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TWO-PARTICLE CORRELATIONS IN NUCLEAR COLLISIONS

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TWO-PARTICLE CORRELATIONS IN NUCLEAR COLLISIONS

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Single-particle inclusive cross sections have been extensively measured in high-energy proton-nucleus and nucleus-nucleus collisions.[2-4] These data show several interesting features to which various models such as the hard scattering model[5] and thermal models[6-8] have been applied. These models, although they are quite different in their physical basis, are able to describe the data rather successfully. Thus the data do not distinguish between the various models.

One of the goals of high-energy nuclear collision research is to learn the properties of high-density and/or high-temperature nuclear matter. It must first, however, be learned whether such an exotic state is really produced in the collisions. No evidence for the existence of such a state has yet been found. One of the difficulties so far has been the lack of understanding of the reaction mechanism. If we understand the reaction mechanism better we may more readily be able to distinguish interesting abnormalities in the data.

To study the reaction mechanism in more detail we have measured two-particle correlations in proton-nucleus and nucleus-nucleus collisions with beams of 800 MeV/A at the Berkeley Bevalac. We report here results which give information about: the mean free path of protons in the nucleus, the contribution of the single-knock-out process in the collisions between equal size nu-

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clei and the nuclear shadowing effect in collisions with a heavy target nucleus.

The experimental system consisted of a magnetic spectrometer, (S), and three sets of counter telescopes (R, U, and D). These telescopes were set at scattering angles $(\theta,\phi) = (40^\circ, 180^\circ)$, $(40^\circ, 90^\circ)$, and $(40^\circ, 270^\circ)$ respectively. The spectrometer was located at $\phi = 0^\circ$ and was rotated between $\theta = 15^\circ$, and 110°. Although it was impossible to identify particles with the telescopes, it was known from the single particle data that the dominant yield at $\phi = 40^\circ$ is protons.

1) Quasi-elastic scattering (QES) in proton-nucleus collisions and the mean free path of protons inside the nucleus.

Protons of 800 MeV energy were incident on targets of C, NaF, KCl, Cu, and Pb. At small angles, 15°-30°, the inclusive proton cross sections were dominated by the QES peak. At larger angles, however, the cross sections show no peak but decrease monotonically as a function of momentum. This indicates that multiple scattering is important at larger angles. This is supported by the larger target mass dependence, $\sim A^{2/3}$, of the cross section at large angles as compared to $\sim A^{1/3}$, at smaller angles.

While the in-plane coincidence data clearly show QES, the out-of-plane data have no structure. Fig. 1 shows the A dependence of the coincidence QES cross sections, b, and of inclusive QES cross sections, a, at $\theta = 15^\circ$. The coincidence QES cross sections are obtained by subtracting the out-of-plane from the in-plane. In contrast with the inclusive cross sections, which increase monotonically with target mass, the coincidence cross sections show a maximum at a target mass around A = 50. As the target mass increases the probability of p-p QES also increases, but, at the same time, the rescattering probability also increases. In the case of the inclusive cross sections, QES is defined as a scattering where the observed proton is not rescattered after the initial nucleon-nucleon collision. In other words, it is independent of whether the partner in the first collision is rescattered. In the coincidence cross sections, however, neither of the protons may be rescattered.

We have made a simple geometrical calculation of these rescattering effects using the mean free path of the proton, λ, as a parameter. Calculated curves with λ = 1.4 fm, 2.5 fm, and 3.0 fm for 800 MeV protons are shown in Fig. 1b. It is shown that the A dependence is quite sensitive to λ. We obtained a best fit to the data for λ = 2.5 fm. Using this value of λ, we have also calculated the inclusive QES cross sections. The result is shown by the solid line in Fig. 1a Although it is systematically smaller than the data, the agreement is fair.

2) The contribution of QES in collisions with equal size nuclei.

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

$$C_i(\theta,p) = 2\,\frac{(S(\theta,p)\cdot R_i)/R_i}{(S(\theta,p)\cdot U_i)/U_i + (S(\theta,p)\cdot D_i)/D_i}$$

for 800 MeV/A C, Ne, Ar beams incident on C, NaF, and KCl targets respectively. Here θ is the scattering angle and p is the momentum of the particle detected in the spectrometer. The i indicates the telescope energy cut: namely, i = 1 for $E_{proton} \gtrsim 100$ MeV and i = 2 for $E_{proton} \gtrsim 200$ MeV. The quantity $(S(\theta,p)\cdot R_i)$ indicates the coincidence counts between the spectrometer and the R-telescope.

