THE LIMITING NUCLEAR TARGET FRAGMENTATION AND THE THERMODYNAMICAL MODEL

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The fragmentation of nuclear targets is considered in the frame of the thermodynamical model. The scaling properties of experimental data concerning backward particles are described.

There are interesting phenomena found in nucleus–nucleus collisions at high energy [1–5], called the limiting fragmentation of nuclear targets (LFNT), that have the following features:

(1) In the laboratory system (LAB) the slope of the energy distribution of particles (elementary and composite as well) produced in the backward hemisphere is quasi-independent of the mass numbers of the target, A_t, and the projectile, A_p.

(2) The slope reaches a limiting value with increasing initial energy.

(3). The absolute cross section reaches a limiting value with increasing initial energy.

(4) The cross section for backward particles are proportional to $A_t^{\alpha} \cdot A_p^{2/3}$, where α depends on the type of produced particles.

The aim of this paper is to show that the quoted experimental facts, ordered in the above four points, can be described in the frame of the thermodynamical model (TM) [6]. The advantage of a thermodynamical description of backward protons is that there are no special assumptions of the structure of the nucleus. Any kind of correlations in the nucleus discussed in various papers [1,6–10] is not assumed. The mechanism of nucleon–nucleon interaction is also not determined, opposed to ref. [11]. The thermodynamical approach to backward particles was firstly proposed by Gorenstein and Zinoviev [12]. However, only a qualitative analysis was done; the temperature and velocity of the source were treated as free parameters. The scaling properties of data were not explained. In this paper we have performed a much more quantitative analysis. Particular attention has been paid to the mechanism which leads to the nuclear scaling described above.

Why can the first two features of LFNT occur in the TM? Let us consider the source of temperature T_0 that moves in the LAB with velocity β and decays as an ideal gas at some critical density. In the center-of-mass frame (CM) of the source the distribution of energy of emitted particles, $\rho(E^*)$, is isotropic and can be approximated by [13]

$$\rho(E^*) = C \exp(-E^*/T_0)$$

where C is a constant. Now we transform this distribution to the LAB. For simplicity, emitted particles are assumed to be ultrarelativistic. In such a case

$$E^* = \gamma(1 - \beta\cos\Theta)E,$$

with E the energy of particles in the LAB, Θ the angle of emission in the LAB and γ the Lorentz factor. The energy distribution in the LAB looks like

$$\rho(E) = C'\exp(-E/T_0^{\mathrm{lab}}),$$

where

$$T_0^{\mathrm{lab}} = T_0/\gamma(1 - \beta\cos\Theta).$$

We will show that for backward particles the slope of the energy distribution T_0^{lab} is a slowly varying function of the velocity of the source and incident (kinetic) energy, E_{inc}. The crucial point of the TM is to determine the temperature of the source. The assumption that the total kinetic energy in the CM of the source converts into heat (thermal motion) is nonrealistic in high energy collisions, since a big part of the energy is transformed into the masses of the particles produced. When the energy goes to infinity, the temperature reaches a finite value of about 140 MeV [14,15]. To find the temperature of the source, chemical equilibrium among the nucleons and produced particles is assumed The system of equations for the temperature and the chemical potentials is solved. When the incident energy goes up, so many types of particles have to be included that the above method is very complicated or even practically useless. We apply the connection between the energy per nucleon in the CM of the source and the temperature found in the statistical bootstrap model [16]. Due to this method, used in ref. [17], we can get a reasonable temperature, which varies from zero to the limiting value, for any incident energy. However, the only particles that we can consider are nucleons. The temperature and the velocity of the source are both defined by the incident energy per nucleon and the parameter

$$\eta = N_p/(N_p + N_t),$$

where N_t (N_p) is the number of nucleons from the target (projectile) in the source. We can eliminate the parameter η and find the temperature as a function of β and E_{inc}. In fig. 1 we present T_0^{lab} as a function of β and E_{inc} for two extreme cases; $\Theta = 0°$ and $\Theta = 180°$. We see that for a backward angle T_0^{lab} is a slowly varying function. For $E_{\mathrm{inc}} = 3$ GeV/N T_0^{lab} changes by less than 5 MeV when β varies from 0.15 to 0.60 light velocity. Let us notice that the limiting value of T_0^{lab} of about 50 MeV agrees with the experimental value [2,3]. In all our considerations the limiting temperature is equal to 140 MeV and the critical density of the source is the same as the normal nuclear density (0.17 GeV fm^{-3}). We conclude that when the target or incident energy varies, the slope of the energy distribution of backward particles cannot be changed practically if the average velocity of the source changes not too much.

