MULTIPLE PARTICLE AND CLUSTER EMISSIONS FROM ^{90}Zr FOLLOWING INTERMEDIATE ENERGIES PHOTOABSORPTION

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A new approach based on a N–α cluster photoabsorption model is proposed for the understanding of the puzzling steady increase behavior of the $^{90}Zr(e,\alpha)$ yield measured at the National Bureau of Standards (NBS) within the Giant Dipole Resonance and quasideuteron energy range. The calculation takes into account the pre-equilibrium emissions of protons, neutrons and alpha particles in the framework of an extended version of the multicollisional intranuclear cascade model (MCMC). Another Monte Carlo based algorithm describes the statistical decay of the compound nucleus in terms of the competition between particle evaporation (p, n, d, α, ^{3}He and t) and nuclear fission. The results reproduce quite successfully the $^{90}Zr(e,\alpha)$ yield, suggesting that pre-equilibrium emissions of α particles are essential for the interpretation of the exotic increase of the cross sections.

I. INTRODUCTION

In a recent work[1], we have shown that the steady increase of the ^{90}Zr(e,p) yield measured at the National Bureau of Standards (NBS)[2] can be attributed by the contribution of a collective Isovector Giant Quadrupole Resonance (IVGQR) and multiple proton emissions during the pre-equilibrium (PE) step following the quasideuteron (QD) channel. The reaction mechanism associated with the QD contribution is supposed to occur via a two-step process, namely, the pre-equilibrium and compound nucleus (CN) decay. The first step is characterized by the presence of few high energy particles embedded in a Fermi gas and is addressed via the Monte Carlo Multicollisional intranuclear cascade model (MCMC)[3,4]. The last step is described under the context of the Weisskopf statistical theory[5] and the fission model proposed by Vandenbosch and Huizenga[6]. The basic concepts and parameterizations used for the calculation of the evaporation process are described elsewhere[1,3,4].

The MCMC model has been widely used in broad domains of target masses and incident energies, as shown in recent works of π^0 photoproduction from ^{12}C and ^{208}Pb near the Delta (1232) resonance and in the range from 4.0 to 6.0 GeV (Refs. 7 and 8). In other recent calculation[9], the MCMC model has also been successfully applied for the interpretation of the η photoproduction yields from Be and Cu obtained at Cornell for a bremsstrahlung end-point energy of 9.0 GeV (Ref.10).

In this work, we propose a preliminary analysis of the ^{90}Zr(e,α) yield taking into account the Giant Dipole Resonance (GDR) and Isovector Giant Quadrupole Resonance (IVGQR) decays, as well as the QD plus an additional N–α cluster photoabsorption mechanism that should compete at higher energies. The highlights and basic features of the calculations are outlined below.

II. THE N–α CLUSTER PHOTOABSORPTION MODEL

The tremendous success of the QD model[11] for the interpretation of photonuclear reactions in the range from 40 to 140 MeV has naturally shadowed the search for additional and more exotic photoabsorption mechanisms that could contribute for the reaction process. However, few open problems at intermediate energies are still not fully understood. For instance, the quasideuteron model cannot account for the progressive increase of the α yield from ^{90}Zr obtained more than two decades ago at the NBS[2]. The total photoabsorption cross section predicted by the QD model presents a smooth decrease in the range $100 \leq E_\gamma \leq 140$ MeV, while the remaining excitation energy of the CN does not increase enough within this energy range for counteracting the general trend of the cross section. Such result leads to a fairly flat (γ,α) cross section due to the nearly constant branching ration (BR) of α decay during the evaporation step.

The photofission cross sections in actinide nuclei within the QD regime[12] depend very strongly upon the excitation energy of the CN and are also strong evidence of another underling photoabsorption mechanism that could account for the increase of the (γ,f) cross section well below pion threshold – a result clearly not consistent with the QD channel.

