jectories leaving with zero velocity the zero-potential curve at $t=0$, as they proceed down the deep valleys except for the unique solution (up to reflections in a and f) which slowly reaches the point $a=f=0$ along the curve $a=f^2$. Figure 1 displays this behavior. We have checked that the virial theorem (21) is satisfied to a great accuracy leading to the value

$$I=7.874. \tag{22}$$

We have of course to presume that our *Ansatz* has picked the nearest singularity of the Borel transform. If this is the case we see that in spite of the new intricacies implied by the gauge field, we have recovered the same situation as in the case of a self-coupled scalar field. After some manipulations we obtain formula (1) with A expressed as

$$A=(2/\pi I) \tag{23}$$

giving the numerical value quoted in (2).

The normalization factors (b_n and c_n, the latter containing all the dependence on external momenta and polarization) can be extracted from the above numerical solution and will involve the renormalization counterterms.

We thank Professor Lipatov for kindly sending us his work prior to publication. We acknowledge many stimulating discussions with E. Brézin, J. Zinn-Justin, and A. Martin.

*Present address: Institut des Hautes Etudes Scientifique, Bures-sur-Yvette, France; on leave of absence from Istituto Nazionale di Fisica Nucleare, Frascati, Italy.

[1]L. N. Lipatov, in Proceedings of the Eighteenth International Conference on High Energy Physics, Tbilisi, U. S. S. R., 15–21 July 1976 (unpublished), and Institute of Nuclear Physics, Lenigrad, Reports No. 253 and 255, 1976 (unpublished).

[2]E. Brézin, J. C. Le Guillou, and J. Zinn-Justin, Centre d'Etude Nucléaires de Saclay Report No. DPhT-76/102 and 76/119, 1976 (unpublished).

[3]G. Parisi, Institut des Hautes Etudes Scientifique Report No. P/76/146, 1976 (unpublished).

[4]C. Bender and T. T. Wu, Phys. Rev. Lett. 27, 461 (1971), and Phys. Rev. D 7, 1620 (1972).

[5]J. J. Loeffel, A. Martin, B. Simon, and A. S. Wightman, Phys. Lett. 30B, 656 (1969).

[6]See for example E. M. Stein, *Singular Integrals and Differentiability Properties of Functions* (Princeton Univ. Press, Princeton, N. J., 1970); J. R. Klauder, Acta Phys. Austriaca, Suppl. No. 11, 341 (1973).

[7]F. J. Dyson, Phys. Rev. 85, 631 (1952).

[8]J. S. Langer, Ann. Phys. (N.Y.) 41, 108 (1967).

Precise Measurements of Axial, Magnetron, Cyclotron, and Spin-Cyclotron-Beat Frequencies on an Isolated 1-meV Electron

R. S. Van Dyck, Jr., P. B. Schwinberg, and H. G. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 5 November 1976)

A sensitive frequency-shift technique is employed to monitor the magnetic quantum state of a single electron stored in a compensated Penning trap. The electron sees a weak parabolic magnetic pseudopotential in addition to the electric well, which causes the axial oscillation frequency to have a slight magnetic quantum state dependence. Transitions at both the spin-cyclotron-beat (anomaly) frequency and the cyclotron frequency have been measured in the same environment to yield a magnetic anomaly $a_e=(1\,159\,652\,410\pm 200)\times 10^{-12}$.

The first measurement of the electron-spin magnetic moment on *free* (relativistic) electrons was carried out in 1953 by Crane and co-workers[1] giving $|a_e|\leqslant 5\times 10^{-3}$ for the "anomaly" defined as $a_e\equiv(\nu_s-\nu_c)/\nu_c$. Here, ν_s and ν_c denote spin and cyclotron frequencies, respectively, in the nonrelativistic limit. This study led to the famous University of Michigan "$g-2$" experiments,[1] finally yielding $a_e=(1\,159\,656\,700\pm 3500)\times 10^{-12}$ which was previously the most accurate experimental value. However, the first definite value,[1] $a_e=(1116\pm 40)\times 10^{-6}$, was obtained in 1958 at the

