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Ineffectiveness of the Quasi-deuteron Mechanism of Interaction in Yielding (γ,nucleon) Reactions on Complex Nuclei above 150 MeV (*)

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In the photon-energy range from the end of the giant dipole resonance up to a few hundred MeV (50 MeV $\lesssim E_\gamma \lesssim$ 400 MeV) it has been generally accepted that the Levinger's quasi-deuteron model of interaction (1) may account for the energy-field distributions of photonuclear reactions. Following this mechanism, the cross section σ of all photonuclear processes is related to the cross section σ_d of the free deuteron photodisintegration by means of the relation

$$\sigma = L \frac{NZ}{A} \sigma_d \qquad (1)$$

where NZ represents the number of neutron-proton pairs in the nucleus of mass number A = Z+N, and L is a measure of the relative probability of two nucleons being near each other in a complex nucleus compared with that of a free deuteron.

Although the model has been proved to be useful in most instances in explaining the trend of the cross sections of some reactions such as (γ,pn), (γ,spallation), and others, it has not been supported by experimental data as far as simple direct reactions of the type (γ,n) and (γ,p) are concerned, at least in its simplest form as given in ref. (1) (see, for example, refs (2,3)). In addition, it has already been pointed out that at energies in excess of about 100 MeV, (γ,n) and (γ,p) reactions represent only a few per cent of the (γ,np) reaction yield (4). On the other hand, the Levinger's quasi-deuteron model gives only phenomenological descriptions of the reactions, without giving detailed information on the physical processes involved.

In some papers dealing with (γ,nucleon) reactions in complex nuclei at energies above 100 MeV (^{5}) a contribution from the quasi-deuteron mechanism of interaction has been considered in order to get pure photomeson contribution for the yields of these reactions. A simple calculation, however, shows that at incident photon energies higher than 100 MeV, the kinematics of the quasi-deuteron photodisintegration leads to a neutron and a proton both with kinetic energies, E_n and E_p respectively , inside the nucleus greater than the neutron- and proton-cutoff energies, E_C^n and E_C^p, of most nuclei. Consequently, they either escape the nucleus simultaneously or, if one or both are absorbed, give the nucleus an energy sufficient to permit the evaporation of other particles. In any case an event different from a (γ,nucleon) reaction would be registered.

We report here the essentials of the calculation we performed in order to show the different energy intervals within which the quasi-deuteron primary photon interaction can lead to a (γ,n), (γ,p) and (γ,np) reactions. The following are basic assumptions:

i) the target nucleus is described by a degenerate Fermi gas of protons and neutrons confined within a nuclear potential spherically symmetric of radius given by $r_o A^{1/3}$. Different values of r_o are assumed according to the mass number A. The Fermi energies as well as the cutoff energies for protons and neutrons are calculated by the usual manner (see table I).

ii) the incident photon interacts with a correlated neutron--proton pair (quasi-deuteron) leaving the A-2 system unchanged. There are NZ possibilities of forming a neutron-proton pair, and the binding energy of the pair is taken to be -10 MeV , independent of the mass number of the target nucleus. This value was chosen following the suggestion of several authors(1,2,6) in their analysis of experimental data on differential cross sections of (γ,p) and (γ,np) reactions in light nuclei.

iii) the energy distribution between protons and neutrons from photodisintegration of quasi-deuterons is calculated within the nucleus, i.e., before the emission of particles by the nucleus and/or interaction with the remainder nucleons. Relativistic kinematics is used in deducing the energetics of the primary interaction but, for simplicity of calculation, we take the momentum of the quasi-deuteron to be zero, i.e., the mean value of a gaussian-shaped momentum distribution centered at the origin (1,2).

Our calculation is restricted to direct $(\gamma,\text{nucleon})$ reactions only, as in the framework of the model described by Stein *et al.* (7) in studying direct (γ,np) reactions in complex nuclei. For a given incident photon of energy E_γ, let E_p and E_n be the laboratory kinetic energies of the proton and neutron, respectively , after the photodisintegration of a quasi-deuteron obtained according to assumptions ii) and iii). Let us denote E_C^p and E_C^n the cutoff energies for protons and neutrons, respectively, as calculated following assumption i), then the conditions which must be satisfied in order simple direct $(\gamma,\text{nucleon})$ reactions to occur in complex nuclei are:

$$(2) \qquad \left\{ \begin{array}{l} E_p < E_C^p \\ \\ E_n > E_C^n \end{array} \right. \qquad , \text{ for a } (\gamma,n) \text{ reaction;}$$

$$(3)\qquad \begin{cases} E_p > E_C^p \\ E_n < E_C^n \end{cases} \quad \text{, for a } (\gamma,p) \text{ reaction,}$$

and for a (γ,np) reaction the conditions read:

$$(4)\qquad \begin{cases} E_p > E_C^p \\ E_n > E_C^n \end{cases} \quad .$$

We must also consider that, even though one or both particles have a kinetic energy below the cutoff energy for the nucleus under investigation, the likelihood there still exists that this particle can give rise to an intranuclear cascade followed by the evaporation step ([8]).

