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A SEMI-CLASSICAL MODEL FOR THE DESCRIPTION OF ANGULAR DISTRIBUTION OF LIGHT PARTICLES EMITTED IN NUCLEAR REACTIONS

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A Semi-classical Model for the Description of Angular Distribution of Light Particles Emitted in Nuclear Reactions

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A semi-classical model of multi-step direct and compound nuclear reactions has been proposed to describe the angular distributions of light particles emitted in reaction processes induced by nucleons with energies of several tens of MeV. The exact closed solution fo the time-dependent master equation of the exciton model is applied. Based on the Fermi gas model, the scattering kernel for two-nucleon collisions includes the influence of the Fermi motion and the Pauli exclusion principle, which give a significant improvement in the description of the rise of the backward distributions. The angle-energy correlation for the first few steps of the collision process (multi-step direct process) yields further improvements in the description of the angular distribution. The pick-up mechanism is employed to describe the composite particle emission. This reasonable physical picture reproduces the experimental data of the energy spectra of composite particles satisfactorily. The angular distribution of the emitted composite particles is determined by an angular factor in terms of the momentum conservation of the nucleons forming the composite cluster. The generalized master equation is employed for the mulit-step compound process. Thus a classical approach has been established to calculate the double differential cross sections for all kinds of particles emitted in multi-step nuclear reaction processes.

1. Introduction

In recent years pre-equilibrium nuclear reaction theories have been developed with great success for the description of the angular distribution of emitted particles based on the exciton model. This success was mainly due to the introduction of a leading particle into the generalized exciton model [1] and application of the pick-up mechanism for composite particle emission[2-4] The influence of Fermi motion and the Pauli exclusion principle have been taken into account based on the Fermi gas model [5].

The most significant improvement is the rise of the double differential cross section at backward angles for the higher energy emitted particle in a multi-compound reaction process. The consideration of the angle-energy correlation was restricted to the first collision by Costa [6] and subsequently extended to higher steps by Iwamoto and Harada [7] in the never-come-back aproximation. By means of the semi-classical multi-direct aproach mentioned above, the pre-equilibrium theories are quite good in reproducing the experimental data of double differential cross sections for the emission of nucleons from nucleon induced reactions at indident energies of several tens of MeV. The comprehensive description for a multi-step nuclear reaction including the multi-step direct process and the multi-step compound process has been proposed by Wen et al.[8] On the basis of the success in the description of the angular distribution of the single particle emission process and the pick-up emission mechanism for composite particles a method for the calculation of double differential cross sections for the emission of composite particles has been proposed [9]. The basic idea is that the leading particle may be emitted alone (single nucleon emission) or may pick up some nucleons in the compound nucleus (composite particle emission). Based on the momentum conservation, the direction of the emitted composite particle could be determined by the vector summation over the momenta of the nucleons forming the cluster.

Section 2 is devoted to the description of the angular distributions of single particle emission processes. The description of the pick-up mechanism is given in section 3. The method to calculate the angular distributions of composite particles is introduced in section 4. In the last section some further improvements are suggested.

2. Angular distribution of emitted single particles

The generalized master equation takes the form:

$$\frac{dq(n,\Omega,\varepsilon,t)}{dt} = \sum_m \int d\Omega' \int d\varepsilon' q(m,\Omega',\varepsilon',t) W_{m\to n}(\Omega'\varepsilon' \to \Omega\varepsilon)$$

$$- \left\{ \sum_m \int d\Omega' \int d\varepsilon' W_{n\to m}(\Omega\varepsilon \to \Omega'\varepsilon') + W_t(n) \right\} q(n,\Omega,\varepsilon,t) \tag{2.1}$$

with

$q(n,\Omega,\varepsilon,t)$= occupation probability of the composite system at time t in exciton state n with leading particle energy ε and direction Ω.

$W_{m\to n}(\Omega'\varepsilon' \to \Omega\varepsilon)$= the transition probability of the system per unit time from state $(m, \Omega', \varepsilon')$ to state (n, Ω, ε).

$W_t(n)$ = the total emission rate of the system in exciton state n.

