Analysis of visible light emissions of tungsten highly charged ions in plasmas

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Outline:

1. Visible M1 Lines in EBIT Ion source
2. Analysis of Visible M1 Lines in Tungsten Ions
3. Collisional-Radiative Model for Tungsten Ions
4. Summary
Analysis of Visible M1 Lines in Tungsten Ions
Experimental:

Electron Beam Ion Trap (EBIT)

Figure 2. (Color online) (a) Electron energy ($E_e$) dependence of the visible spectra of tungsten ions trapped in the EBIT. (b) Intensity ratio between the lines at 387 nm and 389 nm as a function of $E_e$.

Komatsu et al, Proceedings of HCI@Shanghai (2010) submitted
EBIT for investigation of Highly charged ions

- Selective production of ions;
- Narrow ion distribution;
- Long confinement for observation

Tokyo-EBIT

Co-(E)BIT
EBIT for investigation on Highly charged ions

A. Selective production of ions; B. Narrow ion distribution; C. Long confinement for observation
Spectrum of $\text{W}^{26+}$ ions

<table>
<thead>
<tr>
<th>Generation Energy in eV</th>
<th>$\text{W}^{30+}$</th>
<th>$\text{W}^{26+}$</th>
<th>$\text{W}^{29+}$</th>
<th>$\text{W}^{25+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{W}^{30+}$</td>
<td>1137</td>
<td>786.3</td>
<td>887</td>
<td>738.6</td>
</tr>
<tr>
<td>$\text{W}^{29+}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$d$ (3894Å) : From $\text{W}^{26+}$
Characteristics of Magnetic Dipole (M1) Lines in Tungsten (W) Highly Charged Ions

- In tungsten highly charged ions with open valence sub-shells, the fine structure splitting comes into the range of visible light emissions.

- Magnetic dipole (M1) resonance transitions are available between the ground state fine structure multiplets.

- Visible lines are of the great advantage for the purpose of plasma diagnostics because of their ease of the spectroscopic measurement.

- M1 lines are expected to suffer less radiation trapping effects from the surrounding ions.
Magnetic dipole transitions between the $W^{26+}$ ground state multiplets using GRASP2K MCDF wavefunctions

Atomic State function

$$\left| \Psi_\alpha (PJM) \right\rangle = \sum_{r}^{n_c} c_\gamma (\alpha) \left| \gamma_r PJM \right\rangle$$

Variation condition

$$\delta [ \langle \Psi_\alpha (PJM) | H | \Psi_\alpha (PJM) \rangle / \langle \Psi_\alpha (PJM) | \Psi_\alpha (PJM) \rangle ] = 0$$

Oscillator Strength of Multipole fields of rank $L$

$$f_{i \rightarrow j} = \frac{\pi c}{(2L+1)\omega^2} \left| \left\langle \Psi_f (P_f J_f M_f ) | O^{LM} | \Psi_i (P_i J_i M_i ) \right\rangle \right|^2$$

Oscillator Strength of Magnetic dipole fields

$$f_{i \rightarrow j} = \frac{\pi c}{2(2L+1)\omega^2} \left| \left\langle \Psi_f (P_f J_f M_f ) | l + 2s \Psi_i (P_i J_i M_i ) \right\rangle \right|^2$$
RATIP
Relativistic Atomic Transition and Ionization Properties
(CPC library)

\[ \psi_{\alpha}(PJM) = \sum_{r}^{n_{r}} c_{r}(\alpha) \left| y_{r}PJM \right| \]

Many-electron basis (wave function expansions)
- Construction and classification of N-particle Hilbert spaces
- Shell model: Systematically enlarged CSF basis
- Interactions
  - Dirac-Coulomb Hamiltonian
  - Breit interactions + QED
  - Electron continuum; scattering phases
- Coherence transfer and Rydberg dynamics

Relativistic CI wave functions including QED estimates and mass polarization
RELCL, CPC 148 (2002) 103

LSJ spectroscopic notation from jj-coupled computations
LSJ, CPC 157 (2003) 239

Auger rates, angular distributions and spin polarization; level widths
AUGER

Photoionization cross sections and (non-dipole) angular parameters
PHOTO

Radiative and dielectronic recombination; angle-angle correlations
REC
The first step to the calculation of tungsten ion M1 transitions

\[ \text{W}^{26+} : [\text{Kr}]4f^2 = \ldots 4s^24p^24d^{10}4f^2 \]

The simplest ion that have multiple 4f orbital electrons.

