Experimental measurement of sizes of emission sources for deuterons and α particles in ^{16}O-p collisions at 3.25A GeV/c

Richard Lednicky,[1,2] Sagdulla L. Lutpullaev,[1] Kosim Olimov,[1] Khusniddin K. Olimov,[1,3,*]
Alisher K. Olimov,[1] and Bekhzod S. Yuldashev[4,5]
[1]*Physical Technical Institute of SPA Physics Sun of Uzbek Academy of Sciences, Tashkent, Uzbekistan*
[2]*Joint Institute for Nuclear Research, Dubna, Russia*
[3]*Inha University in Tashkent (IUT), Tashkent, Uzbekistan*
[4]*Institute of Nuclear Physics of Uzbek Academy of Sciences, Tashkent, Uzbekistan*
[5]*Academy of Sciences of Uzbekistan, Tashkent, Uzbekistan*

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The sizes of emission sources of deuterons and α particles were determined in minimum bias ^{16}O-p collisions at 3.25A GeV/c from the analysis of experimental one-dimensional correlation functions of these particles, based on a theoretical model assuming the simultaneous excitation and decay of sources (of identical particles), whose coordinates are distributed according to a Gaussian function. The peak was observed in the experimental correlation function of the pairs of α particles in the region of $q < 25$ MeV/c, which was deduced to be due to decays of unstable ^{8}Be and ^{9}B nuclei at various kinetic energies. This result does not contradict the popular assumption of other authors about the existence of the α-condensate state in the ^{16}O nucleus since unstable ^{8}Be and ^{9}B nuclei themselves can probably be formed from decay of the α-condensate state of the oxygen nucleus if such a state does exist.

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I. INTRODUCTION

An investigation of the correlation of identical particles allows one to obtain information on the spatial picture of the emission of particles in relativistic hadron-nucleus and nucleus-nucleus collisions [1,2]. Presently, quite much experimental data exist on the sizes of emission regions of pions and protons in nuclear reactions at intermediate and high energies [3–7]. However, the experimental data on sizes of emission regions of deuterons and α particles are considerably less. To our knowledge, there are just two works [8,9] devoted to finding a size of an emission source of α particles based on their correlation analysis.

The WA98 Collaboration's experiment measured [7] the correlation function for protons and deuterons in Pb + Pb collisions at 158A GeV in the target fragmentation region and determined the sizes of their emission regions, which proved to be 3.14 ± 0.21 and 2.50 ± 0.28 fm, respectively. In Ref. [8], the sizes of the emission sources of α particles in collisions of ^{22}Ne and ^{24}Mg nuclei with nuclei of nuclear emulsion at 4.1 and 4.5A GeV/c, respectively, were measured. For correlation measurements, the authors considered only those collision events in which at least three particles with $Z = 2$ were observed (all of them were assumed to be α particles) in the central pseudorapidity region. Under such conditions, the size of the emission source of α particles proved to be 2.84 ± 0.28 fm [8], which coincided within the uncertainties with the sizes of the emission sources of protons and deuterons, obtained in the WA98 Collaboration's experiment. The above given results were obtained based on the analysis of the one-dimensional correlation function,

$$C(q) = N[Y_{i,j}(q)/F_{i,j}(q)], \tag{1}$$

where $q = |\mathbf{p}_i - \mathbf{p}_j|/2$—is the half of a modulus of a difference of momenta of identical particles i and j when $i \neq j$, $Y_{i,j}(q)$ is the summed value of q, measured and calculated in each hadron-nucleus or nucleus-nucleus collision event; $F_{i,j}(q)$ is the background distribution, obtained by mixing momenta $\mathbf{p}_i$ and $\mathbf{p}_j$ of identical particles i and j emitted in different collision events; and N is a normalization coefficient. The above given correlation function $C(q)$ was approximated by the expression,

$$C(q) = 1 + \lambda \exp(-q^2R^2), \tag{2}$$

where λ is a normalization coefficient and R is the size of the emission region (source) of identical particles. The above expression was derived in a theoretical model [1,8,9], which assumed the simultaneous excitation and decay of sources (of identical particles), whose coordinates are distributed according to a Gaussian function.

