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Proton Source Size Measurements in the $eA \to e'ppX$ Reaction

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Two-proton correlations at small relative momentum q were studied in the $eA(^3\text{He}, ^4\text{He}, \text{C}, \text{Fe}) \to e'ppX$ reaction at $E_0 = 4.46$ GeV using the CLAS detector at Jefferson Lab. The enhancement of the correlation function at small q was found to be in accordance with theoretical expectations. Sizes of the emission region were extracted, and proved to be dependent on A and on the proton momentum. The size of the two-proton emission region for He was measured in eA reactions for the first time.

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One of the outstanding issues in nuclear physics is the nature of dense nuclear matter [1]. There are experimental indications [2,3] that density fluctuations of nuclear matter manifest themselves in so-called "cumulative processes," in which particles are produced in the kinematic region forbidden to interactions with a single motionless nucleon. Cumulative particle spectra remain unexplained when finite-temperature Fermi-gas momentum distributions are taken into account [4], leading to the association of the reaction strength in this kinematic region with density fluctuations or correlations. These objects can be described in various ways [5,6], but all authors consider them to be fluctuations. In this Letter, we will not rely on a specific model, and, following Ref. [5] and others, we will refer to this type of object as a "flucton." The electroproduction from nuclei of an energetic nucleon pair with small relative momentum is also an example of a cumulative process: it cannot be due to the interaction of the virtual-photon with a single nucleon followed by rescattering of the first nucleon on a second, since this leads to large angles (and hence large relative momenta) between the two nucleons. Therefore, such a process can be used to study the flucton—its size (density), in particular.

Cascade calculations [7] fail to describe the whole set of experimental data, but rescattering can affect experimental spectra and particle correlations. The relative importance of rescattering processes depends on the mass number A of the nucleus. We believe that an extrapolation to the smallest A will provide reliable information on the true properties of the flucton.

To estimate the density of the flucton, one needs to measure its size and the number of contributing nucleons, the minimum number of which can be determined from the kinematics. The flucton size is expected to be commensurate with the size of a nucleon [5].

Two-particle correlations at small relative momenta $\vec{q} = \vec{p}_1 - \vec{p}_2$ ($\vec{p}_1$ and $\vec{p}_2$ are the individual proton momenta in the pair rest frame) are sensitive to the source size [8–10] (see also the reviews [11]). We will use the term "femtoscopy" (1 fm $= 10^{-15}$ m) for the study of source sizes within nuclei in analogy with microscopy.

Two-proton correlations at small q were theoretically described in [9,10]. The interference of identical particles [8], as well as Coulomb and strong final-state interactions (FSIs) [12], were taken into account. Strong FSIs are dominant, causing an increase of the pair production cross section near $q \sim 0.04$ GeV$/c$. The intensity of this effect depends inversely on the root mean square radius r_{rms} of the source from which the protons are emitted.

Here we understand the FSIs to be only the interactions in the two-proton system at small relative momenta. The interaction time in this system is much larger than the characteristic collision time, and so this system can be considered in isolation of other particles and described by the same wave function as in the scattering problem. For proton interactions with other particles during the collision process we use the term "rescattering." Rescatterings are essentially localized, and can be considered as new emission points. FSIs are our "tool" for measuring the flucton size, while the rescatterings wash out the original emission region, and thus distort this measurement.

Although femtoscopy has been used widely to study a number of processes (hh, e^+e^-, AA [11]), this is not the case for the cumulative process. Hadroproduction data exist for carbon and heavier nuclei [3,13], but lepton-nucleus data are scarce in any kinematical domain [14,15]. In Ref. [14] the size of the pion emission region was studied in high-energy νD interactions. In Ref. [15] data on two-proton and two-pion correlations were obtained in e^{16}O interactions at 5 GeV. However, the scattered electron was not identified, the transferred 4-momentum squared Q^2 was small, and the transferred energy ν was about 1.5 GeV. The measured source-size proved to be commensurate with the nuclear size, and showed a tendency to decrease with particle momenta.

We present here our study of the correlation between two detected protons with small relative momenta in $eA(^3\mathrm{He}, ^4\mathrm{He}, ^{12}\mathrm{C}, ^{56}\mathrm{Fe}) \rightarrow e'ppX$ reactions, for an incident electron energy of 4.46 GeV. The measurements were performed with the CEBAF Large Acceptance Spectrometer (CLAS) [16] in Hall B at the Thomas Jefferson National Accelerator Facility. The CLAS detector is a six-sector toroidal magnetic spectrometer. The detection systems consist of drift chambers to determine the trajectories of charged particles [17], scintillation counters to measure time-of flight [18], Cherenkov counters to distinguish between electrons and pions [19], and electromagnetic shower calorimeters to identify electrons and neutrons [20]. The CLAS was triggered on scattered electrons detected in the calorimeter with energies above 1 GeV.

