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Measurements of $2s^22p^n$-$2s\,2p^{n+1}$ transitions in krypton XXVIII and XXIX ions

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We report measurements of the $2s^22p^n$-$2s\,2p^{n+1}$ transitions in the ions Kr XXVIII and Kr XXIX, fluorinelike and oxygenlike krypton. The measured line positions are used to determine fine-structure intervals in the ground-state configurations of these ions. The results are compared with semiempirical and Dirac-Fock calculations.

INTRODUCTION

Interest in transitions between levels in the ground-state configurations of highly ionized atoms has grown in recent years because of the value of these lines for spectroscopic diagnosis of astrophysical and laboratory plasmas.[1-3] For example, line intensity ratios between electric dipole ($E1$) and magnetic dipole ($M1$) transitions between levels in the lowest-lying configurations of ions with 4—7 electrons can be very sensitive to the electron density of a plasma.[4,5] In addition, the long-wavelength $M1$ lines from transitions in the ground-state configuration can conveniently be observed with enough resolution to detect Doppler effects due to ion thermal motion and bulk mass velocities in low-density plasmas.[6] Unfortunately, the $M1$ lines typically fall in spectral regions where many other lines occur. Thus accurate measurements of the positions of the $M1$ lines are necessary to distinguish them from $E1$ transitions from lower charge states.

These $M1$ transitions are of particular interest for highly ionized systems because the nonrelativistic (electrostatic) energies of the two states involved are roughly equal, leaving relativistic and quantum electrodynamic effects as the largest contributors to the fine-structure splitting observed from $M1$ lines. This is particularly true of the fine-structure splitting of the $2s^22p^5$ fluorinelike configuration, since only one configuration is possible for each fine-structure level. The resulting absence of configuration interaction makes the prediction of the fine-structure interval of $2s^22p^5$ in fluorinelike ions a particularly good test for relativistic theories.[7] Conversely, the oxygenlike system is a relatively simple system for which correlations are important in the calculation as well as relativistic effects.[8]

In this paper we present our measurements of $2s$-$2p$ transitions in krypton produced in a 3.5×10^{12} W gas-puff z pinch, and compare them with the results of Dirac-Fock and semiempirical calculations. This work represents an extension of numerous previous measurements[9,10] in lower atomic number ions to charge states higher than previously reported in oxygenlike systems and complements recent data near the highest observed charge states in fluorinelike systems.[1] Some of the transitions classified in this paper have also very recently been seen in the TFR tokamak (TFR denotes Tokamak Fontenay-aux-Roses) by Wyart *et al.*[11]

EXPERIMENTAL APPARATUS

The spectra were produced from the electromagnetic implosion of a hollow gas puff driven by the PITHON relativistic electron-beam generator at Physics International Co., San Leandro, California.[12] This source, which forms a cylindrically symmetric rod of plasma, was viewed both axially and radially with 1-m grazing incidence spectrographs fitted with 1200-line/mm gratings at 88° angle of incidence. The spectral resolution of both spectrometers was 0.1 Å across the spectrum. The source was imaged on the entrance slit with an external mirror, and spatially resolved in the radial direction in each case with the use of a crossed slit. The spectra were recorded on Kodak 101-05 film. On the radial line of sight spectrometer, wavelength calibration was obtained with lines due to argon impurity atoms added to the krypton puff.

The lines used for calibration were radiated primarily from Ar XVI, which have been measured previously on PITHON.[13] Accurate empirical interpolations also exist for these transitions.[14] The deviation of the instrumental dispersion from its theoretical value measured with these lines was fit to a second-order correction polynomial to obtain an accurate wavelength scale. Systematic errors due to plasma radial motion or pressure-dependent shifts have been minimized by using only data taken from regions of the plasma slightly off of the axial core of the discharge.

Because the imploding plasma reached velocities in excess of 5.0×10^7 cm/sec in the gas-puff z pinch, the influence of Doppler shifts on our data must be accounted for. This has been considered in some detail by Stewart *et al.*[13] for argon gas-puff implosions. As expected from the cylindrical symmetry of the device, no net radial differential velocities were measurable in an argon plasma between charge states. Thus we feel confident that argon

TABLE I. Wavelengths and identifications of Kr XXVIII and XXIX lines.

Configurations	Levels	Weighted oscillator strength (gf)	λ(theory) (Å) *ab initio*[b]	λ(theory) (Å) Semiempirical[a]	λ(expt.) (Å)
Kr XXVIII					
$2s^2 2p^5$-$2s2p^6$	$^2P_{1/2}$-$^2S_{1/2}$	0.19	52.08	52.589	52.60±0.03
	$^2P_{3/2}$-$^2S_{1/2}$	0.07	67.83	68.728	68.75±0.03
Kr XXIX					
$2s^2 2p^4$-$2s2p^5$	$^3P_2$-$^3P_1$	0.17	53.32	53.631	53.64±0.03
	$^1D_2$-$^1P_1$	0.36	53.48	53.975	53.97±0.03
	$^3P_1$-$^3P_0$	0.08	58.16	58.416	58.48±0.05
	$^3P_0$-$^3P_1$	0.07	58.39	58.734	58.69±0.05
	$^3P_2$-$^3P_2$	0.24	59.43	59.689	59.73±0.03
	$^3P_1$-$^3P_1$	0.04	68.84	69.412	69.46±0.03
	$^3P_1$-$^3P_2$	0.07	79.39	79.909	80.03±0.05

[a]Reference 9.
[b]Reference 16.

