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Fig. 2. Dependence of total blackening $P = (I_\phi - I_c)/I_\phi$ on range for fragment III and nitrogen ions N_7^{14} .

Figure 1: Fig. 2. Dependence of total blackening $P = (I_\phi - I_c)/I_\phi$ on range for fragment III and nitrogen ions N_7^{14} .

Abstract

Full Text

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TRIPLE FISSION OF URANIUM BY FAST PARTICLES

(Presented by Academician L. A. Artsimovich, 15 XII 1956)

1. Experimental data. On examining plates impregnated with uranium and irradiated with protons of energy 660 MeV, several cases of uranium fission were recorded which were accompanied by the emission of a multiply charged particle with charge $Z > 4$. Among them a planar triple fork was found, a microphotograph of which is shown in Fig. 1. The tracks of all three particles forming the fork, from their external appearance (grain density, presence of δ -rays on two tracks), must be assigned to multiply charged particles—two to fragments of the fission of a heavy nucleus, while the third, in its density of blackening, substantially exceeds the tracks of α -particles.

In the experiment a special fine-grained photoemulsion P-9 was used, with a sensitivity limit for protons of ~ 35 MeV and with good differentiating power with respect to particles of different nature.

The density of blackening along all three tracks was measured by means of a photometric apparatus. Photometry was carried out with slit dimensions in the object plane of $5 \times 0.8\mu^2$. The value of the total blackening was measured,

$$P = \frac{I_\phi - I_c}{I_\phi},$$

where I_ϕ is the current at the output of the photomultiplier when the slit is located next to the particle track; I_c is the current when the track and the slit coincide.

Fig. 2. Dependence of total blackening

$$P = \frac{I_\phi - I_c}{I_\phi}$$

on range for fragment *III* and nitrogen ions N_7^{14} .

The results of measuring the total blackening along track *III* (from the end of the range) are shown in Fig. 2. There, for comparison, the results of photometry of tracks of nitrogen ions are also given.

The data obtained from the angle of inclination of the curve $P = f(R)$ make it possible, as was shown in the work of O. V. Lozhkin ⁽¹⁾, to determine the value of Z . For the particle that gave track *III*, the value obtained for the charge was $Z_{III} = 9.8 \pm 1$. The value of the mean blackening for tracks *I* and *II* is, respectively, 0.350 and 0.400. In this same emulsion, measurements of the mean blackening densities for tracks of binary-fission fragments and tracks of α -particles gave, respectively, 0.380 and 0.220.

The results of the comparison show that tracks *I* and *II* are indeed tracks of multiply charged ions of the fission-fragment type. Since the ranges of particles *I* and *II* are equal, we shall regard these particles as identical. Taking $Z_{III} = 10$, we obtain $Z_I = Z_{II} = 41$.

2. Calculation of the triple fork.

As already noted, the fork we found proved to be coplanar, and the trajectory of the incident proton also lies in the plane of the fork. Using the range-energy dependences ^(2,3), we estimated the kinetic energies and momenta of the two heavy fragments and of the third, lighter particle. In Fig. 3 the momentum diagram of the analyzed triple fork is shown by solid lines. The direction of motion of the incident proton in Fig. 3 is made to coincide with the X axis and, from the experimental conditions, is specified with an accuracy of up to $3-4^\circ$.

Fig. 3. Momentum diagram of the analyzed triple fork. $P_I; P_{II}$ –orientations of the momenta of the fission fragments; P_{III} –orientation of the momentum of the light fragment ${}^{20}_{10}\text{Ne}$; P_r –orientation of the resultant momentum of the triple fork; P_{lost} –orientation of the missing momentum; P_0 –momentum of the incident proton

For the magnitude and direction of the resultant momentum P_r of the triple fork, according to the diagram in Fig. 3, we shall have the following equations:

$$P_r = \sqrt{(\Sigma P_x)^2 + (\Sigma P_y)^2} = 1820 \frac{\text{MeV}}{c},$$

$$\tan \varphi = \frac{\Sigma P_y}{\Sigma P_x} = \frac{1290}{1280} \simeq 1, \quad \varphi = 45^\circ.$$

