Lawrence Berkeley National Laboratory

Recent Work

Title

SPECTROSCOPY OF ONE- AND TWO-ELECTRON URANIUM

Permalink

<https://escholarship.org/uc/item/0rm2r2hs>

Author

Gould, H.

Publication Date

1984-08-01

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

RECEIVED
LAWRENCE
BERKELEY LABORATORY

Materials & Molecular Research Division

OCT 9 1984

LIBRARY AND
DOCUMENTS SECTION

Presented at the International Conference on the
Physics of Highly Ionized Atoms, Oxford, England,
July 2-5, 1984

SPECTROSCOPY OF ONE- AND TWO-ELECTRON URANIUM

H. Gould

August 1984

For Reference

Not to be taken from this room

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

SPECTROSCOPY OF ONE- AND TWO- ELECTRON URANIUM

HARVEY GOULD

*Materials and Molecular Research Division,
Building 71-259, Lawrence Berkeley Laboratory,
University of California,
Berkeley, California 94720 U.S.A.*

The spectra from $n=2 \rightarrow n=1$ transitions of hydrogenlike and heliumlike uranium have been observed. Possible experiments to study quantum electrodynamics in these systems are discussed.

1. Observed charge states and spectra

Charge state distributions containing approximately 50% heliumlike uranium and 20% hydrogenlike uranium have been observed¹ by stripping 200 MeV/nucleon uranium in approximately 30 mg/cm² of aluminum. Beams of up to 85% bare U⁹²⁺ have been produced by stripping 962 MeV/nucleon uranium in Cu and Ta foils.² Relativistic uranium is obtained from the Lawrence Berkeley Laboratory's Bevalac- the Super-HILAC and the Bevatron operating in tandem.

High energy x-rays produced by radiative electron capture (REC) onto bare- and one electron- uranium have been observed.³ The angular dependence of the REC radiation and the REC cross sections for capture of electrons into the uranium K shell from materials of different atomic number has been measured.³ These and other experiments⁴ have observed $n=2 \rightarrow n=1$ transitions from hydrogenlike and heliumlike uranium.

2. Quantum Electrodynamics

The fine structure splittings of hydrogenlike and heliumlike very high-Z atoms have large contributions from quantum electrodynamics (QED). The Lamb shift in hydrogenlike uranium is approximately 75 eV.⁵ The major contributions to the Lamb shift in hydrogenlike uranium: the self energy⁶; the vacuum polarization;⁷ and the finite nuclear size⁷ contribute 66 eV, -17 eV, and 35 eV respectively to the $2^2S_{1/2}$ state binding energy and 10 eV, -3 eV, and 2 eV for the $2^2P_{1/2}$ state. (A positive value indicates a decrease in binding energy.)

While the size of the QED terms is impressive, even more striking is the contribution of higher order terms in the self energy. These are terms which are not observed in present Lamb shift and fine structure measurements. If we write the self energy Σ_n in a power series in α and $Z\alpha$, where α is the fine structure constant we have:

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

Where n is the principal quantum number and m_e is the electron mass. Values of the coefficients $A_{40} - A_{70}$ can be found in Ref. 8,9. Comparing an exact calculation of the self energy by Mohr⁶ with Eq. 1. yields a value for the sum of the higher order terms. In hydrogen the higher order terms contribute less than 1 ppm to the Lamb shift. By comparison the most precise measurement of the Lamb shift in hydrogen is has an uncertainty of about 8 ppm¹⁰. In hydrogenlike argon ($Z=18$) the higher order terms contribute about 1%. Present measurements¹¹ in this range of atomic number have accuracies, which at best, allow the higher order terms to be observed but not measured. Figure 1 shows that the higher order terms in the self energy become dominant as Z becomes very large. A consequence of this high-Z behavior is that it would be possible to have a large break-down of QED at very high-Z and yet have no evidence

from present experiments.

3. Experiments in hydrogenlike and heliumlike uranium

An examination of the energy level diagrams of hydrogenlike uranium (Fig. 2) and heliumlike uranium (Fig. 3) suggest a number of experiments. Because of unusual features of the energy levels, some of these experiments are only appropriate in very high- Z atoms. (The energy levels of hydrogenlike uranium were tabulated using the Dirac energy¹² plus self energy, vacuum polarization and finite nuclear size correction.⁵⁻⁷ The finite nuclear size correction to the self energy and vacuum polarization is neglected. The non-QED contributions to the energy levels for heliumlike uranium were obtained from Lin, Johnson and Dalgarno¹³ to which were added the one-electron self energy and vacuum polarization.^{6,7} The lowest order correction¹⁴ 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 by Goldman and Drake¹⁵ and 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.)

