Photoexcitation mechanisms investigated through the fission channel

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An approach for the delineation of the compound nucleus excitation energy, from the photofission cross section at intermediate energies, is worked out. An application for ^{182}W, Au, and Ta is presented. The potential of this formalism, for the study of pion properties inside the nuclear medium, is discussed. [S0556-2813(96)04312-9]

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Pion propagation in nuclear matter is a key issue in pion physics, and the available information so far obtained has come mostly from pion absorptions studies [1]. However, pions interact so strongly that whatever process they induce is likely to originate in nucleons in the low-density nuclear surface. On the other hand, since nuclear matter is very transparent to photons, pion photoproduction would occur, in principle, with equal probability in the nuclear volume. This would allow the study of pions behavior in the *dense portion* of the nuclear medium, too. In this report we propose a new formalism for the analysis and interpretation of photonuclear reaction through the fission decay channel, as an alternative for the study of pion-nucleus interaction. This formalism was applied in the interpretation of recent electrofission data obtained at Sendai for ^{182}W, Ta, and Au.

The absorption of an intermediate energy photon initiates an intranuclear cascade (the fast step) in which particles of the continuum leave the nucleus (preequilibrium emission) all along until thermal equilibration (compound nucleus formation). In the second step (the slow step) the compound nucleus evaporates or goes into fission. Thus, because of preequilibrium emissions, the excitation energy E_x of the compound nucleus is only a fraction of the incident photon energy ω. For photon energies above the pion threshold m_π ($\sim$140 MeV) the amount of energy deposited (E_x) is strongly dependent on the ''story'' of the photopion as, e.g., if the pion escapes or not from the nucleus. Therefore, the experimental extraction of the function $E_x = E_x(\omega)$ would provide us with information about pions in the nuclear medium, as shown below.

Assuming that the fission decay proceeds through compound nucleus formation, the experimental photofission cross section is given by [2]

$$\sigma_{\gamma,f}(\omega) = \sum_{(A_c,Z_c)} \sigma_c(A_c,Z_c;E_x)\cdot P_f(A_c,Z_c;E_x), \quad (1)$$

where σ_c is the cross section for the formation of the compound nucleus (A_c,Z_c), P_f is its fission probability, and $E_x = E_x(\omega)$.

In the photon energy range pertinent to this paper, the A_c and Z_c distributions are not broad. In fact, we know from Monte Carlo calculations that, for $\omega \approx 200$ MeV, $A_c \cong A - 1.5$ and that $Z_c \cong Z - 0.5$, where (A,Z) is the target nucleus [3]. Thus, we can simplify our approach by assuming that *only one* compound nucleus is formed: the mean compound nucleus $(\overline{A_c},\overline{Z_c})$ with a mean excitation energy $E_x = E_x(\omega)$. With this approximation we obtain

$$\sigma_{\gamma,f}(\omega) = \sigma_c(\overline{A_c},\overline{Z_c};\overline{E_x})\cdot P_f(\overline{A_c Z_c};\overline{E_x}). \quad (2)$$

We also note that [4]

$$\frac{\sigma_c(\overline{E_x})}{\overline{E_x}} = K\cdot\frac{\sigma_T(\omega)}{\omega}, \quad (3)$$

where σ_T is the total photoabsorption cross section, and K is a factor phenomenologically introduced in Ref. [4] and physically defined in Ref. [5].

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

$$\omega\cdot\frac{\sigma_{\gamma,f}(\omega)}{\sigma_T(\omega)} \equiv F^{\exp}(\omega) = K\cdot\overline{E_x}(\omega)\cdot P_f(\overline{A_c},\overline{Z_c};\overline{E_x}). \quad (4)$$

The quantity $F^{\exp}(\omega)$ is entirely obtained from the experimental data, while the function $K\cdot E_x\cdot P_f$ is obtained by means of a theoretical calculation (details below). The solution of Eq. (4) for $\overline{E_x}(\omega)$ is achieved graphically; this is done for ^{182}W, Ta, and Au (see below). The reasons for the choice of preactinide nuclei were discussed at length elsewhere [2,6].

