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PENETRATION PROBABILITIES OF HIGH ENERGY HEAVY ION PROJECTILES INTO A TARGET NUCLEUS

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Вероятность проникновения высокоэнергетических ионов в ядро мишени

Проведены оценки тремя способами вероятности проникновения тяжелых ионов в ядро мишени при высоких энергиях. Результаты в каждом случае согласуются между собой. Показано, что α-частицы могут входить в ядро серебра с вероятностью 1,5%.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Penetration Probabilities of High Energy Heavy Ion Projectiles into a Target Nucleus

Penetration probabilities of high energy heavy ion projectiles into a target nucleus are estimated in the framework of three approaches. The results in each case are in accord with each other. It is shown that α-particles can enter a silver nucleus with the probability of 1.5%.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1978

1. INTRODUCTION

The opening of the facilities in Dubna and Berkeley to accelerate heavy ions up to relativistic energies has raised interest for studying what happens when two heavy nuclei collide at high energies. These reactions provide a unique opportunity to investigate properties of nuclear systems far outside the traditional realm of nuclear physics, and one may hope that new phenomena can be found. However, the calculation of observable quantities resulting from these exotic phenomena are not yet possible. The collisions are usually quite complex and non of the presently existing theoretical approximations is entirely appropriate which means that it is important to pursue simultaneously several different approaches.

The collision process can be divided mainly into three different phases of evolution (Stöcker et al.[1]). During the diving phase the projectile enters the target. Throughout the penetrating stage the two nuclei interpenetrate each other and interact wildly. Finally, during the last phase the system explodes. It is safe to say that the behaviour of the nuclear system in the diving phase fixes the conditions for a further course of the reaction. Therefore, among other things the question arises how deep can a projectile dive into a target without loosing its individuality and how large is the percentage for that. The answer is important for the reaction mode which can be expected, in the course of which, e.g., collective phenomena may be formed leading to phase transitions in the nuclear system called pion condensation.

The present work is aimed at giving an estimation with justification of the probability that projectile particles can penetrate the target without interaction. The estimations will be carried out in the framework of three approaches. First, the target is treated as an absorbing medium, and the penetration probability of the projectile as a function of the run through distance is calculated. Second, the same is done on the basis of a microscopic consideration in the framework of a one-dimensional scattering model. Finally, these results are compared to those got by intranuclear-cascade model calculations.

2. *PENETRATION PROBABILITY OF PROJECTILES INTO A TARGET NUCLEUS*

Let us first consider a projectile interacting with a nucleus. The coordinates of its c.m. are $\vec{r} = (\vec{s}\ ,\ z\ )$ and it moves along the z-direction. If we treat the target as an absorbing medium, the intensity of a projectile penetrating the nucleus is damped. The probability that it can go to position z_0 in the target with an impact parameter $\vec{s}$ without suffering any collision elastically or inelastically is given by

$$P(\vec{s}\,,z_0) = e^{-\sigma T(\vec{s},z_0)}\,. \tag{1}$$

Here σ is the total nucleon-nucleon cross section and $T(\vec{s}\,,z_0)$ is the integrated nucleon density along the projectile's trajectory obtained by integration over the folding product of the densities:

$$T(\vec{s},z_0) = \int_{-\infty}^{z_0} dz \int d\vec{r}\,'\rho_p(\vec{r}\,'-\vec{r}\,)\,\rho_t(\vec{r}\,'). \tag{2}$$

The densities ρ_p and ρ_t are single-particle densities normalized to the corresponding nucleon numbers A. At high energies an expression similar to eqs. (1) and (2) can be derived in the Glauber theory (Fäldt and Gislén /2/).

In the following we shall evaluate the integral (2) using spherical nuclear distributions $\rho(r) = \rho_0\bar{\rho}(r)$, where ρ_0 is the equilibrium density. We shall restrict ourselves only to head-on collisions ($\vec{s}=0$). As an example, we regard the reaction $\alpha + Ag$ at a laboratory bombarding energy per nucleon of 2.1 *GeV*. For the incident α-particle we take a short-range Gaussian density with an r.m.s. of 1.71 *fm* which is equivalent to $b = 1.4$ *fm* (Inopin et al. /3/).

$$\rho_p(r) = \rho_p^\circ\, e^{-(r/b)^2} \quad \text{with} \quad \rho^\circ = \frac{A_p}{b^3\pi^{3/2}}\,. \tag{3}$$

For the heavy target nucleus a rectangular density is used.

