Appendix: Abstracts of Contributed Papers

Edited by S. G. Karshenboim and F. S. Pavone

The following papers are reproduced in full on the enclosed CD-ROM.

Part VI. Hydrogen and Helium

Towards a Precise Measurement of the He^{+} 2S Lamb Shift

S. A. Burrows, S. Guérandel, E. A. Hinds, F. Lison and M. G. Boshier
SCOAP, University of Sussex, Falmer, Brighton, BN1 9QH, UK

We report progress towards making a precise measurement of the 2S Lamb shift in singly-ionised helium by spectroscopy of the 2S–3S transition. The motivation for the experiment is discussed with reference to recent developments in the theory of quantum electrodynamics (QED) and a description of the apparatus and techniques used is given.

High Precision Measurements on Helium at 1083 nm

P. Cancio Pastor[1,2], P. De Natale[1,2], G. Giusfredi[1,2], F. S. Pavone[1,3], and M. Inguscio[1,4]
[1] European Laboratory for Non-Linear Spectroscopy (LENS), I-50125 Firenze, Italy
[2] Istituto Nazionale di Ottica Applicata (INOA), I-50125 Firenze, Italy
[3] Dipartimento di Fisica, Università di Perugia, Perugia, Italy
[4] Dipartimento di Fisica, Università di Firenze, I-50125 Firenze, Italy

We present a review of the helium spectroscopy, related to transitions between 2^3S and 2^3P states around 1083 nm. A detailed description of our measurements, that have produced the most accurate value of the $2^3P_0 - 2^3P_1$ fine structure interval, is given. It could produce an accurate determination (34 ppb) of the fine structure constant α. Improvements in the experimental set up are presented. In particular, a new frequency reference of the laser system has been developed by frequency lock of a 1083 nm diode laser to iodine hyperfine transitions around its double of frequency. The laser frequency stability, at 1 s timescale, has been improved of, at least, two orders of magnitude, and even better for longer time scales. Simultaneous $^3He -^4 He$ spectroscopy, as well as absolute frequency measurements of 1083 nm helium transitions can be allowed by using the I_2-locked laser as frequency standard. We discuss the implication of these measurements for a new determination of the isotope and 2^3S Lamb shifts.

Absolute Frequency Measurement of the 1S-3S Transition in Hydrogen

G. Hagel[1], R. Battesti[1], C. Schwob[1], F. Nez[1], L. Julien[1], F. Biraben[1], O. Acef[2], J.-J. Zondy[2], and A. Clairon[2],
[1] Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Paris cedex 05 France
[2] Laboratoire Primaire du Temps et des Fréquences, 75014 Paris , France

This paper deals with high resolution spectroscopy of hydrogen and deuterium atoms. The 1S-3S and 2S-6S/D transitions have been used to determine the ground state Lamb shift with an accuracy of 46 kHz. The aim of the present experiment is to make an absolute frequency measurement of the 1S-3S transition. We present in this paper the improvement on the experiment and the developpment of a new method to compensate the second order Doppler effect by the application of a magnetic field.

2s Hyperfine Structure in Hydrogen Atom and Helium-3 Ion

S. G. Karshenboim
D. I. Mendeleev Institute for Metrology, 198005 St. Petersburg, Russia
Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

The usefulness of study of hyperfine splitting in the hydrogen atom is limited on a level of 10 ppm by our knowledge of the proton structure. One way to go beyond 10 ppm is to study a specific difference of the hyperfine structure intervals $8\Delta\nu_2 - \Delta\nu_1$. Nuclear effects for are not important this difference and it is of use to study higher-order QED corrections.

Three-Loop Slope of the Dirac Form Factor and the 1S Lamb Shift in Hydrogen

K Melnikov[1] and T. van Ritbergen[2]
[1] Stanford Linear Accelerator Center, Stanford University, CA 94309, USA
[2] Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128, Germany

The calculation of the last unknown contribution to hydrogen energy levels at order $m\alpha^7$, due to the three loop slope of the Dirac form factor, is described. The resulting shift of the nS energy level is found to be $3.16/n^3$ kHz. Adding this result to many known contributions to the $1S$ Lamb shift and comparing with experimental value, we derive the value of the proton charge radius $r_p = 0.883 \pm 0.014$ fm.

Radiative Decay of Coupled States in an External dc Field

V. Pal'chikov[1], Yu. Sokolov[2] and V. Yakovlev[3]
[1] VNIIFTRI, Mendeleevo, Moscow Region, 141570 Russia
[2] Kurchatov Institute, OGRA, Moscow 123182, Russia

[3] Moscow Engineering Physics Institute, 115409, Moscow, Russia

This paper examines two theoretical aspects of the interference of atomic states in hydrogen which comes from the application of an external electric field F to the $2s$ metastable state. The radiative corrections to the Bethe-Lamb formula and anisotropy contribution to the angular distribution, which arises from interference between electric-field-induced E1-radiation and forbidden M1-radiation, are analysed.

Atomic Interferometer and Coherent Mixing of 2S and 2P States in the Hydrogen Atom

Yu. Sokolov
Kurchatov Institute, OGRA, Moscow 123182, Russia

New direct observation data on the $2S$–$2P$ atomic states coherent mixing upon hydrogen atoms passage through a metal-wall slit are presented. The experimental results are interpreted in terms of atomic states interference.

Ground State Energy of the Helium Atom

A. Yelkhovsky
Budker Institute for Nuclear Physics, Novosibirsk, 630090, Russia

With an eye on the high accuracy ($\sim 10\,\mathrm{MHz}$) evaluation of the ionization energy from the helium atom ground state, a complete set of order $m\alpha^6$ operators is built. This set is gauge and regularization scheme independent and can be used for an immediate calculation with a wave function of the helium ground state.

Part VII. Muonium and Positronium

Two-Loop Corrections to the Decay Rate of Orthopositronium

G.S. Adkins[1], R.N. Fell[2], and J. Sapirstein[3]
[1] Franklin & Marshall College, Lancaster PA 17604, USA
[2] Brandeis University, Waltham MA 02254, USA
[3] University of Notre Dame, Notre Dame IN 46556, USA

Order α^2 corrections to the decay rate of orthopositronium are calculated in the framework of nonrelativistic QED. The correction is ≈ 45 in units of $(\alpha/\pi)^2$ times the lowest order rate.

