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ELEMENTARY PARTICLES AND FIELDS
Experiment

Role of ^{8}Be $\rightarrow 2\alpha$ Intermediate Nuclei in the Fragmentation of ^{16}O Relativistic Nuclei in Nuclear Track Emulsions

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Abstract—In searches along a track in the chamber irradiated at the Laboratory of High Energies at the Joint Institute for Nuclear Research (JINR, Dubna) with oxygen ions accelerated to a momentum of 4.5 GeV/c per nucleon, 215 events containing two or more doubly charged fragments of the primary nucleus were found. Emission angles in the track-emulsion plane were measured in these events. Their distribution is consistent with that which alpha particles are expected to have in an oxygen nucleus prior to its interaction with a track-emulsion nucleus. Events of the $^{16}\mathrm{O} \rightarrow 2^{8}\mathrm{Be} \rightarrow 4\alpha$ type were discovered for the first time. They are treated as events of the coherent electromagnetic dissociation of an oxygen nucleus. Among all events, about 14% of the $^{8}\mathrm{Be} \rightarrow 2\alpha$ decays proceed through the ground state of spin–parity 0^{+}; an approximately the same fraction of such decays proceed through the first excited state of spin–parity 2^{+}.

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1. INTRODUCTION

The fragmentation of ^{16}O relativistic nuclei interacting with other nuclei has been investigated in a number of studies [1–7]. In the course of time, it became clear that the study reported in [1] yielded results closest to the true picture. In that study, it was shown that the variance of the angles φ in the track-emulsion plane is consistent within the experimental errors with the variance of the angles α in the vertical plane. Moreover, the values measured for $\sigma(\varphi)$ agree with the values that are expected on the basis of calculations employing the Fermi momentum obtained from data on electron scattering off ^{16}O nuclei [8]. Below, we will show that we obtained the same result at an oxygen-nucleus momentum of 4.5 GeV/c per nucleon inclusive.

However, data whose reliability is questionable were published in some of more recent articles—for example, in [7]. The weakest point of those studies was that their authors employed only integrated distributions associated with the angle $\theta \sim (\varphi^2 + \alpha^2)^{1/2}$ and did not present a proof of the equality of the variances of angles in the vertical and horizontal planes. In tens of studies published since that time, it was found that the transverse-momentum $(P_\perp(\theta))$ distribution is not a Rayleigh distribution. In experiments, there is an excess of high $P_\perp(\theta)$ values, which is a consequence of the fact that the variance of the angle in the vertical plane is substantially greater than the variance of the angle in horizontal plane.

Those studies were criticized in the literature several times [9, 10], as well as in the open letter of one of the present authors [11]. However, no arguments against this criticism appeared, and this gives sufficient grounds to believe in its validity.

In the present study, we abandon an analysis of data based on estimating the spatial angle θ, even though such estimates were obtained in the experiment. The point is that, at our energy, it is already impossible to ensure an experimental accuracy that is required in estimating the angle θ for separating the $^{8}\mathrm{Be} \rightarrow 2\alpha$ channel.

Our interest in the fragmentation of the oxygen nucleus was also motivated by the fact that, according to the calculations reported in [12, 13], this is the only nucleus in which the cascade production of alpha particles through the $^{16}\mathrm{O} \rightarrow 2^{8}\mathrm{Be} \rightarrow 4\alpha$ channel proceeds with a probability of about 28%. Below, we demonstrate that we were able to separate events originating from this channel. Special features of the procedure for separating this channel, which involves the ^{8}Be intermediate state [14], are considered in the following. After that, we discuss the details of our experiment and, in conclusion, present its result.

2. SEPARATION OF THE CHANNEL $^{8}\mathrm{Be} \rightarrow 2\alpha$

If all product doubly charged particles originate from a single center and if their transverse momentum depends exclusively on the Fermi momentum before the interaction with a track-emulsion nucleus, the distribution of these particles with respect to the angle φ in the track-emulsion plane must correspond to a normal distribution whose mean value is zero and whose variance is readily calculable. This follows from the results reported in [10, 15], where the authors showed that, for relativistic nuclei of ^{10}B, ^{11}B, ^{32}S, ^{22}Ne, and ^{24}Mg and of lead with momenta in the range between 2 and 200 GeV/c per nucleon, the experimental values of $\sigma(\varphi)$ agree within the experimental errors with their counterparts calculated on the basis of the Fermi momentum for these nuclei, so that one must not reject the hypothesis of a normal distribution of experimental angles φ. There is every reason to believe that this regularity survives for oxygen nuclei as well, which we study—that is, there are no high transverse momenta of relativistic-nucleus fragments.

