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NEW EXPERIMENTS ON FEW-ELECTRON VERY HEAVY ATOMS

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ABSTRACT

New experiments, to test quantum electrodynamics (QED) in strong Coulomb fields and to study atomic collisions at ultra relativistic energies, are proposed. A 0.1% measurement of the $2^2P_{1/2} - 2^2S_{1/2}$ splitting in lithiumlike uranium ($Z=92$) and the $2^3P_0 - 2^3S_1$ splitting in heliumlike uranium is proposed as a sub 1% test of the Lamb shift in a strong Coulomb field. Measurements of the hyperfine splitting of hydrogenlike thallium ($Z=81$) and the g_J factor of the ground state of hydrogenlike uranium are proposed as a test of the QED contribution to the magnetic moment of an electron bound in a strong Coulomb field. Measurements of capture cross sections for ultra-relativistic very heavy nuclei are proposed to look for the capture of electrons from pair production.

INTRODUCTION

The production¹ in 1983 of a beam of bare U^{92+} at the Lawrence Berkeley Laboratory's Bevalac² -the Bevatron and Super-HILAC operating in tandem- demonstrated the feasibility of experiments using few- electron uranium. X rays from $n=2 \rightarrow n=1$ transitions in hydrogenlike uranium and heliumlike uranium were observed³ in 1984 (Fig. 1) and a low-precision determination of the $2^3P_0 - 2^3S_1$ splitting in heliumlike uranium was operating in 1985 using beam intensities of 10^5 ions per second⁴. Experience from these experiments and higher uranium intensities will make it possible to perform a sub 1% measurement of the Lamb shift at $Z=92$. In addition, new experiments are being developed to measure the QED contribution to the magnetic moment (anomalous magnetic moment) of an electron bound in a very strong Coulomb field. Beyond present accelerators, a proposed heavy ion facility at Brookhaven National Laboratory will use the Alternate Gradient Synchrotron to produce 15 GeV/nucleon very heavy ions⁵, will extend atomic collisions of very heavy ions to ultra-relativistic energies. A new mechanisms for charge capture from pair production is expected. This mechanism may be very important to the physics of relativistic heavy ion colliders.

SELF-ENERGY AT VERY HIGH Z

At $Z=92$, the contributions to the Lamb shift ($2^2S_{1/2} - 2^2P_{1/2}$ splitting) (Fig 2) are the self-energy⁶ of ≈ -57 eV, the vacuum polarization⁷ of $\approx +14$ eV and the finite nuclear size correction⁷ of ≈ -33 eV. Vacuum polarization, but not self-energy, is well tested in muonic atom experiments. High-Z Lamb shift measurements primarily test the self-energy in a strong Coulomb field⁸.

In addition to being the largest contribution to the Lamb shift, the self-energy makes up a large fraction of the splittings between states of $2p_{1/2}$ and $2s_{1/2}$ electrons in heliumlike and lithiumlike uranium. The $2^3P_0 - 2^3S_1$ splitting in heliumlike uranium⁹ (Fig. 3) is ≈ 254 eV and the $2^2P_{1/2} - 2^2S_{1/2}$ splitting in lithiumlike uranium (Fig. 4) is ≈ 283 eV.

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Fig. 1 - X rays from $n=2 \rightarrow n=1$ transitions in hydrogenlike uranium (U 91+) and heliumlike uranium (U 90+) observed in a beam-foil experiment. The x-rays from 430 MeV/nucleon uranium were observed by a germanium x-ray detector looking perpendicular to the beam at a 15 mg/cm² mylar target. Because of relativistic Doppler shift, the x rays seen in the Laboratory are red shifted by a factor of 1.46. The peak at about 64 keV corresponds to transitions $2^2P_{1/2}$ and $2^2S_{1/2} \rightarrow 1^2S_{1/2}$ in hydrogenlike uranium plus 2^3S_1 and $2^3P_1 \rightarrow 1^1S_0$ in heliumlike uranium. The peak near 67 keV corresponds to transitions $2^2P_{3/2} \rightarrow 1^2S_{1/2}$ in hydrogenlike uranium and the 2^3P_2 and $2^1P_1 \rightarrow 1^1S_0$ in heliumlike uranium. The background is caused in part by bremsstrahlung photons produced when target electrons scatter off the uranium and by high energy electrons scattered out of the target.

