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CIRCUMSTANTIAL EVIDENCE FOR A STIFF NUCLEAR EQUATION OF STATE

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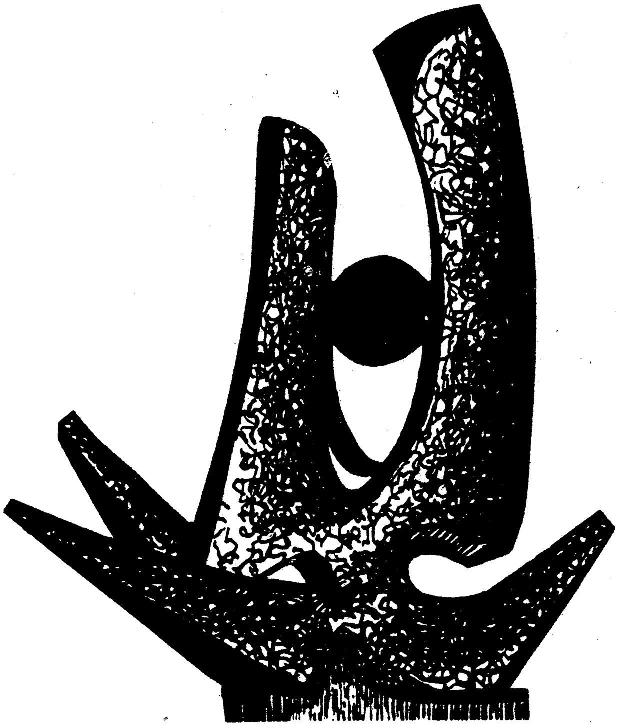

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Circumstantial Evidence for a Stiff Nuclear Equation of State

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We discuss the recent attempts to extract the nuclear equation of state from event-by-event data on high energy heavy ion collisions via the Vlasov-Uehling-Uhlenbeck theory. In this approach, the time evolution of the Wigner function is followed in configuration and momentum space. Rapid stopping of the projectile occurs at small impact parameters. For intermediate impact parameters, the theory predicts simultaneously the bounce-off effect of the projectile fragments and the sidewards flow of the participant matter. The latter can be displayed via a peak in the distribution of the flow angle Θ_F at large values of Θ_F, while the bounce-off is most easily observed via a pronounced maximum of the transverse momentum transfer $p_x(y)$ at the projectile rapidity. A drastic dependence of p_x and Θ_F on the mass of the colliding system, impact parameter, and bombarding energy is predicted. Recent data are used to extract an equation of state. The resulting EOS is consistently the same and in quantitative agreement with results obtained from pion multiplicities via various methods.

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High energy heavy ion collisions offer the unique opportunity to explore the properties of nuclear matter at extremely high densities, 10^{15} g/cm^3, and temperatures, $T > 10^{12}$ Kelvin,[1] where novel, exotic forms of matter may exist. We only have cognizance of matter at these densities and temperatures from our knowledge of parts of the universe remote in space and time, such as the big bang, supernova explosions, and the interior of neutron stars, for which the nuclear equation of state (EOS) is of special importance.[2] To prevent the collapse of neutron stars, for example, the pressure of the nuclear matter in the star must counterbalance the tremendous attractive gravitational forces.

More earthly access to the investigation of the nuclear EOS has opened recently with the availability of beams of heavy nuclei with energies up to 1 GeV/nucleon at the BEVALAC. Observable compression effects are the collective sidewards flow[1,3-5] and the lower than expected values of the pion multiplicity at high incident energies.[6] These are the results of the formation of a high pressure zone, which causes both a large transverse momentum transfer and the transformation of kinetic energy *to* compression energy. Recently, both effects have been observed[3-6] experimentally by the GSI/LBL and UC Riverside collaborations.

These experimental collaborations found a puzzling difference between near central collisions with high associated multiplicity and reactions with larger impact parameters or a smaller number of ejectiles. For example, a clear sidewards emission pattern was observed for the former events in the system Nb + Nb, while the less central reactions result in forward peaked angular distributions.[3] For intermediate impact parameters the projectile and target remnants get a strong sidewards kick (the bounce-off effect[1,3]) by the high pressure built-up in the overlap region. Quite analogous results were obtained in the streamer chamber experiments[4,5] for the reaction Ar(400 and 800 MeV/nucleon) + Pb. More recently also collisions of Au (150, 250, and 400 MeV/nucleon) on Au and U (900 MeV/nucleon) on U have been studied.[5,7] It is observed that the collective flow effects are even more strongly pronounced in the Au + Au system,[7] although for U + U at the higher energy, the flow angle is smaller.[5] These pioneering experiments establish a collective fluid-like behaviour of dense and hot matter in high energy nuclear collisions, which is governed by the nuclear equation of state.

