Atomic–Charge-State Distributions of Fusion-Evaporation Residues and Nuclear Shape Changes at High Spin

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The average internal-conversion probabilities as a function of spin for continuum γ transitions are deduced from the energy dependence of the evaporation-residue atomic–charge-state distributions. Strongly enhanced internal-conversion probabilities are observed at high spin. The implications of these results for nuclear shapes at high spin are considered.

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The high-spin properties of nuclei with $64 \leq Z \leq 71$ and $82 \leq N \leq 90$ have been the subject of intense theoretical and experimental study recently.[1] The interest in this region was first spurred by the discovery of an island of high-spin yrast isomers[2] and the complimentary observation[3] of doubly closed-shell behavior of ${}^{146}_{64}Gd_{82}$. Detailed cranked shell-model calculations have now been performed[4] throughout this region which predict the existence of the observed isomeric behavior and a wealth of new and as yet largely unverified high-spin phenomena. In particular, the equilibrium configurations of these nuclei along the yrast line are predicted to evolve with spin through a number of more or less sharp transitions through prolate, triaxial, and oblate shapes. The critical spin values at which these transitions occur and the exact sequence of shapes are strong functions of neutron number but are only weakly dependent on proton number.

For the most part, the critical spin values at which the predicted shape changes occur are beyond the range accessible to discrete γ-ray spectroscopy, and evidence for this new and unusual behavior must therefore be sought in the continuum γ decay of high-spin evaporation residues produced in heavy-ion reactions. In this Letter we will be concerned with the prolate-to-oblate transition which is consistently predicted for nuclei with $N \sim 88$ and 90. In particular, for ${}^{156}_{68}Er_{88}$ and ${}^{158}_{68}Er_{90}$ the predicted transition spins are $J = 45\hbar$ and $35\hbar$, respectively.

The experimental manifestation of a prolate-to-oblate shape transition at high spin has been discussed by Peker *et al.*[5] Briefly, in the prolate region, stretched electric quadrupole transitions, $J \to J-2$, are anticipated at an average energy

$$\langle E_\gamma \rangle = (\hbar/\mathcal{I})(2J-1), \tag{1}$$

where $\mathcal{I}$ is the effective moment of inertia. Above the oblate transition, collective rotation about an axis perpendicular to the symmetry axis leads to high-K rotational bands in the yrast region with $J = K, K+1, K+2, \ldots$. Deexcitations along these bands will proceed mainly via stretched $M1$ radiation since the crossover $E2$ radiation is inhibited for large K.[6] The prolate-to-oblate transition is expected to proceed with negligible change in the effective moment of inertia. Hence, the average γ-ray transition energy in the oblate region should be

$$\langle E_\gamma \rangle = (\hbar^2/\mathcal{I})J, \tag{2}$$

or one-half the energy of the neighboring prolate region.

In reporting the first results from the new generation of very large γ-ray multiplicity filters, Jääskeläinen *et al.*[7] recently reported evidence for the predicted prolate-to-oblate transition in ${}^{158}_{70}Yb_{88}$ and ${}^{160}_{70}Yb_{90}$. Their evidence was based on an observed change in $\langle E_\gamma \rangle$ at high multiplicity along with an indication of a reduction in the anisotropy of the γ-ray angular distribution. These observations provide some evidence for the predicted change from dominant $E2$ to dominant $M1$ radiation following a prolate-to-oblate shape transition at high spin. An unambiguous identification of the new radiation, however, requires γ-ray angular-correlation or internal-conversion data as a function of spin. We note that conventional measurements of continuum internal-conversion probabilities or γ-ray angular correlations are normally performed as a function of γ-ray transition energy. Such measurements would be less useful in the present case where $\langle E_\gamma \rangle$ is not monotonic with J.

