If the data of Ref. 6 are combined with our data, but only in the region $W^2 > 1.6$, $q^2 > 0.6$ $(\text{GeV}/c)^2$, we obtain $\Lambda^{-2} = +0.012 \pm 0.013$ $(\text{GeV}/c)^2$, $N_\Lambda = 0.982 \pm 0.032$, as shown by the solid ellipse of Fig. 3. Thus we conclude that with 95% confidence $|\Lambda^{-2}| \leq 0.038$ $(\text{GeV}/c)^2$. Results on μ-e universality of similar accuracy have been obtained from the $g-2$ experiment[7] and from μ pair production in e^+e^- collisions.[8] Comparison of elastic μ-p and e-p scattering[9] gives weaker bounds on the value of $|\Lambda^{-2}|$. These results are summarized in Table II.

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†Present address: Department of Physics, State University of New York, Stony Brook, N. Y. 11790.

‡Present address: Department of Physics, University of California, San Diego, LaJolla, Calif. 92037.

§Present address: National Accelerator Laboratory, Batavia, Ill. 60510.

‖Present address: Department of Physics, University of Illinois, Urbana-Champaign, Urbana, Ill. 61801.

¶Present address: Department of Physics, Rockefeller University, New York, N. Y. 10021.

**Present address: Department of Physics, New York University, New York, N. Y. 10003.

††Present address: Nuclear Physics Laboratory, Oxford University, Oxford, England.

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[2]J. D. Bjorken, Phys. Rev. 179, 1547 (1969).

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Muon-Proton Deep Elastic Scattering*

I. Kostoulas,† A. Entenberg, H. Jöstlein,‡ A. C. Melissinos, L. M. Lederman, P. Limon,§ M. May, P. Rapp, H. Gittleson, T. Kirk,‖ M. Murtagh, M. J. Tannenbaum,¶ J. Sculli,** T. White,†† and T. Yamanouchi

University of Rochester, Rochester, New York 14627, and Columbia University, New York, New York 10027, and Harvard University, Cambridge, Massachusetts 02138, and National Accelerator Laboratory, Batavia, Illinois 60510

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We have measured muon-proton elastic scattering in the range $0.6 < q^2 < 3.2$ $(\text{GeV}/c)^2$. We compared these data with the corresponding elastic electron-proton cross sections by forming the ratio $r(q^2) = G^2(\mu\text{-}p)/G^2(e\text{-}p)$, where $G(q^2) = G_M(q^2)/\mu$ is the form factor of the proton. By fitting $r(q^2) = N(1 + q^2/\Lambda^2)^{-2}$ we find $N = 1.043 \pm 0.080$ and $\Lambda^{-2} = +0.064 \pm 0.038$ $(\text{GeV}/c)^{-2}$. Combining our data with those of two previous μ-p elastic scattering experiments yields $\Lambda^{-2} = +0.051 \pm 0.024$ $(\text{GeV}/c)^{-2}$ which is a much weaker limit on muon-electron universality than that obtained from μ-p inelastic scattering.

In the preceding Letter[1] we discussed muon-electron universality as deduced from deep inelastic scattering. During the course of that experiment we also measured the elastic scattering of muons from protons in the q^2 interval $0.6 < q^2 < 3.2$. At an incident beam mean energy of 7.3 GeV we observed 119 events, and 314 events at 5.8 GeV. From the known incident and outgoing muon energy and the scattering angle we form the (missing) mass spectrum of the recoil hadrons $(\text{MM})^2$. In addition the apparatus was such that the recoil proton from elastic scatter-

