the $(32-36)\times10^3$-cm^{-1} region. Thus, the data given above strongly support the existence of excitons in the molecular liquids.

Current efforts are directed toward obtaining the reflection spectra of the anthracene melt and studying the effect of guest molecules on the spectrum of a molecular liquid.

Support by a Texaco summer fellowship is gratefully acknowledged by L.F.N.

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[1] A. S. Davydov, *Theory of Molecular Excitons* (Plenum, New York, 1971).

[2a] S. A. Rice and J. Jortner, J. Chem. Phys. 44, 4470 (1966).

[2b] G. Nicolis and S. A. Rice, J. Chem. Phys. 46, 4445 (1967).

[2c] S. A. Rice, G. Nicolis, and J. Jortner, J. Chem. Phys. 48, 2484 (1968).

[2d] S. Fischer and S. A. Rice, Phys. Rev. 176, 409 (1968).

[3] D. Beaglehole, Phys. Rev. Lett. 15, 551 (1965).

[4] C. J. Eckhardt and R. R. Pennelly, Chem. Phys. Lett. 9, 572 (1971).

[5] L. B. Clark, J. Chem. Phys. 51, 5719 (1969).

[6] W. Liptay, Z. Naturforsch. 20a, 1441 (1965).

[7] E. G. McRae, J. Phys. Chem. 61, 562 (1957).

[8] P. R. Monson and W. M. McClain, J. Chem. Phys. 56, 4817 (1972).

Simultaneous Ion Heating of He^+ and Ar^+ in Linear Turbulent-Heating Experiments

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(Received 22 June 1972)

Turbulent-heating experiments have been carried out in a linear machine with a driving gas of helium mixed with 7% argon in order to see the mass dependence of ion heating. Observation of optical line broadening of the ions showed that both kinds of ions were heated almost simultaneously by almost the same amount during the process. Several mechanisms for ion heating are examined on the basis of the experimental results obtained.

Many experiments on turbulent heating of plasmas have been carried out during the past ten years,[1] resulting in some cases in the heating of ions in the plasma up to a few keV. It has been thought that the mechanism of electron heating is probably an anomalous Ohmic process[2] of electrons accelerating under the applied electric field. The mechanism of ion heating, however, has not been clear so far. It cannot be explained by the anomalous Ohmic process. This is because, in a coordinate system moving with the ion drift velocity, the excited ion acoustic waves have a phase velocity nearly equal to the sound velocity c_s, which is much larger than the ion thermal velocity; so there exist few particles interacting strongly with the ion acoustic waves if a Maxwellian velocity distribution of ions is assumed.

It should be expected, then, that the ion heating is due to some process associated with turbulent heating,[3] or some other process such as nonlinear Landau damping in which the ion acoustic waves are absorbed by ions. Since the virtual waves are absorbed by the resonant particles, test particles should not be heated as much as the field particles provided the atomic mass of the former is much larger than that of the latter. In this scheme, therefore, the heating rate and the resulting temperature should have an ion-mass dependence when more than two species of ions exist in a plasma and suffer turbulent heating simultaneously.

We have carried out turbulent-heating experiments in a linear magnetic field with a driving gas of helium (93%) mixed with argon (7%), the argon ions playing the role of test particles. The BSG II machine[4] has been used for the experiment