How can one connect these collective flow effects quantitatively to an equation of state? Thermodynamic concepts have long been used to characterize the properties of excited nuclear matter formed in relativistic heavy ion collisions. However such systems must exhibit substantial nonequilibrium features. To study this question one must go beyond the fluid dynamical model. However, it turns out that the data - which are qualitatively explained by the macroscopic fluid model - represent a challenge to any microscopic theory. The cascade approach,[8] which assumes that nuclear collisions proceed via a sequence of independent free space nucleon-nucleon collisions, predicts forward peaked angular distributions even in central collisions, in contrast to the data. This is because the cascade neglects the repulsive nuclear compression potential.

A microscopic theory of heavy ion reactions based on the Uehling-Uhlenbeck equation has recently been developed.[9] It incorporates nonequilibrium effects, the Pauli principle, pion production, the density dependence of the compressional potential energy and enables a study of the approach to equilibrium via n-n collisions. Recall that the Vlasov-Uehling-Uhlenbeck equation[9] gives the time evolution of the single particle distribution function $f(\vec{r},\vec{p},t)$ under the influence of a mean potential field U in a system with two body collisions, where the particle obey the Pauli principle. The equation may be derived from the quantum Liouville equation by introducing the

Wigner function and truncating the BBGKY hierarchy; as in the analogous but classical derivation of the Boltzmann equation, one then makes the 'Stossansatz' for the collision term based upon the gain and loss of particles in phase space. We actually go beyond this equation in the VUU theory by introducing both particle creation and as much of special relativity as possible.[9] Protons, neutrons, deltas and pions of different isospin are included separately with their experimental scattering cross sections.

For the baryon density dependent potential field $U(\rho)$, two different local Skyrme interaction are used: one with a compressibility coefficient of $K = 200$ MeV at $\rho = \rho_o$:

$$U(\rho) = -356\ \rho/\rho_o\ \text{MeV} + 303\ (\rho/\rho_o)^{7/6}\ \text{MeV} \qquad (1a)$$

the second

$$U(\rho) = -124\ \rho/\rho_o\ \text{MeV} + 70.5\ (\rho/\rho_o)^{2}\ \text{MeV} \qquad (1b)$$

with $K=380$ MeV. The latter, stiff equation of state has been found necessary to explain the pion yields and collective flow effects[9,10] in symmetric and asymmetric collisions within the context of the present model.

In Fig. 1 and 2 we show the stopping and the approach to equilibrium by simulating the time development of Ar + Pb reactions in the VUU[9,10] approach. The time development of the nucleonic distribution function in configuration and momentum space is shown for Ar (770 MeV/nucleon) + Pb collisions at different impact parameters. Observe in Fig. 1 that the Ar projectile is completely consumed by the Pb target at low impact parameters. The squashed elliptical shape at $b = 1$ fm, $t = 10$ fm/c indicates the high density formed in the collision.

The directed sidewards flow of nucleons is easily seen in configuration space (Fig. 1) at $b = 3$ and 5 fm by the excess of nucleons with non-zero p_x in the quadrant with $x < 0$ and $z < 0$ as early as $t = 20$ fm/c. Spectator fragments are also observed, especially at $b = 5$ fm. The projectile is seen to not just shear off the target; it rather experiences a substantial transverse momentum transfer away from the region of high density - the bounce-off effect.[1]

The momentum space evolution of the single particle distribution function in Fig. 2 exhibits rapid equilibration at low impact parameters: observe that the projectile sphere in momentum space is rapidly depopulated by two body collisions at $b = 1$ and 3 fm. At $t = 5$ fm/c substantial filling of the nucleon-nucleon center of momentum region is visible, signaling the formation of a participant zone. At $t = 10$ fm/c, there are practically no nucleons left in the originally densely populated projectile momentum sphere; almost all of the projectile nucleons have been scattered out of their initial momentum states.