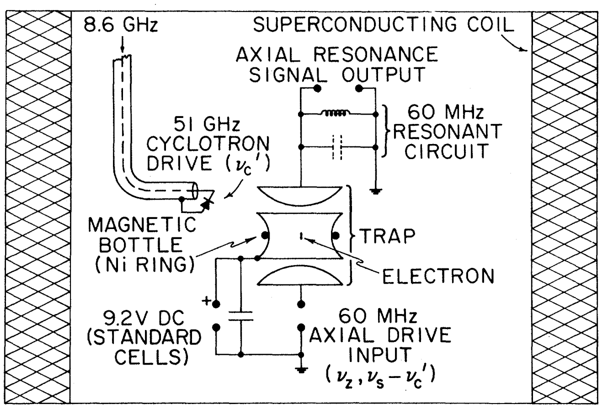

FIG. 1. Geonium spectroscopy experiment (schematic). This apparatus allows the measurement of the cyclotron frequency, ν_c', and the spin-cyclotron-beat (or anomaly) frequency, $\nu_a' = \nu_s - \nu_c'$, on a single electron stored in a Penning trap at $\simeq 4$°K ambient. Detection is via Rabi-Landau level-dependent shifts in the continuously monitored axial resonant frequency, ν_z, induced by a weak magnetic bottle.

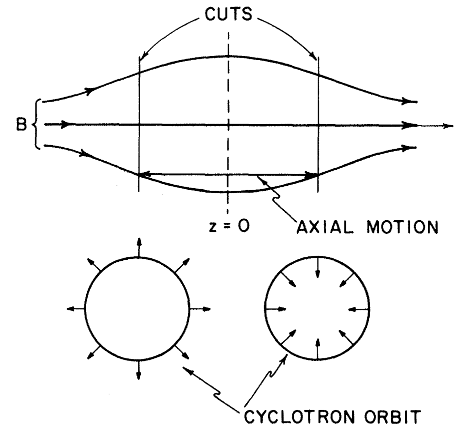

FIG. 2. Mechanism for inducing spin flips by the electron's axial motion in the magnetic bottle. From the electron's frame of reference, a magnetic field is seen rotating at ν_c', but modulated by the axial motion at ν_a', yielding sidebands at $\nu_c' \pm \nu_a'$ with $\nu_s = \nu_c' + \nu_a'$.

University of Washington. None of the above workers simultaneously measured ν_c; hence in 1969, Gräff and co-workers[1,2] first measured both $\nu_s - \nu_c$ and ν_c on electrons in a Penning trap, obtaining $a_e = (1\,159\,660 \pm 300) \times 10^{-9}$. Sharper cyclotron resonances[2,3] had been reported earlier by Walls.

Our experiment, proposed[4] and briefly reported upon earlier,[5] is the culmination of work initiated at the University of Washington several years ago by one of the authors after the realization that for a Penning trap the small shift $-\delta e$ in ν_c due to its electric field is constant throughout its volume and measurable.[2] The experiment (see Fig. 1) is carried out on a *single* electron, confined in such a trap at ~4°K, whose axial oscillatory resonance at frequency $\nu_z \simeq 60$ MHz is easily observed.[6] This system may profitably be looked upon as a synthetic ultraheavy metastable atom, which we chose to call "geonium" because ultimately the electron is bound to the earth via the trap structure and the magnet. The geonium energy levels[7] are given by

$$h^{-1}E_{mnkq} = m\nu_s + (n+\tfrac{1}{2})\nu_c' + (k+\tfrac{1}{2})\nu_z - (q+\tfrac{1}{2})\nu_m, \qquad (1)$$

