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FISSION HINDRANCE IN HOT NUCLEI

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FISSION HINDRANCE IN HOT NUCLEI

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INTRODUCTION

The role of dynamics in fission has attracted much interest since the discovery of this process over fifty years ago. However, the study of the dynamical aspects of fission was for many years hampered by the lack of suitable experimental observables against which theoretical calculations could be tested. For example, it was found that the total kinetic energy release in fission can be described equally well by very different dissipation mechanisms, namely the wall formula, that is based on the collisions of the nucleons with the moving wall of the system, as well as a bulk viscosity of the nuclear matter. Although early theoretical work [1] suggested that the fission process may be described as a diffusion process over the fission barrier, this was largely forgotten because of the success of a purely statistical model which instead of enumerating the ultimate final states of the process argues that the fission rate is determined at the 'transition state' as the system traverses the fission saddle point [2].

It was therefore significant when Gavron *et al* [3] showed that the transition state model was unable to describe the number of neutrons emitted prior to scission at high excitation energy in reactions of ^{16}O+^{142}Nd. Subsequent experimental work using different methods to measure the fission dissipation/viscosity has confirmed these initial observations. It was therefore very surprising when Moretto *et al* in recent publications [4, 5] concluded that their analysis of fission excitation functions obtained with α and ^{3}He induced projectiles was perfectly in accord with the transition state model and left no room for fission viscosity. In this paper we'll show that Moretto's analysis is flawed by assuming first chance fission only (in direct contradiction to the experimental observation of pre-scission neutron emission in heavy-ion induced fission), and reveal why the systematics presented by Moretto looked so convincing despite these flaws.

DISSIPATIVE FISSION

In measurements of the fission cross section from highly excited nuclei it is normally not possible to measure the mass and charge of the fission fragments to a precision that would allow for a unique identification of the fissioning system. In general, it is expected that the measured fission cross section has contributions from several steps of the evaporation cascade of the system as illustrated in Fig. 1. Only at low excitation energies where the removal of the first neutron lowers the excitation energy below the fission barrier is multi-chance fission effectively excluded. In hot nuclei one expects, however, that on average several neutrons are evaporated before the system traverses the saddle point on its way toward scission.

Figure 1. Schematic illustration of the neutron evaporation cascade and multichance fission

The effect of dissipation or viscosity in the fission process is to lower and possibly delay the fission decay rate over the saddle point. This lowers the fission cross section, and increases the evaporation residue cross section, both of which can be measured. For the nuclei that fission despite this reduction one expects that a larger number of neutrons are emitted before the saddle point is traversed.

Within the diffusion model of fission [1, 6, 7] the fission decay width of the transition state model [2], Γ_{BW}, is modified in two ways: 1) it is reduced by a factor $(\sqrt{1+\gamma^2}-\gamma)$, which depends on the dissipation strength, γ, and 2) there is a buildup time of τ before the constant decay width is achieved:

$$\Gamma_f = \Gamma_{BW}(\sqrt{1+\gamma^2}-\gamma)[1-\exp(-t/\tau)] \tag{2}$$

In addition, the descend from saddle to scission would be substantially slower in case of high viscosity, allowing for a larger number of neutrons to be emitted before the system scissions. Similar conclusions apply to the emission of GDR γ-rays prior to scission. With no dissipation, the saddle-to-scission time, t_{ss0} is of the order 2 - 5×10^{-21} sec. This descend time is prolonged by a factor $(\sqrt{1+\gamma^2}+\gamma)$ in the presence of dissipation [8] resulting in

$$t_{ss} = t_{ss0}(\sqrt{1+\gamma^2}+\gamma). \tag{3}$$

The value of the normalized dissipation strength, γ, is in most cases taken as a free parameter to be determined from comparisons to data. In most cases it is found that $\gamma \approx$ 5-10 is required to obtain agreement with data. It is of interest to note that the one-body dissipation mechanism [9, 10] predicts $\gamma \approx$ 5-6 for the heavy nuclei studied in these experiments, in quite good agreement with those obtained from experiment. Although most analyses do not discriminate between the fission motion inside and outside the saddle point, there is no á priori reason to expect that the strength of the dissipation be constant over the range of shaped needed to describe the fission process. In fact, it has been suggested that a rather strong shape dependence may be present [11]

The experimental observables for viscosity in the fission motion are therefore clear: 1) The combined effects of a reduced fission rate and an slowed down descent from saddle to scission are enhanced emission of pre-scission neutrons, γ-rays and charged particles, and 2) the reduced fission rate alone may be observed in a reduced fission cross section, which is counterbalanced by an increased cross section for evaporation residues. All of these effects have been observed in fission of heavy nuclei.

