Eur. Phys. J. A **13**, 59–62 (2002)

THE EUROPEAN
PHYSICAL JOURNAL A

In-beam gamma-ray spectroscopy with exotic beams at the NSCL

T. Glasmacher[1,2], B.V. Pritychenko[1,2,a], P.D. Cottle[3], R.W. Ibbotson[1,b], K.W. Kemper[3], and H. Scheit[3,c]

[1] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI, 48824, USA
[2] Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA
[3] Department of Physics, Florida State University, Tallahassee, FL 32306, USA

Received: 1 May 2001

Abstract. Projectile fragmentation provides radioactive beams at intermediate velocities ($v/c = 0.3$–0.5) by physical means of fragment separation. With the development of position-sensitive photon detectors it has become possible to measure the energies and directions of photons emitted in-flight from such fast-moving exotic beams. This allows the reconstruction of the photons' energies emitted from an exotic projectile with high accuracy. It can be advantageous to employ photon detection in experiments with exotic beams since photons can traverse matter easily and their attenuation can be calculated. 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). Experimental success in this field is strongly correlated with the development of photon 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 in intermediate-energy heavy-ion inelastic scattering experiments, knockout reactions and fragmentation reactions. Here, we focus on experimental results for neutron-rich exotic nuclei in the $\pi(sd)$-shell. Measurements and detector developments carried out at the NSCL at Michigan State University during the last four years are discussed.

PACS. 27.30.+t $20 \leq A \leq 38$ – 25.70.Bc Elastic and quasielastic scattering – 25.70.De Coulomb excitation

Intermediate-energy Coulomb excitation allows the simultaneous measurements of the energy of excited bound states with respect to the ground state in exotic nuclei and of the Coulomb excitation cross-section to excite these states. The presence of γ-rays in a photon spectrum establishes the energy of the transition between two bound states in the nucleus experimentally. Photons emitted in-flight from the projectile can be easily distinguished by their Doppler-broadening from γ-rays originating in the target. In the event that only one γ-ray from the projectile is observed, its energy likely corresponds to a transition between the ground state and an excited state, thus establishing the energy of the excited state. The yield of γ-rays with a particular energy is a direct measure of the Coulomb excitation cross-section to the particular state. In addition, the conversion from γ-ray yield to γ-ray excitation cross-section is largely model independent (only the angular distribution of the observed γ-rays has to be calculated if it cannot be measured).

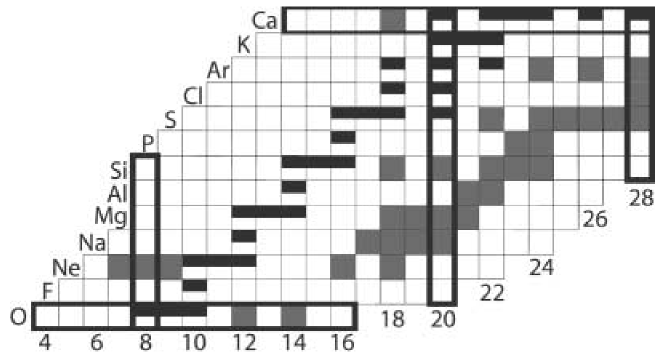

Fig. 1. Nuclei studied at the NSCL via intermediate-energy Coulomb excitation between 1996 and 2000 are indicated in grey.

The measured Coulomb-excitation cross-section is a direct function of the electromagnetic matrix elements $B(E\lambda)$ and $B(M\lambda)$. These matrix elements are directly related to the measured cross-sections through the theory of relativistic Coulomb excitation established by Winther

---

[a] *Present address*: Plumtree Software, Inc., 500 Sansome Street, San Francisco, CA 94111, USA.

[b] *Present address*: Brookhaven National Laboratory, Upton, NY 11973, USA.

[c] *Present address*: Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany.