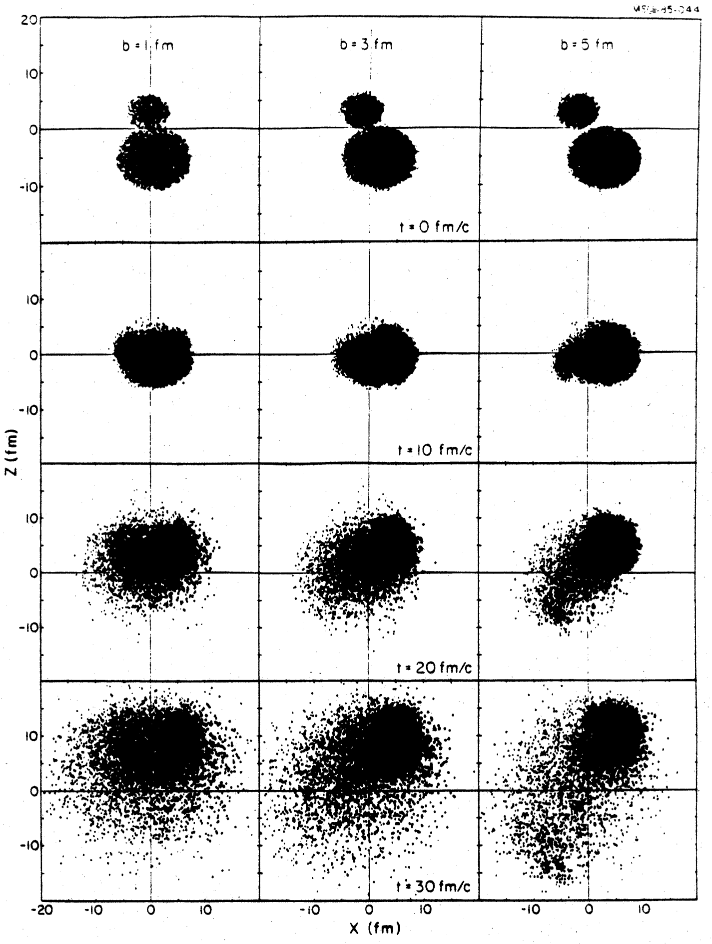


FIGURE 1
The evolution of Ar (770 MeV/N) + Pb in configuration space at b=1, 3, and 5 fm. The results from 30 ensembles are superimposed in order to represent the distribution function.

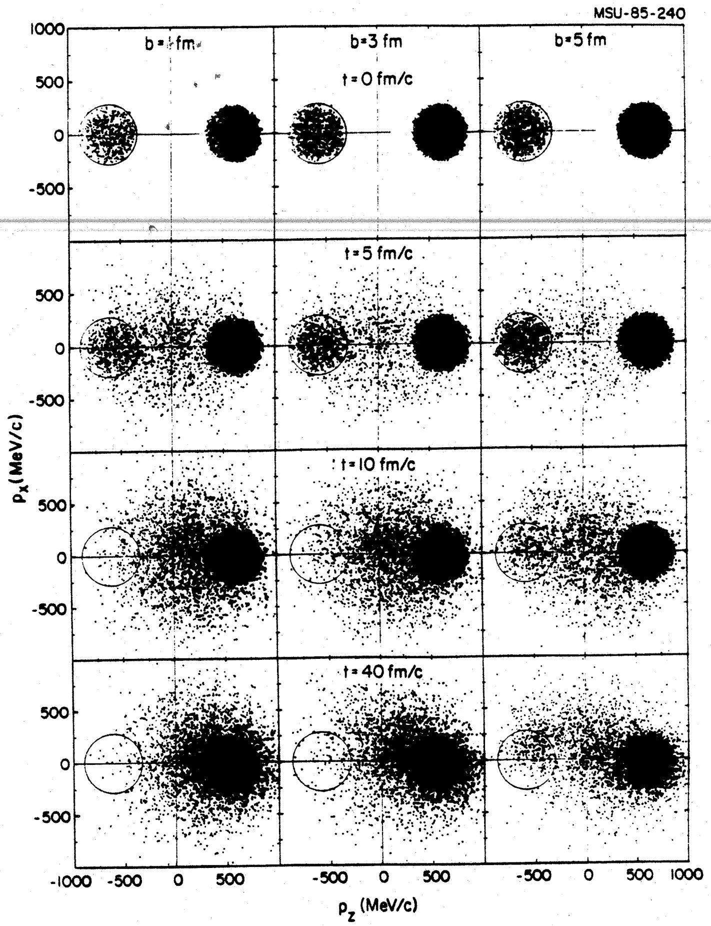


FIGURE 2
Same reaction as Figure 1, but the time development in momentum space is shown.

At t = 40 fm/c hard n-n collisions cease, the final state in momentum space is closely approached.

At the intermediate impact parameter, b = 5 fm, the situation is more complicated: since projectile and target exhibit only about half overlap, there is a substantial number of projectile nucleons which do not collide with target nucleons. Hence the depopulation of the projectile momentum sphere is incomplete, part of the projectile is stopped and forms the participant zone together with the struck nucleons from the target, while the projectile spectator nucleons move ahead with nearly their initial longitudinal momentum.

