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S-Wave Pion-Pion Scattering Length from Reaction $\pi^- + p \rightarrow \pi^0 + \pi^0 + n$ at 378 MeV

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ABSTRACT

The differential energy distributions of neutrons from the reaction $\pi^- + p \rightarrow \pi^0 + \pi^0 + n$ were measured at four different neutron lab angles. Fitting the distributions with the Chew-Mandelstam solution for π-π phase shift, we obtain a value $a_{SO} = (.28 \pm .21)\ \mu^{-1}$ for the S-wave π-π scattering length.

Differential energy distributions of neutrons from the reaction

$$\pi^- p \to \pi^0 \pi^0 n \quad (1)$$

have been measured in order to study the I = 0, S-wave π-π interaction near the pion production threshold. Results at higher energies have been reported by several authors, most recently at the Argonne Conference[1)]. The experiment was performed at the Berkeley 184 inch Synchrocyclotron using an incident π^- kinetic energy of 378 MeV and laboratory neutron angles of 30, 35, 40 and 45 degrees.

Figure 1 shows the experimental arrangement. Scintillation anti-counters, A1 and A2, completely surround the liquid hydrogen target (3" diam. x 10" long). Three 30-gap lead plate spark chambers covering three sides of the target were used to detect the γ-rays from the π^0 decay. The thickness of each plate was 0.15 radiation lengths of lead. On the fourth side, neutrons were detected with an array of fourteen plastic scintillators (10" diam. x 6" thick) at a distance of 20 feet from the target. This neutron counter array could be positioned at any desired azimuth angle, θ (cf. Fig. 1). Scintillation anti-counters, A3 and A4, were placed in front of the shower chambers and the neutron counters, respectively, to veto charged particles coming from the target.

A gate trigger, $\{B1 \times B2 \times B3 \times \overline{(A1 + A2 + A3)}\}$, indicating a beam pion entering the target and no charged particles coming out or entering the shower chambers opened a 100 nsec long gate. A subsequent neutral particle signal during this gate time from any one of the neutron counters constituted an event. At each event the spark chambers were pulsed and the resulting shower information was recorded on film together with time-of-flight, pulse height, and address information from the neutron counters.

The timing and resolution of each neutron counter were calibrated by measurement with the prompt γ-ray and neutron from the charge exchange reaction

$$\pi^- + p \to \pi^0 + n. \quad (2)$$

The absolute efficienceis of the neutron counters were measured in a separate experiment by scattering mono-energetic neutrons off protons in a hydrogen target and detecting the scattered neutrons together with their coincident recoil protons.[2)]

The film was scanned for those events in which two or more γ-ray showers occurred in the spark chambers. By fitting the γ-ray directions and using the incident pion energy and the neutron angle and energy, a kinematic check was made to see if the detected neutron was a charge exchange neutron from reaction (2). Such events were rejected. The remaining events gave a time-of-flight distribution of inelastic neutrons from reaction (1) with a residual contribution in the charge exchange region. This latter contribution could be accounted for as arising from two sources. First, some charge-exchange events were included due to uncertainties in measuring the directions of the lowest energy γ-rays. Second, due to the relatively long sensitive time of the chambers, accidental γ-rays were sometimes seen in the chambers when a charge-exchange neutron was detected in the neutron counters. Since these two types of events could not be excluded by our selection criteria, a Gaussian distribution whose width was determined from the measured timing resolution was fitted to the charge-exchange peak and used to subtract out the background. The subtraction amounted to a maximum of ten percent in the first four-channel bin of the inelastic neutron time-of-flight spectrum (see Fig. 2). The time-of-flight distributions were converted to differential cross sections (Fig. 3) by using the calculated efficiencies for the detection of γ-rays in the shower chambers and the measured efficiency of the neutron detectors. Monte Carlo calculations have shown that the γ-ray detection efficiency in the shower chambers does not introduce biases in the measured neutron energy distributions, although it may introduce an error of about 25 percent in the overall normalization due to uncertainty in the calculated efficiencies. These cross sections are in qualitative agreement with previously published data at this energy,[3] but disagree significantly in the actual neutron energy distributions.

