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Sensitivity of small-angle correlations of light charged particles to reaction mechanisms in the $^{16}O+^{27}Al$ reaction at 40 MeV/nucleon

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Small-angle p-p, p-d, d-α, and α-α correlation functions were measured following the reaction $^{16}O+^{27}Al$ at 40 MeV/nucleon ^{16}O. These light charged particles (LCP's) were measured with a closely packed hexagonal array of CsI detectors, located at 35°, with a center to center opening angle of 2.35° for adjacent detectors. Coincident particles were simultaneously detected in the NSCL 4π detector. This measurement was intended to be a complement to earlier results from the same system. Based on studies of this system at lower energies and other published correlation measurements, it was expected that at 40 MeV/nucleon there would be significant positive correlations from the nuclear force and deep anticorrelations from Coulomb repulsion. However, correlation functions from this higher energy are remarkably similar to those previously measured at ≈ 15 MeV/nucleon. Correlation functions formed from events with a high multiplicity or high total detected energy (central collisions) are not significantly different from the inclusive measurements. As a possible explanation we suggest that significant correlations are most readily seen in experiments sensitive to LCP's from fast preequilibrium processes and that measurements at more backward angles are primarily sensitive to LCP's from a longer-lived source formed after preequilibrium processes are done. This idea is supported by trends of p-p correlation functions from a wide range of systems. A schematic calculation based on a Boltzmann-Ueling-Uhlenbeck (BUU) model and statistical emission qualitatively reproduces the results from this work. [S0556-2813(97)00407-X]

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I. INTRODUCTION

Over the years a substantial number of small-angle correlation measurements have been made on a variety of systems over a wide range of energies [1–29]. This work is another step in a series of measurements of a single system from energies where the major source of light charged particles (LCP's) is statistical evaporation to energies where nonequilibrium phenomena dominate the LCP production. The goal was to track the evolution from reactions where the deexcitation mechanisms are straightforward and well understood (statistical decay) into regimes where nonequilibrium phenomena control the LCP production. Past results for the O+Al system have shown that the lower energy p-p and p-d results could be described by a model based on sequential emission from a cooling compound nucleus [3–6]. This model is not expected to describe the results as the beam energy is increased and fast nonstatistical processes (which tend to have shorter emission times) become important.

Since the results were found to be similar to the correlation function results at lower energies, we systematically examined a number of other small-angle correlation measurements to look for trends and similar results (Refs. [3–29]). The wide variety of experimental protocols make precise comparisons difficult. However, after adjusting for differences in the various experiments (scattering angle, excitation energy, system size, etc.) there is a trend that suggests the detection angle plays an important role in determining the specifics of the measured correlation function. This leads to the interesting conclusion that small-angle correlation experiments may be extremely sensitive to the type of LCP emission process selected by the experimental biases.

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

This experiment was performed using a 40 MeV/nucleon ^{16}O beam from the K1200 cyclotron of the National Super-

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conducting Cyclotron Laboratory at Michigan State University. The beam was incident on a target of ^{27}Al with an areal density of 0.75 mg/cm^2 located at the center of the MSU 4π array. Light charged particle coincidences were detected with two arrays of CsI detectors situated on nearly opposite sides of the beam. These hodoscopes were positioned in place of two of the standard 4π ball modules. Nearest-neighbor detector pairs had an opening angle separation of 2.35°. The detectors were placed 65 cm from the target and each detector was collimated to a diameter of 1.5 cm. The detectors spanned angles from 34° to 43° with respect to the beam axis. The trigger condition required hits in any two of the CsI detectors. All the 4π ball information was also recorded for all valid triggers to provide information on the centrality of collisions. Particle identification was based on pulse-shape discrimination [30]. Identifications and calibrations were made for protons, deuterons, tritons, ^{3}He, and α particles. Calibrations were based on elastically scattered particles from calibration beams as well as the kinematics of ^{6}Li* and ^{8}Be breakup.

