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ABSTRACT

The absolute electrofission cross sections of Au and Ta were measured in the range 25–250 MeV. The deduced photofission cross section shows, for both Au and Ta, a pronounced dip around the photopion threshold ($\sim$ 140 MeV). This (γ, f) dip is interpreted as a consequence of a probable photopion absorption in a "stopped pion regime".

Photonuclear reactions (induced by real or virtual photons) are very suitable to probe the nuclear and nucleonic structure, for the reaction mechanism is well understood comparatively to nucleon-nucleon interactions.

The decay channels characteristics of a nucleus following photoexcitation depend on the amount of energy deposited (nuclear excitation energy) which, by its turn, is closely related to the photoexcitation mechanisms. For photon energies above $\sim$ 140 MeV, in particular, pion production is the dominant process responsible for photoabsorption. At these energies, the absorption of a photon (with energy ω) initiates an intranuclear cascade in which particles of the continuum leave the nucleus (preequilibrium emission) all along until equilibration (compound nucleus formation with excitation energy $E_x < \omega$). Therefore, 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 pion (λ_π) inside the nucleus (which determines if the pion scapes or not from the nucleus).

In fact, the role played by the photopion production in the fission of ^{209}Bi and ^{208}Pb was addressed by us elsewhere[1,2]. It was observed, for these preactinide nuclei, structures in the photofission cross sections curves at $\omega \approx$ 200–220 MeV, which were interpreted as signatures of the drastic fall of λ_π at $T_\pi \approx$ 50–70 MeV (pion kinetic energy). Above these T_π region λ_π is smaller than the nuclear radius.

The above mentioned findings, for ^{209}Bi and ^{208}Pb, motivated us to perform detailed electrofission cross section measurements for two other preactinides, Au and Ta, in order to delineate a possible systematics for this pion related structure in the photofission cross sections around $\omega \approx$ 200–220 MeV. Quite surprisingly, however, we observed a new (γ, f)-structure near the photopion threshold ($\sim$ 140 MeV), which cannot be explained on the basis of known cooling-down mechanisms of the nucleus, like preequilibrium emissions and small photopion absorption probability (described by λ_π). We propose a

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possible explanation in terms of the known "stopped pion absorption" mechanism (discussed below).

Thus, targets of Au and Ta, ~ 2.5 mg/cm^2 thick each, were irradiated with the electron beam of the Tohoku University Linac (Sendai), with energies from 40 to 250 MeV in steps of 5 and 10 MeV, and using mica foils as detectors (we refer the reader to Ref. 1 for more experimental details). Preliminary results for the energy interval 110–250 MeV were published elsewhere[3]. Since a reliable unfolding of the (γ, f) cross section requires (e, f) data down to the fission barrier, we performed electrofission cross section measurements of Au and Ta, in the interval 25–40 MeV, with the electron beam of the University of São Paulo Linac and with the same targets used in Sendai.

Our results for the (e, f) cross sections $\sigma_{e,f}$ are shown in Fig. 1, for electron energies E_e up to 170 MeV. An inflexion around m_π (~ 140 MeV) shows up for Au and Ta, which corresponds to a structure in the photofission cross section $\sigma_{\gamma,f}$, since

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

where $N^{E1}(E_e,\omega)$ is the $E1$ virtual photon spectrum. We would like to stress that the unfolding of $\sigma_{\gamma,f}$ is necessary for quantitative analysis purposes, since the visual inspection of the (e, f) curve already revealed the location of the (γ, f) structure.

