FRAGMENTATION OF OXYGEN NUCLEI INTO α-PARTICLES AND ^{12}C NUCLEI IN ^{16}Op-COLLISIONS AT 3.25A GeV/c

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New experimental data on decay of relativistic nuclei of oxygen into α-particles and ^{12}C nuclei during their interactions with protons are presented for the first time in the 4π-geometry. It is shown that the main mechanism of this decay is due to the quasi-elastic knock-out of one of the α-clusters of the original ^{16}O nucleus by a proton-target.

1. Introduction

The study of the processes of nucleus fragmentation under the relatively low excitation energies allows one to obtain an important information about the nucleus structure and the equation of state of the nuclear matter. Favorable conditions for such processes occur under a peripheral (particularly coherent) reaction of multifragmentation of a relativistic nucleus-projectile with a target, during which the target and the projectile interact as whole objects, and the target does not disintegrate. During the study of the processes of fragmentation of relativistic oxygen nuclei in their interactions with protons [1—7], we have found a number of characteristic features of this phenomenon. In particular, it was shown that, among all multicharged fragments, the most probable yield was for two-charge fragments, more than 80% of which were nuclei of ^{4}He, i.e. α-particles [1]. It should be noted that the disintegration of relativistic nuclei of oxygen into multi-charged fragments occurs only through topologies with even charges (224), (222) and (26), where the charges are shown in brackets [5]. The possible channels of disintegration with charges (233), (35) and (44) are missing. A more detailed analysis has shown [8] that the absence of channels (233) and (35) is connected with the high level of the excitation energy of nuclei required for these topologies to occur in comparison with the energy in channels observed experimentally and also with the restructuring of the initial (α-cluster) structure of the oxygen nuclei. With regard to topology (44), it should be noted that, in the case where the both four-charge fragments are nuclei of ^{8}Be, we observe in experiments topology (2222) as a result of the decay of these nuclei according to reaction (^{8}Be $\rightarrow \alpha + \alpha$). If one of the fragments is a nucleus of ^{7}Be and the other is ^{9}Be, then the realization of this channel is again related to the restructuring of the initial structure of the oxygen nucleus.

During the disintegration of relativistic nuclei of oxygen into two or more multi-charged fragments with conservation of the charge and the number of nucleons we observe only two channels [7], namely, four α-particles or nuclei of ^{12}C and ^{4}He, i.e. the splitting occurs with the creation of even-even nuclei.

