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Abstract

The polarization of protons from the $He^3(d,p)He^4$ reaction has been studied at incident deuteron energies of 1.49, 2.06, and 2.63 MeV for outgoing proton angles between 30^o and 150^o in the laboratory system. The target was a He^3 gas cell at 152 cm Hg pressure. The polarimeter detected, in nuclear emulsions, protons scattered from He^4 gas at 18 atmospheric pressure. The polarization of the scattered protons from the reaction was determined by measuring the left-right asymmetry of the elastically scattered protons, employing the well known double-scattering method. A proton polarization of $-21 \pm 4\%$ (Basel convention) was observed at a laboratory angle of 60^o with an incident deuteron energy of 2.63 MeV at the center of the gas cell. For $E_d = 2.06$ MeV, the polarization shows a negative broad extreme near a laboratory angle of 60^o and decrease to zero for backward angles. The effective polarization of the p-He^4 analyzer was derived from a careful study of the p - He^4 phase shifts. A measurement of the asymmetry of protons from the reaction at resonance shows that the analyzer's inherent asymmetry is less than 0.01. The inherent asymmetries due to finite geometry and possible misalignments of the experimental apparatus were calculated. These were found to give negligible corrections to the measurements.

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I. Introduction

The $He^3(d,p)He^4$ reaction has been much investigated and it has been established that a broad resonance level exists at a deuteron energy of 430 keV, described in terms of a resonance forming Li^5 with s-wave deuterons in a state of total angular moment and parity $3/2^+$.[1-6] A satisfactory theoretical description of the reaction has not been made for deuteron energies off the resonance. Likewise for the mirror reaction $T(d,n)He^4$, deviations from the single level prediction begin a few hundred keV above the resonance.[7] At higher energies, the crude Butler stripping theory assuming zero angular momentum transfer by the captured nucleon reproduces the general features of the angular distribution over the angular region of the forward maximum.[8,9] This plane-wave Born approximation, however, predicts zero polarization for the outgoing protons. Distorted wave theories of (d,p) reaction have recently given greater insight into the mechanism of the reactions.[9-12] One of the most sensitive tests of distorted wave stripping theory is the prediction of the polarization of the outgoing nucleons. The polarizations of protons in this reaction at incident deuteron energies from 3 to 12 MeV have been reported by Brown et al[13] and at 1.8 MeV by Valter et al[14]. It is of great interest to extend the polarization measurement for incident deuteron energies between 1.5 and 2.5 MeV.

II. Experiment

1. Experimental Description

The polarization of the protons from the $He^3(d,p)He^4$ was determined by measuring the left-right asymmetry of the protons elastically scattered from helium. The over-all experimental arrangement is shown in Fig. 1. The deuteron beam from the 3 MeV Van de Graaff of the University of Maryland was focused by a pair of quadrupole magnets and led through a double slit box into the center of a He^3-filled gas cell. The partially polarized protons from the reaction at angle θ_1 were collimated by a set of slits and entered the helium polarimeter. The helium analyzer was set on an arm which rotated about the center of the He^3 gas cell. The elastically scattered protons were defined at a scattering angle $\theta_2 = 61^o$ with a set of vanes. They were detected by two sets of nuclear emulsions: one placed on each side of the analyzing chamber. The transmitted protons were detected with a CsI crystal, which served as a monitor.

2. Apparatus

a) He^3 gas cell

The double slit box consists of two rectangular apertures with openings of 1/8" x 3/8" separated by a distance of 5 3/4". The He^3 gas cell was made from a 1" outside diameter brass cyclinder with a window section removed. The window covered an angular range of about 240°. Havar foil of 0.000125" was fastened around the window section with an epoxy resin. The target cell held up to 230 cm Hg pressure. A He^3 gas pressure of 152 cm Hg was used during the experiments. The length of the sensitive region

(3/16" to 3/8") of the gas target corresponded to an energy loss of 50 - 100 keV for 2.6 MeV deuterons. The havar foil withstands 2 μA of deuteron beam at 2.5 MeV machine energy for about 50 hours of continuous bombardment. The gas cell was centered in the vacuum chamber, which had a window sealed with 0.001" mylar foil to permit exit of protons for angles between 30° and 150°. The deuteron beam current was integrated by a conventional integrator circuit to provide an approximate monitor.

b) He^4 analyzer

Because of the high Q value of the $He^3(d,p)He^4$ reaction, a rather simple design was possible. The He^4 analyzer is shown in Fig. 1. A collimation pipe with two apertures of 3/16" x 7/16" at 5" apart was used to define the scattered proton beams into the helium analyzer. The series of vanes, which define the He^4 target thickness and detector solid angle, were spaced 1/4" apart along the axis of the analyzing chamber. They were fabricated of 1/32" brass sheet. By using many vanes the target thickness was increased without introducing excessive angular acceptance. Both left and right sets of vanes were held in slots machined in two brass plates, one above and one below the vanes, and the whole assembly was located in the analyzing chamber by a pair of pins.

