The Quantum Vacuum: An Introduction to Quantum Electrodynamics. Peter W. Milonni. 522 pp. Academic Press, New York, 1994. Price $69.95 ISBN 0-12-498080-5. (Reviewed by Claudia Eberlein.)

Quite a few books carry the words "Introduction to Quantum Electrodynamics" in their titles; whereas most of them should rather be called "Introduction to the *Formalism* of Quantum Electrodynamics," Milonni's book actually deserves the title "Introduction to the *Physics* of Quantum Electrodynamics." The book is, as the author repeatedly emphasizes, thoroughly old-fashioned. It is old-fashioned in the sense of those times way back when physics was a quest for the elucidation of nature's secrets rather than a wrestle with symbols and formulary detached from any real phenomenon and deficient in motivation. The maxim throughout the book is that "if QED is indeed the nonpareil physical theory [...] then it is worthwhile to look carefully at the *physical* ideas underlying QED vacuum effects, including not only such things as mass and charge renormalization, Lamb shifts and Casimir effects, but even more 'elementary' things such as spontaneous emission, van der Waals forces, and the fundamental linewidth of a laser" (p. xiii).

Indeed, the book provides plenty of motivation and applications. It is unusual as a textbook in that it gives also a close historical account of how QED was developed. Quotations from original work and reminiscences of the pioneers are judiciously interwoven with lucidly presented calculations. The few more involved derivations are well annotated—at one place, in complete honesty, by the remark that "the calculations are sufficiently tedious that the author has not himself attempted to verify them in detail" (p. 408, fn. 8). The reader, who is always patiently guided, needs no previous knowledge of quantum field theory or relativistic quantum mechanics; the sole prerequisites are classical electrodynamics, some thermodynamics, very little Hamiltonian mechanics, and basic nonrelativistic quantum mechanics. Thus, the book is a very readable introduction for the graduate student who first learns QED. It will serve well as summer reading before a standard course in quantum field theory or beside such a course—particularly for those who might have lost track of what is really happening in the intricate formulae of a more conventional textbook on the subject.

Central to the book is the quantum vacuum. Zero-point fluctuations are inherent in any quantized theory since observables whose corresponding operators do not commute with the Hamiltonian exhibit fluctuations even when the system is in the ground state; this makes for a wide range of nonclassical effects. Hence, the reality of the zero-point energy, comprehensively established in the book, is a clear testimony for quantum theory. Conversely, it is commonly less well appreciated that, although classical electrodynamics does not predict zero-point fluctuations, it also does not forbid them. Milonni devotes some attention to this point; he mentions the basic ideas of exotic theories like stochastic electrodynamics, acknowledges their successes, and indicates their shortcomings.

Zero-point energy, which nowadays appears so naturally in the standard quantum-mechanical treatment of the harmonic oscillator, played a quite important role in the development of quantum theory. In an introductory chapter the reader is told about the conception of the idea of zero-point energy in connection with black-body radiation, spontaneous emission, and related problems. Then follow seven chapters on nonrelativistic quantum electrodynamics which make slightly more than half the book and are, in my opinion, the most valuable part of it, since they contain material hardly found in any other books. The elaborate discussion of the Lamb shift includes not only four different ways of calculating the theoretical value, but also a brief description of the experiment by Lamb and Retherford. The basics of nonrelativistic quantum field theory as used in quantum optics are introduced very intuitively and applied to several topics of current interest, such as the modification of spontaneous emission due to mirrors, the behavior of an electron in a Penning trap, and the observation of strong and weak transitions in atomic shelving experiments. Two entire chapters are devoted to Casimir and van der Waals forces; various viewpoints, including unconventional ones, are thoroughly examined and presented with a clarity that is truly striking for one who has worked in this field and appreciates the intricacy of the subject. Again, the discussion extends to pertinent experiments.

The last four chapters deal with relativistic QED. A concise introduction to the Dirac equation is followed by discussions of physically important examples like pair creation in uniform electric fields, the Klein paradox, *zitterbewegung,* and the fine structure of the energy levels in the hydrogen atom. Second quantization is handled both nonrelativistically and relativistically. The formalism that comes with it is well motivated and not excessively technical, though still sufficiently detailed; this book is the first I have ever seen where the field propagators are introduced by their physical meaning rather than by pure definition. Relativistic QED is then applied to some of the problems treated nonrelativistically in the earlier chapters. The language of standard canonical quantization makes the differences of relativistic and nonrelativistic theories particularly easy to spot. Only the last chapter brings in Feynman rules and things like Wick's theorem and the S matrix, which make up QED in conventional textbooks. The analyticity of the S matrix and similar *ne plus ultra* of bone-dry quantum field theory do not appear anywhere in the book. Feynman diagrams are presented deliberately as one way among many to handle QED, with the intent of "avoiding confusion between the diagrams and the *physics*" (p. xv).

Although laid out as a textbook, the book is also a valuable source of expert knowledge for anyone who does research on the Casimir effect, cavity QED, and the like. Furthermore, it can be recommended to nonspecialists as an enlightening introduction to the vacuum effects in QED. For myself, the book widened my view, systematized things I knew, and taught me a few new things. In summa summarum, Milonni's book was definitely the most enjoyable reading I have come across in a long time.

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