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 $E_{\{\gamma\max\}}=1$
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Abstract

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PHYSICS

Academician of the Academy of Sciences of the Ukrainian SSR A. P. KOMAR,
B. A. BOCHAGOV, A. A. KOTOV,
G. G. SEMENCHUK, G. E. SOLYAKIN

NUCLEON COMPOSITION AND EXCITATION ENERGIES OF FISSIONING NUCLEI UPON IRRADIATION OF TARGETS OF Bi^{209} , Pb^{208} , AND Au^{197} WITH PHOTONS OF ENERGY $E_{\gamma \max} = 1 \text{ GeV}$

In the fission of nuclei by high-energy particles, problems always arise concerning the nucleon composition A , Z and the excitation energy E_{exc} . Until now these problems have been solved by considering the processes preceding fission. A , Z and E_{exc} were determined by calculation without invoking experimental data relating to the fission process, although they are connected with the characteristics of the fission fragments. In the present work, to determine A , Z and E_{exc} , data on the characteristics of fission products are used, in particular the effect of the decrease in the kinetic energy of fragments when neutrons are emitted from them, and the calculation ⁽¹⁾ of the mass and energy distributions of fragments at a specified nuclear temperature. The article uses results pertaining only to the "light target nuclei" Bi^{209} and Au^{197} , presented in ⁽²⁾, as well as new data for a target of Pb^{208} and refined data for a target of Au^{197} , calibrated against Cf^{252} fragments ⁽³⁾. The restriction to the region of light nuclei is due to the fact that the results of the calculations of Nix and Svyatetskii are valid only for symmetric fission of nuclei lighter than radium. In addition, for these nuclei, according to Pleasonton ⁽⁴⁾, neutron evaporation before fission is insignificant.

The starting formula for our calculations was the Seaborg-Viola formula ⁽⁵⁾ for the mean kinetic energy of fragments E_k^i before the emission of neutrons from them, established on the basis of numerous experimental data. According to this formula,

$$E_k^i = 0.1071z^2/A^{1/3} + 22.2 \text{ MeV}, \quad (1)$$

where A is the mass number and Z is the charge of the fissioning nucleus.

In the course of fragment separation, their excitation is removed by the emission of neutrons and γ quanta. By comparing the experimentally determined value of the kinetic energy of the fragments E_k^f after neutron emission with E_k^i , one can in principle determine the number of these neutrons.

An essential question here is the time of neutron emission from the fragments, their spectrum, and the relation between the mass of the fragments and the number of neutrons emitted by them. Numerous and careful measurements of neutron spectra from fission fragments^(6,7) make it possible to conclude that: 1) the neutrons are emitted by fully accelerated fragments; 2) in the inertial system of the moving fragment their distribution is isotropic; 3) as regards the connection between the number of neutrons and the mass of the fragment, measurements carried out in⁽⁸⁾ on fission of U^{238} by α particles with energy 25.5 MeV lead to a dependence of the form

$$\nu_l/\nu_h = m_l/m_h,$$

from which it may be concluded that, with increasing energy of the bombarding particles, the excitation energy of the nucleus is distributed among the fragments in proportion to their mass. The authors of⁽⁹⁾, on fission of U^{238} by protons with energy 450 MeV, arrive at similar conclusions regarding the character of the distribution of excitation energy among the fragments.

Taking into account the above-mentioned regularities in the emission of neutrons from fragments, the relation between E_k^i and E_k^f has the form

$$E_k^f = E_k^i (1 - \nu_p/A) + 2\nu_p \bar{\eta}/A, \quad (2)$$

where ν_p is the total number of neutrons from both fragments; $\bar{\eta}$ is the mean kinetic energy of a neutron from the fragments.

The experimental values of the kinetic energies E_k^f for fission fragments arising upon irradiation of targets of Bi^{209} , Pb^{208} , and Au^{197} by γ -quanta with $E_{\gamma_{\max}} = 1$ GeV are presented in Fig. 1. More detailed information on the mass and energy distributions of the fragments is contained in Ref. (2). Using the experimental values E_k^f , as well as relations (1) and (2), one can obtain the total number of neutrons emitted from the fragments:

$$\nu_p = A \left(1 - E_k^f/E_k^i \right). \quad (3)$$

The second term on the right-hand side of relation (2) has been omitted because it is small in comparison with the first term.

Knowledge of the total number of neutrons emitted from the fragments makes it possible to determine the excitation energy of each of the fragments. The total excitation energy of the fragments is calculated from the obvious relation

Figure 1: Dependence of the mean total kinetic energies of fragments E_k^f on the mass of the heavy fragment for targets Bi²⁰⁹ (1), Pb²⁰⁸ (2), Au¹⁹⁷ (3)

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$$W = \sum_{j=1}^{\nu_l} (B_{j1} + \bar{\eta}_{j1}) + \sum_{j=1}^{\nu_t} (B_{jt} + \bar{\eta}_{jt}) + W_\gamma. \quad (4)$$

Here B_j is the binding energy of neutrons in the light and heavy fragment, respectively; W_γ is the energy carried away from the fragments by γ -quanta (taken to be equal to 8 MeV).

