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INTERACTIONS OF 9.4 GeV/*c* DEUTERONS IN AN EMULSION: MULTIPLICITY AND ANGULAR DISTRIBUTIONS

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Abstract: An analysis of 1650 stars induced by 9.4 GeV/*c* deuterons in a nuclear emulsion is presented. Multiplicity and angular distributions of secondaries are discussed.

E | NUCLEAR REACTIONS Ag, Br, O, C, N, H, I, S (d, X), $E = 9.4$ GeV; measured multiplicities and emission angles. Deduced probabilities of interactions of single nucleons and pairs of nucleons with nuclei.

1. Introduction

A great deal of experimental work has been done on proton-nucleus interactions above a proton kinetic energy of 1 GeV. We believe that it is also interesting to investigate high-energy nucleus-nucleus interactions as they provide us with information on both nuclear and elementary-particle physics [1-3]. The acceleration of deuterons up to 11 GeV/*c* with the JINR proton synchrophasotron in Dubna made it possible to carry out some experimental work in this field. Up to now, there have been practically no data on deuteron-nucleus inelastic interactions, with the exception of stripping [refs. [4-6]]. Therefore, an investigation of the general, phenomenological characteristics of such interactions seems to be of great importance.

Several stacks of BR-2 nuclear emulsion †, composed of layers of dimensions 10 cm × 20 cm × 400 μm, have been exposed to the deuteron beam in the Laboratory of High Energies of JINR in Dubna. The average intensity of the extracted mono-energetic beam of 9.4 GeV/c deuterons was about 2×10^4 particles/cm^2. The admixture of protons in this deuteron beam was less than 5 %.

The emulsion layers were distributed to six collaborating laboratories. This paper presents some results of the analysis of deuteron interactions with emulsion nuclei performed by the collaboration.

2. Experimental procedure

The deuteron interactions were found by the well-known standard method of "scanning along the track". Since the main interest of this experiment was in the inelastic interactions, events with only one secondary "relativistic track" were not looked for with special care. Such events have not been fully included in the final sample. In all, 2650 interactions have been found along the track length of 604 m. This leads to the mean free path $L_1 = 22.8 \pm 0.4$ cm. Subtracting 235 "one-prong events" from our sample one obtains the value $L_2 = 25.0 \pm 0.5$ cm. The corresponding cross sections are $\sigma_1 = 560 \pm 9$ mb and $\sigma_2 = 512 \pm 9$ mb, respectively.

All secondary tracks have been classified into four categories with the use of the standard criteria of the nuclear-emulsion technique:

(i) $g/g^0 < 1.4$ for minimum tracks †† (s);

(ii) $g/g^0 \geqq 1.4$, and the range $R \geqq 3000$ μm for gray tracks (g);

(iii) 5 μm $\leqq R <$ 3000 μm for black tracks (b);

(iv) $R <$ 5 μm for recoil nucleus tracks (r).

These limiting criteria correspond to the following proton kinetic energies: 425, 25 and 0.5 MeV, respectively. Every star has been scrutinized for the presence of an Auger electron, defined as an electron track of more than 4 grains, and for the presence of a blob at the star centre. Emission angles of all secondary tracks, except recoils and Auger electrons, have been determined by the coordinate method or with the use of a goniometer attached to a standard microscope. About one-half of the final sample has been measured with semiautomatic devices.

In the course of the analysis, no significant differences have been noticed in the multiplicity and angular distributions obtained separately by each laboratory.

† The composition of the emulsion was:

	ρ(g/cm^3)		ρ(g/cm^3)
Ag	1.8235	H	0.0492
Br	1.3518	N	0.0861
J	0.0050	S	0.0019
C	0.2766	O	0.2851

†† The term g represents the blob density on a secondary track in the neighbourhood of the parent star, and g^0 the blob density corresponding to primary deuterons.

In all, 1650 stars found and measured in the manner described above have been used for further analysis. Some results are presented and discussed in the following.

3. Experimental results

3.1. MULTIPLICITY DISTRIBUTIONS

The multiplicity distribution of charged secondary particles is shown in fig. 1.

