

ATOMS

Atomic physics now takes its place in modern fundamental physical theory, principally through the study of electromagnetic interaction of the elementary particles in the atom.

VERNON W. HUGHES

A WEALTH OF KNOWLEDGE, theoretical and experimental, is encompassed in the ever expanding field of atomic study, one of the oldest branches of modern physics. Quantum electrodynamics, one of the most complete and best verified modern physical theories, has been developed largely through studies in atomic physics and has sustained all experimental challenges of the past 20 years, including precise measurements of the Lamb shift, electron and muon gyromagnetic ratios, and of positronium and muonium hyperfine structure. Yet major questions remain unsolved, such as the divergences in the theory, the calculation of the value of the fine-structure constant and the relation of the muon and the electron—questions that must be formulated in the broader framework of elementary-particle physics. Invariance and symmetry principles play an important role in atomic physics; space reflection, time reversal and charge-conjugation invariances can be tested for the electromagnetic interactions. Atomic structure, atomic collisions, muonic and mesic atoms, quantum electronics and applications in astrophysics and other fields of science are parts of the frontier of modern atomic physics.

As the knowledge in a field expands,

the extent of the field's frontier also increases. Because atomic physics comprises a most extensive body of knowledge, its frontier is very large indeed, and I shall only discuss briefly certain frontier problems with which I have some familiarity.

QUANTUM ELECTRODYNAMICS

The connection of atomic physics with modern fundamental physical theory and with elementary-particle physics occurs through the electromagnetic interaction, which dominates the behavior of atoms. High-precision experiments on the energy levels of simple atoms and on the properties of atomic particles provide critical tests of the modern theory of quantum electrodynamics (QED) that are complementary to high-energy experiments testing directly the high-energy behavior of QED. In addition to the electron and positron, the positive and negative muons appear to be structureless Dirac particles whose principal interaction is the conventional electromagnetic interaction. Indeed some of the most sensitive tests of QED can be made on the muon because its Compton wavelength $\lambda = \hbar/m_\mu c$ is 1/200 that of the electron.

The profoundly revolutionary discoveries of the Lamb shift in hydrogen and the anomalous magnetic moment of the electron in precision atomic-beam spectroscopy experiments at Columbia in 1947–48 disagreed with the predictions of the Dirac theory and soon led to the modern renormalized theory of quantum electrodynamics. During the past 20 years the precisions of the measurements have been dramatically improved, often by several orders of magnitude. Sometimes the improvements were



Vernon Hughes is a professor of physics at Yale University where he has been since 1954. After working on radar during the World-War-II period from 1942 to 1946 he studied at Columbia with I. I. Rabi and obtained his PhD in 1950. His major interests are elementary-particle and atomic physics.

achieved through the introduction of new experimental principles or methods such as the maser, or optical-pumping spectroscopy, but often also through improved instrumentation and more careful experimentation. The variety and number of atoms, atomic levels and elementary particles that have been carefully studied are impressively large. This success has been achieved in part by the discoveries of new atoms such as positronium (e^+e^-), muonium (μ^+e^-) and muonic atoms (μ^-Z).

Theoretical calculations

During the 20 years since the most heroic period of QED, theoretical calculations of radiative corrections to particle properties and atomic energy levels, which are associated with virtual photons and virtual particle-antiparticle pairs, have been extended greatly to meet the need of comparisons with the higher-precision experiments. The calculations are formulated in perturbation theory as a series expansion, principally in powers of the fine-structure constant α or $Z\alpha$ (Z = atomic charge number). Evaluation of the higher-order terms in the series is extremely laborious and fraught with the danger of making a computational error. The computer has sometimes been introduced to enumerate the "Feynman" graphs and to perform some of the algebra, but as yet the computer has certainly not conquered the problem of calculating radiative corrections. Although most of the relevant experimental measurements refer to single particles or to single-electron atoms for which the Dirac wavefunction is known exactly, some measurements have been made on helium energy levels. The rele-

vant theoretical calculation requires a highly accurate two-electron Schrödinger wavefunction for helium; sufficiently accurate wavefunctions have been computed by variational techniques with modern computers. These modern helium wavefunctions are many orders of magnitude more accurate than the best achieved in the classic work of Egil Hylleraas; they provide accuracies of the order of a part in 10^9 or better in the computation of a Schrödinger binding energy. Despite all the theoretical labor devoted to precise QED calculations, in the present situation the theoretical accuracy is seldom better than the experimental accuracy, and usually a more accurate theoretical value is badly needed. We quite clearly need more powerful theoretical or computational approaches to precise atomic and QED calculations.

