## Research and Publications:

### 1. Dr. Srijit Bhattacharya

### Three published items published in last five years worth mentioning:

**(i)** ***Investigation of Growth Kinetics and Multiplar Plasmonic properties of Silver nanoparticle cluster by experiment and numerical simulation.***

Md. Moinul Islam, S. Mandal, and **Srijit Bhattacharya** (corresponding author). Plasmonics 13(5), 1803 (2018). impact factor: 2.335 (2018-19)

**-----------------------The complete experimental work was performed at Barasat Govt. College.**

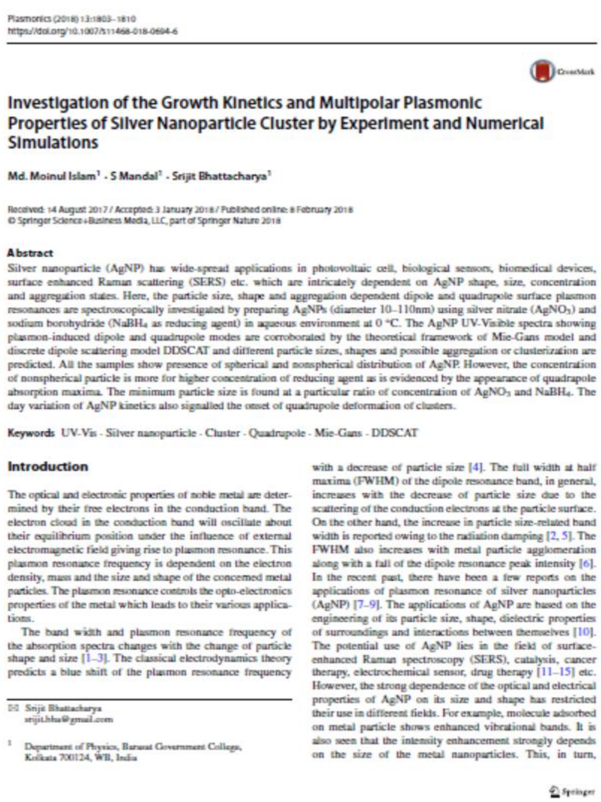
https://doi.org/10.1007/s11468-018-0694-6

**(ii)** ***Experimental determination of eta/s for finite nuclear matter.***
**Srijit Bhattacharya** in D Mondal et al, Physical Review Letters 118, 192501 **(2017).**

**-------------------------------------high impact factor journal (9.23 in 2018-19) .**
https:10.1103/PhysRevLett.118.192501

**(iii)** ***Effect of high angular momentum on $\eta$/s of nuclear matter.***
**Srijit Bhattacharya et al. Physical Review C 103, 014305 (2021). Impact factor:3.132 (2018-19)**
**----------------------------The complete theoretical work was performed at Barasat Govt. College**
https:10.1103/PhysRevC.103.014305

**(i)**



Plasmonics (2018) 13:1803–1810
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**Investigation of the Growth Kinetics and Multipolar Plasmonic Properties of Silver Nanoparticle Cluster by Experiment and Numerical Simulations**

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**Abstract**
Silver nanoparticle (AgNP) has wide-spread applications in photovoltaic cell, biological sensors, biomedical devices, surface enhanced Raman scattering (SERS) etc. which are intricately dependent on AgNP shape, size, concentration and aggregation states. Here, the particle size, shape and aggregation dependent dipole and quadrupole surface plasmon resonances are spectroscopically investigated by preparing AgNPs (diameter 10–110nm) using silver nitrate ($AgNO_3$) and sodium borohydride ($NaBH_4$ as reducing agent) in aqueous environment at 0 °C. The AgNP UV-Visible spectra showing plasmon-induced dipole and quadrupole modes are corroborated by the theoretical framework of Mie-Gans model and discrete dipole scattering model DDSCAT and different particle sizes, shapes and possible aggregation or clusterization are predicted. All the samples show presence of spherical and nonspherical distribution of AgNP. However, the concentration of nonspherical particle is more for higher concentration of reducing agent as is evidenced by the appearance of quadrapole absorption maxima. The minimum particle size is found at a particular ratio of concentration of $AgNO_3$ and $NaBH_4$. The day variation of AgNP kinetics also signalled the onset of quadrupole deformation of clusters.

**Keywords** UV-Vis · Silver nanoparticle · Cluster · Quadrupole · Mie-Gans · DDSCAT

**Introduction**

The optical and electronic properties of noble metal are determined by their free electrons in the conduction band. The electron cloud in the conduction band will oscillate about their equilibrium position under the influence of external electromagnetic field giving rise to plasmon resonance. This plasmon resonance frequency is dependent on the electron density, mass and the size and shape of the concerned metal particles. The plasmon resonance controls the opto-electronics properties of the metal which leads to their various applications.

The band width and plasmon resonance frequency of the absorption spectra changes with the change of particle shape and size [1–3]. The classical electrodynamics theory predicts a blue shift of the plasmon resonance frequency with a decrease of particle size [4]. The full width at half maxima (FWHM) of the dipole resonance band, in general, increases with the decrease of particle size due to the scattering of the conduction electrons at the particle surface. On the other hand, the increase in particle size-related band width is reported owing to the radiation damping [2, 5]. The FWHM also increases with metal particle agglomeration along with a fall of the dipole resonance peak intensity [6]. In the recent past, there have been a few reports on the applications of plasmon resonance of silver nanoparticles (AgNP) [7–9]. The applications of AgNP are based on the engineering of its particle size, shape, dielectric properties of surroundings and interactions between themselves [10]. The potential use of AgNP lies in the field of surface-enhanced Raman spectroscopy (SERS), catalysis, cancer therapy, electrochemical sensor, drug therapy [11–15] etc. However, the strong dependence of the optical and electrical properties of AgNP on its size and shape has restricted their use in different fields. For example, molecule adsorbed on metal particle shows enhanced vibrational bands. It is also seen that the intensity enhancement strongly depends on the size of the metal nanoparticles. This, in turn,

