Final-State Interactions between Noncompound Light Particles for ^{16}O-Induced Reactions on ^{197}Au at $E/A = 25$ MeV

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(Received 27 August 1984)

Correlations between protons, deuterons, and tritons at small relative momenta were measured for ^{16}O-induced reactions on ^{197}Au. Final-state interactions are observed for all measured correlations. Analysis of the measured two-deuteron correlations favors the d-d phase shifts extracted by R-matrix techniques over those found from the resonating-group approach. The two-deuteron correlations, which cannot be explained by the decay of unbound resonances, yield source radii which are considerably larger than those extracted from two-proton correlations.

PACS numbers: 25.70.Gh

Two-particle correlations at small relative momenta may contain information about the space-time characteristics of the emitting source because of their sensitivity to final-state interactions[1] and quantum statistical effects.[2,3] Previous investigations of the space-time characteristics of highly excited nuclear systems were based on analyses of two-pion[4-7] and two-proton[8-10] correlations. Because of their larger reaction cross sections, composite light particles may be expected to stay in thermal equilibrium for a longer period of time, corresponding to a lower freezeout density, as compared to nucleons or pions.[11] Furthermore, the interpretation of light-particle correlations may be complicated by additional sensitivities to ensemble averaging,[12] reaction dynamics,[12] momentum conservation,[9] and the sequential decay of particle unbound resonances.[13-15] Correlations between different light particles are expected to exhibit different sensitivities to these effects. As a consequence, the simultaneous measurement of correlations between several light-particle pairs, including composite light particles, may provide a unique tool to investigate the dynamical expansion of the interaction region and to reduce the uncertainties of interpretation. In this Letter, we demonstrate the existence of sizable correlations between composite light particles emitted in ^{16}O-induced reactions on ^{197}Au at $E/A = 25$ MeV. The observed two-deuteron correlations, for example, cannot be interpreted in terms of the emission of particle-unstable resonances. They yield source radii which are considerably larger than those extracted from two-proton correlations.

The experiment was performed at the Holifield Heavy-Ion Research Facility. A gold target of 9.7 mg/cm^2 was bombarded with ^{16}O ions of 400-MeV incident energy. Small-angle correlations between coincident light particles were measured with six ΔE-E telescopes consisting of silicon ΔE and NaI(Tl) E detectors. The detectors were mounted in a closely packed hexagonal array that was centered at the scattering angle of 15°. Each telescope subtended a solid angle of 0.76 msr; the angular resolution and angular separation between adjacent telescopes were 1.6° and 5.1°, respectively. The energy calibration of the detectors is accurate at 3%. Coincidence and down-scaled singles events were written on magnetic tape and analyzed off-line. All data presented here were corrected for random coincidences.

For a quantitative presentation of the data, we define the correlation function, $R(\mathbf{p}_1,\mathbf{p}_2)$, in terms of the singles cross sections, $\sigma(\mathbf{p}_1)$ and $\sigma(\mathbf{p}_2)$, and the coincidence cross section, $\sigma(\mathbf{p}_1,\mathbf{p}_2)$:

$$\sigma(\mathbf{p}_1,\mathbf{p}_2) = N\sigma(\mathbf{p}_1)\sigma(\mathbf{p}_2)[1+R(\mathbf{p}_1,\mathbf{p}_2)], \qquad (1)$$

where $\mathbf{p}_1$ and $\mathbf{p}_2$ denote the momenta of particles 1 and 2. The normalization constant, N (used for all correlations shown in Fig. 1), was determined previously[9] by the requirement that the two-proton correlation function vanish for sufficiently large relative momenta at which final-state interactions are negligible. The experimental correlation functions shown in Fig. 1 were obtained by insertion of the measured cross sections into Eq. (1) and summation of both sides of the equation over all energies and angles corresponding to a given momentum of relative motion, $\Delta p = \mu|\mathbf{p}_1/m_1 - \mathbf{p}_2/m_2|$, where m_1 and m_2 denote the masses of particles 1 and 2 and μ is the reduced mass. This procedure corresponds to a significant averaging process and tends to reduce the measured correlation function.[9] Because of limited statistical accuracy we did not make energy cuts for the composite-particle correlation functions.