After particle identification and calibration of the various light charged particles were complete, relative momentum spectra were formed for the p-p, p-d, p-α, d-α, and α-α systems. The correlation functions were formed by dividing the relative momentum spectra by a suitable, correlation-free reference spectrum. In this work the reference spectrum was formed by event mixing. This means that the events which were analyzed to form the reference spectrum were artificially created by combining two halves of different coincident events. Random coincidences from different beam pulses were also recorded so that spectra of ‘‘true’’ coincidence events (both LCP from the same beam burst) could be corrected. During analysis it was found that the random rate was typically only a few percent for any given period of time. Therefore, the data were not corrected for randoms as the low random rate resulted in poor statistics and very poorly determined random spectra. The uncertainty in the correction would have been larger than the possible effects of the correction.

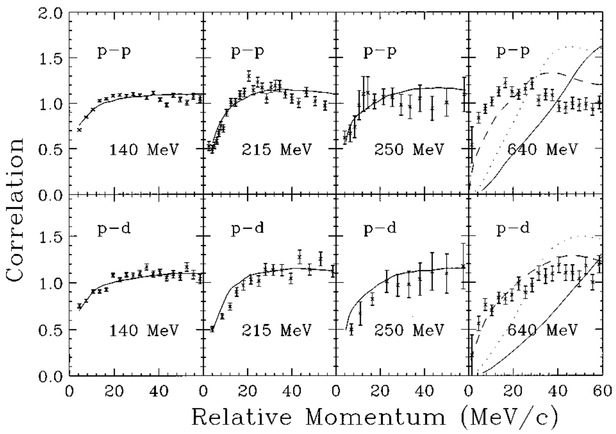

FIG. 1. Experimental p-p and p-d correlation functions from the reaction ^{16}O+^{27}Al. The beam energy is indicated in each panel. The solid lines are the results of calculations assuming statistical emission from a compound nucleus and assuming full momentum transfer. The dotted lines are the results of calculations assuming incomplete momentum transfer. The dashed lines are similar calculations but the emitting system was taken to be an equilibrated system predicted by BUU to remain following prompt emission.

III. RESULTS AND DISCUSSION

The resulting correlation functions are shown in Figs. 1 and 2 along with a subset of the available correlation functions from studies at lower energies [3–6]. The most surprising feature of the p-p correlation function is that no strong positive correlation is observed near a relative momentum of 20 MeV/c. This is in contrast to many other similar measurements where a strong positive correlation, due to the attractive strong nuclear force, is prominent (Refs. [7–16]). It was expected that at 640 MeV the O+Al system would have moved into a regime where the emission processes would be much faster than at the low-energy studies and thus result in an observable positive correlation. In fact, an examination the p-p and p-d results for this system over a wide range of energies really shows very little change in the character of the correlation functions implying minimal changes in the space-time characteristics of the source of the LCP. An examination of Fig. 2 (α-α, d-α, and p-α) reveals similar behavior. Instead of the positive correlations becoming more pronounced, as would be expected if the space-time extent of the source of the LCP was becoming smaller, one sees results which are comparable to the lower energies. (The narrow positive correlations are slightly lower for α-α and d-α at the highest energy because the resolution of the hodoscope in momentum space was somewhat poorer than in the lower-energy works. Thus the narrow positive correlations are slightly wider at the expense of height. The broad positive and negative correlations of the p-p, p-d, and p-α channels are not affected because of their already large width.)

Two simple explanations for the observed similarities between the lower-energy results and this measurement were investigated. It was suggested that the expected positive correlation might be more pronounced if the one considered only coincidence events involving nearest-neighbor detectors

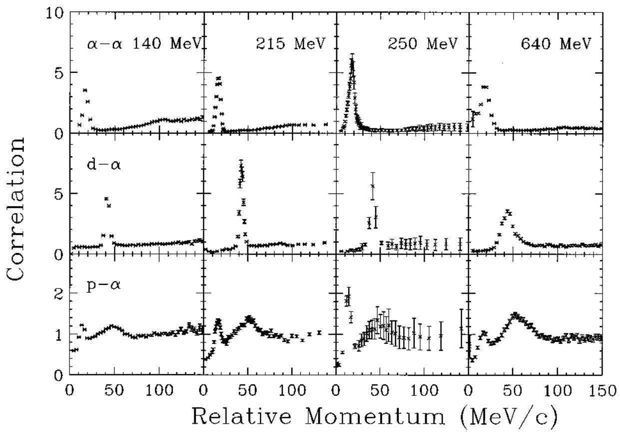

FIG. 2. Experimental α-α, d-α, and p-α correlation functions from the reaction ^{16}O+^{27}Al. The beam energy is indicated in each panel. The size, geometry, and type of the detector resulted in a relative momentum resolution which was inferior to past experiments. Thus the narrow states in the α-α and d-α correlation functions appear less pronounced, but also wider, than those of the lower energies.

