η/s ratio of nuclear matter at high angular momentum and its theoretical validation

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Introduction

The ratio of shear viscosity to entropy density (η/s) is a key property of an ideal fluid. The conjecture of Kovtun-Son-Starinets (KSS) lower bound has initiated avid research work in this field, especially in strongly correlated Fermionic systems like quark-gluon-plasma at very high temperature (T). The relation between nuclear collectivity and η has been established by references such as Auerbach and Shlomo, using isovector giant dipole resonance (IVGDR)[1]. IVGDR width and energy may be used to understand η and η/s ratio. However, GDR is a collective phenomenon and hence the trend of T-dependent η is different from that of classical fluids. Dang [1] unveiled a new elegant but simple formalism to connect GDR width and the ratio. In a recent work, interestingly, Mondal et al [2] has shown that at low T and angular momentum (J) values, atomic nucleus behaves as almost an ideal fluid with η/s very similar to quark-gluon-plasma at high temperature. This probably indicates that strong fluidity could be the universal feature in strong interaction. The behaviour of atomic nuclei at high J and T in terms of η/s has also been studied in a few nuclei in our recently published work[1]. The Fermi liquid drop model, which was highly instrumental to explain the ratio at low T and J, could not explain the experimental η/s at high J (12-54$\hbar$) and T (1.2-2.1 MeV) and hence modified as J-FLDM. It was found, however, that critical temperature included fluctuation model (CTFM) successfully predicts the experimental data.

So far there are a few interesting investigation in this field. But the study of η/s at high J and T is still very rare. In this work, η and η/s of ^{80}Zr, ^{81}Rb, and ^{86}Mo are extracted from the existing experimental data of GDR width. The entropy density (s) is also explored from the experimental data and finally η/s ratio has been found out. We also investigated the validity of J-FLDM as well as CTFM to explain the experimental data.

Data analysis

The nuclei ^{80}Zr, ^{81}Rb are selected from the existing literature. These compound nuclei (CN) were populated in the reactions ^{40}Ca+^{40}Ca, ^{37}Cl+^{44}Ca [3] (beam energy E_{lab} at 136 and 95 MeV, excitation energy Ex of 54 and 83 MeV, respectively). The nucleus ^{86}Mo was populated in the reaction ^{28}Si+^{58}Ni at E_{lab} 125 MeV and Ex of 66 MeV [4]. The average angular momentum J has been 35$\hbar$ and temperature T is 1.8-1.9 MeV in the first two reactions. For the latter, J and T were kept at 35$\hbar$ and 1.23 MeV. The average J and T have been found out using statistical model code CASCADE selecting only the decay steps that directly contribute to the GDR γ-ray emission. The angular momentum J is greater than the critical angular momentum J_C beyond which its effect can be observed on the GDR width Γ. The GDR width at ground state (Γ_0) is taken as 4.5 MeV that was measured experimentally in photoabsorption experiment [3]. The viscosity η at temperature T is extracted in this work using the experimental GDR width as proposed by Dang in the equation:

$$\eta(T) = \eta(0)\frac{\Gamma(T)}{\Gamma(0)}L(\Gamma_T)\,\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where η(0) is constant at T=0 MeV, taken as 1u or 1 MeV s fm^{-3}, E(0) and Γ(0) is the GDR energy and width at ground state (T=0). Γ(T) is the T-dependent GDR width, L(Γ_T) is a function depending on the GDR width [1].

Results and discussions

Using equations (1) and (2), the temperature dependent viscosity is found out for the mass number A=80-86. The entropy density s is calculated from the formula s=S(T)ρ/A, where ρ is the nuclear matter density taken as 0.16 fm^{-3}. S(T) is the entropy at temperature T, given by S(T)=2*a* (T) T. The nuclear level density parameter *a*(T) is formulated from well-known Reisdorf-Ignatyuk expression [1]. The entropy density calculated in such way is used to extract the ratio η/s.

The T-dependent η shown in Fig. 1. in red filled and blue unfilled circles denotes the data points for average <J> 35 and 38 *ℏ*, respectively. The error bars are calculated from the errors of the experimental GDR width. The experimental η is nicely corroborated by the theoretical model CTFM (pink short dashed line). However, the FLDM (green large dashed line) could not explain the data with in-medium N-N scattering cross-section taken as 4.6 MeV that is 50% of that of free space and Fermi energy as 36 MeV. FLDM can explain the data if the cross-section is taken 80% of that of the free space, which is highly unrealistic considering the range of experimental T. The FLDM only considers the expressions for two-body collision and therefore cannot account for the full width at half maximum (FWHM) of the GDR line shape. Earlier, we have modified the FLDM (renamed as J-FLDM) to explain the high J data by adding a term bexp(b_1ξ), where b and b1 are constants and ξ=J/$A^{5/6}$ [1]. Here J-FLDM again successfully predicts the T-dependent η at J=35*ℏ* with b and b_1 are 0.05 and 3.20 units, respectively. CTFM on the other hand is a macroscopic model that takes into account the J and T dependent Γ. The experimental η/s is shown in Fig. 2 (with markers) and also explained by the CTFM and J-FLDM successfully. Intriguingly, the experimental η/s shows the J-independent behaviour of the data.

Conclusion

In this work we have studied the η, s and η/s for the mass range A=80-86 at high J=35*ℏ* and found that CTFM successfully predicts the data. FLDM could explain the data only after modifications done. The η/s ratio, though obeys the KSS bound, comes out very close to that of a partonic system like quark-gluon-plasma of high T. The experimental η/s shows the J-independent behaviour.

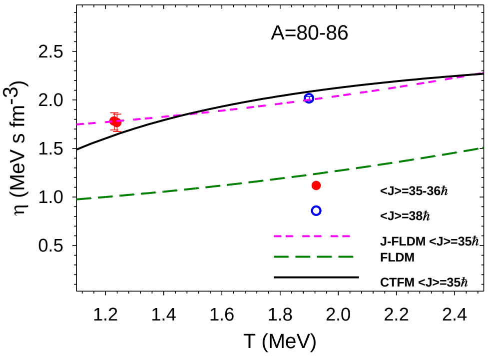

Fig. 1 T-dependent η with model predictions

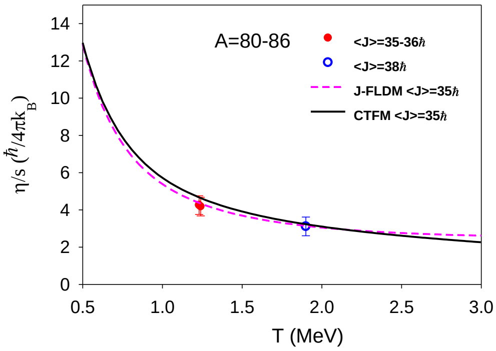

Fig. 2 T-dependent η/s with model predictions

References

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