Angular distribution of fast protons from the pre-equilibrium process of the ^{165}Ho(α,p) reaction

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(Received 18 December 1990)

The concept of the exciton model for nucleon-induced nuclear reactions has been extended to α-induced pre-equilibrium reactions in order to calculate angular distributions and energy spectra of fast ejectile nucleons. The effect of the nucleon motion on the cascade nucleon-nucleon scattering inside the nucleus and the geometrical optical effects at the exit channel are taken into account for the first time in the α-induced pre-equilibrium reaction. Angular distributions of protons from the ^{165}Ho(α,p) reaction at $E_{\alpha}=109$ MeV were calculated. The observed distributions of the fast protons in the pre-equilibrium region were found to be reproduced well by the calculation.

PACS number(s): 25.55.Hp

I. INTRODUCTION

Phenomenological models for pre-equilibrium nuclear reactions have been successfully applied to describe angle-integrated energy spectra of ejectile nucleons for nuclear reactions induced by light projectiles in the energy range of several tens of MeV [1]. Recently these models have been extended to calculate angular distributions of the ejectile nucleons [2–7]. Beside the quantum mechanical approach [6], the angular distributions have been studied in terms of the exciton model [2–5]. For light projectiles, the calculated values agree with the experimental data at forward angles, but the cross sections at backward angles are underpredicted often by as much as an order of magnitude. Inclusion of effects of refraction at the nuclear surface into the exciton model does not much improve fits with the experimental data.

Multiple nucleon-nucleon scattering kinematics inside the nucleus are calculated in order to obtain angular distributions. Here the Fermi motion of target nucleons affects the angular distribution. The Fermi motion, however, has been either completely neglected [2,3,7] or only the ground-state Fermi motion has been taken into account [4,5] in most of the exciton model calculations so far. For nucleons emitted backward it is important to take into account not only the first collision but also the second collision and so on. Thereby the target nucleons are in the ground state at the first collision, but they are in excited states at the second collision and so on. Then it is more realistic to use the Fermi motion of nucleons in excited states for the second collision and so on, as pointed out by De *et al.* [8,9]. They have extended the work of nucleon-nucleon scattering kinematics [10] to the case of the excited nuclear system by taking into account the Fermi motion of the nucleon in the excited nucleus and the Pauli blocking effect there. Their calculations for angular distributions of the ejectile nucleons improve the fits with the experimental data for nucleon-induced reactions [8,11,12].

The purpose of the present work is to calculate angular distributions of fast particles emitted in medium energy (≈ 100 MeV) α-induced pre-equilibrium reactions. There are three types of reaction processes, the direct, the pre-equilibrium, and the equilibrium processes. The present work is concerned with fast nucleons emitted in the pre-equilibrium process. These nucleons show continuum spectra. Calculations for angular distributions of such nucleons emitted from reactions induced by complex projectiles such as α particles are scarce. Existing works on α-induced reactions are limited to the case where the projectile energy is so low that the reaction proceeds mainly through the equilibrium process [2,7]. Important processes producing fast particles for the reaction induced by medium energy (≈ 100 MeV) complex projectiles are the direct break-up process [13–15] and the pre-equilibrium decay of highly excited nuclei. Contribution of the break-up process is limited to the forward angles ($\geq 30°$). The pre-equilibrium process plays an important role for fast particles in a rather wide angular range. In the present work angular distributions of fast nucleons from the medium energy α-particle-induced reaction are studied in a wide angular range in order to see contributions of the pre-equilibrium process.

The exciton model approach used for nucleon projectiles (proton or neutron) [8,12] is modified so as to be used for the α projectile. Refraction effects at the nuclear surface are taken into account at the exit channel only. In Sec. II we will discuss the formulation for calculating angular distributions of ejectiles from α-induced pre-equilibrium nuclear reactions. In Sec. III a method to take into account the effect of the excited nucleus is given. In Sec. IV calculated results for the ^{165}Ho(α,p) reaction at $E_{\alpha}=109$ MeV are compared with the experimental data for ejectile protons in the pre-equilibrium region [16]. Conclusions are given in Sec. V.

