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TITLE Nuclear Fission - An Inherently Non-Equilibrium Process?

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Heavy Ion Fission - An Inherently Non-Equilibrium Process?

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Recent measurements of neutron emission in coincidence with fission fragments indicate a strong enhancement of the neutron multiplicity preceeding fission compared with statistical model calculations. This enhancement has enabled the determination of the reduced nuclear dissipation coefficient β which, in turn, indicates that nuclear collective motion is overdamped. We examine some possible sources of error in this determination and speculate on the consequences of the obtained value of β.

Introduction

Over the past decade, numerous measurements of charged-particle and neutron emission in coincidence with fission fragments in Heavy-Ion reactions have been made[1-4]. The dominant feature in all the measurements was the increase in the multiplicity of particles preceeding fission compared to expectations based on statistical-model calculations. The implication of this enhanced emission is that the compound nucleus, formed by the colliding heavy-ions, moves relatively slowly towards scission, compared to the time scale of particle emission. The particles can be emitted as the collective deformation coordinate starts moving towards the saddle point and up to the point when the fragments have completely separated and obtained their final relative velocity. Details of the model used to analyze the data of ref. 1 were presented in ref. 5. In this report we will analyze several sources of errors which affect the value of the reduced dissipation coefficient β, inferred from these models. We find that despite a possible uncertainty in the magnitude of β, the conclusion that the motion of the fission coordinate is overdamped remains unchallenged. We examine possible consequences of this high dissipation, which include: 1) the inherent non equilibrium nature of the fission decay of ^{158}Er, and 2) the effect of the reaction channel dependence of compound nucleus decay, which has been observed in the ^{156}Er system[6].

Experimental

The experimental techniques that were used have been described in detail in previous publications: Neutrons are detected, in coincidence with fission fragments, using a combined time of flight and pulse shape discrimination technique. The angular distribution of the neutrons, with respect to the

fragments, can be fit using a model which contains three emission sources. 1) Non-equilibrium neutrons that can be described by a moving-source model, 2) Neutron emission from the composite system, which is approximately isotropic in the C.M. system, and 3) Neutron emission from the fission fragments during and after acceleration. The efficiency of the neutron detectors is calculated for the detector pulse-height threshold that we select and checked by neutron measurements with a ^{252}Cf source mounted in 2π geometry on a solid-stated surface-barrier detector. For the $^{16}O+^{142}Nd$ system at 207 MeV beam energy, we obtained 2.7±0.4 neutrons preceeding fission; in addition, 0.9±0.1 non-equilibrium neutrons are emitted. In a recent paper, Hinde et al obtained 4.2±0.3 neutrons preceeding fission for the same system at a beam energy of 178 MeV[4]. Evaporation calculations using PACE2[7] (which reproduce xn results on rare-earth nuclei) predict 7.5 neutrons in coincidence with evaporation residues. We obtained 5.7±0.2 neutrons, a discrepancy we attribute to contamination of the residue singles spectrum, and which has no obvious bearing on the fission neutron results. If, however, we arbitrarily assume that we have a normalization error in the fission data, the maximum factor that should be applied to the data is 7.5/5.7. The renormalized number of neutrons preceeding fission would then be (2.7±0.4)X(7.5/5.7) = 3.6±0.5 which is still lower than Hinde's value extrapolated to 207 MeV[4]. We consider this discrepancy to be due, most probably, to angular-momentum effects. In our original analysis, we neglected it since we estimated it to be only a few-percent effect on the in-plane angular distribution of neutrons. This estimate is correct for neutrons in coincidence with evaporation residues. However, when considering neutron emission preceeding fission, one is dealing with an angular momentum window spanning approximately 65 to 72ħ for the ^{158}Er system. If the quantization axis is defined as the perpendicular to the plane containing the beam axis and the fission axis, evaporation calculations[7] show that the angular distribution of neutrons preceeding fission is sharply peaked in-plane as shown in Fig. shown in Fig. 1a. If the quantization axis is defined as the beam axis, the neutron angular distribution is significantly forward peaked in this angular momentum window (Fig. 1b). This effect would lead us to underestimate the pre fission neutron multiplicity when assuming an isotropic distribution. In fact, we do not know how well the quantization axis is defined with respect to the beam axis and the reaction plane: The fission process breaks the azimuthal symmetry of the reaction, but does not select a well defined axis perpendicular to the plane.