PRE-SCISSION EMISSION OF NEUTRONS AND γ-RAYS

The initial observation of an excess in the emission of pre-scission neutrons by Gavron *et al* [3] spawned further studies of this effect in a large number of systems [12, 13, 14, 15, 16, 17], which firmly established the fact that the motion toward scission is highly viscous resulting in a reduced fission probability and a slowing down of the fission motion. As an example we show data for the reactions ^{16}O+^{208}Pb [16], and ^{19}F+^{232}Th [12], see Fig. 2a-b. We observe that the experimental data are in good agreement with model predictions assuming a dissipation strength of $\gamma = 5$ [18], whereas the purely statistical model ($\gamma = 0$) severely underestimate the multiplicity, ν_{pre} of pre-scission neutrons.

The effect of fission dissipation is also clearly seen in the emission of pre-scission γ-rays, especially in the Giant Dipole Resonance region. This has been studied for a number of reactions by the Stony Brook group [20, 19, 7, 21]. One example is shown in Fig. 2c-d for the system ^{32}S+^{208}Pb at E_{beam} = 230 MeV [20]. Again, this analysis shows a clear effect of the dissipation in the fission motion requiring a strength of $\gamma \approx$ 5-10 inside the barrier and a saddle-to-scission time of $\tau_{ss} = 30\times10^{-21}$ sec, corresponding to $\gamma = 5$ outside the saddle point as well.

A strong effect of fission viscosity is also observed in the cross sections for evaporation residues in heavy fusion reactions [22, 21, 23]. Thus it is found that the survival probability of the fused system does not decrease as additional decay steps are added to the evaporation cascade by increasing the excitation energy. It appears that the fission decay branch at high excitation energy is essentially hindered due to high viscosity.

Figure 2. Pre-scission neutron multiplicity nu_{pre} (open circles) for the ^{16}O+^{208}Pb [16] (panel a) and ^{19}F+^{232}Th [12] (panel b) reactions are compared to statistical model calculations with (γ=5) and without (γ=0) fission dissipation as a function of excitation energy. Panel c: γ-ray spectrum in coincidence with fission fragments for ^{32}S+^{208}Pb at 230 MeV [20] is compared with statistical model calculations with (γ=5) and without (γ=0) fission dissipation. The contributions from pre-saddle and saddle-to-scission for γ=5 are also shown. Panel d: The γ-ray anisotropy relative to the fission axis is compared to calculations including fission dissipation (solid curve).

MORETTO'S ANALYSIS OF FISSION CROSS SECTIONS

In a recent publication Moretto *et al* [4] have analyzed a large number of α induced fission excitation functions on targets ranging from ^{182}W to ^{209}Bi. More recent measurements of ^{3}He+^{197}Au,^{208}Pb, and ^{209}Bi [5] have been analyzed in the same manner. This analysis is based on the branching ratio between neutron emission and fission of the fused system (i.e. first chance fission *only*) using the transition state model with Fermi-gas expression for the respective level densities. The partial decay width for first chance fission, Γ_f, is

$$\Gamma_f \approx \frac{T_{sad}}{2\pi}\frac{\rho_{sad}(E - B_f - E_r^{sad})}{\rho_{gs}(E - E_r^{gs})} \tag{4}$$

where T_{sad} and ρ_{sad} is the nuclear temperature and level density at the saddle point and ρ_{gs} is the level density at the ground state deformation, all taken at the excitation energy E and back-shifted for the rotational energy E_r and the fission barrier B_f. The cross section for *first chance* fission is

$$\sigma_f = \sigma_0 \frac{\Gamma_f}{\Gamma_{total}} \approx \sigma_0 \frac{1}{\Gamma_{total}} \frac{T_{sad}\rho(E - B_f - E_r^{sad})}{2\pi\rho_{gs}(E - E_r^{gs})}, \tag{5}$$

where σ_0 is the fusion cross section, and Γ_{total} is the total decay width, which is dominated by the neutron decay branch. This expression may be re-written as

$$\frac{\sigma_f}{\sigma_0}\Gamma_{total}\frac{2\pi\rho_{gs}(E - E_r^{gs})}{T_{sad}} = \rho_{sad}(E - B_f - E_r^{sad}). \tag{6}$$

