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# Island of High-Spin Isomers near $N = 82$

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Experiments aimed at testing for the existence of yrast traps are reported. A search for delayed $\gamma$ radiation of lifetimes longer than $\sim 10$ ns and of high multiplicity has been performed by producing more than 100 compound nuclei between Ba and Pb in bombardments with $^{40}Ar$, $^{50}Ti$, and $^{65}Cu$ projectiles. An island of high-spin isomers is found to exist in the region $64 \lesssim Z \lesssim 71$ and $N \lesssim 82$.

Interest in the structure of nuclei at very high angular momentum has been stimulated by the growing availability of heavy-ion beams. Bohr and Mottelson[1] proposed some time ago that one manifestation of special structure effects in nuclei with high spin could be the occurrence of yrast traps. At high angular momenta, some nuclei may become oblate and are expected to carry angular momentum most efficiently not by collective rotation, but rather by successive alignment of particle spins along the symmetry axis. The yrast states will, on the average, have a rotationallike dependence of energy on spin with a mean effective moment of inertia equal to that of a rigid body rotating about the oblate symmetry axis. However, deviations from the mean, enhanced by shell effects, may cause such large irregularities in the yrast sequence of energies that yrast isomers can occur. In addition, since transition probabilities between such states are determined by single-particle matrix elements, isomers may occur by virtue of selection rules for single-particle transitions.

A number of groups have performed detailed

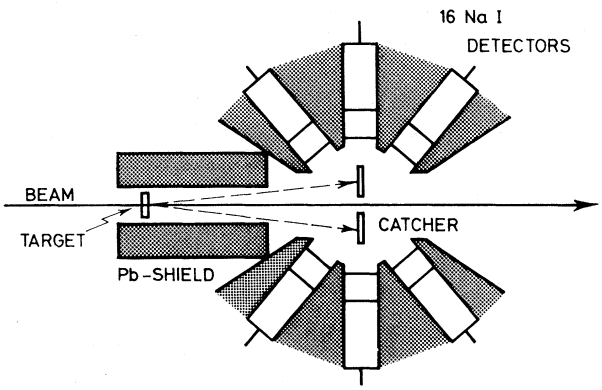


FIG. 1. Schematic diagram of recoil catcher and sixteen-element multiplicity filter apparatus used in search for high-spin isomers.

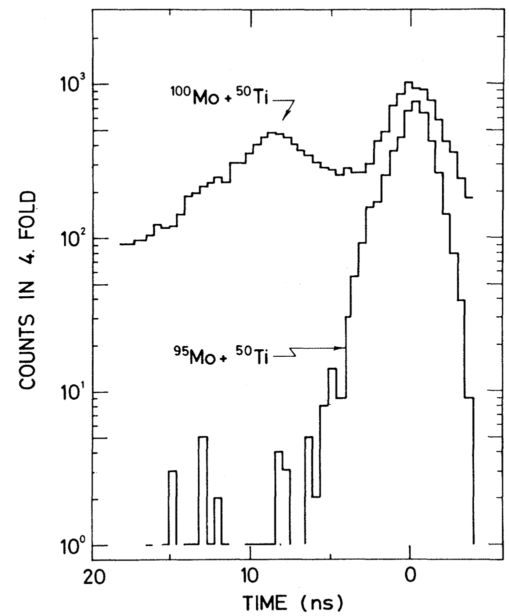


FIG. 2. Time spectra of fourfold events for 230-MeV $^{50}Ti$ projectiles on $^{100}Mo$ and $^{95}Mo$ targets.

theoretical studies of the equilibrium shape of the nucleus as a function of angular momentum and have examined the sequence of yrast states at high spins in an attempt to predict the most likely location of yrast isomers.[2-5]