Experimental data of the GSI-LBL streamer chamber group[4] on the momentum distribution of the fragments are available for Ar + Pb. They have been analyzed using the momentum flow tensor $P_{ij} = \sum_\nu [p_i(\nu)p_j(\nu)/|p(\nu)|]/\sum_\nu |p(\nu)|$. The event by event analysis proceeds in a rather non-trivial way.[4] The center of mass velocity for each event is computed from the momenta of all charged particles with transverse momenta per nucleon greater than the Fermi momentum and then only the forward hemisphere of this participant center of mass frame is analyzed. The results are shown in Fig. 3, upper frame. The corresponding predictions of the VUU-theory, derived with the stiff equation of state, are shown in the middle frame of Fig. 3. Both in theory and experiment a broad bump is observed in the angular distribution of flow angles for near central collisions, while a rather sharp peak occurs at 15 - 30 degrees for the medium impact parameters, i.e. intermediate multiplicity events. This contrasts strongly with the results of intranuclear cascade calculations,[8] which exhibit forward peaked angular distributions independent of impact parameter as well for asymmetric as for symmetric collisions.

We have also done the flow analysis in the more rigidly defined nucleon-nucleon center of momentum system with the coalescence invariant kinetic energy flow tensor:[11] $K_{ij} = \sum_\nu p_i(\nu)p_j(\nu)/2m(\nu)$. The analysis is restricted to the projectile momentum hemisphere $p_z < 0$, since this will avoid the distortion of the event shape by the large number of target spectators at rather small momenta and thus best reflect the flow of the participant nucleons. We see in Fig. 3, lowest frame, that the flow distribution changes it's characteristics in particular for the high multiplicity events. One now sees a distribution skewed towards 90° for the small impact parameters, while the peak remains near 20° degrees for the intermediate impact parameters. This is similar to the results for symmetric systems; the peak of the flow angle distribution decreases with increasing impact parameter[1,3,10,12].

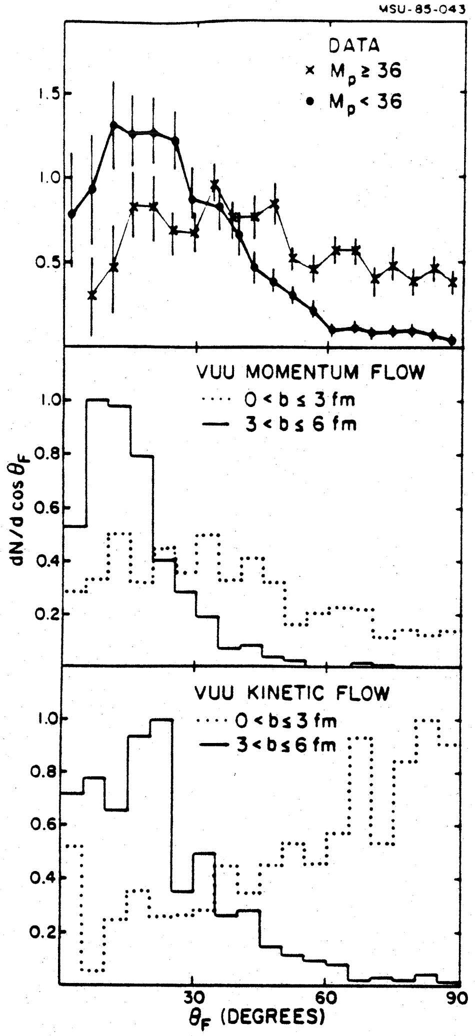


FIGURE 3
Flow angle distributions for Ar (770 MeV/N) + Pb: (upper frame) the experimental data with high and low multiplicity cuts analyzed using the momentum flow tensor; (lower frame) a standard kinetic energy flow analysis done in the N-N center of momentum frame using only the projectile momentum hemisphere.

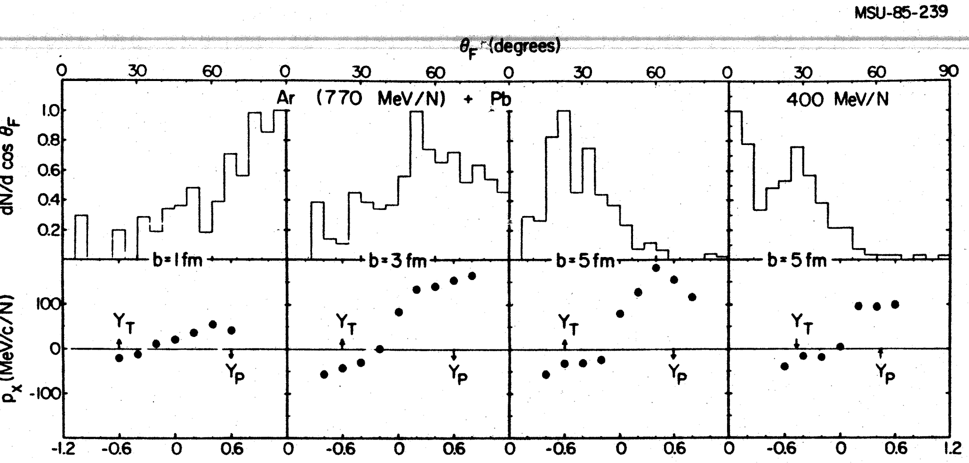


FIGURE 4
Two different methods for detecting collective flow for Ar (400 and 770 MeV/nucleon) are shown: (upper frames) the standard kinetic energy flow analysis is done on the forward hemisphere for b=1, 3, and 5 fm; (lower frames) the transverse momentum analysis is shown at the same impact parameters.

