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ABSTRACT

The H-like spectrum of chlorine emitted from the Alcator C tokamak has been measured using a Bragg crystal x-ray spectrometer and in situ wavelength calibration. The 1s-2p transition energies were determined to an accuracy of 34 ppm allowing for a test of the theoretically calculated Lamb shift of the 1s level in Cl^{16+} at the 10% level. This new technique of spectroscopy of highly ionized atoms could be further refined to approach the 5 ppm accuracy level in the absolute transition energy determination.

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In this letter we present the results of a precision measurement of the wavelengths of x-ray transitions in highly ionized atoms. Such experiments have been done with the aim of determining the radiative QED corrections to the Dirac energy which cause a significant Lamb shift of strongly bound $\ell = 0$ atomic orbitals. The information can be obtained by accurately measuring the energy of the 1s-2p transitions in H-like atoms, for which the Dirac energies are well known, and comparing the data with theoretically calculated energies including the Lamb shift. Only two such experiments[1,2] have been reported which determined the Lamb shift of the 1s ground state through direct measurement of the 1s-2p resonance transition. Accuracies of 18% and 13% were achieved for the Lamb shift in iron[1] and chlorine[2], respectively. These two experiments used energetic ion beams and the greatest source of error was the experimental Doppler shift correction due to the high ion velocities involved. Our approach to circumvent this problem is to observe the x-ray emission from highly ionized atoms in tokamak plasmas. These plasmas provide the high thermal velocities needed, i.e., electron temperatures of $T_e > 1$ keV, for the formation and excitation of the ion species of interest while the velocities connected with any net ion motion are favorably much smaller. High resolution atomic plasma spectroscopy studies have been reported[3,4]. Here, however, we present the first experiment of this kind designed for precise absolute determination of the wavelengths of x-ray transitions of particular interest to the fundamentals of physics.

The experiment was carried out at the Alcator C tokamak at MIT. The plasma conditions for our measurements were: electron temperature of $T_e = 1.2\text{-}1.8$ keV and densities of $N_e = 1\text{-}3\ 10^{14}\text{cm}^{-3}$ for toroidal magnetic fields of $B_T = 8$ or 10 T with plasma currents of $I_p = 400\text{-}500$ kA. A discharge lasts typically some 500 ms of which the middle 200 ms represent constant conditions. In the plasmas

of hydrogen or deuterium, there are small amounts of impurities among which chlorine is usually present at a concentration of 10^{-4} to 10^{-5} relative to N_e. This ambient Cl concentration could be boosted by gas puff injection (HCl+He mixtures) between discharges; injection during discharges was inhibited by condensation on the walls of the entrance port due to the liquid nitrogen cooling of the Alcator C vacuum vessel. The plasma temperature values mentioned favor the formation of the ionization states Cl^{15+} and Cl^{16+}. The H-like spectrum of n = 2 to n = 1 transitions studied here emanate from electron impact excitation of the Cl^{16+} ground state leading to the principal $1S_{1/2} - 2P_{2/3,1/2}$ transitions (which are also known as Lyman α_1 and α_2 denoted here by W_1 and W_2) and from dielectronic recombinations leading to satellite lines such as the strong transitions $1s2s\,^1S_o - 2s2p\,^1P_1$, $1s2s\,^3S_1 - 2s2p\,^3P_2$, $1s2s\,^3S_1 - 2s2p\,^3P_1$, $1s2p\,^3P_2 - 2p^2\,^3P_2$ and $1s2p\,^1P_1 - 2p^2\,^1D_2$ denoted by T, Q, R, A, and J[5]. The plasma was viewed through a 130 μm thick Be-window with the line of sight being perpendicular to the toroidal axis and the vertical field of view intersecting about 10 cm of the central part of the plasma whose minor radius is 16.5 cm. Furthermore, the Cl^{16+} ions are found predominately in the hot core of the plasma where they are confined for time periods of the order 10 ms and reach temperatures generally 200–400 eV below T_e, i.e., the thermal velocities for our conditions are $V_i = 6\text{–}9\ 10^6$ cm/s and hence the Cl x-ray lines have a Doppler broadening amounting to $\Gamma_D = 1.0$ to 1.7 eV (FWHM). In comparison, ion velocities due to net mass motions in our ohmically heated plasma are small ($<10^6$ cm/s)[6] and mainly in the toroidal direction so that along our line of sight we estimate the Doppler line shifts to be at the most 0.01 eV.