(Single-photon electric dipole [E1] and magnetic quadrupole [M2] decay rates for hydrogenlike uranium are calculated using matrix elements from Hillery and Mohr.¹⁶ For the $2^2S_{1/2}$ state, the 2E1 rate is taken from Ref. 17,18 and the relativistic magnetic dipole [M1] rate from Ref. 18. For heliumlike uranium, the decay rates for the 2^3P_2 and 2^3S_1 state are taken from Ref. 13. For the 2^3P_0 state, the E1M1 has been calculated by Drake,¹⁹ and the E1 rate to the 2^3S_1 state is calculated using the electric dipole matrix element from Ref's. 16,20. 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 self energy contribution⁶ to the $2^2P_{3/2} - 1^2S_{1/2}$ transition in

hydrogenlike uranium is roughly 350 eV out of a transition energy of 102.2 keV. However the $2^2P_{3/2}$ state also decays to the $2^2S_{1/2}$ state about 0.2% of the time. This much higher branching ratio than for lower-Z hydrogenlike atoms is a consequence of the higher Z dependence for the fine structure splitting than for the Rydberg levels. The self energy contribution here is about 57 eV out of a transition energy of 4490 eV - a substantially higher ratio and an easier photon energy to measure than the 102.2 keV x-ray. It should be noted however that the radiative width of the $2^2P_{1/2}$ and $2^2P_{3/2}$ states is about 30 eV.

In heliumlike uranium the 2^3P_0 and 2^3P_2 states have much smaller radiative level widths since single photon E1 decay to the ground state is forbidden. Also the 2^3P_2 state, the analog of the hydrogenlike $2^2P_{3/2}$ state, has a branching ratio to the 2^3S_1 state of 30%. This transition has roughly the same QED terms and transition energy as the hydrogenlike $2^2P_{3/2} - 2^2S_{1/2}$ but with a narrow linewidth and a much higher intensity due to a favorable branching ratio.

The other metastable P state, the 2^3P_0 state, decays by E1 to the 2^3S_1 state, some 255 eV below. Since the self energy contribution⁶ to this splitting is 56 eV the photon wavelength is very sensitive to QED effects. Directly measuring the photon energy in this energy region from a source moving at roughly half-the-speed-of-light may be difficult with presently available 10^5 uranium ions per second. An alternate method is to measure the lifetime of the 2^3P_0 state, and subtract out the calculated E1M1 decay rate¹⁹ to obtain the E1 decay rate for $2^3P_0 - 2^3S_1$. From the experimental decay rate and the E1 matrix element the $2^3P_0 - 2^3S_1$ energy splitting can be deduced. (The E1M1 decay rate is not sensitive to QED effects and the E1 matrix element for $2^3P_0 - 2^3S_1$ is accurately known.^{16,20,21}) This technique was used²¹ in 1975 to determine the $2^3P_0 - 2^3S_1$ fine structure splitting in heliumlike krypton (Z=36).

Measurements of transition energies in heliumlike (and

hydrogenlike) uranium can be interpreted as a test of QED only to the extent that the non-QED terms are accurately known. The agreement between theory and experiment of the $2^3P_2 - 2^3S_1$ and $2^3P_0 - 2^3S_1$ fine structure splittings^{15,22} for lower-Z heliumlike ions sets an upper limit of about 1 eV for the uncertainty in calculating the contribution from the interaction between the electrons. Since measurements in heliumlike uranium are primarily a test of the higher order terms in the self energy, a few eV uncertainty in the theory for the fine structure splitting is not presently a serious handicap. For both hydrogenlike and heliumlike 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.

Figure 3 also shows that there is a near degeneracy between the 2^1S_0 and the 2^3P_0 states in heliumlike uranium. Thus at or near $Z=92$ these levels may be close to degenerate. Since the 2^3P_0 state decays with a lifetime of ≈ 50 ps, (roughly 1 cm decay length at half-the-speed-of-light) any mechanism which produced a significant mixing of the 2^3P_0 and 2^1S_0 states would produce an experimentally observable signal. It should be noted however that no single photon transition can connect these $j=0$ states.

I thank Dr. Robert Anholt, Professor Gordon Drake, Professor Walter Johnson, Professor Walter Meyerhof, Professor Peter Mohr, Mr. Charles Munger, and Dr. Farid Parpia for their helpful conversations and for communicating unpublished results. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Chemical Science Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

- (1) P. Thieberger, H. Wegner, and H. Gould, Private communication; H. Gould, D. Greiner, P. Lindstrom, T.J.M. Symons, P. Thieberger, H. Wegner, and H.

