GAMMA RADIATION FROM HIGH-SPIN NUCLEI

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Submitted to JETP editor November 16, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) 44, 1171-1179 (April, 1963)

The energy spectra of the γ rays produced in the interaction of accelerated O^{16} and Ne^{22} ions with Cu, Ta, W and U nuclei were investigated in the 74—145 MeV energy range with the help of a single-crystal scintillation spectrometer. In each decay of the compound nucleus, up to 13 γ quanta with energies from 0.7 to 1.1 MeV were observed. The effect of the spin of the excited nucleus on the decay mechanism is discussed.

INTRODUCTION

THE compound nucleus produced in reactions with heavy ions is marked by a large angular momentum. At energies above the Coulomb barrier, under the assumption that any contact of the surfaces of two nuclei leads to their complete fusion with a production of a compound nucleus, the maximum angular momentum of the latter can be determined in a classical way from the relation

$$j_{max} = \frac{R_1 + R_2}{\hbar} [2M(E - B_C)]^{1/2},$$

where R_1 and R_2 are the radii of the ion and target nuclei, M is the reduced mass, E is the kinetic energy, and B_C is the Coulomb barrier in the center-of-mass system. Thus, for example, for Ne^{20} ions with an energy of about 140 MeV in the l.s. bombarding a copper target, the compound nucleus of yttrium will have an excitation energy of 110 MeV and a maximum spin $j_{max} \approx 70\hbar$.

The presence of such a high angular momentum in the compound nucleus is of importance for the mechanism of its decay. The theoretical investigations of the decay of rotating nuclei are very limited. The general picture of the evaporation of particles from an excited nucleus with a high angular momentum in the quasi-classical statistical approximation has been considered by Strutinskiĭ.[1]

Strutinskiĭ obtained expressions for the mean kinetic energy and angular momentum of the evaporated neutrons. A quantitative analysis shows that in the compound-nucleus decay process practically the entire excitation energy and a comparatively small part of the initial angular momentum are carried off by nucleons. It is assumed that the residual energy and the angular momentum of the nucleus, after evaporation of the nucleons, are carried away by the cascade emission of soft γ rays.

Using the independent-particle model, Pik-Pichak[2] also considered the evaporation of nucleons. In the case of a compound nucleus with a high rotational energy, a "centrifugal" mechanism for the emission of nucleons was predicted. Estimates made within the framework of this model also indicate that, after the emission of the nucleons, the nucleus retains a high angular momentum.

The γ radiation arising in the decay of a compound nucleus of high spin has been investigated experimentally in [3,4].

In the present work, we studied the γ spectra resulting from the bombardment of Cu, Ta, W, and U targets by O^{16} and Ne^{22} ions in the 74—145 MeV interval.

For the Cu + Ne^{22} and Ta + O^{16} reactions we determined the upper limit of the cascade γ-transition lifetimes.

EXPERIMENTAL CONDITIONS

The experiment was carried out with the internal beam of the 300-centimeter cyclotron of the Nuclear Reactions Laboratory of the Joint Institute of Nuclear Research. Ions of $O^{16(+3)}$ and $Ne^{22(+4)}$, accelerated to 4—9 MeV/nucleon, impinged on a target fixed to a special probe. The beam intensity in the experiment was between 1 and 7 μA. The ion energy was varied by placing the target on orbits of different radii; for a fixed position we determined the ion energy from the stopping of ions in aluminum foils [5] to an accuracy of at least 3%.

As targets we employed foils of Cu, Ta, W, and U of natural isotopic composition mounted on the cooled copper surface of the probe. In the experiment we used "thick" targets to avoid contamination from the background radiation arising in the

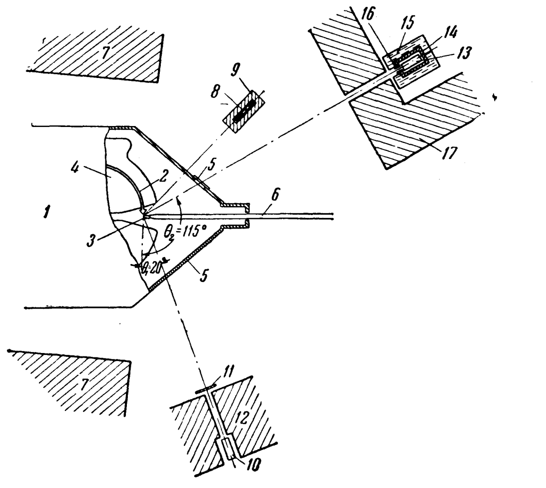

FIG. 1. Experimental arrangement. 1) Cyclotron chamber, 2) ion beam, 3) target, 4) dee, 5) diaphragm, 6) probe, 7) magnet, 8) BF_3 counter, 9) paraffin, 10) neutron counter, 11) Pb shield for γ quanta (0.02 m), 12) concrete, 13) scintillation γ spectrometer, 14) lead (0.05 m), 15) H_2O + B (0.2 m) shield, 16) Pb diaphragm (0.05 m), 17) concrete shield (1.0 m)

