# $4s^24p\ ^2P$ intervals in the Ga isoelectronic sequence from $Rb^{6+}$ to $In^{18+}$

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Measurements of the fine-structure splitting of the $4s^24p\ ^2P$ ground-state term of the gallium isoelectronic sequence using low-inductance sparks, laser-produced plasmas, and tokamak plasma sources are presented. The observations are in excellent agreement with semiempirical predictions using screening parametrizations, and permit a refinement of these predictions.

Fine-structure intervals for highly ionized systems with ground-state electron configurations of the form $ns^2np$ have recently come under scrutiny because of their applications in plasma diagnostics. These intervals correspond to intraterm magnetic dipole transitions which produce strong line radiation for highly charged ions at wavelengths much longer than other strong emissions in the same ion. $M1$ transitions between the $^2P$ fine-structure levels of the $2s^22p$ ground-state configuration of the boron isoelectronic sequence[1–4] and the $3s^23p$ ground-state configuration of the aluminum isoelectronic sequence[4–6] have already been identified in tokamak plasmas. These identifications can be greatly aided by semiempirical extrapolations if a sufficiently large base of reliable isoelectronic observations is available. An approach utilizing a semiempirical screening parametrization has recently been used to make extrapolative predictions for the $ns^2np$ intervals in the boron $(n=2)$ sequence[7] and the aluminum $(n=3)$, gallium $(n=4)$, indium $(n=5)$, and thallium $(n=6)$ sequences.[8] In the data-rich B and Al sequences, the screening parametrization has been shown[7,8] to provide an excellent representation, and (with small systematic corrections[9] for very high ionization stages) highly precise predictions are possible.

Prior to this work, reliable observations of the $4s^24p\ ^2P$ homologous intervals for the Ga sequence were available for only the first six stages of ionization, so that the extrapolation to higher stages was somewhat speculative. We have now determined these intervals for Ga-like ions from Rb VIII to In XIX from high-resolution spectra made with low-inductance vacuum sparks and laser-produced plasmas. We have also directly observed the magnetic dipole transition within the $4s^24p$ term for galliumlike Mo and Ag with a tokamak. A semiempirical parametrization of these observations permits highly accurate interpolations and extrapolations of these intervals along the isoelectronic sequence. Our study increases the number of known intervals in the gallium sequence from 6 to 17, corrects earlier misclassifications, and verifies and sharpens the semiempirical predictions.

The spectra of galliumlike ions from Rb VII to In XIX were observed at the National Bureau of Standards (NBS) with a 10.7-m grazing incidence spectrograph. For the ions Rb VII through Mo XII the light source was a low-inductance vacuum spark. For the ions Ru XIV through In XIX the source was a laser-produced plasma. The observed $4s^24p\ ^2P$ intervals are given in Table I. The uncertainties listed for the intervals determined in the NBS observations correspond to an estimated uncertainty of $\pm 0.005$ Å in the measured wavelength intervals. For nearly all of the ions the $4s^24p\ ^2P$ intervals were derived from lines of the $4s^24p$-$4s4p^2$ transition array in the region 180–520 Å. For Ru XVI some of the lines of this array were too blended with neighboring lines to permit an accurate value of the $4s^24p\ ^2P$ interval to be determined. Our value for this interval was derived from the $4s^24p$-$4s^25s$ transitions, which in Ru XVI lie at about 100 Å. The uncertainty for this interval is consequently higher than the uncertainties for other intervals. For Cd XVIII some of the $4s^24p$-$4s4p^2$ lines were again blended and since the $4s^24p$-$4s^25s$ transitions could not be unambiguously identified, a value for the $4s^24p\ ^2P$ interval could not be obtained.

The tokamak measurements were made by using the Princeton Large Torus (PLT) with Mo and Ag introduced into the discharge by laser blowoff.[16] The intervals derived from the observed $4s^24p\ ^2P_{1/2}$-$^2P_{3/2}$ $M1$ transitions are given in Table I.

In the ions Y IX–Mo XII, wavelengths for lines classified as $4s^24p\ ^2P$-$4s^25d\ ^2D$ transitions have been reported by Alexander, Even-Zohar, Fraenkel, and Goldsmith.[17] However, with any reasonable estimate of the $^2D$ separation, the resultant $^2P$ interval is inconsistent with our measurements. We conclude that these lines were incorrectly classified in Ref. 17.

The semiempirical parametrization was obtained by replacing the nuclear charge $Z$ by an effective screened charge $Z-S(Z)$ in the theoretical expression for the corresponding $4p$ fine-structure separation in a hydrogenlike atom. The expression is given in Refs. 7 and 8 and includes a high-order Sommerfeld expansion of the Dirac energy as well as quantum electrodynamic corrections. The derived screening parameter $S(Z)$ is characterized by a slow and regular variation along the isoelectronic sequence. As observed earlier[7,8] for the B and Al sequences, the experimental values of $S(Z)$ for the Ga sequence are very well represented by a weighted least-squares adjustment of the

TABLE I. Fine-structure separations of the $4s^24p$ ground configuration in the gallium isoelectronic sequence (in $cm^{-1}$).

