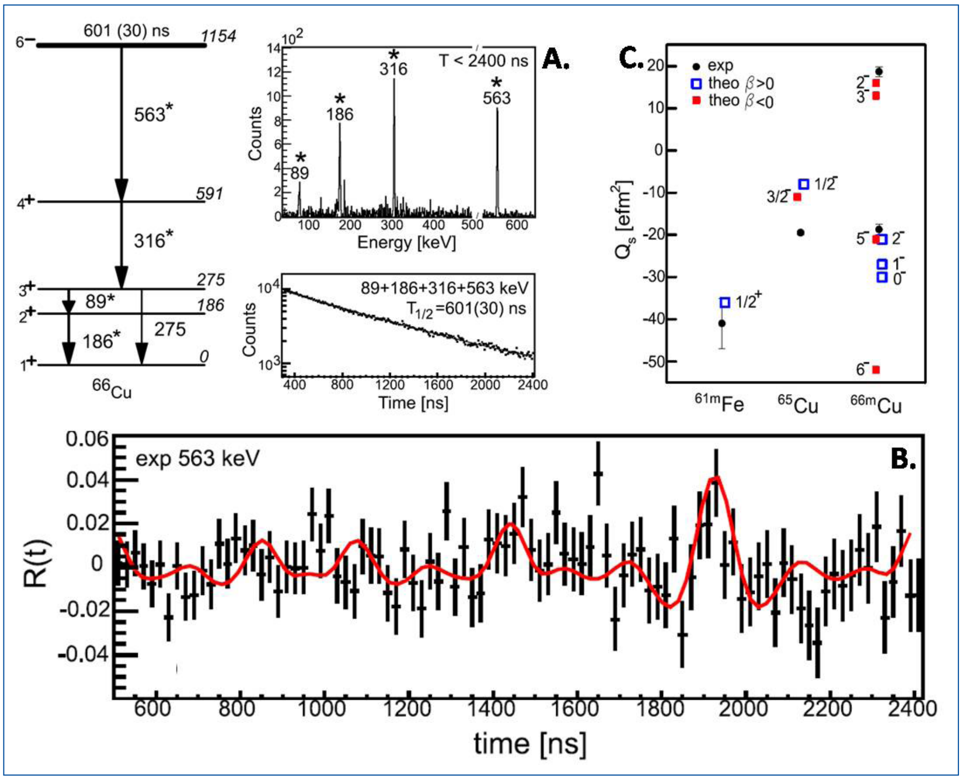
For this region it has been predicted that where nuclear deformation sets in, the magic numbers disappear, leading to very localized effects as the sub-shell closure at *N*=40 *[O. Sorlin et al., Phys. Rev. Lett. 88 (2002) 092501, C. Guenaut et al., Phys. Rev. C 75 (2007) 044303]*. Because the energy of the $\nu g_{9/2}$ decreases with increasing *N*, beyond 36, the down-sloping ν[440]1/2⁺ and ν[431]3/2⁺ orbitals are more likely to be occupied than the spherical orbitals. This generates a region around *N*=40 with an increased deformation, where the configuration functions of the nuclear states involve proton holes in $f_{7/2}$ and neutrons in $g_{9/2}$ *[M. Hannawald et al., Phys. Rev. Lett. 82 (1999) 1391]*.

The 66Cu nuclei were produced in a (d, p) reaction by a pulsed 6 MeV ^{2}H beam (pulse width of < 2 ns, repetition rate of 5 μs and mean intensity of about 0.4 nA (~2 × 10^9 p/s)) on a polycrystalline Cu_2O target at the Tandem-ALTO facility of Orsay. The spin alignment of the isomers of interest was obtained in the transfer reaction. At the same time the target was used as a host providing an electric field gradient (EFG) for the quadrupole interaction.

The detection set-up consisted of 8 HPGe single crystal detectors, placed at a distance of ~10 cm from the target, resulting in a total detection efficiency of about 5% at 1.3 MeV. Time–γ correlations were recorded in the 2.5 MeV energy and 5 μs time range. The later were triggered by gammas and stopped by the beam pulsing. The time resolution of the Ge detectors was of the order of 15 ns. Six of the detectors were positioned in a horizontal plane at ±30°, ±90°, ±150°with respect to the beam direction, while the other two were placed top/bottom at ±90° with respect to the horizontal plane in order to observe the change in the γ-angular distribution using the Time Dependent Angular Distribution Technique (TDPAD).

This experiment is the first direct determination of the nuclear deformation involving both the $\pi p_{3/2}$ and the $\nu g_{9/2}$ orbitals in this region by measuring the spectroscopic quadrupole moment of the 6^- isomeric state (E_x = 1154 keV, $T_{1/2}$ = 595(20) ns) *[J. Bleck et al., Nucl. Phys. A 197 (1972) 620]* in ^{66}Cu to be be $|Q_s|$ = 18.6(12) efm^2. In addition, it provides an important test for the experimental methodology to study the quadrupole moments of nuclei, aligned in a reaction of nucleon transfer. The 6^- isomeric state in ^{66}Cu, which results from a weak coupling of the $\pi p_{3/2}$ and the $\nu g_{9/2}$ orbitals, correspondingly leads to sizable deformation at oblate and prolate shapes in the ^{68}Ni region. The measured spectroscopic quadrupole shows the interplay between these two different deformation driving orbitals, and that coupling of deformations of the same type is preferred at *N*=37 for the 6^- state resulting in a most probable oblate shape.

