Impact-Parameter-Selected Two-Proton Intensity Interferometry for ^{36}Ar + ^{45}Sc at $E/A = 80$ MeV

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(Received 4 March 1993)

The momentum dependence of the two-proton correlation function is studied for central and peripheral ^{36}Ar+^{45}Sc collisions at $E/A = 80$ MeV. Calculations with the Boltzmann-Uehling-Uhlenbeck transport theory reproduce well the measured momentum dependence of the correlation functions for central collisions, but underpredict the momentum dependence for peripheral collisions.

PACS numbers: 25.70.Pq

Microscopic models based on the Boltzmann-Uehling-Uhlenbeck (BUU) equation make definite predictions for the time evolution of the one-body phase space density created in intermediate energy heavy ion collisions [1-8]. Detailed tests of these predictions are possible through the technique of two-proton intensity interferometry, which makes use of the space-time sensitivity of the two-proton correlation function at small relative momentum [1,9-14]. Model predictions of the behavior of the correlation function depend strongly on impact parameter [1,13], indicating that the space-time evolution of the one-body phase space density is different for central and peripheral collisions. Separate tests of these model predictions for central and peripheral collisions are crucial to distinguish the impact parameters for which the model provides a reasonable description of the reaction from those impact parameters for which there may be physical effects that are poorly understood [1]. The present work provides the first study of the two-proton correlation function with simultaneous cuts on the event centrality and on the total momentum of the proton pair. These measurements are used to test BUU predictions of the space-time geometry of the one-body phase space density separately for central and peripheral events.

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University (MSU). A beam of ^{36}Ar ions at $E/A = 80$ MeV incident energy bombarded a ^{45}Sc target of areal density 10.0 mg/cm^2. The beam intensity was typically 3×10^8 particles/sec. Charged particles were measured in the MSU 4π detector array [15], which consisted of 209 plastic ΔE-E phoswich detectors covering polar angles between 7° and 158° in the laboratory frame. Particles stopping in the slow (E) plastic scintillators of this array were identified by their particle type and energy; the energy calibrations for these detectors are accurate to approximately 10%. One of the hexagonal modules of the 4π array, located at 38° in the laboratory frame, was replaced by a 56-telescope high-resolution hodoscope [16-18]. Each ΔE-E telescope of the hodoscope consisted of a 300 μm thick Si detector backed by a 10 cm long CsI(Tl) detector and subtended a solid angle of $\Delta\Omega = 0.37$ msr. The nearest-neighbor separation between telescopes was $\Delta\theta = 2.6°$, and the energy resolution of each telescope was about 1% for 60 MeV protons. During the experiment, both two-proton coincidence and singles events in the hodoscope were recorded in coincidence with the corresponding data from the 4π array.

The experimental two-proton correlation function $1 + R(q)$ is defined in terms of the two-proton coincidence yield $Y_2(\mathbf{p}_1,\mathbf{p}_2)$ and the proton singles yield $Y_1(\mathbf{p})$ [19, 20]

$$\sum Y_2(\mathbf{p}_1,\mathbf{p}_2) = C[1 + R(q)] \sum Y_1(\mathbf{p}_1) Y_1(\mathbf{p}_2) . \qquad (1)$$

Here, $\mathbf{p}_1$ and $\mathbf{p}_2$ are the laboratory momenta of the two protons, and q is the momentum of relative motion. For a given experimental gating condition, the sums on each side of Eq. (1) extend over all proton energies and detector combinations (of the 56-element hodoscope) corresponding to each q bin. The normalization constant C is determined by the requirement that $R(q)$ vanish for large q.

Following Ref. [21], impact parameter selection was achieved via cuts on the transverse energy of the coincident charged particles, defined by

$$E_t = \sum_{i=1}^{N_C} E_i \sin^2\theta_i . \qquad (2)$$

Here, N_C is the charged particle multiplicity measured in the 4π array. [To reduce the effects of "self-biasing," particles detected in the 56-element hodoscope were excluded from the sum in Eq. (2).] Gates on the transverse energy were used to construct impact-parameter-selected two-proton correlation functions.

Figure 1 shows energy-integrated correlation functions gated on central (high E_t) and peripheral (low E_t) collisions. In a purely geometrical interpretation [21], the employed cuts on E_t represent "reduced" impact parameter cuts of $b/b_{\max} \approx 0.0$–0.36 and 0.44–0.82. The peak of correlation function at $q \approx 20$ MeV/c is stronger for

