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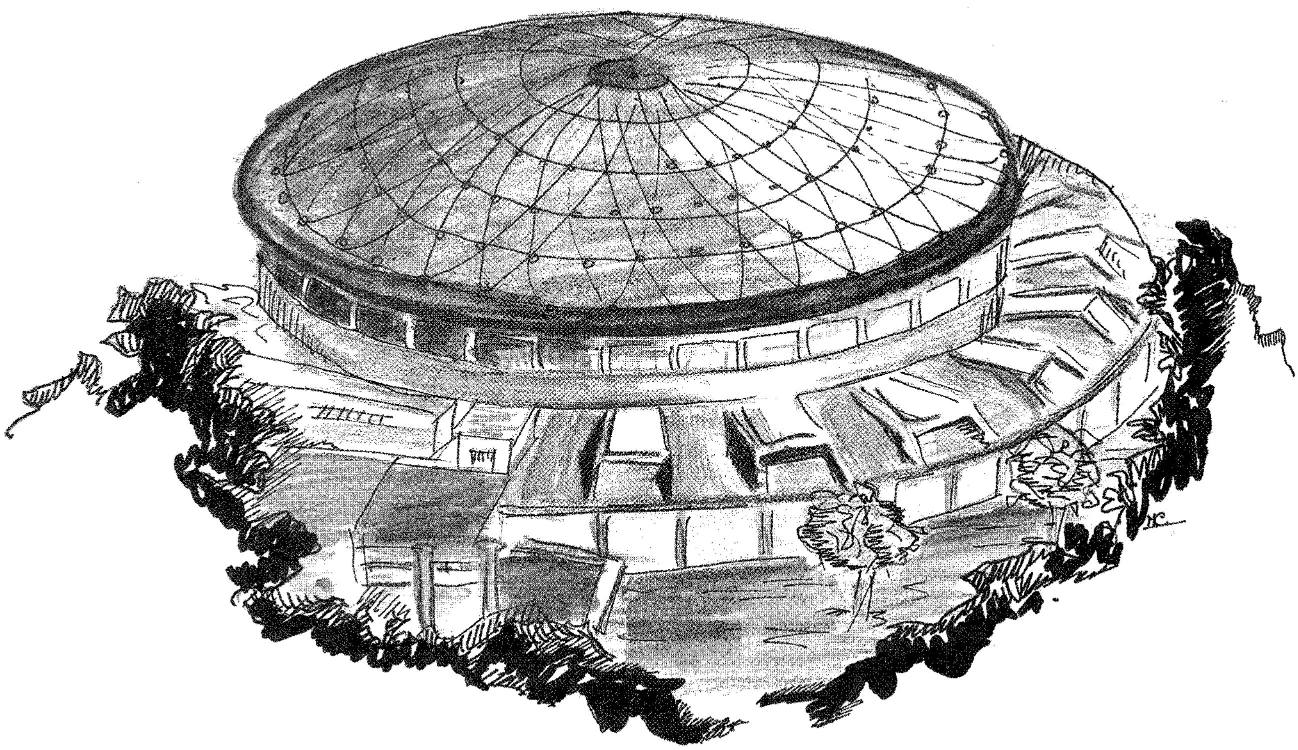

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ON THE EXCITATION ENERGY DEPENDENCE OF PHOTO-FISSILITY IN PREACTINIDE NUCLEI

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Abstract: The dependence on average excitation energy $<E^*>$ of photo-fissility P_f of preactinide nuclei is examined. An accurate evaluation of $<E^*>$ and of mass and charge configurations of the compound nuclei is obtained by means of an intranuclear-cascade model. It is found that, at high excitation energy, there is no linear relation between $\ln P_f$ and $<E^*>^{-1/2}$.

