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The Nuclear Equation of State

Part A: Discovery of Nuclear Shock Waves and the EOS

Edited by

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MEDIUM EFFECTS AND NUCLEAR TRANSPORT THEORY

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1. INTRODUCTION

It is commonly believed nowadays that an acceptable nuclear transport theory for heavy ion collisions in a very broad energy range (from a few MeV/u to several GeV/u) should include a correct description of : (1) mean field effects ; (2) two-body collisions ; (3) particle production. A complete theory embodying these features does not exist yet. However, considerable progress has been made in the recent years. On the theoretical side, it was recognized that the Landau-Vlassov equation phenomenologically introduced by Landau for Fermi fluids, had many attributes of a good nuclear theory (for a review, see Ref. 1), despite the fact that it appears as a truncation[2] of the BBGKY hierarchy of the density matrices[3], which is the exact theory in a nonrelativistic approach with potential forces. On the practical side, a variety of models (BUU, VUU, QMD, quasi-particle methods,...) aiming at the solution of the Landau-Vlassov equation, give more and more satisfactory descriptions of the experimental data (for a review, see Ref. 4). The appealing feature of the Landau-Vlassov theory is the presence in the mean field term of physical quantities directly related to the equation of state. Therefore it is a priori a suitable tool to investigate the nuclear matter equation of state at several times normal nuclear matter density. However, the equation of state is not the only ingredient of the Landau-Vlassov equation : collision cross-sections are also needed. At the beginning free space cross-sections were used, despite the fact that for a long time corrections were introduced in studies of p-nucleus collisions.[5] In fact, baryons (and hadrons) do not interact in the nuclear medium as in free space. The simplest way of accounting for that consists in introducing effective cross-sections, which incorporate medium effects. By this term,

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we here mean genuine medium effects which change the interaction, and which do not merely originate from Pauli blocking of final states, something which is trivially (if not satisfactorily) included now in all numerical simulations. Our purpose is to discuss these medium effects and to study the sensitivity of the results upon them. We will be interested in medium effects occurring in elastic scattering as well as in production processes. We will say a few words on medium effects influencing other quantities than the cross-sections.

2. THE TRANSPORT THEORY

As we said in the introduction, a suitable formulation of the nuclear transport theory has the structure of the Landau-Vlassov equation

$$\{\frac{\partial}{\partial t} + \frac{1}{m^*}\vec{p}.\vec{\nabla} - (\vec{\nabla}U).\vec{\nabla}_p\} f_1(\vec{r},\vec{p},t)$$
$$= \int \frac{d^3p_2}{(2\pi)^3}\frac{d^3p_3}{(2\pi)^3}\frac{d^3p_4}{(2\pi)^3}[W(\vec{p}_3\vec{p}_4 \to \vec{p}\vec{p}_2)\tilde{f}_3\tilde{f}_4(1-\tilde{f})(1-\tilde{f}_2)$$
$$-W(\vec{p}\vec{p}_2 \to \vec{p}_3\vec{p}_4)\tilde{f}\tilde{f}_2(1-\tilde{f}_3)(1-\tilde{f}_4)]\delta(\vec{p}+\vec{p}_2-\vec{p}_3-\vec{p}_4)\delta(e(\vec{p})+e(\vec{p}_2)-e(\vec{p}_3)-e(\vec{p}_4)) \quad , \qquad (2.1)$$

where f_1 is the Wigner representation of the one-body density matrix, U is the average field, m* is the effective mass and e(p) is the single particle density. We used the notation

$$\tilde{f}_i = f_1(\vec{r},\vec{p}_i,t) \quad . \qquad (2.2)$$

The structure of this equation implies that some parts of physics are somewhere neglected : relativity, some aspects of the quantum motion, retardation effects, three-body forces, two-body correlations,.. Nevertheless, the remaining physics is sufficient for the description of many aspects of heavy ion collisions (except of course those which are related to many-body distribution functions), as testified by the success of the actual calculations.

