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Neutron Polarization in π^-p Charge-Exchange Scattering at 310 MeV*

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Abstract

We report the measurement of the polarization in the reaction $\pi^- + p \rightarrow \pi^o + n$ at an incident-pion kinetic energy (lab) of 310 MeV and at an angle of 30 deg in the c.m. system. The polarization was obtained from measurements of the left-right asymmetry in the scattering of the neutrons from liquid helium at lab-scattering angles of 75 and 125 deg. The measured polarization is 0.24 ± 0.07.

I. INTRODUCTION

The experiment reported here was performed some time ago as part of a program to obtain sufficient experimental data on pion-nucleon scattering at T_π = 310 MeV so that a unique set of π-N phase shifts could be determined. Although this goal was only partly realized, subsequent experiments and detailed phase-shift analyses have established the π-N phase shifts rather uniquely up to 1 GeV, and possibly up to 2 GeV.

Although the result reported here has been used in some of the detailed phase-shift analyses performed over the last few years, [1-4] it has apparently been omitted in some of the others.[5-7] Because of this, and because our result has been omitted from a recent compilation of pion-nucleon scattering data,[8] we feel that it should be properly published rather than only be available in its present obscure form.[9-10]

Apart from the result of our polarization measurement, the experimental technique of using liquid helium as a polarization analyzer continues to be of interest.[11-13]

II. MOTIVATION

In 1959 an extensive set of measurements was begun on pion-proton scattering at an incident lab kinetic energy of 310 MeV. Measurements were first made of the total cross section, differential cross section and recoil proton polarization in $\pi^+ p$ elastic scattering.[14] Subsequently, measurements were made of the same quantities in $\pi^- p$ elastic scattering.[15] All these results were combined with data on the differential cross section in charge-exchange scattering at the same energy,[16] and a phase-shift analysis was performed.[17] Three acceptable phase-shift solutions were found including partial waves up to F waves ($\ell = 3$). All three solutions gave good fits to the differential cross sections and to the elastic polarizations in the angular region where they had been measured (100 to 150 deg in the c.m. system). However, the solutions predicted very different polarizations at small angles, particularly 30 to 60 deg. This region is inaccessible to the double-scattering technique of measuring polarizations, and is also difficult with the polarized-proton-target technique.[4]

However, this limitation is not present in measurements of the recoil neutron polarization in the charge-exchange process. Moreover, it appeared that the phase-shift ambiguities could be resolved just as well by a measurement of the polarization in charge-exchange scattering. This is illustrated in Fig. 1, where the predictions for $P_{ex}(\theta^*)$ are plotted for each of the three phase-shift solutions of Vik and Rugge.[17] In this paper we report on a measurement of $P_{ex}(\theta^*)$ at $\theta^* = 30$ deg in the c.m. system.

III. EXPERIMENTAL METHOD

For an incident pion lab kinetic energy of 310 MeV (momentum 430 MeV/c), neutrons from the reaction $\pi^- + p \rightarrow \pi^o + n$ are emitted at a lab angle of 74.2 deg and with a kinetic energy of 14 MeV for a pion scattering angle of 30 deg in the c.m. system. This particular angle was chosen because 14-MeV neutrons are readily made by the $d + t \rightarrow He^4 + n$ reaction, which could be used for test and calibration purposes. Liquid helium was chosen as the polarization analyzer because the polarization in n-α elastic scattering is well known and is large at some angles. Also, liquid helium acts as a scintillator,[18] and this feature can be used to reject background and to make sure that the neutrons were actually scattered by the liquid helium before being detected.

A. Apparatus

The experimental apparatus is shown schematically in Fig. 2. A focused and momentum-analyzed beam of 310 MeV π^- mesons was defined by a coincidence between counters A and B, with C1 and C2 in anticoincidence. The latter two counters formed an annulus with a central hole

of 7 cm diam through which most of the beam passed. The liquid hydrogen target (LH_2) of 7.6 cm diam was surrounded by a U-shaped scintillation counter D with its open end facing the beam entrance window. Counter D was operated in anticoincidence to select interactions with neutral final states.

