Two-temperature shape of pion spectra in relativistic heavy-ion reactions

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We propose that the two-temperature shape of π^- spectra observed in heavy ion collisions with beam energies of ≈ 1 GeV/A is due to the different contributions of Δ-resonances produced early and late during the course of the heavy ion reaction. No significant effect of collective motion of the nucleons or the decay of N*-resonances on the pion spectrum has been seen within the model calculations.

It has been observed that pion spectra in central heavy ion collisions of beam energy between 500 MeV/A and 1800 MeV/A show a concave shape [1–3]. The spectra can be fitted with a superposition of two Boltzmann distributions of widely different temperatures. It is also found that the higher temperature component of the spectra has a nearly isotropic angular distribution in the half-beam-rapidity frame. Extensive experimental studies in Ar+KCl, La+La and Au+Au systems indicate that the importance of the higher temperature component increases with both increasing mass and beam energy.

Several hypotheses have been made by the groups who discovered this effect in order to explain these results. These include the superposition of thermal pions and the pions from the final state Δ decays, higher resonances [1] and the effect of baryon flow on the pions [3]. Based on an equilibrium model calculation [4], it was also conjectured that the concave shape of the pion spectra may come from an isotropic hydrodynamical expansion of the hot compressed nuclear matter. The two slopes do appear in this model calculation, but no quantitative comparison with the experimental data has been made.

The cascade model predicts purely thermal pion spectra [1], although it has been very successful in predicting many other experimental observables in relativistic heavy ion collisions. The original Boltzmann–Uehling–Uhlenbeck (BUU) model used the frozen delta approximation and also failed to explain the two-temperature shape [3]. Therefore, so far none of the currently available dynamical models for heavy ion collisions have been able to reproduce the two-temperature shape observed. The origin of this shape have been a challenge to both experimentalists and theorists.

In this letter we report on the results of a study using an extended BUU transport model. We have extended the original BUU model to include Δ and N* decays and their inverses during the reaction process and therefore give up the frozen delta approximation. We are evolving a hadronic system of nucleons, Δ's, N*'s, and pions in order to treat pion dynamics in a more complete way. We also assign isospin quantum numbers and use parametrizations of the experimentally available elementary cross sections. Details of the physics and numerics of this model can be found in ref. [5].

Following ref. [6], Δ and N* production cross section for each charge state in all possible isospin channels have been estimated by using VerWest and Arndt's isospin decomposition formula [7] for pion production in nucleon–nucleon collisions. Of the higher baryon resonances, only the N*(1440) is included; resonances with even higher mass have negligible production cross sections in the energy range of interest here. The shape of the N* resonance mass distribution is parameterized with a Breit–Wigner

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function with a constant width of 200 MeV [7].

The width for the Δ is parameterized following Kitazoe et al. [8] as

$$\Gamma(q)=\frac{0.47q^3}{[1+0.6(q/m_\pi)^2]m_\pi^2}, \tag{1}$$

where q is the momentum of the pion in the Δ rest frame.

During each time step, the decay probability of the Δ's and N*'s present in the system is determined by an exponential law using the proper time obtained from their widths. The branching ratios for the allowed final states are determined from the appropriate Clebsch–Gordan coefficients. The cross section for the pion–nucleon resonance is also parameterized using the Breit–Wigner formula with the maximum cross section from the experimental data [9].

$$\sigma_{\max}(\pi^+p\to\Delta^{++})=\sigma_{\max}(\pi^-n\to\Delta^-)$$
$$=200\text{ mb}, \tag{2}$$
$$\sigma_{\max}(\pi^0p\to\Delta^+)=\sigma_{\max}(\pi^0n\to\Delta^0)$$
$$=135\text{ mb}, \tag{3}$$
$$\sigma_{\max}(\pi^-p\to\Delta^0)=\sigma_{\max}(\pi^+n\to\Delta^+)$$
$$=70\text{ mb}, \tag{4}$$
$$\sigma_{\max}(\pi^-p\to N^{*0})=\sigma_{\max}(\pi^0n\to N^{*0})$$
$$=50\text{ mb}, \tag{5}$$
$$\sigma_{\max}(\pi^+n\to N^{*+})=\sigma_{\max}(\pi^0p\to N^{*+})$$
$$=50\text{ mb}, \tag{6}$$

Pions have an attractive potential energy in matter due to their p-wave interaction with nucleons [10]. Because the form of this potential is very uncertain and pions have a short mean free path we have ignored the pion potential energy, but with the realization that it might be important. The mean field for Δ and N* is even more uncertain; we assumed it is the same as for nucleons. The standard Skyrme type density dependent mean field [5] has been used in this calculation.

