The Spectroscopy of Hydrogen-Like Highly Ionised Atoms

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When the organisers of this meeting on the hydrogen atom very kindly asked me to give a lecture, they asked me to give something of an *overview* of the spectroscopy of hydrogen-like highly ionised atoms. This is now a fairly active field of study, so I shall concentrate on some recent work which has been carried out by my group in collaboration with Daniel Dietrich of Lawrence Livermore National Laboratory, and I shall only give brief references to the work of other groups. I hope they will forgive me, and not think that by magnifying our work, I am seeking to minify theirs. I shall also speculate a little on how the field might develop in the reasonably near future.

Our primary aim in studying the hydrogenic ions is to make good measurements of the Lamb shift. We are interested in the Lamb shift because it is a purely quantum-electrodynamic (QED) quantity. One of the inventors of the modern theory of QED, Richard Feynman, recently wrote " ... The theory of quantum electrodynamics has now lasted for more than fifty years, and has been tested more and more accurately over a wider and wider range of conditions. At the present time, I can proudly say that there is *no significant difference* between experiment and theory! ... We physicists are always checking to see if there is something the matter with the theory. That's the game, because if there is something the matter, it's interesting! But so far, we have found nothing wrong with the theory of QED ... " [1]

There is nonetheless something a a little bit strange about the apparent success of the QED theory. This relates to the fact that certain of the procedures used to calculate experimentally measurable quantities such as the Lamb shift do not appear to be mathematically sound. The problem has been stated by Dirac [2] , who suggested that the remarkable agreement between the results of renormalisation theory in QED, and experiment, should be looked on as a "fluke", in much the same way that the agreement between the Bohr theory and experiment for the spectrum of hydrogen turned out to be a fluke.

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The "holy grail" of those that test QED is that they will make a measurement of a QED effect which will not agree with the predictions of QED theory, thereby indicating the need for a different theory. So far,however, most measurements seem to agree well with the theory [3].

Our reason for studying hydrogenic *ions*, rather than the neutral hydrogen atom, is that the single electron is subject to a coulomb field whose strength is determined by Ze for an ion of atomic number Z. The Lamb shift scales with Z approximately as Z^4, becoming larger relative to the electron binding energy as Z^2 for increasing Z. So for an ion such as U^{91+}, the Lamb shift is approximately 10^4 times as large as in neutral hydrogen, for a bound electron of given principal quantum number, n . In addition, it is conceivable that the sought for "breakdown in QED" might be detectable for "strongly bound" electrons , ie when Z is large, and yet not show up in the very precise measurements which exist for free electrons (for example g-2) or low Z atoms . Unfortunately, the study of highly charged ions is experimentally difficult. The most widely used technique is the fast beam, or beam-foil method [4]. In this method, ions are accelerated to high energy, and electrons are removed by fast collisions with solid or gaseous targets. The method has the advantage that relatively large numbers of ions may be produced, and essentially *any* charge state can be reached. However, the disadvantage is that the charge state reached is determined by the beam velocity, with high charge states being necessarily associated with high velocities. Spectroscopic measurements on fast beams of highly charged ions are therefore generally prone to errors arising from the Doppler effect, although methods have been devised to overcome these problems, and I shall describe some of these.

Highly charged ions may also be produced in plasmas of various kinds. In general, these plasmas must be heated to generate hydrogenic ions of high Z, so that, again, Doppler effects can become problematic. Another source of highly ionised atoms is the recoil-ion source [5]. This is a most interesting source spectroscopically, since the highly charged ions are produced with *directed*,low velocities. The low recoil ion velocities have already been exploited to make precise measurements of Lyman α wavelengths in recoil ions of few-electron argon [6] although these measurements demonstrate one of the apparent limitations of the technique, namely that the transitions of interest are very often surrounded by "satellites" arising from the lower charge state ions which are also present in a recoil-ion source. The *directed* nature of the recoil-ion source means that almost Doppler free spectra could be

obtained by *axial* observation, as suggested by Martin Laming and myself[7]. Spectral resolutions of order 10,000 might be expected for resonance transitions in hydrogenic or helium-like argon, so that there is some hope that the satellite problem might be overcome with this new method.

Finally, there have been recent significant advances in techniques for the production of highly charged ions in what one might term "novel ion sources". There are three important types of device which have received attention, the Electron Cyclotron Resonance (or ECR) source, invented by R.Geller, the Electron Beam Ion Source (or EBIS), invented by E.D. Donets[8], and the Electron Beam Ion Trap (or EBIT) which is a derivative of the EBIS due to M.A. Levine [9] . This latter device is currently of serious interest, since useful numbers of very highly charged ions, such as Au^{69+}, have already been trapped, and it is believed [10] that an improved device (the SuperEBIT) can be built within the next year or two which will be able to generate and trap the most highly charged species, such as U^{92+}.The SuperEBIT is also planned to trap a larger number of ions than the original EBIT device, so that it will more nearly approach the spectroscopic brightness of an accelerator source.

