AN INVESTIGATION OF π^+-μ^+-e^+ DECAY WITH THE AID OF A PROPANE BUBBLE CHAMBER AND SCINTILLATION COUNTERS

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The angular distributions of μ^+ mesons and positrons from π^+-μ^+-e^+ decays were investigated with a propane bubble chamber. It was found that the angular distribution of the μ^+ mesons was isotropic, while the angular distribution of the positrons, if described by the expression $(1 - a \cos \theta)/4\pi$, was characterized by the quantity $a = 0.116 \pm 0.035$. This value for a is much smaller than the values obtained in other investigations with propane bubble chambers. Scintillation-counter experiments carried out to determine the cause of this discrepancy showed that the magnitude of anisotropy depends significantly on the degree of purity of the commercial propane sometimes used in bubble chambers. A simultaneous analysis of data obtained with a bubble chamber containing propane of a given composition and scintillation counters showed that the quantity $\lambda(1 - W_C)$ is 0.78 ± 0.26, where W_C is the probability of depolarization of mesons in graphite and λ is a fundamental parameter in the neutrino theory.

INTRODUCTION

AFTER the discovery[1,2] of the non-conservation of parity in weak interactions, a number of publications appeared on the study of μ-e decay. These publications dealt with data obtained both by electronic methods[3,4] of detection and by photographic emulsions.[5,6] During 1957 reports also appeared on the study of μ-e decay with hydrogen[7] and propane[8,9] bubble chambers.

The emulsion and bubble-chamber methods differ from the electronic method of detecting μ-e decay in that (a) in both bubble chambers and emulsions the asymmetry is determined for all the electrons, i.e., without any significant energy cut-off; (b) when the particles are detected with bubble chambers and emulsions, it is possible to investigate the asymmetry of electrons from the μ mesons produced when μ mesons are stopped, i.e., from μ mesons that are altogether longitudinally polarized, while investigation of μ-e decay with scintillation counters depends upon meson beams of an undetermined degree of polarization.

This article (which was nearing completion when similar studies appeared in print[8-11]) describes an investigation whose main purpose was to determine the asymmetry of positrons emitted by μ^+ mesons resulting from the decay of π^+ mesons stopped in a propane bubble chamber. The measured positron asymmetry proved to be much less than that reported by other authors[4,10,11] who also obtained their data by the propane method. The reason for this discrepancy is that sometimes commercial propane is used in bubble chambers, and as is shown here by an experiment with scintillation counters, a difference in the degree of propane purity has a great effect on positron asymmetry.

Moreover, the present experiment with scintillation counters and the same commercial propane as is used in the bubble chamber provide data on the value of the product $\lambda(1 - W_C)$, where λ is a parameter dependent on the coupling constant and W_C is the probability of depolarization of μ^+ mesons in graphite, which was used as a standard.

We have also investigated the angular distribution of the mesons formed from the decay of stopped π^+ mesons.

THE EXPERIMENTAL TECHNIQUE

Figure 1 shows the experimental setup with the bubble chamber, which had an expansion device with a volume limit. A propane bubble chamber[12] 9 cm in diameter was located behind a concrete shield 4 meters thick and in the path of a π^+ meson beam. The π^+ mesons were produced in a polyethylene target located in the path of a 670-Mev proton beam extracted from the accelerator chamber. The mesons that emerged from the target were deflected

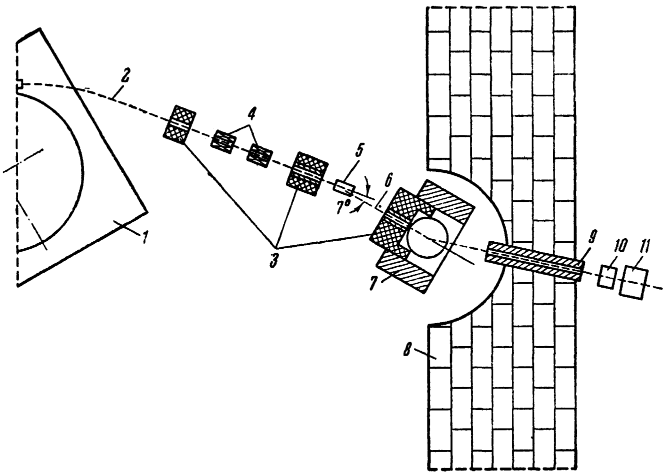

FIG. 1. Experimental setup. 1 – synchrocyclotron vacuum chamber, 2 – extracted proton beam, 3 – lead shield, 4 – quadrupole focusing lens, 5 – polyethylene target, 6 – π^+ meson beam, 7 – deflecting electromagnet, 8 – cast-iron plates in the window of a concrete shield 4 meters thick, 9 – steel collimator, 10 – aluminum filter, 11 – propane bubble chamber.

