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Central Collisions with a Projectile of
1.8 GeV/nucleon $^{40}$Ar

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ABSTRACT

Single particle inclusive spectra and the associated multiplicity were
obtained with a magnetic spectrometer and an azimuthal array of 30 Cerenkov
counters from collisions of 1.8 GeV/nucleon $^{40}$Ar on Be and Cu targets. No
change is seen in the shape of the spectra obtained by the spectrometer for
various multiplicity requirements.
Central or small impact parameter collisions between high energy heavy ions have generated much interest recently. In such collisions one may hope to study nuclear matter at high densities and temperatures where exotic effects such as shock waves\textsuperscript{1-5} or density isomers\textsuperscript{4-6} may occur. A possible experimental signature for central collisions is the emission of a large multiplicity of charged fragments. The success of Gosset et al.\textsuperscript{7} in fitting their single particle inclusive spectra with the fireball model suggests that fragments having momentum transfers large compared to the Fermi momentum originate predominantly from small-impact-parameter collisions. The fireball model, however, does not even qualitatively fit the proton inclusive spectra for $^{20}\text{Ne}$ on $^{238}\text{U}$ at 2.1 GeV/nucleon of Westfall et al.\textsuperscript{8} who attributed the failure of the model to "transparency," i.e., the persistence of the longitudinal momentum of the projectile nucleons. Unfortunately, the large experimental uncertainties make it difficult to draw firm conclusions from their high energy data.

We have conducted an experimental study to develop selection criteria for central collisions and to examine these collisions for evidence of anomalous density effects. A movable magnetic spectrometer (Fig. 1) has been used to measure the production of light fragments ($p$, $d$, $t$, $^3\text{He}$, $^4\text{He}$) from collisions of a heavy projectile ($^{40}\text{Ar}$) on light (Be) and heavier (Cu) targets at 1.8 GeV/nucleon, the highest available bombarding energy (for $^{40}\text{Ar}$) at the Lawrence Berkeley Laboratory Bevalac. Data were taken at nearly all laboratory angles between $3.5^\circ$ and $15.2^\circ$ and at all rigidities between 1.5 and 7.5 GeV/c-Z. The momentum, scattering angles $\theta$ and $\phi$, charge and mass were measured for each particle detected by the spectrometer. The rapidities of the detected particles extend to regions midway between those of the beam and the target. The momentum transferred to these fragments is typically much larger than the internal momentum of nucleons in the projectile.
An array of 30 lucite Cerenkov detectors (Fig. 10) was used to measure the multiplicity distribution of fast-charged particles associated with each particle detected by the spectrometer. This array has a $\theta_{\text{Lab}}$ acceptance of $4 - 12^\circ$ or $5 - 16^\circ$ which was selected by varying the target-to-detector distance. The Cerenkov detectors have a velocity threshold of $\beta > 0.7$ (about half of the beam rapidity) and are in the form of azimuthal segments covering all of the azimuthal coordinate not occupied by the spectrometer acceptance. The kinematics of the reaction ensure that the multiplicity array accepts a large fraction of the fragments from the projectile that have received momentum transfers greater than the Fermi momentum.

We present in Fig. 2 results for the production of hydrogen isotopes for $^{40}\text{Ar} + \text{Cu}$ and $^{40}\text{Ar} + \text{Be}$ collisions. The invariant inclusive cross-section is plotted as a function of the laboratory momentum for $\theta_{\text{Lab}} = 5, 12$ and $14.7^\circ$. At small laboratory angles ($5^\circ$) the fragment distributions peak near $\beta_p$, the projectile velocity. The energy of the fragments in this peak corresponds to about 25 MeV/nucleon in the projectile rest frame. No peak is observed at larger laboratory angles (above $12^\circ$) where the minimum kinetic energy in the projectile rest frame is 150 MeV/nucleon. For a given fragment, the cross-sections are nearly equal for the different laboratory angles in the midway rapidity regions, which are at $P_{\text{Lab}} = 1, 2$ and $3$ GeV/c for protons, deuterons and tritons, respectively.

