High-Resolution Gamma-Ray Spectroscopy of Relativistic Radioactive Beams : From RISING via PreSPEC towards HISPEC/DESPEC at FAIR

Rudolph, Dirk

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High-Resolution Gamma-Ray Spectroscopy of Relativistic Radioactive Beams: From RISING via PreSPEC towards HISPEC/DESPEC at FAIR

D. Rudolph, on behalf of the RISING, PreSPEC, and HISPEC/DESPEC collaborations
Department of Physics, Lund University, S-22100 Lund, Sweden

Abstract
The study of atomic nuclei far from the line of β-stability by means of radioactive ion beams is undertaken at several large-scale facilities throughout the world. These proceedings summarize high-resolution γ-ray spectroscopy investigations based on relativistic radioactive ion beams produced and prepared by the SIS/FRS facility of the GSI Helmholtz-Centre for Heavy-Ion Research and a brief outlook towards the next-generation experiments at both GSI and FAIR.

1 Introduction

Fingerprinting excited nuclear states by γ-ray spectroscopy has been a viable tool to benchmark nuclear models for decades. Since contemporay nuclear structure investigations aim at the study and understanding of very exotic nuclei at the limits of stability and their decay properties, large and thus highly efficient γ-ray spectroscopy instruments have been installed at several radioactive ion beam facilities. These beams are being produced either by means of separated and subseqeuently re-accelerated radioactive isotopes (ISOL-method) or in-flight fragmentation or fission of relativistic heavy ions.

Several seemingly basic but central questions have been raised in the most recent Nuclear Physics European Collaboration Committee (NuPECC) long-range plan [1], for example,

– What are the limits for existence of nuclei, i.e., where are the proton and neutron driplines located?
– How does the nuclear force depend on varying proton-to-neutron ratios, i.e., what is the isospin dependence of the spin-orbit force or how does shell structure change far away from the line of stability?
– How to explain collective phenomena from individuell motion, i.e., what are the phases, relevant degrees of freedom, and symmetries of the nuclear force?
– How are complex nuclei built from their basic constituents, i.e., what is the effective nucleon-nucleon interaction?
– Which are the nuclei relevant for astrophysical processes and what are their properties, i.e., what is the origin of the heavy elements?

As a consequence, a considerable fraction of experimental nuclear structure efforts are presently devoted to the hunt for the very first information on isotopes located as far away from the line of stability as possible; let it be the observables mass, (exotic) decay modes, isomeric decays, or specific characteristics of the first few excited states, to name but a few.

The answers to the above questions provide also the foundation of coming upgrades of or completely new facilties for nuclear structure research. In preparation for the Facility of Antiproton and Ion Research (FAIR) [2], an umbrella organisation for nuclear structure, astrophysics, and reactions (NuSTAR) has been formed at GSI Darmstadt. The NuSTAR plans and experiments are outlined in the respective section of the FAIR Baseline Technical Report [3].

One NuSTAR branch has its origin in the major pan-European programme 'Rare Isotope Spectroscopic INvestigations at GSI' (RISING), which started in the year 2003. It combined the concept of efficient and high-resolution γ-ray spectroscopy based upon 105 Ge-detector crystals confined in fifteen former EUROBALL Cluster-detectors [4] with well-defined relativistic radioactive ion beams. The latter are produced in-beam by fragmentation or relativistic fission of primary beams from the heavy-ion synchrotron (SIS) at GSI, and subsequently the reaction products are separated, identified on an ion-by-ion basis, and finally focussed towards the RISING spectrometer by means of the FRagment Separator (FRS) [5].

The roadmap for Ge-based nuclear structure investigations at presently GSI Darmstadt and later-on FAIR Darmstadt is depicted in Fig. 1, which serves as a guideline for these proceedings: Following upon the successful RISING campaigns, the PreSPEC phase foresees physics-driven implementation and commissioning of FAIR instrumentation for high-resolution in-flight spectroscopy (HISPEC) and decay spectroscopy (DESPEC) within the NuSTAR frame [3].

