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Lifetime Measurements for Excited Levels in Cr II

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Abstract

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Lifetimes for ten odd terms in Cr II which decay by transitions in the region 2 000–4 000 Å have been measured using the beam-foil technique. The results are compared with previous experimental data and available theoretical calculations.

1. Introduction

This paper reports experimental lifetimes for a number of levels in Cr II, measured by the beam-foil technique. Beginning with the study of Fe I lifetimes, by Whaling et al. [1] the beam-foil method has often been applied to the 3*d* transition metals [2]. Previously we have studied Sc [3] and Mn [4]. Lifetime measurements for the transition metals are usually motivated by the astrophysical need [5] for accurate transition probabilities.

A number of beam-foil studies of Cr lifetimes have already appeared in the literature. Using a low-energy accelerator Cocke et al. [6] determined a number of Cr I lifetimes and they later complemented these data by a measurement of relative intensities [7]. The lifetimes of ref. [6] were essentially confirmed by Andersen et al. [8] who used higher ion energies, typically 300 keV. A preliminary beam-foil study of level lifetimes in Cr I and Cr II has been reported by Pinnington et al. [9]. We have here remeasured a number of the Cr II lifetimes and also extended the work to other multiplets. Thanks to 5–10 times higher spectral resolution than obtained in ref. [9] certain ambiguities in assigning the lines in beam-foil spectra to Cr II multiplets have thereby been resolved.

The Cr II lifetimes obtained by a density-independent technique, such as the beam-foil method, are valuable checks of the oscillator strengths obtained from emission measurements. In their famous monograph Corliss and Bozman [10] give the *f*-values for 172 Cr II lines in the region 2 000–4 600 Å. On the basis of emission measurements and calculations with the Coulomb approximation Warner [11] has given absolute *f*-values for more than 600 Cr II lines (2 800–4 900 Å). Warner has further suggested that the Corliss and Bozman *f*-value scale for Cr II is high by a factor of 5.6 (0.75 dex). Additional studies of Cr II *f*-values by the shocktube technique [12] have also appeared in recent years.

2. Experiment

Intense and steady beams of Cr^+ (200–300 keV) were obtained from our 400 kV accelerator [13], by inserting Cr_2O_3 into the ion source and using the CCl_4 method. To increase the lifetime of the foils the beam currents through the 4 mm diameter foils were kept as low as 0.1–0.3 μA. The spectra (2 000–5 500 Å) were recorded with a Heath EUE 700 35 cm monochromator, equipped with a Peltier-cooled EMI 6256 photomultiplier. The lifetimes were measured in the usual way, by moving the foil in steps of 0.25 mm or larger and recording the counting rate. The optical normalization technique [14] was used to reduce the effects of beam instabilities and changes in foil properties.

Fig. 1 shows a partial spectrum in the UV, recorded with 80 μ slit settings. The line widths of about 3 Å are partly instrumental, partly caused by Dopple reffects. Although our linewidths represent an improvement over previous experimental conditions [9], careful studies of possible line blending are still required for obtaining meaningful lifetime data. Between 2 600 and 3 000 Å our spectra showed 80 resolved lines, to be compared to the 400 Cr I and 600 Cr II lines found by Kiess [15] in this region. A satisfactory separation of Cr I and Cr II lines can be achieved in the beam-foil case, by varying the beam energy; at e.g. 280 keV the Cr I lines below 3 000 Å were quite weak. However, the blending of different Cr II multiplets still causes appreciable problems. These could sometimes be reduced by comparing the beam-foil line intensities to those given in ref. [15] or expected for *LS*-multiplets. Furthermore, we tried to measure the lifetime of a term from as many lines as possible. Whenever the decay times differed significantly, this was ascribed to blending and the results were discarded. This method is admittedly an unsafe one for eliminating all measurements on blended lines. Different Cr II multiplets arising from e.g. the $3d^4 4p$ configuration have namely very similar lifetimes.

It is thus clear that line blending may lead to erroneous lifetimes in a complex spectrum such as Cr II. Additional uncertainties are introduced by cascading and energy loss in the foil. The majority of our decay curves showed comparatively slight cascading, with replenishment ratios $R(0)$ usually below 0.2, in agreement with ref. [9]. (For a definition of $R(0)$ see ref. [16]). Spectral studies further showed that cascading transitions, from higher-lying levels, into the terms under study were usually quite weak in our beam-foil spectra. The counting statistics were usually good enough to allow differentiation of the decay curves, resulting in elimination of the background and reduction of cascade effects [3].

