BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review.** *A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.*

Correlation measurements of light charged particles emitted from $^{32}S+^{27}Al$ reactions at energies of 105 MeV and 215 MeV

P. A. DeYoung,[1] N. N. Ajitanand,[2] J. M. Alexander,[2] V. Datar,[2] C. J. Gelderloos,[1,*] G. Gilfoyle,[2,†] M. S. Gordon,[2] R. L. McGrath,[2] G. F. Peaslee,[1] and J. Sarafa[1]
[1]*Physics Department, Hope College, Holland, Michigan 49423*
[2]*State University of New York, Stony Brook, New York 11794*
(Received 6 September 1995)

Previous work has examined light particle correlations from O+Al reactions over a range of energies within a framework of statistical emission from a composite source. The source of these light particles was assumed to be an excited composite nucleus because the excitation energy of the source was not so high that exotic processes such as fragmentation or preequilibrium emission were significant. In this Brief Report we examine correlation functions between light charged particles emitted from reactions of S+Al at 105 MeV and 215 MeV. As in previous work, the proton-proton and proton-deuteron correlations are well described by the results of Monte Carlo simulations based on statistical emission. In this Brief Report we will also compare the results of alpha-alpha and deuteron-alpha correlations to the predictions of models which include the emission of heavier unstable particles (such as ^8Be and $^6Li^*$) from the excited source. The results presented here can serve as additional validation of the correlation technique and also as tests of the statistical model.

PACS number(s): 25.70.Gh, 24.60.Dr, 25.70.Pq

Measurements of correlation functions involving particles emitted from heavy-ion collisions give insight into properties of the source of the particles. At higher energies (tens of MeV/nucleon) the measurements are applied to understanding the nonequilibrium and fragmentation phenomena that occur [1,2]. At lower energies (below 20 MeV/nucleon), the work has confirmed the validity of assuming statistical emission. The lower energy works have also strengthened the assumption that the particle-particle interactions can be modeled with three-body trajectory methods [3–10].

The lower energy measurements typically have focused on proton-proton (p-p) and proton-deuteron (p-d) correlations. While other correlation functions have been measured, the presence of strong particle-unbound resonant states in the various two particle systems makes it difficult to relate the measured correlations back to properties of the source. For example, the shape of the α-α correlation function is determined by the lifetime of the emitter of the two α particles and by the number of ^8Be that are emitted from the composite source [5,7]. In this Brief Report we present measured correlations between two LCP's that can arise from particle-unbound states (^8Be and $^6Li^*$) to determine the fraction of unstable particles that would be needed to give the observed correlation function. These results are compared to the predictions of the statistical model, which agree with the results for p-p correlations.

A beam of ^{32}S was accelerated to 215 MeV and 105 MeV with the superconducting linear accelerator at Stony Brook. The target was a 0.4 mg/cm^2 foil of natural aluminum. The particles were detected in NaI detectors arranged in a hexagonal close-packed configuration with the center of the array located at 45° in the laboratory. (This large angle serves to suppress the yield of particles from direct reactions which are focused forward.) The angular separation between nearest neighbors was 4.62°. Particle identification was based on both pulse shape discrimination and time of flight, the latter made possible by the good time structure of the beam from the Stony Brook linear accelerator. The detector calibrations were based on discrete lines from reactions (such as $^{16}O+^{12}C$ and $^{32}S+ZrH_2$) and from the breakup kinematics of unstable particles ($^6Li^*$ and ^8Be).

In previous work on the O+Al systems [3–6] the compound nucleus had between 65 MeV and 170 MeV of excitation energy over a range of beam energies from 80 MeV to 250 MeV. For that system, at all energies, good agreement between a Monte Carlo trajectory calculation (described below) and the p-p and p-d correlation functions was observed suggesting that the behavior, including lifetime and cooling effects, predicted by the statistical model is reasonable even at the highest excitation energies (early steps). The S+Al systems presented here have excitation energies similar to the two lower energies studied for O+Al but as there are more nucleons in the composite system there is a lower average excitation energy per nucleon. At 215 MeV the total excitation energy is approximately 110 MeV and for a beam energy of 105 MeV the total excitation is approximately 61 MeV. At these excitation energies, the Monte Carlo simula-

*Present address: Department of Physics, University of Colorado, Boulder, CO 80309-0446.
†Present address: Department of Physics, University of Richmond, Richmond, VA 23173.

