# Recent research using the Oxford electron beam ion trap

H.S. Margolis [a,*], J. Asada [b], T.V. Back [a], D.J. Bieber [a], F.J. Currell [b], E.G. Myers [c], N. Nakamura [b], S. Ohtani [b], P.K. Oxley [a], M. Sakurai [d], J.D. Silver [a] and H. Watanabe [b]

[a] *Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK*
[b] *University of Electro-communications, Chofu, Tokyo 182, Japan*
[c] *Florida State University, Tallahassee, FL 32306, USA*
[d] *Institute for Molecular Science, Okazaki 444, Japan*

An overview is given of the current spectroscopic effort on the Oxford electron beam ion trap. Recent results from three different experiments are discussed: a precision measurement of the $1s2s\,^3S_1$–$1s2p\,^3P_2$ transition in helium-like neon by VUV emission spectroscopy, a measurement of the two-electron contribution to the ground state energy of helium-like argon using absorption edge spectroscopy, and a study of the lifetime of the $1s^2 2s2p\,^3P_2$ level in beryllium-like argon.

**Keywords:** EBIT, highly charged ions, QED, lifetimes

## 1. Introduction

Since the construction of the first electron beam ion trap (EBIT) [1] it has proved to be a versatile spectroscopic source for the study of slow highly charged ions. In this paper we describe briefly three recent experiments carried out using the Oxford EBIT [2].

## 2. VUV emission spectroscopy of helium-like neon

The $1s2s\,^3S$–$1s2p\,^3P$ transitions in helium-like ions have been studied over a wide range of nuclear charge $Z$. The motivation for this work lies in the large contributions to these intervals of relativistic and quantum-electrodynamic effects. Recently we have measured the $1s2s\,^3S_1$–$1s2p\,^3P_2$ transition wavelength in helium-like neon using the Oxford EBIT.

VUV radiation emitted from the trapped ions was transmitted through a magnesium fluoride window and focused onto the 50 μm entrance slit of a 1 m normal-incidence concave-grating spectrometer. A 1200 lines/mm grating was used in first order, and the spectrum recorded photographically using Kodak 101-01 film. Neon

* E-mail: h.margolis1@physics.ox.ac.uk.

atoms were introduced into the EBIT from the gas injector attached to one of the side ports, and ionized up to $Ne^{8+}$ by the 1 keV, 35 mA electron beam. Nitrogen gas was introduced into the trap in the same way, to produce the resonance lines of lithium-like $N^{4+}$. External calibration lines were superimposed on the spectrum using a hollow-cathode source. The photographic density of the film was measured using the Automated Photographic Measuring facility in Cambridge [3], and the densities converted to exposure levels using a characterization of the film [4]. The wavelengths of the $N^{4+}$ resonance lines were found to be $1238.827 \pm 0.015$ Å and $1242.77 \pm 0.05$ Å, in good agreement with the tabulated values of $1238.821 \pm 0.010$ Å and $1242.804 \pm 0.010$ Å [5]. Our result for the $1s2s\,^3S_1$–$1s2p\,^3P_2$ wavelength in $Ne^{8+}$, $1248.092 \pm 0.015$ Å, is similarly in excellent agreement with previous measurements [6]. This work demonstrates for the first time the potential of the EBIT for precision spectroscopy in the VUV region of the spectrum, and is described in more detail by Bieber et al. [7].

## 3. Absorption-edge spectroscopy of highly-charged argon

To date, all X-ray spectroscopy on the Oxford EBIT has used lithium-drifted silicon (Si(Li)) detectors, which have high efficiency but relatively poor resolution (around 150 eV at 5.9 keV). To achieve improved spectral resolution, we have developed the new technique of absorption-edge spectroscopy. This has been used to measure the two-electron contribution to the ground state energy of helium-like $Ar^{16+}$.

