High p_t pions as probes of the dense phase of relativistic heavy ion collisions

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The properties of pions from the hot and dense reaction stage of relativistic heavy ion collisions are investigated with the quantum molecular dynamics model. Pions originating from this reaction stage stem from resonance decay with enhanced mass. They carry high transverse momenta. The calculation shows a direct correlation between high p_t pions, early freeze-out times and high freeze-out densities. A measurement of the mass distributions of $p-\pi$ correlations (e.g., the Δ^{++}) in different p_t bins is proposed to distinguish different reaction stages.

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Recent experiments performed by the KaoS [1,2] and TAPS [3,4] collaborations at GSI and the EOS collaboration at the BEVALAC have revived the interest in pion spectra as tools for the investigation of relativistic heavy ion collisions at incident energies around 1 GeV/nucleon. Heavy ion collisions are the only experimentally accessible way of investigating hot and dense nuclear matter [5–14]. Early measurements of pion spectra in this energy domain were performed at the BEVALAC approximately 10 years ago [6,7]. The pion multiplicity was believed to be correlated to the thermal energy per nucleon, in addition to the compressional energy of high nuclear density [15,16]. However, the large cross section for pion-nucleon interactions in the intermediate and later phases of heavy ion collisions has severely hampered the usefulness of pion spectra in the investigation of nuclear properties and reaction dynamics.

With the new powerful KaoS, TAPS, and FOPI spectrometers at GSI and the EOS–TPS at LBL, it is now possible to systematically investigate pions with energies above the kinematic limit of 447 MeV for pion production in nucleon-nucleon collisions at 1 GeV/nucleon. The first measurements of such high p_t pions were performed at the BEVALAC [6], their main characteristic being that they can only be produced via multistep or collective processes. This means that either one of the colliding nucleons must have gained energy in a preceding collision or the intrinsic fermi momenta of the nucleons must add up to increase the available energy so that the mass of the produced Δ resonance is large enough to emit such a high energetic pion after its decay. Due to their production process, these pions are therefore thought to yield interesting information about the hot and dense reaction phase [1].

It has already been established that high p_t pions undergo less rescattering and freeze-out early during the heavy ion collision, especially when emitted perpendicular to the reaction plane [17]. In this paper we want to present direct theoretical evidence that high p_t pions indeed probe dense nuclear matter. For our investigation we have calculated 5000 collisions of Au+Au at 1 GeV/nucleon with the IQMD model which is an extension of the quantum molecular dynamics model (QMD) [18–21]. The IQMD model explicitly incorporates isospin and pion production via the Δ resonance [22–24]. In the QMD model the nucleons are represented by Gaussian shaped density distributions. They are initialized in a sphere of a radius $R = 1.14A^{1/3}$ fm, according to the liquid drop model. Each nucleon is supposed to occupy a volume of h^3, so that the phase space is uniformly filled. The initial momenta are randomly chosen between 0 and the local Thomas-Fermi momentum. The A_P and A_T nucleons interact via two- and three-body skyrme forces, a Yukawa potential, momentum-dependent interactions, a symmetry potential (to achieve a correct distribution of protons and neutrons in the nucleus), and explicit Coulomb forces between the Z_P and Z_T protons. They are propagated according to Hamiltons equations of motion. Hard N-N collisions are included by employing the collision term of the well known VUU/BUU equation [11,25–28]. The collisions are done stochastically, in a similar way as in the cascade models [29,30]. In addition, the Pauli blocking (for the final state) is taken into account by regarding the phase space densities in the final states of a two body collision.

Pions are treated in the IQMD model via the Δ resonance. The following inelastic reactions are explicitly taken into account and constitute the imaginary part of the pion optical potential, which is dominant in our energy domain: (a) $N\,N \rightarrow \Delta\,N$ (hard-Δ production), (b) $\Delta \rightarrow N\pi$ (Δ-decay), (c) $\Delta\,N \rightarrow N\,N$($\Delta$-absorption), (d) $N\pi \rightarrow \Delta$(soft-Δ production).

