Studies of meson production at SIS energies

Ch. Hartnack[a], Ch. David and J. Aichelin
SUBATECH
(Laboratoire de Physique Subatomique et des Technologies Associées)
University of Nantes - IN2P3/CNRS - Ecole des Mines de Nantes
4 rue Alfred Kastler, F-44072 Nantes, Cedex 03, France

We present IQMD results on kaon and pion data. The influence of the equation of state and of the elementary kaon cross sections on the excitation function and on the system size dependence is analysed. Effects of density dependent threshold reductions for the production of positive and negative kaons are studied. The influence of the Delta lifetime on the pion production is discussed.

1 Introduction

A major goal of studying heavy ion reactions is the unique opportunity to create hot and dense nuclear matter in the laboratory [1,2]. Unfortunately, this novel state of nuclear matter exists only for a very short time and expands afterwards. In order to gain information about nuclear matter under these extreme conditions, one must find probes which are most sensitive to the properties of this dense matter at the time of maximum density.

The production of secondary particles has recently gained much attention since they are expected to yield direct information on the hot high density region. Pions had been proposed as direct messengers from the high density region [3,4] since they are produced during the time of maximum compression. However, pions have a large cross section for reabsorption by a nucleon forming a delta. This delta may decay, reemitting another pion: Thus, most of the observed pions have interacted several times with rather 'cold' nuclear matter and the signals from the high density region may have been washed out. [5]

Kaons are assumed to conserve the density signature much better since they undergo much less interactions with the nuclear matter than pions. Especially the absorption of kaons is strongly suppressed due to strangeness conservation.

[a] invited speaker at the International Conference on Heavy Ion Physics at low, intermediate and high energies using 4π detectors, Poiana Brasov (Romania), Oct. 1996

2 Quantum Molecular Dynamics

The QMD model [6] is a n body theory which simulates heavy ion reactions at intermediate energies on a event by event basis. It has been successfully used for the description of fragmentation processes The major aspects of the formulation of QMD shall now be discussed briefly. For a more detailed description we refer to ref. [2].

In QMD each nucleon is represented by a coherent state of the form (we set $\hbar, c = 1$)

$$\phi_\alpha(x_1,t) = \left(\frac{2}{L\pi}\right)^{3/4} e^{-(x_1-x_\alpha(t)-p_\alpha(t)t/m)^2/L}\, e^{i(x_1-x_\alpha(t))p_\alpha(t)}\, e^{-ip_\alpha^2(t)t/2m}$$

Thus the wave function has two time dependent parameters x_α, p_α. The parameter L which is related to the extension of the wave packet in phase space, is fixed. The total n body wave function is assumed to be the direct product of coherent states. We apply a Quantum Variational Principle and end up with a formula which looks similar to the classical Hamiltonian equations.

$$\dot{p}_i = -\frac{\partial\langle H\rangle}{\partial q_i} \qquad \dot{q}_i = \frac{\partial\langle H\rangle}{\partial p_i} \tag{1}$$

The Wigner distribution function f_i of the nucleons can be easily derived from the test wave functions (note that antisymmetrization is neglected).

$$f_i(\vec{r},\vec{p},t) = \frac{1}{\pi^2\hbar^2} e^{-(\vec{r}-\vec{r}_{i0}(t))^2\frac{2}{L}}\, e^{-(\vec{p}-\vec{p}_{i0}(t))^2\frac{L}{2\hbar^2}} \tag{2}$$

The expectation value of the Hamiltonian can be written down as

$$\langle H\rangle = \langle T\rangle + \langle V\rangle = \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r},\vec{p},t)\, V^{ij} f_j(\vec{r}\,',\vec{p}\,',t)\, d\vec{r}\,d\vec{r}\,'d\vec{p}\,d\vec{p}\,' \quad . \tag{3}$$

The Hamiltonian includes in the potential part local Skyrme-type potentials, Yukawa potentials, Coulomb interactions and momentum dependent interactions.

Additional to the potentials which correspond to the real part of the G-matrix we implement collisions which correspond to the imaginary part of the G-matrix. In our simulation we restrict us to binary collisions (two-body level) only and may therefore apply the Boltzmann collision ansatz. The collisions are performed in a point-particle sense in a similar way as in the cascade models [3,9]:

Two particles collide if their minimum distance d in their CM frame fulfills the requirement:

$$d \leq d_0 = \sqrt{\frac{\sigma_{\rm tot}}{\pi}}, \qquad \sigma_{\rm tot} = \sigma(\sqrt{s},\ \text{type}).$$

where the cross section is assumed to be the free cross section of the regarded collision type ($N - N$, $N - \Delta$, ...).