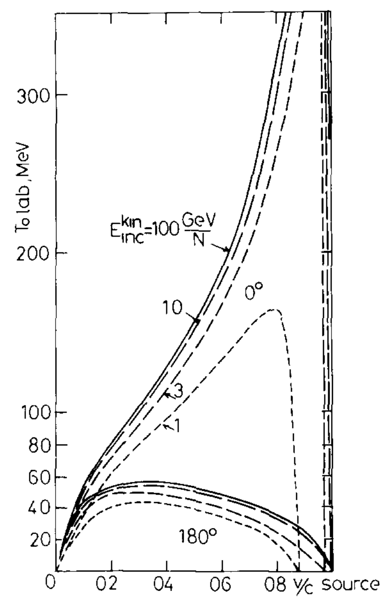

Fig. 1 The slope of the cross section in the LAB for proton emission at $\Theta = 180°$ and $\Theta = 0°$ as a function of the incident kinetic energy and the velocity of the source.

To obtain quantitative results we have tested two models: firestreak [18,19] and firetube [20]. These models differ in the geometrical aspects of nuclear collisions, but the thermodynamical parts are the same. We have used totally relativistic thermodynamical formulas without any ultrarelativistic approximations applied in our previous qualitative considerations.

In the firestreak model [18,19] diffuse surfaces of colliding nuclei are assumed. Interactions occur independently between infinitesimal collinear streaks of projectile and target matter. The total kinetic energy in the CM of the fire-object undergoes thermalization. Due to an independent interaction of the streaks, we get the temperature and the velocity gradient in the interaction volume. We restrict our calculation to such values of η for which the temperature of the source is greater than 9 MeV.

In the firetube model [20] collinear tubes are assumed to interact independently. The geometrical sections of the tubes are $\sigma = \sigma_{tot}^{NN} = 42$ mb. The cross sections for colliding N_p nucleons from a projectile with N_t nucleons from a target are found from Glauber type probability considerations. In this model fluctuations of the nuclear density are taken into account e.g. all nucleons from the nucleus can occur in one tube. On the other hand, there are no "pieces of nucleons" as in the firestreak model. In this model the absolute values of the cross sections are determined without additional assumptions.

We use Fermi type nuclear density distributions in our calculations. In our opinion, the Fermi type distribution is in better agreement with the data on electron scattering on nuclei [21] than the Yukawa type used by other authors [18–20]. To describe proton–nucleus interactions in the firestreak model, we have used the proton form factor taken from ref. [21].

To find the slope of the differential cross section in the LAB, we have evaluated Lorentz-invariant cross sections. Then we have fitted them as in experiment by

$$C \exp(-T/T_0^{lab}),$$

where T is the secondary proton kinetic energy. The slope changes with the energy interval of the protons being considered, since it is not possible to describe the calculated as well as the experimental cross sec-

