Experimental investigation of spontaneously fissile isomers

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The review discusses the results of experiments carried out in recent years and the prospects for future research on the properties of spontaneously fissile isomers. The principal attention is devoted to effects permitting determination of the value of the equilibrium quadrupole deformation of isomeric states.

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INTRODUCTION

In recent years the idea of shape isomers of nuclei has been widely discussed. At the present time this hypothesis is invoked in connection with the existence of isomeric states from which electromagnetic transitions to states at lower energies are strongly suppressed as the result of a large difference in nuclear shape. The impetus to development of ideas of this type was the study of spontaneously fissile isomers which were observed at Dubna in 1962.[1] The question of existence of nuclear shape isomers having high excitation energy was in its essence posed for the first time by Hill and Wheeler,[2] who suggested, it is true only qualitatively and without theoretical evaluations, that there exist metastable states with excitation energy of the order of the neutron binding energy which correspond to nuclei with the shape of an oblate ellipsoid, in contrast to the ground states of the nuclei, which have the shape of a prolate ellipsoid of rotation.

A considerable amount of experimental data has now been accumulated on the excitation energies, half-lives, and other properties of approximately forty isomeric states which have been observed in the region U—Cm (for example, see the compilation by Britt[3]). In recent years the experimental study of the properties of spontaneously fissile isomers has come into a qualitatively new stage.[4–7] Detailed study has been undertaken of such characteristics of isomers as spin, moment of inertia, and magnetic moment; different means of population and decay of isomeric states are being studied.

To explain the features of fission of nuclei not described by the simple liquid-drop model, including spontaneous fission of isomeric nuclei, various models have been suggested: the superfluid model of Solov'ev and Arsen'ev,[8] the two-center model of Greiner and Cherdantsev,[9–12] the pion-condensate model of Migdal,[13] and so forth. The most fruitful procedure has been the shell-correction method of Strutinskiĭ,[14,15] which is now considered to give a general description of a broad class of effects associated with the change of nuclear shapes. In this method a quantitative basis is given to the role of shell effects in nuclear deformation processes, which was noted for the first time by Geĭlikman,[16] and the representation of spontaneously fissile isomers as states with anomously large equilibrium deformation is confirmed.

As yet there are no direct experimental data which confirm this or that model. Definite results have not yet been achieved by the methods proposed, for example, study of effects associated with optical anisotropy of nuclei,[17,18] measurement of the isomeric shift of atomic levels in x-ray and optical transitions[19] and also in μ-mesic atoms, determination of the quadrupole and magnetic moments of isomeric nuclei, and the search for isomeric states with low spin in the rare earth region.

A number of reviews[3,20–32] devoted to the problem of investigation of spontaneously fissile isomers have been published recently, but most of them do not mention the results obtained in 1973–1975. In the present review we discuss the recent experimental data and the prospects for research on spontaneously fissile isomers.

1. SPECTROSCOPY OF ISOMERIC STATES

Measurement of the moments of inertia of the isomeric nuclei ^{240m}Pu and ^{236m}U was one of the most impressive experiments carried out recently, and the results have been discussed in detail in the literature (see for example Nilsson[32]). Identification of a rotational band built on the 0^+ isomeric state of ^{240m}Pu (Ref. 4) and ^{236m}U (Ref. 32) made it possible to determine that the moment of inertia of isomeric nuclei is about twice that of nuclei in their ground states. We have shown in Fig. 1 the experimental data, which agree for the two nuclei within ± 1.5%, on the moments of inertia of the ground and isomeric states, and also theoretical curves[33] obtained in the scaling model for two cases: 1) The pairing force G is proportional to the nuclear surface, and 2) G = const. For both cases the moment of inertia of the isomer corresponds to an equilibrium quadrupole deformation $\beta = 0.6$. The accuracy of the experiment is insufficient to determine the dependence of G on S.

In Fig. 2 we have shown curves reflecting the difference in the change of the distance between the levels of the rotational band of the ground state and the isomeric state of ^{240m}Pu.[32] It can be seen from the figure that $A^{\text{ground}}/A^{\text{isomer}} = 2.15$, where A is the rotational constant. We can therefore consider it established that the mo-

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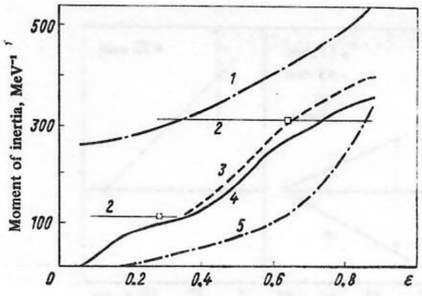


FIG. 1. Theoretical and experimental values of the moments of inertia of the nuclei ^{236}U and ^{240}Pu as a function of the deformation ϵ[32]: 1—rigid rotator, 2—experiment, 3—G = const. 4—$G \sim S$, 5—liquid drop.

ment of inertia of isomeric nuclei is anomously large, but there is as yet no unique interpretation of it. This fact can be explained, not only by the generally accepted hypothesis of shape isomers, but by violation of nucleon pairing in the nucleus, i.e., by a phase transition from the superfluid state to the normal state.[34] The moment of inertia is increased immediately by a factor of two, since the paired nucleons do not contribute to the total moment of the nucleus. Therefore it is particularly important to measure, in addition to the moments of inertia, the quadrupole and magnetic moments. Kalish *et al.*[6] have reported an experimental study of the g factors of the isomeric states of ^{237m_1}Pu, $T_{1/2} = 1.1$ μsec, and ^{237m_2}Pu, $T_{1/2} = 100$ nsec, obtained by measurement of the nuclear spin precession frequency in an external magnetic field. The experimental g value 0.14 ± 0.02 (for the state with $T_{1/2} = 1.1$ μsec) does not agree with the theoretical estimates:

$$g = \left[1 - \frac{k^2}{I(I+1)}\right] g_R + \frac{k^2}{I(I+1)} g_\Omega, \tag{1}$$

where g_R is the magnetic moment of the collective nucleon flux, which is 0.35 ± 0.04 (from other measurements); g_Ω is the magnetic moment of the unpaired nucleons:

$$g_\Omega = \frac{g_l}{\Omega}\langle l_z\rangle + \frac{g_s}{\Omega}\langle s_z\rangle; \tag{2}$$