copper base; the target thickness in the experiment was between 25 and 100 μ.

The experimental arrangement is shown in Fig. 1. The flux of particles impinging on the target was measured by a sensitive detector [6] and was monitored with the aid of an all-wave BF_3 neutron counter placed close to the cyclotron chamber.

The γ radiation in the 0.05—3 MeV interval was recorded by a single-crystal scintillation spectrometer located outside the accelerator chamber at a distance of 5 m from the target. In the measurements we used a NaI(Tl) crystal 40 mm in diameter and 40 mm thick. Pulses from an FÉU phototube were applied to the input of a 100-channel AI-100/1 pulse-height analyzer. The spectrometer was calibrated with monochromatic γ-rays from Hg^{203} (0.280 MeV), Cs^{137} (0.660 MeV), Zn^{65} (1.11 MeV), Co^{60} (1.13 and 1.33 MeV), and Na^{24} (2.75 MeV).

To eliminate background from Compton scattering along the path from the target to the crystal, the γ-ray beam was diaphragmed twice. The absolute efficiency of the spectrometer was determined with the aid of strong calibrated γ sources of various energies placed in the position of the target. The value obtained was 4×10^{-7}. Special attention was paid to sources of background γ radiation.

During the work it was found that a large part of the background radiation over the entire range of measured γ-ray energies was due to the interaction of neutrons with the NaI crystal.

According to the experimental data, the excited compound nucleus produced in the reactions studied by us evaporated an average of 3—5 neutrons, whose spectrum has the shape of a Maxwell distribution with an energy of $\sim$ 2.5—3.0 MeV at the maximum.

It should be noted that to avoid distortion of the γ spectrum due to the Compton scattering on the individual components of the accelerator chamber, the γ radiation was recorded in a narrow solid angle. Shielding from scattered γ rays is "transparent" for neutrons, and the ratio of the γ-ray and neutron intensities can differ considerably from the expected value. The cross section for the inelastic scattering of 2.5-MeV neutrons is 1.96 b for iodine and 0.47 b for sodium. The γ radiation in inelastic scattering contributes mainly to the soft part of the γ spectrum ($E_\gamma \leq 0.6$ MeV).

The cross section for activation on iodine at $E_n \approx 1$—2 MeV is small ($\sim$ 0.1 b), but sharply increases in the energy region $E_n \leq 1$ keV, attaining 50—100 b. On the other hand, it is known that each act of capture of a slow neutron by an excited I^{128} nucleus is accompanied by the emission of an average of three γ quanta of energy 2.0—2.5 MeV. In view of the fact that in our experiment the detector was at a large distance from the target, scattered neutrons, whose spectrum was considerably softer than those in the case of neutrons close to the target, could have impinged on the crystal.

In this connection we constructed shielding to protect the spectrometer from the scattered neutron flux. The phototube was placed in a lead shield (wall thickness 50 mm) which, in turn, was surrounded by a 200-mm layer of a three-percent solution of boric acid in water; in addition, a 5-mm layer of B_4C powder was placed around the crystal.

The entire apparatus was placed behind a concrete shield 1.0 m thick in which was mounted a collimator of 100-mm diameter aimed at the target. Control experiments showed that the contribution from the γ-ray background due to neutrons did not exceed 7% of the total γ-ray intensity recorded by the spectrometer. In the energy region $E_\gamma < 0.2$ MeV we observed a high counting rate of γ quanta due to electron bremsstrahlung inside the cyclotron vacuum chamber.[7]

The maximum energy of the bremsstrahlung spectrum was essentially dependent on the h. f. voltage on the dees, and hence we were faced with the problem of obtaining the necessary beam current on a given orbit of the accelerator with a minimum value of the accelerating potential.

