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Particle-particle correlations: Independent particle emission versus sequential decay of heavy fragments

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Particle-particle coincidence measurements for both large and small separation angles are reported for the reactions 140 MeV $^{16}O+^{27}Al \rightarrow p\text{-}p$, $p\text{-}d$, $d\text{-}d$, $\alpha\text{-}\alpha$, $d\text{-}\alpha$, and $p\text{-}\alpha$. Two clusters of seven detectors were used at $\pm 50°$, on both the right and left sides of the beam axis. Coincidence data were compared for nearest-neighbor and across-beam geometries. For $p\text{-}p$, $p\text{-}d$, and $d\text{-}d$ pairs, the results of this symmetry test are consistent with independent particle evaporation. For the $\alpha\text{-}\alpha$, $d\text{-}\alpha$, $p\text{-}\alpha$ pairs, the results indicate significant contributions from breakup of preformed fragments. These results suggest that small-angle correlations for the former pairs are useful as probes of the space-time extent of the emitters, but that the latter pairs are compromised for this task.

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Recent papers have demonstrated [1–4] that correlations between light particles emitted from hot composite nuclei provide information on timescales for evaporative emission. Detailed analysis of data for proton-proton and proton-deuteron pairs shows quantitative consistency with the notation that the correlations arise mainly from the long-range Coulomb repulsion of particles emitted with mean initial lifetimes of order 10^{-22} s, increasing as the system cools. For such processes the interparticle separations are typically much larger than the range of the nuclear force so their role is much less important than the Coulomb force. In this paper additional correlation data are presented from the same set of reactions studied in the earlier work which exhibit peaks clearly related to nuclear forces. We interpret these peaks as being due to sequential decay of intermediate mass fragments (IMF's) and discuss the implications for correlation studies done at higher incident energies where, *a priori,* the characteristics of the emission processes are not as well known [5–7].

Most of the data come from the $^{16}O+^{27}Al$ reaction studied at 140 MeV using the Stony Brook LINAC facility. Single element NaI(Tl) detectors were arranged in two clusters (seven each) placed in the horizontal plane and centered at $\pm 50°$ with respect to the beam. Individual detectors subtended 1.2 msr, and the nearest-neighbor angular separation was 3.93°. Particle identification and energy calibrations for $^{1,2}H$ and ^{4}He were made as described elsewhere [8,9]. The data from reactions at other incident energies were obtained at Stony Brook and the Argonne Atlas facility, and the experimental details are given in Ref. [2]. Correlation functions, as shown in Fig. 1, were constructed from coincidences between pairs of

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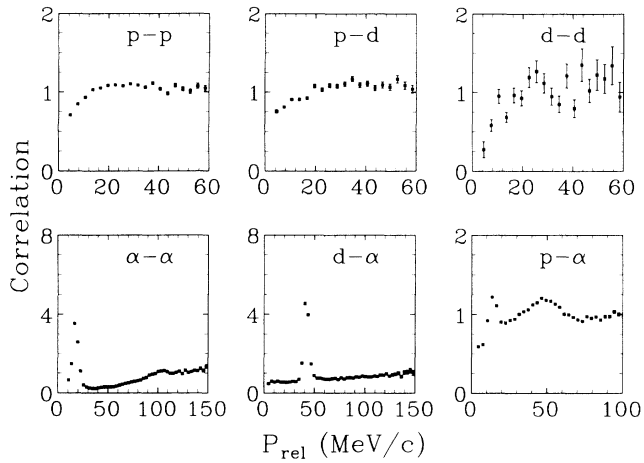

FIG. 1. Particle-particle correlation functions $A(p_{\rm rel})/B(p_{\rm rel})$ versus relative momentum $p_{\rm rel}$.

particles registered in one of either cluster. To construct these correlations functions, coincidence events were binned in relative momentum $p_{\rm rel}$ to form a spectrum $A(p_{\rm rel})$. A reference spectrum $B(p_{\rm rel})$ was formed by the same procedure, but after mixing corresponding particles registered in the same detectors but from separate events. The correlation function is defined as $A(p_{\rm rel})/B(p_{\rm rel})$, as in earlier work.

