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Photofission of ^{182}W following reabsorption of photopions

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The electrofission cross section of ^{182}W was measured in the range 80–180 MeV. A pronounced inflexion, corresponding to a sharp structure in the (γ,f) curve, shows up around 140 MeV. A photofission model, based on a photopion-deuteron reabsorption process, was worked out to explain this finding. Good agreement between calculation and experimental data was achieved.

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It has been shown recently [1,2] that subtle peculiarities of the photofission cross section, in preactinide nuclei, are originated by the reabsorption mechanisms of photopions, which mainfest themselves determining the total amount of energy deposited in the nucleus. It was found that near the photopion threshold (~140 MeV), in particular, structures in the photofission cross sections of Au and Ta can be interpreted qualitatively in terms of a high photopion absorption probability, like in a "stopped pion absorption regime [1]." It was pointed out that there was a clear necessity of both new experiments, to confirm the existence of the photofission structures, and a better description of the photofission process. In this Rapid Communication we report on results for another preactinide nucleus: ^{182}W. Also, we propose a "photofission model" for energies near the photopion threshold, which explains previous results, for Au and Ta [1], and those now obtained for ^{182}W.

A target of ^{182}W, ~650 μg/cm^2 thick, was irradiated with the electron beam of the Tohoku University Linac (Sendai) with energies from 80 to 180 MeV in steps of 5 (around 140 MeV) and 10 MeV. The electron beam was monitored by means of a secondary emission device. Mica foils were used as fission detectors. We used the same apparatus and experimental conditions of previous experiments (details in Refs. [1] and [2]).

In Fig. 1 is shown the electrofission cross section $\sigma_{e,f}$ of ^{182}W; a well-delineated inflexion shows up at ~140 MeV confirming, thus, the findings reported for Au and Ta [1]. It is a well-known fact that inflexions in the (e,f) curve correspond to structures in the photofission cross section $\sigma_{\gamma,f}$, because

$$\sigma_{e,f}(E_e)=\int_0^{E_e}\sigma_{\gamma,f}(\omega)N^{E1}(E_e,\omega)\frac{d\omega}{\omega}\,, \tag{1}$$

where E_e is the incident electron energy, ω is the photon (real or virtual) energy, and $N^{E1}(E_e,\omega)$ is the $E1$ virtual photon spectrum. The inclusion of $E1$ transitions, only, was justified elsewhere [2].

The unfolded (γ,f) cross section, obtained by means of a least-structure unfolding technique (as described in Ref. [2]), is shown in Figs. 1 and 2. The pronounced structure, with a peak at 140 MeV, cannot be explained as a consequence of fluctuations in the fissility, which is a smooth function of the energy (see detailed discussion in Refs. [1] and [2]). We propose here a model to describe the photofission cross section structure around the photopion threshold, as described below.

The starting point of our approach is the definition of photofission cross section at intermediate energies, proposed by us elsewhere [1–3],

$$\sigma_{\gamma,f}(\omega)=\sum_{A_c,Z_c}\int_0^{\omega}N(E_x,\omega)\sigma_c(A_c,Z_c;E_x,\omega)\times P_f(A_c,Z_c;E_x)dE_x\,, \tag{2}$$

where $\sigma_c(A_c,Z_c;E_x,\omega)$ is the cross section for the formation of a compound nucleus (A_c,Z_c) with excitation energy

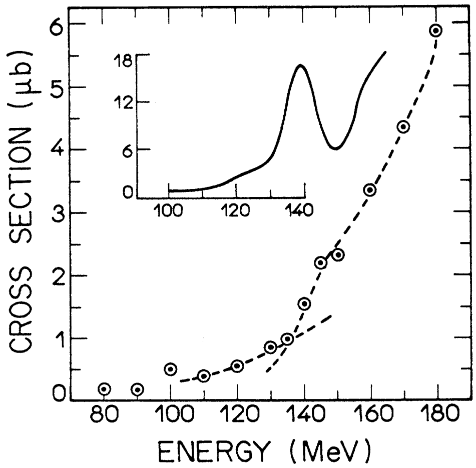

FIG. 1. Electrofission cross section of ^{182}W (data points); the dashed lines are to guide the eye. The inset shows the corresponding unfolded photofission cross section (also shown in Fig. 2).

