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INTERMEDIATE AND HIGH ENERGY NUCLEAR REACTIONS AT THE HADRONIC STRUCTURAL LEVEL

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Dedicated to Professors Z.S.Strugalski and A.A.Tyapkin
in honour of the 70 anniversary of their Birthday

I. INTRODUCTION

The interaction of high enough energy (i.e. above about 100 MeV) hadrons and nuclei with nuclear targets is a very complex process involving - to different extent - a great variety of phenomena: quantum structural, wave (diffraction, interference, coherence), collective, statistic, relativistic, microscopic and (quasi)macroscopic, subhadronic etc. At the same time it may reveal different space character, most often volume, surface, tube-linear or local and displays hadronic (barionic, mesonic, resonance such as the $\Delta(1232)$ and cluster) and quark-gluon degrees of freedom. Finally, it can give rise to particle absorption and emission, excitation of resonance states of nuclei, nucleons and clusters' knock-out, partial or even total disintegration of colliding nuclei and - as a rule - it leads to particle production (mostly π mesons). Our knowledge about this process comes mainly to ample experimental information, predominantly on cross sections of different channels of the reaction and multiplicity, energy, momentum and angular distributions of produced and emitted particles. Because of vast and intricate diversity of the phenomena under discussion there is no till now any common consistent and reliable approach to the problem of intermediate and high energies nuclear reactions although recently founded quantum hadrodynamics [1] is just called to play such a part, at least in what it concerns the description of nuclei as relativistic nuclear many-body systems. Nevertheless, for some practical purposes (i.e. for dosimetry, radiation protection and radiation damage) it is quite satisfactory to use sufficiently simple and at the same time general enough models allowing to get quantitative information about main properties of secondary particles produced and/or emitted in these reactions, as well as about the characteristics of remaining nuclei. Such models are often based on the quasiclassical analogy to the process of penetration of particles through extended medium using a notion of the trajectory of particles and the classical probabilistic nature of their interaction in nuclear matter. (For a fundamental discussion about the representation of that kind we refer the reader to ref.[2]). Roughly speaking, with increasing energy of interacting particles and consequently, on the average, the momentum transfer between colliding hadrons, all quantum effects vanish rapidly and subhadronic degrees of freedom begin to reveal. A corresponding quantitative criterion has been introduced by A.M.Baldin [3], based on the four-momentum transfer, b_{ik}, between interacting and produced particles. In particular, according to this classification hadrons are no more quasi-particles of nuclear matter when $b_{ik} >> 1$ and nuclei should be then considered as quark-gluon systems. Experimentally it has been found that this domain begin as early as at ~3.5 GeV of primary hadrons initiated interactions [4] and the phenomenon, called the cumulative effect, has a local character. Moreover, it is commonly believed that at much higher energy (i.e. far above 1 GeV/A in the center-of-mass system) a quark gluon plasma may be created in head-on collisions of two heavy nuclei [5], although there exist suggestions that such a phase transition is already available at about E_{lab}=30 GeV/A and even at E_{lab}=3-5 GeV/A, at least to the mixed phase of nuclear matter [6].

In the present work we briefly discuss some typical and still actual models of interaction of fast hadrons with nuclear targets based on simple geometrical and probabilistic conceptions.

II. QUASIFREE INTERACTIONS

Among the multiplicity of channels of the reaction of fast hadrons with nuclei quasifree channels are the simplest ones having at the same time special practical value. They may be defined as such [7] when a projectile particle (for instance, a proton or π meson) impinging on a target nucleus with the radius R at the impact parameter r_o

experiences only one inelastic collision with an intranuclear (quasifree) nucleon and the particles produced in this collision leave the nucleus without any inelastic scattering inside it, as shown schematically in Fig.1.

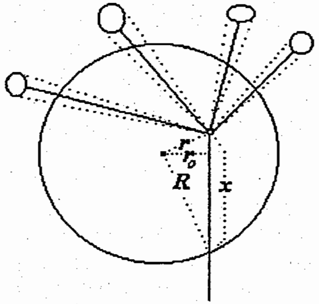

Fig.1

The probability density function for such event is [7]:

$$f(r_o)=\sigma_N\int_{-\sqrt{R^2-r_o^2}}^{\sqrt{R^2-r_o^2}}\rho(\sqrt{r_o^2+x^2})\exp\{-[\sigma_N\int_{-\sqrt{R^2-r_o^2}}^{x}\rho(\sqrt{r_o^2+x^2})dx+\sum_i f_i(r_{o_i})]\}dx\text{.......}(1)$$

Here σ_N is the total cross section for interaction of the primary particle with a nucleon, $\sigma_N^{(i)}$ is the total cross section for inelastic interactions of the i-th particle produced in the collision, $\rho(r)$ is the single nucleon density distribution (SNDD) in the target nucleus, and

$$f_i(r_{o_i})=\sigma_N^{(i)}\int_{(\varphi_i,\vartheta_i)}\rho(\sqrt{r_{o_i}^2+x_i^2})dx_i\text{............................}(2)$$

where (φ_i, ϕ_i) are emission and azimuthal angles of the trajectory of the i-th produced particle.

