Magnetic dipole lines in the $3s^2 3p^x$ configurations of elements from copper to molybdenum

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(Received 17 January 1983)

A number of spectrum lines arising from magnetic dipole transitions in the $3s^2 3p^5$, $3s^2 3p^4$, $3s^2 3p^3$, $3s^2 3p^2$, $3s^2 3p$, and $3s 3p$ electron configurations in elements $29 \leq Z \leq 42$ have been identified. The lines were observed in the Princeton Large Torus tokamak discharges into which the appropriate elements were introduced by means of laser blowoff. The identifications are based on time and space dependence of the observed emissivities, and the systematic consistency of the observed wavelengths with isoelectronic extrapolations based on known lower-Z elements.

I. INTRODUCTION

The energy-level structure of the $3s^2 3p^x$ configurations (i.e., the chlorine, sulfur, phosphorus, silicon, and aluminum isoelectronic sequences) are fairly adequately determined for elements up to nickel ($Z=28$), largely as a result of solar coronal observations and the analysis of Edlén[1] and his co-workers. These energy levels are tabulated in National Bureau of Standards compilations.[2] Empirically adjusted analytical expressions have been developed[3,4] that allow accurate interpolations for any elements that have not been observed directly. However, there are practically no experimental data for the heavier elements because of their low abundances in solar spectra and the difficulties of observing the relatively weak radiative transitions in the high-density short-duration discharges of many laboratory plasmas.

But it is precisely in the range of elements, about $29 \leq Z \leq 42$, where the magnetic dipole transitions within these configurations become sufficiently intense to be of major interest for localized spectroscopic diagnostics in tokamak-type discharges. The reasons for this, both physical and technical, have been described elsewhere[5–7] together with references to actual applications. In the present paper we shall discuss recent identifications of such magnetic dipole transitions observed in Princeton Large Torus (PLT) tokamak discharges and, with a few exceptions, not previously published.

The identification, as in the case of the $n=2$ shell transitions,[6] is based on time- and space-distribution measurements and absolute intensities, all in comparison with known resonance lines of neighboring states. The expected approximate wavelengths are predicted from isoelectronic extrapolations of empirical fits in lighter elements or from theoretical calculations.[4,8,9]

II. RESULTS

Tables I–IV present the results of the wavelength measurements. There are three types of entries: (1) The numbers without brackets indicate wavelengths, where we consider the indicated transitions reliably established. (2) In many cases, especially those of weaker lines, the time and space dependence of the emissivity cannot be adequately established. Such tentative identifications are indicated with square brackets. (3) The numbers in parentheses give interpolated values, based on measured wavelengths in the same column, as a guide for future measurements.

In general, the facility of measurements and reliability of interpretations are greatest for the simple configurations at the ends of the period, shown in Table I. However, the quality of the results deteriorates for the more intricate configurations given in subsequent tables.

The measurements have been performed only with copper, germanium, selenium, zirconium, and molybdenum, mostly because of the scarcity of available experimental time on the PLT tokamak. Also, because of spectrometer sensitivity limitations, there have been no measurements of weak line intensities in the 1000–1400 Å in-

TABLE I. Wavelengths (Å) of the indicated transitions in the magnesium, aluminum, and chlorine sequences. (Numbers in parentheses are interpolated wavelengths. Measurement uncertainties are ±0.3 Å unless stated otherwise.)

Z	$3s\,3p\ ^3P_2$-$^3P_1$	$3s^2 3p\ ^2P_{3/2}$-$^2P_{1/2}$	$3s^2 3p^5\ ^2P_{1/2}$-$^2P_{3/2}$
$_{29}$Cu	3941.6	3007.6±0.2	3500.4
$_{30}$Zn	(3296.8)	(2532.0)	(2924.0)
$_{31}$Ga	(2775.4)	(2146.7)	(2459.6)
$_{32}$Ge	2350.2	1832.7	2085.1±0.1
$_{33}$As	(2001.7)	(1573.1)	(1780.0)
$_{34}$Se	1714.1	(1358)	1527.8
$_{36}$Kr	(1275)	(1027)	(1145)
$_{38}$Sr	(965)	(791)	(875)
$_{40}$Zr	741.5	618.5	679.1
$_{41}$Nb	(653.3)	(549.7)	(601.7)
$_{42}$Mo	577.5	490.1	534.9

TABLE II. Wavelengths in the $3s^23p^4$ configuration of the sulfur sequence. [Numbers in square brackets are tentative identifications. In the interpolations (values in parentheses) it is assumed that the tentative identifications are correct.]