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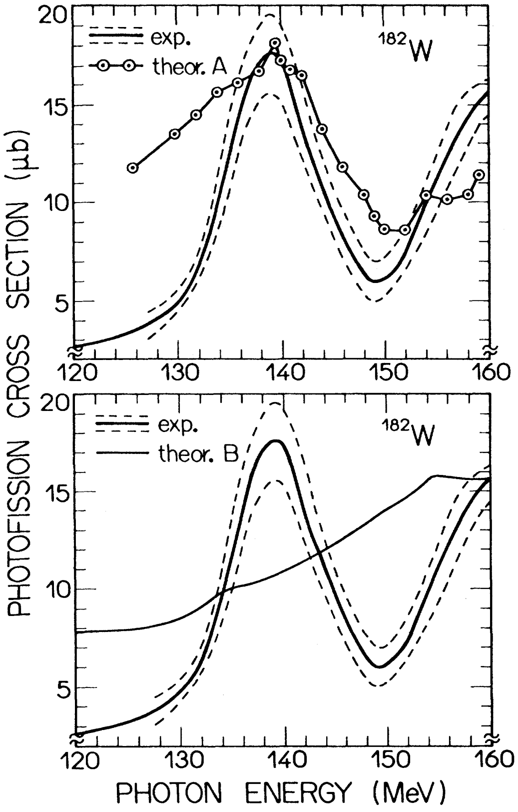

FIG. 2. Photofission cross section of ^{182}W experimentally deduced in this work (solid curve with uncertainty band). The single solid curve and the curve —⊙—⊙— were theoretically obtained (details in the text).

E_x, P_f is its fission probability, and $N(E_x,\omega)dE_x$ is the probability of finding a compound nucleus with excitation energy between E_x and E_x+dE_x; all possible E_x values are comprised in the interval $0-\omega$.

In the photon energy range pertinent to this paper, the A_c—and Z_c—distributions are sharp [4]. Thus, we can simplify our theoretical approach by assuming that *only one* compound nucleus, a "mean compound nucleus" $(\bar{A}_c,\bar{Z}_c)$, is formed. Also, we can relate $\sigma_c(\bar{A}_c,\bar{Z}_c)$ to the total photoabsorption cross section $\sigma_T(\omega)$, as deduced elsewhere [3], by

$$\sigma_c(\bar{A}_c,\bar{Z}_c;E_x)=K\,\frac{E_x}{\omega}\,\sigma_T(\omega),\quad \text{with}\quad E_x=E_x(\omega), \tag{3}$$

where K is a phenomenological factor (details in Ref. [3]).

Substituting Eq. (3) in Eq. (2) we obtain

$$\sigma_{\gamma,f}(\omega)=K\,\frac{\sigma_T(\omega)}{\omega}\int_0^{\omega}N(E_x,\omega)E_xP_f(\bar{A}_c,\bar{Z}_c;E_x)dE_x. \tag{4}$$

We note that at $\omega\lesssim180$ MeV the E_x distributions are sharp and symmetric around the mean value $\bar{E}_x$; thus, it is reasonable to replace E_x by $\bar{E}_x$ in Eq. (4), obtaining

$$\sigma_{\gamma,f}(\omega)=K\sigma_T(\omega)\,\frac{\bar{E}_x}{\omega}\,\langle P_f(\bar{A}_c,\bar{Z}_c;\omega)\rangle, \tag{5}$$

where $\langle P_f(\bar{A},\bar{Z}_c;\omega)\rangle=\int_0^{\omega}N(E_x,\omega)P_f(\bar{A}_c,\bar{Z}_c;E_x)dE_x$ is the energy-weighted fission probability of the compound nucleus.

All the physical quantities appearing in Eq. (5) are structureless functions of the photon energy ω, particularly around the photopion threshold ($\omega\approx140$ MeV). Therefore, for the description of the (γ,f) structures systematically observed around 140 MeV in preactinide nuclei (Ta, Au, and ^{182}W), and less pronounced in ^{232}Th [1], it is necessary to introduce, explicitly, a mechanism responsible for drastic variations in the total amount of energy deposited in the nucleus (i.e., the excitation energy E_x). It has been suggested that a strong photopion reabsorption near the threshold (like the "stopped pion absorption regime"; see discussion in Ref. [1]) could account for the experimentally observed (γ,f) structures around 140 MeV.

In this regard, we propose to define the mean excitation energy in the following way:

$$E_x=\left(\frac{\sigma_{QD}}{\sigma_T}\right)E_{QD}+\left(\frac{\sigma_{\pi}}{\sigma_T}\right)E_{\pi}, \tag{6}$$

where σ_{QD} and σ_{π} are the cross sections for the two leading photointeraction mechanisms, quasideuteron and photopion production, respectively, while E_{QD} and E_{π} are the corresponding energies deposited in the nucleus; it is obvious that $\sigma_T=\sigma_{QD}+\sigma_{\pi}$.