I, l, and s are quantum numbers; k is the projection of I on the nuclear symmetry axis; Ω is the Larmor precession frequency; g and s are given by Bohr and Mottelson.[35] The theoretical estimates of the g factor for $I = 7/2$ and $9/2$ give values 0.32 ± 0.03 and 0.25 ± 0.03, respectively. The values of the spin I for the state ^{237m_1}Pu were determined independently, as we will mention below. Hamamoto and Ogle,[36] who investigated in detail the properties of single-particle levels in the second potential well of the nucleus ^{237}Pu, have pointed out that as the result of the increase in deformation the g factor should increase, although insignificantly (for an increase of the deformation parameter by a factor of two the g factor increases by 10–15%). Thus, the experimental value $g = \mu/I$, where μ is the magnetic moment, is less than the theoretical value in the case of the ^{237m}Pu excited level. In regard to the second state ($T_{1/2} = 100$ nsec), the experimental value for it, $g = 0.56 \pm 0.06$, agrees satisfactorily with the theoretical values if we assume $I = 3/2$. This spin value is in agreement with data obtained from angular distributions.

It should be noted that experiments on the magnetic moments of spontaneously fissile isomers are a natural extension of studies of the angular distributions of delayed fission fragments. The difference in technique is only that as the result of the presence of an external magnetic field the angular distribution function turns out to depend also on time:

$$W_I^k(\theta, t) = \sum_\lambda A_\lambda G_\lambda P_\lambda(\cos(\theta - 2\Omega t)), \quad \lambda = 0, 2, \ldots, 2I,$$

where θ is the angle between the direction of fragment emission and the beam direction; P_λ are Legendre polynomials; G_λ are coefficients describing the weakening of the degree of spin alignment, mainly as the result of the action of extranuclear fields;

$$A_\lambda = \frac{1}{2}(2I+1)\langle IKI-K|\lambda 0\rangle \sum_M (-)^{K-M} \langle IMI-M|\lambda 0\rangle a_M^I;$$

a_M^I are the probabilities of distribution of the spin I in projections on the beam axis (M are the magnetic quantum numbers), which are described by a Gaussian distribution $a_M^I = \exp[-M^2/2\sigma_M]/2\pi\sigma_M$ with a width $\sigma_M \approx \mu\sqrt{n}$, where μ is the average moment carried away by cascade particles; n is the number of evaporated particles.

The principal value of the method is in that the measured parameter Ω—the precession frequency—does not depend on the degree of spin alignment, the angular and phase resolutions, and other experimental conditions which are difficult to define precisely and which affect only the attenuation coefficients G_λ in the angular anisotropy function.

Ordinary spectroscopic methods of spin determination give no results in work with isomers, since numerous attempts to observe the γ, β, and α decay of isomeric nuclei have ended in failure. It can be assumed[37–39] that spontaneous fission is the main form of decay of the nuclei ^{239m}Pu, ^{241m}Pu, ^{240m}Am, and ^{241m}Am. The only experiment in which γ decay of an isomer has been observed (^{238m}U, $T_{1/2} = 200$ nsec) was carried out by Russo, Pedersen, and Vandenbosch.[5] The γ decay scheme from the 0^+ isomeric state at 2.559 MeV to the levels of the first potential well, 2^+ at 0.045 MeV and 1^- at 0.680

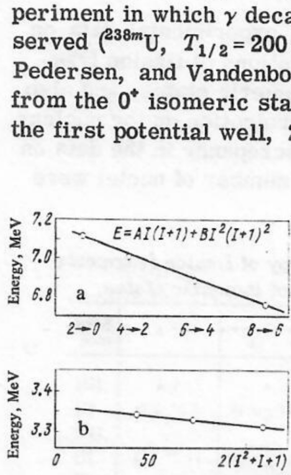


FIG. 2. Energies of transitions between levels of the rotational bands built on the ground state and isomeric states of ^{240}Pu (Ref. 2): a—ground state, $A = 7.156$ keV, $B = -3.55$ eV; b—isomeric state, $A = 3.331 \pm 0.008$ keV, $B = -0.17 \pm 0.10$ eV.

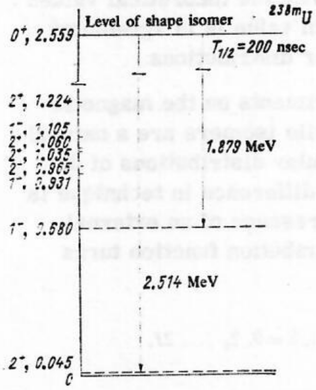


FIG. 3. Gamma-ray decay scheme of the nucleus ^{238m}U from the isomeric state to levels of the first potential well.[5]

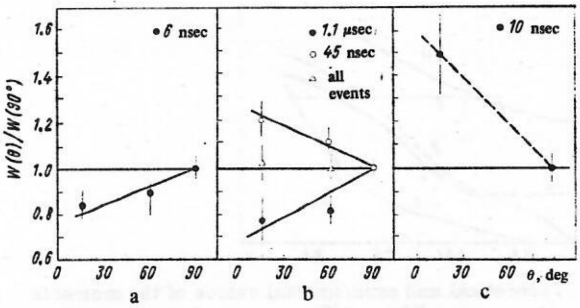


FIG. 4. Angular distributions of fission fragments from oriented nuclei of isomers[7]: a—^{236}U(α, 2n)^{238m}Pu; b—^{235}U(α, 2n)^{237m}Pu; c—^{239}Pu(α, 2n)^{241m}Cm.

MeV, is given in Fig. 3. The probability of γ decay is approximately twenty times the fission probability. This indicates that the penetrability of the inner fission barrier in the nucleus ^{238}U is higher than that of the outer barrier. The absence of a γ cascade confirms the hypothesis of a two-humped barrier, but the fact of the γ transition between states with different deformations requires further explanation.

Important spectroscopic information can be obtained not only by study of the decays of isomeric states but also by study of the population of the isomeric levels. In addition to the already cited results of Specht, Weber, Konecny, Heunemann, and others, who used the technique of measuring electron conversion spectra in delayed coincidence with fission fragments, there are no other data. Working with this technique is very complicated and laborious. Most information on spin values of isomers is now obtained from experiments on the angular distribution of fission fragments of oriented isomeric nuclei. In all experiments the orientation was accomplished as a result of the momentum transferred to the target nucleus from the incident particle. The degree of orientation for reactions induced by α particles, and also the effect of various factors on it, mainly evaporation of neutrons and γ rays, have been considered in Refs. 36 and 40.

