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Measurement of QED effects in $Z = 24$ to 34 lithiumlike ions

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The wavelengths of the $2S_{1/2}$-$2P_{1/2,3/2}$ transitions for five $Z = 24$ to 34 lithiumlike ions have been measured with an accuracy of about 50 ppm. These results can be combined with a recent multibody perturbation calculation to determine the remaining QED effects in these three-electron ions with an uncertainty of about 0.2–0.6%. The observed QED effects are in agreement with a one-electron calculation that uses a screened nuclear charge.

The determination of the energy levels of three-electron high-Z ions are important in the understanding[1] of many-electron atomic structure and quantum electrodynamics (QED). These measurements in high-Z ions examine bound QED effects of short distances and high-field strengths and could possibly show the breakdown of the standard perturbative expansion[2] in $Z\alpha$. The first resonance lines ($2S$-$2P$) of lithiumlike ions are particularly interesting since QED effects[3] contributes about 1–2% of the total-energy separation for $Z = 24$ to 34. The importance of QED effects for these transitions is larger by an order of magnitude than for the first resonance lines of similar one- or two-electron ions[4] and is comparable to weaker $2\,^3S$-$2\,^3P$ transitions in heliumlike ions. In order to accurately determine the QED effects in these three-electron ions, it is necessary to have correspondingly accurate calculation of the non-QED contributions to these energy levels. There have been recent calculations[5] that use many-body perturbation theory (MBPT) to determine the non-QED part of the $2S_{1/2}$-$2P_{1/2,3/2}$ energy separations with an accuracy of better than 10 ppm for these high-Z ions. This paper reports the measurement of eight $2S_{1/2}$-$2P_{1/2,3/2}$ transitions in lithiumlike ions with $Z = 24$ to 34. The accuracy of the measurements is about 50 ppm which when combined with the MBPT calculations allows the determination of QED effects in these high-Z ions with an accuracy of about 0.2–0.6%.

These measurements were made using the Tokamak Fusion Test Reactor, Princeton Plasma Physics Laboratory (TFTR) tokamak at Princeton. A typical plasma had a central electron temperature of 2–4 keV, central electron density of $(1-3)\times 10^{13}$ cm^{-3}, and the minor radius was 80 cm and were heated using only Ohmic heating. The dominate intrinsic ions were deuterons or helium and carbon with the latter arising from the carbon-limiter–plasma interaction, along with smaller amounts of chromium, iron, and nickel. The element of interest was injected into the plasma using the laser blow-off technique.[6] For these plasma conditions, the $Z = 24$ to 34 ions will be mostly in the heliumlike and lithiumlike charge states at the plasma center and in a large fraction of the plasma volume.[7]

Spectra from 20 to 330 Å were observed using a 2-m grazing incidence (Schwob-Frankel) spectrometer.[8] A 600-grove/mm grating and a microchannel plate coupled to 1024-element photodiode array were used so that it was possible to simultaneously observe a wavelength range of about 50 Å with an instrumental resolution of about 0.2 Å. The instrumental profile of the spectrometer was determined from observation of transitions originating from cold ions and was used to fit all the transitions. The nominal wavelength was determined using the grating equation along with geometrical factors.[8] A final calibration was performed using C VI and C V lines along with a few C IV and He II lines as reference transitions and are listed in Table I. The strong C VI and C V lines could be observed up to seventh order so that for a particular detector setting six to eight reference lines were used to calibrate the spectrometer for every plasma shot. The difference between the nominal and predicted reference lines were fitted to a fourth-order polynomial in λ. This procedure allowed the determination of a particular wavelength with a systematic uncertainty that was estimated to be about 0.005 Å. Since the spectrometer viewed the plasma at normal incidence and the expected plasma rotations are small, possible Doppler shifts should be negligible. Other systematic effects such as Zeeman and Stark shifts are also negligible.

Data were accumulated and stored every 0.1 sec which allowed temporal resolution of spectra originating from the injected elements. Data obtained before injection were subtracted from data obtained after injection in order to eliminate light originating from intrinsic ions. The $S_{1/2}$-$P_{1/2,3/2}$ transitions for $Z = 24$ to 34 lithiumlike ions were among the strongest lines observed and it was possible to achieve a signal-to-noise ratio of 10 to 100 within

TABLE I. Reference wavelengths utilized for spectrometer calibration. When the transition consisted of more than one line, the wavelength was determined assuming a statistical population.

Ion	Transition	Wavelength (Å)	Orders utilized
C VI	$2P$-$1S$	33.7360^{a}	3,4,5,6
	$3P$-$1S$	28.4655^{a}	4
	$4P$-$1S$	26.9897^{a}	4,5
	$n=4$-$n=2$	134.95(2)^{a}	1,2
	$n=3$-$n=2$	182.17(4)^{a}	1
C V	$2\,^1P$-$1\,^1S$	40.2680(6)^{b}	3,4,5,6,7
	$2\,^3P$-$1\,^1S$	40.7306(6)^{b}	3,4,5,6,7
	$3\,^1P$-$1\,^1S$	34.9728(8)^{b}	3,4
	$3\,^3P$-$2\,^3S$	227.192(5)^{b}	1
	$3\,^3D$-$2\,^3P$	248.704(15)^{b}	1
	$3\,^3S$-$2\,^3P$	260.188(22)^{b}	1
C IV	$4P$-$2S$	244.906^{c}	1
	$5D$-$2P$	259.514(15)^{c}	1
	$4D$-$2P$	289.199(20)^{c}	1
	$4S$-$2P$	296.919(10)^{c}	1
He II		243.027^{a}	1
		256.317^{a}	1

[a] Reference 9.
[b] Reference 10.
[c] Reference 11.

