arXiv:nucl-th/9607015 v1   11 Jul 1996

COLLECTIVE FLOW IN HEAVY ION REACTIONS AND THE PROPERTIES OF EXCITED NUCLEAR MATTER

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Quantum Molecular Dynamics (QMD) calculations of central collisions between heavy nuclei are used to study fragment production and the creation of collective flow. It is shown that the final phase space distributions are compatible with the expectations from a thermally equilibrated source, which in addition exhibits a collective transverse expansion. However, the microscopic analyses of the transient states in the intermediate reaction stages show that the event shapes are more complex and that equilibrium is reached only in very special cases but not in event samples which cover a wide range of impact parameters as it is the case in experiments. The basic features of a new molecular dynamics model (UQMD) for heavy ion collisions from the Fermi energy regime up to the highest presently available energies are outlined.

1   Introduction

The only possibility, how excited nuclear matter can be probed in the laboratory are nucleus–nucleus reactions [1]. In particular when two heavy ions like Au or Pb collide most centrally, the combined system forms a zone of high density and high random agitation of the involved constituents. However, it is still an open question, to which extent the system equilibrates and hence allows for the application of thermodynamical concepts [2,3,4].

From the experimental point of view it is clear that the measurable final state has to be compatible with an equilibrium configuration. Two basically different approaches are commonly used: i) analysis of the final spectra in terms of emission from a thermally equilibrated source, i.e. they should fall off as $\propto \exp(-E/T)$ and ii) analysis of the final fragment composition in terms of a chemically equilibrated source, i.e. the population of a state j is $\propto \exp(\mu_j/T)$, where the chemical potentials of all states are connected via some Gibbs equilibrium conditions.

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For the theory there are many other "observables", which may indicate the degree of equilibration reached. In this article we use the Quantum Molecular Dynamics model (QMD) to analyze the complete space time history of heavy ion collisions on a microscopic basis. The conclusions, which are drawn from the final state of the reaction only are confronted with that information, which is obtained from the knowledge about the intermediate reaction stages.

2 Quantum Molecular Dynamics

Quantum Molecular Dynamics [5,6,7] is a dynamical model which calculates the time evolution of a heavy ion collision in the entire many-body phase space. Nucleons are represented as gaussian wavefunctions

$$\varphi_j(\boldsymbol{x}_j) = \left(\frac{2\alpha}{\pi}\right)^{\frac{3}{4}} \exp\left\{-\alpha\Big(\boldsymbol{x}_j - \boldsymbol{r}_j(t)\Big)^2 + \frac{\mathrm{i}}{\hbar}\boldsymbol{p}_j(t)\boldsymbol{x}_j\right\} \tag{1}$$

and their centroids are propagated according to the canonical equations of motion

$$\dot{\boldsymbol{r}}_j = \frac{\partial H}{\partial \boldsymbol{p}_j} \quad \text{and} \quad \dot{\boldsymbol{p}}_j = -\frac{\partial H}{\partial \boldsymbol{r}_j}, \qquad j = 1, \ldots, A. \tag{2}$$

If two particles approach too close in configuration space, so that

$$d_{jk} \leq \sqrt{\sigma/\pi} \tag{3}$$

a hard collision is carried out in a similar fashion as in intranuclear cascades. The final state of each binary collision is checked to obey the Pauli-principle, otherwise the collision will not be performed – in other terms, the collision is Pauli-blocked.

3 Collective flow effects in heavy ion collisions

Collective flow effects in heavy ion collisions are known as a sensitive probe of compression of nuclear matter. For semicentral collisions the bounce-off in the reaction plane and the squeeze-out of matter perpendicular to the reaction plane have been predicted by nuclear hydrodynamics [1] and were later on observed at the Bevalac [8,9].

Meanwhile there have been numerous experimental as well as theoretical studies on impact parameter-, mass-, and bombarding energy-dependence of these phenomena. Presently there are two systematic studies of sideward flow excitation functions under way: The Ni+Ni system will be studied jointly by the INDRA and FOPI collaboration from 30 MeV/nucleon to 2 GeV/nucleon (GANIL–SIS energies). The Au+Au system is presently under intense investigation in the 1–4 GeV/nucleon energy regime with the EOS TPC at the

AGS [10]. The event shapes are very complex and only triple differential cross sections are suited for a complete characterization of such collisions.

