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Nucleon effective mass effects on the Pauli-blocking function

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The effects of nucleon effective mass on the Pauli-blocking function are worked out. We have shown that such effects on the quasi-deuteron mechanism of photonuclear absorption are rather relevant. The Pauli-blocking function has been evaluated by applying a Monte Carlo calculation particularly suitable for simulation of intranuclear cascade processes of intermediate-energy nuclear reactions. The nucleon binding in the photonuclear absorption mechanism is accordingly taken into account.

Key-words: Pauli-blocking; Photonuclear reactions; Intranuclear cascade.

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I. INTRODUCTION

Since the early studies of the semiclassical [1–4] and quantum molecular [5,6] dynamics for intermediate-energy heavy-ion collisions, the problem of implementing the Pauli exclusion principle for interacting fermionic many-body systems has been discussed as one of the key aspects for the models. Different levels of refinement in the prescriptions have been presented in the literature [7–12] in order to overcome this difficulty. The most recent version of quantum molecular dynamics, with explicit antisymmetrization of the many-packet nucleon trial wave function for the system, seems to be a reasonable self-consistent tool for calculation of the interacting many-nucleon system, including the Pauli principle [9,10,13–17]. We also refer the reader to a recent and comprehensive review article by Feldmeier and Schnack for details on the different versions of these models [18]. It is important to remark the relevance of having a practical and consistent prescription to include Pauli-blocking in a microscopic description of the nuclear medium in order to better discuss the liquid-vapor phase transition [19–21], and its implication on the fragmentation of hot nuclei appearing in the final state of heavy–ion collisions at the intermediate energy region. Pauli-blocking is decisive to determine the many-nucleon clusterization process during the stage of the compound nuclear system disassembling [15,22–24], being necessary to have a more complete knowledge of the N-body distribution function in the phase space.

On the other hand, when we are dealing with nuclear processes at lower excitation energies such that the nucleus is not so drastically modified by fragmentation processes, it is unnecessary to have a detailed description of the complete N-body distribution function. In these cases, Pauli-blocking effects for internucleon collisional processes can be introduced in a more simplified way. This is, for example, the case for photonuclear reaction processes at energies below the meson photoproduction threshold, the so-called quasi-deuteron photonuclear absorption region ($\sim$30–140 MeV). The first proposal for a phenomenological Pauli-blocking function in these processes was presented by Levinger [25], who reformulated his original model [26] to better describe the nuclear photo-absorption cross section.

In the beginning of the nineties an attempt by Chadwick and co-workers [27] arises to establish theoretical bases for the phenomenological Pauli-blocking function introduced by Levinger. The theoretical scenario considered to discuss the blocking has been the non-interacting Fermi gas, therefore Chadwick *et al.* have used the free nucleon mass for defining kinematic relationships and nucleon phase-space boundaries. However, we show that there is still room to extend Chadwick's calculation to interacting nucleon gas by considering the change in the kinematic relationships and phase-space boundaries introduced by the use of a nucleon effective mass. Such a change can be qualitatively understood in terms of inclusion of the nucleon interaction in a mean field approximation for relativistic meson-nucleon as it is done in Walecka's theory [28–30]. In fact, a number of calculations for the nucleon effective mass have been carried out including phenomenological adjustment to the nuclear properties or by considering many-body approaches for different forms of the nucleon-nucleon interaction in the context of both non-relativistic [31–34] and relativistic [28–30] mean field theories.

II. PAULI BLOCKING FUNCTION IN QUASI-DEUTERON NUCLEAR PHOTOABSORPTION

To discuss the Pauli blocking in quasi-deuteron photoabsorption, Chadwick *et al.* [27] introduced a Fermi gas model to describe the nucleus, and defined the blocking function at zero temperature as

$$f(\epsilon) = \frac{\int_0^{k_F}\int_0^{k_F} d^3\mathbf{k}_\nu\, d^3\mathbf{k}_\pi \rho(1p,\mathbf{k}_\nu)\ \rho(1p,\mathbf{k}_\pi)\ \sigma_{qd}\ (\mathbf{k},\epsilon_\gamma)\ F(\mathbf{k}_\nu,\mathbf{k}_\pi,\mathbf{k}_\gamma)}{\int_0^{k_F}\int_0^{k_F} d^3\mathbf{k}_\nu\, d^3\mathbf{k}_\pi \rho(1p,\mathbf{k}_\nu)\ \rho(1p,\mathbf{k}_\pi)\ \sigma_{qd}\ (\mathbf{k},\epsilon_\gamma)}, \tag{1}$$

where

$$F(\mathbf{k}_\nu,\mathbf{k}_\pi,\mathbf{k}_\gamma) = \frac{\rho^P(2p,E,\mathbf{k})}{\rho(2p,E,\mathbf{k})}. \tag{2}$$

