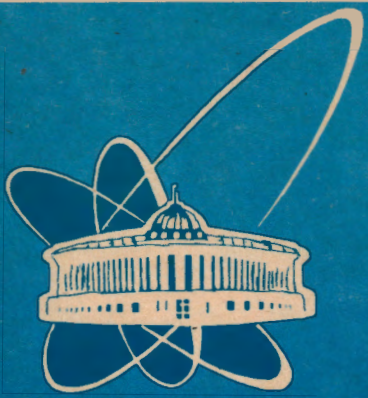

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PERCOLATION MODEL OF NUCLEAR MULTIFRAGMENTATION IN HIGH ENERGY NUCLEUS-NUCLEUS INTERACTIONS

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1 Introduction

Recent experimental data shows that the simultaneous fragmentation of highly excited nuclei into many fragments with charge $Z > 2$ appears as a dominant reaction channel in nucleus-nucleus (AA) collisions at incident energies above 50 $MeV/nucleon$. Nowadays the mechanism(s) of the reaction receives considerable debate. There are only few models [1]-[3] that attempt to describe AA interactions from the initial impact through to the final formation of clusters. But these models were not able to give perfect description of the distributions of fragment mass number or charge even in the range of its applicability. A systematic study of relativistic heavy-ion collisions from the peripheral to the most central in impact parameter are the main goal of the experiments at $RHIC$ and LHC in USA, which will be completed at the end of this century. Now new experimental fragmentation data [4] of Kr, Xe and $U + Em$ at ~ 1 $GeV/nucleon$ appears and it is rather suspicious that these models can correctly describe them. A model is therefore needed to describe fragment production in AA interactions at high and super high energies.

To explain the fragment production, it is necessary to couple a model being able to describe the fast stage of the interaction with another one which can describe the de-excitation of nuclear residue. By tradition the first fast stage of the interaction is usually described with the help of the intranuclear cascade model (ICM) [5, 6]. However its region of applicability is limited in the energy range of ≤ 10 $GeV/nucleon$. At high energy one has the so-called Reggeon theory inspired model ($RTIM$) [7], which was successful in explaining the cascading of particles in proton-nucleus (pA) and AA collisions. Concerning the de-excitation models, one immediately remembers the standard Weisskopf model for light particle production. The popular models of nuclear multifragmentation are: statistical multifragmentation [8]-[11], aggregation [2], [12]-[15] and percolation models [16]-[17] (see additional references in [18]-[19]). Among these models the percolation one gives the simplest description.

Now the bond-percolation model is widely used to describe mass yield curves. It is assumed that in an initial state of the nucleus the nucleons are occupied the sites of a simple cubic lattice. Each nucleon has a maximum of six neighbors and bonds. Due to an interaction the bonds are broken with a probability p_b which is constant over the whole lattice. A constant p_b can only

give a qualitative description of mass yield curve in pA reactions. Obviously, the energy deposited into the target nucleus by the projectile is larger for central than for peripheral collision and p_b should reflect this. Thus the p_b dependence on impact parameter has been introduced [20] for pA interactions and the desired agreement was reached. Unfortunately such dependence is not based on any theoretical approach and considered only as a fitting function. Moreover this dependence cannot be applied for AA interactions because the mass number of the projectile and target could be varied in broad ranges and many such fitting functions would be required.

Recently [21] the p_b dependence on excitation energy of nuclear residue has been proposed. For events at a given excitation energy E_x, the authors were able to reproduce the fragmentation data of *600 MeV/nucleon* $Au + C$, Al and Cu.

In the present work this dependence is going to be used to describe the fragmentation data of $p + Ag$ [22], $p + Au$ [23] at 350 GeV and $C + Ag$, Au at 3.6 $GeV/nucleon$[24]. It is found that by using this dependence the model underpredict the yield of medium mass fragments. A new dependence is therefore introduced by us. With the improvements of this dependence the experimental distribution of mass for the above reactions as well as the distribution of charge for the recent experimental data [4] of Kr, Xe, $U + Em$ are described.

This paper is organized as follows. In Sec.2 the model is described together with the connection of breaking probability and excitation energy. In Sec.3 the model predictions are compared with the experimental data while Sec.4 is devoted to a few conclusions.