The entrance and side exit window of the He^4 analyzing chamber, which contained He^4 at 18 atomospheres pressure, were sealed with 0.0006" havar foil. The exit slot windows (5/32" x 15/16") were machined very carefully to avoid any asymmetry. At one end of the analyzing chamber, a 3/8" diameter window was made for detecting transmitted protons with a CsI crystal as a monitor. The collimator pipe and the center line of the analyzing chamber were carefully aligned within $\pm$ 0.5°.

Commercial helium gas was found to be of sufficient purity for the experiment and no further purification was attempted. The proton energy drop across the scattering region viewed by 12 vanes in 18 atmospheric pressure of He^4 was between 0.5 MeV and 1 MeV depending on the mean energy of the protons. The He^4 analyzing chamber was shielded with paraffin to reduce the neutron background.

c) Detector

The protons were detected by Ilford K2, 200μ, 1 x 3-in nuclear emulsions on glass backings. Two plates were mounted on each plate holder located on both sides of the analyzing chamber equidistant from the center (Fig. 2). The plate holders were designed so that the protons would enter the emulsion plates at an average angle of 30° in order to yield a convenient track length projection when the emulsion plates were placed on the stage of a microscope.

3. Procedure

a) Asymmetry measurement

The left-right asymmetry of the second scattering was measured at deuteron incident energies of 1.49, 2.06 and 2.63 MeV. The measurements included $He^3(d,p)He^4$ reaction angles between 30° and 150° in the laboratory system. For each measurement, the protons from the p-He^4 scattering were detected by a set of nuclear emulsions for about 10 hours of exposure time at 2μA of incident deuteron beam. There were then about 1000 proton counts on each plate.

The measured left-right asymmetry of the outgoing protons in the p-He^4 scattering is related to the polarization of the outgoing protons in the first reaction P_1 and the effective polarization of the He^4 polarimeter P_{eff} by

$$A = P_1 \cdot P_{eff} \quad .$$

The sign convention for the polarization is that the positive direction is that of $\overline{k}_{inc} \times \overline{k}_{out}$, where $\overline{k}_{inc}$ and $\overline{k}_{out}$ are the incident and outgoing wave vectors respectively (Basel convention).

b) Scanning

After development the plates were scanned in 0.5 mm wide strips using an oil immersion objective. In order to discriminate against background tracks, several acceptance criteria were applied to the tracks. The track length, dip angle and azimuthal angle had to lie within set limits, which were determined for each plate position. And the acceptable tracks had to start at the surface of the emulsion. The sufficiency of these criteria was demonstrated with background plates. At higher incident deuteron energy, the plates corresponding to right-right scattering did usually contain noticeable numbers of proton recoil tracks from neutrons. However, these recoil tracks were rejected by the criteria placed on acceptable track criteria. The accepted tracks were recorded against position on the plate. Several plates were double checked by two scanners and by the same scanner several times. It was found that the difference in absolute scanning efficiency was less than 0.05. Because the right and left plate scanning times were carefully intermingled the corresponding uncertainty in asymmetry is less than 0.02.

c) The effective polarization of He^4 analyzer

In order to deduce the polarization P_1 of the scattered protons from the measured asymmetry A, it is necessary to know the effective analyzing power P_{eff} of the helium analyzer. The effective analyzing power P_{eff} is the mean proton polarization in the p-He^4 elastic scattering. The polarization in p-He^4 elastic scattering at any point in the helium polarimater, $P_2(E_2,\theta_2)$, depends on the energy of proton E_2 and on the proton scattering angle θ_2 at that point. P_2 must be averaged over the energy spread and possible scattering angles for all scattering points in the helium analyzer. The polarization $P_2(E_2,\theta_2)$ was calculated from the p-He^4 elastic scattering phase shift data. The energy dependence of the p-He^4 phase shifts used in the calculation is shown in Fig. 3. The curves were drawn through the reported experimental points[15-18]. For a (typical) proton energy of 16.75 MeV at the center of helium analyzer and a He^4 target thickness of 600 keV, the calculated effective analyzing power is $P_{eff} = -0.52 \pm 0.03$.