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(ii)

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## Experimental Determination of $\eta/s$ for Finite Nuclear Matter

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We present, for the first time, simultaneous determination of shear viscosity ($\eta$) and entropy density ($s$) and thus, $\eta/s$ for equilibrated nuclear systems from $A \sim 30$ to $A \sim 208$ at different temperatures. At finite temperature, $\eta$ is estimated by utilizing the $\gamma$ decay of the isovector giant dipole resonance populated via fusion evaporation reaction, while $s$ is evaluated from the nuclear level density parameter ($a$) and nuclear temperature ($T$), determined precisely by the simultaneous measurements of the evaporated neutron energy spectra and the compound nuclear angular momenta. The transport parameter $\eta$ and the thermodynamic parameter $s$ both increase with temperature, resulting in a mild decrease of $\eta/s$ with temperature. The extracted $\eta/s$ is also found to be independent of the neutron-proton asymmetry at a given temperature. Interestingly, the measured $\eta/s$ values are comparable to that of the high-temperature quark-gluon plasma, pointing towards the fact that strong fluidity may be the universal feature of the strong interaction of many-body quantum systems.

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The understanding of fluidity of matter, measured by the ratio of shear viscosity ($\eta$) to entropy density ($s$), has been the subject of intense investigations in different areas of physics. The crucial ratio of $\eta/s$ is related to the Reynolds number and is well defined for both relativistic and nonrelativistic fluids [1]. The temperature variation of $\eta/s$ also 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 $\eta/s \geq \hbar/4\pi k_B$ [2], $k_B$ being the Boltzmann constant. In strongly coupled systems, momentum transport is highly inhibited, resulting in a small shear viscosity. The prime examples of such highly correlated systems are the Bose and the Fermi liquids [3–5] at extremely low temperatures and the quark-gluon plasma (QGP), produced at high temperatures [6–8]. These quantum systems have very low $\eta/s$ ($\sim 5 - 10\,\hbar/4\pi k_B$) [1] and behave as nearly perfect fluids.

An atomic nucleus is a many-body quantum system in which the constituent particles, called nucleons, are governed by strong interaction and show highly correlated behavior. A finite nucleus, therefore, is an ideal system to search for near perfect fluidity in matter. Different model-dependent calculations for $\eta/s$ have been performed earlier at intermediate-energy heavy ion collisions in search for a liquid-gas phase transition [9–12]. The first theoretical study for $\eta/s$ in relation to the damping of giant resonances

They showed that $\eta/s$ values for heavy and light nuclei were $\sim(4 - 19)\hbar/4\pi k_B$ and (2.5–12.5) $\hbar/4\pi k_B$, respectively. Recently, Dang [15] 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. The empirically calculated values of $\eta/s$ for different systems have been compared with various model calculations. A model-independent high-temperature limit of $\eta/s$ has also been proponed for finite nuclear systems.

Viscosity is inherently related to the damping of the GDR, which is conceived, macroscopically, as out of phase oscillation (isovector) of the proton fluid against the neutron fluid. It is a highly damped motion characterized by a very small lifetime ($\sim 10^{-21} - 10^{-22}$ sec). According to the Brink-Axel hypothesis [16], the GDR can be built on the ground state as well as on every excited state of the nucleus. The GDR built on the ground state (henceforth called as the ground state GDR) is studied by photo absorption reactions, while that built on excited states is studied by fusion evaporation and inelastic scattering reactions. The line shape of the GDR is a Lorentzian, characterized by the peak energy ($E_{GDR}$), the width ($\Gamma_{GDR}$), and the resonance strength ($S_{GDR}$). It is observed, both experimentally and theoretically, that the $E_{GDR}$ and $S_{GDR}$ do not depend on the excitation energy ($E^*$), but $\Gamma_{GDR}$

(iii)

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## Effect of high angular momentum on $\eta/s$ of nuclear matter

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The shear viscosity ($\eta$) of nuclear matter is investigated in different nuclei (nuclear mass $A \approx 59$–194) using experimental giant dipole resonance (GDR) width ($\Gamma$) at high angular momenta ($J = 12$–54 $\hbar$) and temperatures ($T = 1.2$–2.1 MeV) collected from the existing literature. $\eta$, calculated from $\Gamma$, is found to increase with $T$ and $J$. We show that critical temperature included fluctuation model (CTFM) successfully describes $J$-induced $\eta$ even beyond critical angular momentum $J_c$ at different values of $T$. However, the Fermi liquid drop model (FLDM) could not explain the data at higher angular momenta. We propose the addition of a $J$-dependent term with the FLDM $\eta$ to improve the prediction at such high-$J$ region. The $\eta/s$ ratio, highly important for measuring fluidity, is calculated using $\eta$ and the entropy density $s$. The latter is estimated using the Fermi gas formula. Interestingly, the experimental value of the ratio is independent of $J$ and $A$ and comes within 2.6–6.0 $\hbar/4\pi k_B$, which is very close to those of a partonic system like quark gluon plasma at high temperature.

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### I. INTRODUCTION

The study of the ratio of shear viscosity to entropy density ($\eta/s$) of fermionic and bosonic fluids has drawn considerable

in the heavy ion collision at the Fermi scale [6]. Theoretically, shear viscosity $\eta$ in nuclear matter has been estimated using different model-dependent classical and semiclassical