On Nuclear Transport at Small Excitations ◇

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In the past decade much progress has been made in the understanding of nuclear transport phenomena in the regime of not too low temperatures, say between 1 and 5 MeV, and for slow collective motion. Studying fission accompanied by the emission of light particles and γ's, it has been possible experimentally to deduce valid information on the time scale of collective motion [1], and, hence, on the size of nuclear dissipation. At present it is commonly understood that collective motion is over-damped, at least for larger T. In this note we want to focus on excitations below $T \approx 1$ MeV. This regime is of great importance for the production of super-heavy elements [2], on the one hand, but it is of great theoretical interest as well. In this domain *quantum effects dominate nucleonic dynamics*, implying that transport coefficients are influenced by *shell effects and pair correlations*. One even must expect *quantum features to be present for collective motion.*

The analysis of the fission experiments previously mentioned are commonly done on the basis of Kramers formula for the decay rate in the "high viscosity limit",

$$R \equiv R_K = \frac{\omega_a}{2\pi}\left(\sqrt{1+\eta_b^2}-\eta_b\right)\exp(-E_b/T) \qquad (1)$$

which treats collective motion classically. For possible extensions to quantum physics there exists vast literature in solid state physics based on "imagionary time propagation". Unfortunately, for many reasons, these studies cannot be taken over to nuclear physics, the most severe one being the fact that for fission the coupling to the nucleonic degrees of freedom (the possible "heat bath") *cannot be linearized globally.* Nevertheless, as reported previously (see [3] or [4]), such a generalization is possible within approximations valid also in nuclear physics. One may derive a transport theory in proper sense based on an application of a locally harmonic approximation (LHA) to "real time propagation" (r.t.p.). In this way transport coefficients may be deduced and calculated microscopically. Unfortunately, for the diffusion coefficients, which represent the fluctuating force, this procedure breaks down at a critical temperature T_c, below which the latter would become negative. In this sense one faces the same problem as one encounters within the path integral formalism for r.t.p.

This critical temperature T_c depends on the transport coefficients for average motion, namely friction γ, inertia M and local stiffness C, as well as on temperature. Above T_c the correction to R_K may simply be accounted for by multiplication by a factor $f_Q \geq 1$, viz $R = f_Q R_K$. This factor is known [3] to deviate from unity only at temperatures at about 1 MeV and below. In this regime it is necessary to account for pairing. Calculations of the transport coefficients on M, γ and C along these lines have been done recently, see this report. Their effect on the decay rate is summarized in fig.1.

The fully drawn curve shows the ratio of Kramers' famous pre-factor $f_K = \sqrt{1+\eta_b^2}-\eta_b$ to its "macroscopic counterpart" as function of temperature (with η_b being given by $\eta = \gamma/(2\sqrt{M \mid C \mid})$ calculated at the barrier). For the "macroscopic model" we took combinations of wall friction with the stiffness and inertia of the liquid drop model (irrotational flow). The main reason for the microscopic result to enhance the decay is seen in the reduction of friction due to pair correlations — although on the mere classical level Kramers' condition for the high viscosity limit still is fulfilled. This result demonstrates the importance of quantum transport for the dynamics of nucleons inside the mean field, approximated here by the Woods Saxon potential of the model with Cassini ovaloids [5]. The quantum effects which are due to collective motion are exhibited by the dashed curve representing $R = f_Q R_K$.

The T_c decreases with increasing damping, but in the presence of pairing friction becomes so small at small T that T_c may be estimated in the zero friction limit, such that one has $T_c \leq T_c(\eta = 0) = \hbar\varpi_b/\pi \approx 0.3$ MeV. As seen from the figure, the f_Q increases with decreasing T, it actually diverges at a so called "cross over temperature" T_0 which for zero friction just is half as big as T_c. To remedy this situation one would have to go beyond the typical "Gaussian approximation". This has successfully been studied with path integrals, but only within the models mentioned above, outside of nuclear physics. Unfortunately, it must be said that to date no extension has been worked out on the level of a quantal transport equation. Most likely, such a generalization is not possible on a level which would allow one to incorporate such features into the Langevin description, as it can be done above T_C accounting for the extension of Kramers' equation.

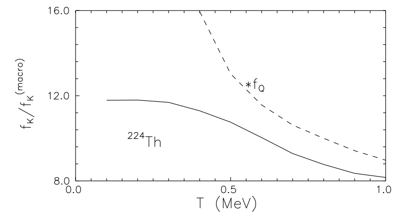

Fig. 1: The ratio of the Kramers correction factor $f_K = \sqrt{1+\eta_b^2}-\eta_b$ to its macroscopic counterpart as function of temperature. The dashed line shows the enhancement which arises from quantum effects in the collective motion, see main text.

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