Precision measurement of the $1s$ Lamb shift in hydrogenlike argon

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Precision measurements of the absolute wavelengths of the Lyman-α doublet $(2p\,^2P_{3/2,1/2} \rightarrow 1s\,^2S_{1/2})$ in hydrogenlike argon (Ar^{17+}), as well as those of some strong dielectronic satellites, are reported. The Alcator C tokamak plasma was seeded with trace amounts of argon and the emission spectra were taken with a high-resolution, crystal x-ray spectrometer. *In situ* wavelength calibration was achieved by utilizing the potassium $K\alpha$ lines from a KCl fluorescence source. For the Lyα_2 line, a precision of 11 ppm was achieved. Comparisons of these data with QED predicted wavelengths show good agreement, yielding a test of the $1s$ Lamb shift at the 3% level. The precision of these measurements was limited by uncertainties in the wavelength calibration, with the uncertainties due to the influence of unresolved satellites being of secondary importance.

I. INTRODUCTION

This paper presents precision measurements of the absolute wavelengths of the Lyman-α doublet $(2p\,^2P_{3/2,1/2} \rightarrow 1s\,^2S_{1/2})$ in H-like argon (Ar^{17+}) emitted from Alcator C tokamak plasmas. Previous measurements of absolute $1s$ energy levels in medium Z ions $(16 \leq Z \leq 36)$ have come primarily from beam-foil experiments,[1-5] where corrections for substantial Doppler shifts limit the attainable precision. More recently, Beyer, Deslattes, Folkmann, and LaVilla[6] used an argon ion recoil technique, eliminating most of the Doppler-shift effects. In their work, relatively strong satellites, due to the decay of doubly excited levels in ionization states lower than H-like, limited the accuracy of the measurements to a precision of 5 ppm. Tokamak plasmas are particularly well suited as a source for spectroscopic studies of highly charged ions. In the plasma conditions of this experiment, satellite lines are not very strong, and the ions have relatively low temperatures (≈ 1 keV). The effects of Doppler shifts due to bulk plasma motions are very small in these Ohmically heated discharges. The Alcator C tokamak plasma has previously been used as the source in an experiment to obtain the wavelengths of the Lyα doublet in H-like chlorine, and results with precision at the 34-ppm level were achieved.[7] The present work constitutes a continuation of those measurements. Several improvements have been made in the instrumentation,[8] and, consequently, the results presented here for argon approach the 10-ppm level of precision, providing a test of the Lamb shift for the ground-state energy of Ar^{17+} at the 3% level.

II. EXPERIMENTAL PROCEDURE

In this experiment, the main parameters for the hydrogen working gas plasmas were central electron temperature of 1500 eV, central ion temperature of 1100 eV, line average density of 2.4×10^{14} cm^{-3}, toroidal magnetic field of 10 T, and plasma current of 460 kA. The discharge was physically limited by molybdenum rings located at the edge of the plasma. Argon was introduced into the plasma through a fast piezoelectric valve, which was opened 50 msec after the beginning of each discharge, for a period of 20 msec. Subsequently, Ar entered the plasma and was increasingly ionized as it diffused into the hot core of the discharge, where the H-like state had its density maximum. The excited states of Ar^{17+} are populated primarily by electron impact excitation from the ground state, and then decay radiatively back to the ground state. Spectra near $\lambda = 3.7$ Å, which include the Ly$\alpha_{1,2}$ doublet, were obtained during the approximately 300-msec quasi-steady-state portion of the discharges. The data were stored in time bins of 20 msec. The Bragg crystal spectrometer, which is in the Von Hamos geometry, has been described in detail previously.[8] Absolute wavelength calibration of the spectrometer was achieved with the use of the potassium $K\alpha$ lines from a KCl fluorescence source. The KCl was excited with a primary x-ray beam from a Cu-anode source, operated at an anode voltage of 45 kV with an emission current of 20 mA.

The experimental procedure was as follows. The argon measurements were taken during the steady-state portions of five consecutive discharges, with the time between discharges being 8 min. Then the spectrometer was turned towards the fluorescence source, and the potassium calibration was performed, with the accumulated data being read out from the histogramming memory every 8 min. The total collection time for the calibration was 170 min. Finally, Ar measurements were again taken for five consecutive discharges. In this way, any possible effects due to drifts could be monitored and minimized. The total accumulation time for recording Ar spectra was 3.0 sec.

