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March 1980

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Two-Proton Correlation Measurements in 800- and 400-MeV/nucleon Heavy-Ion Reactions

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ABSTRACT

Energy and angular correlations of two protons emitted in collisions of C + C, C + Pb, Ne + NaF, Ar + KCl, at $E_{\text{Lab}}^{\text{Beam}} = 800$ MeV/A, and Ne + NaF at $E_{\text{Beam}}^{\text{Lab}} = 400$ MeV/A have been measured. A strong correlation due to p-p quasi-elastic scattering is observed except for C + Pb where nuclear shadowing is observed. A simple model is proposed to estimate the magnitude of the knock-out process in these heavy-ion collisions.

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In high-energy heavy-ion collisions, single-particle inclusive cross
sections\(^1\)-\(^3\) have already given an overall picture of fragment emission to
which several models such as the clean knock-out model\(^4\) and thermal
models\(^2\),\(^3\),\(^5\)-\(^7\) have been applied. These models, although they are quite dif-
ferent in their physical basis, describe certain aspects of the spectra, but
further experimental studies are required in order to quantitatively test
them. As pointed out in a previous paper,\(^1\) p-p quasi-elastic scattering (p-p
QES) is observed in C + C collisions. We have extended the measurement to
several projectile and target combinations as well as to different beam ener-
gies in order to make a systematic study of the importance of clean knock-out
processes. These results are described in the first part of the present
paper. A simple model to estimate the contribution of the knock-out process
is proposed in the second part. We also present experimental data pertaining
to nuclear shadowing effects in C + Pb collisions.

The experimental system consisted of a magnetic spectrometer (S) and
three sets of counter telescopes (R, U, and D). These telescopes were set at
angles (θ, φ) = (40°, 180°), (40°, 90°), and (40°, 270°). respectively, with
the beam being the z-axis. This $\theta$-angle corresponds to $\approx 90^\circ$ in the nucleon-nucleon c.m. frame. The spectrometer was located at $\phi = 0^\circ$ and rotated between $\theta = 15^\circ$ and $110^\circ$. Each telescope consisted of three plastic scintillators with absorbers sandwiched in between which allowed us to make a rough energy selection; a double coincidence corresponds to $E \geq 100$ MeV and a triple coincidence selects $E \geq 200$ MeV for protons. Although it was impossible to identify particles with the telescopes, it is known from the spectrometer data that the dominant yield at $\theta = 40^\circ$ is protons. The solid angle of each telescope was 48 msr, subtending $\Delta \theta = 10^\circ$.

We measured an azimuthal (or coplanar) correlation function $C_\langle (\theta, p)$ defined as

$$C_\langle (\theta, p) = \frac{(S(\theta, p) \cdot R_\langle) / R_\langle}{(S(\theta, p) \cdot U_\langle) / U_\langle + (S(\theta, p) \cdot D_\langle) / D_\langle}$$

where $\theta$ is the scattering angle and $p$ the momentum of the particle detected in the spectrometer, and $\langle$ indicates the telescope energy cut: namely $\langle = 1$ for $E_{\text{proton}} \geq 100$ MeV and $\langle = 2$ for $E_{\text{proton}} \geq 200$ MeV. The quantity $(S(\theta, p) \cdot R_\langle)$ indicates the coincidence counts between the spectrometer and the $R$-telescope, and $R_\langle(U_\langle)$ indicates the single counts of the $R(U)$-telescope.

In Fig. 1 contour lines of the observed values of $C_2(\theta, p)$ are shown for collisions of $C + C$, $Ar + KCl$, and $C + Pb$ at $E_{\text{Lab}} = 800$ MeV/A. The data are displayed in the plane of $p_\parallel$ and $p_\perp$ in the nucleon-nucleon c.m. frame. In the cases of $C + C$ and $Ar + KCl$ the value of $C_2$ is always larger than 1 and has a peak right on the circle but on the opposite side of the cross-hatched area. The data clearly show the existence of the p-p QES in $C + C$ and $Ar + KCl$ collisions. On the other hand, no peak is observed for $C + Pb$ and the value of $C_2$ in this case is smaller than 1.
We first discuss the p-p QES component observed in light-mass nuclear systems. The observed maximum values of $C_1$'s are summarized in Table I. We see that the $C_1$'s are smaller for heavier-mass systems. The in-plane correlation is dominated by p-p QES, while the coincidence rate between two particles in general is proportional to the square of the total event multiplicity. Therefore the correlation function, $C$, approaches 1 as the event multiplicity increases. Experimental values of the average total charged-particle multiplicity, $m$, which were determined from the total inclusive yield divided by the total reaction cross section ($\sigma_0$), are listed in the 7th column of Table I. These values of $m$ are very close to the total nuclear charges of the participant piece calculated by the participant-spectator model, as shown in the 8th column of the table. It is worthwhile to note that $(C_1 - 1) \cdot m$ stays almost constant for all the systems. We also see that $C_1$(at peak) $< C_2$(at peak). This means that the lower-energy cut of the telescope includes more uncorrelated particles.

