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Study of fission process and neutron-rich nuclei

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Prompt triple γ coincidence studies of the nuclei produced in the spontaneous fission of ^{252}Cf were carried out at Gammasphere. The relative yield matrix for the Ba-Mo and Ba-α-Zr charge splits was determined using an improved analysis. An upper limit for the second mode of 0.5 % is found for the binary case, while the ternary case shows evidence of a strong second mode. Half-lives of several states in neutron-rich nuclei were measured by using a new time-gated $\gamma-\gamma-\gamma$ coincidence technique. A large deformation of β=0.47 was observed in ^{104}Zr using this method. New band structures were found in several odd-A Y, Nb, Tc, and Rh nuclei. These nuclei show a smooth evolution from axial symmetry in Y to maximum triaxiality in Rh. Particle plus triaxial rotor calculations have been made for these odd-A nuclei. The gamma band staggering in ^{108,110,112}Ru will be discussed.

1. Search for second mode in binary and α- ternary fission[1].

Observations of prompt gamma rays produced in the spontaneous fission (SF) of ^{252}Cf have shown evidence for a "hot" fission mode (also called second mode) in the Ba-Mo channel. The evidence for this mode is observed as a higher relative intensity for the 7-10 neutron channels. In recent years, more complete data on the levels and relative intensities in Ba and Mo isotopes has become available. Because fission spectra are often complex and the events of interest are rare compared with other channels, this type of analysis is difficult and prone to errors caused by random coincidences. Therefore an improved method which avoids many of these complexities was developed in order to determine the relative intensity of the second mode in both the binary and ternary cases.

The number of prompt neutrons emitted in a fission event can be determined by finding the mass and atomic number of the fragments produced in the event. The atomic number is inferred from the known γ- transitions in the isotope. For example, if the fission

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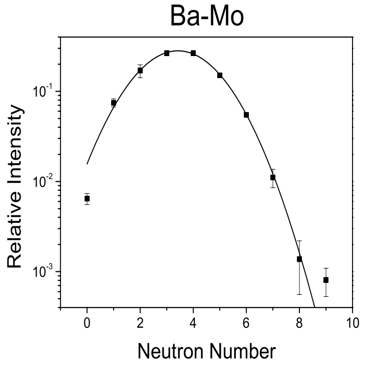

Figure 1. Ba - Mo relative yield curve.

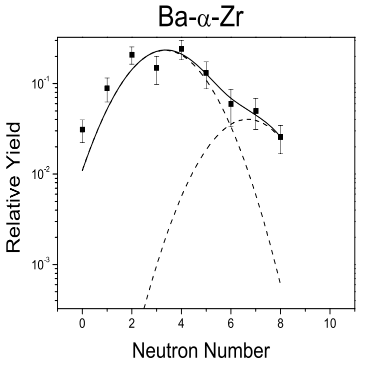

Figure 2. Ba - α - Zr relative yield curve.

fragments of ^{252}Cf are determined to be ^{144}Ba and ^{103}Mo, then five neutrons must have been emitted. The relative intensity of the possible neutron channels can be found by double gating on a pair of transitions in the heavy fragment, then measuring the intensities of all the transitions to the ground state in its partners. This must be done for each isotope of the heavy partner. The yield as a function of neutrons emitted can then be determined by summing the contributions of all possible pairs. However, for this analysis, the known values for the relative intensities of secondary transitions feeding the ground state were used in order to avoid random contamination in the gating process.

The data for this analysis comes from two experiments using the Gammasphere detector array located at Lawrence Berkeley National Laboratory (LBNL). A 62μCi source was placed between two iron foils in order to stop fission fragments. The source was placed in a 7.62 cm polyethylene ball and placed at the center of Gammasphere. A total of 5.7$\times$10^{11} $\gamma-\gamma-\gamma$ events were recorded. The analysis was carried out using the Radware software package. The ternary data were also taken at LBNL. A 35μCi source was placed between two Al foils. Eight ΔE-E detectors were placed around the source to detect light charged particles (LCPs). A total of 9.0$\times$10^5 LCP-γ- γ events were recorded and an α -gated γ-γ matrix was constructed.

The binary channels Xe-Ru and Ba-Mo were analyzed, as well as the Ba-α-Zr, Mo-α-Xe, and Te-α-Ru ternary channels. The relative neutron yields for Ba-Mo and Ba-α-Zr as a function of neutron number are shown in Figs. 1 and 2. In the binary case, an upper limit for the intensity of the second mode was set at 0.5 %. An increased neutron distribution width of 3.8 neutrons was seen for the ternary case. However, if the widths and positions of the peaks are held constant, then a relative intensity of 17.0 % is found for the second mode in the ternary case, as shown from the fit in Fig. 2.