In Table I we have given the experimental data on anisotropy of the angular distributions of fission fragments from nuclei in various isomeric states, and also data on the spin value I and its projection on the nuclear symmetry axis K. A certain discrepancy in the data on angular anisotropy, which for a number of nuclei were

TABLE I. Table of angular anisotropy of fission fragments and most probable values of I and K of isomeric states.

Nucleus	$T_{1/2}$, nsec	$W(\theta)/W(90°)$			I K	Reference
		$\theta = 0°$	$\theta = 13°$	$\theta = 55°$		
^{236m}Pu	30	0.70±0.15	—	—	4.4	[41]
^{237m_1}Pu	45	—	0.58±0.16	0.67±0.16	5/2; 5/2	[7]
^{237m_1}Pu	114	0.90±0.15	—	—	—	[41]
^{237m_2}Pu	1100	—	1.41±0.14	1.17±0.20	11/2; 7/2	[7]
^{238m}Pu	6	—	0.68±0.09	0.78±0.20	3; 3	[7]
^{240m}Pu	3.8	1.50±0.80	—	—	0.0	[41]
^{241m}Cm	10	—	2.00±0.04	—	11/2, 3/2	[7]
^{241m}Cm	15	1.87±0.40	—	—	—	[41]
^{243m}Cm	40	1.20±0.20	—	—	—	[41]

obtained by two groups of authors, is apparently explained by use of different techniques to detect the fission fragments. Galeriu *et al.*[41] studied the angular distribution of recoil nuclei decaying in flight in vacuum. Here the initial orientation of the nuclear spin changes substantially as the result of interaction between the magnetic or electric moment of the recoil nucleus and the external fields, for example, the magnetic field of the highly ionized recoil atom. Here, the greater the ratio of the lifetime of the fissile isomer to the nuclear precession period, the more strongly will the anisotropy in the fragment angular distribution decrease. In order to avoid this difficulty partially, Specht and others used a technique in which the recoil nuclei stopped in metallic lead, whose cubic lattice facilitates preservation of the orientation.[7] Data on the angular anisotropy for the nuclei ^{241m}Cm, ^{238m}Pu, and ^{273m_1m_2}Pu are given in Fig. 4.

Particular interest is presented by the spectroscopy of isomers in which two isomeric states have been observed. At the present time five such isotopes are known: ^{242m}Bk (9.5 nsec, 600 nsec),[42] ^{236m}Pu (0.05 nsec, 30 nsec),[43] ^{242m}Pu (3.5 nsec, 30 nsec).[43] The most detailed study has been made of the states of ^{237m}Pu (100 nsec, 1 μsec)[44–46] and ^{238m}Pu (0.6 nsec, 6.5 nsec).[43,47]

Attempts to observe isomeric states in the odd-odd nuclei of americium have not given a positive result.[48] The existence of several isomeric states is explained quite naturally in terms of the two-humped barrier model. Experiments on the angular distributions show that different states of a single isotope differ in the sign of the anisotropy and that excited states have higher spin (see Table I and Fig. 4). The excitation energies of different states in even-odd nuclei differ by about 1 MeV, and in odd-even nuclei—by a considerably smaller amount. The production cross sections differ by about an order of magnitude. On the basis of these data, the nature of the excited isomeric states of even-even nuclei is usually associated with two-quasiparticle excitations. The level structure ($2\Delta = 1$ MeV) in isomers is analogous to the level structure in heave even-even nuclei in their ground states, as is shown in Fig. 5.[47]

For odd nuclei forbiddenness with regard to electromagnetic transitions arises as the consequence of the large difference in the spins of the states. Calculations carried out for various nuclear potentials show that near

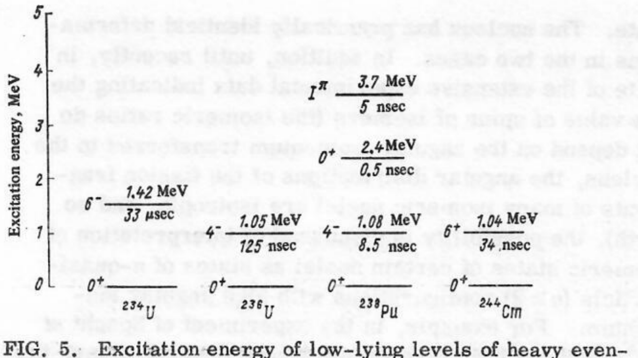


FIG. 5. Excitation energy of low-lying levels of heavy even-even nuclei.[47]

the Fermi surface there is a sufficient number of single-particle levels with high spin (for an equilibrium deformation corresponding to shape isomers $\beta \approx 0.5$). This is evident from Fig. 6, where we have given the single-particle level scheme calculated by V. V. Pashkevich for nuclei of the transuranium region,[48] obtained with use of a Woods-Saxon potential and with inclusion of a spin-orbit interaction proportional to the potential gradient. In terms of the shell-correction method the existence of several isomeric levels is not excluded even in the case of low spins, if we assume that a thinning out of the single-particle levels (a minimum of the potential energy) can be observed for nuclei not only with a ratio of axes of the nuclear ellipsoid $\omega_1 : \omega_2 = 1:2$, but also with $\omega_1 : \omega_3 = 1:3$, $2:3$, and so forth.[32] Forbiddenness with regard to γ transitions arises as the result of the difference in the deformations of these states.

Measurement of the mass and energy distributions of fission fragments from isomeric nuclei serves as an additional source of information on the structure of the barrier. The energy distributions of fission fragments from the nuclei ^{239m}Am, ^{237m}Pu, ^{238m}U, ^{239m}Am, and ^{240m}Pu have been studied in reactions induced by charged particles: protons, deutrons,[49] and α particles.[4] The recoil-nucleus technique was used,[50] and the fragments were detected by semiconductor surface-barrier detectors. All of the distributions obtained for isomeric states in general follow the corresponding distributions of prompt fission fragments measured at low nuclear excitation energies. The peak-to-valley ratio for ^{239m}Am is ≥ 30, for ^{237m}Pu—≥ 11, and for ^{238m}U—≥ 7. The large asymmetry in mass in the case of fission from an isomeric state leads to the result that the energy spectrum of the fragments of delayed fission, measured, for example, in the $(\alpha, 2n)^{240m}$Pu reaction, is closer to the spectrum of spontaneous fission fragments than that of induced fission at $E_\alpha = 25$ MeV.[4] The analogy of spontaneous fission of isomers with induced fission at low excitation energies has been noted also by Vilcov *et al.*,[45] who report measurements of the energy distribution of fission fragments from the isomer ^{237m}Pu in the $(d, 2n)$ reaction.

