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MULTIPARTICLE EMISSION IN
RELATIVISTIC HEAVY ION COLLISIONS

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Abstract

We analyze the scattering of the heavy ion Ne off NaF at relativistic energy. We study the spectra of the emission fragments for evidence of a thermodynamic - hydrodynamic collective motion. Using fixed beam and target, we are able to fit the spectra of pion, deuteron and proton emission. The fit is consistent with an interpretation of an expanding hot fluid of interacting nucleons.

During the past few years, a need for theoretical understanding of the relativistic heavy ion collision phenomenon has arisen. There exists a vast amount of literature on the subject which cannot be adequately referenced in this letter. However, a completely thermodynamic (and hydrodynamic) picture of such phenomena has presented itself as a viable theory. In a previous paper¹ (hereafter referred to as GR), we discussed the first phase of energetic heavy ion collisions in the framework of a hydrodynamic and thermodynamic picture, consistent with the nuclear fluid model. For reasons discussed in GR, one expects a dense intermediate stage of baryonic matter, a "fireball," to be formed during relativistic heavy ion collisions. (We use the term "fireball" rather loosely; the "fireball" referred to here is significantly different from the original fireball model. See GR.) Such an intermediate fireball has a very high temperature and pressure and is therefore unstable and consequently fragments into hadrons and light composite nuclei like deuterons, helium, etc., which are the observed features of heavy ion collisions. Thus, an important test of a "fireball" model or in general, a thermodynamic and hydrodynamic interpretation is in understanding such emitted particles in heavy ion collisions. In a recent article, Siemens and Kapusta² have looked at the case of deuterons being emitted in heavy ion collisions. The motivation of their work is, however, quite different from ours. They looked at the deuteron-to-proton

ratio in the observed spectrum in order to draw some conclusions about the softness of the equation of state for nuclear matter appropriate to densities attainable in energetic heavy ion collisions. But more importantly, such partitioning into light composite nuclei is a crucial test of the consistency of a thermal picture. The fact that $kT \gg$ binding energy per nucleon for these observed light nuclei implies, naively, that all light species should be approximately as abundant as individual nucleons. Different experimental observations, therefore, compel us to reexamine the data to analyze the validity of any thermal model and the conditions for such validity. In this letter, we confine our attention to the observed proton, pion (π^-) and deuteron spectra at 90° CM frame for 800 MeV/A Ne on NaF target. We insist on looking at one beam-target setup in order to eliminate uncertainties due to unknown arbitrary normalizations.

Following Mekjian,³ Siemens and Kapusta² (called SK hereafter) have also looked at the detailed balancing and the resulting distribution of deuterons. We will look at nucleons, pions and deuterons in the same experiment. They also use a Boltzmann distribution for all species, claiming that the temperature at the instant of breakup is high enough to justify this approximation. Siemens and Rasmussen⁴ previously showed that the temperature at breakup is about 44 MeV for a beam energy of 800 MeV/A and this result has been used in ref. 2. At densities somewhat greater than nuclear density,

44 MeV is not a high enough temperature to justify Boltzmannian approximation and in the following, we made it a point to use the proper statistics for the respective species. In addition, these densities at these temperatures require relativistic treatment for all species.

Our analysis of the detailed balancing also differs from SK in that we require more than baryon conservation for the deuteron. Detailed balancing of SK, using only baryon number conservation, implies $\mu_d = \mu_p + \mu_n$ corresponding to the two-body channel $pn \rightarrow d\gamma$. Obviously, this is not on the strong interaction time scale. The only operative two-body channels on a strong time scale will be

$$pn \leftrightarrow d\pi^0, \text{ or}$$

$$pp \leftrightarrow d\pi^+, \text{ or}$$

$$nn \leftrightarrow d\pi^-.$$

SK justify the use of the more restricting baryon conservation requirement based on a detailed balancing argument using the three-body final state with a nucleon spectator. We argue that these higher order process (in the sense of constituent structure) scatterings are actually built up from the elementary two-body channels available and therefore if there is no two-body channel which will thermalize the reaction on the allowed time scale, the higher order process will be also too slow. Thus to look at the reaction rate for

