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Charged-particle exclusive analysis of central Ar + KCl and Ar + Pb reactions at 1.8 and 0.8 GeV/nucleon

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An event by event analysis is carried out for all charged particles observed in central collisions of $^{40}\text{Ar} + \text{KCl}$ and $^{40}\text{Ar} + \text{Pb}$ at 1.808 and 0.772 GeV/nucleon, respectively. Total transverse energy is used for impact parameter selection within the central trigger condition. The central Ar+KCl reaction exhibits a forward-backward oriented momentum flux. The flux distribution of the most central Ar + Pb events is approximately isotropic in the fireball center of mass.

[NUCLEAR REACTIONS $^{40}\text{Ar} + \text{KCl}$, $E/A = 1.808$ GeV, and $^{40}\text{Ar} + \text{Pb}$, $E/A = 0.772$ GeV. Central collision trigger, all charged particles measured event by event, streamer chamber. Momentum flux distribution parameters deduced.]

Our present understanding of the dynamics of relativistic nucleus-nucleus collisions is derived primarily from single particle inclusive measurements. Deeper insight into the interaction may be obtained by a study of multiparticle observables^{1,2} derived from all charged particles produced in these collisions. In this paper we present the results of an analysis of charged particle exclusive data in terms of multiparticle variables. Two types of reactions were studied. The near symmetric nuclear system $^{40}\text{Ar} + \text{KCl}$ at 1.808 GeV/nucleon was chosen in order to determine the extent to which transparency becomes important at top Bevalac energy and the extent of equilibration in each event. In contrast, the asymmetric nuclear system $^{40}\text{Ar} + \text{Pb}$ at 0.772 GeV/nucleon was studied to search for effects resulting from the predicted hydrodynamical flow of compressed nuclear matter.²

The experiment was carried out using the streamer chamber facility at the Bevalac. The targets used were 1.98 g/cm² KCl and 1.31 g/cm² Pb₃O₄. The streamer chamber was triggered³ whenever a beam particle interacted in the chamber and the net charge of projectile fragments observed in the forward direction ($\pm 8^\circ$ in the laboratory) was $\sum Z_i^2 \leq 4$. This trigger eliminated all Ar reactions with the oxygen in Pb₃O₄, and suppressed 90% (75%) of the total cross section for the reaction Ar + KCl (Ar + Pb). The remaining near-central collisions correspond to a trigger cross section of 0.18 b (1.0 b) which in a geometrical picture is represented by a cutoff in the impact parameter at $b \leq 2.4$ fm ($b \leq 5.5$ fm). Results on pion and lambda production from the Ar + KCl exposure have been reported earlier.⁴ In the present analysis 334 Ar + KCl events and 102

Ar +Pb events were processed by measuring all tracks in three views on film. On-line geometrical reconstruction in three dimensions kept measuring losses below 10% of all tracks. Magnetic rigidity, ionization density, and phase space considerations permitted identification of all π^- , 95% of protons, deuterons, and tritons, and separation of π^+ from baryons for momenta below 550 MeV/c. Misidentification of π^+ is estimated to be less than 15%. The small number of particles with charge greater than unity was disregarded.

For comparison with a first-order theory and to understand the effect of experimental biases such as inefficiencies and the neglect of neutral particles, we used an intranuclear cascade program⁵ to produce events which were subjected to a Monte Carlo filter program simulating the experimental biases. The results from this procedure will be referred to as "filtered cascade." Throughout the analysis of the experimental data, only the energy and momentum carried by the proton in deuterons and tritons were included, thus disregarding not only the unobserved neutrons but also those bound in clusters.

To provide a better determination of impact parameter than that given by the streamer chamber trigger the dependence of several observable quantities on the impact parameter was studied using the filtered cascade events. For the reaction Ar +KCl the total transverse energy

$$E_t = \sum [(M_i^2 + p_{\perp,i}^2)^{1/2} - M_i \delta_i] \quad (1)$$

where $\delta_i = 0$ (1) for pions (protons), was found to exhibit the tightest correlation with impact parameter. This correlation is shown in Fig. 1(a) where E_t and its rms deviation are plotted as a function of impact parameter. For subsequent discussion E_t will be used as a measure of impact parameter within the range already selected by our trigger condition. Figure 1(b) presents the distribution of E_t in the data sample and, for comparison, in the filtered cascade events.