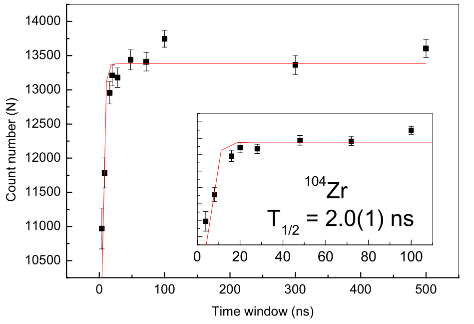

Figure 3. Normalized count N vs. coincidence time window in ^{104}Zr.

2. New technique for half-life determination[2]

We have developed a new technique using the time gated triple γ coincidence spectra in order to measure half-lives on the ns scale. This method takes advantage of the fact that the normalized triple γ coincidence counts of two prompt cascades with similar transition energies are similar. Therefore, transition energy dependent effects such as time-walks, time-jitters, amplitude-walks, and possible timing fluctuations of Ge detectors that contribute to the width of the time window are taken into consideration by comparing prompt and delayed cascades with similar transition energies. Also, it is observed that the real triple γ coincidence counts in the prompt cascades change systematically with the change of the coincidence time-window and three transition energies. The half-lives

Table 1
Measured half-lives and deformations in ^{104}Zr, ^{106}Mo and ^{148}Ce.

Nucleus	Half-lives (ns)	B(E2) (e^2b^2)	β_2(exp.)	β_2(Theory)
^{104}Zr	2.0(3)	0.40(6)	0.47(7)	0.45,0.43
^{106}Mo	1.2(2)	0.29(4)	0.36(7)	
^{148}Ce	0.9(3)	0.45(12)	0.27(7)	

of the states are determined by fitting the normalized counts with the radioactive growth equation. One example is shown in Fig. 3. Half-lives of several states found with this new technique are shown in Table 1. The half-lives of the 2^+ states in ^{104}Zr and ^{106}Mo are measured as 2.0(3) and 1.2(2) ns, respectively. The B(E2; $2^+ \rightarrow 0^+$) (e^2b^2) values and quadrupole deformations (β_2) are 0.40(6) (e^2b^2) and 0.47(7) for ^{104}Zr and 0.29(4) (e^2b^2) and 0.36(7) for ^{106}Mo. Except for ^{102}Sr, ^{104}Zr has the most deformed 2^+ state among medium and heavy nuclei. This large deformation for ^{104}Zr is in agreement with Hartree-Fock-Bogoliubov calculations[3,4]. In general, this method can be used to measure ns

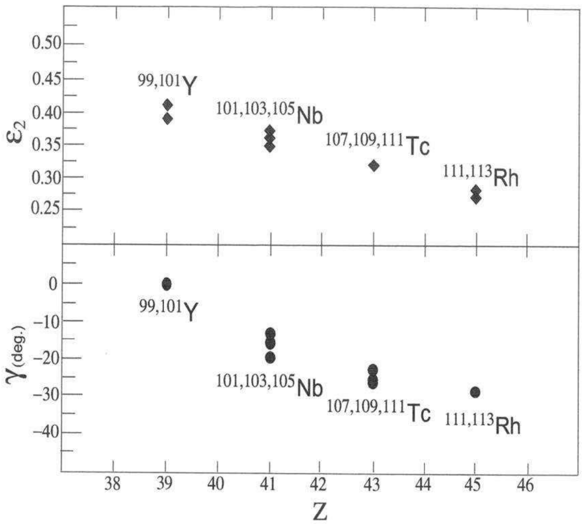

Figure 4. Quadrupole deformations and γ values in several isotopes.

half-lives in any experiment with a prompt cascade and a delayed cascade with similar energies.

3. Shape transition from axial symmetry to triaxiality

Studies of shape transitions and shape coexistence in neutron-rich nuclei with A≈100 have long been of major importance[5]. Large quadrupole deformations, the onset of superdeformed ground states and identical bands, shape evolutions, and shape coexistence were observed in the even-even Sr(Z=38), Zr(Z=40), and Mo(Z=42) region. Evidence for triaxiality was reported in Mo and Ru nuclei[6]. The levels of these neutron-rich nuclei were investigated by measuring the prompt γ-rays emitted in the SF of ^{252}Cf[5].

Evidence of triaxiality was observed in Tc (Z=43) and Rh (Z=45) isotopes[7,8]. A shape transition from axially-symmetric to triaxial deformation in odd-Z nuclei of this region is of particular interest. New level schemes[5] of odd-Z ^{99,101}Y (Z=39) and ^{101,105}Nb (Z=41) are established from these measurements. It was found that the quadrupole deformations of the N = 60 (and N=62) isotones with Z = 39 - 45 follow a similar trend in the neighboring even-even neutron-rich nuclei of Z = 38-42. The very small signature splitting and delay of band crossing observed for Y and Nb isotopes are in pronounced contrast to the results in Tc and Rh isotopes.