III. RESULTS AND DISCUSSION

All the measured potassium $K\alpha$ spectra have been added together, and Fig. 1 shows these data, along with the fit used to obtain the absolute wavelength calibration.
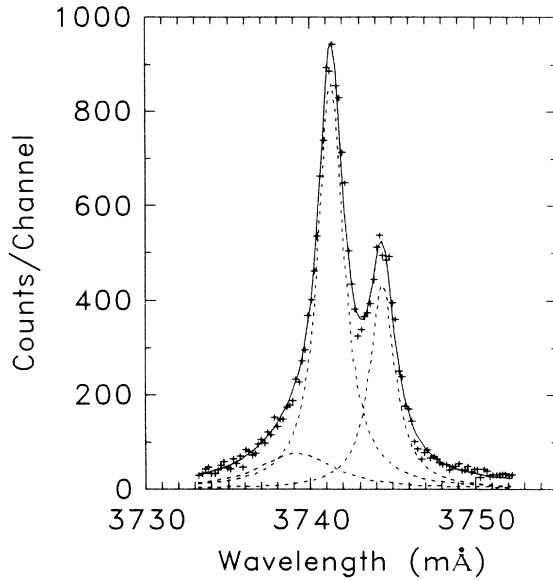

FIG. 1. The measured potassium $K\alpha$ fluorescence spectrum with Lorentzian line fits of $K\alpha_1$, $K\alpha_2$, and the satellite $K\alpha''$.

Lorentzian line shapes have been fitted to the $K\alpha_{1,2}$ doublet data, along with $K\alpha''$ on the short wavelength side of $K\alpha_1$ and a straight-line background. The positions of both $K\alpha_1$ and $K\alpha_2$ have been used to obtain the absolute wavelengths in the H-like Ar spectrum. The wavelengths of the potassium lines are[6] $\lambda(K\alpha_1) = 3741.296(5)$ mÅ, $\lambda(K\alpha_2) = 3744.405(5)$ mÅ, and $\lambda(K\alpha'') = 3739.1(2)$ mÅ.

The results of the argon measurements are shown in Fig. 2, which depicts the Lyα doublet, as well as several satellite lines due to doubly excited He-like argon; the standard notation from Ref. 9 is used to designate the lines. Figure 3 shows the results of an iterative least-squares fit to the data of Fig. 2, in the region around the Lyα doublet. The linewidths are dominated by thermal Doppler broadening
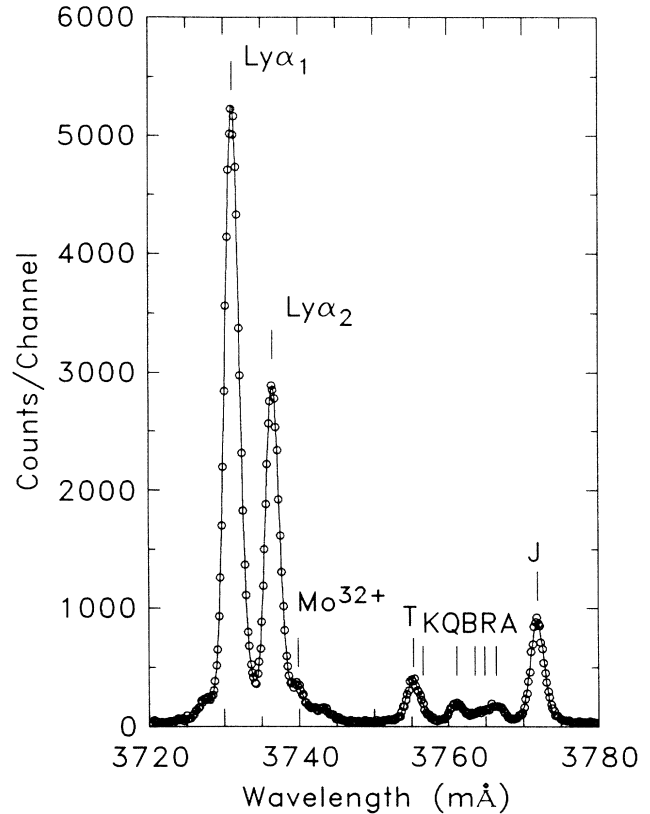

FIG. 2. The measured argon spectrum with the Ar^{17+} Lyman-α doublet and several strong satellites identified. The satellite identification follows the conventions of Ref. 9.

