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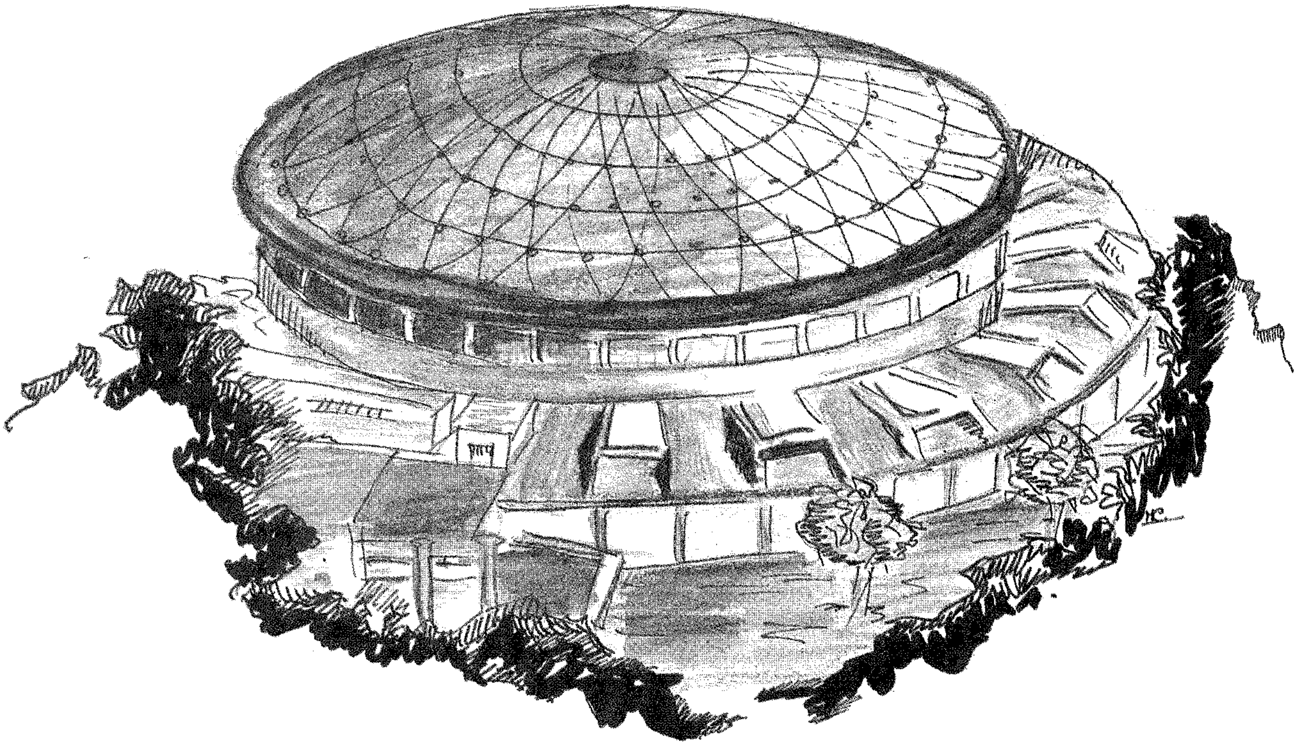

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Comparison of fission of heavy nuclei induced by different probes

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Abstract. The fission induced in heavy nuclei ($Z^2/A>30$) by photons, pions and protons of intermediate energy was studied. The fissilities were deduced from measured fission cross sections using the total reaction cross sections specific for each probe. The energies of the projectiles were chosen in such a way to produce similar configurations of the residual compound nuclei: to this end an intranuclear-cascade model was employed. With this choice, the obtained fissilities, plotted as a function of the $<Z^2_{cn}>/<A_{cn}>$ of the compound nuclei formed, are found in a nice agreement irrespective of the probe used, and also in agreement with the fissilities calculated with the cascade-evaporation model based on the two-step picture of the process.