The polarimeter used in the experiment consisted of a liquid helium (LHe) target at the center of an array of neutron detectors, charged particle anti-counters, and shielding. The entire polarimeter assembly was mounted on a base which could be rotated about the vertical axis of the LH_2 target. The center-to-center spacing of the LH_2 and LHe targets was 76 cm. The LHe target consisted of a 7.6 cm-diam pyrex flask, 15 cm high, enclosed in a 14 cm - diam vacuum jacket. The flask was coated on the inside with the wave-length shifter p,p'-diphenylstilbene and crazed on the outside cylindrical surface. The scintillation light was viewed by two 12 cm - diam photomultiplier tubes through windows in the vacuum vessel.

Two sets of neutron counters made from plastic scintillator were used to detect neutrons scattered by the LHe target. Counters V and X were at 75 deg to the recoil neutron beam and U and W were at 125 deg. A thin scintillation counter used in anticoincidence was placed between each neutron counter and the LHe target. The counters labeled Q1 and Q2 in Fig. 2 were also used in anticoincidence.

B. Procedure

The electronic coincidence requirements discussed in the preceding section were supplemented by two additional requirements in order to select the neutron production and scattering events of interest. For each event satisfying the coincidence requirement

$$\overline{AB(C_1 + C_2)}\ \bar{D}\ (\text{He-1})\ (\text{He-2})\ \bar{Q}_1\bar{Q}_2(U+V+W+X)\ \overline{(\bar{U}+\bar{V}+\bar{W}+\bar{X})},$$

where He-1 and He-2 refer to the two phototubes viewing the LHe target, and $\bar{U}$, $\bar{V}$, etc. are the anti-counters in front of U,V, etc., the pulse height of the mixed (He-1 + He-2) signal due to a recoil α-particle was measured and also the time-of-flight of the neutron from the LH_2 target to the final detecting neutron counter. This information was displayed on a dual-beam oscilloscope and photographed; one trace recorded the pulse height in the LHe counter and the other trace recorded the output of a time-to-height converter which measured the time-of-flight. In addition, four indicator lights, which designated the particular neutron counter into which the final scattering took place, appeared in each photograph.

To measure scattering asymmetries, basically two measurements are needed; the event rate for each neutron counter is measured, say with the configuration shown in Fig. 2, and then counters U and W, and V and X are interchanged and the measurement repeated. To avoid any experimental false asymmetries one has to be sure that:

(a) The neutron counters are positioned accurately each time. This was achieved by mounting the counters on an accurately machined and

positioned turntable and by careful surveying.

(b) The efficiency of each neutron counter remains constant. Between runs the four neutron counters were exposed to a ^{60}Co source and the pulse-height spectra recorded on a pulse-height analyzer. The analyzer was gated and routed by signals from the threshold discriminators on each counter. In this way the ratio of threshold level (2-MeV neutron energy) to Compton edge could be checked and readily adjusted.

(c) The response of the LHe counter remains constant. The response was first calibrated by observing n-α elastic scattering with 14-MeV neutrons from the d-t reaction and by using ^{241}Am α-particles. Between runs the response was checked by lowering the ^{241}Am source into the LHe target flask.

The remaining problem is to calculate the analyzing power of the polarimeter.

C. Polarimeter Analyzing Power

Because of the finite geometry of the experiment it is necessary to calculate the effective analyzing power of the polarimeter and to correct for any false asymmetry. The analyzing power calculation is based on knowledge of (a) the polarization in n-α elastic scattering as a function of energy and angle, (b) the differential cross section and kinematics of π^+p charge-exchange scattering, and (c) the geometry of the experiment and the efficiencies of the detectors. A set of n-α phase shifts[19] was adjusted to fit n-α polarization data at 6, 10, 16.4,

and 23.7 MeV[20] in order to interpolate in energy and angle in the region of interest. A more recent phase-shift analysis gives polarizations in satisfactory agreement with the ones we used.[21] The calculation of the analyzing power was performed in a similar manner and with similar results to a calculation published recently.[22] The finite geometry has little effect upon the analyzing power except that the large ϕ acceptance of the neutron counters (which were 30 cm high and 20 cm away from the LHe target) reduces the analyzing power by 10%. Plural scattering of neutrons in the LHe target also resulted in a reduction of about 10%. The effective analyzing powers are given in Table I.