A reduction of the effective cross section is obtained by the "Pauli-blocking". For each collision the phase space densities in the final states are checked in order to assure that the final distribution in phase space is in agreement with Pauli's principle.

3 Kaon production

Let us first regard an observable which is strongly motivated by its dependence on the nuclear equation of state (eos). The production of kaons has obtained very much interest both from the theoretic as from the experimental side [10,11,12,13,14,15,16].

In this contribution we will study the production of kaons within the QMD model within the isospin version (IQMD). Differences of IQMD to other QMD versions are discussed in [17]. In these calculation rescattering of kaons has not been taken into account. The influence of rescattering on the observables can be found in [18].

In the calculations presented here we use a novel parametrization of the channel $NN \rightarrow NYK$ which is given by

$$\sigma = 0.558(\sqrt{s} - \sqrt{s_{\rm threshold}})^{1.482} \quad \text{mbarn}$$

with $\sqrt{s}$ given in GeV. This parametrization is a fit to low energy $p+p \rightarrow K+X$ data including a recent point at low energies [19]. For the reaction channels $N\Delta \rightarrow NYK$ and $\Delta\Delta \rightarrow NYK$ we use isospin reduction factors of 0.75 and 0.5. For the channel $N\pi \rightarrow YK$ a parametrization of Cugnon et al. is used [20]. It is found that in the calculated systems this channel has a rather small contribution. For comparison we also employed the parametrizations of Randrup and Ko [21] and of Schürmann and Zwermann [22]. For both parametrizations we implemented the same isospin reduction factors of 0.75 and 0.5 for the $N\Delta$ and $\Delta\Delta$ channels.

Furthermore we studied the influence of a density dependent threshold. We used the ansatz motivated by chiral perturbation theory

$$\sqrt{s_{\text{eff.threshold}}} = \sqrt{s_{\text{threshold}}} - 0.2 \cdot \frac{\rho}{\rho_0} \cdot m_{\text{kaon}}$$

which simulates a reduction of the kaon mass in the nuclear medium. Calculations using a combination of vector and scalar potentials predict only a small change of the K^+-mass but - due to G-parity - a large effect for the K^- [25]. Nevertheless a study of the influence of an additional density dependence on the K^+ production may be of interest.

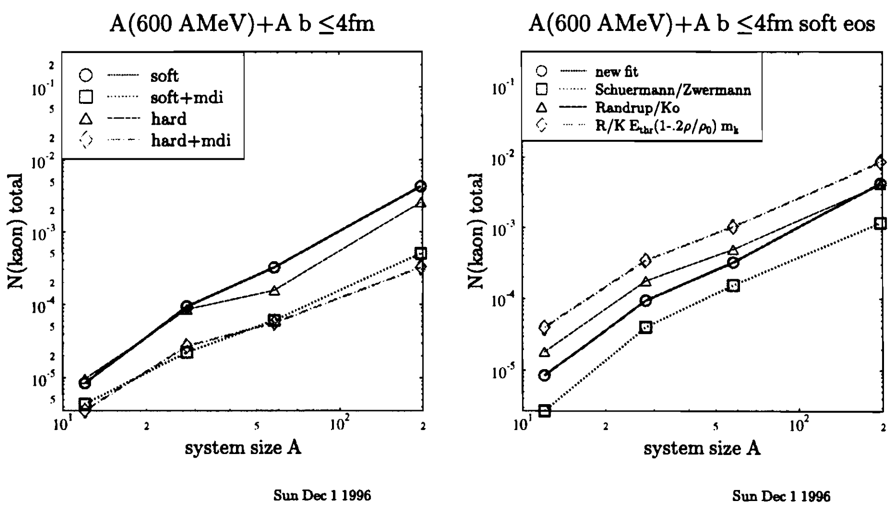

Figure 1: System size dependence of the kaon production for A+A at 600 AMeV incident energy with $b \leq 4$ fm, left for hard and soft eos with and without momentum dependence, right for a soft eos with different cross section parametrizations.

Let us first regard the system size dependence of the production of kaons much below the threshold. Fig. 1 shows the total kaon number ($K^+ + K^0$) obtained for the hard and soft eos with and without momentum dependent interactions. We see for light systems nearly no influence of the nuclear equation of state but some influence for heavy systems. This corresponds to the fact that compression effects can easier be obtained for heavier systems. In contrast the repulsion from the momentum dependent interactions can be found for all system sizes. Therefore the kaon numbers obtained with mdi are overall smaller.

