Temperature Measurements of Dense Plasmas by Detailed Balance

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Plasmas at high electron densities of $n = 10^{20} - 10^{26}\,\mathrm{cm}^{-3}$ and moderate temperatures $T = 1 - 20\,\mathrm{eV}$ are important for laboratory astrophysics, high energy density science and inertial confinement fusion. These plasmas are usually referred to as Warm Dense Matter (WDM) and are characterized by a coupling parameter of $\Gamma \gtrsim 1$ where correlations become important.

The characterization of such plasmas is still a challenging task due to the lack of direct measurement techniques for temperatures and densities. We propose to measure the Thomson scattering spectrum of vacuum-UV radiation off density fluctuations in the plasma. Collective Thomson scattering provides accurate data for the electron temperature applying first principles. Further, this method takes advantage of the spectral asymmetry resulting from detailed balance and is independent of collisional effects in these dense systems.

In thermal equilibrium the macroscopic state of the plasma is completely characterized by its temperature T and density n. Following [1, 2], the density fluctuations in the plasma, described by the dynamic structure factor $S(\boldsymbol{k},\omega)$, are related to the dissipation of energy, described by the dielectric function $\varepsilon(\boldsymbol{k},\omega)$. This fundamental relation is based on the fluctuation–dissipation theorem [3]

$$S(\boldsymbol{k},\omega) = -\frac{\varepsilon_0 \hbar k^2}{\pi e^2 n}\,\frac{1}{1-\mathrm{e}^{\hbar\omega/k_BT}}\,\mathrm{Im}\varepsilon^{-1}(\boldsymbol{k},\omega)\ , \qquad (1)$$

where $\hbar\boldsymbol{k}$ and $\hbar\omega$ denotes the momentum and energy transfer of the incident photon. The structure factor determines the scattering spectrum. A calculation of the structure factor via Eq. (1) requires the evaluation of the dielectric function which needs modeling of collisional effects in the WDM regime. Independent of these theories the dielectric function ε has to fulfill the requirement $\varepsilon(\boldsymbol{k},\omega) = \varepsilon^*(-\boldsymbol{k},-\omega)$. Together with Eq. (1) one finds

$$\mathcal{Y}(\boldsymbol{k},\omega) \equiv \frac{S(\boldsymbol{k},\omega)}{S(-\boldsymbol{k},-\omega)} = \exp\left(-\frac{\hbar\omega}{k_BT}\right)\ . \qquad (2)$$

Equation (2) is referred to as "detailed balance" relation. As a consequence, the structure factor shows an asymmetry with respect to $\boldsymbol{k}$ and ω. This relation is extremely valuable since $\mathcal{Y}(\boldsymbol{k},\omega)$ is related directly to the plasma temperature independent of a detailed formulation of dissipative processes in the plasma.

Equation (2) is valid for arbitrary $\boldsymbol{k}$ and ω, however, in order to measure the temperature the following requirements must be met: (*i*) $\hbar\omega/k_BT \gtrsim 0.1$ in order to find a sizable asymmetry, (*ii*) $S(\pm\boldsymbol{k},\pm\omega)$ must be sufficiently large to give a measurable scattering signal. As a consequence, such a temperature measurement is preferably performed in the collective scattering regime, where the structure factor shows two distinct plasmon peaks. The peaks are separated from the ion feature at $\omega = 0$ by the plasmon dispersion relation $\omega^2 \approx \omega_{pl}^2 + 3k^2v_T^2 + (\hbar k^2/2m_e)^2$, with the electron thermal speed v_T and the electron plasma frequency $\omega_{pl}^2 = ne^2/\varepsilon_0 m_e$. Evidently, WDM is a preferred target with moderate temperatures and high densities to develop a measurable temperature asymmetry in the spectrum. A calculation of the dynamic structure factor in the standard Random Phase Approximation (RPA) and considering collisions in Born approximation [4] is shown in Fig. 1. This demonstrates that the asymmetry is independent of approximations made in ε. This result is a direct consequence of Eq. (2). Further, the result for T together with Eq. (1) provides a test of the model for ε which in turn determines the electron density by the plasmon dispersion. In this sense, collective Thomson scattering is a unique tool to probe temperature and density of WDM.

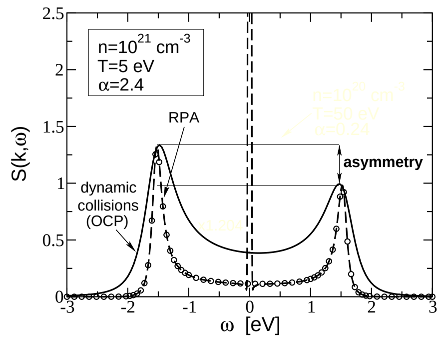

Figure 1: Dynamic structure factor at $E_0 = 91\,\mathrm{eV}$ for hydrogen in RPA (bold line: for two component plasma; circles: one component plasma (OCP)) and using dynamic collisions (OCP). The right peak is normalized to one. The asymmetry is due to detailed balance and provides T. For a resolution of $\Delta\omega/\omega \approx 10^{-2}$ the plasmon peaks can be resolved with current experimental techniques.

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