Proton source size measurements in the $eA \to e'ppX$ reaction

A.V. Stavinsky,$^1$ K.R. Mikhailov,$^1$ R. Lednicky,$^2$ A.V. Vlassov,$^1$ G. Adams,$^{33}$ P. Ambrozewich,$^{12}$ E. Anciant,$^4$ M. Anghinolfi,$^{18}$ B. Asavapibhop,$^{24}$ G. Asryan,$^{43}$ G. Audit,$^4$ T. Auger,$^4$ H. Avakian,$^{38,17}$ H. Bagdasaryan,$^{29}$ J.P. Ball,$^3$ S. Barrow,$^{13}$ V. Batourine,$^{22}$ M. Battaglieri,$^{18}$ K. Beard,$^{21}$ M. Bektasoglu,$^{29}$ M. Bellis,$^{33}$ N. Benmouna,$^{15}$ N. Bianchi,$^{17}$ A.S. Biselli,$^6$ S. Boiarinov,$^{38,1}$ B.E. Bonner,$^{34}$ S. Bouchigny,$^{20,38}$ R. Bradford,$^6$ D. Branford,$^{11}$ W.K. Brooks,$^{38}$ V.D. Burkert,$^{38}$ C. Butuceanu,$^{42}$ J.R. Calarco,$^{26}$ D.S. Carman,$^{28}$ C. Cetina,$^{15}$ S. Chen,$^{13}$ P.L. Cole,$^{19,38}$ V. Codreanu,$^{22}$ M. Cordero,$^{18,25}$ P. Corvisiero,$^{18}$ D. Crabb,$^{41}$ J.P. Cummings,$^{33}$ N. Dashyan,$^{42}$ E. De Sanctis,$^{17}$ R. De Vita,$^{18}$ P.V. Degtyarenko,$^{38}$ H. Denizli,$^{31}$ L. Dennis,$^{13}$ A. Deur,$^{38}$ K.V. Dharmawardane,$^{29}$ C. Djalali,$^{36}$ G.E. Dodge,$^{29}$ D. Doughty,$^8,38$ P. Dragovitsch,$^{13}$ M. Dugger,$^3$ S. Dybtma,$^{31}$ O.P. Dzyubak,$^{36}$ H. Egiyan,$^{38,42}$ K.S. Egiyan,$^{43}$ L. Elouadrhiri,$^{38,8}$ A. Empl,$^{33}$ P. Eugenio,$^{13}$ R. Fatemi,$^{41}$ R.G. Fersch,$^{42}$ R.J. Feuerbach,$^{38}$ T.A. Forest,$^{29}$ H. Funsten,$^{42}$ M. Garçon,$^4$ G. Gavalian,$^{26,43}$ S. Gilad,$^{29}$ R. Geyh,$^8,38$ D. Gillaud,$^{38}$ J. Gloyd,$^{20,38}$ V. Gyurjyan,$^{38}$ C. Hadjidakis,$^{20}$ R.S. Hakobyan,$^7$ J. Hardie,$^8,38$ D. Hedde,$^8,38$ F.W. Hersman,$^{26}$ K. Hicks,$^{28}$ I. Hleiqawi,$^{28}$ M. Holtrop,$^{26}$ J. Hu,$^{33}$ C.E. Hyde-Wright,$^{29}$ D.G. Ireland,$^{16}$ M.M. Ito,$^{38}$ D. Jenkins,$^{40}$ K. Joo,$^{9,41}$ H.G. Juengst,$^{15}$ J.H. Kelley,$^{10}$ J.D. Kellie,$^{16}$ M. Khandaker,$^{27}$ D.H. Kim,$^{22}$ K.Y. Kim,$^{31}$ K. Kim,$^{22}$ M.S. Kim,$^{22}$ W. Kim,$^{22}$ A. Klein,$^{29}$ F.J. Klein,$^7,38$ A.V. Klimenko,$^{29}$ M. Klusman,$^{33}$ M.V. Kossov,$^1$ L.H. Kramer,$^{12,38}$ V. Kubarovski,$^{33}$ S.E. Kuhn,$^{29}$ J. Kuhn,$^6$ J. Lachniet,$^6$ J.M. Laget,$^4$ J. Langheinrich,$^{36}$ D. Lawrence,$^{24}$ G.A. Leksin,$^1$ T. Lee,$^{26}$ Ji Li,$^{33}$ K. Livingston,$^{16}$ K. Lukashin,$^{38,1}$ J.J. Manak,$^{38}$ C. Marchand,$^4$ S. McAleer,$^{13}$ J.W.C. McNabb,$^{30}$ B.A. Mecking,$^{38}$ S. Mehrabyan,$^{31}$ J.J. Melone,$^{16}$ M.D. Mestayer,$^{38}$ C.A. Meyer,$^{6}$ M. Mirazita,$^{17}$ R. Miskimen,$^{24}$ V. Mokeev,$^{25}$ L. Morand,$^4$ S.A. Morrow,$^4,20$ V. Muccifora,$^{17}$ J. Mueller,$^{31}$ G.S. Mutchler,$^{34}$ J. Napolitano,$^{33}$ R. Nasseripour,$^{12}$ S.O. Nelson,$^{10}$ S. Niccolai,$^{20}$ G. Niculescu,$^{21,28}$ I. Niculescu,$^{21,15}$ B.B. Niczyporuk,$^{38}$ R.A. Niyazov,$^{38,29}$ M. Nozar,$^{38}$ G.V. O’Rielly,$^{15}$ M. Osipenko,$^{18,25}$ A.I. Ostrovidov,$^{13}$ K. Park,$^{22}$ E. Pasyuk,$^3$ G. Peterson,$^{24}$ S.A. Philips,$^{15}$ N.A. Pivnyuk,$^1$ D. Pocanic,$^{41}$ O. Pogorelko,$^1$ E. Polli,$^{47}$ S. Pozdniakov,$^1$
B.M. Preedom, J.W. Price, Y. Prok, D. Protopopescu, L.M. Qin, B.A. Raue, G. Riccardi, G. Ricco, M. Ripani, B.G. Ritchie, F. Ronchetti, G. Rosner, P. Rossi, D. Rowntree, P.D. Rubin, F. Sabatié, K. Sabourov, C. Salgado, J.P. Santoro, V. Sapunenko, R.A. Schumacher, V.S. Serov, Y.G. Sharabian, J. Shaw, S. Simionatto, A.V. Skabelin, E.S. Smith, L.C. Smith, D.I. Sober, M. Spraker, S. Stepanyan, S.S. Stepanyan, B.E. Stokes, P. Stoler, I.I. Strakovsky, M. Taiuti, S. Taylor, D.J. Tedeschi, U. Thoma, R. Thompson, A. Tkabladze, L. Todor, C. Tur, M. Ungaro, M.F. Vineyard, L.S. Vorobeyev, K. Wang, L.B. Weinstein, H. Weller, D.P. Weygand, C.S. Whisnant, M. Williams, E. Wolin, M.H. Wood, A. Yegneswaran, J. Yun, and L. Zana