In Fig. 4 we compare, within the VUU calculation, the standard kinetic energy flow distributions for individual impact parameters to the transverse momentum analysis proposed recently by Danielewicz and Odyniec[13]. The flow angle distribution in Fig. 4 is skewed to 90 degrees at b = 1 fm, i.e. the projectile momentum hemisphere exhibits sidewards peaking as is evident from Fig. 2; a significant number of particles are thrust to the side perpendicular to the beam axis. A broad peak around 55 degrees is observed at b = 3 fm. For b = 5 fm, there is a clear peak at 20-30 degrees. Thus it is only at the intermediate impact parameters that the flow is evident by a sharp peak in such asymmetric systems.

A strong dependence of p_x on the impact parameter is also predicted in the transverse momentum plots, lower row of Fig. 4. The maximum value of p_x is zero for central collisions (for symmetry reasons). It rapidly rises with impact parameter up to b = 5 fm and drops to zero again for the largest impact parameters. This phenomenon should be experimentally observable via a decrease of p_x at small and very large multiplicities.

The bombarding energy dependence of the $p_x(y)$ values shows the following behaviour: the transverse momentum transfer $p_x(y_P)$ decreases from nearly 150 to 100 MeV/c/nucleon for Ar + Pb at 5 fm for E_{lab}/nucleon equal to 770 MeV or 400 MeV, respectively (see Fig. 4). As the energy is decreased further to E_{lab}= 90 MeV/nucleon, the transverse momentum at beam and target rapidities is zero to within 10 MeV/c/nucleon.[9,10]

Let us now test our equations of state with recent data from the Ar + KCl[6,14] and Nb + Nb[3] systems. First, consider the bombarding energy dependence of the negative pion multiplicities $<\pi^->$ (Figure 5)[6]. A comparison of the experimental data and the VUU calculation with the stiff equation of state is shown. As a reference case, we have also plotted the results of a "cascade" calculation, obtained from the VUU approach by neglecting the interaction and applying Cugnons "Pauli principle" (n-n collisions with c.m. energy below 50 MeV/nucleon are inhibited). Our "cascade mode" agrees quantitatively with the classical cascade[6,8], while it differs substantially from the results of the VUU, when we include a repulsive interaction potential and the phase-space Pauli blocker.

Take the 360 MeV/nucleon data, for instance: the negative pion yield is 1.05 in the "cascade mode", but drops by a factor of 2 - to 0.56 - if the stiff equation of state is included; the suggested large influence of the nuclear matter equation of state[1,6] is observed. The pion yield drops further (to 0.46) when the Uehling-Uhlenbeck Pauli blocking is applied. These numbers differ by a factor of 3 from results published in Ref. 15, where a method similiar to the present one has been used to solve the Boltzmann equation. A revised version of that program now produces our results.

Over the whole energy range from 400 MeV to 1.8 GeV, the VUU approach with the stiff equation of state plus phase space Pauli blocker compares well with the Ar + KCl data[6], while the "cascade mode" overestimates the pion yields by factors > 2 at energies up to 1 GeV, just like the cascade calculations themselves[6,8]. The drop in the pion yield is found due to the transformation of kinetic energy into potential energy during the high density phase of the reaction as well as due to Pauli blocking. To check the sensitivity of the pion yields on the equation of state, we have repeated the VUU calculations with the medium potential (1a). At 772 MeV per nucleon we find $\langle \pi^- \rangle = 2.45 \pm 0.09$ and 2.13 ± 0.07 with the medium and the stiff equation of state, respectively. At lower energies, statistical error bars of 30% preclude an accurate assessment of the influence of the potential. At all other energies, where the statistical error bars are smaller, the yields are systematically higher (by about 10%) with the medium equation of state than with the stiff one. Thus the experimental multiplicity selected pion yields in the Ar + KCl system[6] point towards a stiff nuclear matter equation of state.