The 1s Lamb Shift

There is a little unclarity in the literature concerning what is meant by "the Lamb shift". Some would rather narrowly understand the Lamb shift to be the $2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$ splitting in atomic hydrogen, and the hydrogenic ions. There is, however, a Lamb shift of the $1s\ ^2S_{1/2}$ state, which is about eight times larger than the $2s\ ^2S_{1/2} - 2p\ ^2P_{1/2}$ splitting, and when using the term Lamb shift, I have in mind the definition of Johnson & Soff [11] . In particular, the energy shift arising from the finite size of the nucleus is, by convention, included in the Lamb shift, although it is not a QED effect. A discussion of this point is given by R.G. Beausoleil [12]. The 1s Lamb shift is of some historical interest, since it appears to have been the *first* Lamb shift to be observed, some fifteen or so years prior to the Lamb and Retherford experiment[13]. The method of measurement is also interesting in that the Lamb shift in question (in Li^{++}) was made via a careful absolute Lyman α wavelength measurement; a comparison of the measured wavelength with the theoretical (ie Dirac) value gave a difference, and that difference was the 1s Lamb shift. This method, which I will call the method of absolute spectroscopy, is still in

use by some researchers. It has the obvious drawback that since the 1s Lamb shift is only a small fraction of the 1s - 2p energy separation, wavelength measurements must be extremely accurate in order to yield an interesting measurement of the 1s shift. It will probably be helpful to qualify what is meant by the terms "extremely accurate", and "interesting" in this context. In the ideal experimenter's situation, there would be some predicted level at which QED would break down, so that an accurate measurement of the Lamb shift at this level could be used to establish whether or not the predicted breakdown had occurred. At present, there is no such predicted breakdown, so that we (that is the Oxford group and our collaborators) aim to make our experiments as accurate as the claimed uncertainty in the most reliable calculations of the Lamb shift [14]. It turns out that for ions with nuclear charge Z in the range 10 to 92, the theoretical uncertainty in the order α self energy correction is about one part in 1000 for both the 1s and 2s Lamb shifts, though the uncertainty in the nuclear charge radius must of course be taken into account in estimating the total theoretical uncertainty. To take a specific example, for the hydrogenic ion Fe^{25+}, the 1s Lamb shift is $\sim 6 \times 10^{-4}$ of the 1s-2p separation. So a 1ppm measurement of the Lyman α wavelengths will yield the 1s shift to ~+/- 0.17 %, just about at the level I call "interesting".

An alternative approach to the problem of 1s Lamb shift measurement is to utilise the simple integral relations between the wavelengths of certain transitions in the hydrogen soectrum. In particular, in the Schrodinger approximation, the Balmer β wavelength is four times the Lyman α wavelength; in a hydrogenic ion of high enough Z, both Lyman α and Balmer β lie in the x ray region of the spectrum, and will "overlap" if studied in first and fourth order of Bragg diffraction respectively. This gives what is effectively a differential method for the measurement of the 1s ground state Lamb shift, as I realised in 1981 after reading about Ted Hänsch's related work on the two photon 1s - 2s transition in atomic hydrogen. The Lyman α / Balmer β technique [15,16,17] and its derivatives might be termed "differential spectroscopy" since the 1s Lamb shift may be extracted as a difference rather than a small change in a large quantity. The method is rather useful when applied to a fast beam source, since it effectively eliminates Doppler shifts, which are often the dominant source of error in such experiments. The need for accurately known external calibrations is also obviated.

In recent years, several experimenters have tried to make interesting measurements of the 1s Lamb shifts in hydrogenic argon, chlorine, iron, germanium and krypton.There have been three experiments on hydrogenic chlorine, two with fast beam sources [18,19] and a third with a tokamak source [20]. There have been two experiments with hydrogenic argon, one with a recoil-ion source [6] and the other with a tokamak source [21]. There have been two fast beam experiments with hydrogenic iron [22,16,17] , a fast beam experiment with hydrogenic germanium [23, 24], and a fast beam experiment with hydrogenic krypton [25] . Of these experiments, only two (those carried out by the Oxford group in collaboration with the Livermore group [16,17,23,24]) used the method of differential spectroscopy.

The number of experiments is still sufficiently small that it is possible to comment on each of them; the earliest fast beam experiment with hydrogenic chlorine [18] was a very straightforward measurement for which the conceptual set-up is shown in figure 1 of Silver [17a] .

