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Nuclear response and hadron formation length in high-energy hadron-nucleus interactions

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A simple Monte Carlo cascade model which gives the exclusive description of the hadron-nucleus collisions is described. Comparison with the data on pAr, pXe collisions at 200 GeV suggests that at this energy all secondary particles are produced basically by the multiple collisions of a projectile and by the cascading of the recoiled nucleons inside the nucleus, while the cascading of the secondary pions is rather negligible.

I. INTRODUCTION

In the last few years, a considerable attention has been paid to the study of hadron-nucleus interactions at high energies (see, for example, Refs. 1–6) where the experimental and phenomenological situation is reviewed. The study is motivated by the hope that the hadron collisions on the nuclear targets could give valuable information about the mechanism of strong interactions not available from the pure hadron-nucleon collisions.

One of the most important questions under study concerns the time development of the secondaries including hadronization after a collision inside the nucleus. From the theoretical point of view, hadronization of the secondary particles is a stage that cannot be described in terms of perturbative quantum chromodynamics (QCD). Moreover, the estimation of a time scale for hadron formation is at present of great importance for correctly interpreting recent heavy-ion collision data,[7,8] in which a signal of the quark-gluon plasma is intensively sought.

In connection with this question, the concept of the formation length has been introduced and, by means of different approaches, studied quantitatively.[9–11] The approach described in this paper is based exclusively on the classical notions of nuclear and high-energy hadron-nucleon phenomenology and the consistent cascading procedure in three space dimensions. That is, roughly speaking, the main difference between our model and those proposed by other authors[9,10] in which more fundamental hadron-nucleon generators are used, but on the other hand their cascading procedures are less consistent. Since the only additional assumptions in our approach concern the formation length of secondaries, the resulting Monte Carlo algorithm is rather simple and clear. In this sense,. the model can be a useful tool for the study of different approaches to the formation length and its influence on the kinematical and multiplicity distributions of the secondaries in the hadron-nucleus interactions.

II. THE MODEL

Our Monte Carlo algorithm is based on the cascading procedure proposed earlier[12] for nucleons recoiled by a projectile passing through the nucleus. The main improvement results from a replacement of an oversimplified particle generator of elementary collision dealing with leading particles only (assuming all hadrons apart from primary projectile and recoiled nucleon to be formed behind the nucleus) by a more consistent one[13] giving complete events according the following distributions: (1) Differential cross sections are as follows: (a) inelastic

$$\frac{d\sigma_{in}}{dp_t^2} \propto \exp(-\beta p_T^2) \;, \tag{1}$$

$$\frac{d\sigma_{in}}{dx_F} \propto (1-|x_F|)^{\alpha}$$

for all secondaries apart from leading ,

$$\frac{d\sigma_{in}}{dx_F} \propto \text{const}$$

$$\begin{cases} 0<x_F<1 \text{ for projectile,} \\ -1<x_F<0 \text{ for recoiled nucleon,} \\ x_F=p_L/p_{\max} \text{ in C.M.S.} \end{cases} \tag{2}$$

(b) elastic

$$\frac{d\sigma_{el}}{dt} \propto \exp(\gamma t) \;. \tag{3}$$

(2) Integral cross sections are as follows:[14]

$$\sigma(s)=a_1+a_2 s^{-b}+a_3 \ln^2 s \;. \tag{4}$$

(3) Charged multiplicity distribution is as follows:[15]

$$P(z)=(3.79z+33.7z^3-6.64z^5+0.332z^7)\exp(-3.04z) \;, \quad z=n/\langle n\rangle \;. \tag{5}$$

(4) Mean charged multiplicity is as follows:[14]

$$\langle n\rangle = A_1+A_2 \ln s + A_3 \ln^2 s \;. \tag{6}$$

Numerical values of needed constants are listed in Table I. The value of α depends on the multiplicity and also, due to the used procedure of generation, is slightly dependent on $|x_F|$. For our purpose it is sufficient that the corresponding rapidity distribution agrees with the hydro-

TABLE I. The parameters used in the single collision generator.

