LAMB SHIFT AND FINE STRUCTURE OF n = 2 IN ^{35}Cℓ XVI

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Résumé. Nous avons mesuré les longueurs d'onde des transitions 2s $^3S_1$ - 2p $^3P_2$ et 2s $^3S_1$ - 2p $^3P_0$ dans Cℓ XVI à 613.825 ± 0.012 Å et 705.975 ± 0.064 Å. Ces resultats donnent unemesure du Lamb shift 2s - 2p pour Z = 17 avec un precision de ±0.3%.

Abstract. We have measured the wavelengths of the 2s $^3S_1$ - 2p $^3P_2$ and 2s $^3S_1$ - 2p $^3P_0$ transitions in Cℓ XVI to be 613.825 ± 0.012 Å and 705.975 ± 0.064 Å. Our precision is sufficient to provide measurements of the $2s_{1/2}$ - $2p_{1/2}$ and $2s_{1/2}$ - $2p_{3/2}$ Lamb shifts to an accuracy of ±0.3% and to test Q.E.D. theory in the strong field region.

We present wavelength measurements of the 2s $^3S_1$ - 2p $^3P_2$ and 2s $^3S_1$ - 2p $^3P_0$ transitions in helium-like chlorine, Cℓ XVI. Our results provide an accurate measurement of the Lamb shift 2s - 2p which enables us to distinguish between the two theoretical values of Mohr[1] and of Erickson and Yennie[2].

Tests of quantum electrodynamics by 2s - 2p Lamb shift measurements in one-electron atoms have been reviewed recently by Kugel and Murnick[3] and by Mohr[1]. They point out that although the highest precision measurements are in hydrogen (20 ppm)[4], the higher order terms of the Lamb shift, which is usually expressed as a power series expansion in (Zα), are more easily tested in higher Z ions. The present most precise measurements are those in $^{19}F^{8+}$(Z = 9)[5] and $^{40}Ar^{17+}$(Z = 18)[6] of ±2% and ±4% accuracy respectively, both of which test the higher order terms of the Lamb shift to approximately the same accuracy as the work in hydrogen[4]. The higher order terms in Zα probe Q.E.D. theory in strong fields where the perturbative theory must eventually break down.

We accelerated chlorine ions in the Argonne FN tandem accelerator to an energy of 80 MeV and further stripped and excited the ion beam in a thin 20 μg.cm^{-2} carbon foil. The observation angle (close to 90°) was deduced from the relative doppler shifts at beam energies between 56 and 88 MeV. Thus, the first and second order doppler shifts are ∿3Å/degree and ∿3Å respectively at 1200Å for 80 MeV ion beam energy. As we were able to use internal calibration lines in the beam-foil spectra, such doppler shifts had very little effect on the values of our measured wavelengths. The monochromator was refocussed for the fast moving light source (v/c = β ∿ 0.07) by adjustment of both the entrance slit and the grating.

In Fig. 1, we show wavelength scans including the 2s $^3S_1$ - 2p $^3P_2$ and 2s $^2S_1$ - 2p $^3P_0$ transitions in second order. Our precision depends primarily on the relative and absolute wavelength measurements. The relative wavelength measurement consists of an accurate determination of the separation between the two wavelengths shown in each part of Fig. 1. The reproducibility of this measurement presently limits our precision to 0.012Å for the line from $^3P_2$. Improved statistics would allow determination of line centers to better than the present 1/50 of the linewidth and a study of possible profile asymmetries. Hyperfine structure of the two electron transitions is small and produces a symmetric broadening of the lines. The absolute wavelengths of the calibration lines n = 8 - 9 in Cℓ XIV and Cℓ XV have been calculated directly from Dirac theory for the 8k - 9ℓ, 8i - 9k, and 8h - 9i transitions. A small core polarization is included in the Cℓ XIV transition from direct measurement of the fine structure of the n = 5 - 6 transition. The mean wavelength $\bar{\lambda}$ was then found using hydrogenic transition probabilities and assuming statistical (2ℓ + 1) population distributions.

Assuming wavelengths of 1234.848Å and 1417.376Å for the Cℓ XV and Cℓ XIV n = 8 - 9 transitions respectively, we deduce wavelengths of 613.825 ± 0.012Å for the 2s $^3S_1$ - 2p $^3P_2$ transition, and 705.975 ± 0.064Å for the 2s $^3S_1$ - 2p $^3P_0$ transition.