Lamb-shift experiments

The most important specific tests of QED based on the properties of particles or atoms include the Lamb shift for hydrogenic atoms in the $n = 2$ state, the g values of the electron and the muon, the hyperfine structure and annihilation rates of positronium, the hyperfine structure of muonium and vacuum polarization for muonic atoms. Table 1 summarizes the present experimental and theoretical results on the Lamb shift for H, D and He^+ in their $n = 2$ states. The theoretical errors shown arise primarily from an estimate of uncalculated terms. The agreement of the experimental and theoretical values for H and D is within about 0.3 MHz or 3 parts in 10^4 . Although this small difference is outside the combined limits of theoretical and experimental errors, it is

not generally regarded as an important discrepancy in view of the difficulties of both the experiments and the theory.

Muon g -value

The determination of the muon gyromagnetic ratio or g value in the famous CERN $g-2$ experiment provides one of the most sensitive tests of QED. This experiment is actually a high-energy experiment because it involves a storage ring for 1-GeV/ c muons. The experimenters can observe the difference frequency between the muon spin-precession frequency in a magnetic field and the muon orbital cyclotron frequency, which provides a measurement of $g_\mu - 2$, the difference of the muon g value from the Dirac value of 2. The principle of this experiment is the same as that of the earlier and equally famous electron $g-2$ experiment. The results for the muon are shown in Table 2. The agreement between the experimental and theoretical values of g_μ for μ^- to within 7 parts in 10^7 can be interpreted as a test of the validity of QED to a distance of about 5×10^{-15} cm or to a high momentum of 4 GeV/ c .

One particularly interesting aspect of the muon g -value experiment is the effect of strongly interacting particles (the hadrons) on the value of g_μ . Through the process of virtual particle-antiparticle pair production by a virtual photon, charged strongly interacting particles such as π^+ and π^- appear, in Feynman diagrams, which contribute to the value of g_μ . In principle the hadrons contribute to all QED processes through this type of Feynman diagram, and hence even electrodynamic processes for the "pure electrodynamic particles" such as the electron and the muon (the leptons) are coupled to strongly interacting particles. Because of the existence of resonant states of the π^+ and π^- system—most importantly, the ρ^0 vector meson with a mass of about 760 MeV—this process contributes about 7 parts in 10^8 to g_μ . (The effect on g_e is much less because of the smaller mass of the electron.) This theoretical estimate of the effect of hadrons on g_μ was not included in the theoretical value for g_μ given in figure 2, and indeed it is a factor of about 5 less than the present experimental accuracy. However, plans of the CERN group for a new $g_\mu - 2$ measurement would improve the

IS THE MOON JUST A HEAVY ELECTRON?

In its Fall 1965 meeting in Philadelphia the American Philosophical Society included a physics symposium in which one of the scheduled talks was a lecture by Henry Primakoff, professor at the University of Pennsylvania. The title of his talk was "Is the Moon Just a Heavy Electron?" I was scheduled to speak on "Muonium." About a week before the meeting Britton Chance of the University of Pennsylvania suggested that to enliven the meeting it might be helpful if I planned a couple of questions or some discussion following Primakoff's talk as there might not be many physicists present. Chance did not know, however, just what viewpoint Primakoff would take in his talk. Willis Lamb agreed with me that the topic was brilliant, and Lamb suggested that Primakoff might have some statistical-mechanics points to make. I imagined that Primakoff might present a critical or even satirical evaluation of NASA's science program. Primakoff clarified the situation quickly, but the clarification, offered apologetically, was somewhat disappointing: The title of his lecture should have read "Is the Muon Just a Heavy Electron?"