0.1 sec.

The difficulty in using a plasma as a source of these transitions is the problem of polluting transitions originating from other ions. As previously mentioned, background frames were subtracted so that only light from various ionization states of the injected element was analyzed. Nevertheless, it is possible to have blending of the spectral line of interest with a line originating from a lower ionization state. Several methods were used to examine each transition to see if there was another blended line. The literature was reviewed to see if transitions from other ionization states have been observed in previous experiments.[12–18] The fitted line was examined for possible asymmetries or an increased width over the expected Doppler broadening. Data obtained within 0.1 sec of injection were compared with data obtained from 0.1 to 0.3 sec. During the initial time period after injection, there are additional transitions originating from lower ionization states until a quasiequilibrium exists where the lithiumlike charge state dominates. Also, plasma shots which showed different intensity ratios of lithiumlike transitions to transitions originating from lower charge states were compared.

For the transitions reported, these tests showed that there was no line pollution to within the experimental uncertainties with the following exceptions. Some plasma shots showed that the 122.70 Å line in germanium ($Z=32$) was blended with a competing line at 122.76 Å originating from Ge XIV. Previous measurements[12] in a cooler tokamak plasma showed that there is a related transition from Ge XIV at 114.0 Å which was about twice the intensity of the 122.76 line. Plasma shots which showed a line ratio of 114.0/122.70 that was greater than 0.1 were eliminated from the analysis. It was estimated that a systematic correction of −0.003(3) Å would account for any small residual line pollution. The selenium ($Z=34$) 105.70-Å line was blended with a Se XVII line at 105.9 Å and this data could not be utilized. The $S_{1/2}$-$P_{1/2}$ chromium ($Z=24$) line was not observed with injection.

Data were obtained with 3–11 plasma shots at each transition. The transition wavelengths were determined by the average of these shots and are shown in Table II. The errors were determined from the scatter of the data and were, in general, consistent with the errors obtained from each shot. These results are consistent and slightly more accurate than the previous best data for these transitions[19] which are also shown in Table II.

In order to determine the QED effects in these three-electron ions, it is necessary to know the non-QED contributions. There has been a recent accurate calculation[5] that uses many-body perturbation theory to evaluate the non-QED part of the $2S_{1/2}$-$2P_{1/2,3/2}$ energy levels with an

TABLE II. Measured and calculated $2S_{1/2}$-$P_{1/2,3/2}$ energy intervals in cm^{-1}. The theoretical values for $Z=29$, 32, and 34 were determined from Ref. 5 using interpolation.

Z	Previous measurements^{a} λ(Å)	Present experiment λ(Å)	Present experiment Energy	Non-QED Theory^{b}	Difference	One-electron Lamb shift^{c}	Screened Lamb shift^{d}
		$2S_{1/2}$-$2P_{1/2}$					
26	255.094(10)	255.111(10)	391 986(15)	395 945(2)	−3959(13)	−4490	−3959
29	224.795(10)	224.774(11)	444 891(22)	450 704(2)	−5813(22)	−6522	−5827
32	200.290(10)	200.295(6)	499 264(15)	507 547(2)	−8283(15)	−9116	−8241
34	186.375(15)	186.360(7)	536 596(20)	546 737(2)	−10 141(20)	−11 024	−10 190
		$2S_{1/2}$-$2P_{3/2}$					
24	223.010(20)	223.019(6)	448 392(12)	451 170(3)	−2778(12)	−3152	−2770
26	192.012(20)	192.046(9)	520 708(24)	524 424(3)	−3716(24)	−4133	−3670
29	153.507(20)	153.506(6)	651 440(25)	656 801(2)	−5361(25)	−5975	−5368
32	122.705(20)	122.705(6)	814 963(40)	822 558(2)	−7595(40)	−8320	−7554

[a] Reference 19.
[b] Reference 5.
[c] Reference 20.
[d] Reference 21.

estimated error less than 10 ppm. These energies were subtracted from the data to determine the QED contribution to these energy levels and are also shown in Table II. These results show that it is possible to determine the QED effects in these high-Z ions with a precision of about 0.2–0.6%. Unfortunately, there has been no direct calculation of QED effects in three-electron ions. The measured QED energies were compared to the one-electron Lamb shift[20] which are also shown in Table II. It can be seen that the measured QED effects are about 10% smaller than the one-electron QED energy which is presumably due to screening effects of the $1s$ electrons. There has been a calculation[21–23] that attempts to account for this effect of screening by reducing the effective nuclear charge Z_{eff} and using it in a one-electron calculation. These results are shown in Table II and it can be seen that there is good agreement with the experimental data. One problem with this calculation is the selection of Z_{eff} is somewhat arbitrary. Presumably, there will soon be a direct calculation of QED effects in three-electron ions that can be compared to the data.[5]

In summary, the QED effects in three-electron ions with $Z=24$ to 36 have been determined with an uncertainty of about 0.2–0.6% which is comparable to, or better than, measurements in one- or two-electron ions of similar Z. It is expected that the precision of some of these measurements could be improved by a factor of maybe 2 by accumulation of further data and this precision may be achievable[19] for higher-Z ions. Stringent test of QED effects in these ions awaits a direct calculation.[5]

Note added in proof. The present results are in good agreement with a recent calculation by Indelicato and Desclaux.[24]

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