Pre-equilibrium particle decay in the photonuclear reactions*

J. R. Wu and C. C. Chang

Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

(Received 2 December 1976; revised manuscript received 5 August 1977)

Calculations of particle energy spectra resulting from the photonuclear reactions at energies below the meson production threshold have been carried out in the framework of combining the pre-equilibrium exciton model and the quasideuteron model. A 2p-2h initial state in the exciton model is assumed because the quasideuteron absorption is the dominant process in the energy region above giant resonance. With this combined model the subsequent secondary interactions of the emerging particle with the rest of the nucleus following the initial photon-nucleus interaction are appropriately taken into account. The experimental difference energy spectra of fast photoneutrons from several elements (Al, Cu, In, Sn, Ta, Pb, Bi, and U) at bremsstrahlung energies of 55 and 85 MeV were compared with the theoretical predictions. General agreements in both spectral shapes and cross sections are obtained. The relative yields of the reactions (γ,xn) resulting from monoenergetic photons on ^{127}I at 50, 100, and 150 MeV are also predicted reasonably well by the combined model together with the conventional evaporation theory.

NUCLEAR REACTIONS ^{27}Al(γ,x), ^{63}Cu(γ,x), ^{115}In(γ,x), ^{118}Sn(γ,x), ^{181}Ta(γ,x), ^{207}Pb(γ,x), ^{209}Bi(γ,x), ^{235}U(γ,x), $E_\gamma=55$ and 85 MeV bremsstrahlung. ^{12}C(γ,x), $E_\gamma=110$ MeV bremsstrahlung. ^{127}I(γ,xn), $E_\gamma=50$, 100, and 150 MeV. Pre-equilibrium exciton, quasideuteron, and statistical compound nucleus models analyses.

I. INTRODUCTION

The statistical compound nucleus model has been very useful in understanding the emission of particles in photonuclear reactions at low energies. Earlier experiments on the energy spectra, angular distributions, and excitation functions from various target nuclei indicated that most of these particles are "evaporated" nucleons.[1,2] The basic feature of the compound nucleus model as applied to photonuclear reactions is that the nucleus is excited by the absorption of the photon via dipole interaction. After the absorption, a compound nucleus is formed which subsequently deexcites by the evaporation of one or more particles.

In the study of the emission of photoproton from heavier nuclei,[3,4] where the Coulomb barrier strongly inhibits the emission of "evaporated" photoprotons, it was found that the yield of higher energy protons was anomalously larger than predicted by the compound nucleus model. Courant[5] proposed a direct photonuclear effect to account for these observations. He suggested that the proton is absorbed by only a small part of the nucleus, perhaps only a single nucleon. A proton or neutron may then be emitted without sharing its energy with the rest of the nucleus. For high energy photons, the experimental results showed a conspicuous forward asymmetry in photoproton angular distribution, particularly for the higher energy protons.[6] The failure of compound nucleus model to predict the forward asymmetry of the photonucleon angular distribution led Levinger[7] to propose the quasideuteron model, in which he assumed that an incident photon is absorbed by a proton-neutron pair in the nucleus. Many experimental features of the high energy photoeffect for light nuclei were explained by this high energy photodisintegration of the quasideuteron inside the nucleus.[8-10] Although the validity of the quasideuteron model has been further confirmed by the observation of angular correlation between coincident neutron-proton pairs emitted by light nuclei,[9,10] this model only accounts for the process in that one or two high energy nucleons are produced in the primary interaction. The subsequent interactions of the neutron-proton pair with the rest of the nucleus after the absorption, which is important for heavier nuclei,[11] were neglected. Gabriel and Alsmiller[12] have incorporated quasideuteron model into intranuclear cascade calculations to take into account the effects of nucleon-nucleus interactions following the initial photon-nucleus interaction. The calculations based on these models gave reasonably good agreement with experiments at high photon energies ($40 \le E_\gamma \le 350$ MeV). Later the same mechanisms were successfully applied by Barashenkov *et al.*[13] in explaining the energy spectra and angular distributions at photon energies $E_\gamma = 50$ MeV–1.3 GeV.

The pre-equilibrium particle emission is now understood as a dominant process in interpreting both the energy spectra and excitation functions resulting from the nucleon and α particle induced reactions.[14-26] It is the purpose of the present paper to apply the pre-equilibrium exciton model to the photonuclear reactions at energies below pion threshold.

For γ-ray energies above 30 MeV, the quasideuteron effect becomes significant. The process can be described as one in which the incident photon is absorbed by a neutron-proton pair (or quasideuteron) and that a composite nucleus is formed in an initial exciton state (2p-2h state). For γ-ray energies in the region of giant resonances, an initial dipole particle-hole state is formed (1p-1h state). This excited nucleus will then either emit particles from this initial state or proceed to the more complicated particle-hole states via the residual two-body interaction until a dynamical equilibrium is reached. During the nuclear equilibration, there is a certain probability for particle emission from any exciton state. This model includes the contributions of particle emission from the first and subsequent interactions.

Details of the models and their formulations will be discussed in Sec. II. In Sec. III, the calculations based on the exciton model together with the quasideuteron model will be compared with the difference energy spectra of fast photoneutrons from several target nuclei (Al, Cu, In, Sn, Ta, Pb, Bi, and U) at bremsstrahlung end point energies of 55 and 85 MeV measured by Kaushal *et al.*[11] and the photoproton energy spectra from ^{12}C at bremsstrahlung end point energy 110 MeV measured by Whitehead *et al.*[10] Finally, the comparisons of the relative yields of the reaction ^{127}I(γ, xn) at photon energies 50, 100, and 150 MeV (Ref. 27) with the predictions of exciton plus quasideuteron models followed by evaporation is made.

II. MODELS AND CALCULATIONS

A. Pre-equilibrium exciton model

The pre-equilibrium exciton model, initially proposed by Griffin[14] and extended by many authors,[15-26] has been successfully applied to explain the energy spectra and excitation functions resulting from particle induced reactions. In this model, the nuclear equilibration process can be described as follows. First, a composite nucleus is formed in an initial particle-hole state (or simplest doorway state) following the projectile-target nucleus interaction. The initial particle-hole number generally depends upon the nature of the projectile. This composite nucleus then proceeds from this simplest doorway state to a series of more complex particle-hole states (or hallway states) via energy-conserving two-body residual interactions until a statistical equilibrium is achieved. During this equilibration process, a particle may be emitted from each intermediate state. The probability for particle emission depends on the probability of finding the particle in a certain energy range within an intermediate state, which is populated with a certain probability, and the ratio of emission width to total width of a given state. The probability of finding the particle in a given state and a given energy range is generally determined by the state densities. As in the Griffin model, the basic assumption is that the intermediate states of the composite nucleus are characterized by the number of excited particles p and holes h (or exciton number n) and by the excitation energy E. The particle-hole state density has the form[28]

$$\omega(p,h,E)=\frac{g(gE-A_{p,h})^{p+h-1}}{p!\,h!\,(p+h-1)!}\ , \tag{1}$$

where g is the single particle state density in the equal spacing model of a nucleus and is related to the level density parameter a by $g=6a/\pi^2$, $A_{p,h}$ is a correction term taking into account the first order effect of Pauli-exclusion principle and is given by $A_{p,h}=\frac{1}{4}(p^2+h^2+p-3h)$. If the pairing effect as well as shell structure effect is considered, a pairing energy δ and/or shell correction S will simply be subtracted from the excitation energy E of the system as in the compound nucleus model. Furthermore, all the levels are assumed to be populated with equal *a priori* probability during the equilibration process. This implies a statistical or quasiequilibrium assumption at each stage. Recently, Blann[21,29] has shown that the particle-hole distribution functions derived from the consideration of the kinematics for nucleon-nucleon scattering in nuclear matter are identical to those obtained using the Ericson formula, which is based on a quasiequilibrium assumption.

During the equilibration process, each intermediate state can either proceed via the binary interactions by creating a particle-hole pair ($\Delta p=\Delta h=+1$), by annihilating a particle-hole pair ($\Delta p=\Delta h=-1$), or simply by exciton-exciton scattering ($\Delta p=\Delta h=0$), or undergo particle emissions with a certain decay width. If these transition rates and particle decay rates are known one is able to calculate the precompound reaction cross sections.