In fig. 2 contour lines of the observed values of $C_i(\theta,p)$ are shown for collisions of C + C and Ar + KCl. The data are plotted in the plane of $p_{\parallel}$ and

$p_\perp$ in the nucleon-nucleon c.m. frame. In these collisions C_2 is always larger than one which implies that there is more coincidence in plane than out. Also, C_2 peaks right on the nucleon-nucleon elastic scattering circle on the side opposite the kinematical region covered by the R-telescope, the cross-hatched area. Thus the data show the existence of p-p QES.

The observed maximum values of the C_i's are summarized in Table I. We see that the C_i's are smaller for heavier-mass systems. The in-plane correlation is dominated by p-p QES. The coincidence rate between two particles in general is proportional to the square of the total event multiplicity. Therefore the correlation function, C, approaches one as the event multiplicity increases. Experimental values of the average total charged-particle multiplicity, m, which were determined from the total inclusive yield divided bye the total reaction cross section (σ_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 as calculated by the participant-spectator model which are shown in the 8th column of the table. It is worthwhile to note that $(C_i - 1) \bullet m$ 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 have estimated the contribution of QES scattering, α/α_0, in a kinematical region around the peak position of the correlation. This estimate is based on the assumption that the two-proton coincidence has two components: the p-p QES with a width characteristic of the Fermi momentum of the colliding nuclei and multiple scattering which produces azimuthally uncorrelated particle. The results are listed in Table I. From the values of α/α_0 we have also estimated the fraction of the single nucleon-nucleon collision component, P, in the same kinematical region. These are listed in the last column of the table. For light-mass nuclear collisions P $\sim$ 50%. Because of several assumptions involved in the analysis, the estimated values of P are thought to have 30-40% errors. Even including these errors the importance of the single scattering process is obvious. It should, however, be noted that the present data also show that the contribution from multiple scattering is significant.

Several theoretical models, like the transport theory,[9] the row on row,[10] and the cascade model,[11] which take the single-scattering component into account, reproduce the observed correlation reasonably. On the other hand, the thermal or fluid dynamical models fail to explain the correlation observed.

3) The nuclear shadowing effect in C + Pb collisions.

As shown in Fig. 2c, different types of correlations have been observed. For C + Pb there is the region where the correlation function is less than one, and a valley extends toward $\theta_{c.m.} \sim 60°$. This observation can be qualitatively understood in terms of nuclear shadowing. When we detect the first proton with the spectrometer the reaction region is effectively biased toward that part of the Pb nuclear surface that is facing in the direction of the R-telescope, because it would have 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 one.

We have made a simple model calculation based on geometry and the mean free path of the proton. We assume that the high-energy protons are emitted uniformly from the participating or overlapping region of the two colliding nuclei. The calculation reproduces the correlation value in the forward direction including the momentum dependence. However the calculated value is always less than one at a larger angles in contrast with the data where the correlation may be greater than one. Several reasons may be considered for this rise at larger angles. One is related to our assumption of the uniformity of this source. The source of the high-energy particle might be concentrated only at the backward hemisphere of the Pb nucleus. This is likely to occur since carbon is much smaller than lead and thus may not punch through. We estimate the effect of the source distribution assuming the exponential distribution from each surface of target nucleus with the decay constant of the proton mean free path ($\sim$3 fm). Results show that the correlation function is rather insensitive to the source distribution.

Another possibility is the correlation due to the energy and momentum conservation of the total or of a few particle systems. Because most of the participants are from the lead nucleus, the direction of the momentum balance after the detection of a particle at 40° is to a large angle. A calculation based on the rows on rows model, which reproduces the C + C correlation data rather well, was done by Knoll and Randrup to see these effects in C + Pb. The correlation function is found to be essentially 1 by their calculation. Furthermore, as shown in Fig. 3, the observed correlation function is larger for the heavier projectile (Ar + Pb) case.

If the correlation of a large angle (>1) is due to energy-momentum conservation, it must be smaller for a heavier system. As a result, we don't understand why the correlation function rises at a larger angle in these reactions.

A suggestion based on fluid dynamical flow (side splash) has been made by Siemens[12] at this summer school. However, we need further theoretical work on this subject to realize the idea.