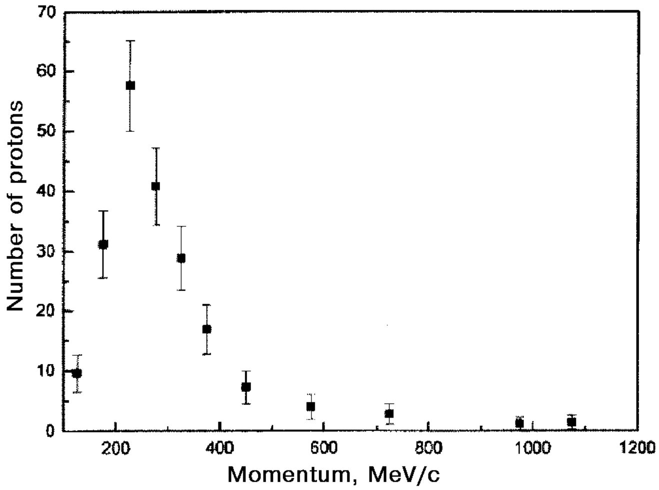

Fig. 1. Momentum distribution of protons

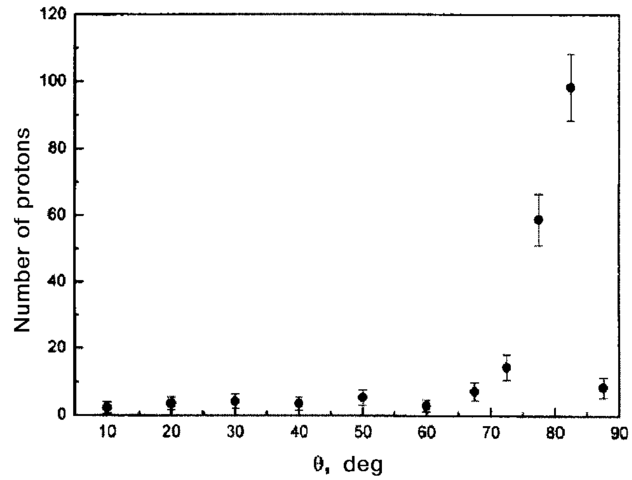

Fig. 2. Angular distribution of protons

From the results of experiments cited above it follows that the structure of the initial nuclei is revealed considerably in peripheral collisions. Thus, the investigation of various characteristic features of nucleus fragments of oxygen in channels with low energy exchange is of great interest for researches.

One of the possible mechanisms that leads to the fragmentation of a nucleus into multicharged fragments with conservation of all nucleons of the initial nucleus, may be a coherent dissociation. Under high energies, the existence of this special type of interactions (the excitation of a nucleus of the collective type with its consequent decay into components) was predicted theoretically in 1956 [9]. Recently, a few publications [10—12] were devoted to the study of the fragmentation of carbon nuclei into three and four α-particles during their interactions with nuclei of propane and a photoemulsion at momenta of 4.2 and 4.5 GeV/c. The authors of these papers came to the conclusion that such reactions belong to the coherent diffraction type. The present work is devoted to the analysis of the disintegration of relativistic nuclei of oxygen into two multicharged fragments (nuclei of ^{4}He and ^{12}C) during their interactions with protons.

2. Experimental Data and Discussion

The experimental data were obtained at the Dubna synchrophasotron with the use of a 1-meter hydrogen bubble chamber LVE OIYAI that was irradiated with oxygen nuclei with momentum 3.25A GeV/c, during which the statistics of 14500 events of ^{16}Op collisions was obtained. The identification of π^+-mesons and protons was carried out visually in the range of momenta $p < 1.2$ GeV/c. During the study of reaction (1) (see below), we considered events in which the measured length of tracks of two- and six-charged fragments exceeded 35 cm, which was necessary for their reliable mass identification. With such a length of tracks, the average error of fragment momenta does not exceed 3.5% and the angles of escape are measured with the accuracy of $\Delta\theta < 0.1$. The separation of fragments in masses were carried out on the basis of their momenta, namely, the fragments with charge $z_f = 2$ and momentum in the range of $p = 10.8 \div 15.0$ GeV/c were identified as α-particles and those with $z_f = 6$ and $p = 36.5 \div 44.0$ GeV/c were identified as ^{12}C. The details related to the processing of stereo-photographs taken from the 1-meter hydrogen bubble chamber, the reconstruction of spatial coordinates, and the calculations of the kinematic parameters of particles and fragments are described in works [1—4].

In the table, we give the cross-section of channel (26) versus the number of one-charged particles $n_{\rm ch1}$. It can be seen that, in this topological channel, the creation of fragments is accompanied mainly by the creation of only one positive particle. Among these particles, the part of protons with momenta $p <$1.2 GeV/c is approximately $\approx$ 80%.

The momentum and angle distributions of protons in the events corresponding to topological channel (26) without any limitations on track lengths of multi-charged fragments are shown in Figs. 1 and 2. As can be seen from Fig. 1, the momentum distribution of protons has a maximum at small momenta ($p_p \approx 225$ MeV/c) and then decreases quickly up to momenta $p_p <$500

