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FERMI MODEL DESCRIPTION OF HIGH MULTIPLICITY COMPOUND NUCLEUS DECAY*

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Calculations are performed in the terms of the Fermi model (the model of simultaneous decay) of the emission frequency and velocity distributions of particles with atomic number $Z \geqslant 2$, emitted from a highly excited heavy nucleus. The theoretical results are compared with the experimental data obtained from proton–nucleus interactions at 25 GeV/c and 9 GeV, registered in nuclear emulsions.

1. *Introduction*

The study of the hadronic interaction with large energy transfer to a heavy nucleus is becoming increasingly popular because of the possibility it affords for obtaining information on highly excited nuclear matter. However, the mechanism of these interactions is still unknown.

The evaporation model which is commonly used for describing these reactions is unsuitable in the case of high excitation of the nucleus because the assumption of a state of statistical equilibrium preceding the emission of the secondary particle is no longer valid.

In this paper phase space factors for the emission of many fragments have been calculated and compared with the experimental data. Such a phase space Fermi type model [1] takes into account the possibility of simultaneous emission of fragments.

2. *Experimental data*

The experimental material was collected on a low sensitivity emulsion (K1)[1] irradiated with a 25 GeV/c proton beam from the CERN Proton Synchrotron and on a normal sensitivity emulsion (G5) irradiated with a 9 GeV proton beam from the Synchrotron at Dubna.

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[1] In the K1 emulsion protons are registered up to 14 MeV.

In the K1 emulsion about 2000 flat tracks stopping in the emulsion, and resulting from about 1000 randomly selected interactions containing a hammer track or two black tracks ("fission like"), were identified. Identification was ambiguous in about 5–10 percent of the events [2] due to the statistical nature of energy losses. In the present paper the experimetal data concerning 733 tracks with a range of $R \leqslant 9.2$ mm (50 MeV proton kinetic energy) coming from 33 stars containing a hammer track [3] were also used.

The average excitation energy was of the order of 0.5 GeV for the interactions observed in the K1 emulsion (the mass number of the excited nucleus $A \approx 80$) and of the order of 1 GeV for the interactions observed in the G5 emulsion (large stars [3]).

3. *Method of calculation*

In the present paper high excitation energies of the nucleus have been considered. The average excitation enei gy is of the order of 500 MeV and $A \approx 80$. Many experimental results concerning high excitation reveal discrepancies between the experimental energy distributions of secondary particles and the predictions of the evaporation model [4, 5]. The Coulomb barrier observed for the emission of charged secondary particles was considerably higher than the values predicted by the evaporation model. This discrepancy is probably due to the invalidity of the basic assumption of the evaporation model, e.g. that the highly excited nucleus acquires after each emission the state of statistical equilibrium. Because ot the small momenta of the particles produced, the nonrelativistic approximation of the Fermi approach to the phase space model is used in the present paper. The formula obtained by Rosental [6] for the decay probability of an excited nucleus into many secondary particles is the starting point for the subsequent considerations:

$$S_n(P_0, T_0) = \left(\frac{V}{8\pi^3 h^3}\right)^{n-1} \frac{2\pi^{3/2(n-1)}}{[3/2(n-1)-1]!} \left(\frac{m_1 \ldots m_n}{m_1 + \ldots + m_n}\right)^{3/2} T_0^{3/2(n-1)-1}, \qquad (3.1)$$

where S_n is a statistical weight of the specific final channel, $P_0 . T_0$ — total momentum and kinetic energy of all secondary particles in the center of mass system, V — volume of interaction, n — number of secondary particles in the final channel, m_i — mass of the secondary particle.

This description was used beforehand but only for relatively low incident particle energies and for nucleus mass numbers lower than 18 [7, 8, 9]. In the latter case it is possible to calculate statistical weights of the majority of permissible final channels without additional approximations. For larger mass numbers of the target and excitation energies comparable to the binding energy of the nucleus it is not feasible to take into account all possible final channels. Therefore in the present work the following simplifying assumptions have been made:

1. The excited nucleus created in the fast process remains on the stability path. The possibility that the recoil nucleus may be off the stability path is neglected.

2. The formula known for low excitation energies, $\varrho = A \cdot e^{\sqrt{BE}}$ has been used for the density distribution, ϱ, of the energy levels, E, of the nucleus.

