RARE ISOTOPES INVESTIGATIONS AT GSI (RISING) USING RELATIVISTIC ION BEAMS.

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The initial experiments performed using the fast fragmentation beams and the RISING gamma-ray spectrometer are reviewed and their results discussed. Plans for the future campaigns using ions which are slowed down and stopped in a catcher will also be presented, including details of experiments which measure magnetic moments (g-factor) and β decays using an active stopper.

1. Introduction

The study of atomic nuclei and their dynamics at low excitation energy has been performed over several decades using more and more sophisticated experimental techniques. The themes of modern day nuclear structure research are changing. On one hand they are refocusing towards the study of low-spin properties and the associated complete spectroscopy; while on the other, nuclear structure research is now able to manipulate an extremely important degree of freedom, namely the neutron-to-proton ratio, with the advent of the new radioactive beam facilities. Here, not only predictions of present day nuclear models can be tested, but effects due to the underlying neutron-proton degree of freedom can be thoroughly studied. Besides this, new properties can be revealed, such as the coupling of bound states with the continuum, dilute nuclear matter, clustering and new decay modes. With the availability of Radioactive Ion Beams (RIB), all essential degrees of freedom will become available for experimental manipulation. Such work, however, requires infrastructure that can only be afforded on a supranational scale. That said, the discovery potential is very large and new facilities, such as RIA and the GSI extension FAIR, will be built in the coming decade.

Essential for RIB and stable-beam research is the use of high-performance detector arrays to study properties of stable and exotic nuclei. Large γ-ray spectrometers such as Euroball and Gammasphere were developed for the study of high-spin physics where they have been very successful. Nowadays they are being partly converted towards lower-spin applications. The challenge is that 'low-spin' physicists need the 'high-spin' technology and high-spin physicists need the low-spin methods and theoretical approaches. The most advanced project in this direction concerns the Euroball spectrometer, which was dismantled in 2003 for this specific goal. The 15 Euroball Cluster detectors are now installed at the Fragment Recoil Separator (FRS) of GSI as part of the RISING project [1] for RIB research. It is also worth noting that the other major components of the Euroball spectrometer have been successfuly installed at the RITU spectrometer in Jyvaskyla and within the CLARA array at INFN-Legnaro for use in stable-beam induced experiments.

2. The RISING fast beam campaign.

The first RISING campaign (spokesman P. Reiter) ran from summer 2003 until spring 2005 and was aimed at γ–ray spectroscopy of exotic nuclei moving at relativistic energies. The set-up was conceived in such a way that the gamma-ray detection efficiency was maximized, with the restriction that the energy resolution was at the one percent level for each individual Euroball Cluster segment for recoil velocities of v/c = 0.43. Due to the Lorentz boost this implied a strongly asymmetric setup whereby all detectors were mounted behind the target in three rings around the 16 cm wide beam tube. With this set up, a photopeak efficiency of 2.81% (at 1.33 MeV) and an energy resolution of 1.56% was attained [1]. In part of the fast beam experiments two additional rings holding seven additional MINIBALL triple detectors were added, increasing the photopeak efficiency to 7.3%. In the backward direction, eight BaF_2 detectors from the HECTOR array were mounted. These were used to measure very high energy γ-rays and also provide a very good timing reference. After the target the Calormetric Telescope array CATE was used to identify the scattered particles and breakup products. It consisted of position sensitive ΔE-E detectors constructed from thin Si and thick CsI(Tl) telescope detectors [2]. To analyze the data each event is tracked and reconstructed. Figure 1 shows a photograph of the complete ‘Fast RISING’ setup.