The procedure for determining the excitation energy from the calculated ν_p was as follows. The process of neutron evaporation from a fragment was considered in reverse order. It was assumed that, after the emission of all neutrons, an energy $W_\gamma/2 = 4$ MeV remains in the fragment. Then the excitation energy before the emission of the last neutron, or, what is the same, after the introduction of the first neutron, will be

$$W_1 = B_1 + \bar{\eta}_1 + W_\gamma/2.$$

Similarly,

$$W_2 = W_1 + B_2 + \bar{\eta}_2 \quad \text{and so on.}$$

Since the kinetic energy of a neutron is determined by the value of the excitation energy before its emission from the fragment ⁽¹⁰⁾,

$$\bar{\eta}_j = \frac{4}{3} \left(\frac{8W_j}{A_{\text{frag}} - A_{\text{frag}} + j} \right)^{1/2},$$

the calculation of W reduced to solving a system of recurrence equations of the form

$$W_j = \left(\sqrt{\frac{32}{9(A_{\text{frag}} - \nu_{\text{frag}} + j)}} + \sqrt{\frac{32}{9(A_{\text{frag}} - \nu_{\text{frag}} + j)} + B_j + W_{j-1}} \right)^2. \quad (5)$$

Fig. 2

Figure 2: Fig. 2

Table 1

Target nucleus	Fissioning nu- cleus	E_k^f , MeV	ν_n	W , MeV	θ , MeV	$\mu_2(E_k^i)$	$\mu_2(E)$	$\mu_2(M)$	$\mu_2(M)$
						exp., MeV ²	theor., MeV ²	exp., a.m.u. ²	theor., a.m.u. ²
${}_{79}\text{Au}^{197}$	${}_{77}\text{Ir}^{193}$	148 ± 3	19	190	2.76	156 ± 7	178	365 ± 8	375
${}_{82}\text{Pb}^{208}$	${}_{81}\text{Tl}^{205}$	128 ± 3	18	170	2.53	148 ± 4	159	280 ± 6	300
${}_{83}\text{Bi}^{209}$	${}_{82}\text{Pb}^{206}$	132 ± 3	17	165	2.51	158 ± 4	159	272 ± 5	287

The neutron binding energy in the fragment nuclei B_j was taken from Seeger's mass table (11). The entire problem was solved on a Minsk-22 computer. Then, on the basis of the energy-balance equation, the excitation energy of the fissioning nucleus at the saddle point was determined:

$$E_{\text{exc}} = E_k^i + W - E_D - B_f. \quad (6)$$

Here E_D is the fission energy, determined from mass tables (11); B_f is the liquid-drop fission barrier (12). The relation between E_{exc} and the temperature θ is given, according to (10), in the form

$$E_{\text{exc}} = \frac{1}{2}A\theta^2 - \theta.$$

Thus, to each possible value

$$x = \frac{(Z^2/A)}{(Z^2/A)_{\text{cr}}}$$

of the fissioning nuclei it was possible, as a result of the analysis performed, to assign a nuclear temperature θ .

Fig. 2. Comparison of experimental (points) and calculated (solid lines) dependences of the variances of the energy distributions on the mass of the heavy fragment for the target Au^{197} . 1 – calculation assuming the fissioning nucleus Au^{197} ; 2 – Ir^{193} ; 3 – Os^{192} .

From these parameters, on the basis of the Nix-Swi tecki model (1), the values of the fragment kinetic energies E_k^i and the variances $\mu_2(E_k^i)$ and $\mu_2(M)$ were calculated. The calculated values of the latter quantities were used to construct the dependences of $\mu_2(E_k^i)$ and $\mu_2(M)$ on the mass of the heavy fragment. The constructed curves were compared with the curves obtained experimentally. Since neutron emission from the fragments leads to a distortion of the variances $\mu_2(E_k^f)$, a correction was introduced into them according to the formula from (13):

$$\mu_2(E_k^i) = \left[\mu_2(E_k^f) - \frac{4\nu_n \bar{\eta} E_k^i}{4A} \right] \left(1 - \frac{\nu_n}{A} \right)^{-2}.$$

No correction was introduced into the values of $\mu_2(M)$, since neutron emission at the ratio $\nu_l/\nu_t = m_l/m_t$ does not distort them.

Figure 2 gives the results of a comparison of the experimental and calculated variances of the energy distributions, which are most sensitive to the choice of the parameters of the fissioning nucleus. It is seen that identification of Ir^{193} as the principal fissioning nucleus in irradiation of a gold target is in the best agreement with the experimental data. The assumption that the initial target nucleus Au^{197} fissions, or else the nucleus Os^{192} , leads to contradictions with them. Analogous calculations for the Bi^{209} and Pb^{208} targets give, respectively, the fissioning nuclei Pb^{206} and Tl^{205} .

It should be noted that allowance for the experimental errors in the measurement of E_k^f leads to a set of possible fissioning nuclei; however, the nuclei least different from the targets turn out to be those listed in Table 1.

A. F. Ioffe Physico-Technical Institute
Academy of Sciences of the USSR
Leningrad

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