Emission times in low-energy heavy-ion reactions by particle-particle correlations

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Particle-particle correlations (p-p and α-α) vs relative momentum ($P_{\rm rel}$) are reported ($\theta_{\rm lab} \approx 19.5°$) for the reaction 140 MeV ^{16}O+^{27}Al. A plot of the Galilean invariant cross section indicates that evaporative emission dominates the gross proton production even at this forward angle. The observed anticorrelation between two protons for small values of $P_{\rm rel}$ is analyzed to give an evaporation lifetime in the range of $1-5\times10^{-21}$ s. The α-α correlation is completely different; it seems to arise from preformed ^{8}Be.

Heavy-ion reactions at energies ≤ 10 MeV/nucleon often proceed via fusion to give a compound nucleus with a temperature (T) of several MeV. The statistical model is commonly used to describe the energy and angular distributions of the particles evaporated from these equilibrated compound nuclei. Validity of this model is limited to energies where the time for evaporation is greater than the thermal relaxation time. The problem of estimating this limiting temperature (probably in the range $T \geq 4$ MeV) has been discussed for many years.[1] Thus, it is of fundamental importance to measure particle-emission times and to establish the domain of strict statistical equilibrium.

In recent years, small-angle correlations between light particles have been widely used to give insights into the space-time extent (effective "size") of the emitter. For heavy-ion reactions at relativistic[2] and intermediate energies,[3,4] the results suggest "sizes" that are smaller than, or comparable to, the sizes of the colliding nuclei, i.e., the spatial extent dominates the observed correlations. At lower energies, one can expect emission times that are long enough to dominate the "size" and hence control the correlations.[5,6] In this work, p-p correlations from the reaction 140 MeV ^{16}O+^{27}Al, are used to obtain a first estimate of the particle-emission times for a system of $T \approx 4$ MeV; α-α correlations are also studied, but are shown to be driven by another mechanism.

For orientation, we recall that the symmetrization of (identical) two-particle wave functions leads to a correlation[6] range in relative momentum $P_{\rm rel} \leq \hbar/R$, where $R \approx (a^2+v^2\tau^2)^{1/2}$. The quantities a, τ, and v are, respectively, the emitter radius, mean lifetime, and mean-particle velocity. One may think of R as an effective source radius. For our case (^{43}Sc* compound nucleus at ≈ 100 MeV excitation energy) a rough estimate of the mean life is 10^{-21} s.[7] Thus, the typical quantities $a=1.25\ A^{1/3}=4.4$ fm, $v=0.1\ c$, and $v\tau=30$ fm might characterize this reaction system, and the above expression gives $P_{\rm rel} \approx 10$ MeV/c for the correlation range. Of course, the correlations also depend on both the nuclear and Coulomb interactions. Classically, the long-range Coulomb interaction between particles with charges z_1, z_2, generates an anticorrelation[8] for $P_{\rm rel} \leq (2\mu z_1 z_2 e^2/R)^{1/2}$. For $R=30$ fm, this also happens to yield $P_{\rm rel} \approx 10$ MeV/c for protons. For such large interparticle separations, the short-range nuclear force is probably less important; Ref. 8 estimates that the influence of the nuclear force scales as $(a/R)^3$ where $a \leq 2$ fm is the nuclear force range. In sum, one can anticipate that the correlations between evaporated particles will probably be confined to rather small relative momenta and will be driven mainly by lifetime effects.

Our experiment was performed at the Stony Brook LINAC facility. Nine detectors separated by 3.9° were positioned 1 m from a 1 mg/cm^2 Al target along an arc of polar angle 19.5°. Particle detectors consisted of 5.0 cm$\times$3.8 cm NaI scintillators collimated to a 3.7 cm diameter and covered by 6 mg/cm^2 Havar foils. Details of the particle identification method have been described elsewhere.[9,10] Energy resolution for protons was better than 1% at 10 MeV, worsening to 4% at 2 MeV. Energy calibrations were made by use of the reactions d(^{16}O,p), d(^{16}O,d), p(^{16}O,p), and ^{12}C(^{16}O,α), The same detectors were also used for inclusive measurements at angles from 20° to 160°.

