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NUCLEAR ISOMERISM

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INVESTIGATIONS of nuclear isomerism have played an important part in the development of modern ideas regarding the structure of atomic nuclei. Igor Vasil'evich Kurchatov and his co-workers discovered nuclear isomerism, and Kurchatov either directed or was interested in all subsequent Russian investigations in this field.

At an early stage of his work Kurchatov foresaw the fundamental importance of the comprehensive study of isomeric transformations. He maintained a constant interest in this branch of nuclear physics during 25 years.

Experimental information regarding nuclear ground and excited states and the electromagnetic transitions between them, obtained through investigations of nuclear isomers, has provided a very important part of the basis for a modern unified nuclear model. Kurchatov participated directly in studies of nuclear isomerism that obtained results of great significance for understanding the details of nuclear structure.

The present paper reviews the principal stages of nuclear isomer research up to the present time.

1. DISCOVERY AND EXPLANATION OF NUCLEAR ISOMERISM

In 1934 Kurchatov began experimentation on artificial radioactivity at the Leningrad Physico-Technical Institute. These experiments were performed at a time when nuclear physics was undergoing very rapid development.

In January, 1934 Irene Curie and Frederic Joliot[1] discovered the artificial radioactivity resulting from the bombardment of a number of light elements with alpha particles from polonium. In March of the same year Enrico Fermi[2] used neutrons as projectiles to induce artificial radioactivity in many elements. In October, 1934 Fermi and his co-workers,[3] through the use of slow neutrons, greatly increased the number of radioactive isotopes and enhanced their activity. This work provided a powerful means of studying nuclear transformations.

In April, 1935 I. V. Kurchatov, B. V. Kurchatov, L. V. Mysovskii, and L. I. Rusinov[4] published the results of their investigations of artificial radioactivity in bromine. They found that neutron bombardment of bromine produces beta-active bromine isotopes with three different half-lives: 18 minutes and 4.2 hours, which had also been reported by Fermi, and a new half-life of 36 hours.

Since only two stable bromine isotopes with mass numbers 79 and 81 were known, the production of three radioactive nuclei by neutron bombardment of bromine made it difficult to determine the reactions involved. Three hypotheses were advanced to account for the existence of a third radioactive bromine isotope:

1. One kind of radioactive bromine is produced in a (n, 2n) reaction.
2. The third half-life indicates the existence of a third stable bromine isotope that had not been detected spectrographically.
3. There are two radioactive bromine isotopes, one of which possesses an isomeric state.

At a session of the U.S.S.R. Academy of Sciences in March, 1936 I. V. Kurchatov, in analyzing these hypotheses on the basis of further studies of the anomalous artificial radioactivity in bromine, stated:[5]

"In order to account for this anomaly we have previously suggested that neutron bombardment of an element can produce radioactive isotopes not only through simple neutron capture but also through non-capture collisions resulting in the ejection of one of the nuclear neutrons.

It was soon necessary to drop such hypotheses. Experiments with neutrons of different energies, performed by L. I. Rusinov, showed that low-energy neutrons produce all three radioactive forms of bromine, while a non-capture reaction, being endothermal, would require a supply of external energy such as the kinetic energy of the incident particle.

If no new assumptions are made, it would thus be suggested that, in conflict with mass-spectrographic analysis, a third unabundant stable isotope exists, which combines with a neutron to form a third radioactive nucleus. Along with this extremely unlikely hypothesis another very improbable assumption would be required. The amounts of the three radioactive bromine nuclei are of the same order; consequently, the rare but stable third isotope would necessarily have a very large cross section for neutron capture.

Another possible way of accounting for the third form of radioactive bromine involves the essentially new hypothesis that nuclear isomers exist. I am not considering nuclear isomerism in the same narrow sense as Gamow. We consider isomers to be nuclei with identical charges and identical mass numbers, which can therefore not be distinguished by a mass spectrograph, but with different structures."

In this report Kurchatov was the first to definitely reach the conclusion that the isomerism of artificially radioactive nuclei had been discovered.

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*Deceased.

In discussing the anomalies in the radioactivity of bromine and other elements, Lise Meitner[6] stated cautiously in June, 1936 at a physics meeting in Zurich:

"At the present time it is difficult to believe in the existence of 'isomeric' nuclei, i.e., nuclei having equal atomic weights and equal atomic numbers but different radioactive properties."

Kurchatov's ideas regarding nuclei isomers were abundantly confirmed during the next few years. In December, 1936 there appeared Weizsäcker's important theoretical paper on isomerism,[7] advancing the hypothesis that isomeric nuclei, while having the same charge and mass number, are in different (ground and excited, respectively) energy states. Calculations of gamma-ray transition probabilities showed that at not too high excitation energies and with large differences between the angular momenta of excited and ground states these transitions are greatly hindered, and that excited nuclear states can have considerable lifetimes that are measurable experimentally along with the lifetimes of ground states.