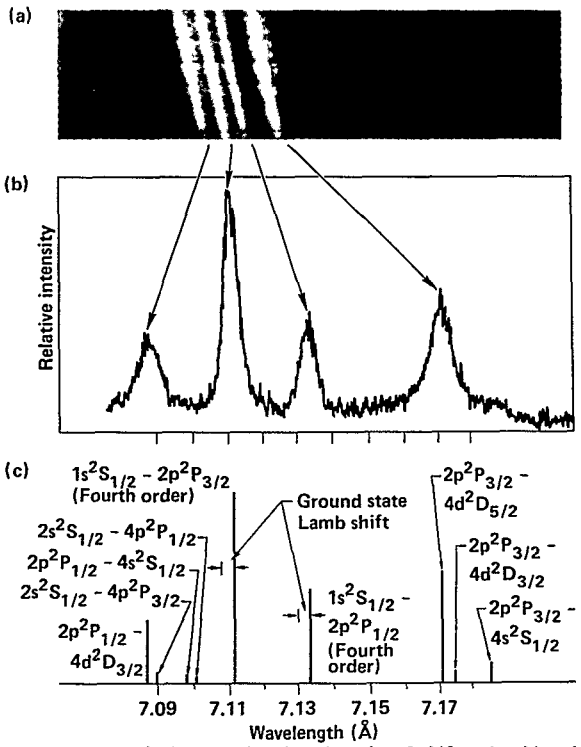

Figure 1: a) A print of a typical film in the Lyman α / Balmer β region for hydrogenic iron [ref 17]. b) A microdensitometer scan of the Lyman α /Balmer β region. c) The predicted spectrum using statistical relative intensities

Experiments of this type suffer from errors arising from the Doppler effect inherent with fast beam sources, and they can also suffer from contamination of the spectrum with satellites to Lyman α from ions of lower charge, and these effects seem to have dominated the final errors in the measurement; the Lyman α wavelengths were obtained with an accuracy of~ 34 ppm , giving the 1s Lamb shift to ~12% .The second measurement of the Lyman α wavelength in hydrogenic chlorine used the accel-decel method originated by Paul Mokler [26]. Here the ions to be studied are accelerated to high energy, stripped, and then decelerated. In the experiment with hydrogenic chlorine [19] decelerated bare chlorine nuclei captured a single electron in a gas target, and it was suggested that the method in principle overcomes both the satellite problem, and the Doppler problem. Unfortunately, the decelerated ions still have appreciable velocity so that residual Doppler shifts are not negligible. Measurements must therefore be made over a range of beam energy,but the capture probability for higher beam energies is small, so that spectra are weak. This in turn means that the Doppler correction cannot be extracted as accurately as hoped . Nonetheless, some of the spectra obtained with this technique are of very high quality and apparently free from serious satellite contamination, the Lyman α wavelengths were obtained with an accuracy of ~41 ppm, giving the 1s Lamb shift to ~15%.The third measurement of the Lyman α wavelengths in hydrogenic chlorine[20] was carried out using a tokamak as a light source. The use of a tokamak as a spectral "lamp" for precision spectroscopy of highly ionised atoms appears to have originated with Peacock and Silver [27] . We were interested in making accurate measurements of the wavelengths of the 1s2s ^{3}S - 1s2p ^{3}P transitions in moderate Z helium-like ions, since such measurements act as a sensitive test of relativistic and quantum electrodynamic effects in the two-electron system. Following this early work with helium-like ions , a tokamak was used to study the Lyman α wavelengths in hydrogenic chlorine . High quality spectra were obtained, but there were uncertainties in the extracted wavelengths arising from instrumental effects, and from the presence of overlapping satellites in lower charge.The Lyman α wavelengths were measured with an accuracy of ~34 ppm, giving the 1s Lamb shift to ~12% . A potential source of error in such measurements arises from possible net motions of the plasma, though Kallne et al pointed out [20] that a dual spectrometer system could possibly overcome this effect.

Of the experiments in hydrogenic argon, the first used the relatively new recoil-ion technique [5,6]. As explained above, the recoil ion technique suffers from the satellite problem. For the experiments in argon[6] , high quality spectra were obtained, and a rather good precision of 5ppm was claimed for the Lyman α wavelengths, which corresponds to 1.5% accuracy for the 1s Lamb shift. A visual inspection of the spectra, however, shows serious satellite contamination, and proper interpretation of the spectra was clearly rendered difficult by this effect. The second experiment in hydrogenic argon [21] was again carried out with a tokamak source. Improved accuracy was claimed (11ppm for Lyman α_2 giving 3% for the 1s shift) compared with the earlier experiment with hydrogenic chlorine, and it was suggested that the influence of satellite lines in the tokamak source was only of secondary importance, although the spectra do show evidence of some satellite contamination.