Atomic ground state has less difficulties for variational calculation.

A large scale MCDF calculation is feasible.
Mean radius of $4l$ orbital in Cd-like ions

**Ground state:**
[Kr]4d$^{10}$4f$^2$

For W$^{26+}$ ions

$\langle r_{4f} \rangle < \langle r_{4p} \rangle$

Strong correlations between 4p, 4d, and 4f orbitals are expected.
Correlation Models for W^{26+} Ground State Energy Levels

Active Space:
AS={4f,5s,5p,5d,5f,5g}

Valence-Valence Correlation:
5SD: 4d^{10}4f^2 \rightarrow 4d^{10}(AS)^2

Core-Valence Correlation:
4p_5SD: 4s^24p^64d^{10}4f^2 \rightarrow 4s^24p^54d^{10}4f^1(AS)^2

Core-Core Correlation:
4p_5SD: 4s^24p^64d^{10}4f^2 \rightarrow 4s^24p^54d^{10}4f^1(AS)^2
# Correlation Models of [Kr]4f² Configurations

<table>
<thead>
<tr>
<th>Model</th>
<th>Inactive core</th>
<th>Core</th>
<th>Valence</th>
<th>Correlation</th>
<th>Number of CSFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>DHF</td>
<td>[Ar]3d¹⁰</td>
<td>4s, 4p, 4d</td>
<td>4f</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>4Complex</td>
<td>[Ar]3d¹⁰</td>
<td>4s, 4p, 4d</td>
<td>4f</td>
<td>VV+CV+CC</td>
<td>6134</td>
</tr>
<tr>
<td>5SD</td>
<td>[Ar]3d¹⁰4s²</td>
<td>4p, 4d</td>
<td>4f</td>
<td>VV+CV</td>
<td>20644</td>
</tr>
<tr>
<td>6SD</td>
<td>[Ar]3d¹⁰4s²</td>
<td>4p, 4d</td>
<td>4f</td>
<td>VV+CV</td>
<td>43526</td>
</tr>
<tr>
<td>7SD</td>
<td>[Ar]3d¹⁰4s²</td>
<td>4p, 4d</td>
<td>4f</td>
<td>VV+CV</td>
<td>76462</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Method B</td>
<td></td>
</tr>
<tr>
<td>5SD</td>
<td>[Ar]3d¹⁰4s²4p⁶</td>
<td>4d</td>
<td>4f</td>
<td>VV+CV+CC</td>
<td>36627</td>
</tr>
<tr>
<td>6SD</td>
<td>[Ar]3d¹⁰4s²4p⁶</td>
<td>4d</td>
<td>4f</td>
<td>VV+CV+CC</td>
<td>49785</td>
</tr>
<tr>
<td>7SD</td>
<td>[Ar]3d¹⁰4s²4p⁶</td>
<td>4d</td>
<td>4f</td>
<td>VV+CV+CC</td>
<td>53005</td>
</tr>
</tbody>
</table>

**Correlation Type**
- Valence-Valence (VV)
- Core-Valence (CV)
- Core-Core (CC)

**Active Space (AS)**
- 4Complex
- 5SD = \{5s,5p,5d,5f,5g\}
- 6SD = \{6s,6p,6d,6f,6g,6h\}
- 7SD = \{7s,7p,7d,7f,7g,7h,7i\}
## Energy Levels of the ground state of W^{26+}