Run conditions are described in detail in Ref. [21]. Events with ν between 0.5 and 3.5 GeV, Q^2 between 0.6 and 5 $(\mathrm{GeV}/c)^2$, and protons momenta between 0.3 to 1.0 GeV$/c$ were selected for the analysis. Only events with at least two detected protons were accepted, and all proton-pair combinations in an event were included in the analysis. Misidentification of electrons or protons was negligible.

In this article we shall use a mixing procedure [8] for calculating the correlation function (CF), i.e.,

$$R(q, p) = \frac{N_r(q, p)}{N_m(q, p)}, \tag{1}$$

where $q = |\vec{q}|$, $p = |\vec{p}|$, and $\vec{p} = (\vec{p}_1 + \vec{p}_2)/2$; N_r and N_m are the numbers of proton pairs from the real events and those combined from protons taken from different events, respectively. Secondary particles are boosted in the direction of the virtual-photon momentum. We select the mixed-pair protons from events for which the magnitude of the momentum difference of the scattered electrons $|\vec{p}_{e1} - \vec{p}_{e2}|$ is less than q_0. We studied the dependence of the N_m distribution on q_0, and found it to be negligible for $q_0 < 0.2$ GeV$/c$. Therefore, we used $q_0 = 0.2$ GeV$/c$. Pairs of tracks hitting a single scintillator were not included in our analysis because they have ambiguous time-of-flight values.

The ability to detect two tracks with a small relative momentum is limited because both particles hit the same or neighboring detector cells. A detailed study of the close-track efficiency $\varepsilon(q)$ has been done in Ref. [22]. It depends on track curvature and then, for a fixed nominal magnetic field, on the proton momentum and emission angle in the laboratory system. The dependence of $\varepsilon(q)$ for the mean momentum and emission angle is shown in the inset of Fig. 1.

Figure 1 shows $R(q)$ for the ^{3}He, ^{4}He, and Fe data corrected for close-track efficiency $\varepsilon(q)$, "long-range" correlations (LRC), and momentum resolution. For selected ranges, the correlation function does not depend within errors on ν and Q^2. The data in Fig. 1 are averaged over proton momenta. LRCs arise mainly from momentum conservation for real events which is not a requirement for mixed pairs. They cause a smooth increase of R with q, which reflects the fact that due to momentum conservation the probability of two particles emitted in the same direction is smaller than that of two particles

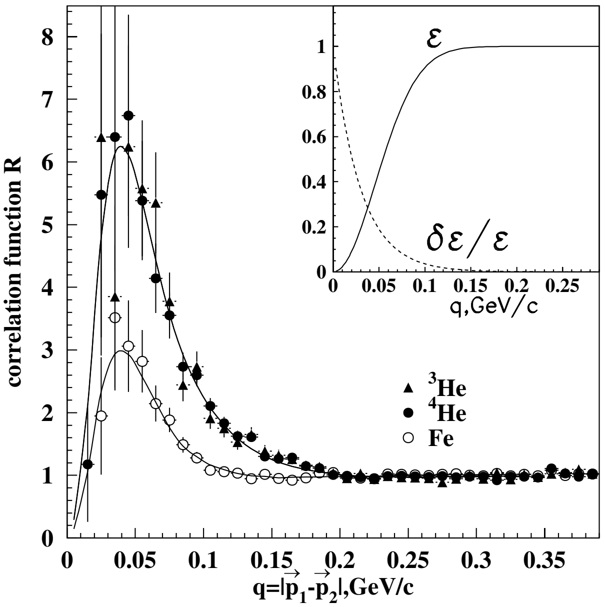

FIG. 1. The two-proton correlation function R for ^{3}He, ^{4}He and Fe nuclei. Curves are calculated for $r_{\mathrm{rms}} = 1.6$ fm (He) and $r_{\mathrm{rms}} = 3.0$ fm (Fe). The inset shows the close-track efficiency $\varepsilon(q)$ and its uncertainty $\delta\varepsilon/\varepsilon$.

emitted in opposite directions. Empirically, LRCs can be parametrized by $R \propto \exp(b \cos\psi)$, in which ψ is the angle between the two protons and b is a constant [23]. The parameter b was fit versus A and p for $q > 0.2$ GeV/c. The corrections to the data were made by introducing a weight $w = \exp(b \cos\psi)$ for mixed pairs, which reproduces the LRCs in the N_m distribution.

