The structure of neutron-rich nuclei explored via in-beam gamma-ray spectroscopy of fast beams

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Abstract

In-beam gamma-ray spectroscopy with fast exotic beams provides an efficient tool to study bound states in exotic neutron-rich nuclei. Specialized experimental techniques have been developed and explore different aspects of nuclear structure. Inelastic scattering experiments with γ-ray detection can measure the response of exotic nuclei to electromagnetic (Coulomb excitation with a heavy target) or hadronic probes (proton scattering with hydrogen target). In-beam fragmentation populates higher-lying bound states to establish levels. Single- and two-nucleon knockout reactions allow for detailed wavefunction spectroscopy of individual levels and for the measurement of spectroscopic factors. Experimental programs employing these techniques are now underway at all projectile-fragmentation facilities around the world. Here we report on several successful in-beam gamma-ray spectroscopy experiments that have been performed at the Coupled Cyclotron Facility at Michigan State University with an emphasis on elucidating the evolution of nuclear structure around neutron numbers $N = 16$, $N = 20$, and $N = 28$ in the π(sd) shell.

1 Introduction

Projectile fragmentation of intermediate-energy heavy-ion beams with subsequent fragment separation is an efficient method to prepare beams of exotic nuclei by physical means [1]. Experiments with standard luminosities can be carried out at intermediate beam energies with thick secondary targets (order of g/cm^2) and very low incident beam rates (order of particle/s or less) provided that inelastic scattering events can be detected. In the last several years

γ-rays have become the probe of choice to indicate inelastic scattering events to excited bound states in thick-target experiments. Photons traverse targets with little and known attenuation. With the development of position-sensitive γ-ray detectors it has become possible to measure the energies and directions of photons emitted in-flight. This allows the reconstruction of the photons' energies in the frame of the moving exotic projectile with high accuracy. Experimental success in this field is strongly correlated with the development of detectors such as position-sensitive scintillation detectors or segmented Germanium detectors. In-beam gamma-ray spectroscopy of fast exotic beams has been successfully used at all projectile-fragmentation facilities and specialized techniques have been developed. Intermediate-energy Coulomb excitation [2] serves as an electromagnetic probe, inelastic protons scattering with γ-ray detection as a hadronic probe, in-beam fragmentation reactions populate a variety of low-lying excited states [3], and nucleon knockout reactions [4] allow for precision wavefunction spectroscopy through the measurement cross section which can be converted into spectroscopic factors.

2 The Michigan State University Segmented Germanium (SeGA) detector array

The final energy-resolution of γ-ray spectra reconstructed in the frame of the moving exotic projectile contains contributions from the uncertainties of the γ-ray scattering angle, the beam velocity, and the intrinsic energy resolution of the detector. In typical experiments the former two contribute an energy resolution of about 1%-2%, much less than the intrinsic energy resolution of scintillation detectors. Thus we have replaced the previously used position-sensitive NaI(Tl) detector array [5] with an array of eighteen 32-fold segmented high-purity germanium detectors [6, 7]. Figure 1 shows the segmentation of one crystal of this new array, SeGA, which is currently the largest operational germanium detector array for gamma-ray spectroscopy with fast beams of rare isotopes. The in-beam energy resolution achievable with this array is dominated by the secondary target thickness and the uncertainty in the γ-ray scattering angle. This uncertainty can be reduced-for a given accuracy with which the interaction point of the photon in the detector can be determined-by moving the detector further away from the target. Therefore, in γ-ray spectroscopy with fast exotic beams, the experimenter has to make a choice in which detection efficiency is traded off against desired energy resolution. This argument also illustrates that doubling the accuracy of determining the first interaction point—for example through pulse shape analysis—would yield

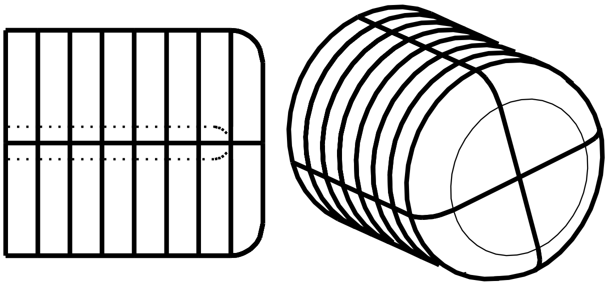

Figure 1: Schematic drawing indicating the segmentation of one SeGA germanium crystal. Each crystal is 8 cm long and 7 cm in diameter. In typical fast-beam experiments the *gamma*-rays enter from the side. The detectors can also be used in the conventional way with γ-rays entering through the front if needed.

a four-fold gain in detection efficiency for a given desired energy resolution. The large degree of segmentation of the SeGA crystals has already allowed for high-resolution in-beam gamma-ray spectroscopy (with analog electronics) by correcting event-by-event for the Doppler shift due to the large recoil velocities (v/c$\sim$0.3-0.4).

