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Wavelengths and lifetime measurements in He-like Cr XXIII and Li-like Cr XXII

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Abstract. — Two and three electron spectra have been investigated in a beam-foil experiment with a chromium ion beam at 7 MeV/amu. The He-like Cr XXIII (Cr 22 +) 3S1 - 3P2 transition is measured at 325.36 ± 0.5 Å, giving a transition energy of 307 350 (360) cm⁻¹; this value is compared to the theoretical values given by De Serio et al. [1] and Hata and Grant [2]. A higher accuracy would be needed to provide a good test of the two-electron QED effects. The Li-like Cr XXII (Cr 21 +) 2S 1/2 - 2P3/2 transition is found at 222.97 ± 0.05 Å leading to a transition energy of 448 490 (102) cm⁻¹ in very good agreement both with previous measurements in a tokamak plasma [9] and with theoretical predictions [3, 13b].

Over the past few years, much experimental and theoretical work has been devoted to the measurement and prediction of the Is 2s 3S1 - Is 2s 3P0,2 transition energies in He-like ions [1-8]. These transition wavelengths can lead to a sensitive test of quantum electrodynamics (QED) and relativistic corrections for high Z two-electron ions. The most recent papers [1, 2] on the theoretical estimation of these energies point out the importance of the QED correlation effects between the two electrons and the given values differ mainly on the methods used to estimate these QED corrections. Experimental tests of these calculations are made either by very high precision measurements on light ions [3-6] or by measurements on the higher Z elements available with the powerful heavy ions accelerators [7, 8]. As pointed out by R. De Serio et al. [1], significant discrepancies are to be noticed between theory and experiments. More precise measurements of these transitions are still needed all along the He-like isoelectronic sequence. Our contribution to this field which is presented here is a measurement of the 3S1 - 3P2 transition energy in He-like Cr XXIII.

Precise measurements of the resonance transitions energies of three electron heavy ions is also of great interest. We have observed the 2S1/2 - 3P3/2 transition in Li-like Cr XXII and we compare our result to that obtained by Hinnov [9] and to the theoretical values compiled by Berry et al. [3].

In addition, as lifetimes were needed for precise interpretation of our spectra, we have measured the lifetimes of the 1s 2p 3P2 level of He-like Cr 22+ and of the 1s 2p 2P3/2 level of Cr 21+. The results are compared to available theoretical values.

I. Experiment.

The experiment has been performed at the ALICE facility at Orsay. A beam of Cr 5+ ions, accelerated by the LINAC to 1.15 MeV/A, is stripped to Cr 16+ and injected in the separated sectors cyclotron to be
further accelerated to 7 MeV/A (total energy 361 MeV and \(v/c = 0.12\)). This beam is then stripped to charge equilibrium in a 220 \(\mu g/cm^2\) carbon foil. The charge state distribution is centred at Cr 22+ and the spectra are dominated by Cr XXII and Cr XXIII lines. The observation is made at 90 degrees with respect to the ion beam by very careful alignment of the collision chamber prior to the experiment; from the diaphragms defining the beam and the construction of the spectrometer, the error on the observation angle is less than \(\pm 0.05^\circ\). The spectrometer is of the Roman-Vodar type equipped with an aluminium coated ruled grating (600 gr/mm) blazed at 250 Å for an 82° angle of incidence. The wavelength drive (or the target position for lifetimes measurements) is controlled by a step motor. The detector is a channeltron associated with a photon counting system. The counting time is controlled by the beam current in the Faraday cup. The slit widths are 150 \(\mu m\), the full width at half maximum (FWHM) is about 0.9 Å and the scan increment 0.2 Å in the two wavelength ranges studied (139-285 and 300-332 Å). The 2s 2p transitions of He-like and Li-like spectra appear surrounded by several hydrogenic \(n = 1\) (\(n > 5\)) lines in 1, 2 and 3 electrons spectra used as reference lines. Figure 1 shows three parts of the recorded spectrum where the lines of interest can be seen. The principle of wavelength determination of unknown lines is the following:

i) theoretical calculation of absolute wavelengths of the reference lines;

ii) calculation of the actual wavelengths due to Doppler shifts;

iii) calibration of the spectrometer;

iv) correction of the determined wavelengths for Doppler shifts to obtain absolute values of the transition energies.

