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FINE STRUCTURE OF THE $1s2s2p\ ^4p^0$ AND $1s2p^2\ ^4P$ DOUBLY EXCITED STATES
OF LITHIUMLIKE Si XII

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Résumé. La mesure des transitions $1s2s2p\ ^4p^0 - 1s2p^2\ ^4P$ du silicium XII a été réalisée en utilisant la technique faisceau-lame sur l'accélérateur linéaire d'Orsay. La structure fine a été déterminée avec une bonne précision et l'écart des centres de gravité des multiplets a été mesuré à $\lambda = 487.4 \pm 0.1$ Å. Les résultats sont comparés à des calculs théoriques récents.

Abstract. The $1s2s2p\ ^4p^0 - 1s2p^2\ ^4P$ transitions of Si XII have been investigated using fast ion beam spectroscopy in the far ultraviolet. The results for fine structure intervals and term separation represent the highest Z test of electron correlation effects and relativistic contributions in doubly excited states of lithiumlike ions.

The $1s2s2p\ ^4p^0_{1/2, 3/2, 5/2}$ and $1s2p^2\ ^4P_{1/2, 3/2, 5/2}$ states are the lowest multiplets in doubly excited three electron ions. In LS coupling, the system is metastable against autoionization and X-ray decay, due to its parity and spin. Main decay is between doubly excited states themselves in the ultraviolet region.

Breit interaction contributes to the fine structure splittings of both multiplets with powers of the nuclear charge as Z^4 (spin-orbit) and Z^3 (spin-spin, spin-other orbit). The multiplet separation only increases approximately linearly with Z. Best tests of fine structure are given by spectroscopic studies in high nuclear charge elements. In this work on Si XII, we present results in the heaviest ion at present time used for fine structure study of $1s2s2p\ ^4p^0$ and $1s2p^2\ ^4P$ states.

Doubly excited states in three electron ions were first detected by Edlen [1]. First measurement of fine structure of $1s2s2p\ ^4p^0$ and $1s2p^2\ ^4P$ states has been published by Livingston and Berry [2,3] in C IV, N V and O VI. Then Cheng et al. [4] calculated these structures using a multiconfiguration Dirac-Fock (M.C.D.F.) code, taking only a partial Breit interaction into account. Results are in poor agreement with available experimental determinations. Hata and Grant [5] repeated the calculations employing M.C.D.F.-E.A.L. (Energy Average Level) method and found a good agreement with experimental results.

The experiment has been performed at 32.4 MeV using the Orsay LINAC facility with beam intensities of about $7\ \mu\text{A}$ (Si^{3+}). Stripping by a $20\ \mu\text{g}/\text{cm}^2$ carbon foil led to charge equilibrium centered on Si^{10+} and Si^{9+} . The ultraviolet radiation emitted in a direction normal to the excited ion beam was spectroscopically analysed by means of a 2.2 meter McPherson 247 grazing incidence monochromator equipped with a $600\ \text{\AA}/\text{mm}$ grating. Spectrometer incidence angle was 82° so that blaze was at 210 Å. Low spectrometer efficiency, combined with low Si^{11+} beam component (6.3%), resulted in a weak light signal from quadruplets. Long data collection times led to important background in observed spectra although the dark count rate of our Bendix channeltron detector, used in single counting mode, was less than two counts per minute.

Spectra we observed from 120 Å to 730 Å will be presented and analysed in a further full paper (to be published later). We are interested, in present work, by a partial spectrum recorded between 475 Å and 502 Å (Fig. 1), the spectral range containing all the fine structure quadruplet lines. Slit widths were 50 μm , the full width at half maximum was about 0.5 Å and stepping motor controlled scan increment was 0.1 Å. Six successive partial spectra have been recorded at same resolution. Spectral

features appear to be reproducible even in detail. Spectral calibration used in-beam lines of silicon ions. The strong $2s_{1/2} - 2p_{3/2}$ resonance line of Si XII, observed in the partial spectrum of figure 1, was one of these calibration lines. Its wavelength is known to be $499.398 \pm 0.015 \text{ \AA}$ from Behring et al. [6], in agreement with semi-empirical calculations of Edlen [7].

Fig. 1. Spectrum of silicon, at 1.16 MeV/nucleon beam energy, showing the fine structure splitting of the $1s2s2p\ ^4P_J^0 - 1s2p^2\ ^4P_J$ transition.

