Sound Modes in Hot Nuclear Matter

V. M. Kolomietz[a] and S. Shlomo
[a]*Institute for Nuclear Research, 03028 Kiev, Ukraine*

We study the propagation of the isoscalar and isovector sound modes in a hot nuclear matter. The approach is based on the collisional kinetic theory and takes into account the temperature and memory effects. Our main goal is to estimate the influence of the Fermi-surface distortion (FSD) and the memory effect on the value of the sound vellocity, the sound wave damping and the instability growth rate in a hot nuclear matter.

Assuming small quadrupole distortion of the Fermi surface and taking the collision integral in the form of the extended ϑ-approximation with memory effects, see Ref. [1], we have reduced the kinetic equation for the Wigner distribution function to the equation of motion for the particle density vibrations $*\Delta\sim\exp(i\mathbf{q}\theta\mathbf{r}-iTt)$. Namely,

$$\omega^2 \delta\rho + c_\omega^2 \nabla^2 \delta\rho = i\omega (4\eta_\omega / 3m\rho_{\rm eq}) \nabla^2 \delta\rho, \quad (1)$$

where c_T and 0_T are the sound velocity and the viscosity coefficient, respectively,

$$c_\omega^2 = c_1^2 + c_F^2 \ \mathrm{Im}\left(\frac{\omega\tau_{r,\omega}}{1 - i\omega\tau_{r,\omega}} \right),$$

$$\eta_\omega = (2/5) e_F \ \mathrm{Re}\left(\frac{\tau_{r,w}}{1 - i\omega\tau_{r,\omega}} \right), \quad (2)$$

e_F is the Fermi energy and c_F^2 = $(8/15m)e_F$. The first sound velocity c_1 in Eq. (2) is given by c_1^2 = $K/9m$ for the isoscalar mode and c_1^2 = $2E_{\rm sym}/m$ for the isovector one, where $K \approx 6e_F(1 + F_0)(1 + F_1/3) \approx 220$ MeV is the incompressibility of the nuclear matter and $E_{\rm symm}$ = $(1/3)e_F(1 + F_0')$ ≈ 30 MeV is the isotopic symmetry energy. (Here F_k and F_k' are the parameters of the Landau's scattering amplitude in both the isoscalar and the isovector channels, respectively.) We point out that the T-dependence of both c_T and 0_T in Eq. (2) is due to the memory effect. In the case of sound propagation in hot nuclear matter, the competition of the temperature smoothing effects in the equilibrium distribution function and dynamical distortions of the particle momentum distribution leads to the following expression for the relaxation time [1,2] $\vartheta_{r,\mathrm{T}}$ = $\vartheta_0/[T^2 + >(\hbar \mathrm{T})^2]$, where T is the temperature. We adopted $>$ = $1/4\mathrm{B}^2$, and $\vartheta_0 = \forall\hbar$ with $\forall$ = 9.2 MeV for the isoscalar mode and $\forall$ = 4.6 MeV for the isovector one.

The memory effects in the equation of motion (1) lead to the characteristic T-dependence of both the refraction coefficient, n, and the absorption coefficient, 6, (both real) derived by $q = T(n+i6)/c_0$ or

$$n + i\kappa = \sqrt{\frac{1 - i\omega\tau_{r,w}}{(c_1/c_0)^2 - i\omega\tau_{r,w}}}, \quad (3)$$

where c_0 = $\sqrt{c_1^2 + c_F^2}$ is the zero sound velocity. In Figs. 1 and 2 we have plotted both coefficients n and 6 as obtained from Eq. (3). In the high temperature limit, the system goes to the frequent collision (first sound) regime with the saturated refraction coefficient $n \approx c_0 / c_1 \approx \sqrt{3}$ and the absorption coefficient *6* ~ $\vartheta_{r,T}$ ~ $1/T^2$. In the opposite low temperature limit, the system is close to the zero sound regime with $n \approx 1$. We point out the shift in both *n* and *6* to nonzero values at $T \rightarrow 0$. This is due to the memory effect in the relaxation time $\vartheta_{r,T}$ in the high frequency limit, the system can exist close to the first sound regime at $n \approx \sqrt{3}$ even at zero temperature. The position of the maximum of *6*(*T*) in Figs. 1 and 2 can be interpreted as the transition temperature T_{tr}, of zero- to first-sound regimes in hot Fermi system. The value of T_{tr}, depends slightly on the sound frequency *T* and it is shifted to smaller values with increase of *T*. We point out that, in contrast to the isoscalar