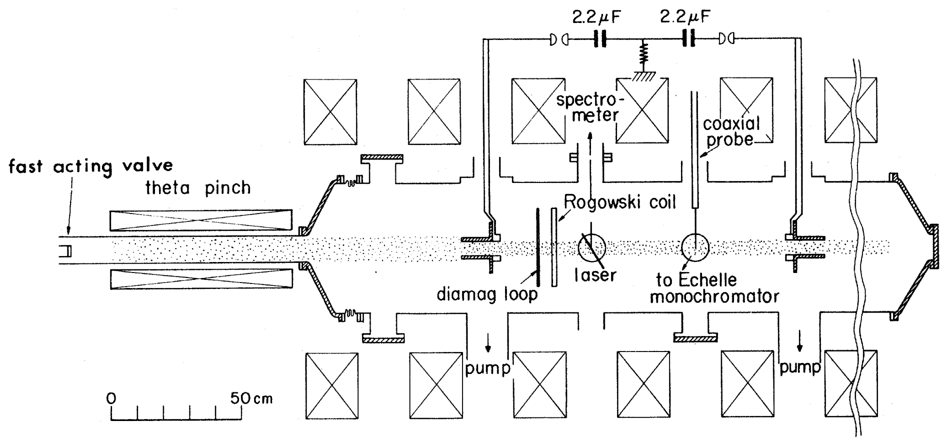

FIG. 1. Schematic drawings of the BSG II.

(Fig. 1). A plasma is produced by a θ pinch discharge, the gas being introduced through a fast-acting valve, and the plasma expands into a chamber 50 cm in diameter and 4 m in length, where a longitudinal and uniform magnetic field of 2 kG is applied. A pair of hollow electrodes for heating are set coaxial to the axis of the chamber at a distance of 120 cm, and their apertures (6 cm in diameter) limit the diameter of the plasma before heating. The plasma density and temperature between the pair of electrodes are rather uniform along the axis and have values of about 3×10^{13} cm^{-3} and 2 eV, respectively, when the heating voltage is applied between the pair. The density and temperature before heating are derived from data from diamagnetic loops, a pulse-biased Langmuir probe, and laser light scattering.

The power of heating discharge is supplied from a capacitor of 1.1 μF with a charging voltage of up to 60 kV. An Echelle monochromator with twelve channels of photoelectric detectors[6] is used to obtain the temporal change of the ion line profiles. Although only one ion line can be measured in any one shot, both the argon and helium ion lines have been obtained by repeating the shots under the same experimental conditions. The line profiles are measured along several chords in a cross section of the plasma column. The space resolution along the line of sight is about 6 mm. A coaxial probe is also provided to pick up electrostatic fluctuations in the plasma.[7]

In Fig. 2, typical wave forms are shown for the time variation of the heating current through the plasma, I_H, the voltage between the electrodes, V_H, and the intensity of the He II 4686-Å line, where the charging voltage is 36 kV. It must be noted that the traces of the time evolution of V_H and I_H show a "resistive hump" about 3 μsec after the current starts to flow and that, corresponding to the resistive hump, an intense He II line pulse is observed for about 1 μsec. Ar II 4348- and 4610-Å lines are observed to show a time variation similar to that of the He II line. Temporal variation of the profiles of the lines of both He II and Ar II are analyzed every 0.1 μsec after the current starts. In Fig. 3 we show typical line profiles for the He II and Ar II lines at the time they take the widest broadening. The measurements are carried out on the line of sight through the center of a cross section of the plasma at a distance of 40 cm from the anode. If we assume those broadenings are due to the Doppler effect, both helium and argon ions have almost the same temperature of about 20 eV. It is observed that there exists little asymmetry in the radial distribution of the line profiles with respect to the

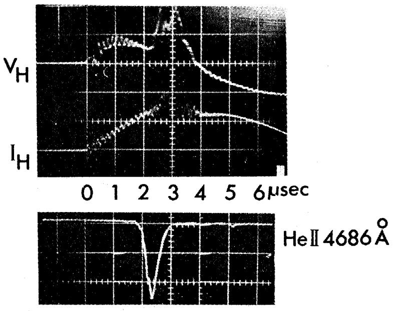

FIG. 2. Typical oscillograms of the heating voltage, V_H and current I_H. A typical temporal behavior of the intensity of He II 4686-Å line is also shown on the same axis, the origin of which corresponds to the time when the heating current starts to flow.