by an electromagnet and entered a collimator. Photographs were obtained when the average energy of the π^+ mesons at the collimator exit was 170 and 273 Mev, hence with thicknesses of the polyethylene target of 70 and 30 cm respectively, and with angles of 7° and 30° between the π^+ mesons emitted by the target and the direction of the incident proton beam. An aluminum filter 29 cm thick was located directly in front of the chamber to stop the 170 Mev π^+ mesons, and a copper filter 15.5 cm thick was similarly used for the 273 Mev π^+ mesons. To minimize the influence of the stray magnetic field of the synchrocyclotron and deflecting magnet, the bubble chamber was surrounded by a double iron screen. Because of this screening the magnetic field in the operating area of the chamber did not exceed 0.3 oersted. The glass units of the chamber were vertical. The charged particle tracks were photographed on 35 mm film by a stereoscopic camera with two "Yupiter-8" objectives (F = 5.24 cm) at a distance of 45 cm from the central plane of the chamber. The photographic base was 12 cm long and was in a vertical position.

The chamber was filled with commercial propane* which was first purified to rid it of its light fractions (CH_4, C_3H_6). This purification was effected at a temperature of 0°C and was stopped as soon as the saturation pressure of the mixture differed by no more than 0.5 atmosphere from the saturation pressure of propane at the same temperature. The normal working conditions for the bubble chamber were as follows: temperature 62°C, initial pressure 32 atmospheres, and expansion 2.6%. The chamber was in operation for 20 seconds at a time and was under remote control. About 5,000 stereoscopic photographs were obtained.

These photographs were examined and processed, without any reproduction of the stereoscopic pictures, by means of a reprojector[13] whose screen was fixed perpendicular to the optic axes of the objectives in the stereoscopic camera. Nevertheless, both photographs of each stereoscopic pair were used in the examination, to obviate the effect of superimposed tracks and to minimize losses.

The μ^+-meson decay events from stopped π^+ mesons (π^+-μ^+-e^+ events) that concerned us were identified by their characteristic outward appearance (Fig. 2). Out of all the π^+-μ^+-e^+ events, only those could not be interpreted unequivocally for which the direction of μ^+ emission appeared on the reprojector screen to form a small angle to the direction traveled by the π^+ meson before the latter was stopped. This limitation was due to the fact that certain cases, to which we shall henceforth refer as "doubtful," could also be interpreted as due to the decay of μ^+ mesons that had left the collimator (μ^+-e^+ events) and had been scattered 2 – 3.5 mm short of being stopped in the chamber.

To determine the positron asymmetry of π^+-μ^+-e^+ decay we measured directly the angle θ', which is the projection on the vertical plane of the spatial angle θ between the directions of the emissions of the μ^+ meson and the positron. The angular distribution $f(\theta')$ thus obtained is simply related to the distribution $F(\theta, \varphi)$ if the angular distribution of the μ^+ mesons and the azimuthal part of function $F(\theta, \varphi)$ are known. Thus, for example, for an isotropic distribution of the μ^+ mesons we have

$$F(\theta, \varphi) = (1 - a\cos\theta)/4\pi \qquad (1)$$

in which case we find that

$$f(\theta') = \frac{1}{2\pi}\left[1 - a\left(\frac{\pi}{4}\right)^2 \cos\theta'\right] \qquad (2)$$

Use of track coordinates to compute the angle θ gives better accuracy but requires considerably more time. Experience has shown that indirect measurement of the angle θ with the reprojector causes uncontrolled distortion of the angular distribution, particularly in the angular interval $0° \le \theta \le 20°$ and $160° \le \theta \le 180°$ where a great increase occurs.

The angle θ' was measured directly for both the μ^+-e^+ and the π^+-μ^+-e^+ decays, in which the direction of emission of the μ^+ mesons was believed to be in the direction of the collimated π^+-

*Commercial propane consists of 80% propane (C_3H_8), 10% propylene (C_3H_6), 6% methane (CH_4), and 4% butane (C_4H_{10}).