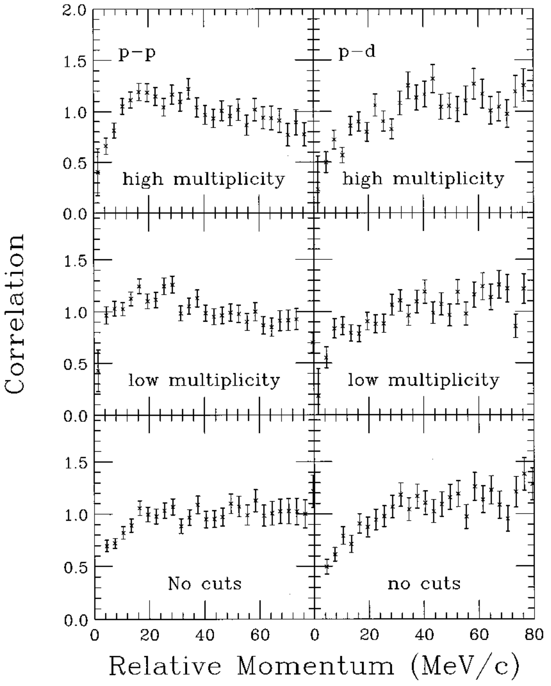

FIG. 3. Experimental *p-p* and *p-d* correlation functions from the reaction $^{16}O+^{27}Al$ at 640 MeV. These functions were formed in ways to maximize the observed positive and negative correlations. The top panels show the results when gated on the multiplicity of particles in the 4π detector and the lowest two panels are based only on events with the smallest opening angle. The correlation functions gated on multiplicity included coincidences for detector pairs separated by 2.35°, 4.07°, and 6.20°. Low multiplicity was defined as two or fewer particles of any type detected in the ball. High multiplicity was defined as three or more.

(2.35° opening angle). It was also suggested that the expected effects might become visible if the correlation functions were made from central events selected based on the information from the 4π ball. The correlation functions for *p-p* and *p-d* formed from only nearest-neighbor detector pairs and the results gated on multiplicity information (but including several opening angles) are shown in Fig. 3. The correlation functions show only minor differences from the ungated, all opening angle results. Again there is little evidence of a positive correlation and the correlations look remarkably similar to the lower energy results. Similar results were obtained when correlation functions were formed with restrictions on the total charge or total mass detected in the 4π ball.

Thus, these results are unlike those of several other correlation studies where gating on the general character of the reactions (total energy, centrality, etc.) had a large effect on the measured correlation functions and where there was an observed signature of a short-lived small source [10,14–17]. There is no observed positive correlation and gating has little effect on the data. Thus it seems that most of the measured LCP must come from a long-lived source.

If there is no short-lived source to yield a strong positive correlation, then one can ask what this lack of strong signal suggests about the reaction characteristics. The results were modeled assuming statistical emission and classical trajectories as had been done with the results from the lower energies [3–6]. However, a naive application of a statistical model approach to the results of this measurement is questionable, since there are likely to be a variety of reaction mechanisms at work and a variety of LCP sources. This straightforward approach, successful at the lower energies, simply assumes that a traditional compound nucleus is formed. At a beam energy of 40 MeV/nucleon, this assumption results in a very energetic, very short-lived source of LCP. A slightly more realistic approach is to include what is known about the experimental systematics of linear momentum transfer [18,19]. Since systematics suggest that only about half of the linear momentum is transferred to the composite system, there is much less energy available in the composite system. However, the energy in the composite system is shared among fewer nucleons so that it is not necessarily true that the resulting source is longer lived.

Two statistical model calculations are shown in Fig. 1. The first calculation assumed an initial excited nucleus was made (with full momentum transfer), then the properties of the particle emission (energy distributions at each decay step, decay probabilities, lifetime of each step, etc.) are determined, and then these properties serve as inputs to a Monte Carlo Coulomb trajectory program which tracks simulated particles to the detectors and forms the correlation function. The results of such calculations for the *p-p* and *p-d* channels are shown in Fig. 1 by the solid lines. As expected for these assumptions, for a beam energy of 640 MeV the lifetimes predicted in this way are unrealistically short, resulting in unrealistic correlation functions and indicating that this model in not applicable to our system.

