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Appendix C

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COMPARISONS OF VUU PREDICTIONS WITH STREAMER CHAMBER DATA

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Abstract

Experimental charged particle inclusive and exclusive parameters for several nuclear systems are compared with microscopic model predictions based on the Vlasov-Uehling-Uhlenbeck equation, for various density-dependent nuclear equations of state (EOS). Inclusive variables and multiplicity distributions are in good agreement, and are not sensitive to the EOS. Rapidity spectra show evidence of being useful in determining whether the model uses the correct cross sections for binary collisions in the nuclear medium, and whether momentum dependent interactions are correctly incorporated. Sideward flow parameters do not favor the same nuclear incompressibility at all multiplicities, and there are indications that the present model may provide only an upper limit on the true stiffness of the EOS. Findings relating to impact parameter averaging and the mass and energy dependence of transverse flow are also presented.

Theoretical estimates of the peak density attained during the compressional phase of relativistic nucleus-nucleus collisions are typically in the range 2 to 4 times normal nuclear matter density. Model simulations indicate that certain observables stabilize at about the same time that the nuclear density reaches its maximum, and remain essentially unchanged during the subsequent stages of the collision process.[1,2] Collective sideward flow is one such observable, and shows promise of providing valuable information about the equation of state (EOS) of compressed nuclear matter. Fluid dynamic models[3] were the first to predict collective nuclear flow, but lack the detailed predictive power of a microscopic approach. The intranuclear cascade,[4] which neglects compressional potential energy, was the first microscopic model to successfully reproduce a wide range of experimental results;

however, the current consensus is that the cascade model yields a collective flow signature that is finite.[5–8] but consistently smaller than experimentally observed.[9,10,5–8] There have been previous comparisons[11–13,8] between experimental flow data and microscopic models with realistic EOS implementation over the full range of nuclear densities. Due to statistical errors, or uncertainties associated with filtering the predictions to simulate experimental sample selection criteria and detector inefficiencies, these comparisons yielded only preliminary estimates of EOS properties. In addition, more basic questions have yet to be resolved - uncertainties in the nucleon-nucleon cross section in the nuclear medium.[14,15] and the neglect of momentum dependence[16–18] in models with EOS implementation through a local density-dependent mean field potential.

The model[12,2] used in this study is a microscopic simulation which can be considered a solution of the Vlasov-Uehling-Uhlenbeck[19] (VUU) equation. It proceeds in terms of a cascade of binary collisions between nucleons, Δ resonances, and pions according to the experimental scattering cross sections for free particles, corrected by a Pauli blocking factor. The isospin of each particle is explicitly incorporated. The dependence on the equation of state enters via the acceleration of nucleons in the nuclear mean field. It is assumed that the local potential, U, is determined by the density of nucleons within a radius of 2 fm, with a functional form $U(\rho) = a\rho + b\rho^{\gamma}$. The parameter γ fixes the incompressibility, K, and the remaining two parameters are constrained by nuclear equilibrium conditions. $\gamma = 2$ corresponds to $K = 380$ MeV, and implies a "stiff" EOS, while $\gamma = 7/6$ corresponds to $K = 200$ MeV, usually characterized as either a "medium" or "soft" EOS. A special "supersoft" case, in which $\partial U/\partial\rho = 0$ above $\rho = \rho_o$ (equilibrium nuclear density), conforms to the assumptions of the intranuclear cascade model. Since K is defined in terms of the second derivative of the binding energy at ρ_o, both the K value *and* the functional form $U(\rho)$ must be specified in order to fix the EOS at higher densities.

Before making detailed comparisons of charged particle exclusive parameters, it is appropriate to verify that inclusive spectra are adequately reproduced by the model. Accordingly, we first present a comparison of inclusive parameters for two experimental samples from the Bevalac streamer chamber and a relatively large set of VUU model events. In order to minimize the difficulty of correctly filtering model predictions to simulate the experimental sample selection criteria and detector distortions, cuts have been imposed to remove the projectile and target spectator regions. These cuts (see below) remove $Z \geq 2$

spectator fragments which are not correctly identified in the streamer chamber, and for which a production mechanism is not incorporated in most models. The experimental samples contain a total of 1357 1.2 GeV/nucleon ^{40}Ar beam events with observed charged multiplicity $M \geq 30$. 571 of the collisions were on a KCl target, the remaining 786 on a BaI_2 target. The condition $M \geq 30$ selects just over 20% of the inelastic cross section in the case of the KCl target, and just under 40% in the case of the BaI_2 target. The streamer chamber, trigger, particle identification criteria, and additional experimental particulars are described elsewhere.[8,9,20] For each of the three values of EOS stiffness mentioned above, we have generated model statistics amounting to typically 5 times the experimental samples, using a total of about 50 hours of Cray X-MP CPU time.