1. It is known that, for not too high excitation energies E^*, i.e., according to Table VII-1 of Ref.1, for $E^* \leq 50 \div 80$ MeV, the fission probability P_f, i.e., the ratio of the fission cross section σ_f to the inelastic cross section σ_{in}, can be approximated by the ratio of the fission width Γ_f to the neutron width Γ_n:

$$P_f = \frac{\sigma_f}{\sigma_{in}} \cong \frac{\Gamma_f}{\Gamma_f + \Gamma_n} \cong \frac{\Gamma_f}{\Gamma_n}, \qquad (1)$$

if $\Gamma_f \ll \Gamma_n$. This approximation holds, in particular, for fission of preactinide nuclei by low energy α particles, when the channel of the compound nucleus formation is the main channel of the inelastic interactions ($\sigma_{in} \cong \sigma_{cn}$, where σ_{cn} is the compound nucleus cross section) and fission barriers B_f of the compound nucleus are much larger than neutron binding energies B_n (typically B_f=20÷30 MeV, $B_n \cong 6$ MeV). For these nuclei , in fact, only a small fraction of the inelastic cross section goes into fission but the relative probability for fission compared to neutron emission is a strongly increasing function of the excitation energy, so that the so called *second-chance* fission (fission after the emission of the *n*th neutron) can be neglected. Moreover, charged particle evaporation is small, with respect to neutron emission, because of the influence of the Coulomb barrier at high Z values.

At higher excitation energies (≥80 MeV), the ratio Γ_f/Γ_n increases more slowly with energy, the contribution from second-chance fission becomes significant, and also charged particles emission begins to compete.

If $E^* \gg B_n$ and $E^* \gg B_f$, and within the hypothesis $a_f = a_n = a$, where a_f and a_n are the level density parameter, respectively, at the fission saddle point and for the residual nucleus after neutron evaporation, the following "high energy limit" can be obtained from statistical considerations:[2]

$$\ln (\Gamma_f/\Gamma_n) = C - a^{1/2}(B_f - B_n)E^{*-1/2}, \qquad (2)$$

where C is slowly varying with energy.

Moretto *et al.*[3] and, subsequently, Arruda-Neto *et al.*[4] assumed that the fission probability retains, also at high energy, the same energy dependence of Γ_f/Γ_n, as given by eq.(2):

$$\ln P_f = C' - D'E^{*-1/2}, \qquad (3)$$

where C' is a quantity varying very slowly with energy, $D' = \langle a \rangle^{1/2}(\langle B_f \rangle - \langle B_n \rangle)$ and $\langle a \rangle$, $\langle B_f \rangle$, $\langle B_n \rangle$ are expected to be some kind of averages of the respective quantities a, B_f, B_n for the nuclei along the evaporation chain. Furthermore, in dealing with fission induced by electrons and photons on medium-heavy and heavy elements, these authors found an *unique* linear dependence of fissility on the incoming particle energy, from few tens of MeV up to some hundreds of MeV It must be noticed, at this regard, that this result could be achieved only under two specific assumptions: i) the δ-like behavior of the compound nucleus excitation energy and its equality to the incoming photon energy; ii) the use of the quasi-deuteron cross section instead of the total photoabsorption one for σ_{in} in calculating the fissility.

In Ref.5, we reported the measurement of the photofission cross section of Bi in the energy range 100÷300 MeV. In that paper, the behavior of fissility, taking also into account all the existing photofission data on Bi from 30 MeV up to 300 MeV, was investigated as a function of the average excitation energy $<E^*>$ of the residual nucleus, calculated in the framework of the intranuclear cascade model (INC) of Barashenkov *et al.*[6] The application of the INC model allowed us to keep away the two above simplified assumptions, because INC model takes into account both the quasi-deuteron photoabsorption mechanism and the single nucleon photoabsorption mechanism via pion production on intranuclear nucleons and also predicts the actual distribution of produced thermalized residual nuclei over excitation energy. With this more correct procedure, it was found that the linearity between $\ln P_f$ and $<E^*>^{-1/2}$ could hardly be considered valid over the whole energy range taken into account. The experimental data, in fact, did display, at low energy, the linear behavior, but, above about 100 MeV, a changing in slope was clearly shown, together with an evident saturation effect.

In this work, we go further into the subject and give a more accurate evaluation of the excitation energy and of mass and charge configuration of the compound nucleus. As a consequence, we show that, at high excitation energy, one does not simply observe a different slope in a linear behavior, but it is the same concept of *linearity* to be put into discussion. This is clearly shown by our photofission data on Bi,[5] and our recent results on Au,[7] which, being far from any saturation effect, are intrinsically in suitable position for checking a possible deviation from the linear behavior.

Moreover, by expressing, through simple relations valid in the preactinide region,[8] $\ln P_f$ in terms of the average mass and charge numbers lost by the target nucleus, $<\Delta A>$ and $<\Delta Z>$, and by taking properly into account the calculated energy dependence of these parameters, it is possible to demonstrate analytically that the relation (3) is not correct in the high energy region.