The r.h.s. of the figure shows the influence of the cross section parametrisation. The parametrisation of Randrup and Ko yield higher kaon numbers for smaller systems and a different dependence of the kaon number on the system size. A density dependent lowering of the threshold enhances the kaon number for all systems but do not change the system size dependence significantly. The parametrization of Schürmann and Zwermann yields a reduced kaon number.At these low energies the production cross sections of the latter parametrization are much smaller than those of the new parametrization which are smaller than those of Randrup and Ko. For higher energies the cross section of Schürmann and Zwermann increases strongly and yields higher values than the cross section of Randrup and Ko.

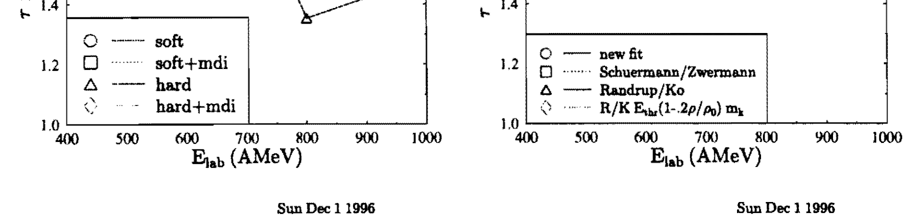

Figure 2: Energy dependence of the mass exponent τ (from $N_{kaon} = A^{\tau}$) for A+A $b \leq 4$ fm, left for hard and soft eos with and without momentum dependence, right for a soft eos with different cross section parametrizations.

Let us now fit the system size dependence of the kaon number by a power law: $N \propto A^{\tau}$. Fig. 2 shows the excitation function of this parameter. We see strong differences from the nuclear equation of state: a soft eos yields a stronger exponent than a hard one. The momentum dependent interactions yield a completely different energy dependence of τ. Further also the influence of the cross section parametrisation can be seen. The Randrup/Ko parametrisation yields smaller values than the parametrization of Schürmann and Zwermann and than the new fit.

It should furthermore be noted that all systems were run with the same absolute cross section, i.e. with $b < 4$fm. If we would use the same fraction to the total cross section i.e. $b < 1.6$, 2.1, 2.7 4 fm for C, Si, Ni and Au we would obtain smaller values of τ: At 600 AMeV we get values of $\tau =$ 1.40, 1.44, 1.37, 1.68 for the hard eos with mdi, a hard eos without mdi, a soft eos with mdi and a soft eos without mdi all using the new parametrization. The soft eos without mdi yields $\tau = 1.43$, 1.44 and 1.59 for the Randrup/Ko parametrization, the same parametrisation with a density dependent threshold and for the Schürmann/Zwermann parametrisation.

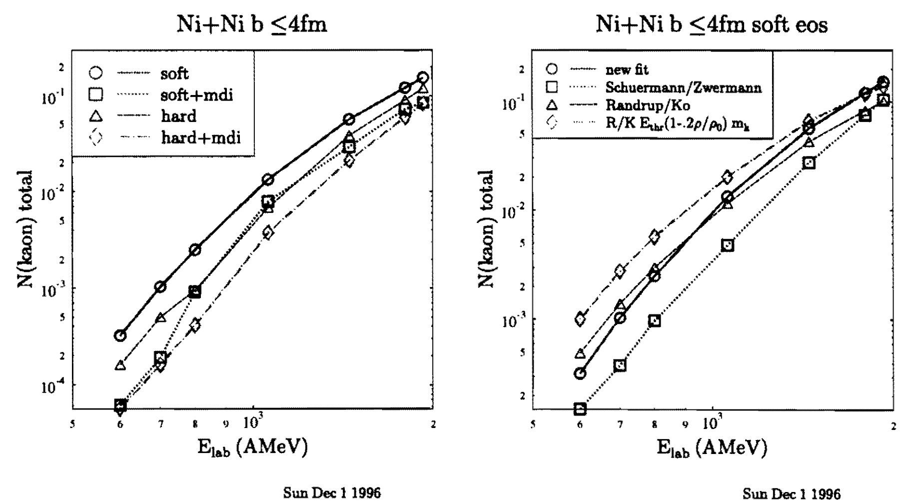

Figure 3: Excitation function of the total kaon number for Ni+Ni $b \leq 4$ fm, left for hard and soft eos with and without momentum dependence, right for a soft eos with different cross section parametrizations.

