COLLECTIVE FLOW IN CENTRAL Au + Au COLLISIONS AT $E \sim 1$ AGeV

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Using the total energy, charge, and baryon number conservations laws the portion of available excitation energy released as collective/thermal energy is deduced. The amount of available energy released as collective energy was found to be rather large and well described as radial flow of emitted particles.

1 Introduction

The chief goal behind the studies of relativistic heavy-ion collisions is to understand the properties of nuclear matter beyond its ground state. At energies of 1−2 GeV per nucleon, realistic phase space simulations [1] predict that in central collisions the nuclear matter is compressed by a factor of 2−3 compared to its ground state density. In the hydrodynamical picture, the reexpansion of the initially compressed nuclear matter produces collective flow of emitted particles [2]. As opposed to hydrodynamics, purely thermal models [3] assume that the energy stored in compression is fully transformed into the thermal motion of particles. In a typical relativistic heavy-ion reaction, it is quite conceivable that the particle spectra are influenced by, both, the thermal and the collective degrees of freedom. In this contribution, we discuss how much of the available excitation energy is in the collective flow of particles, and how much energy is left in the thermal motion. To this end, we used the blast model [4] which combines a local thermal equilibrium assumption with the global collective expansion of particles. Using this model, general conservation laws were imposed on the data in order to extract the energy in the collective/thermal degrees of freedom.

2 Outline of the experiment

The experiment was performed at the UNILAC/SIS accelerator facility in GSI/Darmstadt using the *FOPI* detection system. The $Au + Au$ reaction was measured at 1.06 GeV per nucleon. The target consisted of 100 μm foil corresponding to 0.5 % interaction probability. The energy loss in the target was minimal and was neglected in the analysis.

The *FOPI* detector is a large multipurpose detector consisting of a forward plastic wall scintillators and a superconducting solenoid which houses the central drift chamber (*CDC*) [5,6]. To select the most central events we used the multiplicity criterion PM5 as described in detail in Ref. [7].

3 The analysis

In the blast model the thermal energy is being converted into the radial flow of emitted particles through the pressure gradient. The particle distribution function which corresponds to this process is given by the following expression:

$$\frac{1}{pE}\frac{d^2N}{dEd\Omega} = c\cdot e^{-\frac{\gamma_f E}{T}}\cdot\left[\frac{sinh\alpha}{\alpha}(\gamma_f + \frac{T}{E}) - \frac{T}{E}cosh\alpha\right], \tag{1}$$

where N, E and T are the number, total energy and temperature of the emitted particles; The symbol c is the normalization constant. The parameter α is given by $\alpha = p\beta_f\gamma_f/T$ where p is the momentum of the particle. The parameters γ_f and β_f are the relativistic β and γ related as:

$$\gamma_f = \frac{1}{\sqrt{1-{\beta_f}^2}}. \tag{2}$$

The spectra of emitted particles are usually fitted by using the Eq. 2 and varying the parameters c, β_f, and T freely. However, by imposing the overall energy conservation not all combinations of the parameters c, β_f, and T will be allowed. Assuming a single velocity radial flow profile, in fact, only one set of β_f and T is needed to describe the spectra of all emitted particles.

In order to be able to determine the amount of energy in the collective/thermal degrees of freedom an overall energy conservation is, of course, required. To accomplish this, we use the full experimental information obtained with our apparatus. To account for the total charge conservation we combine the measured meson and baryon multiplicities using the expression:

$$N_{norm}(n_p + n_d + n_t + 2n_{^3He} + 2n_{^4He} + ...+) + N_{\pi^+} - N_{\pi^-} = Z_P + Z_T, \tag{3}$$

where n_p, n_d, n_t, and $n_{^3He}$ are the measured numbers of protons, deuterons, tritons, and ^3He per events. Z_P and Z_T are the charges of the target and projectile. The pion multiplicities N_{π^+} and N_{π^-} are taken from Ref. [7].

Using Eq. 3 one immediately obtains N_{norm}. This charge correction factor is a result of the incomplete solid angle coverage. The angular coverage of the *FOPI* device in the present experiment amounts to $\sim 75\%$ of the full solid angle. In Eq. 3 we have used the same charge correction factor for all measured charge particles. Nevertheless, we have found that if one uses different charge correction factors for different particles the final result is practicaly unchanged.

Having determined the N_{norm}, the total particle multiplicities simply follow from the relations:

$$\begin{array}{l} N_p = N_{norm} \cdot n_p \\ N_d = N_{norm} \cdot n_d \\ N_t = N_{norm} \cdot n_t \\ N_{^3He} = N_{norm} \cdot n_{^3He} \\ N_{^4He} = N_{norm} \cdot n_{^4He} \\ \ldots, \end{array} \tag{4}$$

where N_p, N_d, N_t, and so on, are the total proton, deuteron and triton multiplicities which will enter into the overall energy conservation. Before employing energy conservation, one needs to calculate the number of emitted neutrons. We do this by using the total baryon number conservation, which reads as follows:

$$N_n = A_P - Z_P + A_T - Z_T - (N_d + 2N_t + N_{^3He} + 2N_{^4He} + ...+), \tag{5}$$

where N_n is the total neutron multiplicity. A_P, Z_P and A_T, Z_T are the mass and charge numbers of the projectile and target, respectively.