2. Global tendencies in the behavior of the excitation energy of heavy nuclei for photonuclear reactions have been investigated by Barashenkov *et al.*[6] in the framework of the INC model for the wide photon energy range 50 MeV÷1 GeV. It was shown that the dependence of $<E^*>$ *vs.* k appears nearly linear up to ≅300 MeV, then it shows a shoulder with a different slope. However, this dependence was built on the theoretical values of $<E^*>$ calculated for fixed photon energy values varying with a 100 MeV bin: due to this large step, some interesting structure in the behavior of $<E^*>$ of the residual nuclei in the energy interval 100÷300 MeV was lost.

In this work, focused on photon energies up to 300 MeV, new calculations of the average excitation energy have been performed with a small photon energy step $\Delta k=20$ MeV. Moreover, the parameter values of the cascade-evaporation model have been chosen to reproduce more recent data on fissilities of nuclei by intermediate energy particles.[9] The new results, shown in Fig.1 for the Au and Bi nuclei, display the detailed dependence of the excitation energy on the photon energy in the chosen interval. This is characterized by a behavior far from linearity, with a maximum at $k \cong 140 \div 160$ MeV. This is precisely what expected according to the two specific mechanisms in photonuclear absorption effective in this energy range:

a) for k<140 MeV, the photon is absorbed by a quasi-deuteron *n-p* pair and the scattering of the two nucleons inside the nucleus is very effective in "heating" it;

b) for k>160 MeV, the photon is mainly absorbed via pion production on the intranuclear nucleons: then the pion is scattered by a nucleon or is absorbed by a nucleon-nucleon pair. At threshold, the pion, having small kinetic energy and small interaction cross section, will leave the nucleus carrying away large part ($\cong m_\pi$) of the photon energy. So the compound nucleus will receive less excitation energy and its average value will decrease, as displayed in Fig.1.

Therefore, if one plots the logaritm of the fissility as a function of the inverse square root of the *correct* average excitation energy, the result over the interval 100÷300 MeV is not simply a line with a slope different from that found in the lower energy region, as we previously obtained[5] for Bi using the Barashenkov *et al.* intranuclear cascade results,[6] but the behavior does not any more display a linearity. This is evident in Fig.2, where the Bi data[5] are plotted as a function of $\langle E^* \rangle^{-1/2}$(top figure), and it is more nicely displayed in our recent Au data[7] (bottom figure), which do not show any saturation effect, being the Au fissility about one order of magnitude lower than that of Bi.

3. The above result can be also obtained analytically by investigating the energy dependence in the 100÷300 MeV region of the coefficients of the expression (3). At excitation energy $E^* \geq 30$ MeV, the shell effects in nuclei are destroyed,[10] so we can take the liquid drop results for B_f and B_n in the expression (2). These quantities, calculated by the method of Myers and Swiatecki,[11] may be approximated by the following relations, suitable in the region $Z \cong 80$:[8] $B_f = \alpha_f Z + \beta_f N + \gamma_f$, and $B_n = \alpha_n Z + \beta_n N + \gamma_n$, where α_j, β_j, γ_j (j=f, n) are constants. Then: $(B_f - B_n) = \alpha Z + \beta N + \gamma$, being $\alpha = \alpha_f - \alpha_n$, $\beta = \beta_f - \beta_n$ and $\gamma = \gamma_f - \gamma_n$.

The specificity of nuclear fission by intermediate energy particles consists in that compound nuclei have wide distributions over excitation energy E*, and mass and charge numbers A, Z. Thus photofission cross section σ_f and fissility P_f from intermediate energy photons are quantities averaged over the ensemble of compound nuclei produced in the photonuclear reaction. By taking the averages over Z and A numbers from the Z_t and A_t of the target nucleus and the average over the mass and charge lost $\langle \Delta A \rangle$ and $\langle \Delta Z \rangle$, we obtain: $\langle Z \rangle = Z_t - \langle \Delta Z \rangle$, $\langle A \rangle = A_t - \langle \Delta A \rangle$, and $\langle N \rangle = (A_t - \langle \Delta A \rangle) - (Z_t - \langle \Delta Z \rangle)$.

