n-p Differential Scattering Cross Section at 22.5 Mev*

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ABSTRACT

A tritium target was bombarded with 5 m.s. pulses of 6.1 Mev deuterons produced by the Los Alamos Variable Energy Cyclotron. A collimated beam of 22.5 Mev neutrons from the $H^3(d,n)He^4$ reaction was directed into a 3.2 liter liquid hydrogen bubble chamber. The resulting proton recoil tracks were photographed with 90° stereophotography. Film scanning, data reduction, and uncertainties in the measurements are described. The measurements cover neutron scattering angles from 60° to 180° in the C.M. system. The measured differential cross section in the C.M. system can be written $d\sigma/d\Omega = A_0 + A_2\cos^2\theta$, where $A_2/A_0 = .092 \pm .04$.

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

I. INTRODUCTION

Accurate data on the n-p differential scattering cross section at different energies are necessary in order to specify the form of the nucleon-nucleon interaction, and to choose between the various potential functions. Although the correct potential function must also satisfy the deuteron binding energy and electric quadrupole moment, and the n-p singlet and triplet scattering lengths, all of which are known from independent measurements, it has not, thus far, been possible to isolate it from all the possibilities. Intermediate energy measurements of the n-p differential scattering cross section have been made both at lower energies (14.1 Mev[1] and 17.9 Mev[2]) and at higher energies (27.2 Mev[3] and 28.4 Mev[4]) than the measurements reported here which are at 22.5 Mev. The present measurements were made with a liquid hydrogen bubble chamber, and are somewhat more accurate than other measurements in this energy range.

II. THEORY

The differential scattering cross section can be written in the form

$$d\sigma/d\Omega = A_0 + A_1 \cos\theta + A_2 \cos^2\theta \tag{1}$$

where θ is the scattering angle. All measurements in the intermediate energy range have shown $d\sigma/d\Omega$ to be symmetric about 90° in the C.M. system, within the accuracy of the measurements. This implies that A_1 is zero, or very small. We write the scattering amplitude as[5]

$$f(\theta) = \bar{f} + g(\theta) \tag{2}$$

where $\bar{f}$ is the spherically symmetric S wave scattering. If the result for $g(\theta)$ is calculated using the Born approximation, and is expanded in a power series in kr, where $kr \ll 1$ for k corresponding to 22.5 Mev and r is within the range of nuclear forces, we obtain

$$g(\theta) \cong \frac{2\mu k^2}{3\hbar^2} \cos\theta \int_0^\infty V(r)\, r^4\, dr \qquad (3)$$

k is the wave number of the incoming particle in the C.M. system, r is the separation distance of the particles, μ is the reduced mass of the particle, $\hbar$ is Planck's constant divided by 2π, and $V(r)$ is the interaction potential. The angular dependence of $g(\theta)$ is characteristic of a P wave scattering amplitude. The term $A_2 \cos^2\theta$ in Eq. (1) is related to the singlet $g_s(\theta)$ and the triplet $g_t(\theta)$ by

$$A_2 \cos^2\theta = \frac{3}{4}\, g_t^{\,2}(\theta) + \frac{1}{4}\, g_s^{\,2}(\theta) \qquad (4)$$

From the experimental measurements A_2/A_0 can be determined. The total cross section at the energy of interest is known, and was not measured in the experiment.

III. EXPERIMENTAL

The Los Alamos Variable Energy Cyclotron was pulsed to produce 5 m.s. bursts of 6.1 Mev deuterons. These were focussed on a tritium-gas target. The resulting 22.5 Mev neutrons from the $H^3(d,n)He^4$ reaction were collimated by passing through two conical-shaped holes (apexes adjoining) in a 30" long block of steel. The 3.2 liter liquid hydrogen bubble chamber was located at the far end of the collimator. The experimental arrangement is shown in Fig. 1. Pulsing the cyclotron was accomplished by means of an arc modulation circuit, and had the additional advantage of producing a sufficiently low background that personnel could work in the vicinity of the bubble chamber.

The bubble chamber and its operation have been described previously.[6] As a neutron spectrometer, the bubble chamber has an energy resolution in the zero to 30° forward cone at 22.5 Mev of ± .65 Mev, with a background in the vicinity of the peak of about 4%. To obtain maximum accuracy in measurement of the proton recoils, 90° stereophotography is used with two Recordak microfilm cameras viewing the chamber from above and from the side. A reduction of 16 to 1 is used in these cameras, the large value being necessary to minimize the variation of demagnification across the chamber, so as to facilitate identification of stereo-pairs.

