TWO-PARTICLE CORRELATION FUNCTIONS AT SMALL RELATIVE MOMENTA FOR ^{14}N INDUCED REACTIONS ON ^{197}Au AT E/A = 35 MeV

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Two-particle correlation functions at small relative momenta were measured for light particles (p, d, t, α) emitted in ^{14}N induced reactions on ^{197}Au at $E/A = 35$ MeV. Energy dependent emission source radii are extracted with final-state interaction techniques.

Models of intermediate-energy nucleus–nucleus collisions often use the assumption of statistical particle emission from highly excited subsets of the composite system. Because of sensitivities to final-state interactions [1,2] and quantum statistics [3–5], two-particle correlation functions at small relative momenta contain information about the space–time characteristics of these subsets. Particles with different reaction cross sections may be expected to decouple from the emitting system at different average densities or source radii [6]. Therefore, the investigation of two-particle correlation functions for *different* particle pairs, emitted in the same reaction, may provide detailed information about the breakup of highly excited nuclear systems [2,6]. Furthermore, particles of different energies may be emitted at different stages of the reaction [7,8]. The energy dependence of the correlation functions can, therefore, provide useful additional information about the space–time characteristics of the equilibration process. In this letter, we investigate the energy dependence of two-particle correlation functions for several different combinations of coincident light particles emitted in collisions between ^{14}N and ^{197}Au at $E/A = 35$ MeV.

The experiment was performed at the National Superconducting Cyclotron Laboratory of Michigan State University. A gold target of 19 mg/cm^2 areal density was irradiated by ^{14}N ions with an incident energy of 490 MeV. Light particles ($Z \leqslant 2$) 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°.

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The center of the hodoscope was positioned at laboratory angles of $\Theta_{av} = 35°$ and $50°$. The energy calibrations of individual detectors are accurate to within 3%. In the off-line analysis, low-energy thresholds of 12, 15, 18 and 40 MeV were placed by software on the energy spectra of protons, deuterons, tritons and alpha particles, respectively.

We present our data in terms of the two-particle correlation function, $R(q)$, which is defined in terms of the singles yield, $Y_1(\boldsymbol{p}_1)$ and $Y_2(\boldsymbol{p}_2)$, and the coincidence yield, $Y_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2)$, of particles 1 and 2:

$$\sum Y_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2) = C_{12}[1 + R(q)] \sum Y_1(\boldsymbol{p}_1) Y_2(\boldsymbol{p}_2). \quad (1)$$

Here, $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ are the laboratory momenta of particles 1 and 2, and q is the momentum of relative motion. For each particle pair, the normalization constant C_{12} was chosen such that $R(q) = 0$ at sufficiently large relative momenta, where correlations due to final-state interactions should vanish. In order to explore the dependence of the correlation functions on the energy of the outgoing particles, the correlation functions were evaluated for different constraints on the sum energy, $E_1 + E_2$, of the two coincident particles. For each constraint, the summation was performed over all energies and angles corresponding to a given value of q; C_{12} was chosen to be independent of these energy constraints.

Two-particle correlation functions measured at $\Theta_{av} = 35°$ are shown in figs. 1 and 2; very similar correla-

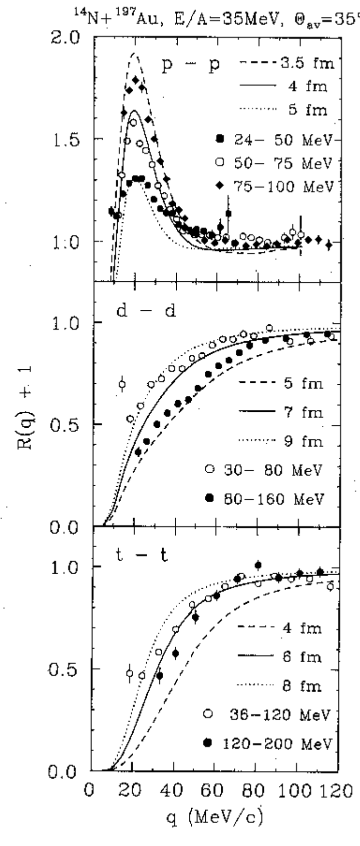

Fig. 1. Two-particle correlation functions for protons (p–p), deuterons (d–d), and tritons (t–t) emitted at $\Theta_{av} = 35°$ in ^{14}N induced reactions on ^{197}Au at E/A = 35 MeV. The constraints on the sum energy, $E_1 + E_2$, are indicated in the figure. The calculations are described in the text.