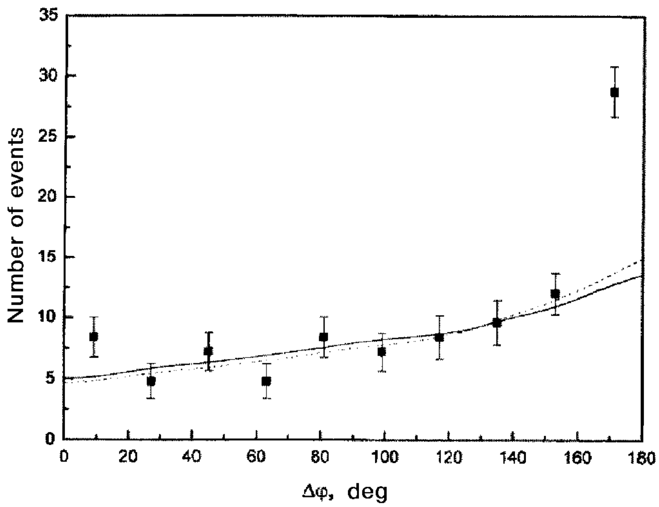

Fig. 3. Distribution over the difference of azimuthal angles of protons and α-particles in reaction (*1*). The solid line shows the results of the calculation according to the phenomenological model and the dotted line shows the results of the calculation using CFEM

MeV/c. Staring from $p_p > 500$ MeV/c, the decay rate becomes considerably lower, which is observed up to the maximum momentum for the identification of protons, p_p <1200 MeV/c.

Fig. 2 shows that the spectrum of the angles of escape of protons remains invariable within the statistical error in the range $5 < \theta < 70°$. Then we observe the quick rise with the sharp maximum in the angular range $80 < \theta < 85°$.

The analysis of momentum spectra of two- and six-charged fragments in topological channel (26) shows that, in the events with $n_{ch1} = 1$ and the creation of a proton (which have cross-sections of 6.82 ± 0.51 mb), we observe mainly the creation of nuclei of ^{4}He and ^{12}C. That is, in these events we observe the conservation of the number of nucleons of the initial oxygen nucleus. The momentum and angular distributions of protons created in these events also have maxima at $p_p \approx 225$ MeV/c and at the angle of escape $\theta_p \approx 82°$ in the local coordinate frame. These experimental data indicate that the process of decay of an oxygen nucleus into two fragments, ^{4}He and ^{12}C, with the creation of one proton is of an "elastic" diffractive type (the scattering of a proton by a multinucleon system).

Cross-section of channel (26) versus the number of one-charged particles n_{ch1}

n_{ch1}	1	3	5
σ, mb	8.940.62	1.120.20	0.090.06

A detailed study was carried out for the events in which the momentum of protons is less than 0.5 GeV/c and the angle of escape exceeds 70°. These events can be described by the reaction

$$^{16}\mathrm{O} + \mathrm{p} \to \mathrm{p} +^4 \mathrm{He} +^{12} \mathrm{C}. \quad (1)$$

In these events the distribution of the difference of azimuthal angles of protons and α-particles $\Delta\phi = |\phi_p - \phi_\alpha|$ is strongly asymmetric and has a pronounced maximum at $\Delta\phi > 150°$ (Fig. 3).That is, a proton and an α-particle tend to flight out in the opposite directions in the azimuthal plane of the reaction. As for azimuthal correlations in the yield of the protons and carbon nuclei, they are not so strongly revealed.

The reaction of decay of the oxygen nucleus into the nuclei of ^{4}He and ^{12}C can be considered as a result of:

1) the quasi-elastic knock-out by the proton of the α-cluster from the ^{16}O nucleus;

2) the diffraction excitation of the oxygen nucleus with its consequent decay into the observed fragments.

The last process can occur also through the creation of the excited states of the oxygen nucleus with the energy levels (in MeV): 11.26 (0^+), 11.6(3^-), 14.02(0^+),...,16.8(4^+), and higher values (in the brackets it is shown the spin and the parity of the states) with the width of the resonance state more than 0.1 MeV [13].