Let us now come to the excitation function of kaon production in the system Ni+Ni. Fig. 3 shows that the differences between the different equations of states decrease with increasing energy. The hard eos yields a stronger rise of the kaon number with energy as compared to the soft eos. The momentum dependent interactions cause an ever steeper rise of the kaon number with the energy. It should be noted that also the cross section parametrization influences the rise of the kaon number. The parametrization of Randrup and Ko yield a softer rise than the new parametrisation and the parametrisation of

Schürmann and Zwermann. This is related to the different energy dependence of the elementary cross sections.

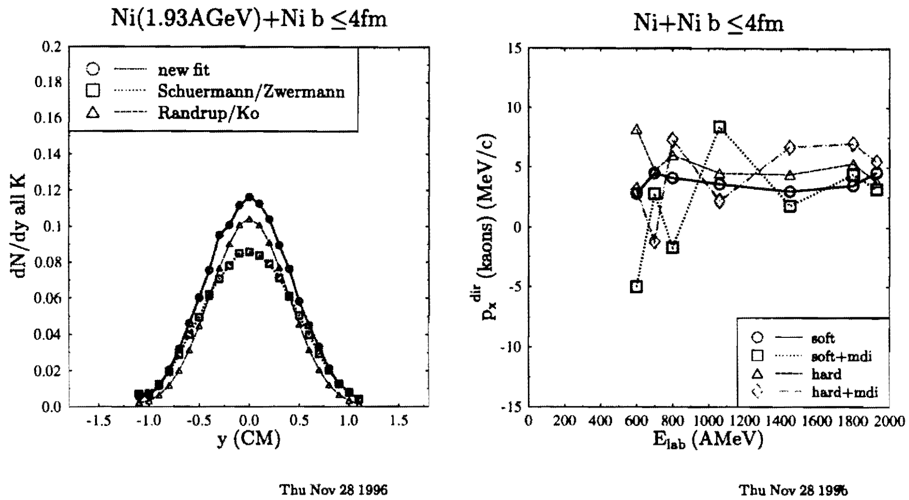

Figure 4: Left: Influence of the cross section parametrization on the kaon rapidity distribution of Ni+Ni at 1930 AMeV. Right: Excitation function of the directed flow of the kaons

This difference can also be seen regarding the rapidity distribution of the kaons. In the parametrization of Schürmann and Zwermann the production cross section is much smaller at low energies than in that of Randrup and Ko but it increases much faster with energy. Thus the Schürmann/Zwermann parametrization yields less low energy kaons and more high energy kaons as it can be seen in Fig. 4. On the other hand the cross section parametrizations do not effect the kaon flow. We find for all parametrizations and all equations of state no significant flow of the kaons. Also if one reduces the threshold of the kaon production as a function of density the sources do not show a significant flow signal.

This result is in discrepancy to the observation of Li and Ko[14] who reported a strong flow signal of the sources. It should be noted that the nucleons show a strong flow signal as demonstrated in fig 5. It can also be found that also the pions show a rather small flow signal. For some more comments on the flow of the pions we refer to[23,27,28].