Reaction	Max. ion energy, E_{max}, MeV	Mean cross section $\bar{\sigma}_c$, b	Excitation energy E*, MeV	Mean angular momentum $\bar{I}$, $\hbar$	Mean number of γ quanta per nucleus $\bar{\nu}$ (expt)	$\bar{E}_\gamma$, MeV	Total energy of γ radiation νE_γ, MeV
$Cu + Ne^{22}$	74	0.36	56	19	6	0.80	5
	94	0.71	66	25	10	0.75	7
	115	0.92	75	29	13	0.70	9
	140	1.06	86	35	11	0.70	8
$Ta + O^{16}$	85	0.27	49	17	7	0.85	6
	100	0.47	61	25	9	0.80	7
$W + O^{16}$	85	0.27	50	16	7	1.05	8
	100	0.47	62	24	8	1.00	8
$U + O^{16}$	145	1.13	78	45	10±2	—	—

The activation of the target and the elements of the accelerator chamber not shielded from the beam was no more than 2% of the total γ-ray counting rate during the bombardment. The background due to Coulomb excitation of the target nuclei and ion bremsstrahlung was negligible.

In a number of runs, we recorded simultaneously the γ rays and the yield of neutrons produced in the bombardment of the target by the ion beam. For this purpose we used a phototube (FÉU-33) with a stilbene crystal shielded from the cyclotron chamber by a two-meter concrete wall. A 20-mm lead plate was placed in front of the collimator to reduce the γ background of the accelerator. Reliable discrimination from γ rays was achieved for neutrons of energy $E_n \geq 3$ MeV.

EXPERIMENTAL RESULTS

1. For a beam intensity of $\sim 10^{12}$ particles/sec the γ counting rate was 100—300 pulses/sec, which allowed us to obtain a good statistical accuracy in the instrument pulse spectra. Practically all the measurements were made with the γ spectrometer at an angle $\theta = 115°$ relative to the direction of the incident beam. The analysis of the instrumental spectra took into account the shape of the lines produced by monochromatic γ rays and the crystal efficiency.[8]

2. For the $Cu + Ne^{22}$ reaction we measured the γ spectra at incident beam energies of 74, 94, 115, and 140 MeV. The shape of the differential γ spectrum for two ion energies, 74 and 94 MeV, is shown in Fig. 2.

We express the absolute intensity of the radiation in terms of a parameter $\bar{\nu}$ numerically equal to the mean number of γ quanta for the decay of one nucleus. The quantity $\bar{\nu}$ was determined from the expression

$$\bar{\nu} = N_\gamma / n_0 \bar{\sigma}_c N_0,$$

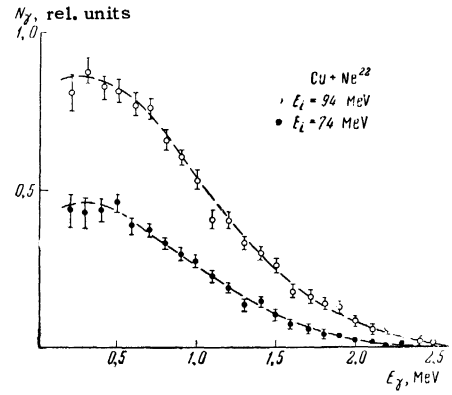

FIG. 2. Spectra of γ radiation from the $Cu + Ne^{22}$ reaction measured for 74- and 94-MeV beams of Ne^{22} ions.

where $N_\gamma = \int_0^\infty N'_\gamma dE_\gamma / \varepsilon_0(E_\gamma)$ is the total number of γ quanta produced in the reaction; n_0 is the ion beam intensity; $\bar{\sigma}_c$ is the cross section for compound-nucleus production averaged over the target thickness[1)] N_0 is the effective number of target nuclei, ε_0 is the absolute recording efficiency of the γ spectrometer.

In each run we determined the mean energy of the γ spectrum from the expression

$$\bar{E}_\gamma = \int E_\gamma N_\gamma dE_\gamma \Big/ \int N_\gamma dE_\gamma.$$

The experimental values of $\bar{\nu}$ and $\bar{E}_\gamma$ for the investigated reactions are summarized in the table, which also includes the basic characteristics of the compound nucleus.