As can be seen from Figures 2 and 3 there is a rather consistent disagreement between the data and phase space. This was also seen in our previous 45 degree data[4] and in the data of Barish et al[3]. The present experiment was set up to obtain data with overlapping regions of c.m. neutron angles. We therefore use our four sets of data to derive an experimental c.m. angular distribution for the neutron. By fitting all the data simultaneously we obtain $1 + (1.7 \pm .2) \cos\theta_N^* + (3.0 \pm .3) \cos^2\theta_N^*$ as the best c.m. distribution (cf. Figure 2).

The neutron time-of-flight distributions at each angel were fitted to the phase-space corrected for the neutron c.m. angular distribution and multiplied by an enhancement factor due to the π-π interaction. Following Booth and Abashian[5] we used the enhancement factor in the form[6]

$$F(q^2) = (q^2 + \mu^2) \frac{\sin^2 \delta}{q^2} \tag{3}$$

with q, the π-π relative momentum, μ, the pion mass, and δ, the π-π phase shift obtained from the S-wave dominant solution of the π-π equation of Chew and Mandelstam,[7]

$$\left(\frac{q^2}{q^2 + \mu^2}\right)^{1/2} \cot \delta = \frac{1}{a_{SO}} + \frac{2}{\pi} \left(\frac{q^2}{q^2 + \mu^2}\right)^{1/2} \ln \left[\frac{q + (q^2 + \mu^2)^{1/2}}{\mu}\right] \tag{4}$$

To compare with the data the chi-square values as a function of the S-wave scattering length, a_{SO}, are shown in Figure 4. Due to the presence of $\sin^2\delta$ in Eq. (3) we get two sets of scattering lengths, one positive and one negative. The best values and their errors are presented in Table I together with their weighted averages. As can be seen from Table I the values of the scattering length obtained from the four sets of data are independent of the lab neutron angle; the four values being consistent with each other within experimental errors.

Our final result for the I = 0, S-wave scattering length is $a_{S0} = (.28 \pm .21)\ \mu^{-1}$. This value is in agreement with the current algebra prediction of Weinberg,[8] the bootstrap calculations of Johnson and Collins[9], and the most recent forward dispersion relation prediction of Morgan and Shaw.[10]

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Table I. Measured a_{SO}, π-π scattering lengths. Note, we obtain a positive and a negative value with equal error.

Lab neutron angle	a_{SO}, the π-π scattering length, in units of pion Compton wavelength	
	positive	negative
30^o	0.16 ± 0.40	- 1.35 ± 0.40
35^o	0.32 ± 0.29	- 1.53 ± 0.29
40^o	0.05 ± 0.57	- 1.27 ± 0.55
45^o	1.0 ± 0.95	- 2.22 ± 0.99
Weighted average	0.28 ± 0.21	- 1.47 ± 0.21

FIGURE CAPTIONS

FIGURE 1: Experimental arrangement showing the three shower chambers and the fourteen neutron counters and the locations of various beam counters and anticounters.

FIGURE 2: Measured time-of-flight distribution for lab neutron angle of 35 degrees showing the subtracted charge-exchange events (CX). Also shown are the (1) phase space, (2) phase space multiplied by the neutron c.m. angular distribution ($a_{SO} = 0$), and (3) the best fit with a scattering length of 0.32 μ^{-1}.

FIGURE 3: Measured differential distributions of neutrons as functions of neutron kinetic energy for various lab neutron angles, showing the phase space and the fit with a π-π scattering length of 0.28 μ^{-1}.

FIGURE 4: Chi-square values presented as functions of scattering length for the four sets of data showing two best values of scattering length for each set.