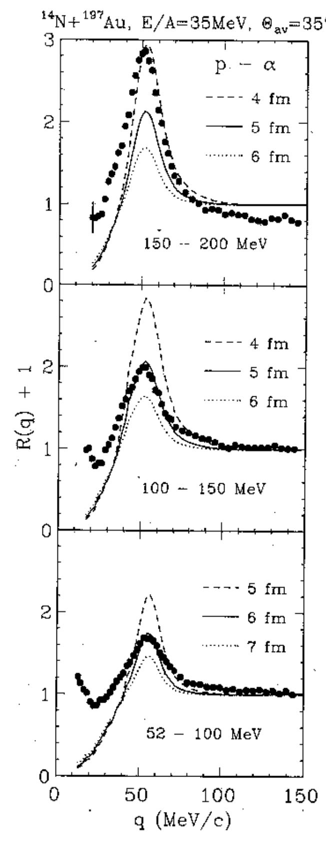

Fig. 2. Correlation functions between coincident protons and alpha particles emitted at $\Theta_{av} = 35°$ in ^{14}N induced reactions on ^{197}Au at E/A = 35 MeV. The constraints on the sum energy, $E_1 + E_2$, are indicated in the figure. The calculations are described in the text.

tions were measured at $\Theta_{av} = 50°$. The correlations for pairs of identical hydrogen isotopes are presented in fig. 1. For the two-proton correlation function, the attractive singlet S-wave interaction gives rise to a maximum at $q \approx 20$ MeV/c. The two-deuteron and two-triton correlation functions, on the other hand, do not exhibit maxima since the interactions between these pairs of particles are not resonant at low relative momenta [2,9,10]. The p–α correlation functions, shown in fig. 2, exhibit broad maxima near $q \approx 50$ MeV/c which are due to the decay of the ground state of ^{5}Li ($J^\pi = \frac{3}{2}$, $\Gamma = 1.5$ MeV) in the Coulomb field of the heavy residue [11]. The rise of the correlation function at small relative momenta, $q \leqslant 25$ MeV/c, is caused [11] by the decay of $^9\mathrm{B} \to 2\alpha + \mathrm{p}$. (Contributions from this decay disappear at higher sum energies because of the increased detection threshold for the relative momentum q.)

The solid, dashed and dotted curves shown in the figures represent theoretical correlation functions predicted by an extension of the final-state interaction model of ref. [1] to particles heavier than protons. Finite lifetime effects were neglected. In this approximation, the model becomes equivalent with the thermal model [12]. Since the inclusion of the temporal evolution of the emitting system is expected to reduce the calculated two-particle correlations [1,6], our source radii represent upper limits for the spatial extent of the emitting system.

In the calculations, the two-particle wave function is folded with a gaussian spatial density distribution, $\rho(r) = \rho_0 \exp(-r^2/r_0^2)$. The two-particle wave functions were generated by numerical integration of Schrödinger's equation using potentials [2,6] which reproduce the experimental phase shifts. For the theoretical p–α correlations, the line shape was corrected, to first order [11], for the acceleration of the emitted particles in the Coulomb field of the heavy reaction residue. For the t + t system, only S-wave phase shifts were available [10]; these phase shifts were reproduced with a repulsive Woods–Saxon potential with the parameters $V_0 = 30$ MeV, $R = 4$ fm, $a = 0.6$ fm. For higher partial waves, only the Coulomb interaction was included. Because of this approximation, source radii extracted from t–t correlations are less reliable than the ones extracted for the other particle pairs. (To estimate the resulting uncertainties, we used the $l = 0$ potential parameters also