The kinematic cuts remove particles with momentum (momentum per nucleon in the case of composites) < 0.27 GeV/c in the rest frames of the target and projectile. Fig. 1 shows distributions of M', the multiplicity of charged particles after imposition of these cuts. In correcting for observational losses and remaining $Z \geq 2$ composites, the detector filtering process reduces M' for each VUU event by about 12%; otherwise, the plotted VUU spectra are unaffected by filtering. Below $M' \sim 25$, the sample selection criterion $M \geq 30$ causes the roll-off in the M' spectra, and events in this lower tail of M' are discarded in the subsequent analysis. The consistently good agreement between experiment and VUU in Fig. 1 is an indication that matching M' distributions is an effective way to establish correct impact parameter averaging for a model.

Fig. 2 shows rapidity distributions, after applying the above spectator cuts and the condition $M' \geq 24$. The dotted curves (labeled $0.7\sigma_{2-body}$) correspond to a version of the VUU model in which all binary collision cross sections have been reduced by 30%. The total number of 2-body collisions decreases by about the same factor. Likewise, the dot-dash curve demonstrates the effect of an increase in collision cross sections. These curves demonstrate that rapidity spectra are useful both for determining whether the model uses the correct 2-body collision cross sections,[14,15] and for addressing questions about momentum dependent interactions[16–18] (MDI), which influence the number of collisions. Thus, these spectra can fulfill the need[18] for collective flow signatures (sensitive to both the EOS and MDI) to be supplemented by another parameter sensitive to just one of these. The factors 0.7 and 1.4 were chosen in light of the study by Bertsch *et al.*[15] of the effect of varying the cross sections over a 2 to 1 range, and the finding of Aichelin *et al.*[18] that MDI reduce the number of

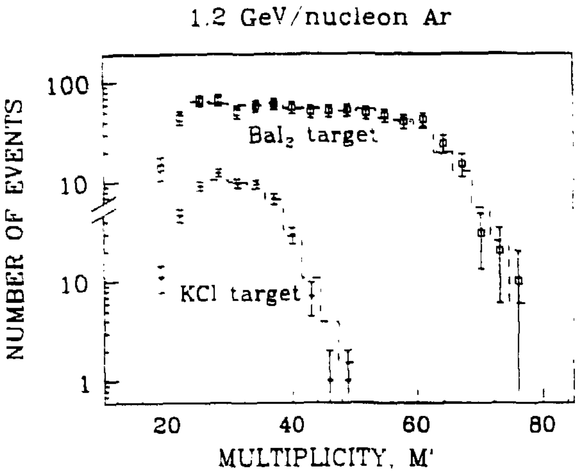

FIG. 1: Distributions of M', the total multiplicity of charged particles after cuts (see text). The dashed lines are the predictions of the VUU model, normalized to the same total number of events. Since the 3 VUU equations of state give essentially the same spectra, the 3 predictions have been averaged together in this plot. (The same is true for Figs. 2 and 3.)

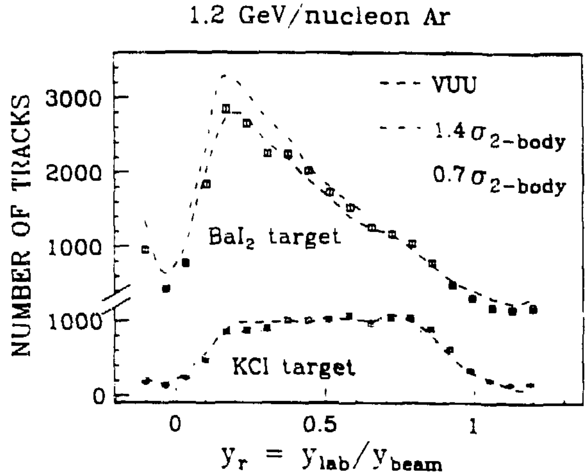

FIG. 2: Nucleon rapidity distributions for $M' \geq 24$, with spectator cuts. The results for the modified binary collision cross sections are shown only at rapidities where there is a significant difference between this calculation and the unmodified VUU model.