PACS: 25.85.Ge charged-particle-induced fission, and 25.85.Jg photofission

1. Introduction

Recent interest has been directed to the question of how an intermediate energy projectile excites the collective modes of nuclei. Answering to this question requires the knowledge of the contributions to the total inelastic cross section σ_{in}, from all the channels that could lead to collective nuclear excitations. Fission is the most interesting and specific channel among them. In the present work we shall try to investigate the pathways which lead from the primary projectile-nucleus interaction to the final result, i.e. the decay of residual nucleus by fission. One of the aims of the present study is to determine whether there is a difference between the fission process induced by photons, pions and protons. In fact, a difference could indicate reaction mechanisms leading to collective phenomena that are specific to the photo-, pion-, and proton-nuclear interaction.

It is reasonable to start this study by adopting the customary assumptions about both the mechanism of interaction of intermediate energy particles with nuclei and the mechanism of fission. As shown in Refs. 1 and 2, the bulk of experimental data on fission of heavy nuclei by different intermediate energy probes (photons, pions, protons, α-particles) is well explained by the concept of a two-step process. In fact, the investigation of the process of relaxation in a nucleus, as a finite open system, in the framework of the kinetic approach,[3] shows that the inelastic interaction of an intermediate energy particle with a nucleus proceeds through two radically different steps. In the first, fast step, the projectile initiates the cascade of subsequent independent collisions of the primary and secondary fast particles with the intranuclear nucleons. The duration τ_0 of this fast step, during which particles of the continuum leave the nucleus, is comparable with the time, τ_{fl}, that the projectile needs to cross the nucleus: $\tau_0 \approx \tau_{fl} < 10^{-22}$ s. This intranuclear cascade step brings to the formation of a highly excited nuclear system, which has a definite number of "holes", equal to the number of collisions of cascade particles in nuclear matter, and a definite number of excited nucleons, equal to the number of slow cascade nucleons captured by the nuclear potential. In this system the thermodynamic equilibrium is established rather quickly, during a time $\tau_{eq} > (5 \div 10)\tau_0$.[3] Then in the second, slow step, the produced compound nucleus evaporates particles successively or undergoes fission. Both processes take place in the same way as for the compound nucleus formed in reactions initiated by low energy particles.[4] The formation of a thermalized highly excited residual nucleus in deep inelastic interaction of intermediate energy particles, which decays independently of the way of formation, allows us to speak of

Fission gives the unique possibility of checking the mechanism of deep inelastic interaction and of investigating the properties of the highly excited nucleus produced in this interaction.[1] Both the fast and the slow steps of the interaction mechanism contribute to other channels of the process (for example, to the emission of secondary particles with different energy spectra). However, fission is a collective process accompanied by maximum rearrangement of nucleonic structure of the nucleus. Therefore, it is certainly a slow process ($\tau_f > 10^{-20}$ s)[5].and, thus, it must take place during the second step. So it is possible to use fission as a clear signature of the establishment of thermodynamical equilibrium in the residual nucleus.

In the present paper we shall compare the fissilities of heavy nuclei by different probes (photons, pions and protons) the energy of which are chosen in such a way that the various characteristics of the produced compound nuclei (excitation energy, nucleonic composition, angular momentum) be similar. The aim of this comparison is to check the two-step nature of deep inelastic processes which lead to fission after the formation of a thermalized residual nucleus, the decay of which is determined only by its excitation energy, nucleonic composition, and angular momentum.

2. Fissility of nuclei by intermediate energy particles

The fissility W_f is defined as the ratio of the fission cross section σ_f to the inelastic reaction cross section σ_{in}: $W_f = \sigma_f / \sigma_{in}$. Within the framework of the two-step picture of the process,[1] the fission cross section σ_f can be written as:

$$\sigma_f = \Sigma_{A_{cn}} \Sigma_{Z_{cn}} \Sigma_l \int dE^* \, \sigma_{cn}(A_{cn}, Z_{cn}, E^*, l) \, w_f(A_{cn}, Z_{cn}, E^*, l) \qquad (1)$$

where σ_{cn} is the cross section for the formation of the compound nucleus, with A_{cn} nucleons, Z_{cn} protons, angular momentum l and excitation energy between E^* and $E^* + dE^*$; and w_f is the probability that this nucleus will undergo fission during the transition from the excited to the ground state.

