GAMMA-SPECTROSCOPY WITH EXOTIC BEAMS*

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Radioactive beams obtained by fragmentation reactions at relativistic energies provide new possibilities for γ-spectroscopy. Decay studies after implantation as well as in-beam single step Coulomb excitation and secondary fragmentation are commonly employed techniques. Isotopes of interest can be selected by particle tracking providing event-by-event Z and A determination. Beam intensities as low as 0.01 ions/s are sufficient to observe discrete γ-transitions using high resolution Ge-arrays and/or 4π scintillator-arrays. Severe background, in particular from Bremsstrahlung and large Doppler effects result from the high beam velocities of $v/c \leq 60\,\%$. On the other hand, thick targets compensating limited beam intensities are an advantage of the high beam energies. Unknown regions of the nuclidic chart become available for detailed spectroscopy for the first time.

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1. Introduction

Radioactive beams from fragmentation facilities [1] like at GANIL, GSI, MSU and RIKEN have recently become available with intensities sufficient for γ-spectroscopy of exotic nuclei. New information on the evolution of the nuclear shell structure, neutron–proton pairing, astrophysical r- and rp-process to name only a few important topics will arise from such investigations. To exploit the possibilities offered by exotic beams novel experimental techniques are required. The main experimental aspects are discussed in the following, taking examples from studies performed with beams from the fragment separator FRS at GSI.

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2. Experimental particularities

Projectile fragmentation and fission in-flight employing projectile energies in the order of 500 MeV/u to 1 GeV/u provide relativistic beams of exotic nuclei along the entire periodic table, irrespective of their chemical properties and with half-lives down to a few hundred nanoseconds. Production targets of typically 1 g/cm^2 to 4 g/cm^2 cause reaction probabilities of several percent. The fragments emerge from the reaction target with kinematical properties close to the primary beam, modified by the reaction kinematics.

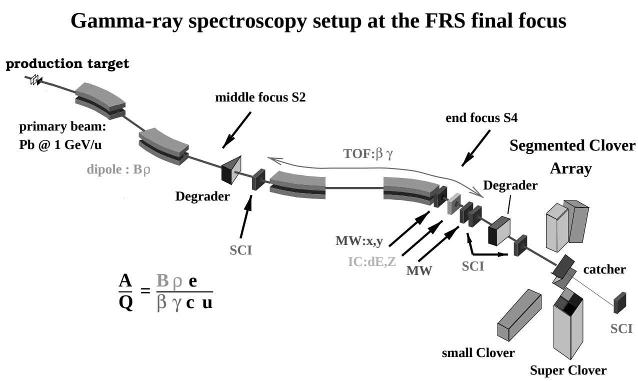
In the fragmentation process angular momentum is induced statistically during the abrasion of nucleons in the pre-fragment formation and the evaporation of nucleons in the following de-excitation. Depending on the mass difference between projectile and final fragment angular momenta of up to 30 $\hbar$ and more are possible. Thus high spin isomers, in particular yrast traps, will be populated with considerable isomeric ratios [2] providing exotic isomer beams.

Clean mono-isotopic separation is achieved by magnetic rigidity analysis combined with energy loss in a shaped degrader assuming that the fragments are fully stripped. The condition that all isotopes are bare, necessary for an efficient separation and transport of the reaction products, is the reason why relativistic beam energies are required. In particular beams of heavy elements can only be separated at the highest beam energies. Magnetic fragment separators like the FRS [3] provide also the option of beam cocktails of well defined isotope composition by an appropriate choice of degrader thickness and shape. This allows a number of neighboured nuclides to be investigated at the same time with the advantages of an efficient use of the beam and simultaneous measurement of reference nuclei and reactions.

Particle detectors trace the trajectories of the separated beam ions individually. In addition energy, charge and mass of each particle is determined by E-loss, time of flight and magnetic rigidity measurement. This rigorous tracking of the beam constituents allows to uniquely select the wanted species with well defined characteristics suppressing virtually all background events. This selectivity provides a high sensitivity to the nuclear structure effects to be studied. Therefore beam intensities can be much lower in many cases compared to conventional stable beam scenarios. In in-beam experiments tracking is continued behind the secondary reaction target. Thus not only the incoming particle but also the outgoing particle and, hence, the reaction process is well determined. Here the sensitivity can be so high that spectroscopic information is only limited by counting statistics and no longer by background contributions.

