Nucleons lost by uranium and bismuth nuclei in high-energy fission

V. E. Shashmin, M. N. Andronenko, I. N. Sinogeev,
G. E. Solyakin, S. T. Trush, and Yu. A. Chestnov

B. P. Konstantinov Nuclear Physics Institute of the USSR Academy of Sciences

(Submitted 23 January 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **27**, No. 5, 309–312 (5 March 1978)

We measured the masses of the correlated fission fragments of the nuclei ^{238}U and ^{209}Bi by protons with $E_p = 1000$ MeV. We obtain, for the first time ever, the experimental distribution of the sums of the fragment masses, which made it possible to determine the total nucleon losses before and after the instant of scission.

PACS numbers: 25.85.Ge

An experimental study of the nucleon emission accompanying the fission of nuclei by high-energy particles is a necessary condition for the understanding of the mechanism of this complicated nuclear reaction. Thus, in[1], direct measurement of the absolute yields and of the angular distribution of the neutrons was carried out for targets of ^{238}U and ^{209}Bi at an incident-proton energy $E_p = 155$ MeV. In[2], for the same targets and at a proton energy $E_p = 2900$ MeV, they measured the mass of one fragment in a single-arm time-of-flight mass spectrometer and the concident fragment was used to generate the starting signal. The total nucleon losses was estimated by subtracting double the average measured fragment mass from the target-nucleus mass.

The two-arm time-of-flight mass spectrometer with independent start-signal pickup, developed at our institute,[3] makes it possible to carry out correlated measurements of the masses and of the kinetic energies of coincident fission fragments. With the aid of this instrument we investigated, using the proton beam of the synchrocyclotron of our institute, with energy $E_p = 1000$ MeV, the processes of nuclear fission in ^{238}U and ^{209}Bi targets.[4] Table I lists the results of the experiments as well as the values of the nucleon losses obtained in[1,2].

$\overline{\Delta M}_{\rm pr}$ and $\overline{\Delta M}_{\rm fr}$ are the average values of the nucleon losses by the fissioning nucleus prior to scission and by the accelerated fragments, respectively. $\overline{M_1+M_2}$ is the average value of the distribution of the fission-fragment masses, $M_{1,2}$ are the measured masses of the coincident fission fragments, FWHM—full width at half maximum of the indicated distributions, ΔA—total average nucleon loss obtained from the formula $A = A_0 - (\overline{M_1+M_2})$, where A_0 is the mass of the target nucleus.

Whereas the average nucleon losses can be estimated from other studies, the half-widths of the distribution of the fragment-mass sums can be measured only by the method of two-arm spectrometry. The reason why the half-widths of ^{238}U and ^{209}Bi differ by a factor 1.5 at almost equal values of ΔA is that the fission barriers of these nuclei differ strongly. In the case of ^{238}U the smallness of the barriers leads to fission of

0021-3640/78/2705-0288$00.60

TABLE I.

Target nucleus	$\overline{M_1 + M_2}$ at. mass un.	FWHM at. mass un.	$\overline{\Delta A}$ at. mass un.	$\overline{\Delta A}$ [1] at. mass un.	$\overline{\Delta A}$ [2] at. mass un.
^{238}U	216 ± 4	31 ± 3	22 ± 4	10.9 ± 1.0	36 ± 7
^{209}Bi	189 ± 4	21 ±3	20 ± 4	11.1 ± 1.0	30.0 ±5.4

the remnant nuclei that are produced in interactions with protons both in central collisions with large nucleon loss, and in peripheral collisions with small nucleon loss.

The nucleon loss before and after scission can be estimated on the basis of the experimental fact that the nucleon emission from a fragment is proportional to its mass,[4] assuming the emission of the nucleons to be isotropic. Recognizing that the initial total kinetic energy of the fragments is constant and that the change of the final kinetic energy is due to emission of the nucleons from the fragments, we can obtain from the experimentally measured correlation of the sums of the masses and the total kinetic energies of the coincident fragments the ratio of the nucleon losses from the accelerated fragments to the total nucleon loss: $R=\Delta M_{\mathrm{fr}}/\Delta A$. Table II contains the results of this estimate and analogous data from[1].