The transition rates for the process $\Delta p=\Delta h=+1$, $\Delta p=\Delta h=-1$, and $\Delta p=\Delta h=0$ based on the first order time dependent perturbation theory are[22,30,31]

$$\lambda_+(p,h,E)=\frac{\Gamma_+(p,h,E)}{\hbar}=\frac{\pi}{\hbar}\,|M|^2\,\frac{g}{(p+h+1)}\,(gE-C_{p+1,h+1})^2\,, \tag{2}$$

$$\lambda_-(p,h,E)=\frac{\Gamma_-(p,h,E)}{\hbar}$$
$$=\frac{\pi}{\hbar}\,|M|^2 g p h(p+h-2)\,, \tag{3}$$

$$\lambda_0(p,h,E)=\frac{\Gamma_0(p,h,E)}{\hbar}$$
$$=\frac{\pi}{\hbar}\,|M|^2 g(gE-C_{p,h})\times\left[\frac{p(p-1)+4ph+h(h-1)}{p+h}\right], \tag{4}$$

where $C_{p,h}=\frac{1}{2}(p^2+h^2)$ is the correction for the first order effect of Pauli-exclusion principle, $|M|^2$ is the square of the average two-body transition matrix element (we assumed $|M|^2=|M|_+^2=|M|_-^2=|M|_0^2$). Γ_+, Γ_-, and Γ_0 are the transition widths from (p,h) state to $(p+1,h+1)$, $(p-1,h-1)$ states and remaining in a given (p,h) state, respectively.

In the following, a general pre-equilibrium formulation is given which includes complex particle emission. In this paper, however, only nucleon emission is included in the calculation because the complex particle emission represents only a small fraction of the total yield.

The general expression for the pre-compound decay probability per unit time of a particle β with channel energy ϵ from a state with p particle and h hole is given by[16,19,23,25]

$$W_\beta(p,h,E,\epsilon)d\epsilon$$
$$=\left[\frac{\omega(p-p_\beta,h,U)}{\omega(p,h,E)}\,R_\beta(p)\gamma_\beta\,\omega(p_\beta,0,E-U)d\epsilon\right]\lambda_\beta^c(\epsilon)$$
$$=\frac{2S_\beta+1}{\pi^2\hbar^3}\,\mu_\beta\sigma_\beta(\epsilon)\epsilon d\epsilon\,\frac{\omega(p-p_\beta,h,U)}{\omega(p,h,E)}\times\frac{\omega(p_\beta,0,E-U)}{g_\beta}\,R_\beta(p)\gamma_\beta\,, \tag{5}$$

where S_β, μ_β, and σ_β are the spin, reduced mass, and the inverse reaction cross section for the emitted particle β, U and E are the excitation energies of residual and composite nuclei, p_β is the nucleon number of the emitted particle. The factor $R_\beta(p)$,[19] which is a pure combinatorial probability, gives the probability that p_β nucleons chosen at random from among the p excited particles has the right combination of protons and neutrons to form the outgoing particle β and γ_β is the formation probability for the particle β in the composite nucleus to have the right momentum to undergo emission as an entity. γ_β is equal to unity for nucleons and is generally less than 1 for complex particles and decreases with increasing nucleon number p_β and the composite nucleus mass number A.[32] The quantity in the first bracket of Eq. (5) gives the particle populations in each energy interval in terms of particle-hole state densities ω of Eq. (1). $\lambda_\beta^c(\epsilon)$ in Eq. (5) is the emission rate into the continuum for a particle β at energy ϵ and is given by[16,29]

$$\lambda_\beta^c(\epsilon)=\sigma_\beta(\epsilon)v_\beta\rho_\beta^c(\epsilon)/g_\beta V\,, \tag{6}$$

where V is the laboratory volume and will be cancelled by a same volume in $\rho_\beta^c(\epsilon)$, $v_\beta=(2\epsilon/\mu_\beta)^{1/2}$ is the velocity of the particle β having a density of states $\rho_\beta^c(\epsilon)=(V/4\pi^2\hbar^3)(2S_\beta+1)(2\mu_\beta)^{3/2}\epsilon^{1/2}$ in the continuum.[16,29]

The total decay probability per unit time for particle β from the (p,h) state can now be obtained by integrating Eq. (5) over the channel energy ϵ, i.e.,

$$\frac{\Gamma_\beta(p,h,E)}{\hbar}=\Lambda_\beta(p,h,E)=\int_0^{E-B_\beta}W_\beta(p,h,E,\epsilon)d\epsilon\,, \tag{7}$$

where B_β is the separation energy for particle β and $\Gamma_\beta(p,h,E)$ is total decay width for particle β at state (p,h). The total particle decay probability per unit time $\Lambda_c(p,h,E)$ or total particle decay with $\Gamma_c(p,h,E)$ from the (p,h) state is simply the sum over all possible decay channels, that is

$$\Lambda_c(p,h,E)=\frac{\Gamma_c(p,h,E)}{\hbar}=\sum_\nu\frac{\Gamma_\nu(p,h,E)}{\hbar}\,,=\sum_\nu\Lambda_\nu(p,h,E)\,, \tag{8}$$

where the summation is generally taken over n, p, d, t, ^{3}He, and ^{4}He particles.

From Eqs. (2)–(8), the total width of an intermediate (p,h) state, can be determined as follows:

$$\Gamma(p,h,E)=\Gamma_+(p,h,E)+\Gamma_-(p,h,E)+\Gamma_c(p,h,E)\,. \tag{9}$$

The average life time of a given (p,h) state has the form

$$\tau(p,h,E)=\frac{\hbar}{\Gamma(p,h,E)}=[\lambda_+(p,h,E)+\lambda_-(p,h,E)+\Lambda_c(p,h,E)]^{-1}\,. \tag{10}$$

The transition probabilities (or branching ratios) from a given (p,h) state into $(p+1,h+1)$, $(p-1,h-1)$ states or undergoing particle emission are $\Gamma_+(p,h,E)/\Gamma(p,h,E)$, $\Gamma_-(p,h,E)/\Gamma(p,h,E)$, and $\Gamma_c(p,h,E)/\Gamma(p,h,E)$, respectively.

With the "never come back" assumption (the assumption to neglect the Γ_- term), the probability of populating any intermediate state starting from (p_0,h_0) initial state is given by

$$P(p,h,E)=\prod_{\substack{p'=p_0\\ \Delta p'=+1}}^{p-1}\Gamma_+(p',h',E)/\Gamma(p',h',E)\,, \tag{11}$$

where $p'-h'=p_0-h_0$ and $P(p_0,h_0,E)=1$. With this assumption, the pre-equilibrium decay probability for a particle β with energy between ϵ and $\epsilon+d\epsilon$ can be obtained by summing from initial (p_0,h_0) state to the most probable $(\bar{p},\bar{h})$ state, that is

$$I_\beta^{\rm PEQ}(E,\epsilon)d\epsilon = \sum_{\substack{p=p_0\\ \Delta p=+1}}^{\bar{p}}\left[\frac{W_\beta(p,h,E,\epsilon)d\epsilon}{\Gamma_c(p,h,E)/\hbar}\right]\left[\frac{\Gamma_c(p,h,E)}{\Gamma(p,h,E)}\right]P(p,h,E)\,, \tag{12}$$

or written in an alternative expression

$$I_\beta^{\rm PEQ}(E,\epsilon)d\epsilon=\sum_{\substack{p=p_0\\ \Delta p=+1}}^{\bar{p}}W_\beta(p,h,E,\epsilon)d\epsilon\,\tau_{\rm PEQ}(p,h,E)\,, \tag{13}$$

with

$$\tau_{\rm PEQ}(p,h,E)=\frac{\hbar}{\Gamma(p,h,E)}P(p,h,E) = \tau(p,h,E)P(p,h,E)\,, \tag{14}$$

where $\tau_{\rm PEQ}(p,h,E)$ is the time spent by the composite nucleus in the (p,h) state at pre-equilibrium stage.

