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Fourth Winter Workshop on Nuclear Dynamics, Copper Mountain, Colorado, February 24-28, 1986
Dedicated to Wladyslaw J. Swiatecki on the Occasion of his Sixtieth Birthday

Tilting Mode in Nuclear Reactions

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Within the last few years, the problem of compound nucleus fission angular distributions has recieved renewed interest. According to the standard theory, fission fragment angular distributions are determined by the orientation dependence of the level density at the saddle shape. For very heavy nuclei, the saddle shapes should become compact, implying wide angular distributions. However, this conflicts with recent experiments [1], which display more narrow distributions, and this empirical evidence has led to the suggestion that fission fragment angular distributions are determined by the level densities and transmission coefficients associated with the more elongated scission shape [2,3].

The scission shape ansatz for angular distributions rests on the assumption that the time for descent from saddle to scission is long compared to the time scale for attaining an equilibrium distribution of orientations. It is thus of interest to investigate this time scale. The orientation dependence of the level density is given by the width of the distribution of the quantum number $K \equiv \vec{J} \cdot \hat{z}$. Here $\vec{J}$ is the total angular momentum, and $\hat{z}$ is a unit vector directed along the principal axis with the smallest moment of inertia of the shape. Since $\vec{J} \cdot \hat{z}$ for colliding systems is a measure of the excitation of the tilting mode [4], the time scale in question is the *relaxation time of the tilting mode* .

The present note gives a discussion of this relaxation time. First the relation between tilting relaxation and the reaction plane dynamics is discussed, providing an intuitive understanding of the expression for the cross section close to the beam direction, which has recently been derived [5]. Second, the tilting relaxation time and the related wriggling relaxation time are discussed, based upon nucleon exchange transport (window friction). Finally, recent experimental information on the tilting mode relaxation is discussed, and the dynamics of the tilting mode is discussed qualitatively for the three different types of nuclear reactions considered, compound nucleus fission, quasifission, and damped nuclear reactions.

In direct heavy ion reactions as well as in compound nucleus fission, the initial and final orbital angular momenta will generally not be parallel. This in turn implies that the entry and exit reaction planes do not coincide. Figure 1 shows schematically on a unit sphere the time evolution of the direction of the orbital angular mometum $\hat{L}$ and the direction of the radius vector $\hat{z}$ connecting the centers of the two nuclei participating in a direct reaction. At time $t = -\infty$ the radius vector points backwards from the target towards the incoming beam nucleus. Then it swings a certain angle along the *entry plane* until the nuclei start to interact (at direction $\hat{z}_0$). The interaction may cause the orbital angular momentum to change direction (into $\hat{L}_1$). (For our purpose of discussing time scales, it is convenient to break up the continous time evolution of $\hat{L}$ into finite steps.) The orbital motion now takes place in a plane perpendicular to $\hat{L}_1$, until the next interaction, and so on. At the end of the reaction, the radius vector moves in the *exit plane*, perpendicular to the final angular momentum $\vec{L}_f$. This motion terminates at a direction $\hat{z}_f$, when the distance between the two nuclei goes to infinity. The *tilting angle* ψ from $\hat{z}_f$ to the original reaction plane is determined by the amount of excitation of the tilting mode of the spins in the two nuclei, $\vec{S}^A$ and $\vec{S}^B$:

$$\sin\psi = \frac{\vec{J}}{J} \cdot \hat{z}_f = \frac{\vec{S}^A + \vec{S}^B}{J} \cdot \hat{z}_f \tag{1}$$

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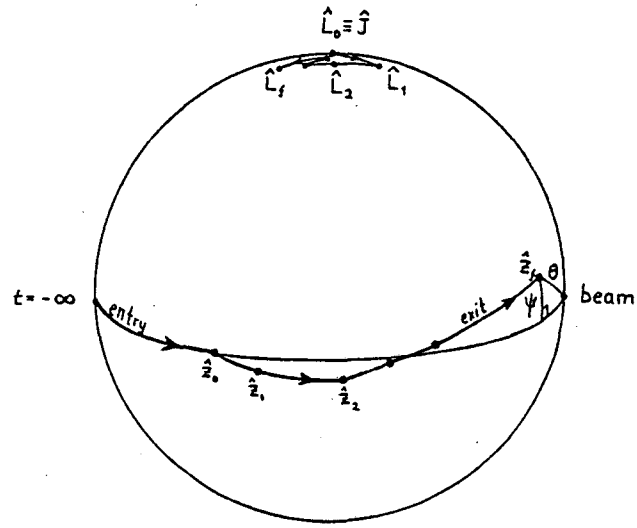

Figure 1

For symmetry reasons, the average of ψ must be 0.