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II. FORMULATION FOR ANGULAR DISTRIBUTION OF EJECTILE

The double differential cross section for the particle of type x in the framework of the exciton model is expressed as [8,12]

$$\sigma_x(\varepsilon,\Omega)=\sigma_a\sum_{N=1}^{\bar{N}}P_N^x(\varepsilon,\Omega)\ , \tag{1}$$

$$P_N^x(\varepsilon,\Omega)=D_N f_N^x P_N(\varepsilon,\Omega)\frac{\lambda_c^N}{\lambda_c^N+\lambda^N}\ . \tag{2}$$

Equations (1) and (2) are the reformulation of Blann's hybrid model [17] as described in Ref. [12]. $P_N^x(\varepsilon,\Omega)d\varepsilon\, d\Omega$ is the probability that the x-type particle is emitted at the Nth nucleon-nucleon collision step in the energy interval between ε and $\varepsilon+d\varepsilon$ and in the direction between the solid angle Ω and $\Omega+d\Omega$. $\bar{N}$ is the average number of collisions needed for reaching the thermal equilibrium configuration of the composite nuclear system. Summation is carried over all possible steps (N) of the collision until N reaches to $\bar{N}$. σ_a is the absorption cross section of the projectile for the target nucleus. D_N is the probability that no particles are emitted before the Nth collision step. f_N^x is the number of excited x-type nucleons in the composite nuclear system at the Nth collision step. $P_N(\varepsilon,\Omega)$ is the probability that a nucleon with energy ε is emitted outside the nucleus toward the direction Ω at the Nth collision step. The emission probability is given by $\lambda_c^N/(\lambda_c^N+\lambda^N)$, where λ^N and λ_c^N are the intranuclear transition rate and emission rate, respectively, for x-type particle with energy ε at the Nth collision step. The probability $P_N(\varepsilon,\Omega)$ is rewritten in terms of the energy E and direction ω of the ejectile inside the nucleus as

$$P_N(\varepsilon,\Omega)d\varepsilon\, d\Omega=P_N(E,\omega)dE\, d\omega\ . \tag{3}$$

Here the surface effect of the refraction at the exit channel is neglected. This relation is somewhat modified [8,11,12] by the surface effect. The recursion relation used for finding out $P_N(E,\omega)$ is

$$P_{N\geq 2}(E,\omega)=\int P_{N-1}(E',\omega')P(E',\omega'\rightarrow E,\omega)dE'd\omega'\ , \tag{4}$$

where the single scattering probability $P(E',\omega'\rightarrow E,\omega)$ transforms the initial configuration (E',ω') to the scattered configuration (E,ω) by any one of the three transition modes, i.e., $n\rightarrow n+2$, $n\rightarrow n$, and $n\rightarrow n-2$, where n is the number of excitons. The single transition probability can be expressed in terms of the initial momentum vector $\mathbf{k}_i$ and the final one $\mathbf{k}$ as [10]

$$P(\mathbf{k}_i\rightarrow\mathbf{k})d\mathbf{k}=\frac{4d\mathbf{k}}{k_i}\int\delta(k_r'^2-k_r^2)P(\mathbf{k}_r,\mathbf{k}_r')P_N(\mathbf{k}_t)d\mathbf{k}_t\ . \tag{5}$$

The first term inside the integration ensures energy and momentum conservation. $P(\mathbf{k}_r,\mathbf{k}_r')$ is the transition probability from the state with the relative momentum $\mathbf{k}_r$ to the state with the relative momentum $\mathbf{k}_r'$ after the nucleon-nucleon collision. $P_N(\mathbf{k}_t)d\mathbf{k}_t$ is the momentum distribution of the target nucleon at the Nth collision step. Considering various limits on $\mathbf{k}_t$ and $\mathbf{k}$, we can include the different transition modes [9]. An analytical solution for $P(\mathbf{k}_i\rightarrow\mathbf{k})$ has been given by Kikuchi and Kawai [10] for the Fermi distribution of the target nucleon in the ground state (i.e., zero temperature) as used in various works [4,5]. $P(\mathbf{k}_i\rightarrow\mathbf{k})$ for the excited nuclear system has been obtained by De *et al.* [9].

