# IN-PLANE CORRELATIONS BETWEEN PROTONS AND DEUTERONS FOR $^{16}$O-INDUCED REACTIONS ON $^{27}$Al AND $^{197}$Au AT 310 MeV

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In-plane correlations between two light particles have been investigated for $^{16}$O induced reactions on $^{27}$Al and $^{197}$Au targets at 310 MeV incident energy. Within the statistical accuracy of the experiment no differences could be established for the shapes of singles and coincidence proton spectra. The importance of kinematical correlations imposed by energy and momentum conservation for finite equilibrated systems is pointed out. The observed angular correlations are not explained by simply assuming a maxwellian spectrum in the rest frame of a single moving source.

The attainment of local thermal equilibrium in heavy ion induced reactions is an important assumption underlying many theoretical models [1–7]. A large set of single particle inclusive data can be described by this assumption [2,5,8–12] which implies that the emission of light particles should be dynamically uncorrelated. Until now, light particle correlations testing the thermalization assumption have been measured only at relativistic energies ($E/A$ = 400 and 800 MeV) where the existence of a non-thermal knockout component was demonstrated [13,14]. In this letter we report the first such measurement at nonrelativistic energies.

Aluminum and gold targets of 16 and 10 mg/cm$^2$ thickness were bombarded with 310 MeV $^{16}O^{6+}$ ions from the 88 inch cyclotron of the Lawrence Berkeley Laboratory. Single and coincident protons and deuterons were detected with four $\Delta E - E$ telescopes consisting of solid state silicon–$\Delta E$ and NaI(Tl)–$E$ detectors. The telescopes were mounted in a plane at the angles of $-110°$, $-30°$, $+30°$ and $+75°$ with respect to the beam axis, subtending solid angles of 62, 49, 49 and 62 msr, respectively. Coincidence and downscaled singles events were recorded on magnetic tape and analyzed off-line.

The singles and coincidence proton spectra measured in this experiment are shown in fig. 1 by the solid points and the histograms, respectively. The singles spectra were found to be consistent with recent measurements of the same systems [12]. Within the statistical accuracy of the present experiment the shapes of singles and coincidence spectra are found to be very similar, indicating that the assumption of statistical emission is not strongly violated.

In order to be more sensitive to the existence of two-particle correlations we present our results in terms of the correlation function $\sigma_{12}/(\sigma_1\sigma_2)$ where

$$\sigma_{12} = \sigma_0 \int_{\Delta E_1} \mathrm{d}E_1 \int_{\Delta E_2} \mathrm{d}E_2 \, \frac{\mathrm{d}^4\sigma(\theta_1, E_1, \theta_2, E_2)}{\mathrm{d}E_1 \mathrm{d}E_2 \mathrm{d}\Omega_1 \mathrm{d}\Omega_2} \tag{1}$$

and

$$\sigma_k = \int_{\Delta E_k} \mathrm{d}E_k \, \frac{\mathrm{d}^2\sigma(\theta_k, E_k)}{\mathrm{d}E_k \mathrm{d}\Omega_k} , \quad k = 1, 2 . \tag{2}$$

The constant $\sigma_0$ was arbitrarily fixed by requiring $\sigma_{12}/(\sigma_1\sigma_2) = 1$ for the proton–proton correlation corresponding to the variables $\theta_1 = -30°$, $\theta_2 = +30°$, $\Delta E_1$