A more serious consideration is false asymmetry. A false asymmetry occurs in our experiment in the following way. The LHe target subtends an angle of $\pm$ 5 deg with respect to the LH_2 target. Because the energy of the charge-exchange neutrons decreases as the emission angle increases, the upstream side of the LHe target sees neutrons of a lower energy on the average than does the downstream side. Also, the lower-energy neutrons correspond to a smaller pion scattering angle where the charge-exchange cross section is larger. In addition, lower-energy neutrons have a higher cross section for scattering in the LHe target. Thus, because of the finite geometry and the close proximity of the neutron counters to the LHe target, in the geometry of Fig. 2, counters U and V will have higher counting rates than X and W. The false asymmetries were calculated in the same computer program as the analyzing power and are given in Table II.

IV. ANALYSIS AND RESULTS

A. Data-Taking Procedure

The number of neutrons detected in each counter for a given number of π^- incident on the LH_2 target was measured under a variety of conditions. The neutron counters were positioned either with U and V at 125 and 75 deg. right, and W and X at 125 and 75 deg. left (as shown in Fig. 2), or in the interchanged position with U and V on the left and W and X on the right. The LHe polarimeter was positioned at $\theta^* = +30$ deg (as in Fig. 2) or at $\theta^* = -30$ deg (i.e., at a neutron angle of 74.2 deg to the left of the beam). The LH_2 flask was either full or emptied of LH_2.

The signal delays were set up to measure either "real" or "accidental" coincidences. No "accidentals" were observed in any of these configurations. With the LHe polarimeter at a given position, data were taken with the neutron detectors in one of the above configurations. The detectors were then interchanged and another run was begun. The runs were typically 8 to 12 hours long, during which $\approx 10^{10}$ π^- were incident on the LH_2. Six runs with alternating neutron detector positions were made at $\theta^* = +30$ deg and eight similar runs were made at $\theta^* = -30$ deg. During each run, data were taken with the LH_2 target in both full and empty conditions.

B. Data Reduction

Each event was accepted or rejected depending upon the time-of-flight and the correlation between time-of-flight and pulse height in the LHe counter. Most of the rejected events had flight times corresponding to

the velocity of light. Scatter plots of time vs pulse height indicated that most of the remaining background events were associated with small pulse heights ($\approx$ 2 MeV energy loss) in the LHe. Time-of-flight spectra for the two sets of neutron counters are shown in Fig. 3 for both the total data and accepted data. The total numbers of events observed in the various categories are given in Table III. The accepted event rates are in good agreement with those predicted by the same calculation which produced numbers for the analyzing power and false asymmetry. The rejected event rates appear consistent with the fact that the backward neutron counters had twice the volume of the forward onces and were closer to the LH_2 target area.

C. Asymmetries

Once the accepted event rates, corrected for LH_2 empty effect, for each run were computed, the scattering asymmetries were calculated by two methods. To illustrate, consider two runs of equal statistical accuracy, one with V on the left and X on the right (run (1)), and run (2) with V on the right and X on the left. Let the observed rates be $V_L(1)$, $X_R(1)$ and $V_R(2)$, $X_L(2)$. Method 1 computes the asymmetry at the n-α scattering angle of 75 deg as

$$\epsilon_1(75^\circ) = \frac{1}{2}\left[\frac{V_L(1) - X_R(1)}{V_L(1) + X_R(1)} + \frac{X_L(2) - V_R(2)}{X_L(2) + V_R(2)}\right] \qquad (1).$$