As shown in Fig. 1 the p-p, p-d, and d-d pairs have only anticorrelations previously understood as caused by the Coulomb repulsion of independently evaporated particles. In striking contrast, the α-α, d-α, and p-α correlations shown in the figure have peaks at relative momenta corresponding to well-known two-body resonances. These same peaks are evident in studies of reactions at higher energies [5]. Clearly, the short-range nature of the nuclear force implies that at least some of these events are associated with a much more compact source in space-time than the compound nucleus. The Koonin correlation model [10], as extended by Boal [11], Pratt [4,12], and others, is often used at higher energies to deduce source sizes. In this context, the coexistence of correlation patterns for different particle pairs which yield different source sizes is sometimes taken as evidence of differing particle freezeout densities as the source evolves in space-time.

The purpose of this paper is primarily cautionary. The data shown in Fig. 1 can be interpreted in a straightforward way as arising both from the final-state interactions of independently evaporated particles, and from the sequential decay of intermediate mass fragments (IMF's). These data were obtained at laboratory angles where Galilean-invariant cross sections of the light particles indicate [1] that emission is primarily from the compound nucleus. Nevertheless, we show that quite small multiplicities of IMF's relative to pairs of evaporated pairs can produce peaks like those in the figure. To do this, advantage is taken of the basic emission symmetry for evaporation after statistical equilibration, namely that of cylindrical symmetry about the emitter spin or (for evaporation following fusion of target and projectile) symmetry about the beam axis and a plane perpendicular to the beam (in the c.m. system). Particle-particle coincidences have been determined between detector pairs on the same side and on opposite sides of the beam axis.

For independent evaporation steps, separated by a long delay time, the cross sections and energy spectra for coincident particles detected on either the same or opposite side of the beam should be identical (neglecting emitter recoil) [13]. Taking into account the effects of recoil, finite emitter lifetimes, etc., the relative momentum spectra observed in same-side detectors can be readily predicted from the spectra observed in opposite-side detectors. This detailed predictive power allows a sensitive probe of contributions from processes such as the sequential decay of IMF's.

The procedure for simulating the correlations of independently evaporated particles is similar to that used in our earlier works [2,14]. However, in this analysis the emphasis is on correcting for recoil effects rather than extracting more detailed information such as lifetimes. Therefore, the evaporation cooling chain is more simply characterized by pseudo-two-step evaporation. The mean parent masses are taken from the Monte Carlo version of the statistical model program CASCADE [15]. The energy distributions of the evaporated particles were described empirically by the function $(E-V)\exp^{(-E/T)}$. The T parameter was initially chosen on the basis of a typical energy loss per unit decay mass. The final values of T and V were adjusted so as to give good representations of both the relative momentum spectra observed in the opposite-side detectors and the energy spectra of coincident particles detected at $\pm 50°$. Energy distributions calculated by the CASCADE code were not used because they gave somewhat harder spectra than those observed. The weighted Monte Carlo simulation takes into account both recoil and the geometry of the detector clusters.

Table I lists the values of average parent mass $\langle A \rangle$, V, and T for the two steps used to represent the evaporation for each of the six pair types. Typical opposite-side results are illustrated in Fig. 2 for α-α pairs. The comparable spectra for the other five pair species were equally well reproduced by this procedure but are not shown. The same-side relative momentum spectra are shown in Fig. 3 for all six pair species. Evaporation simulations are given for two situations: the second particle is assumed evaporated with a mean lifetime $\tau = 5\times10^{-21}$ s (relative to the first); or with an infinite delay between emissions. These lifetime effects are made manifest in the

TABLE I. Values of the average parent mass $\langle A \rangle$ and V and T parameters in the $(E-V)\times\exp^{-(E/T)}$ energy distributions used in the pseudo-two-step evaporation simulations. The subscripts 1 and 2 label the evaporation stage. V's and T's are in MeV.