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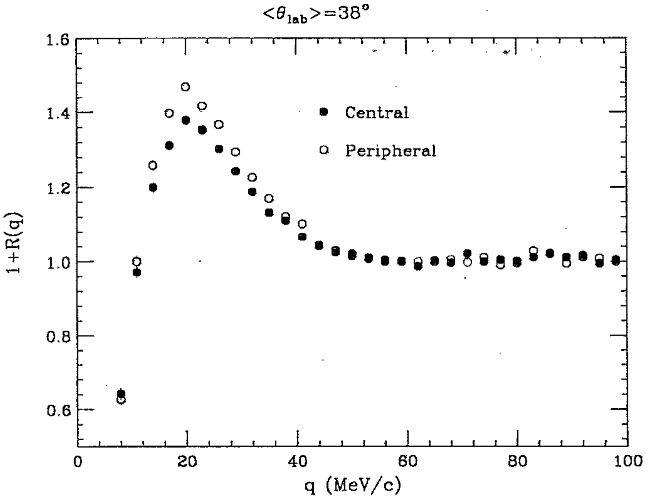

FIG. 1. Two-proton correlation functions measured for central and peripheral ^{36}Ar+^{45}Sc collisions at $E/A = 80$ MeV. The correlations were summed over all protons with energies above the detection threshold (about 9 MeV) in the 56-element hodoscope.

peripheral than for central collisions. This observation is qualitatively consistent with the findings of Refs. [22–24]. In a static picture, this suggests smaller proton-emitting sources for peripheral collisions.

Considerably more information is obtained when the correlation function is gated on the total momentum of the proton pair, $P = |\mathbf{p}_1 + \mathbf{p}_2|$. Figure 2 shows correlation functions for central and peripheral events for two protons with a total momentum in the range $P = 400$–520 MeV/c (upper panel), and for $P \geq 880$ MeV/c (lower panel). Qualitatively consistent with previous inclusive measurements [16,25–34], stronger correlations are observed for proton pairs with high total momentum. Quantitatively, this momentum dependence is also a function of impact parameter. Proton pairs with low total momenta are more strongly correlated in peripheral collisions than in central collisions. In contrast, the correlation functions constructed from high-momentum pairs in central and peripheral collisions are quite similar.

The total momentum dependence of the two-proton correlation function in central and peripheral events can be used to test detailed predictions of the BUU transport theory. The BUU equation describes the time evolution of the one-body phase space density under the influence of the nuclear mean field and individual nucleon-nucleon collisions. The fact that the emission of fragments is not treated in the theory complicates the comparison of our data to BUU predictions: An observable such as E_t cannot be accurately reproduced by the BUU model because it depends strongly on fragment emission. In order to overcome this difficulty, we impose "equivalent" E_t cuts on model events to allow cuts on impact parameter that are similar to those applied to the data. If we denote the

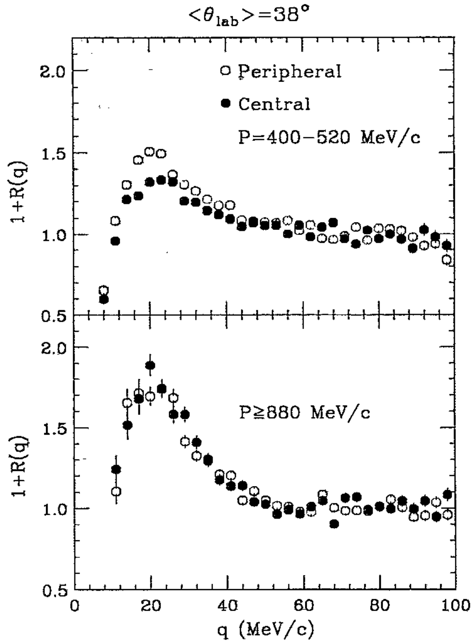

FIG. 2. Two-proton correlation functions measured for central (solid points) and peripheral (open points) ^{36}Ar+^{45}Sc collisions at $E/A = 80$ MeV. Top and bottom panels show results for cuts on low and on high values of the total momenta of the proton pairs.

measured and calculated inclusive E_t distributions as dP/dE_t and $d\hat{P}/d\hat{E}_t$, then the "equivalent" transverse energies, E_t and $\hat{E}_t$, are defined through the relation

$$\int_{E_t}^{\infty} dE_t' \, dP/dE_t' = \int_{\hat{E}_t}^{\infty} d\hat{E}_t' \, d\hat{P}/d\hat{E}_t' . \qquad (3)$$

For the ideal case of a strictly monotonic relationship between transverse energy and impact parameter, the equivalent cuts on E_t and $\hat{E}_t$ defined by Eq. (3) select identical regions of impact parameter.

Theoretical two-proton correlation functions were calculated with the Koonin-Pratt formula, which relates the correlation function to the one-body phase space distribution [9,12,13]. The theoretical correlation function is obtained by convoluting the one-body phase space distribution with the two-proton relative wave function. The phase space distribution of emitted particles was calculated with the BUU transport model. Averages over impact parameter were performed and equivalent cuts on transverse energy were applied to the BUU events. The BUU calculations were performed for a stiff equation of state and in-medium cross sections which are equal to the free nucleon-nucleon cross sections. These parameters were successfully used for the description of inclusive correlation functions in this energy domain [13,16,26]. Following Refs. [1,13,16,25,26], a particle was considered emitted if it was located in a region where the local mass density was less than one-eighth normal nuclear density.

