Measurement of the Polarization Parameter for the Reaction $\pi^- p \to \pi^0 n$ between 1.03 and 1.79 GeV/c*

S. R. Shannon, L. Anderson, A. Bridgewater,† R. Chaffee,‡ O. Chamberlain, O. Dahl, R. Fuzesy, W. Gorn,§ J. Jaros, R. Johnson, R. Kenney, J. Nelson, G. O'Keefe, W. Oliver,|| D. Pollard, M. Pripstein, P. Robrish, G. Shapiro, H. Steiner, and M. Wahlig
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 1 April 1974)

The polarization parameter for the reaction $\pi^- p \to \pi^0 n$ has been measured at five incident beam momenta between 1.03 and 1.79 GeV/c. The results are compared with predictions of recent phase-shift analyses.

We report here the results of an experiment at the Lawrence Berkeley Laboratory (LBL) Bevatron in which we measured the polarization parameter $P(\theta)$ for the reaction $\pi^- p \to \pi^0 n$ ($\pi^0 \to \gamma\gamma$) at the five incident beam momenta 1030, 1245, 1440, 1590, and 1790 MeV/c. Charge-exchange polarization measurements have been made previously at higher energies,[1] primarily to test high-energy interaction mechanisms, but except for one very rough measurement by Hill *et al.*,[2] at 310 MeV, this marks the first time that measurements of $P(\theta)$ have been made in a region where phase-shift analyses are available (< 2 GeV/c). These measurements of $P(\theta)$, together with recent results on the differential cross section for the charge-exchange reaction,[3] should provide a strong constraint on the solutions to the various phase-shift analyses. Preliminary results from this experiment have been reported elsewhere.[4]

The experimental layout is shown schematically in Fig. 1 (and detailed by Shannon).[5] The π^- beam with a typical momentum bite of ±1.5% was focused onto a polarized-proton target (primarily propylene glycol), with length along the beam direction of 7.5 cm and a cross-sectional area 2.5 ×2.5 cm. The polarization of the target averaged between 50 and 55% (at 1°K). The target polarization was reversed every 2–3 h to reduce possible systematic errors. The free protons constituted only about 14% of the protons in the target, the rest being protons bound in the carbon and oxygen nuclei of the propylene glycol and in the heavier nuclei of the cavity. To measure the nonhydrogen background, we also collected data from a "dummy" target at each momentum. This dummy (essentially graphite) contained no free protons but otherwise simulated the target as closely as possible.

Neutrons produced in the final state were detected in twenty 20-cm-thick scintillation counters. These neutron counters, each subtending a lab angle of ~2.5°, at a distance of ~5 m from the target, typically spanned the angular range $-0.78 < \cos\theta_{\text{c.m.}} < 0.87$ in the center-of-mass system; further, they provided neutron time-of-flight measurements accurate to ±0.6 nsec. The photons from the π^0 decay were detected in two lead-plate optical spark chambers. The chamber plates were made thin (~0.14 radiation lengths) to ensure a low energy γ-ray detection threshold of about 10 MeV.[3,6] The downstream chamber (1.52×1.52 m) was 9 radiation lengths thick, and the side chamber (1.22×1.22 m) was 8 radiation lengths thick.

Surrounding the target was a system of scintillation counters that allowed identification of those $\pi^- p$ interactions having neutral final states. Those veto counters not in the incident beam were also used to veto events that had γ rays emitted in directions other than toward the spark chambers.

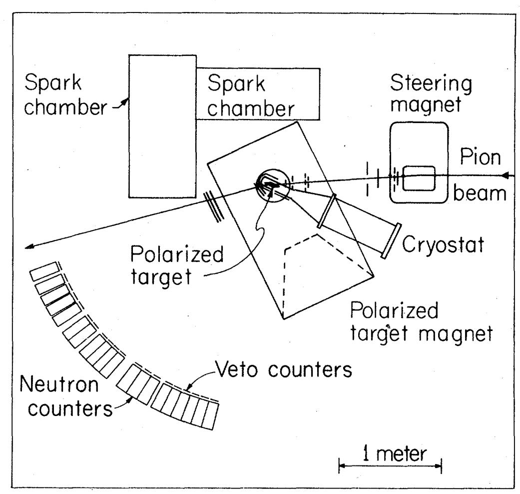

FIG. 1. Experimental layout (the distances of the neutron counters from the target are not to scale). Scintillation counters are indicated (but not labeled) along the beam line.

