Direct Versus Thermal Particle Emission in High-Energy Heavy-Ion Collisions: Light Fragment Emission and the Ratio of Neutron to Proton Inclusive Cross Sections

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An additive two-component model (direct plus thermal) is used together with an empirical power law for composite particle production to calculate inclusive cross sections for light fragment emission. The ratio of neutron to proton inclusive production is also studied. We compare our results with recent experimental data.

1. Introduction

Purely thermal models like fireball [1] and firestreak [2] fail to reproduce the shapes of forward-angle proton inclusive energy spectra measured in heavy-ion collisions at 250 and 400 MeV/N [3]. Taking account of the fact that a direct reaction mechanism appreciably contributes in certain kinematical regions [4], a very simple model consisting of a direct and a thermal component has been quite successful in explaining the observed shapes [5]. Deviations from the slopes of the energy spectra as obtained in thermal models have also been found in other approaches like the blast-wave model [6] or the phase space model [7] but the latter have only been compared with data around the GeV-region.

Apart from its application to genuinely inclusive spectra the two-component model [5] has also been applied to multiplicity (M)-selected proton inclusive cross sections [8]. Qualitative differences in the shapes of high-M as compared to low-M energy spectra have been found, as well as a strong dependence on mass asymmetry. This is in rough agreement with recent experimental results [9]. Although the broad peak observed in the high-M proton angular distributions for unequal colliding nuclei [9] is neither reproduced by our model nor by more elaborate numerical cascade calculations [10] this cannot as yet be considered as evidence for shock wave formation [11] because of the quite large error bars in the data of [9]. In view of the presently rather inconclusive stage concerning the observation of new phenomena in existing experimental data we continue the validity test of our model in the present work. The aim is to detect through eventual deviations from experimental results kinematical regimes where particle emission occurs via mechanisms which go beyond direct and thermal production. The specific processes we will study are the inclusive production of protons with large longitudinal momenta, neutron inclusive production, and composite particle inclusive production.

2. Light Fragment Production within the Two-Component Model

We start from the expression for inclusive proton production obtained in an incoherent multiple scattering formalism [12-14].

\[
\frac{d\sigma}{d^3p} = \sum_{j=1}^{\infty} \left[ Z_B \sigma_B^T p_B^T(p) + Z_T \sigma_T^B p_T^B(p) \right].
\]

Here, \( p \) is the proton momentum, \( j \) denotes the number of collisions, \( B \) and \( T \) are the mass numbers of projectile and target, and \( Z_B \) and \( Z_T \) are the corresponding charge numbers. The geometrical weights \( \sigma_B^T \) and \( \sigma_T^B \) are partial cross sections for a projectile nucleon impinging on the target and vice versa. They are determined by the elementary total
cross section and the respective nuclear densities. Their explicit form can be found, e.g., in [5]. The functions $P_B^{p}$ and $P_T^{p}$ are the momentum distributions of a projectile or target nucleon after $j$ collisions.

The essential step for obtaining the two-component model from (1) consists in the separation of the single scattering contribution from the higher-order multiple scattering terms the momentum distributions of which are approximated by a common thermal (Maxwell) distribution of mean temperature $\tau$.

$$\left( \frac{d\sigma}{d^3p} \right)_{s.p.} = \left( \frac{d\sigma}{d^3p} \right)_{s.p.}^{T_H} + \left( \frac{d\sigma}{d^3p} \right)_{s.p.}^{J} \tag{2}$$

with

$$\left( \frac{d\sigma}{d^3p} \right)_{s.p.}^{T_H} = \sum_{j \geq 1} (Z_B \sigma_j^p + Z_T \sigma_j^p) P_T^{p}(p, \tau) \tag{2a}$$

and

$$\left( \frac{d\sigma}{d^3p} \right)_{s.p.}^{J} = \left[ \sum_{j \geq 1} (Z_B \sigma_j^p + Z_T \sigma_j^p) \right] P_J^{p}(p, \tau). \tag{2b}$$

