EFFECT ON DEUTERON TEMPERATURE ON IRON FORBIDDEN LINE INTENSITIES IN RF-HEATED TOKAMAK PLASMAS

K. Sato, S. Suckewer, A. Wouters

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K. SATO[(1)], S. SUCKEWER and A. WOUTERS

Princeton University, Plasma Physics Laboratory, Princeton, NJ 08544, U.S.A.

Abstract

Two line ratios, the forbidden line at 845.5 Å to the allowed line at 135.7 Å in Fe XXII and the forbidden line at 592.1 Å to the forbidden line at 1118.2 Å in Fe XIX, have been measured as ion temperature-sensitive line ratios during rf heating in the Princeton Large Torus. The results indicate that deuteron collisions in plasmas of high deuteron temperature have a noticeable effect on the intensity of the forbidden lines. Measured relative intensities are compared with values from level population calculations which include deuteron collisional excitation between the levels of the ground configuration. The agreement between the observed and calculated ratios is within 30%. A method for deuteron (or proton) temperature measurement in tokamak plasmas is discussed.[1] More details about this experiment can be found in Ref. 2.

I. INTRODUCTION

A number of forbidden lines arising from magnetic dipole transitions of highly ionized ions have been identified in tokamak discharges and intensity measurements of these lines have been used extensively in tokamak diagnostics. For theoretical purposes, Bhatia, Feldman, and others have calculated level populations in the ground state configuration for the major metallic constituents of a tokamak (iron, nickel, chromium, titanium, and other elements).[3] Feldman and Doschek proposed the method of using ratios of highly ionized lines from optically allowed and forbidden transitions for electron density measurements.[4]

We discuss the effect of heavy particle (proton and deuteron) collisions on the intensity of forbidden lines of highly ionized ions. Except for the excitation of plasma impurity ions by charge-exchange recombination with energetic neutral beam hydrogen, inelastic collisions between heavy particles are not generally considered to be significant excitation processes in plasma because of the relatively low velocity of the impacting particle, but this process may become significant for excitation from high temperature ions between the closely spaced levels of the ground state configurations. This effect can be applied for ion temperature measurements in tokamak plasmas from intensity ratios of forbidden to allowed[1] or forbidden to forbidden lines.

The importance of proton collision on the state populations for the $2s^22p^k$ configurations was discussed by Feldman *et al.*[3,4] and there exist quantitative measurements of forbidden and resonance line intensities on PLT. For instance, relative intensities $2s^22p^k$-$2s2p^{k+1}$ transitions in metallic ions gives indications[5] that for the C I-like ions, calculations which include proton- collisional excitation and deexcitation between the levels of the ground configuration are in better agreement with the measurements than calculations that do not include the influence of proton collisions. In ohmic-heated discharges with moderate electron densities (below 10^{14} cm^{-3}), the ion temperature is roughly half the 1-2 keV electron temperature. In this case, proton collision excitation has a small effect on the populating mechanism compared with the cascading processes from $2s2p^{k+1}$ levels. However, proton excitation might become quite significant during additional heating and the intensity ratio of a forbidden line to an allowed line of Fe XVIII was measured during rf heating on the JIPP T-II-U tokamak. The results at an electron density of 2×10^{13} cm^{-3} indicated that proton collisions had a noticeable effect on the intensity of the forbidden line at the time of heating

In this paper, we present the measurement of forbidden line intensities during the ion-cyclotron-range-of-frequency (ICRF) heating in the PLT deuterium discharges for the three lines: Fe XXII 845.5 ± 0.1 Å ($2s^22p\ ^2P_{1/2}$ - $^2P_{3/2}$),
Fe XIX 1118.2 ± 0.1 Å ($2s^22p^4\ ^3P_2$ - $^3P_1$) and,
592.1 ± 0.1 Å ($2s^22p^4\ ^3P_2$ - $^1D_2$).

