$4s$-$4p$ Resonance Transitions in Highly Charged Cu- and Zn-like Ions[(a)]

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The $4s$-$4p$ resonance transitions in the copperlike and zinclike ions from Rb to Mo have been observed by means of a low-inductance open spark and a 10.7-m grazing-incidence spectrograph. Lines belonging to highly charged ions could be distinguished by their abnormally large widths. The observations confirm the identification of the resonance lines of Mo XIII and Mo XIV in the Princeton University *ST* tokamak by Hinnov, Johnson, Meservey, and Dimock.

The spectra of heavy ions having simple atomic structures are currently of great interest because of their use in the diagnosis of hot plasmas encountered in controlled fusion experiments. Of particular importance are ions in the copper and zinc isoelectronic sequences. These ions contain either one or two valence electrons outside of core electrons in tightly bound closed shells and their spectra remain simple, even for very highly ionized species. These sequences thus play a special role in controlled fusion research.

The spectral transitions most commonly observed in fusion-type plasmas are transitions to the ground state from low-lying excited states having the same principal quantum number n. In the Cu and Zn sequences these transitions are of the type $4s$-$4p$. Unfortunately, experimental data for these transitions generally exist for only the lower sequence members. Until recently, the $4s$-$4p$ transitions in the Cu sequence were known only through Rb IX.[1,2] In the Zn sequence they were known only through Kr VII.[1,2] Recently, Hinnov *et al.*[3] observed three lines in the Princeton University *ST* tokamak that were identified as the $4s\,^2S_{1/2}$-$4p\,^2P_{1/2,3/2}$ transitions of the copperlike ion Mo XIV (424 and 374 Å) and the $4s^2\,^1S_0$-$4s4p\,^1P_1$ transition of the zinclike ion Mo XIII (341 Å). The presence of Mo ions in the discharge was caused by sputtering at the aperture limiter, which is made of molybdenum. Although these lines have not yet been observed in more conventional light sources and their wavelengths have not been accurately measured, they are being used regularly for plasma diagnostics.[4]

In this Letter we report the observation of the $4s$-$4p$ resonance lines in the Zn and Cu isoelectronic sequences through Mo XIII and Mo XIV with a spark light source. The observations confirm the tokamak identifications for Mo and indicate trends in the isoelectronic sequences that support Hinnov's[4] more recent tokamak observation of Xe XXV and Xe XXVI. Our measurements for the Mo XIII and Mo XIV lines provide wavelength calibration points for spectroscopists working with tokamaks having Mo limiters as well as experimental data for the evaluation of relativistic calculations of the energy levels and spectra of atoms in the Cu and Zn sequences.

The spectra of the present ions generally occur in two different wavelength regions. For $\Delta n \neq 0$ transitions, the spectra fall at relatively low wavelengths (100–250 Å) and are well separated from spectra due to lower ionization stages. (A number of $\Delta n \neq 0$ transitions for copperlike and zinclike, Y, Zr, Nb, and Mo have been reported by Alexander *et al.*[5]) However, for $\Delta n = 0$ transitions, the spectra fall at longer wavelengths (400–600 Å) and lie in the midst of numerous lines due to lower ionization stages. The problem of trying to identify a few lines of highly ionized atoms among the complex spectra of lower ionization stages in the long-wavelength region, in all likelihood, accounts for the lack of observation of the $4s$-$4p$ transitions in these ions before now. Our present success is due largely to a detailed knowledge of these spectra developed in recent investigations[6] and to what we believe is a new method of distinguishing lines of different ionization stages in hot sparks.

The spectra were excited in a low-inductance open spark, essentially the same as that described by Feldman *et al.*[7] The spark takes place between metallic electrodes in vacuum after being triggered by a high-frequency discharge from a third electrode. In the present work we used capacitors of either 4.7 or 14.2 μF at voltages varying between 1 and 15 kV. No external inductance was used. Observations were made with the National Bureau of Standards 10.7-m grazing-incidence spectrograph at an angle of incidence of 80°. The grating had a groove spacing of 1200 lines/mm, providing a plate factor of 0.25 Å/mm at 300 Å.