Experimental cross sections are used for processes (a) and (d) [31]; for the Δ absorption, process (c), we use a modified detailed balance formula [32] which takes the finite width of the Δ resonance into account. A mass-dependent Δ-decay width has been taken from [33]. In-between these inelastic reactions, pions are propagated on curved trajectories with Coulomb forces acting upon them. The different isospin channels are taken into account using the respective Clebsch-Gordan coefficients:

$$\Delta^{++} \rightarrow 1(p+\pi^+) \; ,$$

$$\Delta^{+} \rightarrow \frac{2}{3}(p+\pi^0) + \frac{1}{3}(n+\pi^+) \; ,$$

$$\Delta^0 \to \frac{2}{3}(n+\pi^0) + \frac{1}{3}(p+\pi^-) ,$$

$$\Delta^- \to 1(n+\pi^-) .$$

After a pion is produced (be it free or *bound* in a Δ), its fate is governed by two distinct processes: (1) absorption $\pi N N \to \Delta N \to N N$, and (2) scattering (resorption) $\pi N \to \Delta \to \pi N$.

The real part of the pion optical potential is treated in the following manner: As far as the pion is bound with a nucleon to a Δ resonance the density and momentum dependent real part of the nucleon optical potential is applied as an approximation to the (yet unknown) real part of the Δ optical potential. Due to the large π-N cross section, intermediate pions are quite frequently bound in a Δ resonance and in those intervals the real part of the pion optical potential is substituted by the real part of the Δ (in our case: nucleon) optical potential. Free intermediate and final charged pions experience Coulomb forces which contribute to the real part of the pion optical potential. Recent investigations on the influence of a nuclear medium correction to the dispersion relation of the free pion on pion spectra have shown conflicting results [34,35]. However, both (otherwise strongly disagreeing) calculations show that the high-energy part of the pion spectrum remains unchanged by this modification. Since our results are mainly achieved using this high-energy contribution we omit this medium correction until a consensus has been achieved on the proper form of the respective medium contribution.

Comparisons have shown, that the IQMD model is well able to reproduce experimentally measured pion spectra [4,36] with their concave shape. The fit parameters employed to fit the spectra with a linear combination of two Boltzmann distributions agree with experimentally extracted fits in the order of $\pm 10\%$. The 5000 events calculated with the IQMD model have impact parameters between 0 and 5 fm, linearly weighted towards 5 fm. Therefore the sample corresponds to the experimentally accessible semicentral impact parameter range.

Figure 1 shows the baryon density in units of nuclear ground state density versus time in fm/c for a sphere of 2 fermi radius around the collision center. For times up to 20 fm/c densities larger than nuclear ground state density are obtained in the collision center. We identify this time interval with the hot and dense reaction phase. Pions which leave this reaction phase without further interaction are the target of our investigation. These pions then can be used to investigate the hot and dense reaction phase. The question to be answered therefore is, whether pions leaving the hot and dense reaction phase have a unique signature by which they can be identified experimentally.

The mean transverse momenta p_t of pions versus their freeze-out time (the time of their final interaction in the heavy ion collision) is shown in Fig. 2 as a contour plot: High p_t pions are produced almost exclusively in the early reaction phase with freeze-out times smaller than 20 fm/c. The scaling of the contour lines in Fig. 2 is linear, far higher transverse momenta are obtained than depicted by the contour lines. Together with Fig. 1 we can establish a correlation between high p_t pions, early freeze-out times and the hot and dense reaction phase. A correlation between high energy pions and early freeze out times has also been observed in BUU calculations of La+La collisions at 1.35 GeV/nucleon [28]. However, the global, fixed event averaged time cut of 20 fm/c for La+La at 1.35 GeV/nucleons employed in Ref. [28] is a rough estimate of the *nucleonic* freeze out time (while in our approach the actual time (event by event) for *pion* freeze-out is employed): The densities in the collision center are then already far lower than ground state density.

