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THE LIMITING NUCLEAR TARGET FRAGMENTATION AND THE THERMODYNAMICAL MODEL

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There are interesting phenomena found in nucleus-nucleus collisions at high energy[1-5], named 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 number of the target, A_t.
2. The slope reaches a limiting value with increasing energy.
3. Cross sections for backward particles are proportional to A_t^{α} with α equal about 1; 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 three points, can be described in the frame of the thermodynamical model (TM). For review of the thermodynamical approach to nucleus-nucleus interactions see ref.[6].

Why can LFNT occur in TM? Let us consider the source of temperature T_0 that moves in LAB with velocity β and decays as an ideal gas at some critical density. In the centre of mass (CM) of the source the energy distribution $\rho(E^*)$ is isotropic and can be approximated by[7]

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

where C is a constant.

Now we transform this distribution to LAB. For simplicity, emitted particles are assumed to be relativistic. In such a case

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

with E being the energy of particles in LAB; θ, the angle of emission in LAB; γ, the Lorentz factor. The energy distribution in LAB looks like

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

where

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

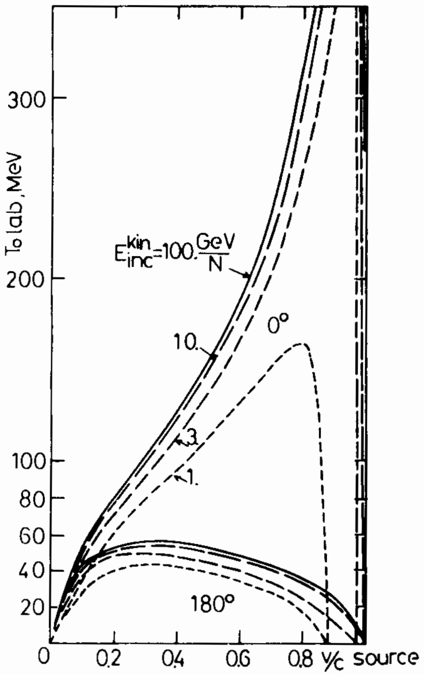

Fig.1. The slope of the cross section in LAB for proton production at $\theta = 0°$ and $\theta = 180°$ as a function of the incident kinetic energy and the velocity of the source.

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 the incident (kinetic) energy (E_{inc}). The crucial point of TM is to determine the temperature of the source. The assumption that the total kinetic energy in CM of the source converts to heat (thermal motion) is nonrealistic in high energy collisions, since a big part of energy is changed to the masses of produced particles. When the energy goes to infinity, the temperature reaches a finite value of about 140 MeV /8,9/. To find the temperature of the source, chemical equilibrium among nucleons and produced particles is assumed. Then the system of equations for temperature and chemical potentials is solved. When incident energy goes up, we have to include so many types of particles 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 statistical boostrap model/10/.Due to this method, we can get a reasonable temperature for any incident energy. However, the only particles that we can consider are nucleons. At high energy not the total energy undergoes thermalization (thermal motion and mass production) since a part of energy is taken by leading particles. We neglect these effects; however, we return to this problem at the end of our paper.

The temperature and the velocity of the source are both defined by the incident energy per nucleon and parameter η

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

where N_t (N_p) is the number of nucleons from 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 backward angle T_0^{lab} is a slowly varying function. For E_{inc} = 3 GeV/N, T_0^{lab} changes by less than 5 MeV when β varies from 0.15 to 0.60 of the velocity of light. Let us notice that the limiting value of T_0^{lab} 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 normal nuclear density.

We conclude that when the target or incident energy varies, the slope of the energy distribution of backward particles cannot be practically changed if the average velocity of the source changes not too much.

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

In the fireball model/11/ nuclei are assumed to be uniform density spheres with sharp boundaries. The source-fireball consists of overlapping parts of nuclei. The total kinetic energy in the CM of fireball undergoes thermalization.

In the firestreak model/12,13/ diffuse nuclear surfaces are assumed. Interactions occur independently between infinitesimal collinear streaks of projectile and target matter. Due to an independent thermalization of the streaks, we get the temperature and the velocity gradient in the interaction volume. We restrict our calculation to η in an interval of 0.025-0.975 independent of incident energy. At E_{inc} = 1 GeV/N such a cutoff excludes sources with the kinetic energy per nucleon less than 15 MeV. This restriction introduces some ambiguities of the absolute value of total cross sections, but it has no influence on the slope of differential cross sections for fast particles under consideration.

In the firetube model/14/ 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 projectile with N_t nucleons from a target are found from Glauber type probability considerations. All cross sections in the firetube model are obtained by summation of the cross sections with definite N_t and N_p over all possible values of N_t and N_p. In this model, fluctuations of nuclear density are taken into account, e.g., all nucleons from nucleus can occur in one tube. On the other hand, there are no "pieces of nucleons" as in the firestreak model. Another advantage of this model is that the absolute values of the cross sections are determined without additional assumptions.