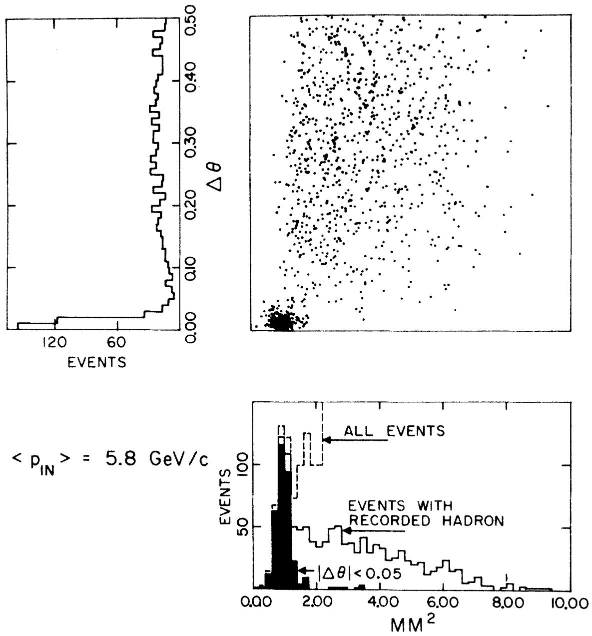

FIG. 1. Scatter plot of $\Delta\theta$ (the space angle between the virtual photon and hadron directions) versus $(MM)^2$ for 5.8-GeV incident energy. The projection on the $(MM)^2$ axis shows all events (dashed), events in the scatter plot (solid), and events with $|\Delta\theta| < 0.050$ (shaded).

ing was recorded in the *front* spark chambers of the hadron spectrometer. Thus, the direction of the recoil is known but not its momentum, and we designate by $\Delta\theta$ the space angle between the recoil proton direction $\vec{p}_r/|p_r|$ and the $\vec{q}$ vector $(\vec{q}=\vec{p}_{in}-\vec{p}_{out})$. A scatter plot of $\Delta\theta$ versus $(MM)^2$ for the 5.8 data is shown in Fig. 1, where the clustering of events around $\Delta\theta = 0$ and $(MM)^2 = 0.9$ GeV^2 indicates the presence of elastic scattering. Elastic events were selected by requiring $|\Delta\theta| < 0.050$ rad^2 and $(MM)^2 < 1.6$ GeV^2.

From our resolution we expect that for $(MM)^2 < 0.9$ GeV^2 the number of events with $|\Delta\theta| < 0.050$ and with no selection in $\Delta\theta$ must be identical. The observed ratio of 0.92 is a measure of the efficiency for detecting the recoil proton (due to absorption in target, chamber and reconstruction efficiency, angular resolution, and radiative effects); the observed value is consistent with an independent estimate of these effects.[3] The flux, acceptance, and corrections to the data were evaluated as discussed in Ref. 1; the above-mentioned recoil-proton detection efficiency was included and the radiative corrections were calculated according to Mo and Tsai.[4] In addition to the elastic events where the forward muon is detected, we obtained a nearly independent sample of 99 elastic events by triggering only on a recoil proton. Candidates for elastic scattering (i.e., protons) were selected by time of flight and momentum measured through the large-angle spectrometer; the missing mass spectrum shows a clear peak at $(MM)^2 \simeq 0$ (the lepton mass).

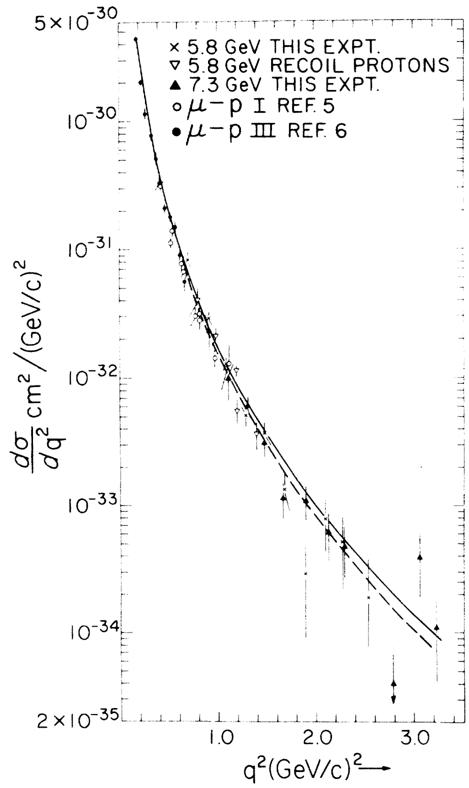

FIG. 2. The differential cross section $d\sigma/dq^2$ for μ-p elastic scattering from this experiment as well as from Ref. 5 and Ref. 6. The solid curve represents the differential cross section obtained from e-p elastic scattering while the dashed curve is the best fit to all the μ-p elastic data. The two curves differ by a factor $(1+q^2/\Lambda^2)^{-2}$ with $1/\Lambda^2 = +0.051$ $(GeV/c)^{-2}$.