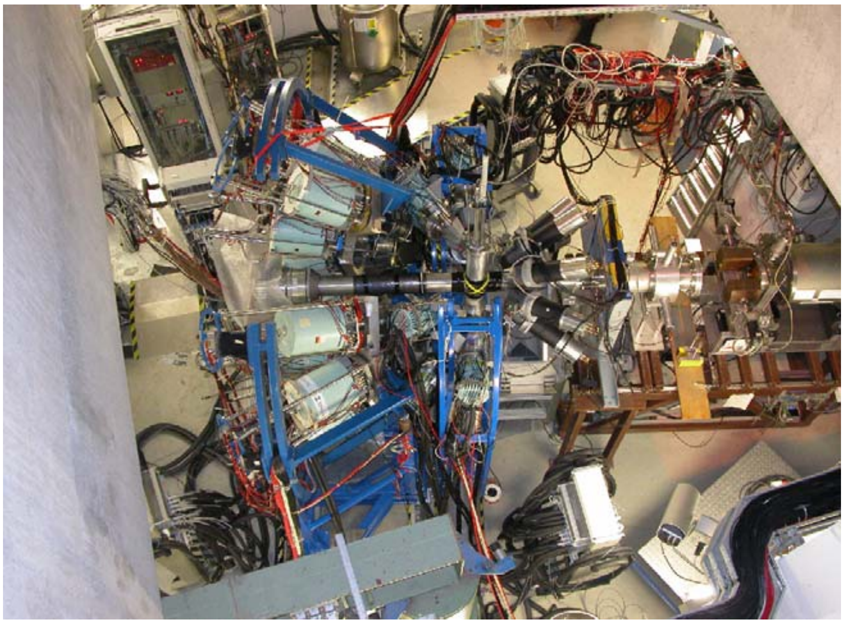

Figure 1: RISING fast beam setup. The beam enters the setup from the right. After hitting the target the ions are detected in the CATE detector. The γ rays are detected using the HECTOR array (right) the MINIBALL detectors (middle) and the EUROBALL Cluster detectors (left).

The first results of the fast campaign are now available. Relativistic Coulomb excitation was used in several experiments in order to extract absolute B(E2) values of the first excited state in a number of unstable nuclei, which provides an independent test of the collectivity of this fundamental excitation. For ^{56}Cr and ^{58}Cr, the results confirm the presence of a subshell closure at N=32, which was already indicated by the anomalous excitation energy of the 2^+ state in ^{56}Cr [3]. The result presents a challenge for large scale shell-model calculations which over predict the B(E2:$2^+ \rightarrow 0^+$) value for this nucleus. In the ^{108}Sn isotope the obtained B(E2:$2^+ \rightarrow 0^+$) value is in agreement with the theoretical calculations [4].

In order to study proton-rich unstable nuclei, two-step fragmentation reactions were used in several experiments. Preliminary results on the T=3/2 mirror nuclei in the A~50 region show the potential of this method [5]. In addition to the first results discussed above, a significant number of other new results are expected following the completion of the complex data analysis associated with these experiments, including those performed with the addition of the MINIBALL detectors to the RISING array.

3. The g-factor campaign

Static nuclear moments (specifically magnetic dipole and electric quadrupole moments) present critical tests for the nuclear wave functions obtained within theoretical models, since only one state is involved in the calculation of the expectation values of these observables. The magnetic moment, μ, being the product of the nuclear g-factor and the spin I, is a very sensitive probe of the single-particle structure of nuclear states. High-spin isomers in the region of doubly-magic nuclei often have a rather pure single particle configuration, for which the g-factor is a very good observable to determine the valence nucleon configuration. Measurements of nuclear g-factors can also serve as stringent tests of spin and parity assignments [6]. This is particularly true in far-from-stability regions where such assignments are often based on systematics and theoretical predictions.

Starting in the Autumn of 2005, the RISING collaboration will perform a dedicated campaign of g-factor measurements (spokeswoman G. Neyens) using the Time Differential Perturbed Angular Distribution (TDPAD) method. The method of g-factor determination (or a spectroscopic quadrupole moment) for an isomer state is based on measuring the perturbation of the γ–ray anisotropy due to externally applied magnetic (or electric) interactions, following the implantation of the spin-oriented isomeric beam into a suitable stopper (i.e., a crystal or foil). This method has been used extensively over the last couple of decades for measurements of static moments of isomeric states which were produce (and spin-aligned) following in-beam fusion-evaporation reactions [6]. However, in order to investigate isomers with lifetimes in the range of 10^{-7} – 10^{-4} s in neutron-rich nuclei, the projectile fragmentation and projectile fission reactions are the most suitable (and often the *only* available) methods for producing, spin-orienting and selecting the isomers in a fast and efficient way.