(The CLAS Collaboration)

1 Institute of Theoretical and Experimental Physics, Moscow, 117218, Russia
2 Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 18040 Prague 8, Czech Republic
3 Arizona State University, Tempe, Arizona 85287-1504, USA
4 CEA-Saclay, Service de Physique Nucléaire, F91191 Gif-sur-Yvette, Cedex, France
5 University of California at Los Angeles, Los Angeles, California 90095-1547, USA
6 Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
7 Catholic University of America, Washington, D.C. 20064, USA
8 Christopher Newport University, Newport News, Virginia 23606, USA
9 University of Connecticut, Storrs, Connecticut 06269, USA
10 Duke University, Durham, North Carolina 27708-0305, USA
11 Edinburgh University, Edinburgh EH9 3JZ, United Kingdom
12 Florida International University, Miami, Florida 33199, USA
13 Florida State University, Tallahassee, Florida 32306, USA
14 Physikalisches Institut der Universitäet Giessen, 35392 Giessen, Germany
15 The George Washington University, Washington, DC 20052, USA
16 University of Glasgow, Glasgow G12 8QQ, United Kingdom
17 INFN, Laboratori Nazionali di Frascati, Frascati, Italy
18 INFN, Sezione di Genova, 16146 Genova, Italy
19 Idaho State University, Pocatello, Idaho 83209, USA
Institut de Physique Nucleaire ORSAY, Orsay, France
James Madison University, Harrisonburg, Virginia 22807, USA
Kungpook National University, Taegu 702-701, South Korea
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307, USA
University of Massachusetts, Amherst, Massachusetts 01003, USA
Moscow State University, General Nuclear Physics Institute, 119899 Moscow, Russia
University of New Hampshire, Durham, New Hampshire 03824-3568, USA
Norfolk State University, Norfolk, Virginia 23504, USA
Ohio University, Athens, Ohio 45701, USA
Old Dominion University, Norfolk, Virginia 23529, USA
Penn State University, University Park, Pennsylvania 16802, USA
University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
Universita’ di ROMA III, 00146 Roma, Italy
Rensselaer Polytechnic Institute, Troy, New York 12180-3590, USA
Rice University, Houston, Texas 77005-1892, USA
University of Richmond, Richmond, Virginia 23173, USA
University of South Carolina, Columbia, South Carolina 29208, USA
Idaho State University, Pocatello, Idaho 83209, USA
Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA
Union College, Schenectady, NY 12308, USA
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0435, USA
University of Virginia, Charlottesville, Virginia 22901, USA
College of William and Mary, Williamsburg, Virginia 23187-8795, USA
Yerevan Physics Institute, 375036 Yerevan, Armenia

(Dated: August 9, 2018)
Abstract

Two-proton correlations at small relative momentum $q$ were studied in the $eA(^3\text{He}, ^4\text{He, C, Fe})\rightarrow e'ppX$ 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 expectation. Emission region sizes were extracted and proved to be dependent on $A$ and proton momentum. The size of the two-proton emission region on the lightest possible nucleus, He, was measured for the first time.

PACS numbers: 21.65.+f, 25.10.+s
One of the outstanding issues in nuclear physics is the nature of dense and/or hot nuclear matter [1, 2]. There are strong experimental indications [3, 4] that density fluctuations of nuclear matter manifest themselves in so-called “cumulative processes” in which particles are produced in the kinematical region forbidden for interactions with a single motionless nucleon, and hence more than one target nucleon must be involved. Cumulative particle spectra remain unexplained when finite temperature Fermi-gas momentum distributions are considered [5], 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 [6, 7, 8, 9, 10], but all authors consider them to be fluctuations. In this paper, we will not rely on a specific model, and, following Blokhintsev [6], Efremov [8] and others, will, for simplicity, refer to this type of object as a “flucton”. The production of an energetic nucleon pair from a nucleus is also an example of a cumulative process, and therefore can be used to study fluctons.

Pairs of nucleons can also be produced due to rescattering of the emitted particles on other nucleons in the nucleus. Cascade calculations [11] also 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 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 [6, 7, 8].

The two-particle correlations at small relative momentum $\vec{q} = \vec{p}_1 - \vec{p}_2$ ($\vec{p}_1$ and $\vec{p}_2$ are the individual proton momenta in the pair reference frame) are sensitive to the source size [12, 13, 14, 15] (see also the reviews [16]). We will use the term “femtoscopy” (1 fm = $10^{-15}$ m) for the study of source sizes within nuclei in analogy with microscopy.