In the case of photopion production we have that

$$E_{\pi}=P_RE_{\pi,R}+(1-P_R)E_{\pi,S}, \tag{7}$$

where $E_{\pi,R}$ and $E_{\pi,S}$ are the energies deposited when the pion is reabsorbed, or when the pion escapes from the nucleus, respectively; P_R is the pion reabsorption probability. Thus,

$$E_{\pi,R}=\omega-E_{PE}, \tag{8}$$

$$E_{\pi,S}=\omega-E_{PE}-(m_{\pi}+T_{\pi}), \tag{9}$$

and

$$E_{QD}=\omega-E_{PE}, \tag{10}$$

where E_{PE} is the sum of the energies of all particles emitted in the preequilibrium stage (the fast stage); m_{π} and T_{π} are the rest and kinetic energies of the pion, respectively.

Since $m_{\pi}\approx140$ MeV, for energies ω around the photopion threshold ($\omega\approx140$–150 MeV) we can assume that $E_{\pi,S}\approx0$; with this approximation we come to

$$E_{\pi}\cong P_R(\omega-E_{PE}). \tag{11}$$

Finally, the pion reabsorption probability is given by

$$P_R=\frac{\sigma_{\pi,R}}{\sigma_{\pi}}, \tag{12}$$

where $\sigma_{\pi,R}$ is the pion reabsorption cross section in the nucleus; this is the most important ingredient of our approach (see below).

Substituting Eqs. (10)–(12) in Eq. (6), we get

$$E_x = (\omega - E_{PE})\left(\frac{\sigma_{QD}+\sigma_{\pi,R}}{\sigma_T}\right). \tag{13}$$

Guaraldo and collaborators [4,5] performed detailed Monte Carlo calculations based on the intranuclear cascade model and obtained $(\omega - E_{PE})$, for several preactinide and actinide nuclei, in the photon energy range 100–300 MeV. For $\omega \lesssim 160$ MeV, $(\omega - E_{PE})$ is a smooth rising function of ω. The cross section σ_{QD} is nearly constant for $\omega \gtrsim 100$ MeV. Therefore, a possible structure in $E_x = E_x(\omega)$, Eq. (13), would be generated by a corresponding abrupt variation in $\sigma_{\pi,R}$. Since the fission probability of preactinide nuclei is a sensitive function of E_x, a structure in $E_x = E_x(\omega)$ would give rise to a structure in the photofission cross section $\sigma_{\gamma,f}(\omega)$. So, our last and most important task is the estimation of $\sigma_{\pi,R}$.

We consider, first, the fact that mostly charged pions are photoproduced [6] and, second, that reabsorption takes place by means of proton-neutron pairs, similarly to the elementary pion absorption process $\pi^+ d \rightarrow pp$, with the remainder of the target acting as a spectator. This is particularly true at low pion energies, while near the Δ resonance the two nucleon absorption process (2NA) represents the major fraction of the pion absorption cross section (see, e.g., Ref. [13] and references therein).

Thus, we assume that photopions inside the nucleus are also reabsorbed by "quasideuterons" with a cross section very close to $\sigma_{\pi d}$ (pion absorption cross section on *free* deuterons), at energies near the photopion threshold. Calling N_{QD} the number of quasideuterons "seen" by one photopion inside the nucleus, and making a full analogy with the modified Levinger quasideuteron model [7], we express the photopion reabsorption cross section by

$$\sigma_{\pi,R}(\omega) = N_{QD} e^{-D/\omega} \sigma_{\pi,d}(T_\pi), \tag{14}$$

where $T_\pi = T_\pi(\omega) \cong \omega - m_\pi$, and D is a phenomenological parameter related to Pauli blocking (details in Ref. [7]).

N_{QD} is a constant characteristic of the target nucleus. More specifically, the number N_{QD} of p-n pairs *effectively* involved in photofission was obtained by Kaniadakis *et al.* [8]; for ^{238}U, $N_{QD} = 243$, while for the low-fissioning preactinide nuclei, $N_{QD} \cong 7$ (see Table 2 of Ref. [8]).