The first experiment in hydrogenic iron to be published [20] used the straightforward "absolute spectroscopy" technique [17a] as for hydrogenic chlorine. The authors claimed that their precision was for the first time sufficient to observe the 1s Lamb shift for any hydrogenlike atom heavier than neutral hydrogen, apparently unaware of the measurement in hydrogenic lithium made by Edlen in 1933 [13] . Rather weak spectra with no apparent satellite contamination were obtained, the dominant source of error appears to have been the Doppler effect , and an accuracy of about 100ppm was claimed for the Lyman α wavelengths, giving ~ 17% accuracy for the 1s Lamb shift. A small disagreement was found between the measurements and the theoretical (Dirac) value of the 2p fine-structure splitting, but this does not seem to have been substantiated by more recent work. The second experiment in hydrogenic iron was carried out by the Oxford group in collaboration with Daniel Dietrich and his group from Livermore, and it was the first succesful demonstration of the "differential spectroscopy" technique using the overlap of Lyman α with Balmer β [16,17].Figure 1 shows one of the first spectra observed using the new technique. This experiment was carried out using the SuperHILAC at Lawrence Berkeley Laboratory in 1986. A beam of bare iron nuclei (Fe^{26+}) was passed through a thin carbon foil, and the n=2 and n=4 levels were populated by capture.The spectra obtained were interesting in that they demonstrated that the technique was actually experimentally feasible. The Lyman α wavelengths were measured to ~107 ppm, leading to ~17% error in the 1s Lamb shift. However, a hundredfold improvement in the accuracy

is required in order to get to the level defined above as "interesting" in the sense that the error is the same as the theoretical uncertainty in the Lamb shift.

The only 1s Lamb shift measurement in hydrogenic germanium [23,24] also used the Lyman α / Balmer β technique, and was a development which grew out of the first experiment with iron. It was carried out at GSI Darmstadt in September 1986. Figure 2 shows a typical Lyman α / Balmer β spectrum of Ge^{31+}, obtained with a 1.108 GeV beam of hydrogenic germanium ions. A comparison of the data between figure 1 and figure 2 shows that the resolution and statistical quality is better for germanium than for iron in our experiments; one reason for this is that the germanium transitions are at shorter wavelength, so that a silicon III diffraction crystal could be used. Another is that the ion beam quality was better with the germanium beams than with the iron beams. Unfortunately, at the time of writing, it is not possible to give final values for the Lyman α wavelengths in Ge^{31+} from our data. Although the purely statistical errors in the best data are at the level of only a few ppm, there are systematic errors which are still under investigation. One source of error which is under examination is an *instrumental* shift between first and fourth orders. One contribution to this shift is the so called refractive index correction [16,23], but for the small radius Rowland circle crystals used in the iron and germanium experiments, we believe that there are other factors to be considered if we are to reach a full understanding of this systematic effect.

Another source of error arises from the uncertainty in the relative intensities of fine structure components of the Balmer β transitions in our spectra. During an analysis of the data from the experiment with hydrogenic Germanium,Martin Laming realised that the assumption of statistical population of the n=4 states which had been made previously is probably not justified [23,28]. One hint that this may be the case comes from the fact that in the Lyman β spectrum, the relative intensities of the two components are not in the statistical ratio of 2:1. We now believe that account must be taken of the presence of the large electric field which the bare nucleus experiences in the carbon target *during* the single electron capture process which populates the n=2 and n=4 states.The eigenstates of the one electron ion formed during capture are those appropriate to a stark mixed system, and in particular the electric field can be strong enough to completely mix the $4p\ ^2P_{3/2}$ and $4d\ ^2D_{3/2}$ states. The relative intensities in the Balmer β spectrum are affected by this , and since not