Based on the above-mentioned experimental data and using the same selection criteria, the authors of Ref. [8] also measured [9] the transverse and longitudinal sizes of the emission source of α particles using the multidimensional parametrization for the correlation function, suggested in Ref. [10] for the approximation of experimental spectra. The transverse and longitudinal sizes of the emission sources of the α particles were found to be 1.81 ± 0.22 and 2.38 ± 0.23 fm, respectively. When the γ factor was accounted for, the longitudinal size (10.6 ± 1.2 fm) of the emission source of the α particles proved to be compatible with the average size of a nucleus in a nuclear emulsion ($\langle R \rangle_{\rm em} = 12.9$ fm) [9].

The present paper is devoted to the investigation of the experimental one-dimensional correlation function of identical particles for deuterons and α particles, emitted in minimum bias ^{16}O-p collisions at 3.25A GeV/c. Experimental statistics consists of 10 014 minimum bias ^{16}O-p collision events with

*drolimov@gmail.com; K.Olimov@inha.uz

the registration of all the charged particles and fragments, measured with 4π acceptance. The paper is organized as follows. The experimental procedures are briefly discussed in Sec. II. An analysis and results are given in Sec. III. Section IV presents a summary and conclusions of the paper.

II. EXPERIMENT

The experimental data were obtained using a 1-m hydrogen bubble chamber at the Laboratory of High Energies of the Joint Institute for Nuclear Research, exposed to beams of ^{16}O nuclei, accelerated to momenta of $3.25A$ GeV$/c$ at the Dubna synchrophasotron. Our experiment is a unique one [11–14] since it allows registration and identification (by charge and mass) of all the charged particles and fragments of ^{16}O-p collision events, measured with 4π acceptance. Emission angles and momenta of the charged fragments and particles were measured with good enough precision [14]. In our case, the fragmenting oxygen nucleus is a projectile impinging on a hydrogen target. Therefore, we could measure the momenta of all the charged fragments and produced particles (mostly pions) starting from the $p = 0$ value in the oxygen nucleus rest frame [14].

For identification of the fragments by their masses, the following momentum intervals were selected in the laboratory frame: singly charged positive particles with $4.75 < p < 7.75$ GeV/c were considered to be deuterons (^{2}H nuclei). The doubly charged positive particles with $10.75 < p < 15.75$ GeV$/c$ were selected as α particles (^{4}He nuclei). The collision events with two or more deuterons (or α particles), whose track lengths were greater than 30 cm in the chamber volume, were considered. At such a condition, the admixtures of isotopes with masses close to those of deuterons (or α particles) among the selected deuterons (or α particles) did not exceed 4%, the average relative uncertainty in measuring the momenta of selected particles was 3% to 4%, and an angle between two emitted deuterons (or α particles) was determined with a precision of $\Delta\theta = 0.1^\circ$. The experimental procedures are described in more detail in Refs. [11–14].

III. ANALYSIS AND RESULTS

The experimental one-dimensional correlation function C(q) given in (1) for deuterons, emitted in ^{16}O-p collisions at $3.25A$ GeV$/c$, is shown in Fig. 1. The background distribution was constructed by mixing deuterons emitted in different ^{16}O-p collision events. The number of combinations in the background distribution was normalized to that of the experimental distribution in a region of $q > 0.2$ GeV$/c$ where no correlations are expected between emitted deuterons. The result of the approximation of the experimental correlation function C(q) by the function in (2) using a minimum χ^2 method is given by a solid curve. As seen from Fig. 1, the function in (2) describes quite well the experimental C(q) spectrum. We obtained the following values for parameters of fitting the experimental spectrum by a function in (2) at a minimum χ^2 value: $\lambda = 0.41 \pm 0.22$ and $R = 11.9 \pm 3.7\,(\text{GeV}/c)^{-1} = 2.4 \pm 0.7$ fm. This value of R for the size of the emission source of the deuterons in ^{16}O-p collisions at $3.25A$ GeV$/c$ coincided within statistical uncertainties with the result of Ref. [7], obtained for the deuterons emitted in the target fragmentation region in Pb + Pb collisions at $158A$ GeV. This result suggests that the size of the emission region for the deuterons, generated in relativistic hadron-nucleus and nucleus-nucleus collisions, does not depend on incident energy and mass number of the fragmenting nucleus.

