LANDAU DAMPING AND ONE-BODY DISSIPATION IN NUCLEI - ITS ROLE FOR THE MONOPOLE AND HIGH MULTIPOLES $\lambda \geq 4$

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Abstract:

The wall formula is not able to describe the increase of fragmentation of the strength with the multipolarity, which is a manifestation of Landau damping for small amplitude collective motion in finite nuclei. A modified wall formula has this property and may also account for the monopole width.

1. Introduction

The Landau or collisionless damping (LD) has been introduced in plasma physics to designate the direct energy transfer from the plasmon to the electrons[1]. In this process the collective energy is picked up by the particles which are moving in phase with the wave.

In the framework of a microscopic theory, the LD accounts for all the width which appears in a ph approach, while the collision damping corresponds to processes of coupling of the coherent ph excitation with 2p-2h or higher order configurations (see Fig. 1) . In a semi-classical analysis , the LD is related to the existence of com-

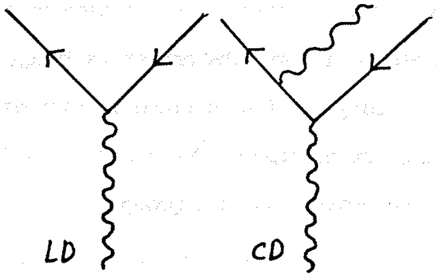

Fig.1

plex solutions of the linearized Vlasov equation, and the collision damping is determined by the collision term of the complete kinetic equation.

In both helium-3 and the electron gas at absolute zero there is no LD at all of the 0-sound or the plasmon, as long as the collective mode is characterized by a wavenumber smaller than the critical value $k_c = \omega / v_F$. The onset of LD corresponds in a diagram ω- k to the intersection of the collective branche with the continuum of single-particle excitations (see Fig. 2) . The sudden broadening of the collective peak and its consequent disappearance have been observed by neutron and electron scattering in helium-3 and in metals , respectively . For helium-3 the cut-off of the 0-sound occurs at $k_c = 1.5\ k_F$ ($k_F = 0.8\ \text{Å}^{-1}$) [2] and for aluminium the cut-off of the plasmon is at $k_c = 0.7\ k_F$ ($k_F = 1.75\ \text{Å}^{-1}$) [3].

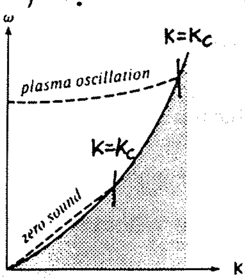

Fig.2

In this work, we adress ourselves the question of the possible manifestation of LD in atomic nuclei. The answer is that, as in infinite matter, there is no or only small LD surface vibrations with large wavelengths (i.e. for the low multipoles $\lambda = 2$ and 3) and there is LD for small wave lengths.On the other hand, the monopole decay seems to be dominated by LD.

The phenomenological study of nuclear damping distinguishes between 1-body friction (wall formula [4]) and 2-body friction (viscosity formula [5]) . Both formulae are subject to criticism. The wall formula is not able to parametrize the implementation of LD for the high multipolarities, while the description in terms of viscosity is relying on the concept of a short mean free path, which is erroneous for nuclei.

We propose here to account for the width of the giant resonances in terms of a modified wall formula [6] , which incorporates self-consistency, plus a long mean free path 2-body formula . The approach seems to shed some light into two of the most outstanding questions about nuclear resonances [7] : i) The non observation of high-lying giant resonances with $\lambda \geq 4$ and ii) the non-observation of monopole strength or the appearance of very fragmented monopole strength for nuclei lighter than ^{58}Ni . Both these negative results may be explained invoking the role of 1-body damping.

2. Nuclear LD for high multipoles

The condition for the occurrence of LD is the approximate equality between the wave velocity and the velocity of the particle. The energy of the surface vibrations $\lambda = 2$ and 3 is very well described by the expression[5)]

$$E_\lambda = \hbar\left[\frac{2}{3}(2\lambda+1)(\lambda-1)\right]^{1/2}\frac{\bar{v}}{R_o} = \hbar\left[\frac{2}{5}(2\lambda+1)(\lambda-1)\right]^{1/2}\frac{v_F}{R_o}$$

which is justified by RPA-sum rules for $\lambda = 2 - 6$ [8)]. The wavenumber corresponding to a distortion of multipolarity λ of the surface is $k=\lambda/R_o$. The phase velocity of the surface wave is then

$$v_{phase}/v_F = \left[\frac{2}{5}(2\lambda+1)(\lambda-1)\right]^{1/2}/\lambda$$

The values of this function are shown in Table I. One concludes that the wave velocity is approaching gradually the Fermi velocity, increasing the possibility for LD to take place.