The hypothesis that isomeric states are metastable excited states required experimental confirmation. Kurchatov's laboratory began to investigate the gamma rays from radioactive bromine for the purpose of observing gamma transitions. It was shown by nuclear cross reactions and by chemical studies that the isomeric isotope is Br^{80}; however, gamma rays accompanying an isomeric transition in Br^{80} were not detected.

In 1938, during further studies of radioactive bromine directed by Kurchatov, intense emission of soft electrons with a 4.2-hr half-life was discovered.[8] Kurchatov suggested internal conversion as the cause of this emission. The fact that the soft and hard components of bromine electron emission are of approximately equal intensity indicated that the isomeric state decays mainly by emitting conversion electrons. The conversion hypothesis was proved for the soft electrons by measuring the electron energy spectrum and investigating the characteristic x rays of bromine.

Theoretically calculated probabilities of internal conversion processes[9] published in 1938 showed that conversion transitions have the highest probability for low energies and a large angular momentum difference; these conditions are usually found in isomeric nuclei. Thus the nature of nuclear isomerism was determined experimentally by I. V. Kurchatov and his co-workers through their detailed investigations of radioactivity in bromine.

An investigation of the decay scheme and measurements of relative conversion coefficients established the octupole character[10] of the isomeric transition in Br^{80}. This completed the cycle of the discovery and explanation of nuclear isomerism, a general review of which ("The Isomerism of Atomic Nuclei") was published by Kurchatov.[11]

2. ISOMERISM AND NUCLEAR STRUCTURE

After it had been shown that nuclear isomerism results from the existence of metastable nuclear states and that the lifetimes of excited states depend primarily on the energies, multipole characters, and types of gamma transitions, a more intensive study of isomers began.

Kurchatov wrote regarding the role of isomers in the clarification of nuclear structure:[11] "Nuclear lifetimes in relation to different forms of nuclear radiation characterize the processes occurring within nuclei. The study of the relationship between the lifetimes and emitted energies has played a large part in nuclear physics. By analyzing the relationship between the half-lives of alpha and beta decays and the energies of the emitted particles many important concepts regarding the nature of nuclear processes have been developed. Bohr's consideration of gamma-ray emission half-lives in neutron capture led to the very important nuclear concept of an intermediate compound nucleus.

Isomeric gamma activity reveals the nuclear lifetimes for the emission of forbidden gamma rays. We can therefore expect that nuclear isomerism will lead to a deeper understanding of the nuclear processes involved in electromagnetic emission."

The subsequent accumulation of experimental data on isomers and the development of the theory of nuclear structure have fully confirmed Kurchatov's remarks.

Attempts have been made to calculate the probabilities of gamma transitions and the associated nuclear lifetimes on the basis of different concepts of nuclear structure and the gamma-ray emission mechanism — the liquid-drop, alpha-particle, independent-particle, and other models. The calculations yielded widely diverging results for the same isomeric transition. This was evidence that the lifetimes of isomers depend on the details of nuclear structure as well as on the energy and multipole character of gamma transitions. Therefore the comparison of experimental and theoretical isomeric lifetimes checks the correctness of the nuclear models on which the calculations are based.

Isomer studies comprised a considerable portion of the experimental information providing the basis of the shell and unified nuclear models.

Spherical nuclei. No rigorous theory has so far been developed for a nucleus as a complex system of strongly interacting nucleons. The forces acting between nucleons in the nucleus have not yet been sufficiently clarified. Approximate models must therefore be used to describe nuclear properties. The many-body problem is reduced to that of a single nucleon moving in a self-consistent field that results from the interaction between this nucleon and the other nucleons comprising the nucleus.

Goeppert-Mayer and Jensen[12] were the first to propose a model on this basis that accounted for the unusual stability of nuclei with specified numbers of protons or neutrons ("magic numbers"). They assumed that the effective nuclear potential is spherically symmetrical and took l-s interactions into account. The state of a nucleon in the corresponding field is characterized by the principal quantum number n, the total angular momentum j, the orbital angular momentum l, and parity $P = (-1)^l$. On this model the nucleons successively fill groups of levels with relatively close energies, forming shells. The spin of a nucleus with odd mass number A is determined by the spin of the odd last nucleon. The spins and parities of the ground states and low-lying excited states were accounted for satisfactorily by this model. The shell model explained the existence of the so-called "islands of isomerism," which are groups of isomers close to the magic numbers.

