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THERMALIZATION RELATED EFFECTS IN THE ELECTROFISSION OF PREACTINIDE NUCLEI

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ABSTRACT

The absolute electrofission cross sections of Au and Ta were measured in the energy interval 40–250 MeV. Pronounced inflexions of the (e,f) curves are observed for both Au and Ta around 220 MeV, which are signatures of structures in the corresponding photofission cross-section curves. We show that these (γ,f) structures are originated in the stage of preequilibrium emissions toward thermalization.

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The electrofission of the practinide nuclei ^{208}Pb and ^{209}Bi have been recently investigated in our Laboratory[1,2]. It was observed in the electrofission cross section curves, around 200 MeV, a clear inflexion for ^{208}Pb and a less pronounced one for ^{209}Bi. These findings were tentatively interpreted as being due to the story of the photoproduced pion inside the nucleus, as revealed by the mean free path of the photopion[2]. Although appealing, the results for ^{208}Pb and ^{209}Bi are not too compeling because: (a) the inflexions were verified only for two cases, and (b) a small number of experimental points (three or four), taken at energy intervals of 10–20 MeV, delineate the inflexions.

In this letter we present results for the electrofission cross section of the preactinides Au and Ta; the data were taken at intervals of 5 MeV around the supposed inflexion region (~ 200–220 MeV). A simple visual inspection of the cross section curves, for both Au and Ta, reveals the presence of the above mentioned inflexions for ^{208}Pb and ^{209}Bi. We show for the first time that these (e,f) inflexions, around 210–220 MeV, are related to the nuclear thermalization process at its stage of preequilibrium emissions.

Structures in the photofission cross section $\sigma_{\gamma,f}$ manifest themselves as inflexions in the corresponding electrofission cross section curve $\sigma_{e,f}(E_e)\,X\,E_e$ (E_e is the incident electron energy) because, by the virtual-photon theory,

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

where N^{E1} is the $E1$-virtual-photon spectrum, and ω is the real (or virtual) photon energy.

In the energy region above the Giant Dipole Resonance ($\omega \gtrsim 50$ MeV) we can write $\sigma_{\gamma,f}$ as

$$\sigma_{\gamma,f}(\omega) \;=\; \sum_{A_c,Z_c} \sigma_{CN}\,(A_c\,,\,Z_c\,;\,E_x)\cdot P_f\,(A_c\,,\,Z_c\,;\,E_x) \quad , \qquad (2)$$

where A_c and Z_c are the atomic masses and atomic numbers of the compound nuclei, respectively. E_x is the excitation energy, σ_{CN} is the cross section for compound nucleus formation, and P_f is the fission probability.

For a given ω, the magnitude of E_x will depend both on the number of particles emitted in the preequilibrium stage, and on the mean free path of the photopion $(\lambda\pi)$ inside the nucleus (which determines if the pion scapes or not from the nucleus); therefore, E_x is distributed between 0 and ω. In this regard, Guaraldo and collaborators3) performed calculations based on the intranuclear cascade model and obtained E_x distributions in several heavy nuclei, for photon energies ω between 100 and 300 MeV. Results for the mean excitation energy $\langle E_x \rangle$ of ^{209}Bi and ^{197}Au are shown in Fig. 1; a broad bump shows up at values of ω around 150–170 MeV. This bump is associated to λ_π as a function of the pion kinetic energy (see discusssion in Refs. 1 and 2), and it could manifest itself in the photofission cross section (Eqn. 2) because:

(1) the fission probability of a preactinide nucleus is a smooth and steep function (nearly exponential) of E_x; and

(2) the compound nucleus cross section can be expressed as4)

$$\sigma_{CN}(E_x) \;=\; \frac{E_x}{\omega}\,\sigma_{\gamma,a}(\omega) \quad , \tag{3}$$

where $\sigma_{\gamma,a}$ is the photoabsorption cross section. At energies below the peak of the delta resonance ($\sim$ 300 MeV) $\sigma_{\gamma,a}$ is a structureless function of ω. Thus, the shape of $\sigma_{CN}\,X\,E_x$ is mostly determined by the function $E_x\,X\,\omega$.

Therefore, the investigation of fine details in the shape of $\sigma_{\gamma,f}\,X\,\omega$ is a sensitive way to access the corresponding characteristics in $E_x\,X\,\omega$ which, in turn, depends on the thermalization process (as discussed below).