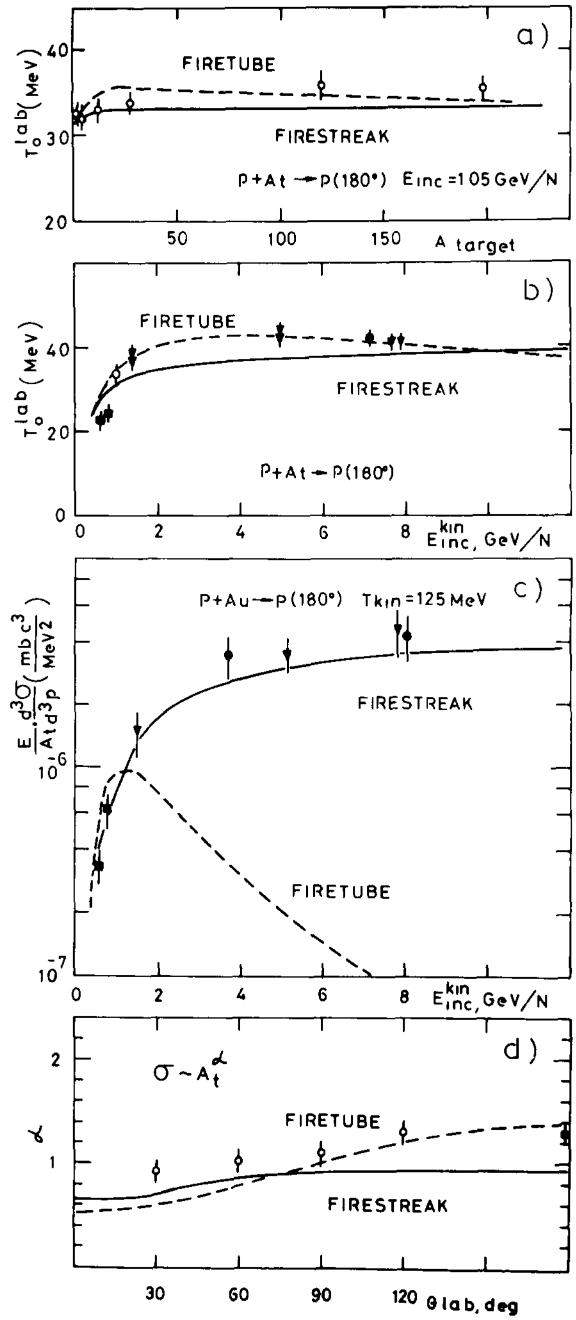

Fig. 2 (a) The slope T_0^{lab} versus target mass at the incident kinetic energy of 1 05 GeV per nucleon compared with the firestreak and firetube models The data are from ref [22]. The energy interval of secondary protons is 75–275 MeV. (b) The slope T_0^{lab} versus incident kinetic energy per nucleon compared with the model calculations. The data are from refs. [2,22–24] The energy interval of secondary protons is 50–300 MeV (c) The absolute values of the cross section for proton emission in p + Pb → p + X with energy 125 MeV at $\Theta = 180°$ versus incident kinetic energy. The experimental points are from refs. [2,23,24]. (d) The exponent $\alpha(E\, d^3\sigma/d^3p \sim A_t^{\alpha})$ as a function of the angle in the LAB. The energy of secondary protons equals 200 MeV. The data γ + A → p + X are from ref [25] The data p + A → p + X are from refs [2,22].

tions by one exponential function in a wide range of energies of emitted protons. See fig. 3.

In fig. 2a the slope T_0^{lab} is shown as a function of A_t for protons emitted at 180°. One can see the agreement of the calculation of the both models with the experimental data [22].

The dependence of T_0^{lab} for backward protons on incident energy is presented in fig. 2b. Data are taken from refs. [2,22–24]. At an energy higher than 3–4 GeV per nucleon the slope seems to reach its limiting value of about 43 MeV. We see that the experimental points are well described by both models.

In fig. 2c we present the incident energy dependence of the absolute cross section for protons emitted in the reaction p + Pb → p + X. The energy of secondary protons equals to 125 MeV, $\Theta = 180°$. The experimental points are taken from refs. [2,23,24]. We observe a complete failure of the firetube model and a surprisingly good agreement of the firestreak with experimental data. The main difference of these two models is the following. The firestreak geometry takes into account the interactions of "pieces of nucleons" (what resembles the Hagedorn approach to nucleon–nucleon collisions [16]). In the firetube model "pieces of nucleons" are absent. The contribution of the interactions of these "pieces" turns out to increase with energy.

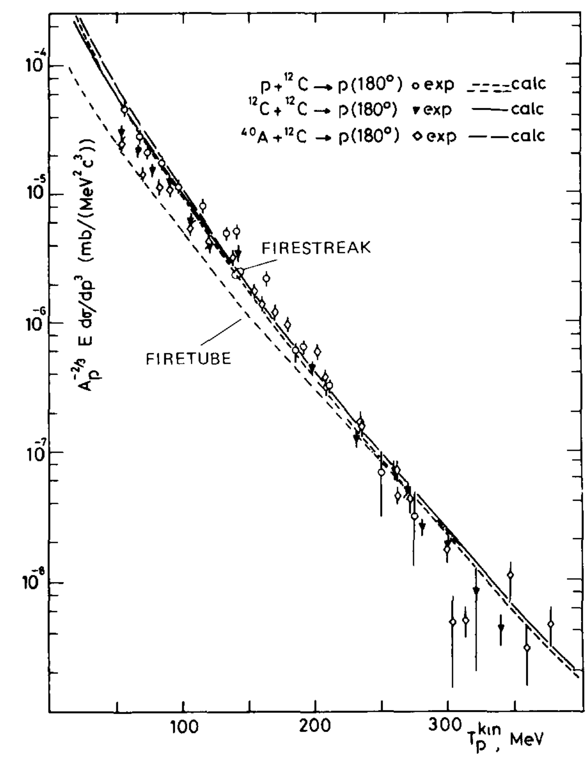

Fig. 3 The Lorentz-invariant cross section divided by $A_p^{2/3}$ for different projectiles at the incident kinetic energy of 1.05 GeV/N. Data from ref [22]. The firetube calculation is done for p + ^{12}C. The firestreak predictions are multiplied by 1/2.

The model predictions concerning A_t dependence are shown in in fig. 2d. Because of the absence of data, we put in fig. 2a a little bit of nonadequate photoproduction data [25]. The reason of a strong A_t dependence for backward particles is the following. The same energy in the LAB of secondary protons correspond to lower and lower energy in the CM of the average source as the target mass increases. Since the cross section for proton production exponentially decreases with the energy of secondaries, it is obvious, that the increase of the cross section with A_t measured in the LAB comes from the energy dependence of secondary protons and from real A_t dependence.

Fig. 3 shows the proton production cross section at $\Theta = 180°$ for various projectile nuclei. Experimental data are taken from ref. [22]. The firestreak predictions have been multiplied by 1/2. The calculations agree with an experimental A_p dependence, namely $A_p^{2/3}$ [2,22].

We conclude that there is a reasonable explanation of LNTF in the thermodynamical model. While the description of points 1 and 2 is independent of a particular formulation of the TM, points 3 and 4 are strongly affected by the geometrical aspects of nuclear collisions. The predictions concerning the incident energy dependence of the absolute values of cross section favour the firestreak model.

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