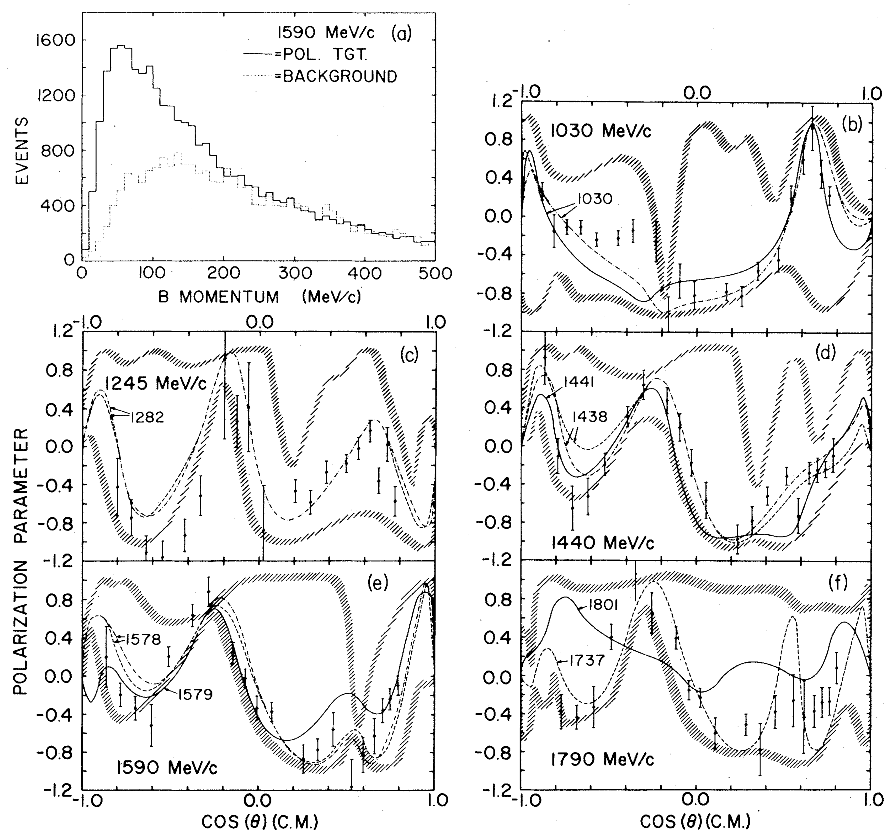

FIG. 2. (a) Fitted momentum distribution for recoil B in the reaction $\pi^- C \to \pi^0 n B$ for both the polarized-target events and (normalized) dummy-target events summed over all neutron counters at 1590 MeV/*c*. (b)–(f) The $\pi^- \to \pi^0 n$ polarization parameter results. The smooth curves are the predictions of Almehed and Lovelace (Ref. 11) (solid), of Ayed *et al.* (Ref. 13) (dash-dotted), and of Bareyre and Ayed (Ref. 12) (dashed) evaluated at the indicated momenta closest to our beam momenta. Isospin bounds given in Ref. 12 are indicated with slashed lines. Only Ayed *et al.* predictions were available at 1737 MeV/*c*; the predictions of both Refs. 12 and 13 at the lower momenta are nearly the same over much of the angular range.

These counters had scintillator and γ converter (1–2 radiation lengths of either Pb, W, or Pt) in a sandwich construction.

An event was recorded whenever the following criteria were satisfied: (1) A charged pion went into the target and no veto counter had a pulse, and (2) a neutral particle went into one of the neutron counters and was detected there. Those events which satisfied our conditions for candidates for $\pi^- p \to \pi^0 n$ (a neutron count within a wide timing window, and two showers in the spark chambers as determined by a scan of the film) were then measured and digitized using the semiautomatic scanner system[7] at LBL.

