Observation of Microwave Scattering from Large-Amplitude Oscillations in an Alkali Plasma

M. IANNUZZI
Laboratorio Gas Ionizzati, EURATOM, Comitato Nazionale per l'Energia Nucleare, Frascati, Roma, Italy
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Microwave scattering has been observed from large-amplitude ion waves in a Cs plasma. The ion wave frequency was 24 kHz. The density fluctuations were 10% of the plasma density, which was approximately 4×10^9 cm^{-3}. An "average" cross section has been obtained for the observed scattering. The result is of the order of 10^{-14} cm^2. Such a large value of the cross section is due to the high level of excitation of the ion wave. In the present experiment nonlinear effects play an important role.

WE have observed microwave scattering from large-amplitude ion waves in a nearly fully ionized Cs plasma.

In the last years, several theoretical investigations[1] have been concerned with the study of plasma-wave instabilities in nonequilibrium plasmas within the validity of the linearized Vlasov equation governing the collective behavior of a fully ionized plasma. In particular, the behavior of ion waves in nonequilibrium plasmas whose electrons had a steady drift velocity with respect to the ions has been studied. It has been found that the energy associated with these ion waves should increase from its thermal value toward extremely large values when the plasma undergoes a transition from a stable to an unstable state. Therefore, near this transition, the cross section for the scattering of electromagnetic waves from the "relatively undamped" ion waves should exhibit a large increase.

Very recently these theoretical results have been confirmed in their essential features by an experiment of Arunasalam and Brown on helium and hydrogen arcs.[2] Stern and Tzoar have observed microwave scattering at the "plasma line" from controlled electron-plasma oscillations.[3]

The experiment we have performed concerns microwave scattering from large-amplitude ion waves, i.e., a situation in which nonlinear effects play an important role. For this reason, the present experiment is very different from that reported in Ref. (2) where nonlinear effects were negligible. For the same reason the experimental results cannot be explained in the light of the quasilinear theory for one-dimensional plasmas by Drummond and Pines and by other authors[4] or of the quasilinear theory for three-dimensional plasmas by Bernstein and Engelmann.[5] All such theories are essentially based on an initial-value treatment, in which the following two main assumptions are made: (a) the plasma is infinite; (b) in the rest frame of the particles, the growth rate γ_k of the instability in the k mode is much slower than the frequency ω_k of the

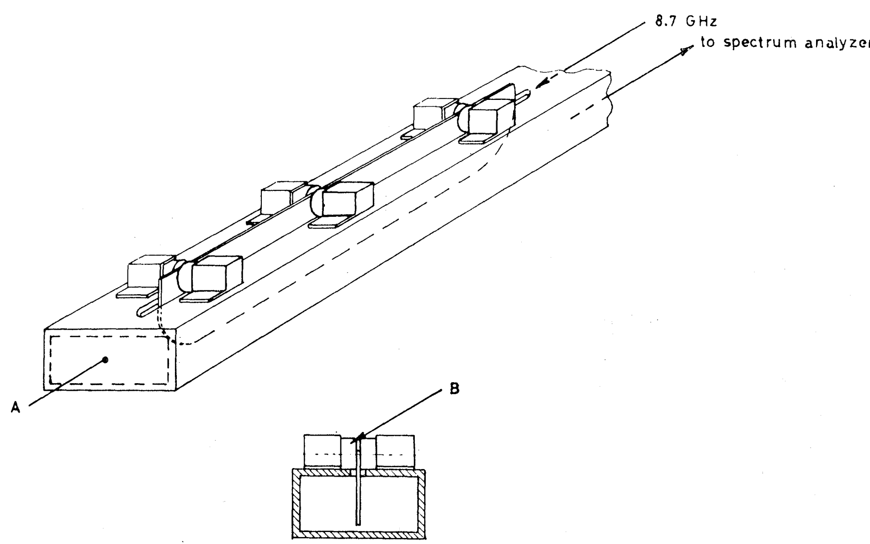

FIG. 1. The plasma container and slotted waveguide kept at 2100°K. A: the shorting tantalum wall. B: the zirconium oxide insulators. At room temperature, the cross section was 2.3×1.0 cm^2. The length was 10 cm.

[1] M. N. Rosenbluth and N. Rostoker, Phys. Fluids **5**, 776 (1962); S. Ichimaru, D. Pines, and N. Rostoker, Phys. Rev. Letters **8**, 231 (1962); S. Ichimaru, Ann. Phys. (N. Y.) **20**, 78 (1962). Other references can be found in these papers.
[2] V. Arunasalam and S. C. Brown, Phys. Rev. **140**, A471 (1965).
[3] R. A. Stern and N. Tzoar, Phys. Rev. Letters **15**, 485 (1965).
[4] W. E. Drummond and D. Pines, Ann. Phys. (N. Y.) **28**, 478 (1964); A. A. Vadenov, J. Nucl. Energy **5**, 169 (1963); E. Frieman and P. Rutherford, Ann. Phys. **28**, 134 (1964).
[5] I. B. Bernstein and F. Engelmann, Phys. Fluids (to be published).

unstable wave, or $\gamma_k/\omega_k \ll 1$. As we shall see, the conditions of our experiment cannot be described by an initial-value model satisfying the above assumptions.