The (γ, f) cross section of Au was measured at Frascati with quasimonochromatic photons, in the energy range 120–300 MeV[4]. Because of the quasimonochromatic nature of the photons,a photofission yield curve (integrated over the photon spectra) is obtained see Fig.2, adapted from Ref. 4, where we drew dashed-lines in order to make salient the three inflexions showing up in this yield curve. These inflexions were not recognized and were smoothed out in the unfolding procedure (see Fig. 4 of Ref. 4). In this regard, we note that the (e, f) cross sections of Au and Ta, up to 250 MeV [3], exhibit

three inflexions each, at nearly the same energy positions of those shown in the Frascati yield curve (Fig. 2). Also shown in Fig.1 is the (γ, f) cross section of Au, obtained from the unfolding of a Bremsstrahlung yield curve measured at Kharkov[9]. Despite the uncertainties associated to this kind of experiment, we note that the Kharkov Au (γ, f) curve also exhibits a dip around 140 MeV. The physical meaning of the inflexions around 180 MeV and 220 MeV was addressed previously[3]. In this paper we discuss the somewhat unexpected inflexion at the photopion threshold (~ 140 MeV) .

In Fig.1 is shown the unfolded (γ, f) cross section of Au, obtained by means of a least-structure unfolding technique developed at this Laboratory. A prominent dip around 140–145 MeV is observed for Au (and for Ta too, at 150 MeV), which indicates that a substantial amount of excitation energy (E_x) was lost between the photoabsorption and the compound nucleus formation processes. This could be better understood by examining the (γ, f) cross section as given by

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

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

We know that for a given (A_c, Z_c), formed from a preactinide target nucleus, P_f is a smooth and steep function of E_x, while the CN cross section could be approximately given by[5]

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

$\sigma_{\gamma,a}$ is the photoabsorption cross section, which exhibits no structure for $\omega < 300$ MeV. Eqn. 3 refers to a "mean compound nucleus" $(\overline{A}_c, \overline{Z}_c)$. For $\omega \lesssim 160$ MeV the A_c

and Z_c distributions are sharp$^{6-8)}$; this fact makes Eqn. 3 a good approximation for σ_{CN}. Also, for a given ω, it is found a distribution of E_x between 0 and ω. Since for $\omega \lesssim 160$ MeV the E_x-distributions are relatively sharper than those for $\omega \gtrsim 180$ MeV$^{6-8)}$, we can consider in our reasonings their mean values $\langle E_x \rangle$, instead of the E_x-distributions themselves.

Recently, Guaraldo and co-workers$^{6)}$ performed detailed calculations to obtain $\langle E_x \rangle \, X \, \omega$ for several nuclei in the range of ω = 100-300 MeV. It was used the intranuclear cascade model with the inclusion of the two leading photoexcitation mechanisms: quasi-deuteron photoabsorption (QD) and single nucleon photoabsorption via pion production ($\gamma N \to \pi$) on intranuclear nucleons (details in Ref. 6). In Fig. 3 are shown results for ^{197}Au and ^{209}Bi (quoted from Ref. 6).

From Fig. 3 we verify that $\langle E_x \rangle$ is increasing with ω up to 160 MeV. The change in the slope of $\langle E_x \rangle \, X \, \omega$ above 140 MeV originates from the fact that λ_π is greater than the nuclear radius R ($R \sim 7$ fm),for ω between 140 and ~ 190 MeV — thus, photopions can leave the nucleus carrying away a substantial fraction ($\gtrsim 140$ MeV) of the photon energy, but *no dip* is observed in $\langle E_x \rangle \, X \, \omega$ around 140 MeV (a shallow valley shows up at ~ 200 MeV). Also, $\langle E_x \rangle$ is slowly decreasing from 160 to 200 MeV ($\Delta \langle E_x \rangle \approx 10$ MeV between these two energies), despite the fact that $\lambda_\pi > R$ and that $\sigma_{\gamma N, \pi} > \sigma_{QD}$ — this means that only a small fraction of the photoproduced pions leaves the nucleus, while the majority is rescattered by single nucleons and finally is absorbed by nucleon-nucleon pairs. So, there is no obvious reason for this (γ, f) dip at 140 MeV, particularly if we note that the photoabsorption cross section is increasing for $\omega \geq 140$ MeV.

Then, we propose an explanation in terms of the well-known stopped pion absorption regime in the nucleus. Since the photopions produced around 140–150 MeV have kinetic energies between 0 and 10 MeV, it is reasonable that part of these pions would be absorbed in some sort of "stopped pion regime", as discussed below.