Pair	$\langle A_1 \rangle$	$\langle A_2 \rangle$	V_1	V_2	T_1	T_2
p-p	41.0	37.4	1.0	1.0	3.8	3.2
d-d	42.0	38.8	1.8	1.8	4.0	3.6
α-α	40.9	35.2	4.25	4.25	4.9	3.8
d-p	40.6	38.4	1.6	1.0	3.9	3.4
d-α	40.3	38.3	1.2	3.9	3.9	4.5
α-p	38.7	38.0	4.25	1.0	4.4	3.4

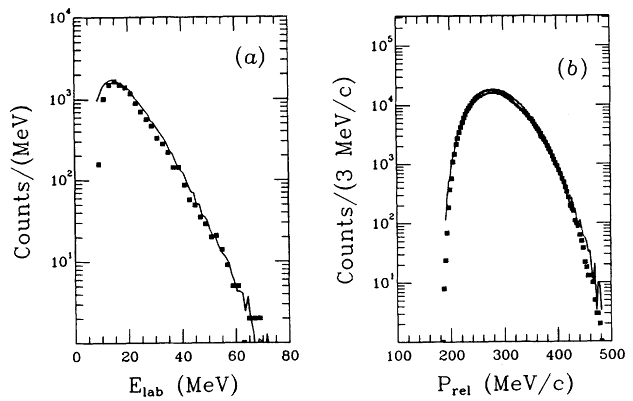

FIG. 2. (a) energy spectrum and (b) p_{rel} spectrum registered in the clusters centered at ±50° with respect to the beam. The curves show the Monte Carlo simulations based on evaporative emission as described in the text. The fluctuations in the curves are due to the finite sampling size.

Coulomb repulsion between the light particles. The finite time interval used here gives correlations comparable to those from the more detailed analysis of p-p and p-d correlations (compare Refs. [1] and [2]). Constraints imposed by fits to the opposite-side data do not fix unambiguously the parameter set. However, variation of the parameters (in ways that preserve reasonable agreement with the opposite-side data such as shown in Fig. 2) give shifts in the predicted same-side spectra yields of less than ≈20%—which are not important for our conclusions.

The same-side spectral shapes and yields for the p-p, p-d, and d-d pairs are well reproduced by the simulation. Observed depletions at small p_{rel} (compared to the curves for infinite lifetime) show the effect of the long-range Coulomb repulsion. More detailed discussion of this effect for p-p and p-d is found in Ref. [2]. The apparently stronger depletion for d-d pairs is consistent with preferential emission of deuterons early in the evaporative cooling process where the average time delay between deuterons is smaller and the Coulomb repulsion is stronger [16].

Results for the α-α, d-α, and p-α pairs are very different. The peaks associated with nuclear resonances stand clearly out above the reference spectra calculated as described above. The most pronounced peaks correspond to the $^8Be_{g.s.}$, the ^6Li 2.18 MeV state, and the ^5Li g.s. (A sequential decay peak due to $^8B_{g.s.} \rightarrow p + {}^8Be \rightarrow p + \alpha + \alpha$ decay also appears in the p-α data [5].) It is natural to infer that these peaks are caused by the decay of unstable IMF's because the integrated yields for the species with peaks are significantly larger than the yields predicted from the simulation based on stochastic emission.

It is clear that the coincidence detection efficiency for IMF decay products can be very high compared to the efficiency for detecting particles emitted stochastically over all space. If the decay cone for a metastable IMF state is Ω_{decay}, then the enhancement in coincidence detection efficiency is of order $4\pi/\Omega_{decay}$. Predicted α-α and d-α spectra are shown in Fig. 3 which include the effect of the $^8Be_{g.s.}$ and ^6Li 2.18 MeV state, respectively. The spectra show the sum of contributions from the evaporative process with $\tau = 5 \times 10^{-21}$ s and the sequential decay of the fragments. It appears that this mix of processes can account for such data, the depletion at small p_{rel} for d-α reflecting effective evaporative emission times somewhat smaller than used here. The multiplicity of the IMF's compared to pairs in these simulations is only 2% and 2.7%, respectively. The primary IMF energy distributions were taken from a CASCADE statistical decay calculation, but, of course, other IMF production mechanisms might have different energy and angular distributions. Nonetheless, the essential conclusion that quite small multiplicities can dramatically alter the observed p_{rel} spectra surely does not depend on this level of detail. Concerning the plausibility of IMF multiplicities of several percent relative to light-particle pairs, we note that the CASCADE statistical model code predicts ^8Be or ^6Li multiplicities relative to α-α or d-α pairs of 20%, i.e., more than enough to generate the peak yields that we observe.