In the present Letter we report on a systematic search for delayed $\gamma$ cascades of high multiplicity in nuclei in the region between Ba and Pb. The apparatus is shown schematically in Fig. 1. It consists of a $\gamma$-ray multiplicity filter of sixteen 5-cm×5-cm NaI scintillation detectors operated in coincidence with 16-ns resolving time and arranged around a catcher foil designed to collect recoiling evaporation residues from the heavy-ion reaction. The target is mounted 15 cm upstream in a cylindrical lead shield. The isomeric nucleus must thus survive a flight of approximately 10-ns duration before reaching the catcher foil. Each NaI detector is embedded in a conical lead shield which serves to minimize Compton scattering between detectors and acts as a collimator. The volume viewed by the detection system is thus confined to a sphere of ~4-cm diameter centered at the catcher foil. The beam is allowed to pass through a 1-cm-diam hole in the center of a 12-mg/cm$^2$ $^{208}Pb$ catcher foil. The evaporation residues are effectively collected due to multiple scattering in the target. For a typical target thickness of 4 mg/cm$^2$ the half-width[6] of the distribution is $\theta_{1/2} \sim 3.5°$, resulting in ~60% collection efficiency. In contrast the beam particles have $\theta_{1/2} \sim 0.4°$.

The detection arrangement discriminates effectively against multiple $\gamma$-ray cascades emitted from the target as opposed to those from the catcher. The higher the number of coincidences the greater the discrimination factor. For a $\gamma$ cascade of multiplicity 20 triggering four counters simultaneously the discrimination factor is 500.

Beams of $^{40}Ar$, $^{50}Ti$, and $^{65}Cu$ of 4.7–5.2 MeV/amu from the Unilac at Gesellschaft für Schwerionenforschung, Darmstadt were used for the survey. The time profile of the beam is characterized by ~6-ms macropulses occurring at 20-ms intervals and 1–2-ns micropulses with a 37-ns period. Accordingly, two time-to-amplitude converters operating in the nanosecond and millisecond regions were used to measure the delay of high-multiplicity events relative to the beam bursts. The sensitivity of the combined system for detecting delayed $\gamma$ cascades with a multiplicity of 10 or higher is typically of the order of 10 $\mu$b for half-lives between 10 ns and 5 ms and 1 $\mu$b for half-lives between 5 ms and 10 min. As an example, Fig. 2 shows the time distributions of fourfold coincidence events in the nanosecond range. The two cases shown, for $^{50}Ti$ projectiles on $^{95}Mo$ and $^{100}Mo$ targets, illustrate the striking difference between a typical target where no evidence is seen for delayed $\gamma$ rays ($^{95}Mo$) and another target ($^{100}Mo$) where a positive result is clearly indicated.

By removing the catcher foil and allowing the recoils to decay in flight as they pass through the sensitive detection volume it is possible to obtain a rough estimate of the half-life by compari-

TABLE I. Isomers observed in nanosecond time range for compound nuclei with $56 \leq Z \leq 82$ produced by $^{40}$Ar, $^{50}$Ti, and $^{65}$Cu projectiles.