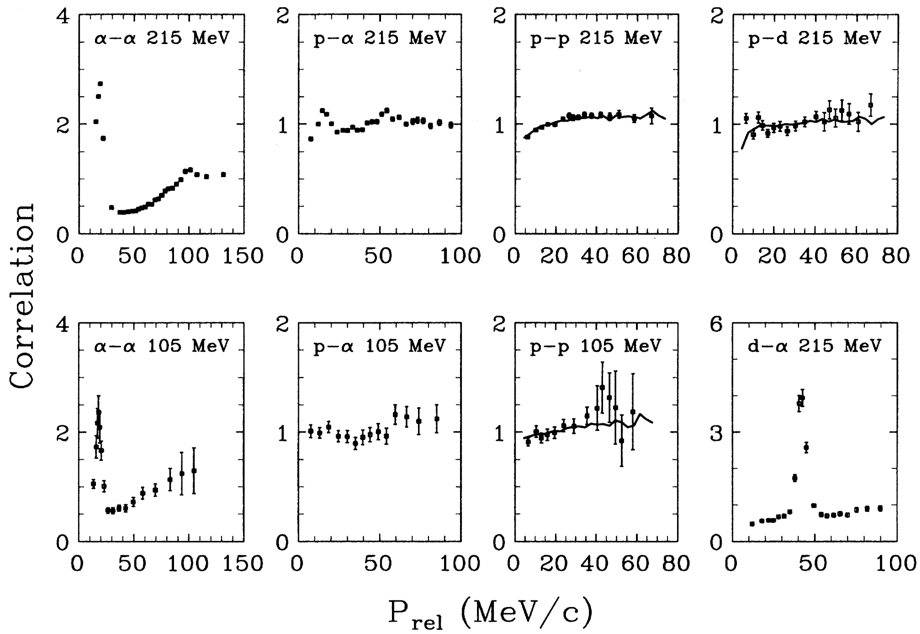

FIG. 1. Correlation functions for pairs of particles emitted from the S+Al system. The solid lines are the predicted correlations based on an assumption of statistical emission. The *p*-*d* and *d*-α results at 105 MeV are not included due to low statistics.

tions should reproduce the *p*-*p* and *p*-*d* correlation functions, as they did for the O+Al systems. The choice of a lower energy system was intentional to remain in the regime where the assumptions of the statistical model should still hold, while also examining the unstable particle emission which has not often been considered within the context of the statistical model.

The correlation functions for various particle combinations from the two beam energies are shown in Fig. 1 for S+Al. In all cases, the correlation functions were formed with an event-mixing approach [8]. The correlations involving deuterons from reactions at a beam energy of 105 MeV are missing because of insufficient statistics. As expected, at the higher beam energy more pronounced correlation effects are seen. The correlations involving α-α, *d*-α, and *p*-α channels also show the usual positive correlations which may be interpreted as corresponding to breakup of the particle unstable states of ^{8}Be, ^{6}Li*, and ^{5}He.

As in previous work, we have modeled the *p*-*p* and *p*-*d* correlation results with a Monte Carlo three-body trajectory simulation [9,10] (the solid curves in Fig. 1). The particular implementation of the trajectory simulation was a computer code, MENEKA [10]. The options in MENEKA were chosen so that the calculation took as its starting point the emission probabilities, lifetimes, and energy distributions (step by step) from a Monte Carlo statistical emission calculation. For the results presented here these parameters were based on a Monte Carlo version of the code CASCADE [11]. At 215 MeV, the first step lifetime was taken to be 4.4×10^{-22} sec and subsequent steps were progressively longer, reaching 2.4×10^{-17} sec for step six, as the emitter cooled. For 105 MeV the lifetimes ranged from 1.6×10^{-20} to 1.3×10^{-17} sec over the five steps of the decay chain. The calculated correlations include the effects of the energy resolution of the detectors, the effects of the actual detector positions, and the effects of the finite solid angle of the detectors. The calculation also forms the correlation function with the same event-mixing scheme that was applied to the data. The simulation randomly picks the various properties (step, energy, direction, etc.) of two emitted particles. No normalization has been made between the model correlation results and the correlation functions determined from the data. Unlike the simulations done in Refs. [4,9], this simulation code includes recoil of the emitter. Again, as for the O+Al work, the *p*-*p* data are well reproduced by the model, indicating that the statistical emission of light charged particles (LCP's) from a composite system is a reasonable model of the source of the light particles. The *p*-*d* results are somewhat ambiguous but are based on less than 10 000 small angle events and the discrepancy is confined to the lowest bin which may suffer from threshold effects.

The remaining correlations, those which could result from the decay of particle unstable nuclei, are not necessarily reliable sources of information about the emitting source. Because the breakup energies for ^{5}He, ^{8}Be, and ^{6}Li* are relatively small, the close-packed detector geometry has very good efficiency for detecting the fragments of such unstable particle breakup. Thus even if the cross section for the production of such particles is small they can be detected in significant numbers. These events yield highly correlated particle pairs which influence each other, not because of their spatial or temporal proximity as they move to the detectors, but because they are the decay products of a composite particle and so cause positive correlations.

