Fission Lifetimes as Mean First Passage Times ◇

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Fission experiments are commonly analyzed with the help of statistical codes which are based on simple rate formulas for the processes of fission and emission of light particles. In the early 80'ies an excess of neutrons was observed over that for which the fission rate is simply estimated by the Bohr Wheeler formula $\Gamma_{\rm f} \equiv \Gamma_{\rm BW}$ (see e.g. the review articles [1], [2]). An improvement was seen in replacing $\Gamma_{\rm BW}$ by the $\Gamma_{\rm K}$ of Kramers in which the fission rate gets reduced by friction, the more the larger the dissipation strength. Additional possibilities for enhancing the relative emission probability $\Gamma_{\rm n}/\Gamma_{\rm f}$ of light particles like neutrons were attributed to two effects which seem to arise in a time dependent description: (i) Starting the dynamics of fission at some time zero, it takes a finite time for the current across the barrier to reach the stationary value from which Kramers derived his formula. This "transient effect" is demonstrated in Fig.1 exhibiting solutions from Langevin simulations [3]. It is seen that the "transient time" depends sensitively on largely arbitrary initial conditions, for a critical discussion of this feature, see also [4]. (ii) To this stationary current a finite time lapse $\tau_{\rm ssc}$ may be associated for the motion from the saddle point down to scission. Often feature (i) is interpreted as a delay of fission during which particles may be emitted on top of the number given by $\Gamma_{\rm n}/\Gamma_{\rm K}$. Likewise, it is believed that also the neutrons emitted during $\tau_{\rm ssc}$ are not accounted for by this $\Gamma_{\rm n}/\Gamma_{\rm K}$.

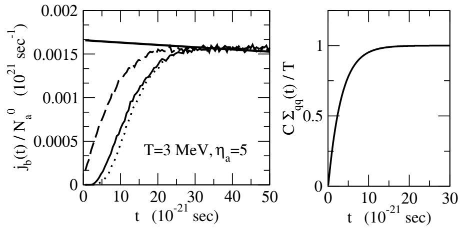

Fig. 1: The current across the barrier for different initial conditions: (i) For the dashed and dotted curves the system starts out of equilibrium in Q; the dashed curve corresponds to the current at the barrier $j_{\rm b}(t)$ and the dotted one to that in the scission region $j_{\rm sc}(t)$. (ii) For the fully drawn line the system starts exactly at the bottom of the well. The delay by about $(5-10)\cdot 10^{-21}$ sec is due to the relaxation of Q to the quasi-equilibrium in the well, as seen by the t-dependence of the width in Q, exhibited on the right in terms of fluctuations of the potential energy $C\Sigma_{qq} = C(\langle Q^2\rangle - \langle Q\rangle^2)/2$.

In [3] the interpretation of fission decay as a sequence of three subsequent steps (minimum-saddle, motion across saddle, saddle-scission) has been re-examined with the help of the concept of the "mean first passage time" $\tau_{\rm mfpt}(Q_{\rm a} \to Q_{\rm ex})$. It is the time the system spends on average in the interval $(Q_{\rm a}, Q_{\rm ex})$ once it is released at $Q_{\rm a}$ initially; here, $Q_{\rm a}$ represents the position of the potential minimum. Restricting to over-damped motion such an analysis can be performed in analytic fashion. In [5] this effect has been examined for the potentials having structure beyond that given by one minimum and one barrier, simulated by representing the potential by polynomials of fifths order. Two examples are shown in Fig.2. The calculation of $\tau_{\rm mfpt}(Q_{\rm a} \to Q_{\rm ex})$ was performed up to regions of the exit point $Q_{\rm ex}$ where the stationary value is reached. This is so even for the example shown on the bottom of Fig.2. There a potential is taken with a shoulder in a region which lies 20 MeV below the first minimum. For heavy nuclei this may thus be said to correspond to the scission region after which the fragments separate. In the figures the ratio $\tau_{\rm mfpt}(Q_{\rm a} \to Q_{\rm ex})/\tau_{\rm K}$ is shown to lifetime $\tau_{\rm K}$ given in Kramer's approximation, in which only the minimum and the barrier are considered to be relevant. These results exhibit clearly the mistake one makes if only Kramers' rate formula is used to estimate the time the system stays together. Rather, the overshoot of $\tau_{\rm mfpt}$ over $\tau_{\rm K}$ indicates that much more time is available for light particles to be emitted before scission. Suppose we look at neutrons. Whenever their average width $\Gamma_{\rm n}$ may be used to calculate the multiplicity per fission event from $\Gamma_{\rm n}/\Gamma_{\rm f}$, the enhancement of this number over that given by $\Gamma_{\rm n}/\Gamma_{\rm K}$ is determined by the ratio $\tau_{\rm mfpt}/\tau_{\rm K}$, viz $\Gamma_{\rm n}/\Gamma_{\rm f} = (\Gamma_{\rm n}/\Gamma_{\rm K}) \times (\tau_{\rm mfpt}/\tau_{\rm K})$.

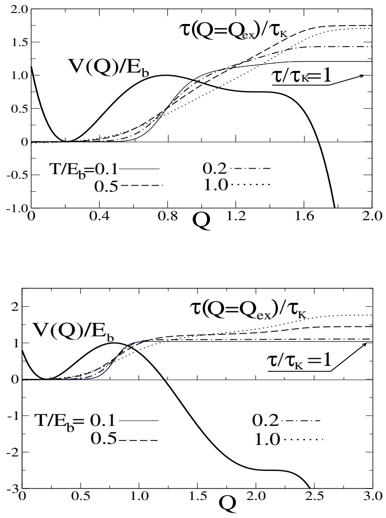

Fig. 2: The mean first passage time $\tau(Q = Q_{\rm ex}) \equiv \tau_{\rm mfpt}(Q_{\rm a} \to Q_{\rm ex})$ normalized to $\tau_{\rm K}$ for different temperatures, defined in units of $E_{\rm b}$, and two potentials having shoulders at some $Q_{\rm s}$ of heights $V_{\rm s}/E_{\rm b}$ relative to the barrier: $V_{\rm s}/E_{\rm b} = 0.75$ top, -2.5 bottom.

For the potentials chosen here this enhancement is at least of the order of that associated to the spurious effects of the transient or saddle to scission times [3], [4].

References

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