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FIGURE CAPTIONS

Fig. 1 Target mass dependence of quasi-elastic-scattered protons: a) inclusive measurement and b) coincidence measurement. The lines are the result of the model calculation which uses the mean free path of the proton as a parameter.

Fig. 2 Contour plot of C_2 defined by Eq. 1 for C + C, Ar + KCl, and C + Pb at E_{Beam}^{Lab} = 800 MeV/A. 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. 3 Contour plot of C_2 for Ar + Pb at E_{Beam}^{Lab} = 800 MeV/A.

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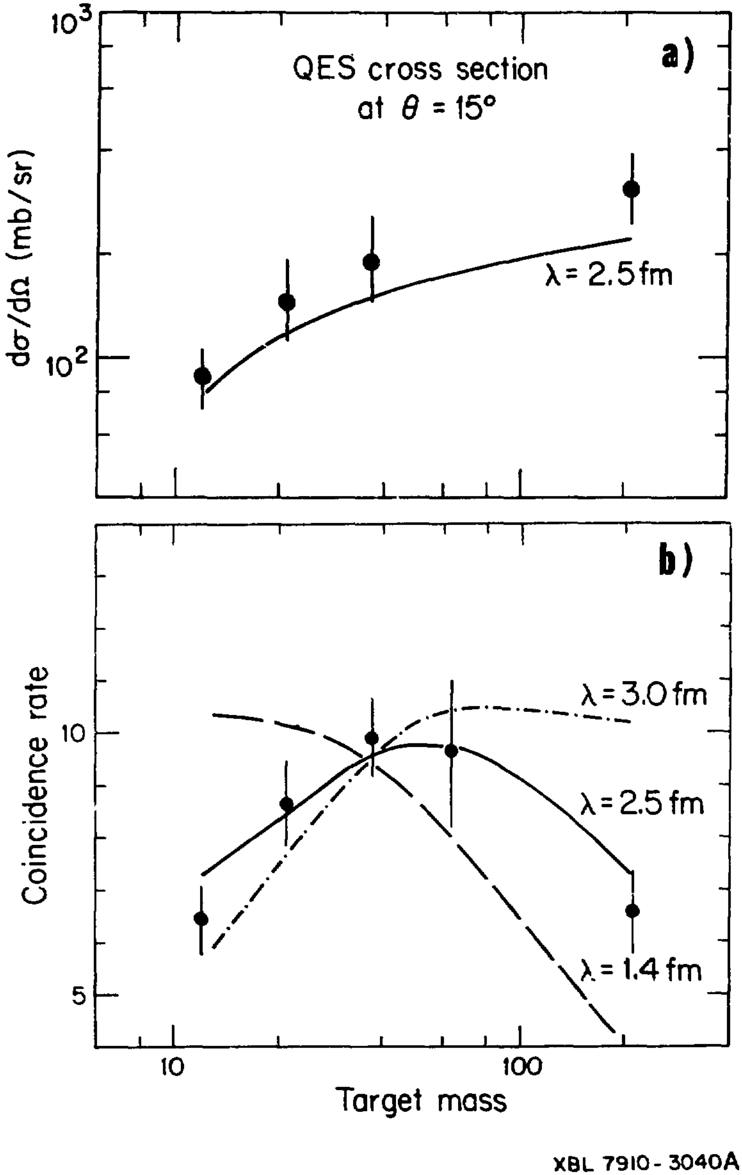
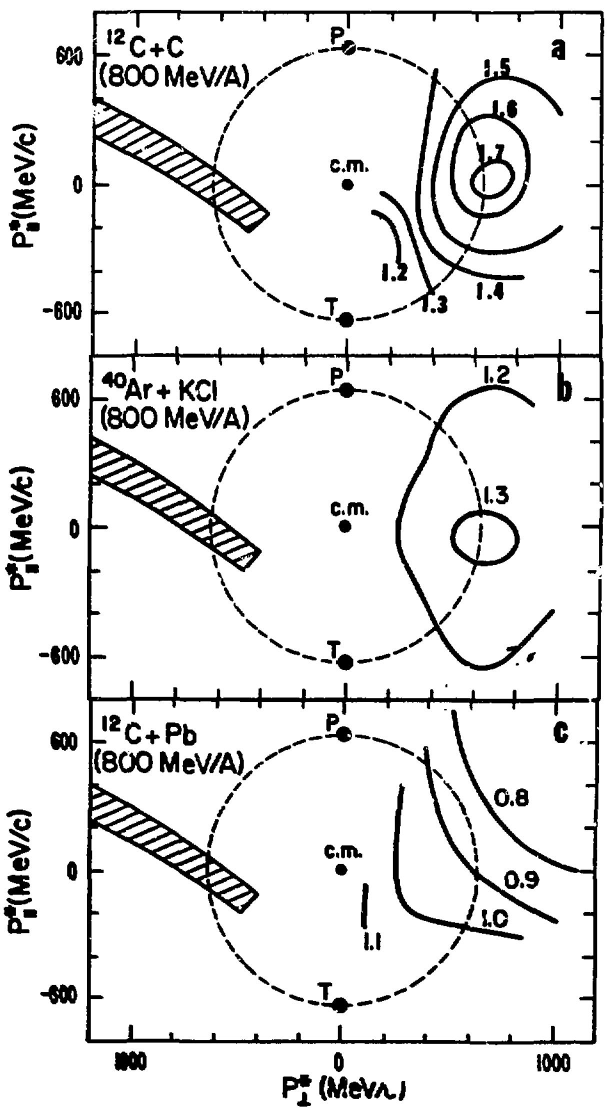