Kurchatov was greatly interested in the first work on the shell model, although at that time some theoreticians were doubtful of this model. It became very important to obtain an experimental check of the basic hypotheses of the shell model. For this purpose, at Kurchatov's initiative, a group of physicists undertook the systematic study of isomeric gamma transitions. Multipolarities and transition lifetimes were determined[13] for the isomers Zn^{69*}, Se^{79*}, Se^{81*}, Nb^{95*}, Rh^{103*}, and Ba^{137*}. It was shown that M4 transitions occur in Zn^{69*}, Nb^{95*}, and Ba^{137*}; these transitions are $g_{9/2} \rightarrow p_{1/2}$ in Zn^{69*}, $p_{1/2} \rightarrow g_{9/2}$ in Nb^{95*}, and $h_{11/2} \rightarrow d_{3/2}$ in Ba^{137*}. These data agreed with the level schemes of the shell model. In addition, the experimental lifetimes τ^{exp} of these isomers agreed well with the theoretical lifetimes τ^{theor} calculated from the independent-particle model. This further confirmed the correctness of the shell model for these nuclei.

In Se^{79*}, Se^{81*}, and Rh^{103*}, E3 transitions between $7/2^+$ and $p_{1/2}$ levels were observed. These transitions involving $7/2^+$ levels do not fit into the independent-particle scheme. States with total angular momentum $7/2^+$ can be accounted for by the shell-model only if it is assumed that the nuclear spin is not determined by a single "odd" nucleon but by a few nucleons in the $g_{9/2}$ state. Comparisons of the experimental and theoretical lifetimes show that a more complex reorganization of the nucleus occurs in the isomeric transitions of Se^{79*}, Se^{81*}, and Rh^{103*}. The experimental lifetimes are about 1000 times greater than the theoretical values calculated from the independent-particle model. E3 transitions in these nuclei will be discussed below.

It was shown that experimental information regarding isomeric transitions in Zn^{69*}, Nb^{95*}, and Ba^{137*} agree with the shell model. Experiments with Se^{79*}, Se^{81*}, and Rh^{103*} had also established that the independent-particle model of nuclear shells is only a first approximation.

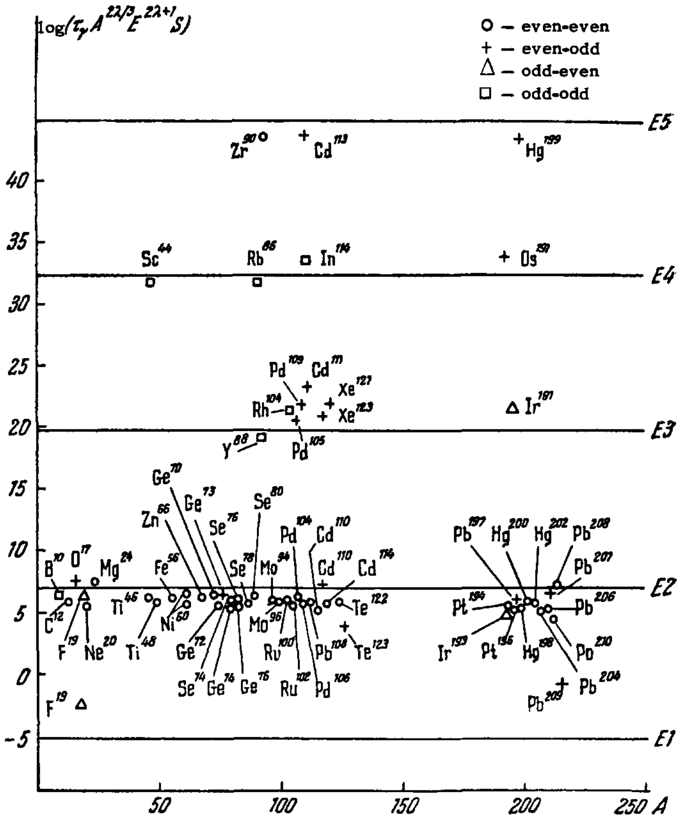

FIG. 1. Allowed electric transitions in spherical nuclei.

The nuclear lifetime τ_γ for gamma transitions depends on the energy E_γ, multipole order L, and transition type σ, which are measured experimentally, and also on the internal structure of the nucleus:

$$\tau_\gamma = \frac{A_L}{E^{2L+1} B(\sigma L)}, \tag{1}$$

where $B(\sigma L)$ is the reduced probability of electric or magnetic gamma transitions.

It is very difficult to calculate the reduced probabilities $B(\sigma L)$, for which the exact initial and final nuclear wave functions would be required. In the independent-particle approximation, where gamma emission results from the change of state of a single nucleon,[14]

$$B(EL) \sim (eR^L)^2, \quad B(ML) \sim \left(\frac{v}{c}\, eR^L\right)^2, \tag{2}$$

where e is the proton charge, R is the nuclear radius, and v is the nucleon velocity in the nucleus.

These calculations furnish only the lower limit of the lifetime for a completely allowed single-particle transition of given multiple order, since the radial matrix elements are represented by their maximum values.