<table>
<thead>
<tr>
<th>LS</th>
<th>Energy (cm⁻¹)</th>
<th>Configuration Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>3H4</td>
<td>0.00</td>
<td>96% ((4f)24)</td>
</tr>
<tr>
<td>3F2</td>
<td>19323.19</td>
<td>86% ((4f)22) + 12% ([(4f)<em>{5/2}(4f)</em>{7/2}]2)</td>
</tr>
<tr>
<td>3H5</td>
<td>52084.83</td>
<td>99% ([(4f)<em>{5/2}(4f)</em>{7/2}]5)</td>
</tr>
<tr>
<td>1G4</td>
<td>68564.31</td>
<td>96% ([(4f)<em>{5/2}(4f)</em>{7/2}]4)</td>
</tr>
<tr>
<td>3F3</td>
<td>68599.82</td>
<td>99% ([(4f)<em>{5/2}(4f)</em>{7/2}]3)</td>
</tr>
<tr>
<td>3H6</td>
<td>77400.42</td>
<td>64% ((4f)<em>{26}) + 35% ([(4f)</em>{5/2}(4f)_{7/2}]6)</td>
</tr>
<tr>
<td>3F4</td>
<td>98302.06</td>
<td>99% ((4f)24)</td>
</tr>
<tr>
<td>1D2</td>
<td>102031.11</td>
<td>76% ([(4f)<em>{5/2}(4f)</em>{7/2}]2 + 14%(4f)_{22})</td>
</tr>
<tr>
<td>1S0</td>
<td>105385.15</td>
<td>81% ((4f)<em>{20} + 18%(4f)</em>{20})</td>
</tr>
<tr>
<td>3P1</td>
<td>116790.74</td>
<td>99% ([(4f)<em>{5/2}(4f)</em>{7/2}]1)</td>
</tr>
<tr>
<td>1I6</td>
<td>119023.48</td>
<td>64% ([(4f)<em>{5/2}(4f)</em>{7/2}]6 + 35%(4f)_{26})</td>
</tr>
<tr>
<td>3P2</td>
<td>136212.13</td>
<td>89% ((4f)<em>{22} + 10%[((4f)</em>{5/2}(4f)_{7/2}]2)</td>
</tr>
<tr>
<td>3P0</td>
<td>185305.97</td>
<td>81% ((4f)<em>{20} + 18%(4f)</em>{20})</td>
</tr>
</tbody>
</table>
Convergence feature in the wavelength of $W^{26+}{}^3H_5 - {}^3H_4$ M1 transitions

transition: $[4f^{-2}]_4 - [[4f^{-}][4f]_{7/2}]_5$
## Energy levels of ground state of $W^{26+}$ (in cm$^{-1}$)

<table>
<thead>
<tr>
<th>LS</th>
<th>DF</th>
<th>DF+Breit</th>
<th>4Complex</th>
<th>5SD(A)</th>
<th>6SD(A)</th>
<th>7SD(A)</th>
<th>5SD(B)</th>
<th>6SD(B)</th>
<th>7SD(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3H_4$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$^3F_2$</td>
<td>20571.40</td>
<td>20854.16</td>
<td>18869.21</td>
<td>18602.94</td>
<td>18593.76</td>
<td>18595.31</td>
<td>18763.30</td>
<td>18671.09</td>
<td>18639.78</td>
</tr>
<tr>
<td>$^3H_5$</td>
<td>26725.54</td>
<td>25251.68</td>
<td>25407.64</td>
<td>25398.61</td>
<td>25406.03</td>
<td>25381.52</td>
<td>25610.54</td>
<td>25708.43</td>
<td>25747.25</td>
</tr>
<tr>
<td>$^1G_4$</td>
<td>39998.52</td>
<td>38704.40</td>
<td>37826.81</td>
<td>37957.84</td>
<td>37918.12</td>
<td>37885.60</td>
<td>38177.84</td>
<td>38240.70</td>
<td>38287.99</td>
</tr>
<tr>
<td>$^3F_3$</td>
<td>40805.81</td>
<td>39816.78</td>
<td>38305.57</td>
<td>38153.69</td>
<td>38148.26</td>
<td>38124.21</td>
<td>38445.70</td>
<td>38514.43</td>
<td>38555.16</td>
</tr>
<tr>
<td>$^3H_6$</td>
<td>49671.56</td>
<td>46960.42</td>
<td>47017.86</td>
<td>47135.20</td>
<td>46884.04</td>
<td>47350.55</td>
<td>46817.23</td>
<td>46798.55</td>
<td>47126.87</td>
</tr>
<tr>
<td>$^3F_4$</td>
<td>71133.76</td>
<td>68560.13</td>
<td>67556.94</td>
<td>67678.19</td>
<td>67651.04</td>
<td>67631.47</td>
<td>67891.07</td>
<td>67828.95</td>
<td>67831.79</td>
</tr>
<tr>
<td>$^1D_2$</td>
<td>76658.19</td>
<td>75883.34</td>
<td>71192.04</td>
<td>70280.30</td>
<td>70119.78</td>
<td>70057.86</td>
<td>70702.25</td>
<td>70600.96</td>
<td>70621.21</td>
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<tr>
<td>$^3P_0$</td>
<td>79850.25</td>
<td>80316.78</td>
<td>74500.90</td>
<td>72797.93</td>
<td>72702.78</td>
<td>72640.82</td>
<td>73277.37</td>
<td>72851.15</td>
<td>72843.28</td>
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<tr>
<td>$^3P_1$</td>
<td>92340.64</td>
<td>91993.65</td>
<td>86620.59</td>
<td>84922.87</td>
<td>84808.95</td>
<td>84727.56</td>
<td>85433.88</td>
<td>85230.53</td>
<td>85223.47</td>
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<tr>
<td>$^1I_6$</td>
<td>94280.68</td>
<td>92014.82</td>
<td>90966.12</td>
<td>88781.85</td>
<td>88189.87</td>
<td>88638.33</td>
<td>88955.93</td>
<td>88939.72</td>
<td>89028.16</td>
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<tr>
<td>$^3P_2$</td>
<td>112722.53</td>
<td>110718.40</td>
<td>105620.90</td>
<td>104339.07</td>
<td>104180.45</td>
<td>104092.33</td>
<td>104822.71</td>
<td>104614.62</td>
<td>104601.61</td>
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<tr>
<td>$^1S_0$</td>
<td>188620.66</td>
<td>187799.37</td>
<td>177739.27</td>
<td>176580.87</td>
<td>176220.02</td>
<td>175980.56</td>
<td>177859.16</td>
<td>177217.11</td>
<td>177420.06</td>
</tr>
</tbody>
</table>
### Possible visible transitions between the W^{26+} ground state multiplets