The two-proton correlations at small $q$ was theoretically described in [14, 15]. The interference of identical particles [12, 13], as well as Coulomb and strong final state interactions (FSIs) [17] were taken into account. Strong FSIs are dominant, causing the increasing of the pair production cross section near $q \sim 0.04$ GeV/c. The intensity of the effect depends inversely on the root mean square radius $r_{\text{RMS}}$ of the source from which the protons are emitted.
It should be noted that here we understand the FSI as the interaction in the two-proton system at small relative momentum only. 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 (up to the opposite direction of the relative momentum vector). For proton interactions with other particles during the collision process we use another term - rescattering. Rescatterings are generally characterized by much higher momentum transfers and correspondingly shorter time scales. They are essentially localized and can be considered as new emission points. FSIs are our “tool” to measure 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 \((hh, e^+e^-, AA)\) this is not the case for the cumulative process. Hadroproduction data exist for carbon and heavier nuclei [4, 18], but lepton-nucleus data are scarce in any kinematical domain [19, 20]. In [19] the size of the pion emission region was studied in high energy \(\nu D\) interactions. In [20] data on two-proton and two-pion correlations were obtained in \(e^{16}O\) interactions at 5 GeV. The scattered electron was not identified; the data correspond to a small \(Q^2\) value and to \(\nu \sim 1.5\) 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 \(eA(^3He, ^4He, ^{12}C, ^{56}Fe)\rightarrow e'ppX\) reactions, for an incident electron energy of 4.46 GeV. The measurements were performed with the CEBAF Large Acceptance Spectrometer (CLAS) [21] in Hall B at the Thomas Jefferson National Accelerator Facility. The CLAS detector is a six-sector toroidal magnetic spectrometer. The magnetic field is generated by iron-free superconducting coils. The detection systems consist of drift chambers to determine the trajectories of charged particles [22], scintillator counters for time-of-flight measurements [23], Cherenkov counters to distinguish between electrons and negative pions [24], and electromagnetic shower calorimeter to identify electrons and neutrons [25]. The CLAS was triggered on scattered electrons detected in the calorimeter with an energy above 1 GeV.

Run conditions are described in detail in Ref. [26]. Events with transferred energy \(\nu\) between 0.5 and 3.5 GeV and transferred 4-momentum squared \(Q^2\) between 0.6 and 5 \((\text{GeV/c})^2\) were selected for analysis. Protons in the momentum range from 0.3 to 1.0 GeV/c were se-
lected for the analysis. The angle $\theta$ between the direction of the virtual photon $\gamma$ and the direction of the detected proton was from $0^\circ$ to $115^\circ$. The analysis was performed for events with at least two detected protons. Misidentification of electrons or protons was negligible.

In this article we shall use the “mixing” procedure \cite{13} for the correlation function (CF) calculations, i.e.

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

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 the value of $q_0$, and found this dependence negligible for $q_0 < 0.2 \text{ GeV/c}$; a cut $q_0 < 0.2 \text{ GeV/c}$ was applied for the $N_m$ distributions. 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 small relative momentum is limited because both particles hit the same or neighboring detector cells. As a rule, the probability for losing at least one of the two tracks is higher for close tracks. A detailed study of the close-track efficiency $\varepsilon(q)$ in CLAS has been done in Ref. \cite{27}. 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 insert of Fig. 1.