Taking into account the "come back" contributions while disregarding the other possible higher order contributions leads one to a simple closed-form expression for the total pre-equilibrium decay probability of a particle β with channel energy ϵ[25]:

$$\begin{aligned}I_\beta^{\rm PEQ}(E,\epsilon)d\epsilon = \sum_{\substack{p=p_0\\ \Delta p=+1}}^{\bar{p}}&\left[\frac{\Gamma_\beta(p,h,E,\epsilon)d\epsilon}{\Gamma_c(p,h,E)}\right]\left[\frac{\Gamma_c(p,h,E)}{\Gamma(p,h,E)}\right]\\ &\times\left[\prod_{\substack{p'=p_0\\ \Delta p'=+1}}^{p-1}\frac{\Gamma_+(p',h',E)}{\Gamma(p',h',E}\right]\\ &\times\left[1+\frac{\Gamma_+(p,h,E)}{\Gamma(p,h,E)}\times\frac{\Gamma_-(p+1,h+1,E)}{\Gamma(p+1,h+1,E)}\right],\end{aligned} \tag{15}$$

where $\Gamma_\beta(p,h,E,\epsilon)=\hbar\, W_\beta(p,h,E,\epsilon)$ is emission width for particle β with energy ϵ from (p,h) state, and $\Gamma(p,h,E)$ is given by Eq. (9). The factor in the first bracket in Eq. (15) represents the branching ratio for particle emission of the type considered, the factors in second and third brackets were defined previously, and the second term in the last bracket gives the transition probability from $(p+1,h+1)$ state back to (p,h) state. Terms such as

$$\left[\frac{\Gamma_-(p,h,E)}{\Gamma(p,h,E)}\;\frac{\Gamma_+(p-1,h-1,E)}{\Gamma(p-1,h-1,E)}\right]$$

or

$$\left[\frac{\Gamma_+(p,h,E)}{\Gamma(p,h,E)}\;\frac{\Gamma_+(p+1,h+1,E)}{\Gamma(p+1,h+1,E)}\;\frac{\Gamma_-(p+2,h+2,E)}{\Gamma(p+2,h+2,E)}\times\frac{\Gamma_-(p+1,h+1,E)}{\Gamma(p+1,h+1,E)}\right]\text{ etc.}$$

may be neglected in the pre-equilibrium component because they require so many transitions. As a matter of fact, these terms are extremely small so that they can be neglected in the pre-equilibrium stage. From Eqs. (14) and (15) and ignoring other contributions, the time spent by the composite nucleus in a given particle-hole state at the pre-equilibrium stage can be written as[25]

$$\tau_{\rm PEQ}(p,h,E)=\tau(p,h,E)P(p,h,E)\times\left[1+\frac{\Gamma_+(p,h,E)}{\Gamma(p,h,E)}\;\frac{\Gamma_-(p+1,h+1,E)}{\Gamma(p+1,h+1,E)}\right]. \tag{16}$$

Finally, the fraction of pre-equilibrium emissions is determined by

$$F_{\rm PEQ}^{(E)}=\sum_\nu\int_0^{E-B_\nu}I_\nu^{\rm PEQ}(E,\epsilon)d\epsilon = \sum_{\substack{p=p_0\\ \Delta p=+1}}^{\bar{p}}\Lambda_c(p,h,E)\tau_{\rm PEQ}(p,h,E)\,, \tag{17}$$

and the fraction of equilibrium emission is $F_{\rm EQ}(E)=1-F_{\rm PEQ}(E)$. Note that the fractions defined above are for the emission of a single particle only.

B. Quasideuteron model

Photonuclear reactions may be grouped into three classes according to the incident photon energy, namely the "giant resonance" region, the region between the giant resonance and the "pion threshold," and the region above the pion threshold. In each energy region, there is a characteristic type of event. In the giant resonance region, the incident photon interacts with the dipole moment of the target nucleus and the nucleus deexcites by emitting particles or γ rays via the compound nucleus mechanism. In the energy range between giant resonance and pion threshold (40–150 MeV), where the wavelength of the incident photon is comparable to the internucleonic distance in the nucleus, the absorption of a photon by a neutron-proton pair (or quasideuteron) appears to be the main process. For the region above pion threshold, the interaction between a photon and an individual internuclear nucleon associated with the pion production competes with the photon absorption by a quasideuteron.

The quasideuteron mechanism proposed by Levinger[7] is now thought to be a dominant process for the absorption of high energy photons. For photon energies above the giant resonance, this process becomes significant because it results from the interaction of the photon with a two-particle cluster rather than a single nucleon. The incident photon interacts with a neutron-proton pair rather than proton-proton and neutron-neutron pair because they have no dipole moment and the electric dipole absorption in the photoelectric effect is dominant at high photon energies. According to Levinger,[7] the high energy photodisintegration involves a large momentum transfer between the two nucleons and therefore requires the two nucleons to be close together where the forces are strong. This is true whether the photodisintegration occurs in a complex nucleus or in a free deuteron. Levinger showed that the cross section for disintegrating a neutron-proton pair in a complex nucleus is proportional to the cross section for the photodisintegration of a free deuteron. The proportionality constant α is the probability that the two nucleons will be close together in the complex nucleus relative to free deuteron. By neglecting the difference between the singlet and triplet neutron-proton cross section, the quasideuteron cross section is given by

$$\sigma_{\mathrm{QD}} = \alpha\sigma_D = L\,\frac{NZ}{A}\,\sigma_D\,, \tag{18}$$

where the coefficient L, called "Levinger parameter," is essentially a measure of the excess of high momenta in quasideuteron as compared to that in free deuteron. A value of 6.8 for L is obtained by Levinger while Garvey *et al.*,[9] obtained a value of 10.3 for L. NZ is the number of neutron-proton pairs in the nucleus and σ_D is the free deuteron photodisintegration cross section which is given by

$$\sigma_D \propto (E_\gamma - B)^{3/2}/E_\gamma{}^3\,. \tag{19}$$

σ_D reaches its maximum at twice of deuteron binding energy, i.e., $\sigma_D \approx 2.3$ mb at photon energy $E_\gamma = 2B = 4.452$ MeV. Because of the healing of the two-nucleon correlations at large internucleon separations, the reduction of quasideuteron process at energies below 100 MeV has been taken into account by multiplying Eq. (18) by a damping factor e^{-30/E_γ}.[11] In our calculations, a different quenching factor $(1 - e^{-0.1(E_\gamma - 40)})$ has been introduced into Eq. (18).[33] With this quenching factor, the expected integrated cross section up to pion production threshold was exhausted.

A number of experiments have been performed to verify the validity of this model at incident photon energies above giant resonance. The measurement of energy spectra and angular distributions of the high energy photonucleons tended to confirm the quasideuteron model, although a number of discrepancies appeared to exist between the experimental results and theoretical predictions.[8] Convincing evidence for the quasideuteron model was further supported by the measurements of neutron-proton in coincidence.[9] The agreement between experimental results and the quasideuteron theory indicates that the absorption mechanism above 40 MeV is dominated by the absorption of photons by correlated pairs of nucleons. Since the introduction of quasideuteron model, a number of calculations and modifications have been made.[8,9,11,34] The effect of scattering of the emerging nucleons by the target nuclei after the photon absorption was also considered. However, the effects of secondary interaction of neutron-proton pair with the rest of the nucleus after absorption which are particularly important and severe for intermediate and heavy nuclei have generally been disregarded.

Recently, effects of rescattering have been taken into account by incorporating the quasideuteron model into the intranuclear cascade model with great success.[12,13] The successful applications of quasideuteron plus intranuclear cascade models in the photonuclear reactions and the preequilibrium exciton model in the particle induced reactions lead us to combine the quasideuteron and exciton models to interpret photonuclear reactions. From the exciton model point of view, the high energy photonuclear reaction (above giant resonance and below pion threshold), can be described as a process that the incident photon is absorbed by a neutron-proton pair (or a quasideuteron) in the target nucleus, forming an initial 2p-2h state (or more strictly a one-proton-particle–one neutron-particle–one-proton-hole–one-nuetron-hole state). This excited nucleus then equilibrates through a series of residual two-body interactions leading to more complicated particle-hole states. During nuclear equilibration, there is a certain probability for particle emission from each intermediate state. From these particle decay probabilities, the information on the photonuclear reactions can be obtained. The process is, in fact, analogous to the particle induced reactions and therefore can be treated in a usual way.

