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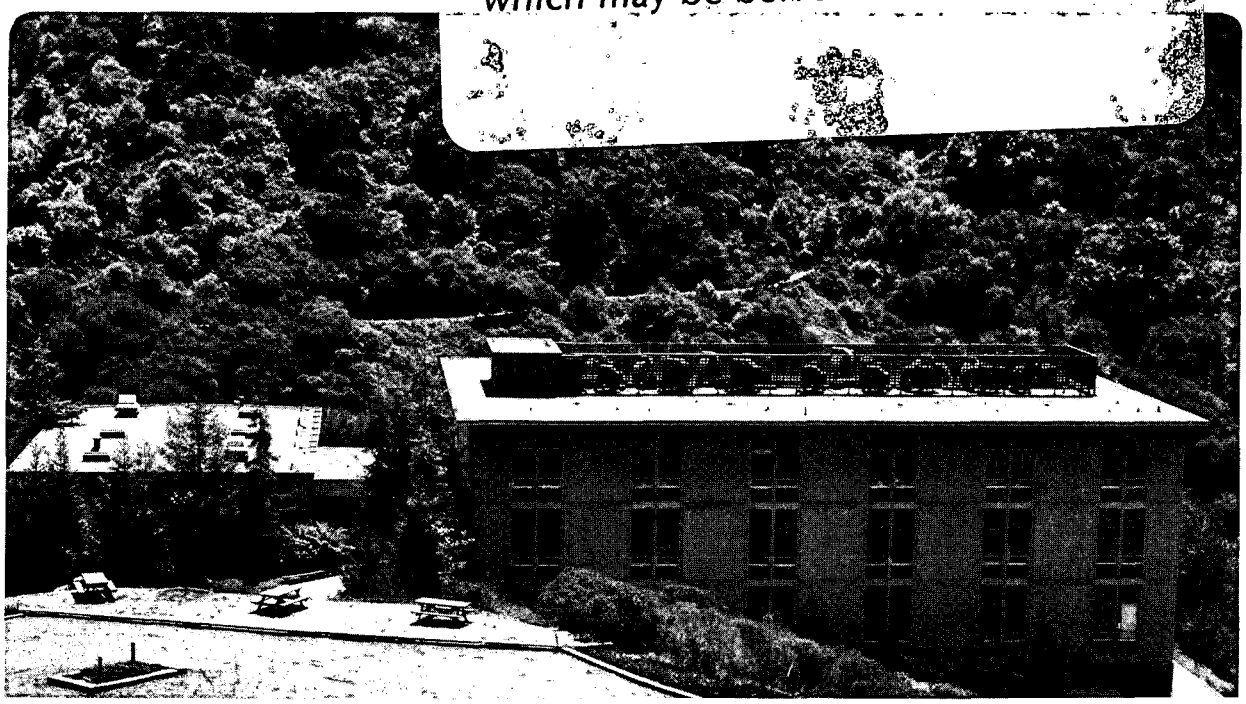

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EXPERIMENTS ON FEW-ELECTRON VERY HIGH-Z IONS

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INTRODUCTION

The production[1] in 1983 of a beam of bare U^{92+} at the Lawrence Berkeley Laboratory's Bevalac[2], the Bevatron and Super-HILAC operating in tandem, demonstrated the feasibility of experiments using few-electron uranium. Since then, experiments by Anholt and collaborators[3-8] have led to an understanding of the physics of charge changing collisions at relativistic energies. Charge changing collisions at relativistic energies are, in many cases, now better understood than charge changing collisions at non relativistic energies. In 1984 x rays from radiative electron capture into the K shell of uranium was observed[3,6] by Anholt et. al. and x rays from $n=2 \rightarrow n=1$ transitions in hydrogenlike uranium (U^{91+}) and heliumlike uranium (U^{90+}) were observed by Munger and Gould[9]. A preliminary value[10] for the Lamb shift in heliumlike uranium was obtained by Munger and Gould in 1986.

