SOVIET PHYSICS

JETP

A translation of the Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki.

Vol. 16, No. 1, pp. 1-258 (Russ. orig. Vol. 43, No. 1, pp. 3-360, July 1962) January 1963

PRODUCTION OF LIGHT NUCLEI BY 660-MeV PROTON BOMBARDMENT OF HEAVY ELEMENTS

A. K. LAVRUKHINA, L. P. MOSKALEVA, V. V. MALYSHEV, and L. M. SATAROVA

Institute of Geochemistry and Analytical Chemistry, Academy of Sciences, U.S.S.R.

Submitted to JETP editor December 26, 1961; resubmitted March 27, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 3-7 (July, 1962)

The cross sections for the production of Be^7, F^{18}, Na^{24}, Mg^{28}, Si^{31}, and P^{32} from Al, Cu, Sb, Sn, Bi, and U by 660-MeV proton bombardment are studied. For all the target nuclei $\sigma(Na^{24}) > \sigma(F^{18})$. The cross sections for light-nucleus production indicate that the production of the heavy fragments Si^{31} and P^{32} from copper and neighboring elements results from spallation and symmetric fission. The formation of lighter isotopes from all the target nuclei occurs via fission and fragmentation. The relative contributions of the different processes to Na^{24} production from Cu are computed from the angular and energy distributions. Na^{24} nuclei having energies above that of Coulomb repulsion are detected in the forward hemisphere. The experimental cross sections for light-nucleus production are compared with certain conclusions of the dispersion theory of direct nuclear reactions.

INTERACTIONS between high-energy particles and complex nuclei can result in the production of light nuclei with Z from 4 to 15 through spallation, fission, and fragmentation. Both fragmentation and evaporation products can appear with $Z = 3$ or 4.[1,2] The fragmentation process, whose mechanism is still undetermined, is of special interest.

It was the aim of the present work to obtain data on the cross sections for light-nucleus production by 660-MeV protons, and also to estimate the contributions of fission and fragmentation to the production of Na^{24}. We have previously [3] studied the production of Na^{24} and P^{32} from Cu, La, and Au bombarded with protons of different energies. In the present work the cross sections for the production of Be^7, F^{18}, Na^{24}, Mg^{28}, Si^{31}, and P^{32} were determined, using a radiochemical identification procedure. The Al, Cu, Sb, Sn, Bi, and U targets enabled us to study the change of light-nucleus yields with increasing target mass number A.

It was also of interest to determine the influence of nuclear spherical symmetry on the ratio of Na^{24} and F^{18} yields from Sn and Bi targets. All targets, with the exception of Sn, were of high purity, having impurities of only 10^{-4}–10^{-5}%; the tin contained 10^{-2}–10^{-3}% impurities.

The proton bombardment of the targets took place in the internal beam of the synchrocyclotron of the Joint Institute for Nuclear Research. The targets of metallic Al, Cu, Sb, and U were bombarded in the conventional manner;[3] Sn and Bi, because of their low melting points, were bombarded in special graphite holders.

The contributions of fission and fragmentation to the production of Na^{24} nuclei were computed from the study of their angular and energy distributions in runs with Cu and U, with absorption in polyethylene terephthalate films from which the radioisotope Na^{24} was separated radiochemically with a carrier. The technique of angular distribution measurement has been described in [4,5]; the

Table I. Cross sections for light-nucleus production in different targets

Target / Isotope	Al			Cu			Sb			Sn			Bi			U		
	σ	n	$\Delta\sigma$	σ	n	$\Delta\sigma$	σ	n	$\Delta\sigma$	σ	n	$\Delta\sigma$	σ	n	$\Delta\sigma$	σ	n	$\Delta\sigma$
Be^7	420	2	30	160	1		250	2	140							$1.9 \cdot 10^3$	4	$0.3 \cdot 10^3$
F^{18}				10.0	2	5	2.8	2	1.3	1.7	2	0.5	2.3	3	0.04	3.2	2	2.0
Na^{24}				25.0	2	3	14	3	4	4.5	2	0.8	3.0	3	1.7	9.0	1	
Mg^{28}							0.7	3	0.1				3.2	3	2.3			
Si^{31}							0.6	2	0.4									
P^{32}				31.0	2	1.2	0.63	3	0.38				4.6	3	3.4	3.2	2	0.8

energy dependence was studied in certain angular intervals.

In the study of the angular distribution the film thickness was 14.5 mg/cm^2, whereas 1.1 and 2.2 mg/cm^2 thicknesses were used to investigate the energy distribution. Polyethylene terephthalate (Terylene) was selected as the absorber because it contains no elements heavier than oxygen and because of its relatively high melting point ($T_{m.p.} \approx 150°C$), which permitted irradiation in an internal synchrocyclotron beam of considerable intensity. The targets were Cu and U filaments 0.35 and 0.5 mm thick, respectively. These thicknesses resulted in some distortion of the angular distribution. For this reason the true Na^{24} energy spectrum could not be obtained; it was possible only to estimate the fraction of nuclei having energies greater than the Coulomb repulsion energy and to determine the overall form of the energy distribution.

