JOURNAL OF APPLIED PHYSICS **99**, 123305 (2006)

# Measurement of the ion feature of collective Thomson scattering in collisionless plasmas

I. E. Olivares[a]
*Departamento de Física, Universidad de Santiago de Chile, Avenida Ecuador 3493, Estación Central, Santiago, Chile*

H.-J. Kunze
*Institute for Experimental Physics V, Ruhr-University, 44780 Bochum, Germany*

(Received 27 February 2006; accepted 10 April 2006; published online 29 June 2006)

It is demonstrated that the collisionless theory of Salpeter [Phys. Rev. **120**, 1528 (1960)] can be fitted rather well to the ion feature of collective Thomson scattering on dense plasmas in equilibrium for elements up to argon. © *2006 American Institute of Physics*.

[DOI: 10.1063/1.2207830]

## I. INTRODUCTION

The ion feature of collective Thomson scattering is now widely used for the diagnostics of dense plasmas as produced in $z$ pinches[1] or by lasers for inertial confinement fusion.[2] Plasma parameters are obtained spatially resolved and even with high time resolution when fast streak cameras are employed. Prerequisite is certainly the reliable theoretical description of the spectral features, which in many experiments are complex due to the presence of multiple ion species, drifts, instabilities, and steep gradients in density and temperature within the scattering volume. Furthermore, at high densities ion-ion collisions will influence the shape.[3,4] In the present study we show how well the collisionless theory of Salpeter[5] still describes the ion feature reflecting the ion acoustic modes in plasmas of densities of up to $6 \times 10^{18}$ cm$^{-3}$, when the plasma is homogeneous and in equilibrium.

## II. BACKGROUND

The differential cross section for scattering by a plasma is of the form

$$\frac{d^2\sigma}{d\Omega_s d\omega_s} = r_e^2 \sin^2\varphi \, S(\mathbf{k},\omega), \tag{1}$$

where the first two factors give scattering characteristic of the single electron ($r_e$ is the classical electron radius and $\varphi$ the angle between the direction of the electric-field vector of the incident wave and the direction of observation), and $S(\mathbf{k},\omega)$ is the dynamic form factor containing the properties of the whole ensemble of electrons. With increasing scattering parameter

$$\alpha = \frac{1}{k\lambda_D} \tag{2}$$

($\lambda_D$ is the Debye length and the absolute value of the scattering vector $k$ is given by the difference of the wave vectors of incident and scattered wave, $k=|\mathbf{k}_s-\mathbf{k}_0|$), the scattered spectrum starts to reflect the collective properties of the plasmas. A narrow central part mirrors collective properties of the ions and is called ion feature, and two side bands reflect those of the electrons (electron feature).

In Salpeter's approximation ($T_e \cong T_i$) the dynamical form factor takes a relatively simple analytical form[5,6] and splits into the two features,

$$S(\mathbf{k},\omega) = S_e(\mathbf{k},\omega) + S_i(\mathbf{k},\omega). \tag{3}$$

With the shape function

$$\Gamma_\alpha(x) = \frac{\exp(-x^2)}{|1+\alpha^2 W(x)|^2}, \tag{4}$$

$S(\mathbf{k},\omega)$ becomes

$$S_e(\mathbf{k},\omega)d\omega = \Gamma_\alpha(x_e)dx_e \quad \text{and}$$

$$S_i(\mathbf{k},\omega)d\omega = \frac{Z\alpha^4}{(1+\alpha^2)^2}\Gamma_\beta(x_i)dx_i, \tag{5}$$

$$x_e = \frac{\omega}{k\sqrt{(2k_BT_e)/m_e)}} \quad \text{and} \quad x_i = \frac{\omega}{k\sqrt{(2k_BT_i)/m_i}}. \tag{6}$$

$W(x)$ is the plasma dispersion function and $\beta$ is given by

$$\beta^2 = Z\frac{\alpha^2}{1+\alpha^2}\frac{T_e}{T_i}. \tag{7}$$

For the determination of the electron density the absolute calibration of the system is usually done by means of Rayleigh scattering. For that purpose the vacuum chamber is filled with a suitable gas. The scattering volumes for Rayleigh and Thomson scatterings are identical. By comparison of Thomson and Rayleigh scattering signals the product $n_eS_i(\mathbf{k})$ simply becomes

$$n_eS_i(\mathbf{k}) = n_R\left(\frac{\sigma_R}{\sigma_{\mathrm{Th}}}\right)\left(\frac{W_S}{L_S}\right)\left(\frac{L_R}{W_R}\right). \tag{8}$$

$W_S$ and $W_R$ are the signals of Thomson and Rayleigh scatterings, $L_S$ and $L_R$ are the intensities of the incident laser beam in both experiments, and $\sigma_{\mathrm{Th}}$ and $\sigma_R$ are the respective cross sections. The density of the gas molecules is obtained from the gas pressure by $n_R=p/k_BT$ and the form factor by inte-

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[a] Electronic mail: ignacioolivares@usa.net

