PHYSICAL REVIEW A VOLUME 27, NUMBER 3 MARCH 1983

CO_2-laser scattering from thermal fluctuations in a plasma with two ion components

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(Received 29 November 1982)

CO_2-laser scattering experiments were performed to measure collective fluctuations in a thermal plasma containing two ion components of different mass. Coherent detection was used to obtain the necessary sensitivity and spectral resolution. Ion temperatures, ion composition, and effective charge numbers $\bar{Z}$ were determined for mass numbers ranging from 1 to 40.

The problem of measuring ion temperatures and densities of plasmas with more than one ion component arises in ionospheric physics and in high-temperature fusion experiments. These parameters can be determined by scattering of electromagnetic waves from thermal electron density fluctuations allowing spatially resolved, nonperturbing measurements. From the intensity and spectrum of the scattered radiation the densities and temperatures of both the electrons and the ions can be obtained.

For singly ionized plasmas experiments have been performed in the ionosphere by using radar[1] and in the laboratory by using laser light scattering.[2,3] In high-temperature fusion plasmas even small traces of highly ionized impurities coming from the wall drastically influence the energy balance. Because of their high charge, heavy impurities like oxygen ($Z=8$) or iron ($Z=26$) are expected to modify the spectrum of the major ion component (usually H^+ or D^+). The importance of ion temperature measurements for fusion has motivated several papers on the evaluation of complex multi-ion spectra.[4–7]. The purpose of our experiment was twofold: namely, to verify for the first time the details of spectra with $Z \gtrsim 1$ in a laboratory plasma and to demonstrate that ion temperatures and composition can be determined by collective laser scattering. A single-mode pulsed CO_2 laser and coherent detection were used. The scattering form factor for a plasma with several ion components of charge number Z_j is given by[8,9]

$$S(k,\omega)=\frac{\left|1-\sum_{j\neq e} G_j\right|^2 F_e+|G_e|^2\sum_{j\neq e} b_j F_j}{\left|1-G_e-\sum_{j\neq e} G_j\right|^2} ,$$

where k is the wave number,

$$F_j=\pi^{-1/2}a_j\exp(-a_j^2x^2)$$

is the normalized velocity distribution,

$$G_j=-\alpha^2(T_e/T_i)\,b_j\,W(a_jx)$$

is the screening integral,

$$x=(\omega/k)(m_i/2KT_i)^{1/2}$$

is the normalized frequency, W is the plasma dispersion function,

$$n_e\sum_{j\neq e} Z_j n_j$$

is the electron density,

$$\bar{Z}=\sum_{j\neq e} Z_j^2 n_j/n_e$$

is the effective charge number,

$$a_j=(m_jT_i/m_iT_j)^{1/2} ,$$

and

$$b_j=Z_j^2 n_j/n_e .$$

The subscript j runs over all particle species with $j=i$ referring to the major ion component and $j=e$ to the electrons. The ion parameters can be measured by collective scattering which requires the scattering parameter $\alpha=(k\lambda_D)^{-1}>1$. In general, the electron temperature T_e and electron density n_e are known from other measurements, and thus α is specified. The quantities to be determined are the ion temperature T_j, ion composition n_j/n_e, and effective charge number $\bar{Z}$.

Characteristic plasma parameters are given in Table I. The plasma source is a stationary magnetically sta-

TABLE I. Characteristic plasma parameters.

Arc current	$I=300$–900 A
Magnetic field	$B=0.35$–0.9 T
Total filling gas pressure	$p=60$–2000 Pa
Electron temperature	$T_e=1.2$–2.7 eV
Electron density	$n_e=1-5\times10^{21}$ m^{-3}
Plasma diameter	$D=30$ mm

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bilized hydrogen arc with argon, nitrogen, or helium as additives. It is well suited to vary in a controlled way the relevant parameters temperature, mass, and composition of the ions. For operation with pure hydrogen the plasma has already been well diagnosed.[10–13]

The characteristic data of the scattering system are listed in Table II. Single-mode output pulses are produced by a CO_2 hybrid laser.[14] To ensure the necessary sensitivity and spectral resolution, coherent detection techniques were used.[15,16] Before the laser passes through the arc the local oscillator beam is derived with a beam splitter and directed into the plasma. Its intersection with the main laser beam de-