Here, $\rho^P(2p,E,\mathbf{k})$ represents the neutron-proton state density when the Pauli principle is taken into account, given by [27]

$$\begin{aligned}\rho^P(2p,E,\mathbf{k}) = \int\int d^3\mathbf{k}'_\nu\, d^3\mathbf{k}'_\pi \rho(1p,\mathbf{k}'_\nu)\rho(1p,\mathbf{k}'_\pi)\delta(E - {k'_\pi}^2/2m - {k'_\nu}^2/2m) \\ \times\delta(\mathbf{k} - \mathbf{k}'_\pi - \mathbf{k}'_\nu)\Theta(k'_\pi - k_F)\Theta(k'_\nu - k_F).\end{aligned} \tag{3}$$

In Eq. 2, $\rho(2p,E,\mathbf{k})$ is the same neutron-proton state density but without considering the Pauli principle. This corresponds to eliminate the step functions in the above expression for $\rho^P(2p,E,\mathbf{k})$. The delta functions in Eq. 3 take into account the energy-momentum conservation in the kinematics of the neutron-proton pair photodisintegration process, and the theta step-functions impose the blocking on the nucleon final state. In Eqs. 1-3 k_F is the Fermi momentum, $\mathbf{k}_\nu$, $\mathbf{k}_\pi$ and $\mathbf{k}'_\nu$, $\mathbf{k}'_\pi$ are, respectively, the initial and final nucleon momenta, $(\epsilon_\gamma,\mathbf{k}_\gamma)$ is the energy-momentum 4-vector of the incident photon, and $(E,\mathbf{k})$ represents the total energy and momentum of the photon and neutron-proton pair.

Note that the two-particle state density is expressed as a product of the one-particle state density for neutron, $\rho(1p, \mathbf{k}'_\nu) = 3N/(4\pi k_F^3)$, times the one-particle final state density for proton, $\rho(1p, \mathbf{k}'_\pi) = 3Z/(4\pi k_F^3)$. In all expressions above the integrals are six-dimensional in phase space, constrained to the hypersurface of momentum and energy conservation for the initial and final nucleon states,

$$\mathbf{k}_\nu + \mathbf{k}_\pi + \mathbf{k}_\gamma = \mathbf{k}'_\nu + \mathbf{k}'_\pi \, , \tag{4}$$

$$\epsilon_\nu + \epsilon_\pi + \epsilon_\gamma = \epsilon'_\nu + \epsilon'_\pi \; . \tag{5}$$

The purpose of the present work is to introduce the blocking for nucleon excitation by means of a procedure which can be applied to photonuclear, as well as to proton-nucleus and nucleus-nucleus reactions. The procedure consists in to simulate by a Monte Carlo calculation the quasi-deuteron photodissociation process, rejecting those events for which the nucleon final state has kinetic energy less than the Fermi energy. The Monte Carlo histories are generated by choosing initial nucleon momenta in the nucleus according to a Fermi distribution. The neutron-proton pair is randomly chosen inside the nucleus, and the kinematic relationships for the disintegration process are solved according to Eqs. 4-5. If the final kinetic energy of one of these nucleons is smaller than the Fermi energy, the process is blocked. Another history is generated, a new neutron-proton pair is chosen and the procedure is repeated for different Monte Carlo configurations of the neutron-proton pair in the target nucleus, until statistical convergence is reached after N_{rep} Monte Carlo trials. To determine the Pauli blocking function we have to calculate the ratio of the number of blocked disintegration events to the total number of Monte Carlo trials,

$$f^P(\epsilon_\gamma) = \frac{\text{Number of blocked disintegrations}}{N_{rep}}. \tag{6}$$

This result substitutes Eq. 1 in our approach.

