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Experimental transition probabilities in the Ar III and Ar IV UV spectra

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ABSTRACT

We present transition probabilities (Einstein's *A* values) for 38 Ar III (doubly ionized argon) and 14 Ar IV (triply ionized argon) spectral lines from the wavelength interval 240–308 nm. Considered spectral lines are recorded in laboratory pulsed discharge. The relative line intensity ratio procedure has been applied in evaluation of transition probabilities. As a reference for transition probability evaluation we have chosen *A* value of 241.884 nm spectral line in Ar III spectrum and *A* value of 280.947 nm in Ar IV spectrum, both obtained theoretically. Careful analysis of experimental and existing theoretical data is conducted in order to deduce uncertainties. Presented Ar III and Ar IV *A* values are for the first time obtained relying on experimental data.

1. Introduction

There is a constant research effort regarding ionized argon transition probabilities (*A* values) in the last few decades [1,2]. In recent years argon spectral lines attract a growing attention [3,4]. In astrophysics [5–7], the argon spectral lines are of importance in determining chemical abundances of elements and for estimation of the radiative-transfer through stellar plasmas. On the other hand, argon plasma sources are applied in various fields of the industry and research [8–11]. The knowledge of the transition probabilities for excited states of multiply ionized argon is of the great importance for argon plasma modeling. Besides, relying on the transition probability values, one can calculate coefficients of the absorption and stimulated emission [12,13], both interesting in the laser physics [14,15]. Due to the large ionization cross sections of the argon atom (Ar I) and its singly charged ion (Ar II), the doubly and triply ionized argon ions (Ar III and Ar IV, respectively) are present in plasmas with low electron temperatures [16].

Regardless of these facts, Ar III and Ar IV *A* values are poorly investigated [17]. Number of Ar III and Ar IV *A* values, obtained theoretically, are presented in [17,18]. These values are calculated using Coulomb approximation with an error of 50%, or more. Some widely used collections of transition probabilities, calculated by different approaches, are published without error margin [19,20]. Comprehensive survey of ionized argon energy levels and spectral lines is given in [21].

Knowledge of uncertainties in calculated *A* values is essential for successful implementation of the relative line intensity ratio procedure, applied in this work. To solve this task, we employed Boltzmann-plot method which relates calculated transition probabilities and relative line intensities of corresponding spectral lines. We note that demanding absolute measurement of line intensities is not necessary. However, to achieve a meaningful result more than just a few spectral lines should be included in the Boltzmann-plot.

In this work we present 38 Ar III and 14 Ar IV *A* values obtained on the basis of the relative line intensity ratio method in the wavelength interval between 240 nm and 308 nm.

2. Experimental setup

Our plasma source is an optically thin, linear low-pressure arc [22,23]. The plasma was created in a quartz

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tube with the inner diameter of 5 mm and the length of 14 cm by means of a capacitor ($C=14\ \mu F$) charged up to 45 J of stored energy. Instead of pure argon we employed mixture of 72% Ar+28% He at the pressure of 133 Pa. Flowing regime of $\sim 10\ \text{cm}^3/\text{s}$ was sufficient to provide a fresh gas mixture for each subsequent shot. It was found that intensity variations of the most prominent Ar III and Ar IV lines are within 4% from shot to shot. The spectroscopic observations were made end-on along the axis of the discharge tube. Two hollow cylinders (l=1.5 cm, d=3.5 mm) made from tin were inserted at both ends of the tube; they serve as specific diaphragms. In this way just a light from the central part of the discharge tube comes to detector. Detection system consists of a McPherson (model 209) spectrograph (1.33 m focal length), equipped with a holographic grating containing 2400 grooves/mm (reciprocal linear dispersion 0.28 nm/mm in the first order) and Andor DH740-18F-03 iStar intensified CCD camera. The width (FWHM) of overall instrumental profile (spectrograph+ICCD camera) is 8.7 pm at 265 nm. The system was calibrated by using a set of pen-light sources (Ne, Ar and Hg) produced by LOT-Oriel. A relative radiometric calibration of the spectrograph+ICCD camera was done by using a deuterium light source (StellarNet SL3-CAL) for UV region from 200 to 400 nm. Measured line intensities were corrected to the sensitivity of the electro-optical detection system and normalized to the 0.5 μs exposure time.

