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Levels in the Transitional Nuclei ^{106}Ru and ^{108}Ru

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Low-lying levels of ^{106}Ru and ^{108}Ru associated with the β^- decay of 36-sec ^{106}Tc and 5-sec ^{108}Tc have been investigated by measurement of γ singles and γ-γ coincidence spectra. The activities have been produced by thermal-neutron-induced fission of ^{235}U and ^{239}Pu using automated chemical separations of the technetium fraction from the fission product mixture. Excitation energies and γ-ray branching ratios indicate a transitional character between the limits of the vibrational and the rotational models for ^{106}Ru and ^{108}Ru, with some evidence for an asymmetric deformation.

A new region of stable quadrupole deformation should exist for neutron-rich nuclei in the mass region $A \approx 100$, as has been pointed out in the theoretical studies by Arseniev, Sobiczewski, and Soloviev[1] and other groups.[2-5] Compared with the well-known deformed nuclei in the rare-earth region, however, nuclei around $A \approx 100$ should be softer towards γ and β deformations. This follows from the calculated potential energy surfaces: Frequently, two minima occur, one for a prolate and one for an oblate shape, having only slightly different energies and separated by a flat barrier that can be easily passed via nonaxial symmetric γ deformations. Unfortunately, the single-particle-model parameters are not known well enough in this region to give reliable predictions for the favored nuclear shapes.[2] Another complication is that in soft nuclei the lowering of the γ band is always accompanied by a partial destruction of the rotational structure.[3] Apparently the rotation-vibration interactions in soft γ-dependent potentials are effective to such an extent that pure rotational bands cannot occur.

From the experimental point of view, studies of neutron-rich nuclei around $A \approx 100$ are hampered by the fact that the most interesting nuclei have rather short half-lives and that nuclear fission of heavy elements is the only way to produce them.

Experimental evidence for the occurrence of extremely large deformations in this region has been reported by Zicha *et al.*[6] In a study of the decay properties of ^{106}Tc and ^{108}Tc, these authors assigned γ-ray cascades of 94, 219, and 343 keV, and of 98.5 and 233 keV to the ground-state rotational bands of ^{106}Ru and ^{108}Ru, respectively, and deduced a deformation parameter $\beta = 0.55$ from the half-life of 2.7 nsec of the supposed 2^+ state in ^{106}Ru at 94 keV. However, simultaneous studies on ^{106}Tc and ^{108}Tc in our laboratory gave no evidence for these γ-ray cascades. Our data indicate a transitional character between the limits of the vibrational and rotational models for ^{106}Ru and ^{108}Ru, with some evidence for an asymmetric deformation.

In the present investigation, heavy isotopes of technetium were produced by thermal-neutron-induced fission of ^{235}U and ^{239}Pu, as well as by fission of ^{238}U with 14-MeV neutrons. Irradiations with thermal neutrons were performed in a pneumatic tube system of the Mainz Triga reactor which was generally operated in the pulse mode. Bombardments with intense 14-MeV neutron beams were carried out at the Mainz Cockcroft-Walton accelerator.

After irradiation, the technetium isotopes were quickly isolated by automated radiochemical procedures based on solvent-extraction techniques as described elsewhere in more detail.[7] In the fastest procedure, the counting samples were available within 7.5 sec after the end of irradiation. High-resolution γ- and x-ray detectors were used in combination with a 16384-channel memory and magnetic tape recorders to obtain singles γ- and x-ray spectra. γ-ray energies were measured to ± 0.2 keV for strong and ± 0.5 keV for weak γ rays. In several experiments, an x-ray detector (0.5 keV full width at half maximum at 14.4 keV) was applied simultaneously with the γ-ray detector to check via characteristic x rays the purity of the samples used for γ-ray spectroscopy. In addition γ-γ coincidence measurements were performed in the two-dimensional mode with a 4096×4096 channel matrix and recorded event by event on magnetic tape. The resolving time of the coincidence setup was about 25 nsec. In most cases, the results of 50 to 100 runs were combined to improve the statistical quality of the spectra.

A γ-ray spectrum of short-lived technetium iso-

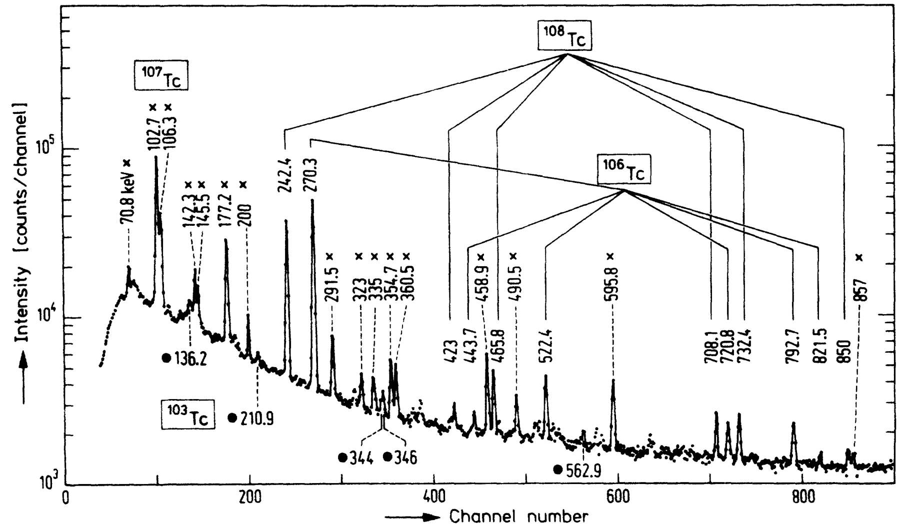

FIG. 1. γ-ray spectrum of short-lived technetium isotopes from thermal-neutron-induced fission of ^{239}Pu.