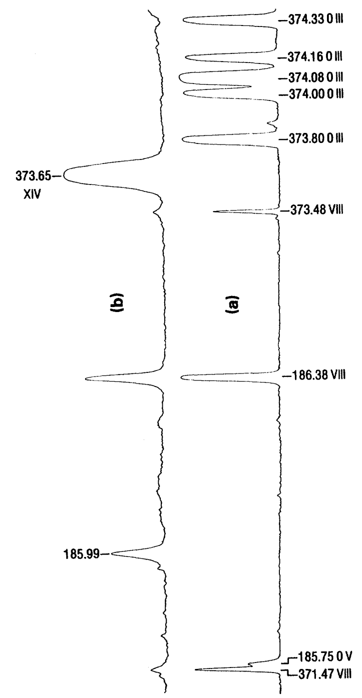

FIG. 1. Microdensitometer tracings of Mo spectra. Wavelengths are in angstroms; lines at 186 Å are in second order. Trace a, low-voltage sliding spark with quartz spacer, 0.8 kV, peak current 3000 A, 5000 sparks. O III lines are due to oxygen in the spacer. Trace b, low-inductance open spark, 5 kV, 50 sparks.

The ionization stages of the observed lines were determined in several ways. First, the spectra obtained with the open spark were compared with spectra obtained with a low-voltage sliding spark. Our previous work[6] showed that the sliding spark would not produce atoms ionized more than about 8 times. Next, the degree to which Cu-like and Zn-like ions were produced in the open spark at various voltages could be determined from the appearance of the $\Delta n \neq 0$ transitions of these ions in the lower-wavelength region. Finally, lines in the long-wavelength region belonging to higher ionization stages could be recognized by their relatively large widths. In fact, the observed linewidths were seen to vary directly with stage of ionization. It seems likely that the various ions of an element are generated in different thermal, or perhaps magnetic, regions of the spark that evolve in time and therefore exhibit different linewidths. This method of distinguishing lines of different ionization stages of course derives from the very high resolving power of our 10.7-m spectrograph.

A tracing of a portion of the spectrum of Mo illustrating the observed broadening is shown in Fig. 1. The full width at half-maximum of the Mo XIV line is 0.11 Å. For pure Doppler broadening this width would imply a plasma temperature of 1.4 keV, which appears unrealistically high

TABLE I. Transitions in Cu-like ions. The transitions for each ion are listed in the following order: $4p\,^2P_{1/2}$–$5s\,^2S_{1/2}$, $4p\,^2P_{3/2}$–$5s\,^2S_{1/2}$, $4s\,^2S_{1/2}$–$4p\,^2P_{3/2}$, $4s\,^2S_{1/2}$–$4p\,^2P_{1/2}$.

Ion	λ(Å)	Int.	Δσ(cm^{-1})	Ion	λ(Å)	Int.	Δσ(cm^{-1})
Rb IX	239.566	25	12 337 ± 12	Zr XII	150.842[b]	10	22 421 ± 30
	246.862	40			156.122[b]	20	
	583.399[a]	80	12 334 ± 2		439.315	80	22 425 ± 3
	628.632[a]	40			487.325	20	
Sr X	202.485	25	15 264 ± 17	Nb XIII	132.349[b]	10	26 710 ± 40
	208.943	40			137.199[b]	15	
	527.141	80	15 266 ± 2		404.302	100	26 723 ± 4
	573.273	40			453.274	20	
Y XI	173.693[b]	12	18 638 ± 20	Mo XIV	117.149[b]	10	31 563 ± 50
	179.504[b]	20			121.647[b]	15	
	479.771	80	18 623 ± 3		373.647[c]	100	31 547 ± 5
	526.844	30			423.576[c]	20	

[a] New measurement of line originally given by Mack, see Ref. 1.
[b] New measurement of line given in Ref. 5.
[c] Originally observed in tokamak, Refs. 3 and 4.