In view of the fact that in the estimate of the quantity $\bar{\nu}$ we used the calculated value of the cross section for compound nucleus production, the accuracy of the absolute value of $\bar{\nu}$ is difficult to estimate. The values for $\bar{\nu}$ obtained in the ex-

1)In the determination of $\bar{\sigma}_c$ we used the theoretical results of Thomas[9] on the cross section for compound nucleus production by heavy ions.

periment indicate an increase in the mean number of γ rays emitted by the nucleus as the energy of the bombarding particles is increased. These data merit an additional check, since, at energies close to the Coulomb barrier of the reaction, the energy spread of the beam ($\Delta E/E \approx 3\%$) can introduce a large error in the determination of $\overline{\nu}$. In the ion energy region $E_i > 6$ MeV/nucleon, competitive direct processes proceeding without the production of a compound nucleus will be observed.

With the given beam energy we determined, along with the measurement of the γ-ray spectrum, the relative yield of neutrons arising in the reaction. In view of the fact that compound nucleus production is a dominating process up to an energy of $\sim$6 MeV/nucleon, the neutron intensity will be determined primarily by reactions of the (Ne^{22}, xn) type, where $x = x(E)$ is an increasing function of the ion energy. Then the neutron yield will increase with the energy somewhat faster than the compound nucleus production cross section.

The ratio of neutron and γ-ray intensities was measured for the Cu + Ne^{22} and Ta + O^{16} reactions as a function of the bombarding ion energy. The observed increase in the ratio N_γ/N_n with increasing ion energy also indicates an increase in the mean number of γ quanta emitted by the compound nucleus.

3. The study of γ radiation in the decay of a "magic" compound nucleus is of particular interest. Isotopes of "magic" nuclei of lead ($Z = 82$) could have been obtained by us in the bombardment of a W target by O^{16} ions. We compared the γ-ray spectra resulting from the bombardment of Ta and W targets by 100-MeV O^{16} ions. The ion energy was chosen close to the value of the Coulomb barrier in order to eliminate the fission process [10] and, along with this, to decrease as far as possible the contribution of reactions involving the emission of charged particles,[11] which could greatly distort the expected effect.

Figure 3 shows the γ-ray spectrum from Ta + O^{16} and W + O^{16} reactions for ion energies of $\sim$100 MeV in the laboratory system. For illustration, Fig. 3 also shows the instrumental pulse distribution. It is readily seen that for "magic" isotopes of lead the mean energy of the γ spectra is approximately 1.2 times that of the neighboring Tl nuclei produced in the Ta + O^{16} reaction.

4. Using the self-modulation of the ion beam in the cyclotron we performed a time analysis of the γ radiation arising in the Cu + Ne^{22} and Ta + O^{16} reactions. In these measurements the γ rays were recorded by a fast scintillation counter with an output to the time analyzer, which converted the

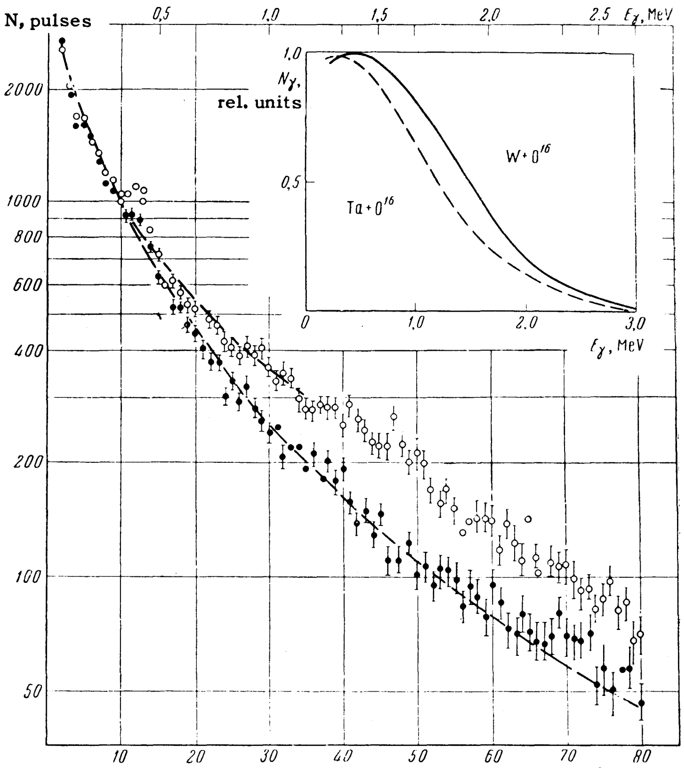

FIG. 3. Apparatus spectra from the reactions Ta + O^{16} (black circles) and W + O^{16} (open circles) measured for 100-MeV ions of O^{16}; inset — corrected spectra.

time interval into an amplitude.[12] The circuit resolution was 4.5×10^{-10} sec and the channel width was 2×10^{-10} sec.