In the present work we deduce internal-conversion probabilities of continuum γ transitions from the atomic–charge-state distributions of evaporation residues. The ${}^{158}Er$ and ${}^{156}Er$ products studied here were produced with (^{32}S,xn) and (^{34}S,xn) reactions on targets of ^{126,128,130}Te at several bombarding energies between $E_{\rm lab}=120$ and 170 MeV. Reaction products were separated by mass and charge with the University of Rochester's recoil-mass spectrometer.

The spectrometer has been described in some detail by Cormier and Stwertka.[8] Here it suffices to note that electric and magnetic dipole fields are arranged to produce a velocity focus in first and second order at the focal plane. As a consequence > 75% of the entire evaporation-residue energy spectrum is accepted. The resulting mass dispersion (actually mass/charge) is ~ 20 mm/% with a resolution of 1/400 to 1/700 which provides clear separation of all masses and atomic charge states. A sample mass spectrum at atomic charge state $Q=15$ is shown for the ^{32}S+^{130}Te reaction in Fig. 1.

At a given bombarding energy the distribution of charge states of evaporation residues is determined by atomic processes which occur within the target and internally converted γ transitions which occur in vacuum after the product has recoiled from the target. The two contributions can be precisely separated with use of the second thin carbon foil mounted at sufficient distance downstream from the target. In our measurements a second carbon foil (5–10 μg/cm^2) was mounted ~ 15 cm after the target (flight time ~ 20 nsec) and could be inserted and removed under computer control.

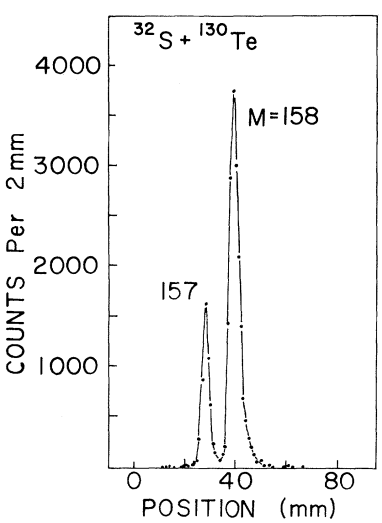

FIG. 1. Typical mass spectrum observed in a position-sensitive gas detector at the focal plane of the spectrometer. The mass resolution in this case is $M/\Delta M \simeq 425$.

With the second foil in the "in" position, the equilibrium atomic-charge-state distribution, which we designate as $\sigma_{\rm in}=\sigma_e(Q)$, is restored. With the second foil removed we measure

$$\sigma_{\rm out}=(1-P)\sigma_e(Q)+P\sigma_N(Q), \tag{3}$$

where $\sigma_N(Q)$ is the charge-state distribution resulting from both atomic processes in the target and internal conversion. $P=P(E)$ is the probability that at least one internal conversion occurs in the γ cascade at a bombarding energy E.

Figure 2(a) shows sample charge-state distributions for ^{158}Er ions produced in the reaction ^{130}Te(^{32}S,$4n$) at $E_{\rm lab}$ (^{32}S)$=130$ MeV measured with ($\sigma_{\rm in}$) and without ($\sigma_{\rm out}$) the second foil.

A precise determination of the total internal-conversion probability P is obtained when a direct measurement of the ratio $\sigma_{\rm out}/\sigma_{\rm in}$ is made. Figure 2(b) shows a sample direct measurement of the ratio $\sigma_{\rm out}/\sigma_{\rm in}$. The asymptotic value of this

