Isotope composition of fragments produced in high-energy $^{16}\mathrm{O}p$ interaction

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New experimental data have been obtained on the isotope composition of fragments of oxygen nuclei produced in $^{16}\mathrm{O}p$ collisions at 3.25 GeV/*c*. The data are compared with the predictions of the cascade-fragmentation evaporation model.

Experimental research on high-energy hadron-nucleus and nucleus-nucleus interactions over the past 20 years has established several general features of nuclear fragmentation.[1–3] For example, at an energy of 2 GeV per nucleon the cross section for the production of fragments of the projectile nucleus becomes constant, nearly independent of the target mass. In the proper frame of the projectile nucleus the angular distribution of fragments is approximately isotropic, and the momentum distribution is Gaussian with a width <200 MeV/*c* (Refs. 1–3).

Important information on the nuclear fragmentation mechanism in *hA* and *AA* collisions can be extracted from data on the isotope composition of the secondary nuclei.

In Refs. 4–7 we reported a detailed study of the multiplicity of various types of charged particles in $^{16}\mathrm{O}p$ interactions at 3.1 GeV/*c* per nucleon. Experimental data were obtained with the help of a 100-cm hydrogen bubble chamber which was exposed to a beam of relativistic oxygen nuclei at the proton synchroton of the Joint Institute for Nuclear Research. The use of a hydrogen bubble chamber in a magnetic field makes it possible to identify the secondary particles in a 4π geometry highly efficiently. This identification includes an identification of fragments by charge.

In this letter we are reporting a continuation of a series of studies of $^{16}\mathrm{O}p$ interactions.[4–7] Specifically, we are reporting the results of a study of the isotope composition of the fragments of oxygen nuclei. Some methodological questions concerning the analysis of stereo photographs of the hydrogen bubble chamber are discussed in Refs. 4–7. The experimental data reported below are based on an analysis of 4500 measured events. The isotope composition of nuclear fragments of charge Z was determined by analyzing distributions with respect to the quantity $X=Z/P$, where Z

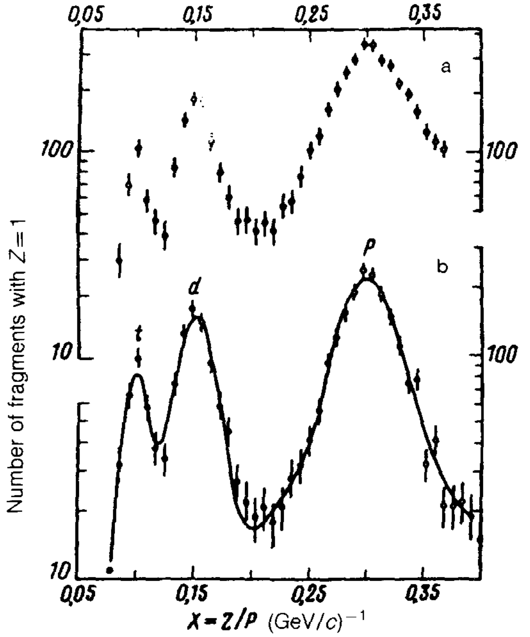

FIG. 1. Distribution of singly charged positive particles with respect to the quantity $X = Z/P$. a—Without a limitation on the fragment emission angle θ_l; b—for fragments with emission angles $\theta_l \leqslant 3.6°$; curve—result of a fit.

is the charge of the fragment, and P its momentum. The quantity X is proportional to the radius of curvature of the track of the fragment in the magnetic field of the chamber. The errors in the measurement of this quantity have a Gaussian distribution. The accuracy of the momentum measurements depends on the length of the track and the charge. To separate isotopes, we subsequently considered only those tracks whose measured length was $L_f > 40$ cm in the working volume of the bubble chamber. This selection of events keeps the error of the momentum measurements below 4% at all values of the charge, and it leads to a more reliable identification of the charge of the fragment. For the selected events with fragments with $L_f > 40$ cm, an additional methodological scan was carried out. As a result, 3% of the events, formed by beam particles with $Z_0 = 7$, were eliminated from the overall statistics.

Figures 1 and 2 show distributions with respect to $X = Z/P$ for singly charged positive particles and for doubly charged fragments. Figure 1a shows a distribution for particles with $Z = 1$ and a momentum $P > 2.5$ GeV/c. The three peaks observed here correspond to the hydrogen isotopes: p, d, and t. The proton peak is asymmetric. This asymmetry can be explained in terms of the contribution of at least two different mechanisms for the production of fast protons: primarily, protons that were knocked out as the result of an intranuclear cascade and "evaporation" protons, produced by the disintegration of the residual nucleus. Figure 1b shows a distribution of particles with $Z = 1$ under the limitation $\theta < 3.6°$ on the emission angle with respect to the projectile in the laboratory frame of reference. For protons this restriction corresponds to a transverse momentum of 200 MeV/c. The proton part of the distribution becomes symmetric. When the distribution is approximated by a sum of three Gaussian distributions corresponding to the contributions of $^1H_1$, $^2H_1$, and $^3H_1$, the value of χ^2 per