The essence of the method was as follows. If in the bombardment of the target the radiation time is less than the duration of the current pulse, the γ-ray distribution recorded by the analyzer should closely follow the time characteristic of the internal ion beam at the given orbital radius. Figure 4 shows the time distribution of pulses obtained for the Cu + Ne^{22} reaction. Measurements made on different segments of the resonance

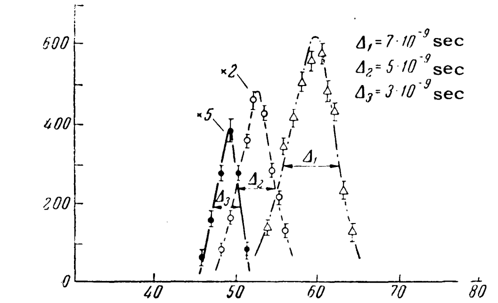

FIG. 4. Time distribution of pulses from the Cu + Ne^{22} reaction for 120-Mev Ne^{22} ions measured on different segments of the beam-current resonance curve.

curve [13] showed that the position of the peaks and the peak widths of the γ-ray distribution accurately correspond to the phase characteristics of the internal ion beam. The narrowest peak has a width of $\sim(2-3) \times 10^{-9}$ sec, and hence the upper limit of the time for the emission of cascade γ radiation is estimated to be $\tau_r < 10^{-9}$ sec.

5. To study the characteristics of the prompt γ radiation in the fission of heavy nuclei with a large angular momentum, a uranium target was bombarded by a beam of accelerated oxygen ions at an energy of 145 MeV. The measured γ spectrum was compared with the γ spectrum accompanying the fission of U^{235} induced by thermal neutrons. According to the data of [14], each act of fission induced by the capture of a thermal neutron is accompanied by the emission of 8 ± 2 quanta, which carry away an average energy of 7 ± 1 MeV. Similar data were obtained by Leachman [15] for the spontaneous fission of Cf^{252}.

In Fig. 5 the experimental points represent the γ spectrum from the fission of U^{238} induced by accelerated oxygen ions and the solid curve represents the prompt-radiation spectrum obtained in the fission of U^{235} induced by thermal neutrons. The calculation of the mean number of γ quanta per compound nucleus can be made in this case with greater accuracy than in the preceding measurements, since the cross section for the fission of uranium induced by heavy ions is well known, [13] and the processes competing with fission are negligible. It follows from our data that the number of γ quanta emitted in the fission of U^{238} induced by O^{16} is $\bar{\nu} = 10 \pm 2$.

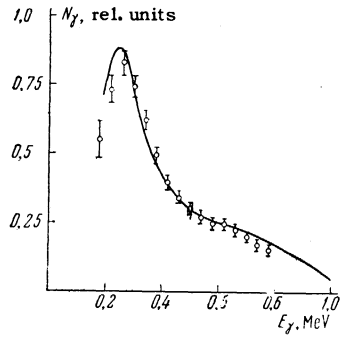

FIG. 5. Spectra of γ rays accompanying the fission of uranium induced by 145-MeV O^{16} ions (experimental points). The solid curve represents the spectrum of prompt γ rays from thermal-neutron induced fission of U^{235}.

DISCUSSION OF RESULTS

From the data obtained in our experiment[2)] it follows that when various targets are bombarded by accelerated heavy ions we observe prompt ($\tau_r < 10^{-9}$ sec) γ radiation consisting of a large number of γ quanta of mean energy 0.7–1.1 MeV.

The mean energy of γ quanta found by us for the $Cu + Ne^{22}$ and $Ta + O^{16}$ reactions is approximately 20% less than in the experiment of Mollenauer, [4] where the γ spectra for the $Ho + C^{12}$ and $V + C^{12}$ reactions were measured at an ion energy of ~110 MeV. This disagreement can be removed if we take into account the contribution of double superpositions which could have occurred in Mollenauer's work, owing to the relatively high recording efficiency for the γ cascade.

Before making a suggestion regarding the machanism of the cascade γ radiation, we compare the γ spectrum obtained by us for the excited Y nucleus (in the $Cu + Ne^{22}$ reaction) with the γ spectrum in radiative capture of a thermal neutron by the Rh^{103} nucleus [18] (close to the Y nucleus).