At the beginning, the transition probability W was taken as in free space, i.e. related to the experimental cross-sections :

$$W(\vec{p}_i\vec{p}_j \to \vec{p}_k\vec{p}_\ell) = v_{ij}\frac{d\sigma_{ij \to k\ell}}{d\Omega} \quad , \qquad (2.3)$$

where v_{ij} is the relative velocity in the entrance channel. Although this approach was successful, at least at high energy, it was proposed to improve the situation by replacing free cross-sections by medium cross-sections, as calculated in local Brueckner approximation.[6-8]

This procedure was justified later by Botermans and Malfliet[7], who derived eq. (2.1) from BBGKY including properly short range two-body correlations by summing particle-particle ladder diagrams, establishing so the link between the Landau-Vlassov transport theory and the usual (perturbative) theory for static properties of nuclear matter.

The medium corrections to particle production is a much harder problem for which one has only embryonic theories[10,11], although some aspects are very much documented for hadron propagation in equilibrium nuclear matter.[11,12] We will discuss some of these aspects but mainly concentrate on the sensitivity of the results on medium corrections to some ingredients entering the description of particle production.

3. MEDIUM EFFECTS IN ELASTIC SCATTERING

If one adopts as starting point the Brueckner approach in the local density approximation, one should replace the free cross-sections by

$$\frac{d\sigma}{d\Omega}(\vec{k},\vec{k}_2) = \frac{m^2}{4\pi^2}|\langle\vec{k}_1\vec{k}_2|G(\rho,T)|\vec{k}_3\vec{k}_4\rangle|^2 \quad , \qquad (3.1)$$

where $\vec{k}_3$ points in the angle dΩ and corresponds to elastic scattering and where G is the Brueckner matrix at the local density ρ and temperature T. Of course, this approximation is better and better for smaller and smaller deviations from local equilibrium. In general, one is interested to have an expression which more or less averages over the struck particle (k_2) :

$$\frac{d\sigma}{d\Omega}(\vec{k}) = \frac{m^2}{4\pi^2}\int\frac{d^3k_2}{(2\pi)^3}n(\vec{k}_2)|\langle\vec{k}_1\vec{k}_2|G(\rho,T)|\vec{k}_3\vec{k}_4\rangle|^2 \quad , \qquad (3.2)$$

where $n(\vec{k}_2)$ is the equilibrium occupation number at density ρ and temperature T. Such quantities have been calculated by several authors[13,14]. These quantities are still hard to handle since they depend upon four variables (k,θ, ρ,T). In Ref. 15, a simplification was proposed, which averages the correction factor over the final phase space available. One so introduces the factor

$$\alpha_m = \frac{\bar{\sigma}_{med}}{\sigma_{free}} = \frac{\int\frac{d^3k_2}{(2\pi)^3}\frac{d^3k_3}{(2\pi)^3}\frac{d^3k_4}{(2\pi)^3}|\langle\vec{k}\vec{k}_2|G|\vec{k}_3\vec{k}_4\rangle|^2 n(k_2)(1-n(k_3))(1-n(k_4))}{\int\frac{d^3k_2}{(2\pi)^3}\frac{d^3k_3}{(2\pi)^3}\frac{d^3k_4}{(2\pi)^3}|\langle\vec{k}\vec{k}_2|T|\vec{k}_3\vec{k}_4\rangle|^2 n(k_2)(1-n(k_3))(1-n(k_4))} \qquad (3.3)$$

where T is the free transition matrix and where we skipped in the summations the energy-momentum conservation delta functions of eq. (2.1). The results are shown in Fig. 1 in the case of the Paris potential, for several densities and two temperatures. At low density and low

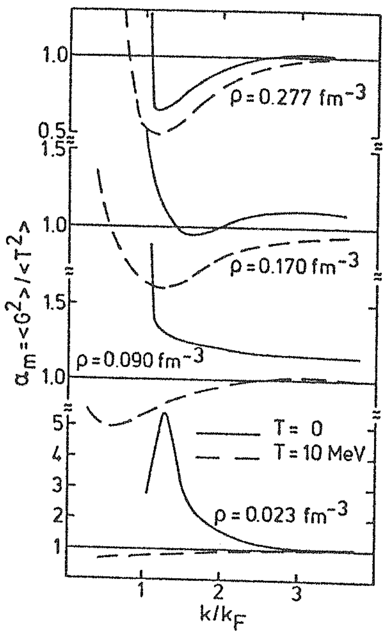

Figure 1. Schematic representation of medium correction (eq. (3.3)) for elastic scattering suffered by a nucleon of momentum k travelling inside uniform nuclear matter of density ρ and temperature T. The quantity α_m is slightly different from the quantity α' defined in Ref. 15, where constant effective mass approximation was used. See text for detail.