In view of the facts and reasonings cited above, we decided to perform a careful and detailed measurement of the electrofission cross section of Au and Ta. The difficulties

associated to possible $(e,e'f)$ exclusive measurements of preactinide nuclei have bee pointed out elsewhere5); typical single-armed fission cross sections are $10^{-3} - 1\,\mu b$. coincidence is imposed, the $(e,e'f)$ cross sections become several orders of magnitud lower than that of (e,f), which makes these experiments very time consuming.

Targets of Au and Ta with high purity were irradiated with electron beams fro the Tohoku University linear accelerator, with energies from 40 to 250 MeV in steps of and 10 MeV. Mica foils were used as fission fragments detectors, and the electron bea was monitored by means of a ferrite core monitor. Details about the procedures an experimental set up were published elsewhere1).

In Figs. 2 and 3 are shown our electrofission results for Au and Ta. Since we a interested in the details of the (e,f) curves, we decided to present linear plots for tw overlapping energy intervals: 110–195 MeV (Fig. 2) and 160–250 MeV (Fig. 3), whe inflexions show up. First of all, we would like to stress the following points:

(1) the reproducibility of the (e,f) experimental points is better than 5%, so that th inflexions and shoulders exhibited in Figs. 2 and 3 are not artifacts of the experiment fluctuations.

(2) the (e,f) curves of preactinides are steep functions of the energy, which make the presence of inflexions and shoulders much more evident.

(3) the remarkable similarity between the Au and Ta (e,f) curves dramaticall demonstrates the physical significance of the inflexions. We would say that the indepe dently obtained Au and Ta curves are "twin curves" in a normalized scale, despite th fact that their absolute values differ by nearly one order of magnitude.

A visual inspection of Figs. 2 and 3 shows that the (e,f) curves of Au and Ta exhib very similar inflexions at two energy regions: 180–185 MeV and 210–220 MeV which, a explained above, correspond to structures in the (γ,f) curves (see Eqn. 1). Howeve for the delineation of the magnitude of the (γ,f) cross section, we need to perform th unfolding of the (ϵ, f) integrated cross section. We used a least structure unfolding technique developed in our Laboratory; the results for Au are shown in Figs. 2 and 3 (solid lines). Two structures (antecipated by the visual inspection of the electrofission data) show up: a pronounced one at ~ 170 MeV, and another (a shoulder) at ~ 205 MeV.

We know from Refs. 3 and 6 that the E_x-distributions for $\omega \gtrsim 180$ MeV are broad, while for $\omega < 180$ MeV they are relatively more sharp. Thus, the function $E_x(\omega)\, X\, \omega$ is similar to $\langle E_x \rangle\, X\, \omega$ for $\omega < 180$ MeV. Therefore, since $\sigma_{\gamma,f}$ reflects shape details of $E_x(\omega)\, X\, \omega$ (see Eqs. 2 and 3), we conclude that the structure obtained for $\sigma_{\gamma,f}(\omega)\, X\, \omega$ around 170 MeV (Fig. 2) is originated by the structure of $\langle E_x \rangle\, X\, \omega$ at 160 MeV (Fig. 1), except that the latter is broader. But, considering the fact that we are comparing an experimental result with a model dependent calculation, the qualitative agreement is good. This structure is physically explained in terms of the mean free path of the photoproduced pion (see e.g. Refs. 1–3).

On the other hand, the (γ, f)-shoulder at 205 MeV is not present in $\langle E_x \rangle\, X\, \omega$. As mentioned above, the E_x-distributions are broad for $\omega > 180$ MeV; the mean values $\langle E_x \rangle$ shown in Fig. 1 exhibit large dispersions (40%–60%). Thus, finer shape details of the function $E_x(\omega)\, X\, \omega$ are smoothed out by the averaging process. We show below that the structure around 205 MeV in $\sigma_{\gamma,f}(\omega)\, X\, \omega$ is directly related to the splitting of the E_x-distribution for $\omega = 200$ MeV (see Fig. 2 of Ref. 7).

For a given ω, the E_x-distribution could be expressed by the histograms calculated by Guaraldo et al.[3], which we represent by $[N(E_{x_i}, \omega)]\, X\, E_{x_i}$, where $(E_{x_i} - \Delta E_{x_i}/2) - (E_{x_i} + \Delta E_{x_i}/2)$ is the width of the i-th histogram centered at E_{x_i}, and $N(E_{x_i}, \omega)$ is its height ($\Delta E_{x_i} = 10$ MeV). We note that E_{x_i} ranges from 0 to ω, and that $N(E_{x_i}, \omega)$ is the probability of finding a compound nucleus with excitation energy equal to E_{x_i}. Therefore, we can calculate the photofission cross section by (to compare with Eqn. 2)

$$\sigma_{\gamma,f}(\omega) = \sum_i N(E_{x_i}, \omega)\, \sigma_{CN}(E_{x_i})\, P_f(E_{x_i}) \quad ;$$

by expressing σ_{CN} as given approximately in Eqn. 3, we get

$$\sigma_{\gamma,f}(\omega) = \frac{\sigma_{\gamma,a}(\omega)}{\omega} \sum_i N(E_{x_i}, \omega) \cdot E_{x_i} \cdot P_f(E_{x_i}) \quad ;$$