C. Calculations

1. Monoenergetic photon induced reactions

The statistical compound nucleus model predicts that the particle energy spectrum from a nucleus excited with monoenergetic γ rays is

$$\frac{d\sigma_\beta^{\rm EQ}(E_\gamma)}{d\epsilon}=\sigma_a(E_\gamma)\frac{\Gamma_\beta(E_\gamma,\epsilon)}{\sum_\nu\Gamma_\nu(F_\gamma)}\,,$$

$$=\sigma_a(E_\gamma)I_\beta^{\rm EQ}(E_\gamma,\epsilon)\,, \qquad (20)$$

where $\sigma_a(E_\gamma)$ is the photoabsorption cross section at photon energy E_γ. The summation ν is over all possible modes of disintegration of the excited nucleus. $\Gamma_\beta(E_\gamma,\epsilon)$ is the decay width of particle β with channel energy ϵ and is given by the well known expression

$$\Gamma_\beta(E_\gamma,\epsilon)=\frac{2S_\beta+1}{\pi^2\hbar^2}\,\mu_\beta\sigma_\beta(\epsilon)\epsilon d\epsilon\,\frac{\rho(U)}{\rho(E_\gamma)} \qquad (21)$$

and

$$\Gamma_\beta(E_\gamma)=\int_0^{E_\gamma-B_\beta}\Gamma_\beta(E_\gamma,\epsilon)d\epsilon\,; \qquad (22)$$

here the notations are the same as those defined in Sec. II A. $\rho(U)$ and $\rho(E_\gamma)$ are the level density of the residual and compound nuclei at excitation energies U and E_γ, respectively.

In analogy with the compound nucleus model, the energy spectrum resulting from the photonuclear reaction in the pre-equilibrium stage can be written as

$$\frac{d\sigma_\beta^{\rm PEQ}(E_\gamma)}{d\epsilon}=\sigma_a(E_\gamma)I_\beta^{\rm PEQ}(E_\gamma,\epsilon)\,, \qquad (23)$$

where $I_\beta^{\rm PEQ}(E_\gamma,\epsilon)$ is given by Eq. (15). In the giant resonance region,[35] an initial particle-hole number of 1p-1h is appropriate in accordance with the photoabsorption process being due to dipole interaction. For the photon energy in the range $40\leq E_\gamma\leq 150$ MeV, 2p-2h is taken due to the quasideuteron mechanism.

The total emitted particle energy spectra can be obtained

$$\frac{d\sigma_\beta(E_\gamma)}{d\epsilon}=d\sigma_\beta^{\rm PEQ}(E_\gamma)/d\epsilon+[1-F_{\rm PEQ}(E_\gamma)]d\sigma_\beta^{\rm EQ}(E_\gamma)/d\epsilon$$

$$=\sigma_a(E_\gamma)\cdot I_\beta(E_\gamma,\epsilon)\,, \qquad (24)$$

where $F_{\rm PEQ}$ is the fraction for pre-equilibrium emissions as defined in Eq. (17). The above expression is for single particle emission only. If energy is high enough so that multiparticle emission becomes possible, the energy spectra resulting from further emissions must be added in addition to Eq. (24). The general expression for the energy spectra with multiparticle emission from the pure evaporation process has the form

$$\begin{aligned}\frac{d\sigma_\beta^{\rm EQ}(E_\gamma)}{d\epsilon}&=\sigma_a(E_\gamma)\Bigg\{\frac{\Gamma_\beta(E_\gamma,\epsilon)}{\sum_\nu\Gamma_\nu(E_\gamma)}+\sum_\mu\int^{E_\gamma-B_\mu}\frac{\Gamma_\mu(E_\gamma,\epsilon')}{\sum_\nu\Gamma_\nu(E_\gamma)}\,\frac{\Gamma_\beta(E_\gamma-\epsilon'-B_\mu,\epsilon)d\epsilon'}{\sum_\nu\Gamma_\nu(E_\gamma-\epsilon'-B_\mu)}\\&\quad+\sum_\eta\sum_\mu\int^{E_\gamma-B_\mu}\int^{E_\gamma-B_\mu-B_\eta-\epsilon'}\frac{\Gamma_\mu(E_\gamma,\epsilon')}{\sum_\nu\Gamma_\nu(E_\gamma)}\,\frac{\Gamma_\eta(E_\gamma-\epsilon'-B_\mu,\epsilon'')}{\sum_\nu\Gamma_\nu(E_\gamma-\epsilon'-B_\mu)}\\&\quad\times\frac{\Gamma_\beta(E_\gamma-\epsilon'-\epsilon''-B_\mu-B_\eta,\epsilon)}{\sum_\nu\Gamma_\nu(E_\gamma-\epsilon'-\epsilon''-B_\mu-B_\eta)}\,d\epsilon'd\epsilon''+\cdots\Bigg\}\\&=\sigma_a(E_\gamma)I_\beta^{\rm EQ}(E_\gamma,\epsilon)\,,\end{aligned} \qquad (25)$$

where the first term represents the spectra due to first emission, the second term from second emission, etc., B is the binding energy of emitted particle at each cascade stage, and the summation is over the particle decay channels which are possible at the preceding stage of evaporation cascade. The multiparticle emission in the pre-equilibrium stage may become possible for high incident energy. However, the resulting spectra have generally a softer component similar to the evaporation one.[21,29] Therefore, it is not too serious to treat further particle emissions following the precompound emission by the evaporation process. The final total energy spectra for particle β can be written as follows

$$\begin{aligned}\frac{d\sigma_\beta(E_\gamma)}{d\epsilon}&=\sigma_a(E_\gamma)\Bigg\{\Bigg[I_\beta^{\rm PEQ}(E_\gamma,\epsilon)+\sum_\mu\int^{E_\gamma-B_\mu}I_\mu^{\rm PEQ}(E_\gamma,\epsilon')\,\frac{\Gamma_\beta(E_\gamma-\epsilon'-B_\mu,\epsilon)}{\sum_\nu\Gamma_\nu(E_\gamma-\epsilon'-B_\mu)}\,d\epsilon'\\&\quad+\sum_\eta\sum_\mu\int^{E_\gamma-B_\mu}\int^{E_\gamma-B_\mu-B_\eta-\epsilon'}I_\mu^{\rm PEQ}(E_\gamma,\epsilon')\,\frac{\Gamma_\eta(E_\gamma-\epsilon'-B_\mu,\epsilon'')}{\sum_\nu\Gamma_\nu(E_\gamma-\epsilon'-B_\mu)}\\&\quad\times\frac{\Gamma_\beta(E_\gamma-\epsilon'-\epsilon''-B_\mu-B_\eta,\epsilon)}{\sum_\nu\Gamma_\nu(E_\gamma-\epsilon'-\epsilon''-B_\mu-B_\eta)}\,d\epsilon'd\epsilon''+\cdots\Bigg]+[1-F_{\rm PEQ}(E_\gamma)]I_\beta\,(E_\gamma,\epsilon)\Bigg\}\\&=\sigma_a(E_\gamma)I_\beta(E_\gamma,\epsilon)\,,\end{aligned} \qquad (26)$$

where $I_\beta^{\rm EQ}(E_\gamma,\epsilon)$ is given in Eq. (25).

2. *Bremsstrahlung-γ induced reactions*

In the case of an incident bremsstrahlung-γ spectrum, the particle energy spectrum has to be integrated over the γ-ray spectrum appropriately. The energy distribution of emitted particle per nucleus excited with cross section $\sigma_a(E_\gamma)$ by a spectrum with $K(E_\gamma, E_0)$ quanta per cm^2 per MeV interval at energy E_γ and a maximum energy E_0 is given by

$$Y_\beta(E_0,\epsilon)=\int_{E_{\rm thr}}^{E_0} d\sigma_\beta(E_\gamma)/d\epsilon K(E_\gamma,E_0)dE_\gamma = \int_{E_{\rm thr}}^{E_0}\sigma_a(E_\gamma)I_\beta(E_\gamma,\epsilon)K(E_\gamma,E_0)dE_\gamma\,, \tag{27}$$

where $d\sigma_\beta(E_\gamma)/d\epsilon$ is either taken from Eq. (24) or Eq. (26). The yield resulting from the pre-equilibrium decay only is given by

$$Y_\beta^{\rm PEQ}(E_0,\epsilon)=\int_{E_{\rm thr}}^{E_0}\sigma_a(E_\gamma)I_\beta^{\rm PEQ}(E_\gamma,\epsilon)K(E_\gamma,E_0)dE_\gamma\,, \tag{28}$$

where $E_{\rm thr}$ represents the reaction threshold. In the present calculations, the total photoabsorption cross section for $E_\gamma \le 40$ MeV is either taken from experimental data or approximated by Lorentz-shaped resonance lines:

$$\sigma_a(E_\gamma)=\sum_{m=1}^{2}\sigma_m E_\gamma^2\Gamma_m^2/[(E_m^2-E_\gamma^2)^2+E_\gamma^2\Gamma_m^2]\,, \tag{29}$$

where the Lorentz parameters E_m, σ_m, and Γ_m are the resonance energy, peak cross section, and full width at half maximum, respectively. The quasideuteron cross section given in Sec. II B was used for the photon absorption in the region $40 \le E_\gamma \le 150$ MeV.

