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Introduction

In the last years the nucleon-nucleus reactions at intermediate energies $T_0 < 100$ *MeV* are of great interest, as just these reactions clearly manifest the effects of the so-called preequilibrium particle emission. The mechanism, connected with this phenomenon, of the particle emission during statistical equilibration of the excited nuclear system is somewhat intermediate between direct reactions and decays through states of a compound nucleus and does not reduce to any simple their combination. The excitation model of the preequilibrium particle emission proposed by Griffin /1/ and its subsequent development (see review articles /2,3/) have allowed one to understand the importance of this mechanism, its connection with the intermediate nuclear structure, and to explain a number of interesting physical effects.

Unfortunately, all the models of preequilibrium decay, based on the use of the idea of relaxation of the excited nucleus system due to collisions between its constituents, do not raise the question about the angular distribution of reaction products. The experimentally observed asymmetry of the angular distribution for secondaries is not explained within this approach.

In this paper we elaborate the model marrying specific features of the direct reactions and preequilibrium decay. We also discuss the sensitivity of measurable quantities to these mechanisms.

The Description of the Model

In considering the mechanism of nuclear reactions we proceed from the following physical picture: A particle entering a nucleus can suffer one or several intranuclear collisions that gives rise to an excited many-quasiparticle state like "doorway state". The latter, in its turn, can develop by emitting particles into the ground state directly or through the formation of a compound nucleus. This picture resembles the model Rodberg proposed to explain the intermediate nuclear structure /4/. Using the common formalism of the nuclear reaction theory Rodberg has succeeded only in treating the elastic and inelastic nucleon scattering through the formation of the doorway state. In our paper the reactions with several particles in the final state are accentuated.

The behaviour of a primary particle, as well as of those of the second and subsequent generations (if they exist) up to their capture or emission from nucleus is treated in the framework of the conventional cascade model /5,6/. The count of the number of the captured by nucleus particles and "holes" produced due to intranuclear collisions determines the initial particle-hole configuration of the remaining excited nucleus which excitation energy is to be found from the energy balance. A further "destiny" of the nucleus is traced by the modified exciton model of preequilibrium emission suggested earlier in Dubna /7/. It should be noted that the model is based on solving the master-equation taking account of the particle emission and three allowed types of intranuclear transitions with changing the number of particle-holes (excitations) by 2 or 0. The averaged matrix element is evaluated by considering the mean free path of a particle in nuclear matter. This version of the exciton model takes account of the possibility of the subsequent emission of several particles and naturally develops into the model of equilibrium statistical decay of the compound nucleus for states with many quasiparticles /7/. In the used model of preequilibrium emission a large amount of data on the reaction (n,n′) at $T_0 \sim 15$ *MeV* has been well described /8/.

Thus, the proposed cascade-exciton model treats the nuclear reaction as proceeding through three stages: cascade, preequilibrium and equilibrium, unlike the two-stage Serber model /9/.

All calculations are performed by the Monte-Carlo method. To reduce the dispersion in calculating the energy spectra of particles emitted at a given angle we make use of a modified method of the local flux proposed for consideration of particle transport through matter /10/.

The Model Parametrization

An important point in our model is the condition to pass from the intranuclear cascade model to that of preequilibrium emission. In the conventional cascade-evaporation approach the fast particles are traced up to some minimal energy, cut-off energy $T_{cut} \sim$ 7-10 *MeV*. As is shown in ref. /5/, a reasonable variation of the value of T_{cut} does not change essentially the average number of particles in a nuclear act. In other words the matter is which particles should be called by cascade and which evaporated. As the zero-order approximation to our model we will consider this "sharp cut-off" method for passing to the prequilibrium decay of a nucleus as well.

In the realistic case one should expect a cut-off somewhat smoothed in energy, and from general physical considerations it is clear that passing to lower primary energies the contributions to particle capture in periphery and interior regions of a nucleus should change. This thing is completely beyond possibilities of the sharp cut-off approximation. Therefore an attempt is natural to connect the condition for fast (cascade) particle capture with the extent of proximity of the imaginary part of the model optical potential to its experimental value obtained by analysing the data on particle-nuclei elastic scattering.