Since P_f is a strong and smooth function of E_x, it is clear to note from Eqn. 5 t peculiarities of the distributions $N(E_{x_i}, \omega)$ are "amplified" by P_f, as we demonstr below.

We performed calculations for $\sigma_{\gamma,f}(\omega)$ of Au at photon energies from 180 to 260 Me using the distributions $N(E_{x_i}, \omega)$ calculated in Refs. 3 and 6, and $\sigma_{\gamma,a}(\omega)$ values tak from Ref. 8. For $P_f(E_{x_i})$ we used well-known relations, obtained from the assumpti that the level density is described by the so-called Fermi gas expression[9]. A m detailed description of our calculations for $\sigma_{\gamma,f}$ will appear elsewhere[10]; the resu are shown in Fig. 3. The qualitative reproduction of the (γ, f)-shoulder at ~ 205 M is striking. We claim that this (γ, f)-shoulder is a consequence of the splitting $N(E_{x_i}, \omega)$, for $\omega \approx 200$ MeV, into two well separate structures at $E_{x_i} \approx 25$ a 105 MeV (see Fig. 2 of Ref. 7). To check such possibility, we repeated the calculati of $\sigma_{\gamma,f}(\omega)$ for $\omega = 200$ MeV using an E_x-distribution with a shape similar to that $\omega = 220$–240 MeV, where the high-E_x structure is much lower than the low-E_x o Now, the new $\sigma_{\gamma,f}$ is lowered by a factor of two eliminating, therefore, the shoulder (in Fig. 3 the dotted curve).

Recently, Lucherini and collaborators[11] measured in Frascati the (γ, f) cross secti of Au with quasimonochromatic photons, in the energy range of 120–300 MeV. Becau of the quasimonochromatic nature of the photons, a photofission yield curve (integrat over the photon spectra) is obtained; after the unfolding of this yield curve the $(\gamma,$

cross section is delineated. It is very interesting to note that the photofission yield of Au (see Fig. 1 of Ref. 11) clearly exhibits inflexions around 180 and 230 MeV, which compare favourably with our (e,f) inflexions at 180–185 and 210–220 MeV. Therefore, the (γ,f) structures reported in this letter were previously detected in the Au(γ,f) experiment of Frascati$^{11)}$, but they were not recognized.

Finally, the physical explanation for the occurrence of a splitting in the E_x-distributions, around $\omega = 200$ MeV, demands further studies (under way at our Laboratory).

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FIGURE CAPTIONS

Fig. 1: Average excitation energy $\langle E_x \rangle$ as a function of the incident photon energy ω, for ^{197}Au and ^{209}Bi target nuclei (quoted from Refs. 3 and 6).

Fig. 2: Electrofission cross section of Au (⊙; left-hand scale) and Ta (⊡; right-hand scale); the dashed curves are to guide the eyes. The solid curve is the unfolded photofission cross section of Au (in arbitrary unit).

Fig. 3: The same as for Fig. 2, plus the calculated photofission cross section of Au (△—△ and the dotted curve; details in the text).