Recent Results in Positronium Theory

A. Czarnecki[1], K. Melnikov[2], and A. Yelkhovsky[3]
[1] Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA

[2] Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA
[3] Budker Institute for Nuclear Physics, Novosibirsk, Russia 630090

We review our recent results on higher order corrections in positronium physics. We discuss a calculation of the recoil $\mathcal{O}(m\alpha^6)$ corrections to the hyperfine splitting [1][1] and energy levels of a positronium atom [2], $\mathcal{O}(m\alpha^7 \ln^2 \alpha)$ contributions to the positronium S-wave energy levels [3] and $\mathcal{O}(\alpha^2)$ radiative corrections to the parapositronium decay rate [4].

Test of CPT and Lorentz Invariance from Muonium Spectroscopy

V. W. Hughes[1], D. Kawall[1], W. Liu[1], M Grosse Perdekamp[2], K. Jungmann[3] and G. zu Putlitz[3]
[1] Yale University, Department of Physics, New Haven, CT 06520-8121, USA
[2] Riken BNL Research Center, Upton, NY 11973, USA
[3] Universität Heidelberg, Physikalisches Institut, D-69120 Heidelberg, Germany

Following a suggestion of Kostelecký *et al.* we have evaluated a test of CPT and Lorentz invariance from the microwave spectrosopy of muonium. Precise measurements have been reported for the transition frequencies ν_{12} and ν_{34} for ground state muonium in a magnetic field H of 1.7 T, both of which involve principally muon spin flip. These frequencies depend on both the hyperfine interaction and Zeeman effect. Hamiltonian terms beyond the standard model which violate CPT and Lorentz invariance would contribute shifts $\delta\nu_{12}$ and $\delta\nu_{34}$. The nonstandard theory indicates that ν_{12} and ν_{34} should oscillate with the earth's sidereal frequency and that $\delta\nu_{12}$ and $\delta\nu_{34}$ would be anticorrelated. We find no time dependence in $\nu_{12} - \nu_{34}$ at the level of 20 Hz, which is used to set an upper limit on the size of CPT and Lorentz violating parameters.

Positronium: Theory Versus Experiment

R. Ley and G. Werth
Institut für Physik, Johannes Gutenberg - Universität, D-55099 Mainz, Germany

We have collected all known theoretical contributions to the energy levels of positronium and present a complete listing for the states $n = 1,\ 2$ and 3. We give the explicit dependence of the energy levels on the quantum numbers $n,\ L,\ S$ and J up to the order $R_\infty\alpha^3$. In the next higher order $R_\infty\alpha^4$ only the contributions to S- and P-states are completely known. We have detected an additional shift of the energy levels 3^3S_1 and 3^3D_1 due to the tensor operator of the spin-spin interaction. The annihilation rates of para- and ortho-positronium are completely listed up to the orders $R_\infty\alpha^5$ and $R_\infty\alpha^6$, respectively. We compare calculated values of energy levels and annihilation rates with experimentally observed quantities.

[1] See paper on CD for references.

Highly Accurate Theoretical Simulation of the Resonant Multiphoton Ionization Processes With Simplest Atoms

Victor Yakhontov[1] and Klaus Jungmann[2]
[1] Institut für Physikalische Chemie, Klingelbergstr. 80, CH-4056 Basel, Switzerland
[2] Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany

We present an advanced theoretical approach enabling highly accurate studies of a wide class of resonant $2 + 1$ photoionization processes involving hydrogeic levels to be carried out. AC-Stark shifts, non-zero ionization rates of all states involved are naturally incorporated into the theoretical setup developed, together with spatial and temporal inhomogeneities of the laser signal, fine structure contributions, as well as second order Doppler shifts. In contrast with the usual perturbative technique, the time evolution of the atomic states is described by direct numerically solving a coupled system of time-dependent differential relativisitic equations. Particular numerical simulations have been carried out to model two-step 3-photon ionization process in muonium, $1S \xrightarrow{2\hbar\omega} 2S \xrightarrow{\hbar\omega} \varepsilon P$, induced by a CW laser signal of high intensity.

Part VIII. Muonic Atoms

Time-of-Flight Spectroscopy of Muonic Hydrogen Atoms and Molecules

M. C. Fujiwara[1,2], A. Adamczak[3], J. M. Bailey[4], G. A. Beer[5], J. L. Beveridge[6], M. P. Faifman[7], T. M. Huber[8], P. Kammel[9], S. K. Kim[10], P. E. Knowles[11], A. R. Kunselman[12], V. E. Markushin[13], G. M. Marshall[6], G. R. Mason[5], F. Mulhauser[11], A. Olin[6], C. Petitjean[13], T. A. Porcelli[14], J. Zmeskal[15]
(TRIUMF Muonic Hydrogen Collaboration)
[1] University of British Columbia, Vancouver, BC, Canada V6T 2A6
[2] Department of Physics, University of Tokyo, Tokyo 113-0033 Japan
[3] Institute of Nuclear Physics, 31-342 Krakow, Poland
[4] Chester Technology, Chester CH4 7QH, England, UK
[5] University of Victoria, Victoria, BC, Canada V8W 2Y2
[6] TRIUMF, Vancouver, BC, Canada, V6T 2A3
[7] Russian Research Center, Kurchatov Institute, Moscow 123182, Russia
[8] Gustavus Adolphus College, St. Peter, MN 56082, USA
[9] Lawrence Berkeley National Laboratory and University of California, Berkeley, USA
[10] Jeonbuk National University, Jeonju City 560-756, S. Korea
[11] University of Fribourg, CH-1700 Fribourg, Switzerland
[12] University of Wyoming, Laramie, WY 82071-3905, USA
[13] Paul Scherrer Institute, CH-5232 Villigen, Switzerland
[14] University of Northern British Columbia, Canada V2N 4Z9
[15] Institute for Medium Energy Physics, A-1090 Vienna, Austria

Studies of muonic hydrogen atoms and molecules have been performed traditionally in bulk targets of gas, liquid or solid. At TRIUMF, Canada's meson facility, we have developed a new type of target system using multilayer thin films of solid hydrogen, which provides a beam of muonic hydrogen atoms in vacuum. Using the time-of-flight of the muonic atoms, the energy-dependent information of muonic reactions are obtained in direct manner. We discuss some unique measurements enabled by the new technique, with emphasis on processes relevant to muon catalyzed fusion.