Table 1
Source radii, r_0, for a source of negligible lifetime and gaussian density, $\rho(r) = \rho_0 \exp(-r^2/r_0^2)$, extracted from two-particle correlation functions; the corresponding rms radii are given by: $r_{\mathrm{rms}} = \sqrt{3/2}\,r_0$; equivalent sharp sphere radii are given by: $R = \sqrt{5/2}\,r_0$. The errors include normalization uncertainties for the different energy gates.

Correlation	$E_1 + E_2$ [MeV]	$r_0(35°)$ [fm]	$r_0(50°)$ [fm]
p + p	24–50	4.9 ± 0.5	5.2 ± 0.5
	50–75	4.3 ± 0.3	4.0 ± 0.3
	75–100	3.8 ± 0.2	3.6 ± 0.2
d + d	30–80	8 ± 2	–
	80–160	5.5 ± 1	–
t + t a)	36–120	6.5 ± 1	–
	120–200	5.5 ± 1	–
p + α	52–100	6 ± 0.5	6 ± 0.5
	100–150	5 ± 0.5	4.8 ± 0.3
	150–200	4 ± 0.5	3.7 ± 0.3
d + α b)	55–100	3.8 ± 0.2	3.9 ± 0.2
	100–150	3.0 ± 0.2	2.8 ± 0.2
	150–220	3.0 ± 0.2	2.7 ± 0.2

a) The calculations include a nuclear potential only for the $l = 0$ partial wave; see text.
b) From ref. [8]; source radii were extracted from the sharp peak at $q \approx 42$ MeV/c; radii extracted from the broad peak at $q \approx 85$ MeV/c are larger by about 0.5 fm.

for the $l = 1$ and 2 partial waves: the extracted source radii increased by about 2 fm.)

For all cases investigated, the measured correlations become more pronounced with increasing energy of the two coincident particles indicating that more energetic light particles are emitted from sources which are more localized in space–time. This feature is quantified by the estimated source radii summarized in table 1. Also included in the table are source radii extracted from the measurements at $\Theta_{av} = 50°$ and those extracted from a previous analysis [8] of the α + d correlation functions. No significant dependence of the correlation functions on angle is established. The observation of considerable correlations at angles significantly larger than the grazing angle ($\Theta_{gr} \approx 10°$) renders interpretations [13] in terms of the sequential decay of projectile fragments unlikely.

The source sizes extracted for the emission of energetic p–p and α–d pairs are smaller than the size of the target nucleus [$r_0(\mathrm{Au}) = \sqrt{2/3}\,r_{\mathrm{rms}}(\mathrm{Au}) \approx 4.3$ fm]. For the other particle pairs, larger source dimensions are obtained. The extracted source radii may be ordered approximately as follows: $r_0(\alpha + \mathrm{d}) \leqslant r_0(\mathrm{p + p}) \leqslant r_0(\alpha + \mathrm{p}) \leqslant r_0(\mathrm{t + t}), r_0(\mathrm{d + d})$. For an interpretation of these results, several questions should be addressed: (i) Different reaction products may have different impact parameter weightings; protons may have larger contributions from larger impact parameters than composite particles [14]. (ii) The problem of sequential feeding from highly excited primary reaction products may alter the two-particle correlation functions. (iii) Different particle species may go out of equilibrium at different densities, depending on their interaction cross sections [6]. A consistent treatment of the temporal evolution of the emitting source is not yet available. (iv) The calculation of the theoretical correlation functions involves several uncertainties. The effects of the Coulomb interaction with the residual nuclear matter have not yet been treated reliably. In addition, there are still uncertainties in the low-energy phase shifts (particularly for the t + t system). The quantitative evaluation of these effects will require considerable experimental and theoretical efforts.

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