decreases rapidly as the energy increases due to the decrease of γ_0. At about 20 Mev γ_0 and γ_1 are of the same order of magnitude and the forward maximum has totally disappeared. As the energy increases still more, γ_1 becomes larger than γ_0 and at the same time γ_2 comes into play. We get again a forward maximum. The forward polarization, however, is now positive. The backward maximum decreases slightly and shifts to somewhat smaller angles as the energy increases. In Fig. 2 the polarization of the proton as well as of the neutron is given for 80.4-Mev γ rays.

The difference between the proton and neutron polarization at lower energies is mainly due to the $M1$-$E2$ interference and at higher energies mainly to the $E1$-$E2$ interference. The neutron polarization is more negative (less positive) at small angles and less negative at large angles. The maximum difference occurs near the maxima of the polarization and is 2% at 9.3 Mev, 5% at 22.4 Mev, and 7% at 80.4 Mev.

We would like to thank Dr. P. S. Signell, Dr. P. J. Eberlein, and Mr. R. A. Bryan for their help with the numerical computations. J. J. deS. wishes to thank Professor R. E. Marshak for his guidance and stimulation in many discussions during the course of this work, and W. C. wishes to thank Professor N. Bohr and Professor A. Bohr for hospitality at the Institute for Theoretical Physics, University of Copenhagen, Denmark.

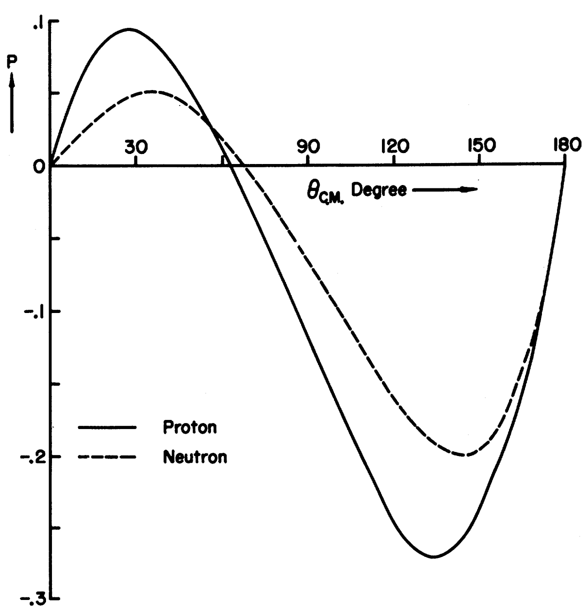

FIG. 2. Neutron and proton polarization at γ-ray energy in the lab of 80.4 Mev.

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[8] The signature of $P(\theta)$ is opposite to the present one if the convention $\hat{n}=\vec{k}\times\vec{\pi}/|\vec{k}\times\vec{\pi}|$ of reference 1 is used.

ELECTRON DECAY OF THE POSITIVE PION*

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In a previous communication[1] from this laboratory an unsuccessful search for the electronic decay mode of the pion was reported which made it seem unlikely that the branching ratio $f=(\pi\rightarrow e+\nu)/(\pi\rightarrow\mu+\nu)$ could be much larger than 2×10^{-5}. The remarkable success of the A-V theory[2,3] in accounting correctly for many related phenomena had raised doubt about our failure to observe this process. Accordingly, we decided to make a new attempt, and this effort was accelerated when we learned of the successful observation of the electronic mode by the CERN group[4] and by Steinberger.[5]

Our new work confirms the existence of the π-e mode in an amount not very different from the value 1.28×10^{-4} predicted by the universal A-V theory (without radiation correction).[6] We also know that additional confirmations have been obtained from experiments similar to ours which are in progress at Stanford[7] and Berkeley.[8] We report here our evidence and our present best estimate of the value of the branching ratio.

We used the same method and much of the same apparatus as in the previous experiment but incorporated a few improvements which served to increase the ease and certainty of detecting the electrons from π-decay. The same double-focussing magnetic spectrometer was used to select the π-electrons of energy E_π = 69.8 Mev and to distinguish them from those originating from μ-decay which have maximum energy E_μ = 52.9 Mev. It was modified to accommodate three detectors, admitting thereby simultaneous measurements in three adjacent momentum channels.