Z	$^3P_1$-$^3P_2$	$^3P_1$-$^3P_0$	$^1D_2$-$^3P_2$	$^1D_2$-$^3P_1$	$^1S_0$-$^3P_1$
$_{29}$Cu	[4193.6]		(1906)	(3492)	(1190)
$_{32}$Ge	2406.9		(1361)	[3131.3]	[952.9]
$_{34}$Se	1727.7	[5645.0]	(1088)	[2935.8]	[808.8]
$_{36}$Kr	(1271)	(3105)	(871.1)	(2767)	(680)
$_{38}$Sr	(956)		(700.0)	(2610)	
$_{40}$Zr	731.8+0.2	(1274)	564.9	[2476]	[474.2]
$_{42}$Mo	569.8±0.1	[889.2]	458.6±0.2	(2348)	[395.7]

terval. Wavelengths above 2000 Å are given in air.

In the magnesium sequence, the $3s\,3p\ ^3P_2$-$^3P_1$ transition energies corresponding to the wavelengths in the first column of Table I are slightly larger than the calculated values,[8] with the deviation increasing slowly with Z. There do not appear to be any published experimental observations of this transition[10] beyond the coronal line of Fe XV at 7058.6 Å. However, the Ge XXI line has recently been identified in the Doublet III spectra by Burrell and Groebner,[11] in very good agreement with our result.

The second column in Table I gives the wavelengths of the $3s^23p\ ^2P_{3/2}$-$^2P_{1/2}$ transitions of the aluminum sequence. In this case, extrapolation of the empirically adjusted (for $Z \leq 28$) formulas[4] systematically give slightly larger transition energies.

The $3s^23p^5\ ^2P_{1/2}$-$^2P_{3/2}$ transition wavelengths of the chlorine sequence are given in the last column of Table I. These transition energies follow quite closely isoelectronic extrapolations of the semiempirical formulas given by Svensson[3] and also (within a constant factor) of the Dirac-Fock energies of Kim and Huang.[9]

In the $3s^23p^4$ configuration of the sulfur sequence there are five magnetic dipole lines, but two of those, the $^1D_2$-$^3P_1$ and $^3P_1$-$^3P_0$ are expected to be weak because the radiative branching strongly favors the other components $^1D_2$-$^3P_2$ and $^3P_1$-$^3P_2$ respectively. In Table II, the measured wavelengths of these weak transitions are all in the tentative category. However, the stronger lines in Zr XXV and Mo XXVII are quite well established, and are sufficient to determine the energy separations of all levels except the $^3P_0$, which needs further confirmation. There have been some difficulties in determining the $^1S_0$-$^3P_1$ transition in selenium and germanium although the line appears quite strong in zirconium and molybdenum—the uncertainty in the latter case is due to strong interfering radiation, rather than a weakness of the line.

In spite of the weakness of the $^1D_2$-$^3P_1$ and $^3P_1$-$^3P_0$ lines, they are of special interest in plasma diagnostics because of their relatively long wavelengths and their potential usefulness for spectrometer sensitivity calibration by means of radiative branching ratios. It is therefore important to establish their wavelengths and relative intensities directly, even in cases where the stronger lines of the same configuration may be more appropriate for many diagnostic purposes.

Isoelectronic extrapolations from the lower-Z data[4] tend to give systematically slightly larger energy separations than the experimental observations in the $3s^23p^4$ configuration.

The measured wavelengths in the $3s^23p^2$ configuration of the silicon sequence are given in Table III. The ^3P levels, and to a lesser extent the $^1S_0$ level, are fairly well established, but so far we have not located the transitions from the $^1D_2$ level, except for a cursory observation of the $^1D_2$-$^3P_2$ transition in Cu and Ge. The comment about radiative branching ratios for intensity calibration also applies to the transitions from the $^1D_2$ level in this sequence.

In this configuration, the isoelectronic extrapolation, from $Z \leq 28$, predicts an energy separation slightly too small for the $^3P_2$-$^3P_1$, and too large for the $^3P_1$-$^3P_0$ and $^1S_0$-$^3P_1$ levels.

