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Radiative lifetimes and oscillator strengths for allowed intra-L-shell transitions in multiply charged chlorine ions

J. P. Forester,* D. J. Pegg, P. M. Griffin, G. D. Alton, S. B. Elston, H. C. Hayden,† R. S. Thoe, C. R. Vane, and J. J. Wright‡
University of Tennessee, Knoxville, Tennessee 37916
and Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

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A systematic study of radiative lifetimes of low-lying levels in Cl XV through Cl IX has been made using the beam-foil time-of-flight techniques. These results are used to derive f values for allowed $\Delta n = 0$ transitions of the type $2s^22p^k$-$2s2p^{k+1}$ and $2s2p^{k+1}$-$2p^{k+2}$.

I. INTRODUCTION

Oscillator strengths (f values) for allowed transitions between low-lying levels of multiply charged ions are frequently useful in the interpretation of spectral data from high-temperature and low-density plasmas. In this paper we describe a systematic study of allowed $\Delta n = 0$ transitions of the general type $2s^22p^k$-$2s2p^{k+1}$ and $2s2p^{k+1}$-$2p^{k+2}$ in highly stripped chlorine ions with from three to nine bound electrons, i.e., Li-like to F-like structures. In many cases the present f-value results are for the highest Z member of the sequence thus far measured. The results are compared to current nonrelativistic, and where available, relativistic calculations.

II. EXPERIMENTAL ARRANGEMENT

The beam foil method was used in this work to make time-of-flight measurements of radiative lifetimes of the low-lying levels of Cl XV to Cl IX. The ORNL EN tandem accelerator produced beams of chlorine ions of energies 8, 18, 38, and 45.5 MeV for this experiment. Thin carbon foils (thickness ~5–20 μg/cm^2) were used to strip and excite the remaining electrons in a well-defined region of space. The beam energy employed in a particular measurement was selected to produce the desired charge state efficiently in the post-foil source. The radiation emitted in flight by these highly ionized systems falls in the extreme ultraviolet (EUV) region of the spectrum. A 2.2-m grazing incidence monochromator equipped with a channel electron multiplier detector was used to disperse the foil-excited radiation emitted at approximately 90° to the beam direction. Thus the spectrometer isolated selected spectral features which signatured the decay of a particular excited level via a radiative transition. Intensity-decay measurements were made in the usual manner by translating the foil relative to the viewing region of the spectrometer. The data thus obtained were normalized to a selected amount of beam charge collected in a shielded Faraday cup. The spatial resolution (i.e., length of beam source viewed by the spectrometer) of the present arrangement is ~0.23 nm which corresponds to a time window of ~16 psec for a 38-MeV chlorine ion beam.

III. RESULTS

Figure 1 shows a typical foil-excited spectrum taken at an incident beam energy of 38 MeV. Figures 2–5 are decay curves showing the change in intensity of a wavelength-selected line as a function of the distance between the foil and the viewing region of the spectrometer. The raw data, once they had been corrected for beam-independent and beam-dependent background contributions, were curve fitted to one or two exponential functions with a least-squares computer program. The lifetime and f-value results obtained in the present work are summarized in Table I. The theoretical results quoted in this table are either extrapolated nonrelativistic calculations or interpolated relativistic calculations. In general, there appears to be good agreement between our experimental results and theoretical predictions except in cases where cascading is expected to cause problems in the analysis of the experimental data. Generally, cascading from higher-lying levels within the same shell causes the most problems since such levels are expected to have lifetimes and initial populations not too different from that of the primary level. For cases when in-shell cascading of this nature is a likely factor we have increased the uncertainty limits on our results.