The fission probability of the compound nucleus is determined from the expression:

$$w_f(A_{cn}, Z_{cn}, E^*, l) = \Sigma_x P_x(E^*, l) \, w_x^f(A_{cn}, Z_{cn}, E^*, l) \qquad (2)$$

where P_x is the probability that the compound nucleus will emit x particles as it passes to the ground state, and w_x^f is the probability that in this case fission will take place in one of the links of the evaporative chains.

The probability w_x^f is equal to 1 minus the probability that fission will not take place at any of the steps of the evaporative cascade:

$$w_x^f = 1 - \prod_{i=1}^{x} \left[1 - \frac{\Gamma_f(A_i,Z_i,E^*_i,l_i)}{\Gamma_{tot}(A_i,Z_i,E^*_i,l_i)}\right] \qquad (3)$$

Here $\Gamma_{tot} = \Gamma_f + \Sigma\,\Gamma_j$ is the total decay width of the compound nucleus, equal to the fission partial width Γ_f plus the sum of the emission widths Γ_j of the *j*th-type particles .

The specificity of nuclear fission by intermediate energy particles is that the compound nuclei have a wide distribution over the mass and charge numbers A_{cn}, Z_{cn}, angular momentum *l* and excitation energy E*. In the present paper the calculations for the fissility were performed with an allowance for the "smearing" of compound nuclei over A_{cn}, Z_{cn}, *l* and E* in the framework of the method described in Ref.1. The averaging of the fission probability in expressions (1÷3) was carried out numerically by the Monte Carlo method. The fast step of the process was calculated on the basis of the intranuclear cascade model, and the slow step was calculated on the basis of the standard evaporation model (see Ref.6 for a review). When we calculated the partial widths Γ_f and Γ_j, we neglected shell effects, since they vanish at excitation energy E*>30 MeV.[7] The a_f/a_n ratio between level density parameters of the nucleus with equilibrium deformation and the nucleus with a configuration corresponding to the fission saddle point was taken equal to 1.02.[1] In order to calculate the fission barrier heights of compound nuclei, we used the modified liquid drop model.[8] Other parameters of the intranuclear cascade model and of the evaporation model were taken the

3. Comparison of ensembles of highly excited nuclei produced in photon-, pion- and proton-induced reactions

From the point of view of the usual assumptions underlying the nuclear reaction mechanisms, fission induced by a beam of intermediate energy monochromatic photons is not much different from fission induced by pions and protons which produce a compound nucleus with similar excitation configurations. In fact, the small mass, zero spin and large contribution of two-nucleon absorption of the pion can lead to fission from a state of relatively low angular momentum and high excitation energy. These are just the specific features displayed in the photoabsorption process. Similarly, an intermediate energy proton transfers to the residual nucleus energy but rather small angular momentum *l* .

However, some marked differences among the processes of nuclear excitation by intermediate energy photons, pions and protons must be stressed.[9] The forward momenta transmitted to the nucleus in the photo- and proton-nucleus reaction are different: the ratio between the incoming proton and photon momenta changes from 4.4 to 1.7, going from 100 MeV to 1 GeV. This means that the nucleon-nucleon pair originating from the primary interaction of the entering nucleon has more forward momentum in the nucleus than the (n-p) pair coming from the photo-splitting of the quasi-deuteron clusters. As a result, the probability for one or both members of the former pairs to leave the nucleus will be different in the photon and proton cases.[9] On the other side, all the photon-induced reactions are dominated, above about 140 MeV, by pion production. Consequently, the intermediate energy photofission features are affected by the behavior of the pion in nuclear medium. On the contrary, in the nucleon induced fission the pion processes are of importance above 600 MeV and never dominate.[9] Finally, in the case of photonuclear reactions, volume absorption dominates, differently from the pion and proton cases, where the surface absorption predominates. As a result, photon is a more effective in "heating" the nucleus than pion or proton.