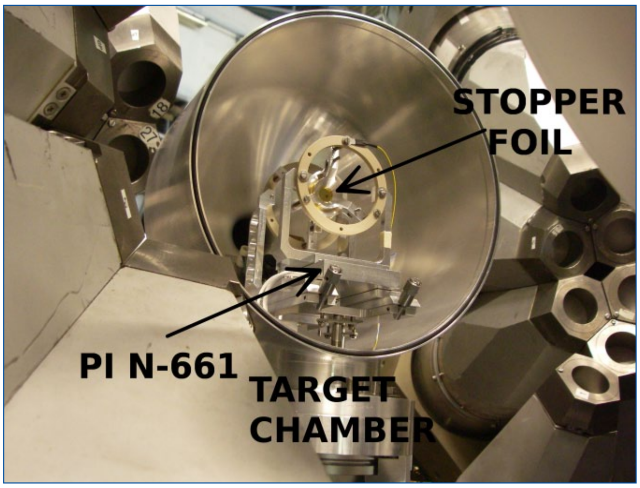
[R.L. Lozeva et al., Phys. Lett. B 694, 316 (2011)]



A. Decay scheme of the 6^- isomer in ^{66}Cu along with the delayed background subtracted gamma and time spectra; B. R(t) function for the 563 keV (M2) transition; C. Experimental Q_s for ^{61m}Fe(9/2⁺), ^{65}Cu(3/2⁻) and ^{66m}Cu(6⁻) (full circles) are compared to the theory for oblate (full squares) and prolate (empty squares) shapes. The theoretical predictions are labeled with their K^π value.

The Orsay Universal Plunger System

A new plunger device for Recoil-Distance Doppler Shift and Time-Differential Recoil-In-Vacuum measurements has been developed at the CSNSM in collaboration with the IPN Orsay. It is conceived to be easily adapted to different experimental setups and facilities, in particular to the future radioactive beam facility SPIRAL2. An electronic feedback system keeping the distance between target and stopper foils constant, imperative for precision measurements of short lifetimes, was also developed. The plunger device was commissioned with an experiment performed at the IPN Orsay Tandem accelerator laboratory using the Orgam germanium detector array with 24 Eurogam Phase 1 Ge detectors. Excited states in ^{76}Kr were populated using the reaction ^{45}Sc(^{35}Cl,2p2n)^{76}Kr. The lifetime of the 4^+_1 state was determined to be 4.3(6) ps, in accordance with previous measurements, confirming the functionality of the new plunger device. The commissioning experiment showed in particular that the electronic feedback system works as expected.



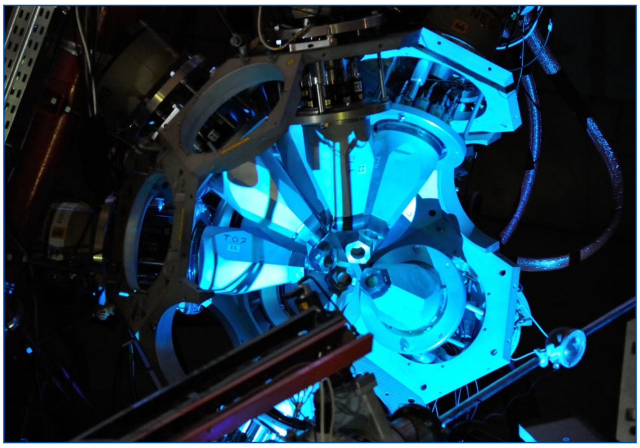
The OUPS Plunger inserted in the reaction chamber of ORGAM.

The 'plunger' consists of a thin target foil for the production of recoiling excited nuclei and a 'stopper' foil at a well defined distance from the target. It is used with the Recoil Distance Doppler Shift (RDDS) method *[A.Görgen, Journal of Physics G: Nuclear and Particle Physics 37 (2010) 103101]*. This method is based on the observation of the gamma rays emitted when the nuclear states de-excite. By stopping the recoiling nuclei in a 'stopper' foil two distinctive velocity regimes are created, and hence the gamma rays emitted before or in the stopper foil can be separated using the observed Doppler shift of the gamma ray energies. Gamma-rays emitted before the stopper foil will be observed with a 'shifted' energy due to the Doppler shift. If the nuclei have been stopped, the gamma rays will be observed without a Doppler shift of their energy, i.e. 'unshifted'. By comparing the relative intensities of the shifted and unshifted components of the gamma ray line, the lifetime can be extracted. Using the RDDS method together with a plunger device, lifetimes of about one to a few hundreds of picoseconds can be measured with a precision comparable to that of the statistical uncertainty. Such experiments therefore deliver high quality data on electromagnetic transition strengths.