Hyperfine Structure in Muonic Hydrogen

K. Jungmann[1], V. G. Ivanov[2], and S. G. Karshenboim[3,4]
[1] Universität Heidelberg, D-69120 Heidelberg, Germany
[2] Pulkovo Observatory, 196140 St. Petersburg, Russia
[3] D. I. Mendeleev Institute for Metrology, 198005 St. Petersburg, Russia
[4] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

We consider the hyperfine structure of the $1s$ and $2s$ states in muonic hydrogen and muonic deuterium. We put emphasis on two particular topics: a possibility to measure the *hfs* interval in the ground state and a calculation of a specific difference $E_{\rm hfs}(1s) - 8 \cdot E_{\rm hfs}(2s)$. Such a measurement and the calculations are of interest in connection with an upcoming experiment at PSI in which different $2s - 2p$ transitions in muonic hydrogen shall be determined. Together all these investigations will improve the knowledge of the internal structure of proton and deuteron.

Towards a Measurement of the Lamb Shift in Muonic Hydrogen

R. Pohl[1],2, F. Biraben[3], C.A.N. Conde[4], C. Donche-Gay[5], T.W. Hänsch[6], F.J. Hartmann[7], P. Hauser[1], V.W. Hughes[8], O. Huot[5], P. Indelicato[3], P. Knowles[5], F. Kottmann[2], Y.-W. Liu[8,1], V.E. Markushin[1], F. Mulhauser[5], F. Nez[3], C. Petitjean[1], P. Rabinowitz[9], J.M.F. dos Santos[4], L.A. Schaller[5], H. Schneuwly[5], W. Schott[7], D. Taqqu[1], and J.F.C.A. Veloso[4]
[1] Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland
[2] Institut für Teilchenphysik, ETHZ, CH-8093 Zürich, Switzerland
[3] Laboratoire Kastler Brossel, F-75252 Paris CEDEX 05, France
[4] Departamento de Fisica, Universidade de Coimbra, P-3000 Coimbra, Portugal
[5] Institut de Physique de l'Université, CH-1700 Fribourg, Switzerland
[6] Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
[7] Physik-Department, Technische Universität München, D-85747 Garching, Germany
[8] Physics Department, Yale University, New Haven, CT06520-8121, USA
[9] Department of Chemistry, Princeton University, Princeton, NJ08544-1009, USA

The availability of long-lived metastable muonic hydrogen atoms (μp) in the 2S state has been investigated in a recent series of experiments at PSI. From the low-energy part of the initial kinetic energy distribution of μp(1S) we determined the fraction of long-lived μp(2S) to be $\sim 1.5\%$ for pressures between 1 and 64 hPa. Another analysis involving μp(1S) with a kinetic energy of $\sim 1\,$keV originating from quenching of thermalized μp(2S) via the resonant process $\mu p(2S) + {\rm H}_2 \to \{[(pp\mu)^+]^* pee\}^* \to \mu p(1S) + p + \ldots + 2\,$keV gives the same result. This is the first direct observation of long-lived μp(2S) atoms.

We are preparing a measurement of the $2S$ Lamb shift in muonic hydrogen, which will improve the uncertainty on the RMS proton charge radius by more than one order of magnitude. Technical aspects of our experiment are presented, including a new low-energy negative muon beam, an efficient low-energy muon entrance detector, a randomly triggered 3-stage laser system providing 0.5 mJ, 7 ns laser pulses at 6.02 μm wavelength, and a large solid angle xenon gas-proportional-scintillation-chamber (GPSC) read out by a microstrip-gas-chamber (MSGC) with a CsI-coated surface for the detection of 2 keV X-rays.

Part IX. Exotic Atoms

Antihydrogen Production and Precision Spectroscopy with ATHENA/AD-1

C. Amsler[10], G. Bendiscioli[6], G. Bonomi[2], P. Bowe[1], C. Carraro[4], C. L. Cesar[7], M. Charlton[8], M.J.T. Collier[8], M. Doser[3], K. Fine[3], A. Fontana[6], M.C. Fujiwara[9], R. Funakoshi[9], J. Hangst[1], R.S. Hayano[9], H. Higaki[9], M. H. Holzscheiter[3], W. Joffrain[4], L.V. Jøergensen[8], D. Kleppner[5], V. Lagomarsino[4], R. Landua[3], D. Lindelof[10], E. Lodi-Rizzini[2], M. Macri[4], D. Manuzio[4], G. Manuzio[4], M. Marchesotti[6], P. Montagna[6], H. Pruys[10], C. Regenfus[10], P. Riedler[10], A. Rotondi[6], G. Rouleau[3], G. Testera[4], T.L. Watson[8], D.P. van der Werf[8], T. Yamazaki[9], and Y. Yamazaki[9]

[1] Inst. for Physics & Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark
[2] Brescia University & INFN, Brescia, Italy
[3] CERN, CH-1211 Geneva 23, Switzerland
[4] Genoa University & INFN, Via Dodecaneso 33, I-16146 Genoa, Italy
[5] AMO Institute, MIT, Cambridge, MA, United States
[6] Pavia University & INFN, Pavia, Italy
[7] Fed. Univ. Rio de Janeiro (UFRJ), BR-21945 Rio de Janeiro, Brasil
[8] University of Wales Swansea, Wales, United Kingdom
[9] Inst. of Physics and Department of Physics, Tokyo University, Tokyo, Japan
[10] Physik Institut, Zürich University, CH-8057 Zürich, Switzerland

CPT invariance is a fundamental property of quantum field theories in flat space-time. Principal consequences include the predictions that particles and their antiparticles have equal masses and lifetimes, and equal and opposite electric charges and magnetic moments. It also follows that the fine structure, hyperfine structure, and Lamb shifts of matter and antimatter bound systems should be identical.