| Compound nucleus | Projectile ($E_{lab}$ MeV)[a] | Multiplicity[b] | $T_{1/2}$ (ns)[c] |
|---|---|---|---|
| $^{150}$Gd [d] | $^{50}$Ti (209) | $9 \pm 2$ | 1.5 |
| $^{150}$Gd [d] | $^{50}$Ti (178) | $11 \pm 2$ | 100 |
| $^{150}$Gd [e] | $^{40}$Ar(165) | $13 \pm 2$ | 100 |
| $^{149}$Tb | $^{40}$Ar(169) | ... | ... |
| $^{152}$Dy | $^{50}$Ti (225) | $15 \pm 2$ | 700 |
| $^{154}$Dy [d] | $^{50}$Ti (225) | $13 \pm 2$ | 400 |
| $^{156}$Dy | $^{40}$Ar(193) | $12 \pm 2$ | 30 |
| $^{153}$Ho [d] | $^{50}$Ti (212) | $15 \pm 2$ | 40 |
| $^{154}$Er [d] | $^{50}$Ti (215) | $18 \pm 2$ | 250 |
| $^{156}$Er | $^{50}$Ti (215) | $15 \pm 2$ | 80 |
| $^{156}$Er | $^{40}$Ar(193) | $17 \pm 2$ | ... |
| $^{158}$Er | $^{40}$Ar(173) | $8 \pm 2$ | 50 |
| $^{160}$Er | $^{40}$Ar(193) | $11 \pm 3$ | ... |
| $^{155}$Tm | $^{65}$Cu(288) | $15 \pm 2$ | 30 |
| $^{156}$Tm | $^{65}$Cu(280) | $15 \pm 2$ | 40 |
| $^{157}$Tm [d] | $^{50}$Ti (215) | $15 \pm 2$ | 50 |
| $^{159}$Tm | $^{50}$Ti (215) | $12 \pm 3$ | ... |
| $^{161}$Tm | $^{65}$Cu(275) | $13 \pm 2$ | 40 |
| $^{158}$Yb | $^{65}$Cu(275) | $14 \pm 2$ | 35 |
| $^{160}$Yb | $^{50}$Ti (230) | $10 \pm 2$ | ... |
| $^{157}$Lu | $^{65}$Cu(275) | $12 \pm 2$ | 50 |
| $^{159}$Lu | $^{65}$Cu(275) | $12 \pm 2$ | 50 |
| $^{161}$Lu | $^{65}$Cu(275) | $8 \pm 4$ | ... |

[a] Mean projectile energy in target.

[b] Derived from 4:5- and 5:6-fold ratios assuming a sharp multiplicity (Ref. 7).

[c] Estimate based on yield ratios with and without catcher foil. Approximate uncertainty $\pm 50\%$.

[d] Ge(Li) $\gamma$-ray spectrum has been obtained. For the $^{150}$Gd compound nucleus the two isomers $T_{1/2} \cong 1.5$ ns and $T_{1/2} \cong 100$ ns belong to $^{146}$Gd and $^{147}$Gd, respectively. In the other cases no assignment has been possible because little is known about the lower-spin sequence of yrast transitions.

[e] Estimated cross section for formation of the long-lived isomer, which belongs to $^{147}$Gd, is $5 \pm 3$ mb as compared to 50 mb for the total $^{110}$Pd($^{40}$Ar, $3n$)$^{147}$Gd cross section (Ref. 8).

son of count rates with and without catcher foil. In the case $^{100}$Mo + $^{50}$Ti, the shape of the time distribution, Fig. 2, is explained by the presence of both a short-lived (1.5 ns) and a long-lived component (> 50 ns). This has been confirmed by excitation-function measurements and by recording $\gamma$-ray spectra in a Ge(Li) detector which replaced one of the sixteen NaI detectors. The delayed spectra show discrete lines in contrast to the more continuumlike prompt spectra.

More than a hundred different target-projectile combinations were studied which should result in the formation of at least 200 residual nuclei of high spin. Twenty different compound systems gave clear evidence of high-spin isomerism with multiplicities between 8 and 18 (Table I).

The spin of the isomers cannot be determined directly from the measured multiplicities because the decay pattern and multipolarities involved are unknown and because the occurrence of intervening delays along a decay chain will yield an apparent multiplicity lower than the actual number of $\gamma$ rays in the cascade. It is also possible that some of the twenty compound systems listed in Table I feed the same isomer, but in those five neighboring cases where Ge(Li) spectra were recorded each spectrum was distinctly different from the others.

The results of the search are summarized in Fig. 3 where the compound systems giving strong evidence for high-spin isomers are indicated as filled squares. Because of neutron evaporation the actual isomeric nuclei are likely to have three to five neutrons less. Little ambiguity exists in deciding between negative and positive cases, Fig. 2 being typical of the actual differences encountered. In the lower-mass region a negative result is more likely to rule out the existence of a high-spin isomer than a similar result in the region approaching lead. In this region fission tends to exhaust the cross section for higher spin values as shown by Newton *et al.*[10] Therefore, negative results do not in the same way exclude the existence of high-spin isomers in this upper region.