d) False asymmetry

In experiments involving measurement of an asymmetry, great care must be taken to avoid or to be able to correct for any asymmetry of instrumentation that may lead to false measurements. One asymmetry which is unavoidable arises from the finite geometry of the experimental apparatus. Calculations were made for the geometric asymmetry due to the finite reaction volume in the gas cell and finite geometry of the analyzing chamber. For proton reaction angles of 60^{o} and 90^{o} at 2.63 MeV deuteron incident energy, the left-right ratios were 1.003 and 0.995 respectively. To minimize the misalignment asymmetry the apparatus was carefully aligned optically. The precision with which the analyzing chamber and the scattering chamber described in previous section were built was such that it was most unlikely that any significant errors arose from this cause. Calculations show that under the most adverse conditions the maximum asymmetry from geometrical misalignment could be 0.03 but with reasonably good alignment should be less than 0.01. A measurement of the asymmetry of unpolarized protons from the reaction at resonance showed that the analyzer's inherent asymmetry was less than 0.01.

III. Results and Conclusion

1. Results:

The polarization data obtained are presented in Table 1. Energies and angles are given in the laboratory system. The first column is the deuteron incident energies at the center of He^3 gas cell. The scattering angles of proton in laboratory system and equivalent angles in the center of mass system are listed in the next two columns. N_R and N_L represent the counts of proton tracks for right-right and right-left scattering respectively. The mean energy of the protons in the He^4 analyzer and the effective analyzing power are given in the sixth and seventh columns. The last two columns are the values of measured asymmetry and the polarization of the scattered protons from the reaction. The values of polarization of the scattered protons are plotted against the laboratory reaction angle in Fig. 4. For a deuteron energy of 2.63 MeV at a reaction angle of 60^o, we observed a proton polarization of $P_1 = -21 \pm 4\%$. The size of the polarization decreases to $-7 \pm 3\%$ at 90^o. For a deuteron energy of 2.06 MeV, the extreme polarization occurs near an angle of 60^o with $-12 \pm 4\%$ and decreases to zero for background angles. The polarization shows a similar dependence on angle with smaller absolute value at a deuteron energy of 1.49 MeV.

Our results were combined with polarization measurements at higher incident deuteron energies (Fig. 5). The plot with solid lines was reported by Brown et al at Wisconsin[12]). The dots with polarization values indicated are data we observed.

Table 1. Polarization of Protons from the $He^3(d,p)He^4$ Reaction

E_d(MeV)	$\theta_{lab}^{(DEG)}$	$\theta_{C.M.}^{(DEG)}$	N_R	N_L	E_p(MeV)	P_{eff}	A	P_1
2.63	60	65.7	1915	1530	16.7	-0.52	0.112	-0.21 ± 0.04
	90	96.6	1040	902	14.7	-0.58	0.071	-0.12 ± 0.03
2.06	30	32.9	1089	1128	17.6	-0.48	-0.018	+0.04 ± 0.04
	40	43.8	1007	964	17.3	-0.50	0.021	-0.04 ± 0.04
	50	54.5	1702	1603	16.8	-0.52	0.030	-0.06 ± 0.03
	60	65.1	1034	910	16.2	-0.54	0.064	-0.12 ± 0.04
	70	75.6	598	519	15.6	-0.56	0.071	-0.13 ± 0.05
	90	95.9	846	788	14.5	-0.59	0.036	-0.06 ± 0.04
	110	115.5	1212	1183	13.3	-0.61	0.012	-0.02 ± 0.04
	130	134.5	934	942	12.5	-0.62	-0.1	+0. ± 0.04
	150	152.9	1008	1037	11.8	-0.63	-0.014	+0. ± 0.04
1.49	30	32.3	1233	1228	16.9	-0.52	0.	-0. ± 0.04
	40	43.2	1192	1194	16.6	-0.53	-0.	+0. ± 0.04
	50	53.9	1281	1237	16.2	-0.55	0.017	-0.03 ± 0.04
	70	74.5	1577	1451	15.3	-0.57	0.042	-0.07 ± 0.04
	90	95.1	1110	1071	14.2	-0.59	0.018	-0.03 ± 0.04
	110	114.8	1195	1191	13.3	-0.61	0.	-0. ± 0.04
	130	133.9	1247	1219	12.5	-0.62	-0.012	+0.02 ± 0.04
	150	152.5	1139	1154	12.0	-0.63	-0.	+0. ± 0.04