2. STUDY OF PRODUCTION OF SPONTANEOUSLY FISSILE ISOMERS IN THE SUB-BARRIER REGION OF EXCITATION ENERGY

One of the means of studying shape isomerism is investigation of the cross sections for deep sub-barrier fission of nuclei. It is natural to suppose that with decrease of the excitation energy of the nucleus the role of the second minimum, to which the existence of spontaneously fissile isomers is related, will increase. This is indicated, in particular, by the features of sub-barrier fission: the existence of broad fission resonances in reactions induced by neutrons, γ rays, and also charged particles; the existence of a fine structure of these resonances, and so forth. The most convenient means of studying sub-barrier fission are reactions induced by γ rays, which permit investigation of the excitation function right down to an energy $E_{exc} \approx 2.5$ MeV, i.e., 3–4 MeV below the barrier.

Bowman[51] proposed, on the basis of the two-humped barrier model, that in bombardment of nuclei by γ rays with energy $E_\gamma \leq 4$ MeV one will observe fission accomplished primarily through isomeric states. Delayed fission becomes more probable because, with decrease of the excitation energy of a nucleus located in the second potential well, the penetrability of the outer barrier decreases much more rapidly than the probability of γ decay. The probability of fission from isomeric states, i.e., from the lowest states of the second potential well, does not depend on the excitation energy; only the probability of population of these states changes. Consequently, the photofission cross section will be determined only by the penetrability of the inner barrier. This obvious reasoning can be obtained on the basis of the phenomenological calculations which are usually used for analysis of formation of spontaneously fissible isomers in terms of the two-humped barrier model:

$$\sigma_f = \sigma_c \frac{P_A}{P_A + P_{\gamma_1}} \left(\frac{P_B}{P_A + P_B + P_{\gamma_2}} + \frac{P_{\gamma_2}}{P_A + P_B + P_{\gamma_2}} \right), \quad (3)$$

where σ_f is the photofission cross section, σ_c is the cross section for compound-nucleus formation, P_A and P_B are the penetrabilities of the inner and outer barriers, P_{γ_1} and P_{γ_2} are the probabilities of α decay in the first and second potential wells, $P_A/(P_A + P_{\gamma_1})$ is the probability of a transition to the second potential well, $P_B/(P_A + P_B + P_{\gamma_2})$ and $P_{\gamma_2}/(P_A + P_B + P_{\gamma_2})$ are the probabilities of

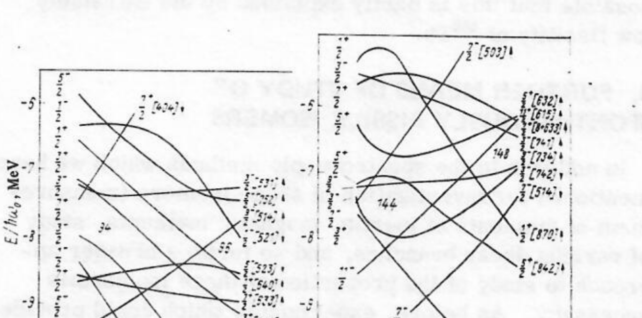
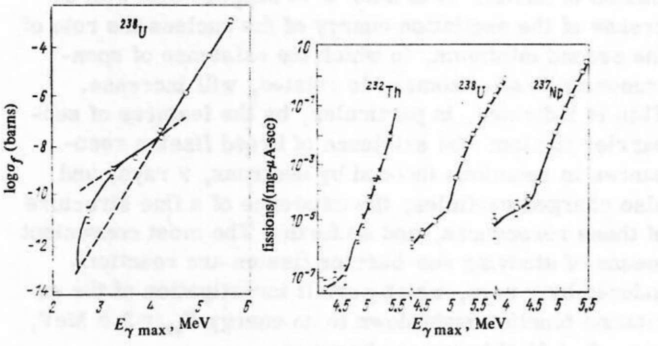


FIG. 6. Diagram of single-particle levels calculated for the deformation region corresponding to shape isomers (calculation with Woods–Saxon potential with inclusion of spin-orbit interaction proportional to potential gradient)[48]: a—protons, b—neutrons.



a b

FIG. 7. Cross section for sub-barrier photofission as a function of γ-ray energy according to the data of Ref. 52(a) and Ref. 53(b).

prompt and delayed fission, respectively. For a parabolic barrier

$$P_i(E) = \exp\{2\pi(E - E_{fi})/\hbar\omega_i\}; \quad E - E_{fi} \gg \hbar\omega_i/2\pi, \tag{4}$$

where E_{fi} and $\hbar\omega_i$ are the height and curvature of the i-th barrier.

For $P_B \gg P_{\gamma 2}$, mainly prompt fission will occur, and in the opposite case—delayed fission. The decrease in the slope of the energy dependence of the photofission cross section due to this effect, which has received the name *isomeric shelf*, was observed experimentally by Bowman *et al.*[52] for ^{238}U, $E_\gamma = 2.75$–5.75 MeV, and by V. E. Zhuchko *et al.*[53] for the nuclei ^{238}U, ^{232}Th, and ^{237}Np at $E_\gamma = 3.8$–5.5 MeV. These functions are shown in Fig. 7.

It should be noted that observation of the shelf in the deep sub-barrier region of photofission of ^{232}Th is still the only indication of the existence of isomeric states decaying by fission in nuclei lighter than *U*. The probability of formation of spontaneously fissible isomers of Th (with respect to the total probability of excitation of the compound nucleus) is at least two orders of magnitude less than in the case of nuclei with $Z \geq 92$. It is possible that this is partly explained by the extremely low fissility of ^{232}Th.