We now turn to our calculation of π^- spectra in the CMS of the projectile and target at 90° for central collisions of La+La at 1350 MeV/nucleon. In fig. 1 we show the number of pions per energy interval, $(pE)^{-1}dN/dE$, as a function of the pion kinetic energy, where p is the momentum and E is the total energy of the pions. The time of $t=20$ fm/c is chosen such that most of the baryon–baryon collisions have already occurred, but the majority of Δ's which were produced late in the reaction has not decayed yet.

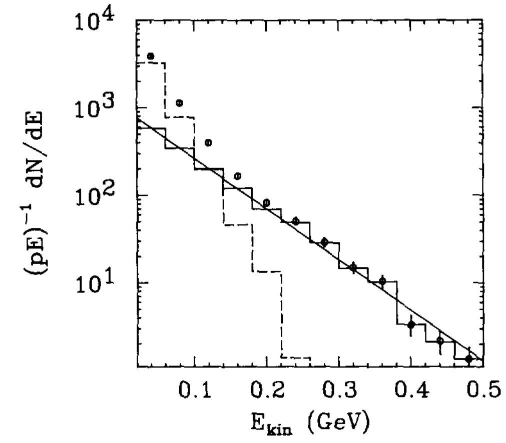

Fig. 1. Calculated contribution to the pion spectrum from free pions (solid histogram) and pions bound in baryonic resonances (dashed histogram), together with their sum (circles) at $t=20$ fm/c.

The real pions which are not bound in resonances are presented by the solid histogram. For a thermally equilibrated dilute pion gas at a temperature T, we can use the Boltzmann distribution function

$$\frac{1}{pE}\frac{dN}{dE}=c\exp(-E_{\text{kin}}/T)\ . \tag{7}$$

As we can observe from fig. 1, the free pions at freeze-out can be well described with a Boltzmann distribution of temperature 78 MeV (straight-line fit).

By assuming sudden decay of all Δ's and N*'s present at this time, the contribution to the pion spectrum from the exited baryons produced in the later stage of the high density reaction phase can be obtained. These are shown by the dashed histogram. It is clear that the bound pions do not show the same temperature as the pions which are already free at freeze-out time.

If we superimpose the two contributions to the pion spectrum, we obtain the result which is represented by the round plot symbols. The error bars are of statistical nature since we solve the BUU equations with a Monte Carlo integration procedure. The concave shape obtained in this way clearly hints at a pion spectrum with a two-temperature appearance. The low temperature is about 50 MeV for pions with $E_{kin} \leqslant 0.2$ GeV and the higher one is about 78 MeV for pions with $E_{kin} \geqslant 0.2$ GeV.

As the system expands, it becomes more and more dilute, and chemical equilibrium between nucleons, Δ's, pions, and higher resonances cannot be maintained. We have followed the time evolution of the system up to $t=40$ fm/c. At this time, practically all baryon resonances have already decayed. We observe that the total pion spectrum at $t=20$ fm/c which is displayed in fig. 1 is almost identical to the one obtained at $t=40$ fm/c. The reason for this is that between these two time instances the Δ's and N*'s are almost moving freely during this expansion phase before they decay. As long as the total pion spectrum is concerned, it is therefore enough to evolve the system until the time when practically all baryon–baryon collisions have ceased. At this time the complete shape of the pion spectrum is already established.