Using the Fermi-gas expression for the level densities $\rho(E) \propto \exp(2\sqrt{aE})$ and taking the natural logarithm this expression reduces to

$$\ln(\frac{\sigma_f}{\sigma_0}\Gamma_{total}\frac{2\pi\rho(E - E_r^{gs})}{T_{sad}})/2\sqrt{a_n} = \ln(R_f)/2\sqrt{a_n} = 2\sqrt{\frac{a_f}{a_n}(E - B_f - E_r^{sad})}. \tag{7}$$

Here a_n and a_f are the Fermi-gas level density parameters for the ground state and saddle point deformation, respectively. Using the measured fission cross section σ_f and the fusion cross section σ_0 obtained from an Optical Model calculation, Moretto plots the left hand side of this relation against the right hand side and finds a convincing linear relationship, when using reasonable choices of the fission barrier B_f, and the ground state shell correction Δ_{shell}. This is taken to prove that the fission decay of these hot systems is in perfect accord with the transition state model and under the assumption of *first chance fission* it is shown that this analysis excludes fission delay times of the order τ = 30-50×10^{-21} sec, as obtained from the analysis of pre-scission neutron multiplicity data. This conclusion presents a serious puzzle and it is in direct conflict with the conclusions drawn from pre-scission neutron- and γ-emission data, as well as evaporation residue cross sections. However, in the following sections we'll show that this conflict is only *apparent* and that it is caused by the unjustified assumption of first chance fission and masked by an unfortunate way of plotting the data, that effectively eliminates the sensitivity to the cross sections.

MULTI-CHANCE FISSION

To determine whether the assumption of first chance fission is justified in these systems we have calculated the first chance fission cross sections for the ^{3}He+^{208}Pb reactions studied by Rubehn *et al* [5], using the parameters given in this reference and a fusion cross section obtained from the modified proximity potential. This is shown as a dashed curve in Fig. 3a and is seen to under estimate the fission cross section by about a factor of three. By taking the multi-chance fission into account in a simplified statistical that uses the Sierk fission barriers [24] and ground state shell corrections from Möller & Nix [25] we find that the fission cross section is *over* predicted by a factor of three at the highest energies. The contributions to the fission cross sections from the various steps in the decay chain is illustrated in Fig. 3b. A similar result is found from a more complete statistical model calculation using the CASCADE code [26]

Since the true model calculation over-predicts the fission cross section, there is now room for the effects of fission hindrance or fission delay. Thus we find that introducing a fission delay time of τ=100×10^{-21} sec gives a reasonable agreement with the

Figure 3. Panel a: experimental fission cross sections σ_f (open circles) are compared to the first chance fission cross section [5] (thick dashed curve), the full cascade (solid thick curve), and a calculation including a fission delay time of τ=100×10^{-21} sec (thin solid curve). The fusion cross section is shown as a thin dashed curve. Panel b: The importance of multi-chance fission is shown in a cumulative fashion. Panel c: Moretto plot for experimental data (open circles), first chance fission (dashed line) and the full cascade (solid line).

data, within this simple model. We therefore disagree with the conclusion of Moretto *et al* [4]and Rubehn *et al* [5], who find that the fission cross section data are not compatible with the notion of fission decay times of the order obtained from pre-scission neutron- and γ-emission data. As demonstrated here, this conclusion was reached on the erroneous premise that only first chance fission occurs in these reactions, an assumption that is directly contradicted by the observation of substantial pre-scission neutron multiplicities in similar systems [12].

LARGE NUMBERS - SMALL NUMBERS

We are therefore left with the question of how the plots presented by Moretto *et al* [4]and Rubehn *et al* [5] could look so convincing when the calculated cross sections deviated by a factor of three from the measurements. This is illustrated in Fig. 3c where the quantity $\ln(R_f)/2\sqrt{a_n}$ is plotted as a function of $\sqrt{E - B_f - E_r^{gs}}$ for the experimental cross sections (solid circles), the first chance fission cross section (same as the dashed line in panel a), and the total fission cross section from the full cascade (same as the wide solid curve in panel a). We see that these are essentially indistinguishable in this plot, despite the fact that they are based on cross sections that are up to an order of magnitude apart. At the highest energies, an order of magnitude difference in the cross sections translates to a 2.3% difference in the plotted quantity, which, of course, is barely noticeable. This arises because the term $\ln(\sigma_f/\sigma_0)$ is completely overwhelmed by the remaining term $\ln(\Gamma_{total} 2\pi\rho(E - E_r^{gs})/T_{sad})$ containing mainly the logarithm of a level density. The Moretto plot is thus dominated by the level densities that appear in both the abscissa and the ordinate. The sensitivity of this plot to the measured quantity is very small, and it is therefore a very unfortunate way of presenting the data. As we have demonstrated, it easily leads to unwarranted conclusions.

