Fluidity of finite nuclear matter – An experimental endeavour

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The fluidity of a system is measured by the ratio of shear viscosity (η) to the entropy volume density (s). The smaller is the value of η/s, larger is the fluidity. In recent years, the quantity η/s has attracted a lot of theoretical and experimental investigations in different areas of physics. It is well defined for both relativistic and non-relativistic fluids and is important in connection with the physics of black hole, quark-gluon plasma (QGP), the low temperature quantum fluids etc. The temperature variation of η/s provides the crucial signature for liquid-gas phase transition in matter. String theoretical calculations have put a universal lower bound, known as the Kovtun-Son-Starinets (KSS) bound, such that $\eta/s \geq \hbar/4\pi k_B$ [1], k_B being the Boltzmann constant. The fluid having the lower limit of η/s is called a perfect fluid. It is also observed that strongly coupled systems such as low-temperature quantum fluids and high-temperature QGP have very small η/s (5-10 $\hbar/4\pi k_B$) characteristic of a good fluid.

An atomic nucleus is a many-body quantum system in which the nucleons are governed by strong interaction. A finite nucleus, therefore, is an ideal system to search for near perfect fluidity in matter. Different model-dependent calculations for η/s have been performed earlier at intermediate energy heavy ion collisions in search for a liquid-gas phase transition. The first theoretical study for η/s in relation to the damping of giant resonances in nuclei was done by Auerbach and Shlomo [2] within the framework of Fermi liquid drop model (FLDM). The authors conjectured that strong fluidity could be the universal feature of strongly coupled nuclear systems. Recently, Dang [3] has proposed a formalism, based on the Green-Kubo relation and the fluctuation dissipation theorem, relating the shear viscosity to the width and the energy of giant dipole resonance (GDR) in hot finite nuclei, namely

$$\eta(\mathrm{T}) = \eta(0)\frac{\Gamma_{GDR}(\mathrm{T})}{\Gamma_{GDR}(0)}L_{GDR}(\mathrm{T}),$$

$$\text{where } L_{GDR}(\mathrm{T}) = \left\{\frac{E_{GDR}(0)^2}{E_{GDR}(0)^2 - \left[\Gamma_{GDR}(0)/2\right]^2 + \left[\Gamma_{GDR}(0)/2\right]^2}\right\}^2 \quad (1)$$

In this symposium, the first experimental determination of η/s [4] will be presented. At finite temperature, the shear viscosity has been determined from the measured GDR parameters, while the entropy density has been extracted from the measured nuclear level density (NLD) parameter (a) and nuclear temperature (T) utilizing the relation

$$s(\mathrm{T}) = \frac{\rho}{A}S(\mathrm{T}) \quad (2)$$

where S(T) = 2a(T)T and nuclear density $\rho = 0.16\ \mathrm{fm}^{-3}$.

A set of experiments was performed at the Variable Energy Cyclotron Centre (VECC), Kolkata using α beams from the K-130 cyclotron. The nuclei ^{31}P, ^{97}Tc, ^{119}Sb and ^{201}Tl were populated at different excitation energies by bombarding α beam of energies 28-50 MeV on ^{27}Al, ^{93}Nb, ^{115}In, and ^{197}Au targets, respectively. The high-energy γ rays from the decay of the GDR were measured by a part of the LAMBDA spectrometer [5]. A 50-element multiplicity filter [6] was used to measure the compound nuclear angular momentum. The neutron and the pile-up events were rejected by

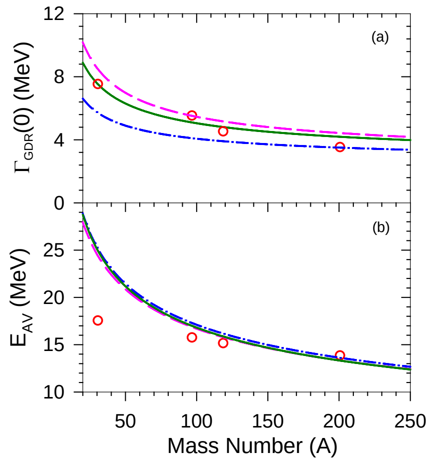

Fig 1. Mass dependence of (a) ground state GDR widths and (b) average GDR energies with the calculations for different values of η(0).

time of flight (TOF) and pulse shape discrimination (PSD) techniques, respectively. Evaporated neutron energy spectra were measured, in coincidence with the multiplicity γ rays, by a liquid-scintillator-based neutron TOF detector [7]. The n-γ discrimination was accomplished following the PSD technique comprising of TOF and zero cross-over time (ZCT). The measured TOF spectra were converted to neutron energy spectra by taking the prompt peak as a time reference. The GDR and NLD parameters were extracted by simultaneously fitting the high-energy γ ray spectra and neutron energy spectra with the statistical model calculations. Thus η/s were determined using Eqs. (1) and (2) for different systems at different temperatures. The value of η(0) was 1u, where u = 10^{-23} MeV.s.fm^{-3}. The justification for adopting this value lies in the fact that the ground state GDR widths were nicely reproduced (green line in Fig. 1a) by the calculations of Auerbach *et al.* [8] performed using η(0) = 1u. The uncertainty in η(0) was also calculated using the same prescription and was found to (0.55-1.25) u. This limit was found to be similar with that obtained from fission data [9].

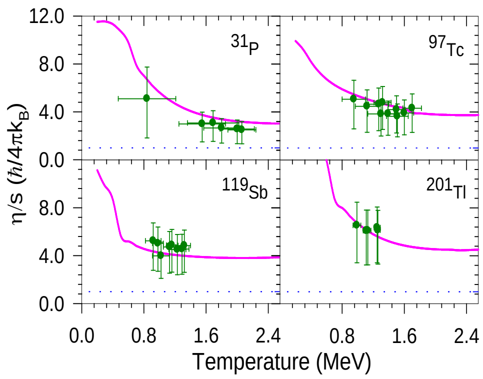

Fig 2. Extracted values of η/s (symbols) with theoretical predictions (solid lines). The blue dashed line is the KSS bound.

The deduced η/s shows a mild decrease with temperature (Fig. 2). Moreover, it is confined in the range (2.5-6.5) $\hbar/4\pi k_B$ for the finite nuclear matter within the temperature range (0.8-2.1) MeV. Therefore, it could be confirmed that nuclear matter conform to the KSS conjecture. Also, the measured values of η/s are comparable to that of the QGP. It, therefore, could be reaffirmed experimentally, that the strong fluidity is a universal characteristic feature of the strong interaction of the many-body nuclear systems and not just of the state created in the relativistic collisions. This result, along the results of low-temperature quantum fluids, suggests that large fluidity could also possibly be the intrinsic characteristic feature of strongly coupled systems.

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