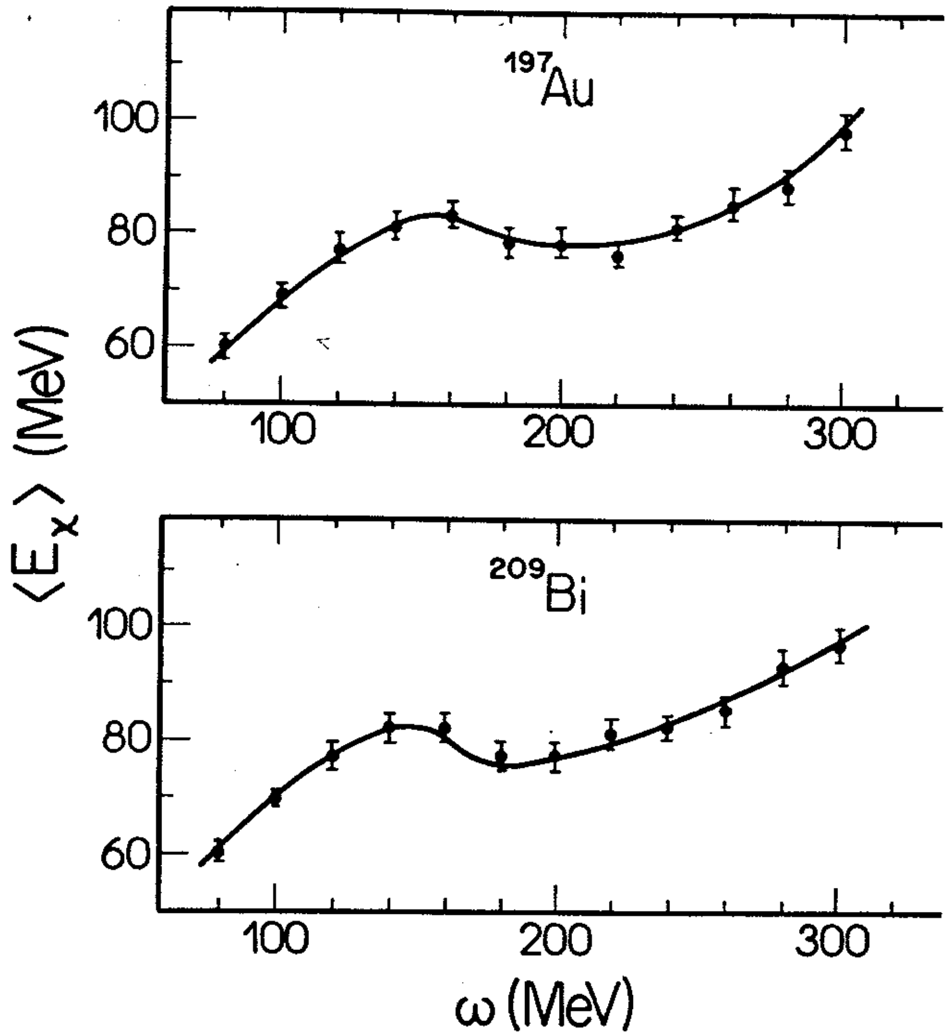

Fig. 1

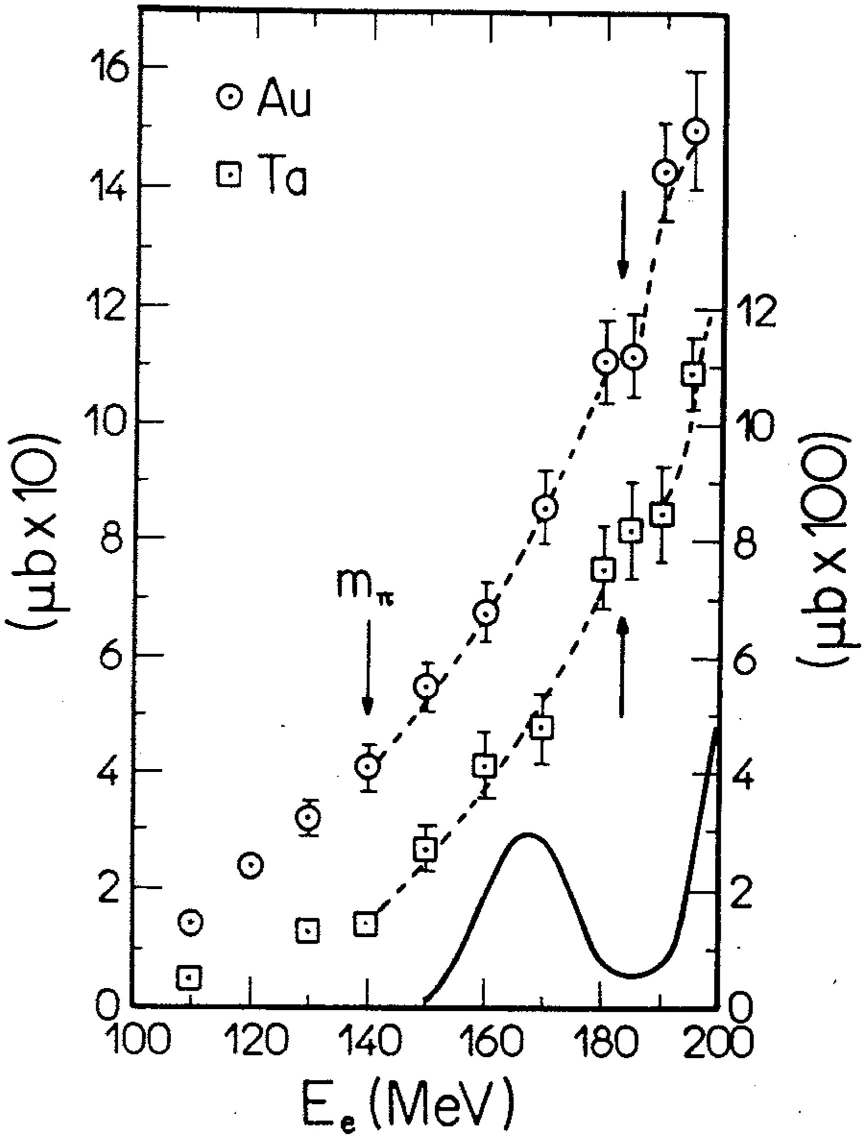
Au
Ta
m$_\pi$
0
2
4
6
8
10
12
14
16
(μb x 10)
0
2
4
6
8
10
12
(μb x 100)
100
120
140
160
180
200
E$_e$ (MeV)