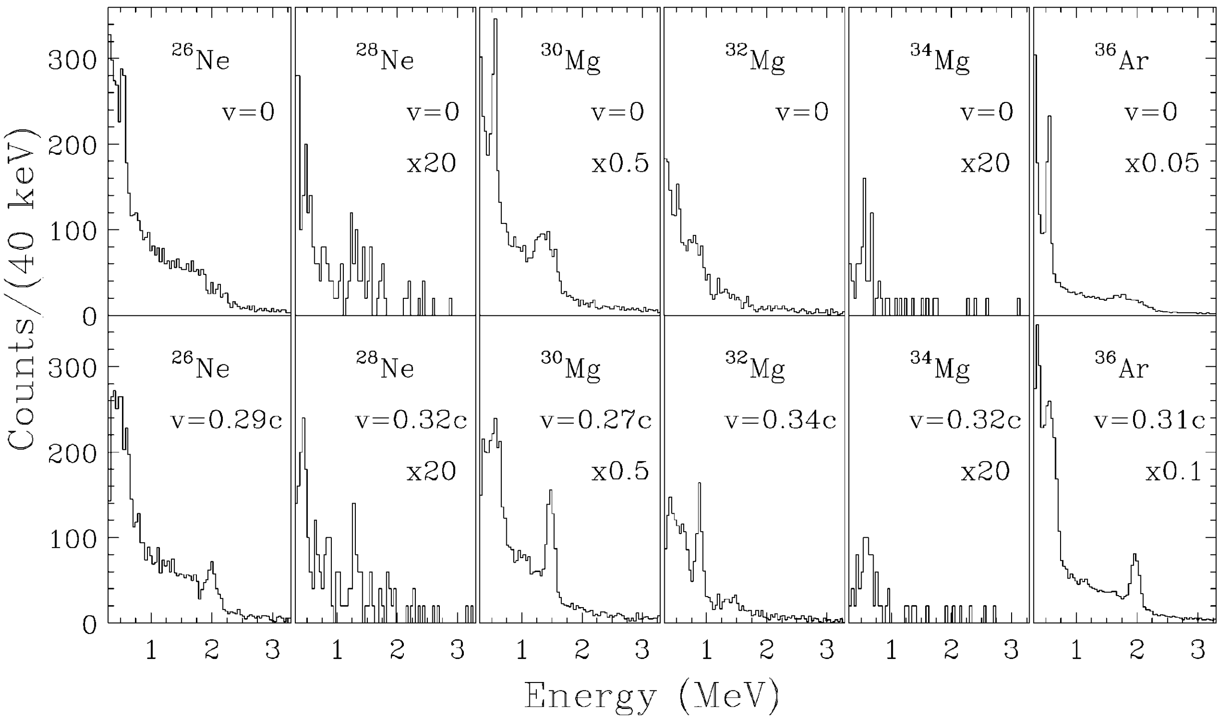

Fig. 2. Experimental γ-ray spectra for even-even isotopes in the laboratory frame (upper panel) and in the projectile frame (lower panel). The 547 keV ($7/2^+ \rightarrow$ g.s.) transition in the gold target is visible as a peak in the laboratory frame, while the $2^+ \rightarrow$ g.s. transitions in each projectile sharpen in the projectile frame.

and Alder [1]. Two basic nuclear structure properties of a nucleus are obtained in one measurement: the excitation energy of an excited state and the corresponding electromagnetic transition matrix element $B(\pi\lambda)$.

During the last four years intermediate-energy Coulomb excitation has been used at the NSCL to measure the properties of low-lying collective states in neutron-rich nuclei in the $\pi(sd)$-shell. The nuclei studied are indicated in fig. 1 and were produced by fragmentation of ^{40}Ar and ^{48}Ca beams with energies of 60–100 MeV/nucleon.

Gold foils with thicknesses of 200–700 mg/cm^2 were used as secondary targets. This choice of element was motivated by a desire to reduce the γ-ray background in the region of interest. The highest-energy γ-ray excited in intermediate-energy Coulomb excitation in gold is the 547 keV ($7/2^+ \rightarrow$ g.s.) transition which is lower in energy than the transitions excited in bismuth or in lead isotopes. The exotic beams slowed significantly in the thick secondary targets and the beam energies used in the analyses were the ones calculated for the middle of the target. In addition, the absorption of γ-rays in the secondary targets was taken into account in the determination of the excitation cross-sections. The exotic beams were identified prior to interaction with the secondary target by their time of flight relative to the cyclotron RF signal. The beam particles were stopped in a cylindrical fast/slow plastic phoswich detector located at zero degrees. The zero-degree detector subtended typical scattering angles of 0° to 2.5–3.0° in the laboratory. While the mass resolution of the