2. Conclusion

In the energy region we observed, the angular dependence of both polarization and cross section changes little. The size of the extreme polarization is, however, beginning here to increase rapidly with energy. As the deuteron energy is raised well into the direct reaction region the angular distributions of both cross section and polarization become complicated, but still vary smoothly with energy. In addition to the measurement at higher energies shown on Fig. 5, there are measurements by Valter et al at Academy of Sciences of Ukrania at lower deuteron energies. Our measurements are consistent with both the higher and lower energy data. Distorted wave theories of (d,p) reactions have recently given greater insight into the reaction mechanism involved. We hope that the present data, which complements other data already available, will aid the analysis of this particular reaction.

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Figure Cpations

Fig. 1. The experimental set-up is shown schematically. The He^4 polarimeter can be rotated about the center of the He^3 gas cell within the angular range $25^\circ < \theta_1 < 155^\circ$.

Fig. 2. The cross sectional view of the He^4 polarimeter and the locations of the emulsion plate holders are shown.

Fig. 3. The S, P phase shifts of the p-He^4 elastic scattering as a function of the incident proton energy in the laboratory system. The experimental points were obtained from Refs. 15-18.

Fig. 4 The polarization of protons from the $He^3(d,p)He^4$ reaction as a function of reaction angle in the laboratory system for deuteron energies of 1.49 and 2.06 MeV. The 2.63 MeV data are shown with open circles.

Fig. 5 Contour map of the polarization of protons from the $He^3(d,p)He^4$ reaction. The solid lines were obtained from Ref. 13. The dotted lines were drawn by freehand interpolation between our measured values.