SUMMARY

In this paper we have discussed the concept of viscosity in the fission process and its observable effects in pre-scission neutron, and γ-emission. Other observables related to the competition between fission and neutron emission in the decay cascade of an excited nuclear system have also provided additional evidence for dissipation in the fission motion. In direct conflict with these observations, Moretto *et al* [4]and Rubehn *et al* [5] have recently concluded that their analysis of a large number of fission excitation functions leave no room for fission delay or hindrance. In this paper we have shown that this analysis is incorrect because, 1) only first chance fission is considered and 2) the method of analysis effectively eliminated the sensitivity to the measured quantities. We therefore conclude that there is no ambiguity between the different experimental observables and we find that a detailed analysis of all the data within a single statistical model, including the effects of fission viscosity is called for.

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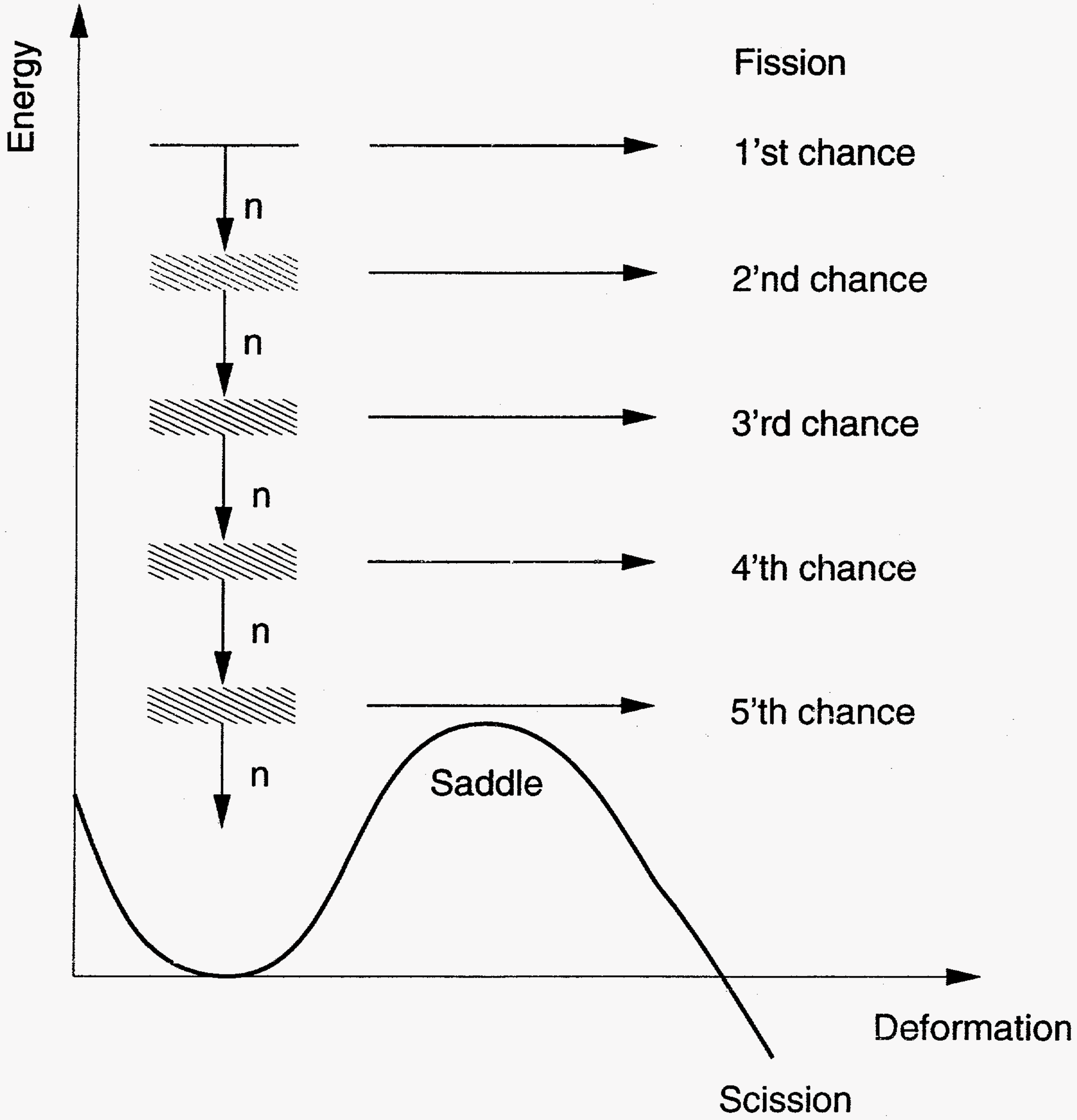