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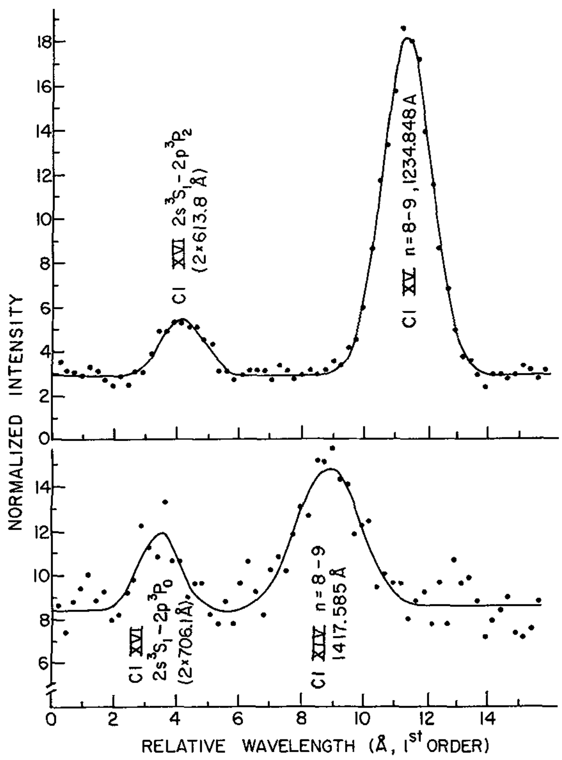

Fig. 1 - Wavelength scans including the Cℓ XVI $2s\,^3S_1$ - $2p\ ^3P_2$ transition near 2 x 614Å (upper) and the Cℓ XVI $2s\ ^3S_1$ - $2p\ ^3P_0$ transition near 2 x 706Å (lower). The wavelength was stepped in increments of 0.12Å (2nd order), and the profiles are non-linear least-squares fitted to gaussian (solid line).

In Table I, we compare our results with theory. The transition energy consists of three main parts: the non-relativistic, the relativistic and the Q.E.D. contributions. The non-relativistic energy has been calculated using Z-dependent variational perturbation theory[7] and is expressible as a power series in 1/Z. Relativistic energy corrections can be developed as a power series expansion in $(\alpha Z)^2$ with further electron correlation corrections providing similar terms to powers of 1/Z.

The Q.E.D. corrections are taken from Mohr[1] for the $2p_{1/2}$ state ($^3P_0$), while the j-dependent corrections for the $2p_{3/2}$ state ($^3P_2$) are taken from Erickson and Yennie[2].

The non-relativistic interaction between the two electrons ($1/r_{12}$) has been evaluated

Table I. Transition energy of 2s - 2p in Cℓ XVI (cm^{-1}). See text for explanation of each contribution.

Contribution	$2p\ ^3P_2$	$2p\ ^3P_0$
Non-relativistic ΣZ^{-n}	135,256.3	135,256.3
Dirac Fine Structure	30,800.2	0.0
Breit $Z^{-1}(\alpha Z)^4$	-2084.0	8201.1
Extrap. $Z^{-2}(\alpha Z)^4$	1.0	-892.
Breit $Z^{-1}(\alpha Z)^6$	-27.	90.9
Mass Polarization	-69.4	-69.4
Total	163,877.1	142,586.9
	(610.213Å)	(701.327Å)
QED terms		
$S_{sE}^{(2)}$ $\alpha(\alpha Z)^4\ \Sigma(\alpha Z)^n$	-1040.7	-1106.9
$S_{vP}^{(2)}$ $\alpha(\alpha Z)^4\ \Sigma(\alpha Z)^n$	69.2	69.2
$S_{sE}^{(4)}$ $\alpha^2\ (\alpha Z)^4$	-0.28	-0.28
S_{RM} $\alpha(\alpha Z)^4$ m/M	0.03	0.03
S_{RR} $(\alpha Z)^5$ m/M	-0.71	-0.71
S_{NS} $[(\alpha Z)^4 + (\alpha Z)^6]$	-6.93	-6.93
Total QED	-979.4	-1045.6
Total Transition Energy		
From above	162,897.7	141,541.3
This experiment	162,913 ± 3	141,648 ± 13
Johnson - rel. RPA	164,186	143,212

"exactly" by the variational perturbation technique. However, the relativistic part, which is represented approximately by the Breit operator, is given as a double expansion in (1/Z) and $(\alpha Z)^2$, and only its leading terms have been calculated. It can be seen from Table I that to our experimental accuracy, only the leading term is significant for the $^3S_1$ - $^3P_2$ transition, while for the $^3S_1$ - $^3P_0$ transition the first three terms are significant, and that further uncalculated terms may also contribute.

Hence, we conclude that uncertainties in electron correlation effects are important in Cℓ XVI only for the $^3S_1$ - $^3P_0$ transition, and that our measurement of the $^3S_1$ - $^3P_2$ transition can be used to check the quantum electrodynamic terms.

Thus, we obtain the following Lamb shift values:

$$S_{expt}(2s_{1/2} - 2p_{3/2}) = 964 \pm 3\ cm^{-1} \quad (1)$$

$$S_{Mohr}(2s_{1/2} - 2p_{3/2}) = 979.4\ cm^{-1} \quad (2)$$

$$S_{Erickson}(2s_{1/2} - 2p_{3/2}) = 998.8\ cm^{-1} \quad (3)$$

We conclude that the level of accuracy of our measurements of two-electron atom excitation energies are sufficient to allow accurate tests of Q.E.D. at $Z = 17$ and that similar measurements can be expected to become more accurate for higher Z. Thus, we are able to differentiate for the first time between the Mohr and Erickson one-electron Lamb shift theories. Our results emphasize the need for a consistent and complete relativistic theory of atomic structure. The discrepancy between experiment and theory may lie in the perturbative treatment of either the Lamb shift or the relativistic correction to the transition energy.

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