The x-ray line emission was measured with a Bragg crystal spectrometer. The instrumentation and methods used were basically the same as described earlier[7] except for the facilities for obtaining the absolute wavelength

determination. For the photon detection, we alternatively used two position sensitive proportional counters of different types for consistency checks. Furthermore, the spectrometer was placed 25 cm from the torus window making the total distance between plasma center and spectrometer entrance slit about 110 cm. The 25 cm gap made it possible to use calibration sources without changing the conditions used for the Cl measurement apart for the simple removal of the He-bag connecting the torus and the spectrometer. For the principal wavelength calibration we used a 5-keV electron beam shining on Ar gas kept at a few millitorr pressure; the $K\alpha_1$ line at $h\nu = 2957.813 \pm 0.008$ eV was our reference line and this together with $K\alpha_2$ at 2955.684 ± 0.013 eV and $K\alpha_4$ at 2977.51 ± 0.06 eV gave the wavelength scale[2]. The Ar source produced count rates up to 50 c/s in the spectrometer compared to those of the Cl emission from the plasma reaching 50 kc/s. Count rates of up to 10 kc/s were obtained with the Ag $L\alpha$ emission, $h\nu(L\alpha_1) = 2984.3$ eV with a line width of 2.6 eV FWHM[8], from an x-ray tube. By measuring the Ag spectrum during the discharge compared with recordings during the quiescent interval between discharges, we could verify that the transient electromagnetic conditions of the discharge did not interfere with the measurement.

An example of a measured Cl spectrum from a single plasma discharge is shown in Figure 1. Such a spectrum was obtained every 6 min and we generally accumulated some 5 Cl spectra before moving the Ar-source into position to record calibration spectra (see Figure 2). A full measuring cycle thus took about an hour's time and was repeated some five to ten times during a day's run. Data were obtained from three production runs (I, II, and III in Table 1), each consisting of several measuring cycles and altogether Cl spectra were recorded from more than 100 plasma discharges. The data were divided into four subsets, according to detector type used (the 10 cm detector[7,9] for data sets I and II

and the 35 mm detector[10] for III) and depending on the Cl emission rate (where Ia is low rate and all others are high). This provided a check on systematic trends in the data. The results are given in Table 1. The first column gives the experimental difference in position (x) between the Ar $K\alpha_1$ reference line and the W_1 line in Cl including two corrections. The position of the Cl spectrum was found to vary with count rate which was later identified with a rate dependent off-set in the electronic modules used for the time-to-analog conversion (TAC). A correction was applied on the basis of the known average count rates for each discharge and the TAC rate dependence determined after the experiment. An additional correction was applied to the data taken with the 10 cm detector because a rate dependent space charge build-up causing an interference between the adjacent $2P_{3/2}$ and $2P_{1/2}$ lines. An empirical correction was established on the basis of the observed rate dependence of the line separation and the assumption that the $2P_{3/2}$ line was shifted proportionally to the distance from the center of charge gravity. The x values given are the mean of all the data points of each set and the assigned error represents the standard deviation. The next column gives the energy scale factor (k) with the energy $E = k \cdot X$ given in column four. The weighted mean value is $E = 4.65 \pm 0.06$ eV. The scatter in the data can largely be ascribed to the uncertainty in the mentioned count rate corrections which are estimated to be about ±15% for an average value of about 0.5 eV. Allowing for some additional systematic uncertainty in the line fitting analysis, the total error is estimated to be ±0.10 eV. Our results for the $1S_{1/2}$-$2P_{3/2}$ transition energy in Cl^{16+} is thus $h\nu = 2962.46 \pm 0.10$ eV. The result for the W_1-W_2 fine structure splitting is $\Delta h\nu = 3.84 \pm 0.03$ eV. Moreover, the two satellite lines (T and J) are determined to lie 20.2±0.2 eV and 33.6±0.2 eV to the low energy side of the W_1 line.