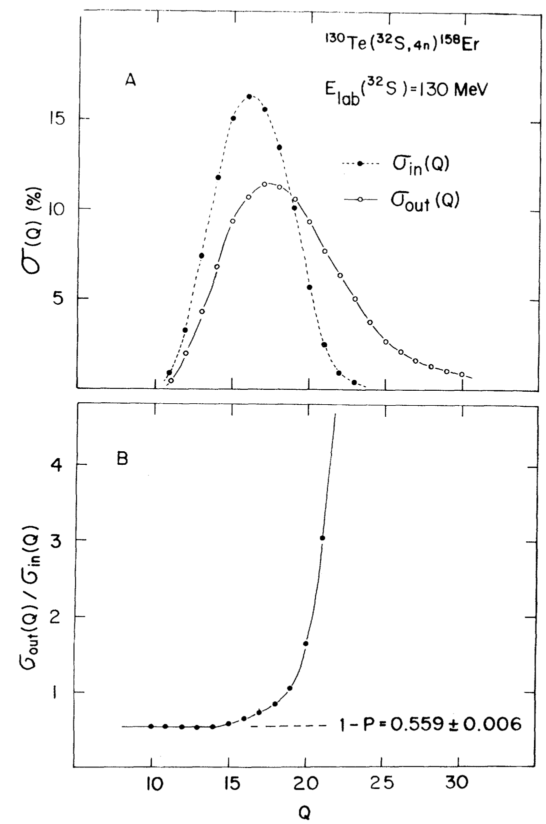

FIG. 2. (a) Sample atomic-charge-state distributions for ^{158}Er ions measured with and without a second carbon foil. (b) The ratio $\sigma_{\rm out}(Q)/\sigma_{\rm in}(Q)$ for the data shown in (a). The asymptotic value of this ratio at low Q is $1-P$.

ratio at low Q is just $1-P$ as is clear from Eq. (3). With this method we find that P can be extracted directly from the experimental data with an internal error which is consistent with counting statistics (< 1%).

To deduce internal-conversion probabilities for specific slices of the continuum we observe the change dP in P which occurs for a change dE in bombarding energy. The quantity dP is just the total internal-conversion probability for the additional γ transitions added to the top of the γ cascade at high excitation energy.

To relate these numbers to theoretical expectations it is most convenient to form dP/dJ where dJ is the increase in the average spin of an evaporation residue corresponding to the energy change dE:

$$\frac{dP}{dJ}=\frac{dP}{dE}\frac{dE}{dJ}. \tag{4}$$

The factor dE/dJ is of course model dependent, but it is nearly constant[9] over the range of our experiment and thus has no impact on our subsequent analysis. We have obtained the factor dE/dJ using two methods which give essentially identical results. First, within the framework of a sum-rule model,[10] the experimental evaporation-residue cross sections define the mean spin in a particular evaporation product at each bombarding energy E. Within this model, then, the experimental product cross sections determine dE/dJ. Alternatively, we have fitted statistical-model calculations to our experimental product excitation functions and thus predict the entire spin distribution for each product. As expected, this method predicts virtually identical mean product spins J as the sum-rule model, but has the additional advantage that a more realistic width for the spin distribution is predicted. The reactions used in this work have been chosen to yield the minimum-width spin distribution for the products of interest. A value of < $6\hbar$ is typical.

Figures 3(a) and 3(b) show our results for dP/dJ for ^{156}Er and ^{158}Er, respectively, plotted versus the mean product spin J. The solid lines are the theoretical results for pure $E2$ and $M1$ radiation using γ-ray transition energies given by Eqs. (1) (for $E2$) and (2) (for $M1$). In these calculations the experimental effective moment of inertia[11] has been used up to $J \lesssim 38\hbar$ matched smoothly to a constant value $2\mathcal{J}/\hbar^2 = 140\ \text{MeV}^{-1}$ at higher spin.

Our results support numerous previous measurements[12] which demonstrate virtually pure $E2$ deexcitation of these and neighboring nuclei up to