Setting the Fermi momentum to 230 MeV/c for the oxygen nucleus, we obtain a value of $\sigma(\varphi) =$ 7.2 mrad for the expected constant of a normal distribution of the projection of the transverse momentum of doubly charged fragments onto the track-emulsion plane. For the $^8\text{Be} \to 2\alpha$ channel, the maximum angle between the directions of the emission of two alpha particles is 2 mrad if the decay process starts from the ground state, whose spin–parity is 0^+, and approximately 9 mrad if the decay in question occurs from the first excited state, for which the respective quantum numbers are 2^+. This is because the energy of this excited state is approximately 20 times as high as the ground-state energy. Accordingly, the momenta of particles originating from the decay of these states are in a ratio of $\sqrt{20}$, the distribution of the angles $\varphi_{1,2}$ between the particle momenta being bound to be uniform.

If we separated, as in [14], the $^8\text{Be} \to 2\alpha$ channel by using the angle $\theta_{1,2}$ between the particle momenta, the distribution with respect to this angle would have the form of a parabola as the angle increases from a zero to a maximum, where it assumes the largest value. Here, it corresponds to the case where two alpha particles fly apart in the direction orthogonal to the transport velocity. In our study, the accuracy in estimating the angle θ is about 2 mrad. Because of the errors, the distribution of this angle over the region extending up to 2 mrad is uniform in this case, not increasing from zero to a maximum, in contrast to what was observed in [14]. This is the reason why we abandoned the idea of employing the angles θ.

3. DESCRIPTION OF THE EXPERIMENT

A track-emulsion chamber was irradiated with oxygen ions of momentum 4.5 GeV/c per nucleon at the Laboratory of High Energies at the Joint Institute for Nuclear Research (JINR, Dubna). Searches for events were performed by means of scanning along the track of the primary particle. In all, we scanned 146.47 m of tracks. Over this length, we found 1121 events of the inelastic interaction of a primary nucleus with a track-emulsion nucleus. In this set of inelastic-interaction events, we selected 215 events containing two or more doubly charged fragments of the primary nucleus. We did not fix the number of other particles in an event. These might be product particles, target fragments, or projectile fragments of charge not equal to two.

The events were measured by an MPE-11 microscope, the readings of its track-point-coordinate sensors being directed to the memory of a PC in response to observer's command [16]. Each event was measured twice in order to rule out random failures in saving data. However, there were virtually no such failures. (All primary data and our treatment procedures are available from the website quoted in [17]. They can be used by anyone who needs them under the condition of referring to the source of these data.)

In each event, we measured the angle φ_0 of the primary track in the track-emulsion plane and its angle α_0 in the perpendicular plane of the microscope reference frame, whereupon we calculated the angles φ_i and α_i at $i = 1, 2, \ldots, n$ in the event reference frame, where, by definition, $\varphi_0 = \alpha_0 = 0$ for all n tracks in an event.

However, this inevitably leads to an error associated with the continuation of the primary track to the region where one measures the coordinates of points of n tracks of fragments in an event. Only within a distance of about 1 mm can one treat tracks in a track emulsion as straight-line segments. At distances of about 1 cm (and these are distances over which one can measure angles of about 1 mrad), tracks inevitably have random S-shaped distortions both in the horizontal and in the vertical plane. In the last case, such distortions are additionally enhanced by a mechanical shrinkage of the thickness of the track-emulsion layer by a factor of 2.5 in relation to the thickness of an undeveloped track emulsion, in which case undeveloped silver bromide is removed from the layer. As a result, a track traversing the layer looks like a parabola rather than like a straight-line segment.

Thus, we have seen that, in order to measure angles of $\varphi \sim 1$ mrad, one has to increase the distance in the coordinate X to the region where there is no primary track any longer, but where there arise distortions, which rapidly become larger than measured values. The possible way out is to go over to relative measurements—that is, to measuring, instead of an angle for which the primary track does not have a

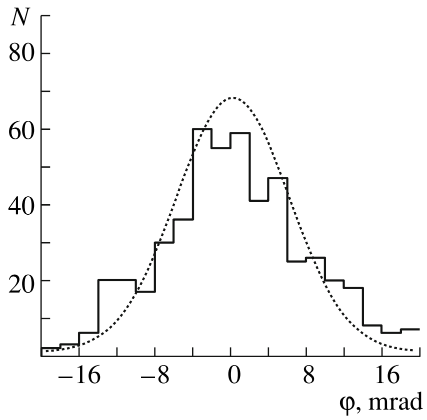

Fig. 1. Distribution of angles φ in the track-emulsion plane: (histogram) experimental distribution and (curve) expected normal distribution with a standard deviation of 7.2 mrad (it is normalized to the number of events in the experiment).