Table I

Phase velocity of a nuclear surface wave

λ	2	3	4	5	6	7
v_{phase}/v_F	0.71	0.79	0.82	0.83	0.85	0.85

The gradually increasing role of LD with increasing λ may also be verified from the distribution of strength given by a typical RPA calculation. For λ= 2 and 3 there is concentration of strength , which is due to the fact that these modes have energies situated in the middle of gaps of the single-particle excitation spectrum. The large splitting of strength that appears thereafter is a clear manifestation of LD. This splitting is due to the fact that the "bands" of single-particle excitations are getting broader with increasing energy. It is difficult to assert a critical value for the appearance of LD but all RPA calculations agree that at least for λ=6 there are no more well-defined collective oscillations.

3. Phase space for one-body decay

The phase space available for 1-body decay is given by

$$g_{1h-1h}=\sum_{ph}\delta(\hbar\omega-\varepsilon_p+\varepsilon_h)=Tr_1 Tr_2\{\theta(\mu-\hat{H}_1)\theta(\hat{H}_2-\mu)\delta(\hbar\omega-\hat{H}_2+\hat{H}_1)\}$$

The semiclassical method is a conveniente tool to evaluate this quantity.[9] It consists essentially in the replacements $Tr\rightarrow\int d\vec{p}_1 d\vec{x}_1$, $\hat{H}\rightarrow H$

$$g^{sc}_{1h-1h}=\iint d\vec{p}_1 d\vec{x}_1 d\vec{p}_2 d\vec{x}_2\{\theta(\mu-H_1)\theta(H_2-\mu)\delta(\hbar\omega-H_2+H_1)\}.$$

The integrand only changes significantly near the Fermi level and therefore it is sufficient to calculate the following energy integral,

$$I_{1h-1h}=\iint d\varepsilon_1 d\varepsilon_2\, n(\varepsilon_1)[1-n(\varepsilon_2)]\,\delta(\hbar\omega-\varepsilon_2+\varepsilon_1),$$

with $n(\varepsilon)=1/\{exp[(\varepsilon-\mu)/K_BT]+1\}$ the Fermi distribution function. The last integral may be carried out exactly, with the result

$$I_{1h-1h}=\frac{\hbar\omega}{1-exp(-\hbar\omega/K_BT)}\quad.$$

In the quantal limit, $\hbar\omega\gg K_BT$, the density of 1p-1h states available and the one-body width are proportional to the energy of the collective excitation: $\Gamma^{LD}\propto\hbar\omega$.

4. The wall formula as LD and its modification

The wall formula for the width of surface vibrations $\lambda\geq 2$ is

$$\Gamma^{WF}_{\lambda}=\hbar\lambda\frac{\bar{v}}{R_0}\quad.$$

The quocient between the width and the energy gives an estimate of the number of periods the oscillacion undergoes before being damped out

$$\frac{\Gamma^{WF}_{\lambda}}{E_{\lambda}}=\left[\frac{2}{3}(2\lambda+1)(\lambda-1)\right]^{-1/2}\cdot\lambda\quad.$$

This quantity does not depend on the particular nucleus but only on the multipolarity (see Table II) . The linear relation between width and energy, which is characteristic of LD is therefore fulfilled in the

Table II

RATIO BETWEEN WIDTH AND ENERGY OF THE GIANT RESONANCES, USING THE WALL FORMULA, THE MODIFIED WALL FORMULA AND THE VISCOSITY FORMULA

λ	2	3	4	5	6	7
$\Gamma_\lambda^{WF}/E_\lambda$	1.09	0.98	0.94	0.92	0.91	0.90
$\Gamma_\lambda^{MWF}/E_\lambda$	0.07	0.24	0.51	0.88	1.37	1.95
$\Gamma_\lambda^{VF}/E_\lambda$	0.17	0.28	0.39	0.50	0.61	0.72

wall model.

Besides the fact that the dependence on λ is rather weak, contrary to what is expected to be the case for LD, an objection against the wall formula consists on the nearly equality between width and energy. The smallest value of $\Gamma_\lambda^{WF}/E_\lambda$ occurs in the limit $\lambda \to \infty$ (we remind in this context that the wall formula has been claimed to be valid in this limit, which may be considered for very large nuclei $R_0 \to \infty$, with λ/R_0 =Constant)

$$\lim_{\lambda \to \infty} \frac{\Gamma_\lambda^{WF}}{E_\lambda} = \frac{\sqrt{3}}{2} = 0.87 \quad .$$

The condition $\Gamma_\lambda \ll E_\lambda$, which is necessary for well-defined modes, is therefore not fulfilled by the wall friction . We must resort to the conclusion that there are assumptions behind the wall formula, which are unjustifiable in the collective processes under discussion. In fact, it is hard to agree that the supposition of a wall external to the particles is here realistic. Yannouleas and Griffin[10] and Dworzecka[11] have recently discussed this issue.