To check these assumptions, we carried out the calculations using the following phenomenological model. Under inelastic scattering of an oxygen by a proton, we assume that an intermediate excited state of the original nucleus is created, whose mass is determined from the measured kinematic parameters of the proton:

$$M(^{16}\mathrm{O}^*) = M(\alpha^{12}\mathrm{C}) = ((E_{\mathrm{Op}} - E_p)^2 - (\vec{P}_{\alpha^{12}\mathrm{C}} - \vec{P}_p)^2)^{\frac{1}{2}}, \quad (2)$$

Here, $\vec{P}_{\alpha^{12}\mathrm{C}} = \vec{P}_{^{16}\mathrm{O}} - \vec{P}_p$ is the total energy of the initial particles, $\vec{P}_{^{16}\mathrm{O}}$ and $\vec{P}_p$ are the momentum vectors of the oxygen-projectile and the secondary proton, respectively. The difference between this mass and the sum of the masses of the α-particle and ^{12}C is the released kinetic energy of the decay:

$$\Delta E = M(\alpha^{12}\mathrm{C}) - M_\alpha - M_{^{12}\mathrm{C}}. \quad (3)$$

The experimental distribution in ΔE has the form close to symmetric with respect to the average value $\langle \Delta E \rangle = (9.1 \pm 1.0)$ MeV with the mean squared deviation of 5 MeV.

In calculations we assumed that the decay of the excited nucleus occurs isotropically in the rest system of α^{12}C. The calculations were carried out in the following order: a) in this coordinate system, we calculated the kinetic energies and the momenta of the fragments α and ^{12}C; b) with the use of the Monte Carlo technique, we simulated the angles of escape of fragments with respect to the direction of the system (α^{12}C) and also their azimuthal angles; c) we then converted the data to the laboratory coordinate system.

In order to take into account the influence of the errors in measurements of momenta and angles, we simulated ΔP, $\Delta\alpha$, and $\Delta\beta$ errors of momentum and the depth and plane angles of escape, respectively, using the normal distribution with the experimentally determined dispersions.

The obtained results are shown in Fig. 3 (the solid line). In the same figure, we show the results obtained using CFEM. It can be seen that the calculations according to our phenomenological model and CFEM are close, but they differ strongly from the experimental data in the range $\Delta\phi > 160°$. The experimentally observed tendency of escape of the proton and the α-particle in the opposite directions may serve as an argument in the support of the quasi-elastic mechanism of knock-out of one of the four α clusters of the projectile nucleus.

The elastic scattering of hadrons by nucleons and nuclei at the energies of several GeV and higher has a diffractive character. In this case, the main part of the elastic cross-section corresponds to small scattering angles, for which the differential distribution in the square of the transferred four-dimensional momentum $-t$ has the exponential form:

$$d\sigma/dt = A\exp(-b/t). \quad (4)$$

The slope parameter of the diffraction peak b in the optical model of hadron-nucleus interactions or in the quasi-classical approximation is related to the radius of the interaction potential or to the characteristic size of the scattering medium: $b = R^2/4$. In the case of the inelastic coherent diffraction with the disintegration of the nucleus analogous to that in elastic scattering, the form of expression (4) remains the same, but, in this case, $t = t' - t_{\min}(\Sigma m_f)$, where t' is the measured quantity and $t_{\min}$ is the minimal value of the 4-momentum that is necessary for creation of the final fragments. The appearance of the second factor in expression (4) related to the creation of fragments and the values of their masses practically cannot change the shape of distribution (4). The longitudinal component of the momentum transferred during diffraction or quasi-elastic scattering is much less than the transversal component and therefore $-t = p_T^2$ and the distribution in the square of the transversal momentum has the same shape as given by expression (4).