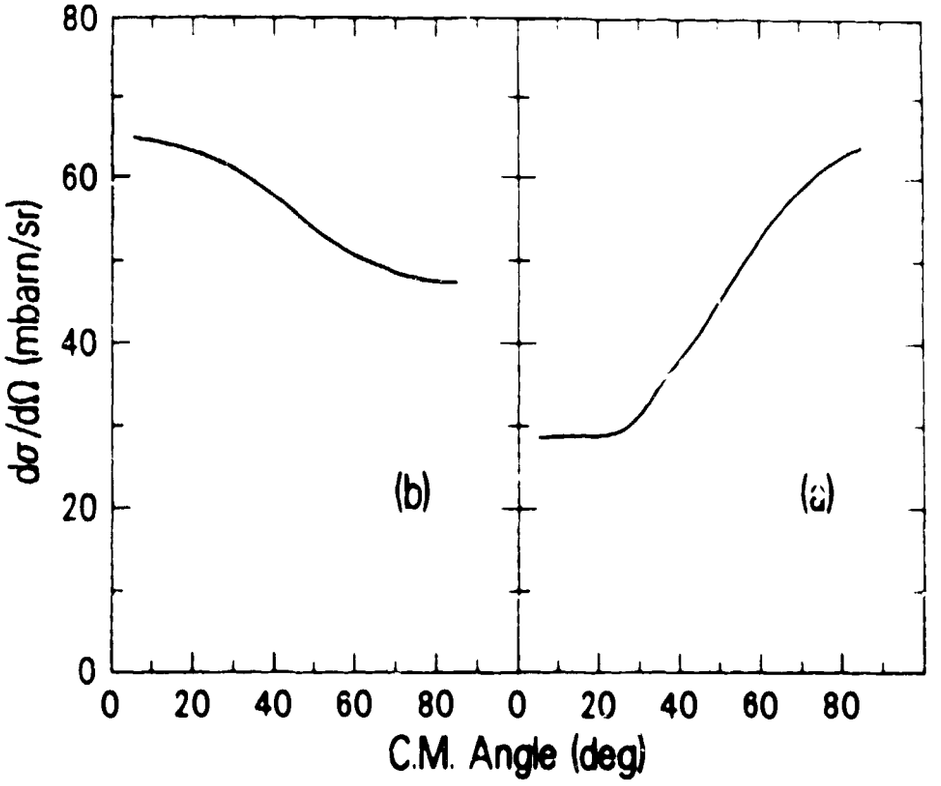

Fig. 1. Angular distribution of neutrons preceeding fission. a) Quantization axis perpendicular to plane. (Angle is with repect to normal to plane). b) Quantization axis perpendicular to beam axis. (Angle is with respect to beam axis) Results are for l=65ħ. There is no significant difference for l=72ħ.

Other effects should be considered when comparing the two results. These are -

1) The shape of the neutron evaporation spectrum we used was $E^{\alpha}e^{E/T}$; The parameter α was taken from PACE2 calculations[7] to be 0.6, which is close to the value determined by Madland and Nix[8]. In comparison, Hinde used $Ee^{E/T}$, where E is the neutron C.M. kinetic energy. There could also be a systematic error in our subtraction of the non equilibrium neutron component at low energies, due to our assumption of the spectrum shape being $Ee^{E/T}$. If we were to assume a $E^{\alpha}e^{E/T}$ shape with $\alpha \neq 1$ we would obtain somewhat different multiplicities.

2) There is an angular correlation between the plane defined by the fission fragments and the beam axis, and the emission direction of non-equilibrium particles[9]. The angular distribution is not azimuthally symmetric around the beam axis and the effect of this distribution needs to be considered in both experimental configurations.