<table>
<thead>
<tr>
<th>Tran</th>
<th>Wavelength(Å)</th>
<th>Type</th>
<th>A_{ij}(s^{-1})</th>
<th>gf</th>
</tr>
</thead>
<tbody>
<tr>
<td>³H₅ → ³H₄</td>
<td>3884.34</td>
<td>M1</td>
<td>3.94(2)</td>
<td>9.80(-6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E2</td>
<td>1.69(-3)</td>
<td>4.21(-11)</td>
</tr>
<tr>
<td>³H₆ → ³H₅</td>
<td>4677.96</td>
<td>M1</td>
<td>2.05(2)</td>
<td>8.75(-6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E2</td>
<td>3.31(-4)</td>
<td>1.41(-11)</td>
</tr>
<tr>
<td>¹I₆ → ³F₄</td>
<td>4721.59</td>
<td>M1</td>
<td>2.90(-2)</td>
<td>1.26(-9)</td>
</tr>
<tr>
<td>³F₄ → ³H₆</td>
<td>4826.63</td>
<td>E2</td>
<td>6.36(-4)</td>
<td>2.00(-11)</td>
</tr>
<tr>
<td>³F₃ → ³F₂</td>
<td>5017.99</td>
<td>M1</td>
<td>1.75(2)</td>
<td>4.62(-6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E2</td>
<td>7.28(-5)</td>
<td>1.92(-12)</td>
</tr>
<tr>
<td>¹G₄ → ³F₂</td>
<td>5090.88</td>
<td>M1</td>
<td>1.82(-4)</td>
<td>6.37(-12)</td>
</tr>
<tr>
<td>³P₂ → ³P₁</td>
<td>5160.06</td>
<td>M1</td>
<td>6.43(1)</td>
<td>1.28(-6)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E2</td>
<td>6.65(-4)</td>
<td>1.33(-11)</td>
</tr>
<tr>
<td>³F₂ → ³H₄</td>
<td>5366.71</td>
<td>M1</td>
<td>7.33(-3)</td>
<td>1.58(-10)</td>
</tr>
<tr>
<td>³P₁ → ¹D₂</td>
<td>6851.63</td>
<td>M1</td>
<td>2.33(1)</td>
<td>4.93(-7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E2</td>
<td>9.59(-6)</td>
<td>2.03(-13)</td>
</tr>
</tbody>
</table>
Collaboration with theoretical group, LHD and EBIT experimental groups

- EBIT/CoBIT measurements of visible spectra for $W^{q+}$ (q=12~30)
- GRASP calculation for atomic structure.
- CR model with atomic data from HULLAC code.
- EUV and visible spectroscopy for LHD plasma. (C. Suzuki)

$W^{26+} (4f^2_{5/2})_J=4 \rightarrow (4f_{5/2}4f_{7/2})_J=5$

\[ \lambda = 3894.1 \text{ (experiment)} \]
\[ \lambda = 3884 \text{ (GRASP2K)} \]
\[ \lambda = 4029 \text{ (HULLAC)} \]
Basics of the Collisional Radiative Model

Collisional-Radiative Model

Emission Line intensity

\[ I_{ji} \propto n_{r,j} A_{ji} \]