Qualitative differences in the spectra are clearly seen in Fig. 6. The γ radiation arising in the $Cu + Ne^{22}$ reaction is much softer than in the radiative capture of a thermal neutron. We suggest, that, according to the hypothesis of Strutinskiĭ, [1] this difference is due to the fact that the emission of γ quanta in the decay of a rotating nucleus occurs from states with greater angular momentum.

Under the assumption of complete statistical equilibrium, the characteristics of γ radiation from nuclei with high spin have been obtained. [19]

Allowance for the high angular momentum of the compound nucleus gave some softening of the γ spectrum, but the obtained results cannot explain the experimental data. The cause of the disagreement is ascribed to the fact that in the process of cascade γ emission the "thermal" component of the excitation energy decreases much more rapidly than the rotational component. Owing to this, in the process of cascade γ emission the relative contribution of the rotational energy increases, and the reliability of the quasi-classical statistical approach becomes doubtful. For a de-

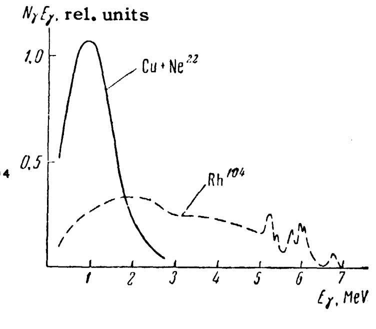

FIG. 6. Spectra of γ radiation plotted in the form $N_\gamma E_\gamma = f(E_\gamma)$ from the $Cu + Ne^{22}$ and $Rh^{103}(n,\gamma)Rh^{104}$ reactions.

[2)]The characteristics of the γ radiation in the $Cu + Ne^{22}$ and $Ta + O^{16}$ reactions found in our experiment somewhat differ from the preliminary data published in [17]. The need for a correction of the initial results arose in connection with additional experiments from which more accurate values of the level of the neutron background and the absolute recording efficiency of the γ spectrometer were obtained.

tailed consideration it is necessary to have information about the structure of the levels of nuclei with high spin at excitation energies of several MeV, and this information is not available at the present time. In the special case of deformed even-even nuclei, the energy of the last quanta will apparently be determined by the γ transitions of the rotational band, which is confirmed by Morinaga's experiments (private communication) with α particles.

In the $Cu + Ne^{22}$ reaction the total energy of the γ radiation is observed to increase with the compound nucleus angular momentum. These results quantitatively explain the character of the shift in the peaks of the excitation functions toward higher energies when neutrons are evaporated from the excited nucleus in reactions with heavy ions.[20]

When Ta and W targets are bombarded by O^{16} ions of energy 90—100 MeV, it is found that the mean energy of the γ rays in the $W + O^{16}$ reaction is approximately 1.2 times that in the case of $Ta + O^{16}$. This difference is of interest, since the excitation energy and the mean angular momentum of the compound nuclei in these reactions are practically identical.

Control measurements of the γ-ray spectra of neighboring nuclei in "crossed" reactions show that the observed effect cannot be explained by the difference in the parity of nuclei produced in the bombardment of Ta and W by oxygen ions. We believe that the difference in the character of the spectra is connected with the occurrence of a "magic" structure in the Pb compound nucleus.

Measurements of the γ-ray spectrum from the $U + O^{16}$ reaction were made to determine what happens to the initial angular momentum of the compound nucleus in the fission process. In fission the initial angular momentum appears in the relative motion of the fragments, which leads to an anisotropy in the angular distribution of the fission products.

The angular distributions of fragments from fission induced by heavy ions has been studied by a number of authors.[21] It does not appear possible to determine from the experiments the fraction of the angular momentum which appears in the relative motion of the fission fragments. The uncertainty of such nuclear parameters as temperature, moment of inertia at the saddle point, etc. does not allow the determination of the quantitative connection between the anisotropy coefficient and the angular momentum of the excited state. At the same time, it follows from data obtained with nonfissioning nuclei that the shape of the γ spectrum and the mean number of the emitted quanta depend on the compound nucleus angular momentum.

For the bombardment of U^{238} by O^{16} ions we obtained good agreement for the shape of the spectrum and the mean number of γ quanta with experiments on the fission of U^{235} induced by slow neutrons and in the spontaneous fission of Cf^{252}. This apparently indicates that, in the fission of nuclei induced by heavy ions, the main part of the angular momentum goes into the relative motion of the two fragments.

The authors thank V. M. Strutinskiĭ, V. V. Babikov, and V. A. Karnaukhov for helpful discussions.

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Translated by E. Marquit
193