SEPTEMBER 1974

MATT-I070

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Impurity Transport in FM-1

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ABSTRACT

The confinement of $Z = 2$ barium test ions in a $Z = 1$ plasma was found to be strongly dependent on density and background plasma ion mass. Most of the characteristics of the parametric dependence of the barium confinement could be related to the superposition of an anomalous outward and a classical inward diffusion.

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The effects of high mass, high-Z impurities on plasma heating, confinement and energy transport have recently received a great deal of attention.^{1,2} Theoretical investigation has focused on the classical and neoclassical transport of the impurity ions.³ The objective of this experiment was to observe the effects of the classical inward transport of a test ion of mass and charge greater than that of the background plasma. A second objective of equal importance was to determine to what extent the phenomena which govern the anomalous outward transport of the background plasma play a role in the impurity diffusion.

The mechanisms which produce an outward diffusion of the background plasma were found to contribute a similar but not necessarily equal component to the diffusion of the test ions. It was found that the classical inward diffusion was superposed on the anomalous outward diffusion and could become important particularly at higher plasma densities. Because of the dependence of the classical inward diffusion coefficient on the background plasma density this variable was used to control the magnitude of the classical diffusion.

Barium was chosen as a test ion for these experiment for the following reasons. (1) Barium is not one of the natural impurities present in the discharge. (2) It is relatively simple to introduce barium into the plasma. (3) Barium neutrals remaining after initial injection adhere to the walls and are eliminated. (4) The high rate coefficient for double ionization at low electron temperatures allows the study of a $Z = 2$ ion in a $Z = 1$ plasma. (5) Barium is detectable spectroscopically.

The rate equations for the two charged states of barium are as follows:

$$\frac{dn_{III}}{dt} = - n_{III} \alpha_R n_e + n_{II} \langle \sigma v_e \rangle_{\text{ionization}} n_e - \frac{n_{III}}{\tau_{III}} \quad (1)$$

$$\frac{dn_{II}}{dt} = n_{III} \alpha_R n_e - n_{II} \langle \sigma v_e \rangle_{\text{ionization}} n_e - \frac{n_{II}}{\tau_{II}} \quad (2)$$

where α_R is the recombination rate coefficient for Ba_{III} , $\langle \sigma v_e \rangle$ the ionization rate coefficient for Ba_{II} and τ_{II} and τ_{III} the barium confinement times for the two charge status. In writing these rate equations: The following processes have been assumed to be negligible (a) recombination of Ba_{II} , (b) ionization of Ba_{III} , and (c) ionization of Ba_I .

For the experiments described here the time constants have the following ordering:

$$1/\tau_{II} \ll \langle \sigma v_e \rangle n_e, \quad \alpha_R n_e \ll 1/\tau_{III},$$

permitting a double time scale solution with

$$n_{II} = n_{III} \frac{\alpha_R}{\langle \sigma v_e \rangle} \quad (3)$$

$$\frac{dn_{III}}{dt} = - \frac{n_{III}}{\tau_{III}} \quad (4)$$

on the slower time scale. If the temperature and density of the background plasma are held constant the rate coefficients will be independent of time and

$$\frac{dn_{II}}{dt} = \frac{\alpha_R}{\langle \sigma v \rangle_e} \frac{dn_{III}}{dt} \quad (5)$$

$$\frac{1}{\tau_{III}} \equiv \frac{1}{n_{III}} \frac{dn_{III}}{dt} = \frac{1}{n_{II}} \frac{dn_{II}}{dt} = \frac{1}{\tau_{II}} \equiv \frac{1}{\tau_{Ba}} \quad (6)$$

The light emitted by Ba_{III} is very small; however, the strong resonance lines for Ba_{II} are in the visible spectrum, of which the 4554A resonance line was used to determine n_{II} and τ_{Ba}. The approximate amount of Ba_{III} could be inferred using Eq. (3). It should be emphasized that the success of these measurements depends strongly on producing a discharge with a constant electron temperature.

The experiments described here were conducted for magnetic field and plasma conditions typical of earlier FM-1 experiments.⁴ A high shear spherator magnetic field configuration was employed with steady state electron cyclotron resonance heating (ECRH) at 5.6 GHz used to produce the discharge. The annular ECRH resonance zone was situated near the center of the confinement region to produce a discharge with density and temperature profiles close to the longest-lived mode and long particle confinement times. This steady state microwave discharge satisfied the conditions for constant electron temperature and density. Typical experimental parameters where: n_e ~ 10¹¹ cm⁻³, T_e ~ 5 eV, T_i ~ T_e/2.

Barium neutrals were injected into this plasma from an external source, comprised of a small barium block and a tungsten filament. A pulsed discharge between the filament and the barium

seeded the plasma with a sufficient number of barium neutrals. The neutral evaporation ceased at the termination of the filament pulse. The mean free path of the barium through the plasma was larger than the plasma thickness so that the initial barium distribution was likely peaked near the plasma density maximum. The fraction of barium ions was kept below 0.1%.