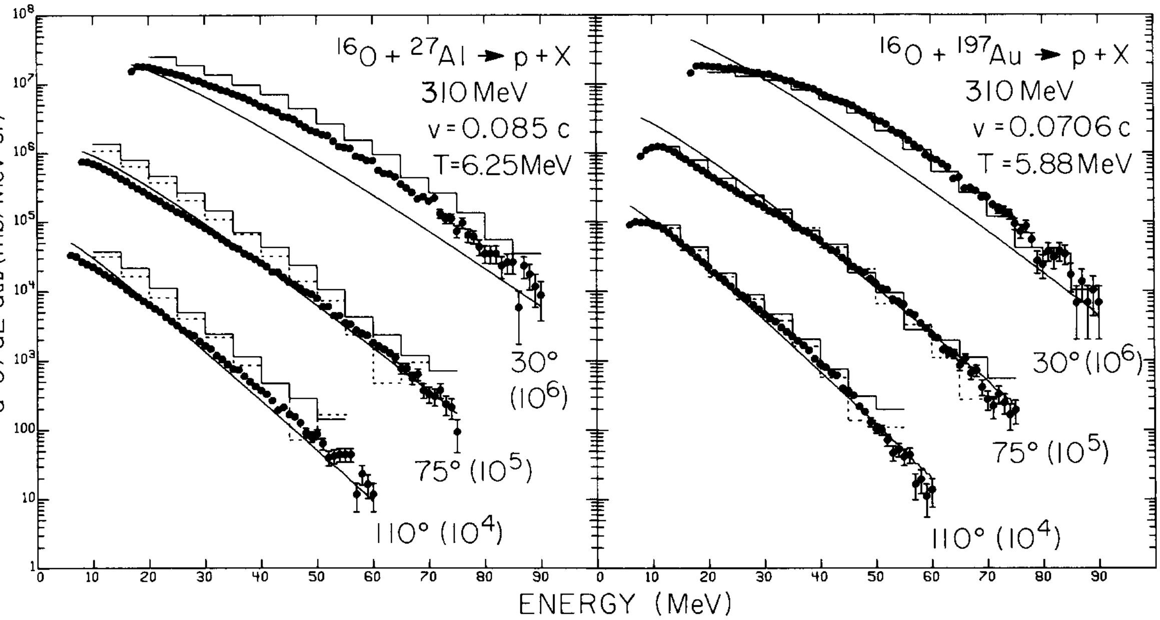


Fig. 1. Comparison of single-particle inclusive (solid points) and two-particle inclusive energy spectra (histograms). The solid histograms show the energy spectra when a coincident proton is detected at the angle of $\theta = -30°$ on the opposite side of the beam axis and the dashed histograms show the energy spectra when the coincident proton is detected at $\theta = 30°$ at the same side of the beam axis. The solid curves are the calculated energy spectra corresponding to thermal emission from a single moving source, see eq. (3) of the text.

= 20–40 MeV, and $\Delta E_2$ = 20–100 MeV.

The experimental correlations are shown in fig. 2. The first light particle is defined to be the one detected at $\theta_1 = -30°$. The range of energy integration for the second particle was fixed at $\Delta E_2$ = 20–100 MeV for $\theta_2 = +30°$ and $\Delta E_2$ = 10–100 MeV for $\theta_2 = \pm 110°, \pm 75°$. The error bars shown in the figure are purely statistical; systematic errors are believed to be of the order of 5%.

The correlation function exhibits sizable variations which are more pronounced for the Al target than for the Au target. It usually has a minimum value for the forward emission of the second light particle. For the Al target a pronounced left–right asymmetry is observed, corresponding to an enhanced probability for coincident emission of the two light particles on opposite sides of the beam.

For the case of thermal emission from an infinite ensemble the correlation function is constant. However, for nuclear reactions finite particle number effects might not be negligible [15] and variations in the correlation function could be imposed by conservation laws. In order to evaluate the magnitude of these kinematical correlations that are imposed on a finite system by energy and momentum conservation we have made the simplifying assumption of isotropic thermal emission from a source of $A$ nucleons that emits light particles with a gaussian momentum distribution. The galilean-invariant cross section is then given by

$$d^3\sigma(\boldsymbol{p}, \boldsymbol{v}_0, T, m)/dp^3$$

$$= C(2\pi m T)^{-3/2} \exp[-(\boldsymbol{p} - m\boldsymbol{v}_0)^2/2mT] \;, \qquad (3)$$

where $C$ is a normalization constant, $m$ is the mass of the emitted particle, $T$ is the temperature parameter and $\boldsymbol{v}_0$ is the velocity of the source in the laboratory.

