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Abstract

Time-resolved visible emission spectra from the PBFA-II argon gas cell were measured in recent light ion beam-target interaction experiments. These emission spectra may be used to study the physics of beam transport and diagnose the cell plasma conditions. We discuss the theoretical analysis of the emission spectra in the wavelength region from 4300 to 4420 Å, where several ArII lines are observed. We examine opacity effects on the emission lines and assess the importance of beam excitation effects. Theoretical spectra are compared with the experimental data.

Introduction

Visible spectral line emission from the PBFA-II argon gas cell is of current interest because it can be used as a diagnostic for both light ion beam properties and cell plasma conditions [1]. For example, spectral line profiles emitted by atoms in the transport region may be sensitive to the electron density. By measuring and modeling the line profiles one may be able to determine electron densities in the gas cell, which in turn can be used to estimate the extent of beam neutralization. Spectral lines can potentially be produced by both ion-impact excitation and thermal electron collisional excitation. If one can identify transitions dominantly produced by ion-impact excitation, then the time-dependent line intensity can be used to measure beam current and beam divergence. It is expected that the ranges for cell plasma conditions are $T_e = 0.5 - 5$ eV and $N_e = 10^{16} - 10^{18}$ cm^{-3}. Under such conditions, opacity effects for the emission lines may be important. If the emission lines are optical thick, spectral line profile interpretation must be in conjunction with the radiation transport analysis.

In this paper, we study the opacity effects on the line emissions from PBFA-II argon gas cell and compare calculated emission spectra with the experimental data. We present results of calculations comparing the effects of beam excitation versus thermal excitations. We also examine the effects of carbon impurity of ion beam on level populations.

Theoretical Models

We present in this section a brief overview of the theoretical models used to compute the spectral properties and related atomic data. A detailed description of these models is presented elsewhere [2-5].

In our calculations, we use a collisional-radiative equilibrium (CRE) code [2] in which steady-state ionization and excitation populations can be computed by solving multilevel atomic rate equations self-consistently with the radiation field. For the plasma

conditions discussed in this paper, the distribution of atomic level populations were found to be close to local thermodynamic equilibrium (LTE). We have therefore neglected photoexcitation and photoionization effects in level population calculations.

Our atomic model for Ar consists of 192 levels distributed over the first five ionization stages (ArI−ArV). Energies for levels related to the lines of interest were selected from National Bureau of Standards tables [6]. Other level energies were obtained from Hartree-Fock calculations. The collisional couplings are complete for the resonant transitions from the ground state to the higher levels and the cross sections are calculated with Born-Coulomb approximation, while the less important cross sections of remaining transitions among the excited levels were approximated by a semi-classical impact parameter model, valid for dipole-allowed transitions. Ion impact excitation and ionization cross sections are calculated using a Plane Wave Born approximation (PWBA) model. It is necessary to indicate that the the beam excitation and ionization effects were not directly included in the CRE calculation in this preliminary study. The beam effects are checked separately by comparing the excitation rate with those of corresponding thermal electron process.

After the level populations are obtained, emission spectra are computed using an escape probability radiative transfer model which includes contributions from bound-bound, bound-free, and free-free transitions. In examining the opacity effects of spectral emission lines, spectral line widths are critical. Voigt line profiles are used to model line shapes. Natural, Doppler and Stark broadening effects are considered. Stark width is calculated in the electron impact approximation using the semi-empirical method of Griem [7]. By comparing the calculated Stark widths with available experimental data [8], the agreement is typically within a factor of 2.

Calculations and Discussions

In this study, calculations were run for the plasma conditions of $n_{ion} = 1.8 \times 10^{17}$ cm^{-3}, $T_e = 1, 2, 2.5, 3,$ and 4 eV. In each case we assumed a planar plasma of width 4 cm which represents the height of the gas cell and therefore the maximum line-of-sight distance through the Ar plasma. The electron density dependence on temperature is given in Table I. We have looked in particular at the wavelength region from 4300 to 4420 Å. All of the lines in this region have been identified as ArII lines. An experimental spectrum and the corresponding transition diagram are presented in Figure 1.