This method eliminates any systematic error due to beam monitoring, but

relies upon V and X (and similarly U and W) having identical detection efficiencies.[23] In method 2 the asymmetry is given by

$$\epsilon_2\,(75^\circ) = \frac{1}{2}\left[\frac{V_L(1) - V_R(2)}{V_L(1) + V_R(2)} + \frac{X_L(2) - X_R(1)}{X_L(2) + X_R(1)}\right] \qquad (2).$$

This method eliminates errors due to different counter efficiencies but relies upon the dependability of the beam monitoring.[24] Both methods are sensitive to the reproducibility of positioning the counters.

Asymmetries were computed by both methods for each pair of runs. Then the weighted means for several pairs of runs were computed and also the probability $P(\chi^2)$ that the deviations from the means were as expected due to random errors alone. The results are given in Table IV. The two methods give results which agree. Because of the somewhat better $P(\chi^2)$, the asymmetries computed by method 1 were used in the final analysis. Note that the asymmetries change sign as expected when θ^* goes from left to right and when the n-α scattering angle goes from 75 to 125 deg (see Table I). Asymmetries computed for the rejected data and the LH_2-empty data were all consistent with zero and showed no correlation for the different conditions.

D. Final Results

Final asymmetries were computed from the measured asymmetries $\epsilon_m\,(\theta^*,\theta)$ with the expression

$$\epsilon = (\epsilon_m - \epsilon_f)/(1 - \epsilon_m\epsilon_f) \qquad (3).$$[10]

Polarizations are then computed from

$$P(\theta^*) = \frac{\epsilon(\theta^*, \theta)}{P_A(\theta)\ |\langle\cos\phi\rangle|} \times \frac{\theta^*}{|\theta^*|}$$

and are given in Table V. The polarizations for the two signs of θ^* and for the two different angles are consistent in sign, are all individually non-zero, show a reasonable statistical spread, and average to a result which is 3.5 standard deviations from zero. Although liberal errors have been assigned to $P_A(\theta)$, to the plural scattering correction, and to $\langle\cos\phi\rangle$, the final error of $\pm$ 0.07 comes largely from the counting statistics.

V. PHASE-SHIFT ANALYSIS

Our result for the polarization in charge-exchange scattering was used, together with the same data used by Vik and Rugge,[17] to determine the π-N phase-shifts at 310 MeV up to F waves. Four possible solutions were found of which two were much more probable than the others.[10] Considerable difficulty was encountered in fitting the charge-exchange cross sections[16] and to some extent the π^-p elastic polarizations.[15] We will not go into the details of the phase-shift analysis here, since it has been superceded by others[3,4] which have included more new experimental data. The phase shifts of our most likely solution all agree within the errors with those of Arens et al.[4] and Bareyre et al.[3] This is remarkable because Bareyre et al. used new data on π^-p elastic scattering[25,26] and new charge-exchange cross-sections[27]. Arens et al. in their analysis supplemented these with their new results on π^-p elastic polarizations.[4]

In Fig. 4 we show the fit of our most likely phase-shift solution to our experimental point for the polarization in charge-exchange scattering. Also shown are the fits from the solutions of Bareyre et al. and Arens et al.

VI. SUMMARY

We have obtained the value 0.24 ± 0.07 for the polarization in $\pi^- p$ charge-exchange scattering at 310 MeV and 30 deg in the c.m. system. This constitutes one of the few measurements of charge-exchange polarization and so far the only one below 2 GeV. This result, together with new data on $\pi^- p$ elastic scattering[4, 25,26] and new charge-exchange cross sections[27], has permitted what appears to be a unique phase-shift solution to be found at this energy.[3,4]

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Footnotes and References

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24. Again, Eq.(2) is independent of an error δ in beam monitoring to first order.