Far more significant than the size of the self energy at $Z=92$ is that the self-energy contribution arises almost entirely from terms which are of very high order in $Z\alpha$ (where α is the fine structure constant). Because these terms are large only at very high Z (strong Coulomb field) they are not tested in present lower- Z Lamb shift and fine structure experiments.

The contribution of the higher order terms in the self-energy can be seen by comparing the series expansion, of the self energy with an evaluation of the $2^2S_{1/2}$ self-energy to all orders^{9,10,11} in $Z\alpha$. If we write the self energy Σ_n in a power series in α and $Z\alpha$, we have:

$$\begin{aligned} \Sigma_n = \pi^{-3} (\alpha/\pi) m_e c^2 & \left[(A_{40} + A_{41} \ln(Z\alpha)^{-2}) (Z\alpha)^4 + A_{50} (Z\alpha)^5 \right. \\ & + [A_{60} + A_{61} \ln(Z\alpha)^{-2} + A_{62} \ln^2(Z\alpha)^{-2}] (Z\alpha)^6 + A_{70} (Z\alpha)^7 \\ & \left. + \text{higher order terms} \right] \end{aligned} \quad (1)$$

Where n is the principal quantum number and m_e is the electron mass. Values of the coefficients $A_{20} - A_{70}$ can be found in Ref. 11. Fig. 5 shows the ratio of the higher order terms in the self-energy to the total self energy. In neutral hydrogen the higher order terms in the self-energy contribute about 0.1 parts per million to the Lamb shift, nearly 100 times smaller than the uncertainty due to proton structure¹². At $Z=18$ the contribution is only about 1% of the Lamb shift, equal to or smaller than the experimental uncertainty¹³. At $Z=92$ however, the higher order terms are essentially the entire self-energy contribution, and make up over half of the total Lamb shift.

Fig 2 - Energy levels of $n=1$ and $n=2$ states of hydrogenlike uranium. The levels were tabulated using the Dirac energy³⁹ plus the self-energy⁶, vacuum polarization⁷ and finite nuclear size correction⁷. The radiative width of the $2^2P_{1/2}$ and $2^2P_{3/2}$ states is not indicated but is about the same as for the radiative width of the 2^3P_1 and 2^1P_1 states of heliumlike uranium (Fig. 3). E1 and magnetic quadrupole (M2) decay rates were calculated using matrix elements from Ref. 15. For the $2^2S_{1/2}$ state, the 2E1 rate is taken from Ref.'s 39,40 and the relativistic M1 rate from Ref. 40.

Heliumlike Uranium

Fig. 3 - Energy levels of $n=1$ and $n=2$ states of heliumlike uranium. Decays without labels are E1 decays. The cross hatching on the $2\ 3P_1$ and $2\ 1P_1$ indicates the approximate radiative width. The non-QED contributions to the energy levels for heliumlike uranium were obtained from Ref. 16 to which were added the one-electron self energy and vacuum polarization^{6,7}. The lowest order correction⁸ to the QED terms for the presence of the second electron, of order $1/Z$, is neglected. These values for heliumlike uranium are in general agreement with values calculated in Ref. 19 corrected for finite nuclear size effects. (The values used here are not intended to be complete. Terms of the order of 1 eV have been neglected and values have been rounded to the nearest eV.)

For the $2\ 3P_0$ state, the E1M1 decay rate is taken from Ref. 14 and the E1 rate to the $2\ 3S_1$ state is calculated using the E1 matrix element from Ref. 15. The E1 decays to the ground state have similar decay rates as the corresponding hydrogenlike transitions. The decay rate used for the $2\ 1S_0$ state is twice the decay rate for the 2E1 decay of the $2\ 2S_{1/2}$ state of hydrogenlike uranium. The $2\ 3S_1$ decay rate is taken from Ref. 18.

Lithiumlike Uranium

Fig. 4 - $n=2$ levels of lithiumlike uranium. Values of the energy levels were obtained from Ref. 17. Decay rates from Ref. 17 are in agreement with hydrogenic values taken from Ref. 14.