One then gets:

$$(B_f - B_n) = \beta A_t + (\alpha-\beta)Z_t - \beta<\Delta A> +\beta<\Delta Z> +\gamma, \quad (4)$$

which can be written:

$$(B_f - B_n) = c_1 + c_2<\Delta A> +c_3<\Delta Z>, \quad (5)$$

where c_1, c_2 and c_3 are constant quantities.

As far as the level density parameter is concerned, the average value $<a>$ can be taken, according to Ref.8, as $<a> = a_0<A>$, where a_0 is a constant.

Then:

$$<a>^{1/2}=[a_0(A_t-<\Delta A>)]^{1/2}\cong(a_0A_t)^{1/2}[1- 0.5(<\Delta A>/A_t)]\cong(a_0A_t)^{1/2}=a_t^{1/2}, \quad (6)$$

being a_t the level density parameter of the target nucleus.

Finally, putting (5) and (6) in expression (2), one obtains in the first chance fission approximation:

$$\ln P_f\cong\ln <\Gamma_f/\Gamma_n> = C - a_t^{1/2}(c_1 + c_2<\Delta A> +c_3<\Delta Z>)<E^*>^{-1/2}. \quad (7)$$

We obtained the $<\Delta A>$ and $<\Delta Z>$ energy dependencies through the above mentioned Monte Carlo calculation, as for $<E^*>$. In Fig.3 the results for Au and Bi are shown. By examining this figure, and recalling Fig.1, one observes that:

i) $<\Delta A>$ is nearly constant in the interval 160 MeV $\leq k \leq$ 240 MeV;

ii) $<\Delta Z>$ is nearly constant in the interval 180 MeV $\leq k \leq$ 280 MeV;

iii) $<E^*>$ is nearly constant in the interval 160 MeV $\leq k \leq$ 240 MeV;

Then in the energy interval 180 MeV $\leq k \leq$ 240 MeV the three quantities $<E^*>$, $<\Delta A>$ and $<\Delta Z>$ can be considered independent on the photon energy. It follows that, as far as this energy interval is concerned, ln (Γ_f/Γ_n) is a constant, independent on the photon energy. In other words, to draw from expression (2) the existence of a linear dependence of $\ln P_f$ on $<E^*>^{-1/2}$ over the whole 100÷300 MeV interval is a too simplified assumption which leads to incorrect results.

As a conclusion, we demonstrated that not only it does not exist an unique linear dependence of $\ln P_f$ on $<E^*>^{-1/2}$ from low up to high excitation energies, as already found in our previous paper[5], but that at high energies this dependence is more complex than a line.

REFERENCES

1) R. Vandenbosh and J.R. Huizenga, *Nuclear Fission* (Academic, New York, 1973), p. 217.

2) J.R. Huizenga, R. Chaudry, and R. Vandenbosh, Phys. Rev. **126**, 210 (1962).

3) L.G. Moretto, R.C. Gatti, S.G. Thompson, J.T. Routti, J.H. Heisenberg, L.M. Middleman, M.R. Yearian, and R.F. Hofstadter, Phys. Rev. **179**, 1179 (1969).

4) J.D.T. Arruda-Neto, M. Sugawara, T. Tamae, O. Sasaki, H. Ogino, M. Miyase, and K. Abe, Phys. Rev. C **31**, 2321 (1985), **34**, 935 (1986).

5) C. Guaraldo, V. Lucherini, E. De Sanctis, P. Levi Sandri, E. Polli, A.R. Reolon, S. Lo Nigro, S. Aiello, V. Bellini, V. Emma, C. Milone, and G.S. Pappalardo, Phys. Rev. C **36**, 1027 (1987).

6) V.S. Barashenkov, F.G. Gereghi, A.S. Iljinov, G.G. Jonsson, and V.D. Toneev, Nucl. Phys. **A231**, 462 (1974).

7) V. Lucherini, C. Guaraldo, E. De Sanctis, P. Levi Sandri, E. Polli, A.R. Reolon, A.S. Iljinov, S. Lo Nigro, S. Aiello, V. Bellini, V. Emma, C. Milone, G.S. Pappalardo, and M.V. Mebel, Frascati Preprint LNF-**88/36(P)**, June 23 1988 (to be published in Phys. Rev. C).

8) E.A. Cherepanov, A.S. Iljinov, and M.V. Mebel, J. Phys. G **9**, 931 (1983).

9) A.S. Iljinov, E.A. Cherepanov, and S.E. Chigrinov, Yad. Fiz. **32**, 322 (1980) [Sov. J. Nucl. Phys. **32**, 166 (1980)].