3. FURTHER MEANS OF STUDY OF SPONTANEOUSLY FISSILE ISOMERS

In addition to the spectroscopic methods which we have mentioned for investigation of shape isomers (measurement of moments of inertia, magnetic moments, study of various decay branches, and so forth) a broader approach to study of the properties of these isomers is necessary. As before, experiments which could provide direct information on values of the equilibrium deformation of isomers are most important. As we have noted, there is a possibility of explaining the existing experimental data without resort to the hypothesis of shape isomerism. For example, according to the super-fluid model[8] in a nucleus at an excitation energy of about 2–3 MeV there may be forms of excitation due to transitions of nuclear matter from the superfluid state to the normal state. The nucleus has practically identical deformations in the two cases. In addition, until recently, in spite of the extensive experimental data indicating the low value of spins of isomers (the isomeric ratios do not depend on the angular momentum transferred to the nucleus, the angular distributions of the fission fragments of many isomeric nuclei are isotropic, and so forth), the possibility is discussed of interpretation of isomeric states of certain nuclei as states of n-quasiparticle ($n \geq 2$) configurations with high angular momentum. For example, in the experiment of Specht *et al.*[4] which we have already mentioned several times, the observed transition $4^+ \to 2^+$, $\hbar\omega = 46.6$ keV, $\beta = 0.6$ in the nucleus ^{240m}Pu is interpretated as a transition between states of a band with large projection on the nuclear symsymmetry axis[19]: the transition $7 \to 6$, $\hbar\omega = 46.6$ keV, $K = 6$, $\beta = 0.3$, which agrees with the experimentally determined anomalous value of the rotational constant $A = 3.33$ keV. According to estimates made by Grechukhin,[19] the lifetime of the γ cascade is 1.4×10^{-10} sec for the $7 \to 6$ transition and 0.3×10^{-10} sec in the case of the $4 \to 2$ transition.

Direct information on the equilibrium deformation of isomeric nuclei can be provided by measurements of the isomeric shift in x-ray and optical transitions. If shape isomerism exists ($\beta \approx 0.6$), then the rms radius of the proton distribution over the nuclear volume will be substantially greater than in the case $\beta \approx 0.3$. The calculations carried out by Grechukhin[19] show that for the nuclei ^{236}U and ^{238}U for the K_{α_1} x-ray line the isomeric shift $\Delta\hbar\omega(u - {}^m u)$ is 6.2 eV. Since the radiative width of the K_{α_1} line in the region of nuclei with $Z \geq 92$ is of the order of 100 eV, a large number of counts ($\sim 10^4$) of x-ray photons of an atom with an isomeric nucleus is necessary to reveal the isomeric shift, which presents significant experimental difficulties. The conditions of observation of the isomeric shift in the optical region may turn out to be more favorable. According to Grechukhin's calculations[19] the isomeric shift for the lines of the ^{242}Am atom $\lambda_1 = 2938.9$ Å, $\lambda_2 = 3258.6$ Å in the case of formation of Am nuclei with equilibrium deformation $\beta = 0.6$ amounts to about 20 cm^{-1}.

One of the proofs of existence in nuclei of states with anomalously large deformation also would be observation in them of optical anisotropy effects.[17,18] It is well known that study of these effects serves as a reliable source of information on the shape of the nuclear surface. By optical anisotropy we mean a tensor nature of the polarizability of nuclei as a function of the relative orientation of the photon polarization vector and the nuclear spin. The clearest manifestation of optical anisotropy is splitting of the giant resonances in highly deformed nuclei. In axially symmetric nuclei the giant dipole resonance is split into two peaks corresponding to two types of vibrations: along and transverse to the symmetry axis. The frequencies of these longitudinal and transverse vibrations, $\omega_\parallel$ and $\omega_\perp$, are related to the ratio of the major and minor semiaxes of the nuclear ellipsoid in the following way[54]:

$$\omega_\parallel/\omega_\perp = 0.91b/a + 0.09. \tag{5}$$

The cross section for total absorption is approximated by the sum of two Lorentz curves:

$$\sigma_{tot} = \frac{\sigma_{\parallel}}{[(\omega^2-\omega_{\parallel}^2)/\omega\Gamma_{\parallel}]^2+1} + \frac{\sigma_{\perp}}{[(\omega^2-\omega_{\perp}^2)/\omega\Gamma_{\perp}]^2+1}, \quad (6)$$

where $\sigma_{\parallel}$, $\sigma_{\perp}$, $\Gamma_{\parallel}$, and $\Gamma_{\perp}$ are the amplitudes and half-widths of the longitudinal and transverse resonances. Relations of this type between the frequencies of the two forms of dipole vibrations follow from practically all existing models of the giant dipole resonance and have a general nature. Having determined a/b experimentally, we can calculate the equilibrium deformation parameter

$$\beta = 3.17\,(d-1)\,(d-2) \quad (7)$$

and the intrinsic quadrupole moment

$$Q_0 = (2/5)\,zr_0^2 A^{2/3}\,(d^2-1)\,d^{2/3}, \quad (8)$$

where $d = a/b$ and $r_0 = 1.2$ F.

Study of the optical anisotropy effects in isomeric nuclei involves major experimental difficulties, since it is necessary for this purpose to measure the cross sections for absorption of photons by rare and short-lived states of the nuclei. (In absorption of γ rays by nuclei, dipole vibrations built on the ground state of the nucleus are excited. As the result of optical anisotropy effects the total absorption cross section or the partial cross sections, which are related to the total cross section through the partial widths, are split into two peaks, and in all cases, including isomer formation, this splitting will be determined by vibrations built on the ground state of the nucleus, i.e., by the doorway states.) It is possible, however, to obtain information on the equilibrium deformation of isomers if we utilize reactions of the type (γ, γ') in which the doorway and exit states are related according to the Franck-Condon principle,[55] or the inverse reactions, for example, radiative capture of neutrons. As shown by Tulupov,[18] the cross section for the reaction $^{241}Am\,(n, \gamma)\,^{242m}Am$ should approximately reproduce in shape the photoabsorption curve in the ^{232m}Am nucleus. In Fig. 8 we have given the cross section calculated on the assumption that the deformation of the isomer ^{242m}Am is $\beta = 0.65$, and also the cross section for formation of the nucleus ^{242}Am in the ground state. The interval between the two maxima in the latter case should amount to about 3–4 MeV, in contrast to a splitting of 6–8 MeV for the reaction with formation of the isomer. As can be seen from Fig. 8, the experimental points in the vicinity of the first maximum, which according to the optical anisotropy model is due to resonance conditions corresponding to longitudinal dipole oscillations of the ^{242m}Am nucleus, are in good agreement with the theoretical curve. However, in order to determine the deformation of a nucleus in the isomeric state it is necessary to make measurements of the energy dependence of the cross section for radiative capture with formation of isomers in the range of neutron energies 5–15 MeV.