The theoretical transition energies are based on the Dirac energy giving $h\nu$ = 2963.310 eV for W_1 with a small correction of -0.006 eV for the finite nuclear size. The radiative corrections due to self-energy (-1.009 eV of which +0.003 eV comes from the $2P_{3/2}$ level) and vacuum polarization (+0.068 eV) gives a Lamb shift of -0.941 eV. The total energy is predicted by Erikson[11] to be $h\nu$ = 2962.266 eV for W_1 with the W_1-W_2 fine structure splitting being $\Delta h\nu$ = 3.827 eV (see Table 2). In another calculation Mohr[12] obtains $h\nu$ = 2962.3765 eV and $\Delta h\nu$ = 3.82718(3) eV. Both these theoretical results on $h\nu(W_1)$ are lower than our data but still within the experimental uncertainty of 0.1 eV or 34 ppm in the energy of the $W_{1,2}$ lines and about 0.03 eV in the fine structure splitting. The experimental Lamb shift is $h\nu_L$ = 2962.46-2963.31 = -0.85 eV and hence smaller than the theoretical one. For the fine structure splitting we find agreement with theory within the error of 0.03 eV. In the experiment of Briand et al.[1] on Fe^{24+}, the Lamb shift was found to be smaller than predicted but not to exceed the error. They, however, reported a rather surprising disagreement between experiment and theory on the fine structure splitting. As an aside we note that the calculated energies of satellites lines (relative to W_1) are 20.2 and 33.8 eV and hence consistent with our results to within the experimental errors.

The present study is important with regard to the implied potential of atomic-plasma spectroscopy as a new technique among high precision measurements. We first point out the possibility for further improvement in the accuracy. We envisage to reach an accuracy of 8 μm in the detector (being one-tenth of the FWHM spatial resolution) which, together with new high-count-rate electronics, should give a line position determination at an accuracy of a few ppm for accumulation times as short as 50 ms. Second, by having designated tokamak runs, plasma conditions could be optimized to give minimum line broadening by

choosing the lowest temperature compatible with the emission rate requirements. Finally, the ion net velocities, which can give line shifts at the 0.01 eV level can be dealt with by using instruments capable of radial plasma scans and ultimately by using a dual spectrometer system for simultaneous viewing of the plasma from opposing directions. The atomic-plasma spectroscopy technique could thus approach the accuracy of the calibration line used which, for instance, is 8 meV or 3 ppm for the Ar $K\alpha_1$. Therefore, these tokamak measurements are particularly suited for high precision work on few-electron systems of highly ionized atoms with Z in the range 10 to 30 which are amenable to accurate theoretical calculations of fundamental interest to atomic physics.

In conclusion, we have demonstrated the use of tokamak plasmas to perform high precision measurements of soft x-ray resonance line spectra. Results are presented on the H-like 1s-2p spectrum of Cl of which the Lyα lines are used to extract the 1s Lamb shift. We find that the predicted Lamb shift is larger than our results but within the experimental uncertainty of 0.1 eV, so that corroborative data are needed to determine at which level present theories cease to be valid. On the other hand, augmented accuracy can be expected. The experience from this study suggests that with certain refinements in the instrumentation and with control over the tokamak to optimize plasma conditions, the plasma-atomic spectroscopy is a viable technique for high precision measurements of energies of highly ionized few-electron atoms at the ppm level of accuracy.

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TABLE 1

Comparison of results on the position (x) and energy (E) separation between the Cl W_1 line and the Ar $K\alpha_1$ line and scale factors (k) for the four subsets of the data.

Set	x [Chs]	k [meV/ch]	E [eV]
Ia	17.98±0.38	257.5±1.5	4.62±0.10
Ib	18.30±0.46	257.5±1.5	4.71±0.12
II	17.68±0.25	258.3±1.2	4.60±0.08
III	19.16±0.32	245.0±2.0	4.69±0.08