The thin target bremsstrahlung spectrum which results from the radiative scattering of fast electrons in very thin target is given by Schiff[36]

$$K(E_\gamma,E_0)=\frac{2Z^2}{137}\left(\frac{e^2}{m_0C^2}\right)\frac{1}{E_\gamma}\left[\left(\frac{E_0^2+E^2}{E_0^2}-\frac{2E}{3E_0}\right)\left(\ln M(0)+1-\frac{2}{b}\tan^{-1}b\right)+\frac{E}{E_0}\left(\frac{2}{b^2}\ln(1+b^2)+\frac{4(2-b^2)}{3b^2}\tan^{-1}b-\frac{8}{3b^2}+\frac{2}{9}\right)\right] \tag{30}$$

and

$$b=\frac{2EE_0Z^{1/3}}{111E_\gamma m_0C^2}\,, \tag{31}$$

$$\frac{1}{M(0)}=\left(\frac{m_0C^2E_\gamma}{2E_0E}\right)^2+(Z^{1/3}/111)^2\,, \tag{32}$$

where E_0 is the energy of the incident electron, E the energy of the scattered electron, $E_\gamma = E_0 - E$ the energy of the radiated quantum, m_0c^2 the rest energy of an electron, and Z is the atomic number of target material.

III. RESULTS AND DISCUSSION

The neutron energy spectra at 67.5° resulting from 85-55 MeV bremsstrahlung-difference photon spectra[11] indicate that a sizable yield of fast neutrons above 10 MeV is present in all the spectra. These fast neutron yields cannot be explained in terms of evaporation mechanism alone. Gabriel and Alsmiller[12] have made the comparisons between these data and the intranuclear cascade plus quasideuteron models with good agreements. Therefore, these data should provide a reasonable check for the validity of the combined pre-equilibrium and quasideuteron models at this energy range over a wide range of nuclei.

Due to the difficulty of coupling the angular momentum effect in the pre-equilibrium exciton model, the calculations can predict only the angle-integrated energy spectra. It is important to compare the theoretical predictions with the angle-integrated energy spectra or a single energy spectrum at some angle which represents an average spectral shape. In the case of (p,x) reactions,[37] the data generally show that any single energy spectrum between 60° and 90° has approximately the same spectral shape as well as the average intensity as the angle-integrated energy spectra. Therefore, the neutron differential cross sections at 67.5° of Kaushal *et al.*[11] have been multiplied by 4π (or the calculated spectra divided by 4π) before comparing with the present calculations.

The absolute yield of the neutron difference spectrum due to 85-55 MeV photon difference spectrum, according to Kaushal *et al.*, was expressed in terms of an effective cross section $(d\sigma/d\epsilon)_{\rm eff}$ for production of neutrons of energy ϵ by photons in the difference spectrum:

$$\left(\frac{d\sigma}{d\epsilon}\right)_{\rm eff}=\frac{\int_{E_{\rm norm}}^{E_0}\sigma_a(E_\gamma)I_\beta(E_\gamma,\epsilon)K(E_\gamma,E_1,E_2,E_{\rm norm})dE_\gamma}{\int_{E_{\rm norm}}^{E_0}K(E_\gamma,E_1,E_2,E_{\rm norm})dE_\gamma}\,, \tag{33}$$

where

$$K(E_\gamma, E_1, E_2, E_{\rm norm}) = K(E_\gamma, E_1) - \frac{K(E_{\rm norm}, E_1)}{K(E_{\rm norm}, E_2)} K(E_\gamma, E_2)\,,$$

$$E_{\rm norm} \leqslant E_\gamma \leqslant E_2$$

$$= K(E_\gamma, E_1)\,,$$

$$E_2 < E_\gamma \leqslant E_1\,. \tag{34}$$

Two bremsstrahlung spectra are normalized for equal photon numbers at $E_{\rm norm} = 18$ MeV.[11,12]

The approximations made and the parameters involved in the present calculations are summarized in the following:

(a) The experimental difference neutron energy spectra are those with neutron energies greater than 10 MeV. The statistical compound nucleus model predicts a relatively small cross section above this energy. Hence, we have neglected the evaporation contributions in the present calculations.

(b) In the pre-equilibrium exciton model, the particle decay channels have been limited to p and n emission only because the complex particle emission represents only a small fraction of the total yield.

(c) The inverse reaction cross sections needed in Eqs. (5) and (21) are either approximated by the formulas taken from Ref. 32 and 38 or from the optical model calculations using a global set of parameters taken from Ref. 39 for n, p, d, t, and ^{3}He, while parameters for the α particle are taken from Huizenga and Igo.[40] No essential differences between these two types of calculations were found. Hence, for simplicity, the empirical formulas from Ref. 32 are used for inverse cross sections throughout the present calculations.

(d) One of the most critical parameters in the model is the initial particle-hole number. If the quasideuteron absorption process is the dominant process in the energy region considered here, a 2p-2h state must be used as initial exciton state. As pointed out in Secs. II A and II B, the initial particle-hole number in the giant resonance region is 1p-1h, due to dipole interaction. For the sake of simplicity in the calculations, however, we used 2p-2h initial state in the calculations over all bremsstrahlung photon energies, instead of using 1p-1h state over the giant resonance region. Of course, one should treat with different initial particle-hole state in different energy regions. Such a calculation was also performed, but no significant differences were observed.

(e) The average square of the transition matrix element $|M|^2$, which plays an important role in the exciton model, has been approximated by an empirical formula developed by Cline[41]: $|M|^2$

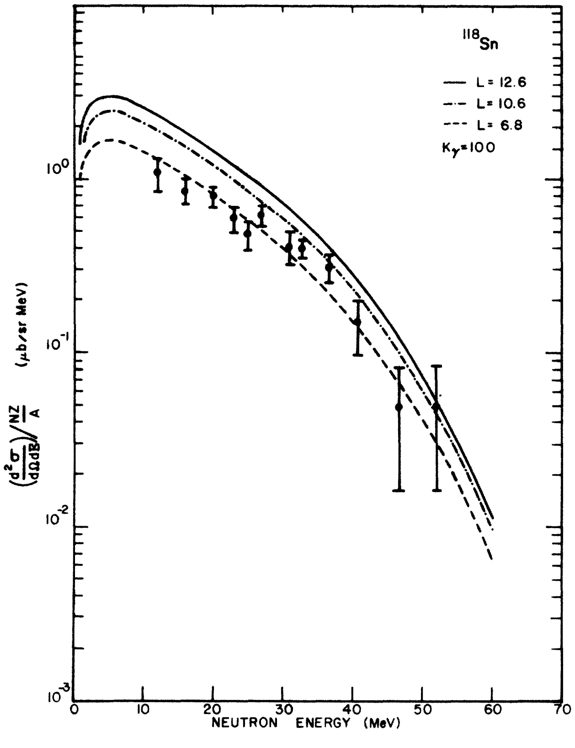

FIG. 1. Differential neutron energy spectrum at 67.5° resulting from 55-85 MeV bremsstrahlung difference photons on ^{118}Sn. The cross section has been divided by NZ/A. Calculations are for L = 6.8, 10.6, 12.6, and for K_γ = 100.

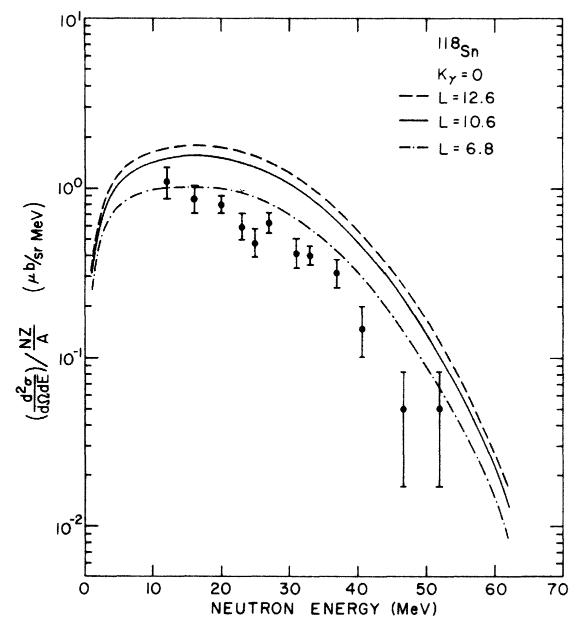

FIG. 2. Same as Fig. 1 except K_γ = 0.