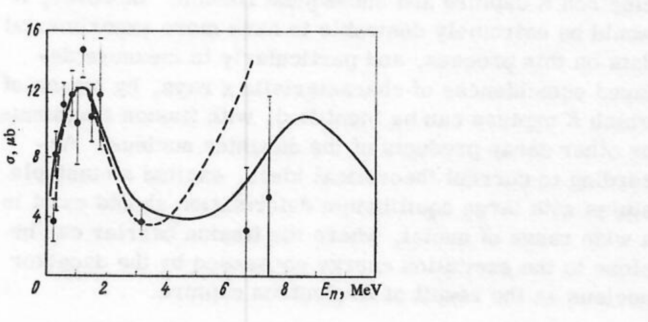


FIG. 8. Calculation according to optical anisotropy model of cross sections for the reaction $^{241}Am(n, \gamma)^{242}Am$: solid curve—formation of ^{242}Am nucleus with deformation $\beta = 0.65$; dashed curve—$\beta = 0.3$.[18]

It should be noted that the isomer-formation reactions associated with excitation of the giant dipole resonance can be interpreted, as is very frequently done, in terms of the phenomenological model of a two-humped barrier (see Eq. (3)). For low excitation energies when the compound nucleus is formed in the first potential well, the fission cross section has the same form as the cross section for isomer formation, with the only difference that the numerator P_B is replaced by P_{γ_2}. Consequently,

$$\sigma^{is} = \sigma_f P_{\gamma_2} / P_B. \quad (9)$$

Here the cross section for isomer formation should initially rise, until the excitation energy exceeds the fission barrier, and then fall, following at least qualitatively the cross section of the corresponding partial reaction leading to formation of the isomer. Good agreement with experiment is obtained for the (γ, n) reaction[56] and for the neutron radiative capture reaction.[57] Nevertheless a more detailed analysis based on the optical anisotropy model presents unquestioned interest both from the point of view of study of the nature of isomers and from the point of view of investigation of the mechanism of their formation. In the latter case we have in mind study of the probability of formation of isomeric states by a direct γ transition from excited levels in relation to population by a γ cascade.

The experimental possibility of checking the hypothesis of shape isomerism by measurement of the isomeric shift in μ-mesic atoms has been discussed by Polikanov.[22] Formation of a μ-mesic atom occurs, as is well known, by cascade transitions of the μ meson over allowed orbits around the nucleus, which are accompanied by x rays. Transitions between levels for which the principal quantum number is $n \leq 3$ correspond to a large overlap of the μ-meson wave function with the region of nuclear charge distribution, and therefore the transition energies are very sensitive to the specific form of the distribution. Calculations of the dependence of the μ-meson binding energy on the equilibrium quadrupole deformation for the inner orbits of the ^{236}U nucleus have been carried out by D. F. Zaretskiĭ and V. M. Novikov[58] and have recently been repeated and supplemented by Leander and Moller[59] as the result of the appearance of new experimental data.[60] All the calculations have been made in the nonrelativistic approximation.

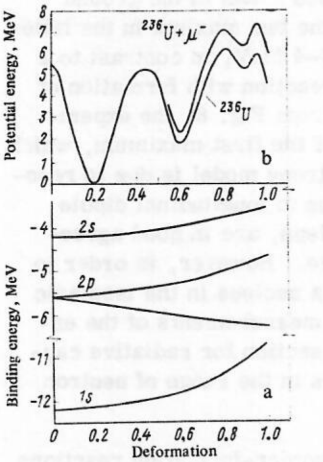


FIG. 9. Excitation energy of low-lying levels of the system (^{236}U nucleus + μ^-) as a function of equilibrium quadrupole deformation (a), and change of fission barrier in the presence of a muon in the 1s orbit[59] (b).

Figure 9a shows how the excitation energy of the low-lying levels of the system (^{236}U nucleus + μ^-) varies as a function of the equilibrium quadrupole deformation. The greatest isomeric shift, i.e., the difference in energy between levels with $\beta=0.3$ and $\beta=0.6$, is observed for the lowest $1s_{1/2}$ level. Strictly speaking, the curves presented reflect only qualitatively the influence of deformation. In order to obtain the absolute separation of the levels, it is necessary to take into account relativistic corrections, i.e., in place of the Schrödinger equation to solve the Dirac equation. However, although the relativistic corrections are large (≈ 200 keV), they do not depend greatly on the deformation and therefore the picture is not changed qualitatively. Calculation of the potential energy by Strutinskii's method as a function of the deformation in the presence of a muon in a nuclear orbit leads to the result that in the vicinity of the second minimum the barrier is raised by about 1 MeV (see Fig. 9b, the calculation for the nucleus ^{236}U). Leander and Möller[59] also showed that the change in the fission barrier as the result of presence of the muon in a nuclear orbit is almost entirely due to the equilibrium quadrupole deformation β_2 and is almost independent of deformation parameters of higher order. Since the calculations have a general nature for nuclei with $Z \geq 92$, we can expect that in reactions induced by μ mesons as a result of the increase in the barrier the isomeric states will become more stable and, possibly, will appear in heavier nuclei $Z \approx 28$).

By analyzing the half-lives of μ-mesic atoms we can draw conclusions about the dynamics of fission. Bloom[61] proposed an explanation of the difference in the half-lives for electronic and fission decays of muonic atoms for the case of ^{238}U: In the process of muonic transitions between levels of the μ-mesic atom, excitation occurs of one or several metastable states of the nucleus, which decay with the observed half-lives.

For investigation of reactions with formation of μ-mesic atoms (μ-mesic atoms are usually obtained by capture of stopped muons by nuclei) intense muon beams are required. In addition, the possibility exists of formation of μ-mesic atoms in radiation processes, in particular by creation of $\mu^+\mu^-$ pair in a nucleus by ultra-relativistic electrons. As Dmitriev[62] has shown, the cross section for electro-production of μ-mesic atoms for large E_e is about 10^{-29} cm^2. The probability of fission per μ capture for nuclei with $Z \geq 92$ is close to unity. Cross sections of this order are quite accessible for measurements in existing electron accelerators and storage rings. (Cross sections for formation of the spontaneously fissible isomers ^{240m}Am and ^{242m}Am per equivalent quantum, measured in the bremsstrahlung beams of electron linear accelerators[63] in the γ-ray energy range $E_{\gamma\,\max}=100$–1300 MeV, are approximately 5×10^{-29} cm^2.) Bloom[61] has stidued theoretically the possibility of excitation of spontaneously fissible isomers by μ mesons in electron storage rings. The use of storage rings apparently provides more favorable possibilities in the technical sense, especially in study of the formation of spontaneously fissible isomers in exotic isotopes, such as neutron-deficient isotopes, since here it is possible to use thinner targets.

