Development of Saturation Spectroscopy for Plasma Diagnostics

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Outline

• Background
• Theory of saturation spectroscopy
• Experiment
• Results and discussion
  • Assignment of saturation spectrum peaks
  • Analysis of saturation parameter
• Summary
Background

- To improve confinement ability of LHD, spatial distribution of ionization is interested, especially edge region of core plasma.
- Zeeman splitting analysis of emission spectrum is a method to identify the position of ionization in helical system.
- For helium plasma, Zeeman splitting analysis carried out successfully.

Large Helical Device
(National Institute for Fusion Science) Cross section of core plasma


Zeeman splitting analysis for helium plasma
Objective

- Hydrogen plasma: difficult to analyze Zeeman splitting of emission spectrum
  - Spectrum has fine structure
  - Wider Doppler broadening masks Zeeman splitting and fine structure
- Saturation spectroscopy is widely used Doppler-free spectroscopy

To apply saturation spectroscopy to hydrogen plasma
To analyze obtained saturation spectrum

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Saturation of absorption

Open 2-level system

\[
\begin{align*}
\frac{dN_1}{dt} &= B_{12} \rho N_2 - (B_{12} \rho + R_1) N_1 + C_1 \\
\frac{dN_2}{dt} &= B_{12} \rho N_1 - (B_{12} \rho + R_2) N_2 + C_2
\end{align*}
\]

\[
\frac{d}{dt} = 0
\]

\[
\Delta N^0 = (N_1 - N_2)_{\rho=0} = \frac{C_1 R_2 - C_2 R_1}{R_1 R_2}
\]

\[
\Delta N = \Delta N^0 \frac{1}{1 + B_{12} \rho (1/R_1 + 1/R_2)} = \frac{\Delta N^0}{1 + S}
\]

Saturation of absorption \( \alpha = \frac{\alpha_0}{1 + S} \)

\[
S = \frac{B_{12} \rho}{R^*}
\]

\[
\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2}
\]

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Configuration of saturation spectroscopy

\[ I_t = I_0 \exp(-\alpha l) \]

Tunable laser

Intense pump beam: decreases population difference (makes hole burning, i.e. decrease absorption)

Weak probe beam: no affection for population

Absorption of probe beam decreases when laser frequency is almost tuned to the line center

Absorption dip:
Lorentzian with homogeneous width
\(<\!<\) Doppler width
Depth and profile of saturation spectrum

\[
\frac{\Delta \alpha}{\alpha_0} = \frac{\alpha_0 - \alpha_s}{\alpha_0} = \frac{S}{\sqrt{1+S}} \frac{1}{1+\sqrt{1+S}} \frac{(\Gamma_s^*/2)^2}{(\omega - \omega_0)^2 + (\Gamma_s^*/2)^2}
\]

\[
\Gamma_s^* = \frac{\gamma + \gamma_s}{2} = \gamma \frac{1+\sqrt{1+S}}{2}
\]

- The shape of the dip is Lorenzian. The width is basically determined by the homogeneous line width, but it is broadened by saturation broadening.
- The width of the dip is much narrower than the Doppler broadening (Doppler-free spectroscopy).
- The relationship between the saturation parameter and the depth of the dip at \(\omega = \omega_0\) is given by

\[
S = \left(1 - \frac{\Delta \alpha(\omega_0)}{\alpha_0(\omega_0)}\right)^{-2} - 1
\]
Cross-over signal

- Cross-over signal is found at the midpoint of two transitions that have overlapped Doppler wings and common lower or upper level.
- Balmer-α line has 7 allowed transitions. 4 lower level common cross-overs and 2 upper level common cross-overs may be observed.
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Experimental apparatus

250-750W
13.56MHz power supply

Solenoid coil (60~1300G)

50~400mTorr, 10sccm
Reference signal detection
APD
H₂

110mW

Helical antenna
60cm

220μW

Collimator
PROBE BEAM

Isolator

Spectrum analyzer
FSR=300MHz

λ/2

Dioode laser amplifier

λ/2

Isolator

Diode laser oscillator (freq. scanning)
Sweep 120GHz/25ms

Probe signal detection
APD

PUMP BEAM
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Absorption spectrum

Absorption spectrum of Balmer-α line

- Without pump laser: good agreement with theoretical calculation of absorption spectrum with Doppler broadening at 500K
- With pump laser: a few sharp dips appeared in the absorption
- Relative depth of dip is proportional to Einstein’s B coefficient, approximately

\[
\frac{\Delta \alpha}{\alpha_0} \propto S_0 \propto B_{23}, I_L, \frac{1}{R}
\]
Saturation spectra with various magnetic field

- Zeeman splitting with various magnetic field was observed successfully.
- In the case of high magnetic field, spectrum was very complicated with many splitting lines and cross-overs.
Assignment of saturation spectrum peaks

Saturation spectrum

Balmer-α (7 allowed transitions)

- 3d²D₅/₂
- 3p²p₀³/₂
- 3d²D₃/₂

3s²S₁/₂
3p²p₀¹/₂
2s²S₁/₂
2p²p₀₁/₂

Anomalous saturation peaks exist

- Zeeman splitting is not observed in the magnetic field of 60Gauss (Δν ~ 200MHz)
- Intense transitions make large saturation peaks
- Several peaks are explained as cross-over peaks with lower level 2S₁/₂ or 2P₃/₂
Analysis of anomalous saturation peaks