The second calculation (shown by the dotted lines in Fig. 1) was done assuming 50% momentum transfer as suggested by the Viola systematics of linear momentum transfer [18,19]. In this case the mass of the composite system is lower than in the first case (35 compared to 43) and the energy of the system is lower (257 MeV versus 402 MeV). Of course the classical nature of the trajectory program precludes any positive correlation (which arises from the nuclear force) and the small positive correlation is a result of particles being pushed apart while traveling to the detectors. Although the calculations are closer to the measurement because the predicted lifetimes are longer than for the first calculation, the predicted correlations are still too deep. This reinforces the idea that the LCP came from a source with an unexpectedly long lifetime.

IV. TRENDS

There still remains the question of what dynamical variables are most relevant if one is seeking to study sources with small space-time extent and why the measured correlations seem to indicate a very long-lived source. To that end, 47 small-angle *p-p* correlation measurements found in the literature were examined in an attempt to understand the necessary conditions for observing very short lifetimes. Obviously, this process involves many variables that can influence the measurements and is somewhat schematic, given the wide variations in experimental details from one measurement to the next. Ultimately, two dynamical variables were selected to compare the data. The first of these was the excitation energy per nucleon of the composite source. Viola systematics [18,19] were used to account for incomplete momentum transfer to achieve a fairer comparison across the wide range of target and projectile masses. The second variable was the center-of-mass angle for the detection. This number is not well defined as this angle varies with the energy and type of the detected particle. Also many of the detector arrays used for correlation measurements spanned a wide range of laboratory angles. Specifically, this angle was taken to be that center-of-mass emission angle which would result in protons with the energy of the barrier in the center-of-mass frame being directed into the center of the detector array. The values for all points are given in Table I. The maximum positive correlation reported is also noted in this table. In some cases, this value is an estimate based on several reported correlation functions with different gating conditions.

One might expect that there would be a correspondence between the energy per nucleon of the system and the lifetime. To some extent this is true but there are many instances in Table I where a system with a high amount of energy has a small or no positive correlation (indicating a lifetime which is not exceptionally short). There is a stronger relation between the center-of-mass emission angle and the peak correlation value. Figure 4 shows the maximum positive correlation observed versus the center-of-mass detection angle (determined as described above).

At backward angles the maximum correlation is usually quite small while there is a tendency that larger values of the maximum correlation are associated with forward angle measurements. This trend may have a simple explanation based on the characteristics of two processes which should coexist at intermediate bombarding energies. The first mechanism is a preequilibrium production process which is primarily due to individual nucleon-nucleon interactions in the colliding nuclei and which takes place with a very short time scale. This process can be modeled within the context of the Boltzmann-Ueling-Uhlenbeck (BUU) formalism. The second process, with a longer time scale, which produces LCP is the more traditional statistical evaporation from an equilibrated composite system. Obviously, there should be a continuum between these two extremes, but the data in Fig. 4 suggest the trend. Of course, the presence of two processes would not necessarily produce the results of Fig. 4 unless the two processes emit particles with different angular distributions as they do here; the angular distribution of emitted particles for preequilibrium processes is very forward peaked while the angular distribution for evaporation is more isotropic. Thus, if one measures correlation functions at more forward angles, the results have the possibility of being dominated by the preequilibrium processes which, because they are fast, can result in large correlations. Of course, the specific shape of the measured correlation function will be an interplay of the lifetimes and relative yields of the processes producing the light particles. At more backward angles it becomes more difficult to ever measure large positive p-p correlations because the fastest preequilibrium particles do not populate the more backward angles and the statistical emission is never fast enough to give the necessary number of p-p pairs with small space-time separation.