The two-proton correlations have been discussed previously.[9] Because of the dominance of the attractive *s*-wave interaction, correlations arising from the emission and decay of unbound ^{2}He nuclei can be very similar to those caused by final-state interactions between protons randomly emitted from a source of small space-time extent.[13-15] More generally, light-particle correlations resulting from final-state interactions should be more pronounced for systems with sharp resonances. The locations of several known particle unbound states of ^{4}He and ^{5}He, decaying into $p+t$ and $d+t$, respectively, are indicated by arrows in Fig. 1. The enhanced correlations at these locations may be interpreted in terms of final-state interactions or, alternatively, in terms of emission of particle-unstable nuclei. However, the strong suppression of the $p+d$, $d+d$, and $t+t$ coincidences at small relative momenta cannot be interpreted in terms of the emission and decay of particle-unstable nuclei.

Clearly it is important to understand the emission and decay of particle-unstable nuclei in addition to the final-state interactions which are related to the space-time characteristics of the emitting system. The complexity of this problem renders it beyond the scope of this Letter. However, fresh insights can be obtained by consideration of those correlations for which resonant emission can be ignored.

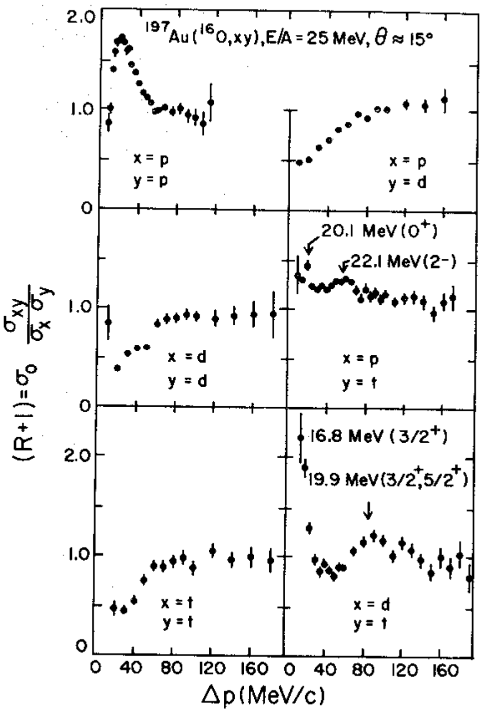

FIG. 1. Experimental correlation functions, $1+R(\Delta p)$, plotted as a function of the momentum of relative motion. The locations of several known particle-unstable resonances are indicated by arrows. The errors are purely statistical.

In order to illustrate that nonresonant final-state interactions between composite light particles contain useful information about the space-time characteristics of the emitting system, we have extended the treatment of hadron interferometry previously applied to two-proton[1] and two-pion[2,3] correlations to two-deuteron and two-triton correlations. In previous investigations, the emitting region was assumed to be of Gaussian form in space and time, characterized by the parameters r_0 and τ, respectively. In order to reduce the ambiguities resulting from the unknown value of τ and to obtain an upper limit for r_0 we used $\tau=0$ corresponding to a source of negligible lifetime. The *d*-*d* correlation function can then be written as

$$1+R(\mathbf{p}_1,\mathbf{p}_2)=(2\pi r_0^2)^{-3/2}\int d^3r\,\exp(-r^2/2r_0^2)\,[\tfrac{1}{9}|^1\psi_{\Delta p}(\mathbf{r})|^2+\tfrac{1}{3}|^3\psi_{\Delta p}(\mathbf{r})|^2+\tfrac{5}{9}|^5\psi_{\Delta p}(\mathbf{r})|^2], \qquad (2)$$