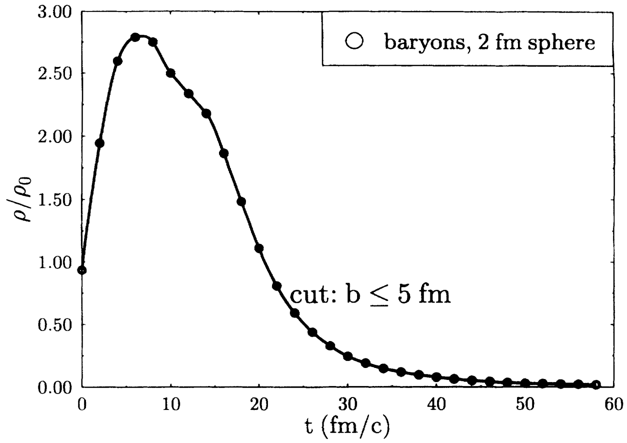

FIG. 1. Baryon density vs time for Au+Au collisions at 1 GeV/nucl. with impact parameter $b \leq 5$ fm. The density has been calculated in a sphere of 2 fm radius around the collision center. For times up to 20 fm/c at least nuclear ground state density is achieved in the collision center. We identify this timespan as the hot and dense reaction phase.

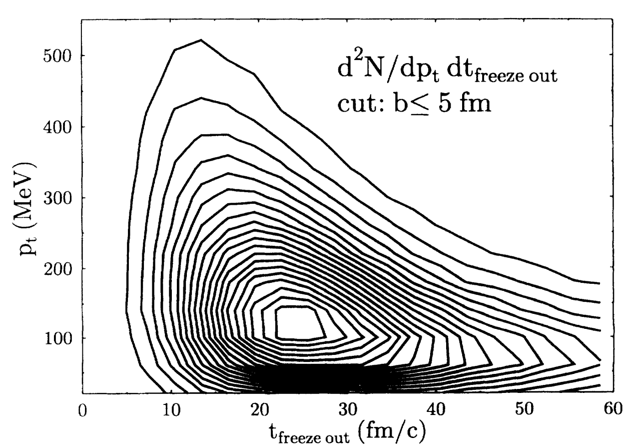

FIG. 2. Transverse momentum versus freeze-out time for pions in semicentral Au+Au collisions at 1 GeV/nucleon. High p_t pions freeze-out predominantly in the hot and dense reaction phase. The scaling of the contour lines is linear; far higher transverse momenta occur than is depicted by the contour lines.

In order to prove this correlation between high p_t and the hot and dense reaction phase conclusively, we calculated the freeze-out density distribution for all pions and compared it with the respective distribution for high p_t pions in Fig. 3 (the distributions are normalized in order to fit into the same frame): The average freeze-out density for all pions lies well below nuclear ground state density; this is well known and has severely diminished the usefulness of pions as probes for the hot and dense reaction phase [22,27,40]. High p_t pions, however, freeze-out at far higher densities: Their average freeze-out density lies between 1.2 and 1.5 ρ/ρ_0 with some of them even freezing out at densities near the maximum density obtained in the collision. In the IQMD model, Gaussian wave packets are used to represent baryons. The freeze-out densities of Fig. 3 were calculated event by event by summing over all contributing Gaussians at the point of creation of the Δ resonance from which the final pion emerges. The width of the Gaussians is adjusted to give the proper ground state phase space densities of the initial projectile and target nuclei.

The special characteristics of high p_t pions also correlate to the number of Δ generations (i.e., number of resorptions), through which the respective pions go before they freeze-out. Figure 4 shows the normalized distributions of Δ generations for all pions and for pions with high p_t. High p_t pions go (on average) through 2.7 generations before freeze-out, whereas normal pions go through 3.8 generations. However, the maximum of the distribution for high p_t pions lies between $n_\Delta = 2$ and 3. This means that the majority of high p_t pions rescatter at least once or twice before they freeze-out from the hot and dense reaction zone which diminishes their freeze-out density. These low density contributions might be reduced by increasing the p_t cut on the pions.