$= KA^{-3}E^{-1}$ with $K_p = 190$ and $K_\alpha = 1450$ MeV^3 for nucleon and α particle induced reactions, respectively. The same empirical formula has been assumed for the photonuclear reactions and the scaling factor K_γ is treated as a parameter. It is obvious that the scaling factor K_γ, in fact, determines the relative branching ratio between the particle emission and internal transitions due to two-body interactions. An assignment of $K_\gamma = 0$ means that the reaction will occur only via the first interaction (direct interaction) and no secondary interactions follow. For the photonuclear reactions analyzed here, various values of K_γ have been chosen such that good agreements between calculations and data are obtained over the entire nuclear mass range.

(f) Different values of quasideuteron constant L have been used previously.[7,9] Recently, Gabriel[12] has shown that L might be energy and nuclear mass A dependent. In this calculation, the energy and mass dependence of L is not clear because another parameter, K_γ, is also involved. Calculations with different L values for ^{118}Sn are shown in Fig. 1. The corresponding L values are shown for each curve with the scaling factor $K_\gamma = 100$. No essential differences exist except for a very large or small value for L.[12] This may be checked further by setting $K_\gamma = 0$ and varying L values, as shown in Fig. 2. On the basis of these curves the value of L between 6.8 and 12.6 seems to be reasonable. In all of the calculations presented here, a value

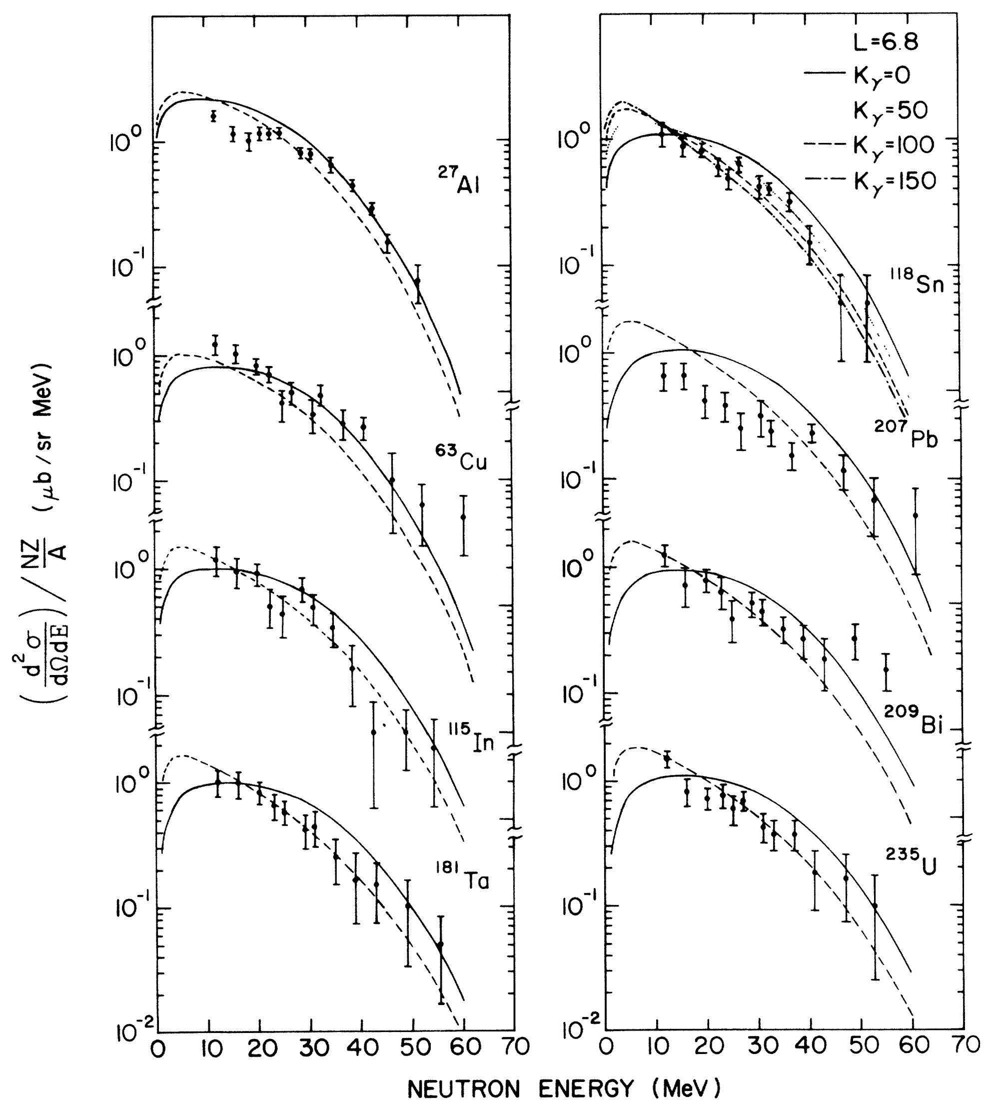

FIG. 3. Differential neutron energy spectra at 67.5° resulting from 55-85 MeV bremsstrahlung difference photons on various target nuclei. The cross section has been divided by NZ/A. All calculations are for $L = 6.8$ and $K_\gamma = 0$ and 100 except ^{118}Sn.

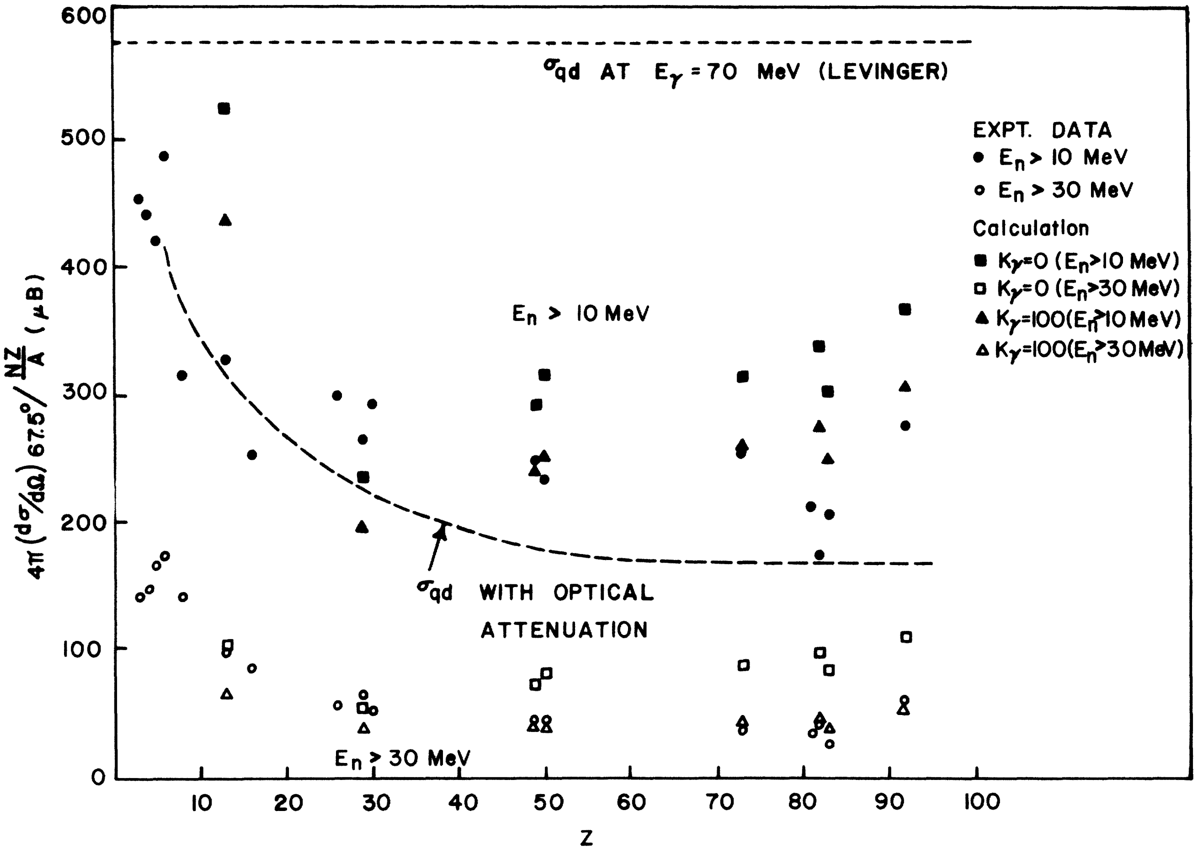

FIG. 4. Effective cross sections for production of fast neutrons with energies greater than 10 and 30 MeV by 55-85 MeV photon difference spectrum. The corresponding theoretical calculations are for $K_\gamma = 0$, 100 and for $L = 6.8$.

of 6.8 is used for quasideuteron constant L.