Angular distributions of ejectiles in the case of α-induced pre-equilibrium reactions are calculated by modifying the procedure [12] so as to be used for the α projectiles. The important factor in this approach is to find out $P_N(\varepsilon,\Omega)$, the probability of having an ejectile with energy between ε and $\varepsilon+d\varepsilon$ in the direction between Ω and $\Omega+d\Omega$. In obtaining this factor through the recursion relation (4) the most crucial factor is $P_{N=1}(E,\Omega)$. In the case of neutron- or proton-induced nuclear reactions all the target nucleons at the initial stage before the first nucleon-nucleon collision are below the Fermi sea, and only one particle, i.e., the projectile, is above the Fermi sea with the excitation energy E_c. Thus in finding out the momentum distribution function after $N=1$, only the single nucleon-nucleon scattering is considered. On the other hand, the initial configuration of nucleons is quite different in the case of α-induced nuclear reactions because the projectile is a composite system of four nucleons.

In the present work we assume the following: (i) the projectile (α particle) breaks up into four nucleons, two being protons and the other two being neutrons, at the nuclear surface under the influence of the target nuclear field; (ii) the nuclear refraction effect at the entrance channel is neglected because the α energy is quite high. The initial nucleons after the break up are assumed to move along the same direction as the α beam. The excitation energy is assumed to be distributed among initial four particles. The probability of the energy distribution is assumed to be proportional to the product of the single-particle level density and the partial level density [18].

We consider the case that one of the projectile nucleons interacts with one of the target nucleons. Then we get

$$P_{N=1}(E,\omega)=\int P(E_1)P(E_1\omega_1\rightarrow E,\omega)dE_1\ . \tag{6}$$

Here $P(E_1)dE_1$, the probability of having initially a particle with energy between E_1 and E_1+dE_1 inside the composite nuclear system, is given by [18]

$$p(E_1)dE_1=\frac{\rho_3(E_c-E_1+E_0)}{\rho_4(E_c)}g\, dE_1\ , \tag{7}$$

where g is the single-particle level density. $\rho_3(E_c-E_1+E_0)$ is the partial level density for three particles ($n=3$) being at the residual excitation $U=E_c-E_1+E_0$ and $\rho_4(E_c)$ is the partial level density for four particles ($n=4$) being at the excitation energy E_c. Here $\rho_3(E_c-E_1+E_0)$ corresponds to the number of possible ways of the energy distribution that the three particles have the remaining excitation energy U and the fourth particle has the excitation energy between E_1 and E_1+dE_1. With the consideration of the abovementioned concept of $P(E_1)dE_1$, $P_{N=1}(E,\omega)$ in (6) can be solved by performing the integration over E_1. The limit of integration is obviously from E_0 to E_0+E_c, where E_0 is the Fermi energy. For the first collision ($N=1$) we consider the zero-temperature Fermi distribution for the target nucleon motion. After the first collision (i.e., $N\geq 2$) the Fermi distribution of the excited composite nuclear system is taken into account [8,11,12]. Thus, $P_N(E,\omega)$ and hence also $\sigma(\varepsilon,\Omega)$ can be solved by using Eqs. (4), (3), (2), and (1).

In the case of α projectiles effects of the nuclear optical potential at the nuclear surface are considered in the following ways: At the initial state of the nuclear reaction we consider the situation having four excited nucleons with energy distribution given by Eq. (7). The momentum distribution of the four initial nucleons depends on the break-up mechanism of the incident α particle in the target nuclear field. In fact the energies of break-up particles are quite large for the medium energy (≈ 100 MeV) α projectile and the refraction effect gets less prominent with the increase of the particle energy. Thus the refraction effect of the projectile at the entrance channel is not quite important. For simplicity we neglect the surface effect at the entrance channel. On the other hand, effects of the optical potential at the exit channel for ejectiles with relatively low energy are important. Therefore, we have taken it into account using the procedure cited in the work [8,11,12]