This article discusses the measurement of the Lamb shift in heliumlike uranium and outlines future experimental tests of QED using few-electron very high atomic number (Z) ions. We conclude with a discussion of the possibility of using ultrarelativistic atomic collisions to produce very heavy leptons.

PRODUCTION OF FEW-ELECTRON VERY HIGH-Z IONS

Few-electron uranium and other very high-Z ions are produced by stripping beams of relativistic atoms. The experimentally determined charge state distributions for relativistic uranium ions which have passed through equilibrium thickness targets is shown in Fig. 1. Equilibrium thickness—the thickness at which additional material no longer changes the charge state is typically a few ten's of mg/cm^2 for high-Z targets. The processes for electron capture and loss by relativistic heavy ions are well understood and cross sections for ionization, for radiative electron capture and for nonradiative electron capture can be reliably calculated[3-8,11,12].

The Bevalac produces uranium beams at energies up to 960 MeV/amu at intensities of 10^6 ions per pulse (duty cycle is typically 12 pulses per minute). An upgrade presently in progress is designed to increase the beam intensity by a factor of ten. The beam emittence is 30π mm-mR or better.

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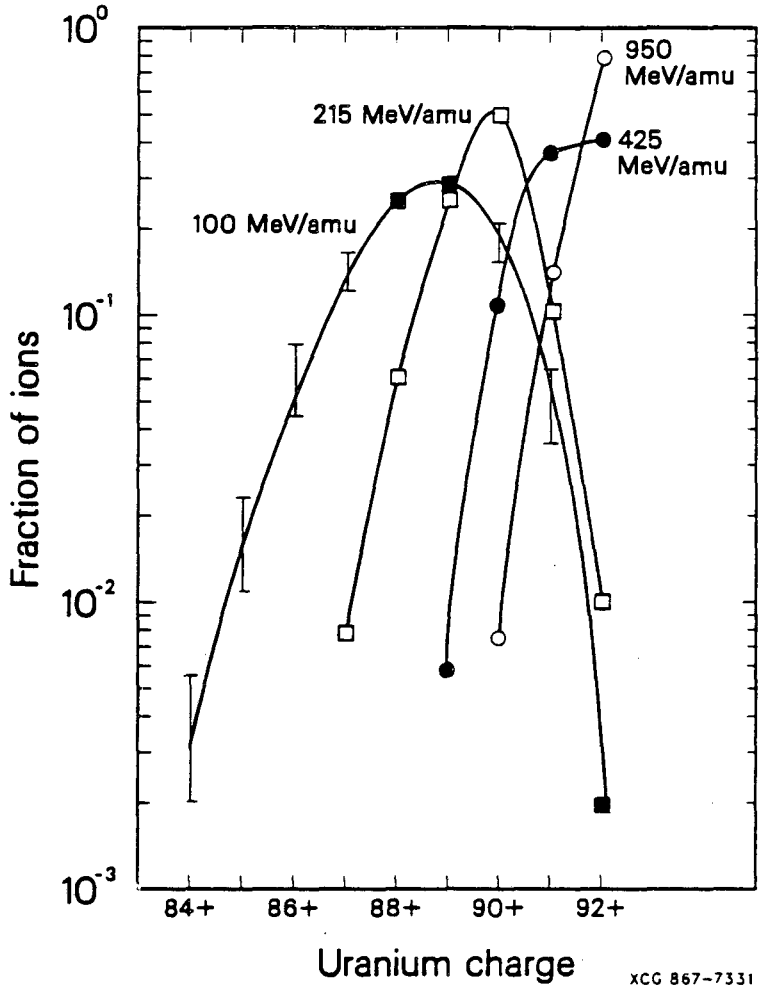

Fig. 1. Charge state distribution of relativistic uranium after passing through an equilibrium thickness target. A Cu (Z=29) target was used for 950 MeV/amu, 425 MeV/amu, and 100 MeV/amu uranium and a Au (Z=79) target was used for 215 MeV/amu uranium.