The question then arises: What is to be taken as the model optical potential for the cascade stage? In the "weak coupling" approximation the imaginary part of the optical potential can be expressed through the cross section σ of scattering of a particle on nuclear constituents

$$W_{opt,\ mod}(r) = -\frac{h}{2}\sigma\cdot\rho(r)\cdot v, \qquad (1)$$

where v is the velocity of an incident particle in matter,

$\rho(r)$ is the density of nuclear matter, and σ should be affected by the Pauli principle. The account for the Fermi motion means the averaging of (1) over an appropriate spectrum. This relation (1) is valid only at sufficiently high energies and for the nuclear interior. And the radial behaviour of the optical potential is followed by the nuclear density $\rho(r)$, as is seen from (1). In general case the function $\rho(r)$ lags behind $W_{opt}(r)$ that is due to the finite interaction radius and nonlinear relation of $W_{opt}(r)$ to $\rho(r)$ /11/. Since at present we cannot consider these effects in a consistent manner, the imaginary part of the model optical potential for the cascade particles is evaluated in the following two versions:

A. The optical potential follows the radial dependence of the mass distribution for which the diffusive nature is taken into account in the cascade model by breaking the volume of nucleus into 7 spherical zones with the constant density equal to the value averaged over a given zone.

B. The optical potential is defined by (1) where $\rho(r)$ is taken to be the Saxon-Woods distribution, but for the values of parameters corresponding to the volume part of the imaginary optical potential extracted from experimental data; indirectly, this trick considers the effect of the nonlinear relation between W_{opt} and ρ.

Monte-Karlo calculations for both variants are shown in *Fig. 1,* also the experimental values are given there for the imaginary optical potential $W_{opt,exp}(r)$ obtained by two different groups /12,13/. It is noteworthy that for $T_0 > 30$ *MeV* their results differ noticeably though these, in practice, coincide in χ^2 for the angular distributions in elastic scattering and even for the polarization measurements. At energy $T_0 = 60$ *MeV*, where the discrepancy is especially large, the values of $W_{opt,mod}(r)$ are between these data. It is natural that when passing to lower values of T_0 the imaginary optical potential calculated in this way does not reproduce the absorption bump occuring at the nucleus periphery. It should be added also that the conditions of validity of the cascade and optical models do not coincide. In particular, the cascade model considers the scattering on bound nucleons rather than

on the potential well as the optical model does. Thus, one may speak of the agreement between $W_{opt,mod}$ and $W_{opt,exp}$ up to a certain degree of accuracy which can be characterized by the proximity parameter

$$\mathcal{P} = \left| \frac{W_{opt,mod}(r) - W_{opt,exp}(r)}{W_{opt,exp}(r)} \right| .$$

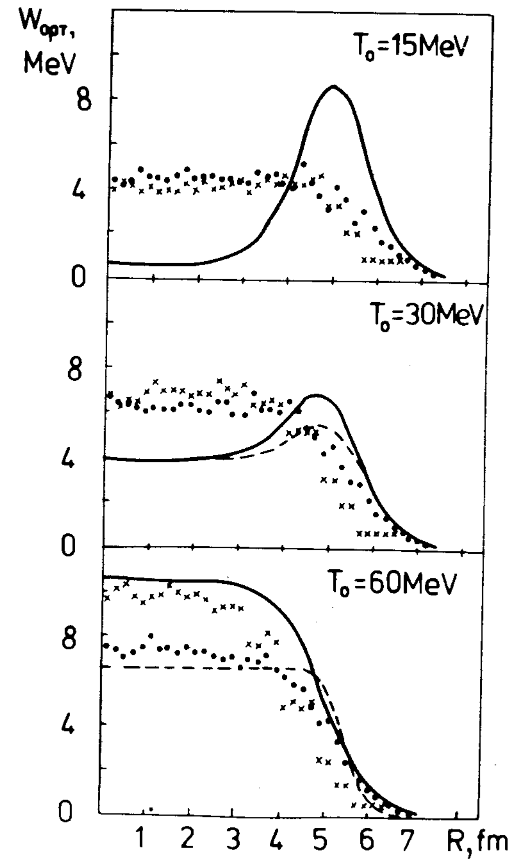

Fig. 1. Results of the model calculation of the imaginary part of the optical potential for the reaction $p + {}^{54}Fe$ *at energy* T_0 *(crosses and circles are the variants A and B, resp., see the text). The solid and dashed lines stand for the experimental data from refs.* /12,13/.