The errors quoted on our results in Table I range from 5% to 25% and reflect the conditions obtaining in the particular measurements. Errors

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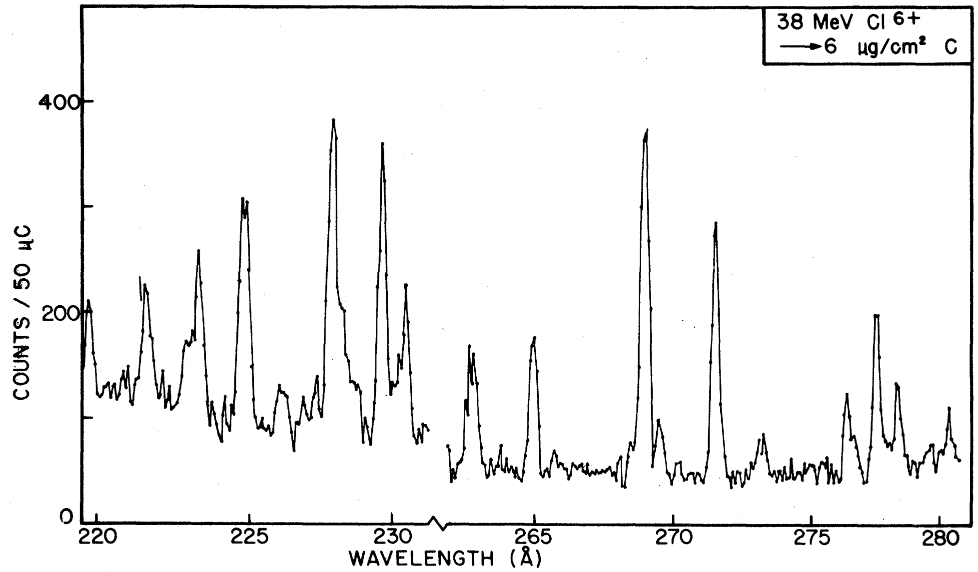

FIG. 1. Portion of the EUV spectrum emitted by multiply charged, foil-excited chlorine ions of incident energy 38 MeV. The instrumental linewidths are 0.375 Å (full width at half-maximum).

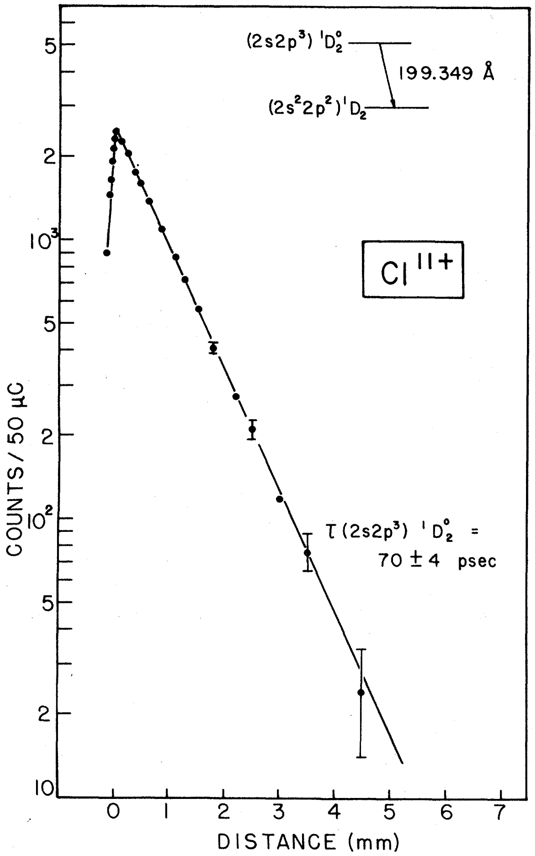

FIG. 2. Intensity-decay-curve for the 199.3-Å line in the carbonlike ion Cl XII taken at a beam energy of 38 MeV.