The electrofission cross sections $\sigma_{e,f}$ of ^{182}W, Ta, and Au, were recently measured at the Tohoku University Linac (Sendai) — the results are shown in Fig. 1; experimental details in Refs. [2,6,7]. It is interesting to note that these three preactinides exhibit shoulders at the same energy posi-

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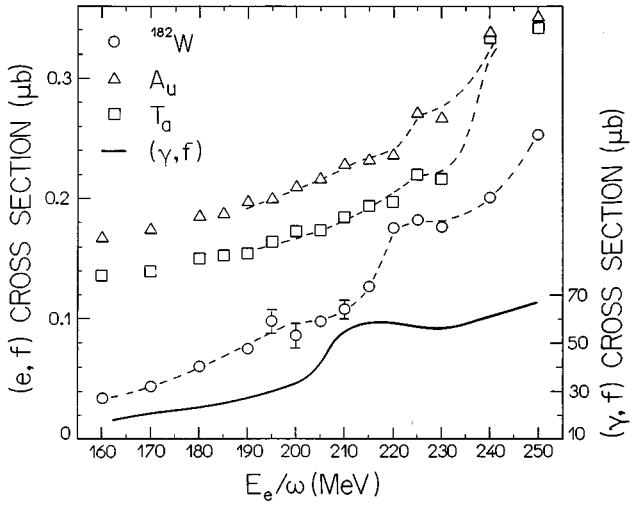

FIG. 1. Data points: electrofission cross section of Ta, Au, and ^{182}W (left-hand scale). Solid curve: unfolded photofission cross section of ^{182}W (right-hand scale) — uncertainties are ~10%. The dashed curves are to guide the eyes.

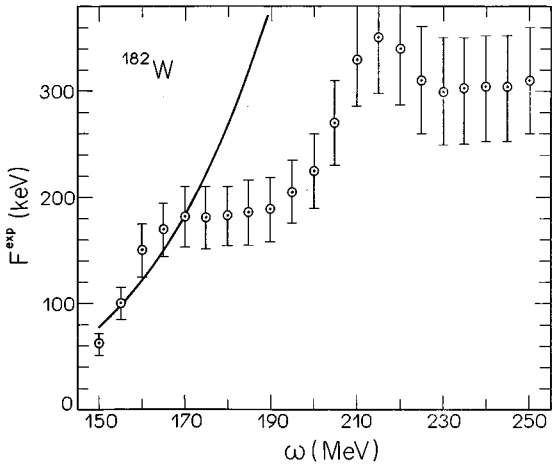

FIG. 2. The experimental quantity $F^{\exp}$, defined by Eq. (4), as a function of the incident photon energy. The solid curve was obtained from a simulation where photopions escaping from the nucleus are not considered.

tion ($E_e \approx 220$–230 MeV; see Fig. 1) — this is a convincing evidence to the fact that the same ''physical effect'' is present in all these nuclei. These structures are associated, of course, with the corresponding ones in the (γ,f) curves.

From the virtual-photon theory we know that

$$\sigma_{e,f}(E_e)=\int_0^{E_e}\sigma_{\gamma,f}(\omega)N^{E1}(\omega,E_e)\frac{d\omega}{\omega}, \tag{5}$$

where N^{E1} is the $E1$-virtual-photon spectrum, and E_e is the incident electron. In Ref. [2] is the detailed justification for the use of only the $E1$ component.

The delineation of $\sigma_{\gamma,f}$ was performed both by the unfolding of $\sigma_{e,f}$ [Eq. (5)] using a least structure unfolding routine, and by means of a new deconvolution technique which does not depend on virtual photon spectra and unfolding procedures (details in Ref. [8]); the results from these two techniques are identical. The curve in Fig. 1 represents the $\sigma_{\gamma,f}$ solution for ^{182}W. Since the results for ^{182}W, Ta, and Au are similar, we discuss the data analysis with more details only for ^{182}W.