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(1) Permanent address : Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan

In the intensity ratio of the forbidden to allowed line, only the forbidden transition is sensitive to deuteron temperature. The ratio is thus expected to be deuteron temperature dependent. Also, in the case of the ratio of the forbidden to forbidden line, the ratio might depend on the deuteron temperature because of a different dependence of the excitation rate of each transition on deuteron energy.

II. CALCULATIONS OF LEVEL POPULATIONS AND INTENSITY RATIOS WITH EMPHASIS ON HEAVY PARTICLE IMPACT EXCITATION

In this section we present calculations of the effect of heavy particle collisions on the populations of the transitions leading to the emission of Fe XXII lines at 845 Å and 135 Å, Fe XIX lines at 592 Å and 1118 Å, and the expected intensity ratios of these lines. Because of the short relaxation time of excited levels relative to ground level (also relative to the tokamak's plasma time evolution), excited level populations in the level n may be described by quasi-steady-state and we consider the case when the excited level populations are given by the set of stady-state rate equations in the form:

$$dN_n/dt = 0 = -N_n \{\Sigma_{n\neq m} \quad (A_{nm} + N_e S_{nm} + N_h S^h{}_{nm})$$
$$+\Sigma_{n\neq m} \quad N_m(A_{mn} + N_e S_{mn} + N_h S^h{}_{mn}),$$
$$[\, n \neq 1 \ (\, n = 1 \text{ corresponds to ground level}).]$$

Here, A_{nm} is the spontaneous transition probability from level n to m ($A_{nm} = 0$ when m ≥n), S_{mn} is the electron-impact excitation (or deexcitation if m > n) rate coefficient, N_h is the density of a heavy particle ion (proton or deuteron), and the superscript h indicates a heavy particle collision.

The state populations for the $2s^2 2p^k$ configurations depend on the balance of the radiative decay rate, the cascading processes from the $2s2p^{k+1}$ levels, the collisional rates of electrons, and especially the collisional rates of protons and deuterons. The excitation energies among the ground state configulations are so small that electron excitation rates are only weakly electron temperature dependent. However, proton and deuteron excitation rates for ground state configulations indicate strong dependence on their temperature. In Fig. 1 there are several representative electron collisional excitation rate coefficients and one for deuteron for the $\Delta n = 0$ levels from the ground level of Fe XXII. The results of the calculation of intensity ratios of the Fe XIX forbidden line at 592 Å to the forbidden line at 1118 Å and of the Fe XXII forbidden line at 845 Å to the allowed line at 135 Å are shown in Fig. 2a and 2b as a function of the temperature and density.