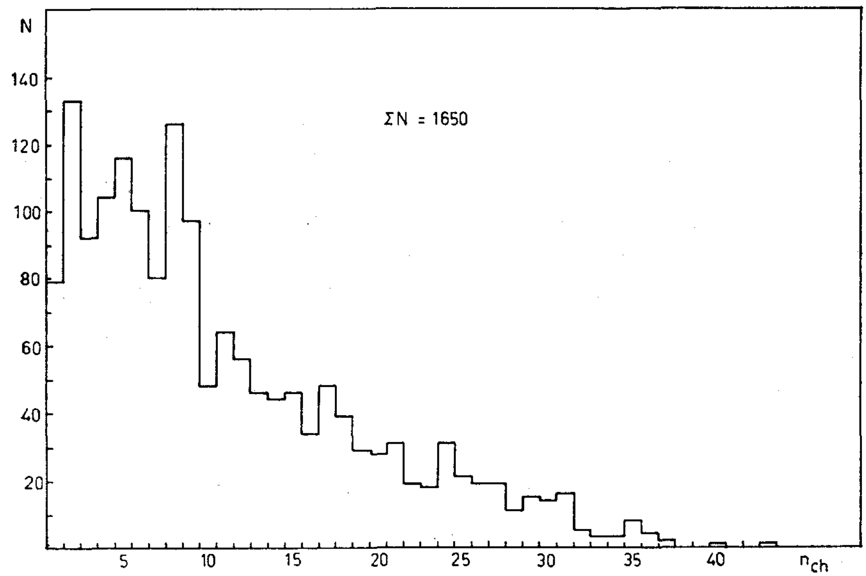

Fig. 1. Multiplicity distribution of charged secondary particles.

This distribution is not biased by any difficulties in distinguishing between the minimum, gray and black tracks. Therefore it can be safely used for the comparison with the results of other experiments, e.g. on the nucleon-nucleus interactions. The most relevant data on interactions with emulsion nuclei of protons with similar energies come from the experiment performed by Winzeler [7]).

Looking at fig. 1 one should remember that one-prong events are not fully included in our sample. As expected, this distribution is slightly broader than that for the proton-nucleus interactions and shows a long tail at high multiplicities. This tail may result from interactions of both nucleons with the nucleus, which leads to an increase in the possible energy transfers from the incident particles to the target nuclei.

The most important information about the primary deuteron-nucleus interaction is contained in the characteristics of the minimum particles. The multiplicity distribution for relativistic secondaries is shown in fig. 2. One obtains a rather poor fit of the Poisson formula to the whole sample of events. For the group of stars with the number of heavily ionizing secondaries (gray plus black ones) greater than 6, this fit

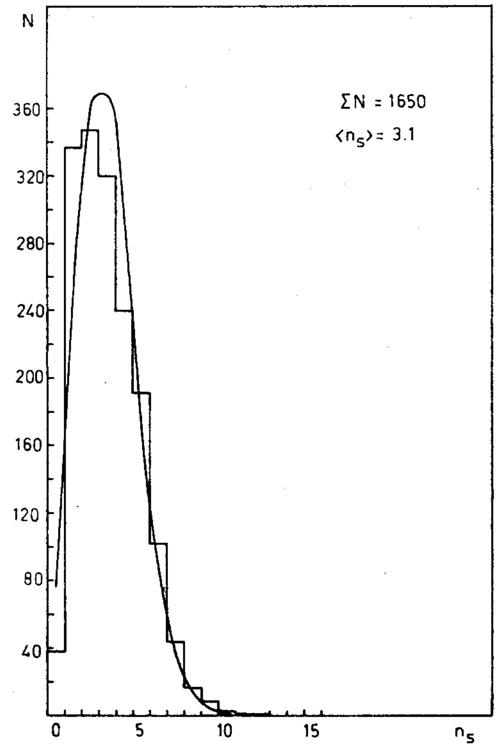

Fig. 2. Multiplicity distribution of relativistic secondaries. The solid curve corresponds to the Poisson formula fitted by the χ^2 method which gives $\langle n_s \rangle = 3.0$ with $\chi^2 = 85$.

