

A DIFFERENTIAL MEASUREMENT OF THE GROUND STATE LAMB SHIFT IN HYDROGENIC GERMANIUM, Ge^{31+}

J.M. LAMING, C.T. CHANTLER and J.D. SILVER,

University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK

D.D. DIETRICH,

Lawrence Livermore National Laboratory, California 94550, USA

E.C. FINCH,

Department of Pure and Applied Physics, Trinity College, Dublin, Eire

P.H. MOKLER,

Gesellschaft für Schwerionenforschung, D-6100 Darmstadt, FRG

S.D. ROSNER,

Department of Physics, University of Western Ontario, London, Ontario N6A 3K7, Canada

The $1s-2p$ Lyman α transitions in hydrogenic germanium, Ge^{31+} , have been observed in fourth order of diffraction from a beam-foil light source, simultaneously with the $n = 2$ to $n = 4$ Balmer β transitions observed in first order of diffraction. This enables a measurement of the Lyman α wavelengths using the Balmer β wavelengths as a calibration. The results are presented, along with a discussion of the experimental errors, and further work which should improve the accuracy with which the Lyman α wavelengths can be determined.

Recently, a new technique for making measurements of the $1s$ ground state Lamb shift in hydrogenic ions of middle to high Z was demonstrated in hydrogenic iron, Fe^{25+} [1]. The Lyman α and Balmer β transitions were observed simultaneously in fourth and first orders of diffraction respectively, from a fast beam. Since the Balmer β transitions are much less sensitive to the effects of quantum electrodynamics (QED), than the Lyman α transitions, these lines may be used to calibrate the spectra obtained in order to extract a measurement of the Lyman α wavelengths, and hence the ground state Lamb shift [2]. This is possible because of the near four to one ratio in wavelengths of Balmer β and Lyman α .

Measurements of this type are now of particular interest, since a comparison between theory and experiment for the Lamb shift in high Z hydrogenic ions is the most precise and sensitive way to test QED at high effective coupling strength $Z\alpha$ [3].

We report here progress on a measurement of the ground state Lamb shift in hydrogenic germanium, Ge^{31+} . The experimental apparatus is shown in fig. 1. A beam of bare germanium nuclei, (Ge^{32+}), at an energy

of 1.108 GeV, (15 MeV/amu, $\beta = 0.1772$, where β is the ion velocity divided by the speed of light), from the Gesellschaft für Schwerionenforschung (GSI) UNILAC was passed through a thin carbon foil. Some of these nuclei capture an electron in the foil, and we find that under these excitation conditions, lines in the Balmer series are clearly seen for upper level principal quantum numbers n up to about $n = 7$. In particular, there is a good probability for the production of the $n = 4$ to $n = 2$ hydrogenic transitions [4].

Using this technique, problems involving Doppler shifts coming from the comparison of transitions from a fast beam with those from a stationary calibration source do not arise. Also, from the low intensities of all helium-like and lithium-like transitions in our spectra, our technique does not appear to be subject to serious contamination of the spectrum with satellite transitions from lower charge states.

The spectrometer used was the dual-arm Johann curved crystal spectrometer developed by the Lawrence Livermore National Laboratory [5–7]. The dispersing crystal used in the experiment was Si 111, with a $2d$ spacing of 6.271 Å [8]. Spectra were recorded with

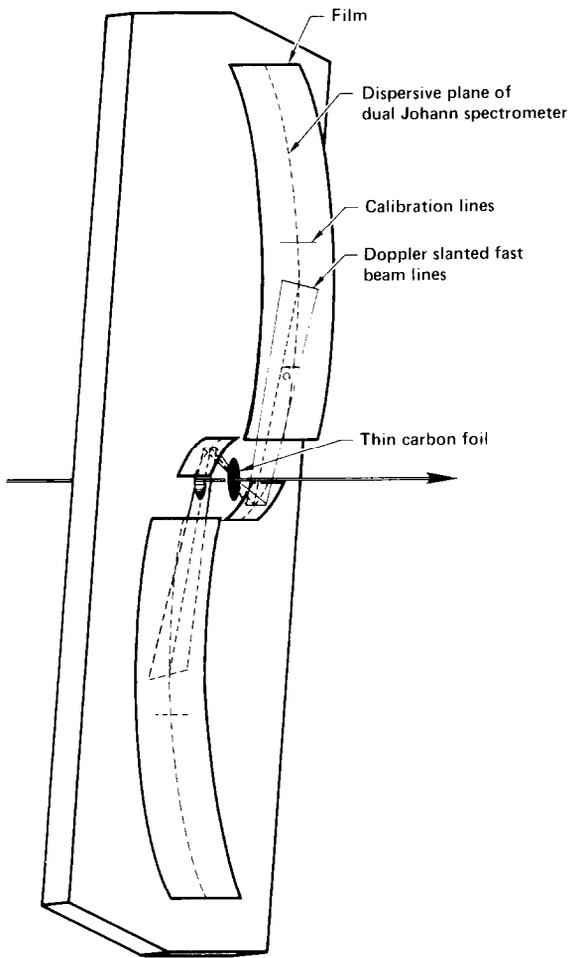


Fig. 1. Schematic diagram of experimental apparatus.

