Two-proton correlations for ^{16}O + ^{197}Au collisions at $E/A = 200$ MeV

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Two-proton correlation functions are measured for inclusive collisions of ^{16}O + ^{197}Au at $E/A = 200$ MeV. Calculations with the Boltzmann-Uehling-Uhlenbeck transport theory overpredict the dependence of the correlation function on the total momentum of the coincident proton pair, but correctly reproduce the energy-integrated correlation function.

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Two protons, emitted at small relative momentum from an excited system, can be used to obtain information about the space-time characteristics of the emitting source formed in nuclear collisions [1–19]. Calculations with the Boltzmann-Uehling-Uhlenbeck (BUU) transport equation have been rather successful [9–11,14] in reproducing inclusive two-proton correlation functions at beam energies below approximately $E/A \approx 100$ MeV, but such calculations predicted too large correlations for inclusive collisions of ^{40}Ar + ^{197}Au at $E/A = 200$ MeV [14]. These latter data revealed a surprising insensitivity of the measured correlation functions to the energy of the emitted protons, in contrast to the strong dependence observed [2,5,7,9,11,15] at lower energies. Further, the data do not show the expected minimum in the correlation function at $q \approx 0$ MeV/c [14].

In this note, we report two-proton correlation measurements for ^{16}O + ^{197}Au collisions at E/A = 200 MeV. These measurements were performed to explore whether the anomalous trends observed for the ^{40}Ar + ^{197}Au reaction at $E/A = 200$ MeV [14] persist also for a lighter projectile.

The experiment was performed at the National Superconducting Cyclotron Laboratory using a beam of ^{16}O ions at $E/A = 200$ MeV, the highest energy per nucleon possible from the K1200 cyclotron. The ^{197}Au target had an areal density of 60 mg/cm^2, and the beam intensity was typically 1.5×10^8 particles/sec. Coincident protons were detected by a 56-element high-resolution hodoscope [20,21] attached to the MSU 4π Array [22] at $\langle \Theta_{lab} \rangle = 38°$. Each element of the hodoscope consisted of a 300- or 400-μm-thick Si detector backed by a 10 cm long CsI(Tl) detector, allowing measurement of protons with energies between 10 and 200 MeV. The telescopes each subtended a solid angle of $\Delta\Omega \approx 0.37$ m sr. The nearest-neighbor spacing between telescopes was $\Delta\Theta = 2.6°$, and the energy resolution for each telescope was about 1% for 50 MeV protons. Events were written on tape when they satisfied the trigger condition of at least two detectors of the 56-element hodoscope and at least three detectors of the 4π-Array firing. This trigger eliminated the most peripheral collisions, but otherwise accepted a broad range of impact parameters. Due to a major power outage, the experiment had to be ended prematurely, and the statistics collected were insufficient to allow significant cuts on impact parameter. Thus we can only present inclusive two-proton correlation functions.

The solid points in Fig. 1 show the measured energy spectrum of protons emitted at polar angles Θ_{lab} = 30° – 45°. The solid curve represents the corresponding energy spectrum predicted by the BUU calculations [13,23–25]. In these calculations, a hard equation of state ($K = 380$ MeV) and an in-medium nucleon-nucleon cross section set to its free values were used. The calculations were filtered for the experimental acceptance and energy thresholds. A proton was considered emitted if it was located in a region of local mass density less than one-eighth normal nuclear density [10,11]. At energies near the Coulomb barrier BUU calculations over