These open problems motivated the development of a N–α cluster photoabsorption model, which is based on the following general assumptions:

i) Pre-equilibrium emissions of α particles require necessarily the clusterization of the nuclear matter;

ii) If an α particle is embedded in a Fermi gas, then a two-body interaction between the α particle and a surrounding nucleon can originate a correlated object, herein denoted N–α cluster. This system could be interpreted as an induced dipole that could absorb E1 radiation from an external field (incoming photon) as far as the interaction between the constituents of the cluster takes long enough compared with the photo-nuclear excitation. Some empirical information that support this assumption are the half lives for the decays ^{5}Li —> pα (~4x10^{-22} sec.) and ^{5}He —> nα (~11x10^{-22} sec.), which are both consistent with a typical time interval for a nuclear reaction;

iii) Neglecting the α particle break-up – which is strongly suppressed in nuclei due to the Pauli principle – the splitting of the constituents of the N–α cluster originate two different cascade branchings;

iv) The mechanism of photoabsorption due to the N–α splitting is also Pauli suppressed, since the constituent nucleon should has final momentum higher than the Fermi momentum. The final momentum of the α particle does not require $k_\alpha > k_F$ since it consists of a spin-zero particle;

v) The cross section of N–α splitting is supposed to be energy independent for this exploratory analysis. An important experimental evidence in favor of such approximation is the cross section of ^{7}Li(γ,α)t break-up, which exhibits a flat behavior above approximately 30 MeV. For lower energies, however, N–α cluster photoabsorption is Pauli suppressed (see below) and the structures of the cross section of ^{7}Li break-up are not relevant.

So, to the extent that these assumptions and approximations are reasonable, the N–α cluster model represents a powerful constraint to account for the pre-equilibrium emissions of α particles. Furthermore, the CN configuration after the cascade stage due to the N–α cluster photoabsorption also contributes for the increase of the α yield, since the remaining excitation energies are considerably high.

III. RESULTS

III. A. Pauli-Blocking Function

Since the N–α cluster is embedded in a Fermi gas one has to account for the short range correlations during the photoabsorption mechanism. Such analysis is performed using Monte Carlo techniques and assuming an isotropic angular distribution for the outgoing constituents of the N–α system in the center of mass frame of the cluster. The final momentum of the nucleon should satisfy $k_N > k_F$ and the ratio between the Pauli-allowed events to the total number of events gives directly the Pauli-blocking function $f(\omega)$.

The results for $f(\omega)$ are presented in Fig. 1 both for the QD and N–α cluster initial interactions. It is clearly observed that below approximately 20 MeV – where structures might be relevant for the elementary cluster splitting – the Pauli-blocking function $f_{N-\alpha}(\omega)$ (solid line) drastically reduces the cross sections in the nuclei. The effect of the short range correlations is negligible for the N–α cluster model above approximately 40 MeV in contrast with the QD model, since the later requires both nucleons to have $k_N > k_F$. Another important consequence of the proposed model is that the outgoing nucleon carries the major fraction of the available kinetic energy of the system, reinforcing our assumption that the α particle break-up is in fact very unlikely to occur at both the photoabsorption step and at each binary αN scattering process during the cascade stage.

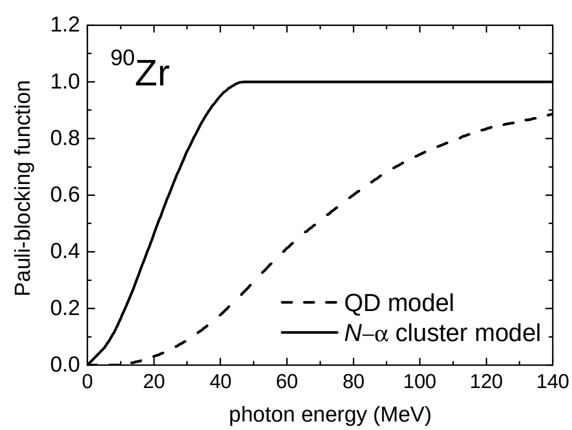

Fig. 1: Pauli-blocking functions for the QD (dashed line) and N–α cluster model (solid line).