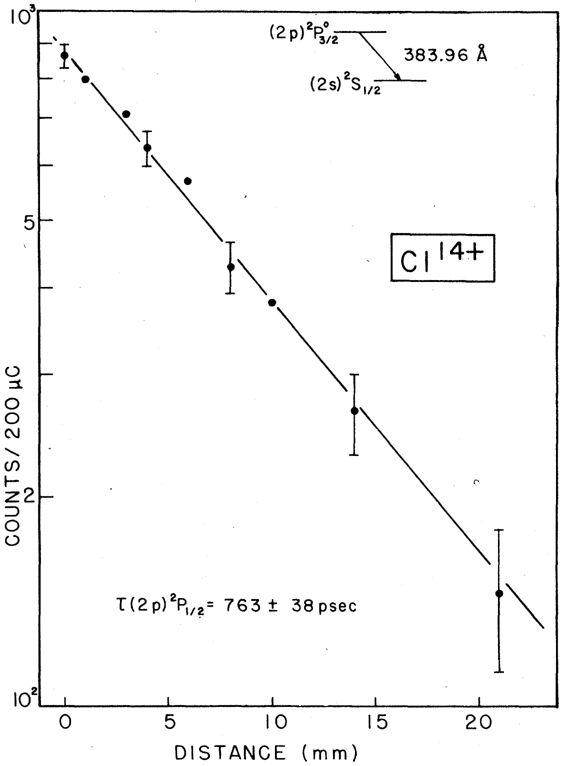

FIG. 3. Intensity-decay curve for the 384.0-Å line in the lithiumlike ion Cl XV taken at a beam energy of 45.5 MeV.

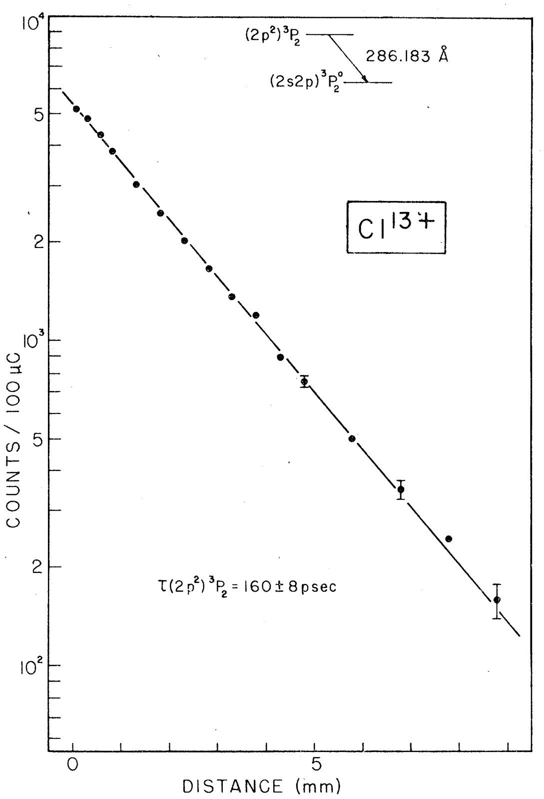

FIG. 4. Intensity-decay curve for the 286.1-Å line in the berylliumlike ion Cl XIV taken at a beam energy of 45.5 MeV.

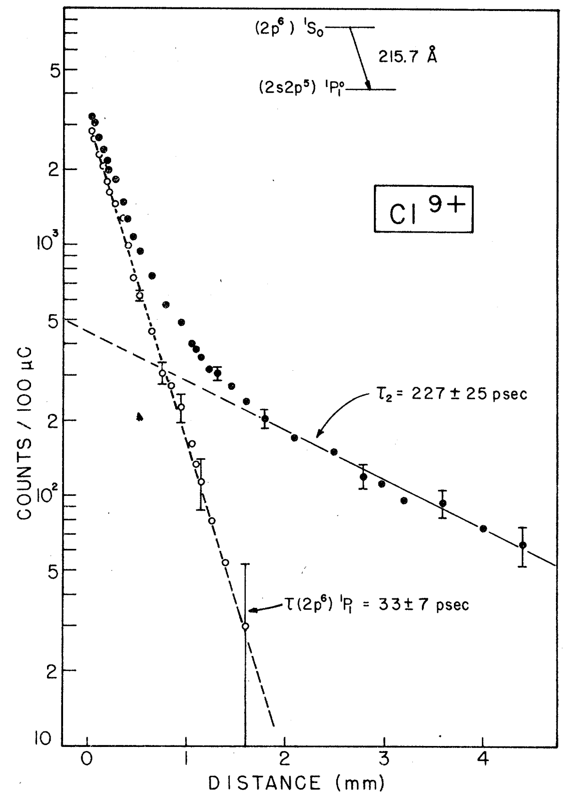

FIG. 5. Intensity-decay curve for the 215.7-Å line in the oxygenlike ion Cl X taken at a beam energy of 18 MeV.