We assumme $W_{m\to n}(\Omega'\varepsilon' \to \Omega\varepsilon)$ to be the product of two factors

$$W_{m\to n}(\Omega'\varepsilon' \to \Omega\varepsilon) = \lambda_{m-n}(n) G(\Omega'\varepsilon' \to \Omega\varepsilon). \tag{2.2}$$

The scattering kernel $G(\Omega'\varepsilon' \to \Omega\varepsilon)$ is the distribution probability of two-nucleon collisions from state (Ω', ε') to the state (Ω, ε) inside the nuclear matter which is independent of the exciton number.

$$G(\Omega'\varepsilon' \to \Omega\varepsilon) = G(\Omega\varepsilon \to \Omega'\varepsilon') = \frac{1}{\bar{\sigma}} \frac{d^2\sigma}{d\Omega' d\varepsilon'} \tag{2.3}$$

with

$$\bar{\sigma} = \iint d\Omega' d\varepsilon' \frac{d^2\sigma}{d\Omega' d\varepsilon'}. \tag{2.4}$$

All of the dynamical information on the angular distribution and angle-energy correlation is contained in $G(\Omega'\varepsilon' \to \Omega\varepsilon)$. To consider the influence of the Fermi motion and the Pauli principle the double differential cross section of nucleon-nucleon interactions in nuclear matter can be found in Ref.[10]. In the exciton model, the intranuclear transition rate is only possible for m-n=0,±2.

The solution of the eq. (2.1) can be obtained in the form of a partial wave expansion [11]:

$$q(n,\Omega,\mathcal{E},t)=\sum_{\ell}\eta_{\ell}(n,\mathcal{E},t)P_{\ell}(\cos\theta) \tag{2.5}$$

and

$$\int G(\Omega'\mathcal{E}'\to\Omega\mathcal{E})P_{\ell}(\cos\theta')d\Omega'=\mu_{\ell}(\mathcal{E}',\mathcal{E})P_{\ell}(\cos\theta). \tag{2.6}$$

Introducing the partial wave lifetime

$$\zeta_{\ell}(n,\mathcal{E})=\int_0^{\infty}dt\,\eta_{\ell}(n,\mathcal{E},t), \tag{2.7}$$

related to the lifetime of state n by

$$\tau(n,\Omega,\mathcal{E})=\int_0^{\infty}dt\,q(n,\Omega,\mathcal{E},t)=\sum_{\ell}\zeta_{\ell}(n,\mathcal{E})P_{\ell}(\cos\theta) \tag{2.8}$$

and

$$\tau(n,\mathcal{E})=\int\tau(n,\Omega,\mathcal{E})d\Omega=4\pi\zeta_0(n,\mathcal{E}). \tag{2.9}$$

In the multi-step direct process under the " never-come-back " assumption the solution of the partial wave lifetime equation is given by

$$\zeta_{\ell}(n,\mathcal{E})=\tau(n)\frac{2\ell+1}{4\pi}\int d\mathcal{E}_1\int d\mathcal{E}_2\cdots\int d\mathcal{E}_{(n+2-n_0)/2}\cdot$$

$$\cdot\mu_{\ell}(\mathcal{E},\mathcal{E}_1)\mu_{\ell}(\mathcal{E}_1,\mathcal{E}_2)\cdots\mu_{\ell}(\mathcal{E}_{(n+2-n_0)/2},\mathcal{E}) \tag{2.10}$$

here

$$\tau(n)=\frac{1}{\lambda_n^{+}+W_t(n)}\prod_{\substack{i=n_0\\ \Delta i=2}}^{n-2}\frac{\lambda_i^{+}}{\lambda_i^{+}+W_t(i)}. \tag{2.11}$$

The expression for $\mu_\ell(\mathcal{E},\mathcal{E}')$ is obtained as follows: [5],[8]

$$\mu(\mathcal{E},\mathcal{E}') = \frac{1}{\bar{\sigma}}\int d\Omega' \frac{d^2\sigma}{d\Omega' d\mathcal{E}'} P_\ell(\cos\theta'). \tag{2.12}$$

Since it is expected that the memory of the angle-energy correlation is gragually lost at more complicated stages, then the energy average kernel $G(\Omega \rightarrow \Omega')$ can be used for the description of the multi-step compound processes.
Thus the generalized master equation becomes

$$\frac{d\varrho(n,\Omega,t)}{dt} = \sum_m \int d\Omega' W_{m\to n}(\Omega'\to\Omega)\varrho(m,\Omega',t)$$

$$\left\{\sum_m \int d\Omega' W_{n\to m}(\Omega\to\Omega') + W_t(n)\right\}\varrho(n,\Omega,t). \tag{2.13}$$

The energy average kernel reads

$$G(\Omega,\Omega') = \frac{d\sigma(\Omega,\Omega')}{d\Omega'}\Big/\int \frac{d\sigma(\Omega,\Omega')}{d\Omega'}d\Omega',$$

$$\text{with} \quad \frac{d\sigma(\Omega,\Omega')}{d\Omega'} = \int \frac{d^2\sigma}{d\Omega' d\mathcal{E}'} d\mathcal{E}'. \tag{2.14}$$