According to the quasi-deuteron model for pion absorption, a pion is absorbed by a pair of nucleons in the nucleus while the remaining nucleons act as spectators. This process is accompanied by the formation of several particles which can be emitted, rescattered or absorbed by the nucleus. In fact, the experimentally obtained spectrum of neutrons formed as a result of the absorption of stopped negative pions by the preactinide nucleus ^{208}Pb (see Fig.2 of Ref. 10) exhibits three groups of neutrons: evaporation stage neutrons, preequilibrium emission neutrons ($T_n \approx$ 20–40 MeV) and cascade stage neutrons (fast neutrons with $T_n \gtrsim 50$ MeV). This last group of fast neutrons shows a distinct peak at $T_n = 55$ MeV. Keeping this information in mind, we now show in Fig. 4 the photofissility $W_f(\omega)$ for Au and Ta, obtained from their corresponding (γ, f) cross sections; we recall that

$$W_f(\omega) = \frac{\sigma_{\gamma,f}(\omega)}{\sigma_{\gamma,a}(\omega)} \quad . \tag{4}$$

We evidence that W_f, at its minimum around $\omega = 140$ MeV, has the same magnitude as for $\omega \cong 85$ MeV indicating, therefore, that the nucleus looses an"extra" amount of excitation energy of about 55 MeV. This finding compares favorably with the fast neutrons region of the ^{208}Pb neutron spectrum (mentioned above), suggesting that the (γ, f) dip is originated by the emission of fast nucleons produced in the absorption of the photopions, with characteristics similar to the "stopped pion absorption regime". Another stringent evidence, supporting this interpretation, is given by the experimentally obtained fission probability of Au and Ta by stopped negative pions, $P_f(\pi^-)$, shown in Fig. 4 (quoted from Fig. 10 of Ref. 10). Taking an average of W_f around the dip region, an excellent agreement between $P_f(\pi^-)$ and $\langle W_f \rangle$ is achieved.

Since to date there is no alternative photoabsorption mechanism to explain our experimental findings, the compelling evidences discussed above strongly suggest that we have detected a "stopped pion absorption regime" in the photofission of Au and Ta near the photopion threshold.