The differential cross sections, $d\sigma/dq^2$, obtained in this experiment are shown in Fig. 2 together with data from two other elastic-scattering experiments.[5,6] To compare our data with those of e-p elastic scattering and the previous μ-p experiments, we have used the Rosenbluth formula[7]

$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha^2}{q^4}\left(1-\frac{q^2}{qME}\right)\left[\frac{G_E{}^2+(q^2/4M^2)G_M{}^2}{1+(q^2/4M^2)}\cos^2\frac{\theta}{2}+2\left(\frac{q^2}{4M^2}\right)G_M{}^2\sin^2\frac{\theta}{2}\right] \quad (1)$$

TABLE I. Maximum-likelihood fit parameters to μ-p elastic scattering (this experiment).

		Normalization constrained[a] to $N=1.0\pm0.1$		Normalization completely free		
$\langle p_{\text{incident}}\rangle$ (GeV/c)	$\langle q^2\rangle$ (GeV/c)^2	N_c	$1/\Lambda^2$ (GeV/c)$^{-2}$	N_f	$1/\Lambda^2$	$\langle N\rangle^{\text{b}}$
5.8	1.02	1.030 ± 0.084	$+0.042\pm0.046$	1.118 ± 0.187	$+0.080\pm0.085$	0.957 ± 0.054
7.3	1.52	0.996 ± 0.097	$+0.070\pm0.046$	0.955 ± 0.313	$+0.056\pm0.112$	0.811 ± 0.074
Combined sample	1.15	1.043 ± 0.080	$+0.064\pm0.038$	1.134 ± 0.160	$+0.099\pm0.065$	0.915 ± 0.044

[a]See text and Ref. 12.

[b]$\langle N\rangle$ indicates the mean ratio of the observed μ-p cross sections to the e-p cross sections. To first order $\langle N\rangle = N_f - 2(1/\Lambda^2)\langle q^2\rangle$ for the free normalization.

to extract the proton form factor $G(q^2)$. We have assumed that[8]

$$G_E(q^2) = \mu^{-1}G_M(q^2) \equiv G(q^2)$$

with μ the magnetic moment of the proton. On the other hand, the values of $G(q^2)$ obtained from e-p elastic scattering can be expressed by the so-called "dipole"[9] form factor $G(q^2) = (1+q^2/0.71)^{-2}$. Deviations from this expression have been measured[10] and for our range of q^2 we have used the following correction:

$$G^2(q^2)_{e\text{-}p} = (1+q^2/0.71)^{-4}[1 - 0.304\sqrt{q^2} + 0.470q^2 - 0.153\sqrt{q^2}\,q^2]. \tag{2}$$

Muon-electron universality demands that

$$r(q^2) = G^2(q^2)_{\mu\text{-}p}/G^2(q^2)_{e\text{-}p} \tag{3}$$

be equal to 1.0 for all values of q^2. A possible model[11] for muon-electron differences was discussed in Ref. 1 and in that case the functional form of $r(q^2)$ is given by $r(q^2) = (1+q^2/\Lambda^2)^{-2}$. Since both the e-p and μ-p data may be subject to an overall normalization error, we fit

$$r(q^2) = N(1+q^2/\Lambda^2)^{-2} \tag{4}$$

with N and $1/\Lambda^2$ as adjustable parameters. $1/\Lambda^2$ is completely free while N is constrained[12] around its expected value of 1.0 with a Gaussian error of $\sigma_N = 0.10$ which is our estimate of the systematic error in the *relative* normalization of the e-p (5%) and μ-p (8.5%) data.

In view of the small number of events at large q^2 we have made a maximum-likelihood fit to the observed events in each bin, according to Eq. (4). The results of the 5.8- and 7.3-GeV data as well as for the combined sample are given in Table I and the best fit, and 1 standard deviation contours in the $(N, 1/\Lambda^2)$ plane, are shown in Fig. 3. We note that the value of $N = 1.043\pm0.080$ is within our systematic normalization error, whereas (in the experiment)

$$1/\Lambda^2 = +0.064\pm0.038 \text{ (GeV/}c)^{-2} \tag{5}$$

favors a deviation from muon-electron universality. The results of the fit to Eq. (4) with N completely free are included in Table I for completeness. They contain less information than the constrained fit but again favor a positive value of $1/\Lambda^2$.

The error in the result of Eq. (5) does not contain any effects due to the error in the determination of q^2. Only if we made a *systematic* error in q^2 would the result be altered; while we can find no such error, the sensitivity is such that an increase of q^2 by 1% will *decrease* $1/\Lambda^2$ by 0.015.

