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PRECISE MEASUREMENTS OF MUON MAGNETIC MOMENTS BY "STROBOSCOPIC COINCIDENCES"*

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The recently proposed[1] technique of "stroboscopic coincidences" has been applied successfully here to the measurement of the magnetic moments of positive and negative muons. These measurements were performed in magnetic fields of ~300 gauss and ~3700 gauss corresponding to muon precession frequencies, f_μ, of about 4 Mc/sec and 48 Mc/sec, respectively. Only the experimental technique used at 48 Mc/sec will be described in what follows, with reference to Fig. 1.

This figure shows a section, perpendicular to the pole faces, through the gap of a large permanent magnet. Two coils S, fed from storage batteries, enable one to vary the field by ±1%. The muons, obtained from a 66-Mev "pion" beam by means of a Cu absorber (26 g/cm^2) placed within the aperture of a collimator C, are incident along the direction perpendicular to the field $\vec{B}$, as indicated by an arrow. They are stopped in a target T of ~8 g/cm^2 thickness and roughly cubical shape. Both graphite and $CHBr_3$ were used as targets, the latter in a brass box of 0.1 g/cm^3 wall thickness. Four scintillation counters are used; the scintillators of these, indicated by the rectangles 1 through 4, are connected by long light-pipes to magnetically well-shielded photomultipliers. The entry of a muon is detected by a $12\bar{3}$ coincidence, while the decay

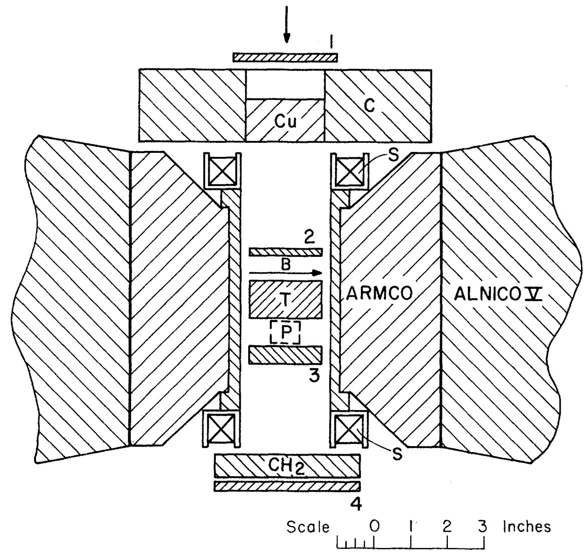

FIG. 1. Experimental set up used in 48-Mc/sec experiments. 1,2,3,4: plastic scintillators; T: target; P: Proton resonance probe location; S: coils: C: lead collimator. B~3700 gauss. Muon flux: 150/sec.

electron may be identified by a $\bar{2}34$ coincidence. The $12\bar{3}$ combination is formed in a fast coincidence circuit. Its output pulse turns on a phase-stable oscillator which then rings for 6 μsec at a frequency, f_{osc}, of 48.63 Mc/sec. This train of rf pulses is fed to two twofold coincidence circuits that respond to negative inputs only. We shall call these circuits "R" and "AR"; their second inputs consists of the pentode-limited output of counter 3, clipped to about three mμsec, but are delayed by different times. These delays are in general so chosen (on the basis of delay curves obtained with the target T removed) that a pulse from counter 3, physically simultaneous with a pulse from counter 2, reaches "R" at the center of one of the early positive rf half-cycles and "AR" half a cycle later. Thus the output counting rate of "R" goes through a maximum ("resonance") and that of "AR" through a minimum ("anti-resonance") when $f_\mu = f_{osc}$. The outputs of "R" and "AR" are fed, after clipping, to two additional coincidence circuits, "SR" and "SAR", respectively, for futher selection. "SR" requires the combination R4$\bar{2}$, "SAR" the combination (AR)4$\bar{2}$. All five coincidence circuits are of the Garwin design,[2] but are followed by fast triggers[3] which are remarkably jitter-free.