Rate equation based on CR model

\[ \frac{dn_{r,x}}{dt} = n_e \sum_{y \neq x} n_{r,y} Q_{yx}(T_e) + \sum_{y > x} n_{r,y} A_{yx} \]

\[ -n_{r,x} \left[ n_e \sum_{y \neq x} Q_{xy}(T_e) + \sum_{y < x} A_{xy} \right] \]

Steady state condition

\[ \frac{dn_{r,x}}{dt} = 0 \]
Rate equations

- Rate equation of excited level \( p \) in steady–state is described as

\[
\frac{dn(p)}{dt} = \Gamma_{\text{in}} - \Gamma_{\text{out}} = 0
\]

\[
\Gamma_{\text{in}} = \sum_{q<p} C^e(q,p)n_e n(q) + \sum_{q<p} C^p(q,p)n_p n(q) + \sum_{q=p} \{ F^e(q,p)n_e + F^p(q,p)n_p + A(q,p) \} n(q) + \{ \beta(p) + \alpha(p)n_e \} n_e n_i
\]

- Excitation by electron & proton impact

\[
\Gamma_{\text{out}} = [S(p)n_e + \sum_{q>p} C^e(p,q)n_e + \sum_{q>p} C^p(p,q)n_p + \sum_{q<p} F^e(p,q)n_e + \sum_{q<p} F^p(p,q)n_p + A(p,q)] n(p)
\]

- Deexcitation by electron & proton impact and radiative decay

- Ionization

Population density of level \( p \) is then obtained as:

\[
n(p) = n_0(p) + n_1(p) = R_0(p)n_e n_i + R_1(p)n_e n(1)
\]

where \( n_0(p) \): recombining plasma component

\( n_1(p) \): ionizing plasma component

Energy levels (transition energies) have been replaced by the results of GRASP2K calculation
Calculated spectrum of the ground state W^{26+} ions

\[ n_e = 1 \times 10^3 \text{ cm}^3 \]
\[ kT_e = 1 \text{ keV} \]
Temperature dependence on the intensity ratio

![Graphs showing intensity ratio vs. electron temperature for different densities](image-url)
Density dependence on the intensity ratio (kT_e=1keV)
Conclusion to “M1 transition”

1. Accurate theoretical calculations for M1 transitions of tungsten highly charged ions are available by means of large scale MCDF procedure using GRASP2K and RATIP.

2. The M1 transitions in visible range are good candidates for diagnostics of the plasmas that contain tungsten ions as impurity.

3. Extension of the calculations are desired for the M1 transitions of the remaining ions that have been observed by Tokyo-EBIT and CoBIT.
Collisional-radiative model for W ions

I. Murakami, D. Kato, H. A. Sakaue, N. Yamamoto, C. Suzuki
NIFS
Measurement and atomic calculations

Disentangling the emissions of highly ionized tungsten in the range 4–14 nm

Putterich et al. (2005)

Figure 7. The EBIT spectra for several electron beam energies compared with tokamak spectra from ASDEX Upgrade discharge #19436 with impurity accumulation. Vertical lines are drawn to guide the eye. For better display, the tokamak spectra for $T_{e, acc} = 2.1$ keV ($t = 6.53$ s) and $T_{e, acc} = 1.7$ keV ($t = 6.60$ s) are scaled relatively to the spectrum for $T_{e, acc} = 1.2$ keV ($t = 7.00$ s) by factors 3.9 and 1.6, respectively. The EBIT spectra are not scaled relative to each other to give an impression of the relative strength of emissions which are superimposed in the tokamak spectra.

MCDF calculations

W 33+

W 34+

W 35+

W 36+

W 37+

Rhee and Kwon (2008)
CR model

- We have tried to construct a collisional-radiative model for W ions with using atomic data calculated by HULLAC code:
  - Atomic structure: parametric potential method
  - Electron impact excitation and ionization cross sections: relativistic distorted wave approximation.
- Recombination processes are ignored here.
- Rate equations are solved with quasi-steady state assumption \((dn(i)/dt = 0)\).
- \(N_e=3 \times 10^{13} \text{ cm}^{-3}, T_e= 100 - 1000 \text{eV} (N_e=1 \times 10^{10}, 1 \times 10^{20} \text{ cm}^{-3})\)
Rate equations