If the 60 *MeV* proton is assumed to obey the conditions of validity of the cascade model, then, as is clear from *Fig.1,* the parameter $\mathcal{P}\simeq(0.3-0.5)$. The proximity parameter can be taken more accurately from comparison of the calculated characteristics of nuclear reaction with experiment.

All other parameters of the cascade-exciton model are fixed and the same as in the models of intranuclear cascade and preequilibrium decay /7/ .

Results and Discussion

Figure 2 shows spectra of secondary protons from the reaction $p + {}^{54}Fe \to p + \ldots$ calculated under different assumptions on W_{opt} : These results indicate that the "sharp

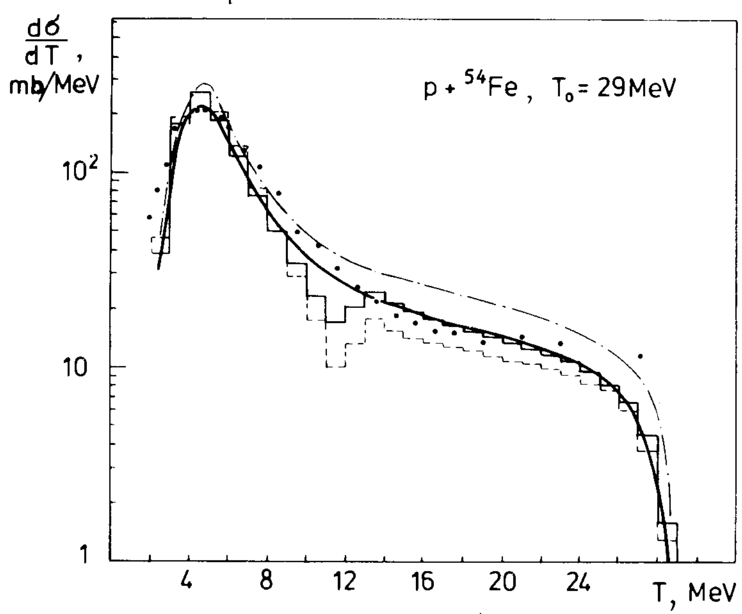

Fig. 2. The calculated spectrum of protons emitted by ^{54}Fe *nucleus in the 29 MeV proton bombardment.* ¬_┘¯ *- the cascade evaporation model;* ¬_┌ *- the present cascade exciton model, in "sharp cut-off" approximation;* -·-· *the variant A;* ——— *the variant B. Points are the experimental data from ref.* /14/.

cut-off" version results in the unphysical dip in the particle spectrum around T_{cut}. When passing to higher energies of an incident proton the dip is masked by the choice of the histogram step, however, at $T_0 \simeq 15$ *MeV* its effect distorts abruptly the general form of the spectrum. The mechanism of preequilibrium particle emission being included smoothes the theoretical curves and improves the agreement with experiment.

It should be noted, however, that the angle-integrated spectrum is not very sensitive characteristic of the reaction, therefore even the conventional cascade-evaporation model provides reasonable results. The most sensitivity to the preequilibrium emission is revealed by spectra of protons emitted at back angles *(Fig. 3).* In