[J. Ljungvall et al., Nucl. Instr. And Meth. A679 (2012) 61-66.]

EAGLE – central European Array for Gamma Levels Evaluation

HIL, Warsaw, Poland



The EAGLE array *[J. Mierzejewski et al., Nucl. Instr. Meth. A 659, 84 (2011)]*) has been designed as a multi-configuration detector set-up for in-beam nuclear spectroscopy studies at the Heavy Ion Laboratory (HIL) of the University of Warsaw. The EAGLE collaboration associates over 60 scientists from 20 institutes all around Europe. The array can accommodate a maximum of 30 Compton suppressed Ge detectors coupled to various ancillary devices, such as a the conversion-electron spectrometer, the Köln - Bucharest plunger, a compact scattering chamber equipped with 110 PIN diodes placed at backward angles, the 4π inner ball consisting of 60 BaF_2 crystals and a 30 element 4π silicon detector array. Until June 2011 EAGLE was equipped with 12 ACS HPGe detectors and had a total photo-peak efficiency of 0.5% at 1.3 MeV. This initial configuration was replaced by a configuration with 15 Eurogam Phase1 ACS HPGe detectors loaned by GAMMAPOOL, with a photo-peak efficiency equal to 1.8%. In addition, 5 GASP-type ACS HPGe detectors were used in spring 2012 by courtesy of the JUROGAM II collaboration, increasing the photo-peak efficiency to 2.4%.

The scientific case for the EAGLE project focuses on the phenomenon of spontaneous symmetry breaking in atomic nuclei. Experiments performed during the EAGLE campaigns (October 2011 – June 2013) revolved around three main research axes:

Experimental study of chiral symmetry breaking

Following the research that led to a discovery of the spontaneous chiral symmetry breaking phenomenon in ^{128}Cs *[E. Grodner et al. Phys. Rev. Lett. 97, 172501 (2006)]* and ^{126}Cs *[E. Grodner et al. Phys. Lett.B 703, 46 (2011)]*, DSAM lifetime measurements of the excited states of the chiral partner bands in ^{124}Cs were performed. Preliminary results indicate the first observation of the critical frequency in nuclear chiral rotation *[P. Olbratowski et al. Phys. Rev. Lett. 93, 052501 (2004)]*.

EAGLE	
Number of detectors	15+5 Eurogam Phase1
Efficiency at 1332keV	1.8 -2.4%
Operational	Years 2011-2013
Number of experiments	13
Beamtime hours	2000+

Tests of K-quantum number conservation: studies of K-isomers by combined gamma and internal conversion electron spectroscopy

The collaboration continued the research on the role of triaxiality in breaking of *K* selection rules that was demonstrated to be important in the decay of the $I^{\pi}= K^{\pi}=8^{-}$ isomeric state in ^{132}Ce (*N*=74) *[J. Perkowski et al. Eur. Phys. J. A 42, 379 (2009)]*. In 2012, the decay of *K*-isomers in ^{134}Nd (*N*=74) and ^{184}Pt (*N*=106) was studied.

Shape coexistence and shape evolution studied by measurements of transition probabilities

To complement the Coulomb excitation measurement of ^{42}Ca carried out in the first run of AGATA at LNL, an experiment was performed aiming at refinement of the low spin level scheme of this nucleus. The excited states in ^{42}Ca were populated in the ^{12}C(^{32}S,2p)^{42}Ca reaction. The results are crucial for the analysis of the Coulex data.

Moreover, EAGLE was coupled for to the Köln - Bucharest plunger device in order to measure lifetimes of low-lying states in ^{140}Sm and ^{125}Cs. The ^{140}Sm experiment complements the Coulex measurements performed at REX-ISOLDE facility.

The experiments mentioned above form a basis of 6 ongoing PhD theses and several MSc and BSc projects.

Besides the rich scientific program, the EAGLE array is also used for teaching and training purposes. During the EAGLE campaigns more than 80 students took part in one of the three major training programmes at HIL: International Workshop on Acceleration and Applications of Heavy Ions (editions II and III, 2 weeks each), Summer School on Acceleration and Applications of Heavy Ions (edition I, one week) and Polish Workshop on Acceleration and Applications of Heavy Ions (editions VII and VIII, one week each) *[http://www.slcj.uw.edu.pl/en/66.html]*. The events were enthusiastically received by the participants, who appreciated the chance to perform in-beam measurements using modern equipment in an accelerator laboratory.

Highlights from EAGLE

Search for spontaneous time-reversal symmetry breaking in ^{124}Cs

The equations of relativistic quantum mechanics show existence of objects propagating backward in time that are physically observed as antiparticles. Hence a question about fundamental time-reversal symmetry breaking arose that has not been clearly answered until now. Numerous experiments have been performed in order to find the time-reversal symmetry breaking in atomic and nuclear physics. The results of those experiments show that the contribution of the *T*-symmetry breaking terms into the total nuclear Hamiltonian is limited to very small relative values.