Table 1: Lamb shift $\Delta E(2^2S_{1/2} - 2^2P_{1/2})$ in MHz.

	Hydrogen	Deuterium	Helium positive ion
Experimental	1057.77 $\pm$ 0.10 1057.86 $\pm$ 0.10	1059.00 $\pm$ 0.10 1059.24 $\pm$ 0.10	14 040.2 $\pm$ 4.5
Average	1057.81 $\pm$ 0.10	1059.12 $\pm$ 0.10	
Theoretical	1057.529 $\pm$ 0.11	1058.793 $\pm$ 0.17	14 038.59 $\pm$ 4.4
$\Delta E(\text{expt.}) - \Delta E(\text{theor.})$	+0.28 $\pm$ 0.15	+0.33 $\pm$ 0.20	+1.6 $\pm$ 6.3

Limit of error is shown for the 95% confidence limit.

$$\Delta E(\text{theor.}) = \alpha^3 Z^4 R_y [0(1) + 0(Z\alpha) + 0(\alpha) + 0(Z^2\alpha^2) + (\text{proton mass, size})]$$

Table 2: Muon g value $g = 2(1 + a)$

	Negative muon	Positive muon
Experimental	2(1.001 166 25 $\pm$ 0.000 000 31) 2(1.001 166 6 $\pm$ 0.000 000 5)	2(1.001 165 75 $\pm$ 0.000 000 74) 2(1.001 162 $\pm$ 0.000 005)
Theoretical	2(1.001 165 54 $\pm$ 0.000 000 01)	2(1.001 165 54 $\pm$ 0.000 000 01)
$a(\text{expt.}) - a(\text{theor.})$	(+71 $\pm$ 31) $\times 10^{-8}$	(21 $\pm$ 74) $\times 10^{-8}$

Errors shown are one standard deviation.

$$-g(\text{theor.}) = 2\left(1 + \frac{\alpha}{2\pi} + 0.766 \frac{\alpha^2}{\pi^2}\right) = 2(1 + 0.001 161 41 + 0.000 004 13)$$

$$\alpha^{-1} = 137.0364 \pm 0.0012$$

accuracy of g_μ by at least an order of magnitude, and hence would provide the first case of what may be called a "natural breakdown" of pure QED in which the hadron field influences the QED properties of a lepton.

To date, in a wide variety of precision experiments on the leptons and on simple atoms, conventional QED has sustained all challenges for the past 20 years. If one looks back at the history of QED tests, one finds a number of experiments in which a difference of about 3 standard deviations between the experimental value and the theoretical value has occurred. However, some error was always present either in the experimental or theoretical value. This history would appear almost to justify the remark that a difference of 3 standard deviations has a 50% probability of occurring.

Reasons for testing QED

Despite the partial frustrations of the excellent agreement between theory and experiment in QED, there still remain good and exciting reasons to continue precise studies of its specific dynamic predictions. QED is perhaps our most complete and best verified theory in physics, but the renormalization theory is unsatisfactory and in-

complete in certain respects because it involves the replacement of infinite quantities, which arise in the theory from integrations over virtual high-energy processes, by experimentally observed quantities such as mass and charge. This procedure raises the question: Does QED have a high-energy limit of validity, or is there some length or distance below which QED is not valid? Furthermore the theoretical question of the convergence of the perturbation-theory expansion in powers of α is unsettled. I have already mentioned that QED, as a theory of photons, electrons and muons, is not a closed theory because other strongly interacting particles such as the pion contribute to the electromagnetic properties of the leptons. The relationship between theories of strong and electromagnetic interactions is of great interest to fundamental physical theory, and indeed the infinities in the renormalization theory may be related to the effects of the strong interactions. The present forms of electromagnetic theory and weak-interaction theory are very similar because both theories involve vector interactions expressible in similar current-current language. This similarity suggests a possible common origin of both electromagnetic and weak interactions. Elec-

trons, muons and photons are very useful for studying the electromagnetic properties of nucleons and nuclei, so it is important to establish QED on as firm a basis as possible.