Most lines observed between 475 Å and 502 Å have been identified to transitions of multicharged silicon appearing in the second grating order, including transitions between Rydberg states. For example, the intense peak at 478.78 Å has been identified as Si XIII [4-5] at $2 \times 239.48 \text{ \AA}$. Line identifications of the $1s2s2p\ ^4P^0 - 1s2p^2\ ^4P$ multiplet were based on isoelectronic comparisons with experimental and theoretical works on other members of the sequence. From comparison of calculated values [5] and experimental results on Ne IV [8], Mg X [9], Al XI [10] one can foresee a deviation of about 0.8 Å for $\lambda_{\text{exp}} - \lambda_{\text{th}}$. On this basis, four lines have been easily assigned to $4p^0_{3/2} - 4p_{5/2}$, $4p^0_{1/2} - 4p_{3/2}$, $4p^0_{3/2} - 4p_{1/2}$ and $4p^0_{5/2} - 4p_{3/2}$ transitions. Two of remaining lines, corresponding to $4p^0_{1/2} - 4p_{1/2}$ and $4p^0_{5/2} - 4p_{5/2}$ components were weak and not completely separated but they were observed without ambiguity. Finally the $4p^0_{3/2} - 4p_{3/2}$ component is blended by the $5s - 6p$ transition of Si XII. Other weak features, not precisely identified, observed at 495.6 and 493.2 Å are probably due to Si X and Si XI. They have been also observed by Trabert [15] at lower beam energy (20 MeV). Wavelength and identifications are displayed in Table I. Lifetimes of different $4P$ levels range from 1 to 40 ps [11], resulting in a loss of intensity in the light observed from short line components.

Errors in wavelength determination result from several sources. The uncertainty on calibration line wavelength is very small compared to the spectrometer inaccuracy. For weak Si XII $4P^0 - 4P$ components, the main parameter in wavelength determination precision was statistics. Doppler shifts of short line have also to be taken into account [12]. Errors given in Table I include reproducibility of measurements.

Fine structure and term separation are deduced from experimental wavelength determinations. Results are compared with several calculations in Table II [4,5,11,13,14].

Table I. Identification of the observed lines in the silicon spectrum of figure 1.

Wavelength (Å)	Classification	Comments
475.36 ± 0.1	XII $4p^0_{3/2} - 4p_{5/2}$	2nd ordre
478.97	XIII 4-5	
480.10 ± 0.05	XII $4p^0_{1/2} - 4p_{3/2}$	
481.24	X $2s2p^2 2S_{1/2} - 2p^3 2p^0_{3/2}$	tentative
485.23 ± 0.1	XII $4p^0_{3/2} - 4p_{3/2}$	] partially blended
486.28	XII 5s - 6p	
488.31 ± 0.2	XII $4p^0_{5/2} - 4p_{5/2}$	] blended
488.85 ± 0.2	XII $4p^0_{1/2} - 4p_{1/2}$	
493.23	XII $4p^0_{3/2} - 4p_{1/2}$	
493.95 ± 0.05		
495.60		
497.00	XII $4p_{5/2} - 4p_{3/2}$	] partially blended
498.50 ± 0.1		
499.398 ± 0.015	XII $2S_{1/2} - 2p_{3/2}$ calibration	

The fine structure splitting of Goldsmith is significantly smaller than indicated by the other calculations. The Z expansion data of Vainshtein and Safronova, when combined with the experimental energy for the Si XII $2p^2 2p_{3/2} - 2s^2 2S_{1/2}$ transition, agree with our experimental values. Fine structure calculations of Cheng et al. [4] are farther from experiment than more recent data of Chen et al. [11] which take the full Breit interaction into account. Same comments apply to Hata and Grant calculation which is closer to our fine structure experimental results. They add also the radiative corrections which, in fact, are almost independent of J and mainly shift, as a whole, the $1s2s2p^4 p^0_J$ level.

The calculated term separation of the doubly excited $2s2p^4 p^0_J$ and $2p^2 4p_J$ states significantly deviate from the experimental value. This difference can be probably attributed to error on the non relativistic correlation as mentioned by Hata and Grant [5].

Table II. Fine structure and term separation of the doubly excited states $2s2p^4 p^0_J$ and $2p^2 4p_J$ of Si XII (cm^{-1}).

	Theoretical data					Our experimental results
	[14]	[4]	[13]	[11]	[5]	
$2p^2 4p$						
5/2 - 3/2	4347	4073	4129.3	4200 ^b	4153.9	4230 ± 100
3/2 - 1/2	2174	3629	3479.4	3710 ^b	3649.3	3690 ± 70
5/2 - 1/2	6521	7702	7608.7	7910	7803.2	7920 ± 60
$2s2p^4 p^0$						
5/2 - 3/2	5364	5432	5646.9	5600 ^b	5498.3	5536 ± 100
3/2 - 1/2	1788	2143	2170.7	2175 ^b	2206.7	2150 ± 70
5/2 - 1/2	7152	7575	7817.6	7775	7705	7686 ± 70
E_{CG}						
$2s2p - 2p^2$	203832	206953	204486	207039	204877	205191
λ_{CG} (Å)	490.6	483.2	489.0 ^a	483 ^b	488.1	487.4

[4] : Cheng et al.

[5] : Hata and Grant

[11] : Chen et al.

[13] : Vainshtein and Safronova

[14] : Goldsmith

a : values obtained by using the experimental Si XII $2s - 2p$ term difference of Ref. [6]

b : values obtained by interpolation along the isoelectronic sequence from the data of Cheng.

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