Two previous measurements of the μ-p elastic cross section have been made, one[6] at low q^2 but

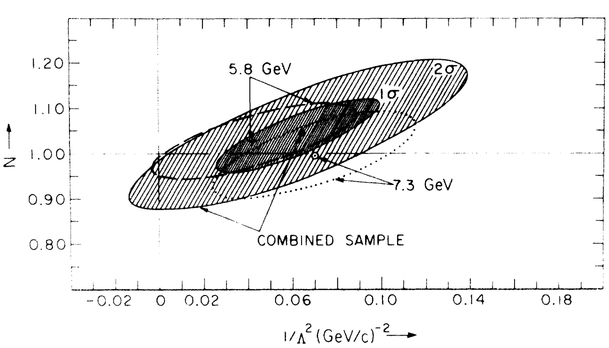

FIG. 3. Maximum-likelihood best-fit values and 1 standard deviation contours in the $(N, 1/\Lambda^2)$ plane for this experiment.

TABLE II. Least-squares fit parameters to world data of μ-p elastic scattering. The normalization has been constrained to $N=1.0\pm0.1$; see Ref. 12.

$\langle p_{\text{incident}}\rangle$ (GeV/c)		$\langle q^2\rangle$ (GeV/c)^2	N	$1/\Lambda^2$ (GeV/c)$^{-2}$
5.8	This expt.	1.02	1.07 ± 0.09	$+0.042\pm0.046$
7.3	This expt.	1.52	0.97 ± 0.10	$+0.034\pm0.042$
5.8	This expt., recoil protons	0.95	1.00 ± 0.10	$+0.037\pm0.066$
2.1	Ref. 5	0.62	0.97 ± 0.08	$+0.107\pm0.075$
6, 11, 17	Ref. 6	0.26	0.96 ± 0.03	$+0.054\pm0.051$

with good statistics and the other[5] at moderate q^2. We reanalyzed the published data of these experiments using Eq. (2) for the form factor and fitted the ratios $r(q^2)$ with the model of Eq. (4) by using a χ^2 fit. The results for N and $1/\Lambda^2$ are given in Table II for each experiment and are in close agreement with those given by the authors. For completeness we have also included our data analyzed by this method, including the sample obtained from the recoil protons. A six-parameter fit to these five independent measurements requiring a common cutoff parameter $1/\Lambda^2$, but allowing for five different normalizations N_i, yields (all elastic data)

$$1/\Lambda^2=+0.051\pm0.024\ (\text{GeV}/c)^{-2}, \tag{5'}$$

where the N_i's were constrained.[12] This should be contrasted to our results from μ-p inelastic scattering[1] where we obtained $1/\Lambda^2=+0.006\pm0.016$ (GeV/c)^2.

In conclusion, we observe a 2.1 standard deviation difference from μ-e universality in elastic μ-p scattering. The statistical accuracy of this observation is not compelling, especially because of the rapid dependence of the elastic cross section on q^2. The good agreement of the inelastic scattering further argues against a breakdown of μ-e universality, as do the related experiments on $g-2$ of the muon[13] and on μ-pair production in e^+e^- collisions.[14] Nevertheless, the recurring μ-e difference in elastic scattering is somewhat disconcerting[15] and must, once again, wait for more incisive data.

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†Present address: Department of Physics, University of California, San Diego, Calif. 92037.

‡Present address: Department of Physics, State University of New York, Stony Brook, N.Y. 11790.

§Present address: National Accelerator Laboratory, Batavia, Ill. 60510.

‖Present address: Department of Physics, University of Illinois, Urbana, Ill. 61801.

¶Present address: Department of Physics, Rockefeller University, New York, N.Y. 10021.

**Present address: Department of Physics, New York University, New York, N.Y. 10003.

††Present address: Nuclear Physics Laboratory, Oxford University, Oxford, England.

[1]A. Entenberg *et al.*, preceding Letter [Phys. Rev. Lett. 32, 486 (1974)].

[2]This criterion is equivalent to selection on coplanarity and on the angle of the recoil proton in the scattering plane.

[3]For the 7.3-GeV incident-energy data the recoil-proton detection efficiency was found to be 0.85.

[4]L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. 41, 205 (1969).

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[7]M. N. Rosenbluth, Phys. Rev. 79, 615 (1950).