Previous Lamb shift experiments are compatible with both the series expansion and numerical calculations to all orders^{6,10} in $Z\alpha$. Again, this is because the higher order terms in the self-energy are large only at very high Z and hence they are unmeasured in present QED experiments. A consequence is that a significant deviation from QED at high Z is unobservable in previous experiments and that the difference between the numerical calculation and the series expansion is not well tested.

2P - 2S SPLITTINGS

A low precision measurement of the 2^3P_0 lifetime to determine the $2^3P_0 - 2^3S_1$ splitting in heliumlike uranium is in progress⁴. The experiment takes advantage of several features of the heliumlike atom. The 2^3P_0 state decays to the 2^3S_1 state by an electric dipole (E1) decay and to the ground state by a two-photon electric-dipole, magnetic-dipole decay¹⁴. (Fig. 2). As the E1 decay to the 2^3S_1 state is the dominant decay of the 2^3P_0 state, the 2^3P_0 lifetime is sensitive to the $2^3P_0 - 2^3S_1$ splitting. Consequently, a measurement of the 2^3P_0 lifetime plus the calculated E1 matrix element¹⁵ and the calculated E1M1 decay rate¹⁴ may be used to determine the $2^3P_0 - 2^3S_1$ splitting. There are no significant QED corrections to the E1 matrix element or to the E1M1 decay rate.

A second feature of this system is that the 2^3S_1 state decays to the 1^1S_0 ground state with a rate of 10^{14} sec^{-1} — much faster than the 2^3P_0 decay. This allows the 2^3P_0 lifetime to be measured by observing the 96 keV x ray from the 2^3P_0 fed decay of the 2^3S_1 state.

In addition to the Lamb shift terms, the interaction between the two electrons ($\approx +330 \text{ eV}$)¹⁶ makes up the rest of the $\approx 254 \text{ eV}$ $2^3P_0 - 2^3S_1$ splitting in heliumlike uranium. The experiment is designed to determine the splitting to about 5 eV, or roughly 10% of the higher order self-energy.

Fig. 5 - Ratio of the higher order terms in the self-energy to the total self-energy obtained by comparing the series expansion value through term $A_{10} (Z \alpha)^7$ with a numerical calculation to all orders^{8,16} in $Z\alpha$. The series expansion changes sign near $Z=80$ allowing the ratio of the higher order self energy to the total self energy to exceed 1 for very high Z.

As more intense uranium beams become available, a Doppler-tuned UV spectrometer will be used to make a direct spectroscopic measurement of the ≈ 263 eV $2^2P_{1/2} - 2^2S_{1/2}$ transition in lithiumlike uranium¹⁷ (or the $2^3P_0 - 2^3S_1$ transition in heliumlike uranium). The goal is to achieve a precision of 0.2 eV (0.4% of the self-energy). Because the $2^2P_{1/2} - 2^2S_{1/2}$ transition occurs within the ground state manifold in lithiumlike uranium (Fig. 4), and contains fewer m_j states than $n=2$ heliumlike uranium, the lithiumlike $2^2P_{1/2} - 2^2S_{1/2}$ transition is expected to be at least an order of magnitude brighter than the heliumlike $2^3P_0 - 2^3S_1$ transition. In addition, lithiumlike uranium can be produced at lower velocities than heliumlike uranium which will result in a relatively lower background from bremsstrahlung in the target. These are strong experimental incentives to choose lithiumlike ions in preference to heliumlike ions for a high-accuracy direct spectroscopic measurement.

In order to interpret a high-accuracy measurement of the $2^2P_{1/2} - 2^2S_{1/2}$ splitting of lithiumlike uranium in terms of the self-energy, theory for the $2^2P_{1/2} - 2^2S_{1/2}$ splitting in lithiumlike uranium must be improved. For lithiumlike uranium, Kim¹⁸ has estimated that present calculations are accurate at the level of a few eV. For heliumlike atoms, agreement between theory¹⁹ and experiment at low Z suggests that for heliumlike uranium present theory is reliable at about the 1 eV level. For hydrogenlike-, heliumlike- and lithiumlike- uranium, the uncertainty in the nuclear radius contributes an uncertainty of about 1 - 2 eV for the $2P - 2S$ transitions (and perhaps 5 - 10 eV for transitions involving the $1S$ ground state)^{7,20}. Measurements on muonic uranium could greatly reduce the uncertainty in the nuclear size correction.