For the α-induced reaction f_N [8,12] is modified to

$$f_N^x=\sum_{n=n_0}^{2N+4} P_n^N p_n F_n^x \ , \tag{8}$$

where P_n^N is the probability of occurrence of the n-exciton state at the Nth collision step. p_n is the total number of excited particles in the n-exciton state and F_n^x is the probability of getting the x-type excited particle in the n-exciton state. The initial exciton number is taken as $n_0=6$ since one excited particle and one hole are created by the α-target interaction, which leads to the α break up, in addition to the four initial particles inside the composite nuclear system. In successive collision, the state at the Nth collision can be expressed as an admixture of different exciton states ($n\leq 2N+4$). The detail of the way to obtain the factor P_n^N has been discussed in Ref. [9]. In the present type of reaction the value of F_n^X is assumed to be $\frac{1}{2}$ all through the nuclear cascade process because the existence of neutron and proton probabilities are the same as the initial stage for the α-induced reaction. D_N is given by

$$D_N=\prod_{N'=1}^{N-1}\left[1-\sum_x \int P_{N'}^x(\varepsilon,\Omega)d\varepsilon\, d\Omega\right] . \tag{9}$$

Detailed discussions on this work have been given in an earlier report [19].

III. EFFECT OF NUCLEONS IN THE EXCITED STATE

One may use the Fermi distribution with a finite temperature to describe the Fermi motion of nucleons in the excited state in the equilibrium stage. The Fermi distribution is given by

$$P(\mathbf{k}_t)d\mathbf{k}_t=\frac{3}{4\pi k_0^3}\frac{d\mathbf{k}_t}{1+\exp[\beta(k_t^2-k_\mu^2)/2m]} . \tag{10}$$

Here $k_\mu^2=2m\mu$, μ is the chemical potential of the excited nucleus, m is the nucleon mass, and K_0 is the Fermi momentum at zero nuclear temperature. β can be expressed in terms of the excitation energy E and the number of degrees of freedom sharing the energy E. For collisions with $N\geq 2$,

$$\beta=\frac{1}{T_N}=\frac{dS_N}{dE}=\frac{d}{dE}\left[\ln\rho_N(E)\right] . \tag{11}$$

Fast particles emitted in the pre-equilibrium process are those emitted in the early stage of the reaction where the sum of the number of excited particles and the number of holes, i.e., the exciton number n, is much smaller than that of the equilibrium state. The temperature (T_N) of the state with small n is high [see Eq. (11)]. Therefore the early stage of the reaction has large T_N and small n. This situation is opposite to the normal case of the Fermi distribution where the number of excitons becomes large as the temperature increases. Therefore the state involved in the pre-equilibrium particle emission cannot be described by the Fermi distribution with a conventional temperature.

In the early stage of the reaction where fast particles are emitted at the pre-equilibrium stage, the excitation energy is shared among a small number of particles and holes. The excitation energy spreads to the whole nucleus through the nucleon-nucleon collision; finally the system reaches the equilibrium state. Thus at the pre-equilibrium stage, the small part of the nucleus has the whole excitation energy and the rest remains in the ground state. Consequently, the temperature of the former is high, while that of the latter remains zero. At the equilibrium stage the excitation energy spreads to the whole nucleus; thus the temperature is low. Therefore one may simulate the pre-equilibrium stage by a complex system of two parts, one at high temperature and the other at zero temperature. In successive collision, an excited particle collides with nucleons in either the high- or the zero-temperature part. Thus pre-equilibrium particle emission at the Nth collision step can be given by the sum of particle emissions after the $(N-1)$th collision with nucleons at high- and zero-temperature parts of the nucleus as

$$\frac{d\sigma_N}{dE\,d\Omega}=\xi_N\frac{d\sigma_N}{dE\,d\Omega}(T=T_N)+(1-\xi_N)\frac{d\sigma_N}{dE\,d\Omega}(T=0) , \tag{12}$$

where the first term of the right-hand side gives the particle emission after the collision with nucleons in the high-temperature part and the second term gives that in the zero-temperature part. The value ξ_N stands for the probability that nucleons are in the high-temperature part. It can be estimated as follows. The number of excited particles N_{ex} above the Fermi momentum for the Fermi distribution $F(k,T_N)$ with temperature T_N is given by

$$N_{ex}=c_0\int_{k_0}^{k_M}F(k,T_N)k^2dk \ , \tag{13}$$

where k_0 is the Fermi momentum at zero temperature and k_M is the maximum momentum of the nucleon in the excited state with the temperature T_N. The total number of nucleons in the high-temperature part (the system with T_N) is given by