Mean charged multiplicity

Collision		A_1	A_2	A_3
πN		0.865	0.777	0.069
NN		0.830	0.467	0.115

Integral cross section

Collision	a_1	a_2	a_3	b
total πN	17.7	29.6	0.136	0.502
total NN	30.8	26.1	0.170	0.418
elastic πN	1.38	14.4	0.034	0.520
elastic NN	4.50	42.0	0.045	0.682

Differential cross section

α	$\beta[c^2/\mathrm{GeV}^2]$	$\gamma[c^2/\mathrm{GeV}^2]$
1.5–13.0	7.0	1.0–11.0

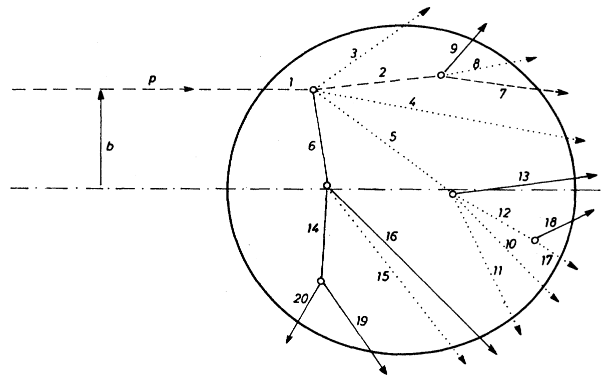

FIG 1. Schematic display of the intranuclear cascade. The dashed line is the projectile, the solid lines are knocked-out nucleons, and the dotted lines correspond to π mesons. For the numbers labeling single links see text.

gen data; see Sec. III. The approximation of energy-dependent γ is based on the tables in Ref. 16. A modification of integral cross sections (4) in the low-energy region ($\sqrt{s} < 3$ GeV) is made in accordance with Ref. 16 as well.

For simplicity the generator gives the two kinds of secondaries: the leading particles having the same masses and charges as the initial ones (projectile and nucleon) and produced particles treated as π mesons regarded with equal probability as π^-, π^0, and π^+. All secondary particles together comply with the condition of momentum-energy conservation.

A generator of this kind enables us to allow all secondary hadrons to take part in a cascade inside the nucleus. For the nuclear density distribution a standard parametrization is accepted:

$$\rho(r)=\frac{\rho_0}{1+\exp[(r-r_A)/c]}, \quad c=0.54 ,$$
$$r_A=1.19A^{1/3}-1.61A^{-1/3} , \tag{7}$$
$$\rho_0=A(\tfrac{3}{4}r_A^{-3})/(1+c^2\pi^2/r_A^2) .$$

After introducing the Fermi motion and the Pauli principle in a similar way as before,[12] the only remaining parameter necessary for the simulation of complete intranuclear cascade is the formation length l_f of secondaries. A common assumption concerning formation length follows from the uncertainity principle applied in the rest system of the created particle:

$$\tau\sim 1/\mu , \tag{8}$$

where τ is a formation time and μ is some characteristic parameter usually fixed from the data. In the laboratory system where the nucleus is at rest, relation (8) gives

$$l_f=p_{\mathrm{lab}}/(M\mu) , \tag{9}$$

where M is the mass of the created particle. Moreover, l_f is understood only as the mean value of a distribution (Ref. 10), e.g., of exponential form

$$P(l)dl\sim\exp(-l/l_f)dl . \tag{10}$$

In the present approach formation length means that the secondary hadrons are allowed to interact only after passing distance l generated according to the formula (10). Behind this distance the interactions take place with usual probability $p=\rho(r)\sigma\Delta r$, where ρ is nuclear density (7) and σ is the corresponding cross section (4). This conception of formation length is equivalent to the substitution in the cross section of an l dependence,

$$\sigma_{\mathrm{tot}}(l)=\sigma_{\mathrm{tot}}[1-\exp(-l/l_f)] . \tag{11}$$

Let us note that in the scheme described, the fact that a considerable portion of the secondaries is produced via decay of the resonances is ignored. This fact should be kept in mind, if μ is interpreted quantitatively. Since our aim is rather to check if the global features of experimental data can be described using some effective value of μ, the considered simplification is acceptable.

Therefore having the rules for the elementary collisions and formation length of secondaries, the intranuclear cascade can be processed. The order of cascade links processing is apparent from Fig. 1, where the following rule holds: From each collision the secondary hadrons are processed in descending order with respect to the corresponding x_F until the next collision or until reaching nuclear boundary. When all particles resulting from the first collision are advanced in this way, there follow processing particles from collisions of second generation starting from that initiated by the particle of highest energy, and similarly for the third and next generations. The distinction between proton and neutron and gradual nuclear density reduction are taken into account equally as in Ref. 12.