Whenever the formulas of the independent-particle model are in satisfactory agreement with experiment, the independent-particle model can be assumed to be applicable. It will be shown that nuclei can be divided into two groups, those whose properties are described

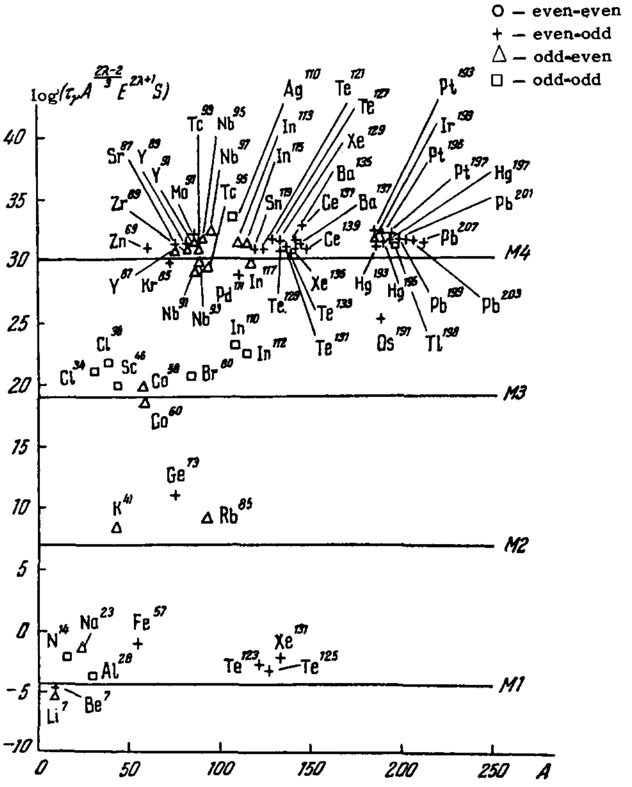

FIG. 2. Allowed magnetic transitions in spherical nuclei.

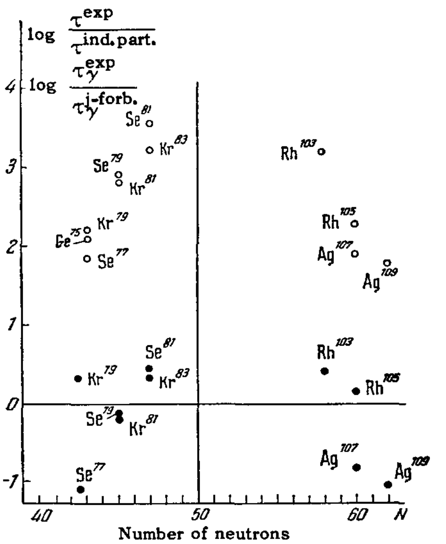

FIG. 4. j-forbidden E3 transitions. ○ – calculated from the independent-particle model; ● – calculated for mixed configurations.

satisfactorily by a model with a spherical potential, and those whose properties are in better agreement with a model involving an ellipsoidal deformed potential.

For spherical nuclei Figs. 1 and 2 show nuclear lifetimes for electric and magnetic gamma transitions calculated from the independent-particle model, which are in good agreement with experiment. A detailed comparison of experimental and theoretical results has shown[15] that for M4 transitions τ^{exp}/τ^{theor} depends on the degree to which shells are filled with neutrons (Fig. 3) and protons. The lifetimes of metastable states are thus sensitve to the details of nuclear structure.

In investigating the details of nuclear structure it is especially important to study gamma-ray transitions that are forbidden by the independent-particle model. For example, in Se^{79}, Se^{81}, and Rh^{103} we find E3 radiation representing $[(g_{9/2})^3]_{7/2+} \rightarrow (p_{1/2})$ transitions. These are cases of so-called j-forbiddenness, since $\Delta j > \Delta I$ (Fig. 4). This cannot be a single-particle gamma transition because the change in angular momentum of the odd particle exceeds the multipole order of the radiation ($L = \Delta I$) in the nuclei with odd nucleon numbers 43, 45, and 47 where E3 transitions occur: $\Delta j = {}^9\!/_2 - {}^1\!/_2 = 4$ and $\Delta I = {}^7\!/_2 - {}^1\!/_2 = 3$.