IV. DATA REDUCTION

In order to make rapid measurements of the recoil proton tracks as recorded in the 90° stereophotography system, it was necessary to construct a special microscope. The microscope allowed the visual presentation of either view of the chamber by means of light-blocking levers, which meant that the scanner could rapidly find the stereo pairs of a track and make the four endpoint measurements necessary to find its energy and recoil angle. The microscope screw positions were sensed by brush-type encoders, and the resulting digital information was put on cards by an IBM summary punch. All measurements were automatically recorded on IBM cards by depressing a foot pedal.

Since a track measurement consisted of four cards for the four endpoints, plus a measurement of the reference origin, it was necessary to combine this information for presentation to an IBM 704. This was accomplished by means of an IBM 1401. The 704 then performed all the necessary computations to obtain the energy and direction of each track. In addition, calculations were made to find the starting point of each track, as well as the projected angle which each camera viewed. These quantities were then used to determine any possible asymmetry in the visible region of the bubble chamber.

Following the computation of the angles and energies of all the tracks, the data were run through a sorting code which separated it into 5° intervals, and also into 0.2-Mev energy intervals within each angular interval. The data falling outside a given fiducial volume for the track starting points were rejected by this code. This latter volume was always less than the volume scanned by the reader, so that edge effects in scanning could be eliminated. Although 6000 tracks were rejected out of a total of 12,000 which were read, in order to eliminate bias, it was still necessary to correct the final results at small angles for long-range recoils which left the field of view. This correction was obtained as a function of angle by the use of a Monte Carlo calculation. This calculation, which took account of the geometry of the chamber and of the neutron source, used a semiempirical differential cross section due to Gammel,[7] which was considered sufficiently accurate for the correction. The correction amounted to about 10% of the uncorrected measurement at the forward proton angles, and fell to a few percent at the larger angles. Uncertainty in the volume of the bubble chamber observed by the cameras produced about a 2% uncertainty in the final result at small proton angles. A new film viewer now in use for scanning bubble chamber photographs will reduce this difficulty in future work, by allowing more efficient scanning of a smaller volume of the chamber.

The tracks which were not discarded by the sorting code were then plotted for each 5° interval. An example of one of these plots is shown in Fig. 2. The total number of tracks under the peak, after a small background correction is made, is proportional to the differential scattering cross section. The background was obtained by drawing a symmetric curve about the peak, and subtracting those tracks on the low energy side which were above this curve. The remaining number of tracks was then identified with the solid angle in the C.M. system which corresponds to the 5° interval in the laboratory system.

V. RESULTS

The best linear function of $\cos^2\theta$ which fit the number of tracks observed in each of twelve 10° C.M. angular intervals was determined by the method of least squares. This determined the ratio A_2/A_0 to be $.092 \pm .04$. The total cross section was then normalized to 425 m.b.[8] for 22.5 Mev, assuming the capture cross section to be negligible. This gave A_0 = 32.8 m.b./steradian, and A_2 = 3.03 m.b./steradian. The data do not extend beyond 60° C.M., due to the short length of the recoil proton tracks at small neutron scattering angles. The protons observed at neutron angles less than 60° C.M. have energies below 5 Mev where the scanning efficiency is known to fall below 100%.

The normalized experimental results are shown in Table I and in Fig. 3, along with the results of previous authors at 14.1 Mev[1] and 27.2 Mev.[3] The dashed line in Fig. 3 is the semiempirical theoretical curve due to Cammel,[7] and is shown because it was used in the Monte Carlo calculation to correct the data for long-range recoils which left the field of view. For this curve, the ratio A_2/A_0 is approximately 0.13.

VI. ACKNOWLEDGEMENTS

We wish to acknowledge the assistance of Dr. Louis Rosen, Dr. Howard Bryant, Mr. John Wooton, and Mr. Ray Rylander. The careful film scanning by Mickey Gibson, Mildred Schroer, Virginia Stovall, and Miriam Woodward

is appreciated. The cyclotron personnel are also to be complimented for their skill in operating this machine.