However, the strongest compression effects and therefore also the most prominent flow effects are expected in collisions at vanishing impact parameter[3,11,12] Since all particles are participating in the reaction, also the possibility of reaching thermalization is highest in this case. By definition, in these collisions the directed component of sidewards flow vanishes. The expansion is azimuthally symmetric around the beam axis and may be divided into two components: a symmetric, but collective expansion of the excited nuclear matter towards transverse direction and an additional transverse momentum component due to the non-zero temperature. This is illustrated in Fig. 1. The directed transverse momentum is close to 0 for grazing reactions, and rises continuously until it reaches its maximum at 4–5 fm for Au+Au, whereafter it drops to 0 at b=0. On the contrary, the average transverse momentum is monotonously related to the impact parameter and can therefore be used as an impact parameter measure.

In the following we concentrate on the extreme case of b=0, where all nucleons involved undergo a rapid sequence of hard collisions which is a necessary condition for the approach of thermal equilibrium starting from a nonequilibrium configuration.

Fig. 2 shows transverse momentum spectra of various charged fragments obtained with QMD for the system Au (150 MeV/nucleon, b=0) + Au (symbols) together with fits to these calculated data, which are based on the assumption of a thermalized source of constant $T(r)$ and $\varrho(r)$ up to a maximum $r = R$ which exhibits an additional azimuthally symmetric transverse expansion with a linearly increasing expansion (flow) velocity profile, $v_\perp(r_t) = a \cdot r_t$, see [3]. In fact, the corresponding count rates have been fitted, rather than the invariant distributions, which are displayed. All spectra seem to be compatible with "temperatures" between 20 and 25 MeV and averaged collective flow velocities of 0.10–0.13 c. Similar temperatures have been obtained from fits to experimental spectra of the EOS [13] and FOPI-collaboration [14]. The large multiplicities of heavy fragments measured in the very same systems, however, suggested much lower temperatures on the order of 8 MeV [2]. This long-standing puzzle will be resolved below.

The collectivity is more emphasized in the spectra of the heavy clusters, since the thermal energy per nucleon drops as $1/A$. This is expressed in Fig. 3, where the averaged kinetic energy in the center of mass frame and the thermal energy per nucleon is plotted as a function of the fragment mass. The thermal energies obtained from the fit to the spectra show the expected fall off, whereas the total energy is shifted roughly by a constant amount due to the collective

expansion. Note: for light ejectiles like protons the collective energy amounts to only 30% of the total energy, for the heavy fragments the collective–thermal energy sharing is reversed (70–80% of the kinetic energy is collective).

Another interesting aspect of the many-body dynamics can be read off Fig. 3: The average available kinetic energy per nucleon in the center of mass after the reaction, which is indicated by the horizontal line, is considerably lower than the averaged kinetic energies of free nucleons. This excess energy can be associated with the heat released due to the formation of heavy fragments, which move with much lower kinetic energy per nucleon as compared to the average. The description of this behaviour is out of scope of one-body models like BUU/VUU, since they lack the many-body correlations, which are responsible for the formation of complex fragments. Thus these models also underpredict the averaged proton kinetic energies at low bombarding energies.

In order to study a macroscopic piece of nuclear matter, one can define a central reaction volume: here we take all cells where the local density exceeds half the maximum density at this instant. In Fig. 4 the properties of the excited matter inside this volume are displayed as a function of time. Even in the late stages of the expansion this zone still contains $\approx 1/3$ of the mass of the entire Au+Au system. The evolution of the widths of the local velocity distributions suggests a rapid cooling, which goes in line with a fast density decrease. The different temperatures tend to converge in the late stages only, therefore perfect thermodynamic equilibrium is not reached and the temperatures are much lower than the flow fit to the spectra would suggest.

At densities around 0.1–0.5 ϱ_0, where the freeze-out of fragments is expected to happen, the corresponding temperatures have dropped below 10 MeV. This is in agreement with the "chemical temperatures" employed for understanding the large intermediate mass fragment multiplicities.

