LABORATOIRE NATIONAL SATURNE

QUATRIEMES
JOURNEES D'ETUDES SATURNE
LA PHYSIQUE AVEC MIMAS

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10 - 14 novembre 1986

Commissariat à l'Énergie Atomique — Institut National de Physique Nucléaire et de Physique des Particules

HEAVY ION COLLISIONS AND EQUATION OF STATE. AN OVERVIEW.

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1. Introduction

For a long time already, heavy ion collisions in GeV/A range have opened the physics of dense and hot nuclear matter. This research has been conducted along three main lines.

(1) Exotic processes : There has been a lot of speculations about a series of various exotic phenomena linked with suspected special phases of hadronic matter[1] : shock waves, π-condensates, π-maser, multiquark states, quark deconfinement,.... This part of the program was rather disappointing, since many of these exotic processes have not been observed. However, quark deconfinement can admittedly be observed in experiments at much higher energies (which should be run very soon). On the other hand, the question of peculiar multiquark states is still under debate. The experimental data from Dubna analysed by Y. Panibratsev in his talk (see below) are in favour of the existence of such states.

(2) Extraction of hadronic matter equation of state (EOS), based on the measurement and the analysis of observables, which are thought to be sensitive to the detail of the EOS.

(3) Study of the reaction mechanism. This has an experimental aspect, but also an important theoretical aspect. The crucial point is the use of an accurate off-equilibrium theory including in a correct manner the EOS, an equilibrium concept.

2. Recent results concerning the extraction of the EOS

Very soon after the opening of this field, it was realized that nuclear matter is compressed to 2-4 times ρ_0 , the ordinary nuclear matter density, for a very short time. After a few fm/c, it decays in many pieces, essentially nucleons and pions, but also some composites. The asymptotic state being so different from the compressed state, it is likely that most of the information on the latter has been washed out. However, theoretical considerations, based essentially on the intranuclear cascade (INC) model, predict the existence of some "robust" observables[2], i.e. observables whose values are fixed

when the matter is compressed. Those observables are : pion multiplicity, flow angle, entropy (hopefully measured by the "d"/"p" ratio) and K^+-multiplicity. For the first three, the predictions of the INC were constantly, although not all the time significantly, smaller than the observed values. This was interpreted[3] as evidence of EOS effects (usually not introduced in INC calculations) and even as a strong indication of a stiff equation of state. When the latter is parametrized as

$$\frac{E}{A} = -16 \text{ MeV} + \frac{K}{18\,\rho\rho_0}(\rho-\rho_0)^2 \quad , \qquad (1)$$

the coefficient K is of the order of 360 MeV[4]. This should be compared to the value extracted from the study of giant monopole resonances in nuclei (K = 220 MeV) and to the value "imposed" by the astrophysics, which should be around K $\lesssim$ 160 MeV (see the talk by M. Arnould). As noted in ref. 5, the last two figures do not really contradict each other, since the first refers to $\rho \approx \rho_0$ and the other deals with the region $\rho \approx (2\text{-}4)\rho_0$. There might be a "softening" of the EOS as ρ increases, induced by a softening of relativistic and 3-body contributions, perhaps dictated by causality.

The K^+ production yield is an attractive quantity to look at, since K^+'s are not reabsorbed and therefore is presumably a "robust" quantity. Furthermore, it may be quite sensitive to the EOS[6]. Measurements of this quantity should be pursued. But they require a new measurement of the basic NN → YNK cross-section, where Y is an hyperon, as suggested by Fig. 1 which indicates for a peculiar example the frequency of collisions with a given c.m. energy $\sqrt{s}$. It can be seen that the cross-section is badly known for the most frequent collisions.

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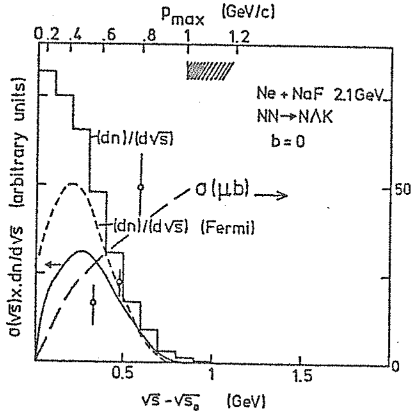

Fig. 1 – Frequency of baryon-baryon collisions $(dn/d\sqrt{s})$, with c.m. energy $\sqrt{s}$ larger than the threshold $\sqrt{s_0}$ of the NN → NΛK reaction. The dots indicate the only available measurements for this reaction (actually pp → pΛK^+) at lowest energy. The long dashed curve is the costumarily used parametrization of the cross-section. The full line is the frequency distribution weighted by this approximated cross-section.

