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Review of Quantum Electrodynamics*

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A review of the book *Quantum Electrodynamics*
edited by T. Kinoshita, World Scientic (1990)

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This collection of specially prepared articles on precision tests of quantum electrodynamics celebrates the triumphant success of the application of theoretical physics to the world of atoms and leptons. The subject itself, QED, is the core theory of atomic and particle physics, and by extension, chemistry and condensed matter physics. No other physical theory has been evaluated and tested to such precision: for example, the gyromagnetic moment of the electron, the ratio of its spin precession frequency to its Larmor frequency in a uniform magnetic field, is predicted to have the value $g = 2$ by the Dirac equation. However, due to the electron's self-interactions with the electromagnetic field, its gyromagnetic ratio is corrected by QED to the value $g = 2(1 + a_e)$, where

$$a_e^{QED} = 1\ 159\ 652\ 140\ (\pm 5.3)\ (\pm 4.1)\ (\pm 27.1) \times 10^{-12}.$$

This prediction for the electron's anomalous moment value includes the contributions of order $(\alpha/\pi)^4$ obtained in a remarkable calculation by Toichiro Kinoshita and his co-workers of QED corrections which are eight orders in perturbation theory beyond Born approximation. The non-linear effects of the theory due to light-by-light-scattering processes begin to make an important contribution to the theoretical value at order $(\alpha/\pi)^6$. The first two uncertainties in a_e^{QED} indicate the level of the theoretical precision. The last uncertainty $\pm 27.1 \times 10^{-12}$ corresponds to the experimental uncertainty in the determination of the fine structure constant α from the quantized Hall effect. The anomalous moment of a single electron confined to Penning trap has been measured by Hans Dehmelt and his collaborators to extraordinary precision:

$$a_{e^-}^{EXPT} = 1\ 159\ 652\ 188.4\ (\pm 4.3) \times 10^{-12}.$$

Thus the gyromagnetic ratio of the electron is successfully predicted by QED to eleven significant figures! In the case of the heavier leptons, the anomalous magnetic moment is sensitive to quantum fluctuations due to virtual quark currents as well as the fields that carry the weak interactions. A new experiment to measure the muon magnetic moment to sufficient precision to check these effects is now being constructed at Brookhaven National Laboratory.

Quantum electrodynamics provides the rigorous theoretical foundations underlying atomic physics, allowing extraordinarily precise predictions of the spectra and properties of one and two electron atoms. The predictions for the Lamb shift, hyperfine splitting, fine structure, and the decay rates of hydrogen, muonium, positronium, and helium take into account not only radiative corrections due to quantum fluctuations of the electromagnetic field, but also subtle relativistic recoil and bound-state corrections. These high order calculations not only verify the applicability and consistency of the perturbative renormalization procedure of gauge theory, but they also are the forerunners of calculations for the non-Abelian extensions of QED, including the radiative corrections needed for precision tests of the unified theory of electro-weak interactions and the gauge theory of the strong and nuclear interactions, quantum chromodynamics. Much of the physics of quarkonium, heavy quark pairs ($\overline{Q}Q$) bound by gluonic interactions in quantum chromodynamics, has a direct counterpart with the physics of positronium (e^+e^-) in QED.

The Kinoshita volume provides a detailed account of the main theoretical and experimental advances in testing quantum electrodynamics of the last two decades. The theoretical articles include a beautiful introduction to bound state systems by Kinoshita and Peter Lepage, a comprehensive survey by Kinoshita and William

Marciano of the physics of the muon magnetic moment including new physics beyond the Standard Model, a detailed review of the theory of hydrogenic atoms by Jonathan Sapirstein and Donald Yennie, and two extensive surveys of perturbative methods for computing lepton magnetic moments: one by Kinoshita and the other by Ralph Roskies, Ettore Remiddi, and Michael Levine. The theory of two electron atoms is reviewed by Francis Pichanick and Vernon Hughes.

At the level of precision required for testing QED, one also needs a detailed understanding of the theory of the measurements themselves. For example, the theory of cavity shifts required for the measurement of the electron magnetic moments is presented in a chapter by Gerald Gabrielse, Joseph Tan, and Lowell Brown. The experimental articles are just as authoritative, and include reviews on the theory and development of the muon anomalous moment experiments by F. J. M. Farley and E. Picasso, on Lamb shift measurements by Francis Pipkin, on hyperfine structure experiments by Norman Ramsey, on positronium studies by Allen P. Mills, Jr. and Steven Chu, and the physics of the muonium atom (μ^+e^-) by Vernon Hughes and Gisbert zu Putlitz. Each article is self-contained.

In the 1950s, the Dover collection, *Selected Papers on Quantum Electrodynamics* edited by Julian Schwinger, and the book, *Quantum Mechanics of One – and Two – Electron Atoms* by Hans Bethe and Edwin Salpeter from Academic Press, became bibles for workers in particle and atomic physics. This new World Scientific collection, beautifully edited and annotated by Kinoshita, is a worthy successor to the earlier volumes, providing a comprehensive technical and historical reference for the field.