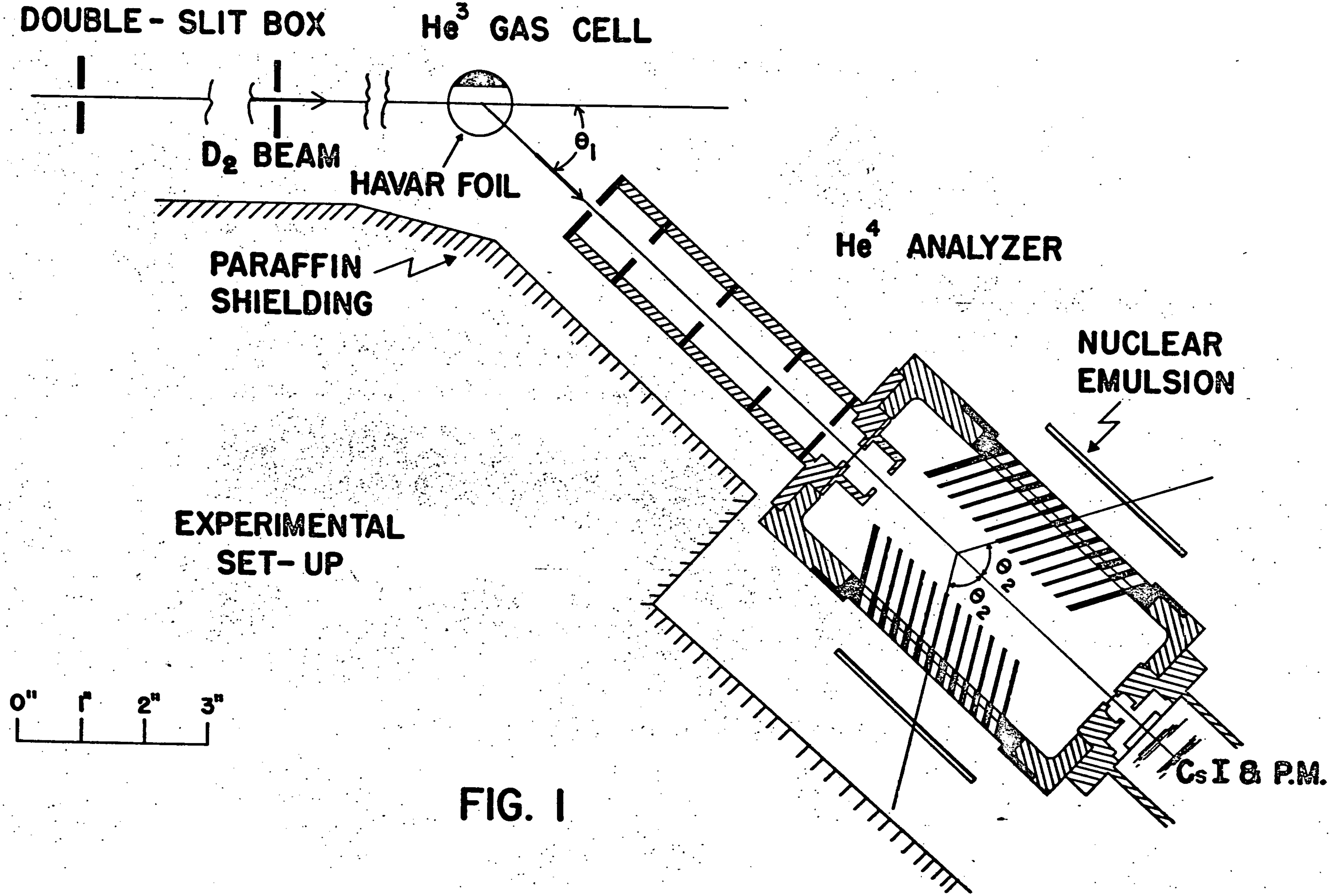

DOUBLE - SLIT BOX
He³ GAS CELL
D₂ BEAM
HAVAR FOIL
θ₁
PARAFFIN
SHIELDING
He⁴ ANALYZER
NUCLEAR
EMULSION
EXPERIMENTAL
SET- UP
θ₂
θ₂
0"
1"
2"
3"
CsI & P.M.