Now the question arises what is wrong with the assumptions underlying the global fit to the spectra in Fig. 2. Assuming an overall thermally equilibrated source at some temperature T which disintegrates not only due to the thermal pressure but also due to some additional collective expansion, the probability of finding a particle which has some collective velocity $v_{\text{coll.}}$, i.e. $\mathrm{d}N/\mathrm{d}v_{\text{coll.}}$ is essentially unknown. It can be expressed as

$$\frac{\mathrm{d}N}{\mathrm{d}v_{\text{coll.}}} = \frac{\mathrm{d}N}{\mathrm{d}r} \cdot \frac{\mathrm{d}r}{\mathrm{d}v_{\text{coll.}}} = \frac{\mathrm{d}N}{\mathrm{d}r} \cdot \left(\frac{\mathrm{d}v_{\text{coll.}}}{\mathrm{d}r}\right)^{-1} . \tag{4}$$

Fig. 5 shows the shape of the local flow velocity profile. It rises linearly with r_{t}, in accord with prescription used for the spectral fit. The temperature $T(r_{\text{t}})$ (not shown) is in fact reasonably constant over the central volume. However, Fig. 5 shows that the density is not at all constant but rather resembles a Gaussian profile! This trivial statement has drastic consequences: The high

transverse momentum components of the particle spectra do not correspond to the high momentum tails of a hot source, but to fastly moving cooled cells[3,15] The microscopic analysis suggests that the combinations of density and temperatures, which are traversed in the course of the expansion, are in agreement with the expectations from expansion along curves of constant entropy per baryon as used in the quantum statistical analysis of the fragment distributions in the final state[2,16].

4 Extension of QMD towards relativistic and ultrarelativistic energies

The Quantum Molecular Dynamics approach has been recently generalized for simulations of the dynamics of heavy ion reactions over a broad range of energies, from 20 MeV/nucleon up to the highest presently available energies around 200 GeV/nucleon[17]. A large variety of baryonic and mesonic states and string excitations have been incorporated to cover continuously varying physics phenomena occurring over these four orders of magnitude in energy. The baryons, mesons, and resonances which can be populated in UQMD are listed in Tab. 1. Note that all charge conjugate states (antiparticles) are included and are treated on the very same footing as the particles. For higher mass excitations a string picture is employed. All states listed below can be produced in string decays, or in s-channel collisions, and decays of resonances.

The UQMD code allows for systematic studies of excitation functions over a wide range of energies in a unique way: the basic concepts and the physics input used in the calculation are the same for all energies. A relativistic cascade is applicable over the entire range of energies. A preliminary molecular dynamics scheme using a hard Skyrme interaction is used between 100 MeV/nucleon and 4 GeV/nucleon.

As an example excitation functions and scaling studies of baryonic stopping and transverse flow have been performed within the framework of the new UQMD model.

Baryonic stopping is a necessary condition for the creation of dense and highly excited nuclear matter[18]. The key observable is the rapidity distribution of baryons which is displayed in Fig. 6 for three presently used heavy ion accelerators. In all cases a system as heavy as Au+Au or Pb+Pb exhibits a gaussian rapidity distribution peaking at midrapidity. However, the physical processes associated are different: A shift in one unit of rapidity corresponds to completely different amounts of energy. Thus the average longitudinal momentum loss in the SIS energy regime is mainly due to the creation of transverse

momentum whereas at the AGS/SPS energy abundant particle production eats up a considerable amount of the incident energy.

The creation of transverse flow is strongly correlated with the underlying equation of state [1]. In particular it is believed that secondary minima as well as the quark-hadron phase transition lead to a weakening of the collective sideward flow. The occurrence of the phase transition should therefore be observable through abnormal behaviour (e.g. jumps) of the strength of collective motion of the matter [19]. Of course, UQMD in its present form does not include any phase transition explicitly. For the purely hadronic scenario the averaged in plane transverse momenta for Ni+Ni and Au+Au in the 0.1–4 GeV/nucleon region are displayed in Fig. 7. Calculations employing a hard equation of state (full symbols) are compared to cascade simulations (open symbols). In the latter case only a slight mass dependence is observed. For the calculation with potentials the integrated directed transverse momentum push per nucleon is more than twice as high for the heavier system which corroborates the importance of a non-trivial equation of state of hadronic matter.