For comparison of fission induced by these different probes, it is necessary to select those initial energies of each probe which produce the same excitation energy, E*, angular momentum, *l*, and nucleonic composition, A_{cn} and Z_{cn}, of compound nuclei. To accomplish this task, the values of E*, *l*, A_{cn} and Z_{cn} were calculated in the framework of the intranuclear cascade model.[6] We considered fission data on Au, Bi and U nuclei. We used the Frascati-Catania experimental results for the photofission by 200 MeV monochromatic photons,[10÷13] the 190 MeV proton induced fission data of Becchetti *et al.*[14], and the 80 MeV pion induced fission results of Hicks *et al.*,[15] since, as it will be shown, they produce compound nuclei with similar configurations.

Calculations demonstrate that, in the inelastic interaction of 190 MeV protons and of 80 MeV pions with Au, Bi and U nuclei, the produced compound nuclei have excitation energy distributions with both similar shape (see Fig.1) and average values (<E*>≅68 MeV, and ≅70 MeV, respectively).

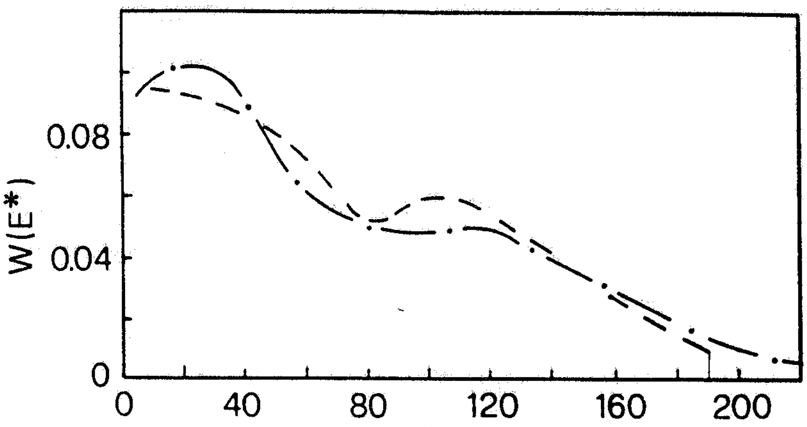

Fig.1 Distributions over the excitation energy E* of the compound nuclei produced by 190 MeV protons (dashed line) and 80 MeV positive pions (dash-dotted line), impinging on an Au nucleus, obtained with the Monte Carlo intranuclear calculations.

In the case of photoreactions, the dependence of E* on the photon energy deserves a more careful analysis.[16] In fact, for 100 MeV photons, the compound nuclei produced have an average excitation energy of ≅68 MeV, that is equal to the previous ones, but the shape is quite different (see Fig.2).