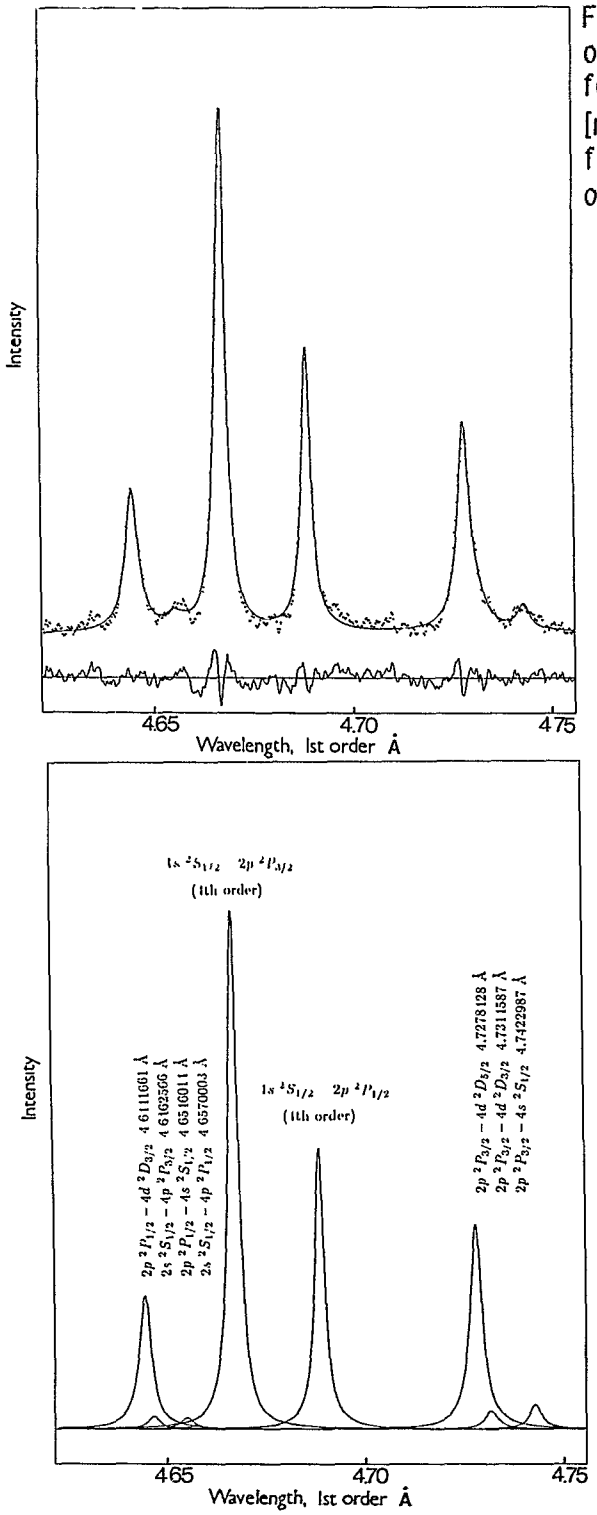

Figure 2: a) Typical spectrum of the Lyman α / Balmer β region for hydrogenic germanium [ref 24] b) Fitted line profiles for the individual transitions of the Lyman α / Balmer β region

all the components are resolved in our spectra, this phenomenon can lead to shifts in the spectrum if statistical rather than stark mixed relative intensities are used in the profile analysis. We currently think that the instrumental first order-fourth order shift, and the non-statistical relative intensity effect taken together can account for the apparent discrepancies noted in table 2 of Laming et al [24]. The germanium data is undergoing further analysis, and we expect final errors for the Lyman α wavelengths in Ge^{31+} from our experiment will probably be about 30ppm, (corresponding to an accuracy of ~3% for the 1s Lamb shift) when these further systematic errors are properly taken into account. We have also more recently carried out a further Lyman α/Balmer β experiment on hydrogenic iron with improved diffraction crystals, and the data from this experiment are currently under analysis by Chris Chantler. It is hoped that this more recent experiment will yield better resolved spectra of Fe^{25+}, giving an improved value for the 1s Lamb shift.

The highest Z system for which the Lyman α wavelength has been measured is currently hydrogenic krypton [25]. Again the measurement was carried out by the absolute spectroscopy method. Discussion of errors is unfortunately a little brief, and no spectra are shown, but it is claimed that 26 ppm error in the Lyman α wavelengths arises from Doppler effects, with a similar error being attributed to the spectrometer itself, including angular errors, statistics and linearity effects. These effects are then combined to give a claimed 36ppm accuracy for the Lyman α_1 line, leading to 4% claimed accuracy for the 1s Lamb shift.

Comparison between experiment & theory, and future work

Figure 3 shows a comparison between experiment and theory for the 1s Lamb shift for the hydrogenic ions of chlorine, argon, iron and krypton. No results are given for germanium since our data are still under analysis. It will be seen that none of the existing measurements can be said to test the theory, in the sense that in no case does the accuracy of the experiment approach the claimed theoretical uncertainty. If the aim of this sort of experiment is to provide a test of QED,then improved measurements are clearly required; in general terms, experimental accuracies for the Lyman α wavelengths of ~1ppm are needed. This might prove possible with the "absolute wavelength measurement" approach using the accel-decel or possibly even the fast-beam method, though extreme care will be needed to make adequate allowance for Doppler shifts and satellite effects. It is also possible that measurements of