We calculated the parameter D around $\omega = 140$ MeV (corresponding to $T_\pi \approx 0$), since at these energies we can assume that $P_R \approx 1$ [6]; then, from Eqs. (12)–(14),

$$e^{-D/\omega} = \frac{1}{N_{QD}} \frac{\sigma_\pi}{\sigma_{\pi d}}. \tag{15}$$

We found out that $D \approx 100$ MeV, which is reasonable for pions since for QD photoabsorption $D \approx 60$ MeV [7]. At $\omega \approx 300$ MeV we obtained, for D, a value $\sim 10\%$ lower reflecting, thus, the fact that near the Δ resonance 2NA is no longer the dominant process (see discussion in Ref. [13]).

Within the theoretical approach proposed in this work, we calculated $\sigma_{\gamma,f}$ from Eq. (5), using $\bar{E}_x(\omega)$ values derived from Eq. (13) [and from Eq. (14) for $\sigma_{\pi,R}$]. The quantities $(\omega - E_{PE})$, σ_T, σ_{QD}, and $\sigma_{\pi d}$ were taken from the literature (see above). For the calculation of $\langle P_f \rangle$ we used $N(E_x, \omega)$ distributions obtained elsewhere [4,5], and $P_f(E_x)$ from the statistical model for fission (using the procedures discussed in Ref. [3]). The results were normalized to the experimental data at $\omega \approx 140$ MeV—Fig. 2(a). We would like to make salient the following points.

(1) Except for the normalization at 140 MeV, there are no free parameters in our approach. Therefore, it is possible to say that good overall agreement with the experimental curve (unfolded curve, in fact) was achieved for $\omega \gtrsim 132$ MeV (see below).

(2) The energy position of both peak (~ 140 MeV) and valley (~ 150 MeV) of the (γ,f) curve is remarkably well reproduced by the calculation.

(3) The calculated peak-to-valley cross section ratio agrees with the experimental one within $\sim 20\%$.

(4) The energy position of the valley at ~ 150 MeV corresponds to $T_\pi \approx 10$ MeV. We observe that the experimentally obtained $\sigma_{\pi d} = \sigma_{\pi d}(T_\pi)$ curve exhibits a valley around $T_\pi = 10$ MeV (see Fig. 4.6 of Ref. [6]).

Also, we calculated the photofission cross section without incorporating the pion-deuteron mechanism described in this paper. In this case, E_x would be equal to $(\omega - E_{PE})$, and not as expressed by Eq. (13). As shown in Fig. 2(b), a structureless curve was obtained (we normalized at $\omega = 160$ MeV).

We note in passing that the calculation of fission probabilities at lower energies is quite sensitive to fission barrier parameters, neutron binding energies, level density parameters, etc., as shown, e.g., by Dias *et al.* [9] for the photofission of actinide. Since fission barrier heights of preactinides are ~ 25–30 MeV, their fission probabilities at $\omega \lesssim 130$ MeV (or, $E_x \lesssim 70$ MeV) [4] are dependent on shell effects, while for $\omega \gtrsim 140$–150 MeV (or, $E_x \gtrsim 80$ MeV) shell effects tend to disappear (see discussion in Ref. [10]). In our calculations of P_f we used liquid-drop quantities calculated by the method of Myers and Swiatecki [11], using procedures and routines from Ref. [3]. This explains the disagreement between our (γ,f) calculations and the experimental data below the photopion threshold [Figs. 2(a) and 2(b)] which, however, does not change our main conclusions at $\omega \gtrsim 140$ MeV.

It is clear that our approach needs further improvements (underway) but, even in its current simple version, it describes reasonably well the photofission structure around the photopion threshold. This is compelling evidence supporting the possibility that the behavior of photopion reabsorption in complex nuclei is driven mostly by elementary πd processes. We note, in this regard, that our calculations underestimate the data above $\omega \approx 155$ MeV (corresponding to $T_\pi \gtrsim 15$ MeV). This is probably due to the fact that non-2NA processes play a very significant role at higher pion energies, while near the threshold $(T_\pi \approx 0)$ $\sigma_{2\mathrm{NA}}/\sigma_{\mathrm{abs}} \approx 100\%$ (σ_{abs} is the total pion absorption cross section)—see, e.g., Fig. 4 of Ref. [13].

We are currently refining our approach by including three-body processes, that is: the photoproduced pion is first inelastically scattered by a single nucleon and then absorbed by a p-n pair. Preliminary calculations indicate that a better agreement in the valley region (around $\omega = 150$ MeV) could be achieved (will appear elsewhere soon [12]).

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