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NEUTRON EMISSION PRIOR TO FISSION

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In recent years, many groups have measured neutrons and light charged particles in coincidence with fission fragments in heavy ion reactions. In most cases, particles emitted with an energy spectrum and angular distribution characteristic of that of compound nucleus evaporation have been measured in excess of statistical model predictions. We have chosen to investigate this effect in detail by studying neutron emission in the ^{158}Er composite system. The advantage of this system is that it can be produced by a variety of projectile target combinations. We have chosen four combinations which form ^{158}Er with similar critical angular momenta but varying excitation energy. The rationale is to form the same system with different neutron emission times; if the enhanced neutrons are being emitted during the fission process, the different emission time scales might possibly be used to time the fission process. In addition, we impose an additional constraint - that we have a significant fission barrier for most of the partial waves involved in the fission process. The reactions we have selected are ^{16}O + ^{142}Nd (207 MeV beam energy), ^{24}Mg + ^{134}Ba (180 MeV), ^{32}S + ^{126}Te (180 MeV), ^{50}Ti + ^{108}Pd (216 MeV).

The experiments were performed at the Holifield Heavy Ion Research Facility (ORNL) using coupled operation between the tandem Van de Graaff accelerator and the ORIC cyclotron. Fission fragments were detected in coincidence using two position sensitive low pressure multiwire detectors. Evaporation residues (in the ^{16}O and ^{24}Mg reactions) were detected using similar detectors placed between 3° and 18° in plane relative to the beam axis. The residues were identified by their time-of-flight (relative to the cyclotron timing) and their pulse height in the multiwire detectors. Coincident neutrons were detected in eight detectors outside the scattering chamber. The detectors were approximately 12 cm in diameter and 5 cm thick, encapsulated NE213 liquid scintillator. Pulse shape discrimination was used to reject gamma rays detected during the time window appropriate for neutron detection. The spectra were corrected for the neutron detection efficiency which was obtained both from calculations and from direct measurement with a ^{252}Cf source. We determine the multiplicity of the evaporated neutrons ("pre-fission neutrons") by fitting the neutron spectra and angular distribution in coincidence with fission fragments with simulated spectra generated by the following three processes: (1) nonequilibrium neutron emission (NNE) - we use a moving source parameterization[1] with the temperature and source velocity taken from the residue data; (2) evaporated neutrons from the composite system; and (3) neutrons evaporated from (and therefore focused by) the fission fragments.

A summary of the reactions, experimental results and statistical model calculations is presented in the table below.

E_{beam} (MeV)	Proj	Targ	E_x (MeV)	$\tau_n^{(1)}(10^{-21}s)$	ν_{SM}	ν_{exp}
207	^{16}O	^{142}Nd	140*	3.5	1.6	2.7 ± 0.4
180	^{24}Mg	^{134}Ba	115	5.4	1.0	2.5 ± 0.5
180	^{32}S	^{126}Te	93	15	0.7	1.7 ± 0.5
216	^{50}Ti	^{108}Pd	72	77	0.3	0.3 ± 0.3

*After subtraction of energy removed by NNE.
$t_n^{(1)} = h/\Gamma_n^{(1)}$ - lifetime of first emitted neutron.
ν - neutron multiplicity. SM - statistical model calculation.
exp - experimental result.

Comparing neutron multiplicities, we note that the discrepancy between ν_{SM} and ν_{exp} vanished at low excitation energies.

We reanalyze these data using a modified statistical model which incorporates effects due to nuclear dissipation, and also calculates neutron emission during the descent from the saddle to the scission point. In all, we consider three effects:

1. The "Kramers effect":[2] One of the effects of nuclear dissipation is to reflect some of the nuclei that have passed over the fission barrier towards scission, back towards the ground state. This causes a decrease in the fission width Γ_f, relative to the traditional Bohr-Wheeler value Γ_f^{BW}:

$$\Gamma_f = \Gamma_f^{BW}\{\sqrt{1 + (\beta/2\omega)^2} - \beta/2\omega\}$$

   where ω is the barrier curvature and β is the reduced dissipation coefficient.

2. The "Transient effect":[3] One has to consider the finite time ("transient time") it takes to build up the equilibrium probability flow over the fission barrier. For $\beta/2\omega = 0$ the coupling between the intrinsic degrees of freedom and the collective motion towards fission is very weak: consequently the transient time is very long. For $\beta/2\omega \gg 1$ the motion is highly damped, again resulting in a long transient time.

3. Neutron emission from the nucleus as it descends from saddle to scission. We consider here the transit time for each partial wave as a function of angular momentum.[4] The neutron emission time τ_n is calculated at the excitation energy at which fission occurs for each partial wave.

In order to reproduce the measured fission cross sections in the barrier region[5] while taking the first two effects into consideration in our statistical model calculations, we need to modify the values of a_f/a_n used: The Kramers effect reduces the fission probability as β increases and consequently we need to increase a_f/a_n simultaneously in order to fit available fission cross section data. This is shown as the full line in Fig. 1. The transient effect further suppresses the fission probability for very small and very large values of β - consequently the values of a_f/a_n are further increased to reproduce the fission cross sections. The final values of a_f/a_n used are shown as the dashed line in Fig. 1.