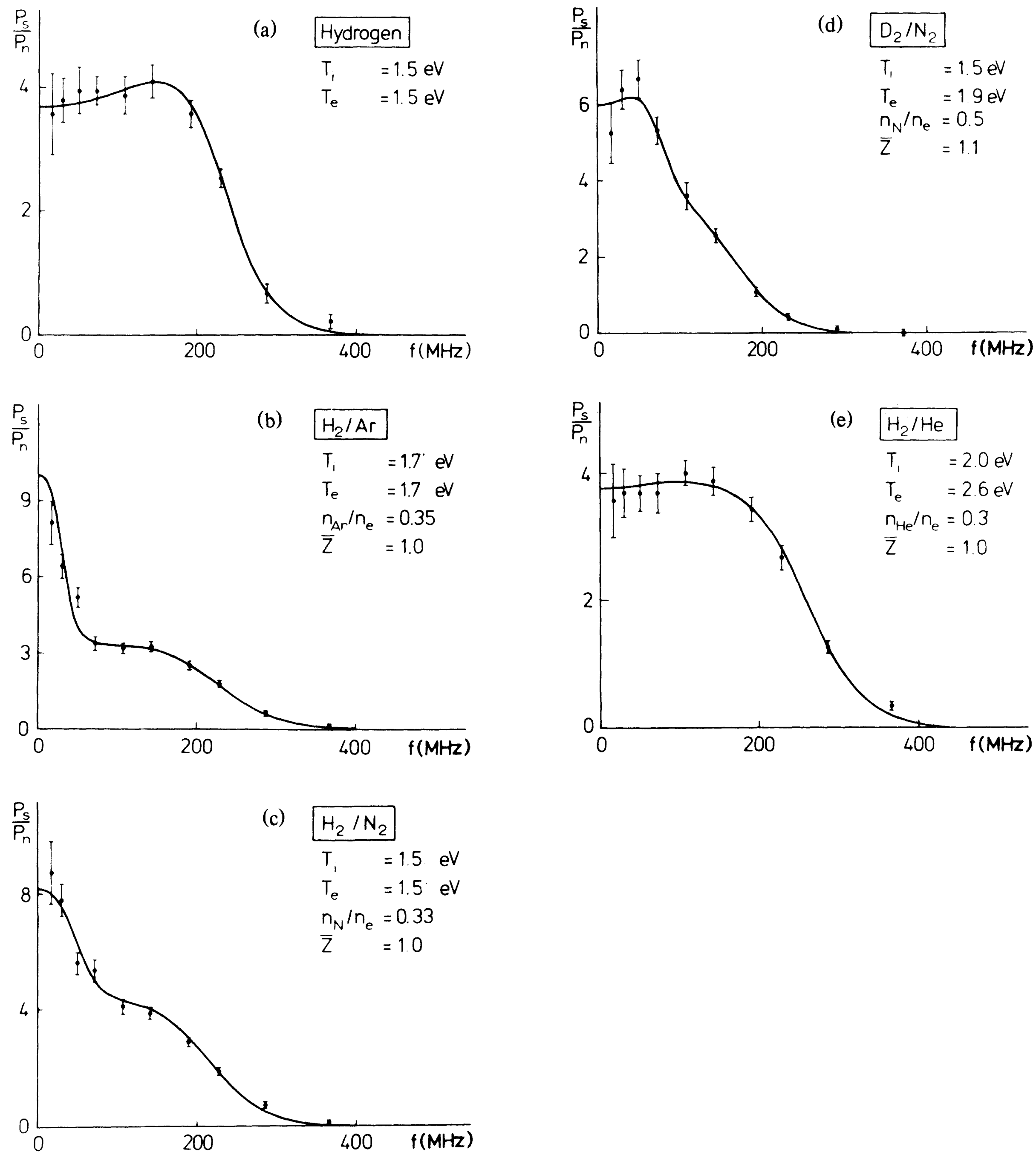

FIG. 1. (a)–(e) Spectra of two-component plasma with different mass ratios. (The scattered power P_s is normalized to the shot-noise power P_N.)

TABLE II. Characteristics of the scattering system.

