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A. K. LAVRUKHINA, E. E. RAKOVSKII, SU HUN-GUI, and S. KHOJNACKI

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## Abstract

## Full Text

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A. K. LAVRUKHINA, E. E. RAKOVSKII, SU HUN-GUI, and S. KHOJNACKI

# FISSION OF ANTIMONY NUCLEI BY FAST PROTONS

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By the present time many characteristics have been obtained for the process of fission of nuclei of elements at the end of the periodic system. Information on the fission of sufficiently light elements is considerably less abundant. Only individual fission fragments of certain elements of medium atomic weight have been isolated ($^{1-3}$). The work ($^{4}$) on the fission of silver cannot fully fill the existing gap, since, owing to the insufficiency of the statistical material, the data obtained do not permit unambiguous conclusions to be drawn.

Fig. 1. Distribution curves of the yields of fission fragments of antimony by protons of energy 660 MeV as a function of mass numbers (dashed curve—distribution of total yields according to $A$)

To obtain the principal characteristics of the process of fission of nuclei of medium atomic weight, we investigated the fission of antimony ($Z = 51$) by fast protons. Particular attention was paid to the purity of the irradiated material, since the fission fragments of such nuclei are formed with much lower yields ($10^{-30}$—$10^{-29}$ cm$^2$) than the products of their spallation. Therefore impurities of the elements being determined in the target substance in amounts greater than $10^{-3}$% can lead to a serious distortion of the picture of the process. Spectral analysis of an ingot of metallic antimony, repeatedly purified by zone melting, showed the absence of any extraneous spectral lines. In addition, the antimony sample was analyzed by the more sensitive method of neutron activation. The results of the activation analysis indicate the absence in the antimony of impurities of Mn, Cu, Zn, As, P, Cr, and Ga in amounts of $10^{-4}$—$10^{-7}$%.

From the target, after irradiation with protons of energy 660 MeV in the synchrocyclotron of the Joint Institute for Nuclear Research, bombardment products in the interval $Z = 11 \div 37$ were separated by chemical methods. The methods used were very laborious, since many fission products of antimony have chemical analogues among its spallation products.

The cross sections for formation of the identified radioisotopes were calculated in the usual way ($^5$). Information on the identified fission products is given in Table 1. The root-mean-square errors of the cross-section values for their formation were calculated from Student' s distribution.

To establish the yields of unidentified fission fragments, the method of interpolation on a map in the coordinates $A, Z$ was applied ($^5$). According to exper –

**Table 1**

Yields of identified fission products of antimony by protons of energy 660 MeV

| Element | Mass number of isotope | Type of decay | $T_{1/2}$, exp. | $T_{1/2}$, tab. | $\sigma_{\text{mean}}$, $10^{-30}$ cm$^2$ |
|---|---|---|---|---|---|
| $_{16}$S | 38 | $\beta^-$ | $\sim 3$ h | 2.9 h | $0.7 \pm 0.4$ |
| $_{17}$Cl | 38 | $\beta^-$ | $\sim 34$ min | 37.3 min | $5.7 \pm 2.6$ |
| $_{17}$Cl | 39 | $\beta^-$ | 58 min | 55.5 min | $1.2 \pm 0.4$ |
| $_{19}$K | 43 | $\beta^-$ | $\sim 1$ day | 22.4 h | $8.0 \pm 4.7$ |
| $_{20}$Ca | 47 | $\beta^-$ | $\sim 6$ days | $\sim 5$ days | $3.5 \pm 2.3$ |
| $_{22}$Ti | 45 | $\beta^+$, electron capture | 3.2 h | 3.1 h | $5.8 \pm 4.0$ |
| $_{23}$V | 48 | $\beta^+$, electron capture | 16.7 days | 16.0 days | $6.8 \pm 2.4$ |
| $_{24}$Cr | 48 | Electron capture | 23.5 h | 23 h | $4.0 \pm 1.8$ |
| $_{25}$Mn | 56 | $\beta^-$ | 2.5 h | 2.6 h | $8.3 \pm 4.1$ |
| $_{26}$Fe | 59 | $\beta^-$ | $\sim 46$ days | 45.1 days | $8.0 \pm 3.6$ |
| $_{27}$Co | $58^m$ | Isomeric transition | 9.8 h | 9 h | $3.1 \pm 0.9$ |
| $_{27}$Co | 61 | $\beta^-$ | $\sim 120$ min | 99–110 min | $5.1 \pm 0.8$ |
| $_{28}$Ni | 65 | $\beta^-$ | 2.7 h | 2.6 h | $5.5 \pm 1.5$ |
| $_{28}$Ni | 66 | $\beta^-$ | $\sim 60$ h | 55 h | $2.2 \pm 0.1$ |