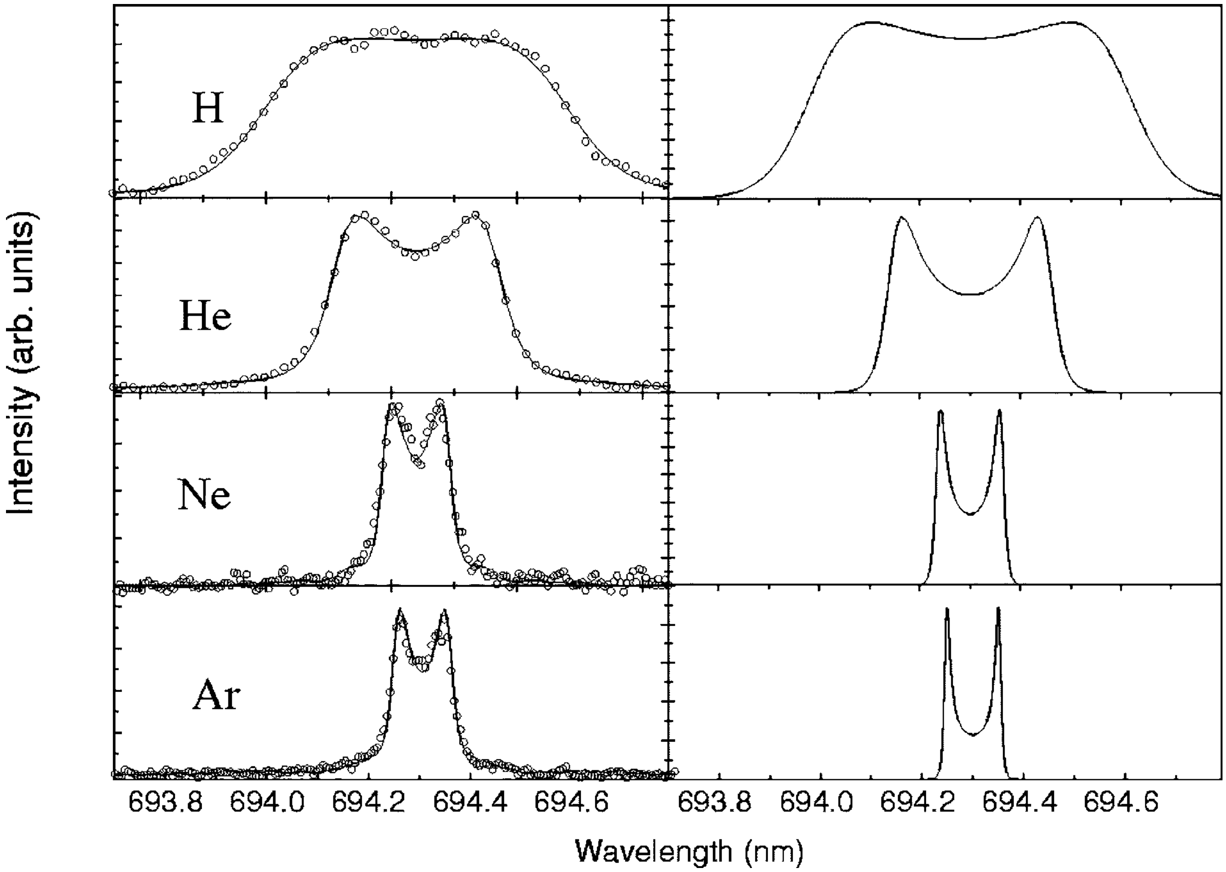

FIG. 1. Thomson scattering spectra of collissionless plasmas at optimal conditions of the gas liner pinch: (a) hydrogen: 0.02 nm/pixel, $n_e=0.62\times10^{18}$ cm$^{-3}$, $T_e=T_i=22$ eV, $Z=1$; (b) helium: 0.02 nm/pixel, $n_e=6.05\times10^{18}$ cm$^{-3}$, $T_e=T_i=16$ eV, $Z=2$; (c) neon: 0.0064 nm/pixel, $n_e=0.55\times10^{18}$ cm$^{-3}$, $T_e=T_i=12$ eV, $Z=2.6$; (d) argon: 0.0064 nm/pixel, $n_e=0.96\times10^{18}$ cm$^{-3}$, $T_e=T_i=14$ eV, $Z=3.6$.

gration over the frequency, i.e., by summation of the signals in the pixels of the detector. In the above approximation

$$S_i(\mathbf{k}) = \frac{Z\alpha^4}{(1+\alpha^2)[1+\alpha^2+Z\alpha^2(T_e/T_i)]}. \tag{9}$$