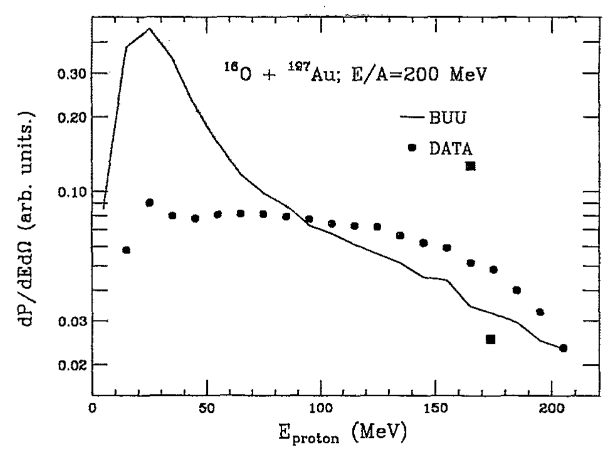

FIG. 1. Energy spectra of protons measured in the laboratory rest frame at Θ_{lab} = 30°–45° for collisions of ^{16}O+^{197}Au at $E/A = 200$ MeV (solid points) are compared with the prediction of BUU (solid line). To allow a better comparison of shapes, the relative normalization between experimental and theoretical energy spectra was chosen to give equal areas for $E_{proton} > 50$ MeV.

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predict the proton yield. Such an over prediction of the proton yields at low energies has been noted previously and attributed to the neglect of light cluster formation [18,19,26]. Light clusters are expected to be predominantly formed in densely populated regions of phase space, thus reducing the flux of free nucleons.

In order to investigate the influence of light cluster production on our calculated two-proton correlation functions, we subjected our single particle phase space distribution of emitted particles to a coalescence analysis. When adjusting the coalescence parameters to the observed $p/d/t$ ratio, the calculated singles yield of protons below 50 MeV was reduced by a factor of two relative to the high-energy protons, in accordance with naive expectations. Despite this change of energy distribution in the singles spectra, however, the calculated two-particle correlation functions remained virtually unchanged. (This effect was noted before [10,13] and attributed to the division procedure employed to arrive at the correlation function as a ratio of the two-particle cross section and the square of the singles cross section.) Even after the coalescence step, the predicted singles spectra were still somewhat steeper than the data. This is due to the fact that we employed our low-density emission criterion ($\rho \leq 1/8$) and indicates that cluster formation is predominantly determined at somewhat higher densities. In light of the insensitivity discussed above, we refrain here from adjusting the model parameters to produce a perfect fit to the data and instead show the singles spectra as produced by BUU and not corrected by a coalescence step.

Two-proton correlation functions, $1+R(q)$, are presented in Fig. 2. The experimental two-proton correlation function, shown by points, was defined in terms of the two-proton coincidence yield, $Y_2(\mathbf{p}_1,\mathbf{p}_2)$, and a background yield, $Y_{\mathrm{back}}(\mathbf{p}_1,\mathbf{p}_2)$, obtained by the event-mixing technique [27]

$$\sum Y_2(\mathbf{p}_1,\mathbf{p}_2)=C[1+R(q)]\sum Y_{\mathrm{back}}(\mathbf{p}_1,\mathbf{p}_2). \qquad (1)$$

Here q is the (invariant) magnitude of the relative momentum four-vector. For a given experimental gating condition, the sums of each side of Eq. (1) extend over all proton energies and detector combinations of the 56-element hodoscope corresponding to each q-bin. The normalization constant C is determined by the requirement that $R(q)$ vanish for large q, where final state interactions between the emitted protons are negligible. Specifically we normalized both experimental and theoretical correlation functions such that $\langle R(q)\rangle = 0$ for 60 MeV/$c \leq q \leq 80$ MeV/c.