Kodak DEF 392 x-ray film. Fig. 2 shows a typical spectrum of the Lyman α /Balmer β region at a Bragg angle of approximately 49° . The spectra were subsequently put into digital form (intensity transmissivity as a function of position) using an accurate computer controlled digital microdensitometer [9], having first removed the emulsion from the reverse side of the film. A number of scans across the film were made, with the microdensitometer viewing a region of the film 1 mm high by $20 \mu\text{m}$ wide. Each scan covered about 10 mm of the film. For each scan the dispersion function of the spectrometer may be written as:

$$n\lambda_0 = \frac{2d}{\gamma} \left(1 - \frac{4d^2}{n^2} \left(\frac{\delta}{\lambda^2} \right) \right) \left(\frac{\cos \alpha}{1 - \beta \sin \alpha} \right) \sin \left(\frac{x - x_0}{2R} \right), \quad (1)$$

where n is the order of diffraction, λ_0 is the rest frame wavelength of the transition studied, and d is the spacing between the diffracting planes of the crystal.

The angle between the direction of observation and the axis of the ion beam is $90^\circ - \alpha$, where α is small. R is the radius of the Rowland circle (15 cm), x is the distance along the film and x_0 is a constant. The term involving δ accounts for the refraction of X-rays by the diffracting crystal, the refractive index of the crystal being $\mu = 1 - \delta$.

Data were taken with foil thicknesses of 10, 25, and $50 \mu\text{g}/\text{cm}^2$, so as to be able to investigate possible systematic errors concerning the target. The data were analysed by fitting Lorentzian profiles to the spectra. Seven peaks were fitted to the Balmer β spectrum, from which values for

$$\frac{2d}{\gamma} \left(\frac{\cos \alpha}{1 - \beta \sin \alpha} \right)$$

(neglecting the refractive index term in eq. (1)), $2R$ and x_0 were obtained using theoretical wavelengths for the Balmer lines from [10]. Wavelengths for the Lyman α components could then be computed using these values, and the centroids found for those peaks from the Lorentzian fitting. Fig. 3 shows the Lyman and Balmer peaks fitted to the data in fig. 2. A calculated correction for the refractive index, (with atomic form factors taken from [11]), was applied to the Lyman α wavelengths to

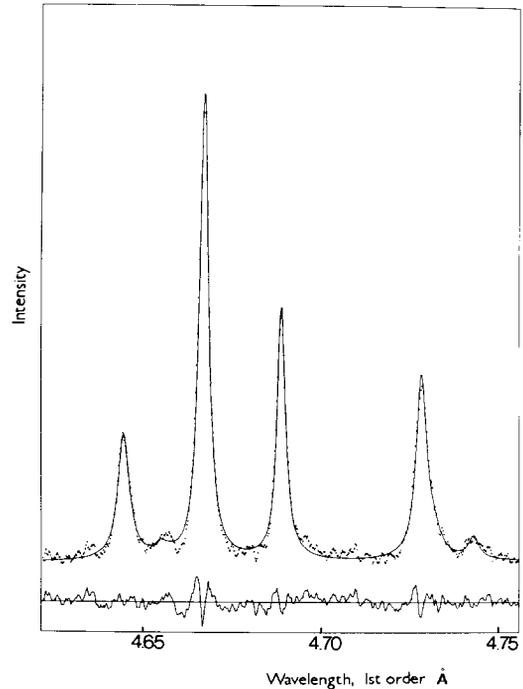


Fig. 2. Spectrum of the Lyman α /Balmer β transitions, taken using a $10 \mu\text{g}/\text{cm}^2$ carbon target. Integrated beam charge 18.0 mC. The smooth lines indicate the fitted and residual spectra. the points indicate the data.

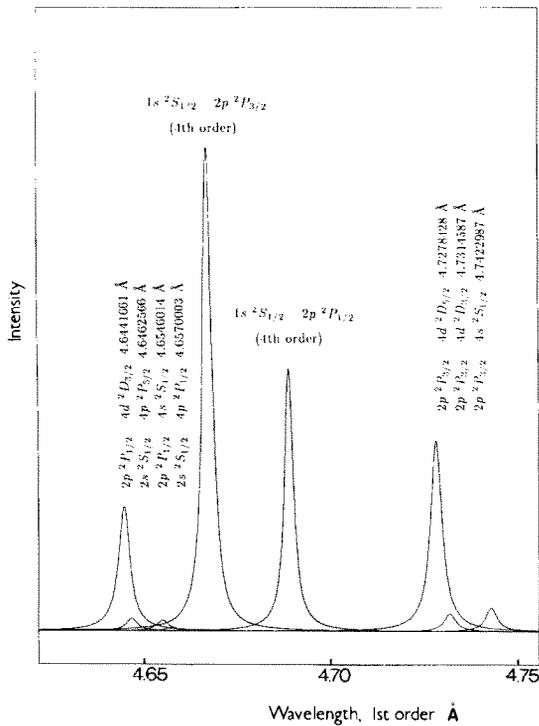


Fig. 3. The fitted line profiles for the individual transitions in fig. 2.