where the superscript on the *d*-*d* wave functions is equal to $2s+1$, s being the spin of the system. A partial-wave expansion of the wave function was used. The radial wave functions were obtained by integration of the Schrödinger equation with both Coulomb and nuclear potentials for low orbital angular momenta ($l \leq 2$); for larger orbital angular momenta, the nuclear potential was neglected. The resulting wave functions were normalized to spherical Coulomb waves at large radii where the nuclear potential is negligible. Convergence of the integral in Eq. (2) was assured by extension of the sum over partial waves to $l=20$ and the radial integration to 100 fm. We believe the numerical accuracy of the calculated correlation function to be better than 4%.

For each partial wave, the nuclear potential was parametrized in terms of a Woods-Saxon potential. The potential parameters V_0, R, and a were determined by fitting the energy-dependent phase shifts extracted from *d*-*d* scattering. The extracted potential parameters for two sets of phase shifts are given in Table I. The most complete set of phase shifts in the energy range required for our calculations was extracted by a coupled-channels *R*-matrix approach[16] and led to predominantly repulsive potentials (labeled RM in Table I and in Fig. 2). We have also performed calculations with potential parameters obtained from an older analysis of *d*-*d* scattering data at higher energy by the resonating-group approach[17] (RG). These phase shifts lead not only to predominantly attractive potentials, but even show resonant behavior in the $l=1$ par-

TABLE I. Woods-Saxon potential parameters determined by fitting the deuteron-deuteron phase shifts of Refs. 16 (RM) and 17 (RG). Attractive potentials are denoted by negative signs and repulsive potentials by positive signs. The rows with $j=3$ and 4 neglect the nuclear part of the potential (Coulomb interaction only).

s	l	j	V_0 (MeV)	R (fm)	a (fm)
			RM		
0	0		29.8	4.21	0.134
0	2		33.6	4.14	0.75
1	1	0	38.0	7.16	0.385
1	1	1	29.4	1.37	1.67
1	1	2	6.9	1.09	1.57
2	0		26.0	1.08	1.25
2	2	0	55.4	5.87	0.74
2	2	1	41.3	6.33	0.65
2	2	2	−11.5	1.85	1.69
2	2	3			
2	2	4			
			RG		
0	0		−10.3	5.85	0.99
1	1		−13.8	3.64	0.87
2	0		−8.5	5.29	0.56
2	2		−15.2	2.56	1.08

tial wave at energies below 2 MeV.

Correlations calculated for $r_0=8$ fm are shown in Fig. 2(a). The attractive-potential set (RG) predicts enhanced correlations at $\Delta p=30$ MeV/c. This enhancement becomes more pronounced as r_0 is decreased. In contrast, the repulsive-potential set (RM) predicts a suppression of the correlation function at these values of Δp. The data clearly favor the phase shifts extracted by the coupled-channels R-matrix method. (For comparison we also show the correlations predicted for the case of pure Coulomb interaction between the two deuterons; see dot-dashed curve.) In order to illustrate the sensitivity of the calculations to the source radius, we show two calculations for the repulsive-potential set (RM) corresponding to $r_0=8$ and 4 fm, respectively. Although the two-deuteron correlations appear to be less sensitive to the source dimensions than two-proton correlations, they indicate a larger source radius of $r_0 \approx 6$–8 fm compared to the values $r_0 \lesssim 4$ fm extracted from two-proton correlations.[9]

For large source dimensions, the neglect of the short-range nuclear interaction might be a satisfactory approximation. Because of difficulties in obtaining appropriate t-t phase shifts, we have calculated two-triton correlations only for the simplifying case of pure Coulomb interaction. In Fig. 2(b), these calculations are compared to the measured two-triton correlations. Although we cannot make a definitive statement, the size of the emitting region appears to be large, just as