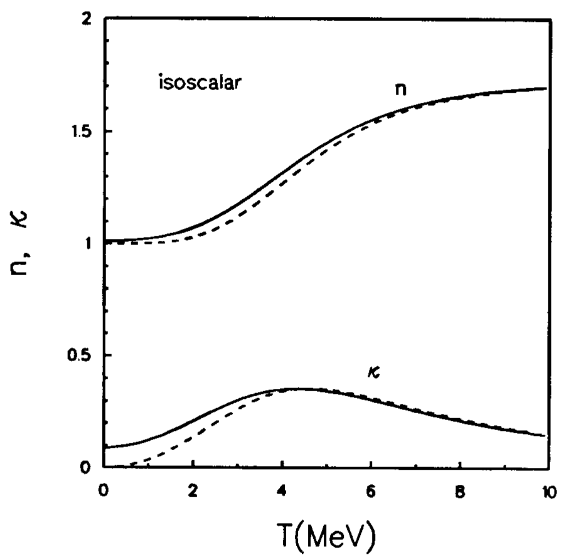

Figure 1: The refraction, *n*, and absorption, *6*, coefficients of the isoscalar sound wave as funcitons of temperature. The calculation was performed for two eigenenergies $\hbar\, T$= 1MeV (solid line) and $\hbar\, T$=1 eV (dashed line).

mode, the Fermi surface distortion effect leads to a relatively small increase of the isovector zero sound velocity c_0 with respect to the first sound one c_1. The transition temperature T_{tr}, of

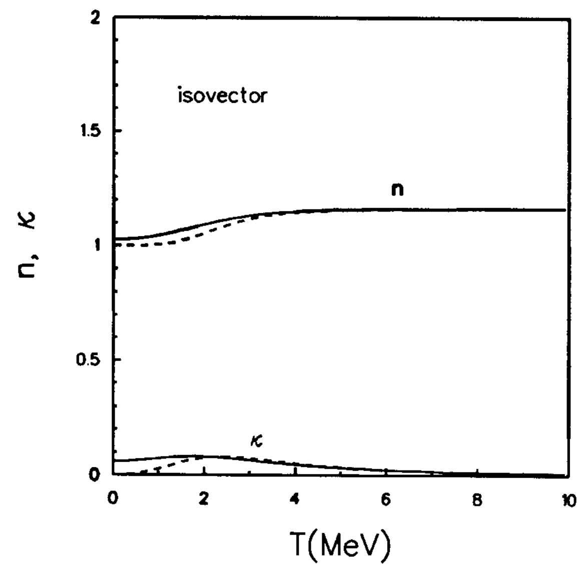

Figure 2: Same as Fig. 1 for isovector mode.

zero- to first- sound regimes for the isovector mode is significantly smaller than T_{tr}, for the isoscalar one.

In an asymmetric nuclear matter, both the isovector and the isoscalar modes are dependent on each other. The particle density fluctuation $\delta\rho$ takes a bispinor form $\delta\rho = (\delta\rho_+, \delta\rho_-)$, where $\delta\rho_+$ and $\delta\rho_-$ are the isoscalar and isovector components, respectively. The solution of the corresponding equation of motion (1) shows that the eigenfrequency *T* and the corresponding sound velocity for both the isoscalar and the isovector modes are independent of each other, in the linear order of the asymmetry parameter $I = (\Delta_n - \Delta_p)_{eq}/(\Delta_n + \Delta_p)_{eq}$ where Δ_n and Δ_p are the neutron and proton densities, respectively. The structure of bispinor $\delta\rho = (\delta\rho_+, \delta\rho_-)$ for the isoscalar-like mode is different than that of the isovector-like mode. For the isoscalar-like mode the main contribution to the bispinor $\delta\rho$ is due to the isoscalar component $\delta\rho_+ \sim 1$ while the isovector component $\delta\rho_-$ is proportional to the