3. Decay spectroscopy

Many nuclei exhibit isomeric states which will be populated in fragmentation reactions. Isotopes of interest can be selected by the FRS, transported and identified on an ion-by-ion basis and implanted into a catcher. A typical experimental set-up is shown in Fig. 1. If the lifetime of an isomer is longer then about 100 ns to survive transport and short enough to be correlated with the particular implantation (typically some 10 ms) the isomeric decay can be measured with an array of γ-detectors surrounding the catcher. By that method the level structure below the isomeric state and its lifetime can be determined. Using state-of-the-art Ge-detectors providing photopeak efficiencies in the order of 10 %, like the VEGA set-up [4], allows discrete γ-spectroscopy of isotopes with beam intensities < 0.01/s, thus species very far off stability are accessible.



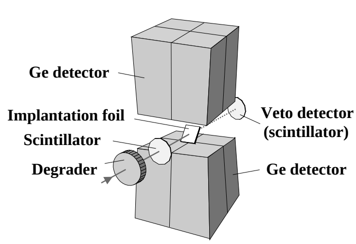


Fig. 1. Experimental set-up for isomer spectroscopy at the FRS at GSI.

During the implantation Bremsstrahlung is emitted. Its energy distribution and intensity depend on the fragment's energy and nuclear charge. The multiplicity of the emitted X-rays may cause hits in a considerable fraction of the Ge-detectors, making them "blind" to the decay of short-lived isomers.

Fast recovery electronics and/or high granularity arrays are essential in that case. An example from a recent experiment is the identification of the rotational band in ^{190}W [5]. The isotope was produced by fragmentation of a ^{208}Pb beam of 1 GeV/u with an average rate of 0.2 ions/s. Fig. 2 shows the identification plot for ^{190}W. By correlating the fragment position at the exit of the FRS (S4) and its A/Q value — determined from the flight time between the central section (S2) and the exit — any isotope can be easily separated. The γ-ray spectrum observed in delayed coincidence is shown in Fig. 3. No excited states in ^{190}W were known prior to this experiment, and the observed lines are assigned to transitions of the ground state band. The deduced level energies are in good agreement with a triaxial rotor with $\gamma \approx 30^\circ$ [6]. It corresponds to the O6-limit in the Interacting Boson Approximation [7]. The line at 46 keV is tentatively assigned as E1 transition between the isomer and the 10^+ state.

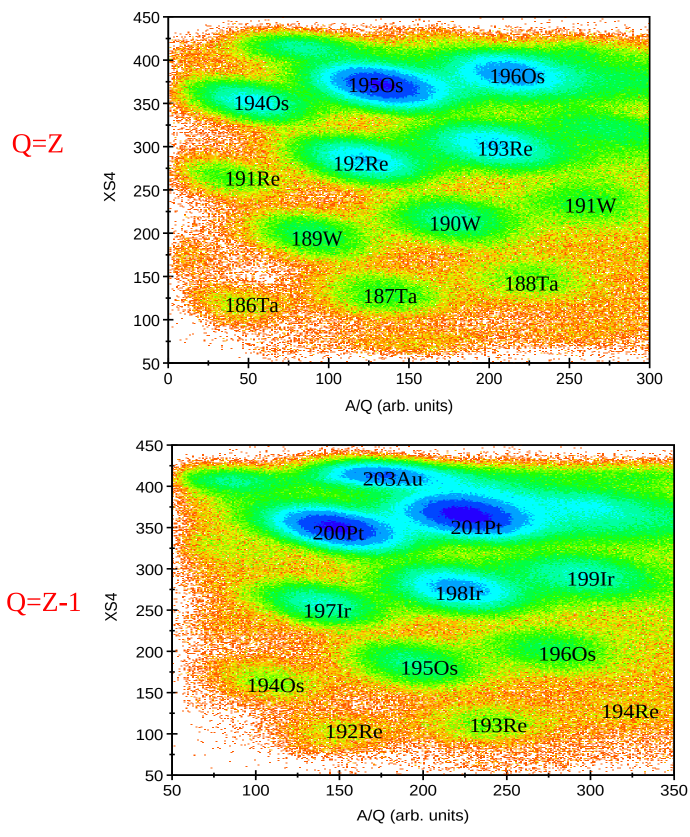


Fig. 2. Identification plot of the fragments by the FRS for the setting centred on fully stripped ^{191}W.