The functions $P_{DI}$ are taken from extended impulse-approximation calculations. For details we refer to [5, 15]. The expressions (1) and (2) account for all protons produced in the reaction ("summed" protons, abbreviated by "s.p."). A considerable number of them are bound in composites formed in the reaction, and therefore, the inclusive cross section for free protons will deviate substantially from [2] in certain kinematical regions. The genuine proton inclusive cross section can be obtained from (2) with the aid of a phenomenological final-state interaction (coalescence) model as described in [16].

$$\left( \frac{d\sigma}{d\Omega dE} \right)_{s.p.} = \sum_{N_Z} \frac{Z}{N_Z} \left( \frac{N_B + N_T}{Z_B + Z_T} \right)^N \cdot \left[ \frac{1}{m_V E(E+2m)} \right]^{A-1} \left( \frac{4\pi p_0^3}{3\sigma_{RT}^2} \right)^{A-1} \left( \frac{d\sigma}{d\Omega dE} \right)_{p}. \tag{3}$$

Here, $\left( \frac{d\sigma}{d\Omega dE} \right)_{s.p.}$ is the double differential cross section in the laboratory system for summed protons, connected with (2) via

$$\left( \frac{d\sigma}{d\Omega dE} \right)_{s.p.} = p(E+m) \left( \frac{d\sigma}{d^3p} \right)_{s.p.} + \left( \frac{d\sigma}{d^3p} \right)_{s.p.}. \tag{3}$$

is the corresponding quantity for free protons.

The individual contributions to the sum in (3) are the inclusive cross sections for production of a fragment with $N$ neutrons, $Z$ protons and $A = N + Z$ nucleons at a laboratory kinetic energy per nucleon $E$. In the numerical results presented in Sect. 3, only light charged fragments up to $^4$He are included in the sum of (3), since the influence of heavier fragments on the proton cross section is negligible small. The quantities $m$ and $\sigma_{RT}^2$ denote the proton mass and the total reaction cross section, respectively. The parameter $p_0$ has the meaning of the momentum below which $A$ nucleons coalesce to form a composite. The power law for the composite particles spectra as expressed in (3) gives very good agreement with the data if one employs the observed proton spectra [17].

In general, the power law (3) will not be correct. It should rather be applied for each event (impact parameter) separately and only then the integration over impact parameter should be performed. This has been pointed out, e.g., in [24]. In a recent paper [25], this problem has been treated in more detail. It is shown there that employing an impact parameter averaged square law for deuteron production like is done in (3) amounts to the neglect of a two-nucleon correlation function in momentum space. For the production of heavier fragments the corresponding terms in (3) will result if multi-nucleon correlation functions in phase space are neglected. Since in our two-component model such correlations are not considered at all it will not be very meaningful within this framework to apply the coalescence idea per impact parameter. Even though (3) may not be justified on the basis of the above discussion we think it is justified empirically regarding its good agreement with experimental data [17]. Our attitude in the present work therefore is as follows: We wish to study the influence of the non-equilibrium component on the nucleon and light particle inclusive spectra. Since within the two-component model such correlations are not considered at all it will not be very meaningful within this framework to apply the coalescence idea per impact parameter. Even though (3) may not be justified on the basis of the above discussion we think it is justified empirically regarding its good agreement with experimental data [17]. Our attitude in the present work therefore is as follows: We wish to study the influence of the non-equilibrium component on the nucleon and light particle inclusive spectra. Since within the two-component model we can only calculate summed nucleon spectra we need an additional recipe to calculate the genuine nucleon and composite particle spectra. This recipe is the empirical power law (3). This admittedly quite modest approach is adequate for a validity test of our two-component model.

For completeness we mention that the power law (3) can be explained in a theory which assumes thermal and chemical equilibrium between all species of particles produced in the collision [18] but because of the strong indications of single scattering effects in the proton cross sections this is probably not a completely satisfactory explanation.

As regards the neutron inclusive cross section there are two possible ways for its calculation: (i) We may calculate the summed $n$-cross section within the two-component model by replacing the charge numbers $Z_B$ and $Z_T$ in (2) by the respective neutron numbers $N_B$ and $N_T$. We then may use an equation analogous to (3) to solve for the neutron spectrum. (ii) Since for those terms in (3) describing composite particle production the relation