topes covering the energy region up to 1.0 MeV is shown in Fig. 1. In this case, the technetium isotopes were produced by fission of ^{239}Pu and separated from their precursors and from other fission products at 1.5 sec after irradiation. The samples were counted for 60 sec beginning 7.5 sec after irradiation. Contributions of longer-lived isotopes were subtracted using the spectrum recorded during the following 60-sec counting interval. A number of γ rays of the 36-sec ^{106}Tc, the 21-sec ^{107}Tc, and the 5.0-sec ^{108}Tc can be seen in Fig. 1 together with weak peaks from the decay of 50-sec ^{103}Tc. The mass assignments of these activities are discussed elsewhere.[7] Briefly, genetic relationships of the 21- and 5-sec components with the well-known nuclides 4.2-min ^{107}Ru and 4.5-min ^{108}Ru, respectively, were experimentally established, and the energies of the strongest γ rays of the 36- and 5-sec components were found to agree with the energies of the first 2^+ states in ^{106}Ru[8,9] and ^{108}Ru.[8]

Zicha *et al.*[6] assigned strong γ rays of 94-, 219-, and 344-keV energy, and only these γ rays, to ^{106}Tc. Figure 1 shows no γ-ray peaks at 94 and 219 keV. Only a 344-keV γ-ray peak is present as a shoulder on the 347-keV peak of ^{103}Tc but it also decays with the half-life of ^{103}Tc. In addition, there is no evidence in Fig. 1 for γ-ray peaks at 98.5 and 233 keV attributed to the decay of an 8-sec ^{108}Tc.[6] An extensive search for these γ rays in technetium samples separated at various times after the irradiation of ^{235}U and ^{238}U also produced negative results. On the other hand, there is evidence that peaks at 94, 219, and 344 keV may be caused by contamination of the technetium samples with noble gas nuclides and their daughter products.[7]

The systematic trends in the low-lying states of even-even ruthenium nuclei are shown in Fig. 2. The level schemes of ^{106}Ru and ^{108}Ru are based on our γ-singles and γ-γ coincidence measurements. The levels of ^{106}Ru are in agreement with recent results from the ^{104}Ru$(t,p)^{106}$Ru reaction.[9] Furthermore, the energies of the first 2^+ and the 4^+ states of ^{106}Ru and ^{108}Ru agree with those obtained in a study of prompt γ rays emitted in the spontaneous fission of ^{252}Cf[8] which also revealed the data on ^{110}Ru and ^{112}Ru given in Fig. 2. The data on ^{100}Ru, ^{102}Ru, and ^{104}Ru were obtained in decay studies of the respective technetium isotopes.[10]

According to Fig. 2, the energies of the first 2^+ states decrease with increasing neutron number asymptotically towards an energy of 240 keV for

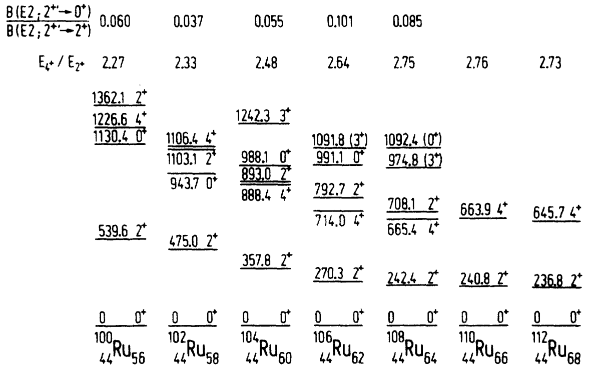

FIG. 2. Low-lying levels of even ruthenium nuclei. The data for ^{106,108}Ru are from this work, for ^{100,102,104}Ru from Ref. 10, and for ^{110,112}Ru from Ref. 8.

the very neutron-rich isotopes. Furthermore, the ratios E_{4^+}/E_{2^+} of the energies of the first 4^+ and 2^+ levels increase towards a constant value of about 2.75, far below the value of 3.3 expected for a good rotator. The energies of the second 2^+ states also decrease with increasing mass number, as well as those of possible 3^+ states which might be interpreted as the first members of γ or quasi-γ bands.

Of particular interest is the behavior of the excited 0^+ states. While in the lighter ruthenium isotopes the first excited 0^+ state can be identified with the third member of the two-phonon triplet, it crosses the other two members in ^{104}Ru and shifts more and more away in the heavier isotopes. In ^{106}Ru and ^{108}Ru the energy spread of the triplet would be even larger than the phonon energy itself and the centroid would occur at an energy more than three times that of the first 2^+ state. Hence, neither the rotational nor the vibrational model leads to a satisfying interpretation of the levels in ^{106}Ru and ^{108}Ru, as has already been pointed out for ^{106}Ru by Casten *et al.*[9]

Of somewhat more success is a comparison with the predictions of the asymmetric rotator model of Davydov and Fillipov.[11] A calculation of the 3^+ level energies of ^{104,106,108}Ru in the framework of this model leads to good agreements with the observed energies. The 4^+ levels, however, are expected to occur slightly higher in energy than the second 2^+ states, while the experimental results show the 4^+ level slightly below. On the other hand, the observed $B(E2)$ ratios for the transitions from the second 2^+ states into the ground states and first 2^+ states given in Fig. 2 agree with the predictions of the Davydov model, 0.11 for ^{106}Ru and ^{108}Ru.

Although a complete interpretation of the level structure of ^{106}Ru and ^{108}Ru seems not to be possible at present, the fairly good success of the Davydov model gives some evidence for the occurrence of asymmetric nuclear shapes in the region around $A \approx 100$ as a possible consequence of the expected softness of these nuclei towards γ deformation. A similar situation seems to occur in adjacent even-Z elements, as indicated by work underway in this laboratory.

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