The experimental one-dimensional correlation function C(q) given in (1) for α particles, emitted in ^{16}O-p collisions at $3.25A$ GeV$/c$, is presented in Fig. 2. The background distribution was constructed by mixing α particles generated in different ^{16}O-p collision events. The number of combinations in background distribution was normalized to that of experimental distribution in the region of $q > 0.2$ GeV$/c$ where we do not expect correlations between emitted α particles. Because the kinematical characteristics of α particles depend on the degree of excitation of the fragmenting oxygen nucleus

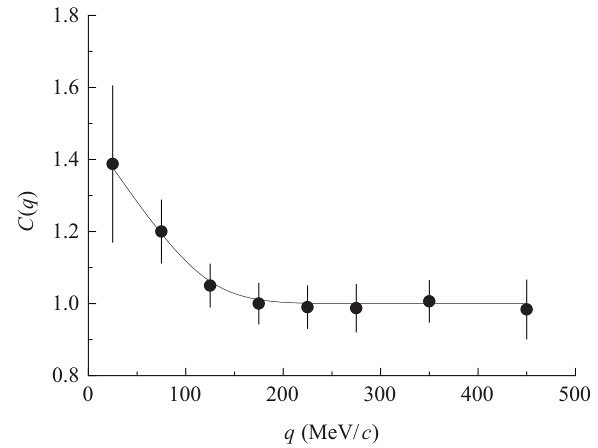

FIG. 1. The one-dimensional correlation function C(q) given in (1) for deuterons, emitted in ^{16}O-p collisions at $3.25A$ GeV$/c$. The solid curve is the result of a minimum χ^2 fitting of the experimental C(q) spectrum by the function in (2).

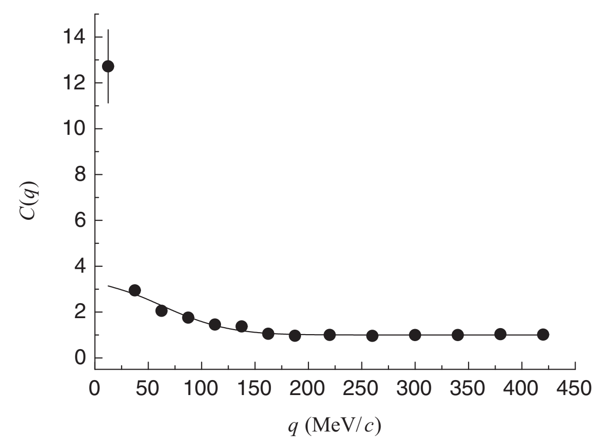

FIG. 2. The one-dimensional correlation function C(q) given in (1) for α particles, emitted in ^{16}O-p collisions at $3.25A$ GeV$/c$. The solid curve is the result of a minimum χ^2 fitting of the experimental C(q) spectrum by the function in (2).

[15], we accounted for the topology of collision events (i.e., the composition of fragments in each individual collision event) while constructing the background distribution. In other words, the background distribution was constructed separately for each type of collision event, i.e., separately for events with the number of doubly charged fragments in the final state equal to two, three, and four, for events consisting of at least two α particles. Then the total background distribution was obtained by adding these separate background spectra, taking into account the weight of each type of collision event in the experimental $C(q)$ spectrum of α particles.