Barium neutrals were injected into steady state discharges of various plasma ions. After the initial transient the rate of decay of the 4554 light was interpreted as that of the barium. These results are plotted in Fig. 1 with plasma density as a parameter which was chosen because of the linear dependence of the inward classical diffusion coefficient on the density. The plasma density was varied by changing the microwave heating power. Other plasma parameters such as electron temperature were relatively independent of microwave power. However, there was a slight change in the resonant heating region at high density since the position of the upper hybrid layer is weakly dependent on the plasma density under these experimental conditions. The shifting of the resonance surface toward the plasma boundary resulted in a reduction in the overall plasma confinement time at higher densities, presumably because of the steeper gradient.

At low electron density the barium confinement time was comparable to that of the background plasma as determined from external loss measurements. As the electron density was increased the barium confinement time began to improve. For argon plasmas an increase in barium confinement of well over an order of magnitude was observed. A peak in barium confinement time was observed

for most background plasma atomic masses and confinement decreased monotonically for larger densities within the limits of the experiments.

The dependence of barium confinement time on electron density differed for plasma ions of different atomic masses. The electron density at which the barium confinement time began to increase times the low density confinement time was an inverse function of the plasma ion mass. This functional dependence was somewhat weaker than linear but not inconsistent with the square root of the ion atomic mass.

The effects on the barium confinement of varying the background plasma confinement time was determined by changing the magnetic field shear length, which was increased by reducing the toroidal magnetic field. This reduction in shear resulted in a decrease in the plasma confinement. The results of these measurements in an argon plasma are also plotted in Fig. 1. The overall behavior of the barium confinement is similar for the low and high shear cases; however, the low density barium confinement time is reduced and the density at which the barium confinement begins to improve is increased. The maximum barium confinement realizable at the maximum plasma density is considerably smaller for the low shear case.

Several mechanisms likely play a part in the barium transport. Whatever mechanisms (turbulence, field errors, etc.) determine the anomalous transport of the background plasma likely give a similar but not necessarily identical outward diffusion of the barium.

Classical collisions between the $Z = 2$ barium and the $Z = 1$ background plasma should give an inward component to the barium diffusion coefficient. This classical diffusion should be particularly important because its magnitude exceeds normal classical diffusion by more than the square root of the background plasma ion to electron mass ratio, since it is driven by unlike ion-ion collisions.

At low density the classical transport should be unimportant and the anomalous diffusion rate can be determined. The experimentally determined low density confinement time of the barium is similar to that of the background plasma. This measurement indicates that the anomalous coupling between electrons and ions which gives rise to their diffusion is relatively mass independent.

To determine the confinement time to be expected if the classical "inward" diffusion is superposed on the anomalous outward diffusion the diffusion equation was solved numerically for a plane slab geometry. This diffusion equation can be written as follows:

$$\frac{\partial n_b}{\partial t} + \frac{\partial}{\partial x} \left[\frac{\alpha n_b}{Z_p} \frac{\partial n_p}{\partial x} - \left(\frac{\alpha n_p}{Z_b} + D_a \right) \frac{\partial n_b}{\partial x} \right] = 0$$

where n_b and n_p are the barium and background plasma densities respectively, D_a is the anomalous diffusion coefficient, Z_b and Z_p are the barium and background plasma charges. α represents the classical effect:

$$\alpha = \frac{\nu Z_b T}{n_p m_b \Omega_b^2}$$

where ν is the barium-plasma ion collision frequency, T the ion temperature, m_b the barium mass, and Ω_b the barium cyclotron frequency.

The result of solving the diffusion equation numerically for a parabolic profile is shown for helium and argon as dashed curves in Fig. 1. The barium confinement time was determined as a function of peak plasma density. The solution was carried out for an anomalous diffusion coefficient corresponding roughly to an FM-1 confinement time of 0.16 sec. The functional dependence of the confinement time on plasma density is approximated quite well by $\tau \sim \tau_0 (1 + n_e/n_0)$. It should be pointed out that the computations were made for a plane slab geometry with constant temperature. There comparison with experimental results in the complicated FM-1 field geometry with spacially varying temperature should be undertaken with some caution.

Several aspects of the experimental results can be compared to the computational results.

A. The density at which the confinement time shows a significant increase multiplied by the low density confinement time should scale inversely with square root of the plasma ion mass. The experimental results are in reasonable agreement with this scaling.

B. The increase of confinement time should approach a linear density dependence. The experimental results indicate an increase in confinement time which occurs at somewhat higher density than would be expected theoretically but then increases with a slope which is steeper than linear.

C. The theory predicts no saturation or decrease in confinement time with increasing density. The experiments show that the confinement time of the barium in argon and xenon peaks and then decreases with increasing density.

There are several possible explanations for the decrease in confinement time with increasing density such as multiple charge exchange of the barium with the background plasma ions. However, the most likely cause of the reduction in confinement is the outward shift in the resonant zone at higher density. Loss measurements show a n_e^{-1} dependence of the plasma confinement time after an initial low density plateau. This density dependence of the anomalous loss would result in the experimentally observed decrease in barium confinement time at higher densities.

The authors would like to acknowledge the valuable discussions with Drs. D. M. Meade, M. Okabayashi, and S. Yoshikawa.

This work was supported by U. S. Atomic Energy Commission Contract AT(11-1)-3073.

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Fig. 1. The observed barium decay times (solid curves) are shown as a function of background plasma peak density for various gases in the FM-1 high shear magnetic field configuration. Also shown is the barium confinement in argon with low shear. The dashed curves are the numerically determined confinement times for a comparable slab geometry using the diffusion coefficients described in the text.

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