$dN \leftrightarrow pnN$, one must envision the following scenario: the deuteron "sees" the N through a photon, a nucleon or a pion. Therefore the relevant cross-sections are for the channels $pn \leftrightarrow d\pi$ or $pn \leftrightarrow d\gamma$. In ref. 3, Mekjian has shown that the reaction rate for $pn \rightarrow d\gamma$ is about $10^{19}/\text{sec}$ at best; consequently such channels must be disregarded for relativistic heavy ion collision phenomena. However $pn \leftrightarrow d\pi$ is a strong interaction channel and therefore is expected to be relevant in these cases. A thermodynamic-hydrodynamic model of very dense, hot nuclear matter is possible if and only if the time scale of the individual particle interactions is comparable to the expected lifetime of the hot dense state of the matter. $\sigma_{el}(pp)$ at low energy (corresponding to $kT \sim 50\text{-}100$ MeV) is about 24 mb which corresponds to a reaction time of about $\sim 8 \times 10^{-24}$ sec, whereas a typical hydrodynamic expansion time may be estimated³ to be about $\sim 5 \times 10^{-23}$ sec. Also for low kinetic energies, $\sigma(\pi^+d \rightarrow pp)$ is about 12 mb. So the thermalization of pions and deuterons proceeds on a comparable time scale. These estimates indicate that typical strong interactions allow enough time for thermalization.

In ref. 4, Siemens and Rasmussen generalized the original formula of Bondorf et al.⁵ incorporating a collective motion to a Boltzmann distribution to include relativistic effects. It is quite straightforward to do the same for Fermi or Bose distribution, the only extra complication being that the integral over angles now have to be done numerically.⁶ Then

the velocity (β) of such a collective motion and the temperature were fitted phenomenologically for the proton data in ref. 4. In our analysis, the velocity β is not phenomenological. The analysis in GR predicts the thermodynamic state of the nuclear matter at the end of shock compression. This highly condensed matter at high pressure (calculable from the equation of state) will relax to normal nuclear density. A crude estimate (dependent on the equation of state) of the energy released during this expansion (pdV work) may be carried out to yield a corresponding velocity β of collective motion. Obviously, one needs to perform a detailed two-dimensional relativistic hydrodynamic calculation to obtain a correct value of this velocity; but the excellent fits obtained from these estimates guarantee that the overall scenario is tenable.

The effects of different equations of state were discussed in detail in GR. In this letter, we present evidence that a thermal picture requires the incorporation of a realistic strong interaction between the baryons at these nuclear and supernuclear densities. We emphasize that this use of relativistic Hartree model of the nuclear fluid has its limitations but that any more realistic model of the fluid would have to have similar gross features such as binding energy and compressibility. Our point is that interaction effects are necessary to reproduce and interpret the data and that this model is the simplest vehicle for the inclusion of such

effects. The pions and the deuterons are treated as free bosons. The specific model of the interacting Fermi fluid for protons was discussed in GR and in references therein; but for the sake of completeness, let us review the physical input very briefly. The baryons interact via the exchange of virtual scalar and vector mesons which mediate the four Fermi interactions with arbitrary coupling strengths λ_s and λ_v respectively. These coupling strengths are fixed by fitting the binding energy of baryons at a Fermi momentum of 1.42 fm^{-1} at zero temperature to -15.75 MeV . Then one can define as scalar and vector self-energies the following quantities,

$$\Sigma_s = -\lambda_s \langle \bar{\psi}_B \psi_B \rangle$$

$$\text{and } \Sigma_v = \lambda_v \langle \psi_B^+ \psi_B \rangle ,$$

$\langle \bar{\psi}_B \psi_B \rangle$ being the proper number density and $\langle \psi_B^+ \psi_B \rangle$ being the physical number density of the baryons. Then the distribution function in the rest frame becomes

$$f(p) = \frac{1}{e^{(E_p^+ + \Sigma_v - \mu)/T} + 1}$$

$$\text{with } E_p^+ = (\vec{p}^2 + (m + \Sigma_s)^2)^{1/2}$$

and $\hbar$, c and Boltzmann constant k all being set equal to

unity. Also because we look only at the π^- spectrum, we use the degeneracy factor $g (=2J + 1)$ equal to 1 for pions, 2 for protons and 3 for deuterons.