2 The model

To describe fragment production, three ingredients must be specified: the mass number of nuclear residue, its excitation energy and the connection between p_b and the excitation energy. First, it will be shown how to determine the first two inputs in the framework of *RTIM*. Second, the percolation procedure is described. Afterwards the connection between the breaking probability and excitation energy is going to be established.

in the simplest approach a nucleon can be represented as a core surrounded by a cloud of virtual mesons. In the course of pA interaction many virtual mesons can simultaneously take part. This picture is taken into account in Reggeon theory. In contrast to the cascade picture of sequential binary collisions between the incident and produced hadrons with target nucleons, a collective interaction scenario here is favorite. This scenario can be imitated as follows: if a nucleon of the target nucleus with impact coordinate $\vec{s}_i$ is knocked out, it can initiate the ejection of other target nucleon with impact coordinate $\vec{s}_j$ with probability $\phi(\mid \vec{s}_i - \vec{s}_j \mid)$. This second nucleon can in its turn eject a third one, ..., etc. This is also true in AA interactions.

The number of interacting or "wounded" nucleons which are involved in the first stage of the interaction can be determined by the following algorithm of Monte Carlo simulation:

1. At a given impact parameter and given coordinates of the nuclear nucleons (in the corresponding reference frames) one can determine the interacting nucleons of the nuclei according to Glauber's approach (see Refs. [25]-[30]).

2. One has to look for all the spectator nucleons of the target nucleus. If the i^{th} spectator nucleon is at the impact parameter distance $b_{ij} = \mid \vec{s}_i - \vec{s}_j \mid$ from the j^{th} interacting nucleon, then it is considered to be involved in the process with a probability

$$\phi = Cexp(-\frac{b_{ij}^2}{r_c^2}), \qquad (1)$$

where r_c is the mean interaction radius, taken as $r_c = 0.7\ fm$.

3. If the number of newly involved nucleons is not equal to zero, one has to repeat step 2. At this point one only needs to consider the newly involved nucleons[1]. If the number of newly involved nucleons otherwise equals zero, then the procedure must be stopped.

The same procedure can be applied for projectile nucleus destruction.

[1]This allows one to take into account the processes when 3, 4, 5 ... etc., nucleons are involved in any block of the interaction.

The new mechanism of particle cascading into the nucleus requires in turn a new procedure for calculating the excitation energy of the nuclear residue, other than *ICM* prescription. In doing so we follow the paper [31] and assume that in the course of interaction each ejected nucleon transfers to its spectator neighbor an energy E distributed according to

$$F_1(E) = \frac{1}{< E >} e^{-E/<E>}. \qquad (2)$$

The problem now is how to decide which nucleons are spectator neighbors. To solve this problem two representations of the initial nuclear state are used. First, the nucleons are placed on the sites of a simple cubic lattice having a nearly spherical volume. Therefore the nucleons which are located in the neighbor sites to the ejected one are supposed to be spectators. Second, the nucleons are placed randomly according to a normal nuclear density, taken as Saxon-Wood density distribution. If any two nucleons are in a distance d_c they are considered as neighbors, $d_c \leq 2\ fm$. In this case the nucleus looks like a percolating cluster. The two representations are connected by the requirement that the average square radius of the cubic lattice nucleus must be equal to that given by Saxon-Wood distribution. This guarantees the right geometry of the collision.

If a spectator nucleon were a neighbor, e.g., of two wounded nucleons, it would obtain the convolution of the two energies chosen according to (2), ..., etc. The sum of the energies transferred to all spectator nucleons is considered as the excitation energy of the residual nucleus.

After the fast stage of the interaction, all spectator nucleons are assumed to acquire kinetic energy (due to mesonic or baryonic fields). Two nucleons in an element of phase space are said to be connected if their relative momentum is less than the negative potential energy between them. Otherwise, the two nucleons are assumed not bound to each other. A cluster is defined if the nucleons are connected directly or indirectly by bonds. These bonds represent attractive interaction between them.

Now, consider the nucleons are on the sites of a simple cubic lattice, i.e., their positions are fixed in space. The energy distributed into the nucleons is assumed to be described by a Maxwell-Boltzmann distribution. Having in mind the criteria of connecting nucleons as described above, the probability

of disconnecting bonds can be written as (compare Ref. [21])

$$p_b = \int_B^\infty \sqrt{E_s} e^{-E_s/T_s} dE_s / \int_0^\infty \sqrt{E_s} e^{-E_s/T_s} dE_s, \tag{3}$$

where B is the binding energy and $T_s = \frac{2}{3}E_s$ are the slope parameter (temperature), with E_s being the excitation energy.

The authors of paper [21] have used an initial cubic lattice of 68 sites, with the bond breaking probability calculated by (3), and the slope parameter T_s was obtained by fitting the data of proton kinetic energy spectra by a single moving source and a binding energy of 7.8 $MeV/nucleon$, they could be able to reproduce the fragmentation data of 600 $MeV/nucleon$ $Au + C$, Al and Cu.