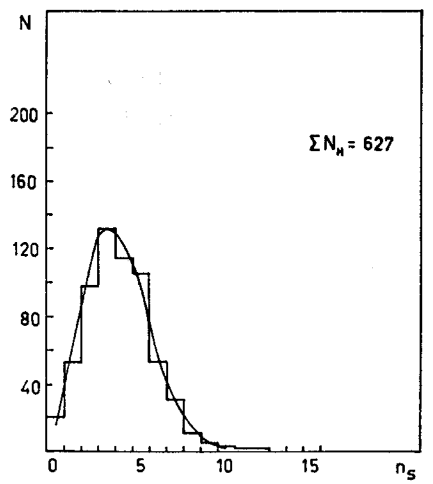

Fig. 3. Multiplicity distribution of relativistic secondaries for the H group. The solid curve corresponds to the Poisson formula fitted by the minimum χ^2 method which gives $\langle n_s \rangle_H = 3.65$ with $\chi^2 = 6.4$.

gives a satisfactory value of the confidence level (fig. 3). In the following, this group of stars is denoted by the letter H, the rest of the sample with the letter L. The H group contains only interactions with heavy nuclei of the emulsion (Ag, Br) with a large energy transfer to the target nucleus. On the other hand, the L group contains interactions with light nuclei (H, C, N, O) for any energy transfer together with interactions with heavy nuclei with a low energy transfer. On the basis of calculations of the Glauber type [8]), one can estimate the contributions of light and heavy nuclei to the total inelastic cross sections. The predicted ratio of the number of interactions with heavy nuclei to the number of interactions with light nuclei is 1.88. In our experiment the ratio of the number of H stars to the number of L stars is only 0.75. This difference indicates the unreliability of the distinction between interactions with light and heavy nuclei by means of the number of heavily inonizing particles. Comparing the mean values of the number of relativistic particles obtained by Winzeler and in this experiment one may evaluate the probability of both nucleons of the deuteron interacting with the target nucleus. Using simple probability considerations, we obtain the following expression:

$$P_{np} = \frac{\langle n_s \rangle_d - \langle n_s \rangle_p}{\langle n_s \rangle_p - 1},$$

where $\langle n_s \rangle_p$ and $\langle n_s \rangle_d$ denote the average multiplicities for interactions induced by protons and deuterons, respectively. Using the value of $\langle n_s \rangle_p = 2.47$, obtained by extrapolating to our energy the corresponding value from the Winzeler experiment [7]), we obtain $P_{np} = 0.42$. It coincides with the theoretical prediction derived from the calculations of Fäldt and Pilkuhn [8]). Fig. 4 shows the frequency distribution of minimum tracks for the so-called quasi-elementary interactions. In this case $\langle n_s \rangle = 2.06$.

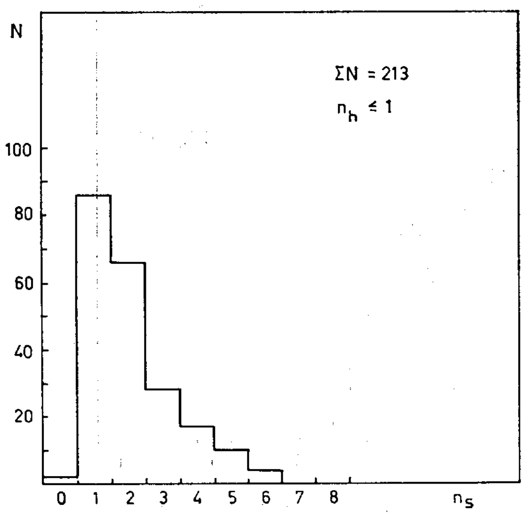

Fig. 4. Multiplicity distribution of shower particles for stars with $n_h < 2$ and without a recoil or an Auger electron.

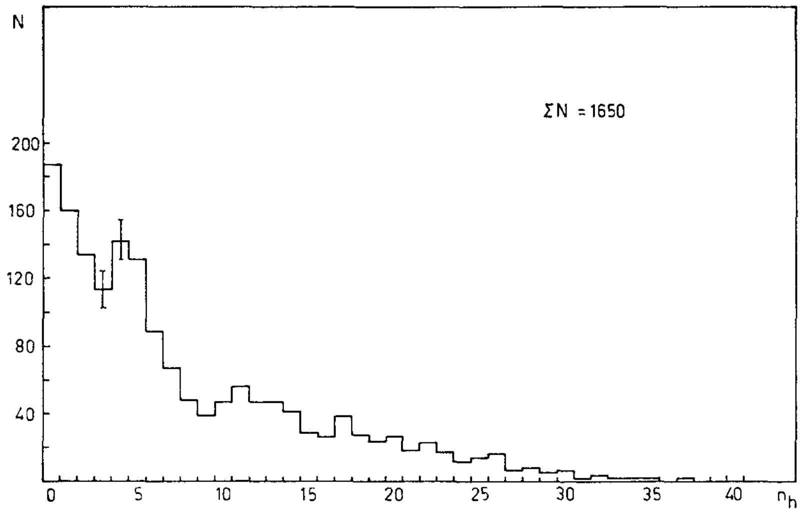

Fig. 5. Multiplicity distribution of heavily ionizing particles.