What is the reason for the pions resulting from the decay of baryon resonances produced closer to freeze-out time to show a lower temperature? We attempt to answer this question in fig. 2. The upper part of fig. 2 shows the rate of processes

$$\mathrm{N}+\mathrm{N}\rightarrow\mathrm{N}+\Delta \tag{8}$$

during the La + La reaction. The lower part of the figure displays the probability distribution of baryon–baryon center of mass energies, $\sqrt{s}$, for two different time intervals during the course of the heavy ion reaction, as extracted from the computer calculation. The dashed histogram corresponds to all baryon–baryon collisions of the type (8) during the initial compressional phase of the reaction (dashed hatched area in the upper part of the figure), $t \leqslant 6$ fm/c. The solid histogram corresponds in the same way to all collisions for $t \geqslant 12$ fm/c (solid hatched area).

We can clearly see that the early baryon–baryon collisions are more energetic on average than the later ones. This is because the central rapidity region is initially free of baryons, but is increasingly more populated as the reaction proceeds. A subsequent interaction of a nucleon at central rapidity with a nucleon at target or projectile rapidity thus becomes more and more probable towards the later time in the reaction. Since it is less energetic than a reaction of a

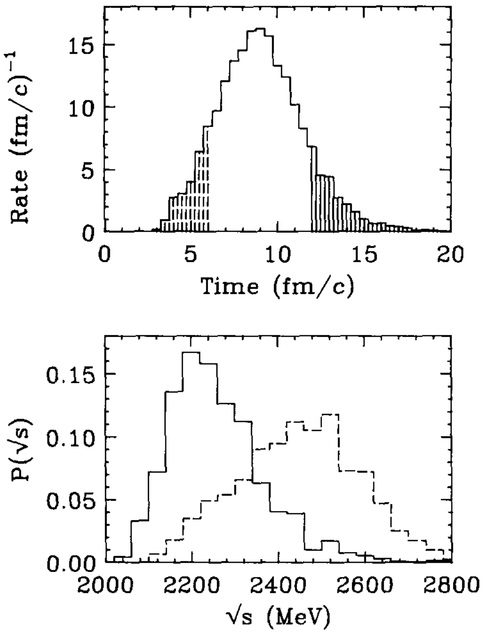

Fig. 2. Upper part: Rate of nucleon–nucleon collisions which lead to the formation of a Δ during the central La + La reaction at $E/A=1350$ MeV. Lower part: Probability distribution of the total energy in the nucleon–nucleon center of mass system for collisions which produce pions or exited baryons. The dashed histogram corresponds to the early collisions ($t \leqslant 6$ fm/c, the dashed hatched area in the upper part), and the solid histogram represents the late nucleon–nucleon collisions ($t \geqslant 12$ fm/c, the solid hatched area in the upper part).

nucleon at projectile rapidity and one at target rapidity (the only kind possible in the initial stage of the reaction), the Δ's produced later are less energetic than the ones produced earlier, and the different contributions to the kinetic energy spectrum of the pions can be understood.

From the above argument, it is clear that we do not have only two contributions of different temperature to the pion spectrum but rather a continuous change from the initial high temperature contribution to the final low temperature. In the study of pion spectra in relativistic heavy ion collisions an important question is to what extent the slope of pion spectra reflects the true temperature of the system in the early high-compression phase of the reaction. From the arguments above, we see that the high temperature component reflects the temperature of system in its early phase. However, one should use caution in applying the term "temperature", because what we observe is not the consequence of an equilibrated system, but rather of a non-equilibrium transport process of a system on its path towards kinetic equilibration.

We finally have to ask why the high temperate pions produced early do not participate in the partial thermalization during the later phases and acquire a lower "temperature" as well. Obviously, free pions cannot exchange kinetic energy with free nucleons via the formation and subsequent decay of pion–nucleon resonances because of four-momentum conservation. However, the reaction $\Delta+N\to\Delta+N$ does not necessarily have to be an elastic one and could in principle result in a different sharing of the total energy between kinetic energy and potential energy stored in the Δ mass. If the Δ's mass would be reduced and the kinetic energy of the N be increased, the subsequent decay of the Δ would produce a less energetic pion. However, this is not likely to significantly contribute to a thermalization of the pion spectrum for the following reason. First, we notice that the Δ would have to collide with a nucleon with a momentum such that the kinetic energy in the relative motion of the pair is small for the above process of thermalization to be effective. This implies small relative velocity and therefore a small reaction rate for this process.