With the independent-particle model we also have the so-called l-forbidden transitions, for which $\Delta l > \Delta I$ (Fig. 5). In these transitions the change of the orbital angular momentum of the odd nucleon exceeds the angular momentum L carried away by the gamma ray. For example, in Cs^{135} the M1 transition $d_{5/2} \rightarrow g_{7/2}$ is l-forbidden:

$$\Delta l = g - d = 2, \text{ and } \Delta I = \frac{7}{2} - \frac{5}{2} = 1.$$

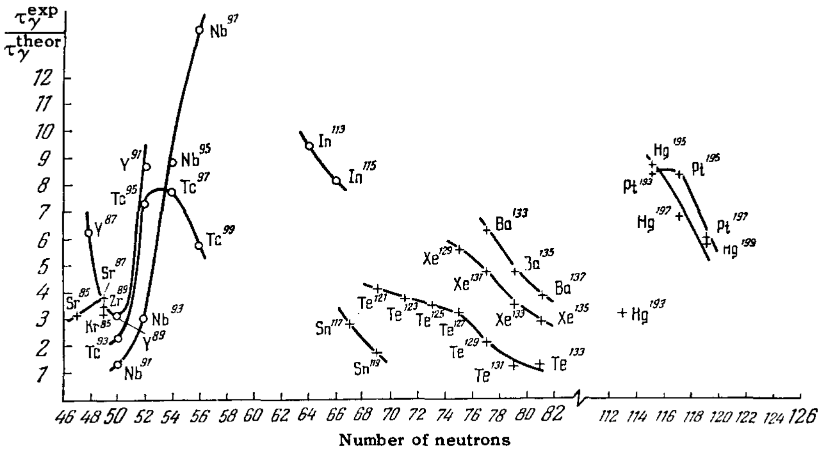

FIG. 3. Dependence of lifetime ratio $\frac{\tau_\gamma^{exp}}{\tau_\gamma^{theor}}$ for M4 transitions on the number of neutrons.

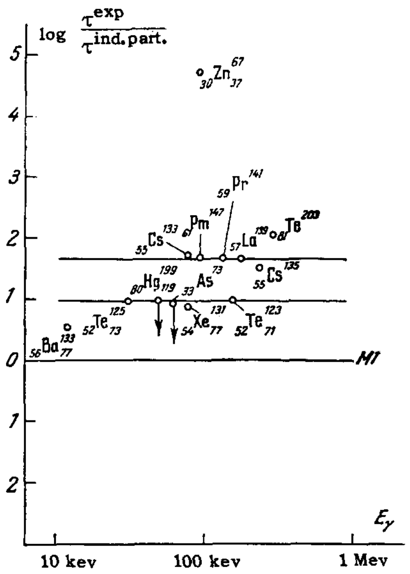

FIG. 5. l-forbidden M1 transitions. τ_γ was calculated on the independent-particle model.

j-forbiddenness and l-forbiddenness would be absolute if the independent-particle shell model were a complete description of nuclear states. However, experimental data show a certain probability of j-forbidden and l-forbidden transitions, although they are considerably hindered compared with the independent-particle estimates for allowed gamma transitions. This results from an additional interaction between nucleons in the same shell, which is not taken into account by the independent-particle model. The investigation of forbidden gamma transitions thus helps to clarify the details of nuclear structure. The known cases of j-forbidden transitions (Fig. 4) show that gamma-transition lifetimes calculates with the additional interaction taken into account are in much better agreement with experiment.[16] The situation if similar in the case of l-forbidden transitions.[17]

It is highly essential to investigate isomers in the region of doubly magic numbers, where the energies, transition probabilities, and other properties can be calculated relatively rigorously.

Golenetskii, Rusinov and Filimonov[18] have studied the isomeric decay $_{83}Bi^{210*}_{127} \xrightarrow{\alpha} {}_{81}Te^{206}_{125}$ (Fig. 6). In this case both the daughter and parent nuclei differ by two nucleons from doubly magic nuclei. This investigation revealed an isomeric state of Bi^{210} and the system of lowest excited Te^{206} levels.

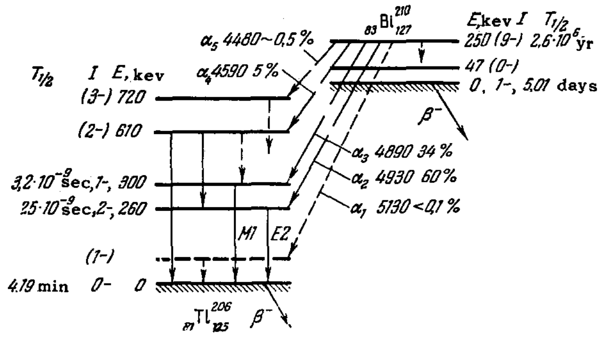

FIG. 6. Decay scheme of Bi^{210*}.

Energy levels of Bi^{210} and Te^{206} have been calculated theoretically by Sliv and Kharitonov[19] using a shell model that took into account pair interactions and interactions with the nuclear surface. The spins, parities and energies of these levels agree with experiment.

It had been assumed until recently that long-lived Bi^{210} ($T_{1/2} = 2.6 \times 10^6$ years) is in the ground state, but that the state with $T_{1/2} = 5$ days (RaE) is metastable. Investigation has shown that RaE is the ground state of Bi^{210} and that the state with $T_{1/2} = 2.6 \times 10^6$ years is metastable.