To compare total transverse and longitudinal momenta and to perform flux analysis one has to transform to an appropriate center of mass (c.m.) system. This is identical to the nucleon-nucleon system for Ar +KCl. For Ar +Pb it obviously depends on the impact parameter. The participant c.m. was determined from the charged particles in each event, excluding spectatorlike particles with $p_{\perp} < 270$ MeV/c. The mean c.m. velocity thus found was $\langle \beta \rangle = 0.43 \pm 0.03$ which is consistent with the fireball model⁶ prediction of $\langle \beta \rangle = 0.41$, as obtained for the impact parameter of maximum weight ($b = 4.5$ fm) resulting from the trigger condition. Further analysis of Ar +Pb was restricted to particles in the forward hemisphere of the event c.m., to avoid the experimental biases concentrated in the target region.

The degree of isotropy⁷ of the momenta of the nu-

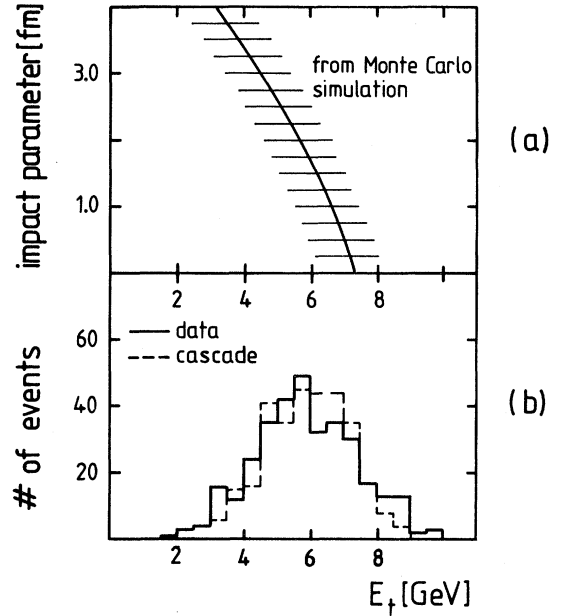


FIG. 1. For the reaction 1.8 GeV/nucleon Ar +KCl: (a) Correlation between the total transverse energy E_t as defined in the text and the impact parameter b for cascade generated events, where the hatched band corresponds to $\pm \sigma$ (rms deviation) of the E_t distribution at a given b ; (b) E_t spectra for data (solid line) and cascade generated events (dashed line).

cleons within one event can be judged by the ratio

$$R = \frac{2}{\pi} \frac{\sum_{\nu} |p_{\perp,\nu}|}{\sum_{\nu} |p_{\parallel,\nu}|} \quad (2)$$

which for an isotropic distribution should be unity. In the Ar +Pb reaction $\langle R \rangle = 0.79 \pm 0.02$ for the set of measured events, whereas events with $E_t > 5$ GeV (the mean value) approach isotropy ($\langle R \rangle = 0.96 \pm 0.03$). In contrast Ar +KCl exhibits an elongation of the momentum distribution along the beam axis. The dependence of R on E_t and b is shown in Table I. Even if R is extrapolated to zero impact parameter a value of $R = 0.64$ is obtained, i.e., complete degradation of longitudinal momentum is not observed.

For a more detailed analysis of the momentum flux pattern on an event by event basis a more elaborate approach was adopted, utilizing the normalized momentum flux tensor⁸

$$T_{ij} = \left(\sum_{\nu} p_{\nu i} p_{\nu j} |p_{\nu}|^{-1} \right) \left(\sum_{\nu} |p_{\nu}| \right)^{-1}, \quad i, j = x, y, z \quad (3)$$

with $p_{\nu i}$ and $p_{\nu j}$ the Cartesian components of the c.m. momentum of particle ν and p_{ν} its total c.m. momentum. The normalized eigenvalues and eigenvectors of T_{ij} define the event shape. The choice of this analysis presupposes an ellipsoidal shape which is

TABLE I. Mean value of the ratio R [see Eq. (2)] and mean transverse nucleon momenta per event for various E_t bins. The corresponding impact parameters are also shown. The reaction is Ar + KCl at 1.8 GeV/nucleon.