It is proposed to generate new stringent tests of CPT using precision spectroscopy on antihydrogen atoms. An experiment to produce antihydrogen at rest has been approved for running at the Antiproton Decelerator (AD) at CERN. We describe the fundamental features of this experiment and the experimental approach to the first phase of the program, the formation and identification of low energy antihydrogen.

Precision Spectroscopy of X-Rays from Antiprotonic Hydrogen

D. F. Anagnostopoulos[1], 2, M. Augsburger[3], G. Borchert[1], C. Castelli[4], D. Chatellard[3], P. El-Khoury[5], J.-P. Egger[3], H. Gorke[1], D. Gotta[1], P. Hauser[6], P. Indelicato[5], K. Kirch[6], S. Lenz[1], N. Nelms[4], K. Rashid[7], Th. Siems[1], and L. M. Simons[6]

[1] Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany
[2] Department of Material Science, University of Ioannina, GR-45110 Ioannina, Greece
[3] Institut de Physique de l'Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland
[4] University of Leicester, Leicester LEI 7RH, England
[5] Laboratoire Kastler-Brossel, Université Pierre et Marie Curie, F-75252 Paris, France
[6] Paul-Scherrer-Institut (PSI), CH-5232 Villigen, Switzerland
[7] Quaid-I-Azam University, Islamabad, Pakistan

Lyman and Balmer transitions of antiprotonic hydrogen and deuterium have been measured at the Low-Energy Antiproton Ring LEAR at CERN in order to determine the strong-interaction effects. In LEAR experiment PS207, the X-rays were detected using Charge-Coupled Devices (CCDs) and a reflection-type crystal spectrometer. A complete set of strong-interaction parameters for the $1s$ and the $2p$ levels is now available for both $\bar{p}H$ and $\bar{p}D$ after evidence was found for the $\bar{p}D$ Kα transition.

Charged Pion Mass Determination and Energy – Calibration Standards Based on Pionic X-Ray Transitions

D. F. Anagnostopoulos[1], 2, M. Augsburger[3], G. Borchert[1], D. Chatellard[3], P. El-Khoury[4], J.-P. Egger[3], H. Gorke[1], D. Gotta[1], P. Hauser[5], M. Hennebach[1], P. Indelicato[4], K. Kirch[5], S. Lenz[1], Y.-W. Liu[5], B. Manil[4], N. Nelms[6], Th. Siems[1], L. M. Simons[5]
[1] Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany
[2] University of Ioannina, GR-45110 Ioannina, Greece
[3] Institut de Physique de l'Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland
[4] Laboratoire Kastler-Brossel, Université Pierre et Marie Curie, F-75252 Paris, France
[5] Paul-Scherrer-Institut (PSI), CH-5232 Villigen, Switzerland
[6] University of Leicester, Leicester LEI 7RH, England

Recent experiments are aiming at an accuracy of 1ppm for the mass of the charged pion using the characteristic X-rays from exotic atoms. Once the pion mass is established with that precision, the narrow lines from medium Z pionic atoms can be used as a calibration standard in the few keV range. The precision of this new standard is not limited by the large natural line width of fluorescence X-rays and their complex structure due to multi-hole excitations.

Pionic Hydrogen: Status and Outlook

D. F. Anagnostopoulos[1], S. Biri[2], G. Borchert[3], W. H. Breunlich[4], M. Cargnelli[4], J.-P. Egger[5], B. Gartner[4], D. Gotta[3], P. Hauser[6], M. Hennebach[4], P. Indelicato[7], T. Jensen[6], R. King[4], F. Kottmann[8], B. Lauss[4], Y. W. Liu[6], V. E. Markushin[6], J. Marton[4], N. Nelms[9], G. C. Oades[10], G. Rasche[11], P. A. Schmelzbach[6], L. M. Simons[6], and J. Zmeskal[4]
[1] Department of Material Science, University of Ioannina, GR-45110 Ioannina, Greece
[2] Institute of Nuclear Research (ATOMKI) H-4001,Debrecen, Hungary
[3] Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany

Search Hits Help

[4] Institut für Mittelenergiephysik, A-1090 Wien, Austria
[5] Institut de Physique de l'Université de Neuchâtel, CH-2000 Neuchâtel, Switzerland
[6] Paul-Scherrer-Institut (PSI), CH-5232 Villigen, Switzerland
[7] Laboratoire Kastler-Brossel, Université Pierre et Marie Curie, F-75252 Paris, France
[8] Institut für Teilchenphysik, ETH Zürich, CH-8057 Zürich , Switzerland
[9] University of Leicester, Leicester LEI7RH, England
[10] Institute of Physics, Aarhus University, DK-8000 Aarhus, Denmark
[11] Institut für Theoretische Physik, Universität Zürich, Switzerland

The measurement of the strong interaction shift and width of the ground state in the pionic hydrogen atom determines two different linear combinations of the two isospin separated s-wave scattering lengths of the pion nucleon system. If both quantities are measured with a precision of about 1% a stringent test of chiral perturbation theory and a determination of the pion nucleon coupling constant can be obtained. Past measurements determined the shift with an accuracy better than 1%, and the width with an accuracy of 9%. Additional information from pionic deuterium measurements has been used in order to extract isospin separated scattering lengths with sufficient accuracy. Future measurements plan to directly measure the width of pionic hydrogen with an accuracy on the level on 1%.

Antiprotonic Helium "Atomcule": Relativistic and QED Effects

V.I. Korobov
Joint Institute for Nuclear Research, 141980, Dubna, Russia

We present theoretical calculations for the $(36, 35) \to (34, 33)$ transition between metastable states in the antiprotonic helium $^4\mathrm{He}^+\bar{p}$, which is supposed to be measured in the two-photon high-precision spectroscopy experiment at CERN.

Towards Laser Spectroscopy of Antihydrogen

J. Walz, A. Pahl, K. S.E. Eikema and T. W. Hänsch
Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Cold antihydrogen atoms in a magnetic trap will open exciting prospects for challenging CPT tests with ultrahigh-resolution laser spectroscopy. Equally exciting is the prospect for experiments on the gravitational acceleration of antimatter. For both types of experiment it is of great importance to have antihydrogen as cold as possible. Laser cooling of antihydrogen can be done on the strong 1S–2P transition at Lyman-α (121.56 nm). We describe the first source for continuous coherent radiation at Lyman-α and possible applications in experiments with antihydrogen.