2. Reference lines.

Reference lines used in the first spectral region (Fig. 1) are the two electron He-like 5-6, 6-7 and three electron Li-like 5-6, 6-7 transitions to determine the 2s \(^2S_{1/2} - 2p \ ^2P_{3/2}\) Cr XXII transition energy. The Li-like 5-6 (2nd order) and hydrogen-like 7-8 lines are used in the same way for the 2s \(^2S_{1/2} - 2p \ ^3P_{2}\) Cr XXIII transition. Following Edlen [10] the term energy of a hydrogenic \(n, l\) level is taken as the pure hydrogenic value corrected by relativistic and core polarization contributions.

\[
T(n, l) = R\xi^2/n^2 + \Delta r(n, l) + \Delta \rho(n, l)
\]

\[
\Delta r(n, l) = R\xi^2/n^2 \left( n - 3/4 \right)
\]

\(\Delta \rho(n, l)\) is expanded in multipolar contributions :

\[
\Delta \rho(n, l) = A(Z) P(n, l) \left[ 1 + k(Z) q(n, l) + \cdots \right]
\]

\(P(n, l)\) and \(q(n, l)\) are given by Edlen [10] and do not depend on the effective charge \(\xi = Z - (N - 1)\). \(A\) and \(k\) have to be determined for each isoelectronic sequence. From the tensor polarizabilities given by Dalgarno and Stewart [12] we derive expressions for \(A(Z)\) and \(k(Z)\) :

\[
A(Z) = (9/2) \left( [Z - 1)/Z]^4 \right.
\]

and

\[
k(Z) = (10/3) \left( [Z - 1)/Z] \right]^2
\]
for the He-like and the empirical fit of Edlen [13a] for Li-like levels:

\[ A(Z) = 9[(Z - 2)(Z - s)]^4 \]

with \( s = 0.3397 + 0.102 (Z - 0.4)^{-1} \) and

\[ k(Z) [A(Z)]^{1/2} = 0.2113 Z + 0.598 - 2.4 Z^{-1} \]

It is well known that \( \Delta n = 1 \) transitions are dominated by the yrast type \((n, l = n - 1) \rightarrow (n - 1, l' = n - 2)\). Nevertheless, for precise determination of the centroid of the non resolved fine structure, the other components \((n, l) \rightarrow (n - 1, l' = l - 1)\) have to be taken into account. They lead to slightly asymmetric line shapes but in the limits of our signal to noise ratio, we fit a global Gaussian profile to the sum of two or three of these components after Doppler correction for each one.

Due to the high velocity \((v/c = 0.12)\) of the emitting ions, the actual wavelength of a transition is

\[ \lambda = \lambda_0 [1 - (v/c)^2]^{-1/2} [1 - (v/c) \cos \theta] \]

(\( \theta \) is the observation angle). The relative error \( \Delta \lambda / \lambda \) due to misalignment with respect to the beam is less than \( 10^{-4} \). The first factor is commonly called the red transverse second order Doppler shift. We have also to take into account a significant blue shift due to the population decrease of the emitting level during the time of flight of the ions through the beam volume sighted by the monochromator. The lifetimes of the upper levels are calculated from hydrogenic transition probabilities, taking cascades into account. As an example of the procedure, we show in figure 2, the different steps used to obtain the actual wavelength of the Li-like 6-7 line used as reference and table I gives the absolute and mean actual wavelengths of these reference lines.