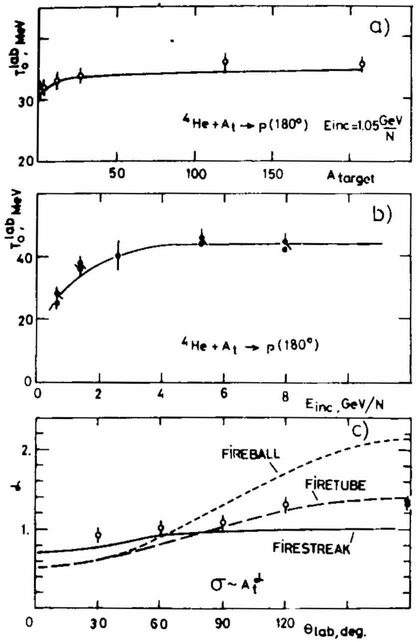

Fig.2. a) The slope T_0^{lab} vs. target mass at an incident kinetic energy of 1.05 GeV per nucleon compared with the firestreak model. Data from Ref.16. The energy interval of secondary protons is 75-275 MeV. b) The slope T_0^{lab} vs. incident kinetic energy per nucleon compared with firestreak calculations. Data from Ref.17. The energy interval of secondary protons is 50-300 MeV. c) Exponent α $(E d^3\sigma / d^3p \sim A_t^{\alpha})$ as a function of angle in LAB compared with fireball, firestreak and firetube. The energy of secondary protons equals 200 MeV, the incident energy 1.05 GeV/N. Data $\gamma + A \to p + X$ (O) from [18]. Data $p + A \to p + X$ (■) from [2,16].

We use Fermi type nuclear density distributions in our firestreak and firetube calculations. In our opinion, the Fermi type distribution is in better agreement with the data on electron scattering on nuclei [15] than the Yukawa type used by other authors [12,13].

To find the slope of the differential cross section in LAB, we have evaluated Lorentz-invariant cross sections. Then we fitted them as in experiments [1-4] by

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

where T is the proton kinetic energy. The slope changes with the energy interval of secondary protons being considered, since it is not possible to describe the calculated as well as the experimental cross sections by one exponential functions 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 a full agreement of the firestreak calculations with the experimental points [20]. The fireball and firetube models give practically the same result. So, we have explained point 1 of LFNT.

The dependence of T_0^{lab} for backward protons on incident energy is presented in Fig.2b. Data are taken from compilation [17]. At energy higher than 3-4 GeV per nucleon the slope seems to reach its limiting value of 43 MeV - point 2 of LFNT. We see that the experimental data are well described by the firestreak model. The fireball and firetube models predict the same behaviour of T_0^{lab}.

While the description of points 1 and 2 of LFNT weakly depends on geometrical aspects of collisions, point 3 is strongly related to geometry. The predictions of the models are different as shown in Fig.2c. Because of the ansence of data, we put in Fig.2c a little bit of nonadequate photoproduction data [18]. The best agreement is obtained in the firetube model. The reason of a strong A_t dependence for backward particles is the following. The same energy in LAB of secondary protons corresponds to lower and lower energy in the CM of the average source when the target mass increases. Since the cross section for proton production exponentially decreases with energy of secondaries, it is obvious that the increase of the cross section with A_t measured in LAB comes from the energy dependence of secondary protons and from real A_t dependence.

Figure 3 shows the proton production cross section at $\theta = 180°$ for various projectile nuclei. Experimental data are taken from Ref.16. The firestreak predictions have been multiplied by 1/2. The calculations agree with an experimental A_p dependence, namely $A_p^{2/3}$ [2,16].

There is a problem to describe the behaviour of the absolute value of cross sections for backward particles vs. incident energy. In the models being considered $E d^3\sigma / d^3p$ decreases with energy when experiment gives a slow increase or no dependence [2]. We have found a good agreement of the predicted absolute value of the cross section at incident energies lower than 3 GeV/N while for higher energies the predicted cross sections are underestimated. In our opinion, such a feature of the model is connected with the assumption that the total CM energy converts to the internal energy of the source. We suppose that underestimation of the cross sections for backward particles (and overestimation of the forward cross sections) comes from overestimation of the velocity of the source. Let us notice that we do not strongly overestimate the temperature since we are close to the limiting temperature. So, the above problems have a weak influence on the slope of the cross sections (scaling properties of data) if we work on the plateau region shown in Fig.1.

We believe that these problems can be overcome when the effects of leading particles and transparency of nucleus are included*. Attempts concerning the transparency have already been done [14,19,20]; however, some free parameters occur in these considerations.

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* Some improvements in describing the absolute values of differential cross sections in the firestreak model can be obtained if one gets the values of $\eta_{min,max}$ dependent on incident energy.