The frequency distribution of stars as a function of n_h, i.e. the sum of the numbers of gray and black tracks, is shown in fig. 5. There is a distinct structure in the shape of this histogram: a small dip at $n_h = 3$ followed by an enhancement at $n_h = 4$. A similar structure has been already observed in proton-nucleus interactions [see ref. [9]) and references cited therein]. We observe also that the L and H groups of interactions have quite different shapes of the n_h distribution. The latter exhibits a linear dependence on n_h. The mean value of n_h is 7.9, while for proton interactions at 6.2 GeV Winzeler obtained the value of 9.3. This fact may be due to a stronger influence of the difference in the energy than in the case of minimum tracks. Although the division of all heavily ionizing tracks into gray and black ones is not sufficiently precise, we present the corresponding multiplicity distributions in fig. 6 and 7. Some structure still remains in the frequency distribution of black tracks while gray tracks are easily described by an exponential formula.

3.2. ANGULAR DISTRIBUTIONS

The emission angles of secondaries from high-energy deuteron-nucleus interactions have been studied up to now only for relativistic particles in the forward peak [4-6]). Differential cross sections for elastic deuteron-nucleus collisions and diffractive dissociation have been also measured [10]). We present here a complete set of angular distributions of all secondary particles produced in deuteron-nucleus interactions at the incident momentum of 9.38 GeV/c. Fig. 8 shows the angular distribution of shower particles in the whole range of angles for the two classes of L and H stars. A well-pronounced forward peak and a small fraction of particles emitted backwards is ob-

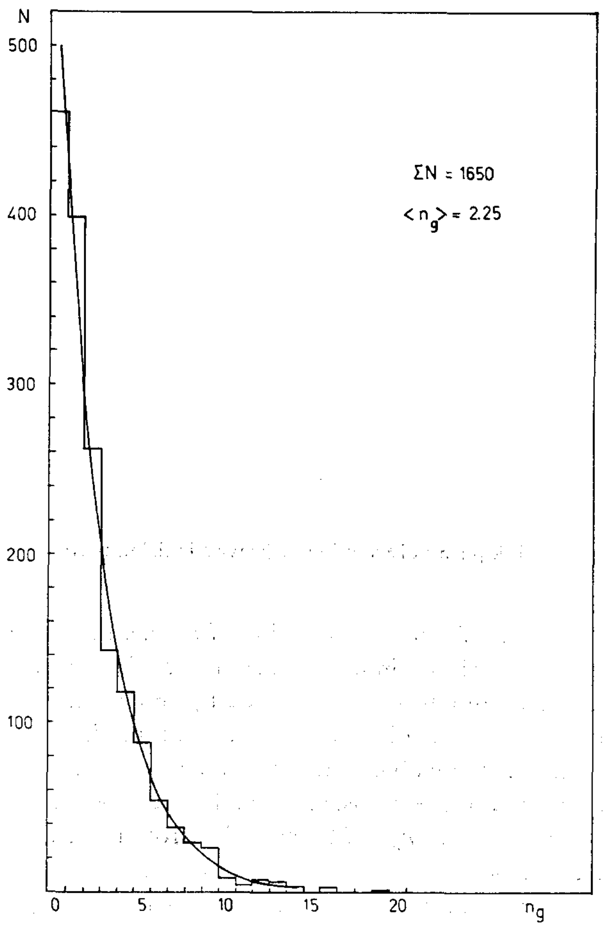

Fig. 6. Multiplicity distribution of gray tracks. The solid curve corresponds to the empirical formula $(N/a)\exp(-an_g)$ which fitted to the data gives $a = 0.36$ with $\chi^2 = 24$.

served. An admixture of secondary interactions is greater in the case of collisions with heavy nuclei leading to a difference between the two curves.