LAMBSHIFT IN VERY HIGH Z FEW-ELECTRON IONS

The measurement of the Lamb shift in a very high-Z atom is a test of quantum electrodynamics (QED) in a strong Coulomb field. QED is well tested for free particles and in the weak fields of low-Z atoms. But just as Newton's laws work well in weak gravitational fields but fail in strong gravitational fields, experiments in low-Z atoms do not rule out a possible failure of QED in the strong Coulomb field of a very high-Z atom.

At Z=92, the contributions to the Lamb shift in a one-electron atom are the self-energy[13,14] of ≈ -56 eV, the vacuum polarization[15] of $\approx +14$ eV and the finite nuclear size correction[15] of ≈ -33 eV, where a negative value indicates the interaction decreases the binding energy. 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 field[16].

What is significant about the self energy at Z=92 is it arises almost entirely from terms[17] 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 they are not tested in low-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[13,14,17-19] in $Z\alpha$. If we write the self energy Σ_n in a power series in α and $Z\alpha$, we have:

$$\Sigma_n = n^{-3}(\alpha/\pi)\, m_o c^2 \Big[[A_{40} + A_{41}\ln(Z\alpha)^{-2}](Z\alpha)^4 + A_{50}(Z\alpha)^5 + [A_{60} + A_{61}\ln(Z\alpha)^{-2} + A_{62}\ln^2(Z\alpha)^{-2}](Z\alpha)^6 + A_{70}(Z\alpha)^7 + \text{higher order terms} \Big] \quad (1)$$

Where n is the principal quantum number and m_o is the electron rest mass. Values of the coefficients $A_{40} - A_{70}$ can be found in Ref. 19. Fig. 2 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 structure[20]. 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.

MEASUREMENT OF THE LAMB SHIFT IN HELIUMLIKE URANIUM

We have obtained a preliminary value for the Lamb shift in heliumlike U^{90+} of 69.1 (8.0) eV which is in agreement with the theoretical value[13-15] of 75 eV for the one-electron Lamb shift at Z=92.

We choose heliumlike uranium over hydrogenlike uranium for this measurement because both the 2 $^2S_{1/2}$ and 2 $^2P_{1/2}$ states of hydrogenlike uranium decay very rapidly making it very difficult to observe the decays outside of the target where the hydrogenlike uranium is formed. With hydrogenlike uranium there is the risk that interactions with the target will perturb the energy levels of the atom. In heliumlike uranium, however, the 2 $^3P_0$ state is metastable[21] (55 ps lifetime) because angular momentum conservation forbids single photon decays to the 1 $^1S_0$ ground state. Consequently decay of the state can be observed well downstream from the target foil.

Our value for the Lamb shift in heliumlike uranium was obtained from a measurement of the lifetime of the 2 $^3P_0$ state (see Fig. 3). In heliumlike uranium about 70% of the 2 $^3P_0$ state decays by an allowed electric-dipole (E1) transition[22] to the 2 $^3S_1$ state, making the 2 $^3P_0$ lifetime sensitive to the 2 $^3P_0$ − 2 $^3S_1$ energy splitting. The remainder decays to the ground state by a two-photon electric-dipole magnetic-dipole (E1M1) transition[21]. The 2 $^3P_0$ − 2 $^3S_1$ splitting arises