III. B. Alpha Emission Branching Ratios and The ^{90}Zr(e,α) Yield

After absorbing the incoming photon, the constituents of the N–α cluster trigger two correlated intranuclear cascade processes. Both particles distribute their energies with the bound nucleons (*p-h* excitations) via secondary scatterings, most likely accompanied by the pre-equilibrium emissions of high energy particles. For low incident energies – typically below 40 MeV – the fraction of kinetic energy carried out by the α particle is not high enough for overcoming the Coulomb barrier, causing a relative increase of the excitation energy of the CN in comparison with the QD channel. As the incoming energy increases, the probability of pre-equilibrium emissions of α particles also increases, propitiating the enhancement of the double α emission probability (one α particle emitted during the PE and another one during the CN decay). The corresponding BR of single and double α emission for the QD and *N*–α cluster photoabsorption mechanisms are shown in Fig. 2.

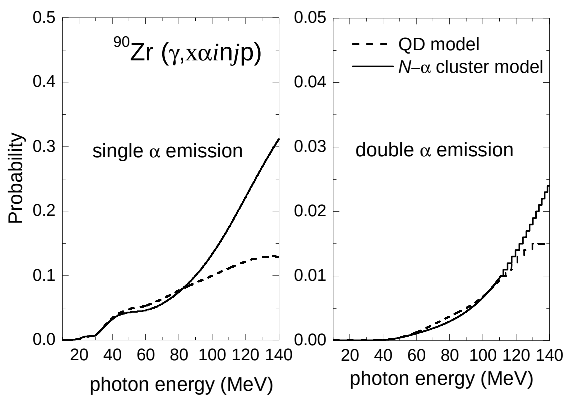

Fig. 2: Probability of single (left) and double α emission (right) from the QD (dashed lines) and *N*–α cluster (solid lines) models.

It is clearly observed that the *N*–α cluster model gives much higher BR above approximately 80 MeV due to the contribution of the PE stage, which does not contribute for α emission in the QD model.

The inclusive α photodisintegration yield can be written as:

$$\sigma_{\gamma,S\alpha} = \sum_x x\sigma_{\gamma,x\alpha} = \sigma_{\gamma,1\alpha} + 2\sigma_{\gamma,2\alpha} + \ldots, \quad (1)$$

with $\sigma_{\gamma,x\alpha} = \sum_{i,j}\sigma_{\gamma,x\alpha injp}$ representing the inclusive cross section for the emission of x alphas with *i* neutrons and *j* protons. So, using the BR for the four mechanisms considered (GDR, IVGQR, QD and *N*–α), we write the α photodisintegration yield in the form:

$$\sigma_{\gamma,S\alpha} = \left(C_0\sigma_{GDR}(\omega) + C_1\sigma_{IVGQR}(\omega)\right)\Gamma^R_{\gamma,S\alpha} + \sigma_{QD}(\omega)\Gamma^{QD}_{\gamma,S\alpha} + C_2 f_{N-\alpha}(\omega)\Gamma^{N-\alpha}_{\gamma,S\alpha}, \quad (2)$$

where the constants C_0 and C_1 and the shapes of σ_{GDR}, σ_{IVGQR} and σ_{QD} were taken from our previous analysis of the ^{90}Zr(e,p) yield[1]. $f_{N-\alpha}$ (ω) is the Pauli-blocking function for the *N*–α cluster, while the strength C_2 is to be determined by fitting the α yield. The branchings labeled with (*R*) are the α emission probabilities from the resonance decay and include only the evaporation part (direct emissions of α particles are neglected for the GDR and IVGQR decay). The other branchings Γ^{QD} and $\Gamma^{N-\alpha}$ refer to the probability of α emission in the QD model (evaporation only) and *N*–α cluster model (PE plus evaporation), respectively.