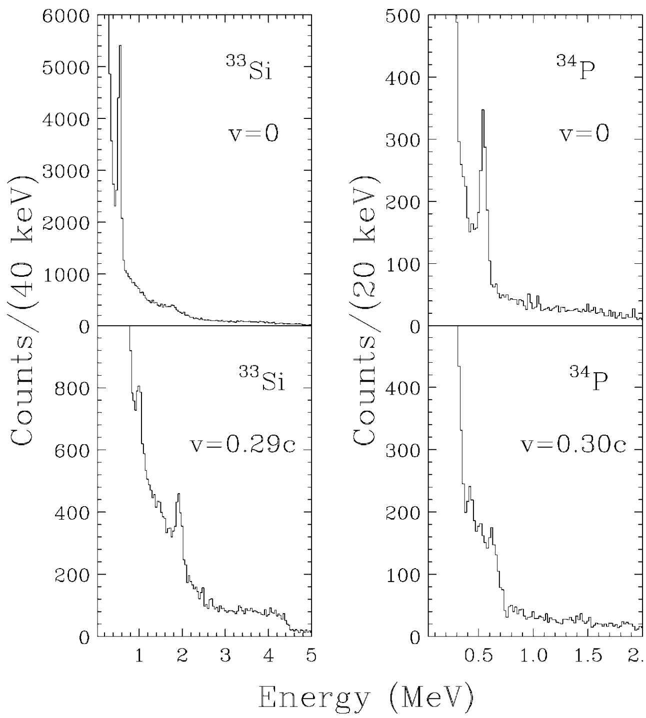

Fig. 3. Experimental γ-ray spectra for an even-odd (^{33}Si) and an odd-odd (^{34}P) isotope in the laboratory frame (upper panel) and in the projectile frame (lower panel).

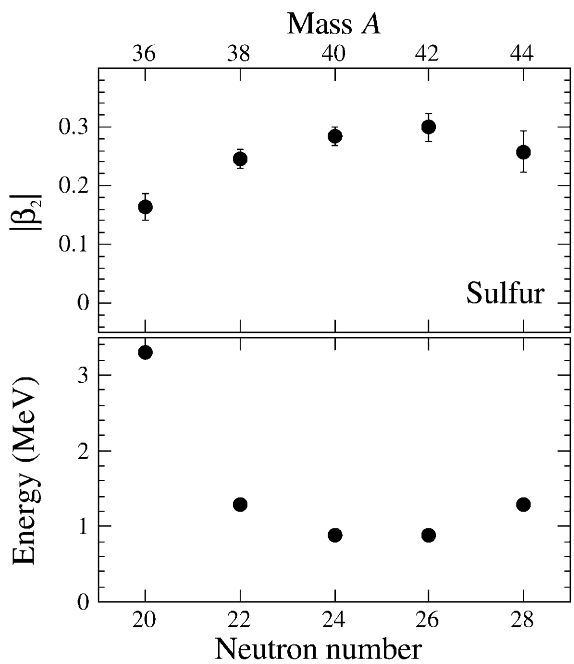

Fig. 4. Experimental values of the reduced quadrupole deformation parameter (assuming a rotational model) and the energies of the first excited states for the $N = 20$–28 sulfur isotopes.

zero degree detector was sufficient to eliminate fragmentation events and most nucleon-stripping reactions for the nuclei studied here, a plastic detector will be insufficent for heavier nuclei (for example ^{86}Kr fragments) we plan to study at the NSCL's Coupled Cyclotron Facility in the near future.

Photons were detected in coincidence with the zero-degree detector by the NSCL NaI(Tl) array [2]. Typical γ-ray spectra measured in coincidence with beam particles for even-even isotopes are shown in fig. 2 and for odd isotopes in fig. 3.

Our earlier experiments focused on a study of the $N = 28$ shell closure [3–5] which is weakened for ^{44}S as indicated by the decreased excitation energy of the first 2^+ state and the relatively large $B(E2\uparrow)$ value. Systematic trends of these two observables for sulfur isotopes are shown in fig. 4. These experiments were followed by studies of ^{11}Be [6] and ^{17}Ne [7]. Then our focus shifted towards the $N = 20$ magic number [8], nuclei close to the island of inversion [9,10] and the $N = 14$ nucleus ^{22}O [11] on the neutron-rich side and ^{38}Ca [12] and ^{18}Ne [13] on the neutron-deficient side of the valley of β-stability. The general physics issues addressed in these studies are the evolutions of magic numbers and nuclear shell structure with isospin. Detailed discussions can be found in the references given.