Hyperfine Structure Measurements of Antiprotonic Helium and Antihydrogen

E. Widmann[1], J. Eades[2], R. S. Hayano[1], M. Hori[2], D. Horvath[3], T. Ishikawa[1], B. Juhazs[4], J. Sakaguchi[1], H. A. Torii[5], H. Yamaguchi[1], and T. Yamazaki[6]

[1] Department of Physics, University of Tokyo, Japan
[2] CERN, Geneva, Switzerland
[3] KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
[4] University of Debrecen, Hungary
[5] Institute of Physics, University of Tokyo, Japan
[6] RI Beam Science Laboratory, RIKEN, Saitama, Japan

This paper describes measurements of the hyperfine structure of two antiprotonic atoms that are planned at the Antiproton Decelerator (AD) at CERN. The first part deals with antiprotonic helium, a three-body system of α-particle, antiproton and electron that was previously studied at LEAR. A measurement will test existing three-body calculations and may – through comparison with these theories – determine the magnetic moment $\mu_{\overline{\mathrm{p}}}$ of the antiproton more precisely than currently available, thus providing a test of CPT invariance. The second system, antihydrogen, consisting of an antiproton and a positron, is planned to be produced at thermal energies at the AD. A measurement of the ground-state hyperfine splitting $\nu_{\mathrm{HF}}(\overline{\mathrm{H}})$, which for hydrogen is one of the most accurately measured physical quantities, will directly yield a precise value for $\mu_{\overline{\mathrm{p}}}$, and also compare the internal structure of proton and antiproton through the contribution of the magnetic size of the $\overline{\mathrm{p}}$ to $\nu_{\mathrm{HF}}(\overline{\mathrm{H}})$.

Part X. Precision Spectroscopy, Fundamental Constants and Fundamental Symmetry

Indium Single-Ion Optical Frequency Standard

T. Becker[1,2], M. Eichenseer[1,2], A. Yu. Nevsky[1,3], E. Peik[1,2], Ch. Schwedes[1,2], M. N. Skvortsov[1,3], J. von Zanthier[1,2], and H. Walther[1,2]
[1] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany
[2] Sektion Physik der Ludwig-Maximilians-Universität, München, Germany
[3] Institute of Laser Physics, 630090 Novosibirsk, Russia

We are investigating the $5s^2\,{}^1S_0 \rightarrow 5s5p\,{}^3P_0$ transition of a single trapped laser-cooled $^{115}\mathrm{In}^+$ ion as a candidate for an optical frequency standard. This line with a natural linewidth of only 0.8 Hz is highly immune to systematic frequency shifts. For sideband laser cooling and fluorescence detection of the indium ion the $5s^2\,{}^1S_0 \rightarrow 5s5p\,{}^3P_1$ transition at 230.6 nm is excited. Temperatures below 100 μK and a mean vibrational quantum number $\langle n \rangle < 1$ of the ion in the trap have been reached. For the clock transition a resolution of $1.3 \cdot 10^{-13}$ (linewidth 170 Hz) has been obtained so far, limited by the short term frequency fluctuations of the clock laser. The absolute frequency of the ${}^1S_0 \rightarrow {}^3P_0$ transition was measured by making a link to the reference frequency of the methane-stabilised HeNe laser using a frequency chain.

Matter Neutrality Test Using a Mach-Zehnder Interferometer

C. Champenois, M. Büchner, R. Delhuille, R. Mathevet, C. Robilliard, C. Rizzo, and J. Vigué

Université Paul Sabatier and CNRS UMR 5589, 31062 Toulouse, France

Neutrality of atoms and neutrons is already well established, with upper limits on the residual charge close to $10^{-21}|q_e|$ where q_e is the electron charge. The present paper proves that the sensitivity of atom interferometry is sufficient to compete with these previous measurements, with the additional advantage of dealing with single isolated particles. An experiment involving a three grating Mach-Zehnder atom interferometer using Bragg diffraction on laser standing waves and a slow lithium atomic beam is discussed with some details. Its sensitivity and the systematic effects due to atomic polarisability are evaluated carefully.

Relativistic Corrections in Atoms and Space-Time Variation of the Fine Structure Constant

V. A. Dzuba, V. V. Flambaum, M. T. Murphy, and J. K. Webb
School of Physics, University of New South Wales, UNSW Sydney NSW 2052, Australia

Comparison of quasar absorption line spectra with laboratory spectra provides the best probe for variability of the fine structure constant, $\alpha = e^2/\hbar c$, over cosmological time-scales. We have demonstrated [1][2] that high sensitivity to the variation of α can be obtained from a comparison of the spectra of heavy and light atoms and have obtained an order of magnitude gain in precision over previous methods [2]. Our new data [3] hint that α was smaller at earlier epochs. Careful searches have so far not revealed any spurious effect that can explain the observations.

Frequency Comparison and Absolute Frequency Measurement of I_2-stabilized Lasers at 532 nm

A. Yu. Nevsky[1,3], R. Holzwarth[1], J. Reichert[1], Th. Udem[1], T. W. Hänsch[1], J. von Zanthier[1], H. Walther[1], H. Schnatz[2], F. Riehle[2], P. V. Pokasov[3], M. N. Skvortsov[3], and S. N. Bagayev[3]
[1] Sektion Physik der Ludwig-Maximilians-Universität München and Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
[2] Physikalisch-Technische Bundesanstalt, D-38116 Braunschweig, Germany
[3] Institute of Laser Physics, 630090 Novosibirsk, Russia

We present a frequency comparison and an absolute frequency measurement of two independent I_2-stabilized frequency-doubled Nd:YAG lasers at 532 nm, one set up at the Institute of Laser Physics, Novosibirsk, Russia, the other at the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany. The absolute frequency of the I_2-stabilized lasers was determined using a CH_4-stabilized He-Ne laser as a reference. This laser had been calibrated prior to the measurement by an atomic cesium fountain clock. The frequency chain linking phase-coherently the two frequencies made use of the frequency comb of a Kerr-lens mode-locked Ti:sapphire femtosecond laser where

[2] See paper on CD for references.

the comb mode separation was controlled by a local cesium atomic clock. A new value for the R(56)32-0:a_{10} component, recommended by the Comité International des Poids et Mesures (CIPM) for the realization of the metre [1][3], was obtained with reduced uncertainty. Absolute frequencies of the R(56)32-0 and P(54)32-0 iodine absorption lines together with the hyperfine line separations were measured.