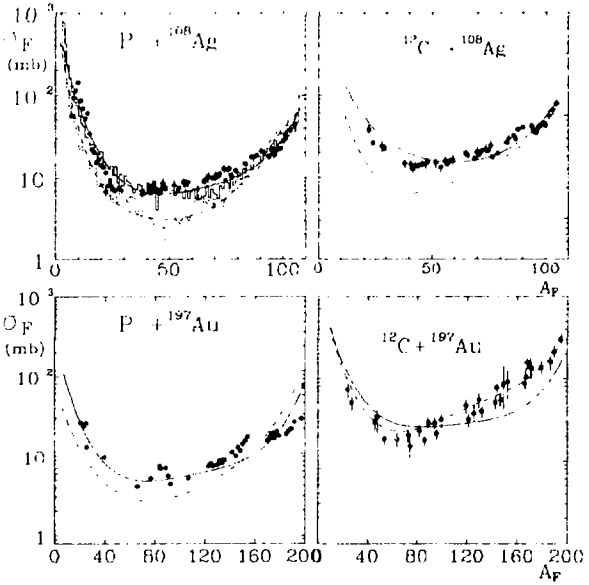

Fig.1 The mass yield curves for the reactions denoted on the legend of the figure. Dashed and solid lines denote the calculations by using the prescriptions of (3) and (4) respectively.

To check the validity of (3) in the framework of the present model, the mass yield curve of $p + Ag$ is calculated. It can be seen from Fig.1 that the model underpredict the yield of medium mass fragments by a factor of 2. In Fig.2 the breaking probability p_b is calculated as a function of excitation energy E_x at $< E >= 20\ MeV$ for the same reaction. The breaking probability is calculated for this reaction by assuming an impact parameter dependence, taken from Ref. [32], while the excitation energy is calculated by the procedure outlined above. In Fig.2 the points denote the simulation of the breaking probability as a function of excitation energy.

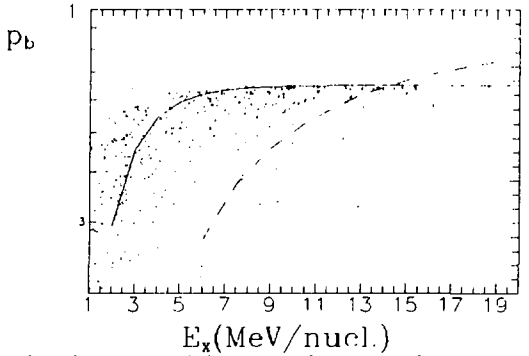

Fig.2 The breaking probability as a function of excitation energy of the nuclear residue for $p+Ag$ at high energy. Points denote the actual dependence (see text), dashed and solid lines are the calculations by using (3) and (4) respectively.

The dashed line represents the model calculations by using the prescription of (3). As one can see, the break-up probability rapidly increases with increasing excitation energy. This contradicts with the actual dependence, shown by points, where p_b increases up to some excitation energy and then levels off that to be limiting fragmentation. The solid line shows the present work parameterization of this dependence which is given by

$$p_b = p_{b0}\left[1 - \exp(-E_x/E_{bond})\right], \tag{4}$$

where p_{b0} is defined as a normalization probability (or "central breaking probability) and E_{bond} is the energy required to break one bond. Following Bauer [32] the two parameters are equal to $p_{b0} = 0.65$ and $E_{bond} = 5\ MeV$.

It should be remarked that the prescription of (3) is in agreement with that of (4) only in the region of E_r from 4 to 10 MeV/nucleon. Beyond this there is a big difference, while the prescription of (4) is limited to $p_b = 0.65$, that of (3) goes to unity.

3 The mass yield curve

Fig.1 shows the complete mass distribution of $p + Ag$ at 300 GeV. The characteristic of this distribution is that the spallation cross section decrease exponentially with decreasing mass over most of the mass range, between $A_f \simeq 48$ and 98. At lower mass numbers, the mass yield curve gradually levels off and then begins to increase sharply below $A_f \simeq 28$, where fragmentation becomes the dominant mechanism. The dashed histogram shows the present work calculations by using (3). In concrete calculations the parameter of (2) is taken as $< E >= 20\ MeV$ and the binding energy at 7.8 $MeV/nucleonin$(3). For a given p_b, a Monte Carlo algorithm decided for each bond individually whether it is broken or not. The procedure is followed by a counting algorithm which looks for clusters and evaluates their size. It should be emphasized that in this approach p_b depends on impact parameter (through the dependence of excitation energy on impact parameter) in contrast to the approach of Ref.[21]. It can be seen that while the agreement for very small and large mass fragments is very good, the calculations by using (3) underpredict the data by a factor of 2 in the medium mass region between 40 and 90. The underestimation of the data in this range can be understood by Fig.2. Due to the rapid increase of break-up probability as a function of excitation energy, one may expect that the probability to have medium mass fragments, using this dependence, is very low.

