Sidney W. Barnes, and the helpful assistance of Mr. Lawrence Ota.

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PRECISE DETERMINATION OF THE MUON MAGNETIC MOMENT*

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When the existence of polarized meson beams and the anisotropic electron emission in decay was first detected,[1] it became possible to measure accurately the magnetic moment of the μ meson. This was first accomplished by a precession technique[1,2] to an accuracy of 0.7%, and to 0.06% by the resonance method,[3] which uses a radio-frequency magnetic field to induce transitions of the muon spin from a state of alignment to one of antialignment (or vice versa). The latter technique does not lend itself to use for experiments of improved accuracy at higher frequencies because of the large rf field required. A stroboscopic method was adopted,[4] in which the muon is brought to rest with its spin perpendicular to a magnetic field, H. The counting rate of the decay electrons in a particular direction varies in time as $\exp(-t/\tau)(1+a\cos\omega_H t)$, where a is the usual experimental electron asymmetry, τ the muon mean life, and ω_H, the rate of muon precession, is equal to $geH/2mc$, where m is the muon mass, e the electronic charge, c the speed of light, and g the muon g-factor. By use of a higher precession frequency and by a different method of utilizing time information of the muon decay, the experiment described in this Letter achieved a muon moment accuracy of 0.007%.

Early experiments[2-5] displayed directly on a pulse-height analyzer (using a time-to-pulse-height converter) the electron counting rate vs time. More accuracy (which means higher fields since the frequency uncertainty is fixed by the muon mean life) requires some method of folding the sinusoidally modulated decay curve into the memory of a pulse-height analyzer and of achieving better linearity than is possible with an analog time-to-pulse-height converter. The natural approach is to use a reference oscillator as in the resonance method, or as one input to a coincidence circuit whose other input is the electron count.[4] In the latter case a resonance curve is generated by the coincidence rate as the field or reference oscillator frequency is varied, although serious attention must be paid to reduce the systematic errors below the possible accuracy of this technique.

In this experiment a cw oscillator was used to measure both the muon and decay-electron times, modulo the period of the reference oscillator (86.200 Mc/sec). That is, one measures both the muon and electron phase with respect to this cw stable oscillator. The phase difference is generated electronically and stored in one of 10 channels of the pulse-height analyzer. If the reference frequency, ω, were exactly equal to the muon spin precession frequency, then the distribution-in-phase $[n(\phi)]$ for electrons emitted during a single period (of the 86.2-Mc/sec oscillator) occurring at delay time T, is independent of T. For $\omega_H \neq \omega$, $n(\phi)$ becomes $n(\phi+\alpha)$, i.e., retains its functional form but is shifted along the ϕ axis by an amount $\alpha=(\omega_H-\omega)T$. Thus a measurement of α vs T gives $\omega_H-\omega$ and thus ω_H itself.

The electrons are grouped into two time intervals. Those immediately following the stopping of the muon are referred to as the early electrons. The remainder are referred to as the late electrons. The average $n(\phi)$ for these two groups are displayed separately, and α determined for each. The quantity $(\alpha_{\rm early}-\alpha_{\rm late})$ is then a direct measure of $\omega_H-\omega$. This subtraction procedure has the important advantage of canceling out systematic errors due to uncertainties in the starting phases.

Figure 1 shows the counter, absorber, and target arrangement. An incoming μ meson is defined by a $123\bar{4}$ coincidence which serves to open a 2×10^{-7}-sec gate for the fast counter pulse in the μ timing channel and a 6-μsec gate that permits a 2×10^{-7}-sec gate to be opened by a decay electron in the electron channel. A forward emitted electron is defined by a $\bar{1}345$ coincidence, a backward one by a $23\bar{1}\bar{4}$ coincidence. Either of

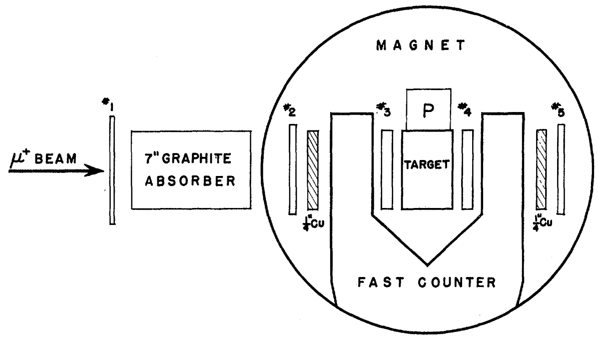

FIG. 1. Experimental arrangement. P=nuclear magnetic resonance probe.

these events opens the electron timing channel but the information obtained is routed to different places in final storage.

A block diagram of the time-analyzing equipment is shown in Fig. 2. The phases of the fast counter pulses for μ's and electrons relative to the free-running 86-Mc/sec source are automatically determined by beating pulsed 85-Mc/sec oscillators against the 86-Mc/sec signal and measuring the starting phase of the beat note. The 85-Mc/sec oscillators are triggered by overclipped fast counter pulses put through a zero-crossing detector to obtain a time independent of pulse height. Our timing accuracy is better than $\pm 5\times 10^{-10}$ second. Suitable delays and gates are included to remove the effects of starting transients. The pulsed oscillators are used only for phase determination so that their phase and frequency stability are not important. A condenser ramp is charged with the μ phase and discharged with that of the electron, thus obtaining an output phase whose height is proportional to $\phi_\mu - \phi_e$. The output is stored in a Penco 100-channel pulse-height analyzer which had been modified so that it was used as four 10-channel analyzers. The output pulse was addressed to the appropriate group of channels depending on whether it was emitted in the forward or backward direction and whether it occurred early or late in the gate interval.