From the experimental and interpolated data, curves were constructed for the distribution of fragment yields in $A$ and $Z$. Figure 1 shows the distribution curves in $A$; they have a dome-shaped form, as in the fission of heavy nuclei U, Th, and Bi ($^5$, $^6$). The difference is that, in the case of heavy nuclei, mainly isotopes with an excess of neutrons are formed, whereas in the fission of Sb fragments are formed over a very broad range of $n/p$ ratios: from isotopes with a deficiency of neutrons to isotopes with a comparatively large excess of them. Therefore the half-widths of the dome-shaped distribution curves in the case of Sb are considerably greater (7–8 mass units) than for U, Th, and Bi (4–5 units). Such features of the fission process of antimony, in comparison with heavy nuclei, lead to a substantial change in the isotopic composition of its fission fragments, consisting in a large increase in the relative contribution of neutron-deficient nuclei (see Table 2).

Information on the distribution of nuclear charge in fission by fast particles is very scarce ($^6$, $^7$). Since most of the nuclei we identified are protected isobars, it proved possible to establish the character of the distribution of nuclear charge in the fission of antimony. As follows from Fig. 2, the distribution curves

**Fig. 2.** Distribution of the yields of isobars formed in the fission of antimony by protons of energy 660 MeV, according to ordinal numbers (upper curve—distribution of total yields in $Z$)

**Table 2**

**Some characteristics of the process of fission of nuclei by high-energy protons**

| Bombarded nucleus | $E_p$, MeV | $\sigma_{\text{fiss}}$, mb | $\frac{\sigma_{\text{fiss}}}{\sigma_{\text{geom}}}$ | Relative contribution of neutron-deficient stable and neutron-rich isotopes | $\frac{\sigma_{\text{sym. fiss}}}{\sigma_{\text{fiss}}}$ | $\Delta Z$—half-width for $\sigma = \sigma_{\max}/2$ | Number of emitted protons | Number of emitted neutrons | Literature source |
|---|---|---|---|---|---|---|---|---|---|
| $^{92}$U | 480 | 1650 | 0.73 | 11:21:58 | 0.32 | 19 | – | 19 | ($^6$) |
| $^{83}$Bi | 480 | 100 | $4.8 \cdot 10^{-2}$ | 12:28:60 | 0.45 | 13 | – | 15 | ($^6$) |
| $^{67}$Ho | 450 | 2 | $1.1 \cdot 10^{-3}$ | – | 0.71 | 10 | 4 | 18 | ($^8$) |

Fig. 3. Distribution of total yields of fission fragments of U, Bi, Ho, and Sb by high-energy protons