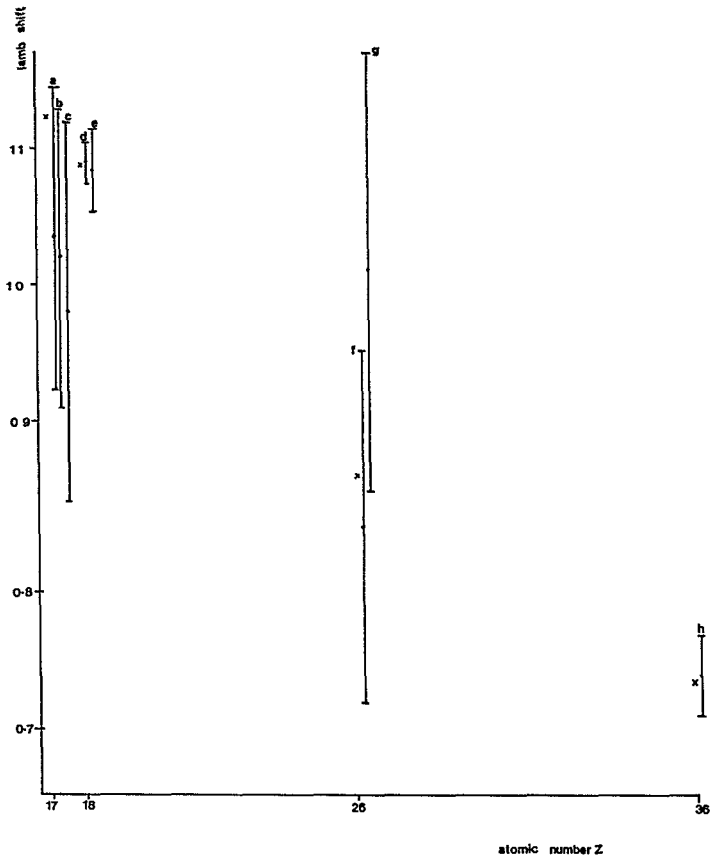

Figure 3: A comparison of theory and experiment for the Lamb shift contribution to the 1s - 2p transitions in hydrogenic ions with Z =17,18,26 and 36. The small crosses give the theoretical values [14], with the theoretical uncertainty too small to show on the scale used. The points with bars are measured values, references are a:18],b:[20], c:[19], d: [6], e:[21], f: [22], g:[17], h:[25]. For convenience of display, the Lamb shifts are given in eV scaled by $10x (Z/10)^4$.

sufficient accuracy might be made with a tokamak source, though again great care will be needed with the same error sources. The "differential" method using Lyman α / Balmer β comparison has already demonstrated *statistical* precisions at the required few ppm level. The purely instrumental problems involved in a comparison of first and fourth order wavelengths at the ppm level appear tractable, and the problem associated with uncertainties in the relative intensities of different fine-structure components can be tackled if we can achieve improved resolution. With

this in mind, we have recently investigated experimentally a rather old suggestion to improve spectral resolution using *axial* viewing of a fast beam source. Axial viewing of a fast beam source under appropriate conditions gives a significant reduction in Doppler broadening , we recently used this method to obtain the best resolved spectra in hydrogenic neon ions and helium-like silicon ions[29], in a collaboration involving Oxford, Leicester and Culham Laboratory, and we believe that this additional "new" technique, when combined with the Lyman α/Balmer β comparison method, offers the promise of eventual ppm accuracies for the Lyman α wavelengths, and, correspondingly, ~0.1% accuracies for the 1s Lamb shifts. We plan experiments with axial viewing of fast beams of Ge^{31+} at GSI Darmstadt within the coming year, to see whether this optimism is justified, and we also anticipate an extension of this series of experiments to the hydrogenic ions of very high Z atoms (ie Pb^{81+}, U^{91+}) when the new SIS high energy heavy ion accelerator is operating at Darmstadt. This new accelerator will give beams of such exotic ions at about the same intensity as is currently available for the systems we have already studied, such as Fe^{25+} and Ge^{31+}.

