Project Title:

Properties of finite systems including nuclei at high temperature and angular momentum (Properties of highly excited nuclei)

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1. Viscosity of hot nuclei (by N. Dinh Dang)

In the verification of the condition for applying hydrodynamics to nuclear system, it turned out that the quantum mechanical uncertainty principle requires a finite viscosity for any thermal fluid. Kovtun, Son and Starinets (KSS) have conjectured that the ratio η/s of shear viscosity η to the entropy volume density s is bounded below for all fluids, namely the value. Although several theoretical counter examples have been proposed, no fluid that violates this lower bound has ever been experimentally found so far. Given this conjectured universality, there has been an increasing interest in calculating the ratio η/s in different systems.

In the present work, by using the Kubo relation and the fluctuation-dissipation theorem, the shear viscosity η and the ratio η/s have been extracted from the experimental systematics for width of the giant dipole resonance (GDR) in copper, tin and lead regions at finite temperature T, and compared with the theoretical predictions by four independent theoretical models, namely, the phonon damping model (PDM), the adiabatic model (AM), the phenomenological thermal shape fluctuation model (pTSFM), and the Fermi liquid drop model (FLDM). The calculations adopt the value $\eta(0) = (0.6 – 1.2)\times u$ ($u = 10^{-23}$ Mev s fm^{-3}) as a parameter, which has been extracted by fitting the giant resonances at $T=0$ and fission data. The analysis of numerical calculations show that the shear viscosity increases between (0.5 - 2.5)u with increasing T from 0.5 up to $T \approx 3$ - 3.5 MeV for $\eta(0) = 1u$. At higher T the PDM, AM, and pTSFM predict a saturation, or at least a very slow increase of , η, whereas the FLDM show a continuously strong increase of η, with T. At $T= 5$ MeV, the PDM estimates η between around (1.3 - 3.5)u.

All theoretical models predict a decrease of the ratio η/s with increasing T up to $T \sim 2.5$ MeV. At higher T, the PDM, AM, and pTSFM show a continuous decrease of η/s, whereas the FLDM predicts an increase of η/s, with increasing T. The PDM fits best the empirical values for η/s extracted at $0.7 \leq T \leq 3.2$ MeV for all three nuclei, ^{63}Cu, ^{120}Sn, and ^{208}Pb. At $T=$ 5 MeV, the values of η/s predicted by the PDM reach $3^{+0.63}_{-1.2}$, $2.8^{+0.5}_{-1.1}$, $3.3^{+0.7}_{-1.3}$ KSS units for ^{63}Cu, ^{120}Sn, and ^{208}Pb, respectively. Combining these results with the model-independent estimation for the high-T limit of η/s, which is $2.2^{+0.4}_{-0.9}$ KSS units, one can conclude that the value of η/s for medium and heavy nuclei at $T = 5$ MeV is in between (1.3 - 4.0) KSS units, which is about (3 - 5) times smaller (and of much less uncertainty) that the value between (4 - 19) KSS units predicted by the FLDM for heavy nuclei. This estimation also indicates that nucleons inside a hot nucleus at $T = 5$ MeV has nearly the same ratio η/s as that of the quark-gluon plasma, around (2 - 3) KSS units, at $T > 170$ MeV discovered the Relativistic Heavy Ion Collider at Brookhaven National Laboratory and the Large Hadron Collider at CERN.

2) Pairing reentrance in hot rotating nuclei (by N. Quang Hung and N. Dinh Dang)

It is well-known from Mottelson-Valatin prediction that pairing correlation decreases with total angular momentum and/or rotational frequency and vanishes at a given critical total angular momentum M_c or rotational frequency ω_c . However, at $M \geq M_c$ (or $\omega \geq \omega_c$), the increase of temperature T will relax the tight packing of quasiparticles around the Fermi surface and makes some levels become partially unoccupied, therefore, available for scattered pairs. As the result, when T increases up to some critical value T_1, the pairing correlation is energetically favored, and pairing correlation reappears. As T goes higher, the increase of a large number of quasiparticles eventually breaks down the pairing at $T_2 > T_1$. This phenomenon is called thermally assisted pairing correlation or anomalous pairing, and later as pairing reentrance. However, the experimental extraction of the pairing correlation in hot nuclei is not simple. Therefore a detection of the pairing reentrance effect by using experimentally extracted pairing gaps seems to be elusive. Meanwhile, the heat capacity has been extracted from the experimental nuclear level densities. A recent calculation of the hot rotating ^{72}Ge nucleus within the shell model Monte Carlo (SMMC) approach has found a local dip in the heat capacity at a rotation frequency of 0.5 MeV at $T \approx 0.45$ MeV, and a corresponding local maximum on the temperature dependence of the logarithm of level density. Such irregularities are associated with the signatures of the pairing reentrance. The goal of this work is to study the pairing reentrance effect within a different microscopic approach, which bases on the BCS theory at finite temperature and total angular momentum, taking into account thermal fluctuations in terms of quasiparticle number fluctuation. The later has been found to be very important for finite nuclear systems, especially for light nuclei. The corresponding approach is called the FTBCS1 plus angular momentum, which has been successfully applied to study the pairing properties of hot rotating systems.

The numerical calculations are carried out for two realistic ^{60}Ni and ^{72}Ge nuclei. The latter is considered in order to have a comparison with the results obtained within the SMMC approach. The results obtained show the appearance of the pairing reentrance in the pairing gap at finite M and T. Instead of decreasing with increasing T, the gap first increases with T then decreases at higher T. It is demonstrated that the heat capacity C, or rather C/T, and the level density ρ can be used to experimentally identify the pairing reentrance effect. The pairing reentrance leads to a clear depletion in the temperature dependence of the heat capacity, whereas the level density weakly changes from a convex function of T to a concave one. The later contradicts the claim of the SMMC calculations, which turns out to be an artifact caused by unphysically large values of the heat capacity at low T.

Fiscal Year 2011 List of Publications Resulting from the Use of RICC

[Publication]

1) **N. Dinh Dang**, Shear-viscosity to entropy-density ratio from giant dipole resonances in hot nuclei,
Phys. Rev. C 84 (2011) 034309.

2) **N. Quang Hung and N. Dinh Dang**, Pairing reentrance in hot rotating nuclei,
Phys. Rev. C 84 (2011) 054324.

[Proceedings, etc.]

3) **N. Dinh Dang and N. Quang Hung**, Thermal nuclear pairing within the self-consistent quasiparticle RPA,
J. Phys.: Conference Series 267 (2011) 012049.

[Oral presentation at an international symposium]

1) **N. Dinh Dang**, Thermal Pairing & Nuclear Viscosity,
Physics Colloquium, Department of Physics, University of Idaho 5 May, 2011, **USA**.

2) **N. Dinh Dang**, Thermal Pairing and Nuclear Thermodynamics,
Institute of Nuclear Study Special Seminar, Department of Physics, University of Washington, 9 May, 2011, **USA**.

3) **N. Dinh Dang**, Viscosity of hot nuclei (*invited talk*)
XIX International School on Nuclear Physics, Neutron Physics and Applications, September 19 - 25, 2011, Varna, **Bulgaria**.

4) **N. Dinh Dang**, Viscosity: From air to a hot nucleus (*invited talk*)
Int'l workshop on theoretical approaches to correlations in nuclei at the limit of stability, November, 20 – 21, 2011, Tan Tao Univ., Long An, **Vietnam.**

5) **N. Dinh Dang,** Viscosity of hot nuclei (oral presentation)
Int'l Symposium on Physics of Unstable Nuclei (ISPUN11), Nov. 23 – 28, 2011, Hanoi, **Vietnam.**