Then an exact closed-form solution of the time-integrated master equation for the partial wave l is obtained [5] by

$$\mathfrak{J}_\ell(n) = \frac{2\ell+1}{4\pi}\tau_\ell(n)\mu_\ell F_n \prod_{\substack{i=n_0 \\ \Delta i=2}}^{n-2} \mu_\ell \lambda_i^{+} \tau_\ell(i) F_i \tag{2.15}$$

with $\quad F_n = \mu_\ell^2 \lambda_+(n)\lambda_-(n+2)\tau_\ell(n)\tau_\ell(n+2),$

$$\tau_\ell(n) = [\lambda_+(n)+\lambda_-(n)+(1-\mu_\ell)\lambda_0(n)+W(n)]^{-1},$$

and

$$t(n,\Omega) = \int_0^\infty dt\, \varrho(n,\Omega,t) = \sum_\ell \mathfrak{J}_\ell(n) P_\ell(\cos\theta). \tag{2.16}$$

In this case

$$\mu_\ell = \int_{E_f}^{\bar{E}} \mu_\ell(E,\mathcal{E}')d\mathcal{E}' \tag{2.17}$$

where E_f stands for the Fermi energy. The double differential cross section from the above-mentioned two approaches is then given by the following expression:

$$\frac{d^2\sigma}{d\Omega\, d\mathcal{E}} = \sigma_a \left\{ \sum_{\substack{n=n_0 \\ \Delta n=2}}^{N} \tau(n) W_b(n,\mathcal{E}) \frac{\tau(n,\Omega,\mathcal{E})}{\int \tau(n,\Omega,\mathcal{E}) d\Omega} + \sum_{\substack{n=N+2 \\ \Delta n=2}}^{\bar{n}} t(n,\Omega) W_b(n,\mathcal{E}) \right\}. \tag{2.18}$$

where σ_a is the absorption cross section calculated by the optical model. The formulation is inspired by the quantum-mechanical FKK theory [12] and could be viewed as a semi-classical approximation to this theory.

In order to gain physical insight, we look at the influence of the Fermi motion with and without the Pauli principle in comparison with the nucleon-nucleon collision (see Fig.1).