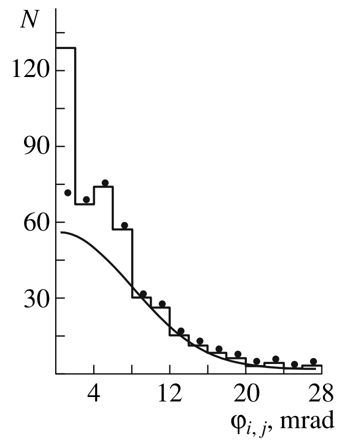

Fig. 2. Distribution of the absolute values of the difference of angles in the track-emulsion plane: (histogram) experimental data, (curve) normal distribution characterized by a standard deviation of 7.2 mrad, and (points) distribution after the elimination of hypothesized events of the decay of a ^{8}Be nucleus to two alpha particles from the ground state. The normalization to the number of events was performed here.

continuation, the angle that forms a pair with it and which has a track identical to the former one. This was done in [15]. If n angles in events are distributed normally with respect to some direction that is unknown to us and if they are independent, then the variance of the paired angle $\varphi_{i,j}$ at $i = 1, 2, \ldots, n-1$ and $j = i+1, \ldots, n$ is twice as great as the variance of the angle φ with respect to the unknown direction. This method of relative measurements, which was used in [15], made it possible to discriminate between the value of $\sigma(\varphi) = 0.25$ mrad for doubly charged fragments of the ^{32}S nucleus with a momentum of 200 GeV/c per nucleon and the value of $\sigma(\varphi) =$ 0.37 mrad for lead of energy 160 GeV per nucleon.

This is the reason why we selected events containing two or more doubly charged fragments in a single event. Since, in the region of measurements, the difference of the coordinates of two tracks, $\Delta Y_{i,j} \sim$ 1 μm, is measured to a precision of about 0.2 μm (this is the microscope resolution), the error in the angle $\varphi_{i,j} \sim 0.1$ mrad at a distance of 1 cm is about 0.02 mrad. The measured points are close to each other; therefore, it is natural to assume that their shifts with respect to the continuation of the primary track are identical and do not have a substantial effect on the value of the measured pair angle.

4. RESULTS

The distribution of angles φ is shown in Fig. 1. It can be seen that the hypothesis of a normal distribution of the respective sample of these angles is not disproved by parameter-free consistency criteria [18]. The constant value of $\sigma(\varphi) = 7.62 \pm 0.32$ agrees with its counterpart expected on the basis of its derivation from the Fermi momentum for the oxygen nucleus before its collision with a track-emulsion nucleus.

Abandoning the idea of employing the spatial angle θ, we do not in fact introduce any limitation in our analysis. The distribution of unmeasured transverse momenta, which is $P_\perp(\theta) = A_F \cdot p_0 \cdot \sin(\theta)$, where A_F and p_0 are, respectively, the mass number of the relativistic-nucleus fragment and the momentum per nucleon of the primary nucleus, must follow a Rayleigh distribution with the constant of $\sigma(P_\perp(\theta)) = 2^{1/2} A_F \cdot p_0 \cdot \sigma(\varphi)$. From here, we find that $\sigma(P_\perp(\theta)) = 193 \pm 8$ MeV/c. This value is greater than the estimates obtained in [3, 7] for the constant of the distribution of the transverse momentum. However, our estimate assumes that all alpha particles are emitted directly from the ^{16}O nucleus, but this is not so.

The distribution of the pair angles between all tracks in an event, $\varphi_{i,j}$, is shown in Fig. 2. From this figure, one can see that only for angles satisfying the inequality $\varphi_{i,j} > 8$ rad do experimental data agree with the expected distribution. For angles smaller than 2 mrad, there is a peak obviously associated with the decay $^8\mathrm{Be} \to 2\alpha$ from the ground state, whose spin–parity is 0^+. As to the distribution of pair angles in the region between 2 and 8 mrad, it remains constant within this interval. A verification showed that the distribution of pair angles in the intervals of 0–2 and 2–8 mrad is consistent with a uniform distribution. The parameter-free Kolmogorov and Cramér–von Mises criteria do not reject a null hypothesis. This must be the case if about 14% of all pairs of alpha particles originate from the decay of an ^{8}Be nucleus in the ground state and if the number of their pairs originating from the decay of its first excited state, whose spin—parity is 2^+, is approximately the same.