Let us now regard the production of negative kaons. For the production

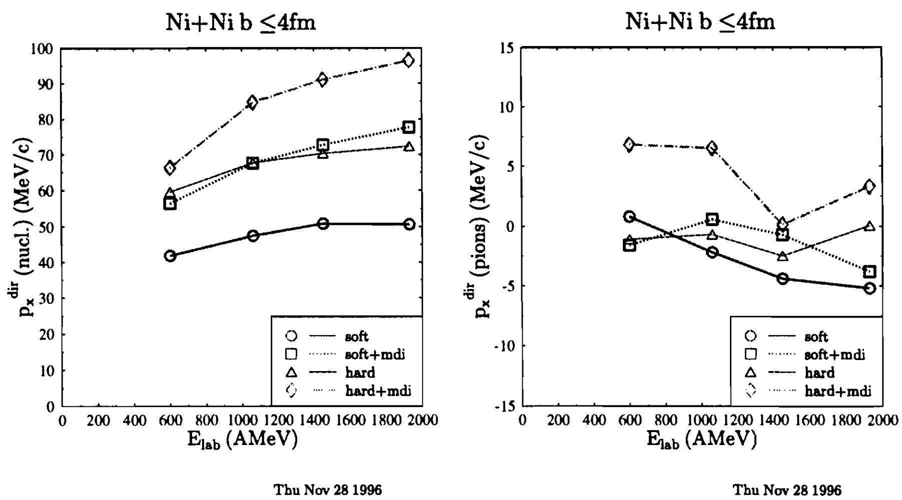

Figure 5: Excitation function of the directed flow of nucleons and pions

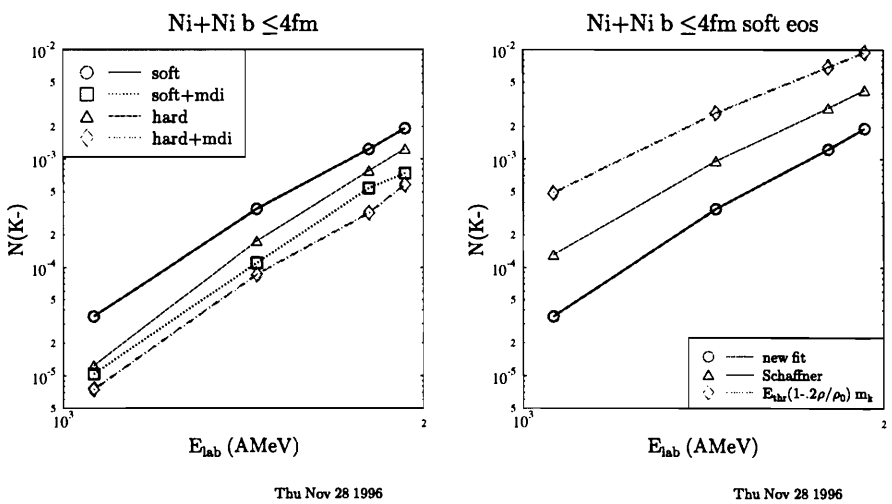

Figure 6: Excitation function of the production of K^- in Ni+Ni, $b \leq 4$ fm, left for hard and soft eos with and without momentum dependence, right for a soft eos with different density dependences of the threshold.

in baryon-baryon collisions we use the parametrization

$$\sigma = 0.063 \cdot (\sqrt{s} - \sqrt{s_{\text{threshold}}})^{1.6} \quad \text{mbarn}$$

with $\sqrt{s}$ given in GeV. This is again a fit to recent data points [19]. Fig. 6 shows the excitation function of the production using this parametrization. We see that again a soft eos yields more negative kaons than a hard one. Momentum dependent interactions also reduce the yield.

In order to study the influence of effective mass reductions we studied the K^- production with a threshold reduced by

$$\sqrt{s_{\text{eff.threshold}}} = \sqrt{s_{\text{threshold}}} - 0.2 \cdot \frac{\rho}{\rho_0} \cdot m_{\text{kaon}}$$

as we already did for the positive kaons. Here a mass reduction of the K^- has to be regarded as quite probable as predicted by relativistic mean field and chiral Lagrangian theory. We additionally use a mass reduction found by Schaffner et al. [25]

$$m_k^{*\,2} = m_k^2 - \Sigma_{KN} \cdot \frac{\rho_s}{f_K^2}$$

where we take $f_K = 93\text{MeV}$ and $\Sigma_{KN} = 300\text{MeV}$ [24] and assume the scalar density to be equal to the baryonic density.

We see that both density dependent mass reductions yield an enhanced yield of negative kaons. The enhancement ranges from about an order of magnitude for the linear parametrization at low energies to about a factor of 2 for the quadratic formula at high energies.

Let us finally give a short estimate on the production of ϕ's, whose decay is strongly coupled to the $K\bar{K}$ channel. For this reaction we assume a constant cross section for $N\pi \rightarrow \phi + X$ of 20 μbarn for all $\sqrt{s} > \sqrt{s_{\text{threshold}}}$. In the regarded energy regime the cross section seems not change too strongly [26]. The obtained values show large statistical errors (to about a factor of 2-3) and thus a dependence on the nuclear equation of state cannot be found within the errors. We see, however, a strong influence of density dependent mass reductions which increase the production probability visibly.