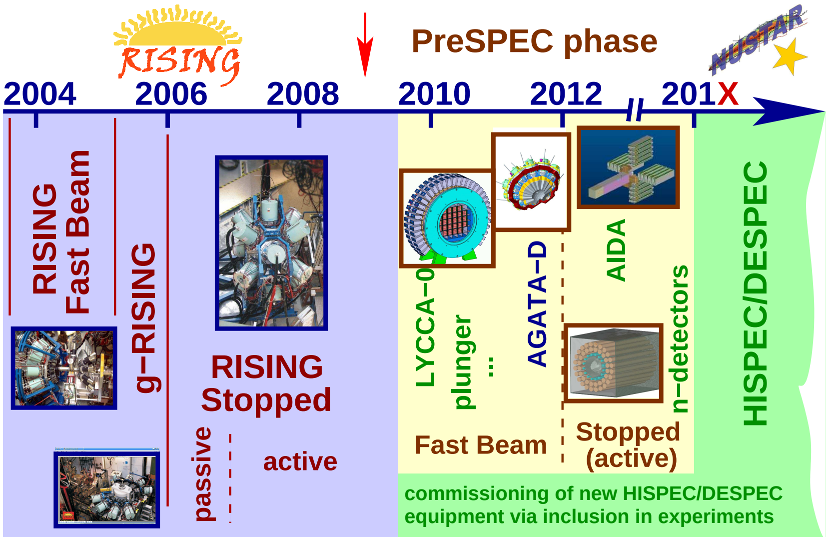

Fig. 1: Timeline of the Ge-detector based, high-resolution γ-ray spectroscopy initiatives using relativistic radioactive ion beams at GSI and FAIR.

2 RISING

During the past five years, the RISING Ge-detector array has been used in different configurations to perform nuclear spectroscopy studies of secondary, relativistic radioactive beams by means of

- in-flight Coulomb excitation or secondary fragmentation reactions: RISING in-beam campaign 2003–2005 (see, e.g., Refs. [6–8]);
- measurements of magnetic moments: g-RISING campaign 2005 (see, e.g., Ref. [9]);
- isomeric decays via implantation-decay time correlations: RISING passive-stopper campaign 2006–2007 (see, e.g., Refs. [10–12]);
- β- and exotic decay modes via additional active position and energy measurements: RISING active-stopper campaign 2007–2009.

Next to the selection of overview articles cited for the individual campaigns, several recent articles have been published summarizing the full or at least major parts of the RISING programme [13–15], in principle similar to the present proceedings. To avoid too much overlap with in particular Refs. [13, 14], I refer to these as well as to the more dedicated descriptions of the various RISING set-ups and specific equipment used [6, 9, 10, 16–18]. Instead, Fig. 2 focuses on the physics addressed with the in-flight and passive-stopper campaigns.