Multiplicities of IMF's are generally quite small compared to those of the more "elementary" p, d, or α particles. However, the influence of their sequential decay can be dramatic because of kinematic focusing as discussed above. Indeed this point was emphasized earlier by Bernstein *et al.* [17], and mentioned in Ref. [5]. Excitation functions for IMF's exhibit an initially rapid increase with incident energy followed by a gently sloping plateau [18]. Figure 4 shows correlation functions for several particle pairs as a function of incident energy. For the α-α, d-α, and p-α pairs the peaks strengthen with energy as if they reflect a growing yield of IMF's relative to lighter particles and perhaps a stronger kinematic focusing as the IMF velocities increase. The p-d pair, which has no sharp nuclear resonances, has a completely different behavior. The anticorrelation for small p_{rel}

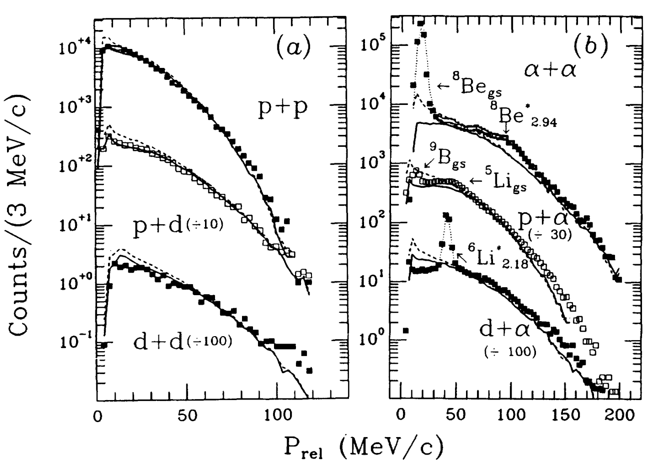

FIG. 3. Relative momentum spectra for same-side particle pairs detected in either of the two clusters. The curves show the simulation predictions based on fits to opposite-side spectra such as shown in Fig. 2. Evaporative emission with infinite time delay (dashed line), and finite delay with $\tau = 5 \times 10^{-21}$ s (solid line) is shown for all six pairs types. The dotted line shows the effect of including sequential decay of the $^8Be_{g.s.}$ and ^6Li (2.18 MeV) states on the α-α and d-α spectra, respectively.

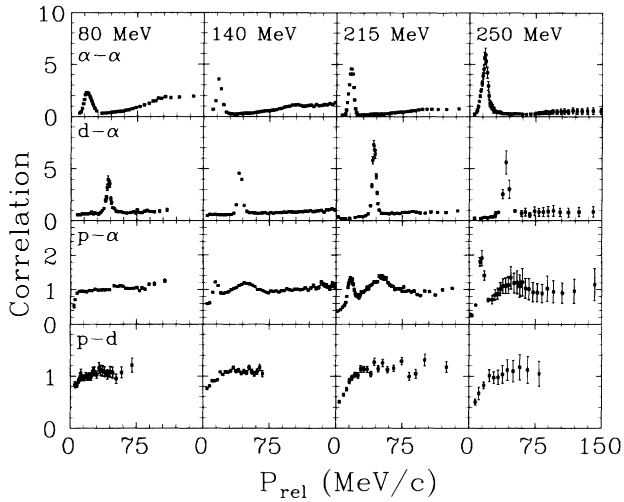

FIG. 4. Correlation functions for *p*-*d*, α-α, *d*-α, and *p*-α particle pairs from the reaction $^{16}O+^{27}Al$ for various incident energies (some of these results are from Ref. [2]).

values becomes stronger with energy. This is consistent with independent particle evaporation and decreasing average emission time with increasing excitation energy. Similar results have been found for the reaction 680 MeV $^{40}Ar+Ag$ [19].