Since the final nucleon state is determined by means of kinematic relationships (Eqs. 4-5), and these should take into account the fact that the involved nucleons are bound, it is interesting to discuss the effect of the nuclear binding o**n** the results obtained for the Pauli blocking function in Eq. 6. For instance, in the context of a simple relativistic field theory [28,29], the nucleon mass receives a shift due to the scalar field, $m^* = m - g_\sigma \sigma$ (m is the free nucleon mass and g_σ denotes the nucleon-σ coupling constant), and the nucleon momentum should be changed correspondingly to an effective value, $\mathbf{k}_{eff} = \mathbf{k} - g_\omega \omega$ (here g_ω is the nucleon-ω coupling constant). However, in the mean field approximation for spherically symmetric system the spatial contribution of the vector field to the effective momentum vanishes. The change in the nucleon energy is represented by the use of the effective mass in the dispersion relation, $[(\mathbf{k}^2 + m^{*\,2}]^{1/2}$, and by the uniform shift in the energy levels, $\epsilon = g_\omega \omega_\mathbf{0} + [(\mathbf{k}^2 + m^{*\,2}]^{1/2}$. From the point of view of quasi-deuteron disintegration kinematic relationships established in Eqs. 4-5, this uniform shift in the energy is completely irrelevant. Therefore, in discussing the blocking of bound nucleons in the mean field approximation, we can solely use the change in effective mass to represent the binding effect. Several approaches to discuss nuclear matter in relativistic or non-relativistic mean field approximation can lead to different values of effective mass. In order to cover possible values obtained in these different approaches we have used the effective mass value as a numerical parameter to discus the effect of the nuclear binding on the Pauli-blocking function.

III. RESULTS AND CONCLUSION

In order to compare our results with those obtained by Chadwick *et al.* [27], we have focused on the quasi-deuteron mechanism for photonuclear reactions. A Monte Carlo sampling method has been used to calculate directly the blocking function. Also, in order to discuss the effect of binding on the Pauli blocking function we have varied the value of the nucleon effective mass $m^* = \alpha\, m$ within the range $0.4 \leq \alpha \leq 1.0$.

Results for the blocking function using the free nucleon mass and characteristic values of effective mass in the range appearing in the literature [28–34] are depicted in Fig.1-a, showing a significant change in the blocking when different values of the effective mass are used. Note that our curve for $\alpha = 1.0$ is in good agreement with the results presented by Chadwick *et al.* [27] obtained for free nucleon mass. The small difference observed in the high energy region is probably due to the fact that in our method the blocking function is extracted from a direct Monte Carlo simulation of the quasi-deuteron photodisintegration, whereas in Ref. [27] it is obtained by solving numerically a multidimensional integral in nucleon phase-space, in terms of which the blocking function is defined.

In Fig. 1-b, Levinger's phenomenological blocking curves for two current values of the damping parameter ($D = 60$ MeV and $D = 80$ MeV in the exponential form e^{-D/ϵ_γ}, where ϵ_γ is the photon energy), and Chadwick's result are presented for the sake of comparison with those in Fig. 1-a . Our Monte Carlo simulation procedure reproduces Chadwick´s results [27] for the blocking functions at finite temperature by sampling the nucleon momentum in the nucleus, using the partially degenerate Fermi distribution. For temperature greater than zero, the decrease of the effective mass increases the blocking effect, which leads to smaller values of the Pauli-blocking function. In Fig. 2 we illustrate this effect on the blocking functions for $T = 10$ MeV (part-a) and $T = 20$ MeV (part-b).

Finally, we call attention to recent experiments with a direct measure of the Pauli-blocking in the context of a two-spin state interacting degenerate Fermi atomic gas where collisions between these two states have been observed as blocked near Fermi temperature (see Ref. [35] and references therein).

In conclusion, in the present work we have studied the relevance of the effective mass to the Pauli blocking function for the quasi-deuteron nuclear photoabsorption mechanism. We have shown that results by Chadwick et al. [27] can be reproduced by our method of defining the blocking function when a free nucleon mass is used, both at zero and finite temperatures. We have also observed that the effect of decreasing effective mass is to make stronger the blocking, both at zero and finite temperatures.In addition, and as it should be expected, the increasing of temperature weakens the blocking. Finally, we wish to emphasize that the present procedure to include Pauli-blocking in semi-classical computational simulation of photonuclear reaction can be directly applied to nucleon-nucleus and nucleus-nucleus reactions as well.