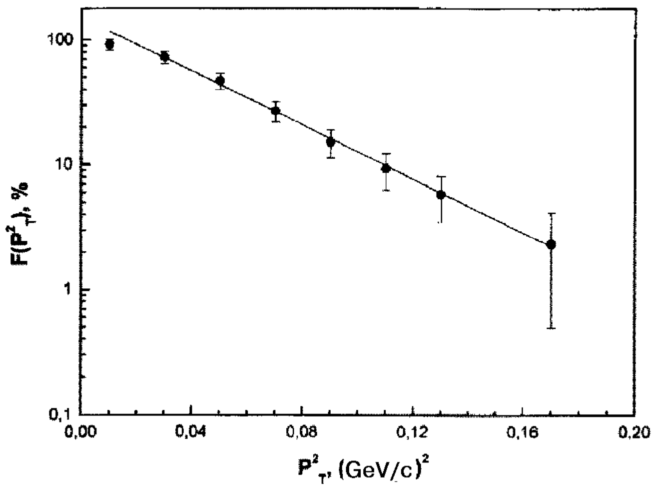

Fig. 4. Integral distribution of protons in the square of the transversal momentum

Fig. 4 shows the integral distribution in the square of the transversal momentum of protons in reaction (1). As can be seen from Fig. 4, this distribution is well approximated by function (5) with χ^2/f.d.n.=0.57, A=1.51 ± 0.15, and b=(24.80 ± 1.92) (Gev/c)$^{-2}$. This value of the slope parameter b corresponds to the radius of the sphere of the scattering medium R=1.91 ± 0.33 Fm, that within the statistical error is the same as the radius of an α-particle. Thus, we can conclude that reaction (1) occurs mainly through the mechanism of the quasi-elastic knock-out of one of the α-clusters of the projectile by the proton-target and the remaining three clusters create the nucleus of ^{12}C. This indicates once more that the α-particle state of the nuclear matter plays an important role in the structure of atomic nuclei and in the creation of fragments in nuclear reactions.

1. *Glagolev V.V., Gulamov K.G., Kratenko M.Yu. et al.*// Pisma Zh. Eksp. Teor. Fiz. **58** (1993) 497; **59** (1994) 316.
2. *Glagolev V.V., Gulamov K.G. et al.* //Yad. Fiz. **58** (1995) 2005.
3. *Glagolev V.V., Gulamov K.G., Lutpullaev S.L. et al.* //Ibid. **60** (1997) 575.
4. *Botvina A.S., Wislicki W., Gaitinov Sh. et al.* //Z. Phys. A **345** (1993) 413.
5. *Abdulaeva K.N., Azimova M., Gulamov K.G., et al.* //Dokl. ANRUz. N5 (1996) 21.
6. *Glagolev V.V., Gulamov K. G., Lipin V. D. et al.* //Yad. Fiz. **61** (1998) 2132.
7. *Glagolev V.V., Gulamov K. G., Lipin V.D. et al.* //Ibid. **62** (1999) 1879.

8. *Belov M.A., E. Kh. Bazarov, Lutpullaev S.L. et al.* //Dokl. ANRUz. **3** (2002) 16.

9. *Pomeranchuk I.Ya., Feinberg E.L.* //Nuovo cim. **3** Suppl. N4 (1956) 652.

10. *Belaga V.V. et al.* //Yad. Fiz. **58** (1995) 2014.

11. *Belaga V.V. et al.* — (Prepr. OIYAI R1-95-218, Dubna, 1995).

12. *Avetjan F.A. et al.* //Yad. Fiz. **59** (1996) 110.

13. *Ajzenberg-Selove F.* //Nucl. Phys. **A490** (1988) 1.

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ФРАГМЕНТАЦІЯ ЯДЕР КИСНЮ НА α-ЧАСТИНКУ ТА ЯДРО ^{12}C В ^{16}Op-СПІВУДАРАХ ПРИ 3,25A ГеВ/c

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Р е з ю м е

Вперше наведено нові експерименталні дані з розвалу релятивістських ядер кисню на α-частинку та ядро ^{12}C у взаємодіях з протоном в умовах 4π-геометрії. Показано, що основним механізмом такого розвалу є квазіпружне вибивання протоном мішені одного з α-кластерів вихідного ядра ^{16}O.