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Table I. Results of calculation of polarimeter analyzing power.

	n-α Scattering angle	
	θ = 75 deg	θ = 125 deg
Effective polarization in n-α scattering with finite geometry.	-0.67 $\pm$ 0.07	+0.76 $\pm$ 0.08
Reduction factor due to plural scattering	0.90 $\pm$ 0.07	0.90 $\pm$ 0.07
Effective analyzing power, P_A	-0.60 $\pm$ 0.08	+0.68 $\pm$ 0.09
Average $\lvert\cos\phi\rvert$	0.90 $\pm$ 0.05	0.90 $\pm$ 0.05

Table II. Calculated false asymmetries, $\epsilon_f(\theta^*, \theta)$.

Pion c.m. angle θ^* (deg)	n-α Scattering angle	
	θ = 75 deg	θ = 125 deg
+30	+0.055	-0.019
-30	+0.055	+0.019

Table V. Final results for the polarization in $\pi^- + p \rightarrow \pi^o + n$ at 310 MeV and 30 deg in the c.m. system.

Pion c.m. angle, θ^* (deg)	n-α Scattering angle, θ (deg)	Polarization
+30	75	$+0.25 \pm 0.13$
	125	$+0.25 \pm 0.16$
-30	75	$+0.17 \pm 0.13$
	125	$+0.31 \pm 0.15$
Final average		$+0.24 \pm 0.07$

Figure Captions.

Fig. 1. Predictions of the polarization in $\pi^- + p \rightarrow n + \pi^o$ at 310 MeV from the SPDF phase-shift solutions of Vik and Rugge (Ref. 17).

Fig. 2. Experimenimental arrangement. The liquid helium polarimeter is shown for a π-N scattering angle $\theta^* = +30$ deg in the c.m. system. The forward neutron counters V and X are shown at n-α scattering angles $\theta = 75$ deg right and left, respectively; the backward counters U and W are at $\theta = 125$ deg right and left, respectively.

Fig. 3. Time-of-flight spectra of total events and accepted events, accumulated by (a) the backward neutron counters U and W, (b) the forward counters V and X. The peaks on the right correspond to particles travelling with the velocity of light. The actual time-of-flight increases from right to left. The lines marked Δt_{calc} indicate the expected time difference between γ-rays and charge-exchange neutrons. Data obtained with the liquid hydrogen target empty have been subtracted.

Fig. 4. Experimental result for the charge-exchange polarization at 310 Mev and fits from three independent phase-shift analyses. The dotted curve is the result of our most likely phase shift solution (see Ref. 10); the solid curve is calculated from the phase-shift solution of Arens et al.[4] and the crosses from the fit of Bareyre et al.[3]