3. Only the emission of n, p, d, t, ^3He, ^4He and the recoil nucleus has been taken into account accurately. The emission of all other nuclear fragments has been replaced in the calculation by the emission of ^7Li fragments with some effective weight only. The value of this weight has been fitted to attain consistency between theoretical and experimental frequencies of fragment emission. Other results of the calculations are weakly dependent on the weight value.

4. The independent calculations was performed under the assumption that two heavy fragments ($M > 14$) was produced in the interaction, for comparison with "fission like" experimental events.

5. Hitherto the Fermi model was used to describe successfully processes with not more than three secondary particles and for nuclei not too highly excited. If the conventional statistical spin weights $(2S+1)$, for each particle, are used, then Eq. (2.1) predicts a too frequent production of fragments. In the described experiment the kinetic energy of secondary particles was of the order of 0–50 MeV, and their relative orbital angular momentum was $l \leqslant 2$. This calls for a modification of the Fermi model. For simplicity, it was assumed that for each pair of secondary particles $l = 0$. In the original Fermi model the angular momentum conservation law does not put any restriction on Eq. (2.1). In our case the momentum conservation law leads to spin conservation and conservation of the third component of the spin. Consequently, the spin weights in Eq. (2.1) must be changed, and become [10]:

$$gS(n) = \frac{(nn+np+nh+nt)!\,nd!\,nf!}{\left[\left(\frac{nn+np+nh+nt}{2}\right)!\right]^2 \left[\left(\frac{nd}{3}\right)!\right]^3 \left[\left(\frac{nf}{4}\right)!\right]^4} \frac{2S+1}{a}, \tag{3.2}$$

$$a = \frac{nn}{2}+\frac{np}{2}+\frac{nt}{2}+\frac{nh}{2}+nd+\tfrac{5}{2}\,nf,$$

where nn, np, nd, nt, nh, nf are numbers of neutrons, protons, deuterons, ^3H, ^3He and fragments emitted in the interactions, S — the total spin (the results of calculations are insensitive to the total spin of the residual nucleus values).

An event with low momenta of the emitted secondary particles can be described more correctly by reducing the frequency of emission of high momentum particles by a factor of e^{-aq^2} as in the "uncorrelated jet" model [11]. As indicated in this paper, similar qualitative results can be obtained when the spin weights are changed.

In the first approximation the parameter V, volume of interaction, can be taken as equal to the volume of the nucleus. One can also reasonably assume that V is equal to the larger volume of an expanding system (when it is large enough to contain n non-interacting particles). In the calculations different values of V were tried.

The kinetic energy T_0 equals the total kinetic energy of all particles in the volume V. This energy is smaller than the total kinetic energy of all secondary particles at large distances. The difference is equal to the energy of the electrostatic interaction, E_c.

In the evaporation model, the estimation of electrostatic energy is straightforward because any single particle emitted is always in the Coulomb field of the remaining nucleus (two body problem). In the model of simultaneous emission the Coulomb energy of the single particle depends on the configuration of the final particles at the decay moment. As different spatial configurations are possible for a given channel one should take the average Coulomb energy. Let us take as an example a particle, even of large charge, surrounded by many homogeneously distributed particles. The Coulomb force acting on this particle is equal to zero. If this particle is on the surface of the nucleus the Coulomb force acting is greater than zero. For this reason the Coulomb barrier value of a single emitted particle is not precisely defined in the model of simultaneous break-up of the nucleus, and depends on the average structure of the final channel.

The total electrostatic energy, for all emitted particles, was assumed to range from 90 to 150 MeV, depending on the final channel. This corresponds to the situation in which the decay particles are distributed on the surface of the nucleus.