It is difficult to envision an experimental test capable of a completely unambiguous differentiation between correlations driven by source size and those arising from sequential decay. In principle, two-body correlations in the many-body nuclear medium describable in, say, the thermal model [5,20] exhibit unitarity. That is, the momentum dependence of phase shifts that enhances the probability that pairs have particular relative momenta means that other momentum regions are depleted compared to pure phase-space distributions. Thus it might be imagined that if a "reference" spectrum could be constructed (of the type calculated here using the opposite-side data and compound nucleus decay symmetries), the actual correlation, or p_{rel}, data could be tested for unitarity. Peaks accompanied by deficits might then point to correlations driven by in-medium effects and, hence, sensitive to source size. Unfortunately, the sensitivity of such tests depends on the phase space spanned by the measuring system. This is clear in the results for the Coulomb-driven correlations of the present simulations. The Coulomb "holes" generated in the same-side simulations for the finite emission lifetime are not compensated by enhanced yields at larger values of relative momentum; this compensation appears only if one considers detector arrays with much larger angular coverage.

The general question of formation mechanisms for resonant pairs is complex. In this comparatively low energy study of $^{16}O+^{27}Al$, direct production of ^{8}Be could result from cluster transfer, deep inelastic reactions, or evaporation. Indeed, many earlier experiments have employed ^{8}Be detectors to study subjects such as $(\alpha, ^{8}Be)$ direct α pickup [21], $(^{16}O, ^{8}Be)$ fragmentation [22], and ^{8}Be emission in heavy ion resonance reactions [23]. Multiplicities of IMF's will surely depend on the target-projectile combination, reaction energy, and observation angle. The fissionlike emission of IMF's is a well-known mode of composite nuclear decay [18,24]. There is no reason to assume that the production rates of direct or fissionlike fragments carry any special information on the space-time extent of the emitter. Instead, if they are emitted from a composite nucleus, then the major physical driving force is the fission barrier as a function of fragment charge and charge of the composite nucleus. As to "prepackaged" fragment emission from hot composite systems, Friedman and Lynch have suggested [25] a criterion for inclusion of such fragments in a statistical model which is intuitively appealing: fragments should have lifetimes that are greater than their evaporation times. The $^{8}Be_{g.s.}$ and ^{6}Li 2.18 MeV state discussed here both have lifetimes ($\sim 1\times10^{-16}$ and 2×10^{-20} s, respectively) that clearly put them in this category. Whether produced by direct or evaporative mechanisms, the long lifetimes lead to sequential decay—and hence add to the coincidence yield from independent particle emission. With increasing resonance widths, or in the nonevaporative disassembly of a hot nuclear system, the decay chronology blurs, and approaches such as those in Refs. [10–12] become more appropriate.

In summary, we have shown two classes of small-angle, particle-particle correlations in heavy ion reactions. The first, typified by the *p*-*d* data, shows only an anticorrelation driven by the final-state interactions of independently evaporated light particles and is consistent with the associated symmetry test for same-side versus opposite-side detection geometries. The second, typified by α-α, exhibits distinct peaks and an overall enhancement in the same-side yield compared to the opposite-side yield. Small multiplicities of IMF's such as ^{8}Be can create such peaks.

Clearly, to the extent the correlations are built from sequential decay events, there is little information about the space-time extent of the source. It is natural to speculate from these results that the other correlation studies of particle pairs with strong resonances might be "contaminated" by decay or preformed fragments. Analyses based on the Koonin model [10] often lead to apparent source sizes that are smaller for particle pairs with strong resonances than for pairs without resonances. Indeed, Cebra *et al.* suggested [26] that correlation patterns observed in some higher energy experiments are more specific to the resonant pairs involved than to the emitting system.

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