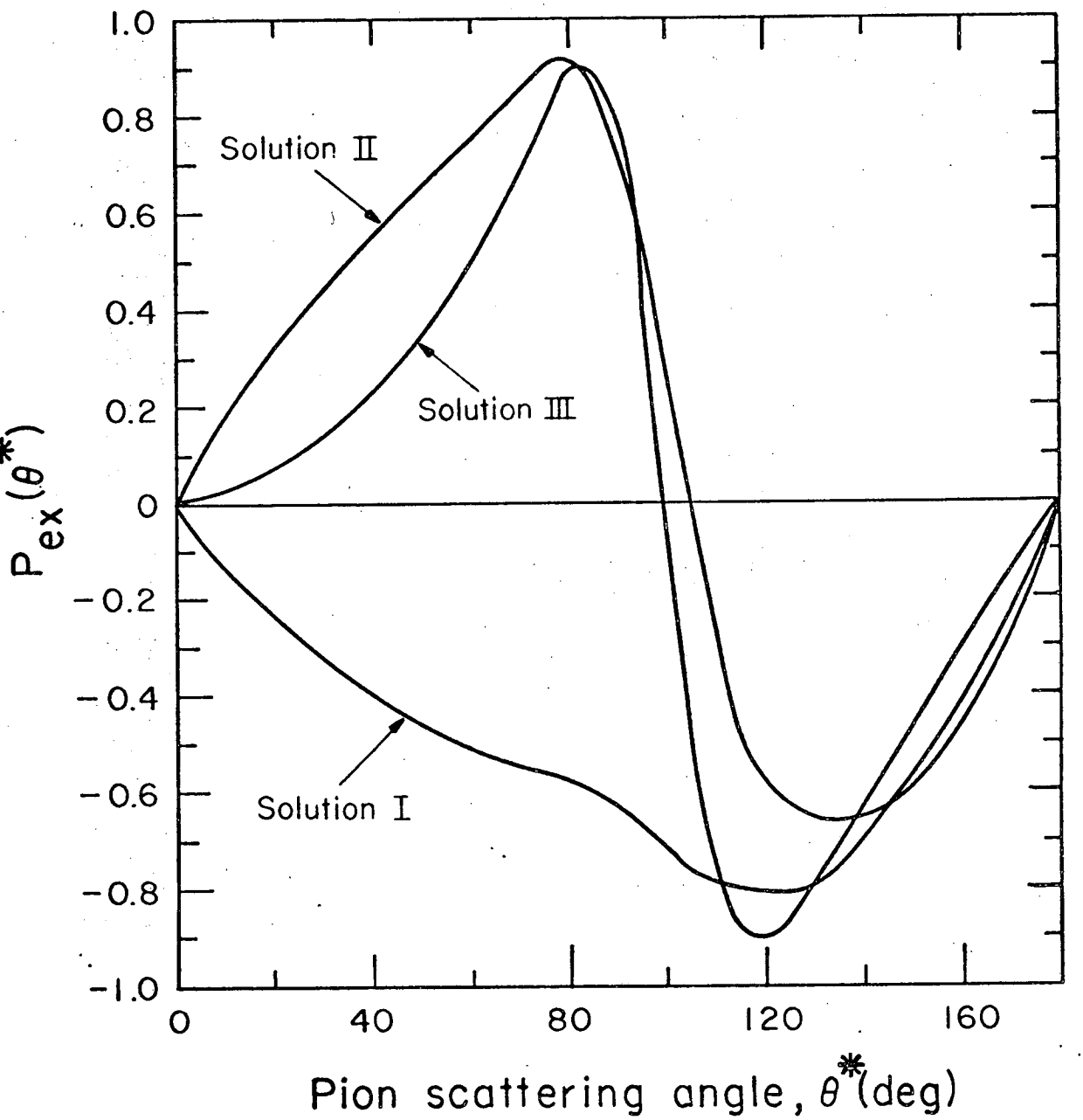

Fig. 1

MU-34025

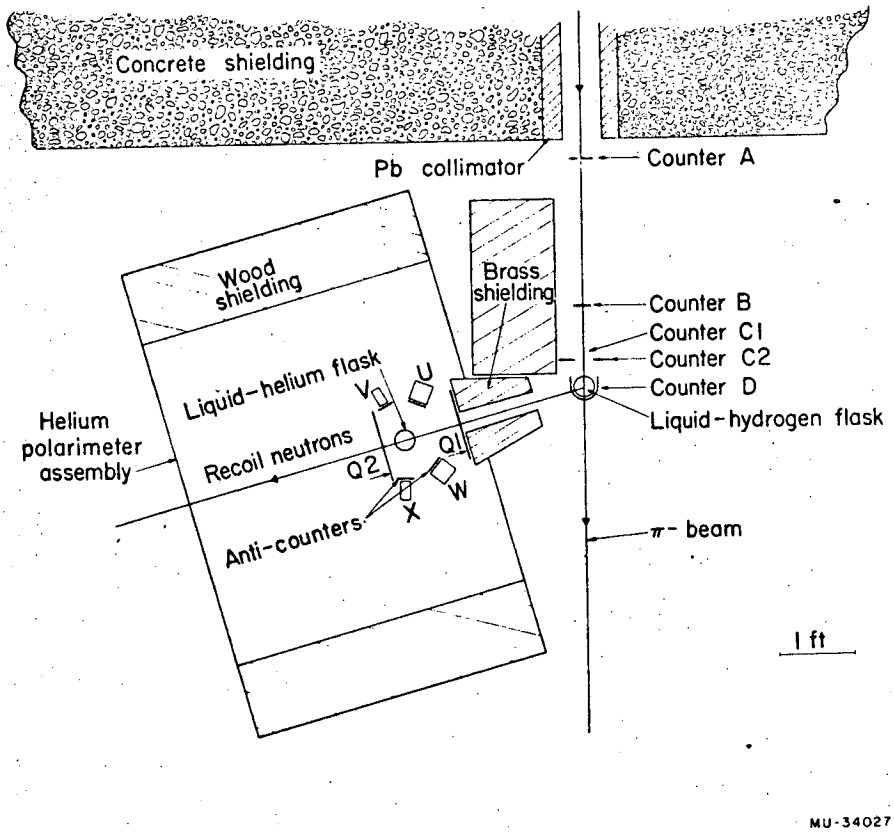
Concrete shielding
Pb collimator
Counter A
Wood shielding
Brass shielding
Counter B
Counter C1
Counter C2
Counter D
Liquid-helium flask
V
U
Liquid-hydrogen flask
Helium polarimeter assembly
Recoil neutrons
Q2
Q1
X
W
Anti-counters