The amount of directed transverse momentum scales in the very same way as the total transverse momentum produced in the course of the reaction. The $p_\mathrm{x}(y)$ therefore depend only on the reaction geometry but not on the incident energy. This is demonstrated through Fig. 8, where the mean p_x as a function of the rapidity divided by the average transverse momentum of all particles is plotted.

5 Summary

Collective motion of excited nuclear matter resulting in very complex event shapes is a well established phenomenon in heavy ion reactions. Triple differential cross sections only provide sufficient information to characterize the events. Even in head on collisions particle emission is non-isotropic and strong collective effects are present. Moreover, thermal equilibrium is established in very special cases and locally only. Slope parameters obtained from fits to the final momentum spectra give a wrong impression about the temperatures even if collective effects have been taken into account.

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N	Δ	Λ	Σ	Ξ	Ω
938	1232	1116	1192	1317	1672
1440	1600	1405	1385	1530	
1520	1620	1520	1660	1690	
1535	1700	1600	1670	1820	
1650	1900	1670	1790	1950	
1675	1905	1690	1775		
1680	1910	1800	1915		
1700	1920	1810	1940		
1710	1930	1820	2030		
1720	1950	1830			
1990		2100			
		2110			

0^-	1^-	0^+	1^+	2^+
π	ρ	a_0	a_1	a_2
K	K^*	K_0^*	K_1^*	K_2^*
η	ω	f_0	f_1	f_2
η'	ϕ	σ	f_1'	f_2'

Table 1: List of baryons, mesons, and resonances which are included in the UQMD model. In addition all charge conjugate states are treated on the same footing. For higher mass excitations meson- and (anti)baryon-strings are included.

Au + Au (150 MeV/nucleon)
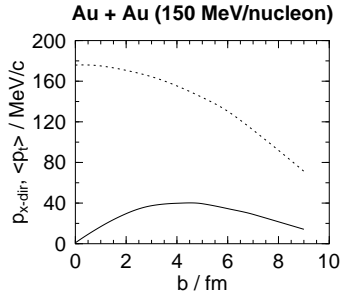
Figure 1: Averaged total and in-plane transverse momentum as a function of the impact parameter in Au (150 MeV/nucleon) + Au reactions.
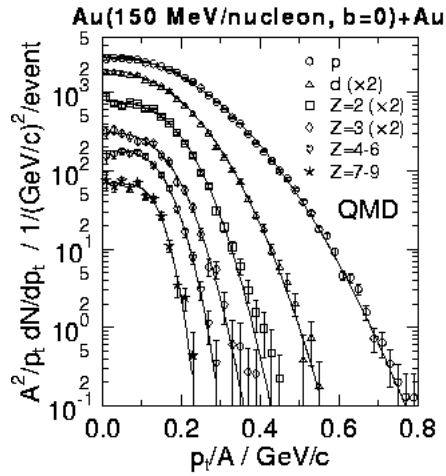

Au(150 MeV/nucleon, b=0)+Au

Figure 2: Invariant transverse velocity spectra of various reaction products of Au (150 MeV/nucleon) + Au at vanishing impact parameter. The predictions of the Quantum Molecular Dynamics model (symbols) have been fitted with a thermally equilibrated source, which expands azimuthally symmetric towards the transverse direction (lines). Note, all spectra are compatible with temperatures between 20 and 25 MeV and an averaged transverse collective velocity of 0.10–0.13 c.