TABLE 2

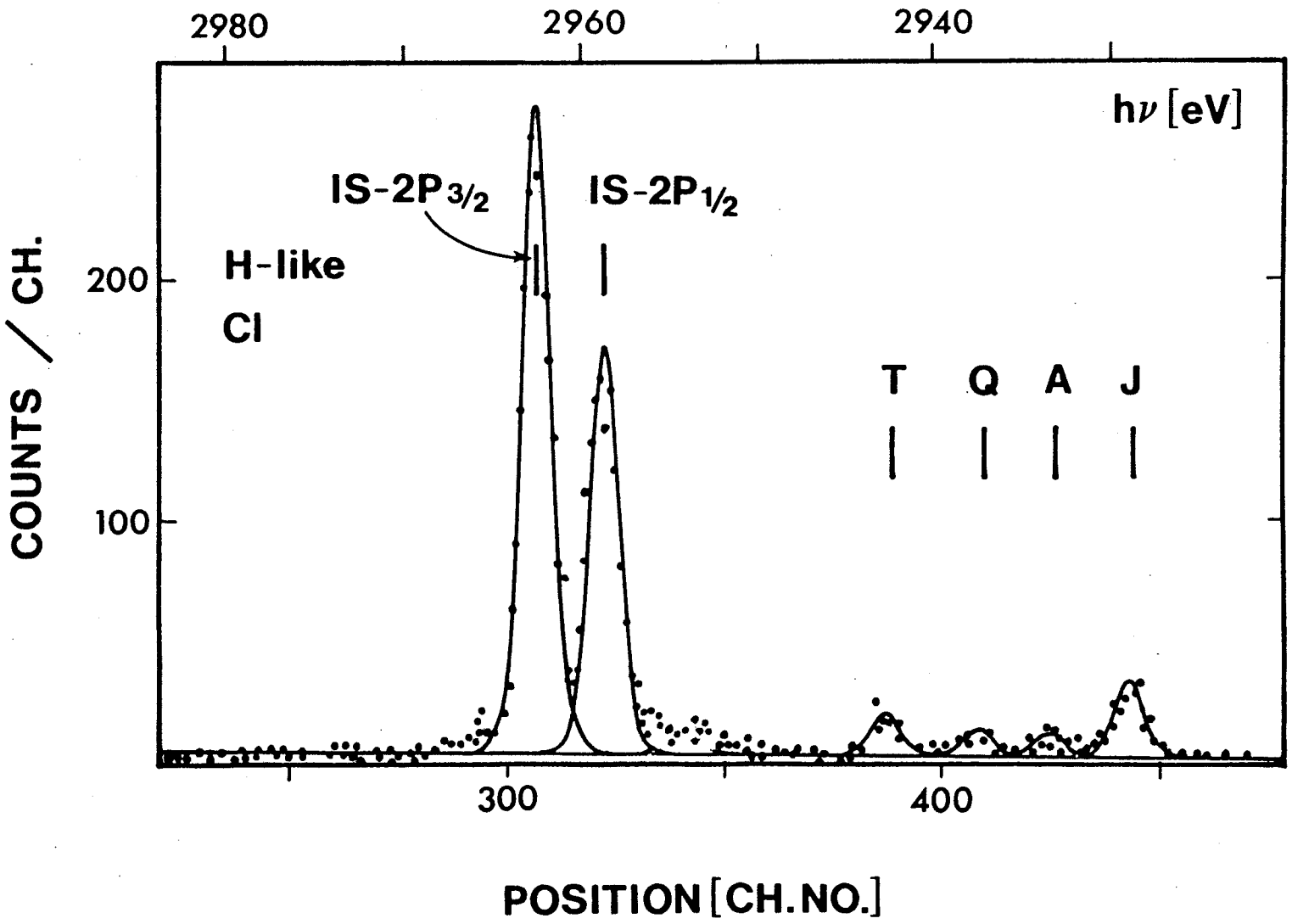
Summary of Results on Energies

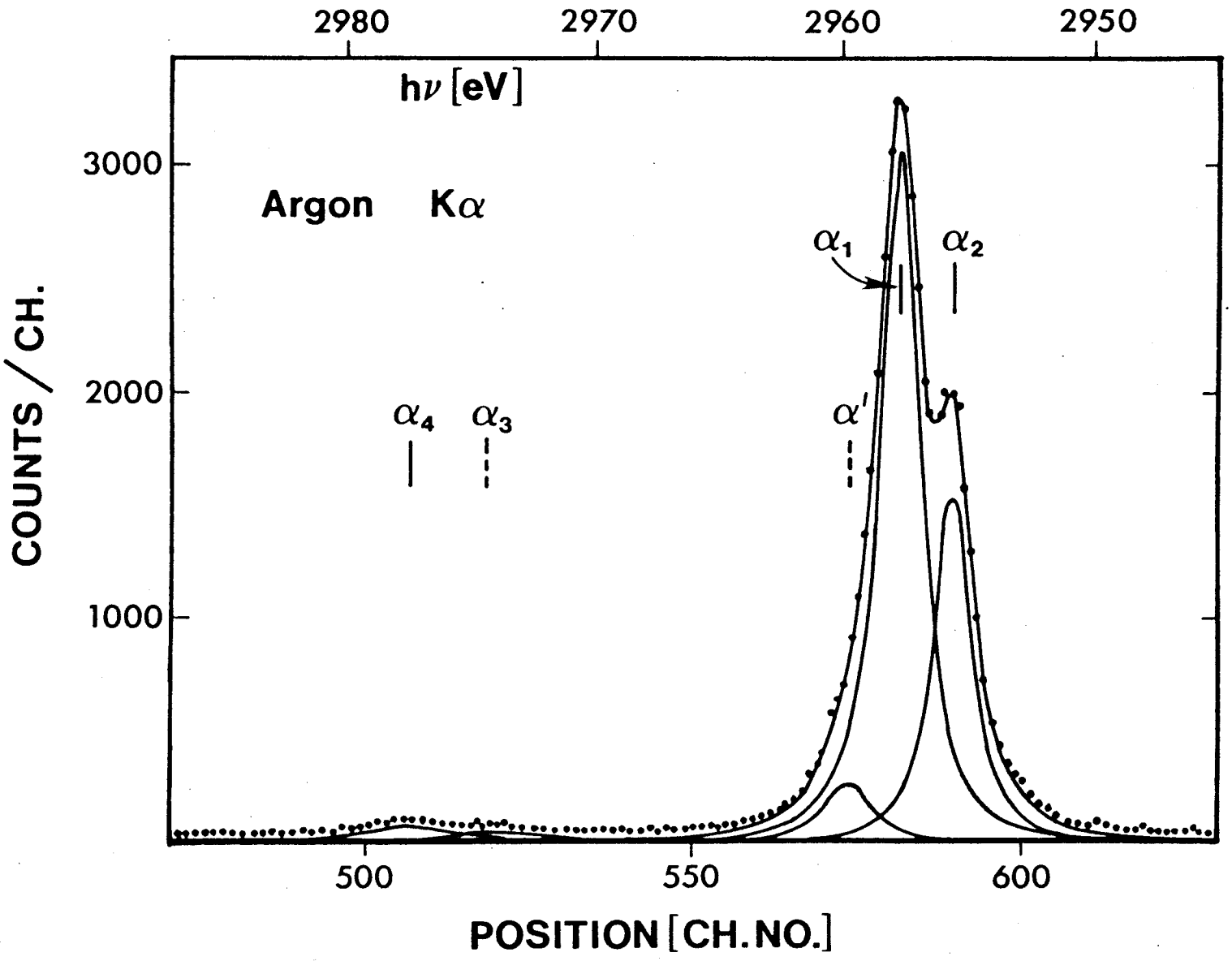
$h\nu$(eV)	Experiment	Theory[11]
W_1	2962.46±0.10	2962.266
W_2	2958.62±0.10	2958.439
W_1-W_2	3.84±0.03	3.827
Lamb Shift	-0.85±0.10	-0.941

FIGURE CAPTIONS

Figure 1: The Kα spectrum from the argon source obtained with the 10 cm detector. The result of the line fit is also shown.

Figure 2: The H-like spectrum of Cl from the Alcator C plasma obtained with the 35 mm detector. The result of the line fit to the main lines (W_1 and W_2) and the n = 2 satellites (T, Q, R, A, and J) is also shown with the latter marked at the positions predicted in Reference 5.


2980
2960
2940
hν [eV]
IS-2P3/2
IS-2P1/2
H-like
Cl
T
Q
A
J
200
100
COUNTS / CH.
300
400
POSITION [CH.NO.]


2980
2970
2960
2950
hν [eV]
3000
2000
1000
Argon Kα
α1
α2
α4
α3
α'
COUNTS / CH.
500
550
600
POSITION [CH.NO.]