4 Pion production and Delta lifetime

Let us finally briefly discuss some aspects of pion production. As it was shown in Fig. 5 pions do not show strong flow effects in Ni+Ni collisions. In heavier systems these flow effects have been reported by theory [27,28] and experiment [29,30]. Pion flow can be assumed to be an effect of a counterplay between absorption effects and potentials. Similar effects have also been reported for

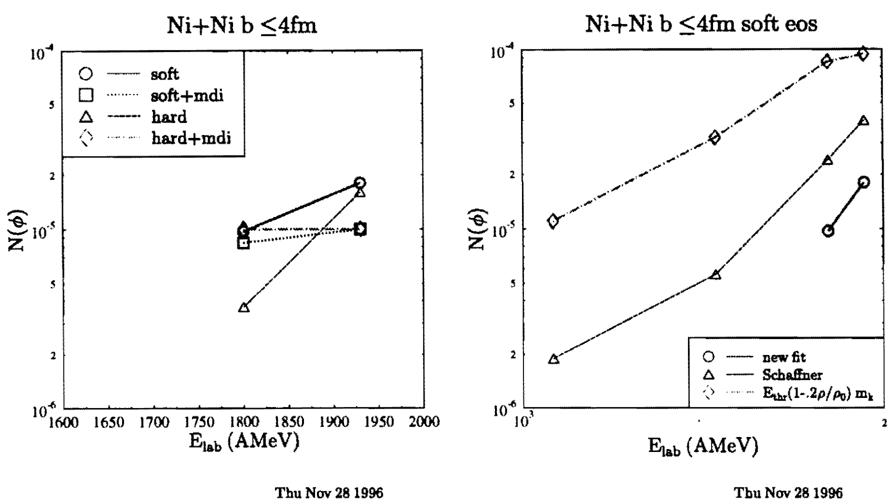

Figure 7: Excitation function of the production of ϕ in Ni+Ni, $b \leq 4$ fm, left for hard and soft eos with and without momentum dependence, right for a soft eos with different density dependences of the threshold.

asymmetric systems [5,31]. In the study of the pion asymmetric flow one important component is the lifetime of the Delta [23].

The lifetime of the Delta have been parametrized in microscopic models in the following way

$$\tau = \frac{1}{\Gamma(m)} \qquad \Gamma(m) = \Gamma_0 \frac{q^3}{1 + aq^2 + bq^4}$$

where Γ_0 is the decay width in the resonance and q is the relative pion momentum in the decaying system. This formula yields that low mass Deltas obtain zero decay widths and thus infinite lifetime.

As a first study we will assume the Delta decay width to be constant $\Gamma = a\Gamma_0$ with a scaling factor a. Fig. 8 now shows the dependence of the pion flow and the pion and kaon numbers on this scaling factors. It is found that the variables and especially the pion numbers are stable against a modification over a wide range.

Let us now describe the Delta lifetime by the following formula

$$\tau = \frac{\Gamma_0/2}{(m - m_{res})^2 - \Gamma_0^2/4}$$

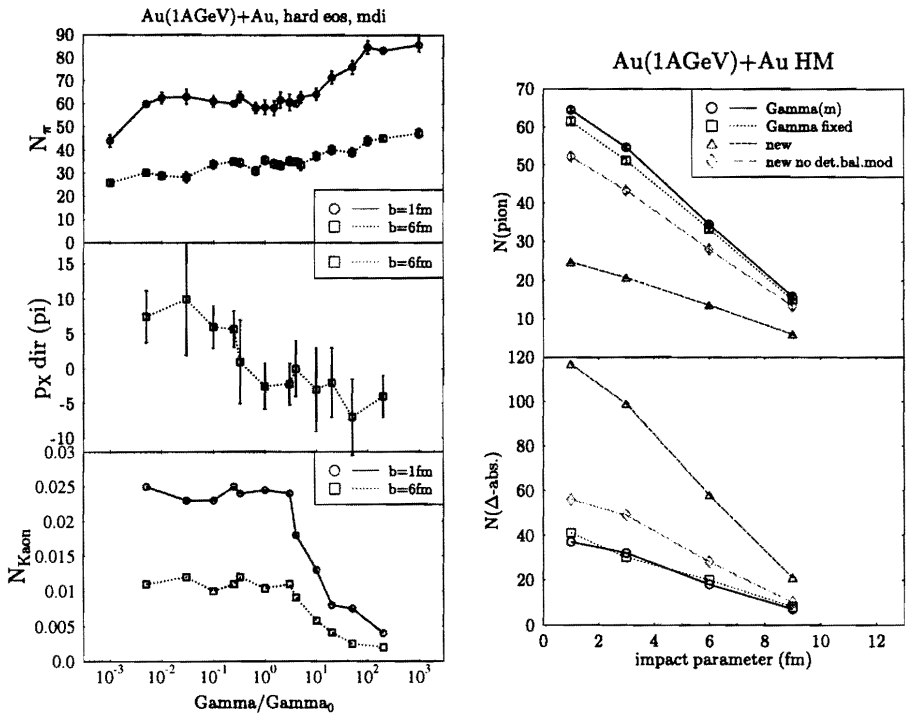

Figure 8: Left: Dependence of pion flow, pion and kaon number on the (fixed) Delta decay width. Right: Comparison of the pion number and the absorption rate on different Delta decay width formulas