The strong clustering of high-spin isomers in the lower region, $64 \lesssim Z \lesssim 71$ and $82 \lesssim N \lesssim 88$, is a truly conspicuous feature which we consider the main result of the search. This observation qualitatively agrees with predictions by the Lund-Warsaw group,[3,11] and also with the more detailed calculations discussed in Ref. 5.

However, the residual nuclei reached in most of the cases where we report positive results are not expected to depart significantly from sphericity until quite high angular momenta are attained, when highly deformed oblate minima may develop.[5] Alternatively, since the isomers lie near the $N = 82$ shell, it is possible they may be explained in terms of spherical particle-hole configurations, similar to those already observed above the $Z = 82$ closed shell.[12] The distinction between these possibilities must await detailed spectroscopic measurements.

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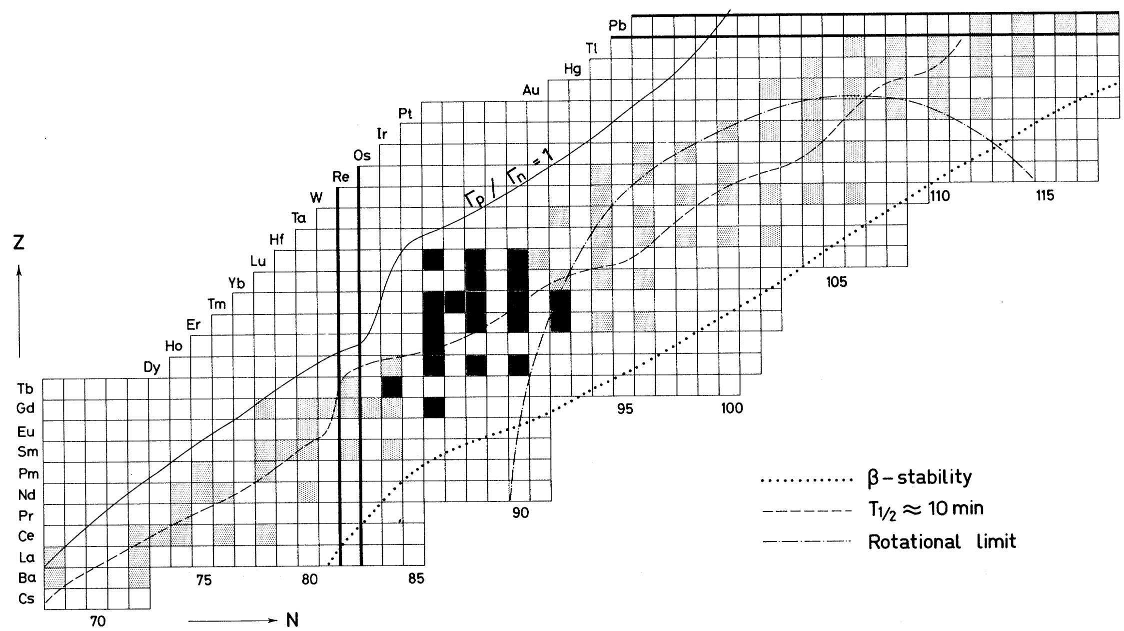


FIG. 3. Region of the nuclear chart searched for delayed high-multiplicity $\gamma$-ray events. Compound systems formed via $^{40}Ar$, $^{50}Ti$, and $^{65}Cu$ reactions are indicated as shaded squares. Cases where positive results were obtained are shown as filled squares. The final nuclei are likely to have 3–5 neutrons less. The approximate borderline of deformed nuclei has been defined by $E_{4+}/E_{2+} \approx 3.0$. The $\Gamma_p/\Gamma_n = 1$ line is taken from Ref. 9.

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