A modification of the wall formula has been proposed by Sierk et al[6] with the scope of implementing self-consistency, i.e. of taking into consideration the fact that the wall is made up by the particles and is not exterior to them. The modified wall width is

$$\Gamma_\lambda^{MWF} = (\lambda-1)^2 \left(\frac{a}{R_0}\right)^2 \Gamma_\lambda^{WF} \quad .$$

The modification lies on: i) the order of magnitude (the parameter a should be of the order of magnitude of the range of nuclear forces) and ii) the dependence on the multipolarity . The Table II displays the values of $\Gamma_\lambda^{MWF}/E_\lambda$ for ^{208}Pb , with a = 1.73 fm. There is a very weak damping of the quadrupole ($\Gamma_2^{MWF}/2E_2 = 0.04$, in agreement with the vanishing 1 -body damping of the quadrupole obtained by Koonin and Randrup[13]) and overdamping of the modes $\lambda \geqslant 7$ ($\Gamma_7^{MWF}/2E_7 = 0.98$).
The situation is very similar to that found in helium-3 and in the electron gas, where the collective mode disappears due to LD at some critical value of k.

It is well-known that the damping of 0-sound in Fermi liquids is, for small temperatures, proportional to the square of the frequence . The viscosity formula, although being only relevant in a different regime, shows up this feature

$$\Gamma_\lambda^{VF} = A\, E_\lambda^2 \quad .$$

The parameter A should be related to the viscosity coefficient but here is to be understood merely as an adjustable parameter , since we are aiming a description of collective motion when the particles have a long mean free path. The value A = 0.014 MeV^{-1}, arising from fission data, leads roughly to the width which complements the modified wall formula in order to reproduce the experimental quadrupole width of heavy nuclei.

The sum of 1- and 2-body contributions provides a description of the dependence on λ of the width of giant modes in heavy nuclei. With the given parameters, the octupole shows a large width $\Gamma_3/E_3 = 0.52$. The octupole is in the fringe of being considered a well-defined mode: This result agrees with recent experimental information about the multipole strength obtained in Saclay by means of α-scattering with kinetic energies 340 and 480 MeV.[12] For $\lambda \geq 4$, LD dominates the total width, which is larger than the energy, indicating that these modes are not expected to be observed. In fact, high-lying $\lambda = 4$ and 5 have not been clearly identified, although a very careful analysis of the background has been made[12].

5. LD for the monopole

Fermi liquid theory teaches us that the collision integral vanishes in the monopole channel. Therefore all the monopole width should be of 1-body type. Microscopic calculations confirm that the width coming from the coupling to 2p-2h is too small when compared with the experimental value.[15]

Let us give a very simple reason why LD should be relevant for the breathing mode. The energy of this mode is given by

$$E_0 = \frac{\hbar}{R_0}\left(\frac{K}{m}\right)^{1/2} = 1.98\ \hbar\omega_0 ,$$

with K = 220 MeV the nuclear compressibility and $\hbar\omega_0 = 41\ A^{-1/3}$ MeV. The predicted energy is in very good agreement with the experimental value for heavy nuclei (for ^{208}Pb, E_0^{exp} = 13.7 MeV). With $k = \pi/R_0\sqrt{3}$ (see ref.[14] for a discussion of the factor $1/\sqrt{3}$), we obtain for the phase velocity $\omega/k = 0.27$ c, which is precisely the Fermi velocity. Therefore particles may escape, taking energy away from the mode. Identical conclusion can be drawn if we notice that the monopole energy has nearly the same position as the $2\hbar\omega_0$ single-particle excitation.

The wall width for the monopole is not given by the expression presented before, which is obtained dividing the wall friction by the incompressible mass, but may be seen to be equal to the wall width of the octupole

$$\Gamma_0^{WF} = 3\hbar \frac{\bar{v}}{R_0} \quad .$$

The rate of damping is then given by

$$\frac{\Gamma_0^{WF}}{E_0} = 0.98 \; \frac{2.64}{1.98} = 1.31 \; ,$$

a result which is unrealistic. On the other hand the modified wall formula gives for the monopole

$$\frac{\Gamma_0^{MWF}}{E_0} = \left(\frac{a}{R_0}\right)^2 \frac{\Gamma_0^{WF}}{E_0} = 0.06 \times 1.31 = 0.08 \; ,$$

which is too low when compared with the experimental result ($\Gamma_0/E_0 = 0.19$). If one wants the monopole width to be accounted only by 1-body processes, one needs to modify the effective distance between wall and particles by a factor 3/2 , leading to a = 2.6 fm.

As the modified wall formula leads to a width which increases for light nuclei, we would expect for ^{58}Ni e.g. a monopole width which is $(208/58)^{2/3} = 2.34$ times the corresponding width of ^{208}Pb. For lighter nuclei the width is still larger, which means that for those systems the monopole strength can only appear very spread.

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