The radioactivity was measured with type T-25 BFL twin end-window counters in anticoincidence with a ring of MS-9 counters. The counter background in a 4-cm lead shield was 20—25 pulses/min with ~ 70% counting efficiency. A 4π counter similar to that described in [6] was also used, operating with a flow of argon saturated with a mixture of alcohol and ether vapors [96% C_2H_5OH and 4% $(C_2H_5)_2O$]. The radioisotopes, with the exception of Be^7, were identified from their half-lives and γ-ray energies. The isotope Be^7 was identified from its 0.479-MeV emission, using a scintillation γ spectrometer in conjunction with a 100-channel pulse-height analyzer.

Table I gives the cross sections for the production of the various isotopes, together with the number of runs n performed to determine the mean cross sections σ and rms errors $\Delta\sigma$ calculated from Student's distribution, in units of 10^{-29} cm^2.

The data obtained on light-nucleus production cross sections indicate that the heavy fragments Si^{31} and P^{32} from Cu and neighboring elements are produced by spallation and symmetric fission. The way in which the cross sections for other nuclei depend on the values of A of the fragment and target, together with the high yield of the neutron-rich nuclide Na^{24} compared with neutron-deficient F^{18}, clearly indicate light-nucleus production by fragmentation. [2] The ratio between Na^{24} and F^{18} yields from Cu, Sb, and U is 2.5, 5.0, and 2.8, respectively. It should be noted that the Na^{24} to F^{18} yield ratio for Bi and Sn is considerably smaller than for the other targets (1.3 for Bi and 1.8 for Sn). Also, the cross sections for the production of all light nuclei from Bi are alike within error limits; this is possibly associated with the spherical symmetry of Bi.

The relative contributions of fission and fragmentation to Na^{24} production were studied from the angular and energy distributions. In the given range of Z a radiochemical technique was required. Angular distributions are shown by the histograms in Fig. 1. The Na^{24} angular distribution from U exhibits more pronounced forward emission than that from Cu, as well as a slight enhancement of activity at large angles (150—170°). The forward-backward ratio is 1.3 and 1.5 for Cu and U, respectively. The anisotropy (the ratio of the activity at 0° to that at 90°) is 2.8 for Cu and 1.4 for U.

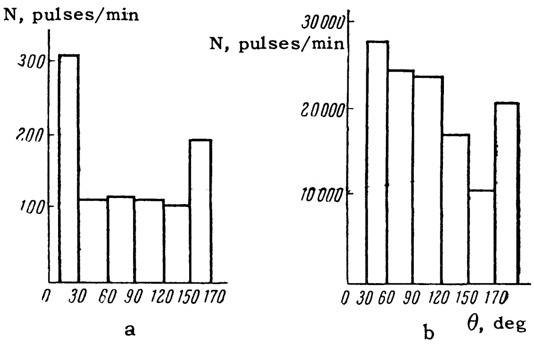

FIG. 1. Angular distribution of Na^{24} from (a) Cu and (b) U.

Table II. Na^{24} range and energy distributions

$\theta = 15-80°$			$\theta = 100-160°$		
Absorber thickness, mg/cm^2	% of Na^{24} nuclei stopped in film*	Na^{24} energy, MeV	Absorber thickness, mg/cm^2	% of Na^{24} nuclei stopped in film*	Na^{24} energy, MeV
2.2	61	4	1.1	94	2
6.6	44	16	4.4	36	9.5
11	14	34	5.5	10	12
13.2	11	44			
15.4	11	58			
17.6	11	70			
22	14	96			

*The percentage of Na^{24} nuclei in each film is given at the start of the measurements with a correction for the chemical yield.

The energy distribution of Na^{24} from Cu was studied in the angular intervals 15—80° and 100—160°. Energies were determined from the range-energy relation measured for Ne^{20}.[7]

Table II gives the Na^{24} range distribution, while Fig. 2 shows the energy distributions in the respective angular intervals. The results for the energy distributions in the forward and backward hemispheres were obtained from different runs. Therefore the activities for the given angular intervals cannot be compared. The Coulomb repulsion energy for Na^{24} was computed assuming that in Cu fission the complementary nucleus of Na^{24} has A = 40 and Z = 18. In this case the Coulomb repulsion energy of Na^{24} is 20 MeV. Figure 2 shows that the forward-emitted fragments include nuclei having energies above the Coulomb energy, whereas in the range 100—160° all fragments have less than the Coulomb energy. For the latter angular region in films thicker than 5.5 mg/cm^2 a weak activity was observed which could not be identified.