Fig. 6 - Schematic diagram of a Doppler tuned spectrometer.

One method of measuring the $2^2P_{1/2} - 2^2S_{1/2}$ splitting in lithiumlike uranium is with Doppler tuned UV spectrometer²¹, shown schematically in Fig. 6. A detector views the UV photons from the decays in flight of the $2^2P_{1/2}$ state with a photon absorber imposed between the beam and a collimated detector. The detector-beam angle at which the photons are Doppler shifted across the K-edge of the absorber is found from the sharp change in the number of photons reaching the detector as a function of the beam - detector angle θ . A photon with an energy of ω_0 in the rest frame of the uranium will be seen with an energy of ω_{LAB} where in the rest frame of the laboratory, where:

$$\omega_{LAB} = \omega_0 \frac{\sqrt{1-\beta^2}}{1-\beta \cos \theta} \quad (2)$$

where $\beta = v/c$ and v is the beam velocity. If the absorber and beam velocity can be chosen to such that the photons are Doppler shifted across the K-edge at $\sin \theta = \beta$, then the measurement is much less sensitive to uncertainties in the beam velocity.

At 400 MeV/nucleon ($\beta = 0.7$), and $\theta = 45^\circ$ an angular displacement of 1 mR produces a Doppler shift of 1×10^{-3} . An angular divergence and horizontal beam width of 5 mR and 0.6 cm respectively, and a detector collimated to view 6 mR, located 1 meter from the beam yields an instrumental line width of about 5 eV. Splitting the line width to 1 part in 25 yields a 0.2 eV measurement.

QED CONTRIBUTIONS TO MAGNETIC MOMENTS OF BOUND ELECTRONS

In addition to the QED contribution to the mass of an electron in a Coulomb field (Lamb shift) there is also a QED contribution to the g -factor of the electron in a Coulomb field. This contribution is a bound state effect and is not tested by experiments which measure the g -factor of a free electron. The effect is observable in the hyperfine structure^{22,23} and g -factor²⁴ of hydrogenlike atoms.

The QED contribution to the electron g -factor in a Coulomb field is tested in the hyperfine structure of hydrogen²³ and the hyperfine structure of muonium^{23,25} and in the g -factor of the ground state of hydrogen²⁶. (These experiments are discussed in the next section.) To the best of my knowledge it has not been observed for $Z > 1$.

For the hyperfine splitting of hydrogenlike atoms the calculated terms are^{22,23}:

$$E_F \frac{\alpha}{\pi} \left[C_1(Z\alpha) + C_2(Z\alpha)^2 \ln^2(Z\alpha)^{-2} + C_3(Z\alpha)^2 (Z\alpha)^{-2} + C_4(Z\alpha)^2 \right. \\ \left. + \text{higher order terms} \right] \quad (3)$$

The contribution to the total hyperfine splitting of the $Z\alpha$ and $(Z\alpha)^2$ terms at different Z computed from Eq. 3 is given in Table I. Terms of higher order than $(Z\alpha)^2$ have not yet been calculated.

Table I. Bound state QED contributions to hyperfine splitting		
Z	$C_1(Z\alpha)$	$C_2(Z\alpha)^2$
1	1×10^{-4}	2×10^{-8}
19	2×10^{-3}	7×10^{-4}
81	8×10^{-3}	1×10^{-2}

The term of order $(Z\alpha)^2$ contributes about 1% of the hyperfine splitting at $Z=81$ (the anomalous magnetic moment of the free electron contributes roughly 0.1%). In addition, at $Z=81$, the $(Z\alpha)^2$ term is larger than the lower order $Z\alpha$ term. At very high Z terms of order $(Z\alpha)^3$ and higher could be larger than the lower order terms. The calculation of higher order terms presents a challenge because it is necessary to consider the energy of the electron bound by both strong Coulomb and magnetic field:²⁷

The g_J factor of a bound electron also has QED contributions which are not present for a free electron and which become relatively large at high Z (Ref. 24). The leading term is $\alpha/\pi (Z\alpha)^2$ which contributes 3×10^{-8} in hydrogen and 3×10^{-4} in hydrogenlike uranium. The relative contribution to the g_J factor is smaller and of higher order than for the hyperfine splitting. This is because the g_J involves a uniform external magnetic field where as the hyperfine splitting arises in the magnetic field singularity at the nucleus.

