LANDAU-ZENER MECHANISM FOR NUCLEAR FRICTION

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The stage of descent from the saddle point to the nucleus scission is of special interest from the dynamical point of view because it involves a nonadiabatical coupling between collective and internal nuclear degrees of freedom. Coupling effects can be taken into account by introducing an effective friction force. In this work its dependence on the velocity and excitation energy is investigated using a statistical treatment of single-particle transitions occurring during any process with large amplitude.

The typical energy related to the descent time is essentially lower than the mean spacing between single-particle levels. Therefore the two-level approximation is valid for the inward dynamics. According to the Landau-Zener effect well-known from molecular physics, the probability of transition between states with the same symmetry is

$$W(q) = \exp\left\{ -2\pi \varepsilon^2 / \hbar G q \right\} \tag{1}$$

where ε is the minimal spacing between the pseudo-crossing levels, G the difference between their asymptotic slopes, and q the collective motion velocity.

The effective friction force is determined by the variation of internal energy over a trajectory interval Δq: $f_S(q,q)=\Delta E^*(q,q)/\Delta q$. The interval Δq must be macroscopically small, that is, small compared to the size of the region of the collective coordinate's variation from the saddle point q_o to the scission q_S but large enough to include much pseudo-crossing between levels. This assumption enables statistical methods to be employed [1]. The overal change in the internal energy is

$$\Delta E^*(E, q, q) = \frac{\Delta q}{\lambda} \int_{-\infty}^{\infty} \varepsilon P(E, q \mid \varepsilon) \exp\left\{-2\pi \varepsilon^2/\hbar G q\right\} d\varepsilon \tag{2}$$

where λ is the mean free path between pseudo-crossing points with respect to the coordinate q, $P(E,q \mid \varepsilon)$ the distribution of minimal distances among the levels in a neighborhood of excitation energy E, and G the level-slope difference averaged over the given interval Δq.

The distribution $P(\varepsilon)$ can be found from the level density $\rho(E)$. At energies far from the fission barrier $P(\varepsilon)$ has two humps. Its maximal values at points ε_+ and ε_- are simply the most probable minimal distances to the nearest higher and lower levels:

$$\varepsilon_\pm = \pm\left\{1 \mp \frac{\partial\rho}{\partial E}/2\rho^2\right\} /\rho(E) \tag{3}$$

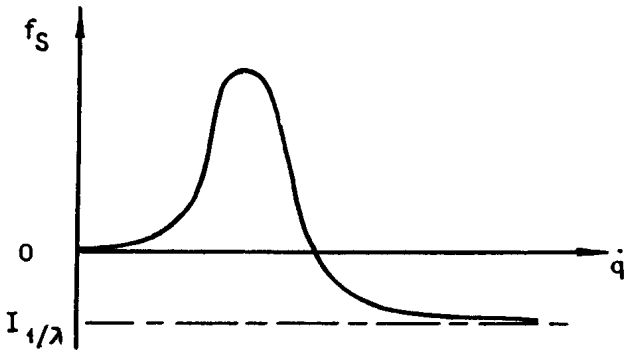

Fig.1 Friction force as a function of the descent velocity for the excitation energy far from the barrier

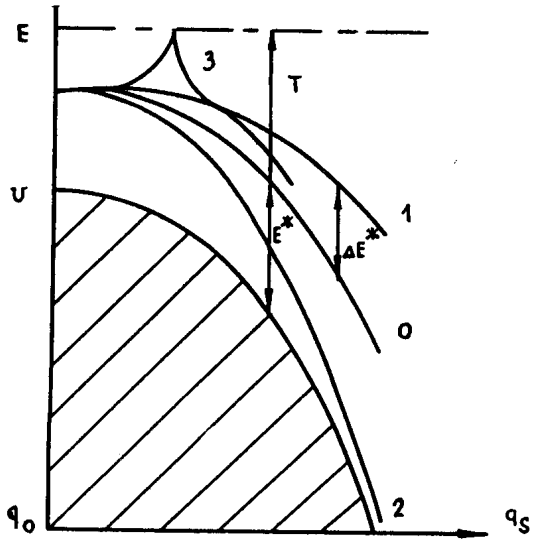

Fig.2. Trajectories of nuclear descent from the saddle point to the scission. 0 — the adiabatic case ($\Delta E^*=0$), 1 - the low velocity mode, 2 — trajectory of cold fission with a high velocity, 3 — the mode accompanied by particle emission

Usually the level density increases with energy: $\rho'(E) > 0$ and $|\varepsilon_+| < |\varepsilon_-|$. The velocity dependence of the friction force for these energies is shown in figure 1. In the small velocity region $f_S \sim q/2$ for any smooth function $P(\varepsilon)$. In the large velocity limit $f_S \to I_1/\lambda$ and gets negative and velocity-independent, where I_1 is the first moment of the distribution $P(\varepsilon)$.

For the simplest parametrization of $E\varepsilon$),

$$P(\varepsilon) = \frac{1}{2}\left\{\delta(\varepsilon - \varepsilon_+) + \delta(\varepsilon - \varepsilon_-)\right\}, \tag{4}$$

the friction force is

$$f_S = \frac{1}{2\lambda}\left\{\varepsilon_+ \exp\left(-2\pi\varepsilon_+^2/\hbar G q\right) + \varepsilon_- \exp\left(-2\pi\varepsilon_-^2/\hbar G q\right)\right\}. \quad (5)$$

Here the upward and downward transitions are equivalent, so that irreversibility results from the asymmetry in the level spacing ($|\varepsilon_+| \neq |\varepsilon_-|$).

At small excitation energy E the fissioning nucleus is found on the barrier with the result that only upward transitions are possible. In this case the distribution $P(\varepsilon)$ changes its character and the friction force gets $f_S = P_1 G^2 q/16\pi$ where P_1 is a linear term in the expansion of $P(\varepsilon)$ in powers of ε. The higher-order terms lead to higher powers of q in the friction force. Thus, the classical friction force (linear in velocity) is a particular case corresponding to low excitation energy and the small descent velocity.

The effect that the friction force has on the fission dynamics can be investigated in the simple model [1]. The equation of motion

$$M\ddot{q} = -\frac{dU(q)}{dq} - f_S(q, \dot{q}) \quad (6)$$

has been solved numerically with the reduced mass M and the parabolic barrier $U(q)$. There are several markedly different modes of descent from a barrier. They differ both in the values of the velocity and excitation energy and in the energy distribution of the nuclear levels. Figure 2 shows the possible descent trajectories from the fission barrier.

In the adiabatic case the internal energy E^* does not change, and the descent velocity increases monotonously. Usually level density increases with energy and transitions to the upper levels are more probable than those to the lower. As a result the trajectory moves upward and the internal energy grows at the expense of the kinetic energy. The decrease in descent velocity leads to a decrease in the probability of subsequent transitions, which again causes the velocity to increase. The resulting trajectory (curve 1 in figure 2) is determined by the balance of these processes.

For large initial velocities the probability (1) does not depend any more on the energy spacing ε. The friction force produces an additional acceleration and the trajectory approaches a barrier. The initial excitation energy is transformed into the kinetic one in this case which corresponds to the cold fission.

If the initial velocity is high enough and an additional increase in the level density with energy takes place (due to shell effects, for example), a rapid increase in internal energy occurs, which pushes the trajectory upward. This mode allows for single-particle transitions to the continuum, which drive the internal energy down but leave the kinetic one almost unchanged. The mode resembles particle emission during fission.

Reference

1. Mitropolsky I.A., Shuvaev A.G. //J.Moscow Phys.Soc., 1991. V.1. P.207.