either an increase in the field, or in the frequency, or both.

The condition for observing pairs in vacuum can thus be summarized as

$$eE \gtrsim \pi m^2 g(\gamma)\,,$$

or, using the very good approximate form for $g(\gamma) \simeq (4/\pi\gamma)\sinh^{-1}\gamma$,

$$eE \gtrsim \frac{m\omega_0 c}{\sinh(\hbar\omega_0/4mc^2)}. \tag{51}$$

Hence even if x-ray lasers would become feasible, $\hbar\omega_0/mc^2$ would still remain very small and the effect could only be observed through a huge increase of the intensity of four orders of magnitude.

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Neutron Polarization in $\pi^- p$ Charge-Exchange Scattering at 310 MeV*

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We report the measurement of the polarization in the reaction $\pi^- + p \rightarrow \pi^0 + n$ at an incident-pion kinetic energy (lab) of 310 MeV and at an angle of 30° 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°. 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 $T_\pi = 310$ 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

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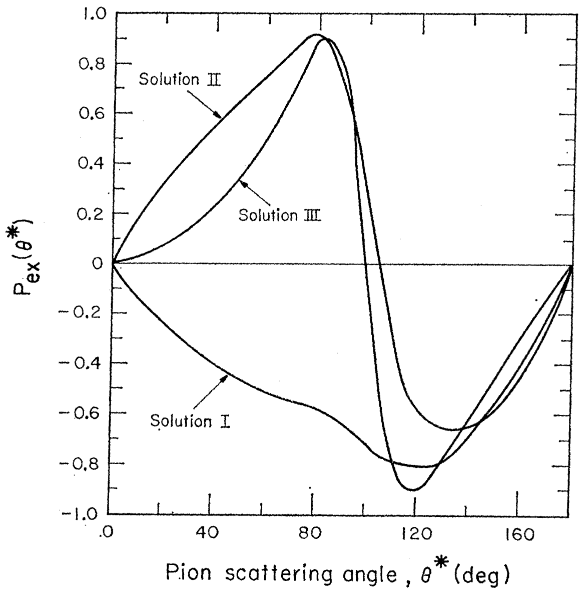

FIG. 1. Predictions of the polarization in $\pi^- + p \rightarrow n + \pi^0$ at 310 MeV from the *SPDF* phase-shift solutions of Vik and Rugge (Ref. 17).

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 ($l=3$). 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°–150° in the c.m. system). However, the solutions predicted very different polarizations at small angles, particularly at 30°–60°. 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 $\theta^*=30°$ in the c.m. system.

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III. EXPERIMENTAL METHOD

For an incident-pion lab kinetic energy of 310 MeV (momentum 430 MeV/c), neutrons from the reaction $\pi^- + p \rightarrow \pi^0 + n$ are emitted at a lab angle of 74.2° and with a kinetic energy of 14 MeV for a pion scattering angle of 30° 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 last 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

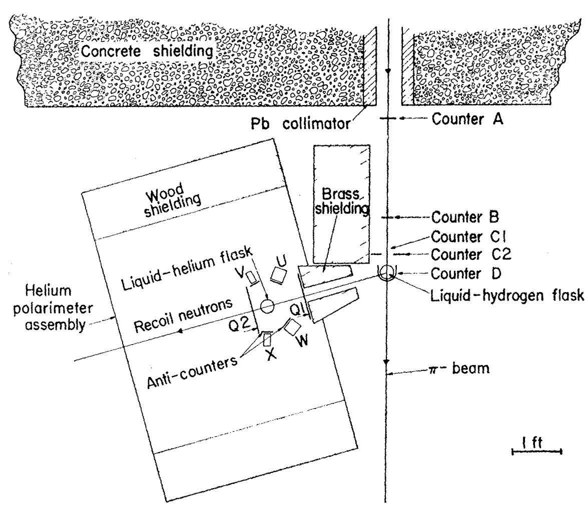

FIG. 2. Experimental arrangement. The liquid-helium polarimeter is shown for a π-N scattering angle $\theta^*=+30°$ in the c.m. system. The forward neutron counters V and X are shown at n-α scattering angles $\theta=75°$ right and left, respectively; the backward counters U and W are at $\theta=125°$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