Regardless of fundamental conservation or non-conservation of the *T*-symmetry, there is a possibility of its spontaneous breakdown and the appearance of nuclear chirality effect. Spontaneous chiral symmetry breaking has been observed in ^{128,126}Cs nuclei as the presence of specific gamma selection rules, following from picosecond lifetime measurements. *[E. Grodner et al., Phys. Rev. Lett. 97, 172501 (2006), E. Grodner et al., Phys. Lett. B703, 46 (2011)]*. The simplest case of nuclear chirality relates to odd-odd triaxial nuclei, where the angular momenta of odd nucleons and the angular momentum of the even-even core can form either left or right handed system. Physics laws do not prefer any of the two possible systems, meaning that the spin-chiral symmetry is fundamentally conserved. However, selection of one handedness minimizes the energy and breaks the symmetry spontaneously.

“The γ−γ coincidences were measured by the EAGLE array equipped with 15 Eurogam Phase1 ACS HPGe detectors loaned by GAMMAPOOL”

The spin-chiral symmetry breaking has been studied recently in ^{124}Cs nucleus *[E Grodner et al., J. Phys.: Conf. Ser. 381 012067 (2012)]*. The ^{124}Cs was produced in the ^{114}Cd(^{14}N,4n)^{124}Cs reaction at the beam energy of 73 MeV. The ^{114}Cd target of 34 mg/cm^2 thickness also played the role of the stopper. The ^{14}N beam was provided by the U200P cyclotron of the Heavy Ion Laboratory, University of Warsaw.

The γ−γ coincidences were measured by the EAGLE array equipped with 15 Eurogam Phase1 ACS HPGe detectors loaned by GAMMAPOOL.

Thanks to high-efficiency HPGe detectors, it was possible to determine picosecond lifetimes of the excited states with the help of the DSA technique. The lifetime results show staggering of the *B(M1)* transition probabilities along the yrast bands of ^{124}Cs which is characteristic for spontaneous spin-chiral symmetry breaking. We expect also to see the phase transition between *T*-symmetry conserving and *T*-symmetry breaking configurations as a function of collective nuclear rotational frequency. The phase transition has been predicted *[P. Olbratowski et al., Phys. Rev. Lett. 93, 052501 (2004)]* as presence of critical rotational frequency.

The data obtained in the experiment are still being analyzed. We expect more complete results soon.

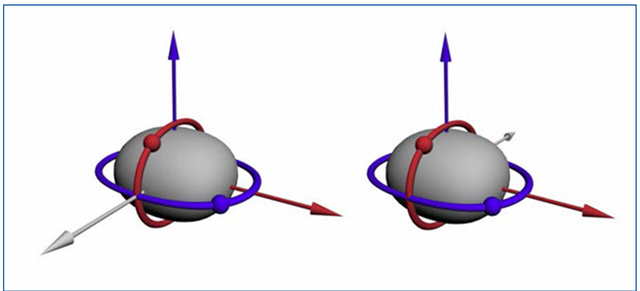


Fig. 1 Left- and right-handed configuration of three angular momenta vectors. Time reversal symmetry is spontaneously broken since operation of time-reversal changes handedness.

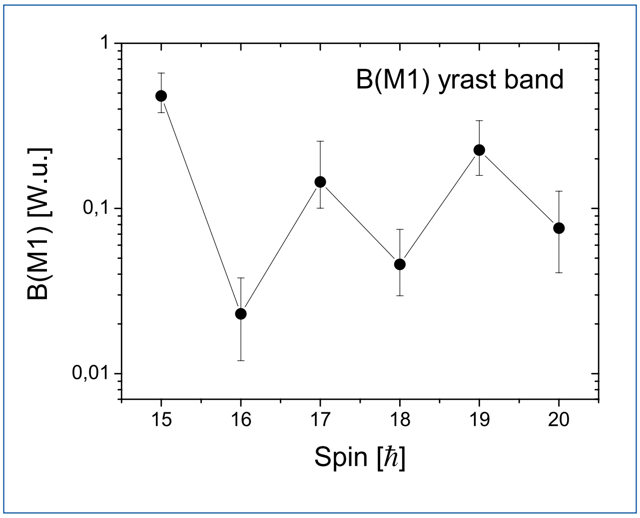


Fig.2 B(M1) reduced transition probabilities in the yrast band of ^{124}Cs.

Dissemination	
Peer reviewed publications	5
PhD thesis	6 (ongoing)

Study of the ^{42}Ca nuclear structure using the EAGLE spectrometer for the first AGATA experiment

The Coulomb excitation experiment to study electromagnetic properties of low-lying states in ^{42}Ca with a focus on a presumably super-deformed band was performed at the Laboratori Nazionali di Legnaro in Italy in 2010 using the γ-ray spectrometer AGATA Demonstrator coupled to the DANTE position sensitive charged particle detector array.