$$\rho_t(r) = \rho_t^\circ\,\Theta(R_t - r). \tag{4}$$

The step function $\Theta(x)$ is unity for positive arguments (*fig. 1*). The target density is taken to be the equilibrium

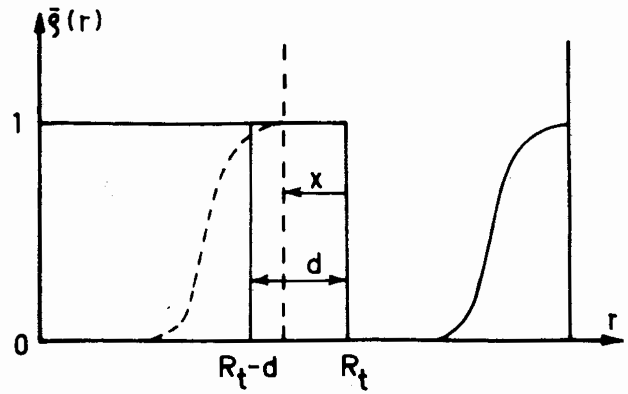

Fig. 1. Schematic illustration of the density distributions of two nuclei penetrating each other.

nuclear density $\rho_t^\circ = 0.17$ *nucleons/fm*^{3}. The radius R_t is written as $R_t = R_t(Ag) + d/2$ which takes account of the fact that the α-particle has to penetrate the diffuse region (d will be chosen of the order 1.08 *fm*), here $R_t(Ag)$ is the usual half-density radius, resulting in

$R_t(Ag) = 5.14$ *fm* so that the increased silver radius simulates the diffuse surface which is taken to be unity.

To characterize, in this model, the ion penetration, we introduce the variable x which gives the diving depth of the projectile into the rectangular distribution, i.e., at $x=0$ the α-particle centre coincides with the sharp target surface (*fig. 1*). According to eqs. (2) to (4) one finds, after extensive manipulations

$$T(\frac{x}{b}) = \pi b^4 \rho_p^\circ \rho_t^\circ /2 \{ \sqrt{\pi} \frac{x}{b} [1+\mathrm{erf}(\frac{x}{b})] + e^{-(\frac{x}{b})^2} + (R_t - x)/7 - 1 \}, \quad (5)$$

Inserting this result in eq. (1) and taking into account the fact that the total nucleon-nucleon cross section σ at 2.1 *GeV* is about 40 *mb* (Hess [4]) we get the penetration probability $P(x)$ of an α-particle into silver which is represented in *fig. 2*.

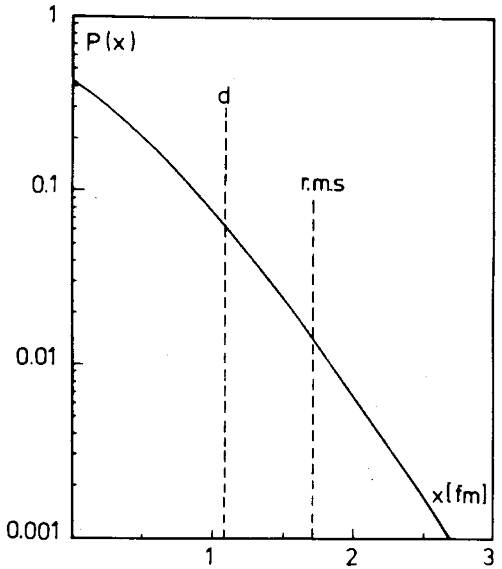

Fig. 2. Penetration probability of the reaction α + Ag at 2.1 GeV/nucleon for head-on collisions as a function of the diving depth x. The dashed lines indicate the position of the centre of an α-particle which has entered the target up to the distance corresponding to the diffuseness (d) and the α-particle radius (r.m.s.), respectively.

From these studies we infer that an α-particle can reach the target surface with the large probability of 40%, behind the region of diffuseness it can be found with 6%. The complete α-particle (if we take the r.m.s.) can still enter the target with the probabilityof 1.5%.

Here we have taken the liberty of reducing the target nuclear distribution to such a simple shape as in eq. (4). The usefulness of this class of distributions for the description of nuclear densities lies in the fact that we can use them in calculating features easily in a closed transparent form. For other distributions like one that is constant over an entire half-space and drops to zero within the surface thickness linearly, or one of a two parameter Fermi function type, only numerical solutions can be found.