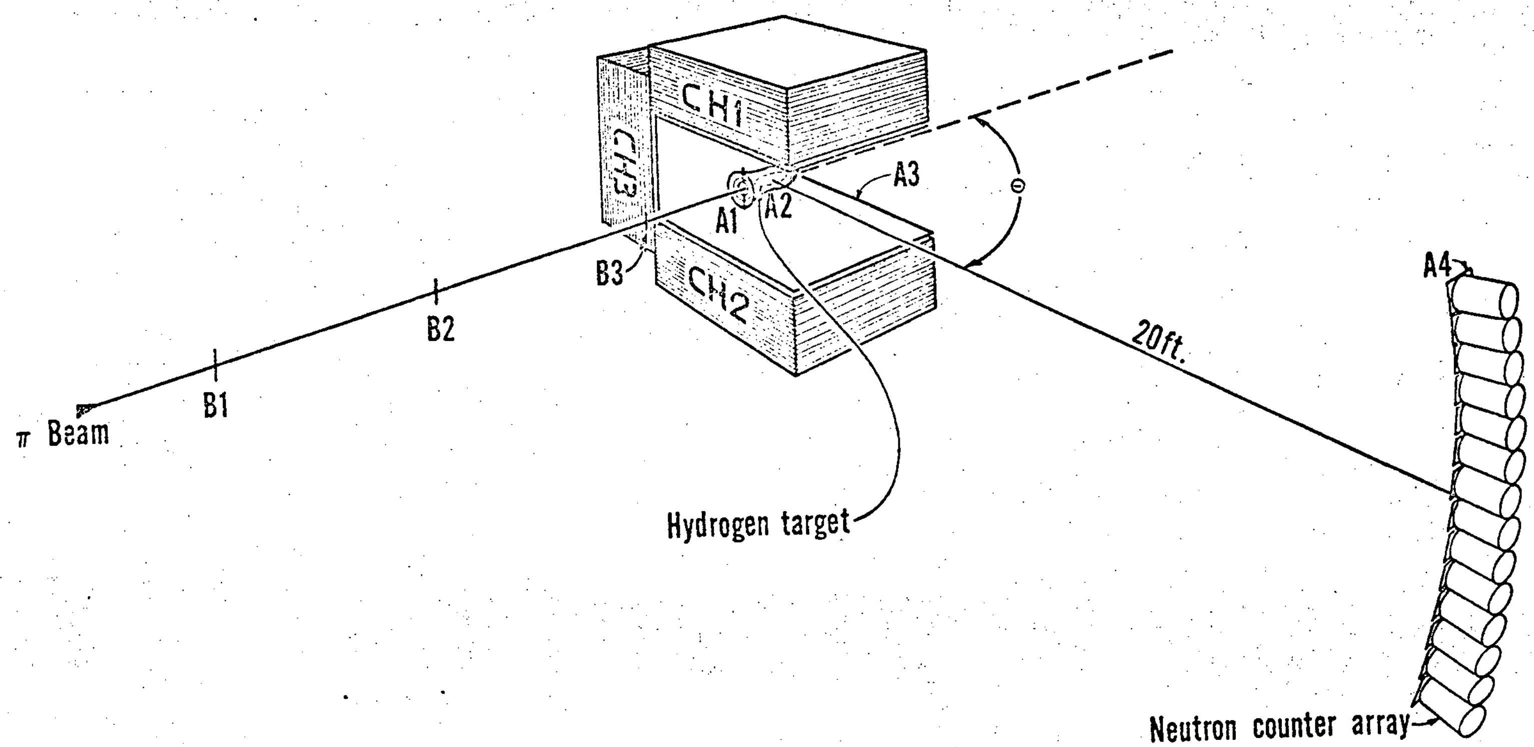

CH1
CH2
CH3
A1
A2
A3
A4
B1
B2
B3
π Beam
Hydrogen target
20ft.
Neutron counter array