As observed from Fig. 2, the value of the correlation function at $q < 25\,\text{MeV}/c$ exceeds by more than six standard deviations that for the next q point (bin). The remaining experimental points decrease gradually until the values of $C(q) \approx 1$ at $q > 150\,\text{MeV}/c$. Then a question arises whether such a large magnitude of the correlation function $C(q)$ at $q < 25\,\text{MeV}/c$ is related to the existence of the α-condensate state in light nuclei, which experimental indication was obtained in Ref. [16] for the carbon-12 nucleus? In Ref. [16], the kinematical analysis of the nuclear $^{40}\text{Ca} + {}^{12}\text{C}$ reaction showed that $7.5 \pm 4.0\%$ from decays of the ^{12}C nuclei in the first excited state (0^+ state with an excitation energy of 7.654 MeV) consisted of direct decays on three α particles with the same (within the errors) kinetic energies, which was associated with the formation of the α-condensate state in the ^{12}C nucleus. Let us note that the first excited state of the ^{12}C nucleus and the sixth excited state of the ^{16}O nucleus (0^+ state with an excitation energy of 15.097 MeV) can be described quite well by α-condensate-type functions, and, hence, are good candidates for the observation of the α-condensate state [17,18]. In Refs. [19,20], it was shown that, at a certain symmetry of the microscopic Hamiltonian, the α-condensate state also can exist at normal nuclear density. The authors calculated the energy spectra of the multi-α-particle state of ^{12}C and ^{16}O nuclei in the generalized Elliyot model. The results of the calculations reproduced quite well the experimentally measured energy spectra of the excited states of these nuclei [19,20]. Because the maximum structure of the experimental correlation function $C(q)$ at $q < 25\,\text{MeV}/c$ in Fig. 2 is due to α particles with very close (practically the same) kinetic-energy values, our result does not contradict the popular assumption about the existence of the α-condensate-like structure in the ^{16}O nucleus. Our result also goes along with the theoretical predictions of Refs. [19,20], which described quite well the experimental spectra about the existence of the α-condensate state in even-even nuclei, including those of ^{12}C and ^{16}O, at normal nuclear density. As seen from Fig. 1, such an anomalous structure is not observed in the experimental correlation function $C(q)$ of identical deuterons at $q < 25\,\text{MeV}/c$, even though they are, such as α particles, bosons as well. This can possibly be explained by the fact that the oxygen nucleus, according to modern perceptions and our experimental results [14,15,21,22], possesses an α-cluster structure, whereas the data on the deuteron cluster structure of this nucleus are absent. Such an α-condensate state of the ^{16}O nucleus can possibly be realized at normal nuclear density when all four α clusters in a nucleus have practically the same kinetic-energy values.

On the other hand, the direct reason for the maximum of the experimental $C(q)$ function at $q < 25\,\text{MeV}/c$, observed in

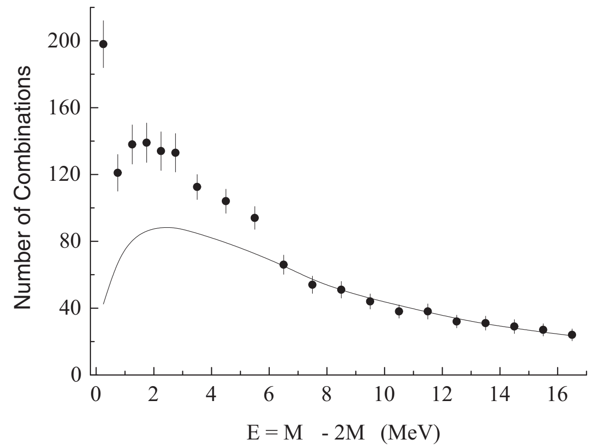

FIG. 3. The distribution on excitation energies of the pairs of α particles in ^{16}O-p collisions at $3.25A$ GeV/c. The solid curve is the background distribution.