where m is the mass of the Delta and m_{res} the resonance mass. This formula (taken from a book of Eugene Wigner) can be derived from the phase shift in the scattering of two wave packets. A detailed derivation is going to be published. Similar calculations resulting in the same lifetime formula have recently been published by Danielewicz [32].

The r.h.s. of Fig. 8 describes the comparison of a calculation with the standard $\Gamma(m)$ calculation, with a fixed decay width and with the new formula. We see a strong decrease of the pion number and an increase of the Delta absorption processes. This strong decrease of the pion number is much less pronounced if the modification of the detailed balance cross section according to the mass distribution is switched off. This modification enhanced the absorption of Deltas at low relative momenta strongly.

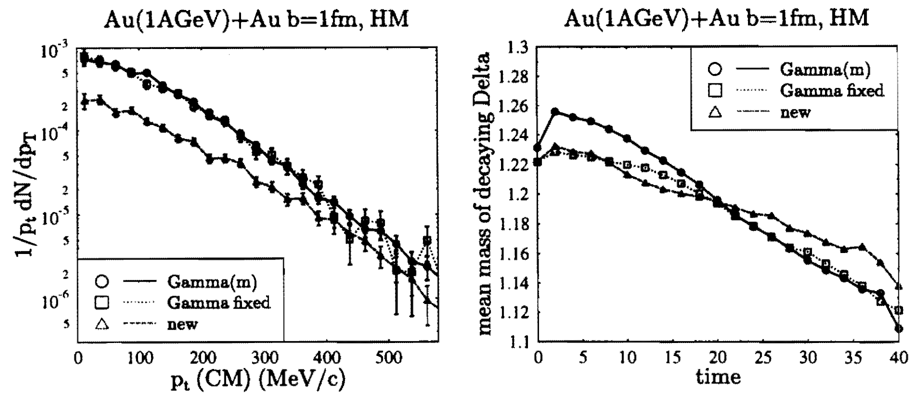

Figure 9: Left: Transverse momentum spectra of the pions obtained with different lifetime parametrizations. Right: Time evolution of the average mass of the decaying Deltas

Fig. 9 compares the pion spectra obtained for Au+Au at 1 AGeV incident energy. We see strong differences between the calculations with $\Gamma(m)$ (which is rather similar to that with Γ_0) and that with the new lifetime formula especially at low pion momenta. This indicates that less low mass Delta survive till the end of the reaction. An analysis of the Delta mass distribution for the outcoming pions yields indeed a large lack of low mass Deltas for the new parametrization.

The time evolution of the mean mass of the decaying Deltas is shown on the r.h.s. of Fig. 9. We see initially lower mass values for the new lifetime formula which corresponds to the rapid decay of the low mass Deltas. At the end of the reaction the mean masses are higher which corresponds to the lack of low mass Delta in the final Delta mass distribution.

The lack of the low mass Deltas as well as the strong change of the pion number when the detailed balance modification to the Delta absorption is disabled (see Fig. 8) indicate a rapid and strong absorption of low mass Deltas.

Low mass Deltas have short lifetime (in the new parametrization) and thus produce rapidly low energy pions. These pions are very slow and may be reabsorbed again. This reabsorption will in most of the cases lead to a Delta with an even lower mass. Thus a rapid chain of Delta decay and pion absorption may be initiated. Finally a Delta with a low mass is absorbed due to its huge absorption cross section. This mechanism can only take place as long as the system is dense enough to allow rescattering. This can only be assured if the lifetime of the Delta is very small.

As stated above an enhancement of pion rescattering is found in the calculations using the new parametrization. This influences (for Au+Au at 1 AGeV) some further observables:

1) the directed flow of the pions gets (slightly) more negative. Pion rescattering causes negative flow [23,27].

2) the ratio of $\pi+/\pi-$ reduces from about 0.57 to about 0.47. This can be explained by rescattering in neutron-rich matter (Au has more neutrons than protons) since the absorption cross section of $\pi^+ + n$ is higher than that of $\pi^- + n$.