HYPERFINE STRUCTURE AND G_J EXPERIMENTS

Tests of the QED contribution to the hyperfine splitting of an electron bound in a Coulomb field are limited in hydrogen at a few ppm due to the uncertainty in the proton polarizability and in muonium to a few tenths of a ppm due to uncertainties in the muon mass and fine structure constant²⁸. These experiments test the term of order $(Z\alpha)^2$ to about 10% and are probably insensitive to higher order terms. By comparison the leading term in the Lamb shift in hydrogen is tested to about 10 parts-per-million.

Measurements of the g_J in the ground state of hydrogen²⁹ achieved a precision of 1×10^{-8} which tests the leading order term to about 30%. Experiments³⁰ in He^+ are not yet of sufficient sensitivity to see the contribution.

Measurements of the ground state hyperfine structure of hydrogenlike thallium using storage rings have been proposed by Bemis²⁹, and fixed target experiments have been proposed by Bemis and Gould³⁰. The ground state hydrogenlike thallium (Fig. 7) ($l = 1/2$) $F=1 - F=0$ transition energy is calculated to be 4800 A° without QED corrections and the magnetic dipole decay (M1) rate for $F=1 \rightarrow F=0$ is $\approx 10^3 \text{ s}^{-1}$. Confinement of hydrogenlike thallium in a storage ring would then produce a spectra from the $F=1 \rightarrow F=0$ allowed M1 decay and optical spectroscopy would be used to determine the ground state hyperfine interval. For a 15 meter radius ring capturing 10^8 ions per second, a highly collimated detector which intercepted 0.01% of the decay photons over 10 cm would detect 100 counts/sec. With 1 mR angular acceptance the Doppler width is of the order of 0.1% of the transition energy, which would immediately allow a measurement of the $(Z\alpha)^2$ term to 1% and almost certainly a sensitive test of higher order terms.

Fig. 7 - Hyperfine splitting of hydrogenlike thallium

The finite nuclear size correction to the hyperfine splitting is about 20% at $Z=81$. The $\approx 1\%$ uncertainty in the nuclear radius presently limits a comparison between theory and experiment to a few-tenths of a percent. To utilize the precision which might be attained in a storage ring experiment a more precise value for the nuclear radius will be needed. Muonic atom experiments should be able to provide an improved value for the radius.

The g_J factor is much less sensitive to the finite nuclear size correction. It appears that in lowest order there is no nuclear size correction to the non-QED part of the g_J factor³¹. If the contribution of the nuclear size to the QED part is the same order as for the hyperfine splitting, then the nuclear size uncertainty is not a serious limitation to a g_J measurement.

An atomic beam resonance technique has been proposed for a Zeeman effect measurement of the g_J factor of hydrogenlike uranium³² and an optical resonance measurement of the hyperfine splitting of hydrogenlike thallium³⁰. The measurements require the production of a beam of polarized hydrogenlike atoms and analyzing the polarization to detect a resonance transition in an interaction region placed between the polarizer and analyzer. For g_J measurements the interaction region would consist of a uniform magnetic field and a pair of rf driven loops, while for hyperfine splitting measurements the interaction region would contain a high power LASER.

Experiments are being carried out at the Lawrence Berkeley Laboratory's Bevalac to produce polarized ground-state hydrogenlike uranium by capturing an electron onto bare uranium nuclei channeled through a magnetized single-crystal ferromagnetic foil. The analyzer would be a second foil. As the Pauli principle prohibits capture of a second electron in to the same ground state, the ratio of heliumlike to hydrogenlike uranium formed in the second target would depend upon whether the hydrogenlike uranium underwent a spin-flip transition between foils. At relativistic energies radiative electron capture (REC), the inverse of the photoelectric effect, becomes a significant capture mechanism.

Unlike nonradiative capture, which preferentially captures the K-shell electrons from the target, REC has a more equal probability of capturing the valence electrons. The valence electrons are aligned in a ferromagnetic target and channeling the ion enhances the probability of capturing them. The technique works at very low energies where K-shell capture is suppressed and has been used to produce polarized deuterium beams³³.