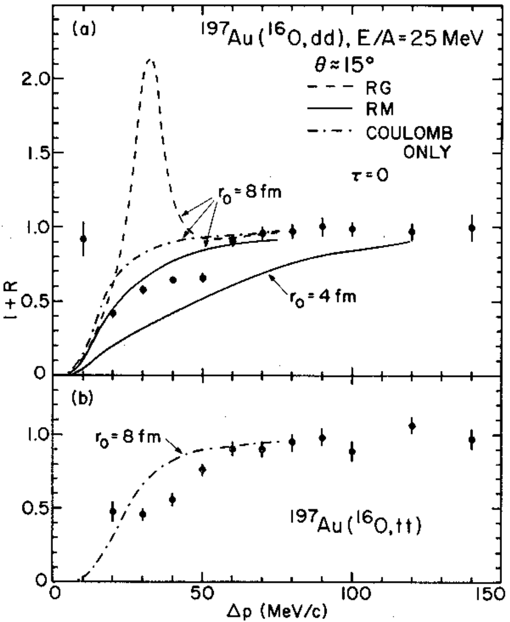

FIG. 2. (a) Comparison of d-d correlation function data with calculations based on phase shifts of Refs. 16 (RM) and 17 (RG). The dot-dashed curve neglects the nuclear part of the potential. (b) Comparison of t-t correlation function data with a calculation using only the Coulomb part of the potential. The radius parameter r_0 is indicated. The experimental correlation functions were normalized to $R(\Delta p)=0$ at large relative momenta.

observed for the two-deuteron correlations.

In terms of the thermal model, final-state interactions were suggested[11] to keep composite light particles close to equilibrium for a longer period of time than nucleons. The freezeout densities for nucleons and composite light nuclei may be estimated by use of a cascade model[18] for the fireball-expansion phase of the reaction. According to such calculations, the freezeout density for deuterons and tritons is lower by about a factor of 3 than the one for protons. While the corresponding change in scale of $3^{1/3}=1.4$ should not be directly equated with the approximate factor of 1.5–2 obtained from the analysis of the correlation measurements ($r_0 \lesssim 4$ fm for p-p, $r_0 \approx 6$–8 fm for d-d and t-t), the scale change is suggestive.

The inclusion of a finite parameter τ into our calculations of the correlation function does not change our qualitative result: The source dimensions extracted from the two-deuteron correlations are significantly larger than the ones extracted from the two-proton correlations. In order to assess the effect of finite values of τ, we have estimated the freezeout time $\tau_f \approx (7 \pm 2)\times 10^{-23}$ s for deuterons and tritons using the cascade model[18] for the expansion phase. If this value of $\tau = \tau_f$ is adopted for the calculation of the correlation function, the radius parameter has to be reduced by less than 10% in order to reproduce the correlation function calculated with $\tau = 0$. The present measurements are not sufficiently precise to be sensitive to these details.

In summary, significant correlations, with different qualitative shapes, were measured for all combinations of p, d, and t for ^{16}O-induced reactions on ^{197}Au at 400 MeV. Our analysis of the two-deuteron correlations favors phase shifts obtained from the R-matrix approach consistent with a repulsive interaction between two deuterons at small relative momenta. The emitting source radii extracted from two-deuteron and two-triton correlations appear to be at least 50% larger than the ones obtained from two-proton correlations. These results suggest that correlations between different light-particle pairs are sensitive to different stages of the reaction. The simultaneous investigation of two-particle correlations between a variety of light particles may provide an unprecedented tool to extract information about the dynamical aspects of intermediate- and light-energy nucleus-nucleus collisions.

We would like to thank Dr. G. M. Hale for valuable discussions and for supplying us with the deuteron-deuteron phase shifts. This work was supported in part by the National Science Foundation under Grant No. PHY 83-12245, the Natural Sciences and Engineering Research Council of Canada, and the U. S. Department of Energy under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems.

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