Table I: Dependence of Electron Density on Temperature

T(eV)	n_e $(10^{17}$cm$^{-3})$
1.0	0.4
2.0	2.2
2.5	3.2
3.0	3.7
4.0	5.1

Figure 2 shows a comparison between calculations with and without opacity at $T_e = 2.5$ eV. The 4348 Å line is most strongly affected by opacity, while some of the other lines are to a smaller extent. This is in qualitative agreement with the experimental spectrum because the 4348 Å line width was found to be considerably broader than the other lines [1]. We checked the sensitivity of the spectrum to the temperature and found that at $T = 1$ eV and $T = 4$ eV the spectral flux is very small. The ArII lines show up best at $T = 2 - 3$ eV. The ratio of the 4348 Å line to other lines increases above $T = 2.5$ eV because the opacity begins to drop. This can be seen more clearly from Figure 3, which shows the optical depth as a function of temperature and wavelength. The 4348 Å line has the greatest optical depth, with its line center value rising to about $5 - 6$ at $T = 2 - 2.5$ eV.
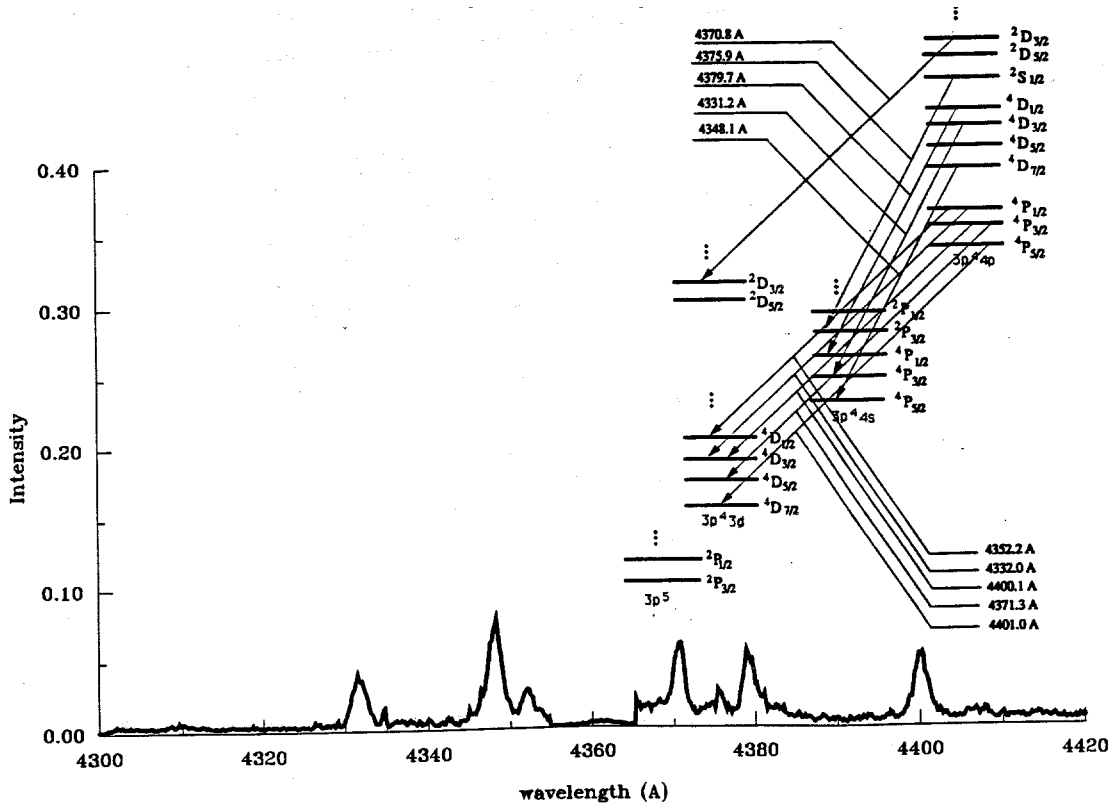
Figure 1. Spectra for shot 4659 in PBFA-II experiment and the corresponding transition diagram.