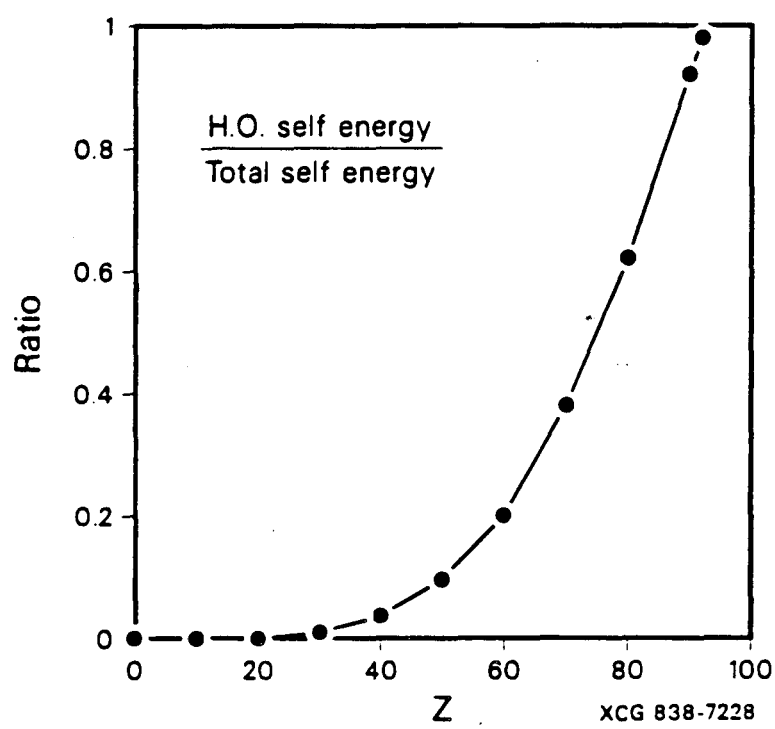

Fig. 2. Ratio of the higher order terms in the self-energy to the total self-energy obtained by comparing the series expansion value through term $A_{70}(Z\alpha)^7$ with a numerical calculation to all orders in $Z\alpha$.

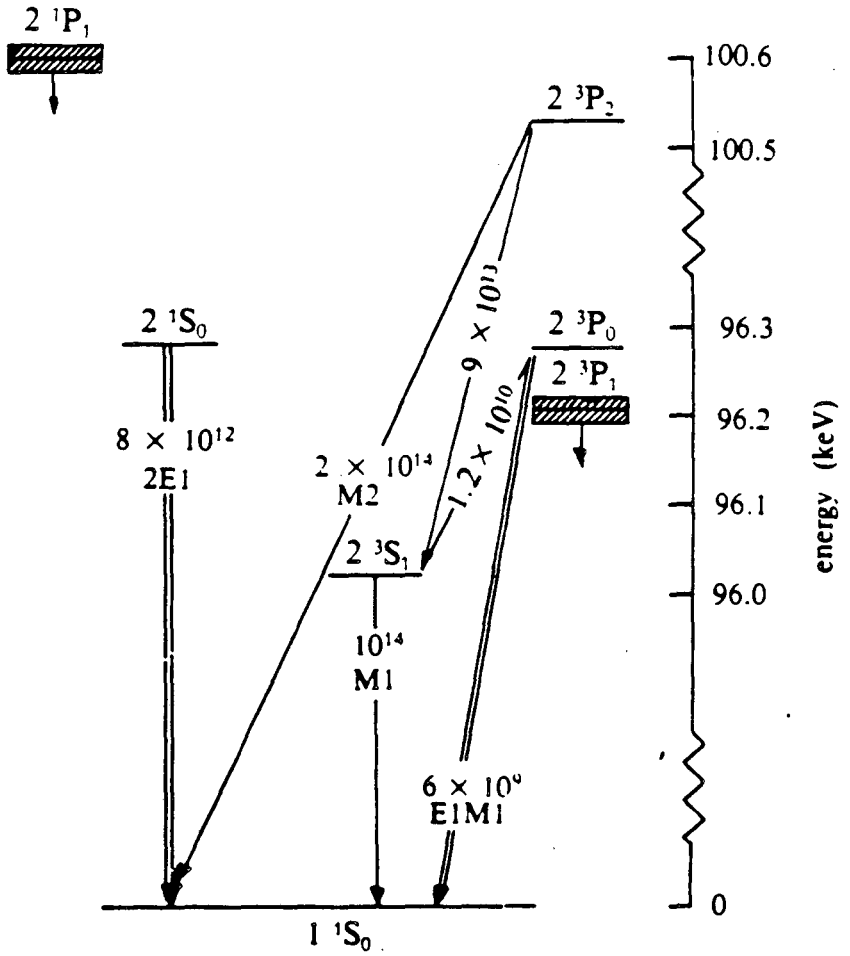

Fig. 3. Energy level diagram of the n=1 and n=2 states of heliumlike uranium. Decays without labels are E1 decays and the cross hatching on the $^1P_1$ and $^3P_1$ states indicates the approximate radiative width. At Z=92 singlet-triplet mixing is close to 100% and singlet-triplet classification (and LS coupling) is used only for the convenience of the authors. The non-QED contributions to the energy levels for heliumlike uranium were obtained from Ref. 23 to which were added the one-electron self energy and vacuum polarization[13-15]. The lowest order correction[16] 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.'s. 21,24. Decay rates are taken from Ref.'s 21,23, and where appropriate from hydrogenic matrix elements given in Ref. 22.