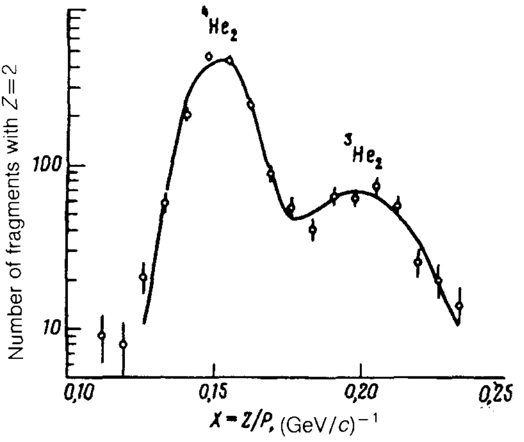

FIG. 2. Distribution of doubly charged fragments with respect to the quantity $X=Z/P$. The curve is the result of a fit.

degree of freedom (χ^2/DOF) is 3. Good agreement is reached under the assumption that the proton distribution is described by a sum of two Gaussian functions, differing in width ($\chi^2/\mathrm{DOF} < 1$).

In Fig. 2, which shows the X distribution for fragments with $Z=2$, we see two peaks, which correspond to the nuclei $^9He_2$ and $^4He_2$. This distribution can be described well by a sum of two Gaussian distributions ($\chi^2/\mathrm{DOF} < 1$).

The average values of the momentum per nucleon found from the approximation parameters are slightly higher than the value of 3.1 GeV/*c* found previously; for $^4He_2$, for example, the value is 3.25 ± 0.03 GeV/*c* per nucleon. A corresponding result was found for the beam of oxygen nuclei; according to the measurements, the value is 3.26 ± 0.003 GeV/*c* per nucleon.

We also studied the X distributions of fragments with $Z=$ 3–7, and we determined their relative yields. These results are shown in Table I. Also shown there are the results of calculations from the cascade-fragmentation evaporation model (CFEM).[8] Isotopes with relative yields less than 1% according to the CFEM are not reflected in this table. The selection of fragments on the basis of measured length loses some of the secondary particles, as a result of the interaction with the working liquid in the chamber. This loss amounts to 5% for protons and 30% for nitrogen nuclei over a distance of 40 cm. The data shown in Table I reflect the loss as a function of the atomic number of the fragment nucleus, as calculated from the cross sections for the *Ap* interaction.[9,10]

As was shown in Ref. 4, the CFEM gives a generally satisfactory description of the multiple production of fragments of oxygen nuclei. There are some discrepancies with the model, which are due in large part to the particular structure of the oxygen nucleus. We know that a clustering of nucleons in α particles plays an important role in light nuclei. At low nuclear excitation energies, this effect can lead to a much larger probability for the decay of the nucleus into α clusters than is predicted by Fermi decay, in which the probability for the decay channel is determined exclusively by its phase volume.

TABLE I. Isotope yields (%) in ^{16}Op collisions.

Z	A	Experiment	CFEM
1	$^{1}H_1$	69.1 ± 2.1	64.3 ± 0.6
	$^{2}H_1$	21.4 ± 0.9	24.6 ± 0.4
	$^{3}H_1$	9.5 ± 0.6	11.1 ± 0.2
2	$^{3}He_2$	19.9 ± 1.0	29.0 ± 0.5
	$^{4}He_2$	80.1 ± 2.0	68.5 ± 0.8
	$^{6}He_2$	< 1	2.5 ± 0.1
3	$^{6}Li_3$	55 ± 6	46.1 ± 1.4
	$^{7}Li_3$	41 ± 5	36.9 ± 1.2
	$^{8}Li_3$	4 ± 2	17.0 ± 0.8
4	$^{7}Be_4$	61 ± 7	55.7 ± 1.5
	$^{9}Be_4$	35 ± 5	16.4 ± 0.8
	$^{10}Be_4$	4 ± 2	27.9 ± 1.1
5	$^{10}B_5$	49 ± 5	42.5 ± 1.2
	$^{11}B_5$	49 ± 5	50.2 ± 1.4
	$^{12}B_5$	2 ± 1	7.3 ± 0.5
6	$^{10}C_6$	3 ± 1	16.2 ± 0.6
	$^{11}C_6$	17 ± 2	38.4 ± 0.9
	$^{12}C_6$	54 ± 4	19.8 ± 0.6
	$^{13}C_6$	19 ± 2	20.1 ± 0.6
	$^{14}C_6$	7 ± 1	5.5 ± 0.3
7	$^{13}N_7$	10 ± 1	8.9 ± 0.4
	$^{14}N_7$	40 ± 4	47.7 ± 1.0
	$^{15}N_7$	50 ± 5	43.4 ± 0.9

A comparative analysis of the data obtained here and the CFEM calculations (Table I) reveals an agreement with experiment in terms of the yields of singly charged fragments. For the isotopes of the helium nucleus the experimental yield of $^{4}He_2$ is considerably higher than the prediction of the model. The greatest discrepancy is observed in the yields of carbon isotopes. Here the maximum yield according to the CFEM is that of $^{11}C_6$, while experimentally half of the observed fragments are $^{12}C_6$ nuclei. There are also significant discrepancies in terms of the yields of beryllium isotopes.

In conclusion we wish to thank our colleagues at the High Energy Laboratory of the Joint Institute for Nuclear Research for acquiring the experimental data, as well as the technical staff of the laboratory for the scanning and the measurements. We are indebted to V. Sh. Navotnyĭ for useful discussions and for assistance in this study.

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