The role of ion beam impact excitation on level populations and line intensities can be examined by comparing the excitation rate with those of corresponding thermal electron collisional processes. For the intercombination transitions ($\Delta S = 1$), ion impact excitation cross sections are extreme small for high energy ion beams ($\mathcal{E}_{ion} \leq 1$ MeV). This is because there is only exchange interaction for intercombination transitions, and when $\mathcal{E}_{ion} \gg 1836 \times \Delta E_{ij}$, the exchange cross section decreases $\propto \mathcal{E}_{ion}^{-3}$. For the transitions with $\Delta S = 0$, ion impact excitation cross sections are substantially larger in the beam energies of interest. The excitation rate can be comparable to or even dominant the thermal electron collisional rate. Figure 4 compares the excitation rate for electron collisional excitation versus proton beam impact excitation as a function of the electron
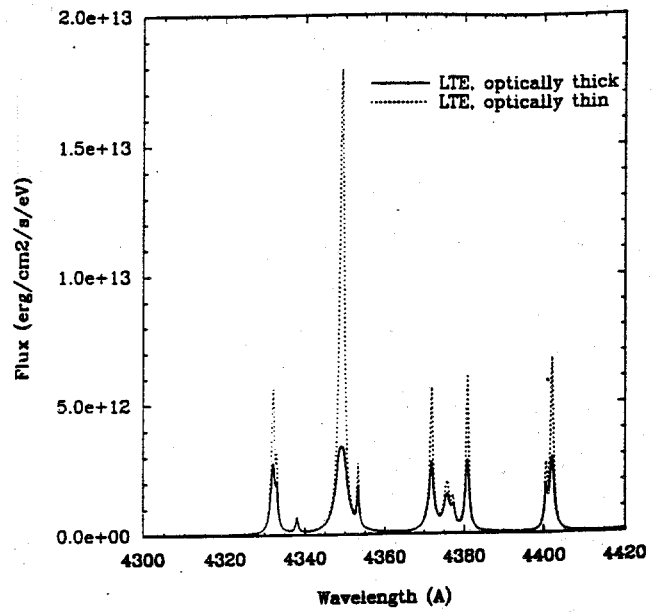
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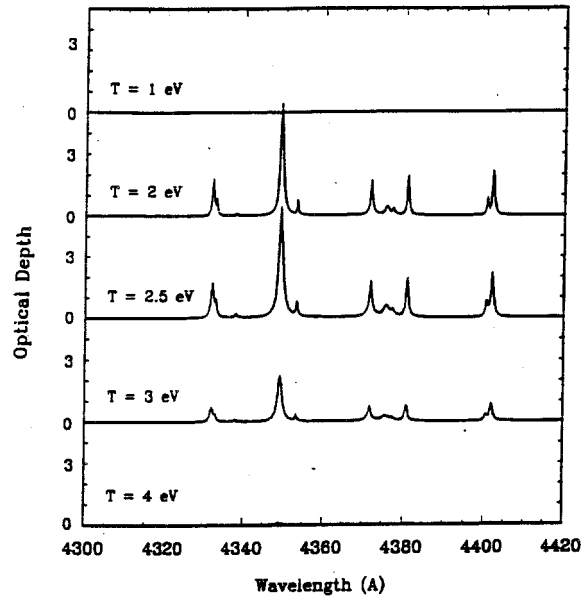Figure 2. Opacity effects on lines of interest.

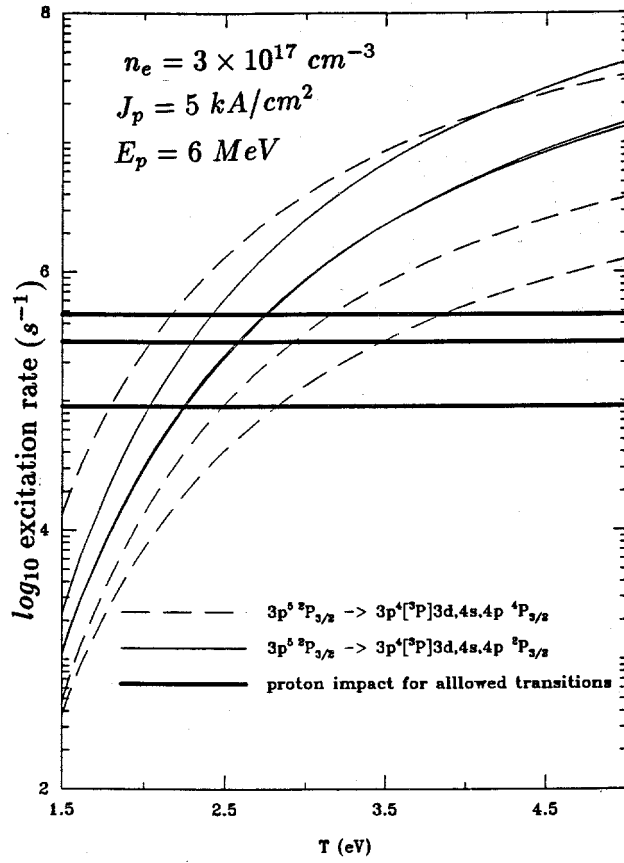Figure 3. Sensitivity of optical depth to temperature for lines of interest.