FIG. I

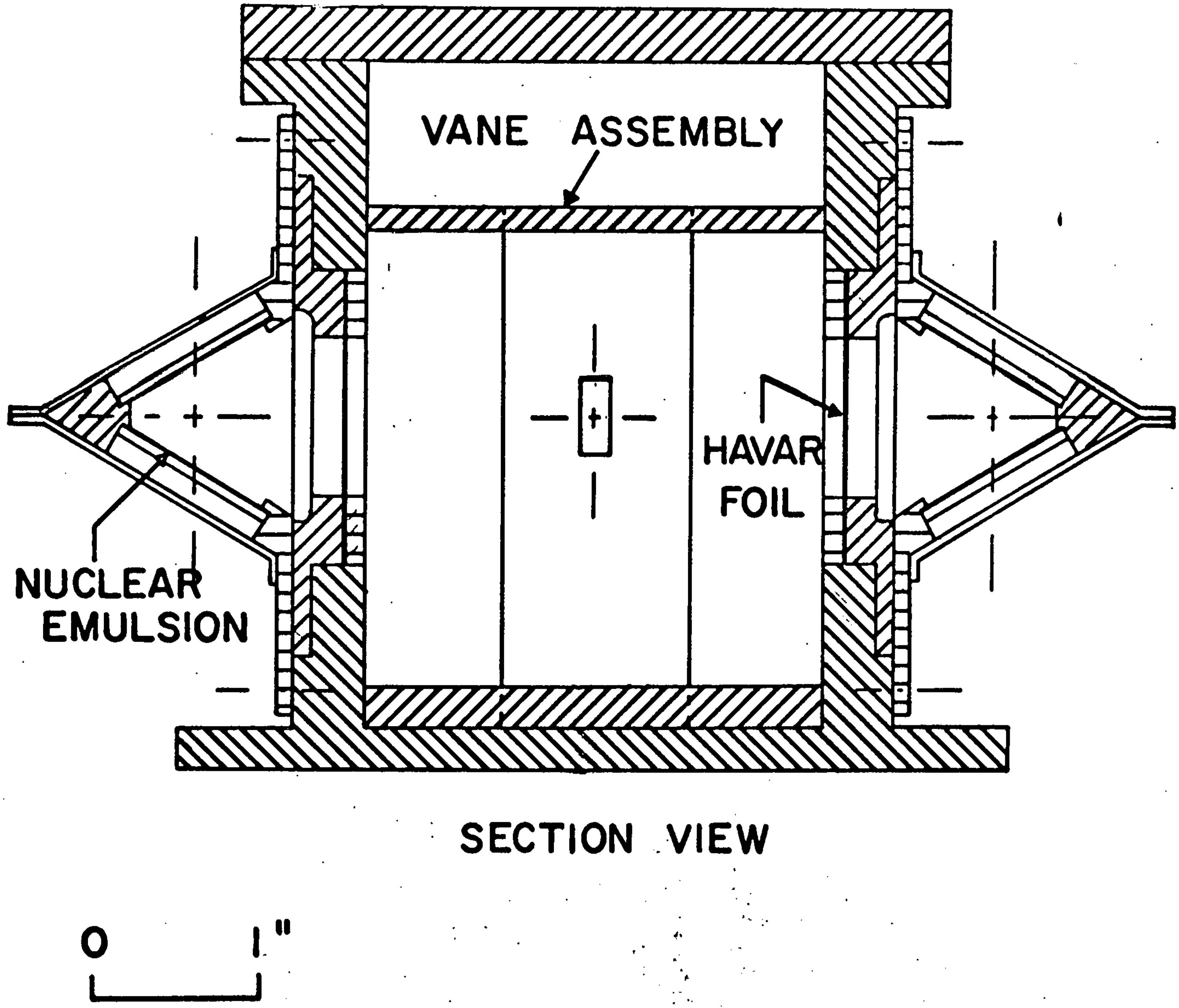


FIG. 2

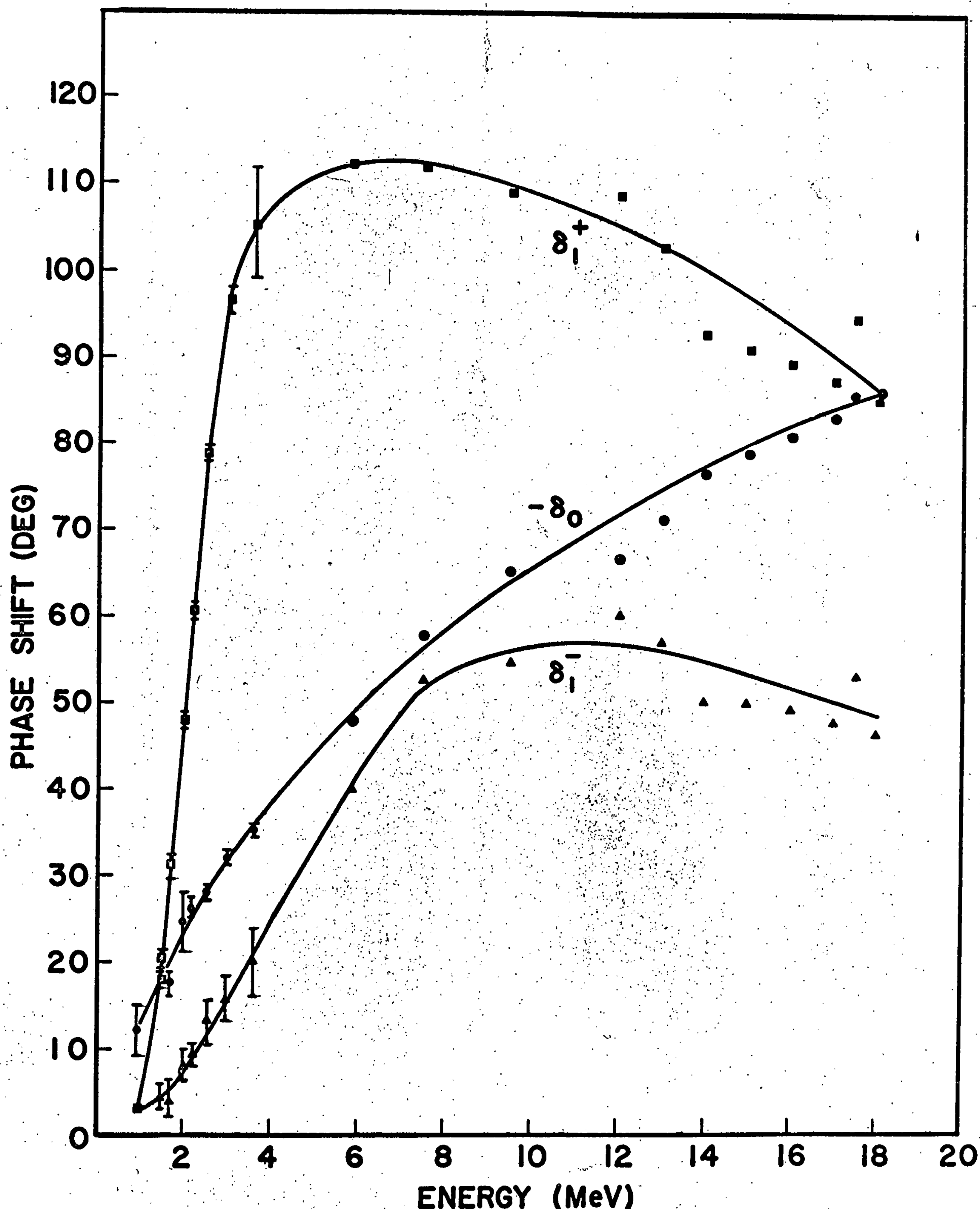


FIG. 3 PHASE SHIFT OF P-He^4 ELASTIC SCATTERING

Ed = 2.63 MeV