π- beam
1 ft
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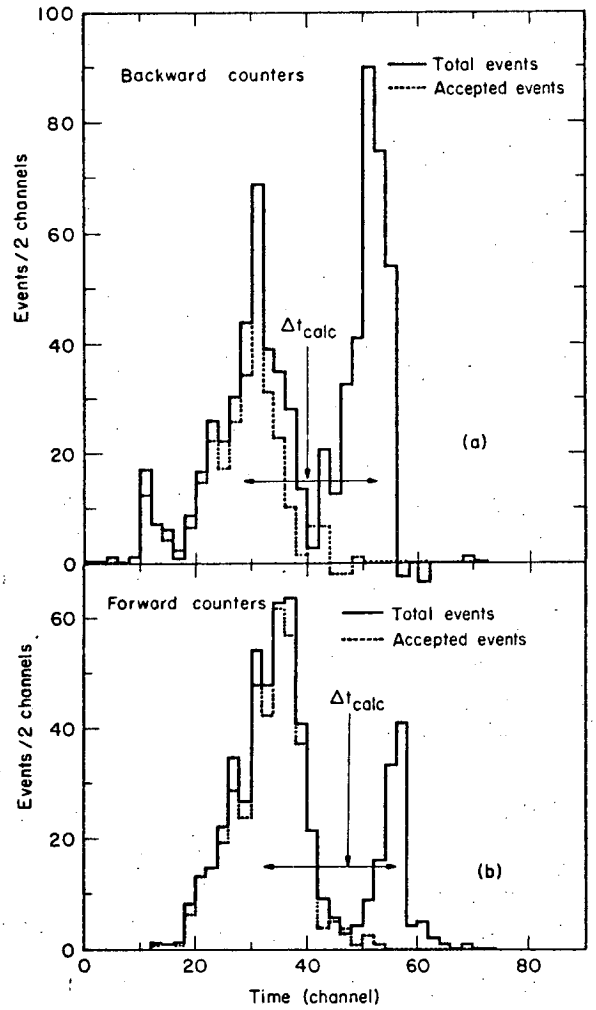
Fig. 2


Backward counters
Total events
Accepted events
Events / 2 channels
Δt_{calc}
(a)
Forward counters
Total events
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Events / 2 channels
Δt_{calc}
(b)
Time (channel)
MU-34032