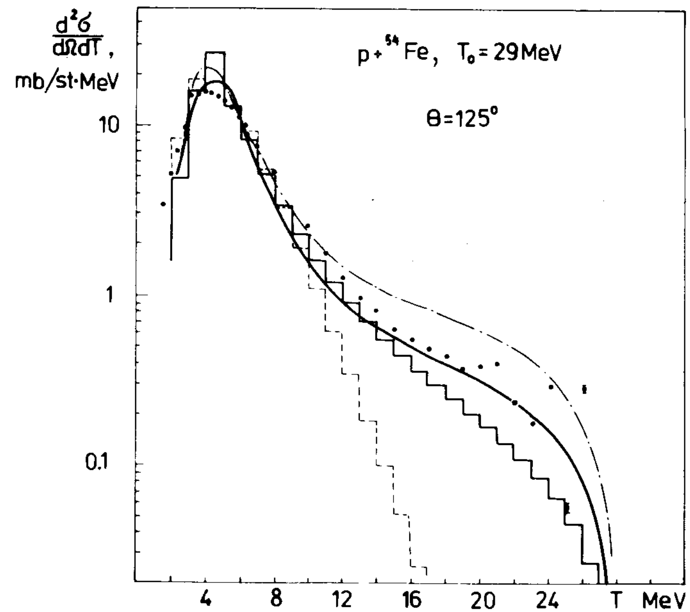

Fig. 3. The spectrum of protons emitted at $\theta = 125°$ *in the reaction* $p + {}^{54}Fe \to p + \ldots$ *at* $T_0 = 29$ *MeV. All notations are the same as in Fig. 2.*

particular, the back yield of protons with energy $T > 15-20$ *MeV* is, in practice, entirely due to the non-equilibrium decay of nuclei. This effect cannot be simulated by any variation of parameters of the conventional cascade-evaporation model.

Due to the high sensitivity to the preequilibrium component, the agreement with experiment for the spectra of back-scattered protons was a basic criterion for the choice of the proximity parameter $\mathcal{P}$. The optimal values of $\mathcal{P}$ turn out to be equal to (0.5-0.6) and (0.2-0.3) for variants A and B, respectively. The increase of $\mathcal{P}$ makes the yield of fast particles overestimated, that is more evident at small energies, say, at $T_0 \simeq 15$ *MeV*. Values of $\mathcal{P}$ smaller than those indicated above result in increasing excitation energy of the initial channel, that affects the spectrum of particles emitted at backward direction, and this phenomenon is seen as sooner as higher the energy of an incident particle.

One should stress that the division into cascade and preequilibrium mechanisms within the model under consideration is rather conditional. This division, and correspondingly the choice of $\mathcal{P}$, is based on the assumption of isotropy of angular distribution for the preequilibrium component; the whole anisotropy is assigned to the cascade nucleons. Actually, the excited many-quasi-particle system resulting from particle cascade may retain some "memory" on the particle which has initiated the cascade and this one is the larger the smaller the number of excited particle-holes. Now it seems impossible to allow for this effect consistently, however, it is clear that, effectively, this would correspond to the choice of more narrow interval of the parameter $\mathcal{P}$.

Since variants A and B provide similar results, all the below listed calculations have been performed for the variant B with $\mathcal{P} = 0.3$ and $W_{opt,exp}$ taken from the Bocchetti and Greenless analysis /12/.

The calculation results drawn in *Figs. 4,5* allow one to trace the dependence of shape of the proton energy distributions on energy of the incident proton and on nucleus-target. There also the contribtuions from all the three mechanisms of particle emission are shown. It is seen that the proposed model reproduces well the change of spectra in going from light to heavier target-nuclei and predicts correctly the absolute particle yield. The absolute calcu-