To date, only a few TDPAD measurements have been made on isomers produced in fragmentation reactions at intermediate and relativistic energies of the primary beam [7,8,9]. The major difference between these and the former in-beam experiments, is that the isomers are first mass separated in-flight using dipole magnets. During the separation process, the reaction-induced spin-orientation needs to be maintained until the moment of implantation. The hyperfine interaction between the nuclear and random-oriented electron spin can cause a loss of orientation during the flight through vacuum. To avoid this hyperfine interaction, we have two possibilities: either (i) the isomer is produced without electrons (fully stripped fragments), or (ii) the isomeric beam is selected in a noble-gas-like charge state. The high primary beam energies used in fragmentation reactions mean that most fragments can be produced fully stripped, and therefore such beams have been used until now. In a pioneering experiment, Schmidt-Ott and collaborators demonstrated that considerable alignment (~ 30%) is observed in the ^{43m}Sc isomeric ensemble selected with the FRS at GSI and produced in the fragmentation of a relativistic ^{46}Ti beam (500 MeV/u) [7].

For the planned experiments at the FRS a dedicated magnet system allowing magnetic fields up to about 1.5 T (with a gap of 5 cm between the poles) up to 1.1 T (with a gap of 10 cm) will be used. The γ decays will be detected using 8 Clusters mounted in a close geometry in the horizontal plane (see Figure 2).

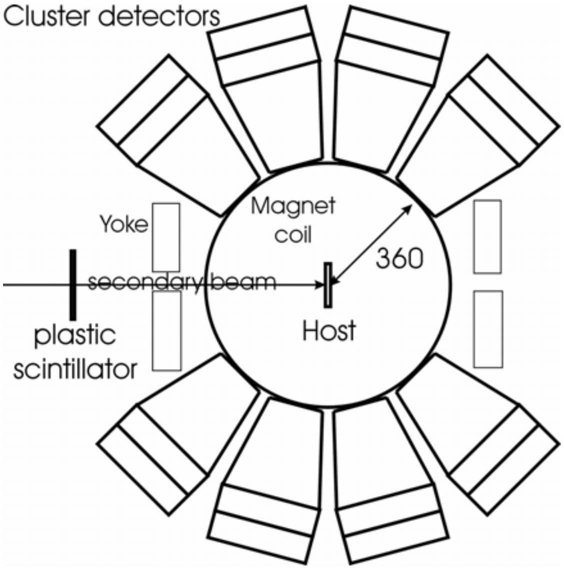

Figure 2: Schematic layout of the TDPAD set-up for measuring isomeric g-factors viewed from above. Detectors are at 36 cm from the stopper, and at relative angles of 60° to each other. The total γ-ray detection efficiency is estimated at 4%.

Experiments with fully stripped fragments were limited up to now to nuclei up to mass number $A_{max} \approx 80$ using intermediate energies as provided at e.g. GANIL, RIKEN and MSU. This is because the probability of picking up electrons increases with Z for a fixed beam energy, while it decreases with the beam energy for a given Z. RISING will address mass $A \approx 100 \rightarrow 200$ nuclei. The proposed experiments can be peformed at present only at GSI, because the energy and charge of the primary beam at other facilities is not high enough. Furthermore, the fragmentation of a relativistic ^{238}U beam (available only at GSI) offers the unique possibility of studying isomers in neutron-rich nuclei approaching ^{132}Sn. The presence of spin-alignment in fragments produced by a relativistic ^{238}U fission reaction will be demonstrated for the first time as part of the g-RISING campaign.