We now estimate the magnitude of the p-p QES component. We assume that the two-particle coincidence has two components: the p-p QES with a width characteristic of the Fermi momentum of the colliding nucleons and the azimuthally uncorrelated particles such as the particle through multiple scattering. We also assume all detected particles are protons. Under these assumptions, let us divide the inclusive cross section ($\frac{d\sigma}{dp}$) into two parts: the p-p QES part ($\frac{d\sigma}{dp}$) and the remaining ($\frac{d\sigma}{dp}$), where, in the former process, neither of the two protons is rescattered after one hard collision.

Because the multiplicities of the reaction play an important role, we rewrite the cross sections as

$$
\frac{d\sigma}{dp} = m \left( \frac{d\sigma}{dp} \right)_p + m \left( \frac{d\sigma}{dp} \right)_{pp} \quad \text{and} \quad \frac{d\sigma}{dp} = m \left( \frac{d\sigma}{dp} \right)_{pp} + m \left( \frac{d\sigma}{dp} \right)_{r}
$$

(2)
where \( m \)'s represent the average multiplicities associated with the relevant processes and \( \frac{df}{dp} \)'s are spectral functions normalized to \( \sigma_0 \). Thus

\[
\frac{df}{dp} = m \frac{df}{pp dp} + m \frac{df}{r dp} \quad m = m_{pp} + m_r.
\]  

(3)

When a proton from the first term of the above equation (p-p QES proton) is detected at \( p_1^* \), (with the probability of \( \frac{m_{pp}}{\sigma_0} \frac{df}{dp} \)), the probability of detecting another proton at \( p_2^* \) is proportional to \( [D(\hat{p}_1, \hat{p}_2) + \frac{(m-2)}{\sigma_0} \frac{df}{d\hat{p}_2}] \) where \( D(\hat{p}_1, \hat{p}_2) \) is the probability that the QES partner of the detected proton at \( p_1^* \) scatters to \( p_2^* \) with normalization \( \int D(\hat{p}_1, \hat{p}_2) d\hat{p}_2 = 1 \). The second term arises from random coincidences. Similarly, when a proton from the second term in Eq. (3) is detected at \( p_1^* \) with \( \frac{m_r}{\sigma_0} \frac{df}{d\hat{p}_1} \), the probability of detecting another proton at \( p_2^* \) is proportional to \( \frac{(m-1)}{\sigma_0} \frac{df}{d\hat{p}_2} \). Thus, the two-proton inclusive cross sections can be written as

\[
\frac{d^2\sigma}{d\hat{p}_1 d\hat{p}_2} = m_{pp} \frac{df}{dp} \frac{df}{dp} [D(\hat{p}_1, \hat{p}_2) + \frac{(m-2)}{\sigma_0} \frac{df}{d\hat{p}_2}] + m_r \frac{df}{dp} \frac{df}{d\hat{p}_1} \frac{(m-1)}{\sigma_0} \frac{df}{d\hat{p}_2}.
\]  

(4)

The correlation function \( C_2(\theta, p) \), defined in Eq. (1), then is written as

\[
C_2(\theta, p) - 1 = \frac{m_{pp}}{\sigma_0} \frac{\alpha \int D(\hat{p}_1, \hat{p}_2) d\hat{p}_2}{(m-1) - \alpha}
\]  

(5)

where integration is over the momentum covered by the R-telescope and \( \alpha = \frac{d\sigma_{pp}}{d\hat{p}} / \frac{d\sigma_{pp}}{d\hat{p}} \) is the fraction of p-p QES cross section which in general depends on \( p_1^* \). Because we restrict our discussion to a narrow kinematical region near QES, we assume that \( \alpha \) is constant. In the extreme case where all the protons are emitted via single nucleon-nucleon collisions without further
multiple scattering, $\alpha$ has its maximum value $\alpha_0 = 0.43$.  

Fig. 2 shows the calculated value of $\left(C_2(40^\circ, p) - 1\right)$ (solid line) based on Eq. (5) for the C + C data. The function $\int D(p^\top, p_R) d\Omega_R$ was calculated using our experimental geometry with a Monte Carlo method, assuming that nucleons have a Gaussian momentum distribution $(e^{-p^2/(177 \text{ MeV/c})^2})$ both in the target and the projectile. This distribution is very close to that obtained from a many-body theory with a Reid soft core potential. The shape of $\left(C_2(40^\circ, p) - 1\right)$ is reproduced well. However, if we use $\alpha = \alpha_0$, the amplitude is six-times larger than the experiment, which indicates that both single and multiple scatterings are involved in these collisions. The observed fraction $\alpha/\alpha_0$ is summarized in the 9th column of Table I. They are essentially the same within an error for all combinations.

In the analysis we assumed that the observed azimuthal correlations are due only to p-p QES. This simplified model neglects residual correlations of secondary scattered particles and also neglects correlations associated with energy-momentum conservation of the whole or of a sub-system (except a two-particle system). Our rough estimate for this process shows that these effects are unlikely to change $\left(C_2 - 1\right)$ by more than 20%. The observed correlations can also be influenced by nuclear shadowing, which gets progressively more important as the masses of the colliding nuclei increase. Quantitative discussion of this effect is, however, left as a subject for the future.