temperature, and for k just above the Fermi momentum k_F, the correction α_m is quite large. This is due to a strong medium reduction of the attractive part of the potential (corresponding to the contribution to the T-matrix). The repulsive part is not so affected at low density because of its shorter range. The large compensation between repulsive and attractive effects is therefore destroyed. At large density, both contributions are equally renormalized (when going from T- to the G-matrix) and then α_m is smaller than unity at intermediate k. Of course the free space value should be recovered at large k.

The medium effects have strong influence on the equilibration times, on the viscosity and on flow properties. We just illustrate this point in Fig. 2, where we show the flow angle (calculated in an intranuclear cascade calculation) in a typical case, for free space and medium corrected cross-sections. A similar conclusion was obtained in a BUU study by Bertsch et al.[16] They observe a stronger dependence of the so-called transverse momentum[17] upon the value of the nucleon-nucleon cross-section than upon the equation of state. Recently[18], a similar claim was made concerning small angle inclusive proton cross-section in heavy systems.

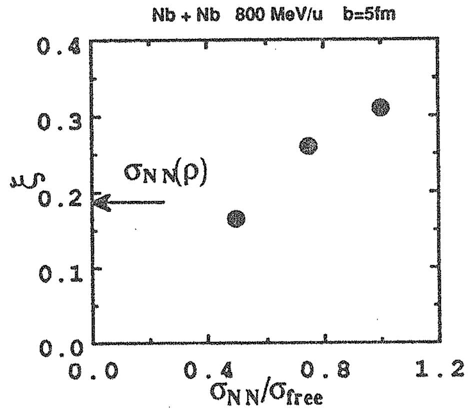

Figure 2. Dependence of the quantity ξ, roughly equal to the flow angle, upon a variation of the NN cross-sections, as given by an intranuclear cascade model. The arrow indicates the value obtained if one takes account of density dependence of the medium correction as calculated in Ref. 24.

Medium effects do not only change the transition probability. Because particles are feeling a mean field the phase space is changed. In other words, the single particle energies e(p) appearing in r.h.s. of eq. (2.1) are different from $p^2/2m$, what they reduce to in free space processes. In the local density approximation, one can write $e(p) = p^2/2m + U_B(p)$, where U_B is the mean field evaluated in the Brueckner approximation at density ρ and temperature T. If $U_B(p)$ is a quadratic function for all values of p, $e(p) = p^2/2mm^*$, m^* being the effective mass. In that case the last delta function appearing in the r.h.s. of eq. (2.1) may be replaced as

$$\delta(e(p)+e(p_2)-e(p_3)-e(p_4)) \to m^*\delta\left(\frac{p^2}{2m} + \frac{p_2^2}{2m} - \frac{p_3^2}{2m} - \frac{p_4^2}{2m}\right) \quad . \qquad (3.4)$$

Therefore, one can make, as usual, simulations with conservation of kinetic energies provided the cross-section is multiplied by the effective mass. At low momenta $U_B(p)$ is quadratic, giving in that range $m^* \approx 0.8$. However, $U_B(p)$ is not quadratic for the momentum range experienced in heavy ion collisions at ~ 100 MeV/u or more. In simulations, the distortion of phase space is usually not implemented. In Ref. 15, medium corrections on the transition probability and on the phase space are put together in a parameter α similar to (2.3) :