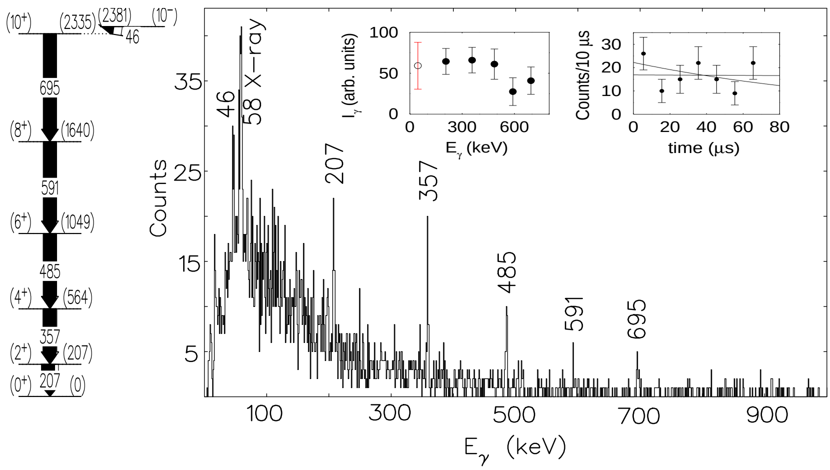


Fig. 3. γ-spectrum of the isomeric decay of ^{190}W.

4. In-beam spectroscopy

In-beam gamma-spectroscopy with relativistic radioactive ion beams is a rather untouched field which offers new opportunities to study the nuclear structure of exotic nuclei: Coulomb excitation, few nucleon removal reactions and secondary fragmentation in general provide rich spectroscopic information. As shown schematically in Fig. 4 relativistic Coulomb excitation probes preferentially collective, excited states up to the giant resonances at low angular momentum. Decay gammas will feed into intermediate energy states. On the other hand, secondary fragmentation populates a broad

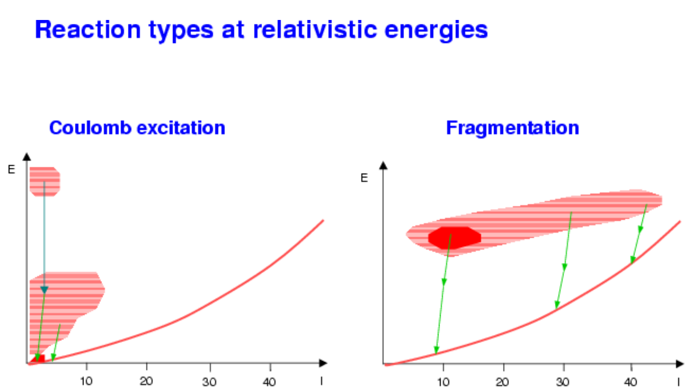


Fig. 4. Schematic of the population pattern observed in reactions at relativistic beam energies.

range of angular momenta with an entry distribution resembling classical compound reactions. Since the energy loss is small, thick secondary targets (ca. 0.5 g/cm^2 at 100 MeV/u) can be used resulting in large yields compensating low beam intensities. Highly selective particle identification and tracking result in unprecedented selectivity and sensitivity. On the other