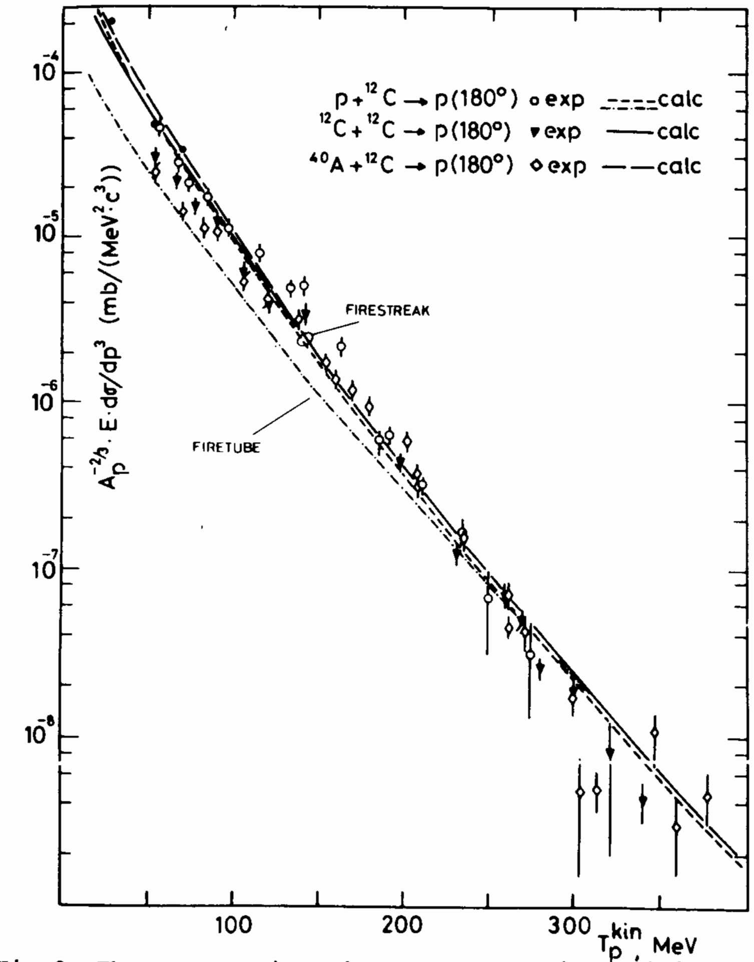

Fig.3. The Lorentz-invariant cross sections divided by $A_p^{2/3}$ for different projectiles at an incident kinetic energy of 1.05 GeV/N. Data from Ref.16. The firetube calculation is done for $p+{}^{12}C$. The firestreak predictions are multiplied by 1/2.

The advantage of a thermodynamical description of backward protons is that there are no special assumptions on the structure of nucleus, e.g., big Fermi momenta of nucleons considered in Ref.[21]. Any kind of correlations in nucleus discussed in various papers[1,22,23] is not assumed. The mechanism of nucleon-nucleon interaction is also not determined. The thermodynamical approach to backward particles was firstly proposed in Ref.[24]. However, only a qualitative analysis was done with the temperature and the velocity of the source as free parameters.

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Авдейчиков В.8., Мрувчинский С. E2-83-353
Предельная фрагментация ядра-мишени и термодинамическая модель

Рассматривается возможность описания экспериментальных данных по предельной фрагментации ядра-мишени с выходом высокоэнергетических протонов под углом 180° в рамках термодинамической модели. Расчет геометрической части ядро-ядро взаимодействия выполнен в рамках файрболл-, файрстрик- и файртьюб-моделей. Термодинамическая часть модели описывает распад возбужденных файрболов как идеального газа Максвелла-Больцмана. Связь энергии с температурой взята из "модели статистического бутстрапа". Модель хорошо описывает основные характеристики явления предельной фрагментации: зависимость формы энергетических спектров протонов от атомного номера ядра-мишени, от энергии бомбардирующего ядра, выход на "скейлинг" параметра, характеризующего наклон энергетических спектров протонов, зависимость сечения образования протонов от типа бомбардирующей частицы и ядра-мишени. Обсуждается возможное влияние эффекта лидирующей частицы и так называемой прозрачности ядерного вещества на расчетные характеристики явления предельной фрагментации.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1983

Avdeichikov V.V., Mrówczyński E2-83-353
The Limiting Nuclear Target Fragmentation
and the Thermodynamical Model

The possibility of describing the experimental data of the limiting nuclear target fragmentation in the frame of the thermodynamical model is considered. Particular attention is paid to the production of protons at 180° angle. The geometrical part of the model is realised following the fireball, firestreak and firetube models. The proton production is described in the thermodynamical part as a decay of an ideal Maxwell-Boltzman gas. The connection between energy and temperature is taken from the statistical bootstrap model. The reasonable agreement is found with the data considering: the dependence of the slope of the energy distributions on the mass of the target, the dependence of the slope on the incident energy, the dependence of the cross sections on the target mass and on the mass of projectile. The influence of the leading particle effect and the so-called transparency of the nuclear matter on the considered characteristics is discussed.

The investigation has been performed at the Laboratory of High Energies, JINR.

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