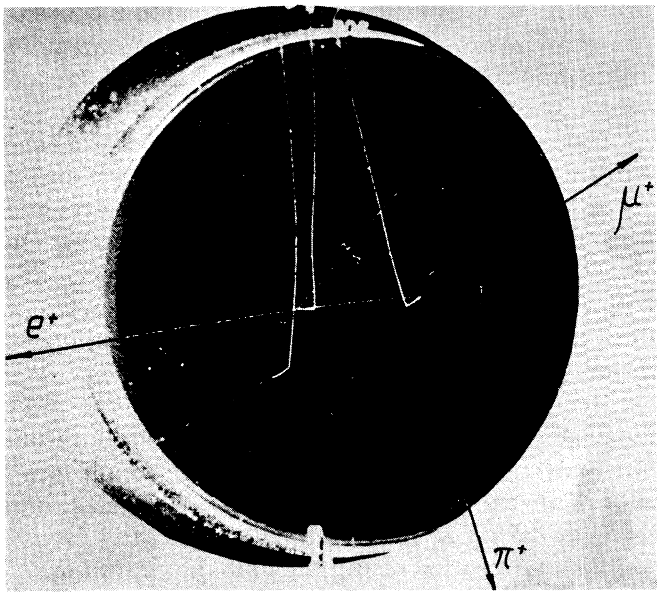

FIG. 2. A typical photograph of a $\pi^+-\mu^+-e^+$ decay in the propane bubble chamber.

meson beam. It can be shown that in this case the distribution Eq. (1) is transformed into

$$\xi(\theta') = \frac{1}{2\pi}\left(1 - a\frac{\pi}{4}\cos\theta'\right). \quad (3)$$

"Doubtful cases were handled as cases of π^+-μ^+-e^+ decay.

All of the photographs were inspected twice independently. To reduce loss during the second inspection we noted in every photograph, besides the events of immediate interest to us, scattering events and stars, since this made possible a more careful review of the stereoscopic shots we had obtained. The first examination disclosed 6,712 cases of π^+-μ^+-e^+ and μ^+-e^+ decay, including "doubtful" ones. During the second examination an additional 346 such cases were found, the combined angular distribution for which is shown in Fig. 3. It is evident from Fig. 3 that the loss of π^+-μ^+-e^+, μ^+-e^+ and "doubtful" events does not depend, roughly speaking, on the angle θ'. If it is also assumed that losses do not depend on the location of the events in the chamber, i.e., that in general they are of a purely random nature, then it can be easily demonstrated that a third examination would reveal no more than 50 new cases of π^+-μ^+-e^+ and μ^+-e^+ decay. This number of events, even if there is some dependence of loss on angle θ', could not distort the obtained angular distributions, and therefore the necessity of a third examination is eliminated.

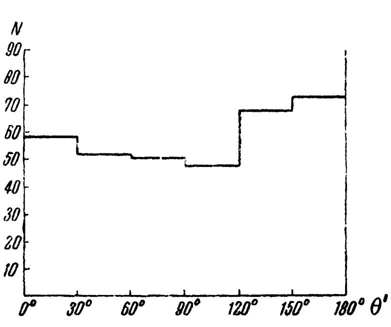

FIG. 3. The angular distribution of positrons for the 346 cases of $\pi^+-\mu^+-e^+$, μ^+-e^+, and "doubtful" events found during a second examination. N is the number of positrons in 30° intervals of the angle θ'.

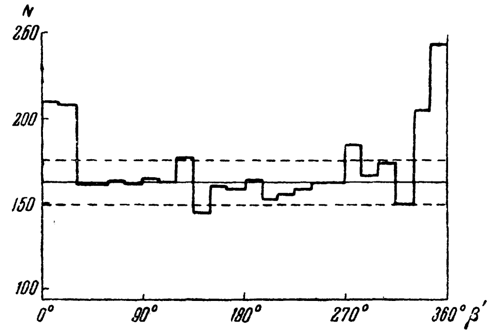

FIG. 4. The angular distribution of μ^+ mesons for 4,107 cases of $\pi^+-\mu^+-e^+$ decay (with all "doubtful" cases excluded). N is the number of μ^+ mesons in 15 intervals of the angle β'.

In order to avoid the possibility of distortion due to boundary effects, π^+-μ^+-e^+ and μ^+-e^+ events were considered only when the π^+ or μ^+ mesons were stopped within an area 6 cm in diameter in the center of the chamber.