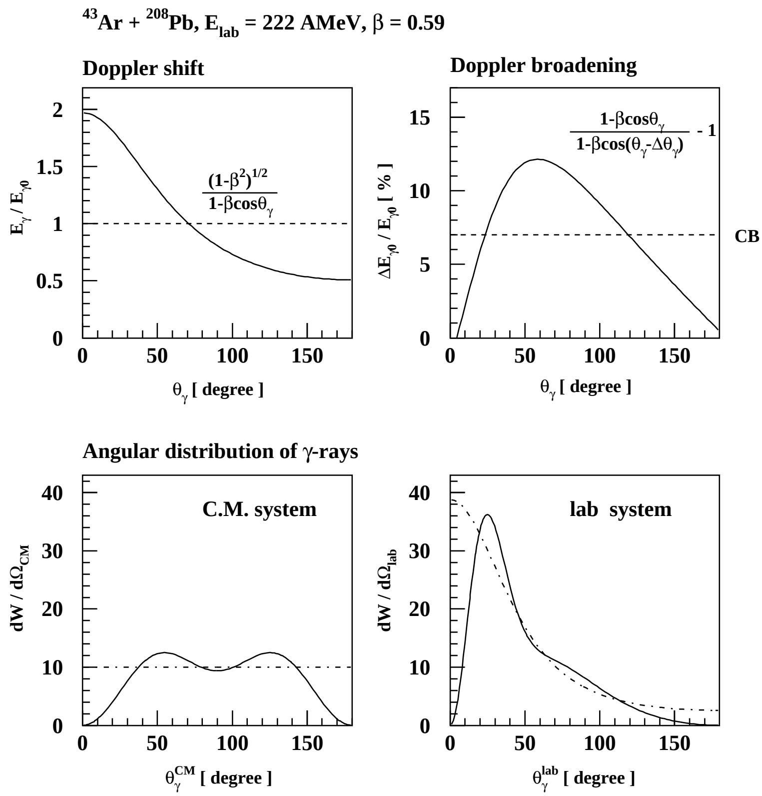


Fig. 5. Doppler effects at relativistic energies.

hand, one has to cope with large Doppler effects. Fig. 5 shows the Doppler shift and the Doppler broadening to be expected in a realistic γ-detector set-up. For a typical detector solid angle of $\Omega_{\rm det}/4\pi = 0.007$ the broadening leads to a mean energy resolution of about 10 % at 200 MeV/u. However, at very forward and backward angles high resolution spectroscopy employing Ge-detectors is possible. Huge atomic background from Bremsstrahlung and X-rays is another limiting factor. Fig. 6 shows the atomic cross section as a function of energy for a ^{43}Ar beam at 222 MeV/u interacting with a Pb target. Depending on the charge of projectile and target between 1 and 10 quanta are emitted per projectile in addition to the nuclear γ-quanta. In a first attempt the feasibility of this new experimental method was inves-

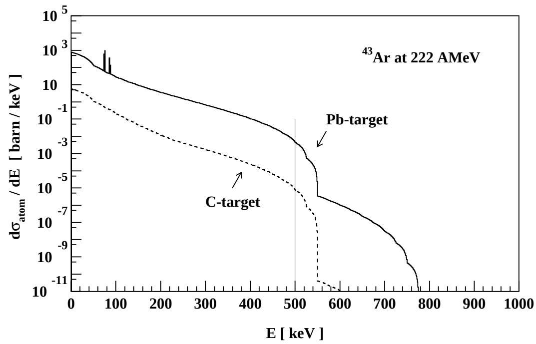


Fig. 6. Atomic radiation cross section at relativistic energies.

tigated, and used to study the nuclear structure of the neutron-rich nuclei below ^{48}Ca with neutron number between the two magic numbers $N = 20$ and $N = 28$ [8]. By fragmentation of ^{50}Ti on ^{9}Be at 330 MeV/u, more than 30 n-rich isotopes from B to Ca with mass to charge ratio $A/Z \approx 2.4$ were selected by the FRS and transported as a beam cocktail to the secondary target (see Fig. 7), which enables simultaneous measurement of several nuclei. To determine A and Z event by event, the energy loss and time of flight were measured before the secondary Pb target (0.9 g/cm^2).

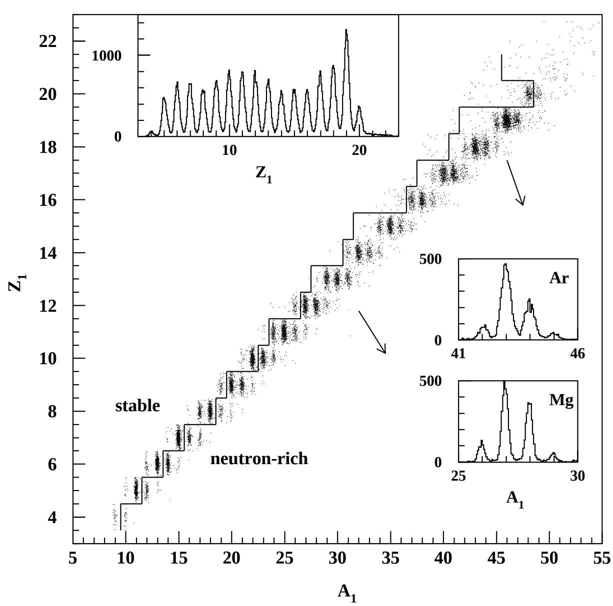


Fig. 7. Beam cocktail transported to the reaction target.