Theoretical two-proton correlation functions (shown by curves in Fig. 2) were calculated with the Koonin-Pratt formalism which relates the one-body phase space distribution with the correlation function [1,6,10,11]. Specifically, the theoretical correlation function was calculated by convoluting the one-body phase space distribution predicted by the BUU calculations described above with the two-proton relative wave function [10,11]. The upper panel of Fig. 2 presents the energy-integrated correlation function for all protons detected by the 56-element hodoscope with laboratory energy above 10 MeV and below 200 MeV. The lower panel shows correlation functions selected by two different cuts on $P_{\mathrm{tot}}=|\mathbf{p}_1+\mathbf{p}_2|$, the total momentum of the detected proton

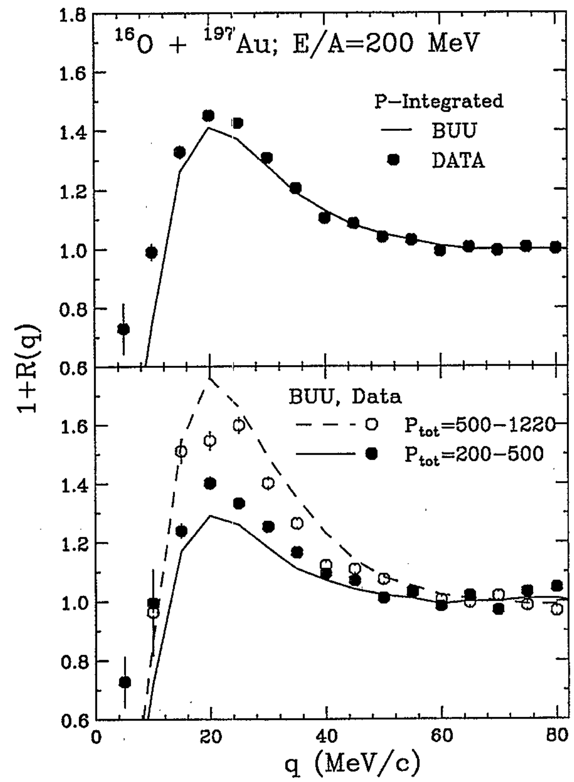

FIG. 2. Two-proton correlation functions for collisions of ^{16}O + ^{197}Au at E/A = 200 MeV. The top panel shows the energy-integrated correlation function, and the bottom panel shows correlation functions for proton pairs selected by the indicated cuts on their total momentum.

pair in the center-of-momentum frame of projectile and target. The peak values, $1+R_{\mathrm{max}} \approx 1.4-1.6$, of the measured correlation functions are larger than the values, $1+R_{\mathrm{max}} \approx 1.2$, reported for the ^{40}Ar + ^{197}Au reaction at $E/A=200$ MeV [14]. Further, the magnitude of the correlation function for the present reaction exhibits a clear dependence on total momentum, P_{tot}, of the detected proton pair as compared to the negligible dependence on proton energy observed for the Ar-induced reaction [14]. Within the resolution of the present experiment, we find no evidence for a disappearance of the minimum at q = 0.

The BUU calculations reproduce the magnitude of the energy-integrated correlation function (top panel), but they predict too strong a dependence on P_{tot} (bottom panel). The calculations underpredict the magnitude of the correlation functions measured for the low-momentum gate, 200 MeV/$c \leq P_{\mathrm{tot}} \leq$ 500 MeV/c, and they overpredict it for the high-momentum gate, 500 MeV/$c \leq P_{\mathrm{tot}} \leq$ 1220 MeV/c.

The results from the Ar-induced reaction [14] do not seem to be repeated in this lighter system. One difference that might account for these results is the difference in total energy in the system. Since the oxygen is lighter, the total amount of energy deposited in the system is a factor of 2 smaller, and the reaction might produce a residue not present with a heavier projectile.

In summary, proton energy spectra and two-proton correlation functions were measured at $\langle \Theta_{\mathrm{lab}} \rangle$ = 38° for ^{16}O +

^{197}Au collisions at $E/A=200$ MeV. The single particle yield for the low-energy protons has a flat slope that is not reproduced well by the BUU transport model, even with a simple coalescence step added. The momentum-integrated correlation function agrees well with the BUU calculations, and the momentum-gated correlation functions show a definite dependence on the momentum of the proton pair. The correlation functions look significantly different from those for the ^{40}Ar + ^{197}Au reaction at $E/A=200$ MeV [14] in both total height and momentum dependence.

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