$$\alpha = \frac{\int \frac{d^3k_2}{(2\pi)^3}\frac{d^3k_3}{(2\pi)^3}\frac{d^3k_4}{(2\pi)^3}\,|\langle \vec{k}\vec{k}_2|G|\vec{k}_3\vec{k}_4\rangle|^2 n(k_2)(1-n(k_3))(1-n(k_4))\delta^3(\vec{k})\delta(e(k))}{\int \frac{d^3k_2}{(2\pi)^3}\frac{d^3k_3}{(2\pi)^3}\frac{d^3k_4}{(2\pi)^3}\,|\langle \vec{k}\vec{k}_2|T|\vec{k}_3\vec{k}_4\rangle|^2 n(k_2)(1-n(k_3))(1-n(k_4))\delta^3(\vec{k})\delta(\frac{k^2}{2m})}$$

where we used shorthand notation for the energy-momentum conservation δ functions. Roughly speaking $\alpha \approx 0.8\,\alpha_m$ at low k and tends to α_m at large k. See Ref. 15 for more detail and for suitable parametrization of α and α_m as functions of ρ and T.

4. MEDIUM EFFECTS IN PION PRODUCTION

4.1. Introduction

The importance of the pion yield has been a subject of great controversy since R. Stock et al.[19] proposed that it could be a good thermometer, and through an analysis not really free of hypotheses[20], serve as a mean to determine the compression energy as a function of density. The method has been criticized, but not from the point of view of the medium distortions on pion production. Furthermore, pion production and pion absorption are generally pictured, in numerical studies, as due to the following processes

$$NN \rightleftarrows N\Delta \quad , \quad \Delta \rightleftarrows \pi N \quad , \qquad (4.1)$$

for which free space data are rather well known. Medium corrections are not so well known, except for pion propagation (and absorption) in cold normal nuclear matter, which has been under intensive study for several years.[11,21] However, this is of limited help, since the propagation of pion implies repeated iteration of the second mechanism in (4.1) and if one sticks with this description, one can have trouble with double counting. This is also true for the so-called three nucleon absorption[22,23], which has been presented as an important source of absorption and which is overlapping with iteration of processes (4.1) in the above scheme. Furthermore, the influence of the medium effect on the Δ-production mechanism has not been studied very much. Therefore, it is very hard to estimate with reliability the medium corrections to pion yield. But, the sensitivity of the pion yield on these corrections can be evaluated since their order of magnitude are more or less known. This is the philosophy of the recent work of Ref. 24, that we summarize below. This work also studied in particular the proton-nucleus case which can be a good test ground, since there compression effects are negligibly small.

4.2. The proton-nucleus system

In the model description for pion production/absorption described above, the dynamical input related to pion production are the inelastic cross-sections $NN \rightleftarrows N\Delta$ (linked by detailed balance), the angular distribution, the mass spectrum for produced Δ's and the Δ lifetime. One should also add the pion mean field. Below, we examine the influence

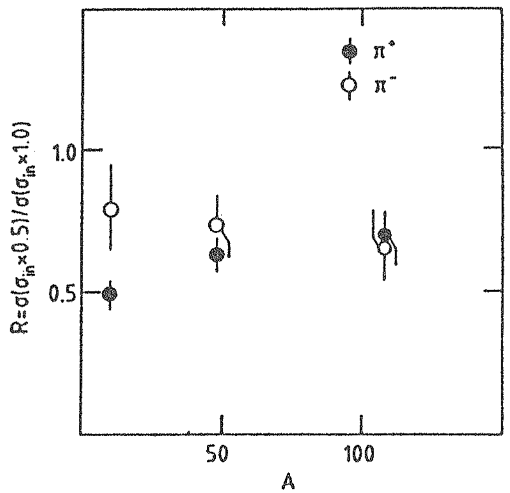

Figure 3. Ratio between pion yield calculated with half inelastic nucleon-nucleon cross-sections and the one calculated with the full cross-section in interactions between 730 MeV protons with several targets. The results are given by the intranuclear cascade calculation from Ref. 24.

of some of them. In Fig. 3, we show the influence of the inelastic cross-section on the pion yield in the interaction of 730 MeV protons with nuclei. A reduction of a factor 2 on the inelastic cross-section directly reflects on a decrease of a factor 2 on the π^+ yield for the ^{12}C target case. For heavier masses, the reduction diminishes to about 30 %. The different behaviour of π^+ and π^- can be understood in terms of multiple scattering. Obviously, π^+'s can be produced by a single pp interaction whereas π^- production necessarily requires further interaction of a proton. The influence of Δ-mass is illustrated by Fig. 4, where it has been artificially raised by 50 MeV. This leads to an overall reduction of the pion yield.