With the program SQUAW,[8] least-squares kinematic fits were made to the hypotheses $\pi^- p \to \pi^0 n$ and $\pi^- C \to \pi^0 n B$, using the measured directions of the two γ rays and the time-of-flight and direction of the neutron. Here C represented ^{12}C, and the mass of the recoil boron (B) was chosen to be one proton mass less than that of C.[9] B was assumed to have zero measured momentum, but with a large uncertainty of ± 300 MeV/*c* in each component.

We used the following method to determine the background contribution. Those events which satisfied the hypothesis $\pi^- C \to \pi^0 n B$ but fit the hypothesis $\pi^- p \to \pi^0 n$ with a confidence level $<0.1\%$ were predominantly nonhydrogen events. Similar failing events from the dummy target, normalized to those from the polarized target, have a fitted momentum (p_B) distribution for B which agrees very well in shape with the corresponding distribution of failing events from the polarized target. (The normalization ratio is consistent with the ratio of beam fluxes incident on the dummy and polarized

TABLE I. Polarization parameter $P(\theta)$ in $\pi^- p \to \pi^0 n$ scattering. The error $\Delta P(\theta)$ is statistical only; the estimated systematic errors are ± 0.06 for each momentum except 1245 MeV/c, for which the error is ± 0.09.

1030 MeV/c			1245 MeV/c			1440 MeV/c			1590 MeV/c			1790 MeV/c		
$\cos\theta_{cm}$	$P(\theta)$	$\pm\Delta P(\theta)$	$\cos\theta_{cm}$	$P(\theta)$	$\pm\Delta P(\theta)$	$\cos\theta_{cm}$	$P(\theta)$	$\pm\Delta P(\theta)$	$\cos\theta_{cm}$	$P(\theta)$	$\pm\Delta P(\theta)$	$\cos\theta_{cm}$	$P(\theta)$	$\pm\Delta P(\theta)$
0.755	0.24	0.10	0.770	-0.57	0.16	0.783	-0.09	0.19	0.792	-0.10	0.10	0.803	0.08	0.17
0.705	0.46	0.15	0.723	0.02	0.18	0.738	-0.24	0.08	0.749	-0.24	0.11	0.761	-0.27	0.14
0.655	0.94	0.23	0.676	-0.36	0.13	0.693	-0.24	0.13	0.705	-0.36	0.13	0.719	-0.28	0.16
0.604	0.61	0.15	0.627	0.17	0.11	0.645	-0.27	0.12	0.659	-0.63	0.18	0.675	-0.38	0.17
0.535	0.20	0.13	0.561	-0.02	0.12	0.582	-0.72	0.19	0.598	-0.82	0.18	0.616	-0.44	0.38
0.464	-0.44	0.12	0.492	-0.18	0.10	0.516	-0.30	0.10	0.533	-1.16	0.29	0.554	-0.26	0.27
0.347	-0.56	0.09	0.379	-0.27	0.12	0.406	-0.52	0.10	0.425	-0.56	0.18	0.449	-0.38	0.17
0.256	-0.82	0.11	0.290	-0.58	0.13	0.319	-0.78	0.15	0.340	-0.77	0.11	0.366	-0.79	0.27
0.168	-0.77	0.09	0.203	-0.47	0.12	0.234	-0.97	0.15	0.256	-0.87	0.15	0.283	-0.52	0.11
-0.014	-0.82	0.15	0.022	-0.88	0.47	0.054	-0.57	0.19	0.077	-0.37	0.10	0.107	-0.61	0.16
-0.099	-0.67	0.18	-0.063	0.41	0.47	-0.031	-0.17	0.14	-0.008	-0.33	0.13	0.022	-0.23	0.10
-0.164	-1.48	0.65	-0.128	0.26	0.27	-0.097	0.20	0.14	-0.074	-0.02	0.10	-0.044	-0.15	0.10
-0.235	-0.26	0.21	-0.200	0.92	0.84	-0.170	0.48	0.14	-0.146	0.24	0.12	-0.117	0.39	0.12
-0.365	-0.14	0.12	-0.332	-0.51	0.21	-0.304	0.65	0.15	-0.283	0.88	0.15	-0.255	0.65	0.21
-0.450	-0.22	0.08	-0.420	-0.93	0.17	-0.394	0.31	0.11	-0.374	0.64	0.12	-0.348	1.06	0.29
-0.572	-0.24	0.07	-0.547	-1.16	0.17	-0.524	-0.19	0.12	-0.507	0.21	0.10	-0.485	0.40	0.13
-0.660	-0.11	0.07	-0.639	-1.11	0.18	-0.620	-0.53	0.19	-0.605	-0.51	0.22	-0.586	-0.33	0.22
-0.741	-0.11	0.08	-0.724	-0.75	0.19	-0.708	-0.65	0.23	-0.697	-0.33	0.12	-0.681	-0.43	0.13
-0.815	-0.15	0.17	-0.802	-0.42	0.30	-0.791	-0.10	0.19	-0.781	-0.19	0.12	-0.770	-0.38	0.18
-0.882	0.26	0.09				-0.866	0.92	0.28	-0.860	0.20	0.32			