3 Intermediate-energy Coulomb excitation experiments

The in-beam performance of SeGA with fast beams was first tested with two known reactions: the intermediate-energy Coulomb excitation of the known nuclei ^{86}Kr and ^{11}Be. For these initial tests one ring of six segmented Germanium detectors was located at an angle upstream from the secondary gold target. ^{86}Kr was produced as a primary beam in the Coupled Cyclotron Facility and impinged onto a gold target. Gamma-rays were measured in coincidence with the scattered projectile and are shown in Figure 2 in the panels on the left. The laboratory spectrum shows some structure where the γ-rays corresponding to the transition of the first excited state to the ground state are expected, but the opening angle of the germanium detector is so large that a peak can hardly be made out. After an event-by-event Doppler-shift reconstruction of the spectrum into the projectile frame the transition becomes visible as a peak. Subsequently ^{11}Be was scattered off the same gold target and the first excited state was populated. The observation of the 320 keV γ-ray corresponding to the $1/2^- \rightarrow$ g.s. transition indicates that low-energy

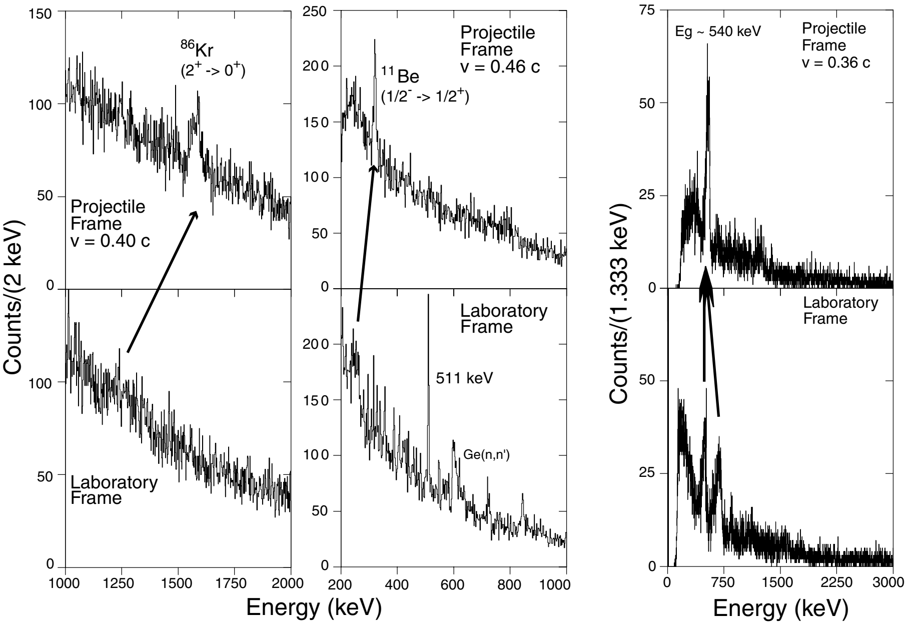

Figure 2: Online spectra from SeGA's first in-beam test experiments with a heavy nucleus (^{86}Kr) and a light nucleus (^{11}Be) impinging on a gold target at intermediate beam energies (left panels). The bottom panels show the energy spectra as they are measured in the laboratory and the top panels show the same spectra after an event-by-event Doppler-reconstruction has been applied. The γ-rays from the first excited states to the ground states become visible as peaks. The right panel shows γ-ray spectra measured in the nucleon knockout reaction ^{46}Ar(^{9}Be,^{45}Arγ) with a setup that contained detectors at 37° and 90°.

gamma-rays (at least in reactions of light projectiles with heavy targets) can be detected successfully in experiments with fast exotic beams at beam energies exceeding 100 MeV/nucleon. Correcting for the beam profile of the incoming beam and measuring and correcting for the scattering angle of the ejectile can further improve the energy resolution of the reconstructed γ-rays shown in Figure 2.

4 Nucleon-knockout experiments

Several one- and two-nucleon knockout experiments were performed by impinging various exotic beams onto a beryllium target. Gamma-rays were measured in coincidence with the scattered heavy residue. SeGA detectors were arranged in two rings, one around 90° and one around 30° in the laboratory. Figure 2 shows the γ-ray spectra measured in the reaction ^{46}Ar(^{9}Be,^{45}Arγ).

5 Summary

Our first experiences with the use of highly segmented germanium detectors for in-beam spectroscopy of fast exotic beams have been very positive. The SeGA array has been successfully used for intermediate-energy Coulomb excitation experiments and nucleon-knockout experiments. The energy resolution of the reconstructed spectra is no longer dominated by the intrinsic detector resolution, but by kinematic broadening which is under the control of the experimentalist: Energy resolution can be traded off versus detection efficiency.

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