TABLE II. $4s^2\,{}^1S_0$-$4s4p\,{}^1P_1$ transitions in Zn-like ions.

Ion	λ (Å)	Intensity
Rb VIII	524.929	100
Sr IX	475.358	100
Y X	433.785	100
Zr XI	398.357	100
Nb XII	367.730	100
Mo XIII	340.909[a]	100

[a]Originally observed in tokamak, Refs. 3 and 4.

for the spark at 5 kV. It is possible, as Feldman and Doschek[8] suggest, that these abnormally wide lines are due to broadening caused by megagauss magnetic fields in the pinched regions of the plasma.

Our measurements for the $4s$-$4p$ transitions in Cu- and Zn-like ions are given in Tables I and II. The intensities are visual estimates of photographic blackening that give approximate relative intensities of lines within limited wavelength regions, the zinclike transitions being assigned an arbitrary intensity of 100. The uncertainty of the wavelengths is ±0.005 Å. The identifications in the Cu sequence are confirmed by our measurements of the $4p$-$5s$ transitions, also given in Table I. As shown, the fine-structure intervals $\Delta\sigma$ $(4p\,{}^2P_{1/2-3/2})$ derived from the two pairs of lines in each ion agree very well. Hinnov's recent values[4] of 373.8 ± 0.5 Å and 423.5 ± 0.5 Å for the Mo XIV lines are consistent with our much more accurate values. Although the identifications in the Zn sequence consist of a single line for each ion without the benefit of confirming transitions, the prominence of the lines and their isoelectronic regularity leave no doubt as to their correctness. Hinnov's value[4] of 341.0 ± 0.5 Å for the Mo XIII line is consistent with our present value.

In an isoelectronic sequence of $\Delta n = 0$ transitions, the wave numbers of corresponding lines should have an approximately linear dependence on the net charge of the atomic core, $Z_c = Z - N_e + 1$, where N_e is the total number of electrons in a particular ion. The present results do indeed show such a nearly linear behavior.

In Fig. 2(a) we plot the deviations from linearity of the $4s\,{}^2S_{1/2}$-$4p\,{}^2P_{1/2}$ transitions in the Cu isoelectronic sequence. Here the observed wave numbers are reduced by a term linear in Z_c. The coefficient of Z_c is the slope derived from the difference between the values for Mo and Zn. The observed point for Xe (with error bars) is Hinnov's recent value.[4] The points for Sn and Xe denoted by a cross represent the theoretical calculations of Cowan.[9] Similar calculations have also been done by Weiss.[10] As the vertical scale is greatly expanded here, the deviations from linearity are actually not large. The linear approximation holds well here, because the wave functions of the $4s$ and $4p_{1/2}$ electrons both become contracted at high values of Z_c as a result of relativistic effects, and the resultant energy shifts nearly cancel in the transition energies.

