RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 27, NUMBER 3 MARCH 1983

Magnetic-dipole transitions observed in highly ionized Ga, Ge, As, and Kr

J. R. Roberts, V. Kaufman, J. Sugar, and T. L. Pittman
Atomic and Plasma Radiation Division, National Bureau of Standards, Washington, D.C. 20234

W. L. Rowan
Fusion Research Center, Department of Physics, University of Texas, Austin, Texas 78712

(Received 22 October 1982; revised manuscript received 27 December 1982)

The Texas Experimental Tokamak (TEXT) was used to observe magnetic-dipole radiation arising from transitions within the $3s^2 3p^n$ ground-state configurations of highly stripped ions heavier than Ni. This device generates a plasma of 3×10^{13}-cm^{-3} electron density and ~ 1.5-keV temperature, ideally suited for ionization of these atoms to the $n=3$ shell. Wavelength and transition-rate predictions were made with scaled Hartree-Fock radial energy integrals.

INTRODUCTION

The use of magnetic-dipole transitions in heavy ions as noninterfering plasma probes has had a significant impact on the diagnosis of ion temperatures and transport in tokamak plasmas.[1] Due to their low transition rates of $\sim 10^2$–10^5 s^{-1} these spectral lines can be seen only in low-density plasmas ($\sim 10^{13}$/cm^3) and have previously been identified almost exclusively in stellar spectra and in the solar corona and solar flares. This fact limited observations to atoms abundant in these sources. Hinnov, Suckewer, and co-workers[1–5] undertook to expand these data by searching for new lines in the tokamak plasma itself, either from impurity ions already present or by injection of selected elements. The first of these newly observed magnetic-dipole lines, reported by Suckewer and Hinnov,[1] was the $2s^2 2p^3\,{}^2D^0_{3/2}$-${}^2D^0_{5/2}$ transition in Fe XX at 2665 Å (in air), whose Doppler broadening was used to obtain a radial profile of ion temperatures in the plasma. Subsequently, additional magnetic-dipole lines of Sc, Ti, Cr, Fe, Ni, Cu, and Ge were reported.[2–5]

Stripping electrons from atoms of Cu through Kr to the $n=3$ shell requires about the same energy range as ionizing elements of the iron period to the $n=2$ shell. These heavier elements can provide diagnostic lines for much higher temperatures if stripped to the $n=2$ shell. Therefore the same element may be used to measure a wide range of temperatures and ionic charge distributions in the plasma. The present observations of magnetic-dipole lines arising from transitions between levels of ground configurations of the $n=3$ shell is intended to expand the number of lines available for diagnostics in the heavier atoms.

WAVELENGTH AND TRANSITION RATE PREDICTIONS

We have predicted the energy levels of the ground configurations of ions of the $3s^2 3p^n$ isoelectronic sequences by the use of the Hartree-Fock (HF) radial energy integrals scaled to fit observed levels of K through Ni. It was found that the scaling is a slowly varying function of atomic number. In this range the scaling of the Slater parameter F^2 varies from 0.81 to 0.86 and the spin-orbit parameter ζ from 1.06 to 1.04. We extrapolated these ratios to obtain values to use in diagonalizations of the $3s^2 3p^n$ ground configurations, slowly increasing the F^2 ratio to 0.88 and the ζ ratio to 1.06 through Mo. Final adjustments of these ratios were made by fitting the magnetic-dipole lines $3s^2 3p^2\,{}^3P_0$-${}^3P_1$ of Ge XIX and Mo XXIX identified by Suckewer and Hinnov and generously communicated to us in advance of publication. The effective operator $\alpha L(L+1)$ was included to take into account far configuration interaction. The coefficient α was found to vary from 70 to 200 from K to Ni. This parameter is usually negative when explicit interaction with the np^{k+2} configuration is included.[6] Except for the spin-orbit interaction, no relativistic effects are included in these calculations. Since we are considering transitions within the ground configuration, the mass and Darwin corrections cancel out. The next order correction separating the $p_{1/2}$ and $p_{3/2}$ orbits is probably small for the $3p$ shell in these ionization stages.

Transition rates $A(J,J')$ for magnetic-dipole transitions were evaluated with the formula given by Cowan,[7] using wave functions obtained from the scaled energy calculations. The predicted wavelengths and transition rates for the magnetic-dipole

TABLE I. Wavelengths of observed magnetic-dipole lines and their predicted values and transition rates. Values above 2000 Å are in air. The uncertainty in the wavelength measurements is ±0.5 Å.

Ion	Transition	Obs. λ (Å)	Calc. λ (Å)	Calc. error (cm^{-1})	Calc. rate (10^3 s^{-1})
Ga XVI	$3p^4\,(^3P_2\text{-}^1D_2)$	1529.8	1523.8	−257	1.0
Ge XVII	$3p^4\,(^3P_2\text{-}^3P_1)$	2406.5[a]	2406.3	0	1.4
Ge XX	$3p\,(^2P_{1/2}\text{-}^2P_{3/2})$	1831.8	1833.9	62	2.9
As XX	$3p^2\,(^3P_2\text{-}^1D_2)$	1608.8	1602.8	−232	2.1
As XXI	$3p\,(^2P_{1/2}\text{-}^2P_{3/2})$	1573.2	1574.9	69	4.6
Kr XXI	$3p^4\,(^3P_2\text{-}^1D_2)$	877.6	873.1	−590	8.3

[a] This line was reported at 2407.0 ± 0.1 Å by K. H. Burrell and R. J. Groebner, Bull. Am. Phys. Soc. 27, 1101 (1982).

transitions observed in the course of this work are given in Table I.

