that an increasing regularity will occur in going towards heavier nuclei, so that the coherent effects can become strong enough to shift the dipole transitions up several Mev. The schematic model is, of course, no substitute for detailed calculations, but indicates the possibility of these coherent effects in a simple way.

---

*Supported in part by the U. S. Atomic Energy Commission.

†Permanent address: Mathematical Physics Department, University of Birmingham, Birmingham, England.

[1] P. Jensen, Naturwiss. 35, 190 (1948).

[2] E. D. Courant, Phys. Rev. 82, 703 (1951).

[3] D. H. Wilkinson, Physica 22, 1039 (1956).

[4] G. E. Brown and J. S. Levinger, Proc. Phys. Soc. (London) A71, 733 (1958).

[5] Schiffer, Lee, and Zeidman (to be published).

[6] Cohen, Mead, Price, Quisenberry, and Martz (to be published).

[7] See, especially, the so-called "degenerate model" for pairing interactions, developed mainly by B. Mottelson, which will appear in an account of the Copenhagen work.

[8] J. P. Elliott and B. F. Flowers, Proc. Roy. Soc. (London) A242, 57 (1957).

[9] This was pointed out to one of the authors by Professor G. Breit.

ANGULAR DISTRIBUTION OF NEUTRONS FOLLOWING THE NUCLEAR CAPTURE OF POLARIZED MUONS

A. Astbury, I. M. Blair, M. Hussain, M. A. R. Kemp, H. Muirhead, and R. G. P. Voss*
Nuclear Physics Research Laboratory, University of Liverpool, Liverpool, England
(Received October 5, 1959)

Measurements[1,2] of the total capture rates of negative muons in complex nuclei have indicated that the magnitudes of the squares of the coupling constants must be about the same size as those in the processes of β and μ decay. Previous results have not shown, however, whether parity conservation is violated in the interaction, and, until recently,[3] no evidence has existed concerning the relative signs of the coupling constants.

In order to examine some of these problems the authors have attempted to measure the angular distribution of the neutron about the direction of muon spin in the process

$$\mu^- + p \rightarrow n + \nu.$$

An asymmetry in this distribution would provide clear evidence of parity nonconservation. In addition, various authors[4-7] have shown that the value of the asymmetry coefficient α in the expression for the angular distribution,

$$D(\theta) = 1 + \alpha\, \vec{\sigma}\cdot\vec{p}/|\vec{p}|, \qquad (1)$$

is dependent upon the relative signs and magnitudes of the coupling constants (here $\vec{\sigma}$ represents the muon spin vector, and $\vec{p}$ the neutron momentum).

The experimental arrangement is shown in Fig. 1. The negative meson beam, of momentum 190 Mev/c, from the Liverpool synchrocyclotron was moderated by an appropriate amount of polythene so that the muons were brought to rest in the target. Pions stopped in the absorber between counters 2 and 3. The target was S^{32}; this was chosen in order to provide a sufficient number of neutrons, and to avoid complete depolarization of the muon beam.[8]

The arrival of a muon was signalled by the coincidence sequence $23\bar{4}$, and the emission of a neutron by $\bar{1}\bar{3}\bar{4}5$ (referred to hereafter as "start" and "stop" events, respectively). Counter 5 was of a type developed by Brooks,[9] and was used in order to discriminate against the γ rays emitted following muon capture. This discrimination is essential, since the rate of emission of γ rays is comparable to that of neutrons.[2] The counter had an average efficiency for the detection of neutrons in the energy range of 4 - 15 Mev of

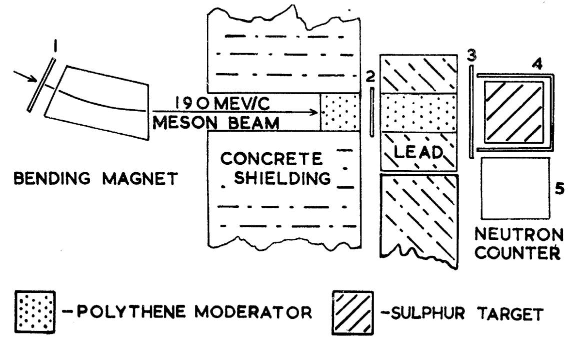

FIG. 1. Experimental arrangement.

~10%, and for γ rays up to 5 Mev of <0.5%.

The time interval between the start and stop pulses was measured by an analog converter (timesorter), which delivered pulses whose height was proportional to the time interval, to a 180-channel pulse-height analyzer (kicksorter). The stop pulses were delayed by 0.6 μsec with respect to the start pulses, thus the pulse heights corresponding to the first 0.6 μsec provided a direct measurement of the occurrence of random events and were displayed in the early channels of the kicksorter pattern.