10) E.A. Cherepanov, A.S. Iljinov, and M.V. Mebel, J. Phys. G **9**, 1397 (1983).

11) W.D. Myers and W.J. Swiatecki, Ark. Fyz. **36**, 343 (1968).

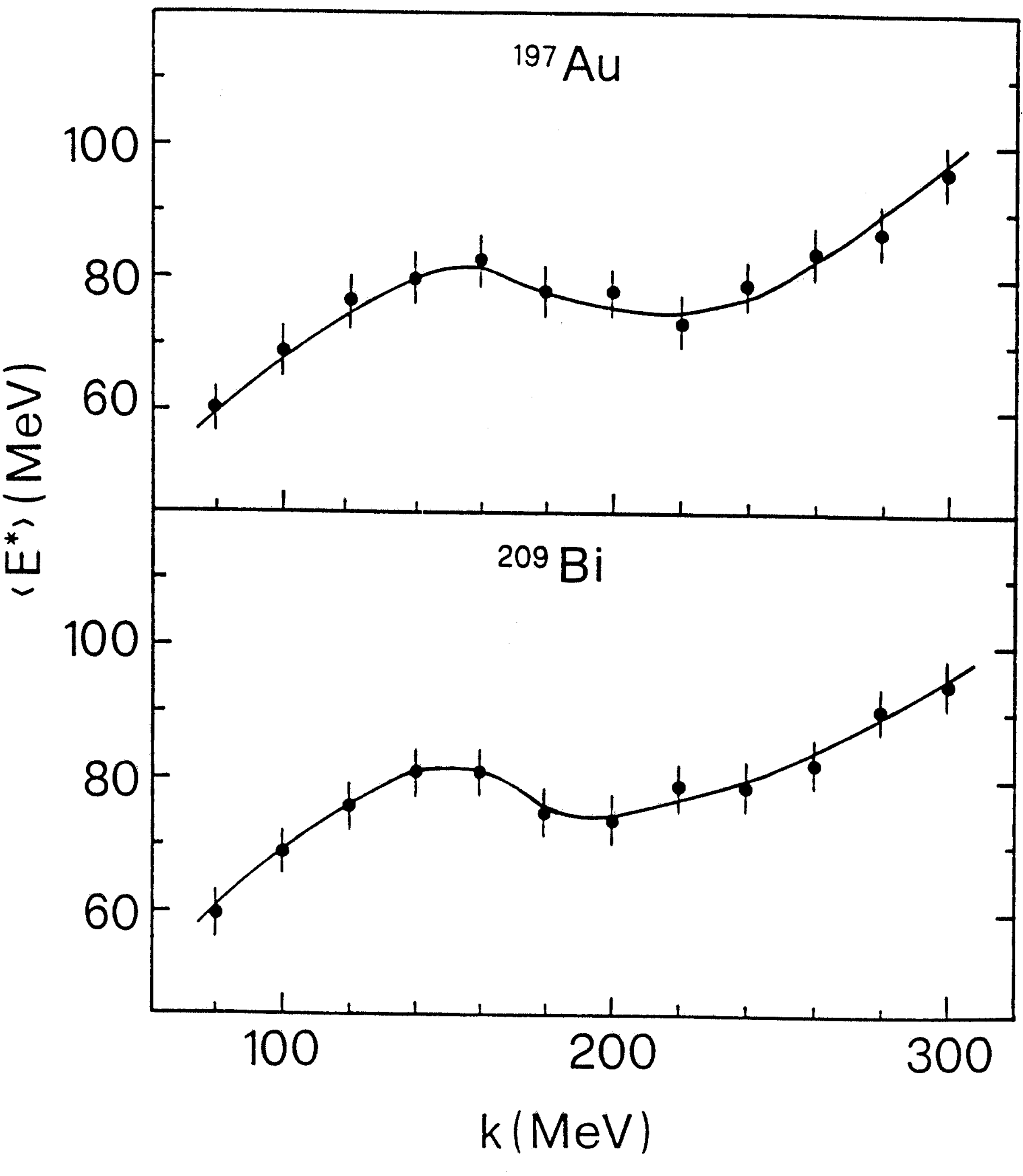

Fig.1 Average photo-excitation energies <E*> of the residual nuclei as a function of the incident photon energies k, for ^{197}Au and ^{209}Bi target nuclei. The points refer to results of the intranuclear Monte Carlo calculation. The curves are only guides for the eye.