Figure 3 shows the results of calculations compared with the neutron difference energy spectra at 85-55 MeV difference bremsstrahlung photon spectrum for the target nuclei ^{27}Al, ^{63}Cu, ^{115}In, ^{118}Sn, ^{181}Ta, ^{207}Pb, ^{209}Bi, and ^{235}U. For each target nucleus, two curves corresponding to two different values of the scaling factor K_γ are presented with $L = 6.8$ and 2p-2h initial particle-hole state. For the case of ^{118}Sn, four different values for K_γ are shown. Good agreement in both spectral shape and magnitudes is obtained with $K_\gamma = 100$ and confirms the importance of pre-equilibrium decay process. Further evidence can be seen from the comparisons of effective cross sections for production of fast neutrons with energies greater than 10 and 30 MeV by the 85-55 MeV photon difference spectrum with the calculations as shown in Fig. 4. The short dashed and long dashed curves are taken from Ref. 11, calculated using the quasideuteron model of Levinger and the modified quasideuteron model with optical attenuation included, respectively. The calculations reproduced the general trend of the cross section data. However, the effects due to secondary interactions, which are particularly important for heavier nuclei, were not included in those calculations. The importance of these effects was also pointed out and estimated by Gabriel and Alsmiller using intranuclear cascade model. From the results of present calculations, as shown in Figs. 3 and 4, a value of 100 for K_γ and 6.8 for L gives good agreement. A nonzero value for K_γ thus indicates the importance of secondary interactions.

Figure 5 shows the result of this calculation compared with the experimental photoproton energy spectrum from ^{12}C at bremsstrahlung end point energy 110 MeV.[10] The angle integrated energy spectrum shown in Fig. 5 is obtained by fitting the original data of Whitehead *et al.* to the expression $A + B\sin^2\theta + C\sin^2\theta\cos\theta + D\sin^2\theta\cos^2\theta$. To make the comparison, the calculated cross section was normalized per equivalent quanta[12]

$$\frac{d\sigma}{d\epsilon Q} = \frac{\int_0^{E_0} \sigma_a(E_\gamma) I_\beta(E_\gamma, \epsilon) K(E_\gamma, E_0)\, dE_\gamma}{(1/E_0)\int_0^{E_0} E_\gamma K(E_\gamma, E_0)\, dE_\gamma} . \tag{35}$$

The good agreement between theory and experiment suggests that the pre-equilibrium exciton

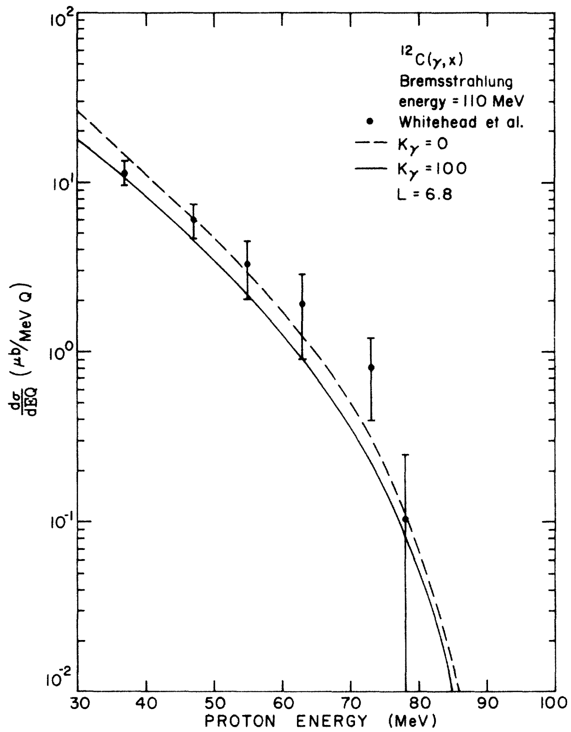

FIG. 5. Angle-integrated proton energy spectrum resulting from 110 MeV bremsstrahlung photons on ^{12}C. Calculations are for L =6.8 and K_γ =0 and 100.

model plus quasideuteron model give a good description of photonuclear reactions at the energy range considered here. Some discrepancies between the theoretical predictions and the data are expected because of the approximations made and the approximation of total photon absorption cross section by Lorentz shape with parameters taken from Ref. 42. Generally, the dipole sum rules are exhausted for heavier nuclei but not for the lighter nuclei because the (γ,p) reaction becomes important for light nuclei and is not included in Ref. 42. In the case of ^{12}C and ^{27}Al, the total photoabsorption cross sections are taken from Ref. 43.

Table I shows the total cross section for the production of various residual nuclei on ^{127}I resulting from monoenergetic photons at various photon energies.[27] In this comparison, no multi-pre-equilibrium emissions are considered. The multiparticle emissions are assumed to be due to evaporation as mentioned in Sec. II C. The calculations are performed in the following way. The excitation energy spectra resulting from pre-equilibrium emission is calculated according to Eq. (15) with a computer code PREQEC,[44] which allows one to perform calculations for a variety of nuclear reactions such as particle, monoenergetic, and bremsstrahlung γ rays, as well as electron induced reactions. Then the excitation energy spectrum for each residual nucleus resulting from the pre-equilibrium emission of a particle and the fraction for pure evaporation as determined according to Eq. (17) were used as input for the evaporation calculations with the code EVAPOR.[45] This code allows one to calculate the yields for all possible residual nuclei in the evaporation cascades and the resulting energy spectra for n, p, d, t, ^{3}He, and ^{4}He particles according to Eq. (26). In the present calculations, the particle separation energies were obtained either from the tabulations of Ref. 46 or from a semiempirical mass formula of Wing and Fong[47] for those not listed in the tabu-

TABLE I. Total cross sections for the production of various residual nuclei resulting from monoenergetic photons on ^{127}I.

Photon energy (MeV)	Type of reaction	Expt. cross section (mb)	Expt. cross section Ratio to $(\gamma,3n)$	INC + quasi-deuteron models from Ref. 12 Ratio to $(\gamma,3n)$	Present work ratio to $(\gamma,3n)$
50	$\sigma(\gamma,3n)$	2.0	1.0	1.0	1.0
	$\sigma(\gamma,4n)$	2.4	1.2	5.98	1.87
100	$\sigma(\gamma,3n)$	0.52	1.0	1.0	1.0
	$\sigma(\gamma,4n)$	1.0	1.92	1.39	1.95
	$\sigma(\gamma,5n)$				3.09
	$\sigma(\gamma,6n)$	0.56	1.08	3.30	3.19
	$\sigma(\gamma,7n)$	0.39	0.75	4.52	3.08
150	$\sigma(\gamma,3n)$	0.53	1.0	1.0	1.0
	$\sigma(\gamma,4n)$	1.0	1.89	1.76	1.95
	$\sigma(\gamma,5n)$				3.10
	$\sigma(\gamma,6n)$	0.36	0.68	3.0	3.24
	$\sigma(\gamma,7n)$	0.20	0.38	3.59	3.51

lations. The level density parameter $a = g\pi^2/6$ is taken to be $A/8$, i.e., $g = 3A/4\pi^2$ MeV^{-1}, where A is the composite nucleus mass number. The pairing energy which was taken into account in the evaporation calculation only was obtained from Ref. 48 and the level density is taken to be $\rho(E) \propto E^{-2}e^{2\sqrt{aE}}$.

