Simple method for measuring the deformation and level of a fission isomer

V. A. Shigin

(Submitted 27 February 1989; resubmitted 5 April 1989)
Pis'ma Zh. Eksp. Teor.Fiz. **49**, No. 10, 536–538 (25 May 1989)

The emission of a charged particle from an excited nucleus which accompanies the formation of a fission isomer might be utilized to determine the deformation and level of the isomer.

As the elongation of a nucleus increases, the Coulomb barrier for the α particles which are emitted from the "spout" of the nucleus becomes lower, and there is a significant increase in λ, the total probability for α decay of the nucleus. According to Ref. 1, in the case of a quadrupole deformation of the nucleus, β_2, this increase is by a factor

$$S = \lambda/\lambda_0 = [\int_0^1 \exp\{8{,}5\beta_2 P_2(\cos\theta)\}\, d(\cos\theta)]^2 \ldots \qquad (1)$$

which for fission isomers ($\beta_2 \approx 0.7$) would be ~ 1000 in comparison with α decay from the ground state ($\beta_2 \approx 0.25$). Despite the large magnitude of this effect, it has yet to be observed. The reason is that the search has been carried out for isomers in the ground state, for which the absolute α yields are exceedingly small.

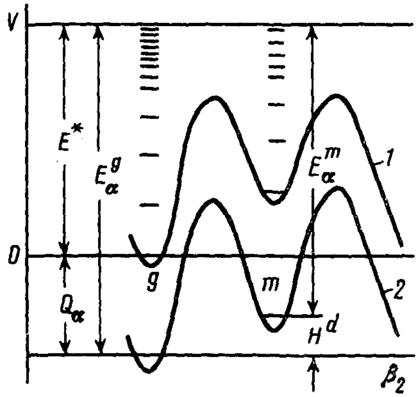

FIG. 1. The potential energy V versus the deformation β_2 for (1) the compound nucleus and (2) the daughter nucleus (schematic).

We suggest searching for excited states of the isomer ($E_6 \approx 10$–20 MeV). The latter arise in an excited compound nucleus which has a fission isomer. The number of these states divided by the number of states of the compound nucleus at statistical equilibrium is $K \approx \rho^m/\rho^g$—the ratio of the state densities in the isomer and ground potential wells of the compound nucleus at accessible energies (Fig. 1). States of both types decay. Among the competing decays from these two states, which differ in deformation, there may be α decays to isomer and ground wells of the daughter nucleus, which would occur without significant changes in the shape of the nucleus (so they would have approximately equal branching ratios for the formation of decaying systems from the α particle and the daughter nucleus).

The ratio of the cross sections of these reactions involving α decay would be $(\sigma_\alpha^m/\sigma_\alpha^g) = K(\Gamma_\alpha^m/\Sigma\Gamma_i^m)(\Sigma\Gamma_i^g/\Gamma_\alpha^g)$, where Γ is the gamma-width, and the superscripts m and g mean the states in the isomer and ground wells. All types of decays in one type of well or the other are summed. The energies which are accessible for each type of decay are shown in Fig. 1.We can use the approximation

$$\frac{\sigma_\alpha^m}{\sigma_\alpha^g} \approx \frac{\rho^m}{\rho^g}\,\frac{p_\alpha^m}{p_\alpha^g}\,\frac{\rho_n^g + \rho_f^g}{\rho_n^m + \rho_f^m} \quad \ldots \tag{2}$$

Here P_α is the penetrability of the barrier for α decay, and n and f specify neutron emission and fission.

The value of ρ in this formula could be calculated from, for example, Fermi's formula $\rho \propto \exp(2\sqrt{aU})$, ($\alpha$ is the level-density parameter, and U is the excitation energy) and from the fission barriers and levels of the bottom of the isomer well in the compound nucleus, found from other experiments. The ratio of the cross sections for the reaction involving α decay to the isomer and ground states, $m_\alpha^\sigma/\sigma_\alpha^g$, is determined experimentally. The result can be used along with (2) to determine p_α^m/p_α^g, which is the ratio of the penetrabilities of the barriers with respect to α decay from the isomer state and in the ground well. Separating out the part of this ratio which is associated with the energy dependence of the penetrability, $p_\alpha^m/p_\alpha^g = S\,[p_\alpha^g(E^m)/p_\alpha^g(E_\alpha^g)]$ (Fig.

1), one can determine S, i.e., the increase in the probability for α decay caused by the pronounced elongation of the isomer; one can also use expression (1) to find the deformation of the isomer itself, β_2. The exponential dependence of S on β_2 means that β_2 can be found quite accurately, despite comparatively large errors in the measurements of $\sigma^m_\alpha / \sigma^g_\alpha$ and despite the simplifications which have been made. Another factor tending to improve the accuracy is that ratios of uniform quantities are used in relation (2).