The results of the analysis as described above are presented in table II. As an example, we illustrate in fig. 1 the case of a 70-MeV incident photon on ^{30}Si.

From inspection of table II, the conclusion can be drawn that, for target nuclei with $A \lesssim 40$, both the (γ,n) and (γ,p) reactions cannot be imputable to the quasi-deuteron mechanism for incident energies in excess of about 100 MeV. Also, it is seen that, for $40 \lesssim A \lesssim 80$, simple photoreactions such as (γ,n) and (γ,p) cannot originate from the primary quasi-deuteron mechanism of interaction at energies $E_\gamma \gtrsim 120$ MeV, and for $A \gtrsim 80$ at energies $E_\gamma \gtrsim 150$ MeV. On the contrary, (γ,np) reactions can always take place for incident energies above about 90 MeV, regardless of the mass number of the target nucleus. The above conclusions are supported by the observation that, at an incident photon energy of 150 MeV, Monte Carlo calculations ([8])

have shown that at least one nucleon is ejected from the target nucleus during the fast intranuclear cascade step, leaving a residual nucleus with an excitation energy of about 50 MeV, regardless of the mass number of the struck nucleus. Such an excitation energy may cause the evaporation of a relative large number of nucleons or, in the case of heavy nuclei, may also lead to fission.

In order to explain the non-zero values of the yields of (γ,n) and (γ,p) reactions above 100 MeV, recent papers by Gari and Hebach (^{9}) and Hebach *et al.* (^{4}) give detailed description of the dynamical aspects of the above photoreactions by introducing nucleon-nucleon correlations through meson exchanges. The physical processes are described by a transition matrix which has contributions from the shell-model, nucleon-nucleon correlations and exchange effects. In the case of (γ,n), (γ,p), (γ,np) and other photoreactions, these authors successfully analyse the cross sections of such reactions at energies above 60 MeV in terms of their transition matrix formalism. From the trends of the (γ,n) and (γ,p) reactions cross sections (^{4,10}), a dependence of the cross section on photon energy of the type aE_γ^{-b} can be deduced, where a and b depend on the particular photoreaction under consideration. For $^{12}C(\gamma,n)^{11}C$ and $^{16}O(\gamma,n)^{15}O^g$ reactions, values of $a \approx 10^8$mb and $b \approx 5$ have been found (E_γ being expressed in MeV). In the case of $^{16}O(\gamma,p)^{15}N^g$ reaction somewhat higher values have been deduced, viz., $a \approx 5 \times 10^8$mb and $b \approx 5.5$ (*).

(*) An analysis of the trends of (γ,n) reaction cross sections in light nuclei at energies above 50 MeV carried out by the authors (J.B. Martins *et al.*, to be published) has shown that, for simple direct (γ,n) reactions, the energy-dependence of the cross sections turns out to be proportional to E_γ^{-10} .

When evaluating the contributions from the low- and intermediate-energy tail to the cross sections measured at energies above 100 MeV, several authors ([5,11,12]) have assumed a E_γ^{-3}-dependence of the cross sections of (γ,n) and (γ,p) reactions for photon energies above about 40 MeV. In this way, though, the low-energy tail is remarkably overestimated with respect to the more recent findings of Hebach *et al.* ([4]). In the case of $^{12}C(\gamma,n)^{11}C$ reaction, in fact, at $E_\gamma = 100$ MeV the cross section arising from a E_γ^{-3}-dependence turns out to be a factor about 4 higher than that calculated from the E_γ^{-5}-dependence. With increasing E_γ, this factor also increases and reaches the value 30 at 300 MeV.

Up now, direct comparison of the predictions from the recent model proposed in ([4]) with measurement is possible only for a little number of light nuclei. More experimental information is clearly needed for to test the validity of the model for somewhat heavier nuclei.