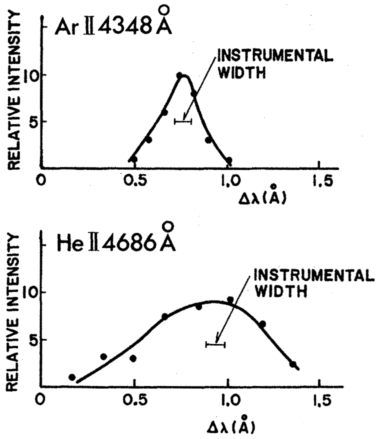

FIG. 3. Measured profiles of the Ar II 4348-Å and He II 4686-Å lines. The 0 point on the axis of abscissas does not mean the line center of the lines, which could not be determined accurately because of the Doppler shift.

axis of the plasma column, and the ion temperature is rather uniform within a radius of 1.5 cm.

A question arises whether this broadening of ion lines is due to the Doppler effect. It is obvious that the Zeeman effect (corresponding to a few kilogauss) is negligible, and that the Stark effect due to the microfield produced by plasma particles is also small since the plasma density is not high enough ($n \leq 10^{14}$ cm^{-3}). In a turbulently heated plasma, however, there may be large electric fields due to collective fluctuations, the effect of which must be taken into account for the Stark broadening. If we assume that the total half-width of the He II line in Fig. 3 ($\Delta\lambda \sim 0.74$ Å) is attributed only to the Stark broadening due to the fluctuation field, then the averaged electric field of plasma waves should be about 18 kV/cm.[8] The effect of this amount of field on the Ar II line broadening is evaluated to be less than 4%,[9] which means that the temperature, or more strictly the averaged kinetic energy of random motion of the argon ions, surely reached 20 eV.

The two profiles shown in Fig. 3 are taken in different shots under the same experimental conditions. There exist some shot-by-shot deviations in the observed line profiles of He II and Ar II, so the statistical data analysis has been made strictly.[10] As a result, we can conclude that the null hypothesis, "the net energy input per argon ion is always much smaller than that per helium ion in our turbulent-heating experiment with a mixed gas," is *denied* experimentally.

On the basis of this experimental result, critical discussions are given below concerning the mechanism for the ion heating.

In this experiment the ion acoustic instability is considered to be excited, as pointed out by many authors.[1] Actually, fluctuation measurements in the frequency range up to 1 GHz show a broad frequency spectrum covering the ion plasma frequency, and the estimate of the electron and ion temperatures and of the electron drift velocity supports this excitation. The dispersion relation of ion acoustic waves in the helium plasma does not change on including 7% argon as test particles.[11] The fluctuation measurements for both plasmas have also shown little difference in intensities, in frequency spectrum, or in the onset time of fluctuations.

Suppose that the fluctuation is due to the ion acoustic instability and is responsible for the heating of ions; then nonlinear Landau damping of ion acoustic waves by helium and argon ions should be taken into consideration as the first case. Under the present experimental condition, where both ions are initially in equilibrium, the thermal velocity of argon ions is 3.3 times smaller than that of helium ions. The time variation of the total energy of ion acoustic waves, which is absorbed by an ion component as a result of nonlinear Landau damping, is expressed[12] as

$$\frac{\partial W}{\partial t}=\frac{{\omega_i}^4}{8\pi m_i}\frac{n_i}{{n_e}^2}\int d^3v\, d^3k\, d^3k'\,\frac{|\vec{E}_{\vec{k}}|^2}{{\omega_{\vec{k}}}^3}\,\frac{|\vec{E}_{\vec{k}'}|^2}{{\omega_{\vec{k}'}}^3}\,(\vec{k}\cdot\vec{v})^2\left(\frac{\vec{k}\cdot\vec{k}'}{kk'}\right)^2(\vec{k}-\vec{k}')\cdot\frac{\partial f(\vec{v})}{\partial\vec{v}}\,\delta(\omega_{\vec{k}}-\omega_{\vec{k}'}-(\vec{k}-\vec{k}')\cdot\vec{v}),$$