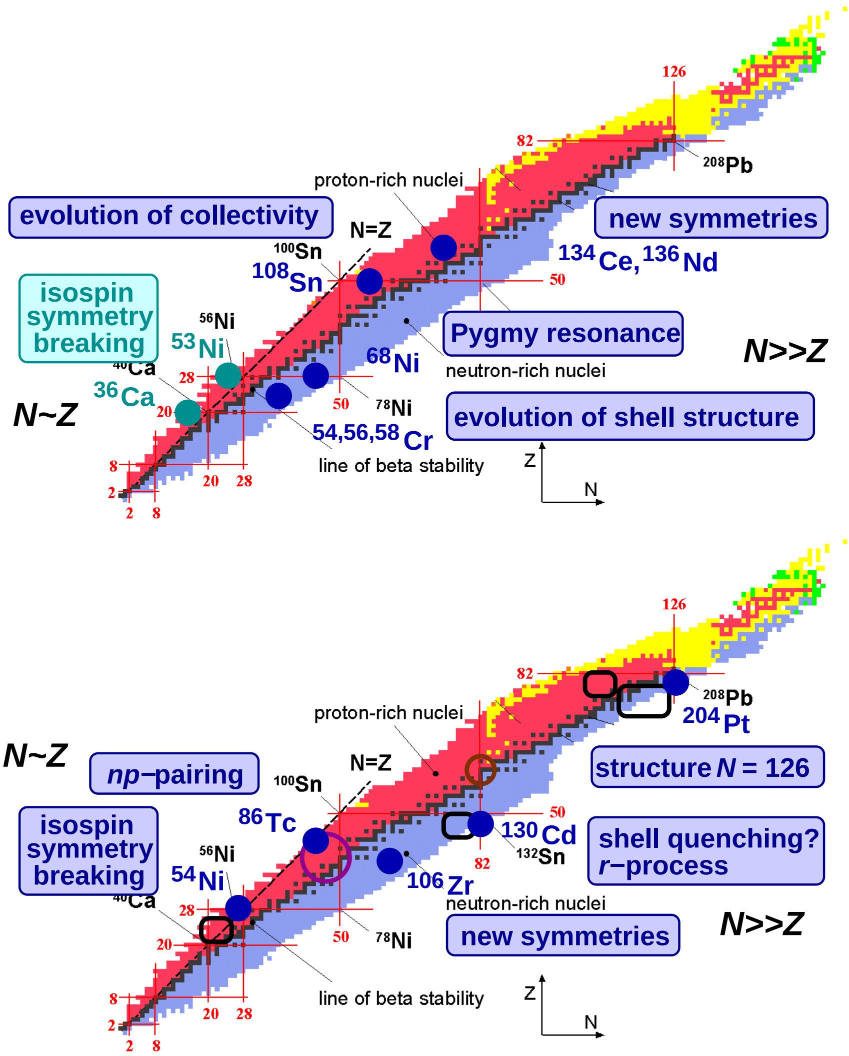

Fig. 2: Major physics goals (filled blue circles and text) of the fast-beam (top) and passive-stopper (bottom) RISING campaigns. Open circles indicate FRS settings scanning for isomers (black) or aiming at cross-section measurements (brown and pink).

Before briefly summarizing the nuclear structure results of the two campaigns, it is intruiging to first discuss a striking difference of the two panels in Fig. 2: Clearly, the passive-stopper campaign aimed (successfully) at much more exotic and also heavier nuclei compared with the in-beam campaign. This is explained by a combination of several technical issues (total γ-ray efficiency of the respective set-up [6,10], difficulties with the identification of fast-moving secondary reaction products [16], or radiation background levels) and methodological; the minimum amount of ions for in-beam γ-ray spectroscopy is about 10 per seconds, while decay spectroscopy can be performed down to a few ions produced per hour – provided clean and unambiguous event-by-event identification.

As prime example of the latter serves the observed decay of the $(1g_{9/2})^2$, 8^+ isomer with $T_{1/2} = 220(30)$ ns in ^{130}Cd [19], which marks the $N = 82$, two-proton hole nucleus with respect to doubly-magic ^{132}Sn. With only a few hundred ^{130}Cd ions arriving in the isomeric state inside the RISING stopped beam set-up within the 2-weeks' beam time, $\gamma\gamma$-coincidence spectroscopy allowed to establish a *cascade* of four γ rays. Moreover, the conversion coefficients of the two low-energy members of the cascade can be investigated and their $E2$ multipolarity be determined [19].

With the beginning of the passive-stopper phase, digital pulse-shape electronics was implemented for the 105 Ge-crystals of RISING. Consequently, the threshold of the γ-ray energy measurements was lowered down to some 40 keV, and at the same time the absolute detection efficiency of low-energy γ rays was boosted by a factor of two to three compared to conventional electronics [10]. This proved essential for isomer spectroscopy, where the very first γ-ray transition below the isomer is typically of low energy and possibly highly converted. In turn, its discrimination is vital for profound physics interpretations. Returning to Fig. 2, the main results of the in-beam campaign include:

- Isospin symmetry breaking in neutron-deficient nuclei close to doubly-magic ^{40}Ca. The 2^+ energy of the isospin $T = 2$ nucleus $^{36}_{20}$Ca$_{16}$ was determined to 3015(16) keV yielding an almost 300 keV lower value as known for the stable mirror nucleus $^{36}_{16}$S$_{20}$. Based on sd-shell model calculations, this large mirror energy difference allows to discuss the isospin symmetry of shell gaps in light nuclei in detail [20].
- Using relativistic Coulomb excitation, the reduced transition probabilities, $B(E2; 2^+ \rightarrow 0^+)$, for a number of neutron-rich Cr-isotopes have been determined. Being consistent with a subshell closure at neutron number $N = 32$, the results probe large-scale shell-model calculations in the fp shell and the evolution of shell structure in neutron-rich medium-mass nuclei [21].
- Coulomb excitation of the neutron-rich isotope ^{68}Ni has been studied at extremely high energies of 600 MeV/u. Gamma-ray spectra measured with three different detector ensembles each show a peak at some 11 MeV. The yield of that peak can be understood in terms of an enhancement of the dipole response below the giant dipole resonance. Such 'pygmy resonances' are expected for neutron-rich nuclei – in a simple picture, a neutron skin oscillates vs. a core of normal nuclear matter [22].
- Similar to the neutron-rich chromium nuclei, the transition rate from the first excited 2^+ state of the neutron-deficient ^{108}Sn isotope has been measured, which at the time was the highest-Z nucleus approached with the method [23].
- For the heavy system ^{136}Nd, the RISING set-up provided for the first time access to the second excited 2^+ state via relativistic Coulomb excitation. Interpreted with geometrical models it is found that the data provide evidence for a distinct softness in the γ-degree of freedom of the nuclear shape [24].

The passive-stopper campaign focused on the following topics:

- The electromagnetic decay properties of a 10^+ 'mirror isomer' in ^{54}Ni showed that indeed a specific $J = 2$, $T = 1$ isospin breaking *nuclear* interaction term is needed in the description of mirror nuclei in the fp shell. Furthermore, a significant $\ell = 5$ proton-decay branch of the 10^+ isomer in ^{54}Ni into the first excited $9/2^-$ state in ^{53}Co is evidenced. This exotic decay is the first of its kind observed following projectile fragmentation [25].
- Low-lying isomeric states in the odd-odd, self-conjugate $N = Z$ nuclei ^{82}Nb and ^{86}Tc have been used to dwell on neutron-proton pairing competition in the hitherto heaviest odd-odd $N = Z$ systems with known internal decays. The results yield a preference for $T = 1$ states at low excitation energies, which can be associated with a $T = 1$ neutron-proton pairing gap [26].
- The decay of an isomeric 8^+ state in the r-process waiting point nucleus ^{130}Cd has been identified (see above). Interpreted with contemporary spherical shell-model calculations there is *no evidence* for previously anticipated $N = 82$ shell quenching at $Z = 48$. Moreover, isomerism can now be followed throughout a complete major neutron shell when comparing the results in ^{130}Cd$_{82}$ with the known valence mirror isomer in ^{98}Cd$_{50}$ [19].
- Similarly, the single-particle behaviour at $N = 126$ *below* doubly-magic ^{208}Pb has been investigated for the first time. For example, the interpretation of isomeric states in the four-proton-hole isotope ^{204}Pt suggests a revision of two-body interaction matrix elements for $Z < 82$, $N = 126$, which has consequences for r-process predictions of the production of the heaviest elements [27].

Besides these major goals, numerous results on the spectroscopy of somewhat less exotic nuclei or more reaction related results on isomeric ratios and cross sections could either be derived [28–33] or still are under analysis.

Since 2007 RISING has been working in the active-stopper phase, which is about to finish with a two-week ^{238}U beam run in September 2009. The bulk of the existing exciting data is still under analysis, but first results are already in the publication phase [34, 35]. A distribution on the nuclidic chart for the active-stopper campaign would, however, look very similar to the bottom part of Fig. 2. A notable technical detail is that already the moderate number of implantation pixels of the double-sided silicon strip detectors [18] allow for considerable correlation times with subsequent β decays of up to 30 seconds.