To make the measurement, we studied radiative recombination (RR) transitions into the vacant 1s states of bare and hydrogen-like argon. An RR peak occurs at an energy equal to the energy of the electron beam plus the binding energy of the final atomic state. Thus by measuring the energy difference between the two RR lines we obtain the difference in the hydrogen-like and helium-like ground state binding energies, which provides a measure of the two-electron contribution to the ground-state energy of the helium-like ion. Previous such measurements have been carried out using germanium X-ray detectors, with spectral line widths dominated by the detector resolution [8]. In contrast, our resolution is determined principally by the energy spread of the EBIT electron beam.

Changing the energy of the EBIT electron beam changes the energy of the RR peaks. By placing a cell containing krypton gas between the trapped ions and the X-ray detector, we could arrange for the RR peaks to be eliminated from the spectrum once they moved above the energy of the K absorption edge in this gas. A multiparameter data acquisition system [9] was used to measure the energies of the emitted X-rays as a function of electron beam energy. During the measurement, the electron beam energy was swept from about 9.6 keV to 10.4 keV by applying a 100 Hz ramp waveform to the input of the Trek $20/20$ power supply which sets the potential of the central drift tube electrode. At these energies, significant numbers of both bare and hydrogen-like argon ions were produced, and the modulation was sufficient to sweep both RR peaks through the K absorption edge of krypton at 14.3272 keV. Our Si(Li) X-ray detector was calibrated using $^{55}Fe$ and $^{57}Co$ radioactive sources. The relative electron

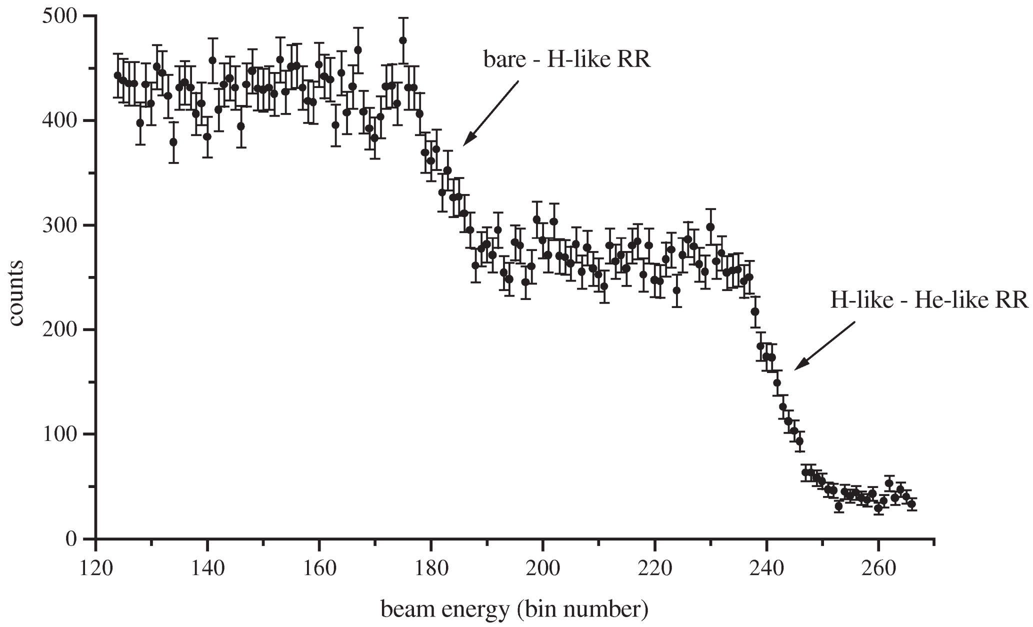


Figure 1. Cut from a 2D absorption edge spectrum of highly-charged argon, showing the total number of RR X-ray counts as a function of electron beam energy.

beam energy scale was derived by examining the shift of the RR peaks as the beam energy was changed. The widths of the spectral features in figure 1 are dominated by the energy spread of the electron beam (about 50 eV), since the absorption edge itself is extremely narrow [10]. Our result for the difference in the helium-like and hydrogen-like argon ionization potentials is $314.5 \pm 10$ eV, in agreement with tabulated values [11]. Further details of the experiment are given in [12]. This technique will be extended to heavier ions using the Tokyo EBIT [13].