3. Experimental wavelength determination.

From the experimental spectra (Fig. 1), one extracts the different lines out of the noise, subtracts the background and fits a Gaussian profile to the experimental points (Fig. 3). The centroid of each line is determined

<table>
<thead>
<tr>
<th>SPECTRUM</th>
<th>TRANSITION</th>
<th>ABS.</th>
<th>OBS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr XXII</td>
<td>5g - 6h</td>
<td>153.935</td>
<td>155.012 ± 0.015</td>
</tr>
<tr>
<td></td>
<td>5f - 6g</td>
<td>153.820</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6h - 7i</td>
<td>255.360</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6g - 7h</td>
<td>255.320</td>
<td>257.158 ± 0.025</td>
</tr>
<tr>
<td></td>
<td>6f - 7g</td>
<td>255.085</td>
<td></td>
</tr>
<tr>
<td>Cr XXIII</td>
<td>5g - 6h</td>
<td>140.84</td>
<td>141.81 ± 0.014</td>
</tr>
<tr>
<td></td>
<td>5f - 6g</td>
<td>140.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6h - 7i</td>
<td>233.63</td>
<td></td>
</tr>
<tr>
<td>Cr XXIII</td>
<td>6g - 7h</td>
<td>233.54</td>
<td>235.27 ± 0.023</td>
</tr>
<tr>
<td></td>
<td>6f - 7g</td>
<td>233.38</td>
<td></td>
</tr>
<tr>
<td>Cr XXIV</td>
<td>7i - 8k</td>
<td>330.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7h - 8i</td>
<td>330.53</td>
<td>332.99 ± 0.033</td>
</tr>
<tr>
<td></td>
<td>7g - 8h</td>
<td>330.39</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. — Determination of the Doppler effects on the Cr XXII 6-7 Li-like line. a) Absolute wavelengths of the three main components. b) Each point gives the amplitude and the wavelength of each component in a 0.11 mm region at a position \( x \) across the beam volume sighted by the spectrometer. (0.2 < \( x < 1.5 \) from the foil surface). c) The dashes are the sums every 0.1 \( \AA \) of the 3 x 12 Gaussian lines defined in b. The dotted line is the Gaussian fit through the calculated points.
Fig. 3. — Gaussian fit to the $^2S_{1/2} - ^2P_{3/2}$ Cr XXII line after background subtraction.

in « channel units ». The dispersion of the spectrometer is fitted, using the reference lines and interpolated to determine, with the best precision, the experimental wavelengths of the transitions being measured. We have also calibrated the spectrograph with a Ne II or He II light source which is simply a Penning vacuum gauge situated just in front of the entrance slit of the monochromator.

4. Results.

4.1 Lithium-like Cr XXII $^2S_{1/2} - ^2P_{3/2}$. — Using the 5-6 and 6-7 Cr XXII and Cr XXIII reference lines (Fig. 1 and table I), the observed wavelength of the transition is found to be:

$$\lambda_{\text{exp}} = 224.66 \pm 0.05 \text{ Å}.$$ 

When corrected for the second order Doppler shifts and lifetime effects, our mean absolute value is:

$$\lambda_a = 222.97 \pm 0.05 \text{ Å}$$

corresponding to a transition energy of 448 490 (102) cm$^{-1}$. Despite the quite poor accuracy of this result, it agrees well with previous measurements in tokamak plasmas by Hinnov [9] (448 430 cm$^{-1}$), with the « variational screening » calculations of Berry et al. [3] (448 450 cm$^{-1}$) and with the semiempirical calculations of Edlen [13b] (448 400 cm$^{-1}$).

4.2 Helium-like Cr XXIII $^3S_1 - ^3P_2$. — We measured the wavelength of this line in two completely separated runs. In the first we used the hydrogen-like Cr XXIV 7-8 transition and the second order Cr XXII 5-6 transition for wavelength calibration. In several spectra, the intensity ratio between the H-like reference and the $^3S_1 - ^3P_2$ line of interest varied considerably, depending on the flatness of the foil, and they have never been well separated (Fig. 1). Because of this may result a small systematic error corresponding to a red shift. Careful analysis of the different obtained spectra leads to an observed wavelength of:

$$\lambda_{\text{exp}}^{(1)} = 328.04 \pm 0.20 \text{ Å}.$$ 

The quoted error is estimated from the statistics of the experimental wavelength determination from the different records of the spectra. The Doppler shift corrections give an absolute wavelength of:

$$\lambda_a^{(1)} = 325.58 \pm 0.2 \text{ Å}.$$ 

In the second run, mainly devoted to lifetime measurements, the wavelength scan was restricted to a few angstroms around the centre of the $^3S_1 - ^3P_2$ line. A better experimental position for the line centre could be obtained but the reference lines emitted by the Cr ions were not registered on the same scan. For spectrometer calibration we have used the He II lines at 256.317 and 303.781 Å, emitted by a very weak discharge in a Penning gauge situated just in front of the entrance slit of the spectrometer and in which a pressure of 10$^{-4}$ torr of helium was maintained by a leak valve. The intensity of these lines apparently gives a more precise calibration but, as they are not emitted by fast ions, the Doppler corrections on the $^3S_1 - ^3P_2$ line may be affected by systematic errors. Careful analysis of the results gives an absolute wavelength:

$$\lambda_a^{(2)} = 325.14 \pm 0.25 \text{ Å}.$$ 

The precisions of the two measurements are estimated from the statistics of the experiments. The two values of the wavelength are slightly different but compatible within the error bars.

To take these possible systematic errors into account, we take the mean wavelength of our two measurements as the final result with an uncertainty including the total estimated errors.

$$\lambda_a = 325.36 \pm 0.5 \text{ Å}.$$ 

The transition energy is then 307 350 (360) cm$^{-1}$ to be compared with the theoretical values given by De Serio et al. [1] (307 627.4 cm$^{-1}$) and by Hata and Grant [2] (307 663.7 cm$^{-1}$). For illustration of the comparison between theory and experiment, we reproduce on figure 4 the plot of the quantity $Q_2 = (E_{\text{exp}} - E_{\text{th}}) \times 100/Z^2$ defined by De Serio [1] in which $E_{\text{th}}$ does not include the two-electron QED corrections. We have plotted on the graph our experimental result as well as previous measurements on iron [7] and copper [8].

As can be seen, the theoretical values of Hata and Grant [2] (dashed line on the graph) differ from those given by De Serib [1] for $Z > 15$. Our experimental values for copper and iron are in better agreement with Hata’s results which seems to indicate that the two-electron QED corrections may be even more important than suggested by the theoretical predictions. The Cr results do not confirm this tendency but, unfortunately the accuracy is quite poor and evidently one needs more results with a better accuracy for this 2s-2p energy transition in very high Z helium-like ions.
5. Lifetime measurements.

We have measured the lifetimes by the conventional beam-foil method, taking advantage of the fast speed of the emitting ions excited in a very short time when passing through the thin foil. The foil is moved upstream by a step motor and photons were counted for each step, the signal is normalized to the beam current. The spectrometer is first tuned to the maximum of the line under investigation and then the foil scan is repeated with the spectrometer set at a wavelength where no lines appear in the vicinity of the previous one. In fact, the background noise may depend on the foil position with respect to the entrance slit of the spectrometer, specially if the beam is not well collimated and hits the target holder. A polynomial is fitted through the background points and then the mean noise for each target position is subtracted from the signal.

Decay curves of the 2p 2P3/2 Cr XXII and 1s 2p 3P2 Cr XXIII are displayed on figures 5 and 6 respectively. No cascade effects are observable so they have been neglected in the derivation of the lifetimes from experimental data. The obtained values are listed in table II and compared to available theoretical results.

Table II. — Lifetimes (ps)

<table>
<thead>
<tr>
<th></th>
<th>Cr XXII 2P3/2</th>
<th>Cr XXIII 3P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>307(20)</td>
<td>303 (14)</td>
<td>253 (30)</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
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</tbody>
</table>

For the Li-like Cr XXII 2P3/2 level, the experimental value is in very good agreement with the theoretical result given by Cheng et al. [15]. For the He-like Cr XXIII 3P2 level, our result is slightly higher than the values published by different authors [16-18].
6. Conclusion.

These experiments show clearly that within the limits of precision obtained in such high Z beam-foil spectroscopy, the present theory of atomic structure of highly charged ions is verified if one takes into account the QED corrections including correlation effects in two-electron atoms. More precise or higher Z experiments are now possible with the recently developed high energy accelerators. New results may further stimulate theoretical developments.

Acknowledgments.

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References