Part XI. Few-Electron Ions

A QED Calculation of Electron Interaction for He-like and Li-like Highly Charged Ions

O. Andreev and L. Labzowsky
Institute of Physics, St. Petersburg State University, 198904 St. Petersburg, Russia

A rigorous quantum electrodynamic (QED) calculation of the corrections to electron interaction for configurations $1s_{1/2}2s_{1/2}\,{}^1S_0$, $1s_{1/2}2p_{1/2}\,{}^3P_0$, $1s_{1/2}2s_{1/2}\,{}^3S_1$ of He-like ions and for configurations $(1s_{1/2})^2 2s_{1/2}$ and $(1s_{1/2})^2 2p_{1/2}$ of Li-like ions for the all nuclear charges $10 \leq Z \leq 92$ is performed. The calculation is carried out in the Coulomb gauge. Coulomb-Coulomb and Coulomb-Breit parts are calculated exactly, Breit-Breit part of the correction is calculated within disregard of retardation.

The g_J Factor of an Electron Bound in Hydrogenlike Carbon: Status of the Theoretical Predictions

T. Beier[1,2], I. Lindgren[2], H. Persson[2], S. O. Salomonson[2], and P. Sunnergren[2]
[1] GSI, Atomphysik, Planckstr. 1, DE-64291 Darmstadt, Germany
[2] Chalmers University of Technology and Göteborg University, S-412 96 Göteborg, Sweden

We present the known theoretical contributions to the g_J factor of an electron bound in hydrogenlike carbon. In particular we outline the calculation scheme for the quantum electrodynamical (QED) corrections of order (α/π) and present their current theoretical uncertainties. The known terms of the $(Z\alpha)$ expansion are found to be insufficient to describe the current experimental data.

Second-Order Self-Energy Calculations for Tightly Bound Electrons in Hydrogen-Like Ions

I. A. Goidenko[1], L. N. Labzowsky[1], A. V. Nefiodov[2], G. Plunien[3], S. Zschocke[3], and G. Soff[3]
[1] St. Petersburg State University, 198904 St. Petersburg, Russia
[2] Petersburg Nuclear Physics Institute, 188350 Gatchina, St. Petersburg, Russia
[3] Technische Universität Dresden, D-01062 Dresden, Germany

[3] See paper on CD for reference.

The second-order electron self-energy is evaluated to all orders in the interaction with the Coulomb field of the nucleus for the ground state of hydrogen-like uranium ions. This completes the nonperturbative calculation of radiative corrections of order α^2. The major theoretical uncertainty is eliminated which provides predictions of the ground-state energy with a relative accuracy of about 10^{-6} for the uranium system. This allows for high-precision tests of QED in the strong field of the nucleus that are expected to be available experimentally in the near future.

Lamb Shift in Light Hydrogen-Like Atoms

V. G. Ivanov[1] and S. G. Karshenboim[2,3]
[1] Pulkovo Observatory, St. Petersburg, Russia
[2] D. I. Mendeleev Institute for Metrology, St. Petersburg, Russia
[3] Max-Planck-Institut für Quantenoptik, Garching, Germany

Calculation of higher-order two-loop corrections is now a limiting factor in development of the bound state QED theory of the Lamb shift in the hydrogen atom and in precision determination of the Rydberg constant. Progress in the study of light hydrogen-like ions of helium and nitrogen can be helpful to investigate these uncalculated terms experimentally. To do that it is necessary to develop a theory of such ions. We present here a theoretical calculation for low energy levels of helium and nitrogen ions.

The *g* Factor of a Bound Electron in a Hydrogen-Like Atom

S. G. Karshenboim[1,2]
[1] D. I. Mendeleev Institute for Metrology, St. Petersburg, Russia
[2] Max-Planck-Institut für Quantenoptik, Garching, Germany

Recently, a precise measurement on the bound electron g factor in hydrogen-like carbon was performed [1][4] We consider the present status of the theory of the g factor of an electron bound in a hydrogen-like atom and discuss new opportunities and possible applications of the recent experiment.

Laser Spectroscopy of the 2S Lamb Shift in Hydrogenic Silicon

H. A. Klein[1], H. S. Margolis[1], J. L. Flowers[1], K. Gaarde-Widdowson[2], K. Hosaka[2], J. D. Silver[2], M. R. Tarbutt[2], S. Ohtani[3], and D. J. E. Knight[4]
[1] National Physical Laboratory, Teddington, Middlesex TW11 0LW, UK
[2] Department of Physics, University of Oxford, Oxford, OX1 3PU, UK
[3] JST, University of Electrocommunications, Chofu, Tokyo 182-0024, Japan
[4] DK Research, 110 Strawberry Vale, Twickenham, Middlesex, TW1 4SH, UK

Transitions in highly charged ions are particularly sensitive to QED effects, which scale

[4] See paper on CD for reference.

rapidly with atomic number, Z. An experiment to determine the 2S Lamb shift in hydrogenic silicon, using ions trapped in the Oxford electron beam ion trap (EBIT) is in progress. The laser system required for the experiment is currently under development at the National Physical Laboratory (NPL); this involves locking a frequency-stabilised Ti:sapphire laser operating at 734 nm to a high finesse build-up cavity. This will be used to drive and measure the $^2S_{1/2}$–$^2P_{3/2}$ transition in Si^{13+}. The transition is much more sensitive to two-loop binding corrections in Si^{13+} than in lower-Z systems. Thus this measurement offers the opportunity to test the uncertainty of theoretical contributions which presently limit the ability of transitions in hydrogen and He^+ to serve as calculable frequency standards. A better understanding of QED effects could also pave the way for calculable X-ray standards based on $\Delta n > 0$ transitions in high-Z hydrogenic systems.