The basis of the following second approach to estimate the penetration probability of a projectile is the geometry appropriate to high energies: Individual nucleons move on straight lines. Then target and projectile nucleons can be divided into two groups: the participants in the overlap volume and the spectators. In a head-on collision the overlap volume between projectile and target is completely defined by the Lorentz-contracted projectile. Only nucleons in the overlap participate in the initial phase of the reaction, while the remaining nucleons situated outside the interaction region are considered as spectators. However, in the overlap not all projectile nucleons interact with all target nucleons, but only with those which lie near projectile straight lines. Our considerations are similar in spirit to the approach made by Hüfner and Knoll [5] in the framework of the "rows on rows" model, which turns out to be a one-dimensional cascade calculation. Because of the straight line geometry the participants are divided into rows of nucleons oriented along and around the beam axis as indicated in *fig. 3*. The distance between the nucleons in a row is the mean free path $\lambda \approx 2$ *fm*.

Accordingly, nucleons of a projectile row scatter only by those nucleons of a target row the straight line

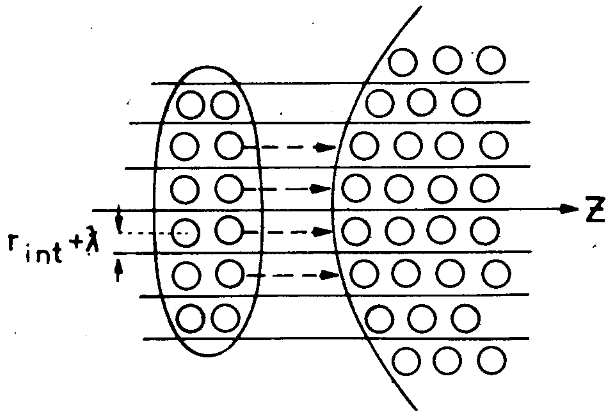

Fig. 3. An illustration of the used scattering model. Projectile and target are decomposed into rows of nucleons parallel to and around the beam direction. In an extreme case all first nucleons of corresponding rows on the same straight line scatter by each other.

paths of which are very close to each other, as is supposed in the nuclear cascade theory, and a projectile particle can only interact with a target nucleon which it sees on the path of its trajectory in a cylinder with a radius $r_{int} + \lambda\!\!\!^{-}$ (Baraschenkov et al.[6]). Here $\lambda\!\!\!^{-}$ is the de-Broglie wave length of the regarded fast particle. The quantity r_{int} is close to the strong interaction radius and in cascase calculations is usually chosen to be $r_{int} = 1.3$ *fm* (Baraschenkov et al.[6]).

Let the section area of each nucleon row be σ. Then the partial interaction probabilty q expressed by σ can be written as

$$q = \frac{\sigma}{\pi (r_{int} + \lambda\!\!\!^{-})^2} . \qquad (6)$$

Now let us calculate the independent probability for the extreme case when all nucleons sitting in each case on the first places of corresponding N target rows and N projectile rows do not interact (*fig. 3*). Then we get

$$w_N = \prod_{i=1}^{N} (1 - q_i). \qquad (7)$$

Using the above given values for an α-particle at a laboratory bombarding energy per nucleon of 2.1 *GeV* we obtain $w_\alpha = 0.01$. This result coincides with the one above for penetration of an α-particle into a target.

In this section we have underestimated the penetration probability for two reasons. First, in getting an estimation we have chosen such correlations which guarantee a lower limit. If one makes these more realistic it leads, of course, to a larger probability.

Second, we have not included "eclipse" corrections" (Fäldt et al.[7]); they come from the fact that two projectile nucleons which happen to have the same impact parameter have a slightly larger chance to get both through because the nucleons will not scatter independently but will cast shadows on each other. If the first nucleon survives, we know there are no target nucleons along the trajectory and the probability that the second nucleon survives will be enhanced. As a result, the probability that both survive is larger than the product of the independent probabilities because this process is not Markovian.

The amount of enhancement will, of course, depend on the cross section, and the distance between the projectile nucleons must not be larger than the range of the forces. Therefore, the assumption that each particle will scatter at most once is impossible for ion-ion interactions. The authors (Fäldt et al.[7]) have shown that it breaks down already for $A = 4$.

The above estimations are in accord with intranuclear-cascade model calculations. In *fig. 4* "instantaneous pictures" of the relative particle number density $\rho(r,z,t)/\rho_0$ are represented for different combinations of colliding nuclei at two bombarding ion energies. The time is measured in units of $\tau_0 = 10^{-23}$ *sec* and $\rho_0 = 0.17$ *nucleons/fm*^{3} is the equilibrium nuclear density at the centre of the silver target nucleus. A detailed description of which procedure these densities were obtained by is given in the paper by Gudima, Iwe and Toneev[8].