A magnetic field was applied perpendicular to the plane defined by the centers of counters 2, 3, and 5, and caused the muon spin to precess in this plane. In this way any asymmetry in the direction of emission of the neutrons about the spin direction of the muons would be observed as a sinusoidal modulation of the characteristic muon decay curve for S^{32}, and it would yield a pattern on the pulse-height analyzer of the form

$$F(t) = N_0 e^{-t/T}[1+\alpha\phi P\cos(\omega t+\delta)]+B. \quad (2)$$

Here T represents the muon lifetime in S^{32}, P the muon polarization before capture, δ a phase factor, $\omega = geH/2mc$ (the symbols have the usual significance), and B is the random background. ϕ is a factor due to the geometry of the apparatus and the presence of evaporation neutrons. In the conditions of the experiment, N_0/B was found to be 2.7.

In order to reduce the background from undesirable sequences of start and stop events, the following precautions were taken. Electrons were present as a contamination in the meson beam. The pulses produced by them in counter 3 were smaller than those from muons, and were therefore rejected by a pulse-height discriminator in the starts channel. In the stops channel all pulses from counter 3 were accepted; counters 3 and 4 together provided 4π geometry in which to veto electrons from muons which decay.

In order to avoid most of the evaporation neutrons, which would yield an isotropic angular distribution, a pulse-height discriminator was used in counter 5. In this way neutrons were rejected when their recoil protons dissipated less than 3 Mev in the scintillator.

An analysis of the experimental data gave a value of 0.46 ± 0.05 μsec for T; this figure is in agreement with existing values.

In Fig. 2 the experimental results are displayed in the form $[F(t) - B]e^{t/T}$. A weighted least-squares fit to the data yielded values of $-(4.5 \pm 1.5)$% for the quantity $\alpha\phi P$ of Eq. (2) and $+(4° \pm 19°)$ for δ (in determining δ allowance has been made for the position of counter 5 with respect to the muon beam). The polarization P may be determined by measuring the asymmetry of the decay electrons; the results of the experiment described in reference 8 yield a value of $P(= 15 \pm 4\%)$ for this quantity, and thus the term $\alpha\phi = -(0.30 \pm 0.12)$. Since the quantity ϕ must be less than unity this figure represents a lower limit for the value of α. The contribution to ϕ arising from the geometry of the apparatus involves a negligible correction factor (0.99); that due to the presence of the evaporation neutrons is larger and more difficult to fix. A rough estimate for the latter effect has been made using the calculated data of reference 4, and the parameters for neutron evaporation given by Lang and Le Couteur[10]; this yielded a figure of ~0.7. Thus the quantity α is ~ -0.4.

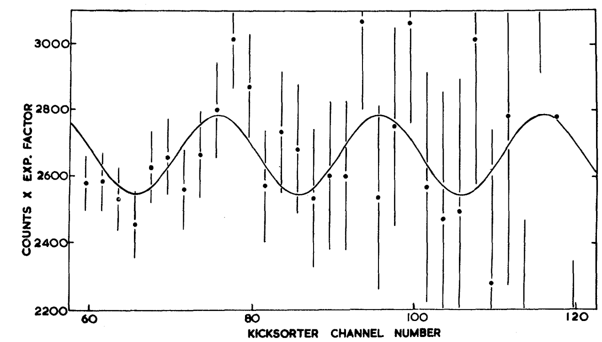

FIG. 2. Plot of the experimental points $[F(t) - B]e^{t/T}$ [see Eq. (2)] versus time t (kicksorter channel). The solid line represents the fitted curve. The kicksorter channels not displayed (prior to No. 60) contain data on the background for 0.6 μsec before zero time, together with a short "blurred" region (~ 0.4 μsec) about the position of zero time.

Since the error is large this result must be treated with some caution. A more accurate experiment is in progress. The result does suggest, however, that parity is not conserved in the muon capture process. Furthermore, since the helicity of the negative muon is almost certainly positive,[11] a comparison of the negative sign and the magnitude of the measured asymmetry coefficient with the theoretical forms for α suggests that there could be some enhancement of the Gamow-Teller part of the coupling constant, either through renormalization or Pauli effects.

Alternatively the large negative value for α could arise through an interference effect, if the signs of the Gamow-Teller and induced pseudoscalar coupling terms in the interaction Hamiltonian were the same. The last conclusion is supported by the theory of Goldberger and Treiman,[12] and by the analysis of Primakoff[5] of the capture rate of muons in C^{12}.