The curves shown in Fig. 2 are predictions from the diffuse firestreak model\textsuperscript{9,10}. There is qualitative agreement between the predictions of the model and the shape and magnitude of our data. The agreement is worse at lower fragment momenta (midway rapidities) and at smaller laboratory angles, where the predictions overestimate the measured cross-sections.

The predictions of the original fireball model for $^{40}\text{Ar} + \text{Cu} \rightarrow d + x$ at $5^\circ$ and $14.7^\circ$ are shown in Fig. 3a. This model does not come close to fitting
the shape and magnitude of the data. Fig. 3b shows the predictions of the fireball model which has been modified to include transparency as in reference 8. The calculation whose results are shown here used a transparency of 50%. While the introduction of transparency improves the fit at 14.7°, the model still does not qualitatively fit the data at 5°. We have found that by varying the value of the transparency parameter we can fit the data at some but not all angles.

The essential difference between the diffuse firestreak and the fireball models is the geometry and therefore the allowable range of impact parameters. The fireball model, which considers the projectile and target nuclei to be spheres with sharply defined radii, allows only central or nearly central collisions. This limited range of impact parameter, together with the assumption of complete inelasticity in the collision process, results in the concentration of the sources of emitted fragments near the midway rapidity region (see the resulting cross-section in Fig. 3a). The relaxation of complete inelasticity (transparency) results in two concentrations of sources; one closer to the projectile rapidity and one closer to the target rapidity. The exact location of these two concentrations depends on the value of the transparency parameter. Myers\(^9\) has shown that the diffuse geometry results in a distribution of sources which are spread out over the rapidity space between the projectile and the target. The sources of particles near the beam or the target rapidities originate mostly from peripheral collisions, while central collisions result in sources that predominantly populate the midway rapidity region. The diffuse firestreak model, even with its drastic assumption of complete inelasticity, fits our data better than the fireball model with or without transparency.

The relative success of the diffuse firestreak model over the fireball model in fitting our data indicates that the single particle inclusive spectra include significant contributions from peripheral collisions. It seems necessary
to use the multiplicity information from the Cerenkov counters to select central collisions. To see how the single particle inclusive cross-section changes for a given multiplicity requirement M, we have studied the ratio

\[ r = \frac{W_M(\theta_L, Y_L)}{W(\theta_L, Y_L)} \]

as a function of the laboratory angle \( \theta_L \) and the rapidity \( Y_L \). The quantity \( W_M \) is the inclusive cross-section for those events satisfying \( M \), and \( W \) is the inclusive cross-section without any multiplicity requirement.

Figure 4 shows \( r \) for protons, deuterons and tritons as a function of rapidity at \( \theta_L = 12 \) for \(^{40}\text{Ar}\) incident on a Be target. The multiplicity requirement is that at least 7 fragments are detected by the Cerenkov detectors. The ratio \( r \) was also examined for the cases (1) requiring at least two particles detected in each of the four azimuthal quadrants, and (2) requiring hits in 10 or more counters. For all cases, no statistically significant variation of \( r \) with fragment type or momentum is seen at a given angle.

According to the work of Baumgardt et al.\(^3\) and Hofmann et al.\(^4\), a shock wave formed in the heavy \(^{40}\text{Ar}\) projectile as it passes through the lighter Be target in a central or nearly central collision should result in fragments being emitted at rapidities indicated by the shaded region in Fig. 4. When viewed in the projectile rest frame the minimum and maximum rapidities in the shaded region correspond to \( \theta = 37^\circ \) (\( \beta_{\text{fragment}} = .53 \)) and \( \theta = 75^\circ \) (\( \beta_{\text{fragment}} = .15 \)), respectively. The absence of a peak in the ratio \( r \) can be interpreted as evidence for not finding shock waves. This conclusion agrees with the results from the emulsion experiments of Jakobsson et al.\(^{11}\) and Heckman et al.\(^{12}\) and with the results of the counter experiment of Poskanzer et al.\(^{13}\)

In summary, the inclusive cross-sections of fragments having momentum transfers large compared to the Fermi momentum seem best fit by a model that includes peripheral as well as central collisions. As discussed in reference 10, the overestimate by this model of the measured cross-sections at low momenta
(midway rapidities) and at small angles may be due to the rather dubious assumption that all of the overlapping projectile and target tubes undergo completely inelastic collisions even when they contain only a few nucleons.