The interactions of deuterons with nuclei show quite a new effect as compared with the collisions of protons with nuclei, namely a very narrow forward peak formed by stripped protons. This phenomenon has been already noticed and is described in a number of papers [see for example ref. [5])]. At this energy, all stripped protons are practically contained within the emission angle of 2°, as may be seen in fig. 9. The shape of the experimental distribution is well fitted by the formula

$$N(\theta) = \frac{K^2}{(\hbar^2\alpha^2+p_0^2\theta^2)^{\frac{3}{2}}}+\beta+\gamma\cos\theta,$$

where K^2 is a fitted normalizing constant, $\alpha = 0.232\ \mathrm{fm}^{-1}$ is a parameter of the deu-

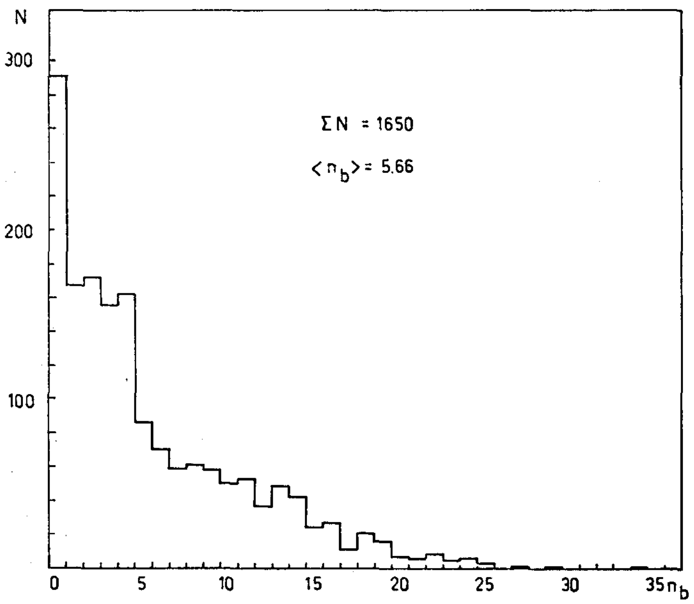

Fig. 7. Multiplicity distribution of black tracks.

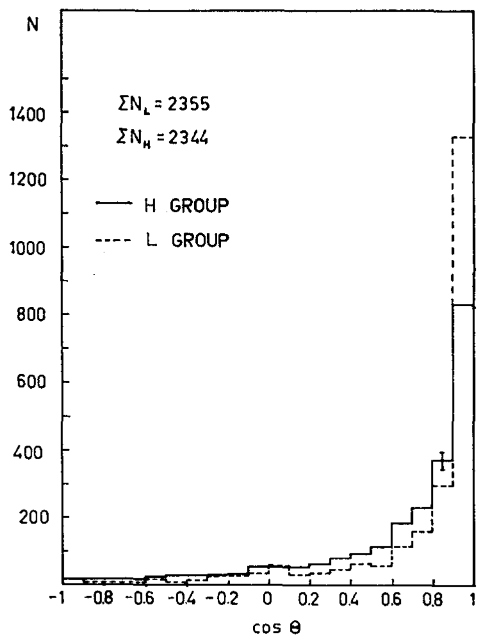

Fig. 8. Angular distribution of shower particles for L and H groups of interactions.

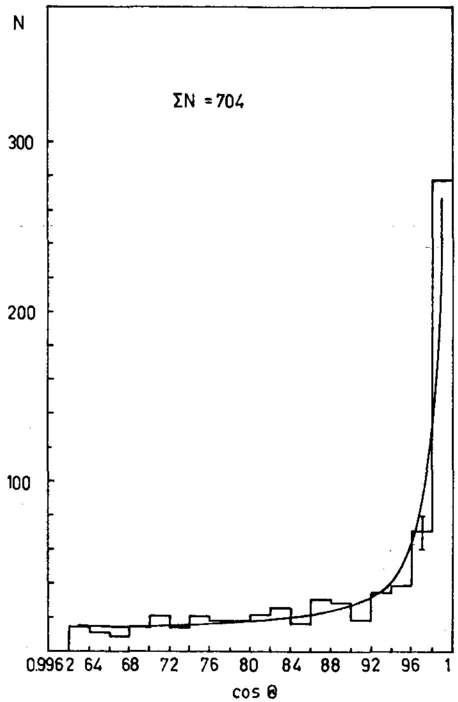

Fig. 9. Stripping enhancement up to 5°. The solid curve corresponds to the formula given in the text. The best fit to the data with $\chi^2 = 17.4$ gives $K = 1.119 \times 10^4$, $\beta = 13.4$, $\gamma = 0.15$.