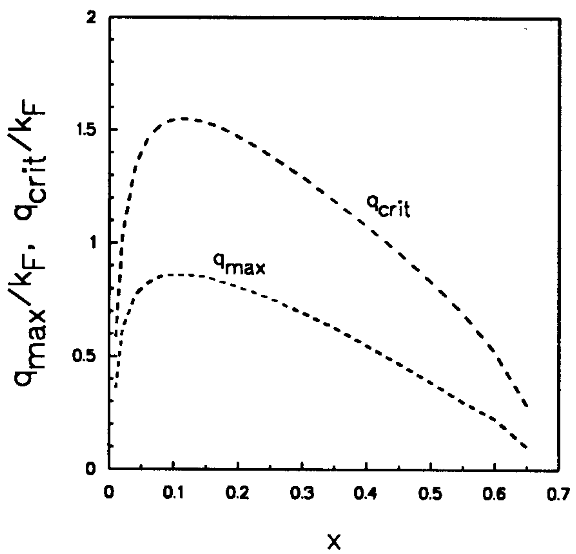

Figure 3: The dependence of characteristic wave numbers of the instability growth rate э(q) on the dimensionless density parameter $x = \Delta_0/\Delta_{eq}$. The calculation was performed for Skyrme force SIII and temperature T = 6 MeV.

asymmetry parameter I. The opposite situation takes place for the isovector-like mode with $\delta\rho_- \sim 1$ and $\delta\rho_+ \sim I$.

We have also considered the bulk instability regime $K < 0$ with $\delta\rho \sim \exp(i\mathbf{q}\theta\mathbf{r} - iTt) \sim \exp(э t)$, where э is the instability growth rate э = $-iT$ (э is real, э > 0). To prevent an unphysical infinite growth of the short wave length fluctuations we have taken into account the velocity dependent contribution to the effective interparticle interaction. Due to the corresponding change in the selfconsistent mean field, an additional anomalous dispersion term $\sim\nabla^4\delta\rho$ appears in the equation of motion (1). We have performed calculations of the dependence of the instability growth rate э(q) on the wave number q for the isoscalar mode. The calculation was performed for the Skyrme force SIII with the bulk density $\Delta_0 = 0.3\Delta_{eq}$, where Δ_{eq} is the saturation density $\Delta_{eq} = 0.1453$ fm^{-3}. The instability growth rate э reaches a maximum э$_{max}$, at a certain $q = q_{max}$ and э goes to zero at $q = q_{crit}$. The distortion of the Fermi surface leads to a decrease of the critical value q_{crit}, i.e., the nuclear matter becomes more stable due to the FSD effect. The presence of viscosity and FSD effect lead to a shift of the position q_{max} of the maximum of э(q) to the left. Thus, the instability of the nuclear matter with respect to short-wave-length density fluctuations decreases due to the viscosity and the FSD effect and the most unstable mode is shifted to the region of the creation of larger clusters in the nuclear matter disintegration. The dependence of the values q_{max} and q_{crit} on the bulk density parameter $x = \Delta_0/\Delta_{eq}$ is shown in Fig. 3. The instability growth rate э(q) as well as the values of q_{max} and q_{crit} are only slightly sensitive to the temperature change at $T \leq 10$ MeV, where the temperature dependence of the bulk density Δ_0 can be neglected. A more sophisticated consideration is necessary near the critical temperature $T_{crit} \approx 17$ MeV where the nuclear matter is unstable with respect to the liquid-gas phase transition.

References

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[2] V. M. Kolomietz, V. A. Plujko and S. Shlomo, Phys. Rev. C **54,** 3014 (1996).