The proposed g-factor studies focus on nuclei in regions along shell closures (Z=50 and Z=82) and near doubly magic nuclei. Near the Z=50 shell closure, the structure of isomeric states which consist of rather pure particle and/or hole configurations with respect to the doubly-magic proton-rich ^{100}Sn and the doubly-magic neutron rich ^{132}Sn cores will be investigated. Study of the g-factors of isomers in these regions will help to pin down the suggested configurations and spin assignments, as well allowing investigation of the properties of the M1 operator and its suggested quenching at the extremes of isospin between ^{100}Sn and ^{132}Sn.

Nuclei along the Z=82 proton shell closure exhibit a variety of nuclear structures at low excitation energy. In the neutron mid-shell region, a transition from a typical shell model type structure towards more collective states seems to set in. Here the g-factors in this region are investigated to probe the onset of collectivity in the isomeric wave functions.

4. The stopped beam campaign

Following the g-factor measurement the RISING Stopped Beam Campaign (spokesman P. Regan) will start. Here the 15 EUROBALL Cluster detectors will be used to build a compact array around a passive or active stopper. They will be used to measure γ-rays following β-decay to excited states and to measure the direct decay of long lived isomers. For the study of the former process, a position sensitive silicon detector will be used as an active stopper so that the incoming heavy ion can be correlated to its subsequent β-decay. The compact set-up is expected to reach a photopeak efficiency of 11% at 1.33 MeV and 20% at 0.662 keV (see Figure 3). It can be extended with 8 BaF_2 fast scintillators for fast-timing experiments. The FRS will be used in monochromatic mode which allows the stopping of selected isotopes in a 1mm thick Si stopper at the focal plane. This allows a spreading of specific species across a wide area of the focal plane, both increasing the sensitivity of the experiments and allowing longer decay times for subsequent heavy-ion-implantation-β–decay correlation measurements to take place.

The physics aims of the Stopped RISING project are focused on obtaining spectroscopic information on nuclei with highly exotic proton-to-neutron ratios. These include specific studies of (i) isospin and seniority isomers along the N=Z line (specifically ^{54}Ni and N=Z=41→43); (ii) the use of 'cold fragmentation reactions' to populate rather neutron-rich nuclei and in particular isomeric states arising from the maximal spin coupling of 2-particle (or hole) states in near doubly magic systems 'south' of ^{132}Sn (^{130}Cd) and ^{208}Pb (^{206}Hg, ^{204}Pt); (iii) the investigation of very neutron-rich Zr nuclei approaching the ^{110}Zr harmonic oscillator double shell closure following projectile fission reactions; (iv) and the utilization of K-isomeric states to map out collectivity and axial symmetry around the valence proton-neutron-product (Np.Nn) maximum nucleus ^{170}Dy.

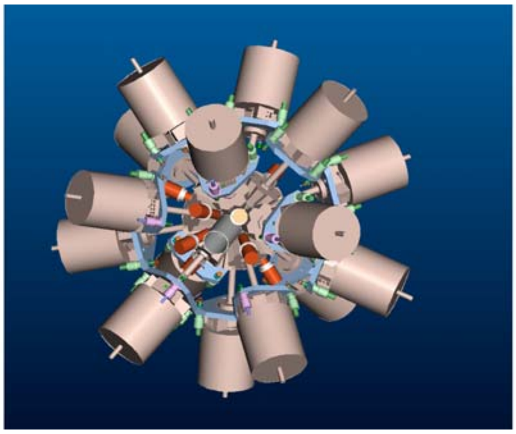

Figure 3. CAD drawing of the Stopped Beam RISING array.

5. Conclusions

The RISING project is aimed at frontier research in nuclear structure physics using relativistic RIB. It therefore has to combine the complicated FRS infrastructure with state-of-the-art γ-ray detectors. Although as expected several technical problems can arise (e.g., atomic background, operation of the FRS in new settings) the project is moving forward and the first experiments are providing new and interesting results and, more importantly perhaps, paving new experimental pathways into the unknown regions of the Segre chart. These experiments will be of vital importance for the future FAIR and RIA facilities. The first results of the fast beam campaign are now available and a new series of experiments using stopped beams will be performed in 2006-7. RISING is a major effort of the European nuclear physics community and has already demonstrated that the traditional low- and high-spin communities can merge and pursue common scientific goals in the future.

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