Fig. 2

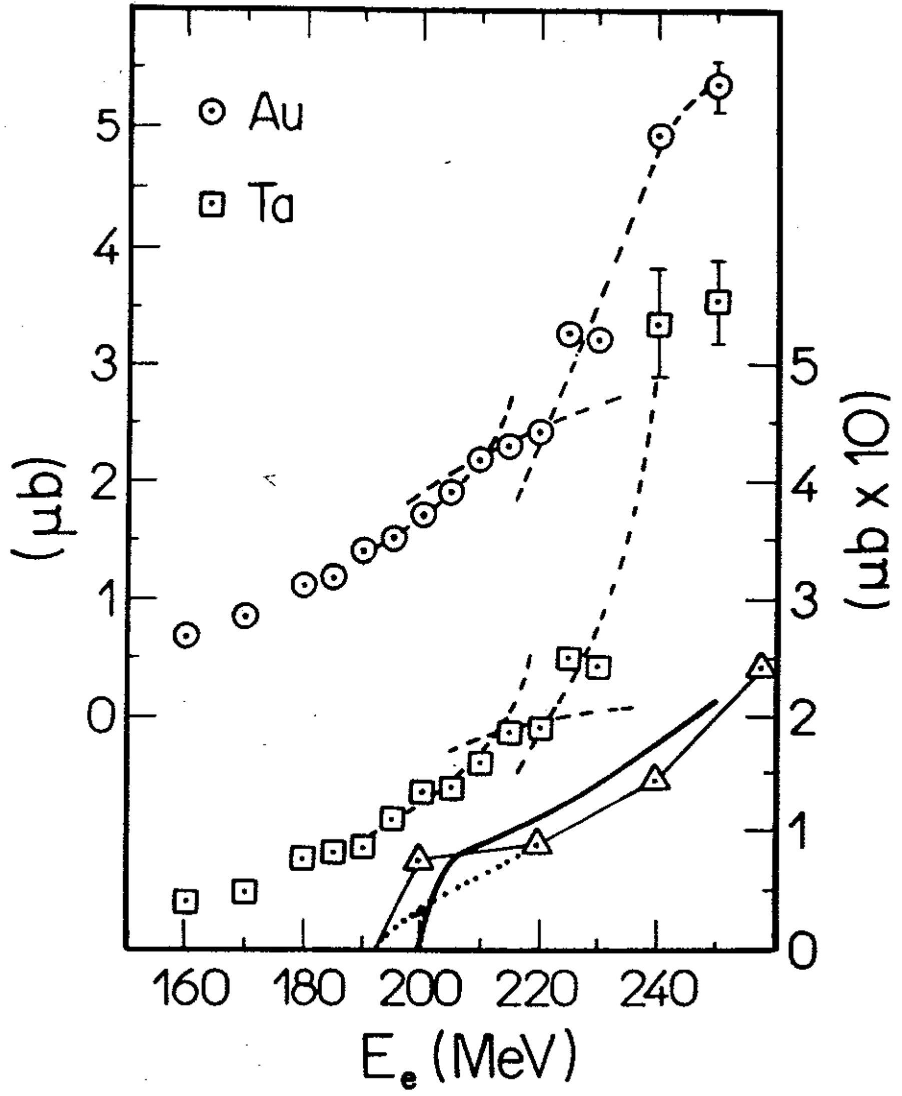
Au
Ta
0
1
2
3
4
5
(μb)
0
1
2
3
4
5
(μb x 10)
160
180
200
220
240
E$_e$ (MeV)

Fig. 3