There has been a notable lack of success in identifying lines in the $3s^23p^3$ configuration of the phosphorus sequence. There are no adequate theoretical predictions of either the energy levels or the radiative transition rates, and the isoelectronic extrapolations are likely to be more precarious than in the sulfur or silicon sequences. As a result, all the lines shown in Table IV are rather tentative identifications and require further confirmation. All these lines are weak. Thus the lines assigned to the $^2D_{3/2}$-$^4S_{3/2}$ transition are some 3—5 times less intense than the neighboring $^3P_1$-$^3P_0$ lines of the silicon sequence. Furthermore, in several cases, adjacent strong O III and O IV resonance lines prevent adequate measurement of both spectral inten-

TABLE III. Wavelengths in the $3s^23p^2$ configuration of the silicon sequence. (See the explanation of the parentheses and square brackets for Table II.)

Z	$^3P_1$-$^3P_0$	$^3P_2$-$^3P_1$	$^1D_2$-$^3P_2$	$^1D_2$-$^3P_1$	$^1S_0$-$^3P_1$
$_{29}$Cu	5375.8	(7105)	[2539.7]	(1871)	952.8
$_{32}$Ge	2933.7±0.2	5170.3	[1810.4]	(1341)	754.1
$_{34}$Se	2042.0	4396.5	(1413)	(1069)	[639.6]
$_{36}$Kr	(1463)	(3840)	(1097)	(854)	(541)
$_{40}$Zr	807.1	3100.5	(669)	(550)	(385)
$_{42}$Mo	618.5	2841.1±0.2	(527)	(445)	[325.3]

TABLE IV. Wavelengths in the $3s^2 3p^3$ configuration of the phosphorus sequence. (See the explanation of the parentheses and square brackets for Table II.)

Z	$^3D_{3/2}$-$^4S_{3/2}$	$^2D_{5/2}$-$^2D_{3/2}$	$^2P_{3/2}$-$^4S_{3/2}$	$^2P_{1/2}$-$^4S_{3/2}$
$_{29}$Cu	[2085.3]		[944.2]	
$_{32}$Ge	[1779]	[5702.3]	[703.6]	[894.8]
$_{34}$Se	[1534]	4276.0	(569.2)	
$_{40}$Zr	(787)	2549.8		
$_{42}$Mo	[609.8]	2285.4±0.1		

sity distribution and time behavior of these lines.

Of the lines shown in Table IV, we currently have the most confidence in the lines ascribed to the $^2D_{5/2}$-$^2D_{3/2}$ transition. Although weak, these lines have no interfering plasma background lines in their vicinity. They would be of substantial interest for plasma diagnostics if the identifications were confirmed.

III. DISCUSSION OF THE RESULTS

It appears from the data that the energy-level separations corresponding to the lines in Table I are well established up to molybdenum, and could be extrapolated slightly beyond, perhaps to $Z=45$–48. All these lines are quite strong and well suited for a variety of spectroscopic plasma diagnostics. However, for interpretation of measured local emissivities in terms of corresponding ion densities, a considerable amount of work is still required, and this applies *a fortiori* to the more complicated configurations mentioned below. In particular, the strength of the $3s\,3p\,^3P_2$-$^3P_1$ line relative to the $3s^2$-$3s\,3p\,^1S_0$-$^1P_1$ and $^1S_0$-$^3P_1$ lines requires quantitative interpretation, both experimentally and theoretically. For this purpose, it would be important to measure simultaneously the emissivities of the three lines for different elements and at different electron densities.

In the sulfur and silicon sequences considerable details are still missing or in need of confirmation; and in the phosphorus sequence the work is only beginning. The lines in these sequences are weaker and hence more difficult to measure quantitatively. But because of their greater variety, especially in the wavelength range, these lines offer a correspondingly greater versatility for potential diagnostic application.

Recently, detailed radiative transition rates have been calculated for the $2s^2 2p^x$ configurations by Cheng, Kim, and Desclaux,[12] and the expected steady-state population densities in plasmas of different electron density by Feldman, Doschek, and Bhatia.[13] Similar calculations for the $n=3$ configurations would be very valuable for further investigation of these energy levels and for quantitative diagnostic applications, particularly for the phosphorus sequence ions.

ACKNOWLEDGMENTS

The authors wish to thank the Swedish Natural Science Research Council (Naturvetenskapliga Forskningsråd) for the scholarship grant that has allowed Dr. B. Denne to participate in these experiments. This work has been supported by the U.S. Department of Energy, Contract No. AC02-76-CHO-3073.

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