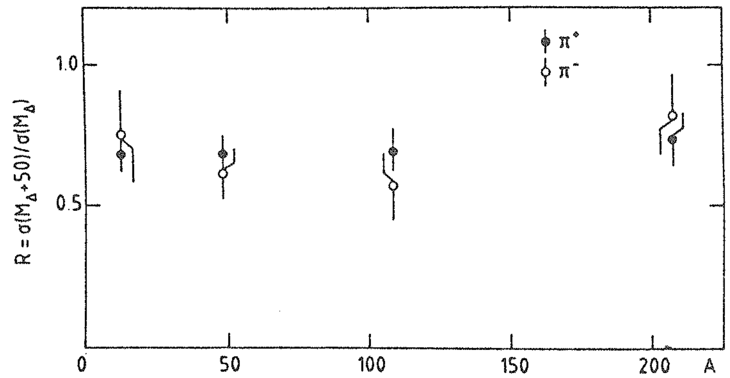

Figure 4. Same as Fig. 3 for a modification of the Δ-mass.

It is shown in Ref. 24 that a good agreement can be reached only if one modifies the pion absorption separately from the production mechanism, a feature which is hardly acceptable at first sight. Roughly speaking, an amplification of the $N\Delta \rightarrow NN$ cross-section by a factor 2-3 and a lengthening of the Δ-lifetime by a factor 2-3 is sufficient to achieve a good description of the pion yield. This may be understood as due to the fact that in the scheme above a finite time is required for a pion to be absorbed after it has first interacted. A modification of the time sequence may be a better alternative to the possibility envisaged above. The usual scheme is quite able to describe the trend of the excitation functions (see Fig. 5), which once again may point to a need for a better description of pion absorption.

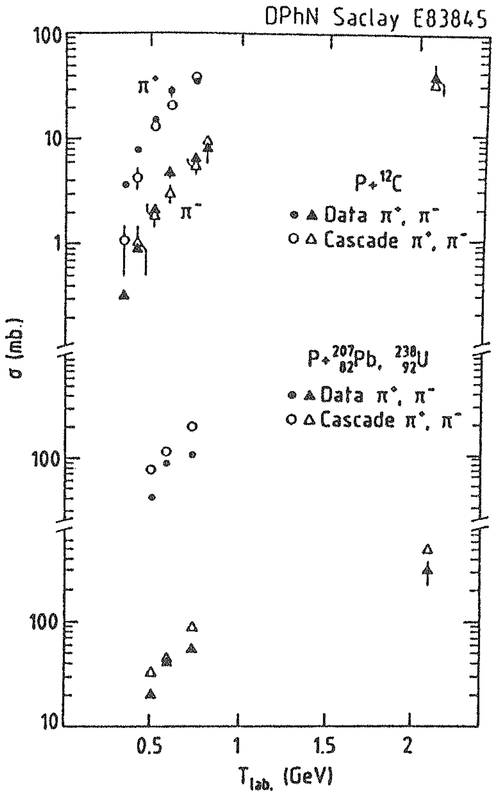

Figure 5. Comparison between cascade calculation (Ref. 24) and experimental data for the excitation function of pion production. From Ref. 24.

4.3. The heavy ion case

As we said above, the average pion multiplicity might be related to the equation of state. In particular, emphasis was put on rather complete data for negative pion multiplicity in Ar + KCl collisions. It is thus interesting to know the sensitivity of this quantity upon medium correction of the dynamical input. Some of the results of Ref. 24 are contained in Fig. 6. One can first see that the more or less realistic treatment of binding energy (left part) already removes half of the discrepancy observed for the original cascade calculations. We recall that this discrepancy was presented as an evidence for a stiff equation of state.[19,27,28] Fig. 6 also shows that a modification of the Δ-mass by 30 MeV or a reduction of the $NN \rightleftarrows N\Delta$ cross-sections are sufficient to bring the numerical results close to the experimental data. In Ref. 24, other modifications are considered. The conclusion is that the pion yield is much more sensitive in the heavy ion case than in the proton-nucleus case, and therefore medium corrections of the expected order of magnitude are largely sufficient to achieve good agreement. The larger sensitivity in the heavy ion case is easy to understand, as in this case the final pion yield results from a large number of pion creations and destructions. If a modification does not change by the same factor (the raising of the Δ-mass is a typical one), the creation and the destruction rates, it will modify the final pion yield more importantly in the heavy ion case.