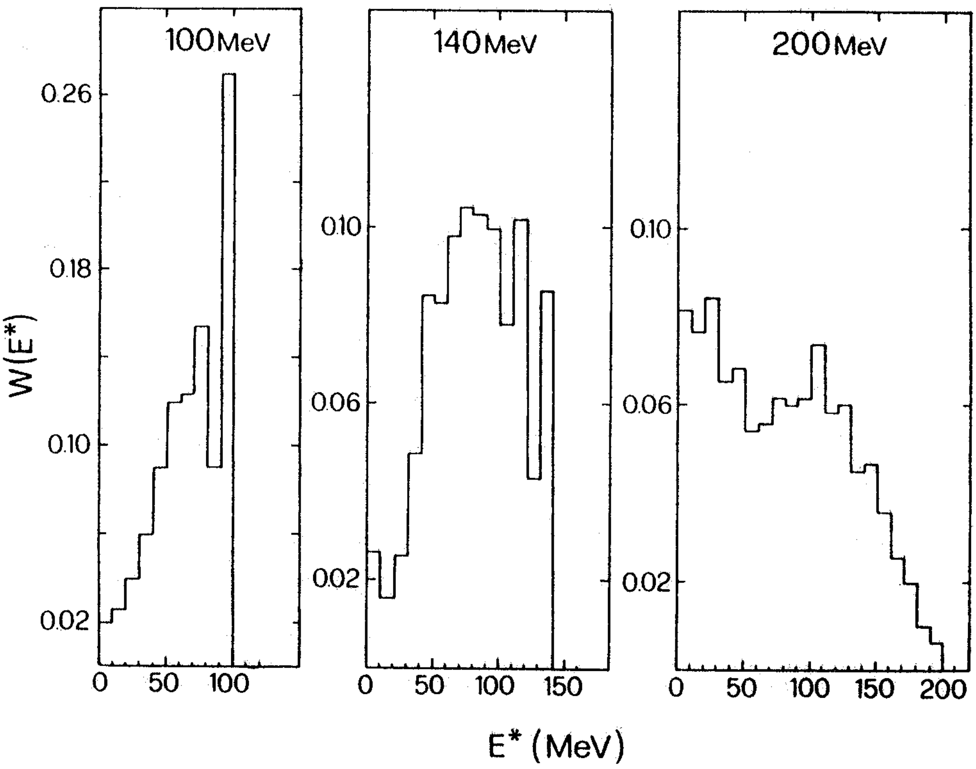

Fig.2 Distributions over the excitation energy E* of the compound nuclei produced by 100 MeV (a), 140 MeV (b), and 200 MeV (c) photons impinging on an Au nucleus. All histograms refer to Monte Carlo intranuclear cascade calculation, and are normalized to one inelastic interaction.

This difference is mainly due to the very effective absorption by the nucleus of the products of (n-p) pair coming from the splitting of quasi-deuteron clusters. As a result, the probability for 100 MeV photons to transfer the largest part, or even the whole primary energy, to the residual nucleus is rather large. With increasing the photon energy, the energy of each nucleon of the pair increases, the escape probability increasing too, and the contribution of events producing compound nuclei with high excitation energy correspondingly decreases. At photon energies near the pion production threshold, the pion, having small kinetic energy and small interaction cross section, will leave the nucleus carrying away a large part ($\cong m_\pi$) of the photon energy. This is clearly seen in Fig.2, where calculated compound nuclei excitation energy distributions are shown for 100, 140 and 200 MeV photons hitting Au nuclei. The 200 MeV energy distribution is clearly the most similar to the 190 MeV proton and 80 MeV pion ones, as shown in Fig.3a. The 200 MeV photons, however, produce a larger value of the average excitation energy: <E*>≅81 MeV, due to their volume absorption. This leads to a smaller yield of weakly excited nuclei ($E^*<40$ MeV), differently from the proton and pion cases, where surface absorption predominates. However, due to the high fission barrier height (B_f=25÷30 MeV) of preactinide nuclei, mainly highly excited ($E^*>40$ MeV) compound nuclei will undergo fission, and this difference will be levelled. In the case of Uranium, which has a low fission barrier (≅5 MeV) but a fissility constant with energy (and roughly equal to unit), this difference is irrelevant.

Fig.3 shows the calculated distributions of compound nuclei over excitation energy E^* (Fig.3a), angular momentum l (Fig.3b), and mass and charge numbers lost by the initially formed system $\Delta A=A_t+A_i-A_{cn}$, (Fig.3c), and $\Delta Z=Z_t+Z_i-Z_{cn}$, (Fig.3d), where the subscripts t, i and cn stand for target, incoming probe and compound nucleus, respectively, produced by 200 MeV photons, 190 MeV protons, and 80 MeV pions impinging on an Au nucleus. As seen in Figs.3b, c, d, at the chosen incoming energies, all probes produce rather similar distributions over angular momentum l and mass and charge numbers lost by the initial formed system ΔA and ΔZ, respectively. Moreover, the ΔA and ΔZ distributions are not only similar but also narrow, allowing a correct labelling of nucleonic composition of the compound nuclei.