ANGULAR DISTRIBUTION OF μ^+ MESONS FROM THE DECAY OF MESONS STOPPED IN THE BUBBLE CHAMBER

When our experiments were still in the process of completion, Lattes reported (at the 1957 conference in Varenna, Italy) on the angular distribution of μ^+ mesons from the decay of π^+ mesons stopped in a photographic emulsion. According to his report, more μ^+ mesons are emitted into the rear hemisphere, in relation to the direction of the π^+ meson beam, than into the front hemisphere, and the probability of μ^+-meson emission increases with increasing size of the angle between the direction of their emission and the horizontal plane. To check this result and also to make a correct transition to the spatial angular distribution for the positrons, we attempted to measure the angular distribution of μ^+ mesons from the decay of π^+ mesons that had been emitted from the target at an angle of 7° to the direction of the incident proton beam and that had been stopped in the chamber. We measured the angle β', which was a projection on the vertical plane of the angle β between the direction of the π^+ meson beam and the direction of the μ^+ meson.

Figure 4 shows the angular distribution $\psi(\beta')$ of μ^+ mesons, obtained by processing the 4,107

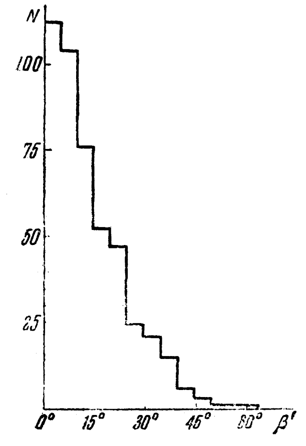

FIG. 5. The angular distribution of μ^+ mesons for "doubtful" cases of decay. N is the number of μ^+ mesons in 5° intervals of the angle β'.

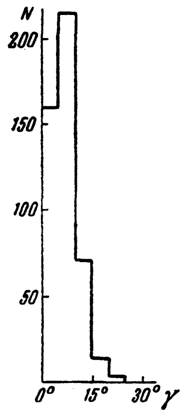

FIG. 7. The angular distribution of μ^+ mesons for "doubtful" cases of decay. N is the number of μ^+ mesons per 5° of γ'.

cases of π^+ meson decay, including "doubtful" cases, for which a separate angular distribution is given in Fig. 5. The solid straight line in Fig. 4 is described by the expression $\psi(\beta') = \overline{N}_\mu$, in which $\overline{N}_\mu$ is the average number of μ^+ mesons in the interval $30° \le \beta' \le 330°$, and the broken lines are described by the expression $\psi(\beta') = \overline{N}_\mu \pm \sqrt{\overline{N}_\mu}$. Figure 4 shows that the obtained angular distribution for μ^+ mesons is in good agreement with the isotropic distribution $\psi(\beta') = \overline{N}_\mu$, if one excludes the intervals $0 \le \beta' \le 30°$ and $330 \le \beta' \le 360°$, where, as is shown in Fig. 5, all the "doubtful" cases are concentrated. Consequently, there is no reason to suppose that the $\psi(\beta')$ angular distribution is not isotropic. If the $\psi(\beta')$ angular distribution is isotropic, the spatial angular distribution of the μ^+ mesons must also be isotropic. On the other hand; if the $\psi(\beta)$ distribution is anisotropic, then one will find anisotropy in the μ^+ mesons with reference to the plane of origin of the π^+ meson, because in this case the π^+ mesons must have a spin and be polarized in a direction perpendicular to the plane of origin, if parity is preserved in strong interactions. For this kind of anisotropy of the spatial angular distribution for the μ^+ mesons, the $\psi(\beta')$ distribution should also be anisotropic, which as is seen from Fig. 4, is not the case. Hence we conclude that the spatial angular distribution for the μ^+ mesons is isotropic. Isotropic angular distributions for μ^+ mesons have also been reported by other authors.[14,15]

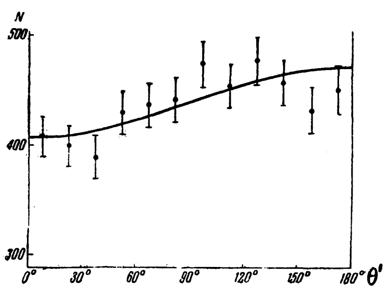

FIG. 6. The angular distribution of positrons for 5,252 cases of $\pi^+-\mu^+-e^+$ decay. N is the number of positrons per 15° of θ'.