$$N_{tot}=c_0\int_{0}^{k_M}F(k,T_N)k^2dk \ . \tag{14}$$

The number of excited particles N_{ex} is equal to the total number of exciton particles p_N at the Nth collision step. Then N_{tot} is obtained from Eqs. (13) and (14) as

$$N_{tot}=p_N\int_{0}^{k_M}F(k,T_N)k^2dk \Big/ \int_{k_0}^{k_M}F(k,T_N)k^2dk \ . \tag{15}$$

Then the probability ξ_N is given by

$$\xi_N=N_{tot}/A \ , \tag{16}$$

where A is the mass number of the nucleus.

IV. RESULT OF CALCULATION

The experimental data of the ^{165}Ho(α,p) reaction at $E_\alpha=109$ MeV are available from the measurements of the Osaka University group [16]. We discuss mainly the high energy part of the proton spectrum. Thus multiparticle emissions, which contribute mainly to the low energy part, are not taken into account in the present calculation. In the course of the intranuclear cascade λ_c^N and λ^N depend in principle on the collision number N as well as on the particle energy ε. However, λ_c^N and λ^N, as functions of N and ε, are not well known. Thus we use λ_c^N and λ^N given in Ref. [17]. The parameter $\kappa=3.5$ in λ^N is used as stated in Ref. [12]. To find out the inverse cross section $\sigma_{inv}(\varepsilon)$ we use the MAGALI program [20]. The optical model parameters used in the program are taken from Perey and Perey [21]. The value of σ_a is taken to be 1.7 b so as to be consistent with data of (α,p), (α,n), (α,pn), and (α,$2n$) reactions [16]. The value of single-particle level density parameter g is evaluated from $6a/\pi^2$ using the a-parameter table of Chatterjee *et al.* [22]. Final calculations for the angular distribution and the energy spectrum of fast nucleons are performed with the computer code PROJECT [23].

The distribution function $P(E_1)$ vs E_1 using expression (7) is shown in Fig. 1. To see the effect of the excited nuclear system, calculations were made for both $T_N>0$ and $T_N=0$ by using the Fermi motion given by Eq. (10), which corresponds to the case of $\xi_N=1$ and $\xi_N=0$ in Eq. (12), respectively. The angular distributions for three proton groups of $\varepsilon=20$, 40, and 60 MeV following the ^{165}Ho(α,p) reaction at $E_\alpha=100$ MeV are calculated. The results are shown in Fig. 2 (a) with inclusion of optical

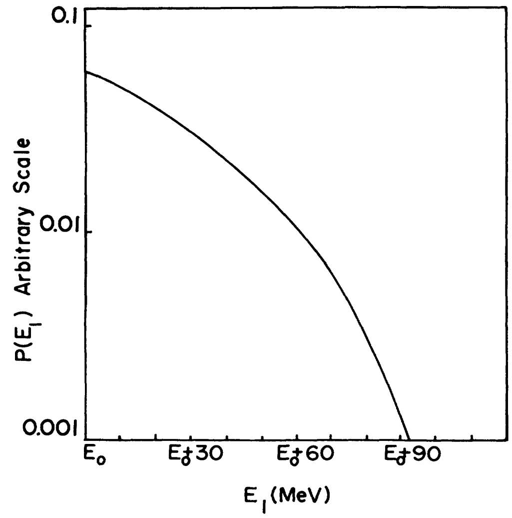

FIG. 1. Distribution function $P(E_1)dE_1$ vs E_1 using the relation (7) (see text). $P(E_1)dE_1$ is the probability of having a particle with energy lying between E_1 and E_1+dE_1 inside the composite nuclear system initially. Excitation of the composite system is produced by the reaction ^{165}Ho+α at $E_\alpha=109$ MeV. $E_0=33$ MeV, the Fermi energy, corresponds to a nuclear radius of approximately $1.2\times A^{1/3}$ fm.