give the final answer for each scan. The value of δ/λ^2 used was $3.14 \times 10^{-6} \text{ \AA}^{-2}$ for first order peaks and $3.17 \times 10^{-6} \text{ \AA}^{-2}$ for fourth order peaks. The results obtained were combined to give a mean and estimated error for each foil thickness which are given in table 1. The quoted errors are the quadrature sum of the one standard deviation statistical error in the centroid determination of the Lyman α and the Balmer β peaks, 0.000005 \AA (4 ppm) arising from uncertainties in the digitization of the photographic spectra, and 0.000014 \AA (12 ppm) from an assumed uncertainty of 10% in the refractive index correction. Shifts of the most sensitive Balmer β peaks due to electric fields experienced by the Ge³¹⁺ ions are assumed to be negligible at our level of precision, since no systematic effects due to foil thickness were observed, and most of the radiation in these transitions comes from downstream of the target. Shifts

Table 1
Lyman α wavelengths for different foil thicknesses

Foil thickness [$\mu\text{g}/\text{cm}^2$]	Lyman α_1 (\AA) ($1s^2S_{1/2}-2p^2P_{3/2}$)	Lyman α_2 (\AA) ($1s^2S_{1/2}-2p^2P_{1/2}$)
10	1.166882 ± 0.000016	1.172326 ± 0.000015
25	1.166858 ± 0.000016	1.172296 ± 0.000020
50	1.166854 ± 0.000017	1.172327 ± 0.000016

Table 2
Apparent discrepancies for varying Bragg angle

Bragg angle (deg)	Transition	Discrepancy (ppm)
39	Lyman β_1	-189 ± 29
39	Lyman β_2	-153 ± 29
49	Lyman α_1	-83 ± 14
49	Lyman α_2	-66 ± 13
59	Ga K α /S K α	$+7 \pm 18$

of the Lyman α peaks are also insignificant for typical wake fields ($\sim 10^9 \text{ V/cm}$) [12] experienced by heavy ions moving through solid targets.

Analyses of the Lyman β /Balmer δ spectrum at a Bragg angle of $\theta = 39^\circ$, and of a calibration spectrum of Ga K α ($\lambda = 1.34 \text{ \AA}$) in fourth order and S K α ($\lambda = 5.37 \text{ \AA}$) in first order, which overlap at a Bragg angle of $\theta = 59^\circ$, show the apparent discrepancies from theory [13,14] for the fourth order lines summarized in table 2. A possible source of systematic error lies in the broadening of the crystal rocking curves, due to the small radius of curvature required in the spectrometer, which may be asymmetrical, and different for first and fourth order lines. Further calibration work on the crystals used in the experiment, specifically the comparison of overlapping K X-rays in first and fourth order for a range of Bragg angles, should allow us to establish these possible instrumental shifts between first and fourth order and allow a more accurate determination of the Lyman α wavelengths.

The authors wish to thank the Erna and Victor Hasselblad Foundation for the provision of a grant to develop the microdensitometer. One of us (C.T.C.) is sponsored by Shell Australia for this work.

References

- [1] J.D. Silver et al., Phys. Rev. A36 (1987) 1515.
- [2] A.F. McClelland, J.S. Brown, B.P. Duval, E.C. Finch, H.A. Klein, J. Laursen, D. Lecler, P.H. Mokler and J.D. Silver, Nucl. Instr. and Meth. B9 (1985) 706.
- [3] S.J. Brodsky and P.J. Mohr, in Structure and Collisions of Ions and Atoms, ed. I.A. Sellin (Springer, Berlin, 1978).
- [4] J. Reed and C.J. Sofield, private communication (1985) and J.-P. Rozet, private communication (1985).
- [5] C.J. Hailey et al., J. Phys. B18 (1985) 1443.
- [6] D.D. Dietrich et al., Phys. Rev. Lett. 54 (1985) 1008.
- [7] D.D. Dietrich, G.A. Chandler, R.J. Fortner, C.J. Hailey and R.E. Stewart, Nucl. Instr. and Meth. B9 (1985) 686.
- [8] R.D. Deslattes et al., Ann. Phys. 129 (1980) 378.
- [9] J.S. Brown et al. Nucl. Instr. and Meth. B9 (1985) 682.
- [10] G.W. Erickson, J. Phys. Chem. Ref. Data 6 (1977) 831.
- [11] B.L. Henke et al., At. Data Nucl. Data Tables 27 (1982) 1.
- [12] J.-P. Rozet et al., Phys. Rev. Lett. 58 (1987) 337.
- [13] P.J. Mohr, At. Data and Nucl. Data Tab. 29 (1983) 453.
- [14] W.R. Johnson and G. Soff, At. Data Nucl. Data Tables 33 (1985) 406.