Coincidence events were summed over energy and angle and binned in relative momentum $P_{\rm rel}$ to form a spectrum $A(P_{\rm rel})$. A two-particle correlation function is defined as the ratio $A(P_{\rm rel})/B(P_{\rm rel})$, where $B(P_{\rm rel})$ is a reference spectrum free from the correlations of interest. In practice, $B(P_{\rm rel})$ is approximated either by mixing true coincidence events or from inclusive spectra. For our data, the two methods give indistinguishable results for protons, and are only slightly different for α particles. The differences do not affect our conclusions. Event mixing is adopted here.

We show in Fig. 1 the p-p correlation function (for all particles with energy grater than 2 MeV), and in Fig. 2 the α-α correlation function (for α particles with energy greater than 8 MeV). For reference, the most probable proton and α energies (laboratory inclusive spectra) are ≈ 10 MeV and ≈ 20 MeV, respectively, with an exponential decrease at higher energy. The proton data in Fig. 1 exhibit a significant anticorrelation for values of $P_{\rm rel}$ less

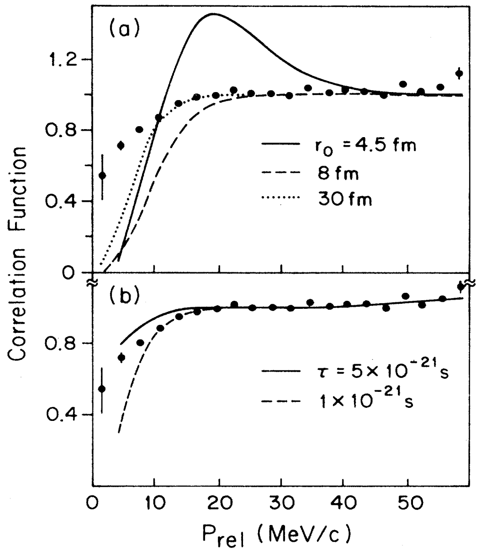

FIG. 1. Correlation function for protons vs their relative momentum P_{rel}. Data points include all detector pairs ($\theta_{lab}=19.5°$). The curves in (a) were calculated from the Koonin model ($r_0=4.8$ and 30 fm) as extended by Boal (Ref. 13). The curves in (b) were calculated by our trajectory model for $\tau=1$ and 5×10^{-21} s.

than ≈ 10 MeV/c. The correlation pattern does not change within statistical uncertainties, if only those events are included where both protons have energy greater than 10 MeV. In contrast to typical correlations at higher incident energies,[3,4,11] there is no peak in the vicinity of 20 MeV/c (associated with the short range $^1S_0$ nuclear interaction).[12] The α correlation has a prominent peak at about 20 MeV/c, related to the ^{8}Be ground state, superimposed on a broad hole extending to about 100 MeV/c.

The interpretation of such correlation functions clearly depends on the mechanism of the reaction. An overall view of the reaction pattern is provided by a contour plot of the Galilean invariant cross section, as shown for protons in Fig. 3. Comparison with the circles, centered on the c.m. velocity, shows that evaporation from the composite nucleus must be the dominant mechanism for proton production, even at 19.5° where the correlation was measured. These inclusive data suggest that a major fraction of the p-p coincidences are associated with particles independently evaporated from a thermally equilibrated, composite nucleus, and thus we first focus our interpretation on this mechanism. No model exists which contains all the ingredients of such low-energy correlations, i.e., a quantum-mechanical treatment that includes Coulomb and nuclear interactions between all evaporation products. Therefore, we discuss the data in the content of two very approximate approaches.

The well-known Koonin model[8] is intended for high-energy physics because the particle-nucleus interaction is ignored and because a Gaussian time distribution is used. With these caveats in mind, three model curves[8,13] are shown in Fig. 1 which have been computed for *zero* lifetime and $r_0=4.5$, 8, and 30 fm. [That is, the source distribution function $D(r,t=0)$ is proportional to $\exp(-r^2/r_0^2)$.] Detector geometry and resolution were taken into account by folding the model correlation with the observed single-particle distributions using Monte Carlo methods. The calculated peak for $r_0=4.5$ fm, due to the $^1S_0$ nuclear interaction, disappears for $r_0\geq 8$ fm; for still larger values of r_0, the half-width of the anticorrelation region narrows as r_0 increases. While no r_0 value yields a curve that closely follows the data, the curve for $r_0=30$ fm suggests a very extended source. Unfortunately, numerical convergence problems prevent model computations with realistically large time scales.[13,14] Lacking these, it is plausible that results for a