QES cross section
at θ = 15°
a)
dσ/dΩ (mb/sr)
10³
10²
λ = 2.5 fm
b)
Coincidence rate
10
5
λ = 3.0 fm
λ = 2.5 fm
λ = 1.4 fm
10
100
Target mass
XBL 7910-3040A

Fig. 1



XBL 793-7588

Fig. 2

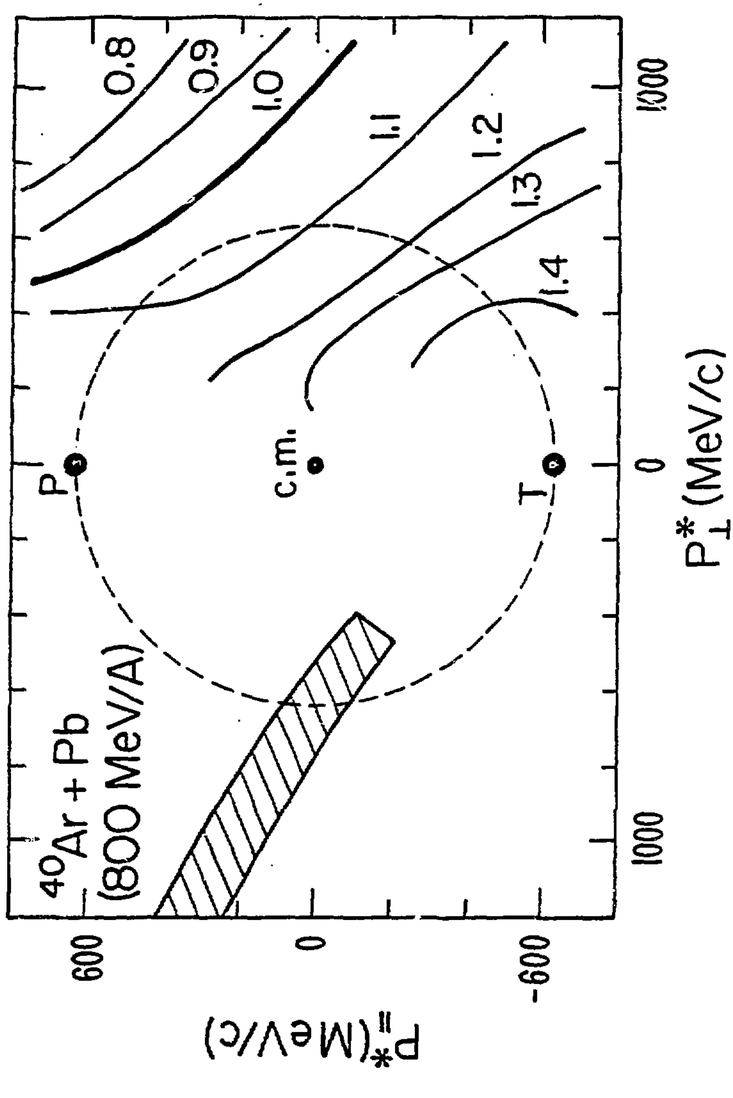


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Fig. 3