Fig. 1 shows $R(q)$ for the $^3\text{He}$, $^4\text{He}$, and Fe data corrected for close-track efficiency $\varepsilon(q)$, “long-range” correlations (LRC), and momentum resolution. The data are averaged over proton momenta. LRCs arise mainly from momentum conservation for the real events which is not a requirement for mixed pairs. It results in a smooth increase of $R$ with $q$, which reflects the fact that due to momentum conservation the probability of particles emission in the same direction is smaller than that in the opposite direction. Empirically, LRC can be parameterized by $R \propto \exp(b \cos \psi)$, in which $\psi$ is the angle between the two protons and $a$ $b$ is a parameter \cite{28}. The parameter $b$ for different $A$ and proton pair momenta, was obtained from a fit to the data in which the region of the effect at small $q < 0.2 \text{ GeV/c}$ was cut out. The correction for LRCs were made by introducing a weight $w = \exp(b \cos \psi)$ for mixed
pairs to reproduce LRC in the $N_m$ distribution. The proton momentum resolution within the selected kinematic range is estimated to be $\delta p/p \sim 2\%$. Since $\delta p$ typically smaller than the width of the effects under study measured correlation functions are only slightly smeared out by momentum resolution. The momentum resolution corrections were made by applying the smearing procedure $n$ times to the measured CF and then by the extrapolation of the results to $n = -1$.

Fig. 1 also shows the theoretical dependencies of $R(q)$ \cite{15} for $r_{\text{rms}} = 1.6$ and 3.0 fm calculated within the model of independent one-particle sources taking 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 in the nucleus rest frame characterized by a dispersion $r_0^2 = r_{\text{rms}}^2/3$. We neglect here the emission duration which enters in the longitudinal component of the relative distance vector through the Lorentz transformation to the pair rest frame (the duration is thus effectively absorbed by the parameter $r_{\text{rms}}$). Both the correlation functions and the theoretical curves are normalized to unity for $0.17 < q < 0.35$ GeV/c. The theoretical approach \cite{14, 15} predicts 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 the calculation of the theoretical CF for different proton-proton potentials \cite{14, 15, 29}: i.e. spherical wave approximation (scattered wave $\sim 1/r$), simple square well potential, Reid \cite{30}, and Tabakin \cite{31}. For large $r_{\text{RMS}}$ 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 \cite{15, 29}. Our results start to depend on the potential choice for $r_{\text{RMS}} < 2$ fm. At $r_{\text{RMS}} < 2$ fm the calculated curves for different potentials also look similar, but the best value of $r_{\text{RMS}}$ depends on the version of the potential. In the present work final results for $r_{\text{RMS}}$ are presented for the realistic Reid potential, and the difference between results calculated for the potential with core (Reid) \cite{30} and without core (Tabakin) \cite{31} ($\approx 3%$ in $r_{\text{RMS}}$ for the He data) is taken as the theoretical uncertainty.

The curves in Fig. 1 represent the best fit to the data by the theoretical curves (the
difference between $^3\text{He}$ and $^4\text{He}$ is negligible) with $r_{RMS}$ as a free parameter. The fits in Fig. 1 are quite reasonable. This is an indication that the theoretical approach is applicable down to a measured size of the order 1.5 fm. The dependencies of $R$ on $q$ for $^3\text{He}$ and $^4\text{He}$ (and the best value for $r_{RMS}$) are the same within errors; the enhancement of $R$ at small $q$ for Fe is much smaller. This means $r_{RMS}$ 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 $r_{rms}$ arise from the close-track efficiency correction ($\approx 2\%$), the correction for “long-range” correlations ($\approx 2\%$), and the correction for momentum resolution ($\approx 1\%$). Non-identified $\Lambda$ particles that decay into $p\pi$ provide a potential background for the measured CF. The cross section for $\Lambda$ production is estimated to be smaller than 1% of the proton production cross section in the corresponding kinematical region. (Additional mass $\delta_m \sim m_K + m_\Lambda - m_p$ must be produced, and in a cumulative process the cross sections falls exponentially with $\delta_m$, having a slope parameter on the order of the pion mass). Therefore, the background from non-identified $\Lambda \rightarrow p\pi$ decay is negligible. The total systematic experimental errors on $r_{RMS}$ is about 3%. In the figure statistical and
FIG. 2. The size parameter $r_{RMS}$ as a function of the mean pair momentum $p = |\vec{p}_1 + \vec{p}_2|/2$. Data [20], 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.

systematic errors have been added in quadrature.