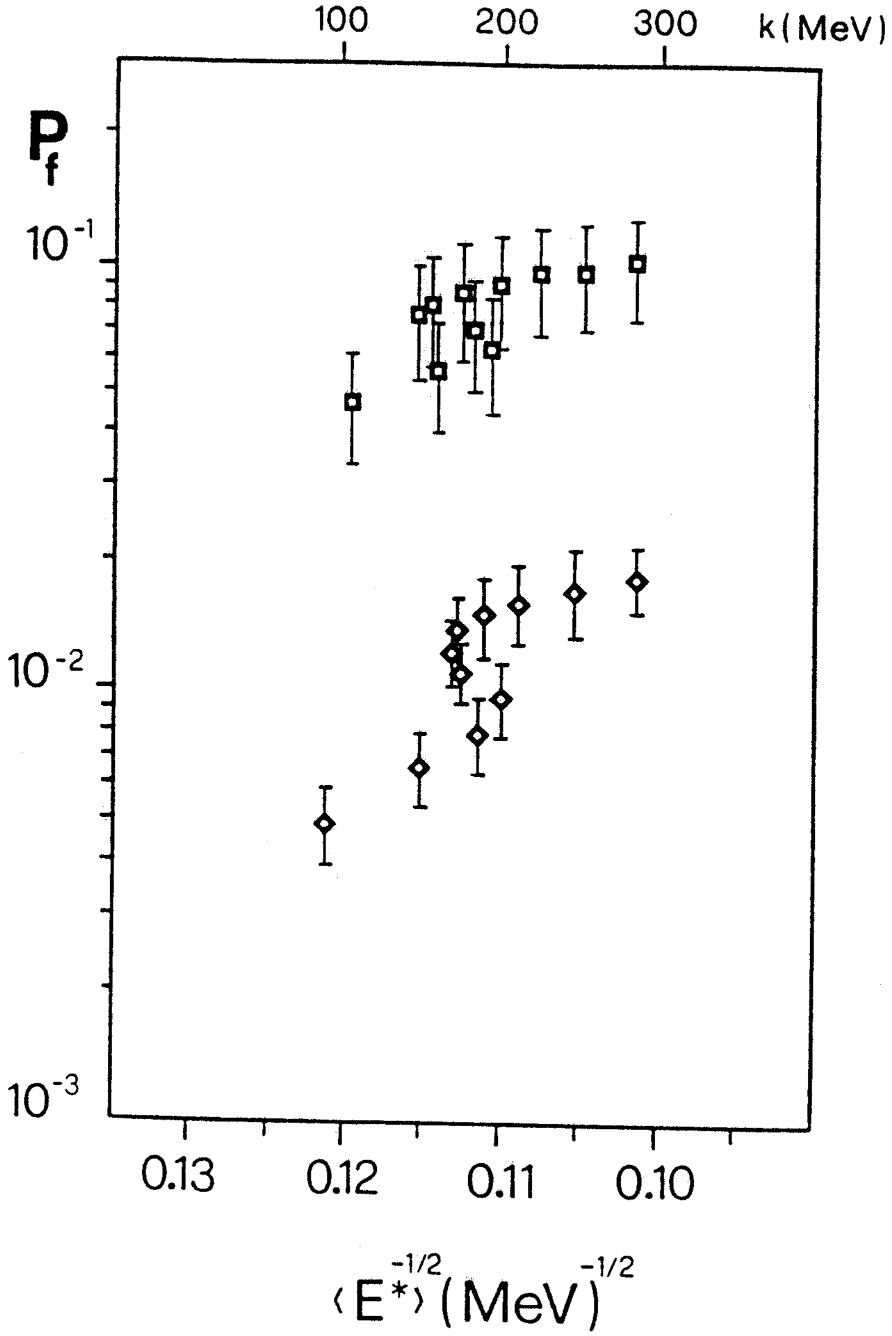

Fig.2 ^{209}Bi (▫) and ^{197}Au (◇) photo-fissilities Pf as a function of $<E^*>^{-1/2}$. The photon energies k are only indicative, due to the slight different $<E^*>$ values of the residual nuclei resulting from the absorption of photons of the same energy on ^{209}Bi and ^{197}Au.