The g-RISING campaign has been summarized in Ref. [9], while the physics results are in the process of publication [36, 37]. Most importantly, the feasibility of g-factor measurements via the time-differential perturbed angular-distribution (TDPAD) method has been established at radioactive beam energies of some 300 MeV/u, both for heavy nuclei produced in relativistic fission [36] and relativistic projectile fragmentation [37].

Another facet are nuclear reaction investigations on the fragmentation process itself, in particular on the population of high-spin states and the spin alignment. While the in-beam spectroscopy of higher-lying states remains difficult [38, 39], the isomeric decay of excited high-spin states provides a rather simple access to the amount of angular momentum being transferred via fragmentation reactions [40]. During the RISING passive-stopper campaign, a record-high $27\ \hbar$ isomeric state in ^{148}Tb has been observed following the fragmentation of a primary ^{208}Pb beam.

Going one step further, so-called isomeric ratios can be studied. These are the number of nuclei produced in a given isomeric state relative to the total number of nuclei of a certain isotope. Ideally, the isomeric ratio is studied as a function of the parallel or perpendicular momentum transfer of the fragmentation reaction [41,42]. Since the intermediate FRS focal plane S2 is dispersive in linear momentum, isomeric ratios and spin alignments are functions of the horizontal S2 positions of the relativistic ions, which naturally becomes an issue for the g-factor measurements [9, 36, 37]. Figure 3 provides a preliminary result on the momentum dependence of the population of the 10^{+} isomer in ^{54}Ni; based on the high statistics of that experiment [25], an exponential depence of isomeric can be suggested.

3 PreSPEC

The RISING Memorandum of Understanding (MoU) ends officially on August 31st, 2009. Therefore, a new collaboration named PreSPEC is currently being formed to enable the European γ-ray spectroscopy community to pursue NuSTAR physics at the existing GSI/FRS facility for the coming years, i.e. until the respective research area, namely HISPEC/DESPEC, becomes available within the NuSTAR collaboration at FAIR. The PreSPEC project aims

'to construct and operate detector set-ups at the SIS/FRS facility at GSI for nuclear spectroscopy' and it 'is also aimed at preparing for the spectroscopy to be carried out with HISPEC/DESPEC at NUSTAR/FAIR'[1]. Furthermore, a coordinated NuSTAR beam-time programme behind the SIS/FRS facility at GSI will ensure both an outstanding physics output *and* a continuous, dedicated preparation phase towards FAIR of the γ-ray spectroscopy community. The PreSPEC collaboration is also described, defined, and established in the GSI funding application covering the coming years, and at least 30 European institutions from some 10 countries are engaged in PreSPEC.

Alike RISING, PreSPEC is envisaged to begin with an in-beam campaign. In a first step, the set-up foresees upgraded, segmented tracking and time-of-flight detection systems inside the FRS, which will increase the throughput of fragments, of which already higher rates are accessible via recent SIS

[1]Quoted from the PreSPEC Memorandum of Understanding.