nucleon-nucleon collisions by 30% in the case of La + La at 0.8 GeV/nucleon. The current agreement between VUU (which does not incorporate MDI) and the experimental rapidity spectra suggests that any reduction in collisions due to MDI may need to be counteracted by an increase in the collision cross sections, possibly attributable to in-medium effects.

Fig. 3 presents distributions of transverse momentum per nucleon in three rapidity intervals. The good overall agreement between predictions and experiment again confirms that the VUU model accurately reproduces parameters which are not sensitive to the nuclear EOS.

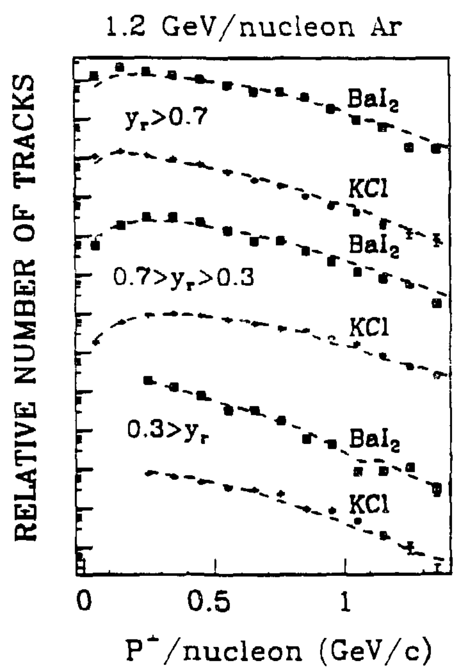

FIG. 3: Transverse momentum spectra for experiment and VUU in three rapidity intervals, where $y_r = y_{lab}/y_{beam}$. The vertical scale is in arbitrary logarithmic units.

The plot of $\langle p^x(y) \rangle$,[6] the mean transverse momentum/nucleon in the reaction plane as a function of rapidity, is now widely accepted[12,8,13,21–23] as the most useful parametrization of sideward flow. Fig. 4 shows $\langle p^x(y) \rangle$ for the same samples as in Figs. 1 to 3, along with VUU predictions for the 3 equations of state. While the multiplicity M' is still defined as in Fig. 1, with target and projectile spectator cuts, the projectile spectator cut has been omitted when calculating p^x. This has been done because the best sensitivity to the EOS coincides with rapidities $y_r \gtrsim 0.7$ in the upper half of the available multiplicity range as plotted in Fig. 1, and this region is excessively depopulated when the projectile spectator cut is applied. Ionization measurements on comparable samples confirm that the level of $Z \geq 2$ spectator-like fragments in this region is not large enough to distort the p^x comparisons.

Over the relatively narrow multiplicity interval available for Ar + KCl, no significant dependence of $\langle p^x \rangle$ on M' can be detected. We have confined the VUU comparisons to the rapidity region where the overall detector efficiency is high, and there is useful sensitivity to K. The Ar + KCl results in Fig. 4 favor incompressibilities in the medium to stiff range.

Fig. 4 also shows $\langle p^x(y) \rangle$ for Ar + BaI_2 in three M' intervals. Here, the VUU predictions show the same qualitative multiplicity trend as the experimental data, with the directed flow effect reaching a maximum at intermediate multiplicity, as expected. The extent of the agreement between the model and experiment is not affected by changing the definition of M' (i.e., changing the cuts). Over most of the M' spectrum, K values in the medium