The novel transverse momentum analysis technique[13] has also been applied to the Vlasov-Uehling-Uhlenbeck results for the Ar + KCl reaction (1800 MeV/nucleon, b < 2.4 fm)[14]. We find that the peak in the transverse momentum spectrum $p_x(y)$ depends strongly on the stiffness of the nuclear EOS: the cascade model predicts $p_x^{max} \approx 25$ MeV/c/nucleon (Fig. 6b); the medium equation of state (1a) leads to $p_x^{max} \approx 50$ MeV/c/nucleon in the VUU approach (Fig. 6d); and the stiff equation of state (1b) yields $p_x^{max} \approx 100$ MeV/c/nucleon (Fig. 6c). Only the latter is in agreement with the data (Fig. 6a)[14]. It is interesting to remark that this equation of state agrees rather well with the one extracted phenomenologically from the pion yields (Fig. 7)[6].

Let us turn now to the heavy, symmetrical Nb + Nb system. Experimentally, probability distributions of the flow angle, derived from the kinetic energy flow tensor, have been determined[3] in multiplicity selected collisions (E_{lab}= 400 MeV/nucleon). Cascade calculations produce forward peaked distributions[3,16] while sidewards peaking was observed (Fig. 8b). We would like to emphasize here the important role of a binding potential: if the binding potential is neglected as in Cugnon's original program[8,16], finite flow angles may be obtained[17] simply as a result of the sidewards expansion of the unbound projectile and target nucleons. This is demonstrated in Fig. 8c, which shows the flow angle distributions obtained with the original Cugnon program[8]

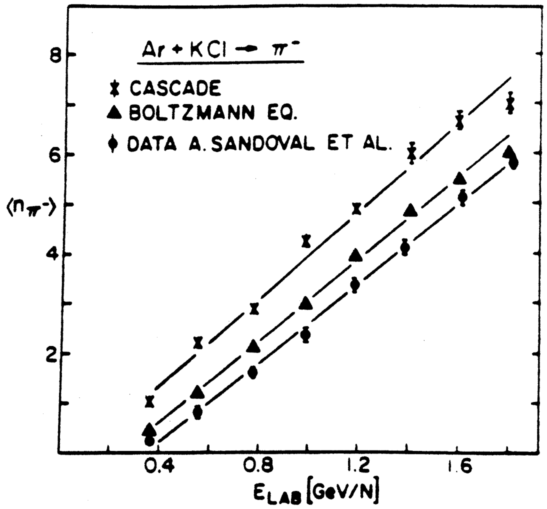
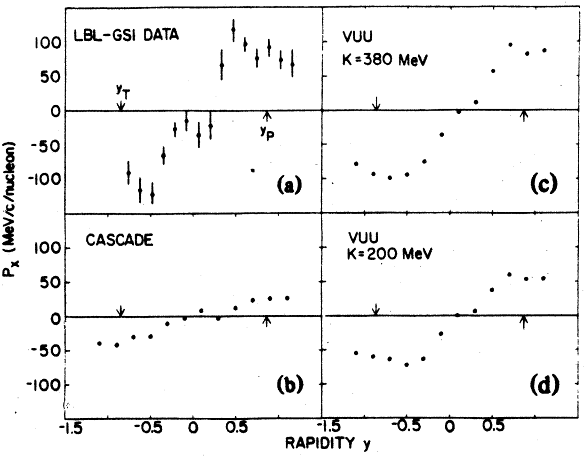


FIGURE 5
Pion multiplicity for central collisions (b<2.4 fm) of Ar+KCl. The data (Ref. 6, circles) are compared to the present theory in the "cascade mode" (crosses) and to the same theory with compression energy and phase-space Pauli blocking included (triangles).

FIGURE 6
In plane transverse momentum vs. rapidity for Ar(1800 MeV/nucleon) + KCl for (a) the experimental results (Ref. 14) based on the Streamer Chamber data (Ref. 13), (b) the intranuclear cascade model (Ref. 8), (c) the VUU approach with the stiffer equation of state and (d) the VUU approach with the softer equation of state.



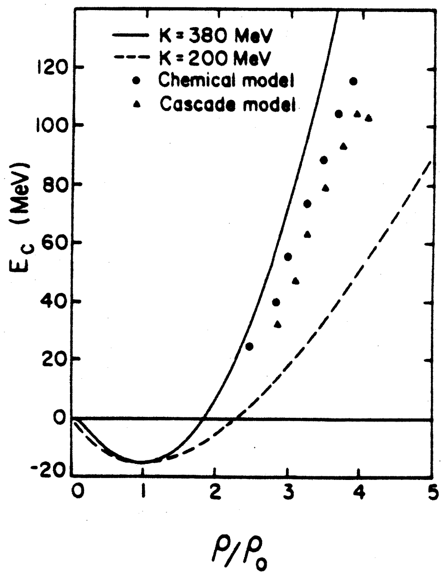


FIGURE 7
The nuclear equation of state with K=200 MeV and K=380 MeV as used in the Vlasov-Uehling-Uhlenbeck theory compared with values extracted from pion yields (Ref. 6).