Fig. 1. "Fission hindrance of hot nuclei", B. B. Back et al.

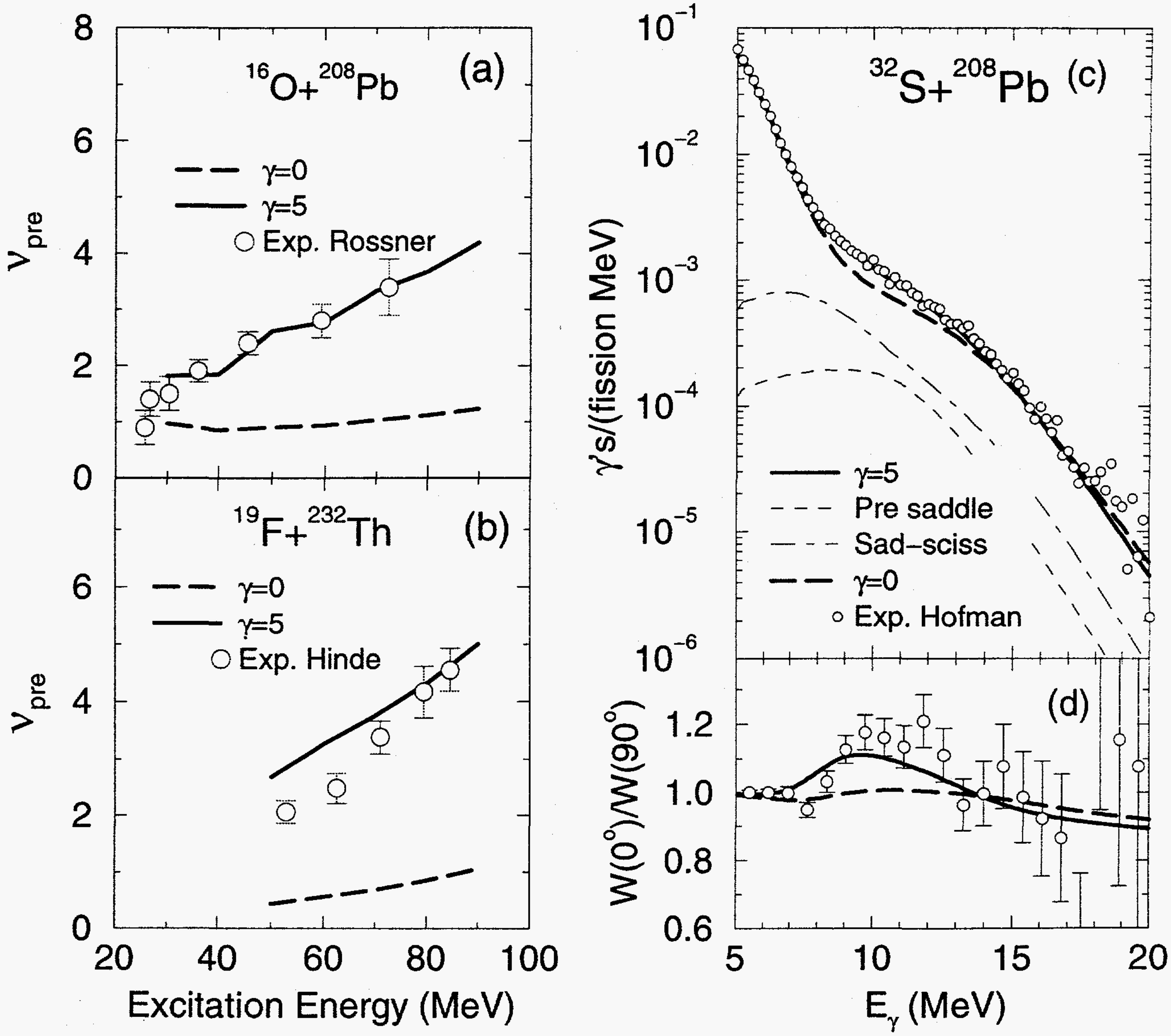

Fig. 2: 'Fission hindrance in hot nuclei' B. B. Back et al.