The α electrodisintegration yield can be calculated folding the photodisintegration yield with the virtual photon spectra $S^{\lambda l}(E_e,\omega)$, which were calculated in Distorted Wave Born Approximation [13]:

$$\sigma_{e,S\alpha} = \sum_{\lambda l}\int_{B_\alpha}^{E_e}\frac{d\omega}{\omega}S^{\lambda l}(E_e,\omega)\sigma_{\gamma,S\alpha} \quad (3)$$

The GDR and QD channels have E1 character, while the IVGQR has E2. The *N*–α cluster channel is interpreted as an induced *N*–α dipole embedded in a Fermi gas and should also present an E1 character. So, one directly obtains:

$$\begin{aligned}\sigma_{e,S\alpha}(E_e) = {} & C_0\int\frac{d\omega}{\omega}S^{E1}(E_e,\omega)\sigma_{GDR}(\omega)\Gamma^R_{\gamma,S\alpha} + \\ & C_1\int\frac{d\omega}{\omega}S^{E2}(E_e,\omega)\sigma_{IVGQR}(\omega)\Gamma^R_{\gamma,S\alpha} + \\ & \int\frac{d\omega}{\omega}S^{E1}(E_e,\omega)\sigma_{QD}(\omega)\Gamma^{QD}_{\gamma,S\alpha} + \\ & C_2\int\frac{d\omega}{\omega}S^{E1}(E_e,\omega)f_{N-\alpha}(\omega)\Gamma^{N-\alpha}_{\gamma,S\alpha}\end{aligned} \quad (4)$$

All the quantities in eq. (4) were previously determined by fitting the proton data[1], except the constant C_2 which has to be obtained by fitting the α yield. The results of the fitting are presented in Fig. 3, where we have obtained $C_2 = 7.46 \pm 14$ mb with χ2/n.d.f. = 1.55. The sum of the GDR, IVGQR and QD contributions is represented by the dashed line and does not account for the steep increase of the cross section at higher energies, providing a poor description of the data above approximately 40 MeV.

The inclusion of the N–α cluster component (dotted line) provides a much better fitting (solid line) to the data at higher energies. On the other hand, the sum of the GDR, IVGQR and QD channels fit the data reasonably well up to 40 MeV, showing that the statistical decay of the CN is properly calculated with our evaporation routine.

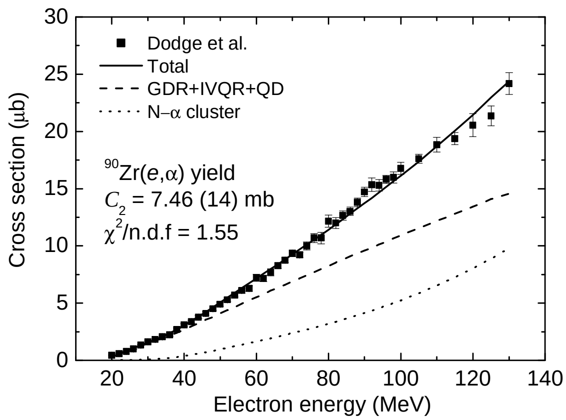

Fig. 3: ^{90}Zr(e,α) yield obtained at the NBS (data points) versus the fitting proposed by eq.(4) (solid line). The sum of the contributions of the GDR, IVGQR and QD channels is represented by the dashed line, while the dotted line represents the prediction from the N–α cluster model.

Clearly this analysis is just the beginning. For our next step, we need to take into account, for instance, the influence of the N–α cluster model in other observables, such as the proton yield from ^{90}Zr. Such deep investigation requires a complete and simultaneous analysis of the (e,p) and (e,α) yields from ^{90}Zr, which will be subject of a forthcoming publication[14].

IV. CONCLUSIONS AND FINAL REMARKS

A preliminary analysis of the ^{90}Zr(e,α) yield measured at the NBS[2] was carried out combining an extended version of the MCMC intranuclear cascade model and another Monte Carlo routine to describe the evaporation step.

A N–α cluster photoabsorption model was introduced assuming that α particles are embedded in ^{90}Zr and interact with the bound nucleons forming a dipole like system. The model accommodates pre-equilibrium emissions of α particles in a straightforward procedure, taking into account short range correlations in a time dependent non-stochastic approach.

The branching ratios of single and double α emissions fit the data remarkably well, providing a consistent explanation for the exotic behavior of the alpha yields from ^{90}Zr in terms of multiple α emission from the PE as well as the CN decay.

A further investigation of the contribution of the N–α cluster to the proton and neutron cross sections is required for a stringent and unambiguous test of the N–α cluster model.

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