3) the kaon number is enhanced by about 10-15% due to more $\Delta - N$-absorptions.

It should also be noted that these effects get smaller for smaller systems. Thus, e.g. the kaon number of Ni+Ni (which was discussed in the previous section) does not show significant influences of the Delta lifetime.

The present work on the effects of the Delta lifetime is only a part of a path towards an improved description of the pion dynamics. Further steps have to follow to give an new consistent picture of pion dynamics.

References

1. H. Stöcker and W. Greiner, Phys. Rep. 137 (1986).
   G.F. Bertsch, S. Das Gupta, Phys. Rep. 160 (1988) 189.
   W. Cassing et al. Phys. Rep. 188 (1990) 361.
2. J. Aichelin, Phys. Rep. 202 (1991) 233.
3. J. Cugnon, Phys. Rev C22 (1980) 1885.
4. R. Stock et al., Phys. Rev. Lett. 49 (1982) 1236.
   J.J. Molitoris and H. Stöcker Phys. Rev. C32 (1985) 346.
   J. Harris et al., Phys. Rev. Lett. 58 (1987) 463.
5. C. Hartnack, H. Stöcker and W. Greiner, Proc. Gross Properties of Nuclear Matter XVI, Hirschegg, Austria, 1988, 138.
6. J. Aichelin and H. Stöcker, Phys. Lett. B176(1986) 14.
7. J. Aichelin et al. Phys. Rev. Lett. 58 (1987) 1926
8. Ch. Hartnack, GSI report 93-05
9. Y. Yariv and Z. Frankel. Phys. Rev. C20, 2227 (1979)
10. J. Aichelin and J. Jaenicke, Proc. on Meson Production, Cracow (1991), ed. A. Magiera, World Scientific Singapore

11. A. Lang et al., Nucl. Phys. A541 (1992) 507.
12. G. Li et al., Nucl. Phys. A 537 (1992) 645.
13. Ch. Hartnack, J. Jaenicke, L. Sehn, H. Stöcker, J. Aichelin, Nucl. Phys. A 580 (1994) 643.
14. G.Q. Li and C.M. Ko Nucl. Phys. A 594 (1995) 460.
15. W. Ahner et al, Phys. Lett. B in press
16. D. Best et al., to be submitted, D. Best for the FOPI collaboration, Proc. on the 12th Winter Workshop on Nuclear Dynamics, Snowbird, Utah, Feb. 1996. ed. W. Bauer.
17. Ch. Hartnack et al, submitted to Z. Phys. A
18. Ch. David et al., nucl-th. 9611016, submitted to Nucl. Phys. A
19. P. Senger, contribution to the International Workshop on Hadrons in Dense Matter, GSI Darmstadt, July 1996.
20. J. Cugnon and R.M. Lombard, Nucl. Phys. A 422 (1984) 635.
21. J. Randrup and C.M. Ko, Nucl. Phys. A 343 (1980) 519, A 411 (1983) 537
22. W. Zwermann and B. Schürmann, Nucl. Phys. A 423 (1984) 525
23. Ch. Hartnack, Ch. David, J. Aichelin, Proc. on the international conference on meson production, MESON 96, Cracow (Poland), 1995, ed. A. Magiera, to be published Acta Polonica.
24. A. Müller-Groeling, K. Holinde, J. Speth, Nucl. Phys. A 513 (1990) 557.
25. J. Schaffner, A. Gal, I.N. Mishustin, H. Stöcker, W. Greiner, Phys. Lett. B 334 (1994) 268.
26. Landolt-Börnstein, New Series, ed. H. Schopper, I/12 (1988).
27. S.A. Bass, C. Hartnack, R. Mattiello, H. Stöcker, W. Greiner, Phys. Lett. B 302 (1993) 381.
28. S.A. Bass, C. Hartnack, H. Stöcker, W. Greiner, Phys. Rev. Lett 71 (1993) 1144.
29. D. Brill and the KaoS collaboration, Phys. Rev. Lett. 71 (1993) 336.
30. L.Venema and the TAPS collaboration, Phys. Rev. Lett. 71 (1993) 835
31. J. Poitou for the Diogène collaboration, Proc. Gross Properties of Nuclear Matter XVI, Hirschegg, Austria, 1988
32. P. Danielewicz and S. Pratt, Phys.Rev.C53 (1996) 249.