- Crawford, U^{88+} - U^{92+} Produced at Relativistic Energies, presented at "The International Conference on The Physics of Highly Ionized Atoms", University of Oxford, England, July 2 - 5, 1984., (Lawrence Berkeley Laboratory report LBL-17625a).
- (2) H. Gould, D. Greiner, P. Lindstrom, T.J.M. Symons, and H. Crawford, Phys. Rev. Lett. 52, 180 (1984) (Errata- Phys. Rev. Lett. 52, 1654 [1984].)
 - (3) R. Anholt, S.A. Andriamonje, E. Morenzoni, Ch. Stoller, J.D. Molitoris, W.E. Meyerhof, H. Bowman, J.-S. Xu, Z.-Z. Xu, J.O. Rasmussen, and D.H.H. Hoffmann, Phys. Rev. Lett. 53, 234 (1984); and private communication.
 - (4) H. Gould and C. Munger, Private communication.
 - (5) see for example, P.J. Mohr, in *Beam Foil Spectroscopy*, edited by I.A. Sellin and D.J. Pegg, (Plenum, N.Y., 1976), Vol. 1, p89.
 - (6) P.J. Mohr, Phys. Rev. A26, 2338 (1982).
 - (7) P.J. Mohr, Atomic Dat. and Nuclear Dat. Tables 29, 453 (1983).
 - (8) Values for the $2^2S_{1/2}$ state are summarized and references to original work is given in P.J. Mohr, Ann. Phys. (N.Y.)88, 26 (1974); J. Saperstein, Phys. Rev. Lett. 47, 1723 (1981).
 - (9) G.W. Erickson, Phys. Rev. Lett. 47, 780 (1971).
 - (10) S.R. Lundeen and F.M. Pipkin, Phys. Rev. Lett. 46, 232 (1981).
 - (11) H. Gould and R. Marrus, Phys. Rev. A28, 2001 (1983); O.R. Wood II, C.K.N. Patel, D.E. Murnick, E.T. Nelson, M. Leventhal, H.W. Kugel, and Y. Niv, Phys. Rev. Lett. 48, 398 (1982); H.D. Sträter, L. von Gerdtell, A.P. Georgiadis, D. Müller, P. von Brentano, J.C. Sens, and A. Pape, Phys. Rev. A29, 1596 (1984). P. Pellegrin, Y. El Masri, L. Palfy, and R. Priells, Phys. Rev. Lett. 49, 1762 (1982);
 - (12) W. Gordon, Z. Phys. 48, 11 (1928); C.G. Darwin, Proc. Roy. Soc. London Ser. A118, 654 (1928).
 - (13) C.D. Lin, W.R. Johnson and A. Dalgarno, Phys. Rev. A15, 154 (1977); W.R. Johnson and F. Parpia, private communication.
 - (14) S.J. Brodsky and P.J. Mohr, in *Topics in Current Physics: Quantum Electrodynamics in Strong and Supercritical Fields*, edited by I.A. Sellin (Springer, Berlin, 1978) Vol. 5, p.3.
 - (15) S.P. Goldman and G.W.F. Drake "Two-electron Lamb Shifts and $1s2s\ ^3S_1$ - $1s2p\ ^3P_J$ Transition Frequencies in Helium-like Ions" To be published in J. Phys. B Lett. (Lawrence Berkeley Laboratory report LBL-16466); G.W.F. Drake, private communication; see also G.W.F. Drake, "Quantum Electrodynamical Effects in Few-Electron Atomic Systems" in *Advances in Atomic and Molecular Physics* edited by D. Bates and B. Bederson (Academic, N.Y., 1982) Vol. 18, p.399.
 - (16) M. Hillery and P.J. Mohr, Phys. Rev. A21, 24 (1980).
 - (17) S.P. Goldman and G.W.F. Drake, Phys. Rev. A24, 183 (1981).
 - (18) F.A. Parpia and W.R. Johnson, Phys. Rev. A26, 1142 (1982).
 - (19) G.W.F. Drake, Bull. Am. Phys. Soc. 29, 781 (1984).
 - (20) H. Gould, R. Marrus and P.J. Mohr, Phys. Rev. Lett., 33, 676 (1974); G.W.F. Drake, Astrophys J. 158, 1199 (1969).
 - (21) H. Gould and R. Marrus in *Beam Foil Spectroscopy*, edited by I.A. Sellin and D.J. Pegg, (Plenum, N.Y., 1976), Vol. 1, p305.
 - (22) J. Hata and I.P. Grant, J. Phys. B. 15, L549 (1982).

Figure Captions

Fig. 1. Ratio of the higher order terms in the self-energy to the total self energy. The series expansion value for the self-energy, calculated from terms through A_{70} , changes sign near $Z=60$, allowing the ratio to exceed 1 for very high- Z .

Fig. 2. Energy levels of $n=1$ and $n=2$ states of hydrogenlike uranium. Decays without labels are E1 decays. The lower-lying $2^2P_{1/2}$ state decays faster than the $2^2P_{3/2}$ state due to different relativistic contributions to the E1 matrix element. (See Ref. 16.)

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 states indicates the approximate radiative width. Singlet - triplet classification (and LS coupling) is used for the convenience of the author. At $Z=92$ the singlet - triplet mixing is close to 100%.

XCG 838-7228

Fig. 1

Hydrogenlike Uranium

XBL 848-8592

Fig. 2

Heliumlike Uranium

XBL 848-8593

Fig. 3

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720