Project Title:

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

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1) Thermodynamic properties of hot nuclei within the self-consistent quasiparticle random-phase approximation

Thermodynamic properties of any systems can be studied by using three principal statistical ensembles, namely the grand canonical ensemble (GCE), canonical ensemble (CE) and microcanonical ensemble (MCE). Because an atomic nucleus is a system with a fixed particle number, the particle-number fluctuations are not allowed. The use of the GCE in nuclear systems is therefore an approximation, which is only good if the effect caused by particle-number fluctuations is negligible. From the experimental point of view, the CE and MCE are usually used to extract various thermodynamic quantities of nuclear systems. However, most of present theoretical approaches, derived within the GCE, cannot describe well these data.

Recently we have proposed a method, which has allowed us to construct theoretical approaches within the CE and MCE to describe rather well thermodynamic properties of atomic nuclei. The proposed approaches have been derived by solving the BCS and self-consistent quasiparticle RPA (SCQRPA) equations with the Lipkin-Nogami (LN) particle-number projection for each total seniority (number of unpaired particles at zero temperature). The obtained results are then embedded into the CE and MCE. Within the CE, the resulting approaches are called the CE-LNBCS and CE-LNSCQRPA, whereas they are called the MCE-LNBCS and MCE-LNSCQRPA within the MCE. The results obtained within these approaches are found in quite good agreement with not only the exact solutions of the Richardson model but also the experimentally extracted data for ^{56}Fe. The merit of these approaches reside in their simplicity and feasibility in the application even to heavy nuclei, where the exact solution is impracticable whereas the finite-temperature quantum Monte-Carlo method is time consuming. The present work applied the above-mentioned approaches to describe thermodynamic quantities of ^{94,96}Mo, ^{162}Dy and ^{172}Yb nuclei. The results obtained show that the CE(MCE)-LNSCQRPA describe quite well the recent experimental level densities, entropies, and heat capacities. They also give a strong indication to the fact that, to construct an adequate partition function for a good description of thermodynamic quantities, the measured level density should be extended up to very high excitation energy E* ~ 180 MeV or 200 MeV.

2) Shear-viscosity to entropy-density ratio from giant dipole resonances in hot nuclei

The recent experimental data from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and Large Hadron Collider (LHC) at CERN have revealed that the matter formed in ultrarelativistic heavy-ion collisions is a nearly perfect fluid with extremely low viscosity. This has driven the attention to the calculation of the ratio η/s of shear viscosity η to entropy density s. Using the string theory, Kovtun, Son and Starinets conjectured a universal value $hbar/(4\pi k_B)$ ≅5.24×10^{-23}Mev s (the KSS bound or KSS unit) for this ratio as the lowest bound for all fluids. For finite nuclei, the recent calculations by Auerbach and Shlomo within the Fermi liquid drop model (FLDM) estimated η/s within (4 - 19) and (2.5 - 12.5) KSS units for heavy and light nuclei,respectively. The obtained η increases with temperature T up to almost T ~ 10 MeV, then slows down to reach a maximum at T ~ 13 MeV. Consequently, within the region $0 \leq T \leq 5$ MeV, the damping width of the giant dipole resonance (GDR) predicted by the FLDM increases with T almost quadratically. However, the experimental systematic has shown that the GDR width in heavy nuclei increases with T only within $0 \leq T \leq 2.5$ MeV. Below T ~ 1 MeV, it remains nearly constant, whereas at T > 3 - 4

MeV the width seems to saturate. The entropy density $s = \rho\ S/A$ (ρ=0.16 fm^{-3}) has been calculated by using a linear temperature dependence $S=2aT$ with a temperature-independent level density parameter a. This approximation too rather poor for finite nuclei. Therefore, although by dividing two quantities, which both increase with T, the obtained result for the ratio η/s does decrease qualitatively to a value within one order of the KSS bound, a refined quantitative prediction for this ratio still remains a challenge.

The present work uses the Kubo relation and the generalized Nyquist theorem to extract the ratio η/s from the experimental systematic for the GDR widths in copper, tin and lead regions at $T \neq 0$. These empirical results are then compared with the predictions by several independent models, as well as with almost model-independent estimations. Based on these results, it is concluded that the ratio η/s in medium and heavy nuclei decreases with increasing temperature to reach (1.5 – 4) KSS units at T = 5 MeV. This is an indication that nucleons inside a hot nucleus at $T \sim 5 - 6$ MeV might behave as closely to a perfect fluid as quark-gluon plasma discovered at RHIC and LHC

Fiscal Year 2010 List of Publications Resulting from the Use of RICC

1) N. Dinh Dang and N. Quang Hung, *Chemical potential beyond the quasiparticle mean field*, Phys. Rev. C 81 (2010) 034301.

2) N. Quang Hung and N. Dinh Dang, *Canonical ensemble treatment of pairing within BCS and quasiparticle random phase approximation*, Phys. Rev. C 81 (2010) 057302.

3) N. Quang Hung and N. Dinh Dang, *Thermodynamic properties of hot nuclei within the self-consistent quasiparticle random-phase approximation*, Phys. Rev. C 82 (2010) 044316.

4) N. Dinh Dang, *Shear-viscosity to entropy-density ratio from giant dipole resonances in hot nuclei*, in submission.

[Proceedings, etc.]

1) N. Dinh Dang and N. Quang Hung, *Thermal nuclear pairing within the self-consistent quasiparticle RPA*, arXiv:1006.2201v1, *accepted in J. Phys.: Conference Series.* (This does not contains acknowledgements because of page limitation. However, the acknowledgements are included in Ref. [3] above, on which the talk is based.

[Oral presentation at an international symposium]

1) N. Dinh Dang, *The Selfconsistent Quasiparticle RPA and Its Description of Thermal Pairing Properties in Nuclei*, invited talk at the Multidisciplinary Workshop on RPA and extensions, January 26 - 28, 2010, Université Pierre et Marie Curie, Jussieu, Paris, France;

2) N. Dinh Dang and N. Quang Hung, *Thermal nuclear pairing within the self-consistent quasiparticle RPA,* talk at 10th International Spring Seminar on Nuclear Physics "New Quests in Nuclear Structure, May 21 - 25, 2010, Vietri sul Mare, Salerno, Italy;

3) N. Dinh Dang, *Nuclear Thermodynamics Properties within Self-Consistent Quasiparticle Random-Phase Approximation,* invited seminar at Departamento de Física, Instituto Superior Técnico, Lisbon, Portugal on 16 November, 2010;

4) N. Dinh Dang, *Nuclear Thermodynamics Properties within Self-Consistent Quasiparticle Random-Phase Approximation,*
invited seminar at Centre d'Études Nucléaires de Bordeaux Gradignan – France on 18 November, 2010;