ULTRARELATIVISTIC PAIR PRODUCTION

The cross section for producing electron - positron pairs from the Coulomb field of two colliding (bare) nuclei is given for the limiting case of kinetic energies much larger than the electron (lepton) rest mass by³⁴:

$$\sigma_{\text{pair}} = (28/27\pi) \alpha^2 Z_1^2 Z_2^2 r_0^2 \log^3 \gamma \quad (4)$$

where $\gamma = (1-\beta^2)^{-1/2}$ with $\beta = v/c$ and Z_1 and Z_2 are the nuclear charges, and r_0 is the classical electron radius.

Table II shows the cross sections computed from Eq. 1 for producing electron - positron pairs in uranium - uranium collisions at collider energies.

Table II. Pair production cross sections for U^{92+} on U^{92+}		
energy/beam GeV/amu	equivalent fixed target energy GeV/amu	cross section kilo-barns
5	70	8
10	240	17
20	860	31
40	3400	54
100	20400	98

A transfer line between a tandem Van der Graff and the Brookhaven alternating gradient synchrotron (AGS) is presently under construction. With the addition of a proposed booster synchrotron³, very heavy ions will be accelerated to energies of over 10 GeV/nucleon. Ultimately the AGS may serve as an injector for a 100 GeV/nucleon on 100 GeV/nucleon relativistic heavy ion collider²⁰. For a 100 GeV/nucleon collider operating with a luminosity of $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ bare uranium nuclei, about 10^9 electron - positron pairs per second are produced in the collision region. As number of muon pairs scales roughly as $(m_e/m_\mu)^2$ about 2000 muon pairs would also be produced and one or two tau pairs. Finally, heavier pairs will also be produced in small quantities and the upper limit to the mass of the pairs which can be observed needs to be explored. (A more detailed discussion of atomic physics effects in relativistic heavy ion colliders may be found in Ref. 35,36.)

Fig. 8 - Predicted ratio of hydrogenlike Au^{78+} to bare Au^{78+} at 15 GeV/nucleon for equilibrium thickness targets of different atomic number Z_T . The ratio of Au^{78+} to Au^{78+} is shown for different fractions of the electrons from pair production captured onto a gold nuclei.

It is possible for the electron produced in pair production, to be captured into the K-shell of one of the uranium atoms which produced the pair. Classically, capture occurs if the electron is found within the potential well of the Coulomb field and has a kinetic energy less than the K-shell binding energy. In uranium this means within ≈ 560 fm and a kinetic energy of less than 130 keV. (If the two uranium are closer than 560 fm, then the binding energy of the combined system will be larger than 130 keV. In collisions at energies close to the Coulomb barrier, uranium nuclei which approach to within 35 fm have a combined binding energy in excess of 1 MeV.)

Experiments can be done to look for capture from pair production in fixed target experiments on ≈ 10 GeV/nucleon gold ($Z=79$). At this energy the only competing capture mechanism in light targets is radiative electron capture and the radiative electron capture cross section can be accurately calculated. K-shell ionization is reliably given by the Bethe theory^{1,37}, so that the fraction of one-electron ions emerging from a target can be interpreted to yield a measurement of the cross section for capture from pair production. The ratio of one-electron gold to bare nuclei as a function of the probability of capturing the electron from pair production is shown in Fig 8.

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- ⁹There is a near degeneracy between the 2^1S_0 and the 2^3P_0 states in helium-like uranium (Fig. 3). It is intriguing to consider a measurement of the $2^1S_0 - 2^3P_0$ splitting since even a large fractional error yields a very sensitive test of the Lamb shift contribution. (The uncertainty in the energy levels is a few eV, too large to determine how close the levels really are.) Since the 2^3P_0 state decays with a lifetime of ≈ 50 ps, any mechanism which produced a significant mixing of the 2^3P_0 and 2^1S_0 states would produce an experimentally observable signal. However no single photon transition can connect these $j=0$ states for atoms with no hyperfine splitting, while in atoms with large hyperfine effects, the 2^3P_0 state is no longer long-lived.
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