Transitions de-exciting the highly deformed band were observed, as well as γ-rays depopulating low-lying states in the yrast band. In both the ground state band and the highly deformed band it was possible to Coulomb excite levels of spin up to 4^+ (left panel of Fig.1). Unexpectedly, two unknown γ lines were observed in the spectrum at energies 2048 and 376 keV. The 2048 keV transition was particularly strong and clearly visible. The widths of these two γ-ray lines indicated that they could be emitted from the ^{42}Ca scattered projectile.

To resolve ambiguities concerning the electromagnetic structure of ^{42}Ca, a dedicated fusion-evaporation experiment aiming at investigation of the low spin level scheme in ^{42}Ca was performed at Heavy Ion Laboratory, University of Warsaw, using the EAGLE spectrometer in the configuration with 15 HPGe detectors in anti-Compton shielding. A ^{32}S beam with the energy of 86 MeV bombarded a very thick (>50 mg/cm^2) ^{12}C target. ^{42}Ca was populated in the 2p reaction channel, one of the strongest channels observed. In addition, states in ^{42}Ca, including the 2424 keV level, were populated in the beta decay of ^{42}Sc, a product of the *pn* channel. In the off-beam analysis it was possible to observe the 2424 and 899 keV transitions de-exciting the 2424 keV state. In the γ-γ matrix, however, there was no sign of the 376 keV transition neither in coincidence with the 2048 keV γ-ray, nor with the 328 keV transition de-exciting the 4^+ state at 2752 keV to the 2^+ state at (2424 keV) (right panel of Fig.1). To conclude, there is no additional gamma branch decaying from the 2424~keV energy level.

