ASYMMETRIC MUON-PAIR PHOTOPRODUCTION FROM HYDROGEN*†

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We have measured the cross section for the reaction $\gamma + p \rightarrow \mu^- + \mu^+ + p$, detecting only the negative muon.[1] The momentum and angle of the detected μ^- and the maximum incident photon energy were chosen such that the undetected μ^+ had to be nonrelativistic. As pointed out by Drell,[2] this experimental method constitutes a sensitive test for possible modifications of the muon propagator from the form predicted by quantum electrodynamics (QED). The method previously used to search for this type of QED breakdown has been through muon-pair photoproduction off carbon nuclei, with both the μ^+ and μ^- detected in coincidence under symmetric conditions.[3]

In this experiment, the kinematic conditions for a typical data run were as follows: a primary photon energy $k \sim 850$ MeV, a momentum for the detected μ^- of $p \sim 700$ MeV/c, and a detection angle of $\theta \sim 10°$. Under these conditions, the virtual muon was off the mass shell by $p^\nu p_\nu - m_\mu^2 = -2km_\mu = -(425\text{ MeV})^2$ for the Feynman diagram most sensitive to modifications of QED [Fig. 1(a) of Ref. 2]. This Feynman diagram contributed about half of our cross section, when evaluated in the transverse gauge in the laboratory. The μ^+, which was not detected, was nonrelativistic.

Large π^- backgrounds were not present in our experiment due to the conditions chosen. Negative pions cannot be singly photoproduced from protons. By keeping the maximum photon energy sufficiently low, it is possible to avoid the production of negative pions at the spectrometer momentum from pion-pair production.

In practice, due to our finite momentum acceptance, there was a small contamination of pair-produced π^- mesons at the energies we used. These were largely rejected by our detectors. In order to keep single-π^- production small, we used a target of specially purified hydrogen with a deuterium concentration of $HD/H_2 \sim 8$ parts per million (see Hildebrand[4]).

The experimental arrangement is shown in Fig. 1. The specially prepared target of deuterium-free hydrogen was irradiated with a bremsstrahlung beam from the Stanford Mark III electron linear accelerator. The electron beam current was measured with two secondary emission monitors (SEM's) which were periodically calibrated with a Faraday cup. The beam position was measured periodically on each of two fluorescent screens separated by 30 in. After passing through 0.065 radiation lengths of copper radiator plus SEM's, the electrons were removed by a ditching magnet. The photons then passed through a $1\frac{1}{4}$-in.-diam lead scraping collimator, the target, and a hole cut in the spectrometer iron before being ditched in the rear of the experimental hall. Muons emerging from the target at 10° were analyzed in Stanford's 90°-bend, 44-in.-radius, single-focusing magnetic spectrometer.[5]

The muon detector, placed at the focus of the spectrometer, was a telescope of six scintillation counters (Fig. 1 insert). Two counters defining the solid angle and momentum acceptance were followed by 17 radiation lengths of tungsten, for electron rejection, and the remaining four counters were interleaved with 11 in. of copper for pion rejection by nuclear absorption. For particles penetrating the whole counter telescope, a factor of $\sim 10^{-6}$ rejection was achieved against electrons, and a factor of $\sim 10^{-2}$ against pions at the spectrometer momentum. The remaining electron and pion contaminations were subtracted out by using the ratios of counts in the various counters that had previously been determined with both pure electron and pion signals. A Monte Carlo calculation using Molière's theory of multiple scattering[6] determined that the sixfold coincidence accepted $(92 \pm 2)\,\%$ of the entering muons which triggered the defining counter under the conditions of our experiment. The set of six small interleaved counters shown in Fig. 1 was used to monitor the counting efficiency of the main counter telescope.

Measurements of muon yields were made with peak photon energies extending from below threshold to 55 MeV above muon threshold, that is, about 11 MeV above the threshold for π^- from pion pairs. Measurements at still higher energies would have had large backgrounds due to π^- mesons from pion-pair production.