TABLE II. Ground-state configuration energy levels in Kr XXVIII and Kr XXIX.

Configurations	Levels	Theoretical energy *ab initio*[a,b]	Theoretical energy Semiempirical[c]	Experimental energy (cm^{-1})
Kr XXVIII				
$2s^2 2p^5$	$^2P_{1/2}$	0	0	0
	$^2P_{3/2}$	446 340[a]	446 532	446 600±500
Kr XXIX				
$2s^2 2p^4$	$^3P_2$	0	0	0
	$^3P_0$	162 911[b]	162 011	160 400±750
	$^3P_1$	422 850[b]	423 933	424 600±520

[a]Reference 16.
[b]Reference 16.
[c]Reference 9.

TABLE III. Magnetic dipole transitions.

Configuration	Level	Theoretical energy[a] (cm^{-1})	Experimental energy (cm^{-1})
Kr XXVIII			
$2s^2 2p^5$	$^2P_{1/2}$-$^2P_{3/2}$	446 532	446 600±500
Kr XXIX			
$2s^2 2p^4$	$^3P_0$-$^3P_1$	−261 922	−264 200±660
	$^3P_1$-$^3P_2$	423 933	424 600±520

[a]Reference 9.

impurities imploding with a krypton plasma produce reliable, unshifted calibration lines for spectra taken along a radial line of sight. For axial exposures, charge-dependent axial velocities as high as 2.0×10^7 cm/sec have been observed in argon. Wavelength calibration for axial exposures was obtained with lines from neighboring krypton ions bright enough to be measured from radial exposures. In particular, we used lines from Kr XXVI and Kr XXVIII to calibrate the weak Kr XXIX transitions. This minimized any differential axial velocities between ions, since all of these ions are created in the core of the plasma at the end of the implosion. Axial data were used only to measure weak lines, which were much stronger in axial exposures because of the larger volume of plasma visible to the spectrometer along this line of sight.

RESULTS

A densitometer trace of the spectrum of a pure krypton implosion viewed axially between 50 and 80 Å is shown in Fig. 1. Lines from Kr XXVIII and Kr XXIX ions are the most prominent features in this region. Also observed are strong 4-5 lines from Kr XXVI, and numerous weak unidentified features, many of which have spatial variations characteristic of lower charge states. Wavelengths and identifications of the observed $2s$-$2p$ lines are given in Table I. The accuracy of the wavelengths is estimated to be 0.030 Å absolute and 0.015 Å relative (limited by the statistical accuracy of line centroid determination) for all but the weakest lines, which have accuracies estimated at 0.050 Å absolute and 0.025 Å relative. The Kr XXIX line at 80.03 Å is definitely visible, but because of the absence of calibration lines near 80 Å, its value was more accurately determined from energy level values determined from the other identified oxygenlike transitions.

The fluorinelike $2p$-$2s$ lines were identified by their strength, spatial variation, and agreement with wavelengths predicted through extrapolations of measurements from lower members of the isoelectronic sequence by Edlén.[9,15] The oxygenlike lines were more difficult to identify because they required a large extrapolation from previous measurements in the oxygenlike isoelectronic sequence. An extrapolation of the existing data to higher charge states has been recently made by Edlén[9] by fitting the differences between the existing data and the Dirac-Fock calculations of Cheng,[16] to a simple physically plausible expression with variable coefficients. This extrapolation, as well as a similar one made earlier independently by the authors of this work, was compared to the observed line positions to identify the oxygenlike transitions. These transitions were also identifiable by their intensity pattern and spatial variation in the plasma. Energy levels in the ground-state configurations of Kr XXVIII and Kr XXIX derived from the wavelengths listed in Table I are tabulated in Table II, and the energies of the allowed magnetic dipole transitions that can be determined from our data are listed in Table III. Figure 2 compares the result for the $2s^22p^5\ ^2P_{3/2}$-$^2P_{1/2}$ fine-structure interval with recent *ab initio*[7,17,18] and semiempirical calculations.[2,3,15,19] All data are plotted as fractional differences from the Dirac-Fock values of Kim and Huang.[2] This normalization is consistent with that of Edlén.[15] The data points delimited with the small error bars are direct measurements of the $M1$ transitions in tokamak plasmas. The remainder are derived from $E1$ intervals in laser plasmas, except for the