ANGULAR DISTRIBUTION OF POSITRONS FROM π^+-μ^+-e^+ DECAY

Figure 6 shows the $f(\theta')$ distribution for positrons in 5,252 cases of π^+-μ^+-e^+ decay. The experimental points in this figure are shown with statistical errors. This angular distribution does not include those cases of π^+-μ^+-e^+ decay for which $\gamma' \le 15°$, where γ' is the projection on the vertical plane of the angle γ between the direction of the μ^+ meson and the direction of the π^+ meson prior to stopping. This has been done because the interval $0 \le \gamma' \le 15°$ includes most of the "doubtful" cases, for which Fig. 7 shows a separate angular distribution $\rho(\gamma')$, which confirms our conclusion. Obviously, all of the doubtful cases should be excluded from the general statistical material, in order to eliminate the distortion of the angular distribution $f(\theta')$ due to the fact that the transformation to a spatial angular distribution for positrons from μ^+-e^+ and π^+-μ^+-e^+ decays is described by quite different formulae. Actually, as stated above, all cases were excluded in the angular interval $0 \le \gamma' \le 15°$, even those which were not doubtful. This was done to facilitate transformation to the spatial angular distribution.

The solid curve in Fig. 6 is given by Eq. (2), with the coefficient $a = 0.116 \pm 0.035$. The value for this coefficient was found from the ratio

$$a = \frac{8}{\pi}\,\frac{N'_b - N'_{forw}}{N'_b + N'_{forw}}, \tag{4}$$

in which N'_{forw} and N'_b represent respectively the numbers of positrons emitted into the forward and back hemispheres with respect to the direction of the μ^+ meson projected onto the vertical plane. From Fig. 6 it is evident that the experimental distribution obtained for the positrons is well described by Eq. (2) when $a = 0.116 \pm 0.035$. This conclusion is also confirmed by the χ^2 criterion. Despite this good agreement, the distribution of the experi-

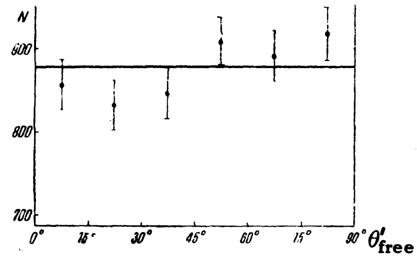

FIG. 8: The angular distribution of positrons for 5,252 cases of $\pi^+-\mu^+-e^+$ decay. N is the number of positrons per 15° of θ'_{free}.

mental points in relation to the solid curve is still of interest. One can see that all of the experimental points in the interval $45° \leq \theta' \leq 135°$ lie systematically above the solid curve, but when $0 \leq \theta' \leq 45°$ and $135° \leq \theta' \leq 180°$, they lie systematically below it. This fact becomes still more obvious if the angular distributions shown in Fig. 6 are folded about 90° in the same way as these angular distributions were originally folded about 180°. The angular distributions thus obtained are shown in Fig. 8. The abscissa θ'_{free}, is given by the following relationship

$$\theta'_{free} = \theta' \text{ for } \theta' \leqslant 90° \text{ and } \theta'_{free} = 180° - \theta' \text{ for } \theta' > 90°$$

If the distribution of observed points were entirely random, then the experimental angular distribution would be isotropic after reflection. In fact, however, the number of positrons in the interval $45° \leq \theta'_{free} \leq 90°$ exceeds the number of positrons in the interval $0° \leq \theta'_{free} \leq 45°$ by 179 ± 72. Such a distribution of points may exist, for example, when the loss of π^+-μ^+-e^+ events in the interval $45° \leq \theta' \leq 135°$ is less than for $0 \leq \theta' \leq 45°$ and $135° \leq \theta' \leq 180°$. The angular distribution in Fig. 3, as well as computations based on it, indicates that even if this effect occurs, it nevertheless is too small to explain the difference of 179 ± 72. It may be that the observed difference is a statistical fluctuation with a probability of 1.5%.

The asymmetry found in our investigation proved to be much less than that reported for "propane" by other authors.[4,10,11] Specifically, in the investigations reported by Alikhanyan et al.[10] and by Barmin et al.,[11] in which propane bubble chambers and the synchrocyclotron of the Joint Institute for Nuclear Research were employed under conditions analogous to ours, the values obtained were a = 0.19 ± 0.03 and 0.22 ± 0.03 respectively. The discrepancy between these data and the value for a obtained by us can hardly be attributed to experimental errors. Therefore, we proposed that the discrepancy be ascribed to a difference in the degree of purity of the commercial propane which was used. To test this idea we measured the asymmetry in the μ^+-e^+ decay by electronic detection methods.