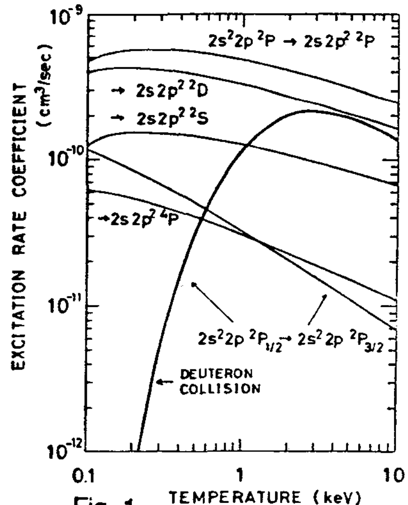

Fig. 1

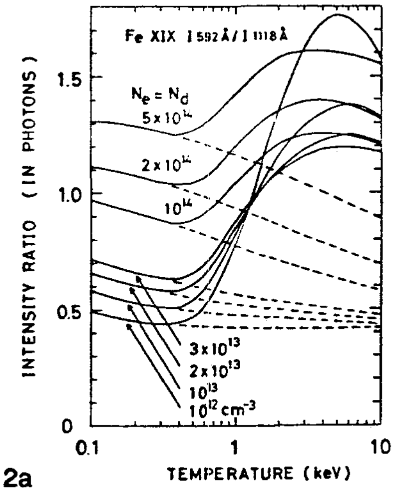

Fig. 2a

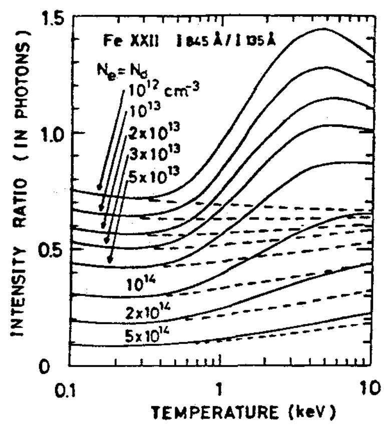

Fig. 2b

III. INSTRUMENTATION AND EXPERIMENTAL RESULTS

Intensity measurements of the time evolution of iron forbidden lines were performed with a modified McPherson 1 m normal incidence spectrometer. This instrument is equipped with two interchangeable gratings (1200 gr/mm Os grating blazed for 450 Å and 1200 gr/mm MgF_2 overcoated aluminum grating blazed for 1500 Å), and multichannel detector (with a funneled CuI microchannel plate, with a P-20 phosphor screen connected by an 18-mm diameter fiber-optics extension to a cooled 1024 element photodiode array). The spectral range is from 250 Å to 2000 Å and the simultaneous coverage of wavelength is about 150 Å, resolution FWHM (with 50 µm entrance slit) is 0.7 Å in first order. Fig. 3 & 4 shows typical spectra obtained with integration time set to 50 ms (normal usage).

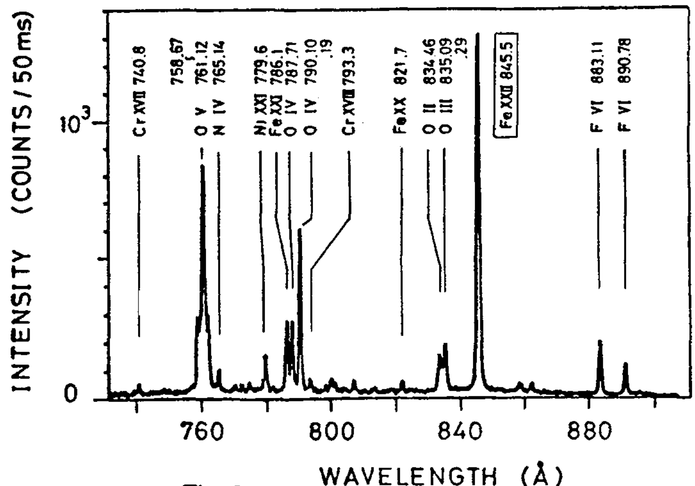

Fig. 3

The time evolutions of the two intensity ratios, the Fe XXII forbidden line at 845 Å relative to the allowed line at 135 Å and the Fe XIX forbidden line at 592 Å relative to the forbidden line at 1118 Å, were measured during an ICRF heating. An rf heating was carried out in an ion minority fundamental ICRF heating regime. An rf at 30 MHz was applied to a deuterium plasma with ~ 5% He^3 minority at B = 32 kG. Since the intensity ratios depend also on electron density, heating with roughly constant density has been set as an experimental condition in order to clarify the influence of deuteron collisions on the forbidden line intensity.

(a)Fe XXII 845 Å/135 Å During 2.3 MW ICRF Heating

An rf power of 2.3 MW was applied for 150 ms at Ip = 460 kA. The time evolution of the 135 Å line were measured simultaneously with the multichannel spectrometer "SOXMOS". Because of a problem of noise during the high-power ICRF heating, the intensity of the 135 Å line in the early period of the heating was uncertain. Figure 5 shows the time evolution of the observed ratio of the 845 Å line to the 135 Å line and the line-averaged electron density during the heating. The central electron temperature obtained by electron Cyclotron Emission (ECE) measurements, and the ion temperature from a charge-exchanged fast neutral and neutron count rate are shown in the lower part of Fig. 5. The observed intensity ratio increases by about a factor of 2 during the heating. This increase may be attributed to the increased ion temperature, because of the constant electron density and small effect of electron temperature on the ratio.