III. RESULTS

In our calculation, two hypotheses concerning the formation length of the secondaries from inelastic interactions have been checked: (A) The formation lengths of the leading particles (and recoiled nucleon correspond-

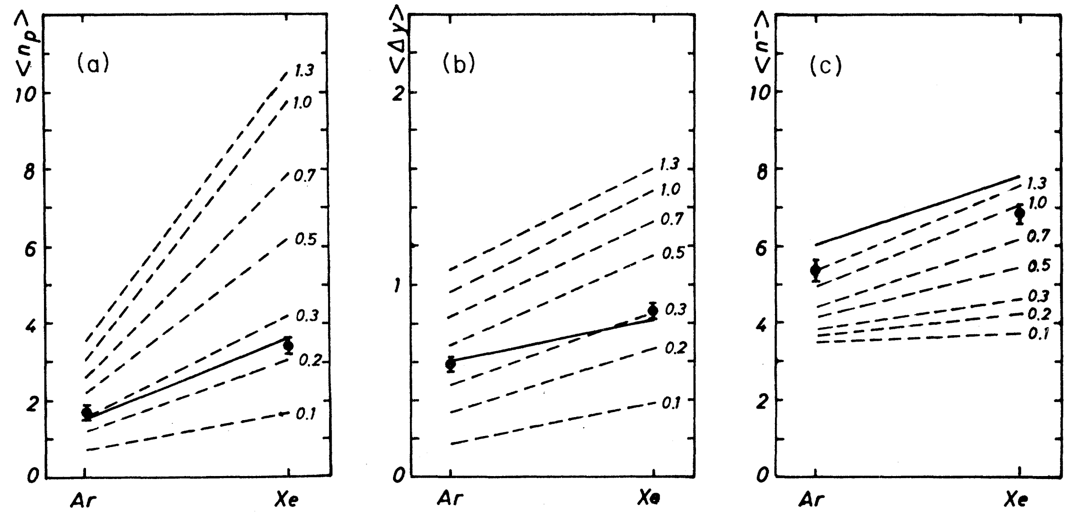

FIG. 2. Average values for (a) the number of identified protons, (b) rapidity shift of produced particles, and (c) the number of negative particles. Full circles are experimental data, the solid line corresponds to the calculation A, and the dashed line to the calculation B performed for various μ.

ingly) are assumed to be $l_f=0$, while l_f of the created pions always exceeds nuclear dimensions. (B) the formation lengths of all secondary particles are controlled by (9) and (10) with the corresponding values of the mass M for nucleons and pions, but with one effective value of μ (the same formation time in the rest system of a particle). In the case of the elastic collisions, it is assumed for both versions $l_f=0$.

The results of the calculation are compared with the streamer chamber data on the collision pAr, pXe at 200 GeV (Refs. 1,2). In accordance with the experiment the following notation is used: n_p is the number of identified protons; their momenta are limited in the region $0.2 \lesssim p_{\mathrm{lab}} \lesssim 0.6$ GeV/c. n is the number of "produced particles," i.e., the total number of all charged particles, but without identified protons: $n=n^+ + n^- - n_p$. In the experiment analysis the produced particles are treated as pions. They are slightly contamined by knocked-out protons of momenta $p_{\mathrm{lab}} \gtrsim 0.6$ GeV/c, so that the most realistic sample of "truly" produced particles are negative ones.

In the calculation the parameter μ has been varied within the limits 0.1–1.3 GeV. The global effect of formation length on the secondary particles is seen in Figs. 2(a)–(c), where the mean number of identified protons, the mean rapidity shift of produced particles, and the average multiplicity of negative secondaries are plotted for both nuclei. It is seen that the most sensitive quantity in respect to the variation μ is the proton multiplicity [Fig. 2(a)]. A good agreement with the data is obtained by $\mu \approx 0.2-0.3$ GeV. The rapidity shifts are well reproduced by $\mu \approx 0.3-0.4$ GeV [Fig. 2(b)]. However, for the calculated mean multiplicity of negative particles to meet the corresponding data [Fig. 2(c)], the parameter μ should be 1.0–1.3 GeV. Obviously, such a value is hardly compatible with that on Figs. 2(a) and (b). On the other hand, Figs. 2(a)–(c) show that the version A, in which only multiple rescattering of leading particles contributes to the production of new hadrons, is in good agreement with the data for all the quantities considered. A slight discrepancy is seen only in the case of the mean multiplicity of the negatives, where the calculation A gives values by 10–15 % above the corresponding data.