where $\nu_c' \equiv \nu_c - \delta_e$ is the shifted cyclotron frequency with[8] $2\delta_e\nu_c' = \nu_z^2$. For an ideal axially symmetric trap the magnetron frequency ν_m equals δ_e. Spin flips and excitation of the cyclotron resonance are detected by making ν_z slightly dependent on spin and cyclotron quantum states, $m = \pm\frac{1}{2}$, $n = 0, 1, 2, 3, \ldots$. By use of weak magnetic bottle[9] the axial magnetic field, B_z, becomes $B_0 + B_2 z^2$, where $B_0 \simeq 18.3$ kG and $B_2 \simeq 120$ G/cm^2 or 300 G/cm^2 for two different applied bottles. The resulting pseudopotential $-\langle\mu_z\rangle B_z$ for a magnetic moment $\langle\mu_z\rangle \simeq (2n+2m+1)\mu_B$ will perturb the large electrostatic potential energy to yield a frequency shift, $\delta\nu_z(m,n) \simeq (m+n+\frac{1}{2})\delta$ with $\delta = 1.0$ or 2.5 Hz depending on the bottle used. The cyclotron resonance at 51 GHz is easily measured via excitation to $n \gg kT/h\nu_c' \simeq 1.5$ by a very modest microwave drive. However, the observation of spin flips is normally obscured by the rapid and random variation of n due to thermal background radiation since the spontaneous emission lifetime of the $n=1$ level is $\simeq 1$ sec and $n \leqslant 4$ levels are frequently populated. It is nevertheless possible to determine m from the minimum values $\delta\nu_z = 0$ or $+\delta$ by following $\delta\nu_z\{m, n(t)\}$ for $\simeq 30$ sec because spin relaxation is extremely slow. In order to minimize the effect of magnetic field fluctuations, spin flips are induced by an auxiliary forced axial oscillation whose amplitude is kept *smaller than thermal* (4°K) through the magnetic bottle field (see Fig. 2) at $\nu_a' \equiv \nu_s - \nu_c'$, chosen near ν_z. Under the assumption of a thermally excited cyclotron orbit circling, for simplicity, about the trap axis at $z < 0$, the outward pointing radial components of the bottle field, B_r, appear to the electron as a field rotating at ν_c'. The forced axial oscillation at ν_a' now periodically carries the electron into the $z > 0$ region where the direction of B_r is reversed. This causes the electron to see a field rotating not at ν_c' but at ν_c'

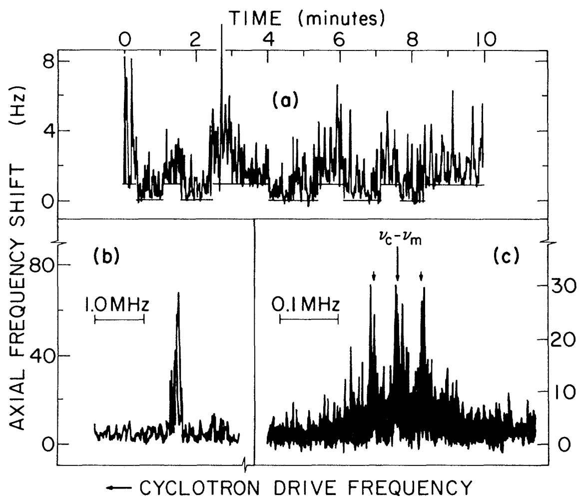

FIG. 3. Observed axial frequency shift, $\delta\nu_z(m,n)$, for a locked electron. (a) Spin flips are signaled in the 1.0-Hz bottle by ± 1.0-Hz changes in the $n = 0$ plateau when ν_a' is applied continuously. The spikes reflect thermal cyclotron excitation. (b) Externally excited cyclotron resonances for the 2.5-Hz bottle with large locking drive and (c) the same for the 1.0-Hz bottle with weak locking drive. For (c), $\nu_c - \nu_m = 51\,073\,965$ kHz.

$\pm\nu_a'$ instead. As $\nu_c' + \nu_a'$ equals ν_s, this component induces spin flips. Thus, upon relating ν_s and ν_c to the experimental data by means of Eq. (1) we can obtain[8] $a_e\,(\text{expt}) = (\nu_a' - \delta_e)/(\nu_c' + \delta_e)$. The magnetron frequency ν_m may be indirectly measured because the electron also absorbs radiation at $\nu_z + \nu_m$. The resulting agreement of the measured ν_m and calculated δ_e values to within one part in 10^4 or 3 Hz constitutes experimental proof that the dc trapping potential is effectively axially symmetric as assumed in the derivation of Eq. (1). The $\nu_z + \nu_m$ absorption has been vital in the present apparatus in continually radially pushing[10] the electron into the saddle point. Here the ν_m-sideband spectrum of the ν_c' resonance, Fig. 3(c), indicates that indeed the magnetron radius has been reduced to $\lesssim 50$ μm. This assures that the electron sees the same magnetic field throughout an entire run and helps stabilize the axial frequency.