Fig. 2, can be $^8\text{Be} \rightarrow 2\alpha$ decays of the unstable ^{8}Be nucleus in its ground state (0^+) with the energy release of 0.1 MeV and decays $^9\text{B} \rightarrow 2\alpha + p$ with the energy release of 0.3 MeV [23]. The final-state interactions of identical particles, not accounted for in formula (2), also can contribute to this maximum structure at $q < 25\,\text{MeV}/c$. To check these assumptions, we considered distributions of the pairs of α particles on their excitation energies $\Delta E = M_{\alpha\alpha} - 2M_\alpha$, where $M_{\alpha\alpha}$ is an invariant mass of a pair of α particles and M_α is the mass of α. The distribution of the pairs of α particles on their excitation energies ($\Delta E = M_{\alpha\alpha} - 2M_\alpha$ in MeV) is shown in Fig. 3. It is seen that, at $\Delta E = 0.25\,\text{MeV}$, the experimental distribution on excitation energies has a maximum, which value exceeds by approximately six standard deviations the corresponding value of the spectrum for the next point (bin). The first maximum in the ΔE spectrum as mentioned above is probably due to the decay of the unstable ^{8}Be nucleus in its ground state (0^+) with the energy release of 0.1 MeV as well as the decays of the ^{9}B nuclei with the energy release of 0.3 MeV. The second wide maximum is likely due to decays of the unstable ^{8}Be nucleus in its first excited state (2^+) with the energy release of 3.04 MeV [23]. Some contribution to these maximum structures also may come from final-state interaction effects. The background distribution was constructed accounting (as in the case of deuterons) for the topology of collision events and normalized in the region of $\Delta E > 6\,\text{MeV}$. As observed from Fig. 3, the background distribution describes quite well the experimental spectrum on ΔE in the region of $\Delta E > 6\,\text{MeV}$. The excess of the number of experimental combinations over the background in Fig. 3 proved to be 554, which makes up $(22.0 \pm 1.0)\%$ of the total number of combinations in the experimental spectrum. This excess corresponds to the cross section of the total yield of unstable ^{8}Be and ^{9}B nuclei equal to 13.6 ± 0.6 mb. This cross section coincided within the uncertainties with the total inclusive cross section (13.3 ± 0.5 mb) of the formation of unstable ^{8}Be and ^{9}B nuclei in ^{16}O-p collisions at $3.25A$ GeV/c, determined earlier in Refs. [21,24,25].

Hence, we can conclude that the peak observed in the experimental spectrum of the one-dimensional correlation function $C(q)$ at $q < 25\,\text{MeV}/c$ is due to decays of unstable ^{8}Be and ^{9}B nuclei in ^{16}O-p collisions at $3.25A\,\text{GeV}/c$. However, this result does not contradict the popular assumption of other authors about the existence of the α-condensate state in the ^{16}O nucleus [16–20] because unstable ^{8}Be and ^{9}B nuclei themselves can probably be formed from the decay of the α-condensate state of the oxygen nucleus.

Due to experimental conditions of the selection of collision events and registration of particles, the authors of Ref. [8] could measure the correlation function for identical particles in the region of $q > 60\,\text{MeV}/c$ only. Besides it, all the particles with $Z = 2$ in Ref. [8] were considered as α particles, which shows considerable admixture of ^{3}He nuclei, used for the calculation of the correlation function of identical α particles. Our experiment revealed [21] that the fraction of ^{3}He nuclei among doubly charged (helium) nuclei makes up about 20%. On the other hand, the conditions of our experiment allowed the identification of α particles with the probability greater than 95% and measured their momenta with the average relative error not larger than 4% [14]. As already mentioned, the usage of a beam of relativistic oxygen nuclei impinging on a hydrogen target allowed us to measure the momenta of all the charged fragments, starting from $p = 0$ in the oxygen nucleus rest frame [14]. Therefore, we could measure the correlation functions for identical deuterons and α particles in minimum bias ^{16}O-p collisions at $3.25A\,\text{GeV}/c$ for the whole interval of the change in q, starting from the $q = 0$ value.

It is interesting to mention that the value of correlation function $C(q)$ at $q < 25\,\text{MeV}/c$ remains constant within statistical uncertainties for different values of momenta (p_1, p_2) of a pair of α particles,

$$C(q) = 12.76 \pm 1.38 \text{ at } p_1, \quad p_2 > 25 \text{ MeV}/c;$$
$$C(q) = 12.73 \pm 1.42 \text{ at } p_1, \quad p_2 > 50 \text{ MeV}/c,$$
$$C(q) = 12.34 \pm 1.45 \text{ at } p_1, \quad p_2 > 75 \text{ MeV}/c;$$
$$C(q) = 11.50 \pm 1.48 \text{ at } p_1, \quad p_2 > 100 \text{ MeV}/c.$$

This fact can be interpreted as evidence that the pairs of α particles with $q < 25\,\text{MeV}/c$ are due to the decay of unstable ^{8}Be and ^{9}B nuclei at various excitation levels of the fragmenting ^{16}O nucleus, and, hence, at different kinetic energies of ^{8}Be and ^{9}B nuclei.