Pions of energy 70 Mev entered our spectrometer through counters 1 and 2, were moderated in polyethylene, and came to rest in the source counter 3. Electrons emerging from counter 3 with the proper energy and direction were focussed to traverse one of the counters 4*a*, 4*b*, or 4*c* and counter 5. The entering pions (Fig. 1) produced a coincidence (2, 3) while the electron leaving counter 3 and arriving at counter 5 produced a coincidence ($\bar{2}$, 3, 5). The anticoincidence $\bar{2}$ reduced accidentals between a pion pulse in counter 3 and a spurious pulse in counters 4 and 5. The pion pulse from (2, 3) was 50 mμsec long and was delayed 100 mμsec to make a coincidence with the 150-mμsec-long output of ($\bar{2}$, 3, 5). There were three final circuits which signalled the delayed coincidence between the pion (2, 3) and its electron ($\bar{2}$, 3, 5) together with the fact that the electron also traversed one of the counters 4*a*, 4*b*, or 4*c*. An output from any one of these circuits was recorded on an appropriate scaler, triggered the sweep of a traveling wave oscilloscope, and stopped the count until it was

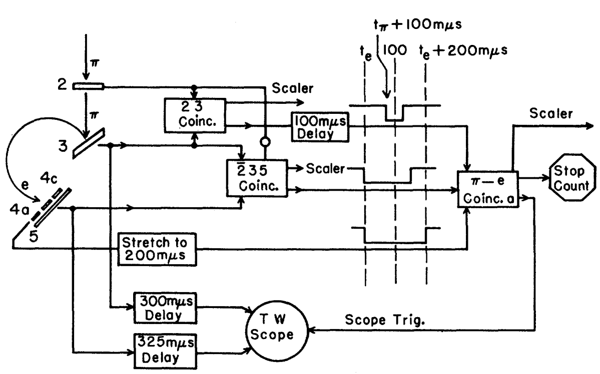

FIG. 1. Arrangement of electronics for detection of π-e events. Connections are shown for channel *a* and are duplicated for channels *b* and *c*.

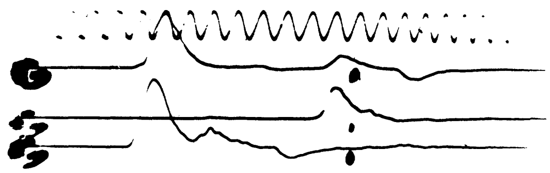

FIG. 2. Oscilloscope traces showing two π-e events. The middle trace is due to an accidental coincidence. Above the traces a 100-Mc/sec sine wave has been recorded to provide a timing scale.

manually reset. The oscilloscope was connected with sufficient delay directly to the anodes of the photomultipliers which looked at scintillators 3 and 5. The signature of a π-e event appeared as a large positive-going pulse due to the stopping pion in counter 3, a second but smaller positive pulse due to the electron leaving counter 3, this being followed by a small negative pulse due to the electron arriving at counter 5. The delays fixed the timing between the final (+, -) pair to be 32 mμsec, the timing of the first two positive pulses was used to verify the pion lifetime. Two signatures of this kind are shown in Fig. 2.

In order to make reliable pulse height and timing measurements, we limited our acceptance of good events to those in which the π-e decay time was greater than 24 mμsec but less than 150 mμsec. The choice of 24 mμsec was made to allow ample time for the anticoincidence pulse to decay and to assure a clear separation between the tail of the pion pulse and the following electron pulse in counter 3. The 150-mμsec upper limit was imposed by the length of the gates in the electronic circuitry. Other criteria which helped to discriminate true π-e events from accidentals were established by setting the spectrometer at 450 amperes (40 Mev/c) and studying the traces produced by the electrons from μ-decay. This study showed that all but 13% of the triggers were included when we required (a) electron pulse in counter 3 to be greater than 0.2 mm; (b) electron pulse in counter 5 to be greater than 0.2 mm but less than 1.0 mm; (c) timing between the final (+, -) pair to be more than 28 but less than 35 mμsec.