## 4. Lifetime of the $1s^2 2s2p\,^3P_2$ level in beryllium-like argon

Lifetimes of metastable levels of highly-charged ions have been extensively calculated, but the accuracy of the calculations is difficult to assess. Only recently have the first measurements been obtained for levels of highly-charged ions with millisecond or longer lifetimes [14], so more experimental data are required for a critical evaluation of the calculational methods. Using the Oxford EBIT, we are currently studying the $1s^2 2s2p\,^3P_2$ lifetime in beryllium-like $Ar^{14+}$. Beryllium-like ions are the simplest ions in which both intra-shell and inter-shell interactions play a role, and thus provide an important testing ground for theory.

Previous lifetime measurements using EBITs have employed two different techniques. In the first, the electron beam energy is modulated around the excitation energy of the level of interest [15]. In the second, which we are using, the electron beam is switched off temporarily and the trap operated in the "magnetic trapping mode" [16,17]. Argon is introduced from the gas injection system, with the argon pressure being varied from run to run. The central drift tube voltage is set to 1.0 keV to optimise the signal from the $1s^2 2s2p\,^3P_2$–$^3P_1$ transition in $Ar^{14+}$ at 594.4 nm. Our detection system comprises a 1 m Czerny–Turner grating monochromator followed by a cooled photomultiplier used in photon-counting mode. Typically, the electron beam is switched on for 120 ms to produce $Ar^{14+}$, then switched off in less than 50 μs and kept at zero for 80 ms. Time-resolved data are obtained over thousands of cycles, by detecting photons in 1 ms time bins using CAMAC timing electronics. A typical decay curve is shown in [18]; we are currently investigating potential sources of systematic error.

## Acknowledgements

We wish to thank A.T. Handford and P.J. Hirst for expert technical assistance. This work was partially supported by the Japan Science and Technology Coorporation and by the Royal Society.

## References

[1] M.A. Levine et al., Phys. Scripta 22 (1988) 157.
[2] J.D. Silver et al., Rev. Sci. Instrum. 65 (1994) 1072.
[3] E.J. Kibblewhite, M.T. Bridgeland, P.S. Bunclark and M.J. Irwin, in: *Proc. of the Astronomical Microdensitometry Conf. NASA-2317* (1984) p. 277.
[4] W.M. Burton, A.T. Hatter and A. Ridgeley, Appl. Opt. 12 (1973) 1851.
[5] R.L. Kelly and L.J. Palumbo, Atomic and emission lines below 2000 Å, NRL Report 7599 (1973).
[6] W.A. Hallett, D.D. Dietrich and J.D. Silver, Phys. Rev. A 47 (1993) 1130.
[7] D.J. Bieber et al., to be submitted to Phys. Rev. A.
[8] R.E. Marrs, S.R. Elliott and T. Stöhlker, Phys. Rev. A 52 (1995) 3577.
[9] F.J. Currell et al., Phys. Scripta 73 (1997) 371.
[10] M. Deutsch and M. Hart, J. Phys. B 19 (1986) L303.
[11] R.L. Kelly and D.E. Harrison, At. Data 3 (1971) 177.
[12] F.J. Currell et al., to be submitted to J. Phys. B.
[13] F.J. Currell et al., J. Phys. Soc. Japan 65 (1996) 3186.
[14] L. Yang and D.A. Church, Phys. Rev. Lett. 70 (1993) 3860.
[15] B.J. Wargelin, P. Beiersdorfer and S.M. Kahn, Phys. Rev. Lett. 71 (1993) 2196.
[16] P. Beiersdorfer, L. Schweikhard, J. Crespo López-Urrutia and K. Widmann, Rev. Sci. Instrum. 67 (1996) 3818.
[17] F.G. Serpa et al., Phys. Rev. A 55 (1997) 4196.
[18] T.V. Back et al., submitted to Hyp. Interact. (these proceedings).