Another very interesting new development concerns the use of the newly developed EBIT [9] device for 1s Lamb shift measurement in hydrogenic ions. The EBIT has already been demonstrated to produce useful quantities of ions of extremely high charge, such as Au^{69+}. The source appears quite well suited to precision spectroscopy; the highly charged ions form a "filament" ~ 50µm in diameter and ~ 1cm long, and the source can be of comparable brightness to a fast beam . Relatively clean spectra of the one electron ion can be expected, free from satellite contamination, and one of the main problems associated with fast beams, namely the Doppler shift, will be much less serious in the EBIT, since ion velocities, though not directed, are many orders of magnitude lower than a fast beam for a given charge. The electric and magnetic fields present in the EBIT , though appreciable, will also only give negligible shifts in the low n levels of highly charged hydrogenic ions. Accurate measurement of Lyman alpha wavelengths in ions such as Fe^{25+}, Ge^{31+} , etc may therefore be expected using the EBIT as a source, and one can also envisage the application of an improved EBIT, (or "SuperEBIT") operating with higher electron currents and voltages than the original EBIT device to the problem of 1s Lamb shift measurement in hydrogenic ions of very high charge such as Pb^{81+}, or U^{91+}

The 2s Lamb shift

When considering the Lamb shift in hydrogenic ions as a test of QED, it is not sensible to look at a comparison of theory and experiment for the 1s Lamb shift alone; indeed, the situation for the 2s Lamb shift is probably the more interesting at the time of writing, since the measurements, at least in the range of Z between 15 and 17, are somewhat more accurate than the measurements of the 1s Lamb shift, and in addition, there is a hint of a discrepancy between experiment and theory, as shown in figure 4. The most recent measurement is that of Muller et al in hydrogenic phosphorus, [30,31] and this measurement lies 1.6 standard deviations below the theoretical result for the 2s Lamb shift. This article is not the

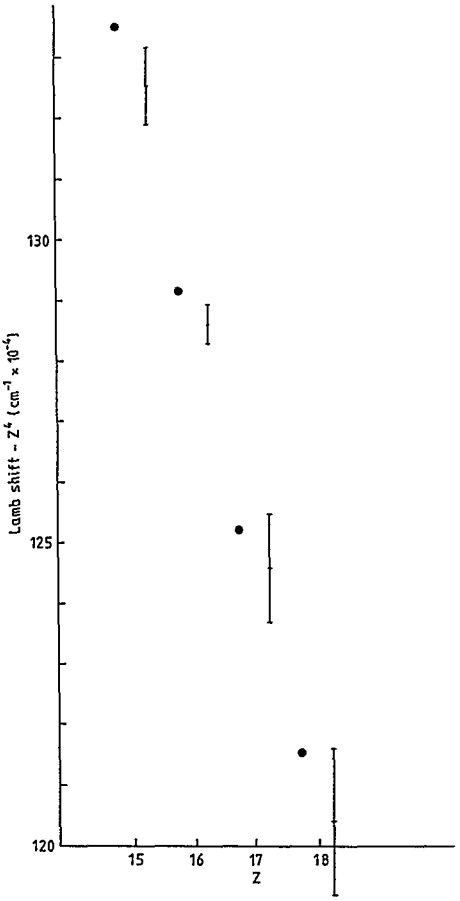

Figure 4: A comparison of theory [ref 14](solid dots with the theoretical uncertainty given by the size of the dot) with experiment [see refs 30,31] (bars give experimental errors) for the 2s Lamb shift in hydrogenic ions with Z = 15,16,17,18.

place for an exhaustive review of measurements of the n=2 Lamb shift, but it is clear that, as in the case of the 1s shift, further experiments are really required. The two most accurate 2s Lamb shift experiments shown in figure 4, for phosphorus [31] and sulphur [32] were carried out using fast beam resonance spectroscopy, and may be viewed in a sense as an extension of the 2s Lamb shift measurements started by Pipkin & collaborators on fast beams of neutral hydrogen [33].

In our group in Oxford we have been interested in the application of accurate laser spectroscopy to highly charged ions for an extended period [34,35,36], and indeed we have made several attempts over the years to secure support from SERC to make a "definitive" laser resonance measurement of the 2s Lamb shift for hydrogenic ions with Z in the range 10 to 20. These attempts have not been very successful, and my own thinking on the problem of how to measure the 2s Lamb shift in medium Z hydrogenic ions to 0.1% accuracy has evolved somewhat, so that we currently have three experiments under consideration which may prove promising.

The first of these is based on the fact that the 2s $^2S_{1/2}$ - 2p $^2P_{3/2}$ transition (from which transition the 2s Lamb shift is extracted using a theoretical value for the 2p finestructure splitting) for hydrogenic ions in the range of Z of interest has a very large natural width on account of the short 2p state lifetime. One is therefore led to ask whether an expensive and specialised laser of the sort used by us[34,35] and others [37,30,32] in earlier experiments is really necessary in order to carry out resonance spectroscopy, or whether indeed a bright lamp might perhaps do instead ! As a further step, one can also ask whether there might perhaps be some sort of coupling optics which could be used to match the spectrally dispersed radiation from our bright lamp to a fast beam in such a way that the beam "sees" a wide range of the spectrum as if it were monochromatic !! It turns out that this apparently rather strange situation seems quite easy to arrange in the laboratory, suitable coupling optics having been investigated some years ago in Oxford [38], and more recently in Canterbury [39]. At the time of writing, we have just set up such a system, which is described more fully elsewhere [40,41], at the SuperHILAC in Berkeley for an experiment whose aim is to measure the 2s Lamb shift in hydrogenic silicon and aluminium via a resonance measurement of the wavelength of the 2s $^2S_{1/2}$ - 2p $^2P_{3/2}$ transition of a fast beam of hydrogenic silicon or aluminium ions. We hope to try this experiment in the next few months. A feasibility study of this new