The detection of a light particle of laboratory momentum $\boldsymbol{p}_1$ and mass $m_1$ changes the values of both the temperature and the velocity of the remaining ensemble. The new source velocity $\boldsymbol{v}_0'$ is given by

$$\boldsymbol{v}_0' = A\,\boldsymbol{v}_0/A' - \boldsymbol{p}_1/A' m_0 \;, \qquad (4)$$

where $m_0$ is the nucleon mass and $A'$ is the number of nucleons left in the residual source. The excitation en-

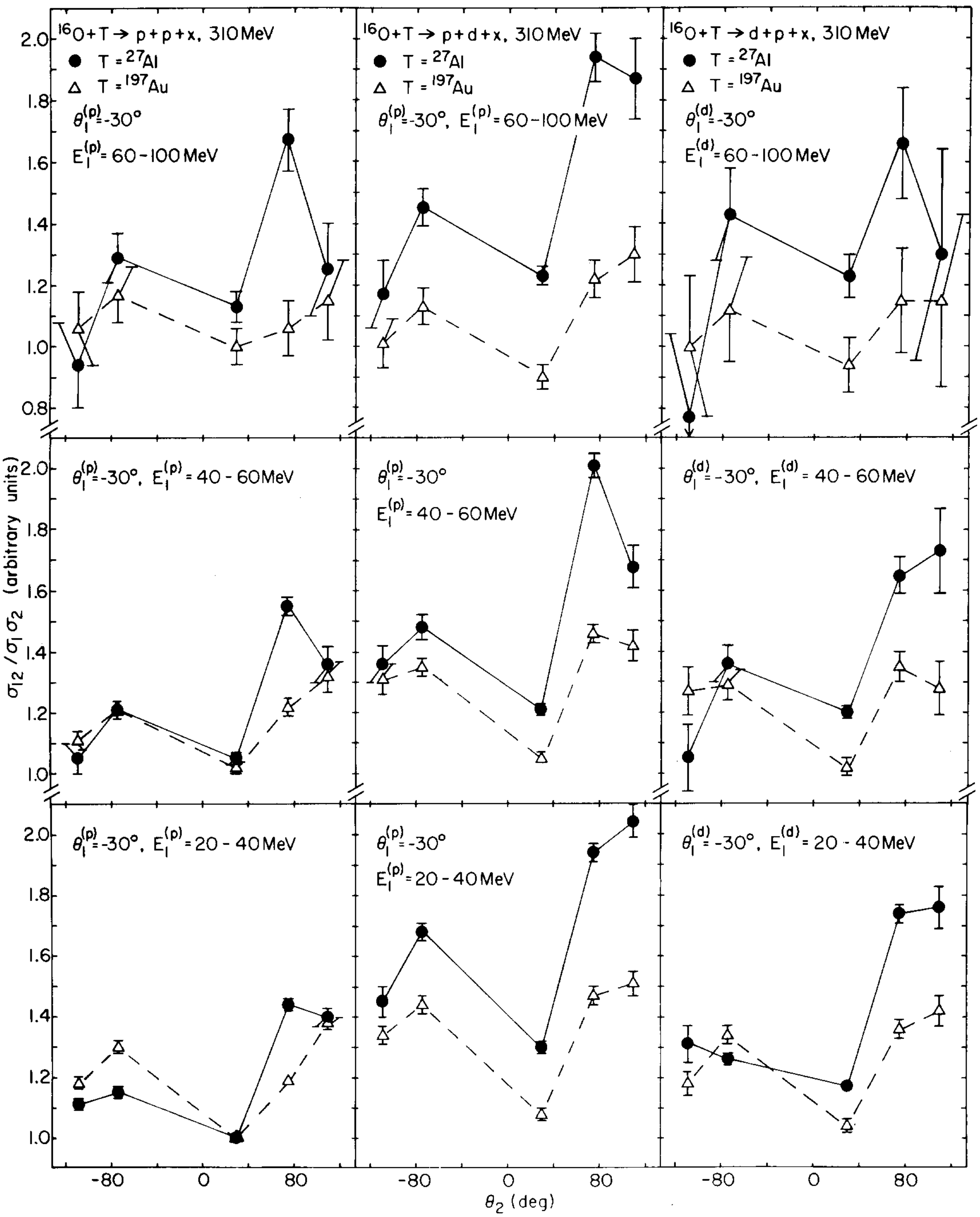


Fig. 2. Angular correlations between protons and deuterons observed in $^{16}O$ induced reactions on $^{27}Al$ and $^{197}Au$ targets at 310 MeV. Particle 1 is detected at the fixed angle $\theta_1$ = −30° with its energy integration range given in the figure. The energy integration range of the second particle is $E_2$ = 20–100 MeV for $\theta_2$ = +30° and $E_2$ = 10–100 MeV for $\theta_2$ = ± 75°, ± 110°. The lines are drawn to guide the eye.