The authors wish to thank F. D. Brooks of the Atomic Energy Research Establishment, Harwell, without whose assistance this experiment would not have been possible.

*Now at CERN, Geneva 23, Switzerland.
[1]Astbury, Kemp, Lipman, Muirhead, Voss, Zangger, and Kirk, Proc. Phys. Soc. (London) 72, 494 (1958).
[2]J. C. Sens, Phys. Rev. 113, 679 (1959).
[3]V. L. Telegdi, Proceedings of the Kiev Conference, 1959 (unpublished).
[4]E. I. Dolinsky and L. D. Blokhintsev, Nuclear Phys. 10, 527 (1959).
[5]H. Primakoff, Revs. Modern Phys. 31, 802 (1959).
[6]H. Überall, Nuovo cimento 6, 533 (1957).
[7]L. Wolfenstein, Nuovo cimento 8, 882 (1958).
[8]Ignatenko, Egorov, Khalupa, and Chultem (to be published).
[9]F. D. Brooks, Atomic Energy Research Establishment, Harwell Report NP/GEN 8, 1959 (unpublished).
[10]J. M. B. Lang and K. J. Le Couteur, Proc. Phys. Soc. (London) A67, 586 (1954).
[11]Culligan, Frank, and Holt, Proc. Phys. Soc. (London) 73, 169 (1959).
[12]M. L. Goldberger and S. B. Treiman, Phys. Rev. 111, 355 (1958).

PION MASS MEASUREMENTS USING NEUTRON TIME-OF-FLIGHT TECHNIQUES*

Roy P. Haddock, Alexander Abashian, Kenneth M. Crowe, and John B. Czirr
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received October 26, 1959)

Measurements of the speeds of neutrons emitted in the capture at rest of π^- mesons in hydrogen provide an excellent method for the determination of mass values for the π^- and π^0 mesons. Using energy balance of the reactions

$$\pi^- + p \rightarrow \gamma + n \ (8.8 \text{ Mev}) \quad (1)$$

$$\searrow \pi^0 + n \ (400 \text{ kev}), \quad (2)$$

we can deduce the mass of the π^- through Reaction (1) and the π^-, π^0 mass difference through Reaction (2). Results obtained by using time-of-flight techniques to measure the neutrons' speeds have already been reported by Gettner et al.[1] and Hillman et al.[2] for flight paths of 2 to 5 ft. This Letter reports preliminary results of our measurements for flight paths of 12.44 ft and 17.50 ft with similar techniques.

Figure 1 is a simplified schematic diagram of the experimental setup and electronics. The 110-Mev pions produced by an internal target of the 184-in. cyclotron were collimated into a 2-in.-high by 8-in.-wide beam; slowed down in carbon; counted by a 1-in.-thick plastic scintillator (π counter), 1.5 in. high by 8 in. long; and stopped in a liquid hydrogen target. The hydrogen flask was a horizontal cylinder 1 in. high and 12 in. in diameter. Neutrons, which travel downward, were detected in a plastic scintillator 18 in. in diameter, 1 in. thick, viewed by seven RCA 7046 photomultipliers, through a 1-in. Lucite light pipe. Photons, from Reaction (1) and π^0 decay, which go upward, convert in a 1/4-in.-thick Pb sheet, 20 in. in diameter, 10 in. from the center of the target, and are detected by a coincidence between two plastic scintillators, each 3/8 in. thick (γ counters).

The electronics (see Fig. 1) is composed of two fast coincidences followed by a slow coincidence. One coincidence is between the π and γ counters and another is between the dynode signals of two sets of tubes of the neutron counter—the latter coincidence mode to reduce

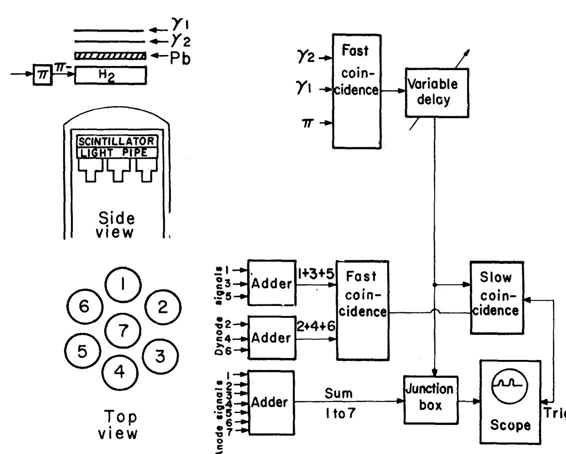

FIG. 1. Experimental arrangement.