Tests of QED are improving and no doubt will continue to do so, both experimentally and theoretically, because of a high level of present activity and many ambitious future plans. The field of QED appears to have a particular appeal because of the simplicity and beauty of the QED theory (not, however, unblemished) and the precision and elegance of the experiments.

Is the muon just a heavy electron?

The relationship between the muon and the electron is a major mystery in physics. Like the electron the muon appears to have no strong interactions; it is a Dirac particle with the conventional coupling to the electromagnetic field. The muon's weak interactions obey the universal V-A theory as do those of the electron. The muon appears to be a heavy electron and hence there are no different interactions that indicate why the muon mass is 207 times that of the electron. The sharpening of the question of the relationship between the electron and the muon has come from QED experiments on the free muon and on muonium establishing that the muon is a heavy electron. Any deviation found in the behavior of a muon from that of a heavy electron could provide an important clue about the mysterious origin of the muon's mass.

The fine structure constant

The dimensionless constant α ($\alpha = e^2/hc \simeq 1/137$) characterizes the strength of the electromagnetic interaction. In principle we can calculate the value of α from a sufficiently general theory. There have been several recent attempts and suggestions on this problem; one suggestion involves the use of Heisenberg's nonlinear spinor field theory of elementary particles, and another proposes the general viewpoint that the comprehensive QED theory of the future will be finite only when α has its observed value. There is no generally accepted theory for the value of α and perhaps the best comment on the present state of the theories of α is contained in a little story Feza Gursey told me about Wolfgang Pauli. After Pauli died he went to Paradise and then had his first audience with God. Pauli said, "God,

Table 3: The fine-structure constant, α

Source	Value of α^{-1}
Deuterium fine structure $2^2P_{3/2} \rightarrow 2^2P_{1/2}$	$137.0388 \pm 0.0012 (\pm 9 \text{ ppm})$
Hydrogen fine structure $2^2P_{3/2} \rightarrow 2^2P_{1/2}$	$137.0353 \pm 0.0016 (\pm 12 \text{ ppm})$
Muonium hyperfine structure $1^2S_{1/2}, F = 1 \rightarrow F = 0$	$137.0383 \pm 0.0026 (\pm 18 \text{ ppm})$
Hydrogen hyperfine structure $1^2S_{1/2}, F = 1 \rightarrow F = 0$	$137.0357 \pm 0.0008 (\pm 6 \text{ ppm})$
Josephson effect	$137.0359 \pm 0.0008 (\pm 6 \text{ ppm})$

Limit of error: 95% confidence limit

Average: $\alpha^{-1} = 137.0364 \pm 0.0012$ (9 ppm; 1 standard deviation)

I have always wondered why you made α equal to $1/137$." God then handed some papers to Pauli and said, "Here is the theory." Pauli studied the papers awhile, oscillated back and forth several times, and then said, "Das ist falsch."

Apart from the general theory of its value, an accurate value for α is important because it occurs in all formula based on QED and must be known in order to compare theory with experiment. Also it is important to know α well as one of the group of fundamental atomic constants. The modern value is obtained from a number of high-precision experiments that include measurements of the fine-structure intervals $2^2P_{3/2} - 2^2P_{1/2}$ in hydrogen and deuterium, of the hyperfine structure intervals in hydrogen and muonium and of e/h from the ac Josephson effect. The values obtained for α are shown in table 3. With the exception of the value from the early measurement of deuterium fine structure all the values of α are in reasonable agreement, and hence it would seem that α is known to somewhat better than 10 parts per million. The agreements of the values of α from these different sources constitute important verifications of the theories of the phenomena involved. One can take the viewpoint, for example, that the value of α is obtained from the fine-structure interval of hydrogen, and then the agreement of α values obtained from hydrogen hyperfine structure, muonium hyperfine structure and the ac Josephson effect constitute verifications of our understanding of proton structure effects on hydrogen hyperfine structure, of the assumption that the muon is a heavy electron, and of the basic theory of the ac Josephson effect.

One of the most promising possibilities for determining α with a con-

siderably higher precision is provided by the fine-structure intervals in the 2^3P_J state of helium. Both the intervals $J = 0$ to $J = 1$ and $J = 1$ to $J = 2$ have been measured with a precision of about 2 parts per million. A great deal of theoretical work has also been done on these fine-structure intervals, and it remains only to calculate the $\alpha^4 R_y$ contribution in order to be able to determine α with a precision of about 1 part per million.