- Rate equation of excited level p in steady-state is described as
  \[
  \frac{dn(p)}{dt} = \Gamma_{in} - \Gamma_{out} = 0
  \]

  \[
  \Gamma_{in} = \sum_{q<p} C^e(q,p)n_e n(q) + \sum_{q<p} C^p(q,p)n_p n(q) + \sum_{q>p} \{F^e(q,p)n_e + F^p(q,p)n_p + A(q,p)\}n(q) + \{\beta(p) + \alpha(p)n_e\}n_e n_i
  \]

  Excitation by electron & proton impact  \hspace{2cm} Deexcitation by electron & proton impact and radiative decay  \hspace{2cm} recombination

  \[
  \Gamma_{out} = [S(p)n_e + \sum_{q<p} C^e(p,q)n_e + \sum_{q<p} C^p(p,q)n_p + \sum_{q<p} F^e(p,q)n_e + \sum_{q<p} F^p(p,q)n_p + A(p,q)]n(p)
  \]

  Ionization  \hspace{2cm} Excitation by electron & proton impact  \hspace{2cm} Deexcitation by electron & proton impact  \hspace{2cm} radiative decay

Population density of level p is then obtained as:

\[
n(p)=n_0(p)+n_1(p)=R_0(p)n_e n_i + R_1(p)n_e n(1)
\]

where  \(n_0(p)\): recombining plasma component  \(\propto n_i(\text{FeXXII})\)

\(n_1(p)\): ionizing plasma component  \(\propto n(1)(\text{FeXXI})\)

The plasma considered here is headed by the neutral beam injection (NBI) and the ionizing plasma component is dominant.
W ions considered here:

- **W 37+** (194 levels)
  \[4s^2 \ 4p^6 \ 4d, \ 4s^2 \ 4p^6 \ 4f, \ 4s^2 \ 4p^6 \ 5l \ (l=s\sim g), \ 4s^2 \ 4p^5 \ 4d^2, \ 4s^2 \ 4p^5 \ 4d \ 4f, \ 4s^2 \ 4p^5 \ 4d \ 5s\]

- **W 36+** (213 levels)
  \[4s^2 \ 4p^6 \ 4d^2, \ 4s^2 \ 4p^6 \ 4d \ 4f, \ 4s^2 \ 4p^6 \ 4d \ 5l \ (l=s\sim g), \ 4s^2 \ 4p^5 \ 4d^3\]

- **W 35+** (296 levels)
  \[4s^2 \ 4p^6 \ 4d^3, \ 4s^2 \ 4p^6 \ 4d^2 \ 4f, \ 4s^2 \ 4p^6 \ 4d^2 \ 5s, \ 4s^2 \ 4p^5 \ 4d^4\]
Electron density effect on the calculated spectra for W³⁵⁺

Atomic data: HULLAC code

45.12A: 4p54d⁴ (J=5/2) – 4p64d³ (J=7/2) (45.12A)
gA=3.538x10¹²

4p54d⁴ (J=9/2) – 4p64d³ (J=7/2) (45.13A)
gA=3.33x10¹²

52.16A: 4p64d²4d (J=5/2) – 4p64d³ (J=3/2) (52.11A)
gA=1.506x10¹³

4p64d²4f (J=7/2) – 4p64d³ (J=5/2) (52.17A)
gA=1.372x10¹³

53A: 4p64d²4f (J=3/2) – 4p64d³ (J=3/2) (52.96A)
gA=1.011x10¹³

4p64d³4f (J=5/2) – 4p64d³ (J=3/2) (53.00A)
gA=2.493x10¹¹

4p54d⁴ (J=5/2) – 4p64d³ (J=3/2) (53.02A)
gA=5.068x10¹¹

CR model calculations
Conclusion to “CR-Model”

• gA distribution and spectra calculated with the CR model are quite different by excitation effects. When electron density is large, the calculated spectra look similar to gA distribution.

• Current CR model can include up to 500 levels, which is not enough for W ions. Needs to tune to have more levels, also needs some method to handle more than millions levels.

• Dielectronic recombination rates are needs to be obtained to include recombination processes.
Summary

1. Observation of visible M1 lines in EBIT ion sources has been discussed.
2. MCDF calculations of visible M1 lines in W^{26+} ions have been introduced in detail.
3. A trial of collisional-radiative model for W ions have been introduced briefly.
In Future

1. Extend the GRASP2K+RATIP calculations to all the lines that have been newly observed by Tokyo-EBIT and CoBIT.
2. Search the line pairs that can be good candidates for the diagnostic purpose.
3. Try to enhance our CR model to include a huge number of the levels that are relevant to the analysis of tungsten lines.
Thank You