If one were to naively apply the approaches suggested to understand the results at very high excitation energies [1,2], one would be forced into a situation of simultaneously needing long lifetimes for the *p*-*p* and *p*-*d* correlations and very short lifetimes (or small space-time sizes) to explain the remaining results [5,7]. This requires rather radical assumptions about the decay process. For example, this approach would require that a proton and deuteron in the decay chain follow the statistical model, but that the α particles do not if there is also a deuteron later in the decay chain. This seems

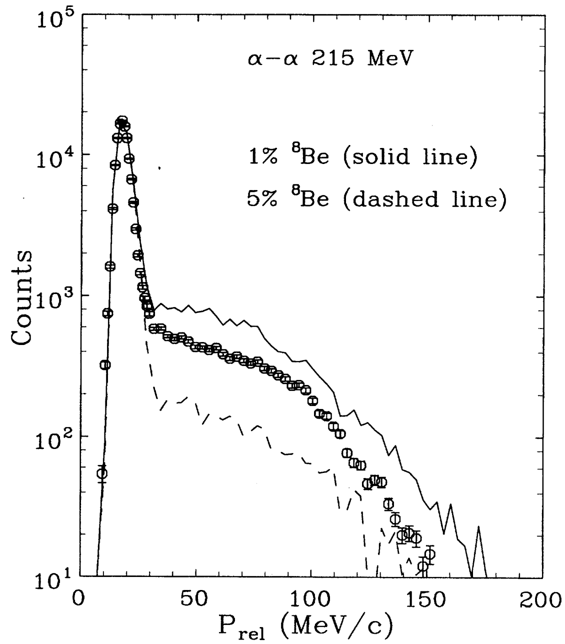

FIG. 2. Relative momentum spectrum for particle pairs associated with unstable particles emitted from S+Al composite system. The solid line and dashed line are the model predictions from MENEKA with unstable emission included. All calculations were normalized to the data at the peak.

impossible to justify. Similarly, it may be incorrect to assume that the observed correlations are due entirely to the breakup of unstable particles. However, the trajectory simulations allow one to model the likelihood that two independent particles are ever close enough to interact via the strong force and so possibly contribute to an observed positive correlation. Based on MENEKA simulations, at most a few percent of the independently emitted and detected particles are calculated to be close enough in space (less than 5 fm apart) at any time during their travel to the detectors to have possibly resulted in a positive correlation. When the relative momenta of particle pairs is also considered, essentially no independent pairs which could contribute to the positive correlation are predicted. Thus, the idea that these correlations functions are really reflecting the production cross section for these unstable particles is more appropriate to these systems.

By including a component of unstable particle emission in the trajectory simulations and by comparing to data, one can extract a measure of unstable particle emission. This measure is essentially the number of the unstable particles emitted into 4π relative to the number of events with two independent particles (adjusted to correctly account for multiplicity). The simulation includes detector resolution and geometry as part of the calculations. This fraction then can be compared to model predictions.

Figure 2 shows the results of varying the amount of unstable particle emission in MENEKA, compared to the actual data for the α-α channel at 215 MeV. This provides an idea of the uncertainties associated with the unstable particle yields. The details of the decay chain for MENEKA were taken from CASCADE [11] (although to achieve the quality of fit seen in Fig. 2 the barriers and temperatures predicted by CASCADE needed to be slightly lowered). This figure demonstrates the sensitivity of the technique and that the fraction of unstable IMF's relative to true two particle emission can be well determined. Table I lists the determined fractions column 3. The ^{5}He channel was not included because the broad width of the state made reliable extraction of the fraction impossible. Also shown in Table I are results from two statistical model calculations. In the statistical model calculation using MODGAN [12], 20 particles were included as allowed decays. All particles of mass 4 and less were included along with the ground states of particles with mass from 5 to 14 and a special particle to model the excited state of ^{6}Li. All the decay probabilities in the statistical model code are determined from Hill-Wheeler transmission coefficients and a Fermi-gas density of states. The angular momentum of the compound system was set by the fusion cross section with the assumption of a triangular distribution of entrance channel spin.

TABLE I. Comparison of the fraction of unstable emission to two-particle emission determined from data and predicted by calculation.

Energy	Channel	Measured	MODGAN	GEMINI
215	α-α	2.2%	3.8%	3.6%
	d-α	3.1%	4.5%	
105	α-α	.12%	1.35%	3.3%

Calculations were also made with the code GEMINI [13]. This statistical decay model code uses the transition-state formalism to predict IMF emission probabilities and, while not optimized for the system under study in this paper, can confirm the general nature of the IMF emission. The results presented in Table I generally agree with the results from MODGAN, although the GEMINI calculations were based on a smaller spin range (due to the sensitivity to the angular momentum dependent barriers for IMF production).