ergies $E_x$ and $E'_x$ of the original and residual sources are related by

$$E'_x = E_x - (p_1 - m_1 v_0)^2/2m_1$$
$$- (p_1 - m_1 v_0)^2/2A'm_0 , \quad (5)$$

where the last term accounts for the recoil energy of the residual source. Finally, we adopt the empirical relation between excitation energy and temperature

$$E_x = AT^2/(8\ \mathrm{MeV}) , \quad (6a)$$

which gives the temperature parameter $T'$ of the residual source as

$$T' = (E'_x \cdot 8\ \mathrm{MeV}/A')^{1/2} . \quad (6b)$$

The coincidence cross section for the emission of particle 1 of momentum $p_1$ followed by the emission of particle 2 of momentum $p_2$ is then proportional to the product

$$P(p_1,p_2) = [\mathrm{d}^3\sigma(p_1,v_0,T,m_1)/\mathrm{d}p_1^3]$$
$$\times\ \mathrm{d}^3\sigma(p_2,v'_0,T',m_2)/\mathrm{d}p_2^3 . \quad (7a)$$

Experimentally, we cannot distinguish the reverse time sequence for which we have analogously

$$P(p_2,p_1) = [\mathrm{d}^3\sigma(p_2,v_0,T,m_2)/\mathrm{d}p_2^3]$$
$$\times\ \mathrm{d}^3\sigma(p_1,v''_0,T'',m_1)/\mathrm{d}p_1^3 . \quad (7b)$$

Here, the parameters $v''_0$, $T''$ are defined in obvious analogy to eqs. (4)–(6). The cross section for the emission of particles 1 and 2 is now given by

$$\mathrm{d}^6\sigma/\mathrm{d}p_1^3\mathrm{d}p_2^3 = C_0 [P(p_2,p_1) + P(p_1,p_2)] , \quad (8)$$

where $C_0$ is a normalization constant.

Upon using $\mathrm{d}^3p = mp\ \mathrm{d}\Omega\ \mathrm{d}E$ eqs. (3) and (8) can be inserted into eqs. (1) and (2) to calculate the correlations predicted by the model. The results of these calculations are compared to the experimental proton–proton correlations observed for the Al target in fig. 3. Calculations of the singles spectra using eq. (3) have been drawn as solid lines in fig. 1. The source parameters of $v_0 = 0.085\ c$, $T = 6.25$ MeV and $v_0 = 0.0706\ c$, $T = 5.88$ MeV for the Al and Au targets, respectively, were obtained from a fit to a more complete set of singles cross sections [12]. The calculations were arbitrarily normalized to the data at a point which is obvious in