The apparatus, as shown schematically in Fig. 1, makes use of two important prior experimental accomplishments. First, Wineland, Ekstrom, and Dehmelt[6] had shown that one single electron could be isolated in a Penning trap and that its forced axial harmonic motion could be detected. The trapped electron was obtained by ionizing a residual gas atom inside the trap with a 1-keV electron beam (< 50 nA) emitted from a field-emission cathode. Secondly, a specially compensated Penning trap, designed and tested by Van Dyck *et al.*,[11] was shown to yield a hundred times narrower axial resonant linewidth (one part in 10^7) than any previous trap. The frequency of this motion is determined by the applied ring-to-endcap potential. When this high-resolution trap is immersed in liquid helium, the excellent signal-to-noise ratio allows us to observe shifts in the axial resonance as small as 0.5 Hz out of 60 MHz. The trap's dc voltage, obtained predominantly from temperature-stabilized standard cells, is phase-locked to a frequency synthesizer by transforming the driven signal, available at the upper cap, into an additive correction voltage which reflects any frequency shift, $\delta\nu_z(t)$. The weak magnetic bottle obtained from a fine Ni wire wound concentrically around the ring electrode is shown in Fig. 1 for the case of $\delta = 1.0$ Hz. A supplementary large iron ring placed outside the vacuum envelope reinforces the Ni ring for the case of $\delta = 2.5$ Hz. For the excitation of the cyclotron resonance, it was convenient to mount a small Schottky diode outside the vacuum envelope, but near the gap between cap and ring. The diode, which acts simultaneously as a frequency multiplier and antenna, is driven from a stabilized $\nu_c'/6$ microwave source through a small coaxial lead.

The above apparatus was now used to measure ν_c' and ν_a' as simultaneously as feasible. (Since it is kept constant, ν_z is known throughout the experiment.) For $B_z = 18.3$ kG and $T = 4°$K, the electron spends about half the time in the $n = 0$ level. Thus, the $\delta\nu_z(t)$ signal will exhibit a very well defined $n = 0$ plateau with a series of positive spikes, as shown in Fig. 3(a) (corresponding to thermally excited cyclotron levels). The cyclotron resonance can be detected through the growth in the positive spikes upon irradiating the electron with the microwave antenna [see Fig. 3(b)]. In this way, the resonance has been measured in the limit of a very small axial drive, as shown in Fig. 3(c). This operation is necessary because of the B_2z^2 term in the magnetic field; the square of the small thermal and large drive amplitudes yields a cross term which effectively enhances the field jitter, thus producing broad resonances. Likewise, the average of the term yields a shift which is ≤ 0.1 ppm for weak locking drives (when $\delta = 1.0$ Hz). In addition, there are also the distinctive motional magnetron sidebands[2] [see Fig. 3(c)] which we attribute to a gradient associated with the twisted ends of the Ni wire producing the mag-

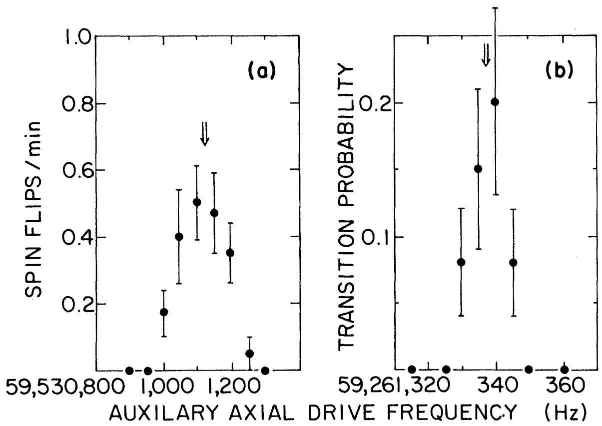

FIG. 4. Anomaly frequency resonances. (a) Data obtained for $\delta = 2.5$ Hz with continuous detection by counting $n = 0$ plateau changes (spin flips) in a fixed time interval (~ 20 min); (b) data obtained for $\delta = 1.0$ Hz with alternating detection by counting $n = 0$ plateau changes in ~ 20 alternating, 1-min excitation/detection time intervals. The error bars indicate counting statistics.

netic bottle. A recent method of alternately pulsing on the microwave and axial drive fields has been shown to reduce the line broadening to 0.1 ppm and to make any shift undetectable. As evident in Fig. 3(a), spin flips have been produced by the previously described mechanism, adjusted to create a rotating magnetic field of ~ 0.2 μG. During a typical anomaly run, there will be both a rf drive at the electron's axial resonant frequency, ν_z, used to lock the electron, and an off-resonance auxiliary axial rf drive near ν_a', used to induce spin flips. If both are on continuously, again the resonance is broad, as shown in Fig. 4(a). However, if the two drives are alternated in order to eliminate the enhanced magnetic field jitter, sharp resonances like that shown in Fig. 4(b) can be obtained.