Because the behavior of correlation function $C(q)$ at $q < 25\,\text{MeV}/c$ differs from that in the region of $q > 25\,\text{MeV}/c$, the approximation of $C(q)$ for the pairs of α particles by the expression in (2) was fit in the region of $q > 25\,\text{MeV}/c$. As observed from Fig. 2, the experimental spectrum $C(q)$ is described quite well by the function in (2). We obtained the following best values of parameters of the function in (2) at a minimum χ^2 value: $\lambda = 2.2 \pm 0.2$ and $R = 11.7 \pm 0.7\,(\text{GeV}/c)^{-1} = 2.3 \pm 0.1$ fm, which practically coincided with the size of the emission region of the deuterons in ^{16}O-p collisions at $3.25A\,\text{GeV}/c$.

IV. SUMMARY AND CONCLUSIONS

In conclusion, we summarize the main results of the investigation of experimental one-dimensional correlation function $C(q)$ of identical particles—deuterons and α particles, emitted in minimum bias ^{16}O-p collisions at $3.25A\,\text{GeV}/c$. The peak was observed in the region of $q < 25\,\text{MeV}/c$ in the experimental $C(q)$ spectrum for the pairs of α particles, which could not be described by the theoretical model [expressed by the function in (2)], which assumed the simultaneous excitation and decay of sources (of identical particles), whose coordinates are distributed according to the Gaussian function. Based on the analysis of the spectrum of invariant masses of the pairs of α particles, we deduced that the peak of the experimental $C(q)$ spectrum in the region of $q < 25\,\text{MeV}/c$ was due to decays of unstable ^{8}Be and ^{9}B nuclei, generated at different excitation levels of the fragmenting ^{16}O nucleus, and, hence, at different kinetic energies of these unstable nuclei. Our result does not contradict the popular assumption of other authors about the existence of the α-condensate state in the ^{16}O nucleus because unstable ^{8}Be and ^{9}B nuclei themselves can probably be formed from the decay of the α-condensate state of the oxygen nucleus if such a state does exist.

The sizes of the emission sources of identical deuterons and α particles were determined from fitting their experimental one-dimensional correlation functions $C(q)$ by the expression in (2) in regions of $q > 0\,\text{MeV}/c$ and $q > 25\,\text{MeV}/c$, respectively. The so obtained sizes of the emission sources of the deuterons (2.4 ± 0.7 fm) and α particles (2.3 ± 0.1 fm), generated in ^{16}O-p collisions at $3.25A\,\text{GeV}/c$, coincided within the uncertainties. The size of the emission source of the deuterons in ^{16}O-p collisions at $3.25A\,\text{GeV}/c$ coincided within statistical uncertainties with the result of Ref. [7], obtained in the WA98 Collaboration's experiment for deuterons emitted in Pb + Pb collisions at $158A$ GeV in the target fragmentation region, suggesting that the size of the emission region for the deuterons formed in the relativistic hadron-nucleus and nucleus-nucleus collisions does not depend on the incident energy and mass number of the fragmenting nucleus. Some differences in the sizes of the emission sources of the α particles, obtained in the present paper and in Ref. [8] (2.84 ± 0.28 fm) for the collisions of ^{22}Ne and ^{24}Mg nuclei with the nuclei of the nuclear emulsion at 4.1 and $4.5A\,\text{GeV}/c$, are likely due to that, in the latter work, all the fragments with $Z = 2$ were considered as α particles (although there is a considerable admixture of ^{3}He nuclei among the doubly charged fragments). Besides it, only the doubly charged fragments in the central pseudorapidity region were analyzed in Ref. [8].

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