The results for the extracted fraction of unstable IMF to two-particle yields from the data and the calculations are shown in Table I. A comparison of the results to the calculations shows several interesting things. First, even with very simple assumptions regarding the coefficients and level densities, there is agreement between the data and the calculation at the higher energy. However, the calculation consistently overpredicts the amount of these heavier unstable particles. Second, in spite of the possibility that the unstable particles could also originate from nonequilibrated sources, the measured yields are lower than the predictions.

It may be that the observed systematic overprediction of the IMF yield is an artifact of the model calculation. The transmission coefficients and level densities for the various channels, incorrectly assumed to be given by a Fermi-gas model, have been parametrized rather than individually optimized. It is also well known that the results of statistical model calculations can be changed significantly if one makes modest changes the parameters. No attempt was made to optimize the calculations presented here because of the limited number of comparison points.

In summary, we have shown that for the mass symmetric reaction $^{32}S+^{27}Al$, the p-p correlations are in excellent agreement with lifetime predictions based on an assumption of statistical equilibrium. This conclusion has also been reached in [5,7] for more mass asymmetric reactions. In addition it appears that the yields of certain unstable IMFs can be accommodated within the framework of a statistical model.

This work was supported by the National Science Foundation.

[1] D. Boal, C. K. Gelbke, and B. K. Jennings, Rev. Mod. Phys. **62**, 553 (1990).

[2] W. Bauer, C. K. Gelbke, and S. Pratt, Annu. Rev. Nucl. Part. Sci. **42**, 77 (1992).

[3] P. A. DeYoung, M. S. Gordon, X. Q. Lu, R. L. McGrath, J. M. Alexander, D. M. de Castro Rizzo, and L. C. Vaz, Phys. Rev. C **39**, 128 (1989).

[4] P. A. DeYoung, C. J. Gelderloos, D. Kortering, J. Sarafa, K. Zienert, M. S. Gordon, B. J. Fineman, G. P. Gilfoyle, X. Lu, R. L. McGrath, D. M. de Castro Rizzo, J. M. Alexander, G. Auger, S. Kox, L. C. Vaz, C. Beck, D. J. Henderson, D. G. Kovar, and M. F. Vineyard, Phys. Rev. C **41**, R1885 (1990).

[5] M. S. Gordon, R. L. McGrath, J. M. Alexander, P. A. DeYoung, X. Q. Lu, D. M. de Castro Rizzo, and G. P. Gilfoyle, Phys. Rev. C **46**, R1 (1992).

[6] R. A. Kryger, J. J. Kolata, W. Chung, S. Dixit, R. J. Tighe, J. J. Vega, P. A. DeYoung, C. Copi, J. Sarafa, G. P. Gilfoyle, and S. K. Sigworth, Phys. Rev. C 46, 1887 (1992).

[7] A. Elmaani, J. M. Alexander, N. N. Ajitanand, R. A. Lacey, S. Kox, E. Liatard, F. Merchez, T. Motobayashi, B. Noren, C. Perrin, D. Rebreyend, T. U. Chan, G. Auger, and S. Groult, Phys. Rev. C **48**, 2864 (1993).

[8] W. A. Zajc, J. A. Bistirlich, R. R. Bossingham, H. R. Bowman, C. W. Clawson, K. M. Crowe, K. A. Frankel, J. G. Ingersoll, J. M. Kurck, C. J. Martoff, D. L. Murphy, J. O. Rasmussen, J. P. Sullivan, E. Yoo, O. Hashimoto, M. Koike, W. J. McDonald, and J. P. Mil, Phys. Rev. C **29**, 2173 (1984).

[9] R. L. McGrath, A. Elmaani, J. M. Alexander, P. A. DeYoung, T. Ethvignot, M. S. Gordon, and E. Renshaw, Comput. Phys. Commun. **59**, 507 (1990).

[10] A. Elmaani, N. N. Ajitanand, T. Ethvignot, and J. M. Alexander, Nucl. Instrum. Methods Phys. Res. Sect. A **313**, 401 (1992).

[11] F. Puhlhofer, Nucl. Phys. **A280**, 267 (1977).

[12] N. N. Ajitanand and J. M. Alexander, MODGAN, A Modular Nuclear Evaporation Code Based on the Weighted Monte Carlo Technique (to be published). This Hauser Feshbach code continues the approach described in [10] and N. N. Ajitanand *et al.*, Nucl. Instrum. Methods Phys. Res. **243**, 111 (1986).

[13] R. J. Charity, M. A. McMahan, G. J. Wozniak, R. J. McDonald, L. G. Moretto, D. G. Sarantites, L. G. Sobotka, G. Guarino, A. Pantaelo, L. Fiore, A. Gobbi, and K. D. Hildenbrand, Nucl. Phys. **A483**, 371 (1988).