TRANSFER OF ENERGY TO PHOTO-EMULSION ATOM NUCLEUS

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Certain aspects of collisions between fast particles and atomic nuclei are studied, especially the transfer of energy to the nucleus and its return to the unexcited state.

I. INTRODUCTION

When a fast particle interacts with a nucleus, a cascade of collisions takes place in the nucleus. Afterwards the nucleus returns to the unexcited state, during which process some particles evaporate from the nucleus.

The purpose of the research reported in the present paper has been the study of computer models of these processes and comparison of the results with experimental data.

II. METHOD OF COMPUTATION

The cascade of collisions in the first part of the process was studied with the help of a Monte-Carlo model very similar to that described in [1]. The computer MINSK-22 was used to implement the model.

After the total energy transferred to the nucleus was calculated, the process of particle evaporation was also simulated by a Monte-Carlo model. A method similar to that given in [4] was used to calculate the return of the nucleus from the excited state (when its energy was higher than in the basic state) to the basic state. We were mainly interested in numbers of charged particles which escaped from various nuclei. The results obtained were compared with the experimental data in [6], [8], [9].

The programs were written in the FEL-ALGOL and the FEL-FORTRAN (fairly standard and complete implementations of these languages for the

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MINSK-22 computer). From the programmer's point of view it seemed advantageous to use a stack during the simulation in such a way that when two particles formed during an interaction, both of which were able to interact further with other particles, the data on one of them were stacked and the other particle was followed until it got involved in a collision after which the emerging particles either did not have sufficient energy for further interactions or had escaped from the nucleus. After each end of this kind of one particle the data on the next particle were unstacked: finally, this led to the investigation of the whole cascade. The computation was limited by the hardware possibilities of the computer.

III. THE INVESTIGATION OF COLLISION CASCADES CAUSED BY PROTONS

Owing to the limited main store size it was necessary to simplify the problem. Therefore only elastic nucleon-nucleon collisions were considered. The nucleus was supposed to be an ideal Fermi-gas with constant nucleon density. The nucleons are in motion and their maximum kinetic energy is the Fermi energy. We were mainly interested in the total amount of the energy U received by the nucleus during the process. These computations were carried out for a nuclear photo-emulsion consisting mainly of Ag and Br nuclei and for a light N nucleus. For all three nuclei we performed 200 simulations for each of the 4 combinations of collision parameters.

In the case of a proton with the initial kinetic energy $T_0 = 400$ MeV the mean value of the energy received by a nucleus of the emulsion $\langle U \rangle = 64.6$ MeV. In [2], $\langle U \rangle = 68$ MeV is given. According to [3] the change in $\langle U \rangle$ with the increasing energy of the particle is small: this encouraged us to simulate the case of protons with an initial kinetic energy of 600 MeV under the same conditions as in the previous case.

IV. THE EVAPORATION PROCESS

The value of energy received by the nucleus is the starting point for the simulation of the evaporation of particles from the nucleus. The tracks of evaporated particles are black to grey in the emulsion. The evaporation process is also simulated by a Monte-Carlo method. Here, too, we consider the nucleus as consisting of an ideal Fermi-gas. The energy of the excited nucleus [4] is $U = kAT^2$, where A is the number of nucleons in the nucleus, k is a constant and T is the temperature increase corresponding to the energy increase U. The evaporation of particles is strongly dependent on the size of the Coulomb

potential barrier: we must also take into account the increase of the radius of the nucleus with increasing temperature.

To calculate the energy of evaporated particles, we used the formula given by Weisskopf

$$P(E)\mathrm{d}E = \frac{E - V}{T^2} \exp\left[-(E - V)/T\right]\mathrm{d}E,$$

where $P(E)\mathrm{d}E$ is the probability that the energy of the evaporating particle lies in the interval $(E, E + \mathrm{d}E)$, T is the temperature increase and V the height of the Coulomb potential barrier for charged particles. The energy of the excited nucleus decreases by an amount equal to the energy of the escaped particle. The ratios of evaporation probabilities for various particles are as in [5]. The particles escape one by one and the evaporation may only start from an equilibrium state. The process ends when the energy of the nucleus drops to U_k, after which it is replaced by gamma-quantum transfers.

The results of this model were compared to experimental data for atomic nuclei with a captured slow π-meson, since in that case the energy received by the nucleus is known. The experimental data are from [6]; the simulations were performed separately for heavy Ag and Br nuclei (in the sequel we shall refer to this case as the HN case) and the N nucleus (LN). For each of these elements 200 simulations were performed; however, even for a relatively high value of $U_k \approx 35$ MeV the obtained results did not agree with experimental data. There are several possible causes of such a discrepancy: it may be due to the fact that the nucleus is not an ideal Fermi-gas, that a new particle may escape before the equilibrium state is reacted, or that the gamma quanta are released during the whole evaporation process.