3) Our configuration employs two large solid-angle gas detectors to detect the fission fragments. The detectors were both position sensitive which enabled us to eliminate edge effects. The configuration of Hinde et al is more constrained - it is conceivable that the fragment coincidence selection requirement introduces a bias into the measured neutron distributions[10].

4) An important parameter that these experiments should provide is the "little-a" parameter a_n. We find that $a_n=A/f$, where A is the atomic mass and $f=7.5\pm1.5$; Hinde et al use a value of $f=10$. These values of a_n result in an error of approximately ±50% in the calculated lifetimes of the emitted neutrons. In principal, this parameter can be determined for the compound nucleus by accurate measurements of neutron spectra in coincidence with evaporation residues.

Theory

The theoretical apparatus we used to determine the reduced nuclear dissipation coefficient β also contains many assumptions and simplifications in order to achieve its goal. These need to be clarified, and, if possible, closely scrutinized.

An important assumption often made is that the non-equilibrium neutrons are emitted on a much shorter time scale than the equilibrium neutrons. This enables us to analyze the data in terms of two distinct neutron sources: The first - a non equilibrium source - completes its emission before the second - a compound-nucleus (equilibrium) source - commences neution emission. In a recent paper, Blann[11] calculates the equilibration time for the $^{16}O,^{60}Ni$ system and obtains $(4-5)10^{-22}$ seconds at a C.M. energy comparable to that of our 207 MeV ^{16}O measurement. This is about 4 times faster than the emission time of the first neutron which would justify the consideration of the two distinct sources.

An additional assumption often made is that the various parameters, considered in the evaporation and diffusion problems, are temperature independent. The temperature dependence of the fission barrier of ^{208}Pb has been calculated by Guet et al[12]. They find that at T=2.6 MeV (the temperature of ^{128}Pr following non equilibrium neutron emission), the

fission barrier is reduced by 30% compared to the T=0 value. At T=2.0 MeV (after emission of the pre-fission neutrons) the barrier is still 20% lower than the T=0 value. Incorporation of this temperature dependence would decrease the number of pre-fission neutrons in the framework of standard statistical model calculations. In the diffusion model, the motion over the saddle-point would proceed more rapidly, leading us to increase β to retain the agreement between the calculations and the measured values of the pre-fission neutron multiplicity.

β is also assumed to be independent of temperature in the framework of the Wall-Window formalism[13]. At energies close to the fission barrier, we may expect β to decrease due to the lack of available states for quantum transitions. Such an effect is not presently considered. One may also need to consider quantum Brownian motion[14] at these energies.

Discussion

The possible discrepancies between experiments and the existing uncertainties in the model applied to the data do not seem to be sufficient to challenge the major conclusion obtained by the various groups involved in neutron emission studies: The motion towards scission is overdamped! The debate is only over the question whether β~6 or whether $\beta \geq 10$ in units of 10^{21}sec^{-1}. In the following, we use the value of $\beta=6\times10^{21}$sec^{-1} we have obtained using four reactions leading to the same composite system with a very similar angular-momentum window[1]. We can now follow the evolution of Γ_f, the fission decay width, and compare it to the total particle decay width Γ_p for different values of the angular-momentum l. The results are presented in Fig. 2. For $l=65\hbar$, asymptotically, $\Gamma_f=\Gamma_p$. This is the angular momentum, above which, fission exceeds charged-particle emission. For $l=70\hbar$, Γ_f passes Γ_p after $t=1.8\times10^{-20}$ seconds. At this point, fission decay will dominate, even though Γ_f is still a factor of three below its equilibrium value. The situation is even more acute for $l=75\hbar$, where fission will occur, on average, when Γ_f reaches 1/10 of its asymptotic value. This implies that even though we have considered a reaction in which a "compound nucleus" is formed inside a well-defined saddle point, the nucleus may fission long before the fission degree of freedom is equilibrated with the other degrees of freedom. This seems somewhat

paradoxical since the "compound nucleus" concept is construed to imply complete equilibration of all degrees of freedom.