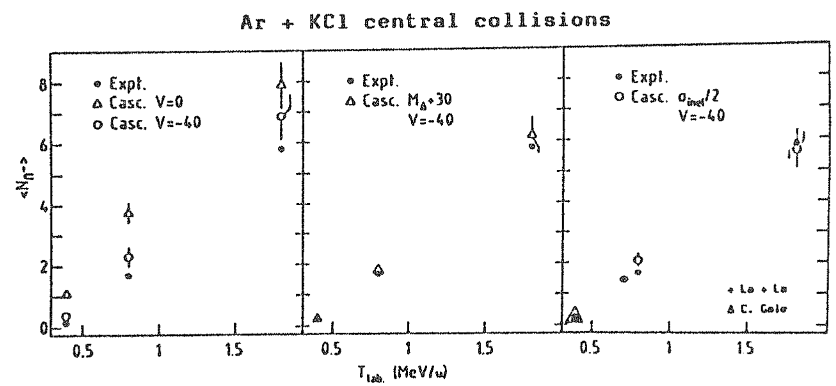

Figure 6. Comparison between cascade calculations of Ref. 24 and experimental data (Ref. 19) for π^- production in central Ar + KCl collisions. The influence of some medium effects is displayed. See text for detail. In the right part of the figure, the cross indicates the La + La data of Ref. 25 (scaled by the ratio of the masses of the two systems) and the triangle gives the results of a similar calculation by C. Gale.[26]

4.4. Discussion

The work of Ref. 24 studies the sensitivity to any modification without presuming of the direction of this modification. However, at least for some of the input data, the direction and the size of the medium modification is known, to some extent. The medium NN → NΔ cross-section has been calculated in a detailed Brueckner-Dirac approach in Ref. 14. The Pauli blocking of the final states is included automatically in the calculation, which is then mixed with genuine medium corrections. It seems however that the latter only slightly reduce (~ 20 %) the cross-section for T=0 and density ρ up to $2\rho_0$. Calculations of the shift of the Δ-mass are rather contradictory.[14,29-31] The work of ter Haar and Malfliet[14], which is the most trustworthy, indicates that altogether the Δ-mass is shifted downward by ~ 15 MeV at ρ_0. However, in usual numerical treatments (see Ref. 24), the Δ is supposed to move in the same mean field as the nucleons. Therefore, in such a scheme, the results of Ref. 14 are equivalent to an upward shift of ~ 25 MeV. This shift is however rather strongly density-dependent. Ref. 14 also indicates a strong reduction of the Δ-width in nuclear matter, much stronger than in conventional nonrelativistic approaches.[11,32]

Let us finally mention that the medium corrections on the pion propagators could be more important than those we discuss here. In particular Bertsch et al.[33] suggested that medium corrections on the pion dispersion relation could increase the pion production by a factor 2 at $\rho = 2\rho_0$. This is rather disturbing since, as we indicated above, the current approaches generally overpredict the pion yield. The authors of Ref. 33 also found a singularity in the clothed pion propagator opening the possibility of pion Cerenkov radiation and of stronger stopping power.

As for elastic scattering, the distortion of phase space may play some role in pion production. This aspect has never been studied so far.

5. MEDIUM EFFECTS IN OTHER PARTICLE PRODUCTION

In the previous two sections, we discussed medium corrections to two-body collisions. In other words, it was implicitly assumed that the scattering wavefunction of the two colliding particles has the time and the place to become asymptotic before another collision takes place. Nevertheless, the presence of the surrounding medium may importantly distort the collision process, because the two particles are feeling the mean field created by their neighbours (and the blocking of the phase space in the intermediate case in the case of fermions).