Fig. 1

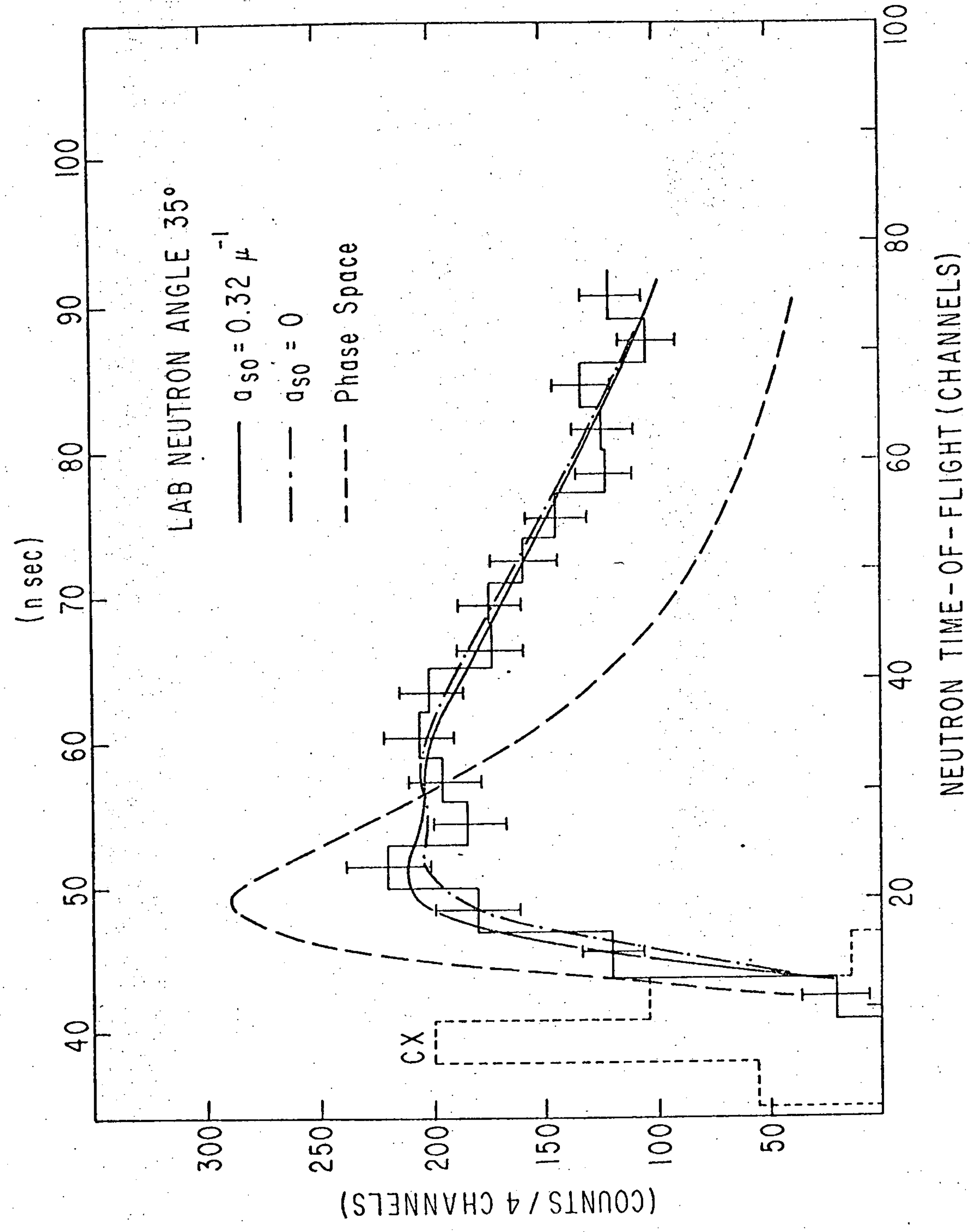

(n sec)
40
50
60
70
80
90
100
LAB NEUTRON ANGLE 35°
$a_{so} = 0.32\ \mu^{-1}$
$a_{so} = 0$
Phase Space
CX
300
250
200
150
100
50
(COUNTS / 4 CHANNELS)
20
40
60
80
100
NEUTRON TIME - OF - FLIGHT (CHANNELS)