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Figure 4. Electron collisional and proton beam impact excitation rate

temperature for several important transitions relevant to the lines of interest. It can be seen that the rate for electron collisional excitation and proton beam impact excitation are approximately the same for allowed transitions when $T = 2 - 3$ eV. For intercombination transitions, the electron collision rate dominates. For the spectral lines of interest, most of the excited levels are coupled to the ground state by intercombination transitions, hence the direct coupling by ion impact excitation is not important for these levels. However, the populations of these levels may be affected by ion impact excitation in an indirect way, i.e., these levels can be strongly coupled to other levels which are related to the ground state via allowed transition by electron collisional excitation.

There is about 15% carbon impurity in the high energy proton beam. Whether carbon impact may play a role in affecting the level populations depends on the magnitude of corresponding excitation cross sections. Figure 5 shows the proton-impact and carbon-impact (CVII) cross sections for several excitation transitions. In PBFA-II experiments, the proton energy is about 6 MeV and the energy of the carbon impurity is about $12 - 21$ MeV. The current density of carbon impurity is a factor of 4 smaller than that of the proton, while the corresponding carbon-impact excitation cross section is about several times that of the proton-impact cross section and hence the excitation rates are about the same. This suggests that for those transitions in which ion-impact excitations are important, both proton and carbon excitation should be considered.

Summary

The preliminary results obtained from this study show that the strongest ArII lines observed in the PBFA-II argon gas cell (e.g., 4348 Å) may have optical depths of order ten, while many of the other lines may have optical depths of order unity. Opacity effects should therefore be considered in interpreting the observed spectra. We also find that the ion beam impact excitation can be important for allowed transitions but can be neglected for intercombination transitions. Carbon- and proton-impact excitation rates
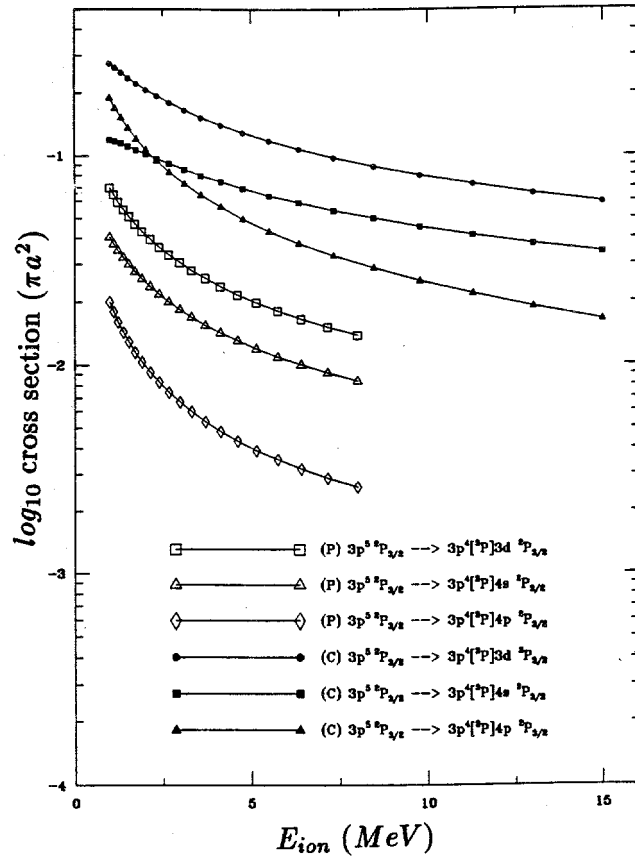
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Figure 5. Proton- and carbon-impact excitation cross sections

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were found to be comparable in magnitude. In the followup study, we intend to perform more detailed calculations to assess the importance of ion beam impact excitation effects on level populations.

Acknowledgements

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