| Ion | NBS Obs. (uncert.) | Fit | Fit-obs. | PLT Obs. (uncert.) | Fit-obs. |
|---|---|---|---|---|---|
| $_{31}Ga$ | 826[a,b] | c | | | |
| $_{32}Ge^{1+}$ | 1 767[a,d] | (1 665) | | | |
| $_{33}As^{2+}$ | 2 940[a,e] | (2 917) | | | |
| $_{34}Se^{3+}$ | 4 376[f] | 4 373 | −3 | | |
| $_{35}Br^{4+}$ | 6 089(6)[g] | 6 093 | 4 | | |
| $_{36}Kr^{5+}$ | 8 108(10)[h] | 8 113 | 5 | | |
| $_{37}Rb^{6+}$ | 10 468(2)[i] | 10 468 | 0 | | |
| $_{38}Sr^{7+}$ | 13 186(3)[i] | 13 192 | 6 | | |
| $_{39}Y^{8+}$ | 16 322(3)[i] | 16 317 | −5 | | |
| $_{40}Zr^{9+}$ | 19 886(4)[i] | 19 880 | −6 | | |
| $_{41}Nb^{10+}$ | 23 915(5)[i] | 23 917 | 2 | | |
| $_{42}Mo^{11+}$ | 28 466(5)[i] | 28 465 | −1 | 28 463(2)[j] | 2 |
| $_{43}Tc^{12+}$ | | 33 563 | | | |
| $_{44}Ru^{13+}$ | 39 187(47)[i] | 39 254 | 67 | | |
| $_{45}Rb^{14+}$ | 45 581(9)[i] | 45 580 | −1 | | |
| $_{46}Pd^{15+}$ | 52 572(9)[i] | 52 585 | 13 | | |
| $_{47}Ag^{16+}$ | 60 322(9)[i] | 60 316 | −6 | 60 317(4)[j] | −1 |
| $_{48}Cd^{17+}$ | | 68 821 | | | |
| $_{49}In^{18+}$ | 78 149(16)[i] | 78 150 | 1 | | |
| $_{50}Sn^{19+}$ | | 88 356 | | | |
| $_{51}Sb^{20+}$ | | 99 492 | | | |
| $_{52}Te^{21+}$ | | 111 614 | | | |
| $_{53}I^{22+}$ | | 124 783 | | | |
| $_{54}Xe^{23+}$ | | 139 057 | | | |
| $_{55}Cs^{24+}$ | | 154 501 | | | |
| $_{56}Ba^{25+}$ | | 171 181 | | | |

[a] Not used in fit.
[b] Reference 10.
[c] No real solution to Eq. (2) for this $Z$, $S_0$, and $b$.
[d] Reference 11.
[e] Reference 12.
[f] Reference 13.
[g] Reference 14.
[h] Reference 15.
[i] This work, NBS.
[j] This work, PLT.

empirical parameters $S_0$ and $b$ in the linear relationship

$$S(Z)=S_0+b/[Z-S(Z)] \ . \tag{1}$$

The goodness of fit is enhanced if the Rydberg constant $\mathscr{R}$ in the hydrogenic equation that defines $S(Z)$ is replaced by an effective value

$$\mathscr{R}\rightarrow\mathscr{R}/(1+\epsilon) \ , \tag{2}$$

where $\epsilon$ is an additional fitting parameter that is introduced to empirically compensate for deviations from the one-electron picture (cf. Refs. 7 and 8), and is evaluated by optimizing the fitting of the data to Eq. (1).

Excluding the first three ionization stages in the data in Table I, we obtained the best weighted least-squares fit using a value $\epsilon=0.020$. This compares with the values 0.017 and 0.016 that were obtained for the corresponding quantities in the boron[7] and aluminum[8] sequences. A plot of $S$ vs $1/(Z-S)$ with this value of $\epsilon$ is shown in Fig. 1. The weighted least-squares adjustment yielded the values $S_0=9.875$ and $b=114.56$. Comparing these with the fitted parameters in Ref. 8 of $S_0=10.14$ and $b=110.88$ one should note that the earlier analysis was based on only four

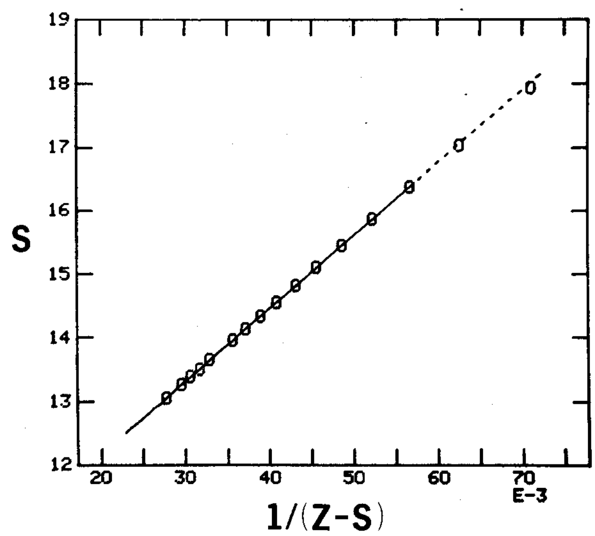


FIG. 1. Plot of the screening parameter $S$ vs the reciprocal screened charge $Z-S$, reduced using a value $\epsilon=0.020$ in Eq. (2). Observations are denoted by (0) for $Z=32$–42, 44–47, and 49. The solid line indicates a weighted least-squares fit to Eq. (1), which becomes a dashed line in the $Z<34$ region where the points were excluded from the fitting.

data points, and the quantity $\epsilon$ was set equal to zero and not fitted. Thus the present fit verifies the trend of the earlier fit, but greatly improves the accuracy of the extrapolations.

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