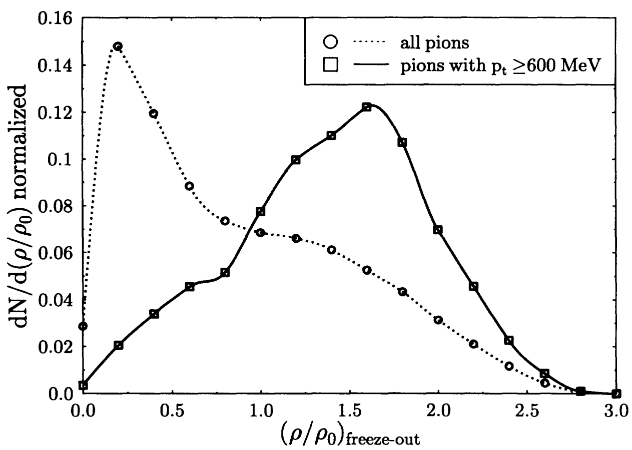

FIG. 3. Freeze-out density distribution for all pions and pions with high p_t in semicentral Au+Au collisions at 1 GeV/nucleon. The distributions are normalized in order to fit into the same frame. The average freeze-out density for all pions lies well below nuclear ground state density. High p_t pions, however, freeze-out predominantly at densities higher than ground state density. They therefore directly probe the hot and dense reaction zone.

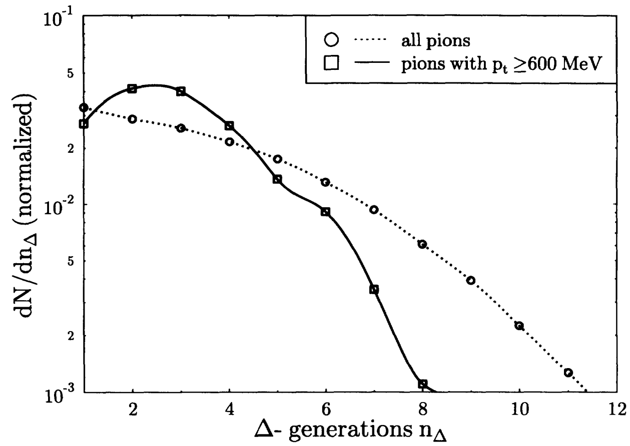

FIG. 4. Distribution of Δ generations n_Δ that a pion goes through before it freezes-out for all pions (dashed line) and high p_t pions (solid line). The distributions are normalized to fit into the same frame. High p_t pions go on average through 2.7 generations before freeze-out and normal pions through 3.8 generations. Only a combination of small n_Δ and early freeze-out times yield good probes for the hot and dense reaction phase.

Pion scattering has a dramatic effect on the density probed by the respective pion: Figure 5 shows the distribution of the maximum density experienced by the pion in the $NN \to N\Delta$ and $\pi N \to \Delta \to \pi N \to \Delta \cdots$ cycle, for all pions and for pions with high p_t, respectively. The distributions are normalized in order to fit into the same frame.

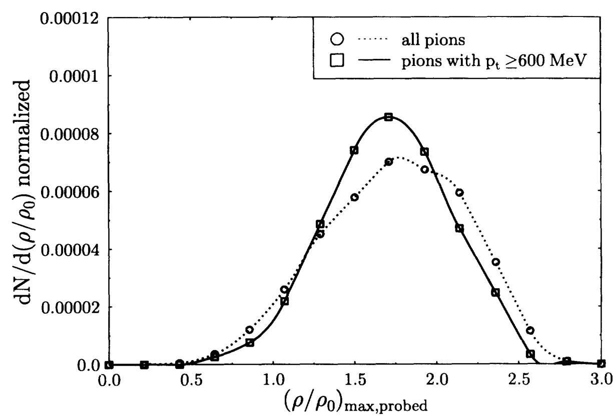

FIG. 5. Distribution of the maximum density probed in the $\pi N \to \Delta \to \pi N \to \Delta \cdots$ cycle for all pions and pions with high p_t. The distributions are normalized in order to fit into the same frame. The maximum density probed is independent of the pion transverse momentum. The density probed with high p_t pions (see Fig. 3) at freeze-out is similar to the maximum density probed by the respective pion or one of its predecessors. Due to frequent rescattering this is no longer the case for low p_t pions: The density probed at freeze-out is far lower than the maximum density probed by one of its predecessors.