The pictures show for each reaction only the first collision phase: the diving phase. The representation is

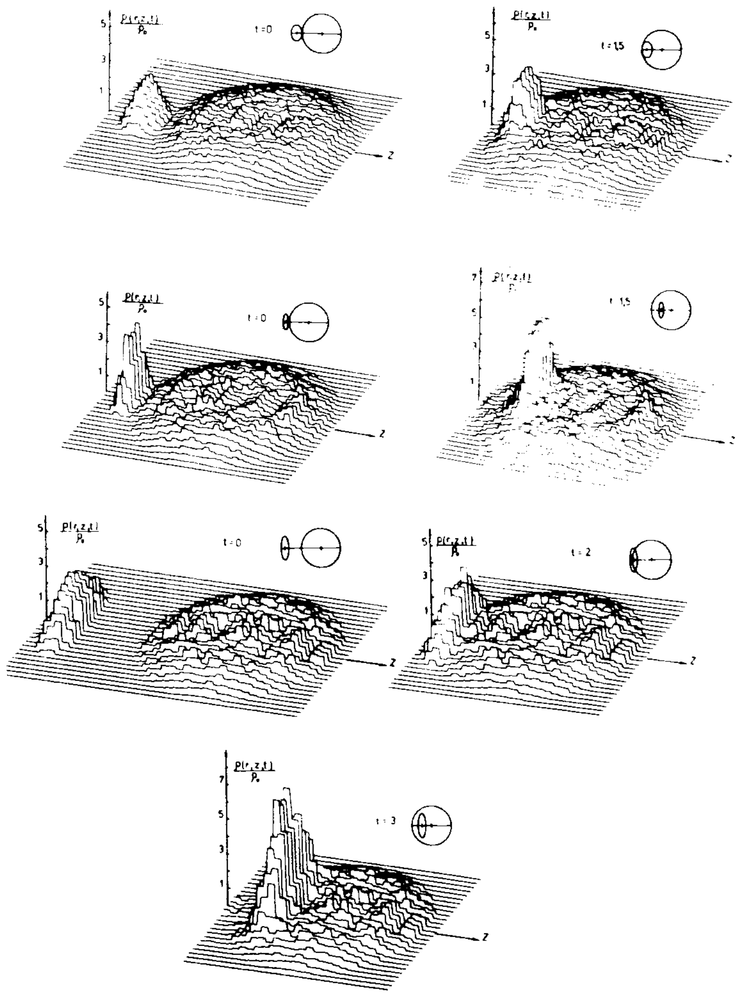

Fig. 4. Space-time evolution of the density for head-on collisions of different projectiles on a silver target nucleus during the very early reaction phases. Both the above reactions are induced by α-particles of the bombarding energies of 0.5 GeV/nucleon and 2.1 GeV/nucleon, respectively. The lower sequence of pictures represents collisions induced by ^{16}O -projectiles at 2.1 GeV/nucleon. The inserts in the figures demonstrate the relative positions of the colliding nuclei at every regarded moment of time.

related to the laboratory system in which the target nucleus is at rest. Therefore the bombarding nucleus is compressed because of the relativistic shrinkage. The projectile retains its shape during entrance into the target, even in the case O + Ag if we forget about the statistical fluctuations and compare the smooth parts. The calculations show that during the early collision phase the fraction of nucleons in the overlap volume involved into the interaction, i.e., the number of cascade particles, amounts in the average only to a few particles. This fact can be stated in like manner for the regarded reactions as α+Ag, O+ Ag and Ca + Ca. Therefore the resulting density in the lab system is only the sum of the partial densities of projectile and target, i.e., each collision partner keeps its individuality up to that moment. After this, of course, the cascade is developing very quickly.

3. *SUMMARY*

This paper has presented calculations for the penetration of relativistic nuclei in head-on collisions. In getting an estimation for the penetration probability that a projectile can interpenetrate a target without loosing its individuality, we have followed three approaches. The results of all of these model calculations are in accord with each other in the framework of the made approximations. So, we have seen, for example, a complete α-particle can enter a silver target without interaction with a rather large probability of about 1.5%. Of course, here such constellations have been chosen which guarantee a lower limit for the penetration probability. If one makes the density distributions more realistic it leads to larger probabilities. Further discussion of these points and the details of these calculations along with the extension to other conditions for the collision will be given in a subsequent paper.

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