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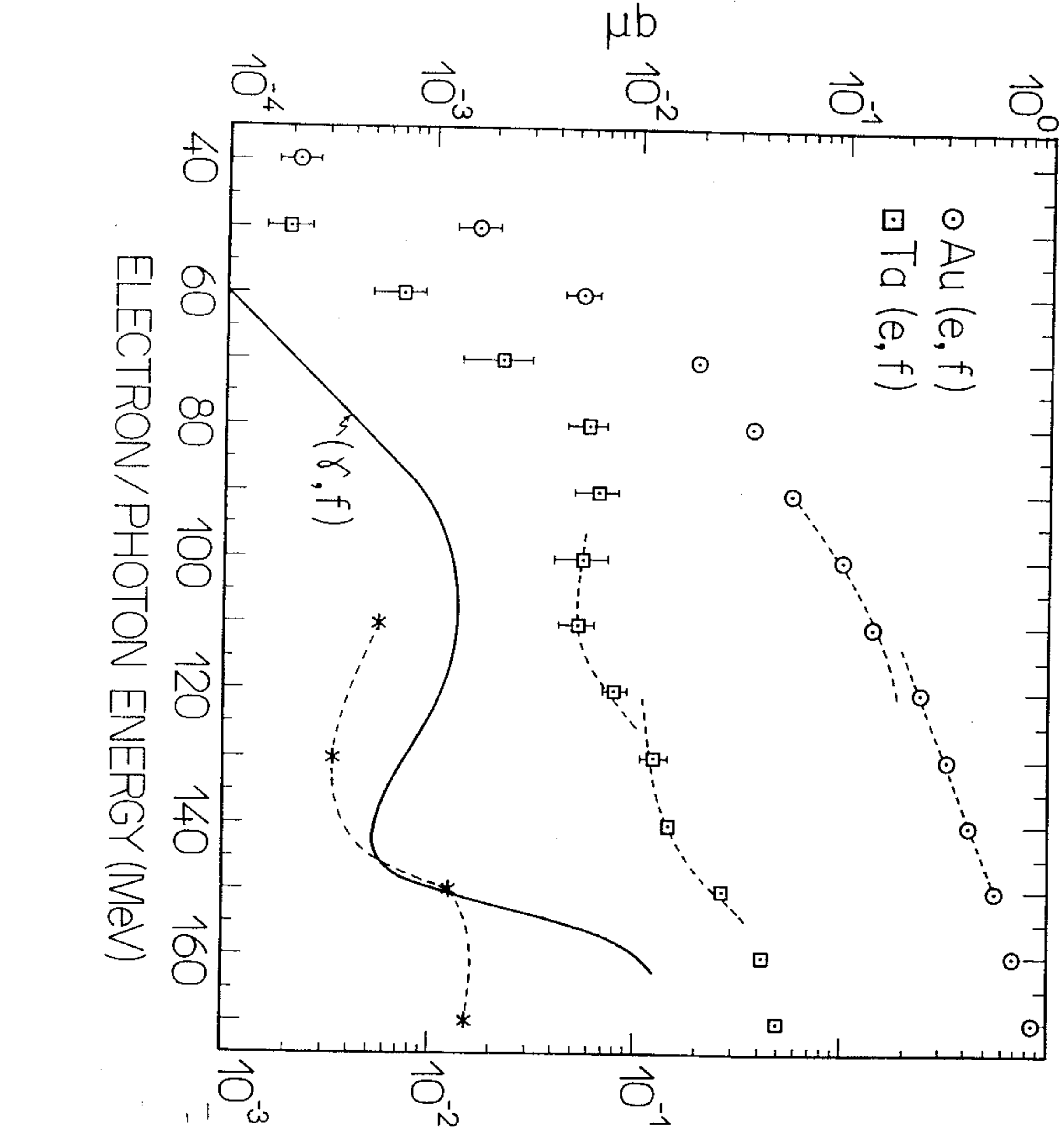
FIGURE CAPTIONS

Fig. 1 — Left-hand scale: electrofission cross sections of Au and Ta (data points — this work). Right-hand scale: photofission cross sections of Au deduced in this work (solid curve; average uncertainties are $\sim 15\%$) and from Ref. 9 ($\times - - - \times$; arbitrary unity). The dashed lines are to guide the eyes.

Fig. 2 — Au photofission yields per equivalent quantum versus the maximum photon energy k_m, measured at Frascati (adapted from Ref. 4) We added dashed lines to guide the eyes and numbered arrows to indicate the inflexions (details in the text).

Fig. 3 — Average excitation energy $\langle E_r \rangle$ as a function of the incident photon energy ω, for ^{197}Au and ^{209}Bi target nuclei (from Refs. 6 and 8).

Fig. 4 — Photofissilities W_f of Au ($\odot$——$\odot$) and Ta ($- \cdot -$) as a function of the incident photon energy, deduced in this work; typical uncertainties are shown only for the dip region around 140 MeV. Probabilities of fission induced by "stopped negative pion absorption" in Au ($\otimes$) and Ta (⊠), quoted from Ref. 10. The dashed line indicates the trend of W_f in the case of dipless (γ, f) cross section. The horizontal arrow shows the ω region where photopions are produced with $\lambda_\pi < R$.