targets.) The normalization ratio was then applied to all the $\pi^0 n$B events from the dummy data to give the total background distribution, indicated in Fig. 2(a) along with the total events (for both signs of target polarization) from the polarized target. For each counter, the polarization parameter was evaluated for a series of cuts in p_B, and was relatively independent of the value of p_B used. The value of the polarization parameter quoted is the one having minimum error (typically for $p_B < 120$ MeV/c). A complete description of the data-analysis procedures, including an independent check[10] on the evaluation of $P(\theta)$, is given in Ref. 5.

The results are tabulated in Table I and are also compared in Figs. 2(b)–2(f) with current phase-shift predictions[11-13] and with isospin bounds calculated from the Bareyre-Ayed phase shifts.[12] Qualitatively, the Bareyre-Ayed phase-shift predictions reproduce reasonably well the general features of the data at all momenta, except for the backward region at 1030 MeV/c. This is also true of the Almehed-Lovelace predictions[11] except at 1790 MeV/c where the disagreement is quite severe. This disagreement is also manifest in the comparison of the charge-exchange differential cross-section measurements of Ref. 3 with the predictions given in Ref. 11 for momenta $\gtrsim 1790$ MeV/c. A quantitative test of the effect of these results on the phase-shift solutions must await further analyses with these data included as input (along with other recent data).

We thank the Bevatron staff for their assistance. We also thank Dr. R. Kelly for helpful discussions, and M. Long and T. Daly for excellent technical support. We are grateful to E. Epstein and D. Stevenson and the group of scanners for their contribution.

*Work done under the auspices of the U.S. Atomic Energy Commission.

†Present address: National Science Foundation, Washington, D.C. 20550.

‡Present address: Stanford Linear Accelerator Center, Stanford, Calif. 94305.

§Present address: University of California at Riverside, Riverside, Calif. 92502.

‖Present address: University of Washington, Seattle, Wash. 98105.

[1]P. Bonamy *et al.*, Nucl. Phys. B16, 335 (1970) (5.1 and 11.2 GeV/c); P. Bonamy *et al.*, Nucl. Phys. B52, 392 (1973) (5 and 8 GeV/c); D. Drobnis *et al.*, Phys. Rev. Lett. 20, 274 (1968) (3.47 and 5.0 GeV/c); D. Hill *et al.*, Phys. Rev. Lett. 30, 239 (1973) (3.5 and 5.0 GeV/c).

[2]R. E. Hill *et al.*, Phys. Rev. D 2, 1199 (1970) (one point at $T = 310$ MeV).

[3]J. E. Nelson *et al.*, Phys. Lett. B47, 281 (1973).

[4]S. R. Shannon *et al.*, Lawrence Berkeley Laboratory Report No. LBL-2114 (unpublished).