Similar results were obtained for Bi and U targets.

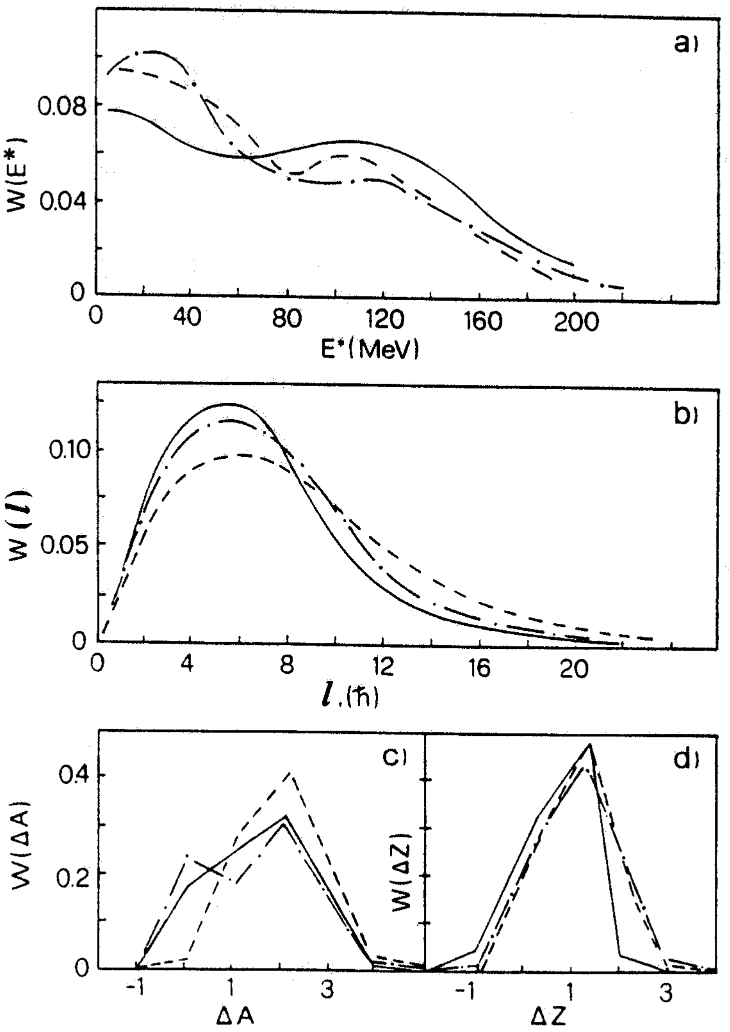

Fig.3 Distributions over the excitation energy E^* (**a**), angular momentum l (**b**), and charge and mass number lost ΔA, ΔZ (**c**, **d**), of the compound nuclei produced by 200 MeV photons (full line), 190 MeV protons (dashed line), and 80 MeV π^+-mesons (dash-dotted line), impinging on a Au nucleus. All curves refer to Monte Carlo intranuclear cascade calculations, and are normalized to one inelastic interaction.

As a conclusion, the calculations show that the ensembles of compound nuclei produced in reactions initiated by 200 MeV photons, 190 MeV protons and 80 MeV pions are very similar each other. This similarity allows us to compare meaningfully the fissilities of nuclei by these probes.

4. Comparison of fissilities of heavy nuclei by different probes

In Fig.4a, we report the experimental fissility values W_f obtained by using 200 MeV photons (solid points), 190 MeV protons (asterisks), and 80 MeV pions (open circles π^+; open squares π^-) on Au, Bi and U targets. To calculate the fissility, the fission cross sections were divided by their respective total inelastic cross sections σ_{in}. For photons, the total photoabsorption cross sections of Carlos *et al.*[17] were used. For protons, we deduced the σ_{in} values from the recent compilation of Bauhoff[18] on reaction and total cross sections in proton-nucleus scattering below 1 GeV. In the case of pions, the σ_{in} values were calculated from the pion optical model, using the parameter set C of Stricker, Carr and McManus.[19]