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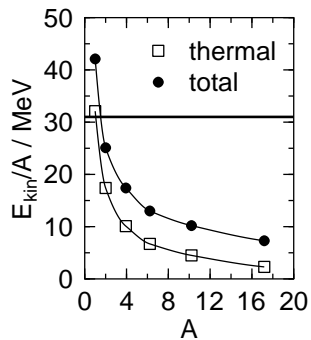
Figure 3: Averaged kinetic energies in the center of mass frame of central Au+Au collisions at 150 MeV/nucleon bombarding energy. The total energy (closed circles) clearly proves a non-thermal behaviour. The horizontal line indicates the kinetic energy per nucleon in the final state averaged over all fragments.
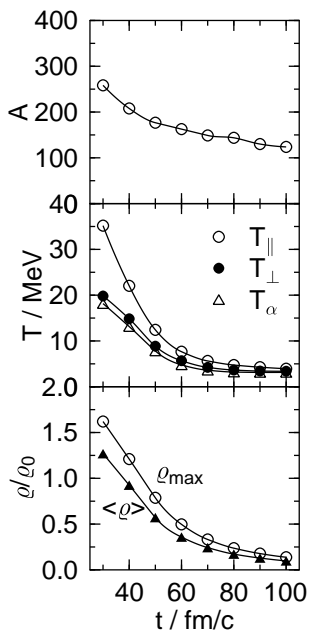

Figure 4: Thermodynamics in the central reaction zone, i.e. the volume where the local density is at least half of the maximum value. Mass content a), widths of the local velocity distributions b), and maximum as well as averaged density c) are displayed as a function of time.
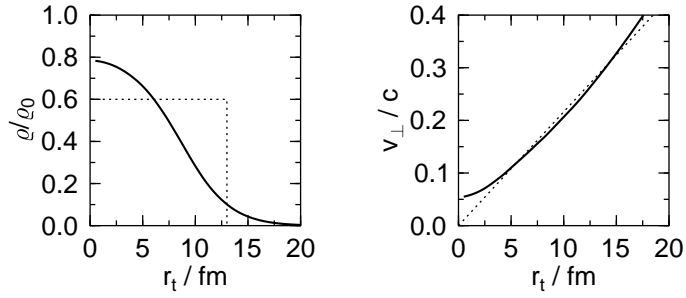
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Figure 5: Local density and collective velocities as a function of the transverse distance in the $z = 0$ plane. The Figure corresponds again to the situation at 50 fm/c. The calculated shape (solid lines) are compared to the assumptions which entered the global fit (dotted lines). The longitudinal as well as the azimuthal collective velocity vanish. $v_\perp$ does not reach 0 for $r_t = 0$ due to the fact that the innermost cell is not symmetric around the beam axis.
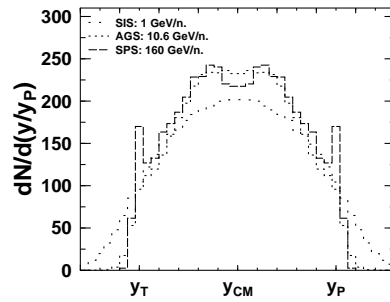

Figure 6: Rapidity distributions for Au+Au collisions at SIS (1 GeV/nucleon), AGS (10.6 GeV/nucleon) and CERN SPS energies (160 GeV/nucleon). All distributions have been normalized to the projectile rapidity in the center of mass frame.
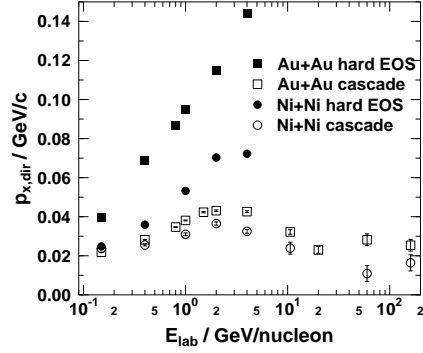
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Figure 7: Excitation function of the total directed transverse momentum transfer (px-dir) for the Au+Au and Ni+Ni systems. UQMD results including a hard equation of state (full symbols) are compared to the predictions of cascade calculations (open symbols).
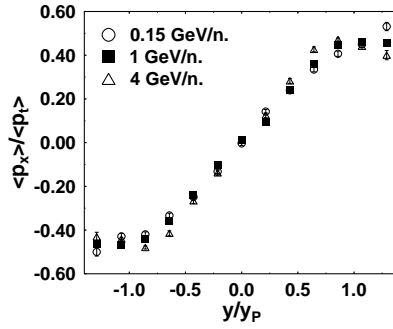

Figure 8: Mean directed transverse momentum as a function of the scaled rapidity. The calculations are performed for Au+Au at a fixed impact parameter of 4 fm. If the transverse flow is scaled with the mean transverse momentum, the directed flow does not depend on the bombarding energy.

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