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0.9 A GeV ^{238}U ON ^{238}U COLLISIONS IN THE LBL STREAMER CHAMBER

MASTER

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ABSTRACT

We report charged particle exclusive data for high multiplicity U on U events. Our analyses are based on comparison with Cugnon's intranuclear cascade model, and the explosion-evaporation simulation of Fai and Randrup. The azimuthal structure of the observed events shows evidence of collective flow. The widely used flow angle methodology proves to be relatively insensitive to collective effects under the conditions of the present experiment. An isotropic pattern of ejectile emission is not reached at maximum multiplicity.

The dynamics of nuclear matter under conditions of high density and temperature is a topic of far-reaching importance, with relevance to fields ranging from Astrophysics to Quantum Chromodynamics. Since the advent of the LBL Bevalac in 1974, many models of nucleus-nucleus collisions at relativistic energies have been compared with experiment; diverse approaches based on thermodynamics, hydrodynamics or intranuclear cascades have been found to be almost equally consistent with the available particle inclusive data. However, inclusive parameters tend to be dominated by properties of the phase space, with a relatively weak sensitivity to details of the collision dynamics. Charged particle exclusive data are not smeared by impact parameter and reaction plane averaging, and as demonstrated by recent results for ^{40}Ar and ^{93}Nb projectiles at the Bevalac streamer chamber[1,2] and Plastic Ball[3], offer renewed hope of unambiguously distinguishing between existing models. With heavier projectiles, we expect any cooperative behavior to become increasingly prominent, due to reductions in surface effects and finite multiplicity distortion. Thus, particle exclusive data for the heaviest systems at the highest multiplicities offer the ultimate test for any model.

In these proceedings, we report results of the first relativistic uranium on uranium experiment with a 4π detector. The maximum uranium bombarding energy of the Bevalac was used; the estimated incident energy at the target was 0.90 A GeV. The streamer chamber configuration, triggering method and particle identification criteria were as previously described,[2,4]

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except that the target, of thickness 0.5 mm, was placed immediately in front of the beam entrance window of the chamber. This prevented the strongly ionizing U^{92+} projectile from entering the sensitive volume, and provided a greater mean length of secondary tracks - this aids in maintaining high multiple track efficiency in the presence of very high multiplicities. We circumvent the acceptance loss associated with this target location by relying on projectile-target symmetry, i.e., we confine our analysis to tracks with center of mass rapidity $y_{cm} > 0$. The overall detection efficiency is estimated to be better than 85% for charged particles in this region. While this value is lower than for lighter beams (such as Ar) at similar energy, the additional losses for U on U are well understood, and can be accurately simulated.

Central collision triggers have been found to preferentially select events with large transverse momentum[2,5] and so our analysis is confined to events triggered in the minimum bias mode; we enhance the fraction of small impact parameter collisions by selecting events with high multiplicity. The fully measured U on U sample contains 41 events, each with ≥120 observed charged particles. This corresponds to the uppermost ~12% of the inelastic multiplicity spectrum. In comparisons with models, we select this same percentage of the multiplicity spectrum.

Previous investigations[1,3] of nucleus-nucleus collisions have focused attention on the thermalization ratio $R = 2\Sigma|p_\perp|/\pi\Sigma|p_\parallel|$ where the longitudinal momenta $p_\parallel$ are evaluated in the center of mass (cm) frame, and the sums extend over the observed particles in an event. $\langle R\rangle$ is a measure of nuclear stopping power, and is of importance in estimating the energy density attained in the collision; isotropic emission of the reaction products yields $\langle R\rangle=1$. Figure 1 shows R for each U on U event in the present sample, plotted as a function of the observed multiplicity of charged particles. Only tracks in the forward cm hemisphere contribute to R and to the plotted multiplicity. To simplify model comparisons, the momenta of singly charged composites[2] are weighted by 1/A, thus giving the protons in deuterons and tritons the same weight as unbound protons. The lower solid line in Figure 1 shows $\langle R\rangle$ for Cugnon's intranuclear cascade simulation[6], suitably filtered to simulate streamer chamber inefficiencies. The upper solid line in Figure 1 shows the cascade prediction with non-colliding nucleons removed.