Excitation of isomers in inelastic electron scattering does not differ in principle from reactions induced by γ rays or μ mesons. However, by using an electron scattering spectrometer and recording delayed coincidences of fission fragments with electrons of known energy, it is possible to study directly the direct population of isomers as a function of momentum transfer. Thus, there could occur the process inverse to that observed experimentally in Ref. 5, where the γ decay of the 0^+ state of ^{238}U, $T_{1/2}=200$ nsec, was identified. In the case of electron scattering the probability of a $0^+\to0^+$ transition to the isomeric state, evaluated from the probability of direct γ decay for the ^{238}U nucleus, is 10^{-35}–10^{-34} cm^2.[64] In spite of this low probability, this experiment is facilitated in a certain sense by the fact that the electrons are detected in the delayed coincidence mode and therefore the counting rate in the β spectrometer can be increased substantially.

It is of interest to search for shape isomers in electron capture from the K shell of an atom. In 1971 it was reported that delayed fission of neutron-deficient nuclei far from the β-stability region has been observed at the Joint Institute for Nuclear Research.[65] The delayed fission was observed in the nuclei ^{228}Np ($T_{1/2}=60$ sec), ^{232}Am ($T_{1/2}=14$ min), and ^{232}Am ($T_{1/2}=2.6$ min). As suggested by Skobelev,[66] this phenomenon involves excitation of the daughter nucleus as a consequence of electron K capture and subsequent fission. However, it would be extremely desirable to have more experimental data on this process, and particularly to measure delayed coincidences of characteristic x rays, by means of which K capture can be identified, with fission fragments or other decay products of the daughter nucleus. According to current theoretical ideas, excited metastable states with large equilibrium deformation should exist in a wide range of nuclei, where the fission barrier can be close to the excitation energy possessed by the daughter nucleus as the result of K-electron capture.

The excitation of metastable states in capture of π^- mesons by nuclei may also become one of the new means of studying shape isomers. A study of exotic atoms (μ^-, π^-, etc., +nucleus) permits investigation of many detailed nuclear and radiation effects,[67] and use of π mesons in this sense presents new, interesting possibilities as a result of the recent study of (π, xn) reactions in medium-heavy nuclei.[68] It turned out that in the reactions $^{181}Ta(\pi, 4n)^{177m}Hf$ and $Pt(\pi, xn)^{190m}Ir$ there are formed states with very high spin ($37/2^-$ and 11^-, respectively). Since the maximum orbital angular momentum of the captured pion is equal to three, it is likely that capture of pions occurs by nucleons or clusters having high intrinsic orbital angular momentum.

All of the shape isomers known at the present time, which have low spin, belong to the region of nuclei with $Z \geq 92$. Attempts to observe isomers with low spin in the region of nuclei with intermediate mass have given negative results, while isomeric states with large angular momentum are observed in many even and odd nuclei with $A \approx 100-214$. In bombardment by heavy ions of the nuclei ^{141}Pr, $^{140-142}Ge$, ^{144}Nd, ^{nat}Ir, ^{197}Au, ^{nat}Pb,[69] Nd–Pu,[70] $^{126-130}Xe$, and $^{134-136}Ba$,[71] by protons, deuterons, and α particles of the nuclei Bi, Pb, Ir, and Pr,[72] and by neutrons of ^{226}Ra[73] it was established that the ratio of the cross sections for isomer formation to the cross sections for formation of the nuclei in the ground state do not exceed $10^{-6}-10^{-8}$. The question of existence of isomers with low spin in deformed nuclei of intermediate mass (the rare earth region) is important from the point of view of verifying existing models which explain the existence of spontaneously fissible isomers, and requires further study. From the point of view of the shell model the existence of shape isomers (islands of isomerism) is quite possible not only for nuclei with $Z \geq 92$, but also for medium and transition nuclei. For example, the level 0.752 MeV, 2^+ $T_{1/2}=16.7$ nsec in the nucleus ^{48}Cr is interpreted as a state in the second potential well.[74] It is possible that the existence of isomeric states in the isotopes of mercury explains the anomalous isotopic shift for the nuclei $^{183-185}Hg$, which recently has been widely discussed with the aid of the hypothesis of a bubble configuration of these nuclei.

Bubble nuclei, first predicted by Wheeler,[3] have been studied theoretically in detail by Wong,[75] who showed that the density of nucleons inside the nucleus ^{200}Hg may be almost a factor of two lower than on the surface. However, recent experiments[76] and also the calculations of Nilsson *et al.*[77] show that the ^{186}Hg nucleus is apparently a very nonrigid rotator and has a second minimum of potential energy as a function of deformation. It must be noted, however, that the question of existence of bubble nuclei remains open. Calculations made for the nucleus ^{236}U show that at least transitional bubble configurations (beyond the saddlepoint) exist.[78]

Recently[78] there has been intensive discussion of questions related to the regions of stability of superheavy elements. Calculations[79] show that in superheavy nuclei the second minimum of potential energy may turn out to be deeper than the first, and therefore the possibility is not excluded of more likely observing superheavy metastable isomeric states than superhevy nuclei in the ground state.

4. STUDY OF ISOMERS AT HIGH NUCLEAR EXCITATION ENERGIES. USE OF SPONTANEOUSLY FISSILE ISOMERS FOR STUDY OF MECHANISMS AND CHARACTERISTICS OF NUCLEAR REACTIONS

According to the most generally accepted point of view (the two-humped barrier model) the process of formation of isomeric states and fission consists of a series of successive stages: First a compound nucleus characterized by strong interaction between single-particle and collective degrees of freedom is excited. For excitation energy above the fission barrier the nucleus possesses a set of arbitrary deformations. Here the nucleus attempts to assume a shape such that the values of N and Z correspond to the nearest filled or almost filled shells. For a deformation corresponding to the second minimum of potential energy, a part of the deformation energy can return again to thermal energy. Then the nucleus undergoes fission, and emits a neutron or a γ ray. Since fission is a slower process, after emission of a particle the nucleus can lose so much energy that, if it is in the second potential well, it cannot return to the first and will drop to the lowest isomeric state. If some level through which de-excitation occurs has sufficiently high spin, existence of several isomeric states in the second potential well is possible. This latter effect, as we have already mentioned, is not excluded also in the case of low spins if we consider that the rarefaction or decrease in density of the single-particle levels, i. e., the minimum of potential energy, is observed not only for nuclei with a ratio of axes of the nuclear ellipsoid 1 : 2, but also for ratios 1 : 3, 2 : 3, and so forth.