in the determination of lifetimes due to systematic uncertainties associated with, for example, the energy loss in the foil, the reproducibility of the position of the foil and the data normalization procedure are all estimated to be $\lesssim 1\%$ in the present work. The magnitude of the uncertainties associated with the analysis of the decay curve data varies from one transition to another. Thus if line blending and cascading are expected to be negligible and the data are well fitted to a single exponential function, we estimate the result to be good to 5% or better depending upon the statistical significance of the data points. If two components are present in the decay curve, due to the line blending or cascading, we estimate that the results can still be good to ~10%–15% if the various components have significantly different lifetimes or initial intensities. The worst situation arises when two components have comparable lifetimes and initial intensities. This can occur when there is strong in-shell cascading for example. We estimate the uncertainty on such measurements to be ~20%–25%. In addition, we also quote an uncertainty of the same magnitude on those lifetime measurements close in value to the estimated temporal resolution of the apparatus which in the present case ranged from 15 to 35 psec.

Previously unreported lines at 215.5, 271.2, and 331.9 Å were tentatively identified with the $(2s2p^5)^1P_1$-$(2p^6)^1S_0$ transition in Cl X, the $(2s2p^3)^1D_2$-$(2p^4)^1D_2$ transition in Cl XII and the $(2s2p^3)^1P_1$-$(2p^4)^1D_1$ transition in Cl XII, respectively. Identification was made by interpolating or extrapolating previously reported wavelengths along isolectronic sequences.

One interesting observation in this work is the presence of long-lived components in the decay curves of all the transitions studied in N-like, O-like, and F-like structures. These components, which vary somewhat in slope and initial intensity from one transition to another, cannot be associated with cascading from levels within the *L* shell or close-lying shells. They are perhaps associated with cascading from highly excited Rydberg levels or a background from continuous radiation underlying all the discrete features. Similar tails have been observed in the *M*-shell studies of Pegg *et al.*[7]

TABLE I. Radiative lifetimes and oscillator strengths for allowed $\Delta n = 0$ transitions in multiply charged chlorine ions.