Figure 2: Fig. 3. Distribution of total yields of fission fragments of U, Bi, Ho, and Sb by high-energy protons

| Bombarded nucleus | $E_p$, MeV | $\sigma_{\text{fiss}}$, mb | $\frac{\sigma_{\text{fiss}}}{\sigma_{\text{geom}}}$ | Relative contribution of neutron-deficient stable and neutron-rich isotopes | $\frac{\sigma_{\text{sym. fiss}}}{\sigma_{\text{fiss}}}$ | $\Delta Z$— half-width for $\sigma = \sigma_{\max}/2$ | Number of emitted protons | Number of emitted neutrons | Literature source |
|---|---|---|---|---|---|---|---|---|---|
| $^{51}$Sb | 660 | 0.25 | $1.7 \cdot 10^{-4}$ | 20:35:45 | 0.73 | 9 | 7 | 16 | Authors' data |

yields for different isobars have a dome-shaped form; their half-width is 3–4 charge units. It should be noted that analogous curves of the charge distribution in the fission of U, Th, and Bi ($^6$) have a smaller half-width (2–3 charge units).

**Fig. 3.** Distribution of total yields of fission fragments of U, Bi, Ho, and Sb by high-energy protons

For all $A$ of the fission fragments, values of the most probable charges were found. It was established that the curve connecting the values of the most probable charges is located near the line of nuclear stability. For all isobars it was found that the charge distribution is constant.

Consideration of the curve of the distribution of total yields of Sb fission fragments in $Z$ (the upper curve in Fig. 2), which has a dome-shaped form, indicates a significant contribution from symmetric fission. This is in agreement with the data ($^4$) on Ag fission. The contribution of symmetric fission and of those close to it, when $(Z_{\text{sym}} - Z) \leqslant 3$, is $\sim 73\%$. If, using the data ($^8$), interpolation is carried out by the method described above, analogous results are obtained also for Ho. From the data of Table 2, as well as Fig. 3, it follows that with a decrease in the $Z$ of the target nucleus there occurs a regular decrease in the half-widths of the distribution curves of the total fragment yields in $Z$, and, consequently, the relative contribution of asymmetric fissions decreases. Apparently, for nuclei of medium atomic weight the asymmetry of fission does not play the role that might have been ascribed to it from theoretical considerations ($^{9}$).

When the energy of the incident protons is decreased to 220 MeV, the yields of products of asymmetric fission of antimony, such as $Cl^{38}$, $Cl^{39}$, $Mn^{56}$, $Co^{61}$, decrease almost tenfold, while the yield of $V^{48}$, which is a product of symmetric fission, remains practically constant. This agrees with previously obtained data ($^{10-12}$) on the increase in the probability of asymmetric fission with increasing energy of the bombarding particles.

In Fig. 3 the arrows show the values of $Z$ of fragments corresponding to fission into two equal parts of a nucleus with $Z = Z_{\text{init}} + 1$. The shift of the maximum of the distribution curves for Ho and Sb toward $Z$ values smaller than $Z = \frac{1}{2}(Z_{\text{init}} + 1)$,

indicates the emission of a considerable number of charged particles in the fission of nuclei of these elements. The calculation showed that fission of Sb is accompanied by the emission, on average, of 7 protons; the corresponding value for Ho is $4^{8}$. The numbers of charged particles $n_{\alpha,p}$ emitted in the fission of Bi and U by 660-MeV protons are 1.77 and $1.16^{13}$, respectively. Consequently, as the $Z$ of the target nucleus decreases, the number of charged particles emitted in fission increases. This indicates very high excitation energies of nuclei of medium atomic weight undergoing fission. The number of neutrons emitted in fission, as is seen from Table 2, is practically independent of the $Z$ of the bombarded element.

As follows from Fig. 3 (and also from Table 2), with increasing $Z$ of the target nucleus there is a significant increase in the fission cross section. The total fission cross section of Sb by 660-MeV protons is 0.25 mb, which is only $1.7 \cdot 10^{-4}$ of the geometrical one. This value is comparable with the value obtained for fission of $Ag^{4}$ (0.32 mb) by protons of the same energy.

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Institute of Geochemistry and Analytical Chemistry
named after V. I. Vernadsky
Academy of Sciences of the USSR

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*Note: Figure translations are in progress. See original paper for figures.*