The branching ratio was obtained by comparing the integrals, with respect to ln$E$, of the π-electron and μ-electron parts of the spectrum. For the π-electrons there were 50 runs in which there was no obvious misbehavior. These runs gave us 950 triggers of which 159 passed our criteria for

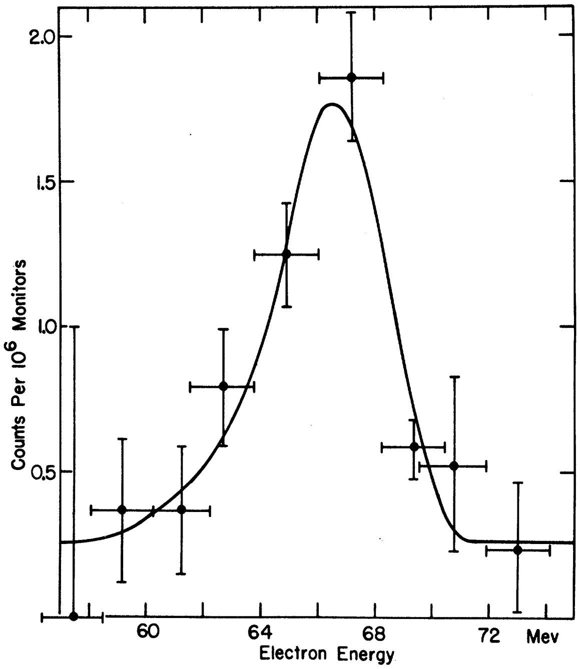

FIG. 3. Energy distribution of π-e events. Curve is best fit calculated by folding in the energy loss in source and the resolution of spectrometer.

a π-e event. These are displayed in Fig. 3. The smooth curve is the best fit calculated by folding into a δ-function at $E = E_\pi$ the known energy loss (including bremsstrahlung effects) in the source, as well as the resolution function of the spectrometer, known from α-particle calibrations, in the manner described previously.[1] A constant background entered as a parameter in the fit. This accounted for 39 ± 15 of our events. We could show from timing measurements that it was likely that 20 ± 5 of these were due to π-μ events in counter 3, in accidental coincidence with spurious counts in (4, 5). We supposed that the remainder were due to μ-electrons which managed, by scattering, to give counts (3, 4, 5) in accidental coincidence with pion counts in (2, 3). Taking account of the time distribution to be expected from such a composition of background events the mean life of the pion obtained from our π-e events turned out to be 25 ± 3 mμsec, close to the accepted value.

In recording the μ-electrons at the lower current settings of the spectrometer, we removed the requirement of a delayed pion coincidence, using simply the coincidence ($\bar{2}$, 3, 5) with one of the counters 4. The data shown in Fig. 4 are from channel b (others were hardly different). It

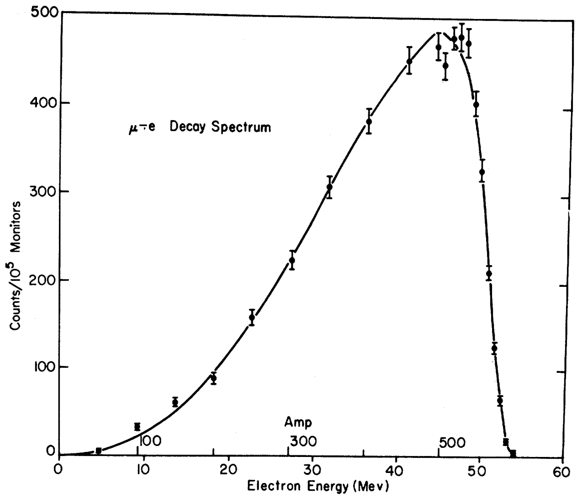

FIG. 4. Energy distribution of μ-e events in channel b. Curve is calculated best fit.

was fitted by adjusting the amplitude, the Michel parameter ρ, and the end-point energy E_μ. From all the data we found $E_\pi/E_\mu = 1.32 \pm 0.01$ as expected, and $\rho = 0.74 \pm 0.03$.

The ratio of the integrals was found to be $(3.49 \pm 0.56) \times 10^{-5}$. This must be multiplied by a factor 2.57 to take into account the pions which decayed outside the measured time interval, a factor 1.13 ± 0.01 for the π-e events missed by our selection criteria, a factor 1.04 ± 0.02 for losses due to bremsstrahlung, and a factor 0.98 ± 0.02 for the muons which escaped from the source. The branching ratio calculated from these data is $f = (1.03 \pm 0.20) \times 10^{-4}$. We have augmented the stated error a small amount to reflect our own uncertainty in the manner of dealing with the background.

Note: See ADDENDUM on page 64.

