Gamma Radiation from the $N = Z$ Nucleus $^{80}_{40}Zr_{40}$

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(Received 1 June 1987)

The very neutron-deficient isotope ^{80}Zr was produced in the reaction $^{24}Mg(^{58}Ni,2n)^{80}Zr$ at 180 MeV with a cross section of $\sigma = 10 \pm 5$ μb and was identified with the Daresbury Recoil Separator. The observation reflects a fiftyfold increase in sensitivity for in-beam spectroscopy of exotic nuclei. Coincidence measurements between the isolated isotope and prompt gamma radiation allowed the identification of decays from low-lying states at $E = 290$ and 828 keV which indicate that ^{80}Zr has an extremely large quadrupole deformation of $\beta_2 \approx 0.4$.

PACS numbers: 21.10.Re, 23.20.−g, 27.50.+e

The domain of nuclides accessible for spectroscopic study has increased drastically during the last two decades. New accelerators and sensitive detector systems have permitted access to regions of isotopes which lie far from the valley of stability. A broader picture of low-energy nuclear behavior has emerged which has stimulated a host of theoretical attempts to generalize nuclear models to encompass all bound systems.

The study of nuclei with $N \approx Z$ and $A \approx 80$ is representative of this progress. Pioneering work with heavy-ion beams[1,2] indicated substantial deformation, and more recent experiments have shown the region to contain some of the most deformed nuclei known.[3-5] Rapid changes of shape have been observed, both with varying neutron or proton number, and with rotational frequency.[2,6] These changes have promoted much theoretical interest, and calculations[7-15] have revealed a delicate interplay between classical collective effects and quantum shell corrections. The shell effects are especially distinct in nuclei with $N = Z$, where both neutrons and protons act together to deform the nucleus to a common shape which is most bound. Thus an experimental determination of low-lying nuclear shapes can be directly related to gaps in the single-particle level sequence predicted from theory.

In this Letter we report on an experiment designed to study excited states in $^{80}_{40}Zr_{40}$. The observation of this nucleus represents a major advance in the study of $T_z = 0$ nuclei; previously, the heaviest $N = Z$ isotope studied in-beam was $^{64}_{32}Ge$ (see Ooi *et al.*[16] and Gorres *et al.*[17]) which can be produced in reactions with a cross section of $\sigma \approx 500$ μb. The observation of excited states in $^{80}_{40}Zr_{40}$, which has 20% fewer neutrons than its nearest stable isotope $^{90}_{40}Zr_{50}$, required an increase of sensitivity for in-beam spectroscopic measurements of a factor of 50 which now presents the possibility of studying exotic isotopes produced at the level of a few microbarns. This advance was achieved by the detection of prompt gamma radiation in coincidence with recoiling nuclei detected in the recently commissioned Daresbury recoil separator.

The inverse compound-nuclear reaction $^{24}Mg(^{58}Ni, 2n)^{80}Zr$ at 190 MeV was used to populate ^{80}Zr. At this energy, 10% of the fusion reaction cross section proceeds via two-nucleon evaporation, which is dominated by two-proton emission forming ^{80}Sr with a cross section of 44 ± 4 mb and proton plus neutron evaporation forming ^{80}Y with a cross section of 2 ± 1 mb. The inverse reaction has a high center-of-mass recoil velocity, $v/c = 5.5\%$, which maximizes the focusing of residues near 0° and improves the conditions for attaining good Z resolution. A target of 500 $\mu g/cm^2$ was found to produce the maximum yield of residues within the velocity acceptance ($\pm 3\%$) of the separator. To compensate for the thin target, beams of up to 20 particle nanoamperes of ^{58}Ni were accelerated to 190 MeV with the Nuclear Structure Facility at Daresbury. The optimum beam energy was selected by the direct measurement of absolute γ-ray yield curves and through use of compound-nuclear evaporation codes.

The recoil separator and its performance are described by James[18] and in a forthcoming paper. It is a 0° electromagnetic separator with a solid angle of 10 msr. It consists of a double Wien filter to reject noninteracting beam particles to a level of $\approx 10^{-7}$ and allows selection of the velocities of the reaction residues to be studied. Residues of suitable velocity were deflected by a 50° dipole magnet onto a focal plane which was dispersed in mass but not in energy. The ions were detected at the focal plane by a carbon foil and position-sensitive channel plate detector before being stopped in a split-anode ion chamber similar to the one described by James *et al.*[19] The transport and focusing of the beam of residues was determined by three quadrupole triplets and two sextupoles.

γ rays were detected in an array of fourteen bismuth germanate shielded, intrinsic germanium detectors. The detectors were situated in rings at 143°, 117°, and 101° to the beam line. Coincidences between any detected γ ray and an event on the focal plane, or between any pair of γ rays, were recorded on magnetic tape together with timing and position information. A total of 1.5 million recoil γ events were accumulated.