Because of the comparatively high Cr^+ ion energies we could not use our 18 cm electrostatic analyzer [4] for velocity measurements after the foil. Theoretical relations [17] for electronic and nuclear stopping were used instead. For 280 keV Cr^+ ions ref. [17] predicts an energy loss of 6.1 keV per 1 μg/cm² carbon foil. Our carbon foils, from the Arizona Foil Company had thicknesses in the interval 4–7 μg/cm². According to the manufacturer the uncertainties in quoted thickness are ±10%.

As a check of our experimental accuracy we also remeasured a number of Cr I lifetimes and generally found good agreement with

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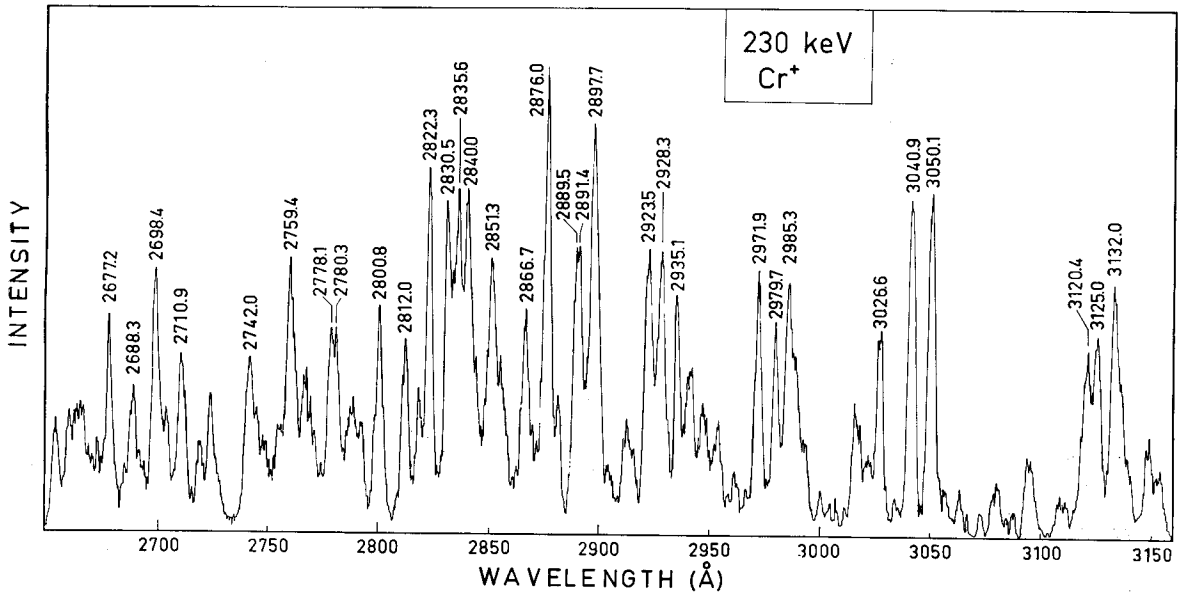

Fig. 1. Beam-foil spectrum of Chromium between 2 650 and 3 150 Å. Most lines observed here are due to Cr II transitions. The wavelengths in the figure are from ref. [15].

previous beam-foil data. For example, our lifetime for the Cr I $y\ ^5H^0$ term of 9.6 ± 0.7 ns agrees well with the value 9.7 ns given in refs. [6] and [8].

3. Results

The lifetimes of ten odd terms in Cr II ($z\ ^6P^0$, $^6D^0$, $^6F^0$, $^4P^0$, $^4F^0$, $^4G^0$, $^4H^0$, $^4I^0$, $^2I^0$ and $y\ ^4H^0$) were measured from 21 spectral lines, as shown in Table I. Each value represents the result of 4–6 individual measurements at 2–3 different beam energies. The estimated error limits, which are about 3 times larger than the statistical errors, also include a 3% velocity uncertainty. Our results are here compared to previous beam-foil data of Pinnington et al. [9] and the lifetimes computed from Warner's *gf*-values [11].

The $z\ ^6P^0$ lifetime was determined from transitions to the $a\ ^6S$ and $a\ ^6D$ terms. Due to low detection efficiency below 2 200 Å statistics were poor for the 2 061 Å line which explains the somewhat larger error. The decay curves for the lines at 2 061, 2 742 and 2 766 Å showed very similar shapes indicating that blending from other multiplets was negligible. As an example of the relative insignificance of cascading we may mention that transitions from e.g. the $e\ ^6S$, ^6P and ^6D terms into $z\ ^6P^0$ were extremely weak in beam-foil spectra.

