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Second spectrum of chromium (Cr II), Part III: Radiative lifetimes and transition probabilities from highly excited $3d^45s$ levels

Safa Bouazza [a,*], Patrick Palmeri [b], Pascal Quinet [b,c]

[a] Département de Physique, Université de Reims-Champagne, UFR SEN, BP 1039 F-51687 Reims Cedex2, France
[b] Physique Atomique et Astrophysique, Université de Mons-UMONS, B-7000 Mons, Belgium
[c] IPNAS, Université de Liège, B-4000 Liège, Belgium

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ABSTRACT

In this study we have extended our previous investigations of Cr II spectrum to levels of the $3d^45s$ configuration. Once again an overall good agreement is observed for these levels between experimental oscillator strength values and our calculated data using two different approaches, namely the oscillator strength parameterization and the HFR+CPOL methods. Recurring to the latter model we have computed radiative lifetime values for 20 $3d^45s$ levels, confirming the well founded basis of recent experimental data, given in literature. From the use of the former method and with the help of a least squares fitting procedure to available experimental gf-values we have taken advantage of extracting for the first time the transition radial integral value for $3d^44p-3d^45s$, $\langle 4p|r^1|5s\rangle = 1.962\pm0.005$, which is confirmed favorably by *ab initio* results, obtained by the HFR method scaled by a factor 0.92 or directly by the HFR+CPOL approach. Finally a long list of semi-empirical oscillator strength, transition probability and branching fraction values is generated for around 500 Cr II transitions depopulating the $3d^45s$ levels. Our new gf data are compared successfully with those given by Kurucz.

* Corresponding author.
E-mail address: safa.bouazza@univ-reims.fr (S. Bouazza).

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Contents

1. Introduction

For many years we have performed atomic structure calculations in order to provide astrophysicists with new or improved radiative data in different ions. Such data play a key role in the investigation and the interpretation of the observed spectra produced by any type of celestial objects. This spectroscopic analysis, with the help of reliable radiative parameters, can be used to derive many properties of distant stars and galaxies, such as their chemical composition, temperature, density, mass, distance and luminosity, for example. Previously we have successfully studied the electronic structure of many different complex atomic systems. The present work is devoted to the calculation of oscillator strengths and transition probabilities in singly ionized chromium, paying a particular attention to transitions depopulating highly excited $3d^45s$ levels. This paper is the third part of a detailed and systematic analysis of the Cr II spectrum. As a reminder, in the first part [1] we have studied the fine structure in order to obtain level eigenvector to transform into actual intermediate coupling the transition matrix beforehand obtained in pure LS coupling with help of Racah algebra while, in the second part [2], our efforts were mainly focused on radiative transitions depopulating low-lying $3d^44p$ levels. For Cr II the most recent compilation of energy levels is due to Sugar & Corliss [3], based on the analysis of Kiess [4] who succeeded in classifying 1843 lines linking 138 even-parity levels of $3d^5$, $3d^44s$ and $3d^34s^2$ configurations to 139 $3d^44p$ odd-parity levels. Johansson [5] extended the Kiess study, particularly in near-infrared region and analyzed 450 additional levels. Sansonetti et al. [6–8] reported in turn new observations of Cr II some years later, in the near-ultraviolet region 1140–3400 Å, and also up to the infrared region: 2850–37 900 Å, using 10.7 m normal incidence vacuum spectrograph and FT700 vacuum ultraviolet Fourier transform spectrometer. In our recent study of the fine structure in Cr II [1], we notably revised the assignments of some levels wrongly classified in earlier lists of energy levels. We also shifted the positions of some quartets like $3d^45d$ ^4F_J for instance and we predicted the positions of still missing levels. Nevertheless we have to point out that $3d^45s$ levels were correctly assigned in previous studies and we have not changed any label of these levels. To compute oscillator strength values we used two different approaches, namely the HFR+CPOL model [9,10] and oscillator strength parameterization (OSP) method [11,12]. For the latter we need experimental data since transition radial integrals are treated as free parameters in the least squares fit to experimental gf values. Here we take advantage of the experimental work of a Swedish team from Lund University [13] which reported lifetime measurements of five $3d^45s$ ^6D levels at energy around 83 000 cm^{-1} and log gf values for 38 transitions from these levels. The lifetimes were obtained using time-resolved laser-induced fluorescence and gf-values were deduced by combining the experimental lifetimes with relative intensities, i.e. branching fractions.

2. Oscillator strength determination

The reader is invited to read one of our previous papers, for instance [2,14,15], in which the formulas and the approaches we have used to achieve our calculations are presented in detail. Usually before performing OSP calculations, we first have to select the strongest lines, not blended, and preferably those corresponding to transitions between levels with a limited number of leading components. In the present work we have not selected beforehand some lines but we have considered the complete set of experimental gf-values for the thirty eight transitions involving $3d^45s$ levels listed in [13]. The compositions of the eigenvectors obtained in the present work for these levels are displayed in Table 1. For odd-parity levels the compositions were already given in our previous paper [1]. When comparing our fitted data to the experimental oscillator strengths, a very satisfactory agreement is observed on the whole except for the lines whose wavelengths are: λ_{air} = 2787.914, 2899.195, 2945.277, 2967.410, 3013.455 and 3194.200 Å. Moreover, our OSP results are in close agreement with those obtained using our HFR+CPOL model, as described in [2], and with those reported by Kurucz [16]. Such comparisons can be found in Table 2. So we suggest that the experimental gf values of lines whose wavelengths are here above mentioned should be re-examined. From our semi-empirical fitting process, we have extracted the main transition radial integral value with a very good accuracy: $\langle 4p|r^1|5s\rangle = 1.962 \pm 0.005$, which corresponds to the HFR+CPOL value (1.969) or the HFR value computed by classical Cowan code [17], i.e. 2.139, scaled by a factor 0.92. This confirms the trends we already highlighted in [15] for several singly ionized ions.

3. Lifetime considerations

Some years ago Engman et al. [18] and Pinnington et al. [19] have used the beam-foil technique to measure radiative lifetimes of low-lying levels of Cr II $3d^4(^5D)4p$ configuration. Later Schade et al. [20], Pinnington et al. [21], Bergeson and Lawler [22] and Nilsson et al. [23] have extended these experimental data using time-resolved laser-induced fluorescence method (TR-LIF) on ions produced in a fast ion beam in a hollow cathode from laser-procured plasma but unfortunately for levels belonging to the same $3d^44p$ configuration. It is only in 2014 that Engström et al. [13] have reported for the first time lifetime measurements of five levels in the $3d^45s$ configuration, all of them belonging to the same ^6D multiplet located around 83 000 cm^{-1}. These data are gathered in Table 3 and compared to HFR+CPOL radiative lifetimes. We could expect some discrepancies between our calculated data and those given in [13] since we have observed for few transitions some divergences between our calculated gf and those given in [13]

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