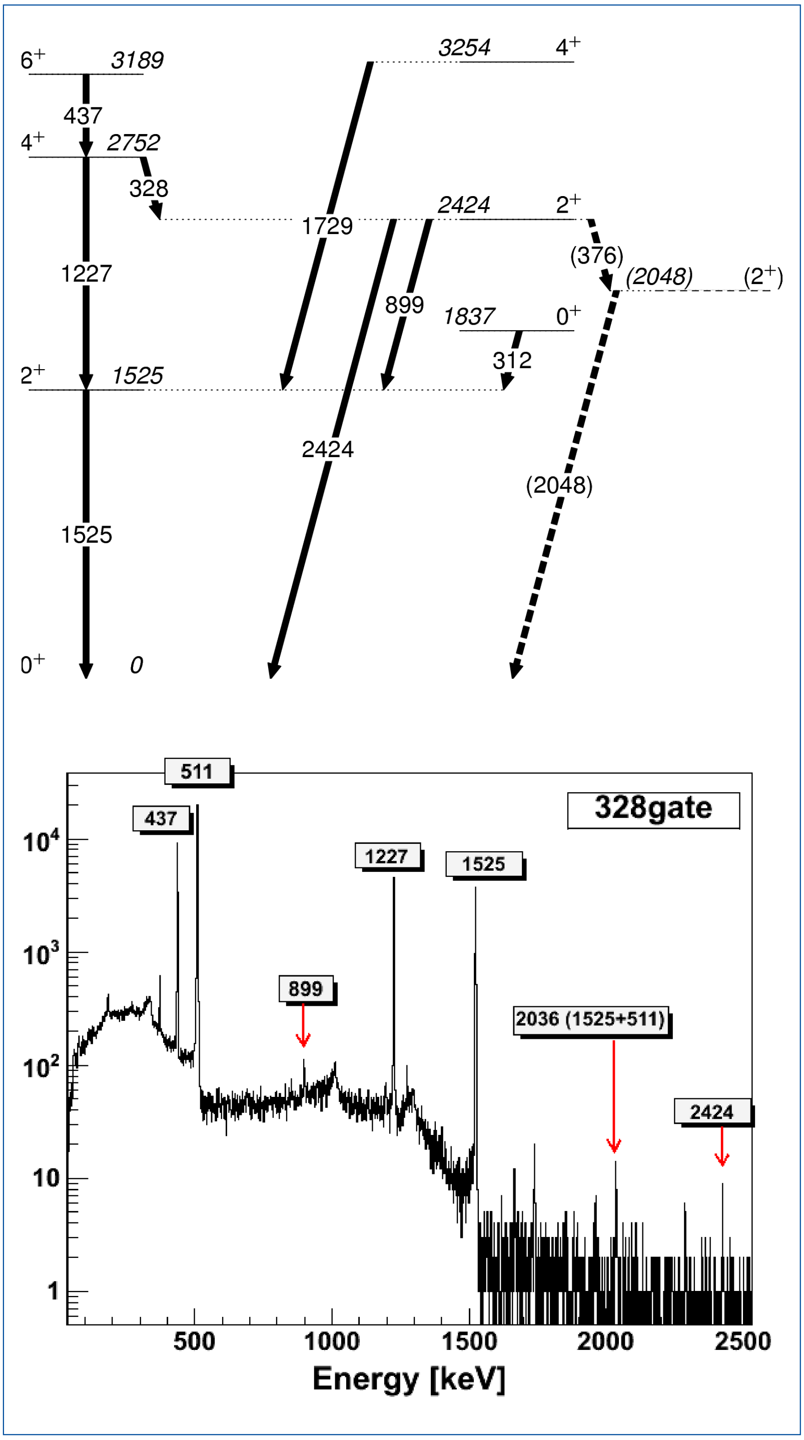


Fig.1 Upper panel: The level scheme of ^{42}Ca showing transitions observed in the Coulomb excitation experiment. A hypothetical state at 2048 keV was connected to the known level scheme using 376 and 2048 keV γ transitions (dashed lines). Lower panel: The full energy spectrum observed in the fusion-evaporation experiment using the EAGLE spectrometer

Results of the fusion-evaporation experiment were crucial for the determination of electromagnetic matrix elements from the COULEX data published in *K. Hadyńska-Klęk, et al., Acta Physica Polonica, Vol. 44 (2013) 617* and presented during the EGAN Meeting 2012, Orsay, France and 2nd European Nuclear Physics Conference 2012 in Bucharest, Romania.

Study of the *K*-isomers by using gamma and internal electron spectroscopy

We studied the violation of the *K* selection rule for electromagnetic transitions in nuclei of mass number *A*~130. We measured the absolute decay transition probabilities of the $I^\pi = K^\pi = 8^-$ isomeric state in ^{134}Nd. This isomeric state is present in the even-even nuclides for the numbers of neutrons: 74, 106 and 150, or the number of protons 74 (tungsten) and an adequate mass number (*A*~130, *A*~180, *A*~250). It was a continuation of our previous measurements for ^{130}Ba *[J. Perkowski, et al., Acta Physica Polonica B 43 (2012) 273]* and ^{132}Ce *[J. Perkowski, et al., EPJ A 42 (2009) 379]*. These isomers can be interpreted as two quasi-particle states: v7/2 [404] $\otimes$ v9/2 [514], v7/2 [514] $\otimes$ v9/2 [624] and v7/2 [624] $\otimes$ v9/2 [734], respectively. The nuclear shell structure behind remains the same in all cases. In spite of the differences in the decay modes, *E1* transitions with the degree of *K* forbiddingness (v) of 7 are present, leading directly to the 8^+ member of the ground state band with *K*=0. These branches severely violate the *K* selection rule.

The measurements were performed at HIL, University of Warsaw, using electron spectrometer *[J. Andrzejewski et al., Nucl. Inst. and Meth A585 (2008) 155]* coupled with the EAGLE spectrometer equipped with 15 Eurogam Phase1 ACS HPGe detectors loaned by GAMMAPOOL (see figure 1). The study of the internal electron spectra together with gamma-ray studies allows determination of the multipolarities and absolute values of transition probabilities. This can help deepen our understanding of the underlying mechanism of the K-selection rule violations, based on the decay of the $I^\pi = K^\pi = 8^-$ isomeric states.

The measurements of $I^\pi = K^\pi = 8^-$ isomeric states are expected to be conducted at HIL in the future, for the cases of ^{184}Pt, ^{186}Hg and ^{188}Pb nuclei. We hope that the knowledge of violations of the K selection rule in decay of the $I^\pi = K^\pi = 8^-$ isomeric state for mass numbers *A*~130 and *A*~80 will help to draw new conclusions about the *K*–isomers physics for super heavy elements (*A*~250).

Fig.1 The EAGLE array of 15 HPGe Gammapool detectors coupled to the electron spectrometer [J. Andrzejewski et al., Nucl. Inst. and Meth. A585 (2008) 155] for electron-gamma and gamma-gamma coincidence measurements.

EURICA

RIKEN Nishina Center, Tokyo, Japan

The EUroball-RIken Cluster Array (EURICA) is a new project established in 2011 to spectroscopically study exotic nuclei. Located at the RIKEN Nishina Center (RNC) in Wako, Japan, EURICA consists of twelve EUROBALL Cluster detectors forming a high efficiency array coupled to the in-flight fragment separator BigRIPS for beta-delayed and isomeric gamma-ray spectroscopy. Combined with the superconducting ring cyclotron (SRC) BigRIPS forms the centerpiece for exotic nuclei production at the Radioactive Isotope Beam Factory (RIBF) of the RNC.

After a construction period of more than ten years, RIBF went on-line in 2006. Stable primary beams are accelerated to 70% of the speed of light and strike a production target for in-flight creation of exotic nuclei following fragmentation and induced fission reactions. A set of magnets and energy degraders are used to separate exotic nuclei interest from other reaction products. EURICA is located at the final focus of BigRIPS, where the exotic nuclei are slowed down and implanted in a stack of Si detectors.

Two independent implantation systems, SIMBA and WAS3ABI are available for EURICA and were developed by the TU Munich and the RIBF to accommodate for the boundary conditions imposed by BigRIPS's large simultaneous acceptance of many different exotic nuclei. A high granularity of these ancillary detectors enables high secondary beam rates without losing correlation between implanted ion and ensuing beta-decay.