With regard to this, a semi-empirical model was adapted for the simulation of the evaporation process. If the energy of the escaping particles is approximately constant [7], we can suppose that the distribution of $\Delta N/N_h$ is binomial. (N_h is the number of black tracks in the emulsion and ΔN the number of cases with a given value of N_h.) From experimental data [6] we obtained the optimum values of $p(t)$ and N_h ($p(t)$ is the evaporation probability; on the basis of [7] we suppose that it does not change in the process). For the HN case $p(t) = 0.17$, while for the LN case $p(t) = 0.36$; $N_h = 7$ for both cases. The results are given in Table 1. From calculations for cascades inside the nucleus we obtain the distribution $\Delta N_k/\Delta U$ (N_k is the number of cases with the transferred energy U). The distribution of $\Delta N/N_h$ for protons with the energy of 600 MeV was obtained independently in two ways:

1. From the binomial distribution, where $p(t)$ was taken with a captured π-meson.

2. Using the formulae [6]

$$U = 37\,N_h + 4\,N_h^2 \quad \text{for} \quad U < 100\ \text{MeV},$$

$$U = 42(N_h + 1) \quad \text{for} \quad U > 100\ \text{MeV}.$$

These values are shown in Fig. 1. In the first case, we have the mean value

Table 1

(the values are in per cent)

N_h	HN			LN		
	Experimental [6]	From Le Couter	From the binomial distrib.	Experimental [6]	From Le Couter	From the binomial distrib.
1	50	0	53	23	21	16
2	31	4	31	27	37	31
3	8	24	12	35	31	27
4	8	32	3	13	8	18
5	2	22	1	2	0	6
6		14			0	2
7		3			3	
8		1				

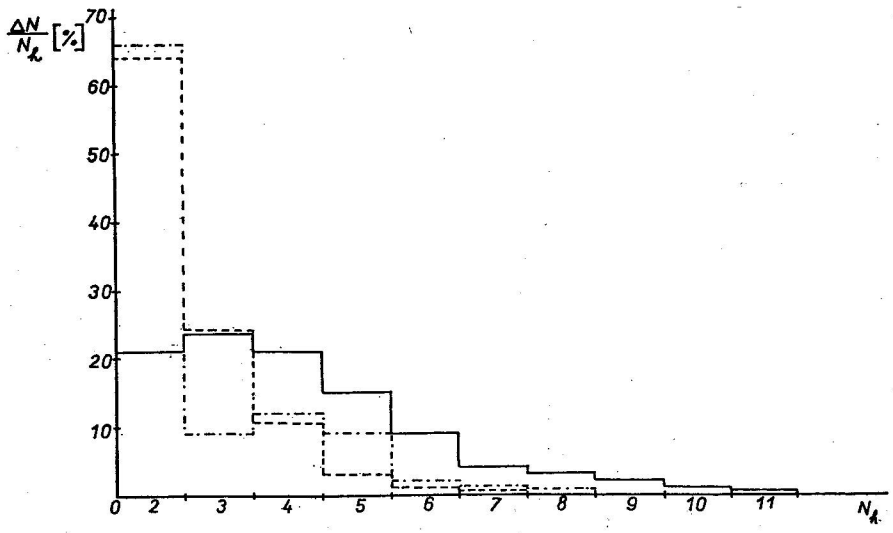

Fig. 1. Percentual representation of interaction stars by N_h values. The primary particle is a proton with $T_0 = 600$ MeV. ———— experimental data [9]; — — — — calculation 1; —.—.—.— calculation 2.

$\langle N_h \rangle = 2.63$, in the second case $\langle N_h \rangle = 2.81$. From experimental data [9], $\langle N_h \rangle = 4.06$.

V. COMPARISON OF THE CASCADE SIMULATION WITH THE EXPERIMENTAL RESULTS

The calculated mean value of the energy received by the nucleus in the cascade process is $\langle U \rangle = 67.3$ MeV. Thus we may conclude that $\langle U \rangle = k\langle N_h \rangle$ (k is a constant). This enables us to calculate the average difference of energy received ty the nucleus in both these cases from experimental data. For case 1, $\langle \Delta U_1 \rangle = 37$ MeV, for case 2, $\langle \Delta U_2 \rangle = 29.4$ MeV.

This difference can be accounted for by the forming of slow π-mesons which are captured in the nucleus or a non-cascade mechanism of energy transfer. The probability that a slow π-meson will be formed and captured by the nucleus is $P_{f_1} = 0.26$ and $P_{f_2} = 0.21$. From the number of collisions in a cascade with the energy in excess of 290 MeV, the probability that a slow π-meson will be formed in one collision was calculated as $p_{\pi_1} = 0.13$, $p_{\pi_2} = 0.1$.

VI. OTHER APPLICATIONS

Similar methods were used in an attempt to simulate the cascade initiated by a deuteron, since emulsions that have been exposed to deuterons were available at our laboratory. From [8] we have $\langle N_h \rangle = 5.29$, which gives the mean transferred energy $\langle U^* \rangle = 135$ MeV. If the deuteron interacts as two particles, we have two independent cacades and a twice higher energy. If the deuteron splits only after the first interaction, then the number of collisions and the energy transferred is less. Considering that the deuteron may survive further interactions as well, we have the probabilty $P_d = 0.67$ that it will survive the first collision. This value is higher than that derived from experimental data, which is not less than $P_d = 0.28$. This method of calculating the probability of deuteron survival is necessarily just a rough approximation. Work is in progress on this aspect of the problem.

VII. CONCLUSION

We may conclude that our simplified model of a cascade initiated in a nucleus by a fast particle yields satisfactory values of energy transferred to the nucleus. It is possible that the calculated probability of the forming of a slow π-meson in a cascade is too high, but we do not know yet all the possible mechanisms of the energy transfer and therefore they could not be incorporated into the model.

The small capacity of the computer used was also a limiting factor. It is further necessary to conclude that the evaporation process cannot be interpreted as a sequence of quasi-equilibrium states of the ideal Fermi-gas; other methods of statistical physics must be used. In conclusion we should like to express our thanks to Associate Prof. RNDr. J. Tuček, CSc., for his valuable advice and unfailing interest in our work, and to Prof. RNDr. J. Dubinský and Ing. Š. Hudák who have made it possible for us to pursue this research.

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