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neutron detectors, charged-particle anticounters, 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 wavelength 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° to the recoil neutron beam and U and W were at 125°. 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

$$AB(\overline{C1+C2})\bar{D}(\text{He-1})(\text{He-2}) \times\bar{Q}1\bar{Q}2(U+V+W+X)(\overline{\bar{U}+\bar{V}+\bar{W}+\bar{X}}),$$

where He-1 and He-2 refer to the two phototubes viewing the LHe target, and $\bar{U}$, $\bar{V}$, etc., are the anticounters in front of U, V, etc., both the pulse height of the mixed (He-1+He-2) signal due to a recoil α particle and also the time of flight of the neutron from the LH_2 target to the final detecting neutron counter were measured. 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 of the following.

(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.

TABLE I. Results of calculation of polarimeter analyzing power.

	n-α scattering angle $\theta=75°$	$\theta=125°$
Effective polarization in n-α scattering with finite geometry	-0.67 ± 0.07	$+0.76\pm0.08$
Reduction factor due to plural scattering	0.90 ± 0.07	0.90 ± 0.07
Effective analyzing power P_A	-0.60 ± 0.08	$+0.68\pm0.09$
Average $\lvert\cos\phi\rvert$	0.90 ± 0.05	0.90 ± 0.05

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 $\pi^- p$ 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[20] at 6, 10, 16.4, and 23.7 MeV 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.

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

Pion c.m. angle θ^* (deg)	n-α scattering angle $\theta=75°$	$\theta=125°$
+30	+0.055	−0.019
−30	+0.055	+0.019

A more serious consideration is false asymmetry. A false assymmetry occurs in our experiment in the following way. The LHe target subtends an angle of $\pm 5°$ 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° right, and W and X at 125° and 75° 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 $\theta^*=+30°$ (as in Fig. 2) or at $\theta^*=-30°$ (i.e., at a neutron angle of 74.2° 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 h long, during which $\approx 10^{10}$ π^- were incident on the LH_2. Six runs with alternating neutron-detector positions were made at $\theta^*=+30°$, and eight similar runs were made at $\theta^*=-30°$. 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 versus 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 ones and were closer to the LH_2 target area.

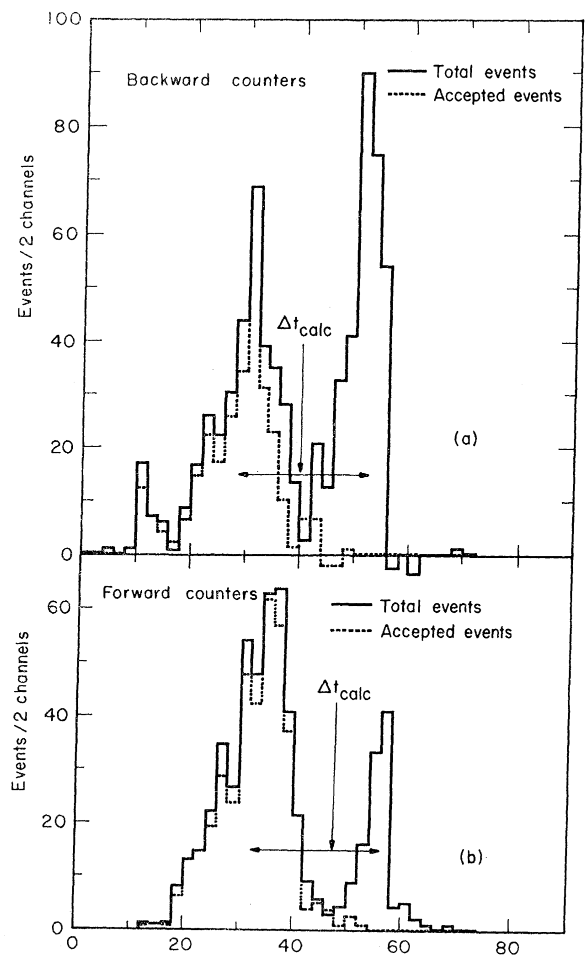

FIG. 3. Time-of-flight spectra of total events and accepted events, accumulated by (a) the backward neutron counters U and W and (b) the forward counters V and X. The peaks on the right correspond to particles travelling with the velocity of light. The actual time of flight increases from right to left. 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.