The difference between the two approaches is illustrat-

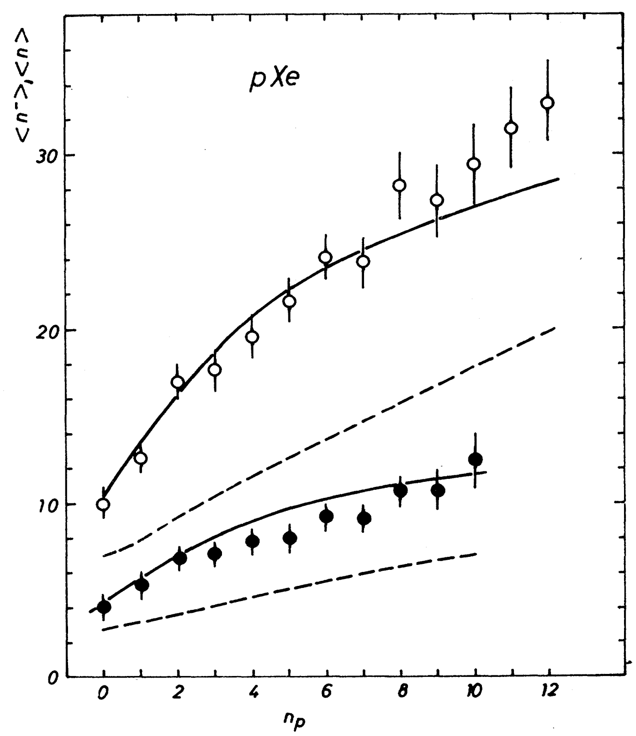

FIG. 3. The dependence of the mean numbers of produced (open circles) and negative (full circles) particles on the number of identified protons in pXe interactions. The solid and dashed lines correspond to the calculations A and B.

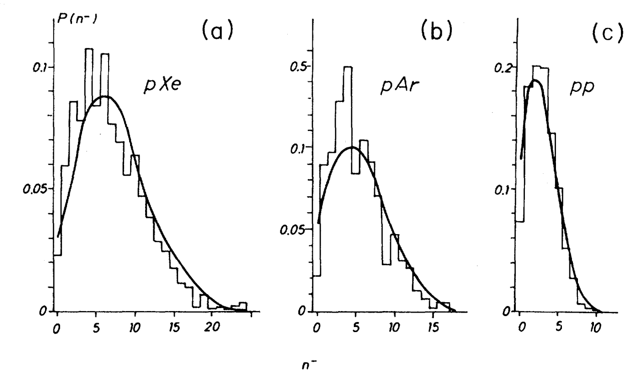

FIG. 4. The multiplicity distribution of negative particles in pXe, pAr, and pp interactions (full circles) and the corresponding result of calculation A (solid line).

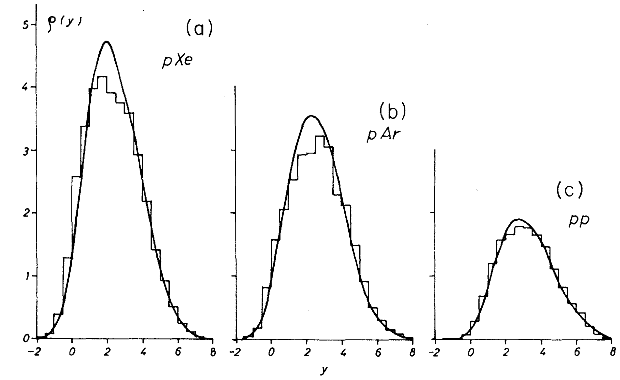

FIG. 6. The normalized rapidity distribution of the produced particles in pXe, pAr, and pp interactions and the corresponding result of calculation A (solid line).

ed also in Fig. 3, where the correlations between $\langle n^- \rangle$ and $\langle n \rangle$ vs n_p are plotted for the collision pXe. Again, version A agrees well with the data, while the curve B, irrespectively of the parameter μ (curves calculated provided $\mu=0.1$ or 1.3 GeV practically do not differ), predicts clearly lower ratios n^-/n_p and n/n_p than experimentally observed.

The results in both Figs. 2 and 3 show that in the case of version B fewer new particles are produced for the corresponding mean (Fig. 2) or arbitrary fixed (Fig. 3) number of protons. Since the number of knocked-out protons serves as a statistical measure of the number of collisions inside the nucleus,[17] regardless of whether collisions are initiated by the projectile or by a secondary hadron, the last statement can be formulated in another way: Version B gives, on the average, fewer secondary particles per single collision than observed in the experiment. That is an obvious consequence of the formula (9) according to which the interactions of the particles of higher energy, potentially resulting in greater multiplicity, are suppressed, while the version A, in which only leading particles having greater energy on the average can interact, gives a correct proportion between the number of protons and the multiplicity of the secondaries. Consequently from the two ways of including the formation length discussed in the present approach, A is preferred.