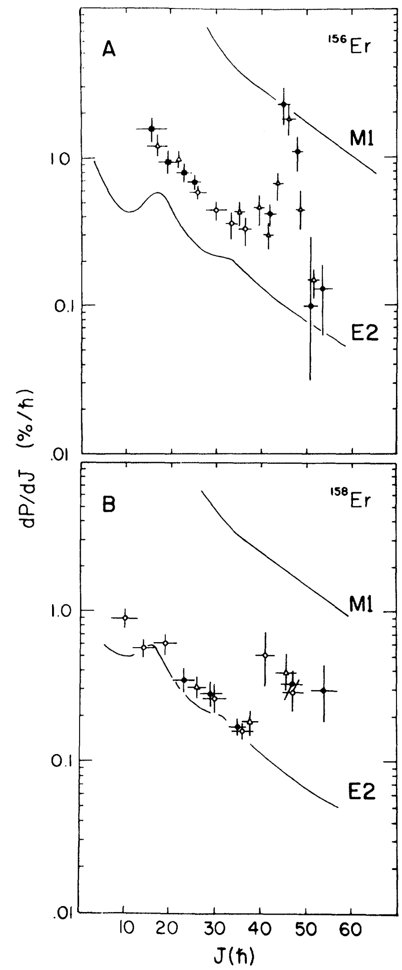

FIG. 3. Experimental dP/dJ vs J for ^{156}Er and ^{158}Er. The solid curves are theoretical results for pure $E2$ and $M1$ decay along the experimental yrast line.

modest spins. It is perhaps worth noting that even the ^{156}Er case at say $J \simeq 30\hbar$ is consistent with > 90% $E2$ radiation.

At the higher spins, however, we observe a sudden increase in dP/dJ which breaks this trend. The results for ^{156}Er are most striking in that dP/dJ rises quickly to a value consistent with virtually pure $M1$ radiation followed shortly thereafter by a rapid decrease to values consistent with pure $E2$ radiation. For ^{158}Er, on the other hand, we observe a rise in dP/dJ to values consistent with 20% to 40% $M1$ radiation where it remains to the highest spins reached in this measurement.

The large increase in internal-conversion probability at high J admits two interpretations: either a change in average γ-ray multipolarity toward increased $M1$ competition as has been predicted by cranked shell-model calculations, or a very large change in nuclear deformation. This latter possibility produces a dramatic increase in the effective moment of inertia with a consequent reduction in the average γ-ray transition energy.

Recent results from the Oak Ridge National Laboratory spin spectrometer mentioned earlier[7] combined with the present results support an interpretation involving enhanced $M1$ radiation, but neither their experiment nor ours is sufficiently definitive to completely rule out some contribution from major deformation changes.

The sudden fall in dP/dJ for ^{156}Er at the highest spins implies a second structural change for this nucleus. This behavior is qualitatively consistent with the cranked shell-model calculations for this nucleus in which the oblate shape is predicted to exist over a narrow spin interval and give way to triaxial shapes at slightly higher spins.[13,14]

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[1]See, for example, Proceedings of Nobel Symposium 50, Phys. Scr. 24 (1981).

[2]J. Pederson *et al.*, Phys. Rev. Lett. 39, 990 (1977).

[3]P. Kleinheinz *et al.*, Z. Phys. A 290, 279 (1979).

[4]See, for example, C. G. Anderson *et al.*, Phys. Scr. 24, 226 (1981).

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[8]T. M. Cormier and P. M. Stwertka, Nucl. Instrum. Methods 184, 423 (1981); T. M. Cormier *et al.*, to be published.

[9]dE_{lab}/dJ varies from 0.71 MeV/$\hbar$ to 0.91 MeV/$\hbar$ across the energy range of this work.

[10]R. S. Simon *et al.*, Nucl. Phys. A290, 253 (1977).

[11]I. Y. Lee *et al.*, Phys. Rev. Lett. 38, 1454 (1977).

[12]See, for example, the following review: R. M. Diamond and F. S. Stephens, Annu. Rev. Nucl. Sci. 30, 85–157 (1980).

[13]The striking behavior observed here in the internal-conversion probability of ^{156}Er closely parallels the evolution of the γ-decay spectra of the isotone ^{158}Yb reported in Ref. 7.

[14]X-ray multiplicity measurements which support these results have been reported. P. Aguer *et al.*, in Proceedings of the International Winter Meeting of Nuclear Physics, Bormio, 1982 (to be published).