Of our measured values for the $z\ ^6D^0$ lifetime, that based on the $a\ ^4D$–$z\ ^6D^0$ intercombination multiplet is more reliable, because of less blending. The region close to 2 677 Å also contains strong transitions from the $z\ ^4P^0$ term. Table I gives the results of three different sets of measurement for the $z\ ^6F^0$ of which the most reliable lifetime is obtained from the decay of the 2 866 Å line. The lines at 2 835 and 2 876 Å might be more affected by blending. It is important to note, however, that the 2 835 Å decay was measured at 30–50% higher resolution than shown in Fig. 1 and possible influences from e.g. the 2 840 Å line ($a\ ^4H$–$z\ ^4I^0$) are thus less significant.

While these odd sextet terms decay to a few lower terms the complexity increases for the lowest odd quartet terms which generally possess several decay channels. The lines of the $a\ ^6D$–$z\ ^4P^0$ intercombination multiplet (2 677–2 724 Å) showed the expected intensity ratio in our spectra which facilitated meaningful decay studies. The $z\ ^4F^0$ lifetime was determined from lines to the $a\ ^4D$ and $a\ ^4G$ terms. Here the virtual absence of blending favours the results obtained from the 3 197 Å line ($a\ ^4G$–$z\ ^4F^0$). The line at 2 898 Å, which has been assigned to the $z\ ^4G^0$ decay (Table I) may also contain contributions from the decays of several other terms, e.g. $y\ ^2G^0$, $y\ ^4G^0$ and $z\ ^2K^0$ [15], and here our result could suffer from a substantial systematical error. On the basis of relative-intensity studies we tentatively assign our measured lifetime 4.2 ± 0.6 ns to the $z\ ^4G^0$ term.

The situation is much clearer for the $z\ ^4H^0$ and $z\ ^4I^0$ terms, the

Table I. *Radiative lifetimes in Cr II*

Wavelength (Å)	Transition[a]	Mean lifetime of upper level (ns) This work	Other experiments	Theory[b]
2 061	$a\ ^6S_{5/2}$–$z\ ^6P^0_{5/2}$	3.3 ± 0.6		
2 742	$a\ ^6D_{3/2}$–$z\ ^6P^0_{5/2}$	3.2 ± 0.4	3.3 ± 0.2[c]; 5.0[d]	4.2
2 766	$a\ ^6D_{9/2}$–$z\ ^6P^0_{7/2}$	3.3 ± 0.4		
2 677	$a\ ^6D_{7/2,9/2}$–$z\ ^6D^0_{7/2,9/2}$	5.1 ± 0.7	3.2 ± 0.2[c]; 5.2[d]	3.4
3 368	$a\ ^4D_{7/2}$ –$z\ ^6D^0_{5/2}$	5.4 ± 0.6		
2 835	$a\ ^6D_{9/2}$–$z\ ^6F^0_{11/2}$	5.0 ± 0.7	3.3 ± 0.3[c]; 4.4[d]	4.6
2 866	$a\ ^6D_{3/2}$–$z\ ^6F^0_{9/2}$	4.8 ± 0.5		
2 876	$a\ ^6D_{7/2}$–$z\ ^6F^0_{5/2}$	5.3 ± 0.7	4.2 ± 0.2[c]	
2 698	$a\ ^6D_{7/2}$–$z\ ^4P^0_{5/2}$	4.1 ± 0.4	2.6[d]	
3 132	$a\ ^4D_{7/2}$–$z\ ^4F^0_{9/2}$	4.7 ± 0.5		
3 197	$a\ ^4G_{9/2}$–$z\ ^4F^0_{7/2}$	4.9 ± 0.5	4.4 ± 0.2[c]; 3.8[d]	4.2
2 898	$a\ ^4F_{9/2}$–$z\ ^4G^0_{11/2}$	4.3 ± 0.6[e]	4.2 ± 0.2[c]; 6.6[d]	
2 971	$a\ ^4H_{13/2}$–$z\ ^4H^0_{13/2}$	4.7 ± 0.5		
2 979	$a\ ^4H_{11/2}$–$z\ ^4H^0_{11/2}$	5.0 ± 0.5	4.0 ± 0.4[c]; 5.3[d]	3.3
2 822	$a\ ^4H_{13/2}$–$z\ ^4I^0_{15/2}$	4.4 ± 0.5		
2 840	$a\ ^4H_{9/2}$ –$z\ ^4I^0_{11/2}$	4.4 ± 0.5	8.4[d]	3.2
2 851	$a\ ^4H_{7/2}$ –$z\ ^4I^0_{9/2}$	4.0 ± 0.5		
2 800	$b\ ^4G_{11/2}$–$y\ ^4H^0_{13/2}$	4.2 ± 0.5	8.9[d]	3.0
2 812	$b\ ^4G_{9/2}$ –$y\ ^4H^0_{11/2}$	3.9 ± 0.5		
3 040	$a\ ^2H_{9/2}$ –$z\ ^2I^0_{11/2}$	5.3 ± 0.8	5.0[d]	3.6
3 050	$a\ ^2H_{11/2}$–$z\ ^2I^0_{13/2}$	5.7 ± 0.6		