- Anomalous peaks are obvious with high hydrogen pressure
- These peaks are located at the midpoint frequency of two transition peaks with different lower level
Anomalous cross-over signal

Two transition lines with overlapped Doppler wings

- Independent transitions do not affect each other
- Cross-over signal arises between transitions with common lower level
- Population exchange between lower levels also arise cross-over-like signal (velocity should be preserved)
Classification of anomalous peaks

- Population exchanges are suggested at each pair of $2S_{1/2}$, $2P_{1/2}$ and $2P_{3/2}$.
- According to Janev, the collisional transfer between 2s and 2p states ($H(2s) + e \rightarrow H(2p) + e$) has a large rate coefficient of approximately $2 \times 10^{-6}$ cm$^3$/s.
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Doppler broadened absorption spectrum

- Theoretical fitting with B coefficient and statistical weight is little different to experimental line shape.
- A better fitting is obtained when assuming the population of 2S state is increased 8% than the statistical weight distribution.
  - 8% seems too small collection factor for metastable 2S state.
- Relaxation probability is estimated through the related saturation parameter $S$.

$$S = \frac{B_{12\rho}}{R^*}$$
Analysis of saturation parameter

- $\Delta \alpha$ have broad tail. Eliminate by fitting $\alpha_0$ to $\alpha_s$. (may be not precise treatment)
- Each peak should be Lorentzian. Dispersion function is subtracted to restore.
- Saturation parameter can be calculated by the pair of Lorentzian peak $\Delta \alpha$ and Gaussian peak $\alpha_0$ for each transition.
- Compare saturation parameter of $2P_{3/2} - 3D_{5/2}$ and $2S_{1/2} - 3P_{3/2}$. 

\[
S = \left( 1 - \frac{\Delta \alpha(\omega_0)}{\alpha_0(\omega_0)} \right)^{-2} - 1
\]
Evaluation of relaxation probability

Saturation parameter $S$

$$S_0 = \frac{B_{23}}{R^*} \frac{I_L}{c} \quad \frac{1}{R^*} = \frac{1}{R_2} + \frac{1}{R_3}$$

Mean relaxation probability $R^*$

$$\frac{B_{2S_{1/2}-3P_{3/2}}}{B_{2P_{3/2}-3D_{5/2}}} \frac{S_{2S_{1/2}-3P_{3/2}}}{S_{2P_{3/2}-3D_{5/2}}} = \frac{R^*_{2S_{1/2}-3P_{3/2}}}{R^*_{2P_{3/2}-3D_{5/2}}} \approx \frac{R_{2S_{1/2}}}{R_{3D_{5/2}}}$$

- Saturation parameter increases with gas pressure decreasing.
- Relaxation probability increases with gas pressure increasing --- collisional relaxation
- Ratio of relaxation probability between $2S_{1/2}$ and $3D_{5/2}$ is roughly unchanged with gas pressure.
Estimation of relaxation probability

Relaxation probability by optical transition

<table>
<thead>
<tr>
<th>level</th>
<th>$R_{\text{opt}}$ ($10^7$ s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D(5/2)</td>
<td>6.47</td>
</tr>
<tr>
<td>3P(3/2)</td>
<td>20.0</td>
</tr>
<tr>
<td>2P(3/2)</td>
<td>62.6</td>
</tr>
<tr>
<td>2S(1/2)</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ \frac{1}{R^*} = \frac{1}{R_2} + \frac{1}{R_3} \]
\[ \frac{R^*_{2S_{1/2}-3P_{3/2}}}{R^*_{2P_{3/2}-3D_{3/2}}} \approx \frac{R_{2S_{1/2}}}{R_{3D_{3/2}}} \]

\[ R_{2S_{1/2}} \approx 0.16 R_{3D_{3/2}} = 1 \times 10^7 \text{ s}^{-1} \]
\[ R_{2S \leftrightarrow 2P} = 2 \times 10^{-6} n_e [\text{cm}^{-3}] \approx 1 \times 10^6 \text{ s}^{-1} \quad (n_e \sim 5 \times 10^{11}) \]
\[ R_{2P_{3/2}} = 6 \times 10^8 \text{ s}^{-1} \]

- Relaxation probability of 2S$_{1/2}$ state was estimated approximately $10^7 \text{ s}^{-1}$, this is one decade greater than 2s-2p exchange rate by electron collision.
- Relaxation probability of 2P$_{3/2}$ is 60 times greater than of 2S$_{1/2}$.
Summary

- Saturation spectroscopy was applied to Balmer-\(\alpha\) line of hydrogen plasma in various magnetic field.

- In the case of weak magnetic field, the saturation spectrum showed the fine structure of Balmer-\(\alpha\) line with sufficient resolution.

- Most peaks of the saturation spectrum were assigned to the transitions of Balmer-\(\alpha\) line and cross-over signals.

- Anomalous cross-over like peaks were also observed. These peaks indicate population exchange among \(2S_{1/2}\), \(2P_{1/2}\) and \(2P_{3/2}\) states.

- The relaxation probability of \(2S\) state was estimated by the saturation parameter of the \(2S_{1/2}-3P_{3/2}\) transition and \(2P_{3/2}-3D_{5/2}\). The estimated relaxation probability is one order of magnitude greater than that expected by the Janev’s rate coefficient.
THANK YOU FOR YOUR ATTENTION