The proton momentum resolution within the selected kinematic range is estimated to be $\delta p/p \sim 2\%$. Since δp is typically smaller than the width of the effects under study, the measured correlation functions are only slightly smeared out by the momentum resolution. The momentum resolution corrections were made by applying the smearing procedure n times to the measured CF and then extrapolating the results to $n = -1$. This correction changes $r_{\rm rms}$ by less than 1%.

Figure 1 also shows the theoretical dependencies of $R(q)$ as calculated within a model [10], which takes into account quantum statistics and FSIs in the two-proton system. The theoretical correlation function is then calculated as a square of the wave function (corresponding to the scattering problem) averaged over the relative distances of the emitters in the pair rest frame. We assume a Gaussian distribution of the emission coordinates characterized by a dispersion $r_0^2 = r_{\rm rms}^2/3$. The curves in Fig. 1 correspond to $r_{\rm rms} = 1.6$ and 3.0 fm. We neglect here the emission duration which is effectively absorbed in the parameter $r_{\rm rms}$. Since the contemporary theoretical approaches do not consider the relation between extracted source-size parameters and the real value of R at large q, both correlation functions and the theoretical curves are normalized to unity for $0.17 < q < 0.35$ GeV/c. Theory predicts [9,10] that the enhancement of R at small q is inversely related to the measured size parameter. The peak at $q \approx 0.04$ GeV/c results mainly from the interplay between the attractive s-wave strong final-state interaction and the Coulomb repulsion. We compared the results of calculations of the CF for different proton-proton potentials [9,10,24]: i.e., the spherical wave approximation (scattered wave $\sim 1/r$) and a simple square well potential, as well as the more realistic Reid [25] and Tabakin [26] potentials. For large $r_{\rm rms}$ values, the correlation function is mainly determined by the solution of the scattering problem outside the range of the strong interaction potential, and is therefore independent of the actual form of the potential, provided that it correctly reproduces the scattering amplitudes [10,24]. Our results start to depend on the potential choice for $r_{\rm rms} < 2$ fm. If $r_{\rm rms} < 2$ fm, the calculated curves for different potentials look similar, but the best value of $r_{\rm rms}$ depends on the version of the potential. The results for $r_{\rm rms}$ are presented for the realistic Reid potential, with the difference between Reid (with core) [25] and Tabakin (without core) [26] ($\approx 3\%$ in $r_{\rm rms}$ for the He data) taken as the theoretical uncertainty.

The curves in Fig. 1 represent the best fit of the theoretical curves to the data with $r_{\rm rms}$ as a free parameter. The fits in Fig. 1 are quite reasonable ($\chi^2/DF \sim 1$ if only statistical errors are taken into account). The dependencies of R on q for ^{3}He and ^{4}He (and the best value for $r_{\rm rms}$) are the same within errors; the enhancement of R at small q for Fe is much smaller. This means that $r_{\rm rms}$ is larger for Fe than for He. The results for carbon (not shown in the figure) lie between He and Fe.

Experimental systematic errors on $r_{\rm rms}$ arise from the close-track efficiency correction ($\approx 2\%$), the correction for long-range correlations ($\approx 2\%$), and the correction for momentum resolution ($\approx 1\%$). A potential background in the measured CF, which comes from nonidentified $\Lambda \rightarrow p\pi$ decays, is estimated to be smaller than 1%. The total systematic experimental errors on $r_{\rm rms}$ is about 3%.

The dependence of $r_{\rm rms}$ on $p = |\vec{p}_1 + \vec{p}_2|/2$ for different nuclei is shown in Fig. 2. The data are averaged over emission angles. Statistical and systematic errors have been added in quadrature. For ^{3}He the momentum dependence looks flat, while for carbon and iron it decreases with increasing pair momentum. Our results for carbon are in good agreement with the data [15] for electron-oxygen interactions. The values of $r_{\rm rms}$ approach the size of the nucleus for the lowest value of pair momentum, which seems to be due to the rescattering of protons in nuclear matter. The importance of rescattering decreases with proton momenta in the chosen momentum range due at least in part to the decrease in the NN cross section.