One source of error in the experiment was the uncertainty in the determination of the absolute energy above μ^- threshold. We used the reaction $\gamma + p \rightarrow \pi^+ + n$ both to calibrate this difference and to cross check the acceptance of the spec-

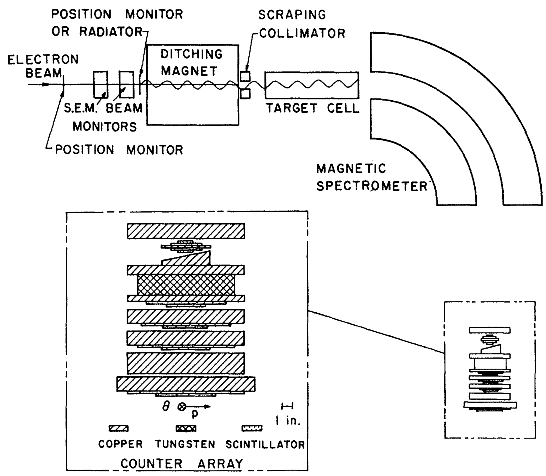

FIG. 1. Experimental arrangement. The insert shows the telescope used to detect the μ^- leptons.

trometer. (The π^+ excitation curves were run periodically with the field in the spectrometer accurately reversed as measured with an NMR probe.) We estimate the final weighted uncertainty in the determination of the peak energy of the bremsstrahlung spectrum above the muon threshold to be less than ±1.1 MeV (one standard deviation).

Another source of error was an uncertainty in the angle of scattering of ±2 mrad. Most of this error came from the uncertainty in determining the angle of the electron beam in the end station. Table I lists the individual measurements and the various contributions to the experimental uncertainty.

Figure 2 shows the experimentally measured muon counting rate as a function of energy. The solid curve in Fig. 2 is the predicted muon counting rate for our experimental conditions. It was obtained from the theoretical cross section[7] by combining it with the known parameters of this experiment. The point near 865 MeV was combined from several runs.

After combining both the statistical errors and the systematic errors listed in Table I, we find for the weighted average of all runs with peak photon energy above 860 MeV the ratio R = exper-

Table I. Sources of uncertainty.

Nominal Peak Photon Energy, MeV	884.6 ± 1.1	869.8 ± 1.6	864.7 ± 1.1	864.3 ± 1.1	869.7 ± 1.1	865.9 ± 1.9	841.2 ± 1.1	828.5 ± 1.9	817.9 ± 1.1
Counts in Telescope	508	214	44	188	54	313	15	12	1
Counts with Counting Rate Corrections	529 ±28	223 ±16	46 ± 7	196 ±15	57 ± 8	344 ±22	15.5 ± 4.0	12.2 ± 4.0	- 0.8[a] ± 1.5
Counts in Telescope Due to Electrons	1.3 ± 1.3	1.2 ± 1.2	0.3 ± 0.3	1.2 ± 1.2	0.3 ± 0.3	1.0 ± 1.0	0.3 ± 0.3	0.6 ± 0.6	0.4 ± 0.4
Counts in Telescope Due to π^-'s from Pairs	95 ±12	3.9 ± 2.0	0.1 ± 0.1	0.4 ± 0.4	0.6 ± 0.6	1.5 ± 1.5	0	0	0
Counts in Telescope Due to Muon Pair Production	433 ±31	218 ±16	46 ± 7	194 ±15	56 ± 8	341 ±22	15.2 ± 4.0	11.6 ± 4.0	- 1.2 ± 1.6
Relative error in Expected Muon Counts Due to the Uncertainty in the Energy Calibration	± 0%	± 5.2%	± 4.8%	± 4.1%	± 3.1%	± 7.8%	±12%	+61% -37%	-
Systematic Uncertainty in the Definition of Solid Angle, Effective Target Length, and Momentum Acceptance of the System	± 5.2%	± 5.2%	± 5.2%	± 5.2%	± 5.2%	± 5.2%	± 5.2%	± 5.2%	± 5.2%
Systematic Uncertainty in Primary Photon Intensity	± 2.3%	± 2.3%	± 2.3%	± 2.3%	± 2.3%	± 2.3%	± 2.3%	± 2.3%	± 2.3%
Systematic Uncertainty in Monte Carlo Calculation of Telescope Efficiency for Muons	± 1.8%	± 1.8%	± 1.8%	± 1.8%	± 1.8%	± 1.8%	± 1.8%	± 1.8%	± 1.8%
Systematic Uncertainty in Expected Muon Counts Due To Measurement of Angle of Production	± 2.4%	± 2.4%	± 2.4%	± 2.4%	± 2.4%	± 2.4%	± 2.4%	± 2.4%	± 2.4%
Systematic Overall Uncertainty in Expected Muon Counts Due to Energy Uncertainty	± 3.3%	± 3.3%	± 3.3%	± 3.3%	± 3.3%	± 3.3%	± 3.3%	± 3.3%	± 3.3%
Systematic Uncertainty in Theoretical Cross Section, Including Radiative Corrections and Compton Term Interference	± 2.1%	± 2.1%	± 2.1%	± 2.1%	± 2.1%	± 2.1%	± 2.1%	± 2.1%	± 2.1%

[a]More randoms than counts received.