4. *Results and comparison with experiment*

Two free parameters: the weight of the ^{7}Li fragment and the volume of interaction, V, are involved in the calculations. The value of V was assumed to be 1 to 8 times larger than the volume of the non-excited nucleus and the weight of the ^{7}Li fragment was fitted for

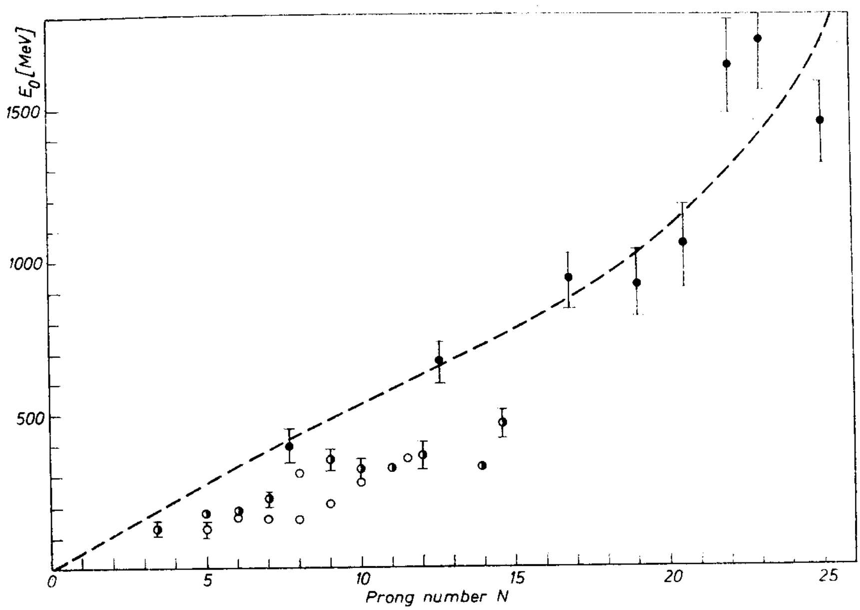

Fig. 1. Dependence of the average prong number, N, in interaction on the excitation energy, E_0. The dashed line shows the calculated results

each V value, in order to attain consistency between the calculated and experimental frequencies of fragment emission. A satisfactory description of the experimental data can be obtained for different pairs of the parameters since they are not independent in our model.

The statistical weights (Eq. (2.1)) were calculated as a function of prong numbers, N, for the different E_0 values. The dependence of the average prong number in the interaction on the excitation energy E_0 is shown in Fig. 1. The dashed line represents the calculated $E_0 = f(N)$ relation for A ranging from 70 to 85 depending on the prong number N. The black points in Fig. 1 correspond to the interactions registered in a normal sensitivity emulsion. An estimation of the excitation energy of the nucleus has been made under the assumption that all charged particles with a range shorter than 9.2 mm were emitted in the slow, statistical process. The presence of neutrons in the interactions has been estimated as in Ref. [3]. The remaining points in Fig. 1 correspond to the experiment made in low sensitivity emulsions. In these emulsions protons were registered up to the energy of 14 MeV and for this reason the excitation energy of the nucleus was underestimated. The experimental points for these emulsions are below the theoretical curve (the error of the energy estimation is of the order of 10 percent [3]). This result suggests that the emission of protons with energy above 14 MeV but lower than about 50 MeV can be explained by the decay of the excited nucleus, described by our modified Fermi model.

The experimental and calculated velocity distributions of secondary particles are shown in Figs. 2, 3, 4. The distribution of ^{8}Li fragments is shown in Fig. 2. For this reason the Coulomb barrier value for the single emitted particle is not defined in our model.

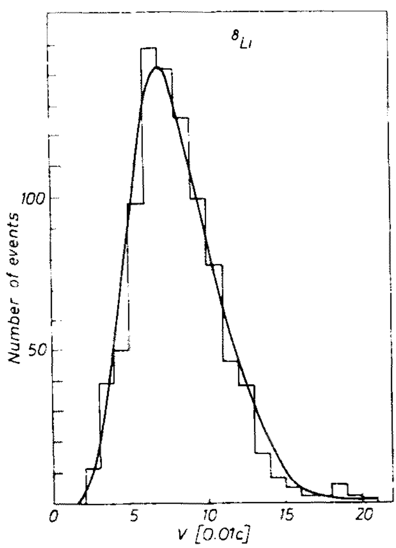

Fig. 2. Velocity distribution of the ^{8}Li fragments. The solid line presents the calculated results. The experimental data come from the works [4, 5, 12]