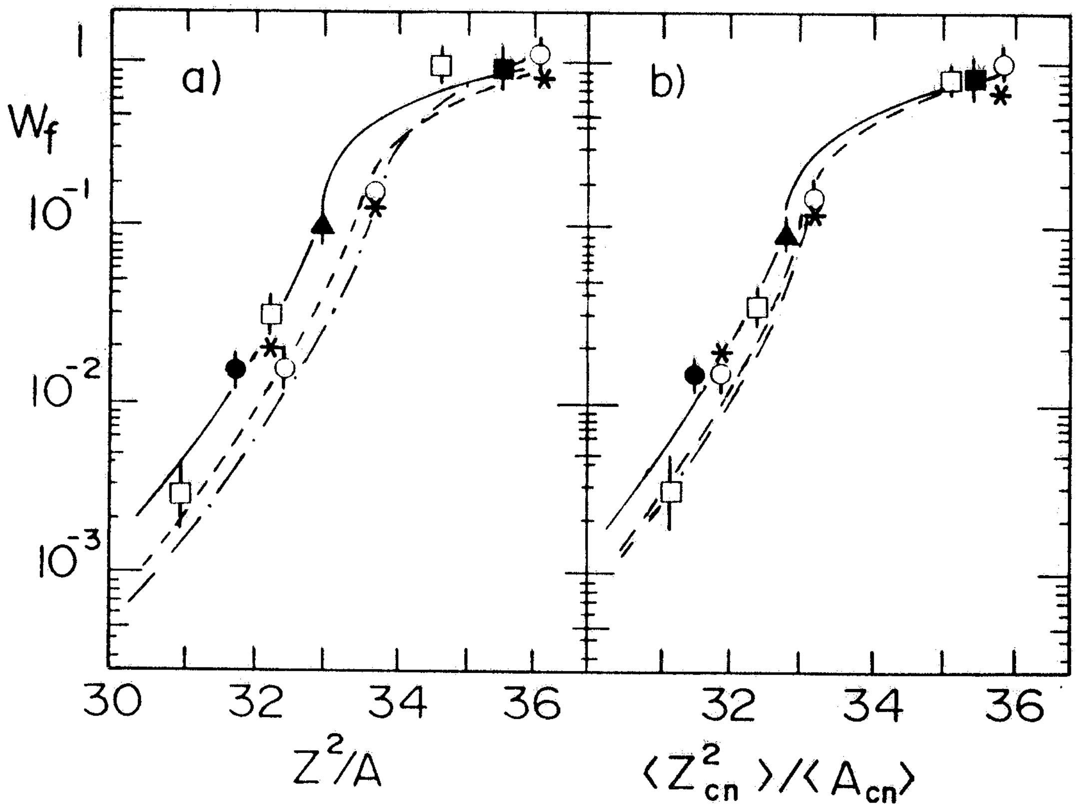

Fig.4 Fissilities values for Au, Bi, U nuclei excited by different probes. Specifically: 200 MeV photons (•, Ref.11; ▲, Ref.12; ■, Ref.13); 190 MeV protons (*, Ref.14), and 80 MeV pions (o, π^+ and □, π^-, Ref.15). The curves are the results of calculations with the cascade-evaporation Monte Carlo code: 200 MeV photons (full line); 190 MeV protons (dashed line); 80 MeV π^+ pions (dash-dotted line). In Fig.4a, the abscissa is the Z^2/A of the initial system; in Fig.4b, the $<Z^2_{cn}>/<A_{cn}>$ of the compound nucleus, calculated, for each target, probe and energy, with the Monte Carlo code, is used.