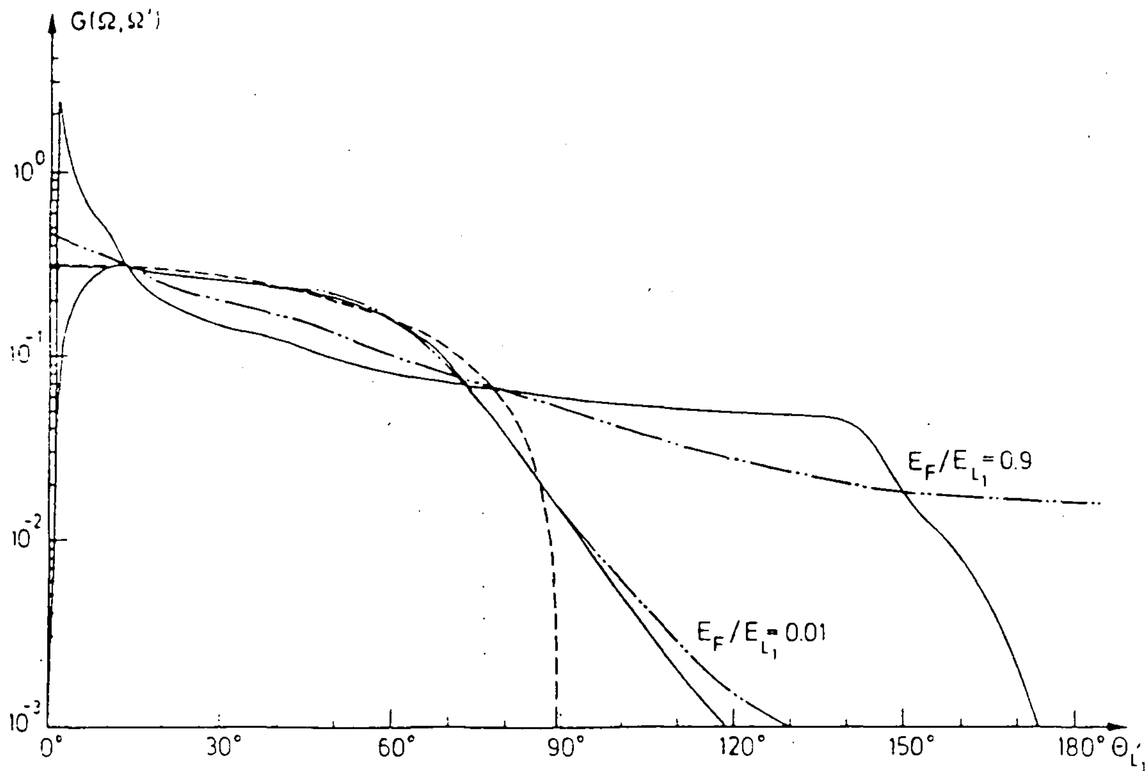


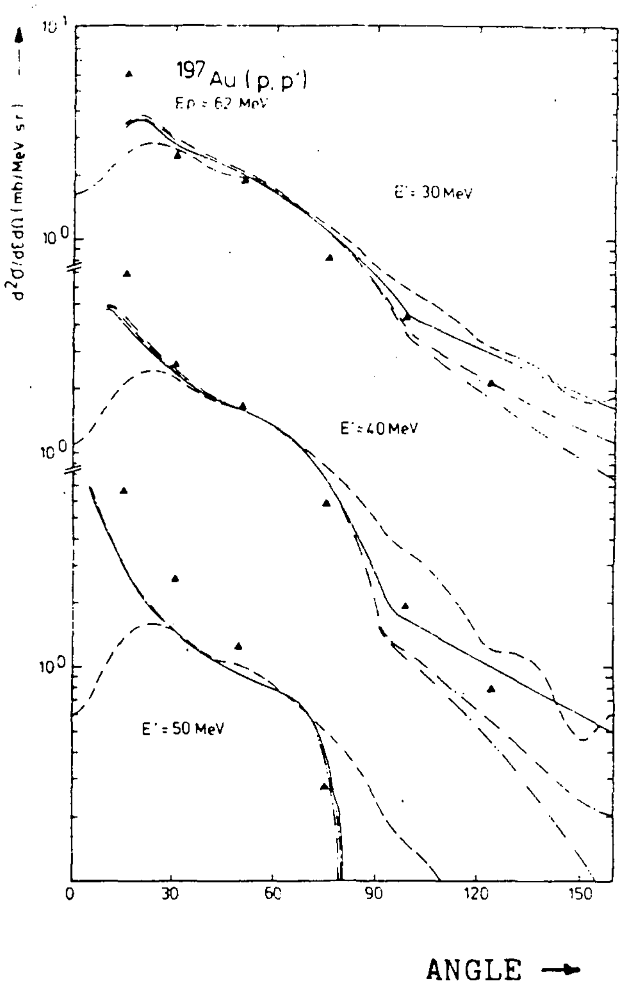
Fig.1. Variation of distribution probability $G(\Omega, \Omega')$ with incident energy E_{L1} ------ for free nucleon-nucleon collision. -·-·-·- for Fermi motion without Pauli principle. ——— for Fermi motion with Pauli principle

The results in Fig.1 show that the angular distribution rises significantly at backward angles due to the Fermi motion as for free nucleon-nucleon collisions no scattering larger than 90 can take place; such an effect is more pronounced as $E_{L1}=E_f+E^*$ becomes smaller. In addition to the Fermi motion the Pauli exclusion principle causes the angular distribution to rise at small angles near 0 , which means that only those nucleons close to the Fermi surface can be scattered with a small momentum transfer. When the incident energy E_{L1} increases the results approach the case of free nucleon-nucleon collisions, the influence of the Fermi motion and the Pauli principle becomes insignificant. This physical picture is intuitively reasonable.

To see the effect of the angle-energy correlation the double differential cross sections of the reaction ^{197}Au(p,p') with 62 MeV incident energy and the reaction ^{93}Nb(n,n') with 14.6 MeV energy are shown in Fig.2 and Fig.3,respectively. It is seen that the angle-energy correlation decreases the spectrum at larger angles. The restriction of the angle-energy correlation at 50 MeV outgoing energy to the first collision is quite sufficient for the Au(p,p') reaction, while at 30 MeV outgoing energy it would be better to take into account the correlation for the first two steps.

3. Formation and emission of light particles based on the pick-up mechanism

The formation facter $F^{b}_{\ell m}(\mathcal{E})$ for the light composite particle b in the compound nucleus has been proposed by Iwamoto and Harada [3]. The model contains two new points, one is the calculation of the formation factor $F^{b}_{\ell m}(\mathcal{E})$ which stands for the probability of formation of the composite particleb with outgoing energy composed of l particles above the Fermi surface and m particles below. The intrinsic wave function of the composite particle is taken to correspond to the ground state of an harmonic oscillator potential, The oscillator parameter $\hbar\omega$ is determined by the experimental "rms" radius of the particle b. The other point is the pick-up type configuration which