Results of the modified statistical model calculations including the Kramers and transient effects are presented as the long dashed line (marked T) in Fig. 2. The short dashed line (SM) depicts results of our original (unmodified) statistical model calculations. The full curve marked SST incorporates neutron emission during the saddle-to-scission transition. We see that the curve (SST) rises above the upper limit of the experimental value (dotted lines) at $\beta \sim 5 \times 10^{21}\ s^{-1}$. Given the fact that the calculated lines actually have a finite width (of the order of 0.1 neutrons, mainly a result of the error bars on the input fission cross) we do not consider the dip below the experimental result at low values of β to be significant - all values of β below approximately $5 \times 10^{21}\ s^{-1}$ should be considered compatible with the data.

To summarize, we are now able to provide a detailed interpretation of enhanced neutron emission preceeding fission in compound nucleus reactions. We are able to set an upper limit on the reduced nuclear dissipation coefficient β.

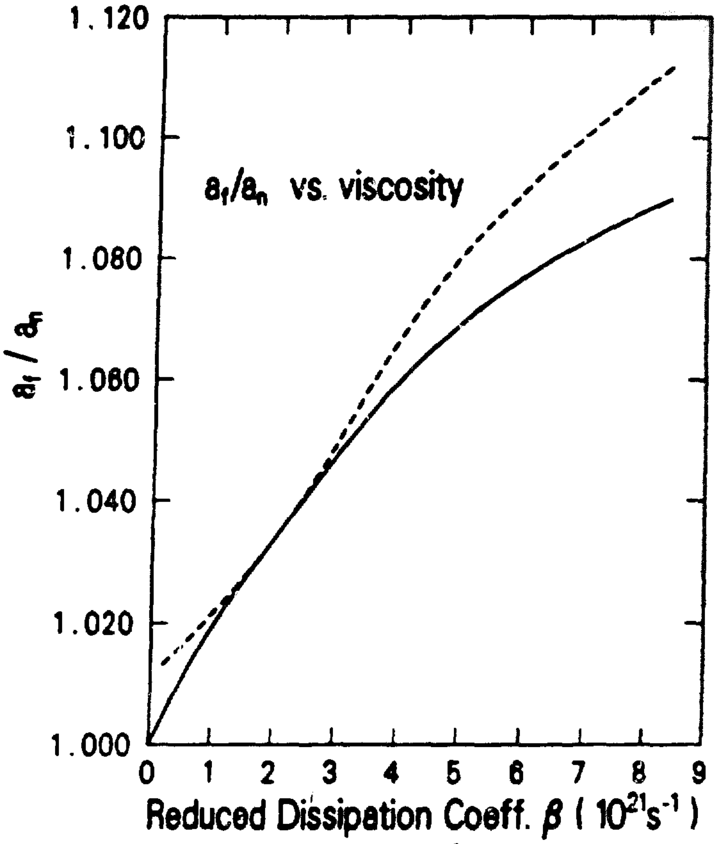

Figure 1

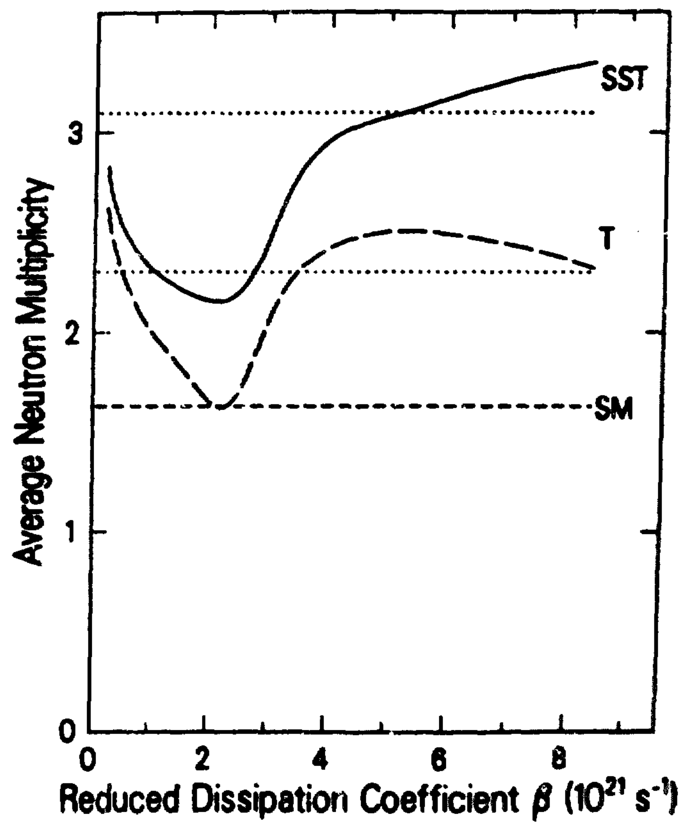

Figure 2

References

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