By combining $\sigma_{\gamma,f}$ with σ_T taken from the literature [9,10] we calculated $F^{\exp}(\omega)$ [Eq. (4)] — Fig. 2. The extraction of $E_x=E_x(\omega)$ is accomplished by the graphic resolution of Eq. (4). To this purpose we calculated the right-hand term of Eq. (4), that is, $KE_x\cdot P_f(E_x)$, by means of well-known statistical based relations [11,12] and procedures [3,12] for P_f, plus the assumption that the level density is described by the so-called Fermi gas expression [11]. Since at $E_x \gtrsim 30$ MeV shell effects in nuclei are small, we used liquid-drop quantities calculated by the method of Myers and Swiatecki [13], in order to obtain fission barriers and neutron binding energies for all nuclei participating in the fission-chain decay (see Ref. [3] for more details). The constant K was obtained by imposing normalization of $\sigma^{\rm calc}_{\gamma,f}$ [Eqs. (2) and (3)] to the experimental (γ,f) curve around $\omega=160$ MeV, where structures are absent. We found out that $K\approx 5$ for the three nuclei, which compares well with results obtained for actinides [4]. The result for the function $K\cdot E_x(\omega)\cdot P_f(E_x)$ is shown in Fig. 3.

Finally, combining the result for $F^{\exp}$ (Fig. 2) with that from Fig. 3, that is, by imposing (Eq. (4) to them, we got graphically the functions $E_x=E_x(\omega)$ shown in Fig. 4. Although the magnitude of $E_x(\omega)$ is uncertain within ~10–15%, its shape is by far more accurate. In fact, the shoulders exhibited by $E_x(x)$ can be observed by a mere visual inspection of the (e,f) primary data (Fig. 1). In this sense, uncertainties arising from the calculation of the smooth curve $K\cdot E_x(\omega)\cdot P_f(E_x)$ do not generate structures in the solution $E_x=E_x(\omega)$; they affect absolute values only. But, anyway, we checked our calculations for $P_f(E_x)$ by comparing them with lower energy (γ,f) data ($\omega \lesssim 140$ MeV); reasonable agreement (within ~10%) was obtained for the three preactinides.

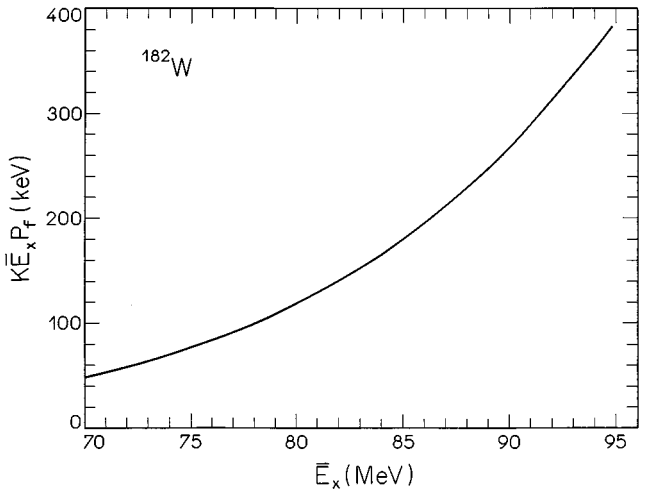

FIG. 3. The quantity $K\cdot\overline{E_x}\cdot P_f(\overline{E_x})$, as a function of the mean excitation energy $\overline{E_x}$, obtained from P_f calculated in the way described in the text.