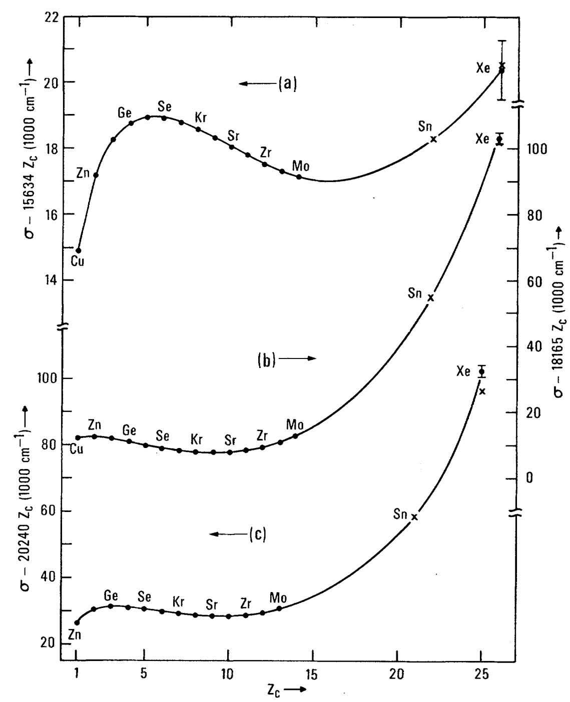

FIG. 2. Z dependence of resonance transitions in the Cu and Zn isoelectronic sequences. (a) $4s\,{}^2S_{1/2}$-$4p\,{}^2P_{1/2}$ transitions in the Cu sequence. (b) $4s\,{}^2S_{1/2}$-$4p\,{}^2P_{3/2}$ transitions in the Cu sequence. (c) $4s^2\,{}^1S_0$-$4s4p\,{}^1P_1$ transitions in Zn sequence. Observed values for Xe from Ref. 4. Crosses are theoretical values from Ref. 9.

Figure 2(b) gives an equivalent plot for the $4s\,{}^2S_{1/2}$-$4p\,{}^2P_{3/2}$ transitions in the Cu sequence. The deviations from linearity are much greater here, because the $4p_{3/2}$ wave function is not greatly affected by relativity, so the transition energies mirror the relativistic contraction of the $4s$ orbital. This is also true of the $4s^2\,{}^1S_0$-$4s4p\,{}^1P_1$ transitions in the Zn isoelectronic sequence, plotted in Fig. 2(c), because the $4s4p\,{}^1P_1$ state has a large component of the jj-coupled state $(4s4p_{3/2})$ $J=1$.

For the Cu-like ions, the present results make it possible to relate a number of previously unconnected levels to the ground state and thereby establish a proper system of energy levels in each ion. A complete report on the spectra, energy levels, and ionization energies will be published elsewhere.

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Measurement of Two-Photon Relaxation Time by Stark Switching

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This Letter report the application of the Stark-switching technique to study the two-photon coherent precession effect. Using this technique, I have made the first time-domain measurement of the collision-induced dephasing time in a two-photon transition in NH_3, and the result is compared with pressure-broadening measurements in the frequency domain.

This Letter reports the first time-domain relaxation-time measurement for a two-photon transition. The study of transient coherent effects has long been most fruitful in yielding precise and detailed information on the relaxation times of the physical systems since the early work in nuclear magnetic resonance.[1] The advent of laser sources made it possible to observe optical analogs of these effects in one-photon transitions in many different systems.[2] Precise relaxation-time measurements were initially hampered by the difficulties in controlling pulsed-laser outputs. However, the introduction of the Stark-switching and subsequent frequency-switching techniques[1] substantially by-passed these difficulties and these measurements can now be accurately performed. Recently, there has been much interest in coherent effects in two-photon transitions, both theoretically[4-8] and experimentally.[9-13] The use of these recently observed two-photon coherent effects to study relaxation times in these two-photon transitions will be very exciting, especially since the relaxation times can be studied under near Doppler-free conditions using the counter-propagating-beam geometry. This Letter reports the application of the Stark-switching technique to the two-photon problem and, with it, the first measurement of the collision-induced dephasing time of a two-photon transition in NH_3.

The experimental configuration consists of two counter-propagating beams interacting with a two-photon transition that is near resonant to the sum of the laser frequencies. Application of a Stark voltage brings the two-photon transition through the sum frequency of the lasers. A coherent two-photon polarization is generated, and, in terms of the two-photon vector model,[7,8] the polarization vector precesses about the effective field. At low laser intensities, this characteristic precession frequency is simply the time-dependent frequency offset between the Stark-shifted transition frequency and the laser sum frequency. The precessing two-photon polarization, depending on the relative phases, induces alternating absorption and emission of light. The