from the Lamb shift and from the Coulomb interaction between the two electrons in the 2 $^3P_0$ and in the 2 $^3S_1$ states. The latter is calculated to be 329 eV (Ref. 23,24) and 326 eV (Ref. 21). The measured 2 $^3P_0$ lifetime, the calculated E1M1 decay rate and the calculated E1 matrix element[22] and the non-QED contributions to the 2 $^3P_0$ − 2 $^3S_1$ splitting are combined to determine the Lamb shift. The E1M1 decay rate and the E1 matrix element are insensitive to QED effects at the present experimental accuracy. The effect of the second electron on the Lamb shift[16] is to decrease it by a term of order 1/Z which we neglect for Z=92 in the present experiment.

The indirect method of measuring the 2 $^3P_0$ lifetime rather than a direct measurement of the 2 $^3P_0$ − 2 $^3S_1$ transition energy was chosen because it is easier than measuring the energy of the 0.25 keV photon from this transition. An attractive feature of the lifetime measurement is that the 2 $^3P_0$ − 2 $^3S_1$ transition is followed rapidly by emission of a 96 keV x ray from the 2 $^3S_1$ − 1 $^1S_0$ decay. The 96 keV x ray is easy to detect. The 10^{-14} sec lifetime of the 2 $^3S_1$ state has no effect on the measurement of the 6×10^{-11} sec 2 $^3P_0$ lifetime provided sufficient distance is allowed for the initial 2 $^3S_1$ population to decay. A spectrum taken 0.5 cm downstream from the target is shown in Fig. 4. The 2 $^3P_0$ lifetime is measured by the beam-foil time-of-flight technique.