It should be noted that the description of nuclear levels by the shell model with a spherical potential is only a first approximation. The character of the isomeric levels has still not been determined for some nuclei in this spherical group. For some isomeric transitions there are large discrepancies between the experimental and theoretical shell-model lifetimes, and further study is needed.

Deformed nuclei. The independent-particle model cannot account for the properties of nuclei with mass numbers 24 — 26, 150 — 190, and above 222. These nuclei exhibit unusually large probabilities of E2 transitions and large quadrupole moments, which are inconsistent with independent-particle nucleonic motion within the nucleus. The given properties indicate that an important part is also played by collective nucleonic motion and that the nuclei have a deformed, rather than a spherical, shape.

Stable nuclear deformation results from interactions between weakly bound nucleons in unfilled shells and other nucleons in the closed shells forming the nuclear core. At low excitation energies of these nuclei single-particle motion can be accompanied by collective rotational and vibrational motions. All of these motions can be regarded as independent in first approximation. Each internal nuclear state has its system of rotational levels with energies given by

$$E_{\rot} = \frac{\hbar}{2J}\left[I(I+1) - I_0(I_0+1)\right]; \qquad (3)$$

I_0 and I are the spins of the ground and excited states, respectively, and J is the nuclear moment of inertia.

In actuality nuclear rotation cannot be considered to be entirely independent of the vibrational and internal motions; this causes some distortion of the rotational spectrum. The significant rotational-vibrational interaction lowers the rotational levels; the correction is

$$\Delta E_{\rm rot} = aI^2(I+1)^2. \qquad (4)$$

In the decay of Hf^{180*} (Fig. 7) levels with spins 2^+, 4^+, 6^+, and 8^+ are excited, forming the ground-state

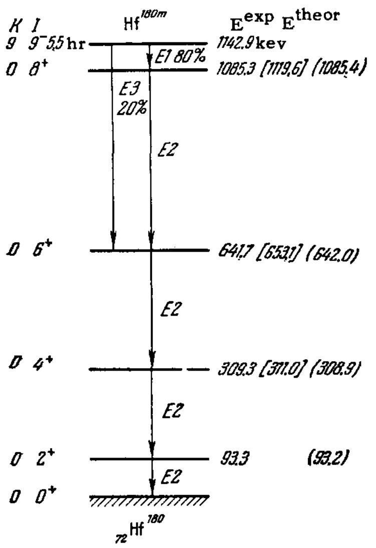

FIG. 7. Decay scheme of Hf^{180*}.

rotational band. An isomeric level with spin 9^- corresponds to another internal state of Hf^{180}. Figure 7 shows the experimental and theoretical rotational energy levels; the theoretical energies were calculated from (1), or from (1) corrected by (2).

M1 or E2 transitions can occur between levels of a single rotational band; in the case of even-even nuclei only E2 transitions are possible. The probability of magnetic dipole transitions is associated with the nuclear magnetic moment, which does not differ greatly from the magnetic moment of a single particle. Therefore the probability of M1 transitions is about the same as that estimated on the independent-particle model. The probability of E2 transitions is associated with the nuclear quadrupole moment, which exceeds considerably the quadrupole moment on the independent-particle model. Figure 8 shows the ratios of calculated nuclear lifetimes in rotational states to the experimental lifetimes measured by delayed coincidences and determined from Coulomb excitation cross sections. The probabilities of E2 rotational transitions are seen to be about 100 times greater than probabilities given by the independent-particle model. However, for the collective model there is good agreement between experimental and theoretical values, since the calculations do not require the unknown nuclear wave functions.

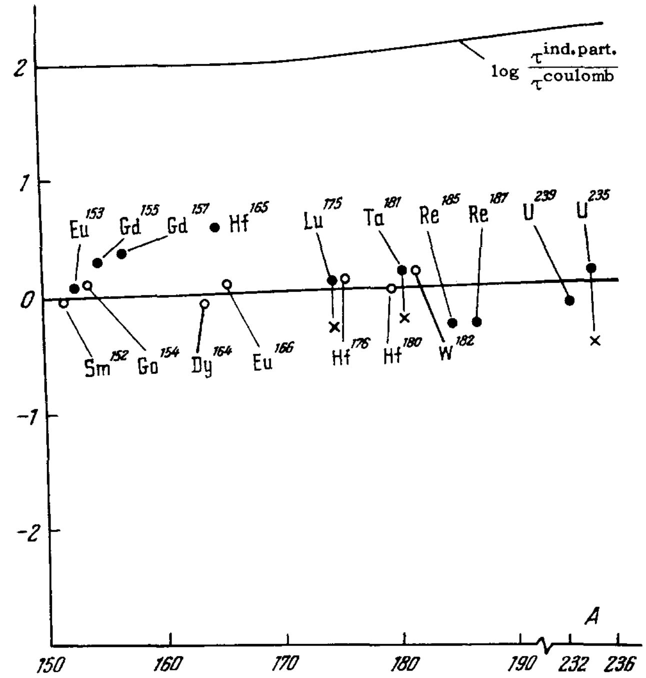

FIG. 8. E2 transitions between levels of a single rotational band.