The dependence of $r_{RMS}$ 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 $^3\text{He}$ the momentum dependence looks flat, while for carbon and iron it decreases with increasing pair momentum. Our results for carbon are in good correspondence with the data [20] for electron-oxygen interactions. The values of $r_{RMS}$ 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 $r_f$ and its modification due to rescattering processes contribute to the measured size. In the case of helium, the probability of rescattering is much smaller than in heavy nuclei. The extracted $r_{RMS}$ values in $^3\text{He}$ and $^4\text{He}$ are about the same, which is additional evidence that rescattering does not affect the helium data within the errors ($\approx 0.1$ fm). Therefore, $r_{RMS}$ in helium ($\approx 1.6$ 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 electro-production of protons (the so-called cumulative number $X_S$) is determined by the kinematics of the process $e + X_S \cdot m_p \rightarrow e' + p + m_e$ and is given by:

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

in which $E_p$, $P_p$, $m_p$, and $T_p$ are the full energy, momentum, mass and kinetic energy of the proton, and $\theta_{p\gamma}$ is the angle between the proton momentum and the virtual photon momentum and $m_e$ is determined by conservation laws for quantum numbers, baryon number in our case. In the limit of large $\nu$, $X_S$ 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 di-proton (a proton pair at small relative momentum) the electro-production cumulative number 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 then 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 when the mass of the target is the two-nucleon mass. An extrapolation of the measured sizes to $A \sim X_S$ provides the pair momentum average value $1.2 \pm 0.1$ fm, where the error arise mainly from the dependence of the result on the extrapolation law. The measured CF and then the extracted $r_{RMS}$ could be affected by background from the decay of short-lived resonances like the $\Delta$. Since the proton velocity in the $\Delta$ decay reference frame is small $v \sim 0.2$ and the lifetime is of the order $c\tau \approx 2$ fm, this background could contribute $\sqrt{(r_{RMS})^2 + (v\tau)^2} - r_{RMS}$ to the measured size, which 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 above. It should also be noted that the flucton size estimate in [6, 7] was indirect, rather imprecise, and based on the model for fitting inclusive data only. This work presents direct measurement of the flucton size.

In summary, the 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 \((q < 0.1 \text{ GeV/c})\) with a peak at \(q \sim 0.04 \text{ GeV/c}\) which is in accordance with theoretical expectation. The helium data on two-proton correlations at small relative momentum have been obtained for the first time. The measured size of the emission region \(r_{\text{RMS}}\) depends on \(A\) and the pair momentum. Our estimate of the flucton size provides a value of \(r_f = 1.3 \pm 0.3 \text{ fm}\).

We would like to acknowledge the outstanding efforts of the staff of the Accelerator and the Physics Divisions at Jefferson Lab that made this experiment possible. This work was supported in part by the Istituto Nazionale di Fisica Nucleare, the French Centre National de la Recherche Scientifique, the French Commissariat à l’Energie Atomique, the U.S. Department of Energy, the National Science Foundation, Emmy Noether grant from the Deutsche Forschungs gemeinschaft, the Korean Science and Engineering Foundation, and the Grant Agency of the Czech Republic under contract 202/04/0793. The Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under contract DE-AC05-84ER40150.

* Current address: Ohio University, Athens, Ohio 45701, USA
† Deceased
‡ Current address: Systems Planning and Analysis, Alexandria, Virginia 22311, USA
§ Current address: Catholic University of America, Washington, D.C. 20064, USA
¶ Current address: James Madison University, Harrisonburg, Virginia 22807, USA