[5]S. R. Shannon (Ph.D. thesis), Lawrence Berkeley Laboratory Report No. LBL-2607, 1974 (unpublished).

[6]J. E. Nelson (Ph.D. thesis), Lawrence Berkeley Laboratory Report No. LBL-1019, 1972 (unpublished).

[7]A. R. Clark and L. T. Kerth, in *Proceedings of the International Conference on Instrumentation for High Energy Physics, Stanford, California, 1966* (International Union of Pure and Applied Physics and U.S. Atomic Energy Commission, Washington, D.C., 1966), p. 355.

[8]O. I. Dahl, T. B. Day, F. T. Solmitz, and N. L. Gould, LBL Group A programming note P-126 (unpublished).

[9]This method is also valid for the other heavy nuclei in the target (e.g., ^{16}O); the significant fact is that the mass difference $m_C - m_B$ equals the proton mass.

[10]This method used the entire event sample (i.e., regardless of γ-ray multiplicities) and completely ignored information on the γ rays. $P(\theta)$ was evaluated from the neutron time-of-flight distribution for each counter. The neutron time-of-flight distributions for the dummy target were used to determine the background. The results from both analyses were in excellent agreement.

[11]S. Almehed and C. Lovelace, Nucl. Phys. B40, 157 (1972).

[12]P. Bareyre and R. Ayed, private communication; R. Ayed *et al.*, presented at the Second International Conference on Elementary Particles, Aix-en-Provence, France, 1973 (unpublished), Paper No. 311.

[13]R. Ayed *et al.*, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972,* edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Paper No. 990, and "Zero Strangeness Baryon States below 2.5 GeV Mass" (to be published).

Measurement of the Branching Ratio $\Gamma(K_L{}^0 \to \pi^{\pm}\mu^{\mp}\nu)/\Gamma(K_L{}^0 \to \pi^{\pm}e^{\mp}\nu)$†

H. H. Williams, R. C. Larsen, L. B. Leipuner, W. W. Sapp,* A. L. Sessoms,‡ and L. W. Smith
Brookhaven National Laboratory, Upton, New York 11973

and

R. K. Adair and R. Turner§
Yale University, New Haven, Connecticut 06520

(Received 28 March 1974)

We present the results of a measurement of the $K_{\mu3}{}^0/K_{e3}{}^0$ branching ratio, obtained from a study of $K_L{}^0$ decays using a multiwire-proportional-chamber spectrometer. The $K_{\mu3}{}^0$ and $K_{e3}{}^0$ events were separated by muon range counters, and $K_{\pi3}{}^0$ events were separated from the $K_{e3}{}^0$ sample kinematically. From a sample of approximately 10 000 $K_{\mu3}{}^0$ and $K_{e3}{}^0$ events, we obtain a value of the branching ratio $\Gamma(K_{\mu3}{}^0)/\Gamma(K_{e3}{}^0) = 0.662 \pm 0.037$.

The decays $K_L{}^0 \to \pi^{\pm}\mu^{\mp}\nu$ and $K_L{}^0 \to \pi^{\pm}e^{\mp}\nu$ have been the subject of intense theoretical interest and experimental investigation for almost a decade.[1] With the assumption of the $V-A$ theory of weak interactions, the amplitude for $K_L{}^0 \to \pi\mu\nu$ may be written in terms of two form factors $f_+(q^2)$ and $f_-(q^2)$ $[q^2 = (p_K - p_\pi)^2]$, and much of the interest in these decays has stemmed from the possibility of comparing the measured form factors with a variety of theoretical predictions. In particular, a determination of the form factors provides an important test of the hypotheses of partial conservation of axial-vector currents and chiral SU(3) ⊗ SU(3) algebra of weak currents. Proceeding directly from these hypotheses, Callan and Treiman predicted that the scalar form factor

$$f(q^2) = f_+(q^2) + q^2 f_-(q^2)/(M_K{}^2 - m_\pi{}^2)$$

should assume the values f_K/f_π at the unphysical point $q^2 = M_K{}^2$.[2]

Although a detailed determination of the form