Let us compare the fraction $\alpha/\alpha_0$ to the fraction $P$ of single collision in an inclusive proton spectrum. A distinction should be made between $\alpha/\alpha_0$ and $P$, because, in the former, none of the particles after NN collisions are rescattered, whereas, in the latter, the detected proton was not rescattered but the other particles involved in the collision could be. Thus the fractions
and $\alpha/\alpha_0$ and $P$ are related by $P^2 \approx \alpha/\alpha_0$. The resulting fraction $P$ is listed in the last column of Table I. This value of $P$ is comparable to the value obtained from the high-multiplicity biased data for Ar + KCl.\textsuperscript{12}

In conclusion, for light-mass nuclear collisions, two coplanar correlations have been used to estimate the fraction of the single NN collision component $P$ in a limited kinematical region ($\theta_{CM} \sim 90^\circ$, $P_{CM} \sim P_{CM}(\text{Beam})/A$) for protons. $P \sim 50\%$ was obtained from the present analysis. Because of several assumptions involved in the analysis, the estimated values of $P$ are thought to have 30 - 40\% errors in them.

Finally let us say a few words on the observed anti-coplanarity for a heavy-mass target. As shown in Fig. 1 for 800 MeV/nucleon C + Pb, the ratio $C_2$ is smaller than 1, and, furthermore, a valley extends toward $\theta_{CM} \sim 60^\circ$. This observation can be qualitatively understood in terms of nuclear shadowing. When we detect the first proton with the spectrometer, then the reaction region is effectively biased toward that part of the Pb nuclear surface that is facing in the direction of the spectrometer. It is then rather difficult for the second proton to be emitted in the opposite direction from the first proton, namely in the R-telescope direction, because the second proton has to penetrate a large amount of nuclear matter. On the other hand, it is relatively easy for the second proton to be emitted in the up or down direction. This causes $C_2$ to be smaller than 1.

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REFERENCES

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9. We used the value calculated using the clean-knock-out model; R. L. Hatch, private communication, 1979.
## TABLE I. Value of $C_1$ at peak position and average charged-particle multiplicity, $m$, for light-mass nuclear collisions. Fraction of the single clean-knock-out component is listed in the last column.

<table>
<thead>
<tr>
<th>$E_{\text{Lab}}$ (MeV)</th>
<th>Reaction</th>
<th>$C_2$ (at peak)</th>
<th>$C_1$ (at peak)</th>
<th>$\sigma_0^{a)}$ (barn)</th>
<th>$\frac{\sigma^{\text{inclusive}}}{\sigma_0}$</th>
<th>$m$</th>
<th>$\alpha/\alpha_0^{d)}$</th>
<th>$p^{d)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C + C</td>
<td>1.75±0.07</td>
<td>1.55±0.06</td>
<td>2.8±0.6</td>
<td>0.80</td>
<td>3.5±0.7</td>
<td>3</td>
<td>0.20±0.07</td>
</tr>
<tr>
<td></td>
<td>Ne + NaF</td>
<td>1.40±0.10</td>
<td>1.35±0.08</td>
<td>7.7±1.6</td>
<td>1.30</td>
<td>5.9±1.2</td>
<td>5</td>
<td>0.21±0.09</td>
</tr>
<tr>
<td></td>
<td>Ar + KCl</td>
<td>1.25±0.10</td>
<td>1.16±0.10</td>
<td>23±5</td>
<td>2.45</td>
<td>9.4±1.8</td>
<td>9</td>
<td>0.23±0.12</td>
</tr>
<tr>
<td></td>
<td>Ne + NaF</td>
<td>1.50±0.07</td>
<td>1.40±0.06</td>
<td>5.2±1.2</td>
<td>1.30</td>
<td>4.0±0.9</td>
<td>5</td>
<td>0.24±0.10</td>
</tr>
</tbody>
</table>

\[ a \] The total yield of charges calculated from the inclusive data taken at $10^\circ < \theta < 145^\circ$, after the extrapolation to $0^\circ$ and $180^\circ$.

\[ b \] Total reaction cross section [Ref. 10].

\[ c \] Calculated nuclear charges for the participant piece calculated from the participant spectator model.

\[ d \] Errors quoted here are statistical only.
FIGURE CAPTIONS

Fig. 1 Contour plot of $C_2$ defined by Eq. (1) for C + C, Ne + NaF, and Ar + KCl at $E_{\text{Lab}}^{\text{Beam}} = 800$ MeV/nucleon. P and T indicate projectile and target momenta per nucleon, respectively, in the nucleon-nucleon c.m. frame. The dashed circle indicates the free proton-proton elastic scattering kinematics, and the cross-hatched area shows the kinematical region of protons detected by the R-telescope.

Fig. 2 Fit of $C_2(40^\circ, p)$ as a function of $p$, using a gaussian internal momentum distribution of nucleons inside the nucleus.
Fig. 1