With the above interacting Fermi distribution function properly boosted by the collective velocity β (calculated to be equal to 0.4 for the interacting case), the proton spectrum from 800 MeV/A Ne on NaF is fitted. The temperature for the spectrum is obtained from the high energy tail. Then the values of μ , Σ_s and Σ_v are all fixed for the protons by virtue of the equation of state, as the number density at the instant of breakup is expected to be the normal nuclear density. Thus, this is a one-parameter fit, the fitted parameter being the temperature. For the fit in fig. 1, the temperature is found to be 46.7 MeV with a corresponding μ of 908.0 MeV. It is noteworthy that the maximum temperature obtained at the end of the first phase (the shock compression) was 114 MeV. One can, naively, expect that the average temperature of breakup should be about half the maximum temperature and the phenomenological value of T supports this intuitive estimate. Of course, there is an overall multiplicative factor which is the product of the geometrical cross section and the thermodynamic volume. Then an assumption of complete thermal and hydrodynamic equilibrium necessitates that the pions and the deuterons must have the same temperature, collective velocity, geometrical cross section and thermodynamic volume as those of the protons. However, the origin of pions

and deuterons is completely thermal and therefore their chemical potentials need to be phenomenologically fitted as they fix the number densities for such species. Pions (π^-) and deuterons were fitted using free Bose distributions (properly boosted) to the data to yield $\mu_{\pi^-} = 105.0$ MeV and $\mu_d = 1680.0$ MeV. These fits are shown in fig. 1. [It should be noted that on a strong interaction time scale, $\mu_p = \mu_n$ in the absence of charge neutrality.] These fits have an uncertainty of about 10 MeV in the chemical potentials. It is evident that the fits shown in fig. 1 are better representative of the features in the spectra than the fits in refs. 2 and 4. We emphasize that since this data utilizes the same beam-target setup, the norms between different fragment curves are the same and, therefore, the relative abundances of different species is being predicted.

Since the chemical potential of each species was fit separately, we can immediately see that instead of satisfying $\mu_d = \mu_p + \mu_n$, they satisfy $\mu_d + \mu_{\pi} = \mu_p + \mu_n$. This agrees with our time scale arguments concerning the correct thermodynamic interpretation of the system. In other words, the data is actually indicative of the fact that a thermal interpretation together with a collective motion is valid on a strong interaction time scale but not on an electroweak time scale. To our knowledge, such an evidence has not been reported in the literature. It must also be mentioned at this point that a realistic description of the strong interaction

is also essential. This is a considerable distinction between our work and those existing in the literature. In fig. 2, fits are shown for protons using a free relativistic Fermi fluid equation of state. For this case, β is calculated to be 0.37. The fit yields a temperature of 39 MeV with $\mu_p = 947.5$ corresponding to normal nuclear density at this temperature. The deuteron spectrum for $\mu_d = 1730.0$ MeV is shown. The pion spectrum, however, yields a value of μ_π equal to 155.0 MeV. Although the relation $\mu_p + \mu_n = \mu_d + \mu_\pi$ is established even for these values, one immediately sees that the requirement that μ_π for a free boson be less than m_π is violated. This high value of μ_π has no consistent thermodynamic interpretation. This value of μ_π lies in the spectrum of the emitted pions and would lead to a large cross section at low energies. Although the data is sparse at energies below 100 MeV, there is no indication of singular behavior.

Thus we are led to conclude that heavy ion collisions even with the few constituents currently available give clear indications of a thermodynamic-hydrodynamic interpretation that could be identified with an expanding fireball of nuclear matter. This interpretation is possible though only if a realistic strong interaction between the nucleons is incorporated into the analysis and only strictly strong interaction conservation laws are applied to the thermal equilibrium conditions. The above analysis may be applied to any light species, data for which are currently available and

from a knowledge of μ (and T), it is straightforward to calculate the relative multiplicities for them.

We conclude by making one final comment. The authors in ref. 2 used the deuteron-to-proton ratio to find evidence for a soft nucleon matter equation of state. But the interacting Fermi fluid equation of state employed here is considerably harder than the free Fermi fluid in the sense that the bulk modulus is of the order of 550 MeV at nuclear density. Therefore, at nuclear density, the rate of change of pressure with number density is much higher than that for the free fluid. (See GR and references therein for a detailed discussion.) Thus we see that conclusions about softness (or hardness) of the nuclear matter equation of state are crucially dependent on a correct interpretation of the thermodynamics and hydrodynamics of the problem and a proper analysis of the interactions involved.

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Figure Captions

Fig. 1: Spectra at 90°CM for 800 MeV/A Ne on NaF. Data for p and π^- are from ref. 7 and data for deuterons are from ref. 8. Collective velocity β is calculated to 0.4, for the interacting Fermi equation of state for protons. T for all species is 46.7 MeV, obtained from the fit for proton spectra.

Fig. 2: Spectra at 90°CM for 800 MeV/A Ne on NaF. Data for p and π^- from ref. 7 and for deuterons from ref. 8. Collective velocity β is calculated to be 0.37, for the free Fermi fluid equation of state for protons. T for all species is 39.0 MeV, obtained from the fit for proton spectra.

FIG. 1

FIG. 2