*Research supported by a joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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ASYMMETRY PARAMETER IN MUON DECAY*

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(Received December 19, 1958)

Increasingly convincing data have established the primary interaction in the weak interactions as V-A. Although it is known that $|C_V| \neq |C_A|$ in β decay, a fact generally attributed to meson cloud effects, no such renormalization effects are expected in muon decay. A precise measurement of the muon decay asymmetry would constitute a sensitive test of the theory, but such a measurement has heretofore been frustrated by the unknown polarizations of cyclotron extracted muon beams. In this experiment, the use of muons emitted near the cutoff angle from π^+ decays in flight results in an accurate knowledge of their polarization; and hence in a much smaller uncertainty in the asymmetry parameter than could be obtained in the original experiment of this kind.[1]

The arrangement used to define the transversely polarized muon beam is shown in Fig. 1. The energy of the incident pions and the muon energy interval defined by the thickness of the bromoform target determine the polarization of the stopped muons. The angular and energy distributions of the muons were studied to verify that the beam had the properties predicted by the

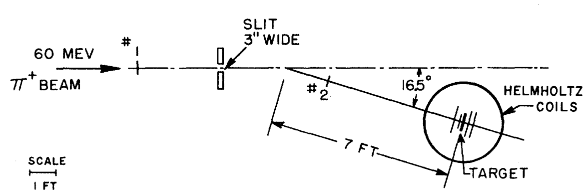

FIG. 1. The bromoform target is placed about two feet from the π^+ beam. Two counters, No. 2 ($2\frac{1}{2}$ in. $\times$5 in. $\times$1/4 in.) and No. 3 (3 in. $\times$ 6 in. $\times$ 1/4 in.), define muons emitted within 0.75° on each side of the cutoff angle. Counter No. 1 (5 in. $\times$ 5 in. $\times \frac{1}{2}$ in.) is placed in the π^+ beam. A set of Helmholtz coils is used to reduce the 15-gauss cyclotron fringing field to less than 0.5 gauss.

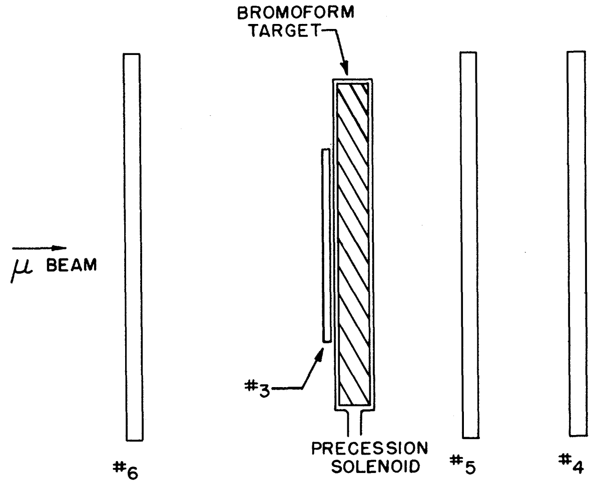

FIG. 2. The target is a Teflon container, 10 in. $\times$ 10 in. $\times$ 1 in., filled with bromoform. Two sets of counters are used to detect the electrons. They are No. 3 and No. 6, in anticoincidence with No. 5 (referred to as telescope 1); and No. 4 and No. 5, in anticoincidence with No. 3 and No. 6 (referred to as telescope 2). Counters No. 4, No. 5, and No. 6 are 12 in. $\times$ 12 in. $\times \frac{1}{2}$ in. The target is wound with an eleven-turn solenoid used to obtain the $\pm 90°$ precession.

kinematics. The setup for counting the μ- decay electrons is shown in Fig. 2. A stopped μ signature, $123\bar{5}$, triggers a pulsed magnetic field of 1 μsec duration which is obtained from the discharge of a condenser through a solenoid wound around the target. After a 1.5-μsec delay, this count also opens a 3-μsec gate during which electrons are counted in telescope 1 and telescope 2. The pulsed magnetic field is used to cause a precession of the transversely polarized muons through $\pm 90°$, first so that the spins point into one telescope, then away from it, in one-hour cycles repeated fifty times. The magnetic field was calibrated by placing the target in the direct muon beam and observing the angular distribution of electrons from the decays of stopped muons.

The electron anisotropy observed with this apparatus is of the form $1+Ka\cos\theta$; where a is the muon decay asymmetry parameter averaged over the electron energy spectrum, θ is the angle between the muon spin and the axis of the detecting telescope; and K is a factor which depends on the polarization of the stopped muons, the energy selection made by the electron detector, and the extent of the target and electron counters. About 5000 events were obtained in