An anti-correlation of quadrupole deformation and triaxiality is seen in nuclei with Z ranging from 39 to 45 as shown in Fig. 4. One may conclude that, in A≈100 neutron-rich nuclei, triaxial shape is prevalent for the bands based on a one-quasiparticle $g_{9/2}$ proton

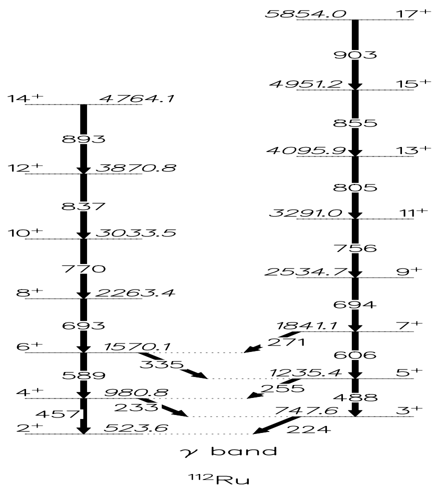

Figure 5. γ band in ^{112}Ru.

state in the region with Z>41. The $g_{9/2}$ proton and $h_{11/2}$ neutron orbitals are involved and their interplay results in rich structure characteristic of various nuclear shapes including triaxiality. So far not much is known about the odd-Z nuclei in this region. New high spin level schemes of ^{105,107,109}Tc (Z = 43) and ^{110,111,112,113}Rh (Z = 45) are proposed [7,8]. Bands built on various proton orbitals, including K = 1/2 intruder orbitals, are observed and band crossings related to $h_{11/2}$ neutron-pair breaking are identified

Triaxial-rotor-plus-particle model calculations performed with $\beta_2 = 0.32$ and γ = -22.5^o on the prolate side of maximum triaxiality yielded the best reproduction of the excitation energies, signature splitting, and branching ratios of the Tc isotopes. This model also gave the best fit to the Rh isotopes near maximum triaxiality with $\beta_2 = 0.28$, γ= -28^o, and β_2= 0.27, γ= -28^o for ^{111,113}Rh, respectively.

4. Gamma band staggering

One of the early surprises for the Bohr-Mottelson model of deformed nuclei was that the predicted branching ratios from the levels in β- and γ- vibrational bands to the ground bands in deformed nuclei were found not to follow the first order rules of Alaga et al.[9]. The Rotation-Vibration Model (RVM) of Faessler and Greiner gave better agreement with the experimental ratios than the Alaga rules. The Generalized Collective Model (GCM) and RVM were subsequently applied to understand the observed gamma- vibrational bands in ^{108,110,112}Ru, which were first observed only up to 9^+_γ. The ground state bands were better described by GCM than RVM for ^{108}Ru. For the gamma - bands, the RVM fits gave unexpected level inversions for spin above 10^+ in ^{110,112}Ru, but the RVM and GCM gave reasonable fits up to 8^+. The GCM gave the same pattern of fits above 5^+

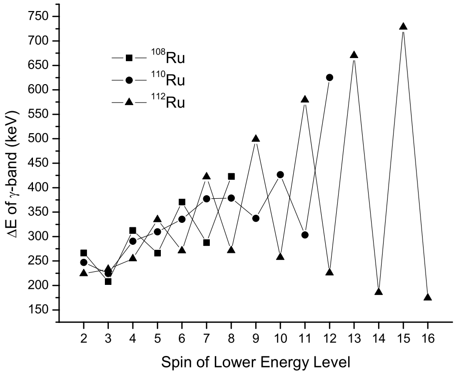

Figure 6. Energy staggering of levels in γ bands of ^{108,110,112}Ru.

for ^{108,110,112}Ru where the even spin states were pushed up nearer to the odd spin states, especially at high spins. We have recently extended the gamma-vibrational bands in $^{108-112}$Ru; up to 17^+ in ^{112}Ru [10]. The γ band in ^{112}Ru is shown in Fig. 5. The even spin energy states in ^{112}Ru are pushed up nearer to the odd spin states as the GCM predicts; also seen in ^{108}Ru. However, while the energy staggering in ^{112}Ru is in agreement with what is expected for a near rigid triaxial rotor, ^{108}Ru has staggering exactly the opposite of that predicted by GCM for higher spins, as well as opposite to the experimental value in ^{112}Ru as shown in Fig. 6. This is a surprising new result that requires more detailed analysis.

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