It should be remarked here that, the same behavior as the dashed histogram has been obtained in paper [32]. In this paper the breaking probability was assumed to depend on the impact parameter of the proton. This dependence was given by integrating over the nucleon density of the target along the path

of the projectile. For their calculations they used a standard Saxon-Wood parametrization of the density.

Fig.1 also demonstrates the distribution of fragment mass for $C + Ag$ at high energy. The dashed line represents the calculations according to [3]. It can be seen that the calculations reproduce the overall shape, but also underestimate the data in the range of $A_f \sim 40 - 80$.

In the case of $p + Au$ interactions at high energy, the calculations reproduce the experimental data much better, nevertheless, there is a slight underesti-

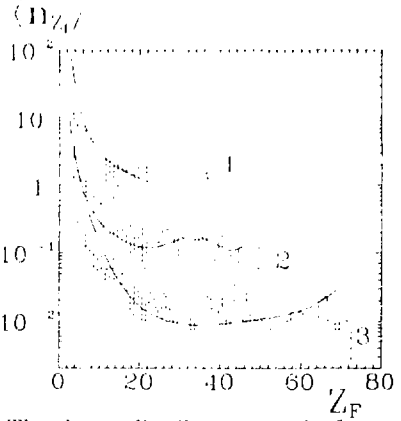

Fig.3 The charge distributions of the fragments from Kr, Xe and $U + Em$ at ~ 1 $GeV/nucleon$ (1 – 3 respectively). Histograms denote the experimental data while the solid lines represent the calculations by using (4). Both data and calculations for Xe and Kr are multiplied by factors of 10 and 100 respectively.

mation in the medium mass fragments. For $C + Au$, the agreement of the calculations with the data is surprisingly excellent.

The model calculation shown by solid line in Fig.1 with the improvements of (4) is compared with experimental mass yield curves of p and $C + Ag$ and p and $C + Au$. The parameter of (4) is fixed at $< E >= 30$ MeV. Now, it is seen that the quality of the fitting is considerably better and the yield from

low to high mass fragments is well described in contrast to the calculations by using (3). One only notices a slight disagreement of the data of $C + Au$ at high mass fragments of $A_f \sim 160 - 197$. But one needs more data to make any definite conclusion.

In the following, the results are obtained using the prescription of (4).

Among the experiments on MF, emulsion measurements are of particular interest because they provide an almost complete identification of the fragment charges emitted in a heavy-ion collision.

The Kr, Xe and $U + Em$ systems have been studied by this method in Ref. [4] at ~ 1 $GeV/nucleon$. The corresponding charge distributions are displayed in Fig.3. Before going any further, it should be stressed that the emulsion data do not have very high statistics. This indicates statistical fluctuations in the observed variables. This point should be kept in mind when comparing numerical simulations with the data.

The main characteristic of the spectra shown in Fig.3 is that the charge distribution contains all events from light to heavy fragments. It can also be seen that a good overall agreement between experiment and calculation is accomplished, without changing the parameters from that of $p + Ag$ case.

4 Conclusion

- The present hybrid model, based on $RTIM$ plus a nuclear multifragmentation model, has furthermore a high predictive power which has not been fully exploited, by far. The model shows a very good description of the experimental fragment mass distributions of p, $C + Ag$ and p, $C + Au$ as well as charge distributions of Kr, Xe and $U + Em$. The model can be used for estimation of nuclear fragment production in AA interactions at high and super high energies. Of course, the percolation model can be replaced by other more reliable model of nuclear multifragmentation. We think that this will not however strongly affect the calculation results.

- The hot nuclei fragment similar to other statistical systems. Only at large values of excitation energy there can be a deviation from statistical laws, see Fig.1. This deviation is perhaps caused by the finiteness of the nucleus. In very hot nuclear matter the nucleons are moving with high

velocities and therefore should leave the interaction volume very fast. So, the statistical equilibrium cannot be reached. At low excitation energy the nucleons have many collisions between themselves and statistical equilibrium is established.

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