The overall total energy conservation can be written as:

$$\begin{array}{rl} E_{avail} = & N_n < E_n > +N_p < E_p > +N_d < E_d > \\ & +N_t < E_t > +N_{^3He} < E_{^3He} > +N_{^4He} < E_{^4He} > +...+ \end{array} \tag{6}$$

where E_{avail} is the available energy after the contribution from nucleon binding (8 AMeV) and the pion emission has been accounted for. This was done by calculating the mean pion kinetic energies using the temperatures as given in Ref. [7].

The mean total particle energies $< E_i >$, $i = n, p, d, t, {}^3He, {}^4He, ...$, where n stands for neutron, p for proton, and so on, were calculated by everaging the total particle energy E with the distribution function as given by the Eq. 1.

This can be written as:

$$
\begin{gathered}
< E_i > = \frac{1}{N} \int \int E(\frac{d^2N}{dEd\Omega}) dEd\Omega \\
i = n, p, d, t, {}^3He, {}^4He, ...,
\end{gathered}
\tag{7}
$$

By varying the temperature T and the flow velocity β_f in Eq. 1 one obtains the mean total particle energies as a function of the model parameters T and β_f. The underlying idea here is to loop over all possible combinations of the parameters T and β_f and find out which sets of parameters T and β_f fulfil the energy conservation.

4 Results and Conclusions

A strict application of the procedure described in the previous section to the experimental data reveals a somewhat unexpected result. Namely, the model parameters T and β_f which fulfil the energy conservation show a good fit only to the proton spectra. In our analysis, this would also be true for the neutrons. Since the neutrons are not measured in the experiment, their spectra are asumed to be the same as the proton spectra. This assumption is a reasonable one in view of the result from Ref. [8] where no discernible difference in the shape of the proton and the neutron spectra was observed. In our case, free protons and neutrons exhaust around $\sim 70\%$ of the total baryon number; the number of all pions amounts to $\sim 7\%$ of the total baryon number. Based on the fit to the proton spectra in Fig. 1 the radial flow energy is of the order of $\sim 70\%$ of the available energy, and yields a temperature of less than 50 MeV for the fireball at freeze-out.

Let us now focuss on the different apparent behaviour of the protons and heavier particles. In fact, such a pattern has already been observed by the *EOS* collaboration [9]. The *EOS* collaboration has studied the $Au + Au$ system at several incident energies. Among these, the 1 AGeV point is almost identical to the situation analyzed in this paper. The *EOS* data for protons are in close agreement with our data. The agreement is not as perfect for the deuterons, but very good again for $mass = 3$ particles. In Ref. [9] the inconsistency between the spectra of protons and heavier particles was attribited to the possible contributions from heavy-baryon decays. However, the small number of pions and also recent theoretical calculations [10] make this explanation rather unlikely. On the other hand, the measured spectra are easily reproduced if the condition of a constant flow velocity for all particles, nucleons and heavier, is abandoned. In this case, the collective flow energy for heavier particles would decrease in accordance with a recent study of the $Ar + Ca$ system [11]. The overall balance between collective and thermal motion in the expanding fireball would hardly change, since the number of heavier particles is low compared to the number of protons.

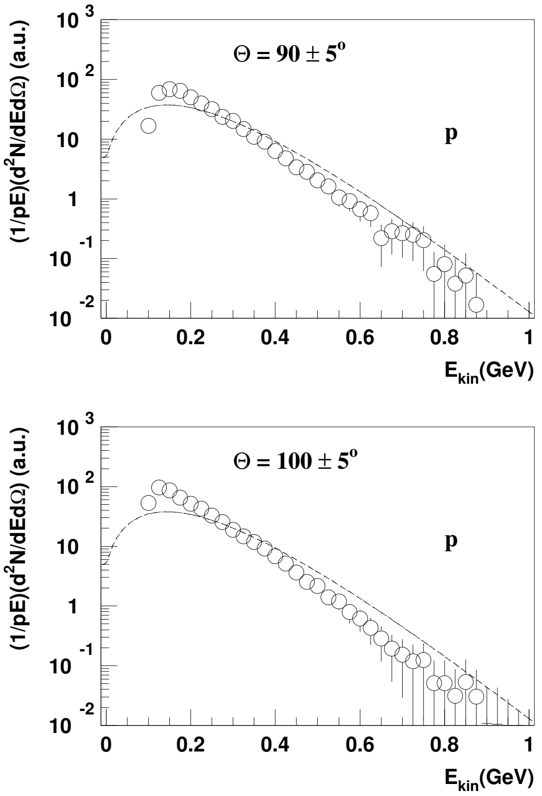

Fig. 1. Measured proton spectra (open symbols) at $\theta_{c.m.} = 90 \pm 5^o$ (top), and at $\theta_{c.m.} = 100 \pm 5^o$ (bottom). E_{kin} is the proton kinetic energy. The lines show the fit to the data obtained by using Eq. 1 with the values of $\beta_f = 0.55$ and $T = 37$ MeV. For particles heavier than proton the values of $\beta_f = 0.32$ and $T = 81$ MeV were used. These two set of values for β_f and T fulfil the total energy, charge, and baryon number conservation.

We thus conclude that also at 1 AGeV mombarding energy the amount of collective energy is suprisingly large and follows the trend from lower incident energies as observed in the work of Ref. [12] ($\sim 60\%$ of collectivity).

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