The intriguing question has been raised as to whether the value of α varies with time, in the spirit of Dirac's original cosmological argument about the variation of atomic constants with time. Present evidence, based principally on nuclear systematics in beta decay and on optical observations of fine-structure splittings from distant sources, indicates that to a very high precision α is a constant of nature.

INVARIANCE AND SYMMETRY

Invariances and symmetries of physical laws play a central role in modern physics; the study of atoms has made a major contribution to our understanding of these principles. Partly this contribution has been through the discovery of new symmetries, such as the discoveries of parity conservation and space reflection invariance through the analysis of selection rules in atomic transitions (Laporte's rule). Partly the contribution consists of precise tests of reasonably well established symmetries. Since the electromagnetic interaction determines the behavior of atoms, it is essentially the symmetries in the electromagnetic interaction that are tested from studies on atoms.

Time-reversal invariance

One of the most important and topical symmetries is time reversal (T)

invariance. This is important because of the recent discovery in high-energy physics that the invariance under CP, the product of charge conjugation (particle-antiparticle transformation) and parity, is violated in the decay of the long-lived K^0 meson into two pions, $K_L^0 \rightarrow \pi^+ + \pi^-$. Because the invariance under the combined transformation CPT is a most firmly held principle, vital to the present form of local quantum field theory, the implication of CP violation is an associated T violation. One of the consequences of T violation (simultaneously P violation is also required) would be the existence of electric dipole moments of elementary particles. A most sensitive search has been made for the moment of the electron by study of the linear Stark effect in alkali atoms by the atomic-beam magnetic resonance method. An upper limit is set of $4 \times 10^{-22} e \text{ cm}$.

Baryons and leptons

Another symmetry to which atomic-physics studies have contributed recently is that of the charge equality of protons and electrons, or, more generally, of baryons and leptons. By an atomic-beam experiment in which the deflection of atoms by a strong electric field has been studied, a most sensitive limit has been placed on the electrical neutrality of individual atoms. With the assumption of the additivity of the particle charges, an upper limit to the difference in magnitude of the proton and electron charges and to the neutron charge of $4 \times 10^{-19} |e|$ is obtained, where e is the electron charge. Another experiment on macroscopic matter by a gas-efflux method has obtained comparable sensitivity.

There appears to be no fundamental principle requiring the equality of electron and proton charges, although it has been pointed out that even a slight charge inequality together with the assumption of charge conservation in any reaction would explain the observed law of conservation of baryons. This observed equality or symmetry of baryon and lepton charges has been referred to as "a symmetry in search of an invariance principle."

OTHER PARTS OF THE FRONTIER

My remarks so far refer only to what might be called the fundamental interactions that determine atomic phenomena. This topic, although a

most important one, is only a small part of the frontier of atomic physics.

Atomic structure

Atomic structure (the many-electron problem) and atomic collisions are rich, active fields of current study. New atomic states are being found and understood as more powerful experimental tools and theoretical approaches are used. In particular there are states with excitation energies considerably greater than the atomic ionization energy, which involve multiple electron excitation and usually decay by autoionization. One example of a class of such states is the quartet metastable ($\approx 10^{-6}$ sec) autoionizing states of alkali atoms, such as the $(1s\ 2s\ 2p)^4\ P_{5/2}$ state of lithium. The famous metastable He^- ion, which is extensively used as a projectile in nuclear research, is believed to be in this state. Large numbers of short-lived ($\approx 10^{-13}$ sec) states of double electron excitation have been discovered in the continuum of atoms up to about 100 eV, and a few in the x-ray range. Genuine "collective" effects involving a large number of electrons, such as are known in nuclei and solids, do not appear to occur in atoms. Group theoretical methods, including the introduction of new groups and the incorporation of relativistic effects, are being used to unravel complex atomic spectra, such as those of rare-earth and actinide elements. Application of group theory to atomic spectra provides a very instructive example as a background for its application to elementary particles. The use of many-body techniques and computers has led to reliable calculations of correlation energies and related effects.