The top and bottom panels of Fig. 3 show theoretical and experimental correlation functions for central and peripheral cuts, respectively. The figure shows the total momentum dependence of the average height of the correlation function in the peak region $\langle 1+R\rangle_{15\text{-}25\,\mathrm{MeV}/c}$. This quantity, which is the primary indicator of the space-time extent of the proton distribution, is relatively free of experimental resolution effects for the present hodoscope [16]. The distortion of the correlation function in the peak region is negligible, and the q resolution at $q=20$ MeV/c is in all cases less than 5 MeV/c, significantly smaller than the size of our average region. For reference, we provide on the right-hand axis the Gaussian radius of a zero-lifetime spherical source that produces a correlation function with the same peak value. Data and model predictions are represented by full and open symbols, respectively. For central collisions (top panel), the agreement between experimental and theoretical correlations is quite good, suggesting that the BUU transport theory provides a reasonable description of the final phase space density distribution of nucleons emitted in these collisions. For peripheral collisions (bottom panel), on the other hand, the BUU transport theory underpredicts the total momentum dependence of the correlation function. While the measured peak value of the correlation function increases with the total momentum of the proton pair, the theoretical correlation function depends very little on the total momentum. We cannot rule out that this disagreement could arise from an incomplete understanding of the experimental impact parameter filter. However, more extensive investigations reveal that this discrepancy persists when one employs different methods of deriving the impact parameter weighting used in the calculations. The results of these investigations will be published in a forthcoming paper [35] where it is also shown that the bias of the two- (instead of a one-) proton trigger in the hodoscope is of minor importance and that the present technique accounts, to a rather good approximation, for the resolution of the impact parameter filter caused by fluctuations of E_t and $\hat{E}_t$ at fixed impact parameter.

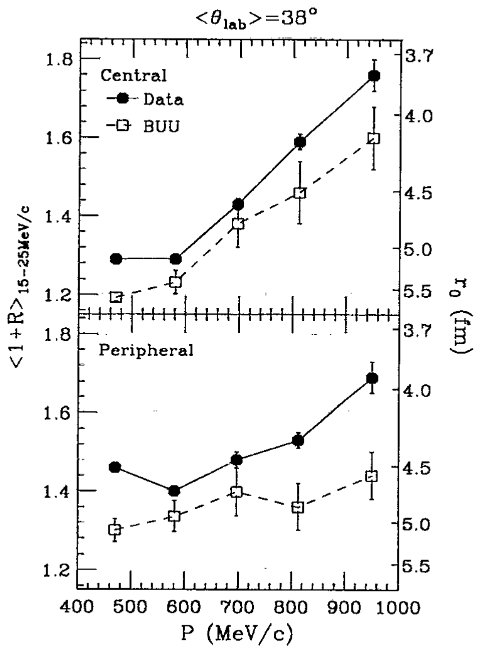

FIG. 3. Total momentum dependence of the average height of the two-proton correlation function, $\langle 1+R(q)\rangle_{15\text{-}25\,\mathrm{MeV}/c}$, for central (top panel) and peripheral (bottom panel) collisions. Solid and open points represent data and transport model predictions, respectively. Details are discussed in the text.

In summary, we have performed the first measurement of the two-proton correlation function with simultaneous gates on both the total momentum of the proton pair and the event centrality. Correlation functions for central collisions depend more strongly on the total momentum of the proton pair than do correlation functions for peripheral collisions. This implies a strong impact parameter dependence of the space-time evolution of the proton-emitting source created in heavy ion collisions. Theoretical correlation functions were calculated with the BUU equation using the Koonin-Pratt formula. The predicted total momentum dependence of the correlation function agrees well with the data for a central event gate, but disagrees for a peripheral gate. This disagreement suggests that the present BUU model inadequately describes the evolution of the single-body phase space distribution for peripheral collisions, or, alternatively, that the Koonin-Pratt formula breaks down for peripheral collisions and that knowledge of the two-particle distribution may be needed [36,37] for the calculation of the correlation function—pointing to areas where future theoretical work is needed. While somewhat unlikely, the disagreement could result from a poor understanding of impact parameter selection. Our calculations were performed with a "standard" set of model parameters which was used successfully in previous work. Illustrative BUU calculations averaged over impact parameter [13] have demonstrated a weak dependence on the equation of state and strong dependence on the in-medium nucleon-nucleon cross section. More calculations need to be done to determine if a change in a physical parameter improves agreement between predicted and measured correlations when cuts on impact parameter are made.

The authors would like to thank Scott Pratt for helpful discussions and suggestions concerning the calculation of the correlation functions. This work was supported by the National Science Foundation under Grants No. PHY-8913815, No. PHY-9107077, and No. PHY-921-4992. One of us (W.B.) acknowledges support from a NSF Presidential Faculty Fellow Award.

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