Mass resolution was measured to be better than 1 part in 250 for each charge state, and thus clean separation of mass was straightforward. Two masses were dominant on the focal plane: $A=79$ and 80, both with charge state $q=24^+$. Of these, the $A=79$ recoils were five times stronger than those with $A=80$. To prevent excessive counting rate in the gas counter, a mask was placed between the position counter and ion chamber. This admitted ions with A/q of 3.333 ± 0.015. Most events involved ions with $A=80$, $q=24^+$, but a few $A=77$, $q=23^+$ ions were recorded. The latter events were from ^{77}Rb (αp evaporation) and ^{77}Sr (αn evaporation) and could be easily separated as they had lower energies and energy losses in the ion chamber. Less than 0.1% of the ion-chamber events were associated with Zr ions, and therefore Z selection was critical for the success of the experiment. Full Z separation in the ion chamber was not achieved although the energy-loss signal ΔE was Z sensitive. After a small numerical manipulation to make the energy-loss signal energy independent, a two-dimensional spectrum of energy loss against γ-ray energy was formed. A series of γ-ray spectra was then produced corresponding to increasing energy loss ΔE_1. The intensities of photo peaks in these spectra are shown in Fig. 1. Z dependence is clear and peaks known to belong to ^{80}Sr and ^{80}Y were partially separated. In the region where ^{80}Zr events were anticipated, tails from Sr and Y events were found which are due to Rutherford scattering from carbon ions in the isobutane gas of the ionization chamber. An energy-loss selection was made which produced the optimum spectrum of Zr events and spectra of transitions known to belong to ^{80}Sr and ^{80}Y (obtained

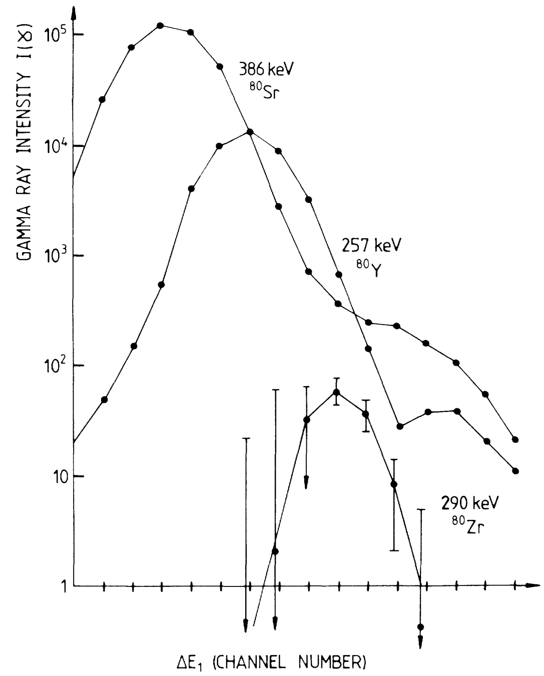

FIG. 1. Distribution of energy-loss signals ΔE_1 in the ion chamber for ^{80}Sr, ^{80}Y, and ^{80}Zr ions. The distributions were obtained by measurement of the intensity of coincident γ-ray photopeaks in spectra gated by energy loss.

from different energy-loss cuts) were carefully subtracted. About 4% of the optimum ^{80}Y and 0.1% of the optimum ^{80}Sr data were subtracted. Figure 2 shows the resulting spectrum of events associated with ^{80}Zr.

Two transitions at 289.9 ± 0.3 keV and 538.0 ± 0.3 keV are clearly seen. Their energy-loss characteristics were extracted. The 289.9-keV line is a doublet with an ^{80}Y transition of 289.5 ± 0.2 keV, but a comparison of the energy-loss curve of the doublet with the shape of a curve for cleanly extracted ^{80}Y transitions permitted a decomposition. The ratio of the intensities of the 289-keV Zr/Y doublet to several strong ^{80}Y lines was measured and found to remain constant for low energy losses but increase by a factor of 3 in the region where the ^{80}Zr contribution was strongest. The component due to ^{80}Zr is shown in Fig. 1.

The data displayed in Fig. 1 can be used to calculate the production cross section for ^{80}Zr using our absolute measurement for the production cross section for ^{80}Sr of 44 ± 4 mb and assuming that the 386- and 290-keV transitions reflect the total decay strength to the respective ground states of ^{80}Sr and ^{80}Zr. The intensities of the peaks can be converted into cross sections after corrections are made for γ-ray detection efficiency and the transport efficiency of the separator. The former is trivial, but the latter requires more care. It can be measured for the strong ^{80}Sr and ^{80}Y channels by direct

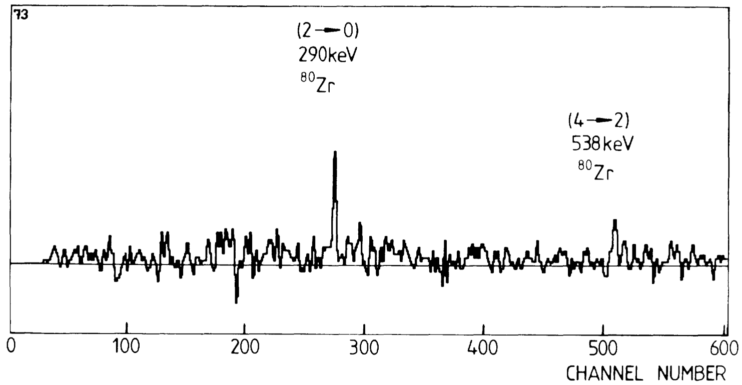

FIG. 2. γ-ray spectrum of ^{80}Zr after subtraction of transitions known to belong to ^{80}Y and ^{80}Sr.

