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Line Ratios within σ and π Components of H_α Lines from High Energy Hydrogen Atom with Motional Stark Effect

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Abstract

The Line ratios within σ and π components of H_α lines from high energy hydrogen atom with Motional Stark Effect are investigated experimentally using the heating beam and plasma in Large Helical Device with the magnetic field of 2.78 T. The line averaged electron density and central electron temperature in the plasma are 2×10^{19} m^{-3} and 1.5 keV, respectively. The emission spectra are measured through four sets of polarizer which tilted by 0, 45, 90, and 135 degree with respect to the magnetic field at the plasma center using an imaging spectrometer. Nine lines of H_α lines (0σ, $1\sigma+$, $1\sigma-$, $2\pi+$, $2\pi-$, $3\pi+$, $3\pi-$, $4\pi+$, $4\pi-$) are observed in the spectra emitted from the hydrogen beam with the energy of $150 - 180$ keV/amu. The line ratio of circular polarized components $1\sigma/0\sigma$, is significantly larger than that caculated although the line ratio of linear polarized components $4\pi/3\pi$ is consistent with the calculation. The discrepancy of the line ratio of $1\sigma/0\sigma$, becomes larger when it is observed more perpendicular to the beam line, which suggest the elliptical polarization of σ lines due to the non-Maxwell proton excitation by high energy beam.

Keywords:

Motional Stark Effect, plasma, spectroscopy

1. Introduction

Since the motional Stark features was observed in the Balmer spectrum radiated from the neutral hydrogen or deuterium beam injected to the plasma confined by magnetic field, the Motional Stark Spectroscopy (MSE) has been a useful tool to measure the radial profile of rotational transform [1-4]. In order to study the fine structure of the σ and π lines the observation from the high energy neutral beam and strong magnetic field are necessary, because the motional stark shift is proportional to the beam velocity and magnetic field, In the experiment in PBX-M, where the magnetic field, B, and beam energy, E, were not high enough ($E = 55$ keV/amu, $B = 1.3$ T), the fine structure of each component, for instance 0σ and 1σ or 2π, 3π and 4π, was not observed [1]. This is in contrast to the measurements in JET, where the magnetic field B is 3 T, the fine structure of each lines are observed and the ratio of 1σ to 0σ or 2π to 3π and 4π to 3π are measured. There are some discrepancy observed between the measurements and theoretical calculation [3]. The Large Helical Device equips high energy beam with the energy of $150 - 180$ keV and high magnetic field of 3 T and is considered to have a big advantage to study the fine structure of the motional Stark spectrum. In this paper, the fine structure of σ and π lines observed in the MSE spectroscopy is described.

2. Motional stark effect

The neutral beam injected in the plasma is excited to the upper energy levels through collisions with electrons and ions in the plasma. The line spectrum emitted from a high energy hydrogen beam is dominated by the motional Stark effect due to the Lorentz electric field $E = vB\sin(\beta)$, where v is the beam velocity and B is the total magnetic field and β is an angle between beam line and magnetic field. This Lorentz electric field causes the H_α line to split into 15 Stark components, 9 of which (0σ, $1\sigma+$, 1σ-, $2\pi+$, 2π-, $3\pi+$, 3π-, $4\pi+$, 4π-) are strong enough to be observed. These components are divided into to polarization groups. The σ lines due to the transition for which $\Delta m = -1$ or $+1$, where m is a magnetic quantum number) are circular polarized perpendicular to the Lorentz electric field, while the π lines due to the transition for which $\Delta m = 0$) are linearly polarized parallel to the Lorentz electric field. When viewed nearly perpendicular to the Lorentz electric field

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(this is the case in this experiment), σ lines are almost linearly polarized perpendicular to the Lorentz electric field. Therefore the σ lines and π lines can be measured separately by inserting the linear polarizer, one is parallel and the other is perpendicular to the Lorentz electric field, in front of the object lens.

3. Spectroscopy system for the MSE measurements in LHD

Figure 1 shows the experimental set up for Motional Stark Effect (MSE) spectroscopy installed in the Large Helical Device. The Large Helical Device (LHD) is a toroidal helical magnetic device (Heliotron device) with a major radius of $R_{ax} = 3.5 - 4.1$ m and a magnetic field B of 0.5 − 3 T. The major radius R_{ax}, an average minor radius, a magnetic field B and the beam energy is 3.6 m, 0.6 m, 2.78 T and 170 keV in this experiment.