In consequence of considerable similarity of a shape of SNDD of intermediate and heavy nuclei and relatively weak energy dependence of total inelastic cross sections for hadron-nucleon interactions at energy above ~1 GeV (for instance, [8]) the behaviour of the function (1) does not change practically with energy and atomic number. Moreover, the effect of increasing multiplicity of secondary particles at higher energy is also efficiently compensated by the narrowing a cone (φ_i, ϕ_i) within which these particles are emitted. It is easy to see it when considering the fraction P of quasifree interactions expressed by the function $f(r_o)$ (1) and the total cross section σ_{in}^{tot} for inelastic channels as:

$$P=\frac{2\pi}{\sigma_{in}^{tot}}\int_0^R f(r_o)r_o dr_o\text{..}(3)$$

The calculated value of this quantity is 0.30±0.01 for π-Xe interactions in the interval of primary pions energy of ~2-9 GeV, which is in good agreement with the experimental value 0.30±0.03 for these interactions, and, in particular, for π-Em interactions at much higher energy, too [7]. Space localisation of quasifree interactions is such that half of all them occur in the region of impact parameters $r_o \geq 0.8R$. As an example the function $f(r_o)$ for the probability of quasifree interactions of π^+ mesons with xenon nuclei at 2.34 GeV/c [7] is displayed in Fig.2.

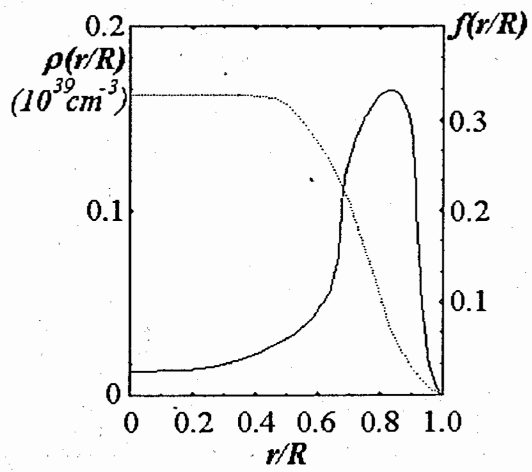

Fig.2

In this figure plotted is also the SNDD for the nucleus $_{54}Xe^{131}$ as a function of relative radius r/R and its trapezoidal simplified approximation used for concrete calculation. One can easily see that if we substitute zero for $\sigma_N^{(i)}$ in (1) and 1 for P in (3) we obtain a simple expression for total inelastic cross section of hadron-nucleus interactions:

$$\sigma_{in}^{tot}=2\pi\int_0^R\{1-\exp[-2\sigma_N\int_0^{\sqrt{R^2-r_o^2}}\rho(\sqrt{r_o^2+x^2})dx]\}r_o dr_o\text{........}(4)$$

which coincides with the similar formula deduced from the optical model. From (4) it follows, at least for heavy nuclei with a sharp boundary and at high enough energy, that $\sigma_{in}^{tot} \sim (4/3)\pi\langle\rho\rangle R_o^3 A\sigma_N$, i.e. energy dependence of σ_{in}^{tot} should be approximately the same as for σ_N. Experimental data do not contradict such an energy behaviour of cross sections within several percents of accuracy [8] (here $\langle\rho\rangle$ means an averaged nuclear density and R_o ~1.2fm). One can also note that the form of the probability density function $f(r_o)$ (1) does not depend remarkably on the specific channel of quasifree hadron-nucleon interactions although the maximum of this function slightly shifts towards the larger values of impact parameter r_o with increasing the multiplicity of produced particles in the channel and at the same time the width of this maximum becomes lower. Such a property of quasifree interactions may be useful for experimental estimation of momentum distribution function of intranuclear nucleons at different depths in a target nucleus even when hadronic probes are applied. In this way a high momentum component of peripheral neutrons and protons of xenon nuclei has been estimated (in the approximation of undistorted plane waves) [9] and pionic degrees of freedom in xenon nuclei observed starting from experimental information about quasi-two body $\pi^+N(Xe)$ reactions at 2.34 GeV/c. As an illustration a two-dimensional plot of total energy E_π vs. emission angle Θ_π of π^o mesons (in the laboratory system) produced in the reaction $\pi^- + Xe \rightarrow \pi^o + \pi^- + A'$ at 3.5 GeV/c is displayed in Fig.3 [10]. Solid curves in the figure correspond to kinematics of two-body reactions $\pi^- + p \to \pi^\circ + n$ and $\pi^- + \pi^\circ \to \pi^\circ + \pi^-$ at the same primary momentum, respectively. One can easy see that experimental points are strongly concentrated around the curve corresponding to the pionic effective mass target which may also be a result of one pion exchange mechanism of the reaction of impinging pions with quasifree intranuclear nucleons and the secondary pions rescattering, as well.