The maximum density probed is *independent* of the pion transverse momentum! The density probed with high p_t pions (see Fig. 3) at freeze-out is similar to the maximum density probed by the respective pion or one of its predecessors.

This is not anymore the case for low p_t pions due to frequent rescattering: The density probed by the (finally) low p_t pion at freeze-out is far lower than the maximum density probed by one of *its* predecessors. The spectra of the pions which have *low* p_t at the *end* have predecessors with *hard* spectra in the *early* high density stage. However, the frequent absorption and reemission cycles soften the spectra of these pions during the course of the expansion. The densities used in Fig. 5 have been calculated in the same fashion as the densities for Fig. 3, that is by summing over all contributing Gaussians at the point of creation of the respective Δ resonance.

It has been implied [28] that the mass distribution of intermediate Δ resonances leading to high energy pions (which originate from the early reaction phase) differs considerably from the mass distribution of intermediate Δ resonances from which low energy pions emerge in the later reaction stages.

Here we demonstrate that the measurement of the nucleon-pion correlation function [39–42] (i.e., the Δ; e.g., $\Delta^{++} \to \pi^+ p$) will yield invariant mass distributions of the Δ versus p_t, which can well be used to distinguish between the different reaction stages, as we will show below.

Figure 6 shows the time evolution of the average Δ resonance mass from which *freeze-out pions* emerge [38]. By using only *freeze-out pions* we ensure that the information on the resonance masses is not lost through the renewed production of a *soft* Δ. A strong decrease in the average mass with increasing freeze-out time is visible. This effect is closely linked to the number of Δ generations a pion goes through before freeze-out: Every time a pion and a nucleon form a *soft* Δ it tends to lose momentum. This momentum loss can be observed in the next Δ generation through a reduced mass of the recreated *soft* Δ (due to energy and momentum conservation, the mass of a *soft* Δ is fixed by the incoming nucleon and pion). However, the constraint of using only *freeze-out pions* is not sufficient for the experimental reconstruction of the Δ resonance mass distributions via, e.g., a proton-π^+ correlation technique [39–42] with background subtraction via event mixing. One has to ensure that *both* decay products of the resonace freeze out after the decay.

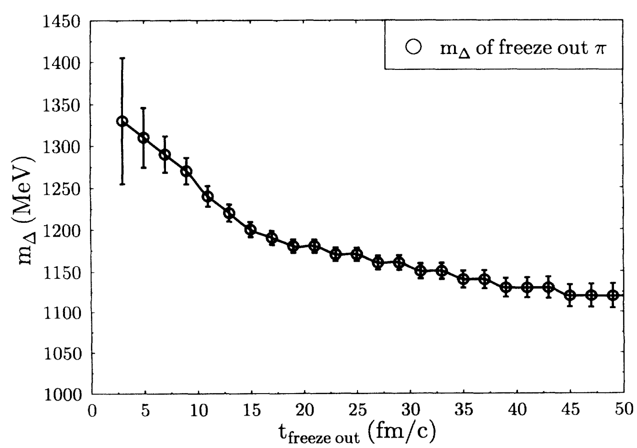

FIG. 6. Time evolution of the mass of the Δ resonances from which final pions freeze-out. Pions with early freeze-out times are emitted predominantly from heavy Δ resonances, whereas pions with late freeze-out times stem from Δ resonances with low mass.