(i.e. unstable nuclei) and the modified version[6,16] of his code with "frozen" Fermi momenta.

Fig. 8a shows the results of the VUU calculation with the medium and the stiff equation of state for the impact parameter b = 1 fm (high multiplicity). Observe the strong sidewards maximum at large angles in both cases and the drastic influence of the equation of state: the average flow angle is 43^{o} with the stiff equation (1b) and 28^{o} with the medium equation (1a). A comparison with the experimental data for high multiplicities ($M_C > 50$) again supports the stiff EOS (1b).

Finally, we present predictions for the Nb + Nb system, concerning the energy dependence of the transverse momenta and the flow angle distributions. Fig. 9 shows transverse momenta for a medium impact parameter b = 3 fm: $p_x(y_P)$ decreases from 135 MeV/c/nucleon at E_{lab}= 1050 MeV/nucleon to 35 MeV/c/nucleon at E_{lab}= 150 MeV/nucleon. At still lower energy, E_{lab}= 50 MeV/nucleon, the transverse momentum distributions are inverted as the attractive part of the nuclear potential and surface effects become dominant: the bounce-off caused by the short range repulsion at high density is converted into the negative angle deflection known from TDHF calculations in this energy region[18] and from experimental data.

A very peculiar structure is predicted for the dependence of the flow angles for Nb + Nb on the bombarding energy. As shown in Fig. 10 for b = 1 and 3 fm, Θ_F decreases with energy for E_{lab}> 400 MeV/nucleon, but it also decreases when going to a lower energy, E_{lab}= 150 MeV/nucleon. This maximum in the flow angle excitation function predicted here should be easily observable. A final word to the dependence of p_x and Θ_F on the mass of symmetric systems: we observe a strong increase of these quantities when going from Ca + Ca to Nb + Nb to Au + Au. Our findings are in agreement with preliminary data from the GSI/LBL Plastic Ball collaboration.[3,7]

In summary, we have studied the systems Ar + KCl, Ar + Pb, and Nb + Nb in the Vlasov-Uehling-Uhlenbeck theory. We find evidence of nuclear stopping at low impact parameters and rapid (t = 10 fm/c) local equilibration with a participant zone forming at intermediate impact parameters. The compressed nuclear matter pushes projectile remnants away from the beam axis, thus creating the bounce off effect at intermediate impact parameters, which is best observed in the p_x- analysis. The collective sidewards expansion of the compressed participant matter is best recognized in the flow angle distributions.

Two nuclear matter equations of state, a medium and a stiff one, have been tested on three different subjects: the pion multiplicities in relativistic

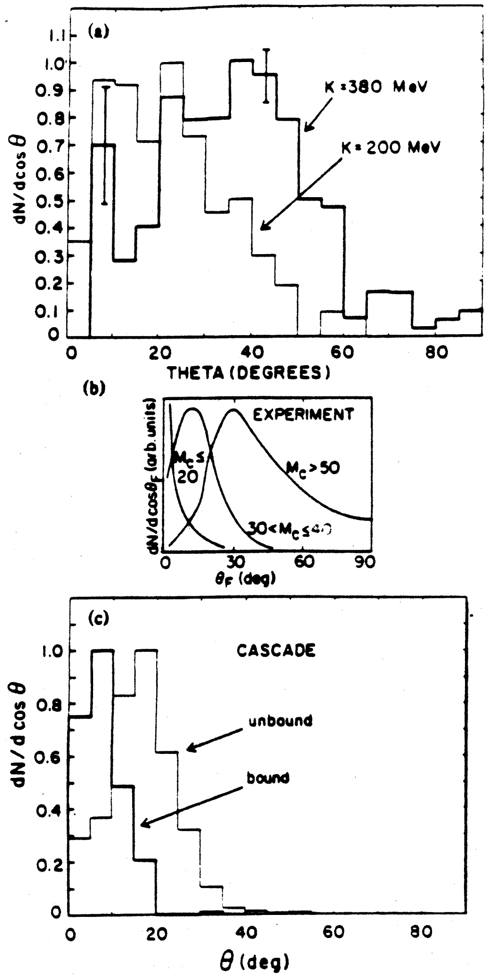


FIGURE 8

Flow-angle distributions $dN/d\cos\Theta_F$ for ^{93}Nb(400 MeV/nucleon)+^{93}Nb: (a) the present theory with the medium and hard equation of state; (b) "Plastic-ball data (Ref. 3) for various multiplicity bins; (c) results obtained with the standard cascade (Ref. 8) and the "frozen" Fermi-momenta approximation (Ref. 16).