Laser wavelength	$\lambda_L = 10.6\ \mu m$
Laser power	$P_L = 200$ kW
Pulse length	$\tau_L = 1.5\ \mu s$
Frequency range of receiver	10 – 420 MHz
Channel bandwidth	$\Delta f = 10 - 80$ MHz
Noise equivalent power	NEP $= 6 \times 10^{-19}$ W/Hz
Scattering angles	$\theta = 95$ mrad; 175 mrad
Scattering wave numbers	$k = 5.7 \times 10^4\ m^{-1}$; $10.3 \times 10^4\ m^{-1}$
Scattering parameters	$\alpha = 80$; 40
Length of scattering volume	$1 = 7$ mm; 4 mm
Diameter of scattering volume	$d = 0.7$ mm; 0.7 mm
Wave number resolution (full width at half maximum)	$k/\Delta k = 4.0$; 6.7

fines the scattering volume. Both scattered light and local oscillator are mixed in a Ge:Hg photoconductor. The scattered spectrum which is transformed into the radio-frequency range is resolved by a set of ten spectrum analyzers in parallel. The scattering wave vector was oriented nearly perpendicular to the arc current to avoid possible drift effects.

A least-squares fit of the experimental points to the possible theoretical spectra yielded the plotted curves, the ion temperature and composition, and the effective charge shown in the following figures. Where T_e was not known from independent scattering experiments, its value was calculated from the corona equilibrium. The temperature ratio of the ions is always $T_j/T_i = 1$ due to the small energy equipartition times. The scattering parameter is $\alpha >> 1$.

In the first set of measurements the ion-mass ratio was increased up to 40, adding different ion components to the dominant hydrogen plasma. Spectra at a scattering angle of $\theta = 95$ mrad are shown in Fig.1. (Note that for thermal fluctuations and coherent detection the size of the error bars depends on signal power P_s and filter bandwidth Δf.[15,17])

The ion temperature $T_i = 1.5$ eV for the pure hydrogen feature in Fig. 1(a) agrees well with previous measurements of T_i (Refs. 9 and 13) and of T_e (Ref. 12) for this type of plasma. The spectrum shows the weak-ion acoustic resonance characteristic of a single-component plasma with $T_e = T_i$.

Figure 1(b) shows hydrogen with argon; the mass ratio is 40: The heavy ions appear in the form of a narrow peak at low frequencies. The ion acoustic resonance in the hydrogen feature has disappeared due to the fact that both ion components interact mutually through the screening integrals G_j.

Figure 1(c) shows hydrogen with nitrogen; the mass ratio is 14. Because of the lower mass of nitrogen the central line has become broader but is still clearly distinguishable from the hydrogen feature.

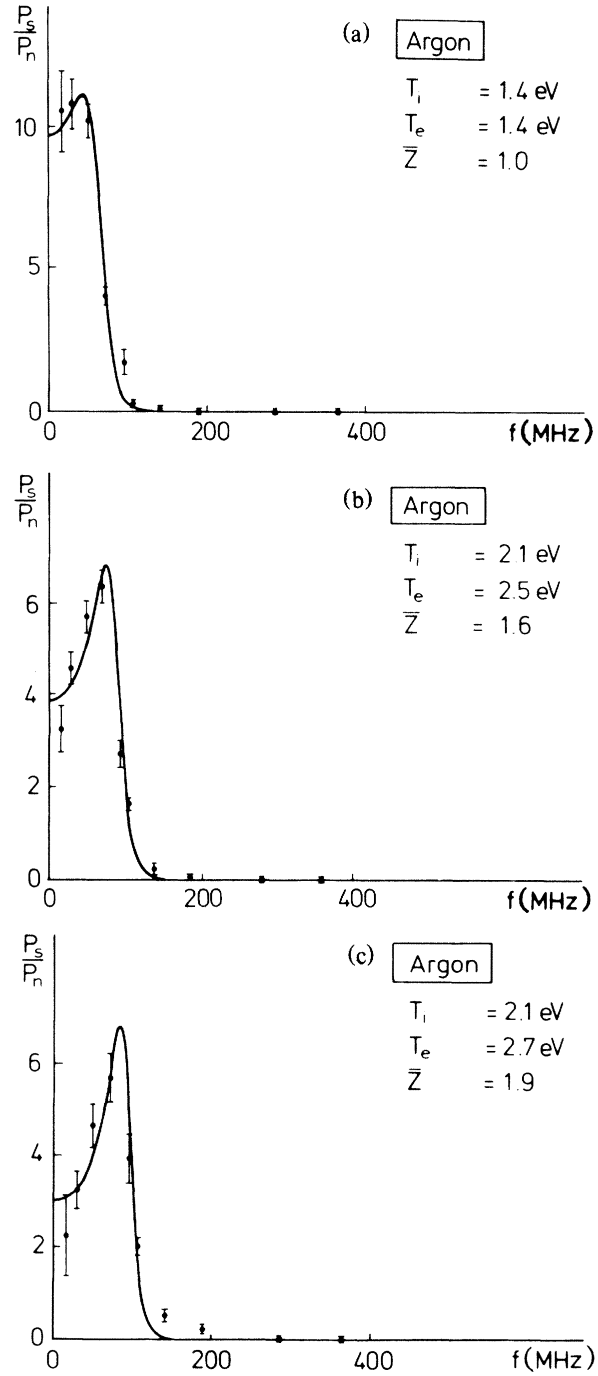

FIG. 2. (a)–(c) Spectra of pure argon with increasing values of $\bar{Z}$ and T_e/T_i.