The implantation systems are surrounded by the twelve EUROBALL Cluster detectors mounted in the same configuration as was implemented for STOPPED BEAM RISING at GSI (with three Cluster detectors missing). Cluster electronics and data acquisition are reused from RISING. EURICA can be considered in many ways as expansion of the successful RISING physics program to a new continent and institute. In fact, among the more than fifty institutes and two hundred scientists collaborating with EURICA more than half are European.

EURICA	
Number of detectors	12 EUROBALL clusters
Efficiency at 1332keV	9 %
Operational	Years 2012-14
Number of experiments	24 (7 performed in 2012)
Beamtime hours approved	3200
Beamtime hours 2012	900

The project's realization began in late 2011 by shipping the Cluster detectors, support structure, and electronics to RIBF. After an assembly phase in early 2012, commissioning of the new setup was performed in March and April using light secondary beams. In June, the first physics experiments were performed to unveil new nuclear structure information in the vicinity of the doubly-magic ^{100}Sn. In Fall 2012, a longer campaign followed. A series of experiments covered a broad range of neutron-rich nuclei extending from the ^{78}Ni to the ^{132}Sn region.

"EURICA enables a simultaneous search for new isotopes and performance of beta-decay, beta-delayed gamma, and isomer spectroscopy within the same experiment."

In future campaigns, new $LaBr_3$ based ancillary detectors provided by the PreSpec collaboration will be employed to measure lifetimes of decaying states in the ns range. In addition, new regions of the nuclear chart will be explored, thereby covering the most exotic neutron-rich nuclei studied to date from calcium to dysprosium isotopes.

The EURICA spectrometer and its implantation detectors are operated in close cooperation with scientists from GSI, TU Munich, and the IBS Korea.

Many of the produced exotic nuclei are not accessible by any other radioactive ion beam facility. EURICA enables a simultaneous search for new isotopes and performance of beta-decay, beta-delayed gamma, and isomer spectroscopy within the same experiment. An example for the potential of EURICA is given in Fig. 1 by the isomer of ^{76}Ni, just two neutrons shy of the doubly magic nucleus ^{78}Ni, and previously observed with very limited statistics *[C. Mazzochi et al., Phys. Lett. B 622, 45 (2005)]*. In contrast, the abundant data collected with EURICA enabled the study of gamma-gamma coincidences of the observed isomer.

The physics case for the EURICA project can be summarized into the following key subjects of research on exotic nuclei:

- Shell evolution and magic numbers far off stability
- r-process nucleosynthesis
- *N*=*Z* nuclei up to the doubly-magic 100Sn (np-pairing, isospin symmetry, rp-process)
- Nuclear deformation and shape coexistence

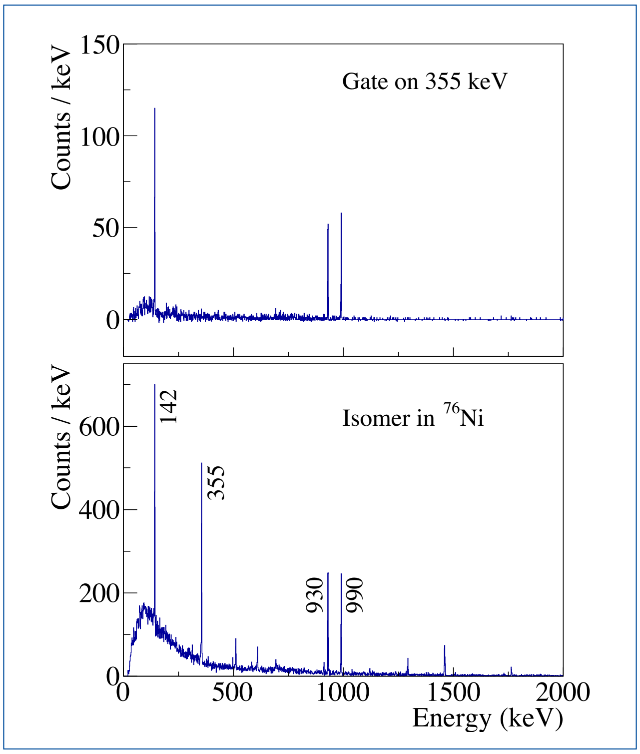


Figure 1: Gamma-ray spectrum following the implantation of ^{76}Ni ions (lower panel). In the upper panel a gate was applied on the 355 keV transition.