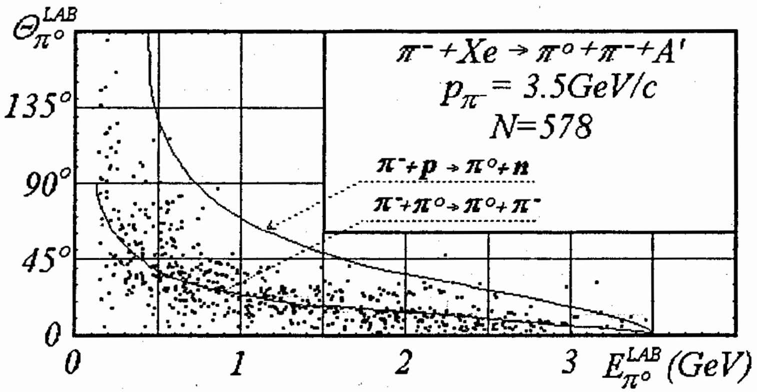

Fig.3

A remark should be made too that it is easy to generalise the formula (1) for the probability density function of quasifree interactions about any type of hadron-nucleus (and, similarly, nucleus-nucleus collisions) by means of setting recurrently instead of $f_i(r_{oi})$ a function of the form $f(r_o)$ again but numbered by i-th step of intranuclear interaction and so on, till the contribution from the subsequent substitution is to be neglected. This way we get a simplified (i.e. based on geometric and probabilistic conceptions only) analytic version of the intranuclear cascade model. But as we have not by now any reliable analytic approximations to calculate the expressions of the form $\Sigma f_i^{(j)}(r_{oi})$ (here *j* numbers a subsequent act of intranuclear collision) the only practical way to get concrete numerical information is to use the so-called Monte-Carlo method, which is at the same time a method of numerical solution of various mathematical problems and a method of computer simulation of many diverse physical processes.

III. CASCADE EVAPORATION MODEL

There exist many versions of the cascade evaporation models (CEM) taking into account - to some extent - all investigated up to now or being discussed dynamical and structural effects accompanying the process of intermediate and high energy hadron/nucleus interaction with nuclei (for example, [5,11-13]). We are going to stress here only that:

1. the CEM is, in principle, free of any shortcomings (expect for computer time and memory) and so it seems to be the most general and practical approach to the problem of nuclear reactions within very large range of energy of colliding particles;
2. this model is open, in principle, for including any new effect;
3. using the CEM we can adjust the results to concrete conditions of an experiment;
4. there is achieved this way a good agreement with experimental data but mostly for integral characteristics of the process;
5. the flexibility of the CEM makes it especially preferable to searching for new phenomena (for example, for a transition to other structural phase of a system created in the interaction region).

It should be also noted that in order to describe experimental data more correctly, particularly in the case of nucleus-nucleus collisions, the CEM needs to be improved in what it concerns the particle cascading process at highly destructing nuclei, as well as the mechanism of excitation transfer to the residual nucleus and the problem of relaxation of highly excited nuclei [13].

IV. PHENOMENOLOGICAL APPROACH

For many practical purposes it is quite sufficient to have reliable enough formulas approximating experimental data on different characteristics of hadron/nucleus-nucleus collisions without going into the mechanism of the process although every formula can be considered as some model of the phenomenon it concerns.

Among various characteristics of high energy hadron/nucleus-nucleus collisions which are investigated both experimentally and theoretically multiplicity distribution of produced and/or emitted particles is the simplest one. To parametrized relevant experimental information a Poisson transform (for example, [14,15]):

$$P_n = \int_0^\infty dx f(x) \frac{(x\bar{n})^n e^{-x\bar{n}}}{n!} \qquad \text{......................................(5)}$$

being a positive weight *f(x)* superposition of Poisson distributions is often used (for example, [15,16]). In particular, P_n is a simple Poisson distribution when $f(x)=\delta(x-1)$ and a Bose-Einstein distribution at $f(x)= exp(-x)$, whereas for gamma weight function P_n is a negative binomial distribution. A superposition and a sequence of binomial distributions is also applied [16].

Another important and often investigated characteristic is an energy dependence of inclusive relativistic invariant cross sections of secondary particles which reveal interesting scaling properties [17-21]. It is successfully parametrized by an exponential (i.e. Boltzman) dependence being the limiting case for nondegenerated both fermionic and bosonic systems. Unfortunately, there is no by now satisfactory parametrizations taking into account correlations even between basic characteristics of nuclear reactions under consideration.

V. CONCLUDING REMARKS

Although the process of interaction of fast hadrons and nuclei with a nuclear target is, in principle, very complicated involving multiplicity of diverse phenomena, its main features may be understood, at least on the qualitative level and within a large enough energy range spreading from several tens of MeV up to several hundred of GeV, starting form simple geometrical and statistical considerations. Such an approach being convenient for concrete realisation may be also very useful for many practical purposes.

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