The only predicted value in this model is the total electrostatic energy for all charged particles. The distribution of this quantity depends on the final channel configurations. For this reason in Figs. 2, 3, 4 the Coulomb barrier values have been fitted to the experimental velocity distributions. The experimental and calculated velocity distributions of the residual nucleus track as well as from randomly selected stars (previously obtained in the analyzed

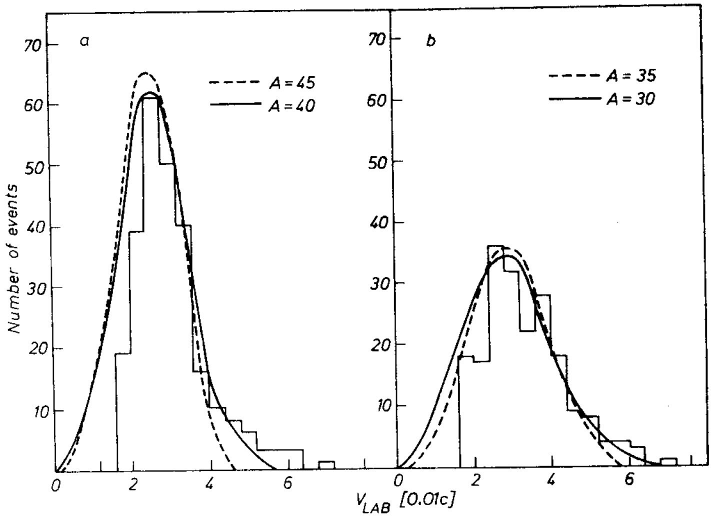

Fig. 3. Velocity distributions of residual nucleus from randomly selected stars (a) and stars containing a hammer track (b)

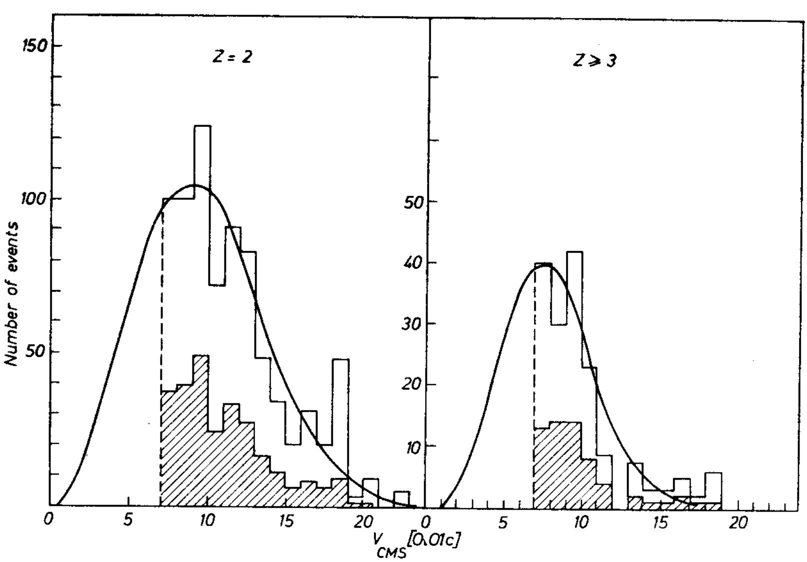

Fig. 4. Velocity distributions of secondary particles corresponding to stars containing a hammer track

interactions [12]) are shown in Fig. 3. The average mass number of the residual nucleus for the interactions containing a hammer track was found to be 30 ± 10 [12] and for the average interactions 40 ± 10. The experiment and the best fit calculations give similar values. The theoretical curves have been normalized to the external parts of the experimental distributions where no loss of tracks is expected ($R > 1$ μm).

For all types of interactions discussed in this paper good agreement between the theoretical and experimental velocity distributions was obtained. The theoretical and experimental velocity distributions of secondary particles of $Z = 2$ and $Z \geqslant 3$, produced