Fig. 3

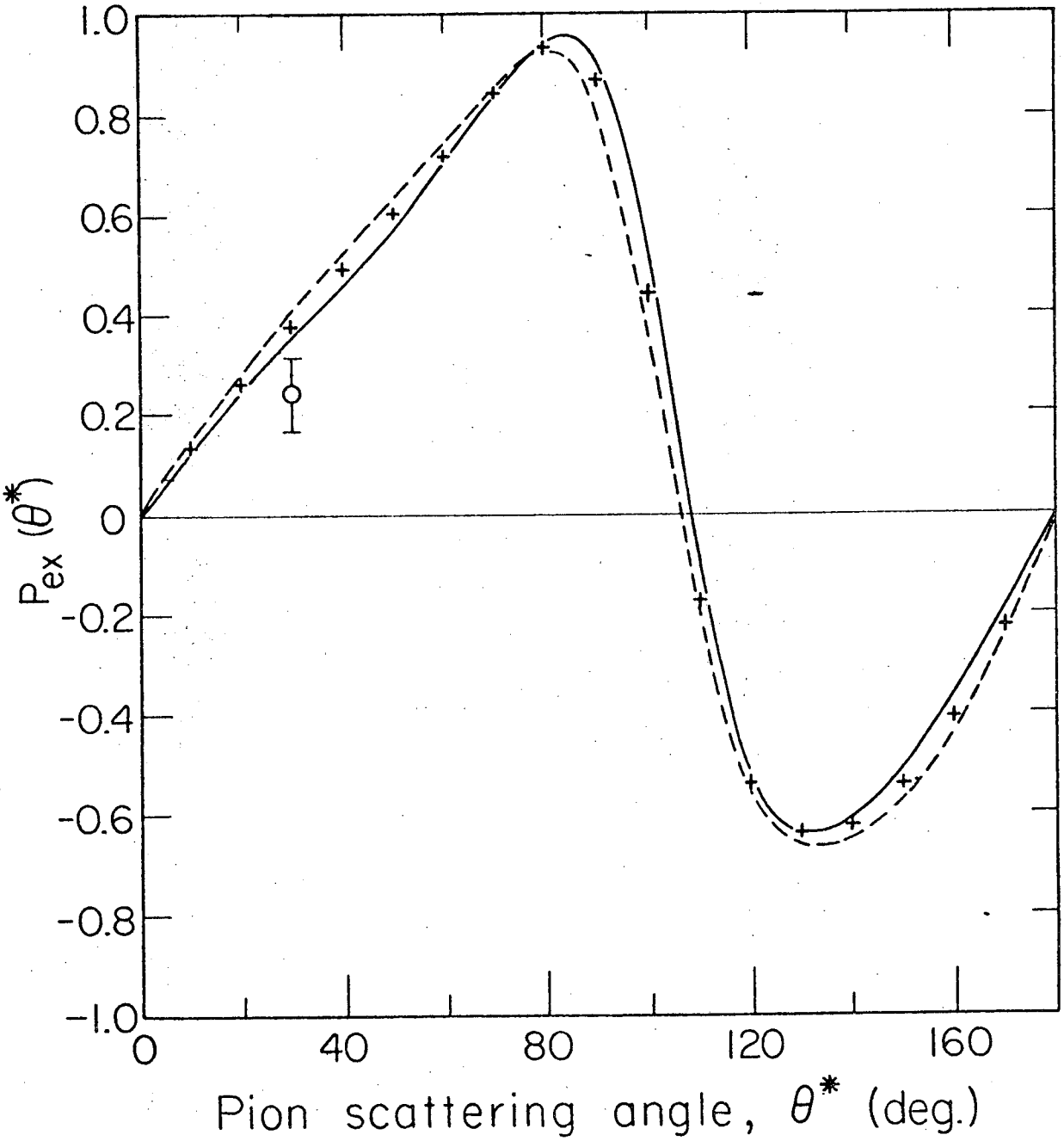
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
$P_{ex}(\theta^*)$
0
40
80
120
160
Pion scattering angle, θ^* (deg.)

Fig. 4

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