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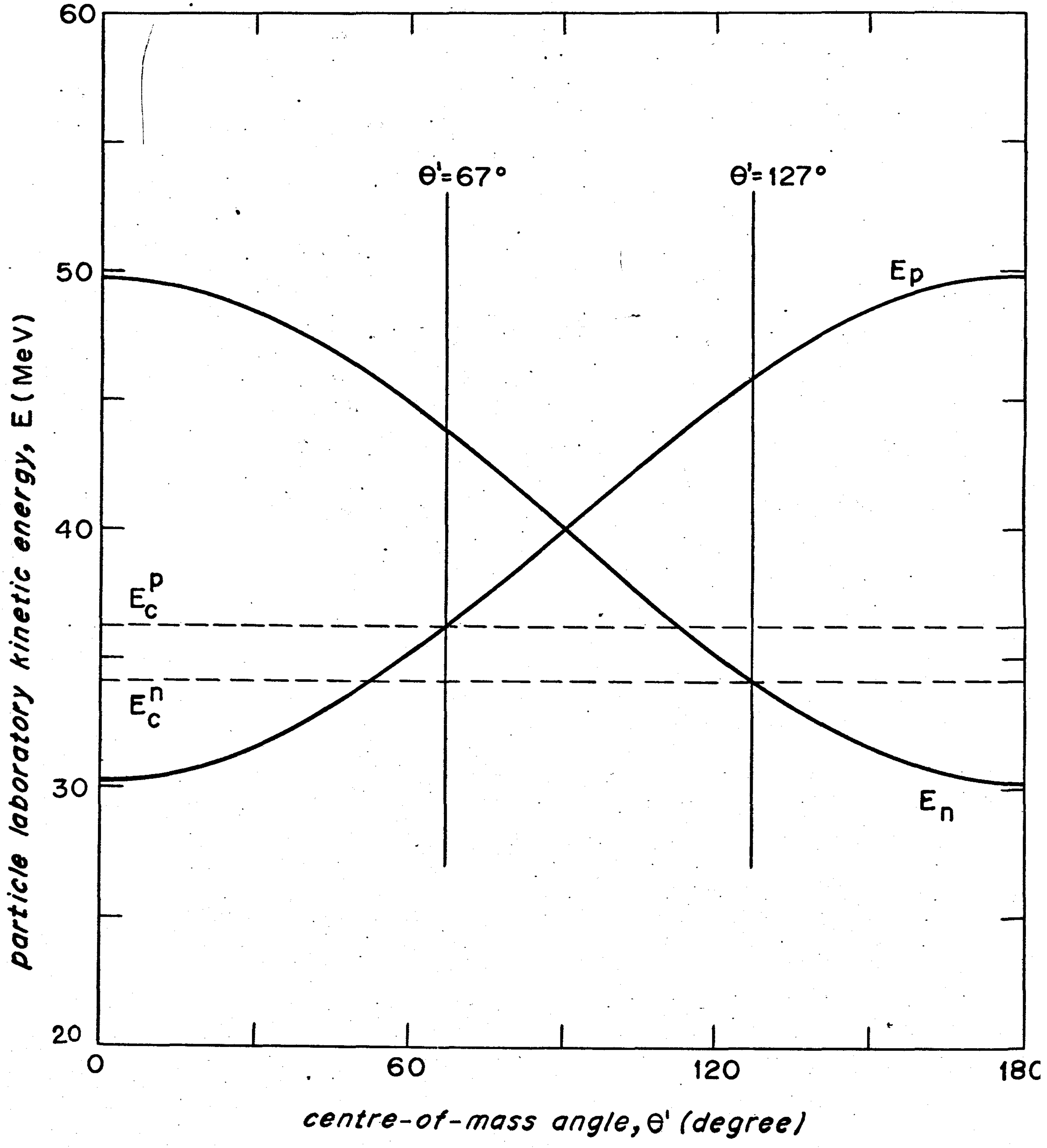
TABLE I - *Nuclear parameters used in the present calculation.*

Nucleus	Radius parameter r_o(fm)	Fermi energy(MeV)		Average binding energy of loosest nucleon (MeV)	Coulomb energy at surface (MeV)	Cutoff energy ([a]) (MeV)	
		Protons	Neutrons			Proton	Neutron
^{9}Be	1.4	22.7	26.3	6.4	1.5	30.6	32.7
^{14}N	1.4	24.6	24.5	7.5	2.6	34.7	32.0
^{30}Si	1.4	23.4	25.6	8.5	4.3	36.2	34.1
^{40}Ca	1.3	28.5	28.5	8.6	6.2	43.3	37.1
^{75}As	1.3	26.1	30.7	8.7	8.4	43.2	39.4
^{127}I	1.2	29.6	37.0	8.5	12.4	50.5	45.5
^{209}Bi	1.2	28.7	37.8	7.9	16.6	53.2	45.7

(a) The cutoff energy was calculated as the Fermi energy plus the average binding energy of the loosest nucleon plus (in the case of protons) the Coulomb energy at surface.

TABLE II - *Photon-energy regions (expressed in MeV) within wich simple* (γ,n), (γ,p) *and* (γ,np) *reactions can occur.*

Type of reaction	Target nucleus ^{9}Be	^{14}N	^{30}Si	^{40}Ca	^{75}As	^{127}I	^{209}Bi
(γ,n)	45-71	44-85	47-91	51-117	55-117	64-146	65-158
(γ,p)	43-78	48-76	50-83	60-94	60-103	73-126	77-129
(γ,np)	> 53	> 57	> 61	> 71	> 73	> 86	> 89



60
50
40
30
20
0
60
120
180
particle laboratory kinetic energy, E (MeV)
centre-of-mass angle, θ' (degree)
θ'=67°
θ'=127°
E_p
E_n
E_c^p
E_c^n