Fig. 2

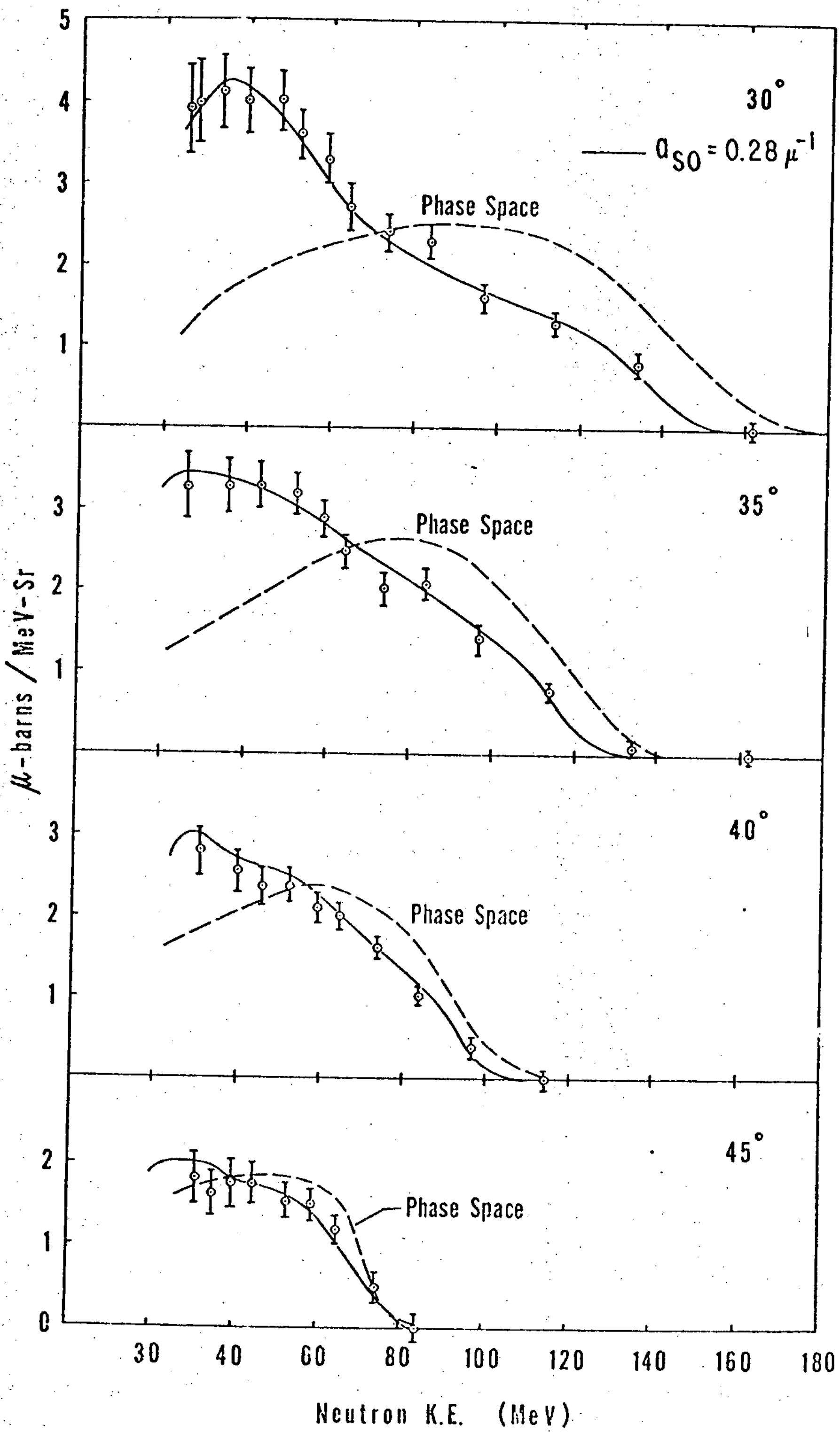
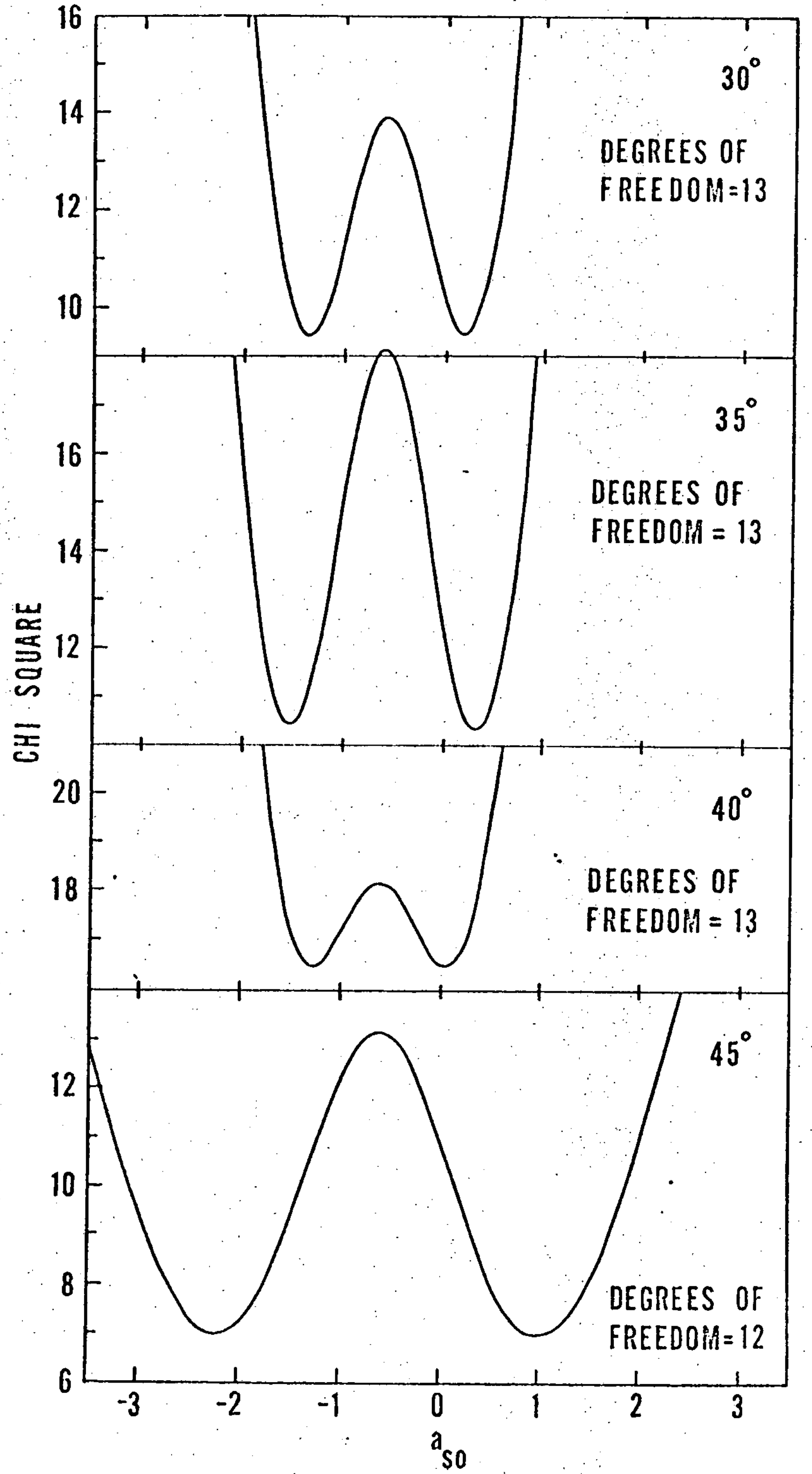

5
4
3
2
1
30°
$a_{SO} = 0.28\,\mu^{-1}$
Phase Space
3
2
1
35°
Phase Space
3
2
1
40°
Phase Space
2
1
0
45°
Phase Space
μ-barns / MeV-Sr
30
40
60
80
100
120
140
160
180
Neutron K.E. (MeV)

Fig. 3



30°
DEGREES OF FREEDOM=13
35°
DEGREES OF FREEDOM = 13
40°
DEGREES OF FREEDOM = 13
45°
DEGREES OF FREEDOM=12
CHI SQUARE
16
14
12
10
16
14
12
20
18
12
10
8
6
-3
-2
-1
0
1
2
3
a_{so}

Fig. 4

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