In our experiment the Cs plasma was produced by thermal ionization in a tantalum container consisting of a 3-cm microwave slotted waveguide, kept at about 2100°K (Fig. 1). At one end the waveguide was shorted by a tantalum wall, and at the other end it was connected to a 3-cm microwave reflection spectrometer. A tantalum electrode was inserted in the slot and kept electrically insulated from the waveguide walls. The microwave signal reflected at the end of the slotted line could be observed on the screen of a 851-A Hewlett-Packard spectrum analyzer. The frequency ω_0 of the microwave radiation was 8.7 GHz, about 14 times higher than the electron plasma frequency $\omega_p \simeq 0.6$ GHz, corresponding to a plasma density $n_0 \simeq 4\times10^9$ cm^{-3}. Therefore the plasma was transparent to the radiation.

By applying a dc voltage between the inner electrode and the waveguide walls, the distribution of electrons and ions could be changed from the Maxwellian corresponding to equilibrium conditions to a distribution exhibiting a small bump in the tail due to ion streaming.[6,7] This mechanism is responsible for the production of standing ion waves within the plasma. These waves attain a large amplitude which is limited only by nonlinear effects. Their frequency is given by

$$f = (1/4d)(2eV_0/m_i)^{1/2}, \qquad (1)$$

where d is the spacing between the electrodes, V_0 the applied voltage, m_i the ion mass.

A detailed account of this mechanism is given in Ref. (6).

In the present experiment an ion-wave frequency of about 24 kHz was excited when applying a dc voltage of 1–5 V between the inner electrode and the waveguide walls. The amplitude of the oscillating current (i.e. of the ion wave) reached the maximum value of about 10% of the dc current flowing to the plasma for voltages above 1.5 V.

A microwave signal of about 2 mW power was beamed at the plasma, and the signal reflected by the wall A (Fig. 1) shorting the waveguide was observed on the screen of the spectrum analyzer. The scattering of the microwave signal resulted in the appearance of two side-bands corresponding to the frequencies $f_s = f_{\text{inc}} \pm f_w$, where f_w is the frequency of the ion oscillations.

Figure 2 shows a typical experimental result. Here $f_{\text{inc}} = 8.7$ GHz and the ion-wave frequency was 24 kHz. The signal observed when no oscillations were excited in the plasma (i.e., no dc voltage was applied between the electrodes) is also shown for comparison.