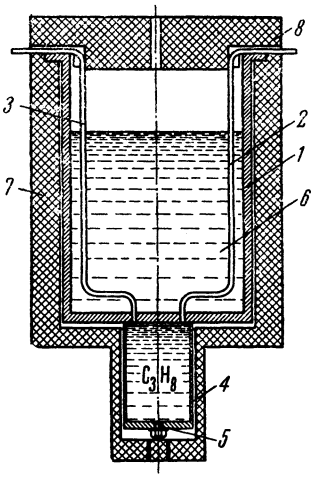

FIG. 9. The propane target. C_3H_8 is liquid propane; 1 – vessel for the refrigerant; 2 – pipe for filling the target with propane; 3 – vent to the atmosphere; 4 – copper foil 0.05 mm thick; 5 – drain plug for the liquid propane; 6 – refrigerant: a mixture of dry ice and alcohol or liquid nitrogen; 7 – polystrene foam jacket; 8 – polystrene lid.

SCINTILLATION-COUNTER STUDY OF THE ASYMMETRY OF POSITRONS FROM μ^+-e^+ DECAY IN PROPANE OF DIFFERENT DEGREES OF PURITY

The asymmetry of positrons from μ^+-e^+ decay was investigated by the scintillation counter method with an apparatus described elsewhere by Mukhin et al.[16]

The μ^+-meson beam employed possessed an energy ~95 Mev, an intensity of 15 cm^{-2} sec^{-1}, and a degree of polarization of 0.81 ± 0.11.[16] The target used to stop the μ^+ mesons consisted of a vessel with two thin plane-parallel walls that contained "propane" of different degrees of purity. This vessel measured 4.5 × 16 × 16 cm and was in the same location with relation to the μ^+ meson beam as the graphite target described by Mukhin et al.[16]

The general appearance of the target is depicted in Fig. 9.

The asymmetry of positrons from μ^+-e^+ decay was determined (a) in "propane" purified of light fractions just as though this "propane" had been intended for use in a bubble chamber, (b) in "propane" that had not undergone any purification, and (c) in the light fractions removed during the purification of the commercial propane.

Asymmetry measurements were performed with a filter in the path of the positrons which had a total equivalent thickness of 13.8 g/cm^2 of polyethylene. This includes the material in the scintillation counters and half of the thickness of the target. Moreover, when the unpurified propane was used, the measurements were performed at the temperature of dry ice (–78.5°C) and at the temperature of liquid nitrogen (–195.8°C). It was discovered that within experimental error the measured asymmetry does not depend on temperature. The obtained asymmetry values were converted to represent the entire positron spectrum by means of measurements[16] of the dependence of asymmetry on positron energy and are as follows:

unpurified "propane" $a' = 0.147 \pm 0.013$,
purified "propane" $a' = 0.104 \pm 0.014$.

The value of the coefficient a' given here for unpurified propane is the average of the values obtained at the temperatures of $-78.5°$ and $-195.8°C$.

It is obvious from these data that the asymmetry definitely depends on the purity of "propane." The findings verify the suggestions that the discrepancy between the values for a obtained in our investigation and those reported elsewhere[4,10,11] is due to differing degrees of "propane" purity. Our measurements have shown that the small value of asymmetry in purified "propane" is not to be ascribed merely to the fact that the light fraction is characterized by a high degree of asymmetry but rather is due to more complex physico-chemical causes.

DISCUSSION OF THE RESULTS

It is known that the value of $\lambda(1-W_C)$ can be found by simultaneous analysis of data on π^+-μ^+-e^+ and μ^+-e^+ decay obtained both electronically and from emulsions.[12] In principle this kind of analysis could be applied to the stopping of π^+ mesons in a propane bubble chamber, provided that data were available on the relative degree of μ^+ meson depolarization in propane and graphite. At the same time attention should be given to the composition of the "propane," since our investigation indicates that the asymmetry depends markedly on the degree to which the commercial propane has been purified. Since the "propane" used in our electronic experiments had the same composition as that in the propane bubble chamber we are in a good position to evaluate $\lambda(1-W_C)$.

Analysis of the data on π^+-μ^+-e^+ and μ^+-e^+ decays obtained electronically and with the bubble chamber indicate a value for $\lambda(1-W_C) = 0.78 \pm 0.26$. The lack of accuracy in this value, despite the large statistical sample, is due to the low degree of asymmetry in the "propane" used.

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