Since the fission occurred as a result of a collision with an incident proton whose energy is 660 MeV, and the momentum is $P_0 = 1290 \frac{\text{MeV}}{c}$, then, proceeding from the law of conservation of momentum for the whole system (incident proton – triple fork), one can obtain the magnitude and direction of the missing momentum. In what follows we assumed that the lost momentum is due to a proton whose track is not visible in the emulsion*:

$$\mathbf{P}_{\text{lost}} = \mathbf{P}_0 - \mathbf{P}_r,$$

$$P_{\text{lost}} = \sqrt{P_0^2 - 2P_0P_r \cos 45^\circ + P_r^2} = 1300 \frac{\text{MeV}}{c},$$

$$\theta = \arcsin \frac{P_r \sin 45^\circ}{P_{\text{lost}}} = 270^\circ.$$

The orientations of P_r and P_{lost} are shown in Fig. 3 by dashed lines. It is evident from the figure that, within the limits of possible experimental errors, the collision as a result of which the nucleus split into three parts occurred without any noticeable change in the initial momentum in magnitude, and consequently also with only a small change in energy. The change in the initial energy corresponds to elastic scattering of the incident proton through an angle of 90° by the uranium nucleus ($\Delta E \sim 8$ MeV).

On the basis of the analysis carried out, it may be concluded that the analyzed triple fork is the result of triple fission of a uranium nucleus whose initial excitation energy is small.

Here, however, we encounter a new difficulty. In a collision of a 660 MeV proton with a uranium nucleus, the probability of elastic or nearly elastic scattering through an angle of 90° is very small. Moreover, it is known that at small excitation energies (under the action of slow neutrons on uranium nuclei) the phenomenon of triple fission is a very unlikely process (⁴⁻⁶). Taking the above into account, we assumed that in the present case, in the collision of a proton of such high energy with a uranium nucleus, triple fission—

* It may also be assumed that the lost or missing momentum is carried away not by one but by several particles of the same mass, or by one heavier particle; however, such a consideration, as applied to the fork analyzed, leads to a number of contradictions.

For the article by N. A. Perfilov, V. P. Shamov, and O. V. Lozhkin, p. 75

Fig. 1. Microphotograph of a case of fission of a uranium nucleus with emission of a multiply charged particle. *I, II*—heavy fragments, $Z_{I,II} = 41$ (range $l_I = l_{II} = 12 \mu$); *III*—light nucleus, $Z_{III} = 9.8 \pm 1$ (range $l_{III} = 42 \mu$).

For the article by N. A. Kolesnikova, p. 191

Fig. 4. Subcutaneous vein of the thigh with a thrombus covered by endothelium. 3 days after 5-hour compression. Formalin. Weigert's hematoxylin. Picrofuchsin. Obj. 8, oc. $10\times$. Microphotograph.

could have occurred with appreciable probability only as a result of a noncentral collision with the transfer of considerable angular momentum.

Below we have attempted to give a qualitative picture of a possible mechanism of ternary fission by fast particles. Owing to the presence of a large quadrupole moment, the uranium nucleus must be elongated to a considerable degree. The elongation of the uranium nucleus makes it possible to assume both a central and, with considerably greater probability, a noncentral collision. In the case of the more probable process it should be assumed that the primary process of interaction of a fast proton with the uranium nucleus had the character of a noncentral elastic collision. As a result of such a collision the uranium nucleus must acquire, in addition to kinetic energy, also a certain angular momentum $M_n = P_r \Delta r$. By the law of conservation of angular momentum, the uranium nucleus must dissipate the angular momentum M_n it has acquired. If the value of the acquired angular momentum is large (a strongly noncentral collision), the nucleus cannot remove it by noncentral emission of light particles (especially if one takes into account that the initial excitation energy is either zero—an elastic collision—or insignificant—a practically elastic collision).

In the case analyzed by us it is natural to suppose that the removal of angular momentum is promoted by noncentral emission of the light fragment Ne_{10}^{20} .

Let us consider the energy aspect of the process. In order for the uranium nucleus to be able to emit a light fragment Ne_{10}^{20} with momentum $P_{\text{Ne}_{10}^{20}} = 1800 \frac{\text{MeV}}{c}$, it must possess an initial excitation energy $E_0 > 100 \text{ MeV}$. By what processes can the uranium nucleus release this energy?

The energy released owing to the mass defect in fission of uranium into two fragments of unequal masses ($A_1 = 20$; $A_2 = 218$) is half as large as the indicated value E_0 . However, if it is assumed that simultaneously with the emission of the light fragment the residual nucleus divides in half, then the energy released in such a ternary-fission process proves to be equal to 240 MeV. The experimentally observed energy of the two heavy fragments and the light fragment (all in the center-of-mass system) proves to be equal to 210 MeV, i.e., it corresponds to the energy released in ternary fission.

Thus, it appears possible to explain the observed ternary fork by assuming a very specific course of the nuclear reaction. For a more or less rigorous solution of the question of the occurrence of reactions of this type, it is necessary to study all cases of uranium fission by multiply charged particles.

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