The anomaly is computed using the measured ν_c' and ν_a' values and δ_e calculated from Eq. (1). The alternating method in the 1.0-Hz bottle typically yields an accuracy per run of ± 0.25 ppm using a linewidth as the limit of our uncertainty. [For a sample run, we had $\nu_c' = 51\,072\,915\,(10)$ kHz, $\nu_a' = 59\,261\,337.5\,(4.5)$ Hz, and $\nu_z = 59\,336$-$170.14\,(10)$ Hz.] The present average of eight runs to date using the 1.0-Hz bottle and the alternating method yields

$$a_e(\text{expt}) = (1\,159\,652\,410 \pm 200) \times 10^{-12},$$

where the error is the sum of the standard deviation from the average (± 100) and the estimated maximum systematic error in ν_c' (± 100). This accuracy is comparable to that obtained by quantum electrodynamic calculations. For three separate numerical determinations of the sixth-order terms in the anomaly,[12] $\{a_e(\text{expt}) - a_e(\text{theory})\}$ is 300 ± 650, -70 ± 310, and -960 ± 530 (all in units of 10^{-12}). Each of the theoretical errors includes ± 245 (in quadrature) contributed by the uncertainty of the fine-structure constant.[13] Our empirical dimensionless ratio $(\nu_s/\nu_c) = 1.001\,159\,652\,410\,(200)$ is the most precisely known characteristic parameter of an elementary particle! It may be compared with[14,15] $(\nu_s/\nu_c)_{\mu+} = 1.001\,165\,895\,(27)$ and $(\nu_s/\nu_c)_p = 2.792\,845\,600\,(1100)$, where it has been more difficult to develop adequate theoretical models. Future operation of our experiment at 60 kG promises a factor of 3 reduction in bottle broadening $\propto B_2/B_0$. In addition, with averaging and line splitting, accuracies of parts in 10^8 for the anomaly will become feasible with relativistic corrections still too small (order 10^{-9}) to be measured!

We thank the National Science Foundation for support.

[1]Descriptions of early work are given in the review article of A. Rich and J. Wesley, Rev. Mod. Phys. 44, 250 (1972).

[2]H. G. Dehmelt, in *Atomic Masses and Fundamental Constants 5* (Plenum, New York, 1976), p. 499.

[3]H. Dehmelt and F. Walls, Phys. Rev. Lett. 21, 127 (1968); preliminary anomaly data by F. Walls and T. Stein, Phys. Rev. Lett. 31, 975 (1973).

[4]H. Dehmelt and P. Ekstrom, Bull. Am. Phys. Soc. 18, 727 (1973); H. Dehmelt, P. Ekstrom, D. Wineland, and R. Van Dyck, Bull. Am. Phys. Soc. 19, 572 (1974).

[5]R. Van Dyck, P. Ekstrom, and H. Dehmelt, Bull. Am. Phys. Soc. 21, 827 (1976), and Nature (London) 262, 776 (1976).

[6]D. Wineland, P. Ekstrom, and H. Dehmelt, Phys. Rev. Lett. 31, 1279 (1973).

[7]A. A. Sokolov and Yu. G. Pavlenko, Opt. Spectrosc. 22, 1 (1967).

[8]This result holds well within the accuracy needed in this experiment even if the electric quadrupole and magnetic fields are misaligned to a much greater extent than is possible in our apparatus. (L. S. Brown, private communication.)

[9]Our scheme owes something to Stern and Gerlach and also to a proposal by F. Bloch, Physica (Utrecht) 19, 821 (1953), unrealized so far: L. Knight (1965), see Refs. 1, 2.

[10]To be discusses more fully in a later article; also see H. Dehmelt, Nature (London) 262, 777 (1976).

[11]R. S. Van Dyck, D. J. Wineland, P. A. Ekstrom, and H. G. Dehmelt, Appl. Phys. Lett. 28, 446 (1976).

[12]M. Levine and R. Roskies, Phys. Rev. D 14, 2191 (1976); M. Levine and J. Wright, Phys. Rev. D 8, 3171

(1973); R. Carroll, Phys. Rev. D 12, 2344 (1975); P. Cvitanovic and T. Kinoshita, Phys. Rev. D 10, 4007 (1974).