Ground-State Hyperfine Structure of Heavy Hydrogen-Like Ions

T. Kühl[1], S. Borneis[1], A. Dax[1], T. Engel[2], S. Faber[1], M. Gerlach[1], C. Holbrow[3], G. Huber[4], D. Marx[1], P. Merz[4], W. Quint[1], F. Schmitt[1], P. Seelig[1], M. Tomaselli[5], H. Winter[2], M. Wuertz[2], K. Beckert[1], B. Franzke[1], F. Nolden[1], H. Reich[1], and M. Steck[1]

[1] GSI Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany
[2] Institute of Physics, Darmstadt University, D-64289 Darmstadt, Germany
[3] Institute of Physics, Colgate University, Hamilton, New York 13346, USA
[4] Institute of Physics, Mainz University, D-55099 Mainz, Germany
[5] Institute of Nuclear Physics, Darmstadt University, D-64289 Darmstadt, Germany

Contributions of quantum electrodynamics (QED) to the combined electric and magnetic interaction between the electron and the nucleus can be studied by optical spectroscopy in high-Z hydrogen-like heavy ions. The transition studied is the ground-state hyperfine structure transition, well known from the 21 cm line in atomic hydrogen. The hyperfine splitting of the is ground state of hydrogen-like systems constitutes the simplest and most basic magnetic interaction in atomic physics. The Z^3-increase leads to a transition energy in the UV-region of the optical spectrum for the case of Bi^{82+}. At the same time, the QED correction rises to nearly 1 fraction of higher order contributions. This situation is particularly useful for a comparison with non-perturbative QED calculations. The combination of exceptionally intense electric and magnetic fields electric and magnetic fields is unique. This transition has become accessible to precision laser spectroscopy at the high-energy heavy-ion storage ring at GSI-Darmstadt in the hydrogen-like $^{209}Bi^{82+}$ and $^{207}Pb^{81+}$. In the meantime, $^{165}Ho^{66+}$ and $^{185,187}Re^{74+}$ were also studied with reduced resolution by conventional optical spectroscopy at the SuperEBIT ion trap at Lawrence Livermore National Laboratory.

Measurement of the 1s2p $^3P_0$ - $^3P_1$ Fine Structure Interval in Helium-Like Magnesium

E.G. Myers[1] and M.R. Tarbutt[2]

[1] Florida State University, Tallahassee, Florida 32306-4350, USA

[2] Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, UK

Using Doppler-tuned fast-beam laser spectroscopy the 1s2p $^3P_0$ - $^3P_1$ fine structure interval in $^{24}Mg^{10+}$ has been measured to be 833.133(15) cm^{-1}. The calibration procedure used the intercombination 1s2s $^1S_0$ - 1s2p $^3P_1$ transition in $^{14}N^{5+}$. The result tests quantum-electrodynamic and relativistic corrections to high precision calculations, which will be used to obtain a new value for the fine structure constant from the fine structure of helium.

Towards a Precision Measurement of the Lamb Shift in Hydrogen-Like Nitrogen

E.G. Myers[1] and M.R. Tarbutt[2]
[1] Florida State University, Tallahassee, Florida 32306-4350, USA
[2] Clarendon Laboratory, University of Oxford, Oxford OX1 3PU, UK

Measurements of the $2S_{1/2} - 2P_{1/2}$ and $2S_{1/2} - 2P_{3/2}$ transitions in moderate Z hydrogen-like ions can test Quantum-Electrodynamic calculations relevant to the interpretation of high-precision spectroscopy of atomic hydrogen. There is now particular interest in testing calculations of the two-loop self-energy. Experimental conditions are favorable for a measurement of the $2S_{1/2} - 2P_{3/2}$ transition in N^{6+} using a carbon dioxide laser. As a preliminary experiment, we have observed the $2S_{1/2} - 2P_{3/2}$ transition in $^{14}N^{6+}$ using a 2.5 MeV/amu foil-stripped ion beam and a continuous-wave CO_2 laser operating on the hot band of $^{12}C^{16}O_2$. The measured value of the transition centroid, 834.94(7) cm^{-1}, agrees with, but is less precise than theory. However, the counting rate and signal-to-background ratio obtained indicate, that with careful control of systematics, a precision test of the theory is practical. Work towards constructing such a set-up is in progress.

Absolute Test of Quantum Electrodynamics for Helium-Like Vanadium

D. Paterson[1], C. T. Chantler[1], Larry T. Hudson[2], F. G. Serpa[2], J. D. Gillaspy[2], and E. Takács[2]
[1] School of Physics, University of Melbourne, 3010, Australia
[2] National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

Absolute measurements of the energies of helium-like vanadium resonances on an electron beam ion trap (EBIT) are reported. The results agree with recent theoretical calculations and the experimental precision (27–40 ppm) lies at the same level as the current uncertainty in theory (0.1 eV). The measurements represent a 5.7%–8% determination of the quantum electrodynamics (QED) contribution to the transition energies and are the most precise measurements of the helium-like resonances in the $Z = 19$–31 range. These are the first precision X-ray measurements on the National Institute of Standards and Technology EBIT and strongly commend the EBIT as a new spectroscopic source for QED investigations.

Relativistic Recoil Corrections to the Atomic Energy Levels

V. M. Shabaev
Department of Physics, St. Petersburg State University, St. Petersburg 198904, Russia

The quantum electrodynamic theory of the nuclear recoil effect in atoms to all orders in αZ and to first order in m/M is considered. The complete αZ-dependence formulas for the relativistic recoil corrections to the atomic energy levels are derived in a simple way. The results of numerical calculations of the recoil effect to all orders in αZ are presented for hydrogenlike and lithiumlike atoms. These results are compared with analytical results obtained to lowest orders in αZ. It is shown that even for hydrogen the numerical calculations to all orders in αZ provide most precise theoretical predictions for the relativistic recoil correction of first order in m/M.