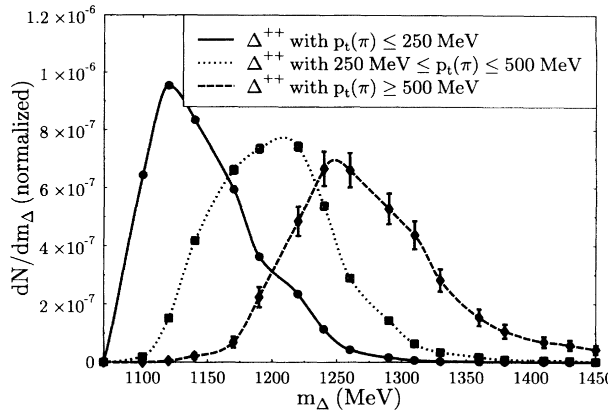

FIG. 7. Mass distribution for Δ^{++} resonances with a cut on the transverse momentum of the emerging π^+. Only proton-π^+ pairs were selected, neither of which scattered any longer after the decay of the respective Δ^{++}. Due to the correlation of high p_t pions with early freeze-out times a mass shift of the resonance towards lower masses for the later reaction stages can be deduced. This mass shift is only governed by the reaction kinematics.

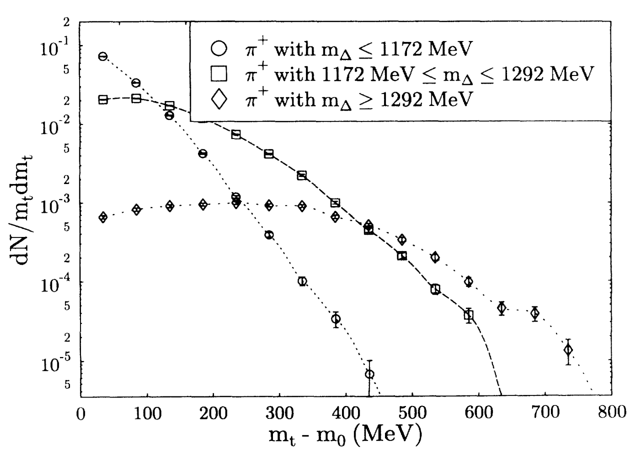

FIG. 8. Transverse mass m_t distribution of freeze-out π^+ with cuts on the mass of the emitting Δ resonance. The connection between high m_t and large resonance mass is obvious: The production of freeze out pions with high m_t is dominated by the decay of heavy Δ resonances. Therefore heavy Δ resonances can be studied by pion-nucleon correlations with a cut on the transverse mass (or transverse momentum) of the respective pion.

This constraint yields a reduction of approximately 40% of the pions used for the analysis due to rescattering of the baryonic decay component of the resonance. Figure 7 shows the mass distribution of Δ^{++} resonances with a cut on the transverse momentum of the emerging π^+. Only proton-π^+ pairs were selected which *both* did not scatter any more after the decay of the respective Δ^{++}. Therefore we propose the experimental reconstruction of the analyzed Δ^{++}. A dramatic shift in the average mass (including a reduction in the width) of the Δ^{++} is predicted between resonances produced in the early reaction stages (characterized by high p_t freeze-out pions as decay products) and those produced in the late reaction stages.

A combination of small n_Δ and early freeze-out times, i.e., high p_t pions, yields good pionic probes for the hot and dense reaction phase. Experimentally, a cut on high transverse momentum with a correlated proton (i.e., a massive resonance) is the key to ensure such conditions. Figure 8 shows the transverse mass m_t distribution of the pions with cuts on the mass of the emitting Δ. The dependence of the pion m_t to the mass of the emitting Δ is obvious.

We have investigated the properties of pions stemming from the hot and dense reaction zone in semicentral Au+Au collisons at 1 GeV/nucleon. Our calculations show that pions with *high transverse momenta* are emitted early in the course of the reaction and stem from heavy (Δ) resonances [43]. They freeze-out at baryon densities larger than ground state density. The measurement of pion-nucleon correlations can serve as a unique tool to discriminate between the high density and low density phase of the reaction. We therefore conclude that high p_t pions stem from the early hot and dense reaction phase and should serve as useful and rather abundant probes for this phase in heavy ion collisions. This message does not only apply to 1 GeV/nucleon, but remains valid at lower and higher energies (e.g., at 10 and 200 GeV/nucleon).

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