DEPENDENCE OF TWO-PARTICLE CORRELATION FUNCTIONS ON LINEAR MOMENTUM TRANSFER TO A COMPOSITE SYSTEM

Z. CHEN, C.K. GELBKE, J. POCHODZALLA, C.B. CHITWOOD, D.J. FIELDS, W.G. LYNCH and M.B. TSANG

Department of Physics and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

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Light particle correlations at small relative momenta were measured in coincidence with two fission fragments for $^{14}_N$ induced reactions on $^{197}_A Au$ at $E/A = 35$ MeV. The selection of large linear momentum transfers to the heavy reaction residue leads to a strong suppression of the beam velocity component of the light particle spectra and to enhanced maxima in the $p-p$ and $\alpha-d$ correlation functions.

Because of their sensitivity to final-state interactions [1–3] and quantum statistics [4,5], light particle correlations at small relative momenta contain information about the space–time characteristics of the emitting system. While two-particle inclusive measurements can provide insights into the average properties of the emitting system, more detailed information must be obtained from more exclusive measurements in which specific classes of reactions can be suppressed or enhanced. We used the linear momentum transferred to the heavy reaction residue as a filter to discriminate between quasi-elastic and more violent, fusion-like projectile–target interactions and investigated two-particle correlation functions at small relative momenta for these two types of reactions. The maxima of the $p-p$ and $\alpha-d$ correlation functions are larger for fusion-like reactions than for quasi-elastic collisions.

The experiment was performed at the National Superconducting Cyclotron Laboratory of Michigan State University. A 1.1 mg/cm$^2$ thick gold target was irradiated by $^{14}_N$ ions with $E/A = 35$ MeV incident energy. Light particles ($Z \leq 2$) were detected by a close-packed hexagonal array of 13 $\Delta E-E$ telescopes, each consisting of a 400 µm thick Si detector and a 10 cm thick NaI detector. Each telescope subtended a solid angle of 0.94 msr; the angular separation between adjacent telescopes was 6.1°. The center of the hodoscope was placed at polar and azimuthal angles of $\Theta_a = 20°$ and $\Phi_a = 0°$ with respect to the beam axis. In the off-line analysis, low-energy thresholds of 12, 15, and 40 MeV were placed on the energy spectra of protons, deuterons, and alpha particles, respectively. Energy calibrations of individual detectors are accurate within 3%. Coincident fission fragments were detected with two X–Y-position-sensitive parallel-plate detectors, with individual active areas of $11 \times 11$ cm$^2$. The detectors were mounted at the distances of $d_1 = 13.6$ cm and $d_2 = 17.3$ cm from the target with the centers positioned at the angles of $\Theta_1 = 95°$, $\Phi_1 = 0°$, and $\Theta_2 = 55°$, $\Phi_2 = 180°$, respectively.

The left-hand part of fig. 1 shows folding angle distributions, $\Theta_{f} = \Theta_A + \Theta_B$, where $\Theta_A$ and $\Theta_B$ denote the polar angles of the two coincident fission fragments. The upper scale indicates the average linear momentum, $\Delta p/p$, transferred to the heavy reaction residue (measured in units of the projectile momentum, $p$). Open points correspond to the inclusive folding angle distribution; full points represent the distribution measured in coincidence with $\alpha-d$ pairs. The inclusive distribution exhibits a maximum at

1 Present address: Institut für Kernphysik, J.W. Goethe Universität, August-Euler-Strasse 6, D-6000 Frankfurt, Fed. Rep. Germany.
\[ \Delta p/p \approx 0.8, \] indicating dominant contributions from incomplete fusion reactions [6]. Small folding angles are suppressed when coincident \( \alpha-d \) pairs are detected in the light-particle hodoscope. To a large extent, this suppression is due to momentum conservation: the coincident \( \alpha-d \) pairs carry away an average linear momentum of 0.35\( p \).

In order to explore the dependence of light particle energy spectra and correlation functions on the linear momentum transferred to the heavy target residue, we have used three gates on folding angle (gate (1): \( \Theta_{\text{eff}} < 145^\circ \); gate (2): \( \Theta_{\text{eff}} = 145-160^\circ \); gate (3): \( \Theta_{\text{eff}} > 160^\circ \)). The right-hand side of fig. 1 shows the dependence of the \( \alpha-d \) coincidence yield on the total kinetic energy, \( E_{\text{d}} + E_{\alpha} \), for \( \alpha-d \) pairs which can be attributed to the 2.186 MeV state in \( ^6\text{Li} \). The spectra are gated as indicated. The vertical scale is in arbitrary units.

The two-particle correlation function, \( R(q) \), is defined in terms of the singles yields, \( Y_1(p_1) \) and \( Y_2(p_2) \), and the coincidence yield, \( Y_{12}(p_1, p_2) \), of particles 1 and 2:

\[
\sum Y_{12}(p_1, p_2) = C_{12} [1 + R(q)] \sum Y_1(p_1) Y_2(p_2).
\]

Here, \( p_1 \) and \( p_2 \) are the momenta of the two detected particles, \( q \) is the momentum of relative motion, and \( C_{12} \) is a normalisation constant which is chosen such that the average correlation function, \( \langle R(q) \rangle \), vanishes for sufficiently large \( q \) where correlations due to final-state interactions become negligible. For each gate on \( \Theta_{\text{eff}} \) and \( E_1 + E_2 \), the sum was extended over all energy and detector combinations corresponding to the given relative momentum, \( q \).