The MSE system consists of spectrometer, optical fibers and linear polarizer tilted by 0, 45, 90 and 135 degree with respect to the horizontal direction. The liner polarizer are arranged in front of object lanes to avoid the change of polarization angle due to lenses. The 100 optical fibers with a diameter of 200 micron core and 250 micron clad are arranged at the focal plane of each object lens. The optical fibers are divided to 25 groups and each group has optical fibers with the linear polarizer tilted by 0, 45, 90 and 135 with respect to the horizontal direction. The object lens of each optical fiber arrays are adjusted to make optical fiber in a same group to view an identical observation point (intersection between beam line and line of sight). The 100 optical fibers are arranged at the entrance slit of the high throughput spectrometer (Bunkou-Keiki CLP-400) which consists a pair of $f = 400$ mm/$F = 2.8$ camera lenses and 2160/mm grating. A back illuminated CCD

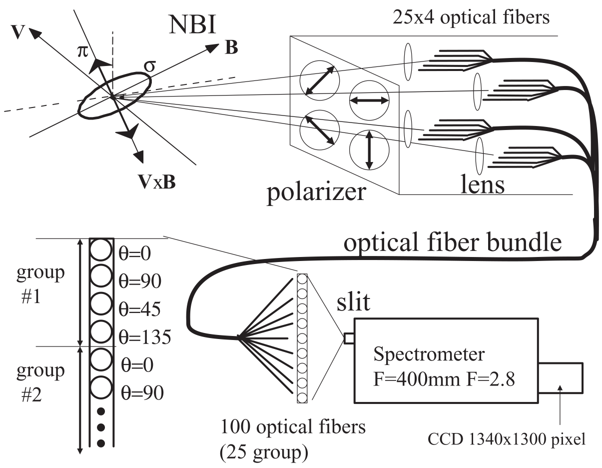

Fig. 1 Experimental setup for Motional Stark Effect spectroscopy in LHD.

(1340×1300 with 20×20 micron pixel) at the exit plane is used to measure 100 spectrum.

4. Fine structure of σ lines and π lines

Figure 2 shows the σ lines and π lines measured with the MSE spectroscopy system. The σ lines are measured with the channel with the polarizer parallel to the horizontal direction (horizontal channel), while the π lines are measured with the polarizer parallel to the vertical direction(vertical channel). Since the Lorentz electric field is slightly tilted from the vertical direction due to the poloidal field produced by the external helical coil current, small σ lines appears even in the vertical channel.

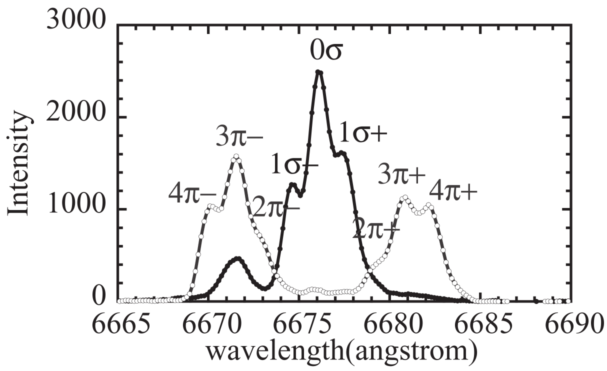

Fig. 2 σ lines and π lines measured MSE spectroscopy system.

The asymmetry of σ lines (higher 1σ in larger wavelength) observed is due to the geometric effect. The motional Stark shift is proportional to $v \times B\cos(\beta)$ and the Doppler shift is proportional to $\cos(\theta)$, where θ is a angle between the beam line and line of sight. Both the angle β and θ changes along the line of sight within the beam width due to the beam divergence with keeping the difference more or less constant. Therefor when the Doppler shift increases, the motional Stark shift decreases. When the direction of Doppler shift and motional Stark shift is in the same direction (in the longer wavelength side) the beam divergence causes the increase of the peak of $1\sigma+$ line. On the other hand, in the shorter wavelength side ($1\sigma-$ line), where the direction of motional Stark shift is in the opposite to the Doppler shift, the beam divergence causes the decrease the peak of line.