$$\circ - \log \frac{\tau_\gamma^{\text{coulomb}}}{\tau_\gamma^{\text{direct}}}, \quad \bullet - \log \frac{\tau_\gamma^{\text{exp}}}{\tau_\gamma^{\text{theor}}}.$$

Electromagnetic transitions between states of different rotational bands in deformed nuclei are governed by both the usual spin and parity selection rules and by a supplementary selection rule for the quantum number K, which is the projection of the total nuclear angular momentum on the symmetry axis:

$$\Delta I \geqslant K. \tag{5}$$

The K selection rule will be obeyed strictly only when K is a "good" quantum number, i.e., when the internal and rotational motions are completely independent of each other. In actuality there is always some coupling between these two forms of motion, and K is only an approximate quantum number. Therefore the K selection rule results in reduced transition probabilities rather than in complete forbiddenness. The degree of forbiddenness of a transition is given by

$$\nu = |\Delta K| - L. \tag{6}$$

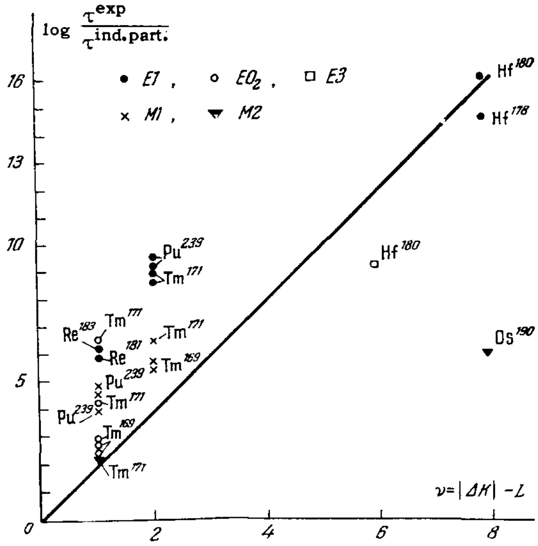

FIG. 9. K-forbidden transitions in deformed nuclei.

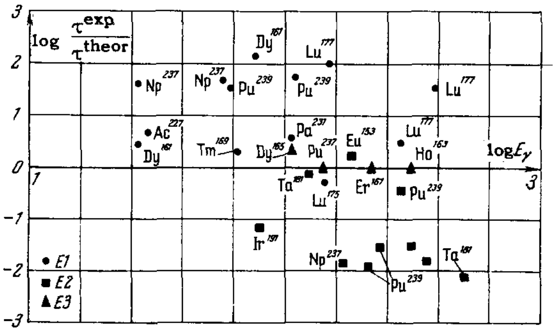

FIG. 10. Single-particle electric transitions in deformed nuclei.

Gvozdev and Rusinov[21] were the first to do work on the decay of Hf^{180*} in which a highly K-forbidden transition was found.

Hf^{180*} decays by transitions to the upper states of the rotational band associated with the ground state (Fig. 7); an E1 transition takes place to the 8^+ level, and an E3 transition to the 6^+ level. The lifetime for the 57.6-kev E1 transition is about 10^{16} times larger, and the lifetime for the 501.2-kev E3 transition is about 10^9 times larger than the lifetimes derived from the independent-particle model.

The lifetime of Hf^{180*} has been calculated[22] taking into account the coupling of collective and single-particle motions. This calculated value of τ_γ is of the same order of magnitude as the experimental lifetime, and thus represents much better agreement than can be obtained by the independent-particle model.

K-forbidden transitions are also observed in other nuclei (Fig. 9), but the degree of K forbiddenness is small in all other instances. The experimental data on K-forbidden transitions show that increase of K forbiddenness by one degree represents the reduction of transition intensity by a factor of about 100. A separate calculation for each individual case is required in order to obtain an accurate theoretical probability of K-forbidden transitions.

The properties of deformed nuclei containing an odd number of nucleons are accounted for satisfactorily by the unified model, which takes into account both the collective motions of nucleons and the internal excitation of the nucleus associated with changed states of individual nucleons. This model predicts the spins and parities of states for the indicated nuclei. Nilsson[23] has calculated wave functions that can be used to estimate the probabilities of different multipole transitions for single-particle excitations in deformed nuclei. These calculations[24] result in much better agreement between the experimental and theoretical lifetimes (Fig. 10) than can be obtained on the independent-particle model. The differences range up to the factor 10^6.

In some deformed nuclei levels are found corresponding to beta and gamma vibrations of the nuclear surface, i.e., vibrations along the nuclear axis and in a plane perpendicular to that axis, respectively. These levels have not yet been studied thoroughly. A. S. Davydov[25] has proposed another interpretation of gamma-vibrational levels, according to which these levels correspond to the rotation of a non-axially deformed nucleus. Future experiments will check the correctness of the hypothesis regarding the non-axial deformation of some nuclei.