## III. EXPERIMENT

The scattering experiments were performed on plasmas which were produced in the Bochum gas liner pinch facility. This is a dynamic $z$-pinch provided with two independently operating fast electromagnetic valves. The first valve injects the working gas into the vacuum chamber next to the inner wall of an 18 cm diameter glass cylinder. In this vessel the two electrodes are placed 5 cm apart. The second valve permits the entrance of a small amount of test gas in the center of the discharge; usually the emission of these ions is the goal of spectroscopic studies. Before the main discharge the working gas is preionized by a discharge of a 50 nF capacitor from 50 needle electrodes placed in a circle 2 mm below the lower electrode (anode). Electrons and uv radiation produced by this discharge flow through small holes in the anode and preionize gas. The pre-ionizing pulse is followed with some delay by the main discharge of a 10 $\mu$F capacitor bank. This is typically charged to voltages between 25 and 35 kV. The best experimental condition was found at 27 kV for our studies. The main discharge of the capacitor bank is switched by a rail gap. The current rises to a maximum of 250–500 kA in 1.5 $\mu$s depending on the voltage. The plasma accelerates radially inward to the center of the cylinder due to a magnetic piston, producing a high density and temperature plasma at the center after stagnation. Best conditions are when the maximum current is next to the maximum density. More details can be found in Ref. 1.

For scattering a 2 J $Q$-switched ruby laser (Korad, model K1) with a 35 ns pulse duration is available. The beam shaping and relaying optics are based on a Galilean-telescope configuration. The beam is focused at the center of the chamber and its diameter there is about 1 mm. The collecting optics is placed perpendicular to the laser beam and is also based on a Galilean telescope configuration. The image of the scattering volume is formed at the entrance slit of a 1 m $f/10$ Czerny-Turner mount monochromator (Spex, model 1704). As the slit is vertical, two mirrors in the collecting beam path are added that rotate the image of the scattering volume in order to obtain the maximum scattered signal into the spectrograph. The first mirror directs the light vertically down and the second mirror placed below reflects the light horizontally to the monochromator. To improve the signal-to-noise ratio an interference filter and a red filter are included in the path of the collecting optics. At the exit of the monochromator an optical multichannel analyzer (Princeton Instruments, model OMAII) is used as detector. Wavelength calibration was done using two lines at 703.1 and 692.9 nm of a neon spectral lamp (Osram, model Ne10). For a

1200 lines/mm grating with a blaze wavelength of 1000 nm, for example, the linear reciprocal dispersion in second order was thus determined to 0.0063 nm/pixel for the above wavelength interval. The OMA is used in the triggered intensified gate mode with variable gate time. In our studies we employed typically a 100 ns duration gate pulse, which was enough to capture the 35 ns laser pulse. To obtain the best Thomson-scattering signal, the gate trigger pulse and Pockels-cell trigger of the laser pulse were obtained from the same source. The coincidence of the pulses at the OMA was achieved by adjusting the lengths of 50 Ohm coaxial cables. As reference signal we used the light of the plasma continuum that was recorded by a fast photodiode (EG&G, Model FND100). The performance test of the system was initially done by carrying out Rayleigh scattering experiments. It was crucial to cover the whole system with black cloth in order to eliminate stray light completely.

For the calibration by Rayleigh scattering we used propane ($C_3H_8$) at a pressure of 300 mbars.

## IV. RESULTS

Dense plasmas were produced with pure $H_2$, He, Ne, and Ar as working gas, no test gas injection along the axis. The left side of Fig. 1 shows typical well-resolved scattering spectra of the ion feature, after the continuum background has been subtracted. The spectra were selected after stagnation on the axis when thermalization was complete, i.e., $T_e = T_i$. The recorded spectra (circles) were fitted with theoretical spectra according to Eqs. (4)–(8) after these had been convolved with the instrument function, which was given by the shape of the Rayleigh scattered signal. For the least-square fit procedure the primary parameters were density and temperature. The effective charge $Z$ of the ions naturally had to be included. For hydrogen and helium plasmas it was set to $Z=1$ and $Z=2$, respectively. For neon and argon $Z$ is given as function of the electron temperature in the corona model by Arnaud and Rothenflug,[7] and this dependence was included in the fit code.

The right side of Fig. 1 displays the theoretical profiles of the best fit. The plasma parameters thus deduced are given in the caption of the figure.

## V. CONCLUSION

Thomson scattering was performed on dense plasmas of hydrogen, helium, neon and argon. It is shown that up to densities of $6\times10^{18}\,\mathrm{cm}^{-3}$ the collisionless theory of Salpeter[5] still describes well the ion feature including the valley between the two peaks of the ion acoustic modes, when the plasma is homogeneous and in equilibrium.

[1] Th. Wrubel, S. Büscher, and H.-J. Kunze, Plasma Phys. Controlled Fusion **42**, 519 (2000).

[2] S. H. Glenzer *et al.*, Phys. Plasmas **6**, 2117 (1999).

[3] Y. Q. Zhang, A. W. DeSilva, and A. N. Mostovych, Phys. Rev. Lett. **62**, 1848 (1989).

[4] J. F. Myatt, W. Rosmus,. V. Yu. Bychenkov, and V. T. Tikhonchuk, Phys. Rev. E **57**, 3383 (1998).

[5] E. E. Salpeter, Phys. Rev. **120**, 1528 (1960).

[6] J. Sheffield, *Plasma Scattering of Electromagnetic Radiation* (Academic, New York, 1975).

[7] M. Arnaud and R. Rothenflug, Astron. Astrophys., Suppl. Ser. **60**, 425 (1985).