Table I

n-p Scattering Data

C.M. Angle (degrees)	$\sigma(\Omega)$ (barns/ster.)	Statistical Error (%)
175	35.9	12.0
165	34.3	7.5
155	34.0	5.7
145	37.0	4.7
135	35.6	4.3
125	34.7	4.0
115	32.4	4.0
105	32.2	3.8
95	33.2	3.7
85	32.7	3.7
75	32.8	4.5
65	33.3	5.7

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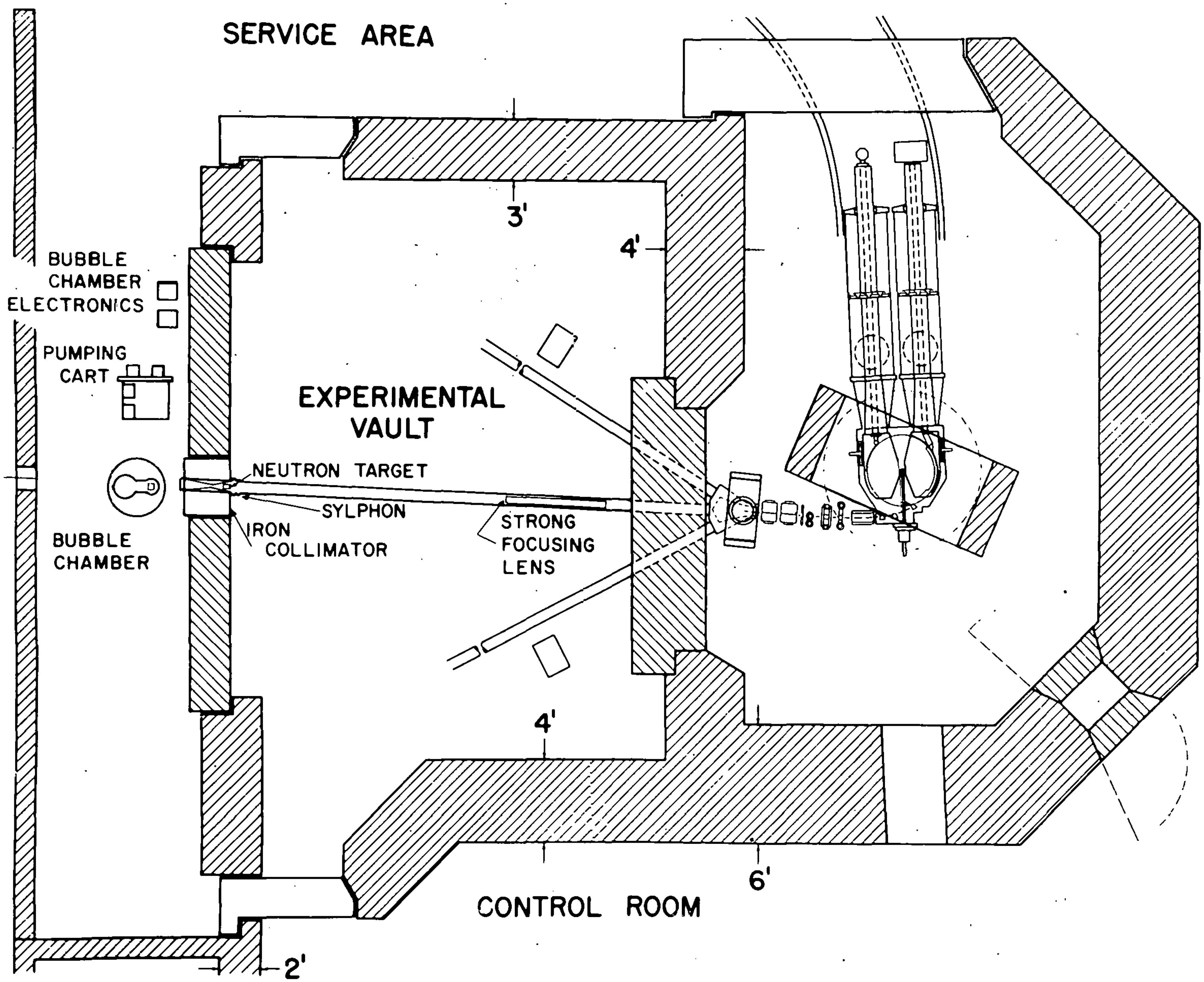
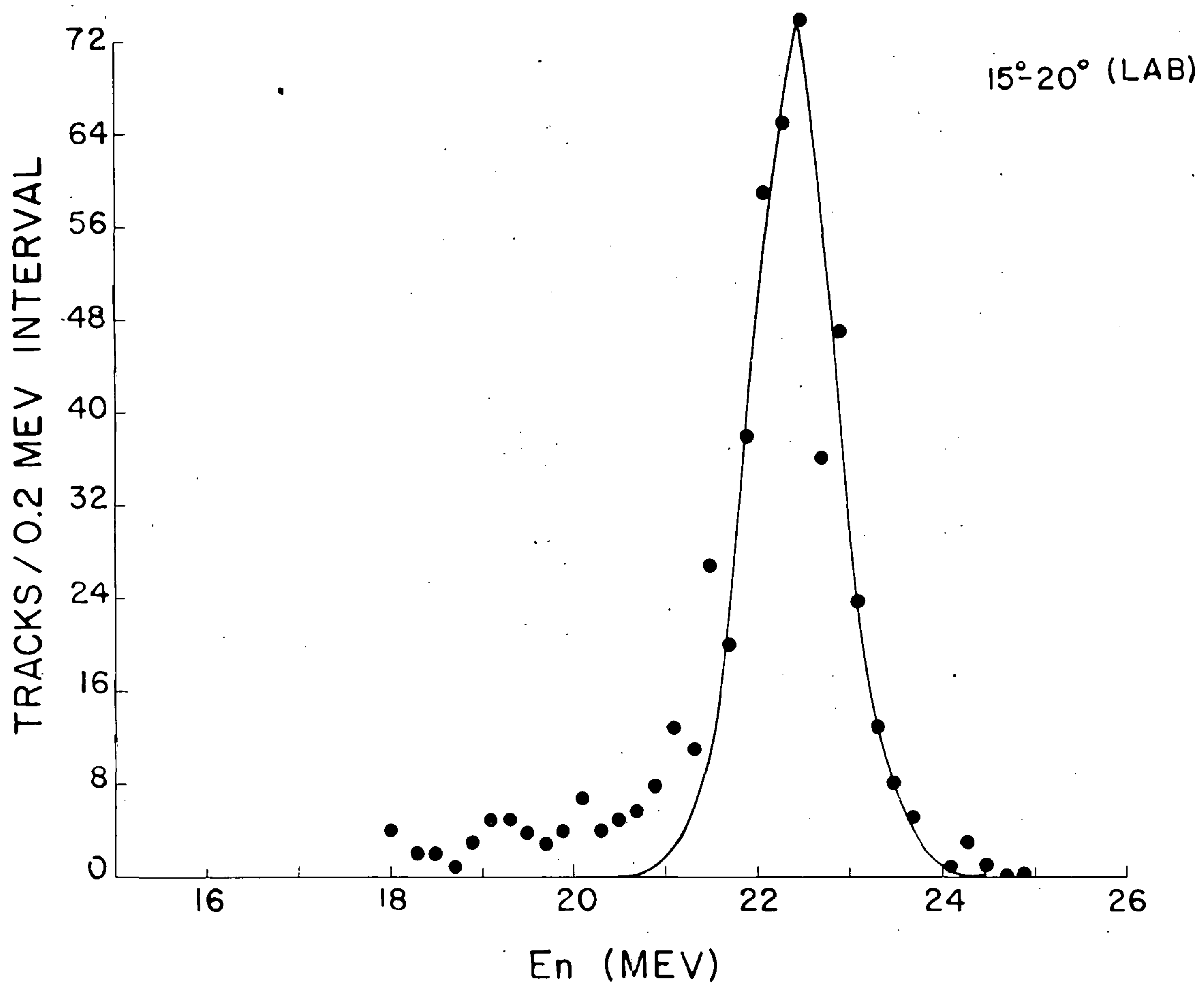
Figure Captions

