SOVIET PHYSICS JETP VOLUME 37(10), NUMBER 5 MAY, 1960

FRAGMENTATION ON BISMUTH NUCLEI

V. F. DAROVSKIKH, N. P. KOCHEROV, and N. A. PERFILOV

Radium Institute, Academy of Sciences, U.S.S.R.

Submitted to JETP editor June 30, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 1292-1295 (November, 1959)

Fragmentation on bismuth nuclei induced by 660-Mev protons was investigated by imbedding small bismuth particles in a nuclear emulsion. Data are obtained on the cross section of the process, on the angular distribution (forward-backward ratio) of the fragments, and on the charge and energy distributions of multi-charged particles.

To explain the mechanism of fragmentation of heavy nuclei it is very important to know the dependence of many characteristics of this process on the atomic number of the target nucleus. Unfortunately, very little experimental data are available in this field. The cross sections for the production of heavy fragments when various elements are bombarded by high energy particles can be determined principally radiochemically. This method makes possible determination of the yields of several radioactive isotopes, the number of which is very limited in the region of small Z. Yet it is known[1-2] that in the fragmentation process there are produced essentially stable isotopes, which make the principal contribution to the yield of fragments of given charge. The ratio between the isotopes may vary in going from one target to another. Therefore the variation of the yield of certain nuclei cannot give a true idea of the variation of the fragmentation cross section with the Z of the target.

By counting the fragments produced in thick targets placed over an emulsion layer, Lozhkin[3] showed that the fragment yield increases with increasing atomic number of the target nucleus. For a more complete study of a fragmentation process on nuclei heavier than silver, it is necessary to introduce suitable elements in the emulsion if the photographic method is used.

Perfilov and Denisenko[4] determined the cross section for fragmentation on uranium, induced by 660-Mev protons. However, since the uranium was introduced into the emulsion by impregnation, cases of fragmentation on uranium were identified only when the residual nucleus was fissioned after the emission of the fragment. Thus, not all the fragments produced on the uranium were investigated. The value of $\sigma_{fr}(U)$ was calculated from the quantity $\sigma_{fis}(86)/\sigma_{nuc}(86)$ for the interaction between high energy protons and heavy nuclei. It was assumed here that the properties of nuclei with $Z = 86$, which are obtained on the average after the emission of the multiply-charged particle, are similar to the properties of nuclei with $Z = 86$ produced as a result of the ordinary cascade process. It may be that this assumption does not correspond well enough to reality.

We have attempted in this investigation to study the fragmentation phenomenon in pure form. Small grains of metallic bismuth (measuring $\sim 8-10\,\mu$) were deposited on an emulsion layer $100\,\mu$ thick, and a second emulsion layer of equal thickness was poured over the first. The plates prepared were bombarded by 660-Mev protons in the synchrocyclotron of the Joint Institute for Nuclear Research, developed, and scanned for cases of fragmentation on the bismuth grains. Simultaneously, all the cases of bismuth fission were counted, in order to determine the relative fragmentation cross section, σ_{fr}/σ_{fis}. In some plates we counted the stars on the bismuth inclusions; this was necessary to determine the size of the uncertainty zone around the bismuth granules. (The uncertainty zone is the emulsion layer around the bismuth granule, the disintegrations in which cannot be distinguished from the disintegrations on the bismuth itself.)

Fragments with charge $Z \geq 4$ and range $\geq 20\,\mu$ were registered. Since cases with a fragment-range ratio greater than 2 and with a total range greater than $30\,\mu$ are not encountered in practice in the fission of bismuth, this criterion excludes the possibility of attributing fission events to the fragments. Fragments with ranges less than $20\,\mu$ were attributed to fissions, even if the second fragment was missing, for it was assumed to be lost in the bismuth granule. In such an operation a certain number of fragments enters into the fission group, and the ratio σ_{fr}/σ_{fis} is underestimated. There are grounds for assuming, however, that there will be few such fragments. Firstly, according to data on fragmentation on silver and bromine nuclei[2] and also on uranium nuclei,[4] much fewer fragments with range $< 20\,\mu$ are produced than fragments with range $\geq 20\,\mu$; in addition, the yield of fragments drops sharply with increasing fragment charge. Secondly, the energy of the fragments produced on the bismuth, with ranges < 20 and charges $Z = 4$ and $Z = 7$, is less than 0.34 and 0.46, respectively, of the magnitude of the nominal Coulomb barrier. Fragments of such energy have a negligibly small probability of penetrating through the Coulomb barrier, even if its true magnitude, as will be discussed below, is somewhat less than the nominal value.