The comparison was made on a relative basis by normalizing the calculated cross section to the $(\gamma, 3n)$ cross section. Reasonable agreement is obtained, though some discrepancies exist. As pointed out in Ref. 27 the monoenergetic photon data are not very accurate. Moreover, the effect of photopion production, which may become possible for 150 MeV, has been neglected. Hence, the present comparisons serve only as a guide in understanding photonuclear reactions in terms of the combined models.

CONCLUSIONS

In view of the overall agreement between the theoretical predictions and the experimental data, one sees that the quasideuteron model together with the pre-equilibrium exciton model gives a reasonably good description of the nuclear equilibration process for photonuclear reaction at energy region below pion threshold. The success of the pre-equilibrium exciton model with the assumption of 2p-2h initial state in the photonuclear reactions further confirms that the quasideuteron absorption mechanism is a major process in the high energy photonuclear reactions. The pre-equilibrium exciton model is useful for the medium and heavier nuclei. Any discrepancy for lighter nuclei should not be surprising.

The comparisons presented here are for neutron and proton energy spectra only. The validity of this combined model is yet to be tested for other types of emitted particles. For this reason, the measurements of complex particle energy spectra resulting from monoenergetic γ rays, as well as bremsstrahlung γ rays over the wide energy range which is kinematically allowed and complete angular distributions are particularly interesting. Although the model is crude, the successful application to various nuclear reactions is encouraging.

ACKNOWLEDGMENT

The authors are grateful to Professor H. D. Holmgren and Professor N. S. Wall for a critical reading of the manuscript and many useful discussions throughout this work. The authors also wish to thank Dr. W. R. Dodge for his encouragement and many valuable discussions.

*Work supported in part by the United States Energy Research and Development Administration.

[1] B. C. Diven and G. M. Almy, Phys. Rev. 80, 407 (1950); P. R. Byerly, Jr., and W. E. Stephen, *ibid.* 83, 54 (1951); L. Eyges, *ibid.* 86, 325 (1952); W. A. Butler and G. M. Almy, *itid.* 91, 58 (1953), and references therein.

[2] G. A. Price, Phys. Rev. 93, 1279 (1953); F. T. Kuchnir *et al.*, *ibid.* 161, 1236 (1967); B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975); and references therein.

[3] O. Hirzel and H. Wäffler, Helv. Phys. Acta 20, 373 (1947).

[4] M. E. Toms and W. E. Stephens, Phys. Rev. 92, 362 (1953); 98, 626 (1954), and references therein; V. G. Shevchenko and B. A. Yuryev, Nucl. Phys. 37, 492 (1962).

[5] E. D. Courant, Phys. Rev. 82, 703 (1951).

[6] C. Levinthal and A. Silverman, Phys. Rev. 82, 822 (1951); D. Walker, *ibid.* 81, 634 (1951); S. Kikuchi, *ibid.* 80, 492 (1950).

[7] J. S. Levinger, Phys. Rev. 84, 43 (1951).

[8] P. C. Stein *et al.*, Phys. Rev. 119, 348 (1960); Y. S. Kim *et al.*, *ibid.* 129, 1362 (1963), and references therein.

[9] J. Garvey *et al.*, Nucl. Phys. 70, 241 (1965); M. Barton and J. H. Smith, Phys. Rev. 110, 1143 (1958), and references therein.

[10] C. Whitehead *et al.*, Phys. Rev. 110, 941 (1958); J. L. Matthews *et al.*, Nucl. Phys. A112, 654 (1968).

[11] Kaushal *et al.*, Phys. Rev. 175, 1330 (1968).

[12] T. A. Gabriel and R. G. Alsmiller, Jr., Phys. Rev. 182, 1035 (1969); T. A. Gabriel, Phys. Rev. C 13, 240 (1976).

[13] V. S. Barashenkov *et al.*, Nucl. Phys. A231, 462 (1974).

[14] J. J. Griffin, Phys. Rev. Lett. 17, 478 (1966).

[15] M. Blann, Phys. Rev. Lett. 21, 1357 (1968).

[16] M. Blann, Phys. Rev. Lett. 27, 337 (1971); 28, 757 (1972); M. Blann and A. Mignerey, Nucl. Phys. A186, 245 (1972).

[17] M. Blann, Annu. Rev. Nucl. Sci. 25, 123 (1975), and references therein.

[18] C. K. Cline and M. Blann, Nucl. Phys. A172, 225 (1971).

[19] C. K. Cline, Nucl. Phys. A193, 417 (1972).

[20] C. Birattari *et al.*, Nucl. Phys. A201, 579 (1973); A. Chevarier *et al.*, Phys. Rev. C 8, 2155 (1973); E. Gadiola, E. Gadioli Erba, and P. G. Sona, Nucl. Phys. A217, 589 (1973).

[21] M. Blann, R. R. Doering, A. Galonsky, D. M. Patterson, and F. E. Serr, Nucl. Phys. A257, 15 (1976).

[22] F. C. Williams, Jr., Phys. Lett. 31B, 184 (1970).

[23] I. Ribansky and P. Oblozinsky, Phys. Lett. 54B, 318 (1973).

[24] G. Mantzouranis, D. Agassi, and H. A. Weidenmüller, Phys. Lett. 57B, 220 (1975).

[25] J. R. Wu and C. C. Chang, Phys. Lett. 60B, 423 (1976).

[26] Y. Krie, M. Hyakutake, M. Matoba, and M. Sonoda, Phys. Lett. 62B, 9 (1976).

[27] G. G. Jonsson and B. Forkman, Nucl. Phys. A107, 52

(1968).
[28] F. C. Williams, Jr., Nucl. Phys. A166, 31 (1971).
[29] M. Blann, A. Mignerey, and W. Scobal, Equilibration Processes in Nuclear Reactions: Nucleons to Heavy Ions, A series of lectures presented by Blann at the Eighth Summer School in Nuclear Physics, Warsaw, Poland, August 1975 [Report No. COO-3494-28 (unpublished)].
[30] C. K. Cline, Nucl. Phys. A192, 353 (1972).
[31] P. Oblozinsky, I. Ribansky, and E. Betak, Nucl. Phys. A226, 347 (1974).
[32] J. R. Wu, Ph.D. thesis, Univ. of Maryland, 1977 (unpublished).
[33] W. R. Dodge (private communication).
[34] K. G. Dedrick, Phys. Rev. 100, 58 (1955); Y. S. Kim, *ibid*. 129, 1293 (1962); E. Ostgaard, Nucl. Phys. 64, 289 (1965).
[35] V. K. Lukyanov, V. A. Seliverstov, and V. D. Toneev, Yad. Fiz. 21, 992 (1975) [Sov. J. Nucl. Phys. 21, 508 (1975)]; A. Veyssiere, *et al*., Nucl. Phys. A159, 561 (1970).
[36] L. I. Schiff, Phys. Rev. 83, 252 (1951).
[37] F. E. Bertrand and R. W. Peele, Phys. Rev. C 8, 1045 (1973); ORNL Reports Nos. ORNL-4450, 1969, ORNL-4455, 1969, ORNL-4460, 1969, ORNL-4469, 1970, ORNL-4471, 1970, ORNL-4638, 1971, ORNL-4799, 1973 (unpublished).
[38] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. 116, 683 (1959); I. Dostrovsky and Z. Fraenkel, *ibid*. 118, 781 (1960).
[39] C. M. Perey and F. G. Perey, Nucl. Data Tables 13, 293 (1974); F. D. Becchetti and G. W. Greenlees, Phys. Rev. 183, 1190 (1969).
[40] J. R. Huizenga and G. Igo, Nucl. Phys. 29, 462 (1962); T. D. Thomas, Phys. Rev. 116, 703 (1959).
[41] C. K. Cline, Nucl. Phys. A210, 590 (1973).
[42] B. L. Berman, Lawrence Livermore Laboratory Report No. UCRL-75694, 1974 (unpublished).
[43] J. Ahrens *et al*., Nucl. Phys. A251, 479 (1975).
[44] J. R. Wu, computer code PREQEC (unpublished).
[45] J. R. Wu, computer code EVAPOR (unpublished).
[46] J. H. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 32 (1965).
[47] J. Wing and P. Fong, Phys. Rev. 136, B923 (1964).
[48] A. Gilbert and A. G. W. Cameron, Can. J. Phys. 43, 1446 (1965).