Fig. 1. Plan view of the experiment, showing cyclotron, tritium target, collimator and bubble chamber locations.

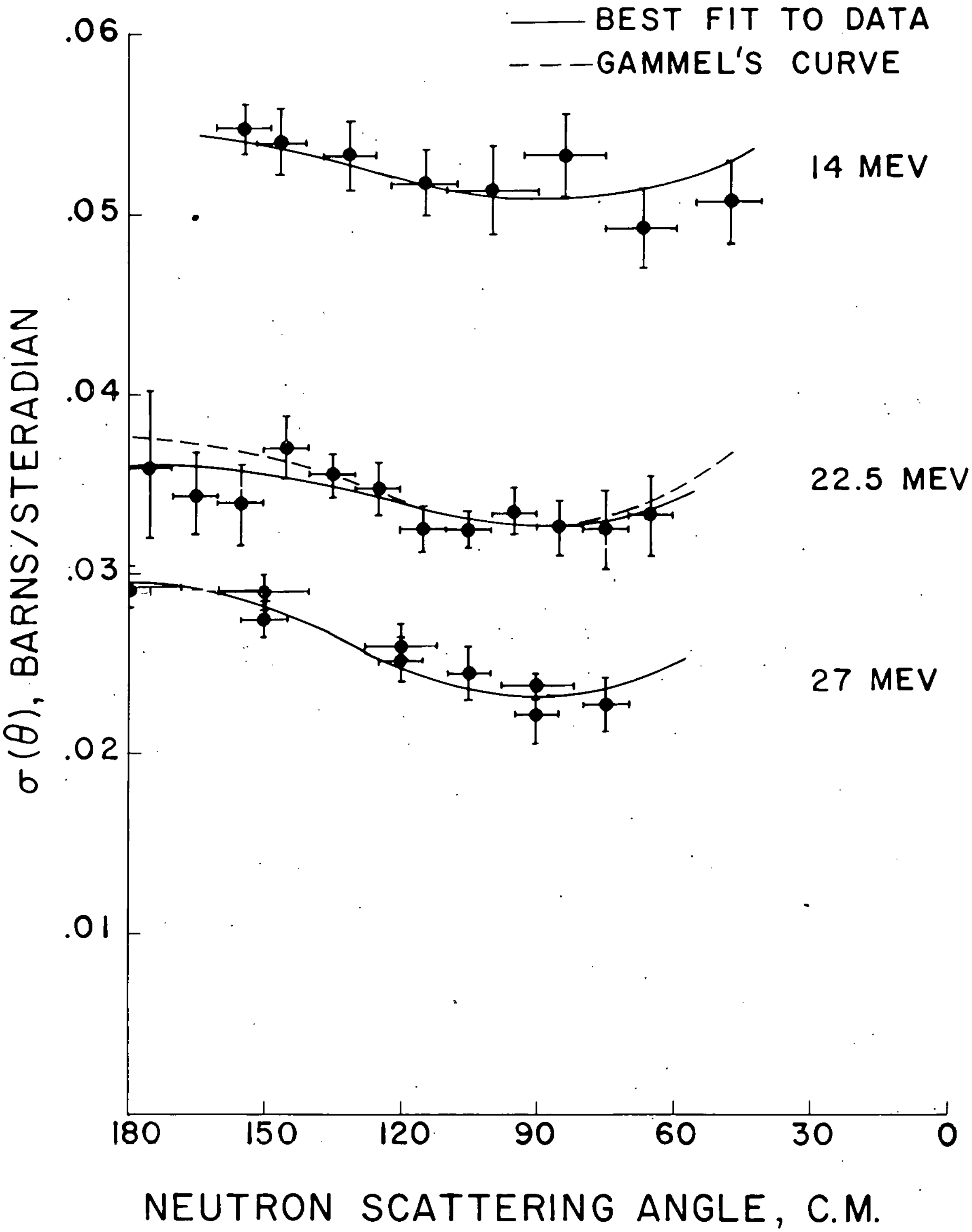
Fig. 2. Recoil protons scattered into the angular interval 15° to 20°, plotted as a function of energy.

Fig. 3. The differential n-p scattering cross section at 14.1, 22.5, and 27.2 Mev. The data at 14.1 and 22.5 Mev are taken from Ref. 1 and 3. The dashed line is the semiempirical theoretical curve by Gammel, Ref. 7. The errors indicated for the 14.1-Mev data and the present data are the statistical errors only.


SERVICE AREA
3'
4'
BUBBLE CHAMBER ELECTRONICS
PUMPING CART
EXPERIMENTAL VAULT
NEUTRON TARGET
SYLPHON
IRON COLLIMATOR
BUBBLE CHAMBER
STRONG FOCUSING LENS
18
4'
6'
CONTROL ROOM
2'



15°-20° (LAB)
TRACKS / 0.2 MEV INTERVAL
72
64
56
48
40
32
24
16
8
0
16
18
20
22
24
26
En (MEV)



BEST FIT TO DATA
GAMMEL'S CURVE
14 MEV
22.5 MEV
27 MEV
σ(θ), BARNS/STERADIAN
.06
.05
.04
.03
.02
.01
180
150
120
90
60
30
0
NEUTRON SCATTERING ANGLE, C.M.