The saddle-point approach to fission width calculations is assumed to be valid as long as the fission barrier $B_f(l)$ is greater than the temperature at the saddle-point[15]. Indeed, this was the rationale behind our selection of reactions and beam energies for this study. The selection resulted in partial waves between l=65ħ and l=72ħ, where $B_f(l) \geq T$ - we had assumed that this partial wave window in ^{158}Er will avoid the complications associated with "quasi-fission". Nevertheless, we find that at the highest excitation energies, the transition over the fission barrier occurs when the fission probability is far below its asymptotic (equilibrium) value!

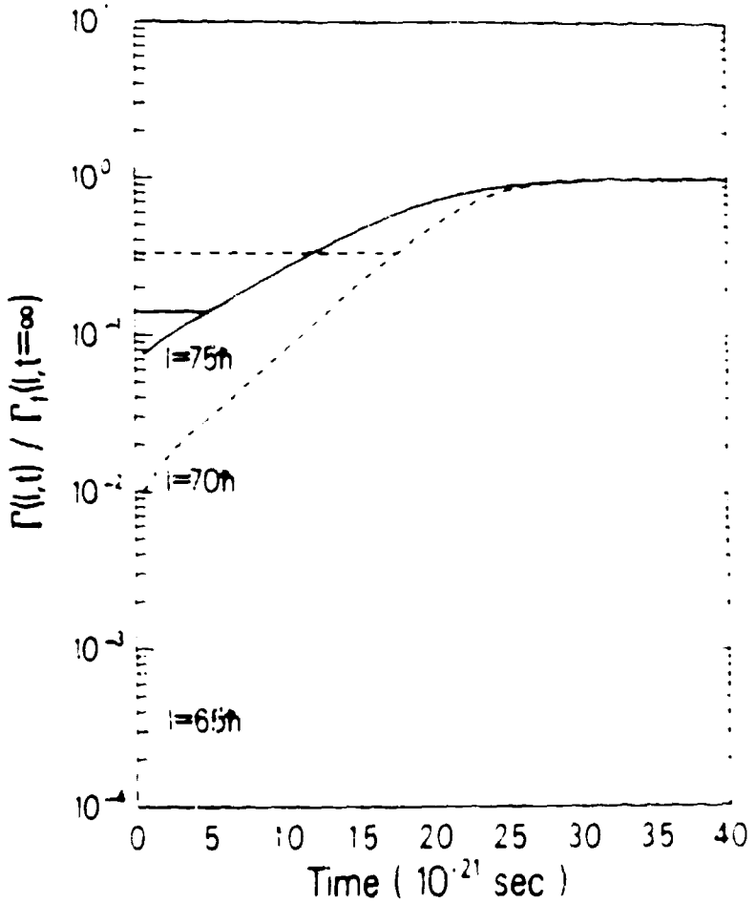

Fig. 2. Calculated decay widths as a function of time. Horizontal lines are $\Gamma(l)$, the total particle decay width. Curved lines are $\Gamma_f(l,t)$. The dotted line is for 65 ħ, the dashed line for 70 ħ and the solid line for 75ħ.

Another possible implication of the large degree of dissipation pertains to the $^{64}Ni+^{92}Zr$ reaction[6]. Differences between evaporated neutron multiplicities in this reaction and in the $^{12}C+^{144}Sm$ reaction have been considered evidence for non statistical behavior in the Ni+Zr system. The possibility of a super deformed minimum in the potential energy surface of the fusing nuclei has also been considered in this context[6]. We wish to

point out that the relative kinetic energy between the Ni and the Zr nuclei is comparable to that between outgoing fission fragments of the ^{156}Er system. Thus, when the distance between the individual centers-of-mass of the Ni and Zr decrease and approach that of the saddle point, the motion should be described by the Fokker-Planck equation. This implies a very slow formation time for the compound nucleus; during this time, particle emission can take place from the deformed fusing system. Indeed, we calculate[7] the lifetime of the first neutron to be $\sim 10^{-19}$sec which is comparable to the transit time over the fission barrier for near-symmetric systems[1]. However, why this should result in a supression of neutron emission[6] is still not clear.

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