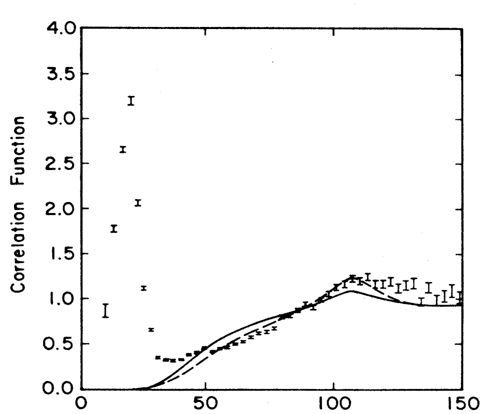

FIG. 2. Correlation function for alpha particles vs P_{rel} as in Fig. 1. Calculated curves are from the Koonin model (Refs. 8, 13, and 14) with $r_0=8$ and 10 fm.

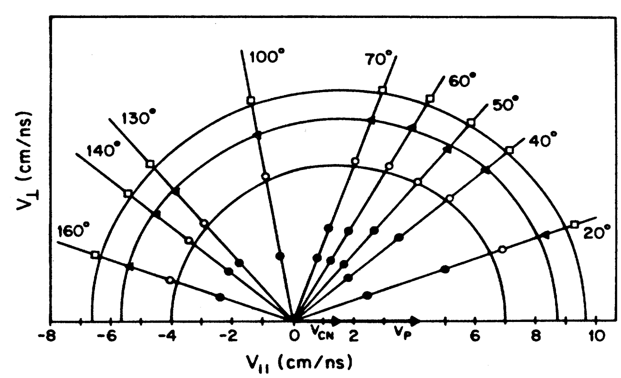

FIG. 3. Galilean invariant cross sections for inclusive protons. Symbols are as follows: ●, 2; ○, 0.2; ▲, 0.02; and □, 0.002 mb/(cm/ns)^3 sr, respectively. The calculated curves are from the evaporation code CASCADE (Ref. 16) assuming isotropic evaporation. Projectile and compound nucleus velocities are indicated.

finite timescale τ would resemble those for zero lifetime and an effective emitter radius $R \approx (r_0^2 + v^2\tau^2)^{1/2}$. It is in this spirit that the comparison to the Koonin model curves in Fig. 1 implies a long-lived source.

Clearly, a model tailored to evaporative emission is needed. We have constructed a very simple classical model in order to demonstrate the features of correlation patterns for particles characterized by evaporative velocity distributions and exponential time distributions. The ingredients of the model are as follows: (a) Particles are evaporated radially at random times from points chosen randomly on the surface of a compound nucleus. (b) Particle velocity distributions are taken from the inclusive spectra, and the time distribution between any two particles is weighted by $\exp(-t/\tau)$, where τ is the mean lifetime. Particles interact via the Coulomb force which produces an anticorrelation for small values of $P_{\rm rel}$. The reference spectrum $B(P_{\rm rel})$ is obtained by event mixing. Calculated curves for τ equal 1 and 5×10^{-21} s are shown in Fig. 1; from this framework one would estimate a mean lifetime in this range. Including quantum mechanics and nuclear forces might well change the quantitative aspects of the calculations. Nevertheless, because the likely mean distances between particles are very large, we feel that this model not only points to a long-lived source but also allows for a first estimate of its lifetime.

It is conceivable that the proton correlations might be influenced by ^{2}He emission. From *p-p* scattering data, a broad resonant state for ^{2}He can be said to have a mean energy of ≈ 0.8 MeV and a width of ≈ 2.8 MeV.[15] Therefore, its signature would be a broad peak in the correlation function at $P_{\rm rel} \approx 20$ MeV/c. The absence of a peak in our data (Fig. 1) argues strongly that the role of preformed ^{2}He emission is negligible here. Nevertheless, we have followed the approach of Ref. 15 to calculate the correlation associated with evaporative ^{2}He emission in the present study (where the compound-nucleus excitation energy is much lower than in Ref. 15). In this approach the correlation of independently evaporated protons is ignored. We calculated the emission probabilities and spectra of ^{2}He and ^{1}H using the evaporation code CASCADE.[16] As in Ref. 15, the two-proton relative energy distribution is given by a product of a Boltzmann factor times a Watson-Migdal term. On the basis of several different sets of optical-model parameters we estimate an upper limit of 4% for the ratio of ^{2}He to proton pairs. The resulting *p-p* correlation is very flat (unity to within $\pm 5\%$) for all $P_{\rm rel}$. We conclude that ^{2}He does not play a significant role in our observations, and that instead, the anticorrelations that we see in Fig. 1 are due to the interactions between independently emitted protons.