The transition region between spherical and deformed nuclei also requires further experimental study and theoretical analysis. It will be interesting to check the hypothesis[26] that in the transition region the degrees of deformations of the ground and excited states can differ greatly; for example, that the ground state can be spherical while an excited state corresponds to some stable deformation. In this case an isomeric transition will be subject to additional strong forbiddenness.

Nuclear isomerism is very interesting in the region of highly deformed heavy and transuranic elements. For example, in a recent investigation[27] of the level scheme of U^{235} it was found that the first excited level is isomeric ($T_{1/2} = 26.2$ min) with the extraordinarily low excitation energy of less than 100 ev.

A considerable number of isomers are found among both deformed and spherical odd-odd nuclei. These have been subjected to the smallest amount of experimental investigation, although they are interesting because the properties of odd-odd nuclei are largely determined by the quantum states of the odd proton and neutron. Gamma-ray transition probabilities in these nuclei can sometimes[28] be represented by the probabilities of the corresponding transitions in neighboring odd nuclei.

Nuclear ground states and low-lying excited states (up to 1.5 or 2 Mev) usually resulting from beta and alpha decays have been studied thoroughly both theoretically and experimentally. It is necessary, however, to develop the study of nuclear properties at higher energy levels, where we can expect to discover new and more complex processes of nuclear reorgani-

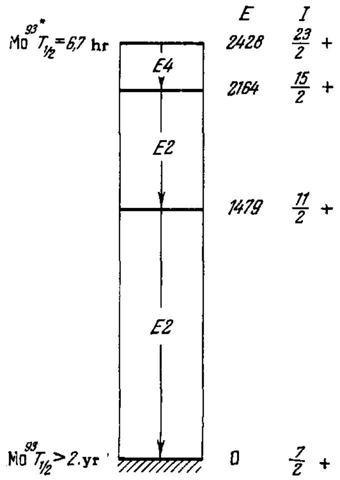

FIG. 11. Decay scheme of Mo^{93*}.

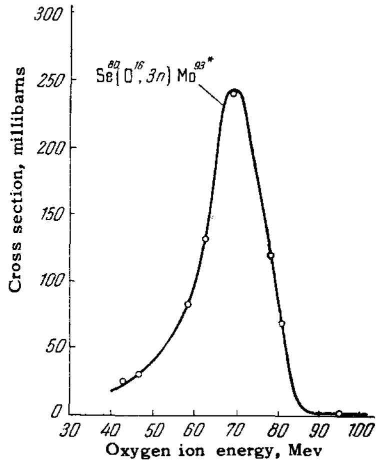

FIG. 12. Cross section for $Se^{80}(O^{16}, 3n)Mo^{93*}$ vs energy of oxygen ions.

zation participated in by both outer and core nucleons. In this connection let us consider the "island of isomerism" involving Mo^{93*}.

The isomeric state of Mo^{93} has 2428 kev and spin $23/2^+$ (Fig. 11). This large spin results from changed coupling of the angular momenta of a pair of core protons in the $g_{9/2}$ level, leading to the configuration

$$(g_{9/2})_p^2 J' = 8 (g_{7/2})_n I = \frac{23}{2}+ .$$

High-energy isomeric states correspond to large values of the total nuclear angular momentum. The excitation of these states can be expected with high probability from processes involving large spin changes. A very promising technique employs nuclear reactions with multiply charged ions, where a heavy ion transfers angular momentum up to 50 — 100ħ to a compound nucleus.

When a highly excited compound nucleus emits nucleons and gamma rays it can drop to a metastable state with large angular momentum and energy below the nucleon binding energy.

In the laboratory of G. N. Flerov at the Institute of Atomic Energy of the U.S.S.R. Academy of Sciences, Mo^{93*} was produced in the reaction $Se^{80}(O^{16}, 3n)Mo^{93*}$ (Fig. 12) with the relatively large cross section 250 millibarns.[29] New possibilities are thus presented for the study of nuclear properties at relatively unfamiliar highly excited isomeric levels.

The investigation of nuclear isomers has to a considerable degree determined the development of ideas regarding nuclear structure. The unified model has accounted basically for experimental data on isomers.[30] However, complete quantitative agreement between experiment and theory has not yet been achieved. We can expect that further studies of isomers will lead to improved concepts of nuclear structure.

The first work by I. V. Kurchatov on anomalous radioactive transformations of bromine thus has led to a new direction of nuclear physics, the investigation of nuclear isomers. Kurchatov himself made a large contribution in this direction. He at first participated directly in isomer studies, and thereafter maintained a strong interest, assisting the development of isomer investigations in every possible way.

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