For a given impact parameter, the stochastic nature of the angular momentum exchange in a nuclear reaction leads to many trajectories like the one shown in fig. 1, each one terminating in different endpoints $\hat{z}_f$. These endpoints determine the cross section. They will cover a band around the original reaction plane, the width of this band being determined by the dispersion in the tilting angle. A final scattering angle θ, which can be observed, collects the cross section along a circle centered at the beam direction. For scattering angles smaller that the tilting angle dispersion $\sqrt{< \sin^2 \psi >}$, the cross section $d\sigma/d\theta$ will be proprotional to the radius of the circle, *i.e.* it will be linear in θ. In ref. [5] the geometry displayed in fig. 1 has been treated mathematically to derive an expression for the cross section close to the beam (0° or 180° scattering angle):

$$\frac{d\sigma}{d\theta} = [f(\theta) + f(-\theta)]\,\frac{1}{2}\sin\theta\,\frac{\sqrt{2\pi}}{K_0}\exp\left(-\frac{J^2\sin^2\theta}{4K_0^2}\right) I_0\left(\frac{J^2\sin^2\theta}{4K_0^2}\right)$$

$$-\frac{\theta^2}{2} f''(0)\sin\theta\,\frac{\sqrt{2\pi}J}{K_0}\exp\left(-\frac{J^2\sin^2\theta}{4K_0^2}\right)\left[I_0\left(\frac{J^2\sin^2\theta}{4K_0^2}\right) - I_1\left(\frac{J^2\sin^2\theta}{4K_0^2}\right)\right] \tag{2}$$

Here $f(\theta)$ denotes the cross section projected onto the entry plane, so $f(\theta) + f(-\theta)$ is the cross section one would observe without tilting excitation. I_0 and I_1 are Bessel functions of imaginary argument, and $K_0 \equiv \sqrt{K^2}$ $(= J\sqrt{< \sin^2 \psi >})$ denotes the excitation of the tilting mode.

For not too asymmetric dispherical systems, the following relaxation times for the wriggling and tilting modes were derived in ref. [6] on the basis of the nucleon exchange transport theory:

wriggling:

$$t_{++} \approx 2\frac{I_A + I_B}{\rho\bar{v}R^2\sigma_{window}} \tag{3}$$

tilting:

$$t_{+z} \approx \frac{1}{4}\omega_R^{-2}\frac{J}{L}t_{++}^{-1} \tag{4}$$

Here I_A and I_B are the moments of inertia af the two nuclei, ρ is the density of nucleons inside nuclei, $\bar{v}$ denotes the average nucleon speed, R is the center distance between the two nuclei, and σ_{window} is

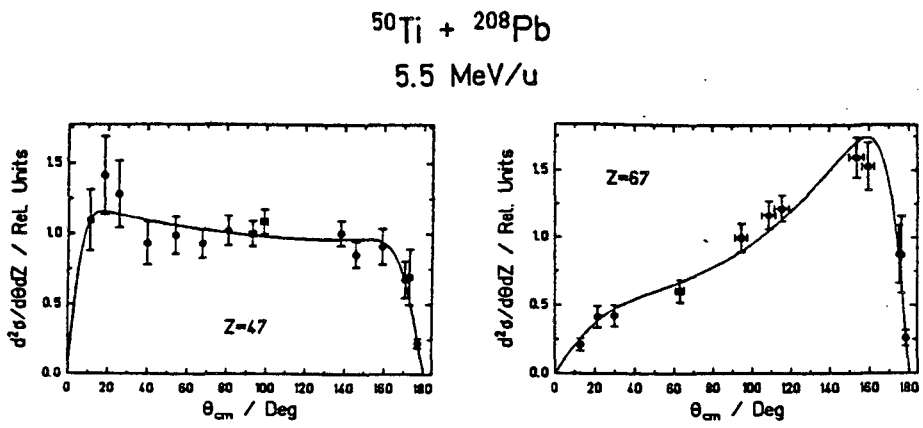

Figure 2

the window area. The wriggling mode is strongly excited by nucleon transfer, and consequently the wriggling relaxation time is very short. The expression (4) for the tilting mode relaxation time can be understood on the basis of fig. 1. If one neglects recoil (as is done in ref. [6]), the tilting mode cannot be excited directly by nucleon transfer, but only indirectly through the orbital rotation. The wriggling relaxation time gives the time scale for the fluctuation in the direction of the orbital angular momentum $\hat{L}$, and thereby the time scale for fluctuations in the direction of the segments of orbital motion schematically shown in fig. 1. The accumulation of tilting angle variance can then be viewed as a random walk process, the length of each step being proprotional to the angular frequency ω_R times the wriggling relaxation time. For a given reaction time t, the total number of steps in the random walk is proportional to t/t_{++}. Thus, neglecting restoring terms in the tilting relaxation, the tilting angle variance for given reaction time would be proprotional to $< \sin^2\psi > \propto t/t_{++} \cdot (\omega_R \cdot t_{++})^2 = t \cdot \omega_R^2 \cdot t_{++}$. This explains the expression (4) for the tilting relaxation time (the factor J/L is close to unity). Actually, as long as the primary interactions between the two nuclei do not excite directly the tilting mode, the relation (4) between the wriggling and tilting relaxation times hold, independent upon the specific mechanism responsible for the direct excitation of the wriggling mode.