Figure 1 indicates that even at maximum multiplicity, complete nuclear stopping ($\langle R\rangle \sim 1$) does not occur. The known streamer chamber inefficiencies can be neglected in interpreting the values of R reached at maximum multiplicity. Moreover, the removal of cascade spectator nucleons has such a small effect that the observed transparency at maximum multiplicity can hardly be attributed entirely to nuclear matter outside the geometrical overlap region.

Table I lists $\langle R\rangle$ values for U on U in two multiplicity bins, and for comparison, data for 1.2 A GeV Ar on KCl (350 events) is also shown. The Ar on KCl sample corresponds to the uppermost 12% of the inelastic multiplicity spectrum, as is the case for the U on U events. For each set of events, the multiplicity binning was chosen so that the sample was divided equally between the two bins. A noteworthy feature is the observed $\langle R\rangle$ for U on U in the upper multiplicity interval; this value is unexpectedly low, as judged either from comparison with the cascade simulation, or from the insignificant increase in $\langle R\rangle$ going from Ar to U. One possible reason for this effect is the deformed shape of uranium nuclei - deformations can decrease the average number of participant nucleons near zero impact parameter. However, preliminary simulations using a modified version of Cugnon's cascade code incorporating spheroidal nuclear shapes suggest that the uranium deformation[8] is not large enough to explain the observed effect within the framework of the cascade model. Further measurements are in progress to allow this question to be studied with better statistics.

	0.9 A GeV U on U		1.2 A GeV Ar on KCl	
	low mult	high mult	low mult	high mult
Experiment	0.58±0.02	0.61±0.03	0.51±0.01	0.59±0.01
Cascade	0.58	0.69	0.52	0.59

Table I: Values of $\langle R\rangle$ in two multiplicity intervals (see text).

The most commonly suggested[9-12] and employed[1-3] prescription for a more detailed shape analysis of 4π data is based on the general sphericity matrix S constructed from cm momentum components P_i: $S_{ij} = \Sigma\, wP_iP_j$; i,j =1,2,3 where the sum extends over the observed particles in an event, and retaining the weighting used above, we set $w = 1/A^2$ for singly charged composites. The eigenvalues, f_n, of S define an ellipsoid, with radii $\sqrt{f_n}$. We follow the convention $f_1 > f_2 > f_3 > 0$, and use θ_1 and ϕ_1 to denote the polar and azimuthal angles, relative to the beam axis, of the eigenvector corresponding to f_1. A peak away from $\theta_1=0$ in the distribution of flow angles, $dN/d\cos\theta_1$, is considered to be a signature of collective flow,[11,13] i.e., it signifies a sidewards deflection of the momentum flux in excess of the random deflection attributable to finite multiplicity.

Figure 2(a) shows the observed flow angle distribution[14] for U on U. Figure 2(b) shows the same distribution for events generated by Cugnon's cascade code. The experimental results, as presented in Figure 2, indicate a collective flow signature that is not substantially greater than the cascade model prediction, and are also consistent with zero flow.[11,13]

An analysis based on $dN/d\cos\theta_1$ distributions is less than ideal for detecting possible cooperative behavior, particularly in a small sample. It constrains events to fit an ellipsoidal shape, reduces the wealth of detail in 4π exclusive data to just one parameter, and greatly increases the statistical weight of events with small θ_1. Furthermore, θ_1 can be quite sensitive to imperfections in model simulations.[2] As an alternative, we present 3-dimensional plots of p_t = transverse proton and pion momenta summed within bins of rapidity, y_{cm}, and azimuth, ϕ. Apart from a loss of resolution through binning, this prescription essentially preserves all the information contained in the original measurements. To coherently average the plots over a number of events, we estimate the azimuth ϕ_b of the reaction plane for each collision, and rotate the event through $-\phi_b$ about the beam axis. ϕ_b can be estimated from the missing transverse momentum vector for tracks with $y_{cm} > 0$, or from the ϕ_1 value yielded by the sphericity analysis; both methods give similar results.