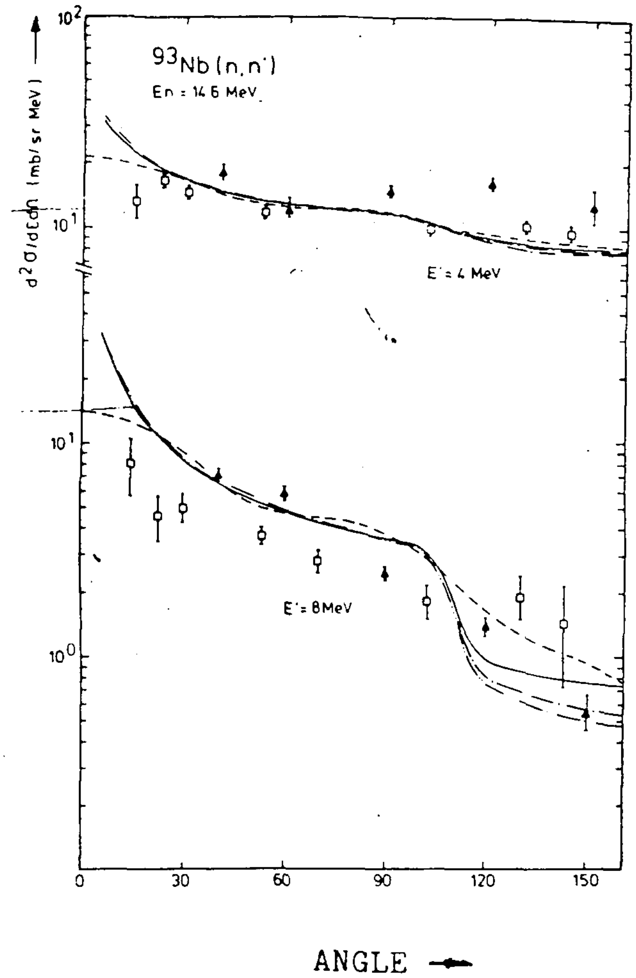


Fig.2. The double-differential cross sections as functions of the angle of outgoing nucleons for the reaction ^{197}Au(p,p'), calculated with the present model. The full curves represent the calculation taking into account the energy-angle correlation for only the first step, the single-dotted-dashed curves for the first two steps, and the double-dotted-dashed curves for the first three steps. The dashed curves are obtained from the model of [5] as a comparison.

Fig.3. The double-differential cross sections for the reaction ^{93}Nb (n,n'). The curves are the same as in Fig.2.

implies that the nucleons of the emitted particle b come from the levels below the Fermi surface.

The formation probability of the composite particle with A nucleons is proportional to the volume of the phase space of the configuration [l,m].

$$F_{lm}^{b}(\mathcal{E}) = \frac{1}{(2\pi\hbar)^{A_b-1}} \int_{\substack{[lm] \\ \vec{P}_b \text{ fixed}}} \prod_{i=1}^{A_b-1} d\vec{P}_i \, d\vec{X}_i \,, \tag{3.1}$$

Here the $\vec{P}i$ and $\vec{x}i$ are the relative momenta and the relative coordinates of the nucleons in the composite particle b. The configuration [l,m] yields the constraint condition:

$$|\vec{p}_j| > P_f \qquad \text{for } j=1,2,\ldots l$$

$$|\vec{p}_k| < P_f \qquad \text{for } k=l+1\ldots A_b \tag{3.2}$$

where P_f is the Fermi momentum.

For the energy conservation the physically observable energy $\mathcal{E}_b$ of the emittedcomposite particle is related to other quantities by

$$\mathcal{E}_b = \frac{P_b^2}{2mA_b} + \frac{3}{4}\hbar\omega_b(A_b-1) - A_bE_f - B_b. \tag{3.3}$$

where B_b is the binding energy of the particle b in the compound nucleus.

The procedure to carry out the integration of the eq.(3.1) and the explicit expression are quite complex. One can find them in Refs.[4] and [16]. The results of the formation probabilities for α, d, ^{3}He, t are shown in Fig.4. The spectrum of the reaction ^{54}Fe(n,α) with the incident energy 20 MeV is shown in Fig.5. The results indicate that the dominant pick-up component is from l=1,which corresponds to the three nucleon pick-up process. We believe that if the excitation energies are not so high, the pick-up type mechanism must be taken into account for composite particle emission processes.