Ion	Wavelength (Å)	Transition	Lifetime of upper level (nsec)	Multiplet Oscillator strengths Present	Theory
Cl XV	384.0	$(2s)^2S_{1/2}-(2p)^2P_{3/2}$	0.76 ± 0.04	0.085 ± 0.004	0.090[a], 0.087[b], 0.082[c]
	415.6	$(2s)^2S_{1/2}-(2p)^2P_{1/2}$	0.95 ± 0.05		
	277.9	$(2s2p)^1P_1-(2p^2)^1S_0$	0.067 ± 0.010		
Cl XIV	458.4	$(2s2p)^1P_1-(2p^2)^1D_2$	0.60 ± 0.06	0.058 ± 0.009	0.052[d], 0.049[c]
	237.8	$(2s^2)^1S_0-(2s2p)^1P_1$	0.15 ± 0.03	0.088 ± 0.009	0.082[d], 0.078[c]
	286.1	$(2s2p)^3P_2-(2p^2)^3P_2$	0.16 ± 0.01	0.17 ± 0.03	0.22[d], 0.21[b], 0.21[c], 0.22[e]
	215.3	$(2s2p^2)^2D_{5/2}-(2p^3)^2P_{3/2}$	0.055 ± 0.006	0.076 ± 0.004	0.079[c]
Cl XIII	272.9	$(2s2p^2)^2S_{1/2}-(2p^3)^2P_{3/2}$		...	...
	419.5	$(2s2p^2)^2P_{3/2}-(2p^3)^2D_{5/2}$	0.12 ± 0.01		
	209.9	$(2s^22p)^2P_{1/2}-(2s2p^2)^2S_{1/2}$	0.080 ± 0.008	...	...
	205.5	$(2s^22p)^2P_{3/2}-(2s2p^2)^2P_{1/2}$	0.058 ± 0.006	0.029 ± 0.003	0.026[d], 0.029[f], 0.026[c]
	264.6	$(2s^22p)^2P_{1/2}-(2s2p^2)^2D_{3/2}$	0.33 ± 0.03	0.10 ± 0.01	0.137[d], 0.14[f], 0.14[c]
	224.6	$(2s2p^2)^4P_{3/2}-(2p^3)^4S_{3/2}$	0.053 ± 0.005	0.057 ± 0.006	0.054[d], 0.054[f], 0.053[c]
	197.5	$(2s2p^3)^3D_1-(2p^4)^3P_1$	0.035 ± 0.004	0.047 ± 0.005	0.055[f], 0.052[c]
Cl XII	197.6	$(2s2p^3)^3D_2-(2p^4)^3P_1$			
	202.5	$(2s2p^3)^3D_1-(2p^4)^3P_2$	0.033 ± 0.004	...	...
	202.6	$(2s2p^3)^3D_3-(2p^4)^3P_2$			
	174.4	$(2s^22p^2)^3P_1-(2s2p^3)^3S_1$	0.027 ± 0.005		
	223.2	$(2s^22p^2)^3P_1-(2s2p^3)^3P_0$	0.13 ± 0.01		
	223.1	$(2s^22p^2)^3P_1-(2s2p^3)^3P_1$		0.055 ± 0.010	0.077[d], 0.075[c]
	262.4	$(2s^22p^2)^3P_1-(2s2p^3)^3D_2$	0.32 ± 0.01	0.058 ± 0.003	0.064[d], 0.062[c]
	262.2	$(2s^22p^2)^3P_1-(2s2p^3)^3D_1$			
	271.2	$(2s2p^3)^1D_2-(2p^4)^1D_2$	0.051 ± 0.005	0.055 ± 0.003	0.055[d], 0.058[c]
	175.8	$(2s^22p^2)^1D_2-(2s2p^3)^1P_1$	0.028 ± 0.003		
	199.3	$(2s^22p^2)^1D_2-(2s2p^3)^1D_2$	0.070 ± 0.004	...	...
	195.6	$(2s2p^4)^2D_{5/2}-(2p^5)^2P_{3/2}$	0.026 ± 0.005		
	192.1	$(2s^22p^3)^2P_{3/2}-(2s2p^4)^2S_{1/2}$	0.040 ± 0.004	0.085 ± 0.004	0.085[d]
Cl XI	166.1	$(2s^22p^3)^2D_{3/2}-(2s2p^4)^2P_{3/2}$	0.022 ± 0.005		
	166.6	$(2s^22p^3)^2D_{5/2}-(2s2p^4)^2P_{3/2}$		0.046 ± 0.005	0.049[d], 0.049[c]
	209.9	$(2s^22p^3)^2D_{5/2}-(2s2p^4)^2D_{5/2}$			
	209.4	$(2s^22p^3)^2D_{3/2}-(2s2p^4)^2D_{3/2}$	0.064 ± 0.06	...	...
	242.7	$(2s^22p^3)^4S_{3/2}-(2s2p^4)^4P_{5/2}$	0.18 ± 0.02	0.15 ± 0.015	0.141[d], 0.149[c]
Cl X	215.7	$(2s2p^5)^1P_1-(2p^6)^1S_0$	0.033 ± 0.007	0.11 ± 0.02	0.133[c]
	164.5	$(2s^22p^4)^1D_2-(2s2p^5)^1P_1$	0.024 ± 0.005	0.10 ± 0.015	0.116[d], 0.120[c]
	205.4	$(2s^22p^4)^3P_2-(2s2p^5)^3P_2$	0.062 ± 0.009		
Cl IX	180.7	$(2s^22p^5)^2P_{3/2}-(2s2p^6)^2S_{1/2}$	0.030 ± 0.006	0.055 ± 0.01	0.063[d], 0.071[c]

[a] Reference 1.
[b] Reference 2.
[c] Reference 3.
[d] Reference 4.
[e] Reference 5.
[f] Reference 6.

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*Present address: Dept. of Physics, U. of Tennessee, Chattanooga, Tenn. 37401.

†Permanent address: Dept. of Physics, U. of Connecticut, Storrs, Conn.

‡Permanent address: Dept. of Phys., U. of New Hampshire, Durham, N. H.

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