In some production processes, the medium can also act differently. Take for instance the production of a low pion, say ~ 20 MeV kinetic energy. Its de Broglie wave length is 2.7 fm, i.e. longer than NN interdistance in normal nuclear matter. This may have several consequences : (1) the source of pion production may not only be the correlated NN scattering system, but involve the (appropriate) current of several nucleons. This could explain why the subthreshold pion yield in heavy ion collisions are so large compared to the collision contribution[34] ; (2) there may be a screening of the pion source due to the surrounding medium. This would deduce the source strength, but more importantly limit the long wave length (or equivalently the low frequency) part of the spectrum. The latter would then appear flatter than the free space spectrum. This might very well explain why the pion spectrum seems to show a large and constant temperature (slope parameter) for a wide range of incident energy in heavy ion collisions (see Fig. 7) ; (3) if production is partly due to meson exchange currents (MEC) and not simply to baryon current, this contribution may be considerably changed inside matter.

These considerations may apply more clearly to photon production, a topic which has been under intensive study these last years (for a review, see Ref. 36). Point (1) above corresponds to gamma emission by the cooperative part of the electromagnetic current carried by several nucleons. In its extreme form, this phenomenon is the elusive coherent bremsstrahlung process.[37] Point (2) has been nicely investigated by Knoll and collaborators.[38,39] They showed that photon production rate (in a thermalized system) should fulfill some sum rule, which

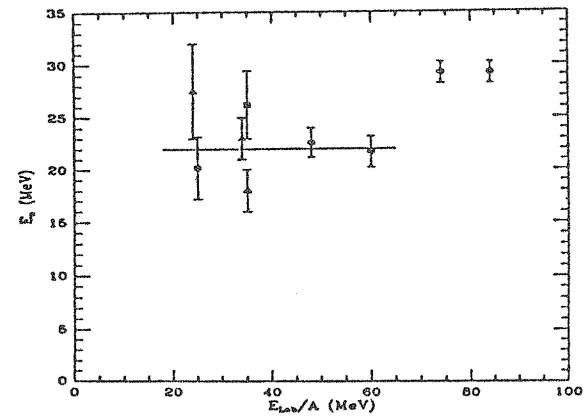

Figure 7. Beam energy dependence of the slope parameter E_0 of pion kinetic energy spectrum for several heavy ion systems. Adapted from Ref. 35.

can be considered as a generalisation of the ordinary dipole sum rule. They also showed that kinetic models using free NN bremsstrahlung cross-section are bound to violate the sum rule for low energy photons ($\lesssim$ 35 MeV in their example). They relate this violation to the diverging bremsstrahlung spectrum at low frequency. In this case, the medium effect is very clear. The bremsstrahlung does not lead to electromagnetic excitations of the vacuum, but to those of the matter, or in this case, to the even more restrictive spectrum of the finite nuclear system. The argument above has been obtained in the soft photon limit, which automatically favours long wave lengths. However, the problem seems to persist if this limit is abandonned. It is not known yet how to correct for this medium effect in collision models, but the question is certainly worth to be investigated. Point (3) above is not very well documented for the photon case, because the importance of MEC in photon production is unclear.[40,41] New measurements of $p+n \to p+n+\gamma$ reaction[42] are in progress, which will help to settle this question.

These kinds of medium effects should be investigated more carefully. In our opinion, it would be instructive to conduct this investigation in parallel for various particle production. Besides pions and gamma's, we think to dileptons (basically related to virtual photons), which are just starting to be studied experimentally[43,44], and to heavier mesons.

The case of K-meson production could perhaps be different from the other ones. The reason is that kaons appear in associated production, whose simplest mechanisms are

$$NN \to N\Lambda K \quad , \quad NN \to N\Sigma K \quad , \qquad (5.1)$$

it is to say reactions with a high threshold energy, thus occurring in violent collisions only. Therefore, it is expected that associated production is highly localized. This property is also consistent with the underlying quark mechanism. Associated production basically results from an $s\bar{s}$ excitation. In the same spirit, pion production results from a mixture of $u\bar{u}$ and $d\bar{d}$ excitations. According to modern views of hadronic physics, the pion can be considered as a collective (rather extended) excitation of the vacuum, whereas $s\bar{s}$ excitations are much more localized. Therefore, one expects less medium correction for associated production. Kaon production (especially K^+) is thus presumably more sensitive to the equation of state than pion production.[45-47] However, before any conclusion can be drawn, medium corrections, even if smaller than those described in sections 3 and 4 should be evaluated. Furthermore, other uncertainties are still to be removed. First, the $NN \to N\Lambda K$ cross-section is badly known close to threshold as illustrated