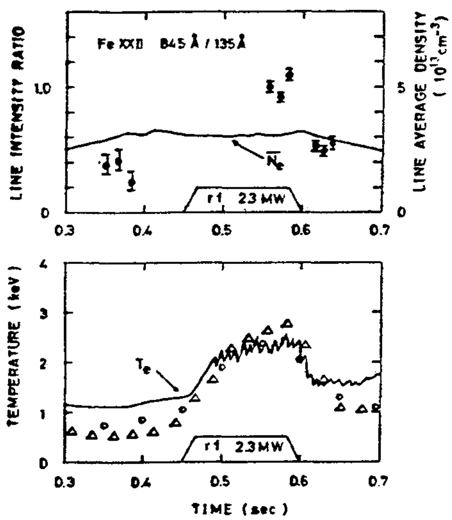

Fig. 5

(b) Fe XIX 592 Å/1118 Å During 400 kW ICRF Heating

An rf power of 400 kW was applied to a relatively low density plasma ($n_e = 1.2 \times 10^{13}$ cm^{-3}) for about 180 ms at I_p = 500 kA. The time evolutions for the 1118 Å line and the second order of 592 Å line of Fe XIX were measured simultaneously with a multichannel normal incidence spectrometer. The change of the plasma parameters and the observed ratio during the heating are shown in Fig. 6. As seen in the figure, electron density was kept constant.

Because of the high central electron temperature of 1.7 keV during the heating, Fe XIX (I.P. = 1.46 keV) ions are expected to be located outside the plasma center. This can be seen also from the smaller values of the ion temperature from the Doppler width of the Fe XX line from the charge-expanded fast neutral and neutron count rate. Thus the ion temperature from the Fe XX 2665 Å line was used to calculate the ratio in Fe XIX. The comparison of the observed and calculated intensity ratio is given in Table II of Ref 2. Agreement of the observed ratio with the calculated one is better than 30%.

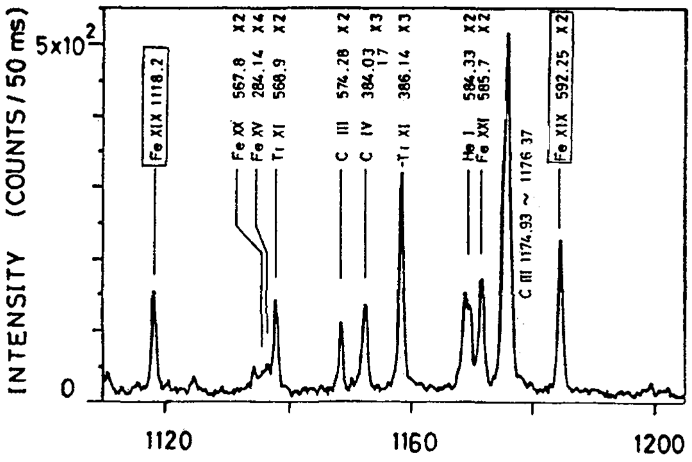

Fig. 4

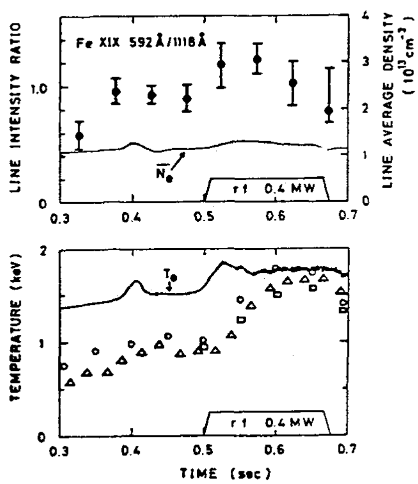

Fig. 6

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