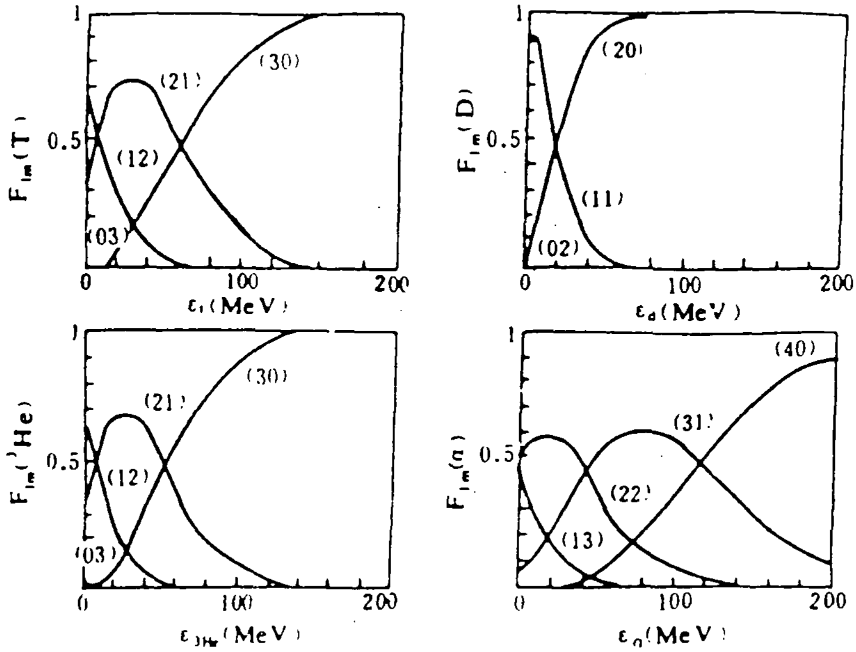


Fig.4 The normalized formation factor $F_{\ell m}$

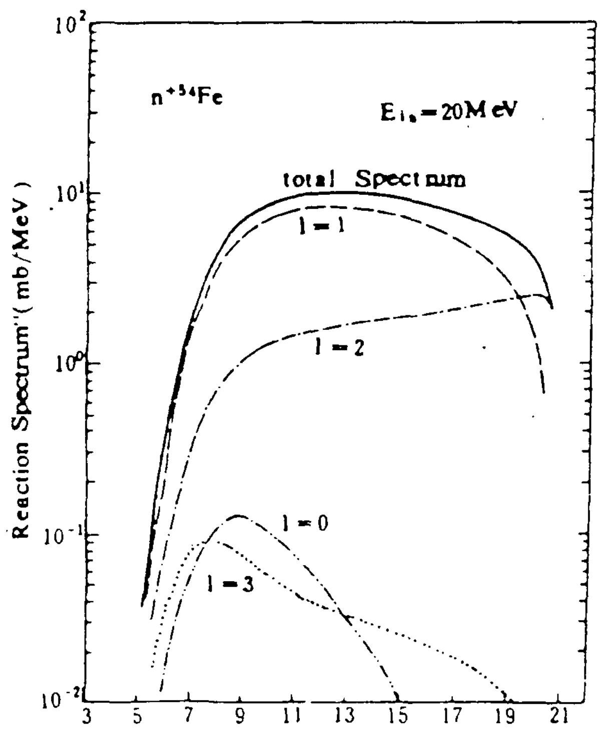


Fig.5 α-outgoing Energy(MeV)

4. Angular distribution of emitted composite particles

One can go one step further to develop the method to consider the angular distribution of emitted composite particles based on the approaches mentioned in section 2 and section 3. If the emitted leading particle pickes up some nuclions in the compound nucleus to form a projectile then the composite particle emission happens.

We denote the momentum distribution of the compound nucleus in the exciton state n with $D_n(\vec{p})$. According to the momentum conservation, the momentum of the outgoing composite particle is the vector summation over the momenta of the nucleons in the cluster. In this model the leading particle must be one of the nucleons of the emitted composite particle. To be consistent with the previous model, when integrating over the angle, one gets the spectra of the outgoing particle. A normalized angular factor is introduced:

$$A_{lm}(n,\Omega_b,\varepsilon_b)=\frac{1}{N_{lm}}\int d\vec{p}_1\ldots d\vec{p}_{A_b}\,\delta(\vec{p}_b-\sum_{i=1}^{A_b}\vec{p}_i)\prod_{j=2}^{A_b}D_n(\vec{p}_j)\tau(n,\Omega_1,\varepsilon_1),$$

$$\text{with}\qquad |\vec{p}_1|>P_f \text{ and } |\vec{p}_i|<P_f,\quad \text{for } i=2,A_b. \tag{4.1}$$

where $\tau(n,\Omega_1,\varepsilon_1)$ is the lifetime of the leading particle with energy ε_1 in the direction Ω_1. The δ function in eq. (4.1) implies the momentum conservation. The normalization condition says

$$\int A_{lm}(n,\Omega,\varepsilon)\ d\Omega=1. \tag{4.2}$$

With eq.(4.2) the normalization factor N_{lm} can be obtained. One can see that if the emitted particle b is a single particle then eq. (4.1) returns to the case mentioned in section 2. The angular factor now becomes:

$$A_{10}(n,\Omega,\varepsilon)=\frac{\tau(n,\Omega,\varepsilon)}{\int d\Omega\,\tau(n,\Omega,\varepsilon)}, \tag{4.3}$$

which is just the factor in eq. (2.18) for single particle emission.