E_t (GeV)	3.5 - 4.5	4.5 - 5.5	5.5 - 6.5	6.5 - 7.5
b (fm)	3.0 - 4.0	2.0 - 3.0	1.0 - 2.0	≤ 1.0
$\langle p_{\perp} \rangle$ (MeV/c)	411 \pm 5	438 \pm 5	462 \pm 6	477 \pm 6
$\langle R \rangle$	0.49 \pm 0.01	0.53 \pm 0.01	0.58 \pm 0.01	0.61 \pm 0.02

described by the lengths of two axes of elongation and three angles. Events were classified using the cosine of the angle θ of the main tensor axis with respect to the beam direction and the aspect ratio a_1/a_2 of the longest to next longest axes.⁹

Figure 2(a) shows the $\cos\theta$ distributions for Ar + KCl and Ar + Pb. The Ar + KCl events are aligned along the beam direction with a width (in $\cos\theta$) at half maximum corresponding to a $\Delta\theta = 16^\circ \pm 1.5^\circ$. Filtered cascade events reproduce the distribution qualitatively. The experimental Ar + Pb events are distributed over a broader range of angles ($\Delta\theta = 43^\circ \pm 4^\circ$). Cascade events generated for Ar + Pb tend to be more forward peaked

($\Delta\theta = 36^\circ$) than the observed distribution. If selection is made on the transverse kinetic energy E_t one sees in Fig. 2(b) that for high E_t the experimentally observed distribution is nearly isotropic. In order to study the shape of the momentum flux tensor (in the forward hemisphere of the participant c.m. system for Ar + Pb) for high E_t events, the aspect ratio was considered. Figures 3(a) and 3(b) depict the mean aspect ratios for both systems studied as a function of E_t of the events. Clearly the aspect ratio decreases as E_t increases. Ideally a completely spherical shape corresponds to $a_1/a_2 = 1$. This value is never reached, however, for events consisting of a finite number of particles. The mean of the aspect ratio distribution of events with spherical shapes (generated by a Monte Carlo procedure with the mean particle numbers ob-

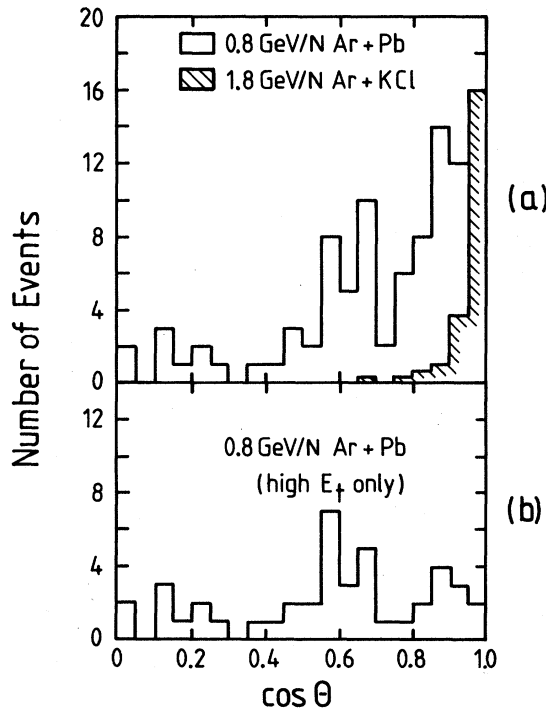


FIG. 2. Distributions of $\cos\theta$, with θ being the angle of the main axis of the momentum tensor with respect to the beam direction (a) for Ar + KCl and Ar + Pb, where the Ar + KCl histogram (hatched) is normalized to the last bin of Ar + Pb, and (b) for Ar + Pb events with E_t greater than the mean E_t ($\langle E_t \rangle = 5$ GeV).