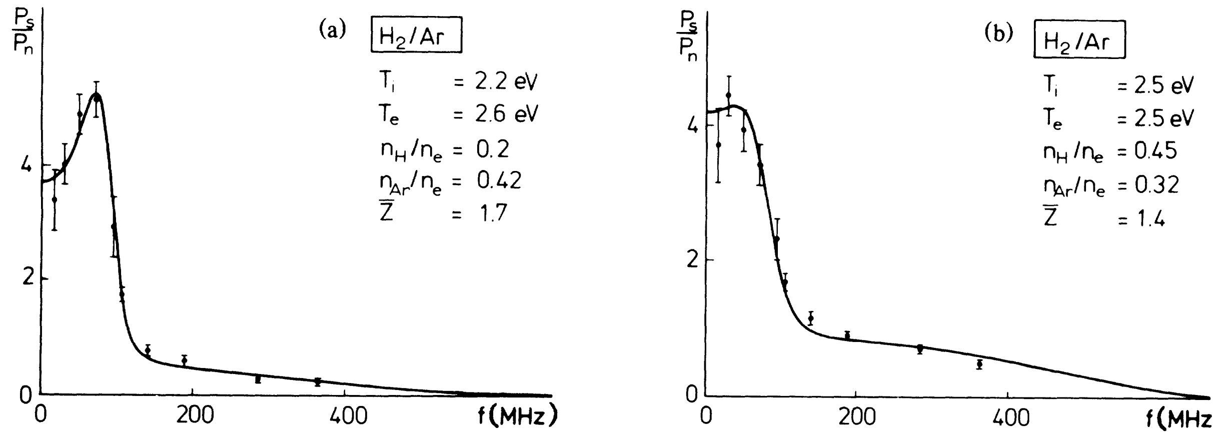

FIG. 3. (a),(b) Spectra of argon with increasing amounts of added hydrogen showing the damping of the heavy-ion resonance by the light ions.

Again, the ion acoustic resonance in the hydrogen feature is heavily damped.

Figure 1(d) shows deuterium with nitrogen; the mass ratio is 7: This is the lowest mass ratio for which a visible separation of the components is evident.

Figure 1(e) shows hydrogen with helium; the mass ratio is 4: The contributions from the two components have merged and the damping of the ion acoustic resonances is strong.

In the next series of measurements the influence of increased charge numbers Z_j on the ion spectrum was investigated. By lowering the density and increasing the current in an argon plasma, effective charge numbers $1 \leq \bar{Z} \leq 2$ were produced. Under these conditions the ions are colder than the electrons. The scattering angle was increased to $\theta = 175$ mrad, assuring the resolution in k and ω space required to resolve details in the narrow argon feature. As discussed by Sheffield[18] the amount of damping of the ion acoustic resonance is expected to decrease for $\bar{Z}T_e/T_i > 1$. With increasing values of $\bar{Z}$ or T_e/T_i the phase velocity of the ion acoustic wave increases and the resonance in the spectrum becomes more marked because the waves propagate further into the tail of the ion distribution function where the damping is reduced. Figures 2(a), 2(b), and 2(c) confirm the predicted increase of the ion acoustic peak in the spectra and give the corresponding values of T_e, T_i, and $\bar{Z}$.

Finally, if light hydrogen ions are added to the dominant argon plasma the argon peak quickly decreases due to Landau damping by the hydrogen ions, as shown in Figs. 3(a) and 3(b).

In conclusion, over a wide range of plasma parameters, the detailed shape of two-component ion spectra predicted from kinetic theory has been confirmed by CO_2-laser scattering. This diagnostic technique was used to determine the ion temperature, the ion composition, and the effective charge number. These results are relevant for future collective scattering diagnostics of fusion plasmas.

The stimulating discussions with H. Hailer, K. Hirsch, and H. Salzmann are gratefully acknowledged.

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