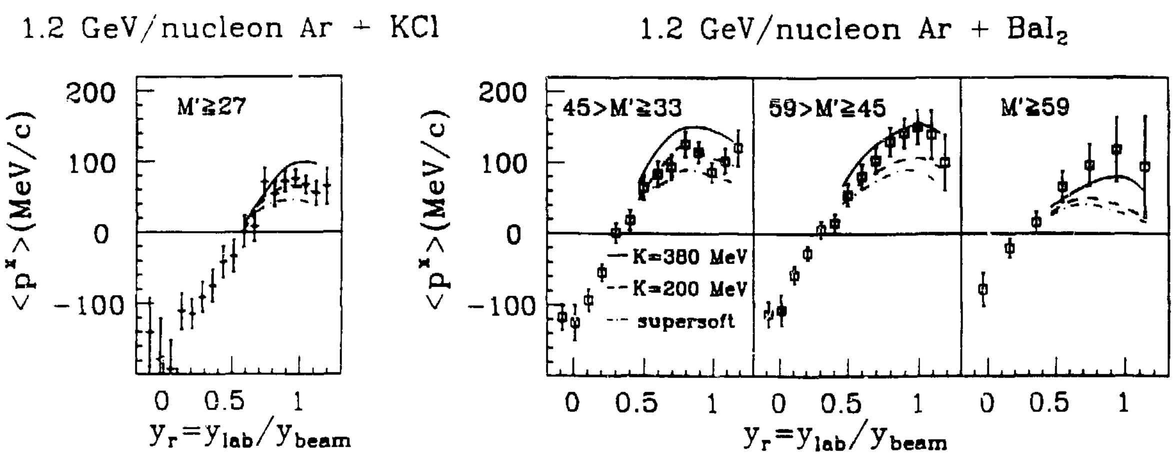

FIG. 4: Mean transverse momentum/nucleon in the reaction plane, as a function of rapidity. The VUU predictions are shown only over the rapidity region where there is useful sensitivity to the incompressibility, K (see text).

to stiff range are again favored. However, the predicted $\langle p^x \rangle$ drops off faster towards the highest multiplicities than indicated by experiment. (The last multiplicity interval, $M' \geq 59$, corresponds to the uppermost 5% of the inelastic multiplicity spectrum for Ar + BaI_2.) If it is postulated that this effect arises from a stiffening of the EOS at the higher densities associated with maximum multiplicity, then Fig. 5, which shows the M' dependence of the peak VUU nucleon density, provides an indication[24] that a very sharp increase in stiffness would be needed. It is also possible that the differing multiplicity dependence is associated with the fact that MDI[16–18] effects are neglected in the VUU model. At the very least, there are theoretical indications that a model without MDI can lead to overestimates of the incompressibility,[17,18] with the consequence that the present work may yield only upper limits on the true stiffness of the EOS.

Fig. 6 shows $\langle p^x(y) \rangle$ for 83 high multiplicity U + U events (~25% of the inelastic cross section). As in the case of 1.2 GeV/nucleon Ar + KCl, the multiplicity dependence is weak, and a medium to stiff K value is favored, but with poor statistical significance.

We emphasize that while appropriate

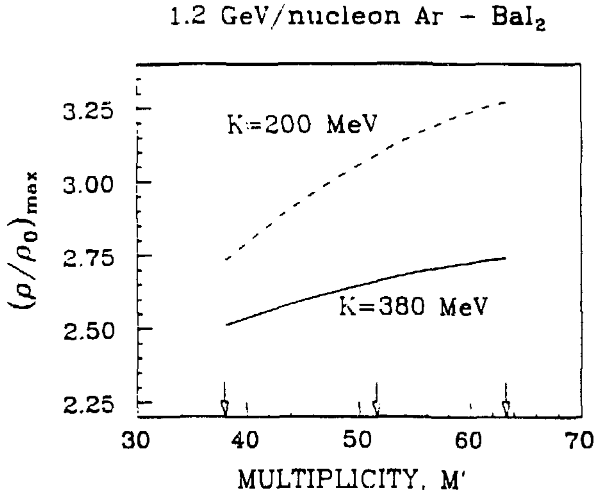

FIG. 5: The M' dependence of the mean nucleon density inside a sphere of radius 2 fm, at the time and position of maximum density in the VUU simulation of Ar + BaI_2 collisions. The three arrows along the M' axis denote the mean values for the three M' intervals for Ar + BaI_2 shown in Fig. 4. The half-maximum half-widths of the distribution of density at the peak are in the range 0.7 - 0.9 ρ_o.