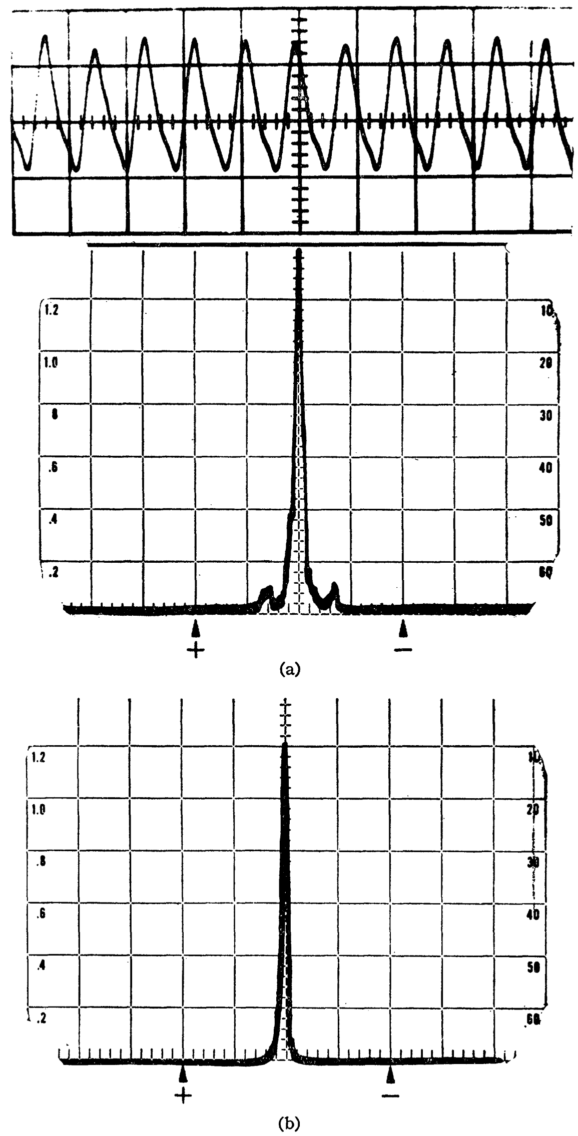

FIG. 2. The scattered signals and current oscillations. (a) *Upper trace:* The current oscillations measured by means of a current probe. Writing time: 20 μsec/cm. Sensitivity: 5 mA/cm. *Lower trace:* The microwave signals on the screen of the spectrum analyzer. The central signal is the 8.7 GHz incident signal reflected by the end of the plasma container. The side bands of this signal show the scattering at the frequencies $f_s = f_{\text{inc}} \pm f_w$. The vertical display is proportional to the voltage on the crystal detector. The frequency resolution is 30 kHz/cm. (b) A photograph of the 8.7 GHz signal reflected by the end of the plasma container when no dc voltage was applied between the electrodes (i.e., with no ion oscillations).

An estimate of an "average" cross section $\sigma(\omega)$ of microwave scattering can be obtained from the relationship

$$P_s(\omega)\Delta\omega = n_0\sigma(\omega)\left(\frac{P_{\text{inc}}(\omega)\Delta\omega}{\text{area of incidence}}\right) \times (\text{volume of scatterer}), \qquad (2)$$

[6] L. Enriques, G. B. Righetti, F. Magistrelli, and A. Boschi, Nuovo Cimento 38, 26 (1965).

[7] M. Iannuzzi and G. B. Righetti, Nuovo Cimento 38, 1931 (1965).

where P_s is the scattered power, P_{inc} the incident power, and n_0 the plasma density. The σ thus calculated is in the order of 10^{-14} cm^2, i.e., about 10^9 times larger than $\sigma_0 \simeq 6.7\times10^{-24}$ cm^2, the Thomson cross section. As is known, the latter is an upper limit for the cross section of electromagnetic scattering from an equilibrium plasma.

This large value of σ of course results from the presence of a strong driving term (the dc voltage between the electrodes) which continuously replenishes the bump in the ion distribution function, and thus produces a high level of the excitation in the unstable modes.

In addition, it may be observed that the geometry of the setup favors the detection of strong scattered signals, because the optical ray-path corresponds to the whole length of the plasma.

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Structure and Resistivity of Liquid Metals*

N. W. Ashcroft
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York

AND

J. Lekner
Department of Physics and the Institute for the Study of Metals, University of Chicago, Chicago, Illinois

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Ion-ion repulsion in a liquid metal is regarded as the principal factor determining the ionic arrangement. This interaction is idealized in a hard-sphere model; the known solution of the Percus-Yevick equation for this model gives a simple closed form for $a(K)$ (the liquid structure factor) which depends only on the effective packing density of the fluid. This fact enables us to make an estimate for the resistivities of most liquid metals for which model potentials are available. Agreement with experiment is generally good, particularly when the potential is known to be accurate. The sensitivity of the resistivity to the depth of the model potential well is indicated.

I. INTRODUCTION

RECENTLY, considerable interest has focused on liquid metals as a possible source of information on the interactions within their solid counterparts. Crystalline metals have obvious simplicity of structure, with considerable simplification yielded in some problems by the use of group theory. Yet the same structural simplicity often gives rise to severe problems in deducing the ion-electron interactions within a solid. One has only to reflect on the consequences of umklapp contributions to scattering processes to realize that inverting, say, the electrical resistivity to give the electron-photon interaction or the effective electron-ion potential is a formidable problem.

At first sight the irregular arrangement of ions in the liquid would seem to increase these difficulties. This is not so, however, since the liquid structure factor $a(K)$, which is needed in the determination of transport properties, is directly observed in x-ray and neutron-diffraction experiments. If $a(K)$ is known, some properties of the condensed state may be elucidated. For example, Ziman,[1] and Bradley *et al.*[2] deduced an average band gap for some metals from a knowledge of the resistivities in the molten state. The Ziman theory of transport properties for liquid metals is remarkably successful when both the interference function and the electron-ion interaction are known in some detail. The success of the theory appears to rest on two facts. First, *all* structural effects are separated into the interference function, which is taken from experiment.[3] Second, the Born approximation on which the theory is based is accurate if calculations are carried out consistently with free-electron-like pseudo wave functions. These wave functions are plane waves orthogonalized to the core states, and satisfy a wave equation where the effective ion-electron potential is small enough to be considered a perturbation. Since the matrix element $V(K)$ is further reduced by the factor $[a(K)]^{1/2}$ in the evaluation of the momentum-transfer integral (see below), the scattering

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[1] J. M. Ziman, Phil. Mag. **6**, 1013 (1961).
[2] C. C. Bradley, T. E. Faber, E. G. Wilson, and J. M. Ziman, Phil. Mag. **7**, 865 (1962).
[3] It has been pointed out by G. Baym [Phys. Rev. **135**, A1691 (1964)] that a similar approach to transport properties can be used in a solid. At present the structure factors for solid metals are not sufficiently well determined.