where $\omega_k = kc_s(1+k^2{\lambda^2}_{De})^{1/2}$ is the frequency of the ion acoustic wave. The other symbols have their usual meaning. If $f(\vec{v})$ and $|\vec{E}_{\vec{k}}|^2$ are isotropic, computation of the above expression shows the energy transfer rate from ion acoustic waves to an ion component to have an approximately inverse-power mass dependence. The second case to be considered is some stochastic mechanism[13] in the turbulent plasma, which also gives an ion heating rate inversely proportional to the ion mass. The third case is the heating of ions due to a breaking of the particle trapping by the large-amplitude ion acoustic waves, showing a large mass dependence according to computer simulation.[14] It is not possible that the mass dependences of the mechanisms discussed above, which are inversely linear or steeper, are erased by Coulomb collisions between the helium and argon ions in our experiment. Comparing these estimates with the present experimental result, which shows rather a mass-independent ion heating, we consider it probable that both argon and helium ions are heated simultaneously by some mechanisms other than mass-dependent ones, such as are considered above. We are tempted to propose that the ion heating in the turbulent-heating experiment is accomplished by a macroscopic instability[15] which reveals itself in the "resistive hump."

The authors wish to acknowledge fruitful discussions with Professor K. Nishikawa, Dr. J. M. Dawson, Dr. R. Sugihara, and Dr. T. Kawamura. They also thank Professor K. Takayama and Professor H. Takeyama for their encouragement throughout this research.

This work was carried out under the cooperative research program at the Institute of Plasma Physics of Nagoya University.

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[1] M. V. Babykin *et al.*, Zh. Eksp. Teor. Fiz. 43, 411 (1963) [Sov. Phys. JETP 16, 295 (1963)]; S. M. Hamberger *et al.*, Phys. Rev. Lett. 19, 350 (1967); Y. Matsukawa, Y. Nakagawa, and K. Watanabe, J. Phys. Soc. Jap. 24, 196 (1968); T. H. Jensen and F. R. Scott, Phys. Fluids 11, 1809 (1968); T. Kawabe, J. Iannucci, and H. P. Eubank, Phys. Rev. Lett. 25, 642 (1970); S. Q. Mah, H. M. Skarsgard, and A. R. Strilchuk, Phys. Rev. Lett. 25, 16 (1970); C. Wharton *et al.*, in *Proceedings of the Fourth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Madison, Wisconsin, 1971,* Special Supplement (International Atomic Energy Agency, Vienna, 1972).

[2] L. I. Rudakov and L. V. Korablev, Zh. Eksp. Teor. Fiz. 50, 220 (1966) [Sov. Phys. JETP 23, 145 (1966)].

[3] B. B. Kadomtsev, *Plasma Turbulence* (Academic, London, 1965); E. K. Zavoiski and L. I. Rudakov, At. Energy. 23, 417 (1967).

[4] T. Uchida *et al.*, Nucl. Fusion 9, 259 (1969).

[5] K. Adati *et al.*, to be published.

[6] K. Miyamoto *et al.*, J. Appl. Phys. 5, 970 (1966).

[7] T. Uyama *et al.*, Annual Review of the Institute of Plasma Physics, Nagoya University, April 1970–March 1971 (unpublished), p. 76.

[8] H. R. Griem and H. J. Kunze, Phys. Rev. Lett. 23, 1279 (1969).

[9] H. R. Griem, *Plasma Spectroscopy* (McGraw-Hill, New York, 1964).

[10] For example, R. A. Fisher, *Statistical Method for Research Workers* (Oliver and Boyd, London, 1959).

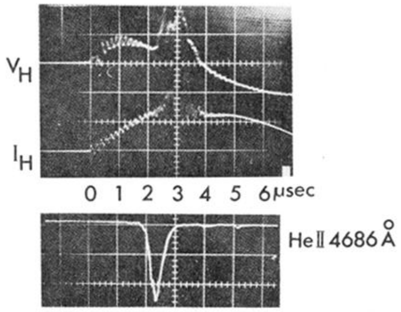
[11] B. D. Fried, R. B. White, and T. K. Samec, University of California, Los Angeles, Plasma Physics Group Report No. R-86, 1971 (unpublished).

[12] V. N. Tsytovich, *Nonlinear Effect in Plasma* (Plenum, New York, 1970).

[13] P. A. Sturrock, Phys. Rev. 141, 186 (1966).

[14] J. M. Dawson, private communication.

[15] K. Adati *et al.*, to be published.



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