θ	A	P
60°	0.11 ± 0.01	-0.21 ± 0.04
90°	0.07 ± 0.02	-0.12 ± 0.03

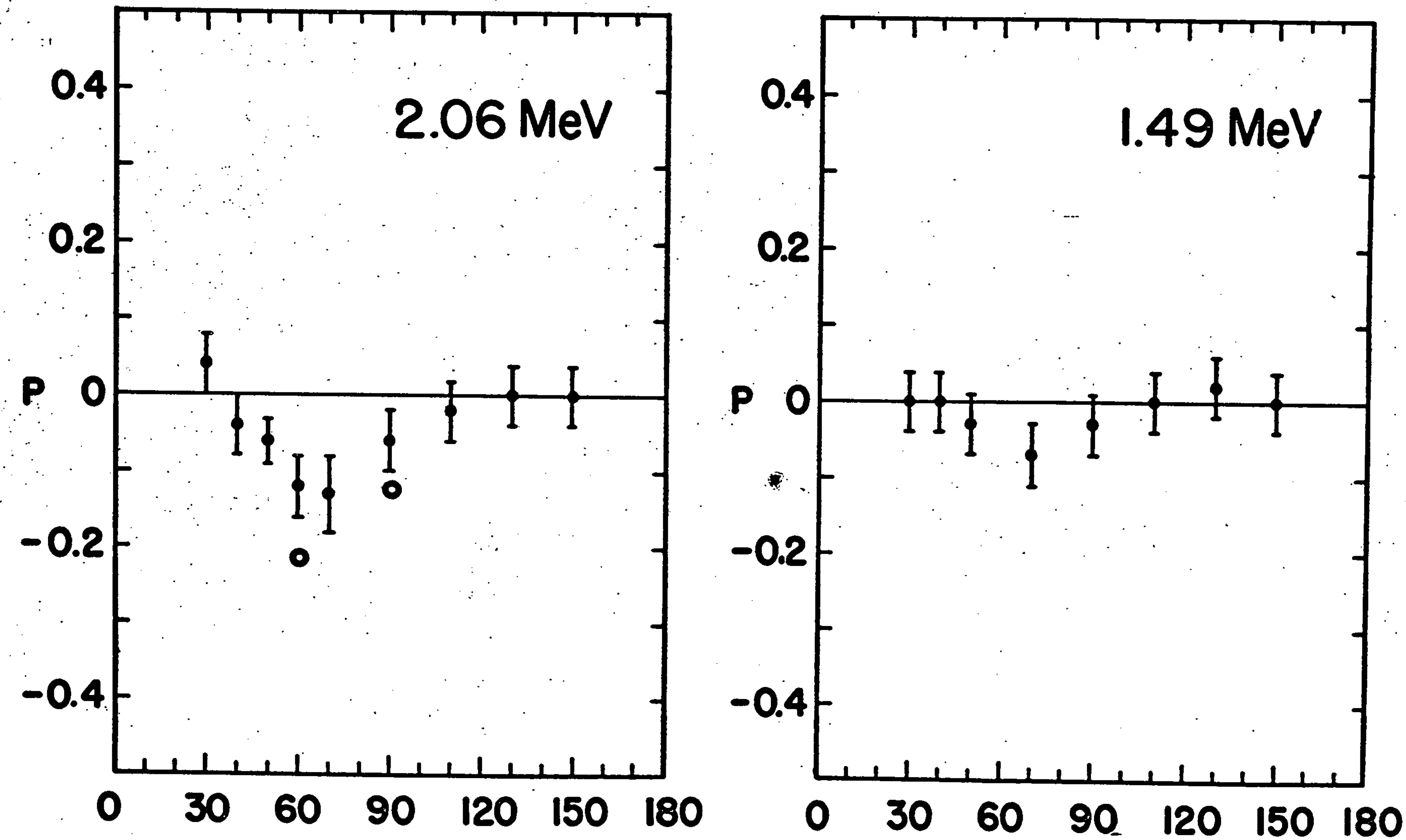
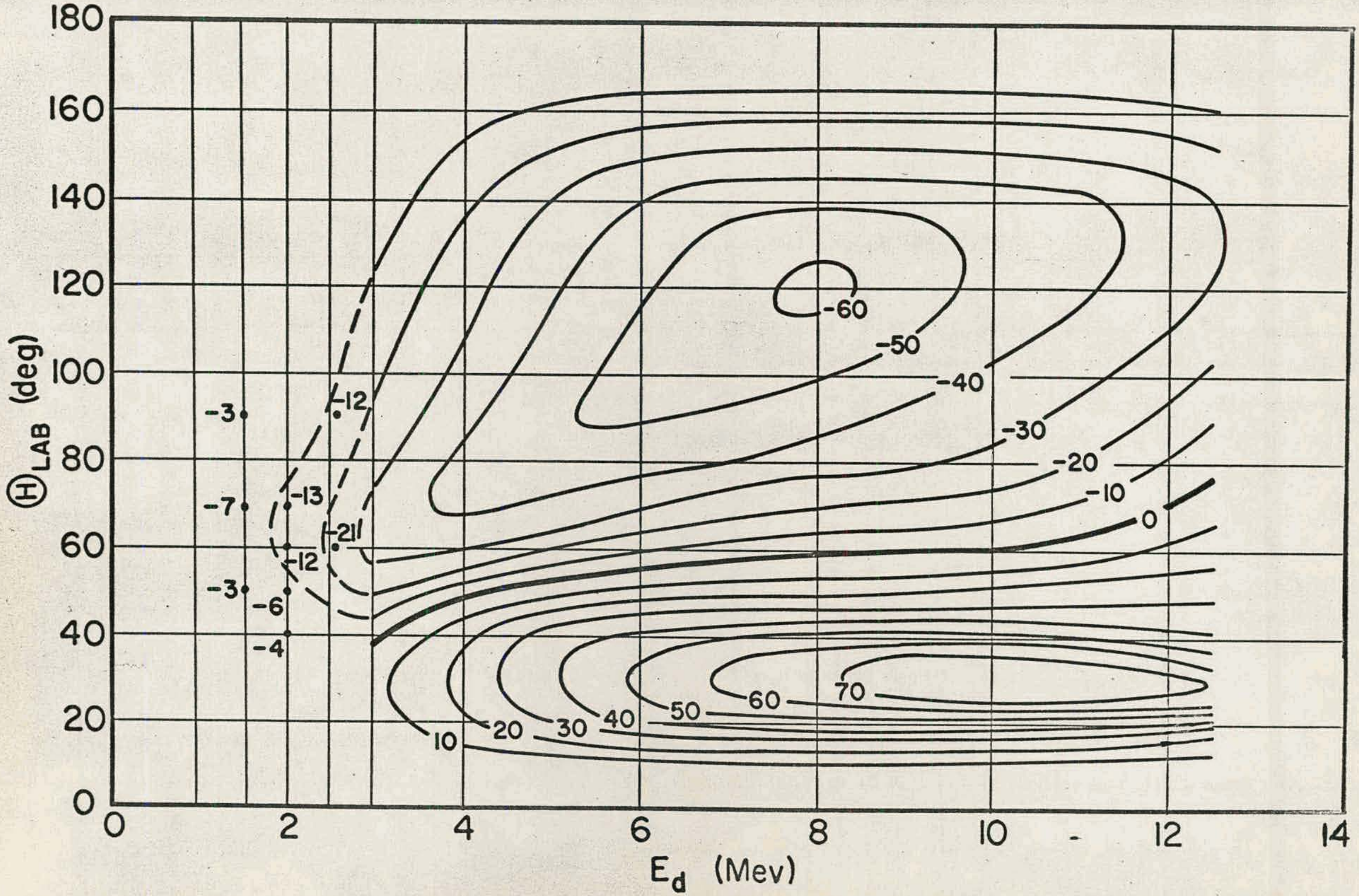


FIG. 4 P Vs Ⓗ LAB



180
160
140
120
100
80
60
40
20
0
Ⓗ LAB (deg)
0
2
4
6
8
10
12
14
E_d (Mev)
-60
-50
-40
-30
-20
-10
0
10
20
30
40
50
60
70
-3
-7
-3
-13
-12
-6
-4
-12
-21

FIG. 5