EXPERIMENT

The Texas Experimental Tokamak (TEXT)[8] was used for these observations. It has a major radius of 1 m and a minor radius of 28 cm, which is set by a stainless-steel aperture limiter. With a toroidal magnetic field of 2.8 T, the plasma current, which was measured with a Rogowskii coil, reached a plateau of about 320 kA. The chord averaged electron density through the geometric center of the minor cross section was about 3×10^{13} cm^{-3}. The density was measured with a 2-mm microwave interferometer.

Injection of GaAs and Ge were achieved by laser blow-off of material deposited in a 2-μm layer on glass plates.[5] The Kr was injected by gas puffing for 2 ms and at ~ 140 ms after discharge initiation.

Four spectrometers were used to search for the magnetic-dipole lines. The relative impurity content of the sample element was monitored with a 2.2-m grazing incidence monochromator with a 600-line/mm grating. Throughout the experiment it was set to observe the strong $3s^2\,{}^1S-3s3p\,{}^1P$ transition of the element under investigation (~ 200 Å). Two 1-m normal incidence vacuum ultraviolet monochromators were used to search for the sample lines. For both instruments, the typical slit width was 100–200 μm, and the gratings were blazed at 1500 Å. One instrument contained a grating with 1200 lines/mm and a reciprocal dispersion of 8.3 Å/mm. The other contained a grating with 600 lines/mm and a reciprocal dispersion of 16.6 Å/mm. Wavelengths above 2000 Å were scanned with a 1-m Czerny-Turner spectrometer with a grating of 1200 lines/mm blazed at 3000 Å.

The sample lines were sought in shot-by-shot scans. One of the two normal incidence monochromators was scanned over the spectral region predicted to contain a magnetic-dipole line. The spectral regions searched were usually 20 Å wide and were centered on the predicted wavelength. The scan was first made with a slit sufficiently wide to encompass about 1.6 Å. If a candidate spectral feature were located, it was then observed with a narrower slit of about 0.8 Å to obtain an accurate wavelength.

An example of a wavelength scan is shown for the 877.6-Å Kr XXI line in Fig. 1. This figure was constructed from a series of seven shots—one at each of the wavelengths shown. For each shot, the signal from the scanning monochromator was integrated between 200 and 266 ms, and then normalized to the signal from the monitor monochromator after it was integrated in the same way. The normalization is

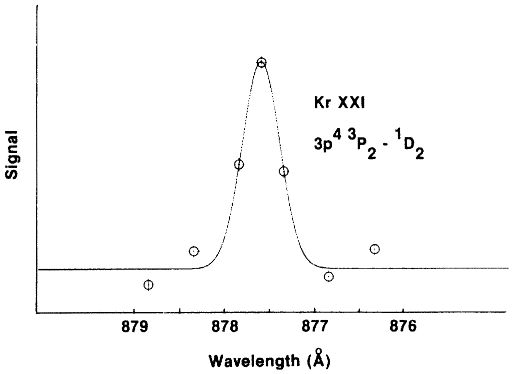

FIG. 1. Scan of 877.6-Å line $3p^4\,{}^3P_2\text{-}{}^1D_2$ of Kr XXI normalized to intensity of Kr XXV electric dipole line at 159 Å [E. Hinnov, Phys. Rev. A 14, 1533 (1976)].

used to allow for shot-to-shot variation in the sample content. The integration simply smoothes the signal. A Gaussian was fitted to the set of points to construct the figure.

The observed and calculated wavelengths are compared in Table I. All the measured values are within ± 6 Å of those predicted. In the worst case, the energy prediction was low by 590 cm^{-1}. As more lines become known, the predictions may be improved by further refinement of the parameter values.

ACKNOWLEDGMENTS

We wish to acknowledge the support of the TEXT professional and technical staff, especially K. Gentle, Director, B. Richards, and D. Patterson. We also express our thanks to M. Bassin. T. Sellner, and D. Jones of the Nat'l. Bur. Stand. (U.S.) for their contributions to this effort. This work was supported under Contract No. EA-77-A-01-6010 from the United States Department of Energy.

---

[1] S. Suckewer and E. Hinnov, Phys. Rev. Lett. 41, 756 (1978).

[2] S. Suckewer, J. Cecchi, S. Cohen, R. Fonk, and E. Hinnov, Phys. Lett. 80A, 259 (1980).

[3] E. Hinnov, Astrophys. J. 230, L197 (1979).

[4] S. Suckewer and E. Hinnov, Phys. Rev. A 20, 578 (1979).

[5] E. Hinnov, S. Suckewer, S. Cohen and K. Sato, Phys. Rev. A 25, 2293 (1982).

[6] V. Kaufman, J. Sugar, and D. Cooper, Phys. Scr. 25, 623 (1982).

[7] R. D. Cowan, *The Theory of Atomic Structure and Spectra* (Univ. of California, Berkeley, 1981).

[8] K. W. Gentle, Nucl. Technol./Fusion 1, 479 (1981).