[a] We use the notation of Kiess [15].
[b] Warner [11] Coulomb approximation calculation.
[c] Pinnington et al. [9], beam-foil measurement.
[d] Warner [11], emission measurement of *f*-values. Warner's measured and calculated lifetimes should in several cases be regarded as upper limits, because certain decay channels have been omitted; see discussion in the text.
[e] Assignment of the 2 898 Å line in beam-foil spectra uncertain, see text.

lifetimes of which would be reproducibly obtained from several multiplet members. Measurements using narrow slits were here facilitated because of sufficient intensity. In comparison to Kiess' data [15] the beam-foil spectra tend to emphasize the transitions from terms with high angular momenta. Also the $y\ ^4H^0$ term was strongly excited and this allowed lifetime studies.

Of the doublet configuration we were able to measure the $z\ ^2I^0$ lifetimes since the transitions to $a\ ^2H$, particularly the 3 050 Å line occur in a relatively clear part of the spectrum.

Table I shows that our new lifetimes for the $z\ ^6P^0$, $z\ ^4F^0$, $z\ ^4G^0$ and $z\ ^4H^0$ terms agree, within the error limits, with the beam-foil data of Pinnington et al. [9]. For the $z\ ^6D^0$ and $z\ ^6F^0$ terms the present study gives 20–50% longer lifetimes than those found in ref. [9]. In view of the good agreement in most cases the main part of this discrepancy is hardly due to improper energy-loss corrections, since these would have yielded an overall disagreement for the two sets of data. Instead we believe that these remaining disagreements are due to different amounts of blending. While our 3 Å line widths are not entirely satisfactory for lifetime purposes, they still facilitate the analyses. In the case of the $z\ ^6D^0$ term, our measurements on the 3 368 Å intercombination line also serve as an extra check.

We also compare our data with Warner's [11] theoretical and experimental results. The lifetimes extracted from Warner's *gf*-values should sometimes be considered as upper limits because certain multiplets were not included in ref. [11]. In the case of sextet terms, ref. [11] gives no *f*-values for e.g. the $a\ ^6S$–$z\ ^6P^0$ and $a\ ^4D$–$z\ ^6D^0$ transitions. There is also a lack of information for the quartet and doublet terms and the following decay modes were not included in Warner's tables: $z\ ^4F^0$ (to $b\ ^4F$ and $b\ ^4G$), $z\ ^4G^0$ (to $a\ ^4G$), $z\ ^4H^0$ (to $a\ ^4G$) $y\ ^4H^0$ (to $a\ ^4H$), $z\ ^2I^0$ (to $a\ ^2I$). The absence of these transition probabilities prevents detailed comparisons between the present lifetime study and ref. [11]. With these reservations in mind we note from Table I that there is relatively satisfactory agreement between this work and ref. [11]. The agreement might even improve in a few cases ($z\ ^4I^0$, $y\ ^4H^0$) if the decay constants for all branches were known.

Shackleford [12] gives the *gf*-values for 21 Cr II lines between 3 100 and 4 600 Å and finds that here the Corliss and Bozman values are too high by a factor of 9. Essentially the same result has been obtained by Byard [12] who studied 13 Cr II lines (3 100–3 400 Å). The *f*-values of ref. [12] are thus slightly lower than those given in ref. [9]. However, this difference is not sufficiently large to be checked by the present lifetime experiment. The lines studied in ref. [12] have usually a relatively low transition probabilities with correspondingly small effects on term lifetimes.

Several authors have studied the Cr abundance in the solar photosphere. In most analyses *f*-values for Cr I transitions have been used. The beam-foil studies of Cocke et al. [6, 7] support a value of $\log N_{Cr} = 5.80$, on the $\log N_H = 12.00$ scale, an increase of previously suggested values [18] by 0.6–0.7 dex. From studies of Cr I and Cr II lines in the solar atmosphere Warner [19] first proposed $\log N_{Cr} = 5.47$ (based on the correction of the Corliss and Bozman *f*-value scale for Cr II by -0.75 dex, as mentioned above), while in a later analysis [20] the value $\log N_{Cr} = 5.67$ was given. Several of the Cr II lines discussed by Warner [19] are transitions (4 000–4 900 Å) from terms studied in the present work, e.g. $z\ ^4P^0$, $z\ ^4F^0$ and $z\ ^6D^0$. However, the astrophysical lines are usually relatively weak and the effects of their transitions probabilities on the term lifetimes are consequently small. In view of the good agreement between our remeasured Cr I lifetimes and those found in refs. [6, 7], the present study seems to support the solar abundance found by Cocke et al. [6, 7].

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