$(\lambda/\Delta\lambda_D \approx 1000)$. To account for the presence of satellites, five lines, in addition to Lyα_1 and Lyα_2, were fitted to the spectrum, with the positions and heights of each as free parameters. The linewidths were also free parameters, except that the two Lyα lines were forced to have a single
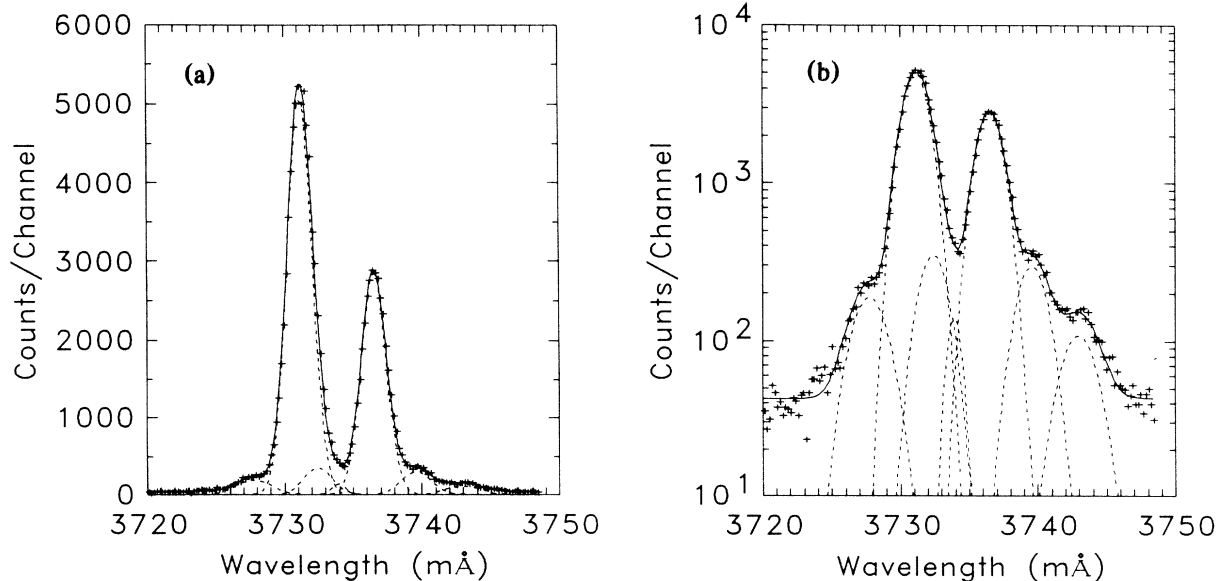

FIG. 3. (a) A portion of the spectrum in the vicinity of the Ar^{17+} Lyα doublet together with the Gaussian line fits. (b) Same as (a) but on a semilogarithmic scale.

TABLE I. Comparison of experimental measurements for the Ar^{17+} Lyα doublet with relativistic quantum theory, including reduced mass effects (Dirac) and QED theory, both from Ref. 10. The results of Beyer *et al.* (Ref. 6) are also included for comparison. All wavelengths are given in mÅ.

Transition	λ (Dirac)	λ (QED)	λ (this experiment)	λ (Ref. 6)
Lyα_1: $2p_{3/2} \rightarrow 1s_{1/2}$	3729.827	3731.101(1)	3731.142(70)	3731.105(19)
Lyα_2: $2p_{1/2} \rightarrow 1s_{1/2}$	3735.227	3736.516(1)	3736.514(40)	3736.522(19)
Fine-structure splitting	5.400	5.415	5.372(40)	5.417

width, also a free parameter. Once again a straight-line background has been included. All lines are taken to be Gaussian in shape, consistent with the facts that the intrinsic Lorentzian linewidth is negligible, and that the instrumental spectral response ($\lambda/\Delta\lambda_I = 3000$) has only a small influence on the line shapes. The weak line near $\lambda = 3739$ mÅ is due primarily to a $2p$-$4d$ transition in Mo^{32+}. Spectra taken under similar plasma conditions, but without Ar in the plasma, show that this is the only Mo line which appears in this spectral region. It is well resolved from the Lyα doublet, and so has negligible effect on the measured positions of the argon lines.

The result of the measured argon Lyα wavelengths are summarized in Table I. The main uncertainties come from fitting the potassium calibration lines and from extrapolating the results to the positions of the Ar lines. These errors lead to estimated uncertainties of ± 0.035 mÅ for Lyα_2 and ± 0.07 mÅ for Lyα_1. The next most important error contribution is the uncertainty in the fits to the argon lines themselves, which is due primarily to the influence of unresolved satellite lines combined with the Doppler widths, and is at the level of ± 0.02 mÅ. This has been estimated by forcing the satellite feature located nominally at about 3732 mÅ to nearby locations (± 0.5 mÅ), and noting the resultant shift in Lyα_1. The overall uncertainty is at the level of ± 0.04 mÅ, or about 11 ppm, for Lyα_2. One further possible influence on the line positions from the tokamak source must be considered, namely, Doppler shifts due to bulk plasma convection. All measurements reported here were made during Ohmically heated discharges; no neutral beam heating has been used. As such, it can be expected that any toroidal or poloidal drifts should be small ($v_T < 10^6$ cm/sec, $v_p < 10^5$ cm/sec).[11] Since the spectrometer views the plasma along a major radius in the horizontal midplane, toroidal rotation would primarily contribute a second-order Doppler shift,