The fragment charge was determined by measuring the integral width of the track.[5-6] The measurements were made with an MBI-8 microscope at a magnification of 4800, which increased the measurement accuracy considerably. The calibration was based on the hammer-like tracks found in the disintegrations of the silver and bromine nuclei in the same emulsions. These tracks can be readily divided into three groups: Li_3^8, Be_4^8, and B_5^8. In addition, we used the proportionality of the width of the track to the square root of the fragment charge, indicated by Nakagawa et al.[5]

Z	4	5	6	7
E_{exp}, Mev	13 15 23 23 26 27 30 39 63	28 29 34 35 58 70	28 45 57	40 54 80
E_{coul}, Mev	39	47	55	63

The resultant fragment charge distribution is given in the table, which lists also the value of the nominal Coulomb barrier E_{Coul} for fragments of various charges, calculated from the following formula

$$E_{coul} = (Z_0 - Z_p - Z_{fr})\, Z_{fr} e^2 / r_0 \,(A^{1/3} + a^{1/3}),$$

where Z_0, Z_p and Z_{fr} are respectively the charge of the polonium nucleus, the number of cascade protons penetrating the Po nucleus prior to the emission of the fragment, and the charge of the fragment. A is the mass number of the residual nucleus, a is the mass number of the fragment, and $r_0 = 1.47 \times 10^{-13}$ cm.

The table indicates also the energies of the obtained fragments, determined by range and by the range-energy curves[7] for the Ilford G-5 emulsion, which has the same stopping ability as the P-9 emulsion.

In determining the ranges of the fragments, a correction was introduced in each case for the fact that part of the fragment range $(\sim 2-4\,\mu)$ lies within the Bi granule. The point from which the fragment is emitted was determined by intersecting the prongs accompanying the fragmentation cases.

To determine the cross section for fragmentation on bismuth, a relative method was used: we determined the ratio of the number of the fragments on the bismuth granules to the number of fissions. With this method it was not necessary to know the bombarding proton current or the volume of the bismuth introduced into the emulsion. However, to calculate the fragmentation cross section it was necessary to estimate the fraction of the fragments actually originating on the bismuth, and how many fragments were produced on the emulsion grains in the uncertainty zone. To reduce the value of V_Z/V_{Bi} (the ratio of the volume of the zone to the volume of the bismuth granule) all the found fragmentation cases were reviewed in an emulsion wetted to increase its thickness seven-fold.[8] For fragments that remained on the granules, the size of the uncertainty zone was considerably reduced. Its value was determined from examination of the stars on the emulsion nuclei, which separated from the granules during the wetting. The resultant value was $V_Z/V_{Bi} = 0.7$.

To calculate the cross section for fragmentation on bismuth, we set up the following system of equations:

$$N_{fr.\,exp} = N_{fr.\,Bi} + N_{fr.\,z};$$
$$N_{fr.\,Bi} = N_0 \sigma_{fr}(Bi)\, N_{Bi} V_{Bi};$$
$$N_{fr.\,z} = N_0 [\sigma_{fr}(AgBr)\, N_{AgBr} + \sigma_{fr}(CNO)\, N_{CNO}]\, V_z;$$
$$N_{fis} = N_0 \sigma_{fis} N_{Bi} V_{Bi}.$$

Here $N_{fr.\,Bi}$, $N_{fr.\,z}$, $N_{fr.\,exp}$, and N_{fis} are the true number of fragments on the bismuth granules, on the emulsion grains in the uncertainty zone, the number of fragments obtained experimentally, and the number of bismuth fissions; $\sigma_{fr}(Bi)$, $\sigma_{fr}(AgBr)$, $\sigma_{fr}(CNO)$, and σ_{fis} are the cross sections of fragmentation on bismuth and on the heavy and light nuclei of the emulsion, and the bismuth fission cross section. N_0, N_{Bi}, N_{AgBr}, and N_{CNO} are the current of incident protons, the number of nuclei per cubic centimeter of bismuth, and the number of heavy and light nuclei per cubic centimeter of emulsion.