To select Coulomb excitation and projectile-like ions from nucleon removal reactions, A and Z were measured by the Bρ-TOF-ΔE method, using the large magnetic spectrometer Aladin. To detect de-excitation γ-rays, the target was surrounded by the Darmstadt–Heidelberg Crystal Ball spectrometer, consisting of 143 NaI detectors with an opening angle of $\Delta\theta_{\mathrm{NaI}} = 18°$. The mean Doppler broadening of 10 % is well adapted to the intrinsic resolution of the scintillators. To discriminate background from atomic radiation Pb absorbers and a trigger threshold of 500 keV was used. Fig. 8 shows spectra of n-rich Mg isotopes obtained by inelastic excitation and one neutron removal. Note that the ^{28}Mg intensity was only 60 ions/s.

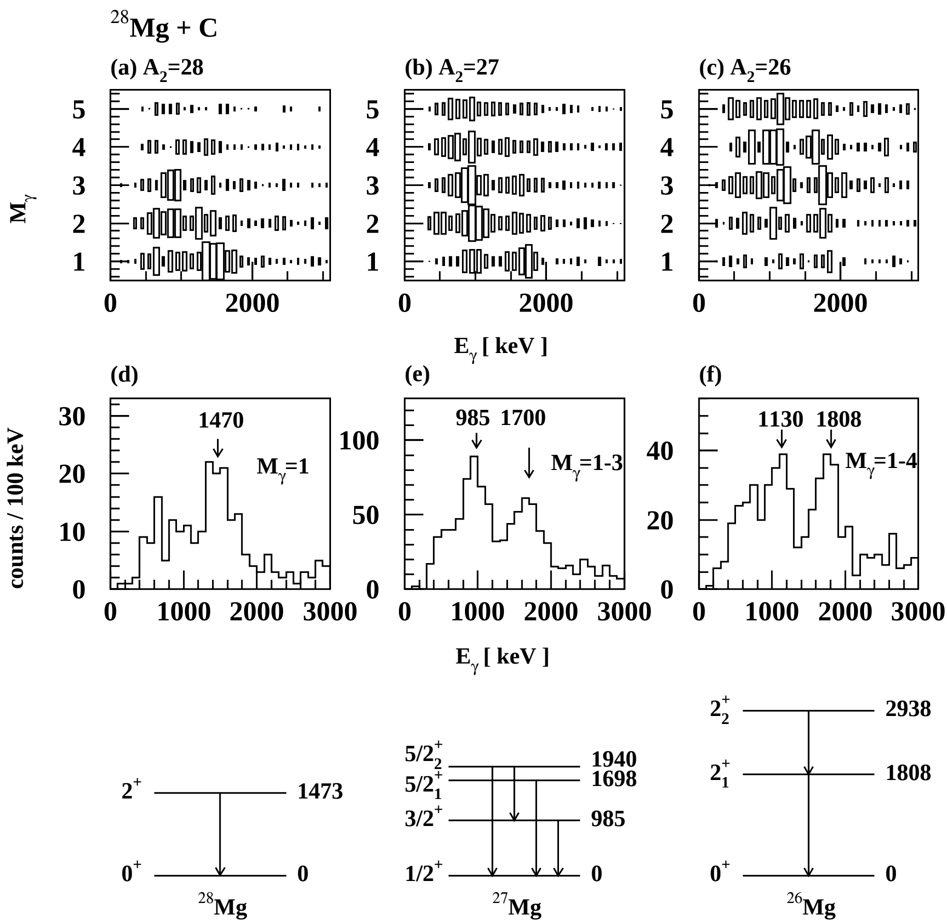


Fig. 8. γ-spectra of n-rich Mg isotopes and deduced decay schemes.

5. Outlook

The examples discussed above demonstrate the potential of γ-spectroscopy employing relativistic exotic beams. Techniques for decay spectroscopy are well established. In-beam spectroscopy obviously will benefit from high resolution Ge-detectors. New set-ups, like the planned RISING [9] array using state-of-the-art Euroball detectors and the future AGATA project aiming at a γ-tracking array will lead into that direction opening new perspectives for nuclear structure research.

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