5. Line intensity ratio of 1σ and π lines to 0σ line

As seen in Fig. 3, the beam divergence causes the difference of peak height between $1\sigma-$ and $1\sigma+$ or $\pi-$ and $\pi+$ lines. Three component of σ lines and π lines

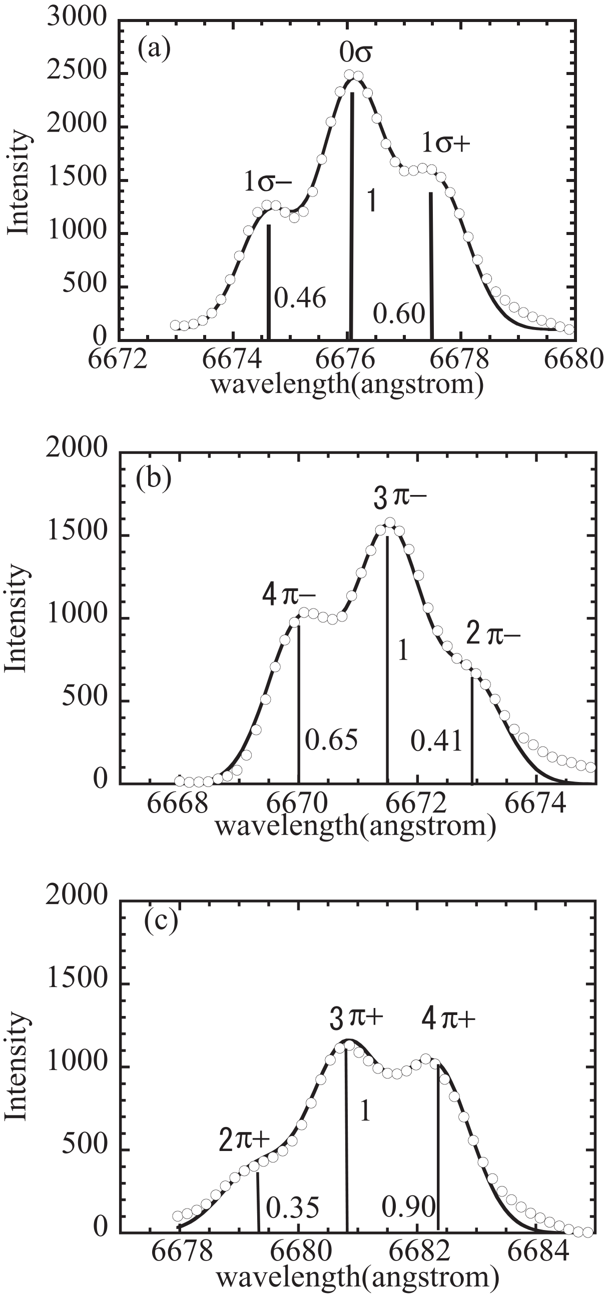

Fig. 3 The spectrum measured and calculated for (a) σ and (b)(c) π lines. The open circles are spectra measured with MSE spectroscopy, while the solid lines are fitting curves with multi Gaussian.

are fitted with three Gaussian profiles. The discrepancy at the longer wavelength tail is due to the overlapping of σ lines to the measurements of π lines measured with the liner polarizer parallel to the vertical direction, because of the tilting of Lorentz electric field due to poloidal magnetic field. In order to eliminate the effect of beam divergence on the estimate of line ratios, the peak heights of $1\sigma-$ and $1\sigma+$ or $\pi-$ and $\pi+$ lines are averaged. The averaged values are compared with that calculated with magnetic field of 3 T for various magnitude of Lorentz electric field as shown in Fig. 4(a). Here the viewing angle is parallel to the magnetic field and perpendicular to the Lorentz electric field. The calculated line ratios are tends to increase as the Lorentz electric field decreases for low Lorentz electric field below 2 MV/m, where the Zeeman effect becomes important. At higher Lorentz electric field above 2 MV/m, the Zeeman effect can be neglected and the line ratios are almost constant does not depend on the magnitude of Lorentz electric field. At higher Lorentz electric field, the line ratio does not depend on the magnitude of magnetic field as seen in Fig. 4(b).

The line ratios of 1σ and π lines to 0σ line measured are significantly larger than that predicted by calculations. The mechanism causing the discrepancy of measured ratio to that calculated is not clear yet, although the discrepancy itself have been observed in the previous work.