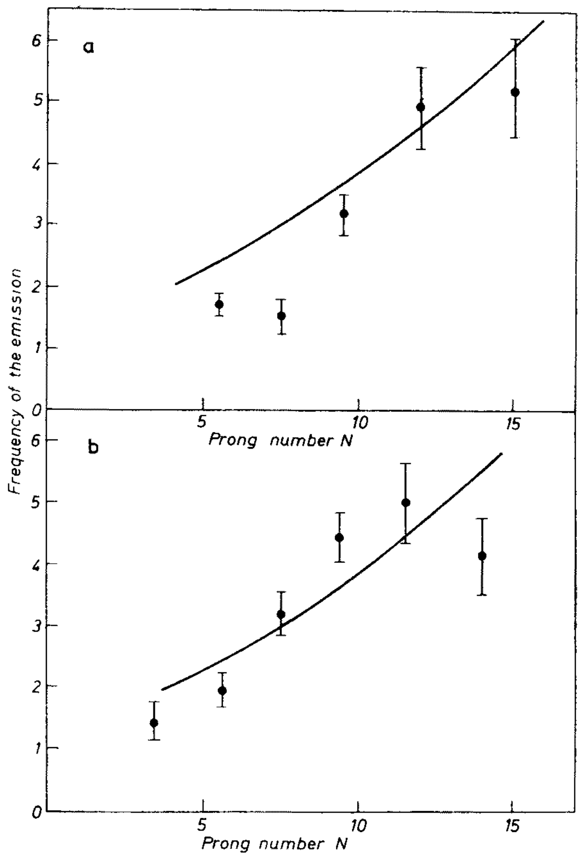

Fig. 5. Frequency of the emission of particles of $Z \geqslant 2$ corresponding to randomly selected (a) and "fission like" (b) stars

in the interactions containing a hammer track, are shown in Fig. 4 by way of example. The shaded areas correspond to the sample of identified events.

The mean number of the secondary particles with $Z \geqslant 2$ normalized to the single interaction, corresponding to randomly selected and "fission like" stars, is shown in Fig. 5. The solid curve represents the calculated results. Similar results, obtained for stars containing a hammer track, are shown in Fig. 6. Fair agreement is observed in both cases although the model does not seem to reproduce the results for the event with a small value of N. This is quite natural since this model is not considered to be valid for low excitation energies.

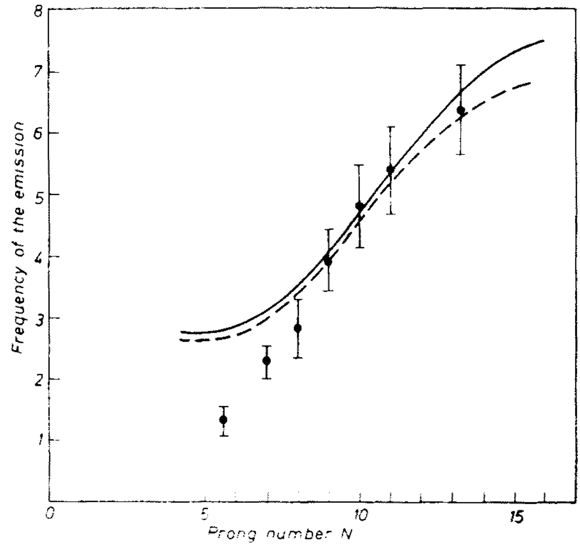

Fig. 6. Frequency of the emission of particles of $Z \geqslant 2$ corresponding to stars containing a hammer track. The solid line — effective weight of ^7Li equal to 4, the shaded line — effective weight equal to 3

5. *Summary*

In the present paper the model of independent production of secondary particles was used to describe the process of deexcitation of highly excited heavy nuclei. Hitherto this model was used only to describe elementary interactions [13, 14] and interactions with light nuclei ($A \leqslant 18$) [7, 8, 9]. The simplifications described in Section 2 were introduced, because in the case of a heavy nucleus there is a very large number of final channels. In order to explain the relatively low kinetic energies and the frequent production of secondary particles, the modification of the Fermi model, connected with some changes of the spin weights, were made.

Estimation of the electrostatic energy in the final channel was particularly difficult, because it was necessary to take into account the Coulomb interactions of all charged particles. The Coulomb interaction depends on the structure and volume of the final channel. Nevertheless, the Fermi model explains the reduction of the Coulomb barrier observed for the emission of charged secondary particles. It seems that this model may relate the Coulomb barrier value and the final channel configuration.

The Fermi model, as it is shown in Figs. 1–6, describes fairly well the dependence of excitation energy of the nucleus and the frequency of emission of secondary particles on the prong number.

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