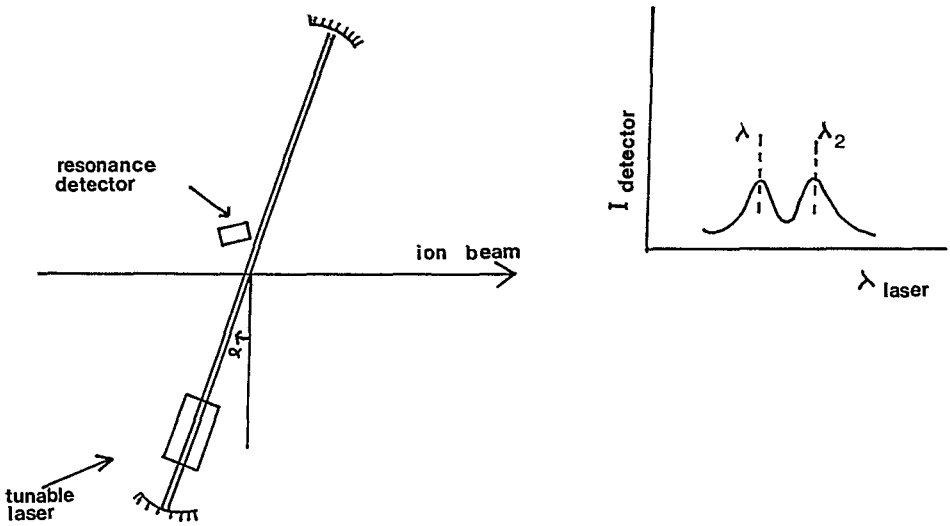

Figure 5: Schematic diagram for a proposed intracavity laser resonance measurement of the $2s\ ^2S_{1/2} - 2p\ ^2P_{3/2}$ interval in a hydrogenic ion such as Si^{13+}. In the resonance spectrum, $\lambda_1 = \gamma\lambda_0(1+\beta\sin\alpha)$, and $\lambda_2 = \gamma\lambda_0(1-\beta\sin\alpha)$, where λ_0 is the wavelength of the resonance in the ion's rest frame, the ion velocity $v = \beta c$ with c the speed of light, and $\gamma = (1-\beta^2)^{-1/2}$. So $\lambda_1 + \lambda_2 = 2\gamma\lambda_0$, and $\lambda_1 - \lambda_2 = 2\gamma\lambda_0\beta\sin\alpha$. If α can be varied precisely, β and λ_0 may be found.

technique [41] (which one might perhaps call laserless resonance) does suggest, however, that we will still encounter problems associated with the large Doppler effect present with fast beam sources. A way to overcome this is to return to the use of laser radiation, but to use intracavity irradiation of the fast beam. The situation will then be as depicted in figure 5, with two counterpropagating waves interacting with the ion beam. If the laser beam direction is slightly offset (by an angle α) from the normal to the ion beam, and the laser is scanned so that the resonance driven by the forward and return beams may each be observed, as depicted schematically in the figure, then a first-order Doppler free result may be obtained for the resonance of interest. If in addition we set the system up so that the angle α may be precisely varied, then a completely Doppler free result may be obtained from a series of spectra taken as a function of α. This suggested method is conceptually similar but

not quite the same as a proposal for accurate Lamb shift measurements made for the new SIS accelerator [42] as well as earlier accurate laser resonance experiments in moleclues, and ions carried out by Dick Holt and Dave Rosner and colleagues [43,44,45].

The third technique which we have under consideration for a resonance measurement of the 2s Lamb shift involves the use of an EBIT. The experiment would be not unlike that proposed for application to a recoil-ion source by McClelland et al[36] , and an analysis similar to that presented by those authors suggests that the $2s\ ^2S_{1/2} - 2p\ ^2P_{3/2}$ resonance transition should be observable in hydrogenic ions with Z~14 - 17 using intracavity laser radiation of these ions in an EBIT, and that the perturbations arising from the fields in the EBIT would not prevent ~0.1% measurements of the 2s Lamb shift for these ions.

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