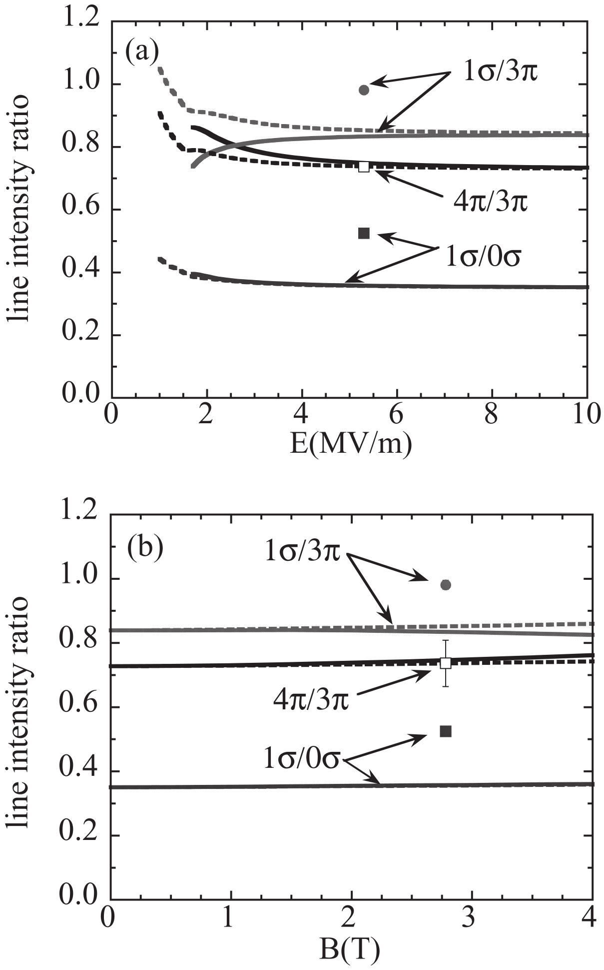

Fig. 4 Comparison of line ratios measured to that calculated (solid line for the emission viewing parallel to the magnetic field and dotted line for the emission viewing perpendicular to the magnetic field as a function of Lorentz electric field with a magnetic field of 3 T and (b) magnetic field with a Lorentz electric field of 5.3 MV/m.

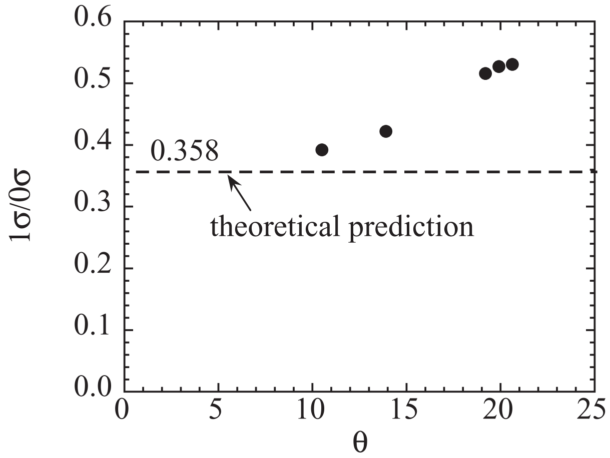

Fig. 5 Viewing angle dependence of line ratio $1\sigma/0\sigma$ for the plasma with magnetic field of 2.78 T and Lorentz electric field of 5.3 MV/m in LHD.

6. Discussions

As discussed in the previous section, the measured line ratio of $1\sigma/0\sigma$ is significant larger than that calculated.

The line ratio of circular polarized components $1\sigma/0\sigma$, is significantly larger than that calculated although the line ratio of linear polarized components $4\pi/3\pi$ is consistent with the calculation. The intensity ratio of $1\sigma/0\sigma$ has viewing angle (intersection angle between line of sight and beam line) dependence as shown in Fig. 5. It should be noted that 1) the discrepancy is significant in the circular polarized line and not the linear polarized line, 2) a degree of the discrepancy strongly depends on the viewing angle with respect to the direction of neutral beam exciting the H_α line.

This data suggests that σ lines are elliptical polarized and there is a difference of the ellipticity between 0σ and 1σlines in the MSE spectrum, where the excitation process is dominated by the collision between the proton in the plasma and neutral beam. When the beam energy is low, the excitation is mainly due to electron impact, which can be treated as Maxwell distribution. However, when the beam energy is high, the proton impact becomes dominant in the excitation process. It should be noted that the discrepancy of line ratios between the measurements and calculation becomes significant for the MSE spectra from the high energy of beam of 150 – 180 keV/amu in LHD. The orientation in the excitation process due to the non-Maxwell ion impact, which is not included in this calculation should be taken into account. The calculation including these effect will be developed in future.

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