tistical speculation.

The second half of the book is devoted to string theory. Strings, abstract one-dimensional extended objects that provide a generalization of point particles, have recently attracted the attention of the theoretical community as a possible basis for the unification of all fundamental forces. This interpretation has been brought forward most forcefully by the work of Michael Green and John Schwarz. Polyakov, however, has long held a different point of view, that a theory of "free strings" should be as general a mathematical tool as the harmonic oscillator or the Klein–Gordon equation, and that this theory will finally give a proper description of such problems as the large-distance behavior of QCD. Such a simple and general theory does not yet exist. In pursuit of this idea, Polyakov concentrates in *Gauge Fields and Strings* on the foundations of the quantum theory of strings, and gives a careful and very complete account of the relation between the geometry of strings and their quantization. Some aspects of the currently popular superstring theories are discussed, but the treatment is rather telegraphic. Polyakov also sets out some broader applications of string ideas, including a beautiful derivation of a string equation describing the three-dimensional Ising model.

Throughout the book, Polyakov never hesitates to go beyond what is actually proved, to speculate and to point to unsolved problems. It is this open-ended quality that makes his book especially fascinating. Theoretical physicists of all varieties will be impressed by the breadth of view and the depth of the arguments that Polyakov offers, but above all by the questions, questions, questions to stew over long after they have put this text down.

MICHAEL E. PESKIN
Stanford Linear Accelerator Center

Physics of Massive Neutrinos

Felix Boehm and Petr Vogel
Cambridge U. P., New York, 1987. 211 pp. $34.50 hc
ISBN 0-521-30567-5

There may be a place already reserved on the shelf for *Physics of Massive Neutrinos* right next to *Descriptive Anatomy of the Unicorn*, but it is hard to believe that such interesting particles could fail to exist. One can only marvel at a particle so craftily designed that after more than 50 years of research we do not even know if it has a distinct antiparticle, let alone mass.

All this ignorance belies the feverish theoretical and experimental activity in neutrino physics, and this book by Felix Boehm and Petr Vogel is both timely and unique. Boehm, who is Valentine Professor of Physics at Caltech and a major figure in the field, is best known for his careful search for neutrino oscillations with reactor antineutrinos. Vogel, a research professor of theoretical physics at Caltech, has contributed fundamental insights to the theory of double beta decay. Together, they have put into sharp relief both the laborious and beautiful efforts of experimenters and the ingenuity of theorists.

The idea that neutrinos could have mass is as old as Enrico Fermi's theory of beta decay itself, but it fell out of fashion when parity was overthrown. The argument was that in beta decay only left-handed neutrinos were seen, and therefore neutrinos had to be massless and always travel at light speed. Otherwise one could overtake a neutrino and see it spinning in the wrong sense. Later, with the development of the "standard model" of particle physics and the discovery of parity violation in neutral currents without neutrinos, it became clear that parity violation is intrinsic to the weak force itself. There was no longer any reason to saddle neutrinos with the job of violating parity, and massive neutrinos ought to be physically acceptable. Still, in the standard model, neutrinos are not provided with right-handed fields and therefore are massless by fiat. Today this seems artificial, and is a likely weak spot in the gleaming armor of the standard model.

What with theory offering little guidance as to how heavy neutrinos might be, experimenters are searching everywhere their techniques permit. There are two strategies: Observe some kinematic variables at the time a neutrino is created, and deduce its mass, or observe the subtle interplay of lepton-number violation and mass in processes like neutrino oscillation and double beta decay. The former method is free of assumptions, but within the framework of specific assumptions, the latter is much more sensitive.

In 1980 a group at the Institute of Theoretical and Experimental Physics in Moscow reported that their kinematic experiment on the beta decay of tritium had yielded evidence for an electron neutrino mass of 35 eV. This caused a great stir, not only because it menaced the standard mod-

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el, but also because such a mass neatly closes the universe and prevents indefinite expansion. At about the same time, an experiment at the Savannah River reactor gave indications of neutrino oscillations, which can only occur if at least one type of neutrino has mass. In addition, Ray Davis (Brookhaven National Laboratory) was not seeing the expected number of electron neutrinos from the Sun, another possible manifestation of neutrino oscillation and mass.

So the race began in earnest, with new experiments on tritium beta decay, on neutrino oscillations at reactors and accelerators, and on neutrinoless double beta decay (which, oddly enough, tells you something about neutrinos). None of the dozen new tritium experiments has yet been able to confirm or contradict the ITEP claim (down now to 26 eV) with absolute conviction. The original Savannah River result has long since been repudiated, in part by the oscillation experiment mounted by Boehm and Rudolf Mössbauer at the Gösgen reactor in Switzerland. Another oscillation experiment, at the Bugey reactor in France, appeared to give new evidence for oscillations, but that result too has been withdrawn (since the publication of *Physics of Massive Neutrinos*). Accelerator experiments from time to time have shown tantalizing but not uncontradicted hints of oscillations. Kinematic experiments on the μ and τ neutrinos have never shown any indication of mass, and the limits have been progressing steadily downward.

To be sure, there are a few minor errors (the neutrino threshold on He^3 is 1.04, not 0.52, MeV), but in general the book is thoroughly researched and very comprehensive. *Physics of Massive Neutrinos* is much more than a snapshot of a field in transition, with limited long-term value. Intended for specialists, it is a compendium of the methods and theoretical underpinnings of neutrino physics, and will likely become the handbook of practicing neutrino physicists everywhere.

R. G. Hamish Robertson
Los Alamos National Laboratory

Theory of Multiphoton Processes

Farhad H. M. Faisal
Plenum, New York, 1987.
408 pp. $65.00 hc
ISBN 0-306-42317-0

The behavior of atoms and molecules subjected to intense electromagnetic fields at optical and infrared frequencies has become a major field of investigation. Developments in laser instrumentation allow the experimenter to deliver large amounts of energy into small volumes during short time intervals. Technological developments have led to an extraordinary enhancement in spectral resolution, and spectroscopic experiments have yielded data of unprecedented precision on the energy-level structures of atomic and molecular systems. The dynamical evolution of the response of atoms and molecules to intense disturbances is accessible to experimental investigation with high fields and short pulses, and many new phenomena have been uncovered in consequence.

The standard treatment of the effects of electromagnetic fields on atoms and molecules makes use of the weakness of their interaction with the radiation field; it also assumes time scales that are long compared with the characteristic periods of the unperturbed systems. First-order perturbation theory suffices to describe the phenomena. Transitions between energy levels occur by the emission or absorption of a single photon with an energy equal to the difference between the unperturbed energy levels of the initial and final states. Transition probabilities for the energy levels can be defined independently of the photon intensity. The selection rules are simple. And the polarization pattern is readily predictable.

As the intensity of the radiation field increases, however, phenomena occur that cannot be reproduced by a first-order theory: multiphoton transitions, complex selection rules, complex polarization patterns and shifts in the energy levels. Multiphoton transitions take place via intermediate resonance states; the relaxation of the resonance states may occur on time scales that compete with those for emission and absorption. In multimode lasers, harmonic generation creates photons with frequencies equal to the sum of the frequencies of individual photons. Multiphoton transitions into the continuum are possible at high field strengths, and the spectrum of the ejected photoelectrons depends on the laser pulse lengths.

Not all the observed effects can, as yet, be explained in quantitative detail, but considerable progress has been made in developing and testing perturbative and nonperturbative methods that have predictive power. In perturbative methods, diagrammatic techniques have been worked out for handling the detailed enumeration of the transition matrix elements, and procedures have been