Figure 3 shows the $\langle p_t\rangle(y_{cm},\phi)$ plot, spanning all y_{cm} values, for a subsample of 20 events. (For the remainder of our sample, tracks which clearly lay at $y_{cm} < 0$ were not measured.) While there is evidence of the expected forward-backward symmetry, the effects of target absorption and lower detector efficiency for $y_{cm} < 0$ are also apparent. We confine quantitative comparisons with models to the forward hemisphere (Figure 4(a)). The predictions of Cugnon's cascade model, and of the statistical explosion-evaporation code of Fai and Randrup,[15] are shown in Figures 4(b) and 4(c), respectively. The statistical code incorporates phenomenological

collective effects, but these are switched off in Figure 4(c); the azimuthal structure in this figure is partly the result of statistical fluctuations coherently aligned by the ϕ rotation procedure, and partly due to angular divergence of the incident beam (a small background effect which is incorporated in the streamer chamber filter). In the case of the cascade simulation, additional azimuthal correlations can arise as a result of geometrical shadowing effects.[9,11,16]

Direct comparisons of the simulations in Figures 4(b) and 4(c) with the experimental data in Figure 4(a) yield values of χ^2 per degree of freedom >10 in both cases. However, factors other than collective behavior probably contribute to these large discrepancies. Changing the flow parameters of the statistical model (see below) results in the projection $\langle p_t\rangle(y) = \int\langle p_t\rangle(y_{cm},\phi)d\phi$ remaining almost constant while the azimuthal structure changes significantly - yet $\langle p_t\rangle(y)$ for Figure 4(c) is markedly different from experiment.[17] To assess the statistical significance of the observed azimuthal correlations alone, χ^2 has been recalculated by several methods such that differences in $\langle p_t\rangle(y)$ do not contribute, including renormalizing each $\langle p_t\rangle$ vs ϕ slice, and applying empirical corrections to the rapidities of the simulated particles. The smallest resulting values of χ^2/dof for the two forward rapidity slices - 3.4 for cascade, 3.7 for the statistical model - are still too large to be explained in terms of random fluctuations. χ^2 values are no smaller if variables independent of particle identification are used, i.e., pseudorapidity $=-\ln\tan\theta/2$, where θ is laboratory polar angle, instead of y_{cm}, and number of particles instead of p_t. Assuming that the cascade code adequately simulates shadowing and other relevant nucleon-nucleon effects, the additional collective flow observed in this experiment is attributable to fluid-like cooperative behavior.

The statistical code incorporates two phenomenological collective effects inspired by hydrodynamical model predictions: (i) a side-splash[18] whereby a participant nucleon moving at an angle ϕ to the event flow axis has a collective cm momentum $P_p\cos\phi$ (the flow axis lies at a cm polar angle $\arctan\sqrt{[(b_{max}/b)-1]}$, where b is impact parameter); (ii) a spectator bounce-off[18] imparting a transverse momentum per nucleon $P_s\sqrt{[4v(1-v)]}$, where $v=b/b_{max}$. Both collective effects must be invoked to adequately parameterize the observed ϕ structure. In common with Plastic Ball results[3] for 0.4 A GeV Nb on Nb, our data are consistent with the azimuths of the side-splash and bounce-off being equal. The best fit reduces χ^2/dof, calculated as above, from 3.7 to 1.1, and corresponds to P_p = 0.21±0.03 GeV/c and P_s = 0.07±0.02 GeV/c, while the mean value of the term $\sqrt{[4v(1-v)]}$ for the simulated events is 0.8. The errors quoted reflect the dispersion arising from the different methods for isolating the azimuthal correlations, and from the different plot variables; the statistical errors are several times smaller. However, this analysis does not test the functional form of the flow parameterization, and the generally poor agreement between the statistical simulation and experiment limits the reliability of parameters based on this code.

The fitted collective parameters indicate that the peak of $dN/d\cos\theta_1$ should occur near 10^0, a value consistent with the observed distribution in Figure 2(a). Moreover, the $dN/d\cos\theta_1$ distributions for the statistical model, both with and without the fitted amount of collective flow, are consistent with Figure 2(a).

We conclude that our data, consisting of 41 high multiplicity collisions of 0.9 A GeV U on U, show signs of incomplete nuclear stopping right up to maximum multiplicity. An analysis in terms of 3-dimensional plots of transverse momentum versus cm rapidity and azimuthal angle shows significant azimuthal correlations, indicative of collective flow. Cugnon's cascade simulation does not reproduce these correlations. The widely used flow angle methodology yields an inconclusive result, indicating that flow angles are relatively insensitive to collective flow under the conditions of the present experiment.