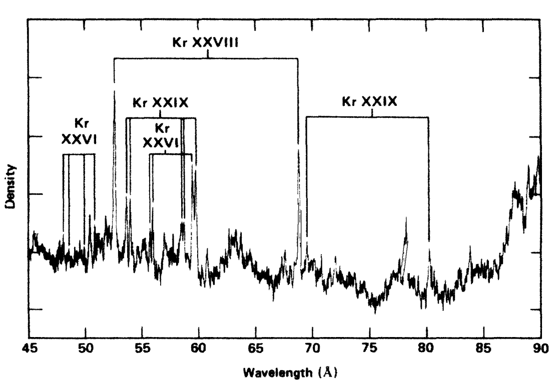

FIG. 1. Densitometer trace of the spectrum of krypton in the gas-puff z pinch between 45 and 90 Å. The lines from Kr XXVI are 4-5 transitions. The Kr XXIX and Kr XXVIII lines are $2p$-$2s$ transitions.

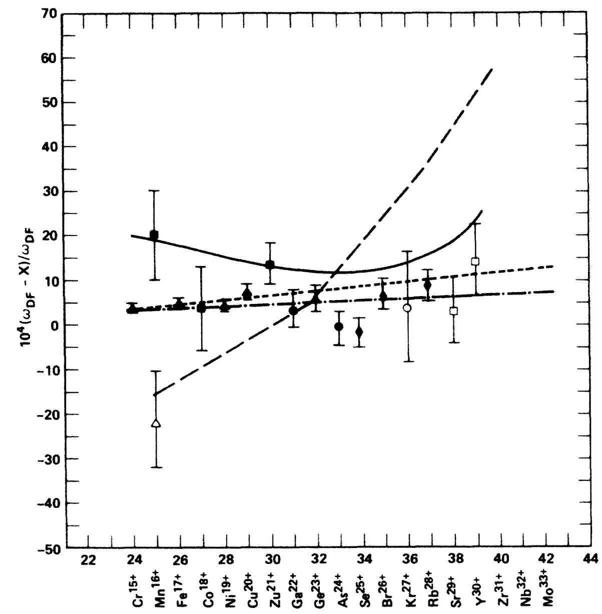

FIG. 2. Fractional energy differences from the multiconfiguration Dirac-Fock results of Huang *et al.* (Ref. 7). Calculated results shown are due to ——, Frye *et al.* (Ref. 18); — — —, Driker *et al.* (Ref. 19); -----, corrected values of Kim and Huang (Ref. 2) and Edlén (Ref. 15); and —·—·—, Curtis and Ramanujam (Ref. 3) and Hata *et al.* (Ref. 17). Experimental results are from △, Hinnov *et al.* (Ref. 20); ■, Doschek *et al.* (Ref. 21); ●, Kononov *et al.* (Ref. 22); □, Reader (Ref. 1); △, TFR Group (Ref. 23); ♦, Feldman *et al.* (Ref. 10); and ○, this work.

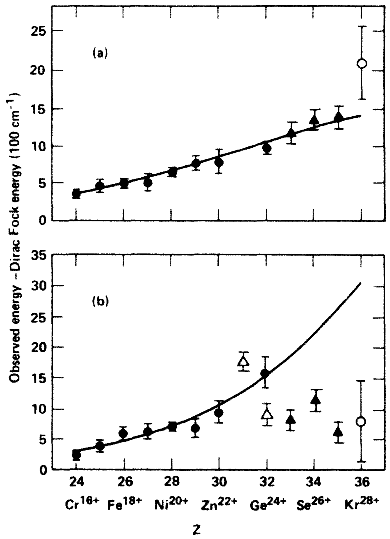

FIG. 3. (a) Differences between experimentally observed values of the $2s^22p^4\,{}^3P_1$-${}^3P_2$ interval in oxygenlike ions with Dirac-Fock calculations of Cheng *et al.* (Ref. 16) as corrected by Edlén (Ref. 9) as a function of atomic number. The experimental points are from ●, references listed in Ref. 9; △, Ref. 24; △, Ref. 10; ○, this work. (b) Differences between experimental and Dirac-Fock values of the $2s^22p^4\,{}^3P_0$-${}^3P_1$ interval as a function of atomic number. Experimental points are labeled as in (a).

interval for Mn XVII, which came from a tokamak. The *ab initio* predictions of Hata[17] are in excellent agreement with the present result, as well as with the higher z measurements of Reader.[1] The semiempirical calculations are all in agreement with the data except for the results of Driker *et al.*,[19] which are based on extrapolations of data from only atomic numbers of 29 and lower. Our data are also in excellent agreement with the recent experiment of Wyart *et al.*[11]

Figure 3 shows the deviations of our results and other measurements of lower members of the oxygen isoelectronic sequence from the Dirac-Fock values of Cheng,[16] as adjusted by Edlén.[15] These are compared with the semiempirical extrapolations of Ref. 15 in the figures. For the ${}^3P_0$-${}^3P_1$ interval, our data and the recent data of Feldman *et al.*[10] indicate that the extrapolation fails as the atomic number increases beyond 30. For the ${}^3P_2$-${}^3P_1$ interval, the disagreement with observations is less than the experimental uncertainty.

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