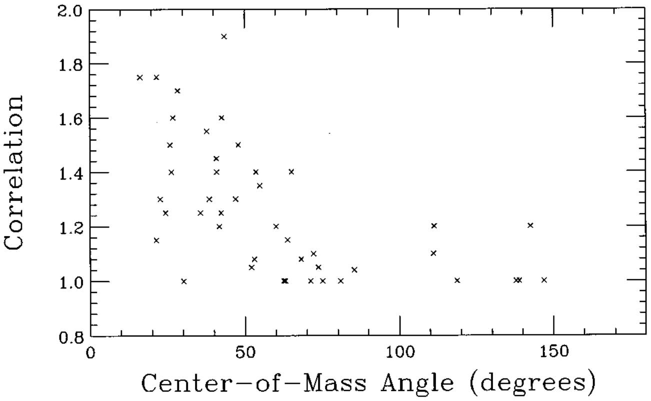

FIG. 4. Relation between the center-of-mass proton emission angle and the maximum positive p-p correlation value for a variety of small-angle p-p correlation measurements.

This idea of different LCP emission processes allows a qualitative understanding of the particular system presented in this work. The time scale for the first of these mechanisms, the preequilibrium emission, is very short. A BUU calculation [31,32] shows that by $\approx 3\times 10^{-22}$ sec the system has reached the point that individual nucleon-nucleon collisions no longer result in significant nucleon emission. The average time between emitted protons is $\approx 1.6\times 10^{-22}$ sec. The time scales for evaporation are expected to be longer. A statistical model calculation of the decay properties of the system formed assuming 50% momentum transfer suggests the average time between emitted protons is $\approx 5\times 10^{-22}$ sec.

In order to investigate this idea a trajectory calculation was made which assumed statistical emission from an average residue predicted by BUU following preequilibrium nucleon emission. An implicit assumption in this calculation is that most of the protons and neutrons emitted by preequilibrium processes (nucleon-nucleon collisions) should be directed to the more forward angles while the particles from evaporation dominate elsewhere. As expected the BUU calculation suggests that the residue left after the preequilibrium nucleon-nucleon collisions stop ejecting nucleons is less massive and colder. In this case, the average mass, charge, and excitation energy of the residue was 33, 21, and 100 MeV. The results of such a calculation are shown by the dashed lines in Fig. 1. Considering the schematic nature of the calculation, the agreement is remarkable. It appears that the model source lifetime is still somewhat shorter than the lifetime implied by the data, but this approach definitely provides a framework with which to understand the data of this work as well as the trend seen in Fig. 4. It seems that at the more backward angles of this measurement we are still sensitive to a relatively long-lived, equilibrated source but that this source is not a typical compound nucleus.

V. CONCLUSIONS

The shallowness of the observed Coulomb hole in the p-p and p-d correlation functions, suggests an unexpectedly long-lived source. However, when the p-p correlation results are considered in the context of other p-p correlation measurements, this may be an indication of multiple sources of LCP emission at these energies. The observed results can be understood if the short-lived processes seen in other measurements at forward angles dominate only at forward angles

TABLE I. Summary of the characteristics of published small-angle correlation measurements. All energies are expressed in MeV/nucleon and all angles are in degrees. The beam energy, mean laboratory angle, and maximum correlation are taken from the cited references. The excitation energy is calculated assuming Viola systematics [18,19] to account for incomplete momentum transfer. The center-of-mass angle is the angle for protons with a center-of-mass energy equal to the barrier and traveling toward the center of the detector arrays. The maximum correlation is the value of the correlation function near 20 MeV/c.