In the experiment, B was varied and monitored through the frequency, f_P, induced in a small proton resonance probe[4] reproducibly located with respect to the target T. The ratio of "SR" and "SAR" coincidences was plotted vs the ratio f_{osc}/f_p; a typical plot, obtained in a $CHBr_3$ run, is shown in Fig. 2. Except for a slight difference between the mean value, $\langle B(T)\rangle$, of the field over the target T, and its value, B(P), at the probe position P, the location of the maximum in Fig. 2 gives directly f_μ/f_P. The following sources of

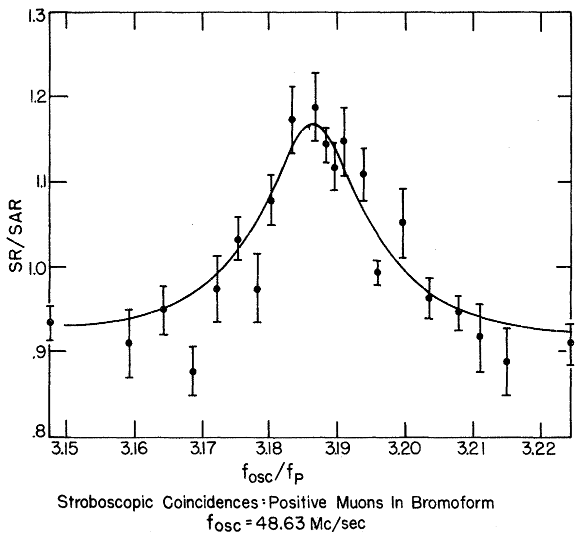

FIG. 2. Stroboscopic coincidences obtained with μ^+ with the setup of Fig. 1. Target: $CHBr_3$. SR/SAR: see text. f_{osc}/f_p = oscillator frequency/proton resonance frequency. f_{osc} = 48.63 Mc/sec.

error need to be considered:

(a) Uniformity and stability of B: A careful survey of the relevant gap volume with a proton resonance probe showed a maximum deviation of 0.11%. $B(P)/\langle B(T)\rangle$ can be estimated with 0.01% error. The stability was checked by measuring B(P) during runs and exceeded 0.01%.

(b) Uncertainty in fp: This frequency could be determined, by beating against the fifth harmonic of a frequency meter[5], with an error of less than 0.01% in a single measurement.

(c) Stability of, and uncertainty in, f_{osc}: The magnitude of f_{osc} was determined, at the beginning and at the end of each measurement at a given f_P, by a beat technique similar to that of Coffin et al.[6] The mean value of f_{osc} for a complete run could be determined to 0.01%, and deviations from this mean did not exceed 0.02%.

(d) Uncertainties in "line shape" and curve fitting: The shape of the "resonance" curve such as fitted to the data in Fig. 1 was first carefully studied in low-field (300 gauss) experiments, and was found to agree quantitatively with theoretical predictions.[1] The high-field data showed half-widths Γ exceeding the theoretical value of 0.3%. This effect was less marked in $CHBr_3$ ($\Gamma \sim 0.6\%$) than in graphite[7] ($\Gamma \sim 1.0\%$), and is attributed to microscopic causes. Using a true resonance technique, Coffin et al.[6] also found appreciable broadening in $CHBr_3$. The theoretical shape was hence fitted to the experimental points, leaving Γ as an adjustable parameter. The fitting error for each run is estimated to be $\leq 0.06\%$.

For positive muons, we obtain from three independent runs with $CHBr_3$ targets, involving a total of 4.0×10^5 positron counts, the following results:

$$f_{\mu^+}/f_P = 3.1830 \pm 0.0011. \qquad (1)$$

Using Crowe's[8] best estimate of the μ^+ mass, $m_{\mu^+} = (206.86 \pm 0.11)\ m_e$, we compute from (1)

$$g_{\mu^+} = 2(1.0015 \pm 0.0006), \qquad (2)$$

which is to be compared with the theoretical value $g_{\mu^+}{}^{th} = 2(1.0012)$ calculated[9] on the assumption that quantum electrodynamics is valid down to the distances involved[10]. Conversely, accepting $g_{\mu^+}{}^{th}$, we can compute m_{μ^+}, and find

$$m_{\mu^+} = (206.81 \pm 0.08)\ m_e. \qquad (3)$$

This value agrees with Crowe's best estimate and satisfies the inequality

$$m_{\mu^+} \geq (206.77 \pm 0.03) m_e, \qquad (4)$$

which is imposed by the results of Koslow et al[11] if one postulates that $m_{\mu^+} \equiv m_{\mu^-}$.