The constancy of R means that the relative value of the nucleon losses from the accelerated fragments does not depend on the energy of the incident particle or on the absolute value of the total nucleon loss.

This fact offers evidence of the constancy of the mechanism of the fission of the nuclei going to high incident-proton energies.

TABLE II.

Quantity / Target nucleus	E_p MeV	$\overline{\Delta A}$ at. mass un.	$\overline{\Delta M}_{\mathrm{pr}}$ at. mass un.	$\overline{\Delta M}_{\mathrm{fr}}$ at. mass un.	R
^{238}U	155	10.9 ± 1.0	5.8 ± 1.0	5.1 ± 0.5	0.47
	1000	22 ± 4	11.4 ± 2.1	10.6 ± 1.9	0.48
^{209}Bi	155	11.1 ± 1.0	6.9 ± 1.0	4.2 ± 0.5	0.38
	1000	20 ± 4	12.0 ± 2.4	8.0 ± 1.6	0.40

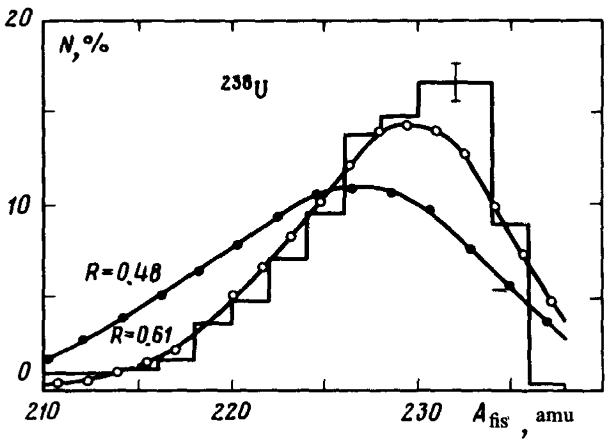

FIG. 1. Mass spectra of fissioning nuclei from a ^{238}U target bombarded by protons of energy $E_p = 1000$ MeV. Histogram—calculation in accordance with the cascade-evaporation model.[5] Dark points—reduction of the experimental results using the experimental value $R = 0.48$. Light points—reduction of the experimental results fitted to a value $R = 0.61$.

The distribution parameters A of the fissioning nuceli can be obtained from the distributions of the fragment-mass sums using the formula

$$A_{\text{fis}} = A_0 R + (1 - R)(M_1 + M_2),$$

which yields average values 226.6±2.1 and 197.0±2.4 amu for ^{238}U and ^{209}Bi targets, respectively. The distribution of A_{fis} shown in Fig. 1 and the calculated histogram from[5], obtained within the framework of the cascade-evaporation model, are close in their average values, but differ in their half-widths, 16.1±1.5 and 11.0±0.5 amu,respectively. These distributions can probably be made equal by changing the particle-width ratio Γ_n/Γ_f used in the calculation. This conclusion follows from the agreement between the aforementioned parameters of the calculated and experimental distributions obtained at $R = 0.61$.

[1] E. Cheifetz, Z. Faenkel, J. Galin, N. Lefort, J. Peter, and X. Tarrogo, Phys. Rev. **C2**, 256 (1970).

[2] L.P. Remsberg, F. Plasil, J.B. Cumming, and M.L. Perlman, Phys. Rev. **187**, 1597 (1960); Phys. Rev. **C1**, 265 (1970).

[3] M.N. Andronenko, I.N. Sinogeev, G.A. Solyakin, Yu.A. Chestnov, and V.E. Shashmin, Prib. Tekh. Eksp. No. **4**, 51 (1977), No. **4**, 53 (1977); No. **4**, 41 (1977).

[4] M.N. Andronenko, I.N. Sinogeev, G.E. Solyakin, S.I. Trush, and Yu.A. Chestnov, and V.E. Shashmin, Preprint, Leningrad Inst. Nuc. Phys., 1977, p. 375.

[5] V.S. Borashenkov, F.C. Geregi, A.S. Iljinov, and V.D. Toneev, Nucl. Phys. **A222**, 1, 204 (1974).