Measurements were performed at several frequencies on either side of resonance. A plot of $\alpha_{\text{early}} - \alpha_{\text{late}}$ was obtained as a function of the magnetic field in which the μ precesses. This is a nearly linear curve whose intercept, $\alpha = 0$, corresponds to the magnetic field at which $\omega_\mu = \omega$. This obviates the necessity of knowing accurately the timing intervals for the early and late electrons. The results of our measurements are given in Table I in terms of the ratio of the

Table I. Ratio of the resonant frequency of the μ meson to that of the proton in water in the same magnetic field.

Target	Measured f_μ/f_p	After correction for Knight shift
Aluminum	3.1850±0.0002	3.1847±0.0003
Copper	3.1850±0.0002	3.1848±0.0003
Bromoform	3.1846±0.0002	3.1846±0.0002

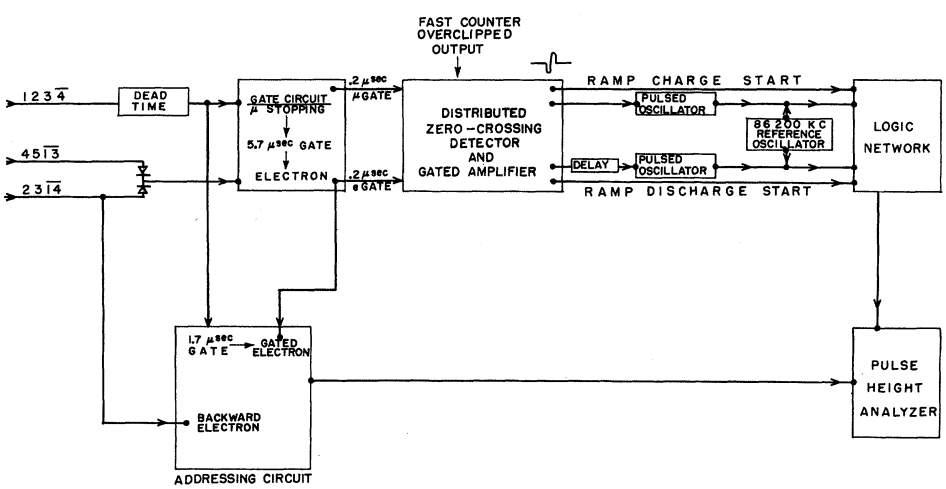

FIG. 2. Block diagram of electronics.

resonant frequency of the μ meson to that of the proton in water in the same magnetic field. The results for copper and aluminum are corrected by a rough calculation of the Knight shift[6] and then agree with that for $CHBr_3$ in which there should be no diamagnetic shift to the accuracy quoted. It should be noted that our result for aluminum disagrees with that of the Chicago group[4,7] to about twice their stated error.

Using our result for $CHBr_3$ and the value for the μ-meson mass given by Crowe,[8] the g-factor is found to be $2(1.0020 \pm 0.0005)$ as compared to $2(1.00116)$ as predicted by theory. Of even greater interest is the lower limit for the μ-meson mass given by Crowe from a determination of μ-mesonic x-rays[9] of $(206.77 \pm 0.04)m_e$. This yields $g > 2(1.00154 \pm 0.00022)$ which is also in disagreement with theory. It should be noted that the error arises mostly from the measurement of the mass which stems from uncertainty in the calculation of the vacuum polarization correction.

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NEUTRAL CASCADE HYPERON EVENT*

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The existence of a neutral cascade hyperon Ξ^0 has been predicted theoretically,[1] on the basis of the strangeness theory of Gell-Mann and Nishijima, as the neutral counterpart of the negative cascade hyperon,[2] Ξ^-, which decays by $\Xi^- \to \pi^- + \Lambda$.

In an attempt to establish the existence of this particle the Lawrence Radiation Laboratory 15-inch hydrogen bubble chamber was operated in a separated beam of (1.15 ± 0.02)-Bev/c K^- mesons produced by the Bevatron. Two Cork-Wenzel-Lambertson parallel-plate spectrometers[3] were used to remove pions from the beam. Typical operating conditions gave ≈ 1.5 K^-, ≈ 0.2 π^-, and ≈ 4.5 beam μ^- mesons per picture.[4] The total number of K^- mesons through the chamber was about 10^5.

A large number of K^- interactions in hydrogen were observed; among them were some 500 single V^0 events, resulting from the reactions

$$K^- + p \to \bar{K}^0 + n, \tag{1a}$$

$$K^- + p \to \Lambda + \pi^0, \tag{1b}$$

$$K^- + p \to \Sigma^0 + \pi^0. \tag{1c}$$

In any of these, additional π^0 mesons may also have been produced.

On the other hand, only seven double V^0 events were observed. Since the reactions (1) lead only to single V^0's, whereas associated production by π^- mesons leads to double V^0's in about 20% of the interactions, the strikingly small ratio of double V^0 events to single V^0 events again shows that we are dealing principally with K^- interactions.

Six of the double V^0's were clear cases of associated production by π^-, five being

$$\pi^- + p \to \Lambda + K^0, \tag{2a}$$

and one

$$\pi^- + p \to \Sigma^0 + K^0, \quad \Sigma^0 \to \Lambda + \gamma. \tag{2b}$$

Most of these were produced by pions of some-