[1] A.M. Baldin, in High-Energy Physics and Nuclear Structure-1975, proceedings of the Sixth International Conference, Santa Fe and Los Alamos, edited by D. E. Nagle et al. (AIP, New York, 1975), p. 621; Sov. J. Nucl. Phys. 21, 517 (1975)
[2] See in Proceedings of the Quark Matter conferences, for example in Proceedings of 16th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, Quark Matter 2002 (QM 2002), Nantes, France, 18-24 Jul 2002, Nucl. Phys. A 715 (2003)
[3] S.V. Boyarinov et al., Sov. J. Nucl. Phys. 46, 871 (1987)
[4] Yu.D. Bayukov et al., Sov. J. Nucl. Phys. 50, 638 (1989)
[5] R.D. Amado and R.M. Woloshyn, Phys. Rev. Lett. 36, 1435 (1976)
[6] D.I. Blokhintsev, Sov. Phys. JETP 6, 995 (1958)
[7] V.V. Burov et al., Phys. Lett. B67, 46 (1977)
[8] A.V. Efremov, Sov. J. El. Part. Nucl. Phys. 13, 613 (1982)
[9] L.L. Frankfurt and M. Strikmann Phys. Rep. 76, 215 (1981) T. Fujita and H"ufner, Nucl. Phys. A314, 317 (1979)
[10] L.A. Kondratyuk and M.Zh. Shmatikov, Z. Phys. A321, 301 (1985); C.E. Carlson et al. Phys. Lett. B263, 277 (1991)
[11] V.B. Kopeliovich, Sov. J. Nucl. Phys. 26, 87 (1977)
[12] G.I. Kopylov and M.I. Podgoretsky, Sov. J. Nucl. Phys 15, 219 (1972)
[13] G.I. Kopylov, Phys. Lett. B50, 472 (1974)
[14] S.E. Koonin, Phys. Lett. B70, 43 (1977)
[15] R. Lednicky and V.L. Lyuboshitz, Sov. J. Nucl. Phys. 35, 770 (1982)
[16] M.I. Podgoretsky, Sov. J. Part. Nucl. 20, 266 (1989); D.H. Boal et al., Rev. of Mod. Phys. 62, 553 (1990); N. Schmitz, Int. Journ. of Mod. Phys. A8, 1993 (1993); U.A. Wiedemann and U. Heinz, Phys. Reports 319, 145 (1999); R.M. Wiener, Phys. Reports 327, 249 (2000)
[17] K.M. Watson, Phys. Rev. 88, 1163 (1952); A.B. Migdal, JETP 28, 1 (1955)
[18] Yu.D. Bayukov et al., Sov. J. Nucl. Phys. 34, 54 (1981); V.A. Budilov et al., Phys. Lett. B243, 341 (1990)
[19] D. Allasia et al., (WA25), Z. Phys. C37, 527 (1988); V.V. Ammosov et al., Sov. J. Nucl. Phys. 53, 609 (1991)
[20] P.V. Degtyarenko et al., Z. Phys. A335, 231 (1990), ibid A350, 263 (1994), ibid A357, 419 (1997)
[21] B. Mecking et al., Nucl. Instr. Meth. 503/3, 513 (2003)
[22] D.S. Carman et al., Nucl. Instr. Meth. A419, 315 (1998); M.D. Mestayer et al., Nucl. Instr. Meth. A449, 81 (2000)
[23] E. Smith et al., Nucl. Instr. Meth. A432, 265 (1999)
[24] G. Adams et al., Nucl. Instr. Meth. A465, 414 (2001)
[25] M. Amarian et al., Nucl. Instr. Meth. A460, 239 (2001); M. Anghinolfi et al., Nucl. Instr. Meth. A447, 424 (2000)
[26] K.Sh. Egiyan et al., Phys. Rev. C68, 014313 (2003)
[27] M.D. Mestayer et al., Nucl. Instr. Meth. A524, 306 (2004)
[28] A.V. Vlassov et al. Physics of Atomic Nuclei 58(4), 613 (1995)
[29] M. Gmitro et al., Czech. J. Phys. B36, 1281 (1986)

[30] R.V. Reid, Jr. Ann. Phys. 50, 411 (1968)

[31] F. Tabakin, Ann. Phys. 30, 51 (1964)

[32] V.S. Stavinskiy JINR communication R2-9572 (in Russian), (1972)