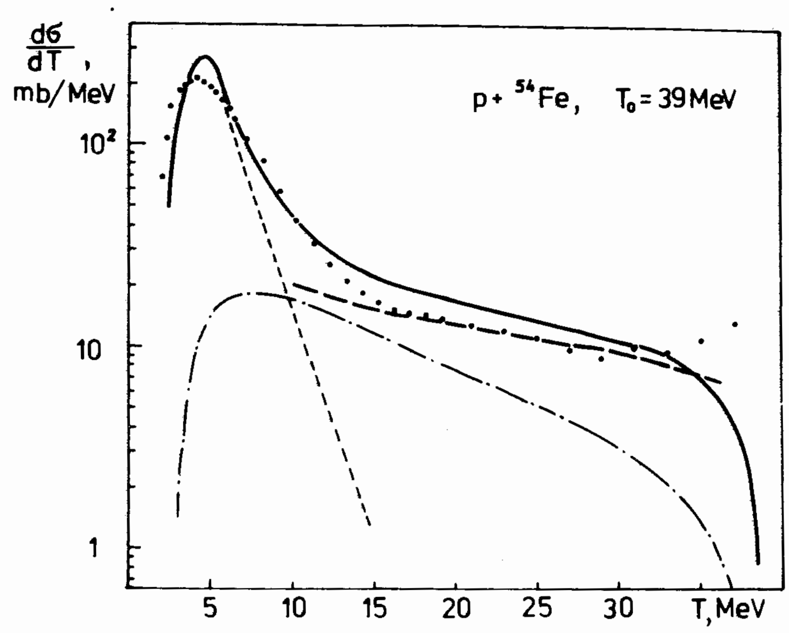

Fig. 4. The angle-integrated spectrum of secondary protons from the reaction $p + {}^{54}Fe \to p + \ldots$ *at* $T_0 = 39$ *MeV:* – – – – *the equilibrium component;* –·–·–· *the preequilibrium component;* ——— *the sum of all three components;* ▬ ▬ ▬ ▬ *the Blann calculations according to the geometry dependent hybrid model* /2/. *Points are the experiment from* /14/.

lations appear to be possible due to the use of the intranuclear cascade model. The relative contributions of cascade and preequilibrium particles depend both on T_0 and on the mass and charge numbers of the target-nucleus unable to be localized within any narrow energy range, if only the angle-integrated spectra are considered, as in the conventional preequilibrium approach. The relationship between these components depends also on the angle of emission of secondary protons (see *Fig. 6*).

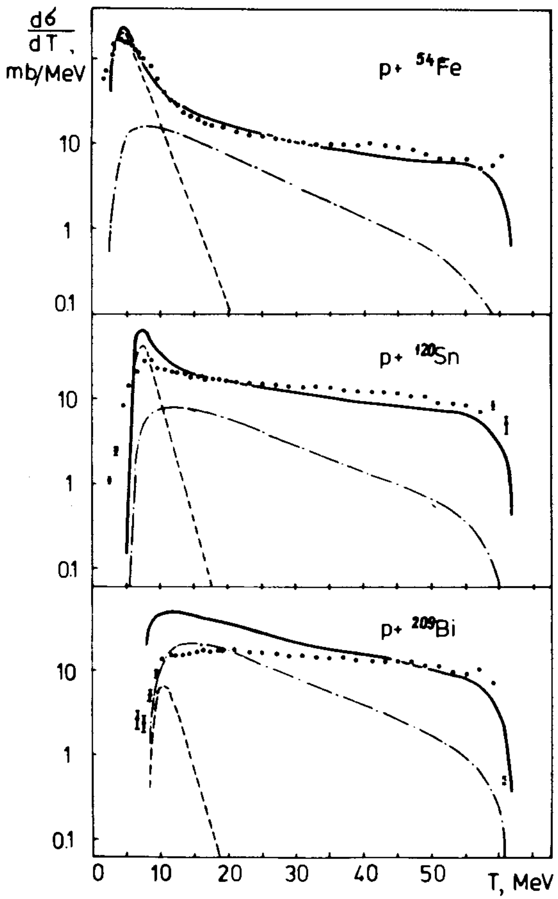

Fig. 5. The spectra of protons emitted in the irradiation of ^{54}Fe , ^{120}Sn and ^{209}Bi nuclei by protons with energy $T_0 = 62$ MeV. Notations are the same as in Fig. 4.

The calculations of the double differential cross sections is examplified in *Fig. 7*. The agreement with experiment is good enough, and for large angles it is considerably better than the results obtained within the cascade evaporation model. As has been mentioned, the angle-integrated energy spectra are not very sensitive

characteristics that has allowed a number of authors to employ, for them, a slightly changed preequilibrium model up to energy $T_0 \simeq 60$ *MeV* (cf. *Fig. 4*).