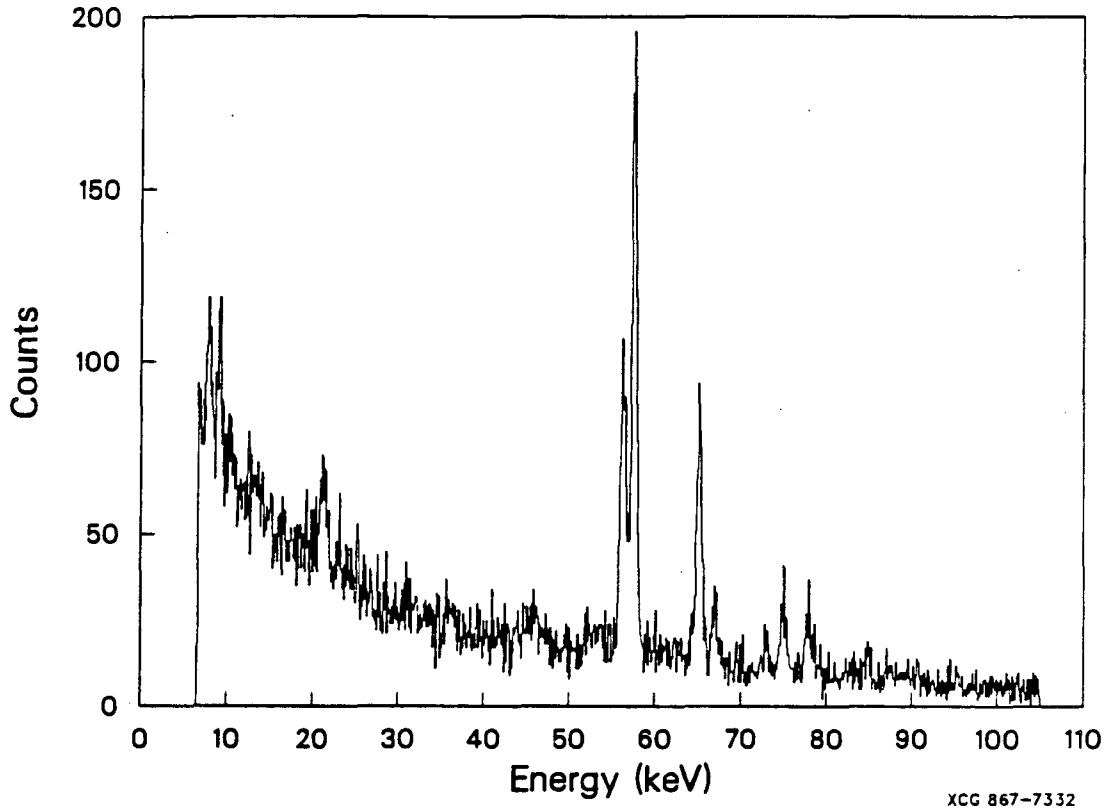

Fig. 4. X-ray spectra 0.5 cm downstream from the target. The Doppler-shifted x-ray peak from the decay of $^2P_0 \rightarrow {}^2S_1 \rightarrow {}^1S_0$ is near 78 keV. Peaks at 73 keV, 75, keV and 82 – 86 keV are from fluorescence of Pb. and at those near 57 keV and 65 keV from Ta which are used used for shielding the x-ray detector and for Soller and slits respectively. Cascades from higher excited states, if present, would produce a peak at 81 keV. This spectra represents 135 minutes of counting, or about 10^8 uranium ions. Background is caused by bremsstrahlung of electrons in the target off of the uranium projectile, elastic scattering of the electrons in the target followed by bremsstrahlung of the electrons either in the target, or, if the electrons leave the target, in the walls of the vacuum chamber, and by fragments from nuclear disintegrations in the target and by nuclear reactions by fast neutrons in the Ge detectors. Other sources of background may also exist.

Heliumlike uranium in the 2 $^3P_0$ state is prepared by stripping a beam of 220 MeV/amu uranium 39+ which is obtained from the Lawrence Berkeley Laboratory's Bevalac. An aluminum target produces an equilibrium charge state distribution of roughly 5% U^{92+}, 30% U^{91+}, 60% U^{90+}, 5% U^{89+}. The hydrogenlike U^{91+} fraction is magnetically selected and transported to a 1 mg/cm^2 Pd target. About half of the U^{91+} ions are converted to heliumlike U^{90+}, with about 1% of these being formed in the 2 $^3P_0$ state or in states which rapidly decay to the 2 $^3P_0$ state.

The price for using the 2 $^3S_1$ decay is to make the measurement more sensitive to possible cascade feeding from long-lived states of high principle quantum number (n) and angular momentum (J). Decays of high n,J states cascade down the yrast chain and reach the 2 $^3P_2$ state which has a branching ratio of 1/3 to the 2 $^3S_1$ state by E1 decay and 2/3 to the ground state by electric quadrupole decay. It is the branch to the 2 $^3S_1$ state which is a potential source of systematic error. In heliumlike uranium , however it takes a state of about n=25 and high angular momentum before the cascade time is comparable to the lifetime of the 2 $^3P_0$ state. The populations of excited states fall rapidly with increasing n and we estimate[4,11] that no more than 2% of the population lies above n=25 and with only a small fraction of these in high J states. We therefore expect no observable effect from cascades on our measured 2 $^3P_0$ lifetime with our present statistical accuracy of 6%. Furthermore we designed the apparatus so that the difference in transition energy to the ground state from the 2 $^3S_1$ and 2 $^3P_2$ states is resolved by our germanium x-ray detector. Cascades through the 2 $^3P_2$ state would show up in our spectra as a resolved peak lying just above the decay peak. Figure 2 shows no evidence of a cascade peak nor does any of our data to within background statistics.