By solving this system of equations for $\sigma_{fr}(Bi)$, we obtain

$$\sigma_{fr}(Bi) = \sigma_{fis} N_{fr.\,exp} / N_{fis} - \sigma_0, \qquad (1)$$

where

$$\sigma_0 = \frac{V_z}{V_{Bi}} \frac{\sigma_{fr}(AgBr)\, N_{AgBr} + \sigma_{fr}(CNO)\, N_{CNO}}{N_{Bi}}.$$

We found 21 fragments in 132 bismuth fissions. Inserting these values in (1) together with $\sigma_{fr}(AgBr) = 10$ mb, $\sigma_{fr}(CNO) = 2$ mb, $\sigma_{fis} = 200$ mb, $N_{Bi} = 2.8 \times 10^{22}$ nuclei/cm^3, $N_{AgBr} = 2.04 \times 10^{22}$ nuclei/cm^3, $N_{CNO} = 2.83 \times 10^{22}$ nuclei/cm^3, and $V_z/V_{Bi} = 0.7$, we obtain $\sigma_{fr}(Bi) = 25$ mb. The possible error may amount to one-third of this quantity, since the result obtained agrees with the values of the cross section for fragmentation on uranium,[4] $\sigma_{fr}(U) = 22$ mb, and is approximately twice the cross section for fragmentation on the nuclei of silver and bromine for bombarding particles of the same energy.[3]

To compare data on the fragmentation on bismuth and on uranium[4] nuclei, we list several characteristics of this process:

	Bi	U
Fragmentation cross section, mb	25	22
Average number of protons and α particles in disintegrations with fragments	4.0	1.6
Average charge of fragment	5	6
Fragments with energy below the nominal Coulomb barrier, percent	71	82
Ratio of the number of fragments traveling with and against the beam	6	5

From an examination of these data it is seen that the characteristics of fragmentation on bismuth and uranium are remarkably identical. The discrepancy between the average number of protons and α particles in disintegrations with fragments on bismuth and on uranium is quite natural. Only approximately 30% of the fragments (accompanied by fission) are recorded in the case of uranium. Multiple-pronged events, in which the fission probability becomes smaller[9] because of the reduced charge and, apparently, because of the increase in the initial excitation energy of the nucleus, were for the most part left out.

The most characteristic feature of fragmentation on bismuth and on uranium is the large number of sub-barrier fragments. The fraction of fragments with $Z \geq 4$ having energies below the nominal Coulomb barrier is 71% for bismuth and 82% for uranium. Quantum-mechanical penetration through the barrier makes no noticeable contribution to these numbers. It must be assumed that the true Coulomb barrier is lower than the nominal one, amounting to approximately 0.6 of its value. A similar reduction in the Coulomb barrier was observed by Fulmer and Cohen[10] in an investigation of the $(p\alpha)$ reaction on heavy nuclei. Their results can be interpreted as the knock-out of an alpha particle from the diffuse region of the nucleus, where α groupings exist with considerable probability.[11] In our case, however, to explain the large fraction of sub-barrier particles it is not enough merely to account for the fact that the fragments can be knocked out from the diffuse region of the nucleus. Fragmentation of heavy nuclei, induced by high-energy particles, is apparently accompanied by considerable nuclear deformations as a result of the strong branching of the nuclear cascade.

[1] V. M. Sidorov and E. L. Grigor'ev, JETP **33**, 1179 (1957), Soviet Phys. JETP **6**, 906 (1958).

[2] O. V. Lozhkin, Dissertation, Radium Inst. U.S.S.R. Acad. Sci., 1957.

[3] O. V. Lozhkin, JETP **33**, 354 (1957), Soviet Phys. JETP **6**, 273 (1958).

[4] N. A. Perfilov and G. F. Denisenko, JETP **35**, 631 (1958), Soviet Phys. JETP **8**, 438 (1959).

[5] Nakagawa, Tamai, Huzita, and Okudairo, J. Phys. Soc. Japan. **11**, 191 (1956).

[6] V. I. Ostroumov and Yu. P. Yakovlev, JETP **35**, 1358 (1958), Soviet Phys. JETP **8**, 949 (1959).

[7] A. Papineau, Compt. rend. **242**, 2933 (1956).

[8] O. V. Lozhkin, J. Tech. Phys. (U.S.S.R.) **34**, 1341 (1955).

[9] Dostrovsky, Fraenkel, and Rabinovitz, Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva (1958).

[10] C. B. Fulmer and B. L. Cohen, Bull. Am. Phys. Soc. II, **3**, 56 (1958).

[11] V. I. Ostroumov and R. A. Filov, JETP **37**, 643 (1959), Soviet Phys. JETP **10**, 459 (1960).

Translated by J. G. Adashko
259