which is negligible at these velocities. Furthermore, the instrument can be scanned vertically, on a shot-by-shot basis, to look for any evidence of the influence of poloidal flows on the line positions. This has been done, and shifts have not been detected, at least down to the level of 0.02 mÅ, corresponding to $v_p < 2 \times 10^5$ cm/sec.

The precision of the results presented here represents approximately a threefold improvement over the previous Cl results from Alcator C,[7] and approaches that of the results of Beyer *et al.*[6] in Ar, obtained using the ion recoil method. In the latter case, the overall quoted precision is 5 ppm, with the dominant uncertainty due to the modeling and subtraction of the fairly strong satellites. Satellites play a much smaller role in the results reported here. Although the overall precision is about a factor of 2 less than in the recoil measurements, the intrinsic uncertainty in the x-ray line positions due to satellites is probably somewhat smaller. The comparison is therefore an interesting one, and the results from Ref. 6 are also shown in Table I. The present results are in excellent agreement with theory[10] for the positions of each of the individual lines; the agreement for the fine-structure splitting is also reasonable.

Table II lists the fitted wavelengths for the strongest satellites to the Lyα lines, as well as theoretical wavelengths for these lines from Ref. 12. Note that there is a systematic shift of a little less than 1 mÅ for each of the lines. In the work of Ref. 12, the QED effects have not been included in the wavelength calculations. From Table I, the measured shift in Lyα_2 is 1.287(40) mÅ.

IV. CONCLUSIONS

In summary, the absolute wavelengths of the Lyman-α doublet in Ar^{17+} have been measured on the Alcator C tokamak. The line positions are in excellent agreement with the predictions of QED theory; the measured fine-structure splitting is also in reasonable agreement with theory. The strongest satellites, due to doubly excited Ar^{16+}, also show a shift to longer wavelength, when compared with predictions which ignore the QED effects.

TABLE II. Wavelengths (in mÅ) of some strong satellites near Lyα. The theoretical wavelengths come from Ref. 12, and do not include any QED corrections.

Transition	λ (this experiment)	λ (theory)
T: $2s2p\,^1P_1 \rightarrow 1s2s\,^1S_0$	3755.26(10)	3754.4
Q: $2s2p\,^3P_2 \rightarrow 1s2s\,^3S_1$	3761.06(15)	3760.3
J: $2p^2\,^1D_2 \rightarrow 1s2p\,^1P_1$	3771.79(20)	3770.9

ACKNOWLEDGMENTS

[1]L. Schleinkofer, F. Bell, H. D. Betz, G. Trollmann, and J. Rothermel, Phys. Scr. **25**, 917 (1982).

[2]J. P. Briand, M. Tavernier, P. Indelicato, R. Marrus, and H. Gould, Phys. Rev. Lett. **50**, 832 (1983).

[3]J. P. Briand *et al.*, Phys. Rev. A **28**, 1413 (1983).

[4]H. D. Dohmann, D. Liesen, and E. Pfeng, *GSI Scientific Report 1982* (Gesellschaft für Schwerionengforschung, Darmstadt, 1983) (unpublished).

[5]P. Richard *et al.*, Phys. Rev. A **29**, 2939 (1984).

[6]H. F. Beyer, R. D. Deslattes, F. Folkmann, and R. E. LaVilla, J. Phys. B **18**, 207 (1985).

[7]E. Källne, J. Källne, Patrick Richard, and M. Stöckli, J. Phys. B **17**, L115 (1984).

[8]E. Källne, J. Källne, E. S. Marmar, and J. E. Rice, Phys. Scr. **31**, 551 (1985).

[9]U. I. Safronova, A. M. Urnov, and L. A. Vainshtein, in *Physics of Atomic Collisions and Spectroscopy of Plasma,* edited by N. Basov (Nauka, Moscow, 1980).

[10]P. J. Mohr, At. Data Nucl. Data Tables **29**, 453 (1983).

[11]K. Brau *et al.*, Nucl. Fusion **23**, 1643 (1983).

[12]L. A. Vainshtein and U. I. Safranova, At. Data Nucl. Data Tables **21**, 49 (1978).