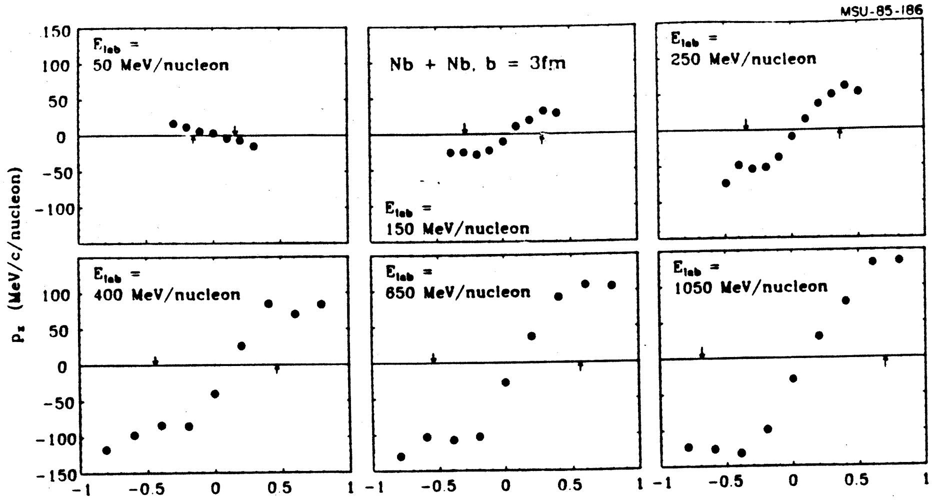


FIGURE 9

Energy dependence of transverse momentum $p_x(y)$ distribution for the reaction Nb+Nb at b=3 fm.

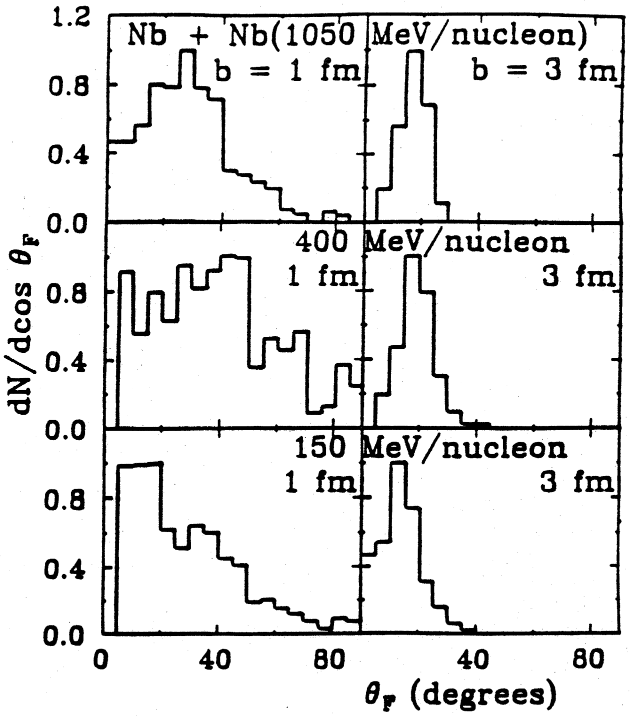


FIGURE 10
Nb + Nb flow angle distributions at 150, 400, and 1050 MeV/nucleon for b=1 and 3 fm impact parameters in the VUU approach.

heavy ion collisions, which are sensitive to the amount of kinetic energy transformed into compressional energy[6]; the transverse momentum dependence on the rapidity, where a stiff EOS increases the peaks at projectile and target rapidity caused by spectator matter (the bounce-off effect); and the sidesplash of the participant matter seen in flow angle distributions derived from the kinetic energy flow tensor. The comparison of the results of the VUU approach with experimental data in the Ar + KCl[6,14] and the Nb + Nb[3] system points in all three cases towards the stiff equation of state.

Much progress has been made both experimentally and theoretically in the methods of studying relativistic heavy ion collisions. Our first glimpse on the nuclear equation of state seems to reveal surprisingly large energies at densities about 2 - 4 times the ground state density. Over the next decade, even more difficult problems will be tackled when going into the ultra-relativistic regime at accelerators in CERN and Brookhaven. There the nuclei might be compressed and heated strongly enough, so that a new state of matter, i.e. the quark gluon plasma, would be created. The observation of such deconfinement constitutes an important test of some of the most fundamental ideas in particle physics and should cast new light on the crucial question of how particles can be composed of quarks. What has been achieved so far in the GeV/nucleon region is encouraging. Qualitative insight has been gained into the nuclear EOS. The precise determination of this equation of state will require much more effort, but it is a prize worth seeking.

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