List of Acronyms

BGO	*Bismuth Germanate*
CATE	*CAlorimeter TElescope*
CLARA	*CLover ARrAy*
DESPEC	*Decay SPECtroscopy*
DSAM	*Doppler Shift Attenuation Method*
DSSSD	*Double Sided Silicon Strip Detector*
EAGLE	*central European Array for Gamma Level Evaluation*
EURICA	*EUroball Riken Cluster Array*
EWSR	*Energy Weighted Sum Rule*
FAIR	*Facility for Antiproton and Ion Research*
FRS	*Fragment Separator*
GAMMAPOOL	*European Gamma-Ray Spectroscopy Pool*
GANIL	*Grand Accélérateur National d'Ions Lourds*
GASP	*Gamma SPectrometer*
GDR	*Giant Dipole Resonance*
GREAT	*Gamma Recoil Electron Alpha Tagging*
GSI	*GSI Helmholtzzentrum für Schwerionenforschung*
HISPEC	*HIgh-resolution SPECtroscopy*
HPGe	*High Purity Germanium*
INFN	*Istituto Nazionale di Fisica Nucleare*
ISOLDE	*Isotope Separator On Line DEvice*
LNL	*Laboratori Nazionali di Legnaro*
LYCCA	*Lund-York-Cologne Calorimeter*
MED	*Mirror Energy Difference*
NEDA	*NEutron Detector Array*
ORGAM	*ORsay GAMma array*
PAC	*Programme Advisory Committee*
PDR	*Pygmy Dipole Resonance*
RBT	*Recoil Beta Tagging*
RDDS	*Recoil Distance Doppler Shift*
RDT	*Recoil Decay Tagging*
RIB	*Rare Isotope Beam*
RISING	*Rare ISotope INvestigations at GSI*
RITU	*Recoil Ion Transport Unit*
RPA	*Random Phase Approximation*
SAGE	*Silicon And GErmanium*
TDR	*Total Data Readout*
TED	*Triplet Energy Difference*
TOF	*Time Of Flight*
ZCO	*Zero Cross-Over*

Publications List

Regular Articles

2013

1 M. Bowry, Z. Podolyák, S. Pietri, J. Kurcewicz et al.
Population of high-spin isomeric states following fragmentation of ^{238}U.
Physical Review C 88, 024611 (2013).
doi:10.1103/PhysRevC.88.024611

2 S. P. Bvumbi, J. F. Sharpey-Schafer, P. M. Jones, S. M. Mullins et al.
Octupole correlations in the structure of 0_2^+ bands in the N=88 nuclei ^{150}Sm and ^{152}Gd.
Physical Review C 87, 044333 (2013).
doi:10.1103/PhysRevC.87.044333

3 A. M. Denis Bacelar, A. M. Bruce, Z. Podolyák, N. Al-Dahan et al.
The population of metastable states as a probe of relativistic-energy fragmentation reactions.
Physics Letters B 723, 302-306 (2013).
doi:10.1016/j.physletb.2013.05.033

4 M.C. Drummond, D.T. Joss, R.D. Page, J. Simpson et al.
Low-lying excited states in the neutron-deficient isotopes ^{163}Os and ^{165}Os.
Physical Review C 87, 054309 (2013).
doi:10.1103/PhysRevC.87.054309

5 A. Gottardo, J. J. Valiente-Dobón, G. Benzoni, A. Gadea et al.
New μs isomers in the neutron-rich ^{210}Hg nucleus.
Physics Letters B 725, 292-296 (2013).
doi:10.1016/j.physletb.2013.07.053

6 J. Henderson, P. Ruotsalainen, D. G. Jenkins, C. Scholey et al.
Enhancing the sensitivity of recoil-beta tagging.
Journal of Instrumentation 8, P04025 (2013).
doi:10.1088/1748-0221/8/04/p04025

7 U. Jakobsson, S. Juutinen, J. Uusitalo, M. Leino et al.
Spectroscopy of the proton drip-line nucleus ^{203}Fr.
Physical Review C 87, 054320 (2013).
doi:10.1103/PhysRevC.87.054320

8 S. Lalkovski, A. M. Bruce, A. M. Denis Bacelar, M. Górska et al.
Submicrosecond isomer in $^{117}_{45}$Rh$_{72}$ and the role of triaxiality in its electromagnetic decay rate.
Physical Review C 88, 024302 (2013).
doi:10.1103/PhysRevC.88.024302

9 S. Lalkovski, A. M. Bruce, A. Jungclaus, M. Górska et al.
Core-coupled states and split proton-neutron quasiparticle multiplets in $^{122-126}$Ag.
Physical Review C 87, 034308 (2013).
doi:10.1103/PhysRevC.87.034308

10 R. Leguillon, C. M. Petrache, T. Zerrouki, T. Konstantinopoulos et al.
High-spin spectroscopy of ^{140}Nd.
Physical Review C 88, 014323 (2013).
doi:10.1103/PhysRevC.88.014323

11 A. I. Morales, J. Benlliure, M. Górska, H. Grawe et al.
β-delayed γ-ray spectroscopy of ^{203,204}Au and $^{200-202}$Pt.
Physical Review C 88, 014319 (2013).
doi:10.1103/PhysRevC.88.014319

12 M. G. Procter, D. M. Cullen, M. J. Taylor, G. A. Alharshan et al.
Proton emission from an oblate nucleus ^{151}Lu.
Physics Letters B 725, 79-84 (2013).
doi:10.1016/j.physletb.2013.06.045

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