[13]P. T. Olsen and E. R. Williams, cited by Dehmelt, Ref. 2, p. 538.

[14]J. Bailey *et al.*, Phys. Lett. 55B, 420 (1975).

[15]Least-squares adjusted; see E. R. Cohen and B. N. Taylor, J. Phys. Chem. Ref. Data 2, 663 (1973).

Possible Deviations from Simple Quark-Parton Models in High-Energy Antineutrino Differential Distributions*

B. C. Barish, J. F. Bartlett, A. Bodek, K. W. Brown, D. Buchholz,† F. Jacquet,‡ F. S. Merritt, F. J. Sciulli, L. Stutte, and H. Suter§
California Institute of Technology, Pasadena, California 91125

and

H. E. Fisk and G. Krafczyk
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 19 August 1976)

We have analyzed differential distributions for a sample of high-energy ν and $\bar{\nu}$ interactions. The antineutrino data require more antiquark component than expected from low-energy results. Also, some hints of energy-dependent effects have been observed in these distributions.

Charged-current neutrino (antineutrino) interactions $[\nu\ (\bar{\nu}) + N \rightarrow \mu^-\ (\mu^+) + \text{hadrons}]$ have long been recognized as providing fundamental information about nucleon structure. From a combination of deep-inelastic electron scattering experiments at Stanford Linear Accelerator Center[1] and studies of neutrino interactions at CERN[2] a rather simple description of this structure has emerged.

Basically, the low-energy data agree with an interpretation incorporating both a scaling hypothesis for the structure functions and the predictions of a simple quark-parton model. In this model, scattering dominantly occurs from pointlike, spin-$\frac{1}{2}$, fractionally charged constituents. Early studies of neutrino and antineutrino interactions at the higher energies of Fermilab have shown striking *qualitative* agreement with this same picture.[3]

The forms of the differential cross sections for an isoscalar target in this quark-parton model are given by

$$\frac{d^2\sigma^\nu}{dx\,dy} = \frac{G^2 M E_\nu}{4\pi}[q(x) + (1-y)^2\bar{q}(x)] \tag{1}$$

and

$$\frac{d^2\sigma^{\bar{\nu}}}{dx\,dy} = \frac{G^2 M E_{\bar{\nu}}}{4\pi}[\bar{q}(x) + (1-y)^2 q(x)], \tag{2}$$

where $x = Q^2/2ME_h$, $y = E_h/E_\nu$, M is the nucleon mass, and E_h is the energy transfer to hadrons in the laboratory system. The incident neutrino energy is $E_\nu = E_h + E_\mu$ and $Q^2 = 4E_\nu E_\mu \sin^2\theta/2$ is the square of the four-momentum transfer. Here E_μ and θ_μ are the laboratory final-state energy and scattering angle of the muon. The structure functions $q(x)$ and $\bar{q}(x)$ are related to the quark and antiquark momentum distributions in the nucleon. At low energies the antiquark component has been determined to be small and confined to small x.[2] This leads to the qualitative predictions that (1) $d\sigma^\nu/dy \sim$ flat and $d\sigma^{\bar{\nu}}/dy \sim (1-y)^2$, (2) the total cross sections σ_ν and $\sigma_{\bar{\nu}}$ grow linearly with energy, and (3) $\sigma^{\bar{\nu}}/\sigma^\nu \sim \frac{1}{3}$.

There are theoretical conjectures which would alter this picture. For example, the functions $q(x)$ and $\bar{q}(x)$ could have some Q^2 dependence, or there could be finite non-spin-$\frac{1}{2}$ contributions of the form $K(x, Q^2)(1-y)$. Energy-dependent effects could also arise from production (beyond some threshold) of new leptons or of hadrons composed of new quarks.

In this Letter we report on the observation of deviations from predictions of the simple quark-parton model. The data were taken with use of the California Institute of Technology–Fermilab apparatus and a narrow-band neutrino beam. The experiment was performed with short-spill (~1-msec) extraction from the accelerator (in order to do a neutral-current experiment simultaneously). The use of this short spill made it impossible to measure directly either the neutrino or antineutrino flux. This represents a serious limitation in the data sample since the absolute cross sections have not been measured and even the determination of the relative normal-