In the same figure, the corresponding results of our intranuclear cascade calculations with the evaporation model of Ref.1 are also reported for 200 MeV photons (solid curve), 190 MeV protons (dashed curve), and 80 MeV positive pions (dash-dotted curve). Both the experimental and calculated fissility values are plotted versus the parameter Z^2/A of the initial system ($Z=Z_t+Z_i$, $A=A_t+A_i$). It is seen that, apart from a similar general trend, with this choice both the experimental and calculated fissilities by different probes are deviated each other. Though mass and charge numbers lost ΔA, ΔZ, are similar for the different probes, the mass and charge numbers A_{cn} and Z_{cn} will be different, due to the different initial system. If we take as abscissa the correct parameter $<Z_{cn}>^2/<A_{cn}>$ of the averaged compound nucleus, as given by our Monte Carlo intranuclear cascade calculations, the data and curves for the fissilities of heavy nuclei by intermediate energy photons, protons and pions display a substantial agreement (Fig.4b). The data and curves for photofission are just a little higher, due to the higher value of the average excitation energy.

By examining Fig.4b, two observations appear of particular significance:

1) The experimental fission probabilities W_f are about the same, independently of the tool used to excite the nuclear matter, provided that the beam energy is chosen in such a way that the competing processes which characterize the absorption of the probe transfer the same energy and angular momentum and give similar nucleonic composition to the compound nucleus . This is indeed important, both from the point of view of the understanding of the effective excitation mechanisms leading to fission, and as a stringent demonstration that the second step must depend uniquely on the transferred energy, angular momentum, and nucleonic composition of the compound nucleus and, hence, under suitable conditions, be independent of the impinging projectile of intermediate energy.
2) The data from different probes, under similar excitation energy, angular momentum, nucleonic composition, show a significative agreement with the theoretical fissility behavior *vs* $<Z^2_{cn}>/<A_{cn}>$ calculated with the cascade-evaporation model.

The agreement found among experimental results and between experimental results and theoretical calculations over the explored Z^2/A range is encouraging, since it is founded on the further internal check represented by the use of different probes utilized under the same physical conditions for fission process.

5. Conclusions

Here we summarize our main results and conclusions.

a) A comparison between photofission and fission induced by pions and protons was performed under similar excitation energy, angular momentum and nucleonic composition of compound nuclei (Fig.3), and the obtained compound nucleus fission probabilities were found to be in substantially agreement for all probes (Fig.4b).

b) The significance of this result was recognized both in a better understanding of the effective excitation mechanisms of nuclei by intermediate energy particles, and in the recalling the two-step nature of the fission process, since it was put in clear evidence the dependence of the second step of the fission process on excitation energy and other compound nucleus characteristics only, and not also on the nature of the probe.

c) The data from different probes were compared with the cascade-evaporation calculation results (Fig.4b) and a satisfactory agreement between the calculated and measured fissility values from photon-, pion- and proton-induced fission reactions in heavy nuclei was found.

The obtained results on the dependence of the simplest characteristic of the fission process, namely the fissility, on the nature of the probe, for a range of Z^2/A values, show that further developments of such a study is desirable. It would be stressed that one needs not only to simply expand the region of targets, energies and probes: one needs coincidence experiments to measure the characteristics of both fission fragments and emitted particles. This will allow to infer the actual excitation energy and nuclear

In particular, from our point of view, two directions in such effort are interesting:

i) Investigation of the manifestations of microscopic thermal effects, namely the disappearance of shell effects, with increasing of the excitation energy at $E^* \leq 50$ MeV.[1] To reach this goal one must study the energy dependence of fissility of nuclides neighboring the double magic nucleus ^{208}Pb by different probes in the region of intermediate primary energies (≤ 300 MeV).

ii) Investigation of macroscopic thermal effects (the thermal decrease of fission barrier height)[1] and of new mechanisms of nuclear decay (*multifragmentation*)[20] at $E^* > 300 \div 400$ MeV. To reach this region of higher excitations of compound nuclei data on fission by monochromatic photons, protons and pions with ≈1 GeV energy and also by low-energy antiprotons are needed.

Moreover, one would compare such data on fission of nuclei by different energetic probes with detailed calculations of more sophisticated cascade-evaporative models, which take into account all the above physical effects.

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