In fig. 3 we perform a comparison between our calculations and the experimental data for central

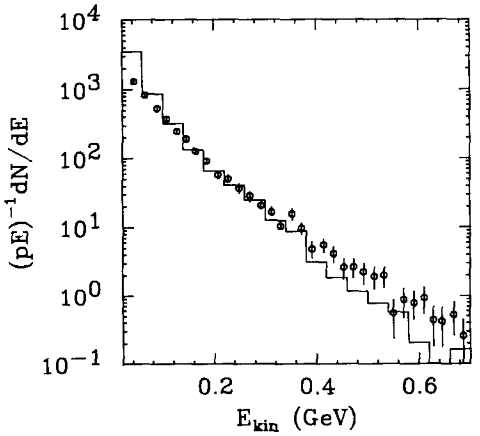

Fig. 3. Comparison between calculation (histogram) and the experimental data of ref. [2] (plotted symbols) for the production of negative pions in central La+La reactions at a beam energy of 1350 MeV per nucleon.

($b<2.8$ fm) reactions of La+La at a beam energy of 1350 MeV per nucleon. The experimental π^- number distribution, $(pE)^{-1}dN/dE$, as a function of pion kinetic energy is shown by the round plot symbols. The data can be fit by a two-temperature fit with a χ^2 per degree of freedom of 0.9, whereas the minimum χ^2 per degree of freedom is 3.4 for a one-temperature fit [2]. The data are in reasonable agreement with our calculation (histogram). A slight tendency of underpredicting the higher energy pions of energy $E_{kin}\geqslant 0.4$ GeV is noticed. One of the reasons is that a semiclassical momentum distribution has been used to initialize nucleons; therefore the calculation lacks the quantum high momentum components. This is a problem we share with all the other semiclassical dynamical models. In the lowest energy bin, we overpredict the data by a factor of 2–3, which is primarily due to the fact that we neglect the Coulomb interaction of the pions with the nuclear system. The overall pion cross section is in good agreement (about 5% difference) with experiment [11].

Previously, it was conjectured that the two-temperature structure of pion spectra might reflect the effect of baryon collective flow on pions [2,3]. Therefore it is interesting to study the extent to which our conclusions might be changed due to the presence of collective flow. The result of our calculation is that no noticeable change of the pion spectrum can be seen when we change the nuclear equation of state from a soft to a stiff one, except that the soft equation of state predicted about 5% more pions in total than the stiff equation of state. Since no potential energy for pions has been taken into account in our calculation, pions are only treated in a classical manner. We can therefore not make any final claims to the effect of collective baryon flow on the pion spectrum. However, our calculations at least indicate that one should at most expect a small effect, and that the main reason for the concave shape comes from the source discussed above.

The comparison of the experimental π^- spectra with the prediction of the cascade model [12] assuming pion production only through Δ production and decay prompted the suggestion that higher resonances, such as the N* could be responsible for the second component of the pion spectrum. We therefore checked the role of the N* resonance in our calculation by turning off the N* production and decay channels. In this calculation we only see a very small reduction in the high energy pion counters without noticeably changing the shape of the pion spectra. This is understandable from the fact that the N* production cross section in proton–neutron collisions at $E_{beam} = 1.4$ GeV is only 3.2 mb and for neutron–neutron and proton–proton collisions even less [7]. Therefore, we do not expect a big influence of the N* on the pion spectrum at the present beam energy domain.

A two-temperature structure has also been observed in the transverse momentum distribution, ($d\sigma/dp_t^2$ versus p_t), for pions in ultrarelativistic heavy ion collisions and proton induced reactions [13]. Recently Brown et al. [14] have suggested a mechanism similar to the one that we have found responsible for the apparent two-temperature shape was put forward to explain this effect. Although our model presented here cannot be applied to ultrarelativistic heavy ion collisions before including more baryon and heavy meson resonances, our success in explaining the two-temperature shape observed in relativistic heavy ion collisions is at least in support of the mechanism proposed by Brown et al. to understand the two-temperature feature observed in ultrarelativistic heavy ion collisions.

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