The level density for the light nuclei we studied is low and the excitation energies of low-lying collective states are relatively large. Thus the energy resolution achievable with the NaI(Tl) detector array is sufficient for even-even nuclei. However, when looking at spectra from odd nuclei it became apparent that a detector array with better energy resolution is needed for detailed studies of odd nuclei and certainly for heavier nuclei available at the NSCL's Coupled Cyclotron Facility in July of 2001. Since the intrinsic energy resolution of the NaI(Tl) detectors is the limiting factor in achieving better energy resolution, we started the design of a germanium detector array in 1997 making use of segmentation techniques which have only recently become available for large crystals [15–17]. In order to accurately reconstruct the first interaction point of the photons, we pursued a detector segmentation which will yield a position resolution of 1 cm without pulse shape analysis. A schematic of the segmentation of the 8 cm long and 7 cm diameter crystals is shown in fig. 5 [14]. Eighteen detectors were ordered from Eurisys Measures and as of Januay 2001, sixteen detectors have been received with the remaining two detectors expected soon.

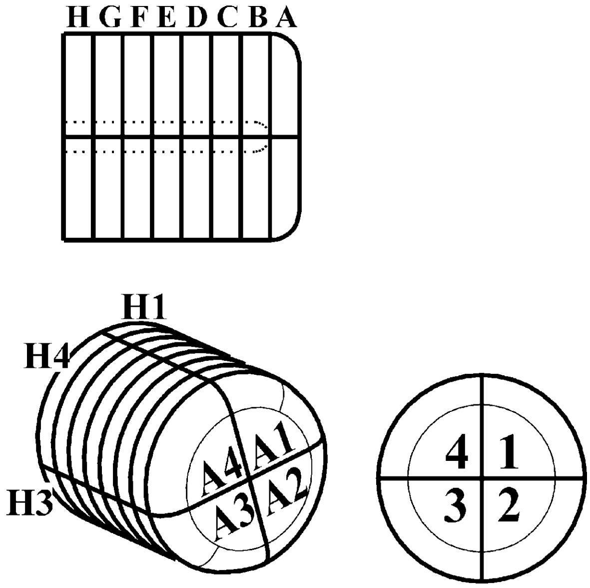

Fig. 5. Schematic segmentation for each crystal of the NSCL segmented germanium detector array [14].

This work has been supported by the U.S. National Science Foundation through grants PHY-9528844, PHY-9523974, PHY-9724299, PHY-9875122, and by the State of Florida.

References

1. A. Winther, K. Alder, Nucl. Phys. A **319**, 518 (1979).
2. H. Scheit, T. Glasmacher, R.W. Ibbotson, P.G. Thirolf, Nucl. Instrum. Methods A **422**, 124 (1999).
3. H. Scheit *et al.*, Phys. Rev. Lett. **77**, 3967 (1996).
4. T. Glasmacher *et al.*, Phys. Lett. B **395**, 163 (1997).
5. R.W. Ibbotson *et al.*, Phys. Rev. C **59**, 642 (1999).
6. M. Fauerbach *et al.*, Phys. Rev. C **56**, R1 (1997).
7. M. Chromik *et al.*, Phys. Rev. C **55**, 1676 (1997).
8. R.W. Ibbotson *et al.*, Phys. Rev. Lett. **80**, 2081 (1998).
9. B.V. Pritychenko *et al.*, Phys. Lett. B **461**, 322 (1999).
10. B.V. Pritychenko *et al.*, Phys. Rev. C **63**, 011305(R) (2001).
11. P. Thirolf *et al.*, Phys. Lett. B **485**, 16 (2001).
12. P.D. Cottle *et al.*, Phys. Rev. C **60**, 031301 (1999).

13. L.A. Riley *et al.*, Phys. Rev. C **62**, 034306 (2000).
14. W. Mueller *et al.*, Nucl. Instrum. Methods A **466**, 492 (2001).
15. J. Eberth *et al.*, Prog. Part. Nucl. Phys. **38**, 29 (1997).
16. K. Vetter *et al.*, Nucl. Instrum. Methods A **452**, 105 (2000).
17. K. Vetter *et al.*, Nucl. Instrum. Methods A **452**, 223 (2000).