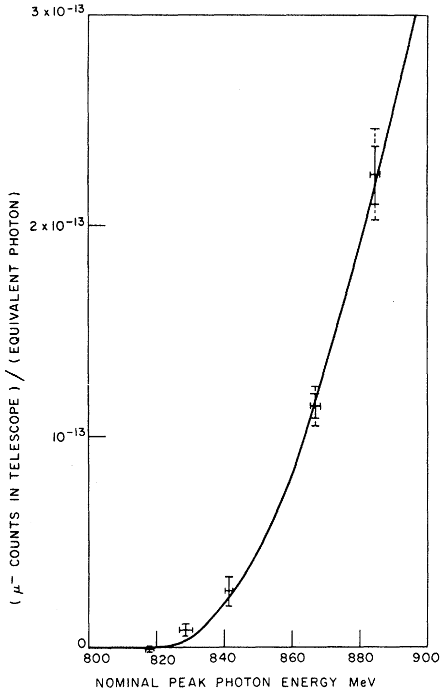

FIG. 2. Experimental results as a function of peak photon energy. The solid line is the expected muon counting rate, calculated from the predictions of QED as described in the text. On the two highest points, the solid vertical error flags represent relative uncertainties only, and the dashed flags include uncertainties in overall normalization.

iment/theory $=1.00\pm0.09$ (one standard deviation).

Interpreted in terms of limits on the breakdown of QED, this corresponded to a "measurement" of the muon propagator at a four-momentum squared of $(425\ \mathrm{MeV})^2$ away from the mass shell, and a limit for the conventional breakdown parameter[2] of $|\Lambda^{-1}|\leq 2\times10^{-14}$ cm to two standard deviations. As this method is different in a large number of respects from previous QED measurements, it strongly reinforces the previous conclusions of no breakdown of QED to similar levels of accuracy obtained by other authors.[3]

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[1]Details of this measurement can be found in D. Quinn, thesis, Stanford University, 1968 (unpublished), and Stanford University High Energy Physics Laboratory Report No. 534, 1968 (unpublished).

[2]S. D. Drell, Phys. Rev. Letters 13, 257 (1964).

[3]A. Alberigi-Quaranta, M. De Pretis, G. Marini, A. Odian, G. Stoppini, and L. Tau, Phys. Rev. Letters 9, 226 (1962); J. K. de Pagter, A. Boyarski, G. Glass, J. I. Friedman, H. W. Kendall, M. Gettner, J. F. Larrabee, and Roy Weinstein, Phys. Rev. Letters 12, 739 (1964); J. K. de Pagter, J. I. Friedman, G. Glass, R. C. Chase, M. Gettner, E. von Goeler, Roy Weinstein, and A. M. Boyarski, Phys. Rev. Letters 17, 767 (1966). QED is also tested with the muon propagator far off the mass shell in the muon $g-2$ experiments. [See, for example, J. Bailey, W. Bartl, R. C. A. Brown, J. Jöstlein, S. van der Meer, E. Picasso, and F. J. M. Farley, in International Symposium on Electron and Photon Interactions at High Energies, Stanford, California, 1967 (to be published).] However, a breakdown of QED is possible which would affect one and not the other of these experiments. It is thus important to pursue both the muon-pair photoproduction and muon $g-2$ experiments to the greatest extent possible. For a recent summary of the field and further references, see Roy Weinstein, in International Symposium on Electron and Photon Interactions at High Energies, Stanford, California, 1967 (to be published).

[4]The hydrogen had been depleted in deuterium content by L'Air Liquide in France. Some of this hydrogen was kindly given us by R. Hildebrand of the University of Chicago.

[5]J. Allaby and D. Ritson, Rev. Sci. Instr. 36, 607 (1965).

[6]H. A. Bethe, Phys. Rev. 89, 1256 (1953), and references therein.

[7]R. G. Parsons, Phys. Rev. 150, 1165 (1966). Parsons' calculation of the radiative corrections gave a 1% correction to the predicted cross section. Following Drell (Ref. 2) we have estimated that interference with the Compton term lowers the cross section by (2.0 ± 1.2) % from that predicted by the Bethe-Heitler terms alone.