Figs. 2 and 3 show the \( \alpha-d \) and \( p-p \) correlation functions measured for large (gate (1), open points) and small (gate (3), solid points) linear momentum transfers to the heavy reaction residue. In order to reduce contributions from later stages of the reaction for which sequential emission of low-energy particles from the fully equilibrated composite system may be important, these correlations were gated on total energies well above the compound nucleus Coulomb barrier: \( E_{\text{c}} + E_{\text{d}} > 100 \text{ MeV} \) and \( E_{\text{p_1}} + E_{\text{p_2}} > 50 \text{ MeV} \). (The dependence of the \( \alpha-d \) correlation function on the total energy, \( E_{\text{c}} + E_{\text{d}} \), is shown in fig. 4.) The selection of events with large linear momentum transfer produces enhanced maxima in both correlation functions as compared to those with low momentum transfer. For the \( \alpha-d \) correlation function, the sharp peak at \( q \approx 42 \text{ MeV/c} \) is enhanced by about a factor of two. For the \( p-p \) correlation function, the enhancement is less dramatic but still appreciable. A similar enhancement is also observed.
Fig. 2. $\alpha$–d correlation functions gated on large (gate (1): open points) and small (gate (3): solid points) linear momentum transfers to the heavy reaction residue. The gate on the total kinetic energy is indicated in the figure; the curves are explained in the text.

Fig. 3. p–p correlation functions gated on large (gate (1): open points) and small (gate (3): solid points) linear momentum transfers to the heavy reaction residue. The gate on the total kinetic energy is indicated in the figure; the curves are explained in the text.

The curves shown in figs. 2 and 3 represent theoretical correlation functions predicted by the final-state interaction model of ref. [1] and its extension [2] to particles heavier than protons. The theoretical $\alpha$–d correlations include corrections for the finite resolution of the hodoscope. The emitting system was assumed to have a gaussian density distribution, $\rho(r) \propto \exp(-r^2/r_0^2)$, and negligible life-time. In this approximation, the model becomes equivalent with the thermal model [3]. Source radii extracted under this assumption of instantaneous emission represent upper limits for the spatial extent of the emitting system [1,2].

For the case of $p$–$p$ correlations, source radii of $r_0 \approx 3.7$ and 4.0 fm are extracted for gates (1) and (3), respectively. Source radii extracted from the sharp peak of the $\alpha$–d correlation function at $q \approx 42$ MeV/c are $r_0 \approx 2.8$ and 3.6 fm, respectively, for gates (1) and (3). Since the exact height of the theoretical $\alpha$–d correlation function depends on the instrumental lineshape, we have extracted these latter source radii from the integral correlation, $R_{\alpha d} = \int dq \ R(q)$, with the integration performed over the range of $q \approx 30–60$ MeV/c; source radii extracted in terms of this quantity are less dependent on the experimental resolution. The extracted source sizes are generally smaller than the size [7] of the target nucleus ($r_0(Au) = \sqrt{2/3} \ r_{rms}(Au) \approx 4.4$ fm). A strictly geometric interpretation of our results would imply that quasi-elastic collisions are characterised by sources significantly larger than the size of the projectile nucleus [7] ($r_0(N) \approx 2.1$ fm). It is, however, likely that temporal effects cannot be neglected when interpreting these results. The time scales characteristic of pre-equilibrium particle emission in violent fusion-like collisions may be shorter than those which characterize particle emission in quasi-elastic reactions thus producing stronger correlations and smaller apparent source radii. Our observation of reduced correlations for peripheral processes may, therefore, reflect longer emission time scales rather than larger source dimensions. The sequential decay of excited projectile residues is an example for reactions which proceed via longer emission time scales. For such processes, Koonin’s formulation may be less useful for the calculation of two-particle correlation func-

Calculations with finite emission times are not yet available.

Source radii extracted from the broad peak of the $\alpha$–d correlation function at $q \approx 85$ MeV/c are larger by about 0.8 fm.
tions and alternative statistical formulations, such as appropriate generalisations of the Hauser Feshbach theory, could be explored. For the case of equilibrium decay of light compound nuclei, Hauser Feshbach calculations have predicted [8] smaller two-proton correlations than expected from the zero-lifetime limit of Koonin's model. Within Koonin's model, reduced correlations are expected due to the long lifetime of the compound nucleus. From these arguments, one expects reduced correlations for peripheral collisions for which contributions from the decay of equilibrated projectile residues may be important. For fusion-like collisions, on the other hand, such processes are suppressed. It is significant that these collisions exhibit larger correlations. They should reflect, more clearly, the space–time localisation of the reaction.

Fig. 4 shows the dependence of α–d correlations on the total energy per nucleon \((E/A)_{\text{tot}} = (E_a + E_d)/6\), of the two coincident particles. Inclusive [9] correlations and correlations measured in coincidence with fission fragments are shown in the right- and left-hand parts of the figure, respectively. The left-hand scale of the figure gives the integral correlation, \(R_{\text{int}} = \int dq R(q)\). The right-hand scale of the figure gives source radii extracted with the model of ref. [2]. At low energies, the α–d correlations are of comparable magnitude. For small linear momentum transfers (gate 3), they are nearly independent of energy. On the other hand, the α–d correlations for larger linear momentum transfers vary strongly with energy. For inclusive correlations, right-hand part of fig. 4, a similar energy dependence exists [9,10] and becomes more pronounced at larger angles, \(\Theta_{\text{av}}\), where contributions from quasi-elastic processes become less important. It was argued [11] that the energy dependence of inclusive two-particle correlations could be due to increasing contributions from the decay of excited projectile residues. Our observation of increasing two-particle correlations in violent fusion-like collisions and nearly energy-independent correlations for quasi-elastic collisions refutes that argument.

In summary, measurements of the linear momentum transfer to the heavy reaction residue were used to discriminate between quasi-elastic and more violent projectile–target interactions. Two-particle correlations at small relative momenta are less pronounced for quasi-elastic than for violent fusion-like collisions. These observations could reflect differences of reaction time scales rather than differences in geometric source dimensions.

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References