The lack of a peak in the ratio \( r \) in the shaded region of Fig. 4 might be due to the energy lost during the collision. The spread in the shock angle could be quite large because the projectile nucleus would not have a well-defined velocity as it passes through the target. The constancy of the ratio \( r \) as a function of rapidity nevertheless surprises us. According to the diffuse firestreak model, one might expect the ratio \( r \) to rise near the midway rapidity region where central collisions should contribute more significantly to the single particle inclusive cross-section. On the other hand, the peak near \( \beta_p \) in Fig. 2 suggests that at \( 5^\circ \) the cross-section is predominantly due to peripheral collisions. The multiplicity of a large number of fragments (even symmetrically emitted) having energies as low as 25 MeV/nucleon in the projectile rest frame \( (\theta_L = 5^\circ) \) might not sufficiently select central collisions.

We feel that models that predict the single-particle inclusive cross-section should also predict the ratio \( r \). These predictions can serve as another constraint with which to test the assumptions in various models and can also tell the experimenter how well a particular multiplicity requirement selects impact parameter.
References


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Figure Captions

Fig. 1 The experimental layout shows the spectrometer consisting of 4 scintillator detectors (S), 6 multi-wire proportional chambers (MWPC) and 3 bending magnets (M). The beam flux is monitored by 4 ion chambers (IC) and 2 scattering telescopes (ML and MR). The 30 azimuthal Cerenkov counters downstream from the target measure the multiplicity.

Fig. 2 The invariant inclusive cross-section $E/p^2 d^2 \sigma / dpd\Omega$ for producing hydrogen isotopes at $\theta_{\text{Lab}} = 5, 12$ and $14.7^\circ$ is plotted as a function of laboratory momentum for $^{40}\text{Ar} + \text{Cu}$ and $^{40}\text{Ar} + \text{Be}$. The beam velocity is indicated by $\beta_p$ for the three different isotopes. The curves are predictions from the diffuse firestreak model.

Fig. 3 The invariant inclusive cross-section for producing deuterons at $\theta_L = 5$ and $14.7^\circ$. In Figure 3a the curves are predictions of the fireball model with no transparency. In Figure 3b the curves are predictions from the fireball model with 50% transparency.

Fig. 4 The ratio $r$ is plotted as a function of rapidity $Y_L$ for hydrogen isotopes detected at $12^\circ$ for $^{40}\text{Ar} + \text{Be}$. The quantity $r$ is defined as $r = W_m > 7 (\theta_L, Y_L) / W(\theta_L, Y_L)$, where $m$ is the observed multiplicity and $W$ is the inclusive cross-section. The shaded regions indicate where the shock wave peak should occur according to ref. 3.
\[ E \frac{d^2 \sigma}{dP d\Omega} \left( \text{mb} \cdot \text{cm}^{-2} \cdot \text{sr}^{-1} \cdot \text{MeV}^{-2} \right) \]

\[ P_{\text{lab}} \left( \text{GeV/c} \right) \]

- Figures showing the distribution of particles for different energies and angular ranges.
- \( \beta_p \) indicates the momentum transfer.
- \( \theta_{\text{lab}} \) values for different data points.

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Fig. 2
(a) $\text{Ar} + \text{Cu} \rightarrow \text{d} + \text{x}$

- $\theta_{\text{lab}} = 5^\circ$
- $\theta_{\text{lab}} = 14.7^\circ$
- Fireball
  (no transparency)

(b) $\text{Ar} + \text{Cu} \rightarrow \text{d} + \text{x}$

- $\theta_{\text{lab}} = 5^\circ$
- $\theta_{\text{lab}} = 14.7^\circ$
- Fireball
  (with 50% transparency)
$r = W_{M=7}/W$ for $Z=1$ from $^{40}\text{Ar} + ^{9}\text{Be}$

TRITONS

REGION OF EXPECTED SHOCK WAVE

DEUTERONS

PROTONS

RAPIDITY
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