Beam+target	Beam energy	Laboratory angle	Excitation energy	Center-of-mass angle	Maximum correlation	Reference
^{32}S+^{27}Al	3.3	45	0.81	63.0	1.0	[20]
^{16}O+^{27}Al	5.0	45	1.17	62.5	1.0	[3]
^{32}S+^{27}Al	6.7	45	1.67	71.2	1.0	[20]
^{40}Ar+$^{\mathrm{nat}}$Ag	7.8	68	1.54	81.0	1.0	[21]
^{16}O+^{27}Al	8.8	50	2.03	75.1	1.0	[4]
^{16}O+^{27}Al	8.8	20	2.03	30.2	1.0	[5]
^{16}O+^{27}Al	13.4	45	2.99	72.2	1.1	[6]
^{16}O+^{27}Al	15.6	45	3.43	73.7	1.05	[6]
^{40}Ar+$^{\mathrm{nat}}$Ag	17.0	68	3.08	85.4	1.04	[21]
^{32}S+$^{\mathrm{nat}}$Ag	22.3	30	3.4	38.5	1.3	[22]
^{16}O+^{27}Al	25.0	15	4.66	26.3	1.4	[23]
^{16}O+^{12}C	25.0	15	5.01	47.0	1.3	[23]
^{16}O+^{197}Au	25.0	15	1.42	16.3	1.75	[7]
^{20}Ne+^{12}C	30.0	30	5.91	ns	1.15	[17]
^{20}Ne+^{59}Co	30.0	30	4.52	42.3	1.25	[17]
^{20}Ne+^{197}Au	30.0	22	1.94	24.4	1.25	[17]
^{40}Ar+^{197}Au	30.0	45	3.31	53.0	1.08	[24]
^{40}Ar+^{12}C	30.0	45	4.17	ns	1.15	[25]
^{20}Ne+^{12}C	30.0	29	5.91	ns	1.1	[8]
^{20}Ne+^{59}Co	30.0	29	4.52	40.9	1.4	[8]
^{4}He+^{58}Ni	30.0	60	1.32	28.4	1.7	[9]
^{20}Ne+^{27}Al	30.0	22	6.39	41.7	1.2	[17]
^{20}Ne+^{27}Al	30.0	60	6.39	111.3	1.2	[17]
^{20}Ne+^{27}Al	30.0	80	6.39	142.6	1.2	[17]
^{139}Xe+^{27}Al	31.0	25	3.25	68.2	1.08	[10]
^{139}Xe+^{122}Sn	31.0	25	6.99	52.1	1.05	[10]
^{14}N+^{197}Au	35.0	35	1.57	37.7	1.55	[11]
^{14}N+^{197}Au	35.0	50	1.57	53.6	1.4	[11]
^{14}N+^{197}Au	35.0	20	1.57	21.6	1.75	[12]
^{16}O+^{27}Al	40.0	35	7.25	63.8	1.0	this work
^{40}Ar+^{197}Au	44.0	90–150	4.18	138.9	1.0	[26]
^{40}Ar+^{108}Ag	44.0	130	6.15	146.9	1.0	[27]
^{12}C+^{58}Ni	46.7	20	4.27	25.9	1.5	[13]
^{12}C+^{115}In	46.7	20	2.51	22.7	1.3	[13]
^{12}C+^{197}Au	46.7	20	1.59	21.4	1.15	[13]
^{40}Ar+^{197}Au	60.0	30	4.81	35.6	1.25	[28]
^{3}He+^{108}Ag	66.7	42	0.85	43.5	1–3.4	[14]
^{3}He+^{108}Ag	66.7	109	0.85	111.1	1.1	[14]
^{14}N+^{27}Al	75.0	25	9.03	42.6	1.6	[10]
^{14}N+^{197}Au	75.0	25	2.07	26.8	1.6	[10]
^{36}Ar+^{45}Sc	80.0	38	11.64	65.1	1.4	[15]
^{16}O+^{197}Au	94.0	45	2.25	47.9	1.5	[16]
^{16}O+^{197}Au	94.0	57	2.25	60.0	1.2	[29]
^{16}O+^{197}Au	94.0	115	2.25	118.7	1.0	[29]
^{16}O+^{197}Au	94.0	135	2.25	137.9	1.0	[29]
^{36}Ar+^{45}Sc	120.0	38	9.56	54.8	1.35	[15]
^{36}Ar+^{45}Sc	160.0	38	1.93	40.8	1.45	[15]

while longer-lived sources are responsible for the LCP seen at larger angles. Thus, a long-lived equilibrated source must still have been formed in this reaction and this measurement was sensitive to this source because of the placement of detectors at more backward angles. Given the energy of the reaction it is unlikely that the source of the light charged particles is a simple traditional compound nucleus made up of most of the target and projectile nucleons. Accordingly, simulations assuming either a compound system formed with either complete or incomplete momentum transfer fail to reproduce the data. Better agreement was obtained when we assumed that there was significant preequilibrium emission (directed forward) and that the LCP measured here come from the residual nucleus remaining after the preequilibrium emission. This speculation suggests that further studies of correlation functions as a function of detection angle would provide more insight into the role of LCP correlation functions in determining the reaction mechanism at intermediate energies.

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