Figures (4a) and (b) show the differential multiplicity distribution of the negative particles compared with calculation A. The agreement is good; the figures only apparently reflect the fact that calculated mean multiplicities are slightly higher than the experimental ones [cf. Fig. 2(c)]. Figure 4(c) represents a test proving that the proton-proton generator in the Monte Carlo works properly. The comparison for the multiplicity distribution of identified protons is shown in Fig. 5. The shape of the

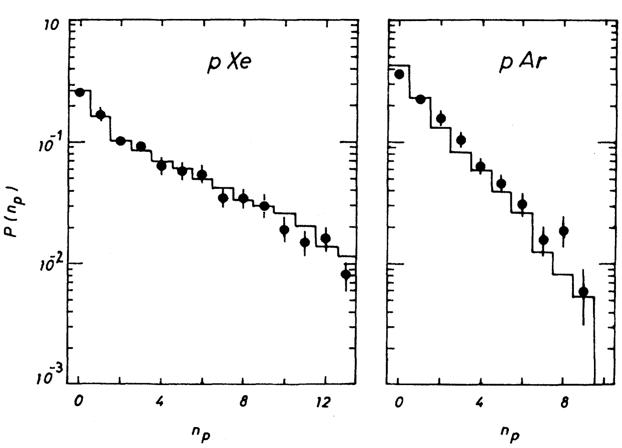

FIG. 5. The multiplicity distribution of identified protons in pXe, pAr interactions (full circles) and the result of calculation A (solid line).

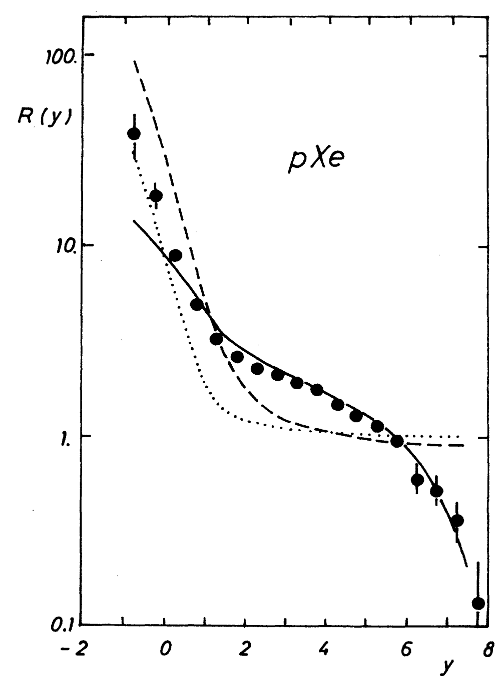

FIG. 7. The ratio of normalized rapidity distributions $R(y)=\rho_{p\mathrm{Xe}}(y)/\rho_{pp}(y)$ (full circles) compared with calculations A (solid line) and B performed for $\mu=0.2$ GeV (dotted line) and $\mu=1$ GeV (dashed line).

calculated distributions fits data well too.

The next result of the calculation A concerns rapidity distribution of the produced particles (Fig. 6). The rapidity is evaluated in the laboratory system and the distributions are normalized in the usual way:

$$\rho(y)=\frac{1}{N_{ev}}\frac{dN}{dy} . \tag{12}$$

The curves calculated for all targets agree with the data very well. Of course, in the case of hydrogen [Fig. 6(c)], where no cascading takes place, the comparison serves as another test showing the basic single collision generator works well.

The influence of the nucleus on the rapidity distribution is more explicitly illustrated in Fig. 7, where the ratio of rapidity distributions of produced particles on Xe and hydrogen is plotted. Again a good agreement is achieved in the case of the version A. Calculation B gives a better result only in the region $y \lesssim 0$, while in the rest of the phase space, where most particles are produced, the agreement is not satisfactory.

IV. SUMMARY AND CONCLUSION

In this paper we presented the simple Monte Carlo cascading model and a comparison of its predictions with the experimental data on pAr, pXe collisions at 200 GeV. We studied two distinct approaches to the formation length and showed that the experimental data are more consistently reproduced in the version (A) in which only the projectile and the recoiled nucleons are allowed to develop the intranuclear cascades, while π mesons resulting from the cascades are prevented from interacting within the nucleus. With this assumption and, in fact, without any additional adjustable parameters, a good agreement has been obtained for the multiplicity distributions of identified protons and π mesons, the rapidity distribution of the produced particles, and their dependence on the nuclear target.

On the other hand, the results of the second version (B), in which all the secondary particles are assumed to have the equal formation time, suggest that at considered energy a cascading of created π mesons (and a slight suppression of projectile collisions) can play a role only as a rather smaller correction to the cascade initiated dominantly by the projectile.

Obviously, the formation length problem requires further study. A consistent analysis of the more experimental data (several nuclear targets at different primary energies), trying the known approaches to the formation length, should be the next step. The Monte Carlo of the kind described in the present paper could be an efficient aid for this purpose.

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