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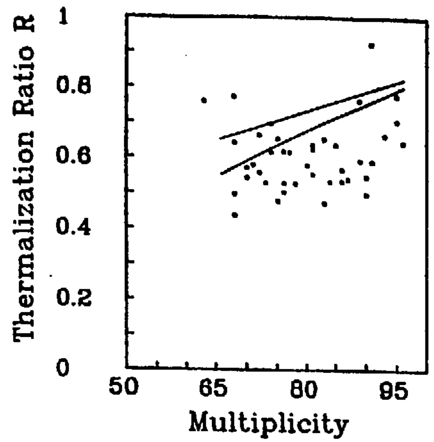

FIGURE 1: Ratio R for 41 observed 0.9 A GeV uranium on uranium events, as a function of the number of detected charged particles with rapidity $y_{cm} > 0$. The lower solid curve is the ⟨R⟩ prediction of Cugnon's cascade simulation, appropriately filtered. The upper solid curve illustrates the effect of removing the spectator matter.

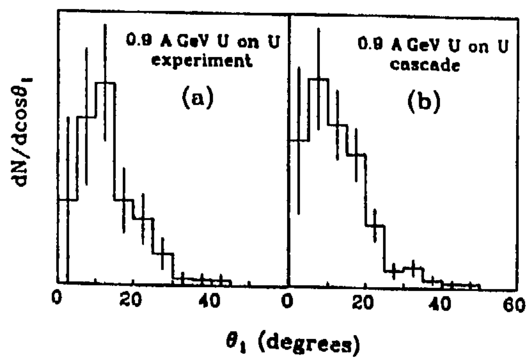

FIGURE 2: (a) Flow angle distribution for the 41 observed high multiplicity U on U events. (b) Corresponding prediction for 100 filtered events generated by Cugnon's cascade code. The vertical axes are plotted in arbitrary units.

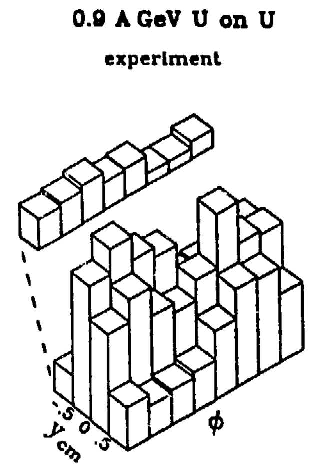

Figure 3: Plot of $\langle p_t\rangle(y_{cm},\phi)$, averaged over a subsample of 20 observed U on U events. Before averaging, each event was rotated about the beam axis to align its plane of preferred emission along $\phi=0$. For clarity, we have chosen $\phi=-90^{\circ}$ to be at the center of the azimuthal axis.

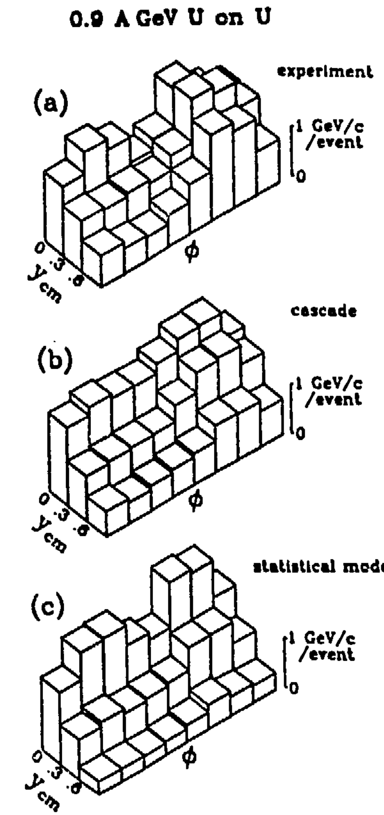

FIGURE 4: (a) Plot of $\langle p_t\rangle(y_{cm},\phi)$ for the full sample of 41 observed events (3296 tracks with $y_{cm} > 0$). (b) $\langle p_t\rangle$ plot for Cugnon's cascade model (100 events).
(c) $\langle p_t\rangle$ plot for the statistical model of Fai and R.ndrup (200 events), assuming no collective motion.