If the excitation energies are not so high only the configuration [1,m] as the dominant part is taken into account. In this case the momentum distribution of the nucleons in the compound nucleus may be described by the Fermi gas model:

$$D_n(p) = \begin{cases} \dfrac{3}{4\pi P_f^3} & \text{for} \quad p < P_f \\ 0 & \text{for} \quad p > P_f \end{cases} \tag{4.4}$$

In this case the integration of eq. (4.1) can be carried out analytically. The explicit expressioin of the angular factor of the emitted particle can be obtained [9] in the partial wave expansion form:

$$A^b_{[lm]}(n,\Omega,\mathcal{E}) = \frac{1}{4\pi} \sum_l \frac{\mathfrak{Z}^b_l(n,\mathcal{E})}{\mathfrak{Z}^b_0(n,\mathcal{E})} P_l(\cos\theta). \tag{4.5}$$

and

$$\mathfrak{Z}^b_l(n,\mathcal{E}_b) = \int_{\max\{1,\, x_b-(A_b-1)\}}^{\sqrt{1+\mathcal{E}/\mathcal{E}_f}} dx_1\, x_1^2\, \mathfrak{Z}_l(n, x_1^2 \mathcal{E}_f) \int_{\frac{x_b^2+x_1^2-(A_b-1)}{2x_b x_1}}^{1} d(\cos\theta)\, P_l(\cos\theta)\, Z_b(Y). \tag{4.6}$$

where $\mathfrak{Z}_l$ is the partial wave lifetime (see eq.(2.7)), x_1 and x_b are the dimensionless momenta of the leading particle and the emitted particle, respectively.

$$x_1 = \frac{P_1}{P_f}, \qquad x_b = \frac{P_b}{P_f}, \tag{4.7}$$

$$Y = (x_b^2 + x_1^2 - 2x_b x_1 \cos\theta)^{1/2}, \tag{4.8}$$

and

$$x_b^2 = A_b^2 + A_b\left(\frac{\mathcal{E}_b + B_b}{E_f}\right) - \frac{3}{4} A_b(A_b-1) \frac{\hbar\omega_b}{E_f} \tag{4.9}$$

The geomentry factor Zb(Y) is expressed by

$$Zb(Y) = \begin{cases} 1 & \text{for } A_b=2 \\ (1 - \frac{1}{2}Y)^2 (4 + Y) & \text{for } A_b=3 \\ \dfrac{(3-Y)^4}{Y} [210 - 126(3-Y) + 21(3-Y)^2 - (3-Y)^3] & \text{for } A_b=4. \end{cases} \tag{4.10}$$

If the angle-energy correlation is not taken into account, then $\mathcal{J}_l$ is independent of energy which can be taken out of the integration of eq. (4.6). Therefore eq. (4.6) can be rewritten in the form:

$$\mathcal{J}_l^b(n, \varepsilon_b) = \mathcal{J}_l(n) R_l(\varepsilon_b) \tag{4.11}$$