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3. The transport equation

The EOS above has been obtained at the price of some assumptions, like global instantaneous thermodynamical equilibrium. If one wants to improve upon this point, one has to resort on a transport equation, which describes the evolution of the system off-equilibrium. The most celebrated transport equation for interacting Fermion systems has supposedly a Landau-Vlassov form :

$$\{\frac{\partial}{\partial t} + \frac{\vec{p}}{m}.\vec{\nabla}-(\vec{\nabla}U).\vec{\nabla}_{\vec{p}}\}f(\vec{r},\vec{p},t) = \int \frac{d^3p_2}{(2\pi)^3} \int \frac{d^3p_3}{(2\pi)^3} \int \frac{d^3p_4}{(2\pi)^4} W(pp_2 \to p_3p_4)$$
$$\delta^3(\vec{p})\delta(e(p))\{f_3f_4(1-f)(1-f_2)-ff_2(1-f_3)(1-f_4)\} \quad , \qquad (2)$$

where $f_i = f(\vec{r},\vec{p}_i,t)$ is the one-body distribution function, and where the δ functions stand for energy-momentum conservation. Several calculations were aimed to solve this equation, but, up to recently, they were using the free collision matrix W and a static mean field $U = U(\rho(\vec{r}))$, which can be related to the equation of state through a HF functional for instance. By comparison with experiment, it is possible to extract the EOS and K comes as larger than 300 MeV. However, this procedure does not respect the specificity of the nuclear interactions and does not introduce them consistently. Actually, the more correct procedure of ref. 7 should be used. This leads to a momentum-dependent mean field, as indicated by Fig. 2, which shows the

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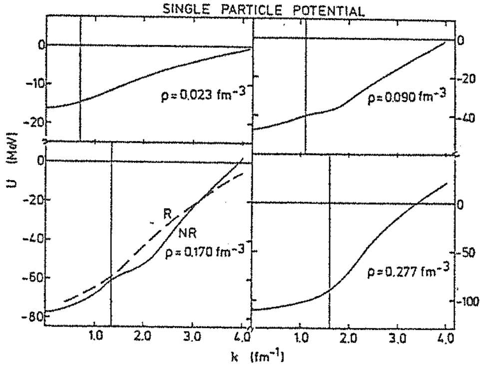

Fig. 2 - Momentum dependent mean field for a nucleon in symmetric nuclear matter, after the non-relativistic calculation of ref. 9 (full lines) and the relativistic calculation of ref. 10 (dashed line).

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value of this quantity for a nucleon of momentum $\hbar k$ moving in an equilibrium nuclear matter. According to ref. 5, this feature would explain why calculation of ref. 4 predicts a stiff equation of state. The average momenta of the particles with respect to their environment is much larger in collision situation compared to an equilibrium situation at zero temperature, like in a nucleus. Indeed, in the frame of the Landau-Vlassov equation, the interaction energy is

$$\frac{E_c}{A} = \tfrac{1}{2} \frac{\sum_k n(k)U(k)}{\sum_k n(k)} \quad , \qquad (3)$$

Obviously, for a given density $\rho = \sum_k n(k)$, the interaction is much more repulsive for a n(k) extended to large k than for $n(k) = \Theta(k_F-k)$, as in a nucleus. The consequences of this feature for the extraction of the EOS are discussed in the talk by J. Aichelin (see below). Other problems are linked with the right definition of W (see ref. 7) and with possible retardation effects in the collision term[8]. Finally, let us mention that the appropriate transport equation is still not very well known in the so-called transition regime. Obviously, there is a transition from the low energy regime where the nuclei keep more or less their cohesion to the high energy regime where they explode litterally. In between, the multifragmentation sets in (see report by C. Volant) and this instability is certainly not described directly by eq. (2).

4. Conclusion

Despite of the progress reported in section 3, there is still a theoretical effort to be done to work out the proper transport equation. On the experimental side, a systematic measurement of the "robust" variables and especially of the K^+ yield should be pursued, as well as the investigation of the multifragmentation regime.

References

1) G. Baym, "Quark Matter Conference 84", Helsinki, June 1984.
2) J. Cugnon, in "Heavy Ion Collisions", ed. by P. Bonche et al., Plenum Press, 1986.
3) R. Stock et al., Phys.Rev.Lett. 49(1982)1236.
4) J.J. Molitoris and H. Stöcker, Phys.Rev. C32(1985)346.
5) T.L. Airsworth et al., Stony Brook preprint 1986.
6) J. Aichelin and C.M. Ko, Phys.Rev.Lett. 55(1985)2661.
7) W. Botermans and R. Malfliet, Phys.Lett. B171(1986)22.
8) L.P. Kadanoff and G. Baym, "Quantum Statistical Mechanics", Benjamin,1962.
9) A. Lejeune, P. Grangé, M. Martzolff and J. Cugnon, Nucl.Phys. A453(1986)189
10) B. ter Haar and R. Malfliet, Phys.Lett. 172B(1986)10, and to be published.