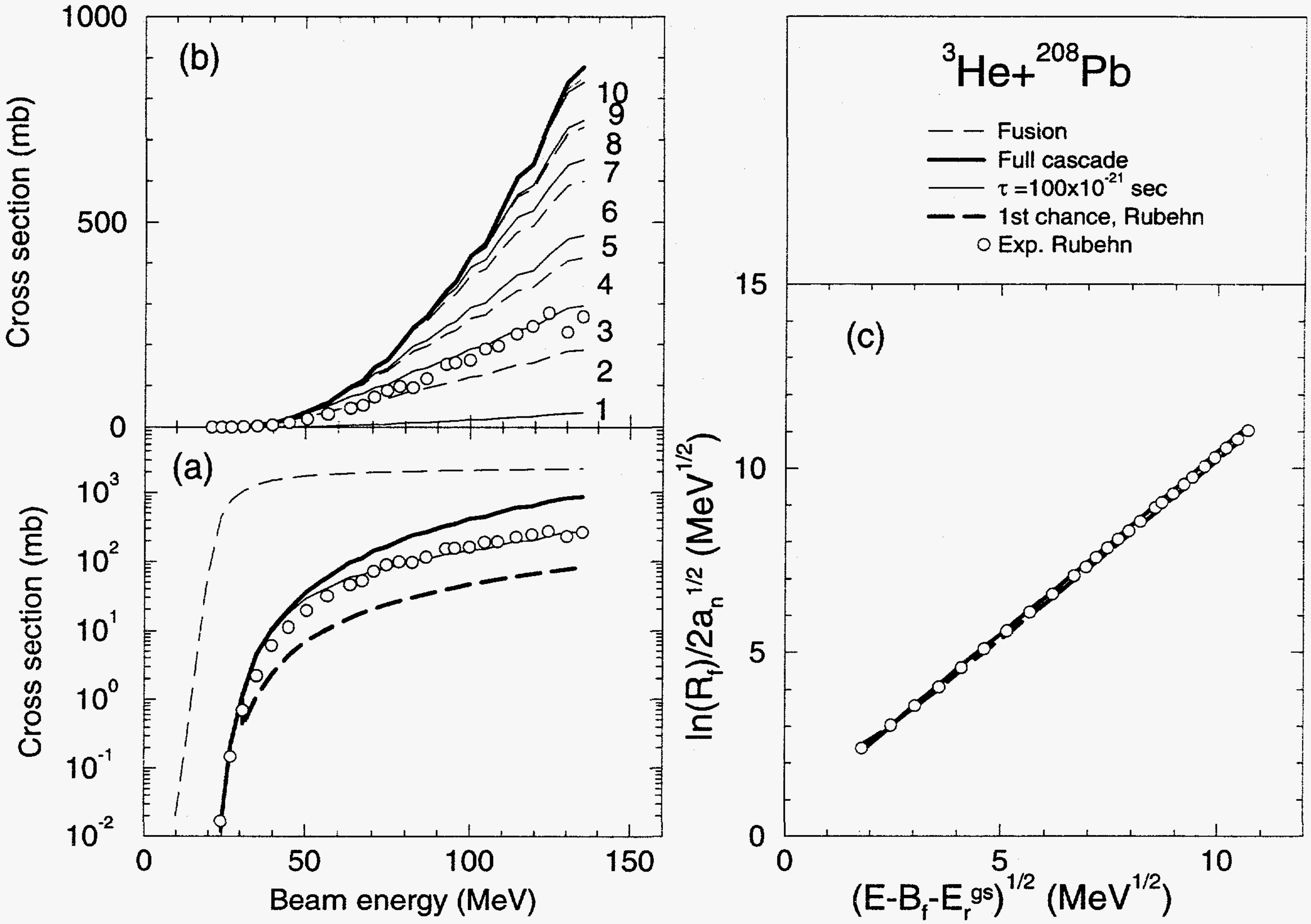

Fig. 3: 'Fission hindrance in hot nuclei' B. B. Back et al.