Six frames of the recorded Ar III and Ar IV spectral lines are presented, as an illustration, in Fig. 1. We have recorded number of intense, well isolated spectral lines, not tabulated by NIST so far. Intensity flow for some of these lines, during the plasma decay [16], is characteristic for typical Ar IV lines. These lines are marked as (Ar IV) to signify that they, very likely, belong to the Ar IV spectrum.

3. Determination of the transition probabilities

The unknown transition probabilities (A_x) can be determined by using the well known equation [12,13], which is a base for relative line intensity ratio method

$$A_x = A_r \frac{I_x g_r \lambda_x}{I_r g_x \lambda_r} e^{(E_x - E_r)/kT} \tag{1}$$

The symbols I, λ, g, and E denote relative line intensity, wavelength, statistical weight, and energy of the upper level of the transition respectively. The index x denotes line with unknown transition probability, while r is associated to the reference spectral line. T is the plasma electron temperature, k is the Boltzmann constant.

The area under the profile, corrected to the sensitivity of the detection system and normalized to the exposure of 0.5 μs, is considered as the relative line intensity. The spectra are recorded at third μs after the beginning of the discharge, although the intensities of Ar III and Ar IV lines achieve the maximum later, after 10th μs [22]. It appears that at the very beginning of the discharge the maximum number of Ar III and Ar IV lines, belonging to the investigated wavelength interval, are well isolated and free from impurities (tin) spectra. At third μs the electron density, measured via broadening of He II Paschen alpha (P_α) line, is about $10^{23}\ \text{m}^{-3}$ and therefore sufficient to provide dominant contribution of the Lorentzian function in the Ar III and Ar IV lines profiles, due to Stark broadening [16].[1]

Applied fitting procedure is based on the numerical method described in [24,25]. We have chosen the 241.884 nm line as the reference for Ar III spectrum transition probability, while transition probability of the line 280.947 nm is taken as the reference in the Ar IV spectrum (see Eq. (1)). These two lines are intense, isolated, and with well defined profiles, they are indicated by boldface font in Fig. 1. Besides, both of them belong to the high lying transitions, minimizing the possibility of the self-absorption. The reference A values are taken from [20,18,26] for the Ar III and Ar IV lines, respectively.

4. Electron temperature

The electron temperature (T) was determined by using the Boltzmann-plot method [12,13,27], relying on the set of measured intensities of 40 Ar III spectral lines (see Table 1). The upper levels of the chosen set of spectral lines span more than 7 eV wide energy interval. We have applied two independent sets of transition probabilities in order to complete the Boltzmann-plot, one from Luna et al. [20] and another one from Kurucz [19]. Scattering of experimental data points was caused by the experimental errors in line intensities and by the uncertainties associated to the A values as well (see Figs. 2 and 3). It is obvious that Boltzmann-plot constructed with A values taken from Luna et al. has significantly lower scattering than the plot based on Kurucz's transition probabilities. It seems that A values of (some) Ar III lines, taken from [19], are inconsistent. Also, one can notice few typical outliers in the Boltzmann-plot constructed with A values from [20], Fig. 2. To avoid influence of these points on the best-fit line we have applied density of least-squares (DLS) method [25], with discrimination level set to 1.4σ. The slope of the best-fit line is -0.400 ± 0.020, which results in T=29,000 K ± 5% for electron temperature. Essentially straight line defined by the points in the Boltzmann-plot implies that all considered levels are in thermal equilibrium with free electrons. According to McWhirter [28] electron density must satisfy the following relation (McWhirter criterion) in order to maintain plasma in LTE condition: $n_e(m^{-3}) > 1.6 \times 10^{18}\sqrt{T}(\Delta E_{nm})^3$, where T is electron temperature in Kelvin, ΔE_{nm} is the largest gap between adjacent levels expressed in eV. In our case (T=29,000 K; $\Delta E_{nm} < 5$ eV) this value is $< 4 \times 10^{22}\ \text{m}^{-3}$, therefore our plasma with $n_e \sim 10^{23}\ \text{m}^{-3}$, estimated via He II P_α, is in LTE.

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[1] We note that fit to the Voigt function requires independent estimate of the electron temperature, for example from oxygen lines. It is common in practice that the electron temperature measured from different ionic species can vary for more than 10%. Since the electron temperature is important in our analysis, it would correlate Ar III and Ar IV transition probabilities to the spectral lines used for the electron temperature estimation. On the other hand Ar III and Ar IV line intensities estimated by the optimal Voigt fit, with all parameters left free, correspond to the values obtained employing Lorentzian function within $\sim 3\%$ in average.