With more intense uranium beams and the knowledge gained from these early experiments a direct measurement of the ≈ 284 eV $2\,^2P_{1/2} - 2\,^2S_{1/2}$ splitting[25] in lithiumlike uranium (U^{89+}) to an accuracy of a few-parts in 10^4 appears feasible. When compared with atomic structure calculations of similar accuracy this would test the Lamb shift to 0.1%. The nuclear size of the uranium nucleus is sufficiently well known from muonic atom measurements[26].

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 splitting[27,28] of hydrogenlike atoms and of muonium and in the g-factor[29] of hydrogenlike atoms.

The QED contribution to the electron g-factor in a Coulomb field is tested in the hyperfine structure of hydrogen[28] and the hyperfine structure of muonium[28,30] and in the g-factor of the ground state of hydrogen[31]. Experiments have not been performed for $Z > 1$.

For the hyperfine splitting of hydrogenlike atoms the calculated terms are[27,28],

$$E_F \frac{\alpha}{\pi} \Big[C_1(Z\alpha) + C_2(Z\alpha)^2 \ln^2(Z\alpha)^{-2} + C_3(Z\alpha)^2 \ln(Z\alpha)^{-2} + C_4(Z\alpha)^2 + \text{higher order terms} \Big] \tag{2}$$

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

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. In the calculation of higher order terms it is necessary to consider the energy of the electron bound by both strong Coulomb and magnetic fields[32].

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. 29). 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.

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 constant[28]. These experiments test the term of order $(Z\alpha)^2$ to about 10% and are probably insensitive to higher order terms. Measurements of the g_J in the ground state of hydrogen[31] achieved a precision of 1×10^{-8} which tests the leading order term to about 30%. Experiments[33] 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 suggested by Bemis and Gould[34]. The ground state hydrogenlike thallium (I = 1/2) F=1 − F=0 transition energy is calculated to be 3800 Å without QED corrections and the magnetic dipole decay (M1) rate for F=1 → F=0 is $\approx 10^3\ s^{-1}$. Confinement of hydrogenlike thallium in a storage ring would then produce a spectrum from the F=1 → F=0 allowed M1 decay and optical spectroscopy would be used to determine the ground state hyperfine interval.

Table I. Bound state QED contributions to hyperfine splitting

Z	$C_1\,(Z\alpha)$	$C_4\,(Z\alpha)^2$
1	1×10^{-4}	2×10^{-6}
19	2×10^{-3}	7×10^{-4}
81	8×10^{-3}	1×10^{-2}

ULTRARELATIVISTIC PAIR PRODUCTION

The cross section for producing electron-positron pairs from the Coulomb field of two colliding (bare) point nuclei is given for the limiting case of kinetic energies much larger than the electron (lepton) rest mass by[35]:

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

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. The formula is for point nuclei and impact parameter cut-off's for real nuclei will reduce the cross sections by an estimated one to two orders of magnitude. Ultrarelativistic heavy ion accelerators which have been proposed[36] (RHIC), approved (the booster synchrotron for the Brookhaven Alternating Gradient Synchrotron)[37] or are under construction (The heavy ion facility for the CERN SPS) will produce large quantities of electron-positron pairs. Production of heavier leptons is also possible. If the cross section scales inversely as the square of the mass, a 10^7 ion per second beam of 15 GeV/amu uranium in a 1 g/cm^2 uranium target would produce one tau pair per minute. Such a beam-dump experiment could be used to search for heavier leptons and other very heavy particles.

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.[8,38] The electrons most likely to be captured after pair production are those having momenta which overlap the momenta of the final bound K electron. This means that electrons with kinetic energies less than the uranium K-shell binding energy may be captured. The energy distribution of the pairs produced by colliding 15 GeV/amu uranium ions with a fixed uranium target extends to about 10 MeV, but is peaked at lower energies. The fraction of electrons within the K shell with kinetic energies of less than 130 keV would then be roughly 130 keV/10 MeV $\approx$ 0.01, hence about 1 percent of the electrons could be captured into the K-shell. For muons, with larger binding energies, the capture fraction could be larger.

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