HEAVY ELECTRONS AND MUONS*

F. E. Low
Physics Department and Laboratory of Nuclear Science,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 15 January 1965)

The quantum electrodynamics (QED) of electrons, muons, and photons has so far been found to be in agreement with experiment.[1-3] This agreement has usually been expressed in terms of a fictitious "radius" down to which the theory has been found to hold.[4] In this language, an experimental deviation from the theory would reveal a "cutoff," or perhaps even a "cut-on."

A much more natural theoretical way of describing a breakdown of QED (and a more likely way for such a breakdown to occur) is in terms of coupling of electrons and muons to other particles.[5] This is consistent with the ideas of ordinary quantum field theory (or S-matrix theory), and is the only theoretically consistent way that we have to describe a real breakdown. In this language, continued experimental confirmation of the predictions of QED would be expressed in terms of upper limits to the coupling strengths and lower limits to the masses of hypothetical particles coupled to electrons, muons, and photons.

This point of view suggests a class of experiments which would search directly for such particles by looking for correlations in the mass spectrum of groups of final electrons and photons just as is done in strong-interaction physics. These experiments would be direct checks of QED. They would in many cases have the additional advantage of isolating the electrodynamic system from the nuclear target without the necessity of waiting for storage rings.

We discuss briefly three possible ways in which a breakdown might occur in the physics of electrons. Evidently, all remarks apply equally well to muons, although the experimental problems in that case are much harder.

(1) The electron might be coupled to a heavy electron, e', with a magnetic coupling of the form

$$\lambda\bar{\psi}_{e'}\sigma_{\mu\nu}\psi_{e}f_{\mu\nu}+\text{H.c.} \tag{1}$$

This is the most favorable case from the experimental point of view. Assuming a mass of the e' in the several hundred MeV range, existing experiments are consistent with a coupling strength $\lambda \sim e/m_{e'}$, provided a reasonable cutoff is assumed and provided the decays $K^{\pm} \to e'^{\pm} + \nu$ and $K^0 \to e'^{\pm} + \nu + \pi^{\mp}$ are moderately forbidden. Otherwise, we must have $m_{e'} > 500$ MeV. The interaction (1) is neither minimal nor renormalizable. It would presumably be the low-energy manifestation of a minimal, renormalizable interaction (necessarily involving other particles) which would provide an automatic cutoff.

The simplest reaction to produce the e' would be

$$\begin{array}{l} p+e\to p+e' \\ \qquad\qquad\ \ \hookrightarrow e+\gamma\ \ (\tau\sim 10^{-21}\,\text{sec}). \end{array} \tag{2}$$

The e' would be observed as a sharp missing-mass peak in the recoil proton energy and angle distribution. This would be direct experimental evidence of an excited state of the electron. It could also be observed directly in a mass plot of the final $e+\gamma$.

The e' could also be produced by photons in the reaction

$$\begin{array}{l} \gamma+p\to p+e+e' \\ \qquad\qquad\qquad\ \ \hookrightarrow e+\gamma. \end{array} \tag{3}$$

If the photons are tagged for energy, the e' could again be observed as a missing mass. With untagged photons, one could still observe a threshold in the missing mass as a function of maximum photon energy, or else detect directly a peak in the e-γ mass spectrum. Depending on the precise experiment under consideration it might be advantageous to use a heavy target instead of hydrogen.

A further consequence of the existence of the e' (and of the minimal interactions coupling it to the electron) would be an anomalous Compton scattering of electrons and photons (at center-of-mass energies comparable to $m_{e'}$), as well as an anomalous electron-positron pair-production cross section at corresponding values of the electron-positron mass, possibly of the kind referred to in reference 3.

(2) The electron might be coupled to a boson,

b, with an interaction of the form[6]

$$g\bar{\psi}_e \Gamma_i \psi_e b_i. \tag{4}$$

Again assuming a mass m_b of several hundred MeV, existing experiments are consistent with $g^2 \lesssim e^2$, i.e., electromagnetic strength of coupling.

This particle would be directly produced in the process

$$\begin{array}{l} p+e \to p+e+b \\ \qquad\qquad\quad\ \llcorner\!\!\to e^+ + e^- \ (\sim 10^{-21}\,\mathrm{sec}) \end{array} \tag{5}$$

and would have to be observed directly as an $e^+ + e^-$ resonance, since strongly produced particles would make a missing-mass analysis difficult to interpret.

The reaction

$$\begin{array}{l} p+\gamma \to p+b \\ \qquad\qquad\ \llcorner\!\!\to e^+ + e^- \end{array} \tag{6}$$

is probably very unfavorable compared to (5) because of the competition with strongly interacting particles.

The b particle would not affect $e+\gamma$ scattering appreciably, nor $e^+ + e^-$ production, unless it were also coupled to the nucleon. In that case, it could well also give rise to a hfs anomaly.

(3) The electron might be coupled to an excited electron and a boson with an interaction

$$g\bar{\psi}_{e'} \Gamma_i \psi_e b_i + \mathrm{H.c.}, \tag{7}$$

in which case there might be a conservation law. If so, the lighter of e' or b would be stable (except to weak decays). The production reaction would be

$$\begin{array}{l} e+p \to p+\underbrace{e'+b} \\ \qquad\qquad\quad\ \llcorner\!\!\to e + l_1 + l_2 \ (10^{-21}\,\mathrm{sec}), \end{array} \tag{8}$$

where l is the lighter of b and e'. The l particle would now have to be found either by its charge or, if neutral, by its weak decay, if any, and the (e,l) mass spectrum measured to ensure that we were observing a deviation from QED. This case would obviously be the most difficult from which to extract information relevant to QED. If there is no conservation law, the decay mechanisms and correlations discussed under (1) and (2) above would also hold here.

The energy now available at the Cambridge Electron Accelerator would permit a mass search up to about 2 BeV with a hydrogen target and considerably higher with heavy targets. The mass range that will be available at the Stanford Linear Accelerator Center with a hydrogen target will go up to about 5 BeV. Thus, a realistic QED breakdown mechanism arising from particles whose masses lie in the resonance region of the strong interactions can, if it exists, be found in the near future. There is at present no reason to believe that the electron and muon are unique, and not coupled to a large family, as are all the other known particles. It will be interesting to learn which is the case.

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*This work is supported in part through funds provided by the U. S. Atomic Energy Commission under Contract No. AC(30-1)2098.

[1] R. Garwin, Proceedings of the Aix-en-Provence Conference on Elementary Particles, 1961 (C.E.N., Saclay, France, 1961).

[2] J. K. de Pagter *et al.*, Phys. Rev. Letters **12**, 739 (1964).

[3] There may, however, be preliminary evidence for a violation in the pair-production experiments carried out by Pipkin and his group at the Cambridge Electron Accelerator. I would like to thank Dr. Pipkin for several valuable conversations on the interpretation of his experiments.

[4] S. Drell, Ann. Phys. (N.Y.) **4**, 75 (1958).

[5] We already know that photons interact with almost all strongly interacting particles. This is not considered a breakdown of QED.

[6] A muon coupling of this form has recently been suggested in order to account for the muon-electron mass difference. The point of view here is purely phenomenological. Connections between interactions and masses are not considered. See J. Schwinger, Phys. Rev. **135**, B816 (1964).