Our results are, within the stated errors, in agreement with those recently obtained at Columbia,[6] although the latter slightly violate inequality (4).

To date, we have completed analogous measurements on μ^- only in a 300-gauss setup (f_{osc} = 3.945 Mc/sec). The data, obtained with a graphite target placed at the center of a Helmholtz coil but in circumstances otherwise similar to those described above, are plotted in Fig. 3. They yield

$$f_{\mu^-}/f_P = 3.176 \pm 0.013, \qquad (5)$$

or

$$g_{\mu^-} = 2(0.9993 \pm 0.0042), \qquad (6)$$

where the 0.05% uncertainty in m_{μ^-} has been included, but Knight shift and Breit-Margenau corrections[12] have been omitted. The presentation of these data is justified by the fact that the

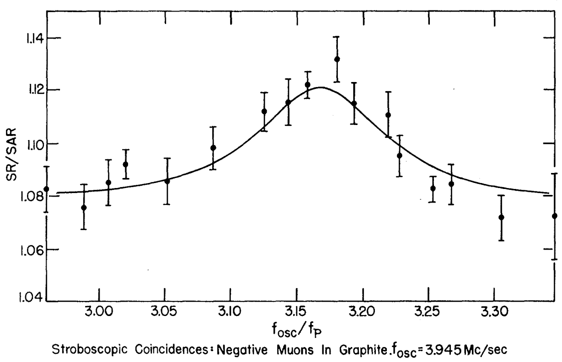

FIG. 3. Stroboscopic coincidences obtained with μ^- in a field of about 300 gauss. Target: graphite. SR/SAR: see text. f_{osc}/f_P = oscillator frequency/proton resonance frequency (f_{osc} = 3.845 Mc/sec).

only published[13] value of f_{μ^-} has an uncertainty of ± 5%.

We are greatly indebted to Professor M. Schein for the loan of a permanent magnet, and to Mr. M. Pyka for able assistance in data taking.

A full account of the novel technique, including many variants not mentioned here, is being prepared.

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REST MASS OF THE NEUTRINO*

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Although the rest mass of the neutrino has been measured to be small by experimentalists[1,2] and assumed to be zero by most theoreticians,[3] it seems worthwhile to examine the old problem of the neutrino mass in the light of recent advances in β-decay physics. Firstly, we investigate the role played by the vanishing mass of the neutrino in the current theories of parity-nonconserving weak interactions. Secondly, we point out modifications necessary in estimating the neutrino mass from the shape of the β spectrum when parity is not conserved. In particular, we show that it is impossible to determine the neutrino mass from the energy difference between the H^3-He^3 mass difference and the *extrapolated* end-point energy in the β decay of H^3, and that the recent results of Friedman and Smith[4] based on such a subtraction procedure throw no light on the neutrino mass.

As is well known, the two-component theory of the neutrino as formulated by Salam,[5] by Landau,[6] and by Lee and Yang[7] rests upon the hypothesis that the neutrino mass is *strictly* zero. Meanwhile, Case[8] has shown that the physical consequences of the two-component theory are indistinguishable from those of a special case of the Majorana theory with a parity-nonconserving Hamiltonian, and has pointed out an interesting relation between the rate of double β decay, the degree of parity nonconservation, and the mass of the neutrino.

Recently, what we may call the universal VA theory has been proposed by several authors.[9-11] The fundamental postulates of this theory (in various equivalent formulations) treat the neutrino and the electron (as well as other fermions) on an equal footing irrespective of the mass of the fermion in question. Although the neutrino mass can vanish, it does not have to vanish, and the fact that $1+\gamma_5$ appears in front of the neutrino field has nothing to do with the vanishing