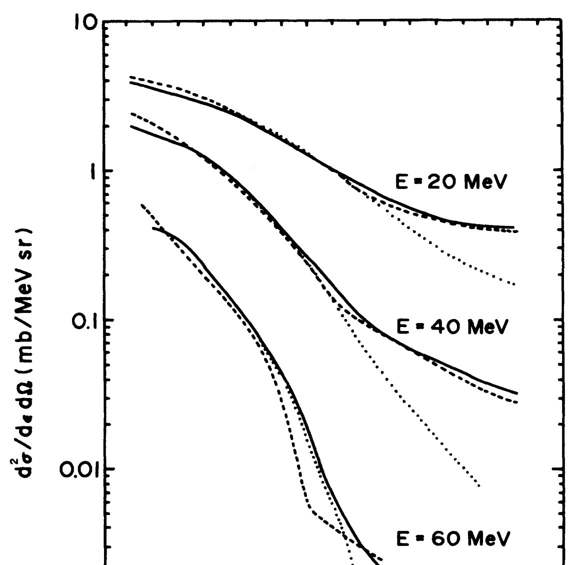

FIG. 2. Calculated angular distributions for protons from the ^{165}Ho(α,p) reaction at $E_\alpha=109$ MeV. The distributions for protons with energies $\varepsilon=20$, 40, and 60 MeV are shown. The dashed lines are calculations with the excitation effects included but without the optical effects. The dotted lines are calculations with the optical effects included but neglecting the excitation effects of the composite system. Calculations represented by the full lines include both the nuclear excitation and the surface optical effects.

effects for emitted particles and using $T_N > 0$ for $N \geq 2$ (shown by full lines), (b) without the optical effects at the surface and considering $T_N > 0$ for collision number $N \geq 2$ (shown by dashed lines), and (c) with the inclusion of optical effects but using $T_N = 0$ for all collision number N (shown by dotted lines).

The angular distribution of pre-equilibrium particles is given by the sum of the contribution from the high-temperature part of the nucleus and that from the zero-temperature part of it, as mentioned in the previous section. The weighting factor ξ_N changes step by step because the number of excitons increases every step. We, however, calculate the angular distribution by summing up two terms using, for simplicity, an effective weighting factor ξ for all through collision processes as

$$\frac{d\sigma}{dE\,d\Omega} = \xi \frac{d\sigma}{dE\,d\Omega}(T=\text{finite}) + (1-\xi)\frac{d\sigma}{dE\,d\Omega}(T=0) \;. \tag{17}$$

Here the first term is the angular distribution calculated by using $T_N = 0$ for $N = 1$ and $T_N > 0$ for all steps with $N \geq 2$ (full lines in Fig. 2) and the second term is calculated by using $T_N = 0$ for all collision steps with $N \geq 1$ (dotted lines in Fig. 2). The weighting factor ξ is estimated as follows. As was discussed in Ref. [16], the escape probability for the initial stage of the ^{165}Ho(α, X) reaction at

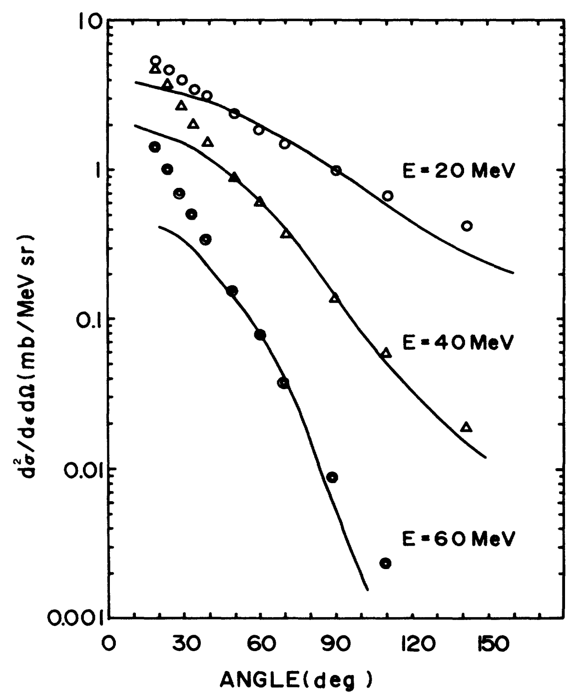

FIG. 3. Calculated angular distributions give by the sum of contributions from both high- and zero-temperature parts of the nucleus. The weighting factor in Eq. (17) of $\xi = 0.14$ is used. Experimental data are taken from Ref. [16].