The comparison shown in Fig. 1(b) indicates a mean-particle evaporation time of $1-5\times10^{-21}$ s. A systematic analysis of Ericson fluctuation studies at lower energies can be extrapolated[7] to give a lifetime of $\approx 10^{-21}$ s for ^{32}Sc* ($E^* \approx 100$ MeV). One should point out that lifetimes from such studies are not necessarily the same as lifetimes found from correlation studies for two reasons: (a) the spin distributions of the participating compound-nucleus states can be very different, and (b) the coincident particles observed here are emitted at all stages of the cooling process.

The α-α correlations (Fig. 2) have a distinct structure which is at least in part a signature of nuclear interactions. The peak at $P_{\rm rel} \approx 20$ MeV/c, associated with the ^{8}Be g.s., might *a priori* originate either from interactions between independently emitted α particles, or from processes that produce preformed ^{8}Be nuclei. Its size undoubtedly depends on a variety of details of the reaction.

In Fig. 2 we show two curves from a Koonin-type calculation ($r_0 = 8$ and 10 fm) utilizing an α-scattering potential from the literature.[17] Recall that this model assumes that the α particles are emitted independently; it is their final-state interactions that drive the correlations. Unfortunately, the computation was not done in small enough steps to reveal the narrow ^{8}Be g.s., but this is not essential for our conclusions. Comparison with the data in the region of the broad hole that extends to about 100 MeV/c implies that the effective source is significantly smaller than its counterpart for protons [compare Figs. 1(a) and 2]. (In the context of our classical Coulomb model, this anticorrelation range would suggest a near zero lifetime for α emission. Of course, this trajectory model is surely unreliable in this domain.)

What makes the apparent source sizes from *p-p* and α-α correlations so different? Evidently, the α-coincidence data reflect a preponderance of events where preformed ^{8}Be is ejected and then decays into α particles. This mechanism is not compatible with either the Koonin model or our trajectory model, both of which assume independently created α particles. Preliminary analysis of our more recent experiments shows that such nonevaporative α particles (i.e., from either direct of evaporative ^{8}Be) dominate the coincidence yield *even* at the comparatively large angle of $\Theta_{\rm lab} = 50°$. These latter experiments employed a detector geometry in which coincidence yields were compared for detector pairs located on the same or opposite sides of the beam.[5,10] It is natural to suppose that direct reactions, e.g., (^{16}O,^{8}Be) are even more important for the α-particle coincidence yield at the forward angle ($\Theta_{\rm lab} = 19.5°$) where this study was performed. This result emphasizes that the apparent source size inferred by the correlation technique depends on the production mechanisms for different particle species. In fact, the dominance of preformed ^{8}Be production implies that the α-α correlation contains no space-time information about the compound nucleus.

It is also possible that this situation could occur in reactions at higher energies and cloud the interpretation of correlation peaks due to unstable resonances. Composite nuclei of $3 \leq T \leq 6$ MeV are known to be formed by heavy-ion beams of $E/A \leq 85$ MeV, and fissionlike fragments of intermediate mass have often been observed. To the extent that preformed ^{5}Li, ^{8}Be, ..., etc. are ejected in such fission or evaporationlike reactions, the often used Koonin model becomes an inappropriate framework for interpretation. This complexity is parallel to that discussed earlier for ^{2}He.[15]

In summary, we have shown two examples of particle-particle correlations for reactions in the low-energy domain. The α-α correlations are dominated by preformed ^{8}Be production. The *p-p* correlations are compatible with an evaporation mechanism and yield a lifetime of $1-5\times10^{-21}$ s. The theoretical analysis is not yet refined, but it allows for this first experimental estimate of the mean time for particle emission. Similar measurements are now in progress for this reaction with incident energies from 80–250 MeV. The combined results should provide a good test of the statistical model near its expected limit of validity.

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