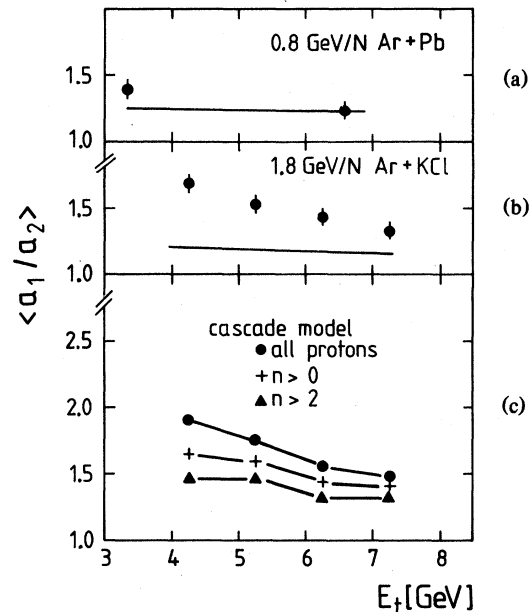


FIG. 3. (a) Aspect ratio (main axis and second largest axis) as a function of E_t for Ar + Pb. The solid line represents the aspect ratio expected for isotropic events with similar multiplicities. (b) The same for Ar + KCl. (c) The same for cascade generated Ar + KCl events: (●) all charged particles; (+) only particles which interacted at least once; (▲) only particles which interacted at least three times.

served in the various data samples) is shown by the solid lines. Thus Ar + Pb events closely approach isotropy at high E_t [Fig. 3(a)] accounting for the $\cos\theta$ distribution of Fig. 2(b). This is not reproduced by the cascade calculation which consistently yields higher aspect ratios. The Ar + KCl final state [Fig. 3(b)] never becomes completely isotropic even for high E_t events. The cascade generated events given by the uppermost set of points in Fig. 3(c) show the same dependence on E_t ; however, they are consistently more elongated.

To understand the apparent nonequilibration of the Ar + KCl final state a closer look into the cascade events was taken. If only participant nucleons, defined as particles making at least one collision, are considered [represented by crosses in Fig. 3(c)], the data and cascade sample of events agree in the aspect ratios. This indicates that for central Ar + KCl collisions the difference between real and cascade events can be attributed to the presence of noninteracting particles in the cascade calculations. In a further step only particles are considered which have undergone more than two collisions [lowest set of points in Fig. 3(c)]. Under this condition the shape of cascade events approaches the finite particle number limit, $\langle a_1/a_2 \rangle = 1.25$ for a spherical shape, suggesting that the core of the interacting system has reached equilibrium.

In summary, a selection of events according to the total transverse energy contained in charged particles enables one to focus on near head-on collisions more sharply than by means of the "central trigger" alone. Of the two systems studied, Ar + Pb at near-zero impact parameter closely approaches an isotropic distribution of momentum flux (determined in the forward hemisphere of the fireball center of mass). This is seen from the combination of three observ-

ables: the event by event ratio

$$R = \frac{2}{\pi} \frac{\sum |p_{\perp v}|}{\sum |P_{\parallel v}|} ,$$

the orientation of the principal axis of the momentum flux tensor, and the average deformation as measured by the aspect ratio. The cascade model predicts a forward elongated momentum distribution for this reaction, even for $b \rightarrow 0$, in disagreement with the data. This model thus predicts too much transparency. Better statistics are needed in order to decide on the existence of the sideways flow predicted by the hydrodynamical model² which would manifest itself in slightly oblate shapes.

For Ar + KCl at 1.8 GeV/nucleon, on the other hand, we observe forward elongation even for $b \rightarrow 0$. No trace of hydrodynamical oblate shape is found. The cascade model reproduces the data qualitatively, again with a slight overestimate of the elongation. Further studies with this model suggest that the observed forward elongation is due primarily to nucleons in the surface "corona" regions of the colliding mass 40 nuclei. Even as b approaches zero these nucleons cause an elongation of the momentum flux tensor along the beam direction. This effect is thus a trivial geometrical transparency. The validity of the hydrodynamical model, which ignores surface transparency due to its zero mean free path assumption, can thus not be conclusively tested in Ar + KCl collisions. It will therefore be interesting to study heavy symmetric colliding systems such as Pb on Pb, now available at the Bevalac, for which corona effects will be less important.

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⁹We have chosen a_1/a_2 instead of a_1/a_3 as used in Ref. 2 because a_3 is affected most by the specific streamer chamber inefficiencies. Differences between a_2 and a_3 are small for all events and of a magnitude similar to the systematic error.