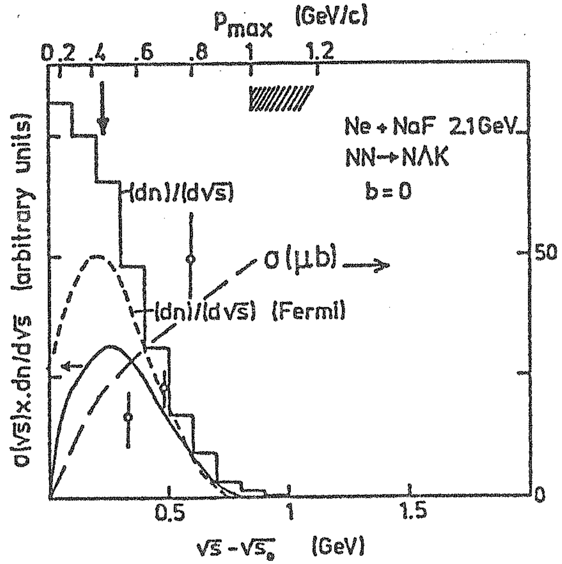

Figure 8. The histogram gives the frequency $dn/d\sqrt{s}$ of baryon-baryon collisions with c.m. energy $\sqrt{s}$ ($\sqrt{s}_0$ is the threshold for $NN \to N\Lambda K$) in the central Ne + NaF collisions at 2.1 GeV/u. The dots indicate the only available measurements (actually $pp \to p\Lambda K^+$) in this energy range. The long dashed is the customarily used parametrisation of the cross-section. The full line is the reaction probability distribution, i.e. the frequency distribution multiplied by the cross-section. The dotted line would correspond to the same quantity (arbitrarily normalized) if only first collisions contributed. The shaded area indicates the border of the kinematical region accessible due to Fermi motion and the vertical arrow indicates the c.m. energy of the pp system with the same kinematics as the heavy ion system. Finally, p_{max} is the maximum K^+ momentum for the corresponding c.m. energy. Adapted from Ref. 46.

by Fig. 8. The latter applies to 2.1 GeV/u (symmetric) heavy ion collision. For subthreshold production in heavy ion collisions, i.e. in the GeV/u range, the most important value of the c.m. energy, i.e. the one which corresponds to the maximum of probability for the above mentioned reaction, is even smaller. Second, it was recently shown that the three-body phase space is strongly distorted[48] close to the threshold because of the ΛN rescattering. One thus expects some further distortion inside matter.

6. CONCLUSION

We have reviewed the question of medium corrections in the dynamics of heavy ion collisions. We started from the Landau-Vlassov equation, which seems to provide a satisfactory framework for the description of nuclear transport in the few MeV/u to few GeV/u energy range. Medium effects appear as mainly renormalizing collision cross-sections. However they may also modify the available phase space. They can also lead to an effective mass different from the bare mass. We did not consider this last aspect here. We discussed carefully the medium effects on elastic scattering, which are the best known by far, though in the limit of local density approximation. We underlined the strong sensitivity of flow properties upon medium effects, apparently stronger than the one related to the equation of state. We discuss the influence of medium effects on the pion yield, which also shows a great sensitivity. We qualitatively discussed the current ideas concerning medium effects in other production mechanisms. Our final conclusion is that a great effort is needed to understand and evaluate reliably medium effects (not only in the collision term) before being capable of extracting nuclear matter equation of state. As La Bruyère[49] told us a long time ago : "Tout le mal vient de ce que nous ne sommes pas seuls" or "The bad thing comes from the fact that we are not alone". But we think also that medium effects should be studied for themselves since they involve an interesting physics.

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