[8]This assumption, referred to as "form factor scaling," is true by definition in the limit $q^2=0$ and it is experimentally verified up to $q^2=1$ GeV/c^2. For high q^2, deviations have been reported but do not affect the conclusions reached here. See for instance L. E. Price *et al.*, Phys. Rev. D 4, 45 (1971).

[9]See for instance P. N. Kirk *et al.*, Phys. Rev. D 8, 63 (1973).

[10]The parameters of Eq. (2) have been obtained by fitting the data of T. Janssens *et al.*, Phys. Rev. 142, 922 (1966), and of W. Bartel *et al.*, DESY Report No. 73/5, 1973 (to be published).

[11]S. D. Drell, Ann. Phys. (New York) 4, 75 (1958); J. A. McClure and S. D. Drell, Nuovo Cimento 37, 1638 (1965).

[12]To impose the constraint we add a term $(1.0-N)^2/\sigma_N^2$ to the χ^2 sum.

[13]J. Bailey *et al.*, Nuovo Cimento 9A, 396 (1972).

[14]V. Alles-Borelli *et al.*, Nuovo Cimento 7A, 331 (1972).

[15]The cross sections probed by elastic scattering are at least 1 order of magnitude smaller than the corresponding inelastic cross sections in the region of our measurement.

Baryon-Conservation Limit*

F. Reines
Department of Physics, University of California, Irvine, California 92664

and

M. F. Crouch
Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106
(Received 17 January 1974)

An improved lower limit of $>2\times10^{30}$ yr against baryon-conservation–violating nucleon decay has been obtained for modes which produce $\mu\rightarrow e$ decays. The detector, employing a 20-ton large-area (180 m^2) liquid scintillator, was operated deep underground (3.2 km) to eliminate stopping muons from cosmic rays, leaving only the background from muons produced by atmospheric neutrinos. A run length of 2.7 yr was required to achieve the sensitivity quoted.

In view of recent interest in the possibility that baryon conservation may not be an absolute principle,[1] we present improved limits obtained incidental to the now completed Case Western Reserve University–University of Witwatersrand–University of California at Irvine deep-underground neutrino program.[2] The best published limit for nucleon stability is $>2\times10^{28}$ to $>8\times10^{29}$ yr,[3] depending on the decay mode assumed. In order to discriminate against penetrating muons from cosmic rays, Gurr *et al.*[3] based their results on those particles which passed through their scintillation hodoscope at zenith angles ranging from 45 to 90°. In the present paper the distinctive delayed coincidence produced by a muon stopping and decaying in the scintillator is used to set a new limit on baryon conservation as revealed by the conservation of nucleons. Five such events were seen during the course of the experiment.[4] The observed number can be accounted for[2] by neutrino-produced muons originating in the rock surrounding the detector, or in the detector itself, and then decaying in the scintillator. Muons produced in the atmosphere, and penetrating the 3.2 km of earth from the surface, are both rare and energetic and so give rise to $<\frac{1}{10}$ the observed decay rate. Although it is not possible to rule out nucleon decay completely as a source of muons which in turn decayed in our detectors,[5] it seems prudent to interpret the signal so as to yield a lower limit on nucleon lifetime.

The following table lists the run times, detector masses, nucleon content, and number of decay events for the two experiments involved:

Expt.	Detector mass (metric tons CH_2)	Number of nucleons	Run length (yr)	Muon decays observed
1	19	1.1×10^{31}	1.7	4
2	21	1.2×10^{31}	0.9	1

In order to interpret the data of the table in terms of nucleon stability, we consider decay modes in which one particle, a muon, is produced either directly or by the decay of a pion. Since our detectors were not thick (~20 MeV) compared with the muon range (~200 MeV), the effective number of nucleons under observation is approximately given by the stopping power per gram of the scintillator (CH_2) relative to that of the surrounding rock (SiO_2) times the number of nucleons in the scintillator. The π or μ range in the scintillator is ~20% shorter than in the surrounding rock[3] so it is conservative to take the effective number of nucleons to be equal to the number of nucleons in the scintillator.

It remains to estimate the detection efficiency for the muon-decay electron. The detector consisted of 54 elements (Expt. 1) or 60 elements (Expt. 2), each measuring $12.7\times55\times500$ cm^3 and containing liquid scintillator ($\rho=0.87$ g/cm^3). Since the electron detection threshold was 10 MeV