We estimate the size of the flucton r_f under the assumption that both the primordial source-size, and its

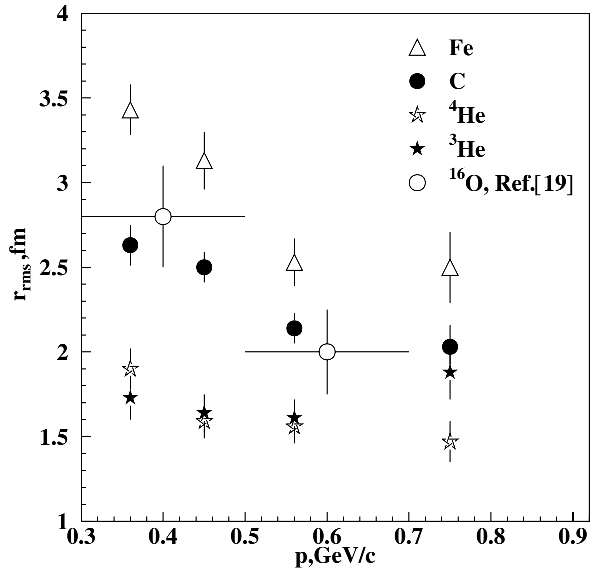

FIG. 2. The size parameter $r_{\rm rms}$ as a function of the mean pair momentum $p = |\vec{p}_1 + \vec{p}_2|/2$. Data [15], which correspond to e^{16}O interactions at initial energy 5 GeV and $Q^2 < 0.1(\text{GeV}/c)^2$, are shown for comparison.

modification due to rescattering, contribute to the measured size. In the case of helium, the probability of rescattering is much smaller than in heavy nuclei. The extracted $r_{\rm rms}$ values for ^{3}He and ^{4}He are about the same, which is additional evidence that rescattering does not affect the helium data within the errors (≈ 0.1 fm). Therefore, $r_{\rm rms}$ in helium (≈ 1.6 fm) is an upper estimate of r_f.

To take into account the possible influence of the rescattering process for helium, we can extrapolate the measured sizes as a function of A to the minimum possible target mass, where rescattering is not possible. This will provide a lower estimate of r_f, because rescattering can only increase the measured size. The minimal target mass (in nucleon mass units) for the electroproduction of protons (the so-called cumulative number X_S [27]) is determined by the kinematics of the process $e + X_S \cdot m_p \rightarrow e' + p + m_c$ and is given by

$$X_S = \frac{\frac{Q^2}{2\nu} + E_p - P_p \cos\theta_{p\gamma}\sqrt{1 + Q^2/\nu^2}}{(1 - T_p/\nu)m_p}, \tag{2}$$

in which E_p, P_p, m_p, and T_p are the full energy, momentum, mass, and kinetic energy of the proton, $\theta_{p\gamma}$ is the angle between the proton and virtual-photon momenta, and m_c is determined by conservation of baryon number. In the limit of large ν, X_S approaches the sum of the Bjorken variable $x_{Bj} = Q^2/2m_p\nu$ and the light cone variable $\alpha = (E_p - P_p \cos\theta_{p\gamma})/m_p$. For a proton-pair at small relative momentum, X_S is given by Eq. (2) in which E_p, P_p, T_p, and $\theta_{p\gamma}$ now refer to the pair.

Cumulative production is defined to occur when X_S is larger than unity. Half of our proton pairs are produced with $X_S > 2$; the remaining events are still close to the kinematic boundary in the reaction where the mass of the target is the two-nucleon mass. An extrapolation of the measured sizes to $A \sim X_S$ yields 1.2 ± 0.1 fm, where the error arises mainly from the extrapolation uncertainty. The extracted $r_{\rm rms}$ could be affected by background from the decay of short-lived resonances like the Δ. Since the proton velocity in the Δ decay reference frame is small ($v \sim 0.2c$) and the lifetime is roughly $c\tau \approx 2$ fm, this background contribution to the measured size is less than 0.1 fm. Given the maximum possible value of this background, the lower estimate for the flucton size is 1 fm. Therefore, we estimate the flucton size as $r_f = 1.3 \pm 0.3$ fm, which is an average of the 1 fm lower estimate and the measured value for He of 1.6. The flucton size estimate in [5] was indirect, rather imprecise, and based on the model for fitting inclusive data only. Yet it agrees reasonably with our direct measurement of the flucton size.

Correlations between protons produced in eA interactions at 4.46 GeV have been investigated. The data clearly show a narrow structure in the correlation function in the region of small relative momenta ($q < 0.1$ GeV$/c$) with a peak at $q \sim 0.04$ GeV$/c$ which is in accordance with theoretical expectations. Helium data on two-proton correlations at small relative momenta in eA interactions have been obtained for the first time. The measured size of the emission region $r_{\rm rms}$ depends on A and the pair momentum. By extrapolating to the minimum A (in the limit where there is no rescattering), we estimate the flucton size to be $r_f = 1.3 \pm 0.3$ fm. Using the well-known radii of ^{3}He (1.90 fm) and ^{4}He (1.68 fm) [28], we find that the flucton density is 3 times that of ^{3}He and 1.7 times that of the relatively dense ^{4}He.

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