X-Ray Spectroscopy of Hydrogen-Like Ions in an Electron Beam Ion Trap

M.R.Tarbutt[1], D.Crosby[1], E.G.Myers[2], N.Nakamura[3], S.Ohtani[3], and J.D.Silver[1]
[1] University of Oxford, Clarendon Laboratory, Oxford, OX1 3PU, UK
[2] Department of Physics, Florida State University, Tallahassee, FL 32306, USA
[3] Cold Trapped Ions Project, ICORP, JST, Tokyo 182-0024, Japan

The X-ray emission from highly charged hydrogen-like ions in an electron beam ion trap is free from the problems of satellite contamination and Doppler shifts inherent in fast-beam sources. This is a favourable situation for the measurement of ground-state Lamb shifts in these ions. We present recent progress toward this goal, and discuss a method whereby wavelength comparison between transitions in hydrogen-like ions of different nuclear charge Z, enable the measurement of QED effects without requiring an absolute calibration.

Part XII. Advanced Quantum Mechanics and QED

CPT-Invariant Eight-Component Two-Fermion Equation

V. Hund
Universität Fridericiana, D-76128 Karlsruhe, Germany

A Dirac equation with hyperfine operator and a recoil structure that remains valid even for positronium is presented and applied to the muonium hyperfine structure to the ordern α^8.

The Two-Time Green's Function and Screened Self–Energy for Two-Electron Quasi-Degenerate States

É.-O. Le Bigot[1], P. Indelicato[1], and V. M. Shabaev[2]
[1] Laboratoire Kastler-Brossel, ÉNS et Université P. et M. Curie, 75252 Paris, France

[2] Department of Physics, St. Petersburg State University, St. Petersburg, Russia

Precise predictions of atomic energy levels require the use of QED, especially in highly-charged ions, where the inner electrons have relativistic velocities. We present an overview of the two-time Green's function method; this method allows one to calculate level shifts in two-electron highly-charged ions by including in principle all QED effects, for any set of states (degenerate, quasi-degenerate or isolated). We present an evaluation of the contribution of the screened self-energy to a finite-sized effective hamiltonian that yields the energy levels through diagonalization.

Higher-Order Stark Effect on Magnetic Fine Structure of Helium Atom

A. Magunov[1], V. Ovsiannikov[2], V. Pal'chikov[1], V. Pivovarov[1], and G. von Oppen[3]
[1] VNIIFTRI, Mendeleevo, Moscow Region, 141570 Russia
[2] Department of Physics, Voronezh State University, Voronezh 394693, Russia
[3] Technische Iniversität Berlin, D-10623 Berlin, Germany

We have calculated the scalar and tensor dipole polarizabilities (β) and hyperpolarizabilities (γ) of excited $1s2p\ ^3P_0$, $1s2p\ ^3P_2$- states of helium. Our theory includes fine structure of triplet sublevels. Semiempirical and accurate electron-correlated wave functions have been used to determine the static values of β and γ. Numerical calculations are carried out using sums of oscillator strengths and, alternatively, with the Green function for the excited valence electron. Specifically, we present results for the integral over the continuum, for second- and fourth-order matrix elements. The corresponding estimations indicate that these corrections are of the order of 23% for the scalar part of polarizability and only of the order of 3% for the tensor part.

Precise Evaluation of the Electron $(g-2)$ at 4 Loops: The Algebraic Way

P. Mastrolia[1] and E. Remiddi[1,2]
[1] Dipartimento di Fisica, Università di Bologna
[2] INFN, Sezione di Bologna, Italy

It is expected that the next generation of $(g-2)$ experiments will pin down the error below the 1ppb (parts per billion) level; to cope with such a precision, the current error on the theoretical value of the 4 loop QED contribution must be reduced by at least a factor ten. To avoid the rounding problems which affect the numerical calculation, we developped and implemented as computer code various exact algebraic algorithms for reducing the very many integrals appearing in the calculation to a much smaller number of master integrals.

Radiation Properties of Diamagnetic Manifolds in Atomic Hydrogen: Line Intensity Dependence on a Magnetic Field

V.D. Ovsiannikov and V.V. Chernushkin
Faculty of Physics, Voronezh State University, 394693 Voronezh, Russia

We study the effect of a magnetic field on the probability of radiative transitions of a hydrogen atom from diamagnetic manifold states. The analytical formulae have been derived for the susceptibilities determining the influence of diamagnetic interaction on the probabilities of radiative transitions. To derive the analytic expressions for the higher-order matrix elements, we use the Sturm expansion of the reduced Coulomb Green function. We also examine the frequency dependence of corrections to the radiative matrix elements and its correlation with the structure of the diamagnetic spectrum of excited levels. We discover the selective action of a magnetic field on the diamagnetic components of emission lines: when the field strength increases, an increase in the intensity of some lines is accompanied by a decrease in the intensity of the other lines.

Relativistic Dipole Dynamic Polarizabilities of Lowest $ns_{1/2}$-States in Hydrogen-Like Atoms

V. Yakhontov
Institut für Physikalische Chemie, CH-4056 Basel, Switzerland

A novel closed-form exact analytical expression for the linear response relativistic wave function of the hydrogenic $ns_{1/2}$-level exposed to external dipole radiation is reported. This result is derived using the method due to Podolsky, that is, by means of direct analytic solving of the appropriate systems of inhomogeneous differential equations, thus requiring no prior knowledge of the relativistic Coulomb Green's function. As an important application of the formulas obtained, new expression for the relativistic dipole dynamic polarizabilities of lowest hydrogenic $ns_{1/2}$-levels are calculated.

Loop-After-Loop Contribution to the Second-Order Self-Energy in Hydrogen

V. A. Yerokhin
Department of Physics, St. Petersburg State University, St. Petersburg 198904, Russia
Institute for High Performance Computing and Data Bases, St. Petersburg, Russia

We investigate the loop-after-loop contribution to the second-order Lamb shift for the ground state of hydrogenlike atoms with low nuclear charge numbers Z. The calculation is carried out in the Fried-Yennie gauge and without an expansion in $Z\alpha$. Our calculation confirms the results of Mallampalli and Sapirstein and disagrees with the calculation by Goidenko and co-workers. A fit to the numerical results provides a detailed comparison with analytical calculations based on an expansion in the parameter $Z\alpha$. We confirm the analytic results of order $\alpha^2(Z\alpha)^5$ but disagree with Karshenboim's calculation of the $\alpha^2(Z\alpha)^6 \ln^3(Z\alpha)^{-2}$ contribution.