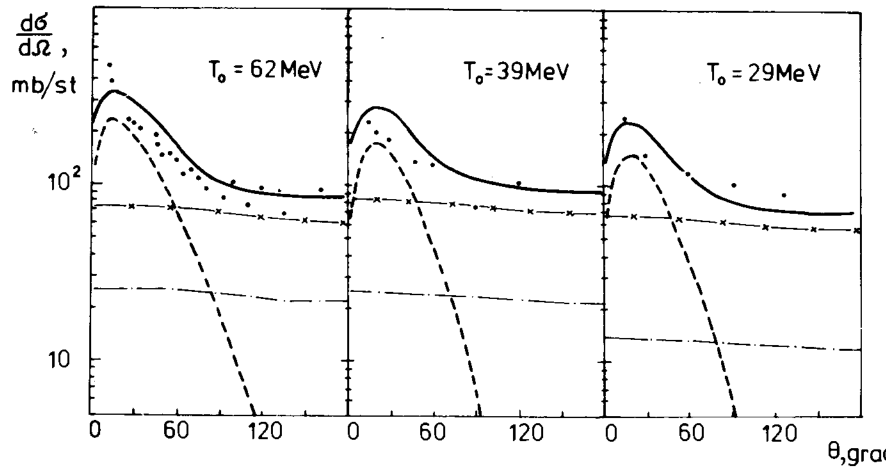

Fig. 6. The angular distribution of protons from the reaction $p + {}^{54}Fe \to p + ...$ at T_0 . −×−×− the equilibrium component; −·−·− the preequilibrium component; − − − − the cascade component; ——— the sum of all the three components. Experimental points are from ref. [14].

Conclusion

Thus, the proposed cascade-exciton model reproduces rather well the double differential cross sections for secondary nucleons. The results presented indicate once again the important role of preequilibrium processes and show under which conditions their contribution can dominate. At the same time one should remember that the boundaries between the three considered mechanisms of the nuclear reaction, direct (cascade), prequilibrium, and equilibrium (compound nucleus), is highly conditional and relative. A further progress along this line is connected both with a more detailed and rigorous theoretical treatment of the problem and with the necessity of new precise measurements. In particular it is interesting to investigate the correlations between emitted particles; an example of successful use of such an approach is given by investigations of multiparticle production in collisions of high energy hadrons.

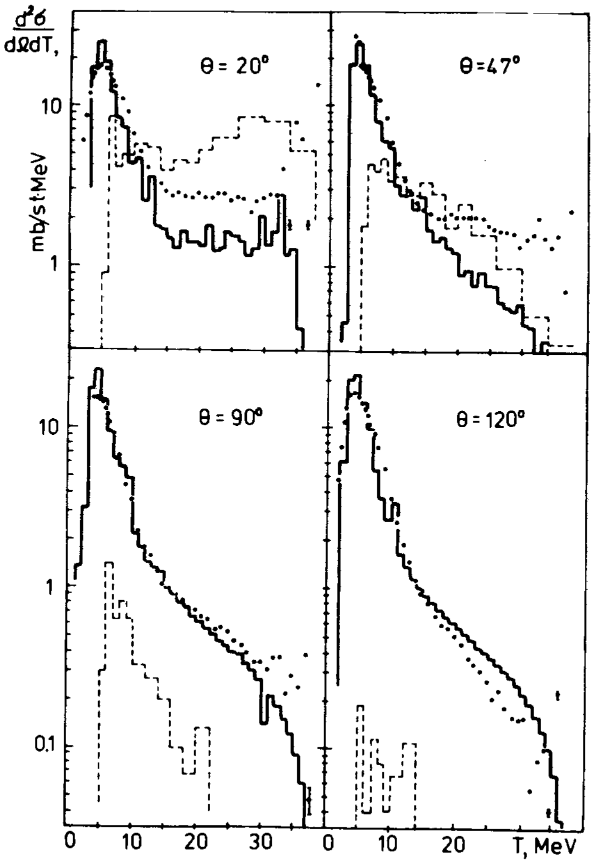

Fig. 7. The spectra of secondary protons emitted in the reaction $p + {}^{54}Fe \to p + \ldots$ *at angle* θ *at energy* $T_0 = 39$ *MeV. The solid histogram is our calculation, the dashed one is the calculation by Bertini et al. by the cascade-evaporation model /15/. Experimental points are from ref. /14/.*

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