It is of importance that the data sample being considered proved to be nonuniform. Eleven events featuring four doubly charged particles in the final state stand out in this sample. They look like narrower events and stand out even at the scanning stage. By way of example, we indicate that one of them has angles of 3.987, 3.352, 1.509, and 0.731 mrad in the track-emulsion plane with respect to the primary track. It is precisely among such events that we found four events of the $^{16}\mathrm{O} \to 2^8\mathrm{Be} \to 4\alpha$ type. In these events, the angles between the pairs of tracks are smaller than 2 mrad. The probability of observing one event featuring an angle smaller than 2 mrad in the case of a normal distribution with a standard deviation of 7.2 mrad is about 10^{-1}, while the probability of simultaneously observing four such angles in a single event is about 10^{-4}. The presence of four such events in the sample of 11 events is a regularity rather than the result of a random coincidence. If we add to them approximately the same number of decays of ^{8}Be nuclei through the 2^+ state, then it turns out that, of eleven events that we observed and which feature four doubly charged fragments, nine originate from the channel $^{16}\mathrm{O} \to 2^8\mathrm{Be} \to 4\alpha$. Oxygen first disintegrates into two ^{8}Be nuclei, and only after that do we see four doubly charged fragments, the standard deviation of the angle between the directions of motion of the two ^{8}Be nuclei being 1.9 mrad. This is approximately one-half as large as the value that would correspond to the case where the ^{8}Be nuclei escape independently from an oxygen nucleus.

For the effect observed in our experiment, the first explanation that naturally suggests itself is based on the assumption that this effect is associated with the coherent electromagnetic dissociation of an oxygen nucleus into two ^{8}Be nuclei [19].

The recent article of Peresad'ko et al. [20] presented calculations of two coherent processes of the dissociation of the ^{7}Li nucleus, electromagnetic and nuclear. In the first of them, the process proceeds through the exchange of a virtual photon, while, in the second, this occurs via Pomeron exchange. The cross section for the first process is concentrated in the region extending up to 50 MeV/c. The second process exhibits a characteristic nonmonotonic dependence of the cross section in the region extending up to 300 MeV/c. This dependence was not confirmed in the experiment reported in [20], but the statement that only low momentum transfers are involved in coherent electromagnetic dissociation remains valid. Such momenta are inevitably associated with small angles. This is precisely what we observed in our experiment. Most likely, all our events featuring four doubly charged fragments are events of the coherent electromagnetic dissociation of an oxygen nucleus to two ^{8}Be nuclei.

5. CONCLUSIONS

We have established that the set of experimental data on the fragmentation of oxygen nuclei with a momentum of 4.5 GeV/c per nucleon to two or more doubly charged fragments is not uniform. Events of fragmentation to four doubly charged particles are substantially narrower than the remaining events—that is, the emission angles in the former with respect to the direction of the primary-particle momentum are substantially smaller. This is because almost all of such events reach the final state through the stage of formation of two ^{8}Be nuclei from the primary oxygen nucleus. In all probability, these are virtual-photon-induced events of the coherent electromagnetic dissociation of oxygen nuclei.

The coherent-dissociation process was claimed to be the subject of investigations in a number of articles [7, 20, 21]. However, none of them contains experimental evidence that the events under study have a bearing on electromagnetic or nuclear coherent dissociation. It is common practice to assume that all so-called white stars, which do not contain target fragments or product particles, are precisely events of coherent dissociation. However, this class of events is substantially wider than the class of events of the electromagnetic or nuclear dissociation of nuclei. Coherent dissociation cannot be separated from the ordinary fragmentation of nuclei by using emission angles alone. The point is that the emission angles are identical in these two cases. Possibly, someone will be able to prove, for the respective cross section, the nonmonotonic momentum-transfer dependence predicted in [20]. However, this have not been done thus far.

The study reported in [7] is worthy of special note. There, 641 events of the $^{16}\mathrm{O} \to 4\alpha$ type were found upon scanning over an area. This sample is not representative, as was indicated in that study. We also made an attempt at searches over an area, but, in our chamber, this search proved to be inefficient because of a low density of primary particles.

All these circumstances, together with a poor accuracy in estimating the spatial angle θ, prevented the authors of [7] from discovering a special class of events characterized by a narrow angular distribution.

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