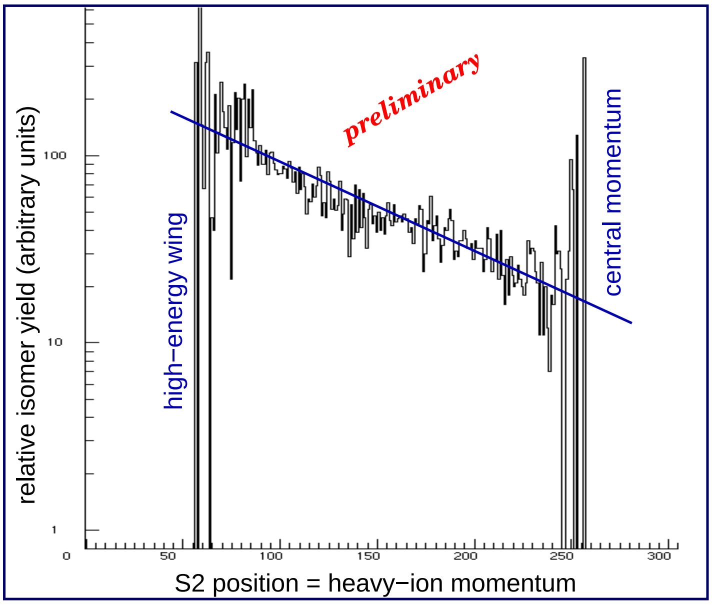

Fig. 3: Momentum dependence of the relative population of the isomeric 10^+ state in ^{54}Ni [25] in arbitrary units. ^{54}Ni nuclei have been produced by 'cold' fragmentation of a ^{58}Ni primary beam via removal of only four neutrons.

upgrades. A physically segmented identification device behind the secondary target, LYCCA-0, is going to be used for particle identification *after* secondary reactions. LYCCA-0 is a prototype of the Lund-York-Cologne CAlorimeter (LYCCA) planned in the end for the HISPEC set-up [44]. Behind the FRS it includes a ~ 3 m long time-of-flight path, using diamond detectors and ultrafast plastic scintillators for picosecond timing. In fact, LYCCA is the first NuSTAR core device with an approved FAIR Technical Design Report (TDR). Different to the previous device CATE [16], LYCCA (and LYCCA-0) will ensure mass measurements of the final residues via total energy *and* time-of-flight information [45]. Information on the proton number Z is obtained by more conventional ΔE-E techniques [44].

In 2011 approximately 10 triple-cluster modules of the Advanced GAmma-ray Tracking Array (AGATA) [46] are going to boost the sensitivity of the in-beam γ-ray set-up by at least one order of magnitude, and a plunger device for direct access to excited state lifetimes as well as a cryogenic hydrogen target will become available. The combination of all these upgrades and new opportunities are certainly very promising. They will allow unprecedented and thus frontline in-beam experiments to answer contemporary key questions in nuclear structure far from the line of β-stability.

The next period of the PreSPEC project, starting late 2012 or early 2013, foresees another decay-spectroscopy campaign, which will incorporate as much DESPEC equipment as possible, and thus provding opportunities for completely new classes of nuclear structure experiments at GSI. These experiments will group, for example, new neutron detectors and existing γ-ray detectors around the novel, central Advanced Implantation Detector Array (AIDA) [47], which provides a much higher granularity than any exisiting implantation device, read-out by application specific integrated circuits.

The PreSPEC community is, of course, ready and eager to support the Super-FRS commissioning at any given time. Eventually, physics-driven Super-FRS commissioning with partial or complete HISPEC and DESPEC equipment bares significant scientific potential for the NuSTAR collaboration and its long-term scientific goals.

4 HISPEC/DESPEC

The most recent definition and brief description of the HISPEC and DESPEC projects within NuSTAR at FAIR is most likely the abstract preceeding section 4.2 of Ref. [3], which modestly updated reads: 'HISPEC/DESPEC deals with a versatile, high resolution, high efficiency spectroscopy set-up to address questions in nuclear structure, reactions and astrophysics using radioactive beams ... The radioactive beams, which will be delivered by ... the Super-FRS ... will be used for γ-ray, charged particle and neutron spectroscopy. The HISPEC ... set-up will comprise beam tracking and identification detectors placed before and behind the secondary target, the AGATA Ge array, charged particle detectors, a plunger, a magnetic spectrometer and other ancillary detectors. The DESPEC ... set-up will comprise Si based implantation and decay detectors, a compact Ge array, neutron detectors, fast BaF_2 detectors, a total absorption spectrometer and equipment for g-factor and quadrupole moment measurements. DESPEC will use the same suite of particle identification and tracking detectors as HISPEC. The two set-ups can be combined for recoil decay studies, with the DESPEC detectors placed at the end of the magnetic spectrometer.' For more details, please see the complete project description in Ref. [3].

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