Examples of these relaxation times for the reaction of 1400 MeV ^{165}Ho + ^{165}Ho are given in refs. [6,7]. Typical *wriggling times*, are of the order of 1 to 2 times 10^{-22} s, also for other systems, while typical *tilting times* are of the order of 10^{-21} s for peripheral collisions, and of the order of 10^{-20} s for more central collisions.

Recently, measurements of the cross section in quasi-fission reactions (defined in this context as damped reactions with a large mass drift) have been extended to very small and very large scattering angles using radiochemical methods [8]. Figure 2 shows examples of such data, gated by fixed proton number Z. The dips in the cross section close to 0° and 180° are caused by the tilting mode excitation, as explained above and expressed in equation (2). From the width of these dips, the tilting excitation has been extracted [8], as shown in fig. 3 for two of the reactions studied.

The full lines in fig. 3 show the value af the thermally excited tilting mode for a geometry of two touching spherical nuclei. The reaction times are here of the order of $5 \cdot 10^{-21}$ s. Thus, the partial relaxation of the tilting mode is in accordance with a tilting relaxation time of the order of 10^{-20} s, in good agreement with the above estimates based upon the expressions (3) and (4). One word of caution should be added here. The estimate (3) for the wriggling relaxation time is derived on the basis of nucleon exchange transport across a narrow window. This same mechanism is not capable of explaining the large mass drift observed in quasifission reactions. At present there exists no theory, giving wriggling relaxation times consistent also with a large mass drift for a compact reaction complex of the two nuclei.

For the damped reaction 710 MeV ^{86}Kr + ^{139}La, which displays only a modest mass drift, the tilting mode excitation was calculated and discussed in ref. [5]. For this reaction, quite large impact

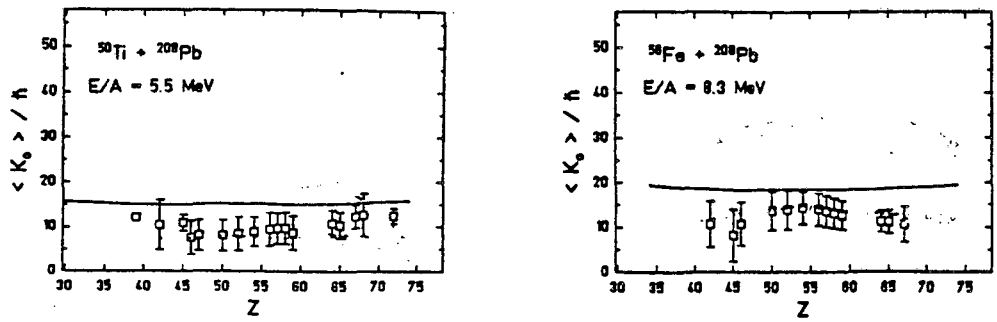

Figure 3

parameters lead to scattering angles close to the beam direction, and in the calculations the tilting mode was found to be almost relaxed. This is due primarily to the smaller tilting relaxation times for peripheral collisions (cfr. eq. (4)), but the excitation of the tilting mode can also be enhanced by two mechanisms, which have not been mentioned yet: (i) The long-time asymptotic value for tilting relaxation contains the effective temperature for nucleon exchange instead of just the ordinary statistical nuclear tempreature. (ii) For large angular momenta, the $\hat{z}$-axis swings a quite large angle on the exit plane, converting part of the wriggling excitation to tilting excitation. measurements of the cross section close to the beam axis in this or equivalent reactions have not yet been carried out. Such data would help testing the prediction of strong tilting excitation in peripheral reactions.

The mechanism for dissipation in fission is currently under lively debate, cf. [9]. The time associated with the motion from the fission saddle point to the scission configuration depends sensitively on the strength and character of the nuclear dissipation. It is generally expected to be of the same order of magnitude as the tilting relaxation times discussed here. Thus, the amount of tilting acquired at the final stage of a fission reaction, which is refelcted in the fission fragment angular distribution, yields important information on nuclear dissipation.

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