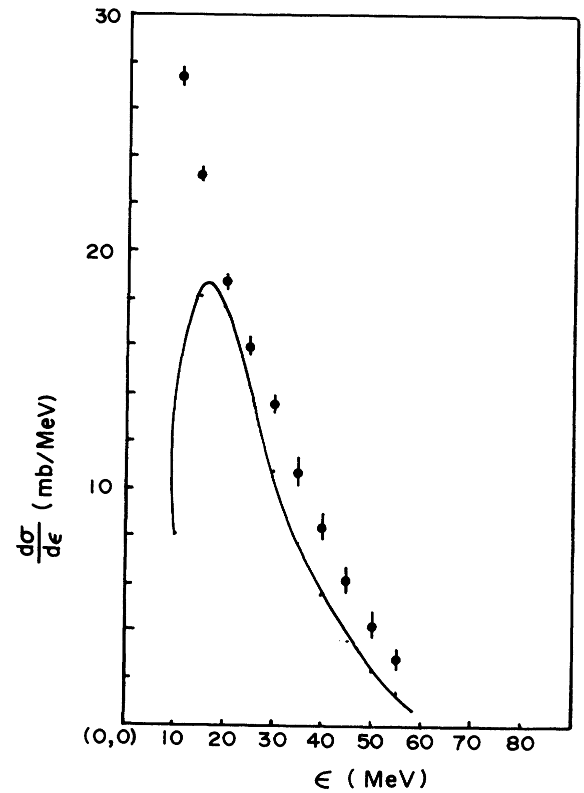

FIG. 4. Angle-integrated energy spectrum for protons from the ^{165}Ho(α, p) reaction at $E_\alpha = 109$ MeV. Full line represents present calculation. Data are taken from Ref. [16].

$E_\alpha = 109$ MeV is about 30% and it decreases as the exciton number increases. Since the sum of the escape probabilities of the first three exciton states is equal to the sum of all states after the fourth exciton state for the pre-equilibrium particle emission, we used the value (ξ_3) of the third exciton state as ξ in Eq. (17) which is calculated to be $\xi = 0.14$. Calculated results are compared with experimental angular distributions in Fig. 3.

It is remarkable to find that calculated angular distributions reproduce gross features of the observed distributions. Calculated values at the forward direction, however, are smaller than the observed ones and the discrepancy increases with the increase of the proton energy. Protons at very forward angles, particularly those with the highest energy of $\varepsilon = 60$ MeV, are considered to be mainly due to the first collision, i.e., the direct process. Some of them may not go into the nucleus to proceed to the intranuclear cascade process but go directly outside the nucleus. Such direct protons contribute to the excess at the forward angles. The calculated energy spectrum is compared with the experimental data in Fig. 4. The calculated value reproduces the major part of the spectrum except for excesses at the high and low energy regions. The main contributions at higher proton energies especially in the extreme forward direction are considered to be due to the direct process. The low energy side of the proton spectrum ($\varepsilon < 20$ MeV) is considered to include the multiparticle emission in both equilibrium and pre-equilibrium processes.

V. CONCLUSIONS

In this work we have extended the exciton model approach of the nucleon-induced reactions [8,11,12] to the α-induced reaction to calculate the double differential cross section of emitted nucleons. The pre-equilibrium contributions are evaluated for the energy spectrum and angular distributions of emitted particles. In comparison with the existing works in this field [2,7] we have included in the present work excited nucleon's motion in successive nucleon-nucleon collisions and optical effects at the nuclear surface for the exit channel.

The calculations reproduce gross features of the observed angular distributions and the angle-integrated energy spectrum for fast protons from the ^{165}Ho(α,p) reaction at $E_\alpha = 109$ MeV. It should be noted here that there is no free parameter to adjust in the present pre-equilibrium calculation. Some parts of the data are not reproduced by the present analysis. They may reflect effects of the direct process and the multiparticle emission process, which are not taken into account in this present analysis of the pre-equilibrium process.

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