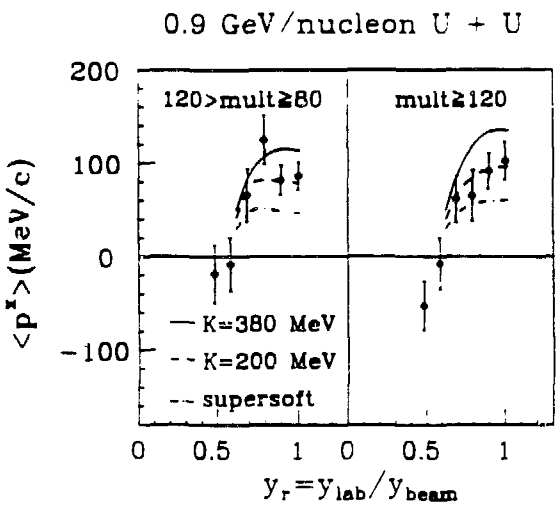

FIG. 6: As Fig. 4, but for collisions of ^{238}U + ^{238}U.

cuts can partly circumvent the need to simulate detector distortions and inefficiencies when comparing a model with experiment, there is no simple substitute for correct simulation of the impact parameter averaging associated with multiplicity and/or trigger selected subsamples. In order to illustrate this effect, we have taken VUU events for $K = 380$ MeV and plotted $\langle p^x(y)\rangle_{max}$ as a function of both impact parameter, b, and participant multiplicity, M'. Taking the peak of these plots, we define the ratio $P_{bM} = \langle p^x(y,b)\rangle_{max}/\langle p^x(y,M')\rangle_{max}$. For 1.2 GeV/nucleon Ar + KCl, we find $P_{bM} \sim 1.24$; for Ar + BaI_2 at the same energy, we find $P_{bM} \sim 1.16$. With the possible exception of the very heaviest systems, it is evident that non-trivial uncertainties arise if it is assumed[2] that $P_{bM} \sim 1$.

Table I summarizes all currently available transverse flow results from the Bevalac streamer chamber, based on a total of over 10^5 fully reconstructed events. VUU predictions have been generated for 6 systems corresponding to the boldfaced entries in Table I. As discussed above, it is not possible to conclude that one particular EOS is unambiguously favored; nevertheless, the percentage changes predicted using either the medium or hard EOS are in each case consistent with the data. Doss *et al.*[21] have reported a plateau or a decrease in the transverse flow with beam energy above 0.65 GeV/nucleon, but point out that it is

TABLE I: Transverse momentum/nucleon in the reaction plane, averaged over forward rapidities ($y_r \gtrsim 0.7$), for streamer chamber samples with a minimum bias trigger and a multiplicity cut which selects ~25% of the inelastic cross section. The Ne beam results are preliminary.

Beam energy: (GeV/nucleon)	0.4	0.8	1.2	1.8
Ne+NaF	25		**48**	**60**
Ar+KCl		50±4 §	**65±5**	**95±5** §
La+La		72±6 §		
U+U		**85±10** †		
Ne+BaI_2				160
Ar+BaI_2			**120±10**	
Ar+Pb	60±7	140±7 §		

§ Central trigger data from the GSI/LBL group; reported in refs. 6 and 23.

† These U+U collisions were at 0.9 GeV/nucleon.

well possible that this effect is influenced by the Plastic Ball response. Moreover, Doss *et al.* parametrized the flow in terms of the slope of $\langle p^x(y)\rangle$ near mid-rapidity; if the *shape* of $\langle p^x(y)\rangle$ changes with energy, then the quantity given in Table I ($\langle p^x\rangle$ at forward rapidities) need not scale in the same way. Overall, it is not clear that the balance of experimental evidence supports the view[2] that there is a softening of the EOS at the higher densities associated with beam energies at and above 1 GeV/nucleon.

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24. The correct implementation of a "stiffening" of the EOS beyond a certain density requires a more elaborate functional form for the mean field potential, $U(\rho)$; however, the data in Fig. 5 imply that even a discontinuous jump from $K = 200$ MeV to $K = 380$ MeV at some critical density would not explain the differences in $\langle p^x(M') \rangle$ shown in Fig. 4.