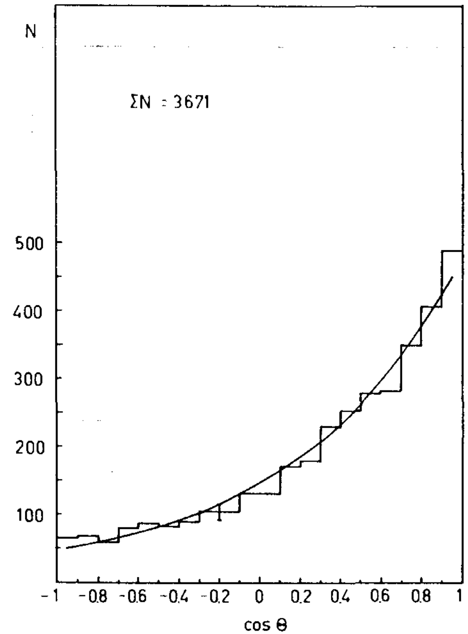

Fig. 10. Angular distribution of gray tracks. The shape of the distribution was fitted by an empirical formula $A \exp(B \cos\theta)$ where $B = 1.1$ with $\chi^2 = 32$. For the interactions of protons with emulsion nuclei B is practically the same.

teron zero-range wave function, p_0 the momentum of a stripped proton and β and γ fitted parameters describing the background.

The first term of the above expression has been used in ref. [5]) for fitting an angular distribution of stripped protons in nuclear processes. In the present work, there is no admixture of Coulomb-dissociation processes because only inelastic events have been recorded.

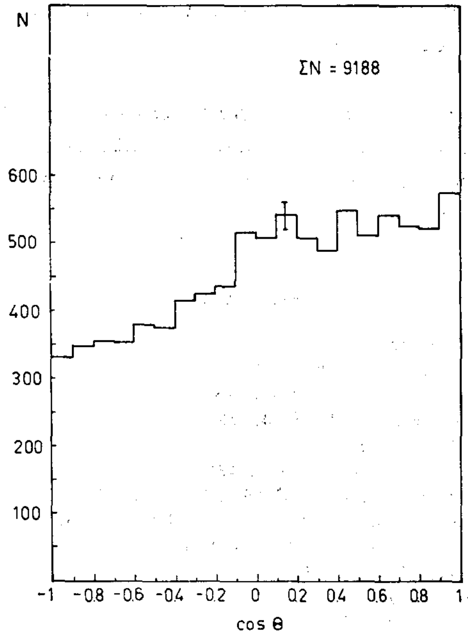

Fig. 11. Angular distribution of black tracks.

Fig. 10 presents the angular distribution of gray tracks with a fitted exponential curve. As has been shown in ref. [11]), the shape of this distribution is independent of the primary energy and we see that it is even independent of the nature of the projectile. Finally, the angular distribution of black tracks is shown in fig. 11. The small value of the asymmetry parameter of 0.145 ± 0.004 is consistent with the assumption that black tracks correspond to particles emitted from an evaporating centre moving with a velocity of $0.05c$.

4. Final remarks

The results presented in this paper should be considered as a first step in the experimental analysis of inelastic deuteron-nucleus interactions at accelerator energies. A further detailed analysis is very desirable, possibly with the use of more advanced experimental methods leading to a quick, reliable and effective identification of secondaries.

Theoretical analyses of nucleus-nucleus interactions have, so far, been confined to somewhat simpler processes, such as elastic scattering or stripping. The cascade model, which is well suited for treating inelastic processes, has been applied to deuteron-nucleus interactions [12]), but calculations have been too simplified to compare them with our results. More reliable calculations are in progress. Due to the fast progress in techniques of ion acceleration up to the energies of several GeV, corresponding progress both in experimental and theoretical analysis of nucleus-nucleus interactions may be expected in the near future.

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