µb
10^-4
10^-3
10^-2
10^-1
10^0
⊙ Au (e, f)
⊡ Ta (e, f)
(γ, f)
40
60
80
100
120
140
160
ELECTRON / PHOTON ENERGY (MeV)
10^-3
10^-2
10^-1

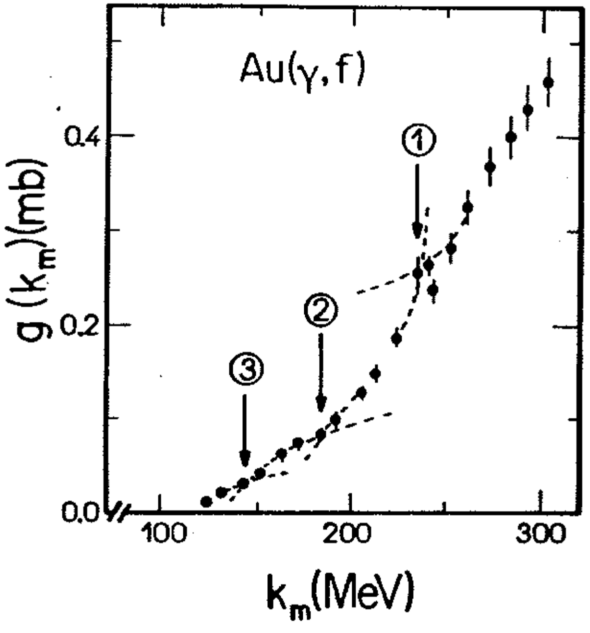
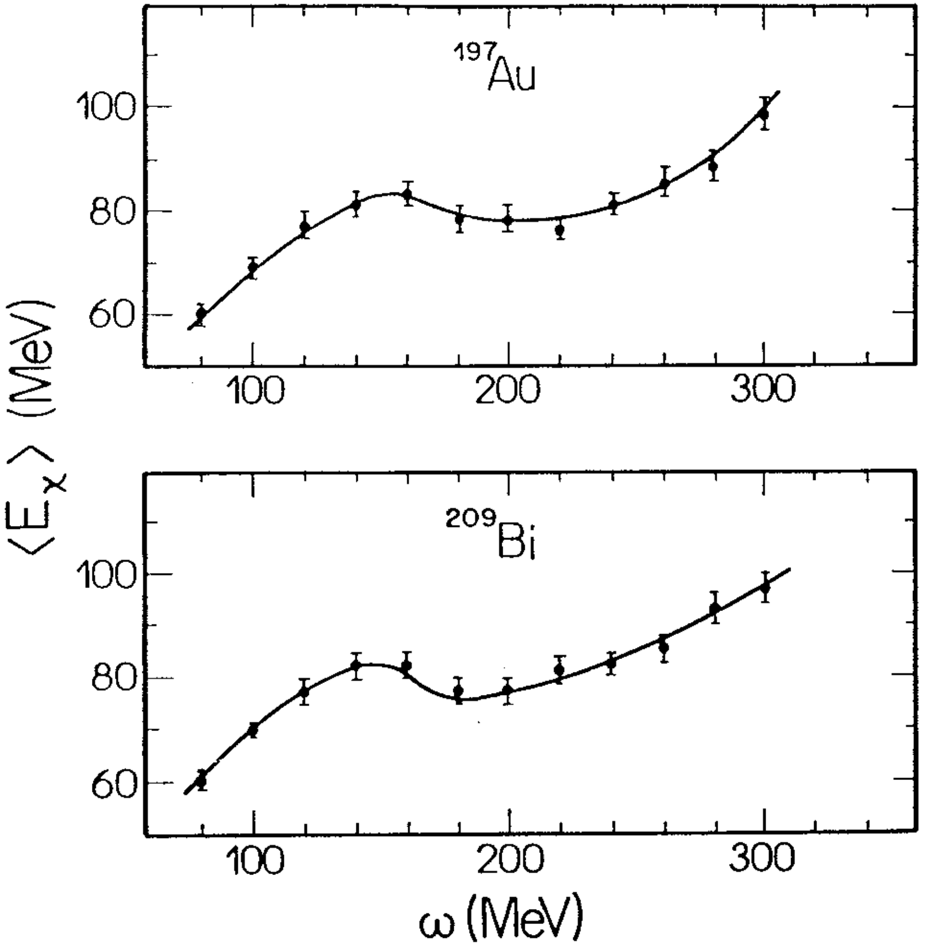
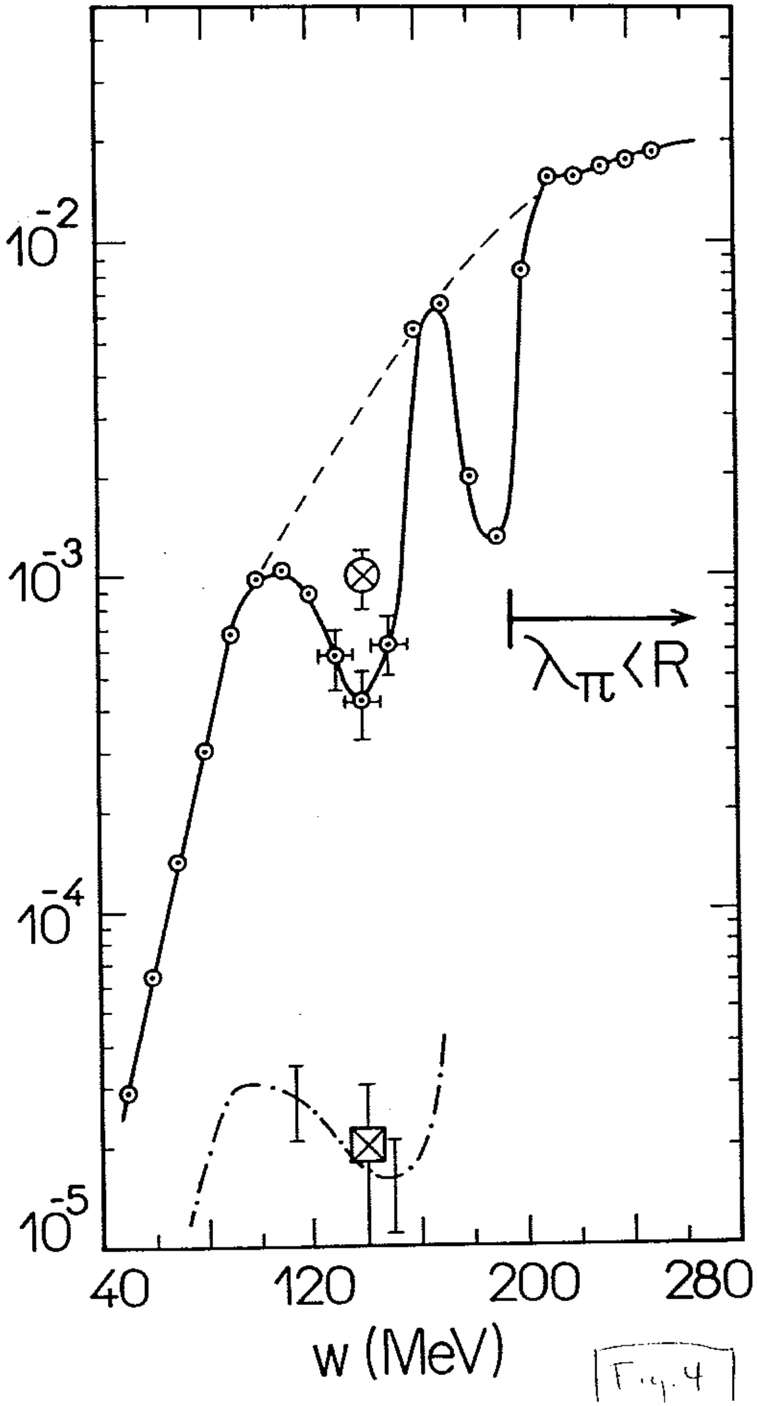

Au(γ, f)
g(k_m)(mb)
0.0
0.2
0.4
①
②
③
100
200
300
k_m(MeV)

Fig. 2



^{197}Au
^{209}Bi
$\langle E_x \rangle$ (MeV)
60
80
100
100
200
300
ω (MeV)

Fig. 1



10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\lambda_\pi < R$
40
120
200
280
w (MeV)

Fig. 4