Atomic collisions

The field of atomic collisions is a rich, broad field full of colorful phenomena. The most dramatic advances are coming on the experimental side where the powerful tools of atomic beams, ultra-high-vacuum technology, particle counting, coincidence methods, high-resolution electron and ion spectrometers and on-line data acquisition and computing techniques are being applied to measure total, elastic, inelastic and differential cross sections. Polarization phenomena are beginning to be studied with polarized electrons and polarized atomic beams. The wealth of new information being produced strains our capacities for orderly compilation. Unexpected narrow reso-

nances have been discovered in the scattering of electrons from hydrogen and helium at energies below the first excited states of these atoms; the resonances are related to the formation of multiply excited compound states of the negative ions. Heavy-particle collisions provide very complicated phenomena for study, and the importance of molecular states in these collisions is being emphasized. The theoretical calculations now being made to analyze collision phenomena are of greatly increased power, sophistication and complexity as compared to earlier work. Both from the experimental and theoretical viewpoints the study of atomic collisions is coming to resemble the study of nuclear reactions.

Muons and mesons

Muonic and mesic atoms (pionic and kaonic) provide a major frontier. The muonic atoms provide hydrogen-like atoms for all nuclei. The mass of the muon has been measured in muonic phosphorus, and vacuum polarization has also been studied in this atom. The muonic atoms provide an ideal tool for the study of nuclear structure, and extensive information has been obtained about nuclear charge distributions, static and dynamic quadrupole moments and isomer effects. Polarization of the nucleus by the muon has recently been observed. The recent studies have been done with germanium-lithium gamma-ray detectors. Pionic x rays have been used to obtain a value for the pion mass and also provide information about the strong interaction between the pion and the nucleus. One of the most precise absolute measurements has been done on the line of pionic aluminum with a crystal diffraction spectrometer. The observation of kaonic x rays in kaonic helium has been reported. When the planned high-intensity proton and electron accelerators to be used as pion and muon factories are constructed, higher resolution gamma-ray spectrometers can be used, and more detailed information will be obtained.

Masers and lasers

Masers and lasers have provided new phenomena to study in addition to giving coherent radiation of high monochromaticity, power and directionality. Both masers and lasers provide unique tools for precision spectroscopic studies. The hydrogen maser has been used to obtain perhaps the most precisely known value of an

energy interval in physics, the hyperfine structure interval of the ground state of atomic hydrogen, and indeed the hydrogen maser is now used as a primary frequency standard. Lasers have opened up the field of nonlinear optics and are used in photoionization studies. Masers and lasers are the most spectacular tools in the new field called quantum electronics.

Astrophysics

The application of atomic physics in astrophysics is a particularly fascinating field. Atomic collision phenomena play a vital role in determining the observed spectra. Discrete line spectra in radioastronomy involve both familiar and unfamiliar atomic and molecular transitions, such as the hydrogen ground-state hyperfine structure transition and the recently discovered transitions in the hydrogen atom between adjacent states of high principal quantum number ($n \approx 100$).

International conferences

Atomic physics is a sufficiently old branch of physics that its activities predate by several decades the post-World-War-II period when many new international conferences were set up on an annual or biannual basis. Perhaps the old Solvay International Conferences in the 1930's can be regarded as the first international conferences on the fundamental problems in atomic physics. Modern workers in the broad field of atomic physics have entered the field with many different viewpoints, objectives and backgrounds. Last June the first general international conference on the entire field was held in New York City at New York University. It was called the International Conference on Atomic Physics and its proceedings subtitled, somewhat more optimistically, *Proceedings of the First International Conference on Atomic Physics* was published last month by Plenum Press (See *PHYSICS TODAY*, January 1969, page 113). Another important broad conference on atomic physics, entitled "International Symposium on the Physics of the One and Two-Electron Atoms," was held in Munich in September of last year in conjunction with the Arnold Sommerfeld Centennial Memorial Meeting. (See page 99). The community of atomic physicists is planning to hold the Second International Conference on Atomic Physics at Oxford in 1970. At last atomic physics has come of age! □