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 one [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° as

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

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

$$\epsilon_2(75°)=\frac{1}{2}\left[\frac{V_L(1)-V_R(2)}{V_L(1)+V_R(2)}+\frac{X_L(2)-X_R(1)}{X_L(2)+X_R(1)}\right]. \quad (2)$$

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° (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.

TABLE III. Number of observed events for various conditions.

Type of data	Hydrogen target	$\theta^*=+30°$, Counters at $\theta=75°$ (V and X)	$\theta^*=+30°$, Counters at $\theta=125°$ (U and W)	$\theta^*=-30$, Counters at $\theta=75°$ (V and X)	$\theta^*=-30$, Counters at $\theta=125°$ (U and W)
accepted	full	426	306	506	372
	empty	25	27	45	41
rejected	full	209	544	286	762
	empty	36	87	51	140

[23] Note, however, that if the efficiency of V is $(1+\delta)$ times the efficiency of X, Eq. (1) is independent of δ to first order provided runs (1) and (2) have equal statistical accuracy.

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

TABLE IV. Measured asymmetries of the accepted events.[a]

Pion c.m. angle θ^* (deg)	n-α analyzing angle θ (deg)	Method 1 Measured asymmetry	Method 1 $P(\chi^2)$ [b]	Method 2 Measured asymmetry	Method 2 $P(\chi^2)$ [b]
+30	75	−0.18±0.07	0.76	−0.18±0.07	0.29
	125	+0.14±0.10	0.63	+0.11±0.10	0.43
−30	75	+0.14±0.07	0.60	+0.13±0.07	0.42
	125	−0.18±0.09	0.74	−0.14±0.09	0.33

[a] The liquid-hydrogen empty effect has been subtracted.
[b] The quantity $P(\chi^2)$ is defined in the text.

D. Final Results

Final asymmetries were computed from the measured asymmetries $\epsilon_m(\theta^*,\theta)$ with the expression[10]

$$\epsilon=(\epsilon_m-\epsilon_f)/(1-\epsilon_m\epsilon_f). \quad (3)$$

Polarizations are then computed from

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

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 nonzero, 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 ±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 $\pi^- p$ elastic polarizations.[15] We will not go into the details of the phase-shift analysis

TABLE V. Final results for the polarization in $\pi^-+p\rightarrow\pi^0+n$ at 310 MeV and 30° in the c.m. system.

Pion c.m. angle θ^* (deg)	n-α scattering angle θ (deg)	Polarization
+30	75	+0.25±0.13
	125	+0.25±0.16
−30	75	+0.17±0.13
	125	+0.31±0.15
Final average		+0.24±0.07

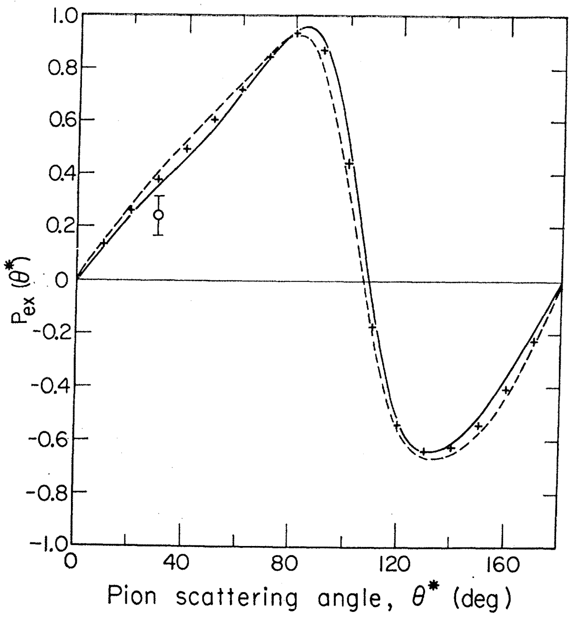

FIG. 4. Experimental result for the charge-exchange polarization at 310 MeV and fits from three independent phase-shift analyses. The dotted curve is the result of our most likely phase-shift solution (see Ref. 10); the solid curve is calculated from the phase-shift solution of Arens *et al.* (Ref. 4)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

here, since it has been superseded 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 $\pi^- p$ elastic scattering[25,26] and new charge-exchange cross sections.[27] Arens *et al.* in their analysis supplemented these with their new results on $\pi^- p$ 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° 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]

ACKNOWLEDGMENTS

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