comparison of photo peaks in the γ-ray singles and recoil-γ coincident spectra. However, this was not possible for ^{80}Zr because of its small cross section. A computer simulation of particle evaporation, scattering in the target, and charge-state fractionation was used together with the experimental measurements to predict the efficiency of transport of Zr ions. A final cross section of 10 ± 5 μb was calculated, the large error mainly reflecting uncertainties in the calculation of the transport efficiency for Zr ions.

The data were also sorted into a series of matrices corresponding to different γ-ray detector angles. The 289-keV ^{80}Zr transition appeared to have a similar angular distribution to the strong $E2$ yrast cascade known in ^{80}Sr with $60\%\pm10\%$ of events in the 143° ring of detectors. However, low statistics prevented any rigorous assignment of spin. We assume that the transitions we have seen correspond to the normal $J^\pi=0^+\leftarrow2^+\leftarrow4^+\ldots$ yrast cascade of γ rays seen in deformed even-even nuclei. Clearly more spectroscopic measurements are required, but under this assumption several observations can be made.

The low-lying first excited state indicates large deformation. A phenomenological relationship due to Grodzins[20] has been established between $E(2^+)$ and the quadrupole deformation, β_2, which indicates $\beta_2=0.39$ for ^{80}Zr. We have tested the reliability of this estimate for the light Sr isotopes where lifetime measurements[21] permit its validity to be investigated. Under the assumption of axial deformation and uniform charge distribution, the deformations extracted from the lifetime data on $^{78-86}$Sr agree within experimental errors ($\approx5\%$) with the Grodzins estimate.

The ratio of the excitation energy of first and second excited states, $E(4)/E(2)$, provides a test of the axial assumption. For ^{80}Zr we obtain $E(4)/E(2)=2.86$, whereas for a perfectly axial shape the ratio should be 3.33. Clearly, some nonaxial behavior is involved, either through triaxiality or softness to triaxial deformation.

These observations may be compared with a host of potential-energy–surface calculations. These theoretical estimates combine the classical collective nuclear properties of the liquid-drop model with quantum corrections due to shell effects obtained by the Strutinsky formalism.[22] Several early potential-energy–surface calculations[7,8] predicted soft, oblate shapes, but more recent estimates[9-12,15] indicate that there is great sensitivity of the most-bound shape to the choice of model parameters. For example, Moller and Nix[9] used a folded Yukawa potential for the quantum correction and considered axially symmetric shapes. They predicted $\epsilon_2=0.39$ and $\epsilon_4=0.09$ ($\epsilon_2=0.95\beta_2$). Heyde *et al.*[11] predicted a near-spherical shape with a harmonic-oscillator potential, while Nazarewicz *et al.*,[12] using a Woods-Saxon potential, predicted $\beta_2=0.38$ and an axially symmetric but γ-soft shape. The great sensitivity of the predicted shape to model parameters has been discussed by Heyde[11] and Galeriu,[15] who both underline the close link between experiment and theory in this region.

Within the framework of the interacting boson model and related $N_\pi N_\nu$ scheme,[23,24] ^{80}Zr and ^{76,78}Sr lie equally far from the major shell closures at nucleon numbers 28 and 50. Consequently, the spectrum of excited states should be identical. The ratios $E(4)/E(2)$ are indeed similar, being 2.81 and 2.86 for ^{78}Sr and ^{80}Zr, respectively. However, the model implies that the restricted valence space which limits the number of active protons or neutrons to less than eleven is not sufficient to allow quadrupole residual interactions to polarize the nuclei into axially symmetric shapes.

Two groups have attempted fully microscopic Hartree-Fock calculations in this region.[13,14] Large prolate deformations are predicted in both cases. Bonche *et al.*[13] predict that ^{78}Sr and ^{80}Zr should be γ soft but that ^{76}Sr should be an axially symmetric rotor, the only one in this region. Clearly, an experimental determination of the low-lying states of ^{76}Sr will be of interest in resolving this difference between interacting-boson–approximation and Hartree-Fock calculations.

In conclusion, γ-ray transitions between states in the

$N=Z$ nucleus ^{80}Zr have been observed. The production cross section for ^{80}Zr was measured to be 10 ± 5 μb which represents a fiftyfold increase of sensitivity for in-beam spectroscopy. This large increase in sensitivity offers the possibility not only of our observing many new isotopes far from stability, but also of a much more detailed examination of less exotic nuclei. $^{80}_{40}$Zr appears to be one of the most deformed nuclei known in nature, with a quadrupole deformation $\beta_2\approx0.4$.

The authors would like to thank Professor H. Morinaga of the University of Munich for inspiring this work and rewarding its completion with champagne. This work was supported by grants from the Science and Engineering Research Council (United Kingdom).

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