An analysis of the angular and energy distributions of Na^{24} from Cu indicates production through asymmetric fission. However, the strong anisotropy at small angles (10—30°) and the presence of fragments having energies above the Coulomb barrier indicate a contribution from fragmentation.

A graphic estimate of the relative contributions of fission and fragmentation shows that the probability ratio of these processes in the angular range 15—80° as determined from the angular and energy distributions is, respectively,

$$W_{fr}/W_{fis} = 0.5, \qquad W_{fr}/W_{fis} = 0.7.$$

For the interval 10—150° the angular distribution indicates $W_{fis}/W_{fr} = 4$.

At the present time it is impossible to arrive at any final conclusion regarding the fragmentation mechanism, since no rigorous theory of this process exists. However, we believe that it is of considerable interest to compare the experimental results with the fragmentation theory recently advanced by Shapiro.[8] We have therefore compared the experimental cross sections for light-nucleus production with certain conclusions derived from the dispersion theory of direct nuclear reactions.

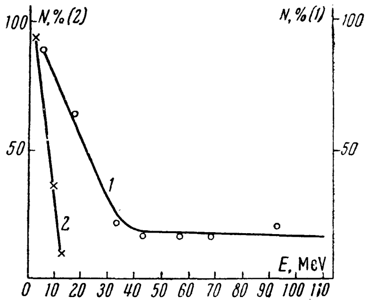

FIG. 2. Energy distribution of Na^{24} from Cu in the angular intervals 15—80° (curve 1) and 100—160° (curve 2).

For this purpose we calculated the separation energy $E = m_B + m_F - m_A$, where m_A is the target-nucleus mass, m_F is the fragment mass, and m_B is the mass of the complementary fragment.

It follows from the dispersion theory of direct nuclear reactions that the differential probability W of fragment ejection is proportional to the square of the process amplitude M, which for the simplest polar diagrams is related to the energy E by

$$M \sim \frac{1}{2m_F E + a},$$

where a > 0 and depends on the transferred momentum and the energies of the participating particles. In the present work we did not measure the differential probability of a reaction resulting in the emission of any particular fragment, since the remaining reaction products were not registered. It would therefore be difficult to carry out any detailed comparison with the theory of direct processes. It is possible, however, to determine the

Table III. Probabilities of fragment production

	Cu target				Sb target			Sn target	
	Be^7	F^{18}	Na^{24}	P^{32}	Be^7	F^{18}	Na^{24}	F^{18}	Na^{24}
w_{exp}	16	1	2,5	3,1	89	1	5	1	2.65
$1/E$	1.03	1	1,04	1.37	0,54	1	8,8	1	2.95
$1/E^2$	1.06	1	1.08	1,88	0,29	1	73.2	1	8.7
$(1/m_F E)^2$	7	1	0.61	0.6	1,93	1	41	1	4.9

dependence of the integral yield of a given fragment on the separation energy E. (This dependence can be largely masked by the different values of the widths for different fragments and for different final states.) As a rough qualitative account of this dependence, Table III gives the experimental cross sections and the quantities $1/E$, $1/E^2$, and $(1/m_F E)^2$ for Cu, Sb, and Sn. All values are given in relative units, with the probability of F^{18} production taken as unity. The data show that some correlation of the aforementioned kind exists for Be^7 and F^{18} production from Cu and for F^{18} and Na^{24} production from Sb and Sn. It should be noted that from experiment and calculations the Na^{24}/F^{18} ratio is considerably smaller for Sn than for Sb. Similar calculations cannot be performed for Bi from U, or for Mg^{28}, Si^{31}, and P^{32} from Sb, since the energy E is negative in these cases.

In conclusion, we wish to thank Prof. I. S. Shapiro and V. N. Mekhedov for valuable suggestions and discussions.

[1] Katcoff, Phys. Rev. **114**, 905 (1959).

[2] J. Hudis and J. M. Miller, Phys. Rev. **112**, 1322 (1958).

[3] Lavrukhina, Moskaleva, Krasavina, and Grechishcheva, Atomnaya energiya **3**, 285 (1957), Soviet J. Atomic Energy **3**, 1087 (1957).

[4] Lavrukhina, Moskaleva, Malyshev, Satarova, and Su Hung-Kuei, JETP **38**, 994 (1960), Soviet Phys. JETP **11**, 715 (1960).

[5] Borisova, Kuznetsova, Kurchatova, Mekhedov, and Chistyakov, JETP **37**, 366 (1959), Soviet Phys. JETP **10**, 261 (1960).

[6] S. A. Baranov and R. M. Polevoĭ, PTÉ (Instr. and Exptl. Techniques) No. 3, 32 (1957).

[7] Schambra, Rauth, and Northcliffe, Phys. Rev. **120**, 1758 (1960).

[8] I. S. Shapiro, Preprint 61-12, Inst. Theoret. and Exptl. Phys., 1961.

Translated by I. Emin
1