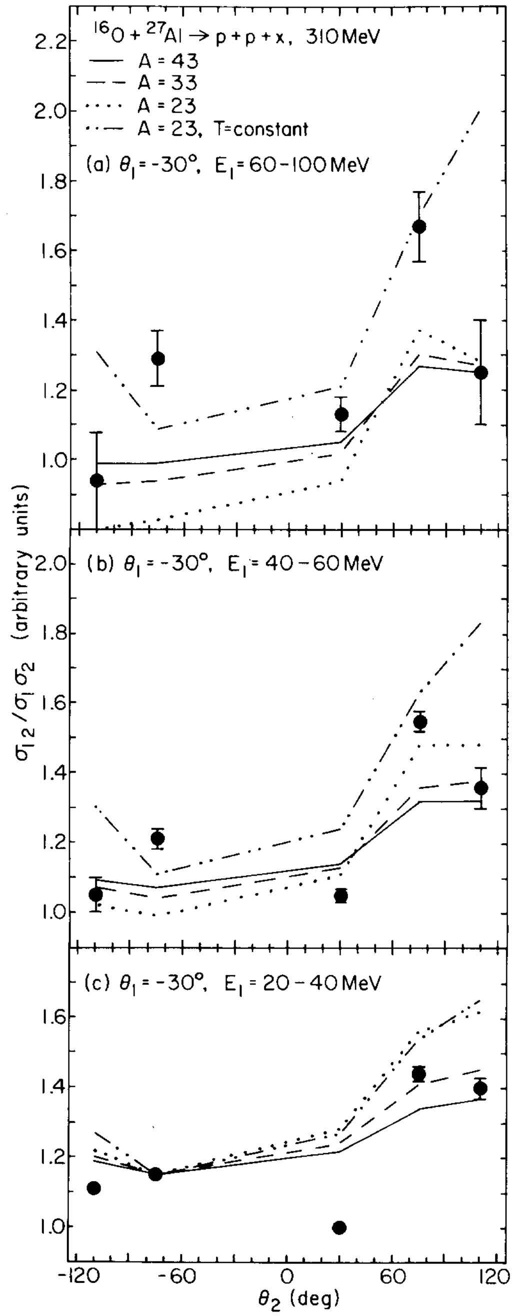


Fig. 3. Proton–proton correlations expected from a moving source of temperature $T = 6.25$ MeV and velocity $v_0 = 0.085\ c$. The number of nucleons $A$, contained in the source is given in the figure. The full points represent the experimental data obtained for the Al target.

the figures. To exhibit the effect of the number of source nucleons on the predicted correlation several values of $A$ have been used for the calculations. In addition, one calculation is shown for the case of $T = T' = T''$ (which violates energy conservation for the ensemble but still exhibits the constraints due to momentum conservation).

The influence of momentum conservation is clearly visible in the enhancement of the correlation for positive $\theta_2$ corresponding to the detection of the two protons on opposite sides of the beam axis over the correlation at negative $\theta_2$ with the two protons detected on the same side of the beam. This left–right asymmetry is understandably enhanced when the number of nucleons $A$ in the source is decreased and also as the energy $E_1$ is increased. The requirement of energy conservation for the ensemble leads to a decrease in the correlation function as $E_1$ is increased. This effect is particularly noticeable when $|\theta_2|$ is large since at those angles particle 2 is emitted opposite to the source velocity.

For the Al target the magnitudes of the observed left–right asymmetries are comparable to those already predicted for the maximum possible number of participating nucleons, $A = 43$. However, this comparison of calculation with experiment cannot quantitatively determine $A$ since neither the small values of the correlation at $\theta_2 = +30°$ nor the large values at $\theta_2 = +75°$ can be explained by these calculations in a consistent way.

Clearly several possibly important aspects of the reaction mechanism have been neglected in these calculations and would be relevant subjects for future investigations. The observed correlations are of comparable magnitude as the ones calculated for a source composed of 20–40 nucleons. Therefore, angular momentum effects could be of comparable importance as in compound nucleus light particle emission where high angular momenta are known to result in sizable anisotropies of the angular distribution.

The present experiment cannot distinguish reactions with different impact parameters and there will be contributions to the light particle spectra from "peripheral" reactions having two heavy fragments in the exit channel which decay by particle emission. Such events could cause additional left–right asymmetries in the light particle correlations due to the binary nature of the primary interaction. It is also conceivable that low multiplicity peripheral collisions could cause the correlation to be small at forward angles (such as $\theta_2 = 30°$), since such reactions would make a larger contribution to the singles cross sections than to the coincidence cross sections.

Of comparable interest are investigations of possible direct knockout components which will produce an enhancement of the correlation function around relative proton emission angles of 90° in the laboratory. Such components might contribute to the enhancement of the correlation at $\theta_1 = -30°$, $\theta_2 = +75°$ for the Al-target. For heavier targets, such contributions could be suppressed due to enhanced absorption and rescattering of the knocked-out nucleons.

In summary, light particle singles spectra and two-particle inclusive spectra have been found to be very similar for $^{16}O$ induced reactions at 310 MeV, indicating that the assumption of statistical emission is not strongly violated; Although the simple model of thermal isotropic light particle emission from a moving source fails to reproduce the details of the observed correlations, this calculation demonstrates the importance of purely kinematic correlations even if local thermal equilibrium is achieved in the reaction.

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