In a similar way, one can determine β_2 from measurements of the ratio of the cross sections for reactions involving the emission of a proton or some other charged particle from excited states in the isomer and ground wells, hving first determined the expression corresponding to (1) for these other cases. The proposed reactions would also make it a simple matter to work from the particle energy E^m to determine the level of the bottom of the isomer well, H^d: $E^m_\alpha = E_6 + Q_\alpha - H^d$. This method can also be used to study other shape isomers. The only important point is that the compound and daughter nuclei have isomers which are similar in shape. This condition is met, in particular, by molecular isomers: nuclear molecules with an elevated stability which arise as metastable states in the course of a fission or binary reaction.[2] A valuable quality of the proposed reactions is that the probabilities for the formation of an isomer in the ground state of the daughter nucleus in these reactions are approximately equal in magnitude and are large enough for measurements. For example, $\sigma(n,\alpha)$ in the case of ^{238}U has the values $\sim$0.01, 0.1, and 1 mb at $E_n = 6$, 10, and 14 MeV, respectively.

In an experiment, α particles from states with different deformations can be identified easily on the basis of their energy (Fig. 1), and in measurements of σ^m_α it is convenient to use the isomer fission associated with the emission of α particles.

Makarenko *et al.*[3] have observed a coincidence of α particles (with $E_\alpha \gtrsim 10$MeV) and isomer fission in the reaction $^{238}U + n$ (4.5 MeV), with a comparatively large cross section for the process, $\sim 1.6\ \mu$b. They assumed that they were observing a large (tenfold) increase in the probability for ternary fission of a fission isomer. We would like to offer another explanation: that they observed the emission of an α particle from an excited state of the isomer ^{239M}U, followed by a fission of the isomer ^{235M}Th, in accordance with the scheme described above.

For a quantitative explanation of the experiment, we started from the assumption that ^{239M}U has the same level as ^{238M}U (for which this level has been measured) and that ^{235M}Th has the same deformation ($\beta_2 \approx 0.7$) as its neighbors, in agreement with the systematics.[4] The total cross section for the reaction $^{238}U(n\alpha)$ at 4.5 MeV was taken to be 4 μb, in accordance with Ref. 5. It follows from our calculations that the level of the bottom of the isomer well of ^{235M}Th is $H = 1.5 \pm 0.2$ MeV. Using this level and the parameter values of the second barrier of ^{235}Th (found through an extrapolation of data on the thorium isotopes[6]), we estimated the lifetime of the isomer to be $\sim 10\ \mu$s. In view of the approximate nature of these estimates, we judge that this value conforms to the interval of times observed in Ref. 3 ($\sim 5\ \mu$s). (This interval was set by the duration of the pulse from the α particle; we determined it from the characteristics—given in Ref. 7—of the α counter which was used in Ref. 3.)

Our explanation can be tested experimentally, by making use of the circumstance that in the case of decay in the isomer state ^{235M}Th the α particles will have an energy ~ 11.8 MeV (and not a broad spectrum, as in ternary fission) or by making use of the strong dependence of the α yield on E^*—not a characteristic of ternary fission. Confirmation of this suggestion would mean that an increase in the probability for α decay of a fission isomer—evidence of a large deformation of this isomer—was observed for the first time in Ref. 3 and also that a fission isomer of thorium—which was believed to have no isomers—was also observed for the first time. The latter conclusion would substantially change our understanding of the existence domain and properties of fission isomers and would make it possible to evaluate the accuracy of the shell-correction method.

An equation similar to (2) could also be derived without difficulty for the cross section for the formation of an isomer in an (n,n') reaction in our model.

In summary, measurements of the yield (from an excited nucleus) of charged particles accompanied by isomer fission would provide a simple method—and one suitable for most nuclei—for determining the deformations of an isomer. Measurements of the energies of such charged particles would provide a simple way for determining the level of the bottom of the isomer well.

[1]V. G. Nosov, Dokl. Akad. Nauk SSSR 112, 414 (1957) [Sov. Phys. Dokl. **2**, 48 (1957)]; P. O. Fröman, Kgl. Danske Vid. Selskab. Mat.-Fix. Medd., Vol. 1, 3, 1957.

[2]V. A. Shigin, Yad. Fiz. **14**, 695 (1971) [Sov. J. Nucl. Phys. **14**, 391 (1971)]; **27**, 67 (1978) [Sov. J. Nucl. Phys. **27**, 35 (1978)]; **45**, 329 (1987) [Sov. J. Nucl. Phys. **45**, 207 (1987)].

[3]V. E. Makarenko, Yu. D. Molchanov, G. A. Otroshchenko, and G. B. Yan'kov, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 489 (1988) [JETP Lett. **47**, 573 (1988)].,

[4]S. Bjornholm and J. E. Lynn, Rev. Mod. Phys. **52**, 725 (1980).

[5]P. D'Hondt *et al.*, in: Symp. on Neutr.-Cap. Gamma-Ray Spctr., Grenoble, 1981, p. 457.,

[6]B. B. Back, *et al.*, in: Physics and Chemistry of Fission, Proceedings of Symposium, Vol. 1, Vienna, 1974, p. 3.

[7]Makarenko *et al.*, Prib. Tekh. Eksp. No. 5, 59 (1988).

Translated by Dave Parsons