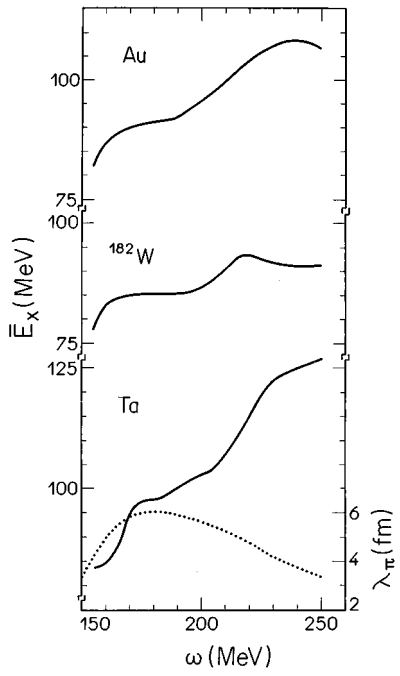

FIG. 4. The mean excitation energy $\overline{E_x}$, as a function of the incident photon energy ω (uncertainties, not shown, are $\sim 10-15$ %). The dotted-curve (right-hand scale) represents λ_π, as calculated in Ref. [15], as a function of the pion kinetic energy T_π; note that, in our case, $T_\pi = \omega - m_\pi$ (see text).

We would like to point out that the purpose of this report is the presentation of an analytical method to deduce the average excitation energy of the compound nucleus, using as main input the photofission cross section. This (γ, f) cross section can be obtained from electrofission, as in this work, or directly from tagged-photon experiments, as, e.g., those planned to be carried out in Saskatoon with actinides and preactinides [14]. Regarding the physics to be obtained from $E_x = E_x(\omega)$, we note that this is an enterprise which demands detailed theoretically based calculations and, therefore, is beyond the scope of this brief report. However, we would like to comment on the following aspects of the results shown in Fig. 4.

(1) We know from literature that at photon energies $\omega \gtrsim 150$ MeV the cross section for pion photoproduction is a steeply increasing function of ω, up to the peak of the delta resonance (~ 300 MeV), in contrast to the flat behavior of the QD-cross section at $\omega < 150$ MeV.

(2) On the other hand, our results for $\overline{E_x}(\omega)$ exhibit distinct shelves at $\omega \approx 170-200$ MeV for Au, Ta, and ^{182}W; that is, in this energy range $\overline{E_x}(\omega)$ does not respond to an increasing ω.

(3) INC–Monte Carlo calculations [3] indicate that the number of protons and neutrons emitted at the preequilibrium stage does not vary substantially for $\omega \approx 170-200$ MeV. In this case, the flat behavior of $\overline{E_x}(\omega)$ would be a consequence of an accentuated increase of the kinetic energies of the emitted particles in a narrow photon energy range; this is unlikely to happen.

(4) The pion mean free path λ_π calculated by Hecking [15], as a function of the pion kinetic energy T_π, exhibits a broad maximum around $T_\pi \cong 40$ MeV corresponding to $\omega \cong 180$ MeV, since for photopions $\omega \cong T_\pi + m_\pi$ (neglecting recoil) — see dotted line in Fig. 4.

(5) Quite compelling is the fact that the maximum of λ_π is ~ 6 fm, while the radii of the three investigated preactinides are in the interval of 6.5–7 fm. Thus photopions would have a greater probability of escaping from these nuclei at energies around the broad maximum of λ_π, which encompasses the region of the shelves ($\sim$ 170–200 MeV). Therefore, the nucleus would lose more energy in this energy region, preventing its warming up.

(6) From these arguments, we are tempted to say that we found experimental evidences supporting the ''nuclear transparency to pions'' calculated by Hecking [15], at least qualitatively.

(7) The physical nature of the shelves at $\omega \approx 230-250$ MeV (less apparent for Ta) is still an open question. However, preliminary calculations suggest that these shelves are associated to the competition between pion reabsorption mechanisms by two and three nucleons [16].

It is our hope that the issues discussed in this report could be retaken by other research groups, particularly the theoretical aspects of our findings.

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