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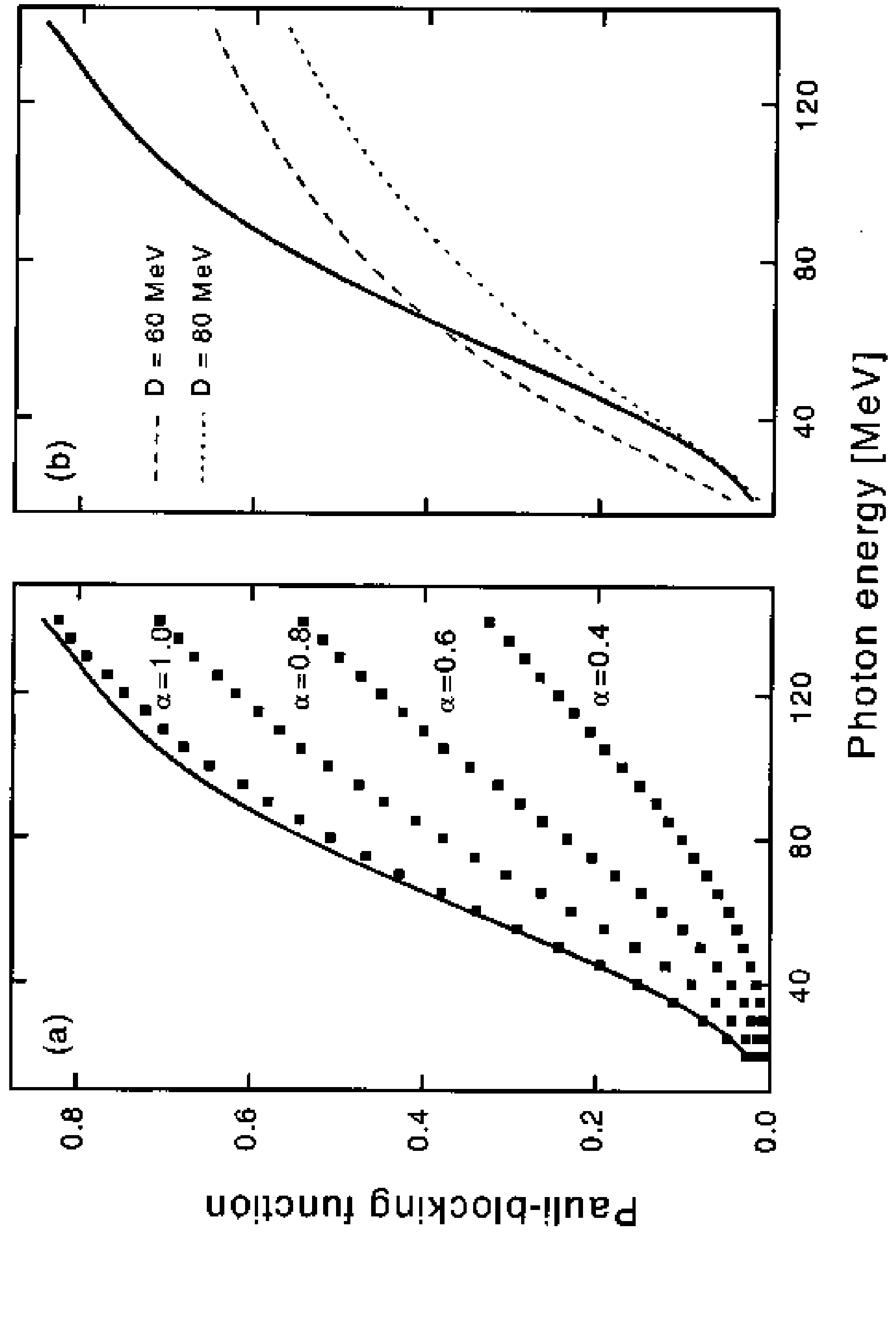
Figure Captions:

Fig. 1: Quasi-deuteron Pauli-blocking as a function of incident photon energy. The full line represents the result by Chadwick *et al.* [27] for $T = 0$. Our Monte Carlo simulation for the blocking function with $m^* = \alpha m_0$ (the in-medium nucleon mass) is represented by squares for different values of α (part-a). For comparison, Levinger's phenomenological function e^{-D/ϵ_γ} is shown for two values of the damping parameter D as shown in part-b.

Fig. 2: Pauli-blocking function at finite temperature for different values of the nucleon effective mass. In part-a we show results for $T = 10$ MeV, and in part-b for $T = 20$ MeV. The full lines represent the results by Chadwick *et al.* [27].

S.R. de Pina et al. Figure 1



S.R. de Pina et al. Figure 2