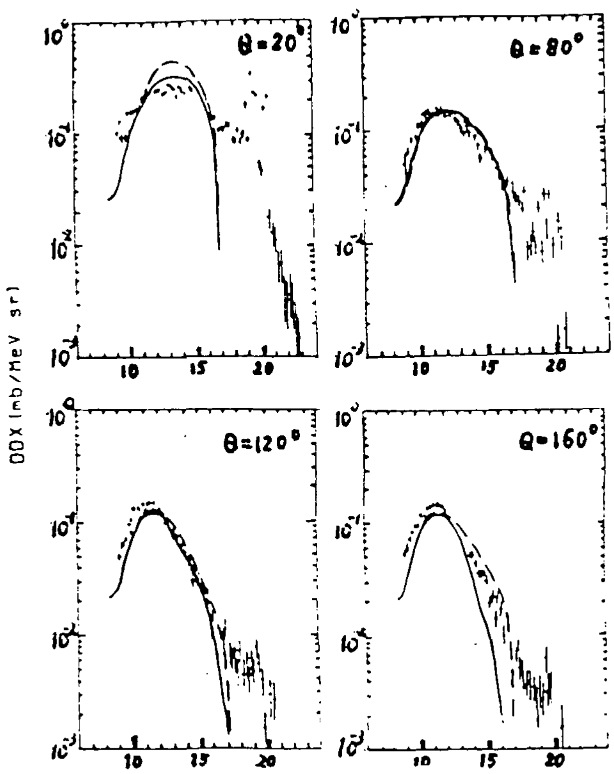
where $R_l(\varepsilon_b)$ is the residual part of eq.(4.6) except $\mathcal{J}_l$ (n). To see the influence of the pick-up process on the leading particle, the ratio of $R_l(\varepsilon_b)/R_0(\varepsilon_b)$ has been calculated for the reaction $^{99}Mo(p,b)$ b=d,t,^3He, α with the excitation energy E^*= 30 MeV. The results are shown in Tab.1 for outgoing energies of 10 MeV and 15 MeV. Since the nucleons below the Fermi surface have an isotropic mementum distribution, the pick-up mechanism may reduce the forward angular distribution of the leading particle.

Tab. 1 The ratio $R_l(\varepsilon_b)/R_0(\varepsilon_b)$ for reaction $^{99}Mo(p,b)$ with the excitation energy E^*=30 MeV and the outgoing energies 10, 15 MeV.

(MeV)	b	l=1	l=2	l=3	l=4
10	d	.986	.958	.917	.865
	^3He	.979	.937	.877	.802
	t	.969	.909	.824	.722
	α	.936	.818	.665	.500
15	d	.993	.978	.957	.929
	^3He	.985	.955	.912	.857
	t	.977	.928	.861	.777
	α	.943	.838	.699	.545

Thus the composite particle should counteract the forward tendency. The results in Tab 1 indicate this fact that the more nucleons are picked up the stronger is the counteraction effect. Meanwhile the counteraction effect increases with increasing partial wave number. In other words, the outgoing deuteron has a behaviour more similar to that of the leading particle while the outgoing α particle distribution becomes more isotropic.

The comparison of the calculated double differential cross section for $^{99}Mo(p,\alpha)$ with the experimental data [17] is shown in Fig. 6, where the discrete level part is not included. The solid lines correspond to the multi-step compound process while the dash lines correspond to consideration of the angle-energy correlation in the first step. Satisfactory fitting can be obtained in the continuum part.



ALPHA ENERGY (MeV)

Fig.6. Double differential cross sections (θ_{lab}=20°-160°) of particles from the $^{98}Mo(p,\alpha)$ reaction for 18 MeV protons.

5. Discussion

Based on the exciton model and the Fermi gas model, a semi-classical method to calculate the cross sections spectra as well as the double differential cross sections for nucleon induced nuclear reactions has ben proposed. The multi-step direct process and the multi-step compound process are taken into account properly. It seems that the present model rather nicely reproduces the experimental data in a broad range of incident energies from 10 MeV to several tens of MeV. The behaviour of the double differential cross section both in the forward-angle region and in the backward-angle region is in accordance with the experimental results due to the fact that the Fermi motion and Pauli exclusion principle are taken into account. The pick-up mechanism provides a way to treat the composite particle emission which yields a significant improvement over the previous method.

Strictly speaking, for the most energetic outgoing particle the present model still fails to provide very satisfactory results, where the collisions are kinematically for bidden in the semi-classical N-N kernel. In this case a complete quantum mechanical treatment might be necessary. On the other hand, in the theory isotropic N-N scattering in the C.M. system is assumed, but experimentally there is considerable forward-backward peaking over much of the energy range. Therefore the assumption of a more realistic N-N angular distribution might be useful in further work.

In the practical calculation one undetermined factor exists i.e. that the cut-off values of l might effect the calculated results considerably. The classical estimation of Lmax seems not good enough to account for the finite size of the nucleus. A possible improvement is to perform the local density approximation, i.e. each l corresponds to a different density, so that the finite size and the diffuseness of the surface can be more properly taken into account.

Since only the configuration [1,m] is included in the treatment of the pick-up process, this means that only the nucleons below the Fermi surface can be picked up. This approxximation is correct for low excitation energies. With the increasing incident energies, the particle-hole excitations become more complicated and the other configurations [l,m] might give contributions. In this case nucleons above the Fermi surface could be picked up. Recently a new approach to study the exciton model has been developed. That is the occupation number calculatioin [18] which is similar to be hybrid model [19], but in the frame of the exciton model. If the momentum and energy distribution of the excited nucleons in a compound nucleus are obtained, then any configuration [l,m] could be considered.

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