It is possible to check the validity of assumptions of this type, particularly by studying the formation of spontaneously fissible isomers at high nuclear excitation energies. At high temperatures the shell corrections do not play an important role (shell effects disappear at an excitation energy of about 60–80 MeV[80]). Therefore the isomeric ratios, i. e., the relative probabilities of formation of isomers in a given partial reaction, should not depend greatly on the excitation energy of the nucleus if the latter exceeds the fission barrier. It should be noted that at the present time in the literature on fissible isomers the term isomeric ratio is usually understood as the ratio of the probability of formation of the isomer to the probability of excitation of the compound nucleus or the ratio of the cross sections of delayed and prompt fission, which are not the same. In fact, as shown, for example, by Kuznetsov *et al.*[63] for the reactions $^{243}Am(\gamma, n)^{242m}Am$ and $^{241}Am(\gamma, n)^{240m}Am$, the isomeric ratios, i. e., $\sigma_{\gamma n}^{is}/\sigma_{\gamma n}^{pr}$, in the excitation energy region 15–25 MeV always remain approximately constant. In this case $\sigma_{\gamma n}^{is}/\sigma_{\gamma f}^{pr}$ falls off with increasing γ-ray energy. In the higher energy region the (γ, n) cross section becomes very small for Am nuclei and formation of the isomers ^{242m}Am and ^{240m}Am is for this reason not observed.

Generally speaking, isomeric ratios, especially in the region of low excitations, should depend on the shape of the fission barrier. In the case in which they do not change greatly with energy or have been determined rather accurately, as occurs, for example, for Am nuclei, study of the cross sections for formation of spontaneously fissible isomers permits data to be obtained on the partial reactions, which in nuclei with $Z \geq 92$ are very difficult to study by other means. Isomeric ratios have been studied in the greatest detail in reactions induced by charged particles.[81] The use of spontaneously fissile isomers in the induced activity method for nuclei with $Z \geq 92$ has been discussed by Alexandrov *et al.*[82] in the example of determination of the ^{241}Am impurity in a ^{243}Am target.

In Fig. 10 we have shown the yields of the reactions ^{241}Am (γ, n) ^{240}Am and ^{243}Am (γ, n) ^{242}Am per equivalent quantum measured in a bremsstrahlung beam in the energy range $E_{\gamma\,\max} = 50-1300$ MeV.[63] The left-hand scale corresponds to the yield of fission fragments of the nuclei ^{240}Am and ^{242}Am which are in the isomeric state, and the right-hand scale corresponds to the nuclei in the ground state. For comparison we have shown in the same figure data for the reaction ^{238}U(γ, n) from Ref. 83. There are no other data on partial photonuclear reactions in nuclei with $Z \geq 92$ in this energy region.

As was noted by L. E. Lazareva, in photonuclear reactions it is possible to separate uniquely processes involving high nuclear excitations if use is made of the recoil-nucleus technique, which was first used for study of spontaneously fissile isomers in reactions induced by charged particles in Ref. 50. This is important, since in measurements in a bremsstrahlung beam the yield of almost any partial reaction is determined to a significant degree by the contribution from the corresponding cross section in the low energy region.

In reactions induced by γ rays the momentum transferred to the nucleus is smaller by a factor of approximately $(\hbar\omega)^2/Mc^2$ than in reactions with incident nucleons (M is the nucleon mass and $\hbar\omega$ is the γ-ray energy). The minimum momentum transfer at which the recoil nucleus is emitted from the target corresponds to $E_\gamma \approx 100$ MeV, and here the energy of a recoil nucleus with $M = 200$ is about 25 keV and its velocity about 1.5×10^8 cm/sec. For $E_\gamma < 30$ MeV, i.e., in the energy region corresponding to the giant dipole resonance, the energy of the recoil nuclei will be so small that their range will be negligible. We can add that the minimum displacement of recoil nuclei, measured, for example, by means of the blocking effect,[84] corresponds to an incident nucleon energy of about 100 eV or $E_\gamma \approx 15$ MeV.

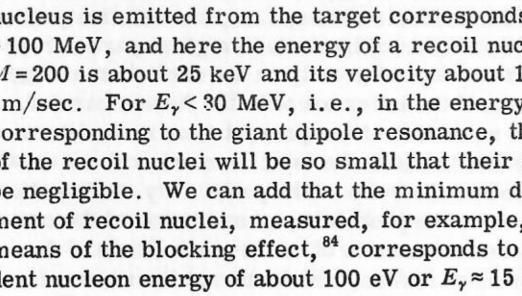


FIG. 10. Cross sections for reactions per equivalent quantum (right-hand scale): ● — ^{241}Am$(\gamma, n)^{240}$Am; ○ — ^{243}Am$(\gamma, n)^{242}$Am (Ref. 63); □ — ^{238}U$(\gamma, n)^{237}$U.[83]

Experiments on measurement of the cross sections for formation of isomers at high excitation energies are very scarce. Protons with energy $E_p = 600$ MeV have been used to search for spontaneously fissile isomers in the nuclei U, Th, Bi, and Pb with negative results: $\sigma^{is} < 10^{-(30-34)}$ cm^2.[85] Attempts also have been made to observe delayed radiation with high energy from a lead target bombarded by 45-GeV protons.[86] Nevertheless, in reactions induced by charged particles when low-lying excited states can be formed, for example, as the result of grazing collisions with the nucleus, formation of spontaneously fissile isomers apparently should take place. In the case of reactions induced by γ rays the question of the possibility of excitation of isomeric states for the known mechanisms of nuclear excitation (the quasideuteron mechanism and the mechanism involving photoproduction and reabsorption of π mesons) remains open. Also unstudied is the possibility of formation of spontaneously fissile isomers in reactions induced by high energy electrons.

In conclusion it should be said that the phenomenon of shape isomerism, which obviously is now being extensively studied in various directions, will in the coming years be one of the very important and interesting problems of nuclear physics.

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