MEASUREMENT OF TOTAL CROSS SECTIONS OF LIQUEFIABLE GASES

JOHN JOSEPH HINCHEY

Mar 22
8154

MEASUREMENT OF TOTAL CROSS SECTIONS OF LIQUIFIABLE GASES

(e)

by

JOHN JOSEPH HINCHEY

B.S., UNITED STATES NAVAL ACADEMY
(1941)

S.M., MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(1948)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN PHYSICS

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MEASUREMENT OF TOTAL CROSS SECTION OF LIQUIFIABLE GASES
by John Joseph Hinchey
SUBMITTED FOR THE DEGREE OF MASTER OF SCIENCE IN PHYSICS TO
THE DEPARTMENT OF PHYSICS, July 1, 1951.

ABSTRACT

The total neutron cross section of nitrogen was measured using a liquid nitrogen scatterer. Monoenergetic neutrons were obtained from the $Li^7(p,n)$ reaction using the Rockefeller Electrostatic generator as a source of monoenergetic protons. Neutron energy range covered was from 0.16 to 1.8 Mev. Measurements were made in "good geometry" and sufficient counts were taken for all points to ensure 3 per cent or less statistical error in the values of total cross section (σ_t). Nitrogen (N^{14}) exhibited 10 resonances; the peak values occurred at the following neutron energies (Kev): 434, 494, 663, 1020, 1120, 1212, 1349, 1403, 1597, and 1782.

A portion of the energy region was covered using Lithium azide (LiN_3) as a scatterer. Agreement was excellent. In addition another resonance was shown at 1182 Kev.

The results obtained in the energy region below 430 Kev indicate that further study using thin lithium targets and making observations at small energy intervals would be of interest. This opinion is based primarily on two features of the cross-section data obtained: (1) in three separate sets

15635

of data taken over this region, the same general trend was observed - the points do not fall on a smooth curve; (2) the cross sections obtained in this region are sufficiently well above the expected potential scattering cross section as to indicate the possible presence of one or more additional resonances.

The results of this experiment indicate that measurement of total neutron cross sections of other liquifiable gases is feasible and could be made with little difficulty.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS AND TABLES

CHAPTER I

INTRODUCTION

One of the interesting problems in present day physics is the determination of the structure of nuclei. The theory of nuclear resonances, originally developed by Breit and Wigner (B4) and more recently extended and simplified by Feshbach, Peaslee and Weisskopf (F1), affords one method of attacking this problem. Valuable information in this regard can be derived from precise total neutron cross section measurements.

The compilation by Adair (A1) contains essentially all of the extensive information available on total cross sections with the exception of the most recently published results. The Rockefeller Electrostatic Generator provides a very precise source of monoenergetic neutrons in the energy range 0.1 to 2.0 Mev using the $Li^7(p,n)Be^7$ reaction.

The total cross section of nitrogen reported by Adair is based on meager data which indicated no resonances.

The compound nucleus, N^{15}, is of particular interest. The excited states are known almost up to the neutron binding energy, while above that energy they are apparently still easily resolved. These higher levels may decay by emission of a neutron, proton, or alpha particle. The residual nuclei, N^{14}, C^{14}, and B^{11} are all available as target materials for study of the reverse reactions. $N^{14}(n,p)C^{14}$ and $N^{14}(n,\alpha)B^{11}$ have been

examined with good resolution by Johnson and Barschall (J1) and $C^{14}(p,n)N^{14}$ by Roseborough *et al.* (R2). Assignment of possible quantum numbers associated with the (n,p) and (n,α) resonances must be consistent with the total cross section (J1).

Bockelman *et al.* (B3) have made a preliminary study of the total cross section of nitrogen up to 900 Kev. They reported (J1) that no resonance was observed at 499 Kev and that the resonance observed at 660 Kev was preceded by a minimum at 620 Kev, indicative of s-neutrons. The observed difference between maximum and minimum was about 1.0 barn.

The usual method of determining total cross sections is to measure the transmission through a solid mass of a single element or through a compound containing the element. In the latter case the cross section of the other element (or elements) should be accurately known. Frequently, it is difficult to obtain convenient chemical or physical forms. Since nitrogen is difficult to obtain in stable, solid compounds having high percentages of nitrogen and accompanied by elements whose cross sections are well known, it seemed desirable to investigate the use of liquid nitrogen as a scatterer in this experiment.

CHAPTER II

EXPERIMENTAL PROCEDURE

The total neutron cross section was determined by direct transmission experiments in which the source, "scatterer," and detector were in "good geometry." The geometry used in this experiment is shown in Figure 1. By measuring the counting rate, N_0, with the scatterer out of the beam and again measuring counting rate, N, with the scatterer in position, the total cross section σ_t may be determined from the relation $N/N_0 = e^{-n\sigma_t T}$; n is the number of scattering nuclei per cm^3 and T is the thickness of scatterer in cm.

The neutron yield of the $Li^7(p,n)Be^7$ reaction is well-known, having been studied extensively at MIT (W1) and elsewhere (T1). The description and operation of the MIT Rockefeller generator has been adequately covered in the recent literature (L1, S1, R1, and W1). Particular note should be made of the energy resolution now obtainable by virtue of the proton resonance control on the field of the analyzing magnet (L1, S1, R1). This refinement permits the measurement of proton energy to within 300 ev thereby greatly increasing the resolution of neutron energy.

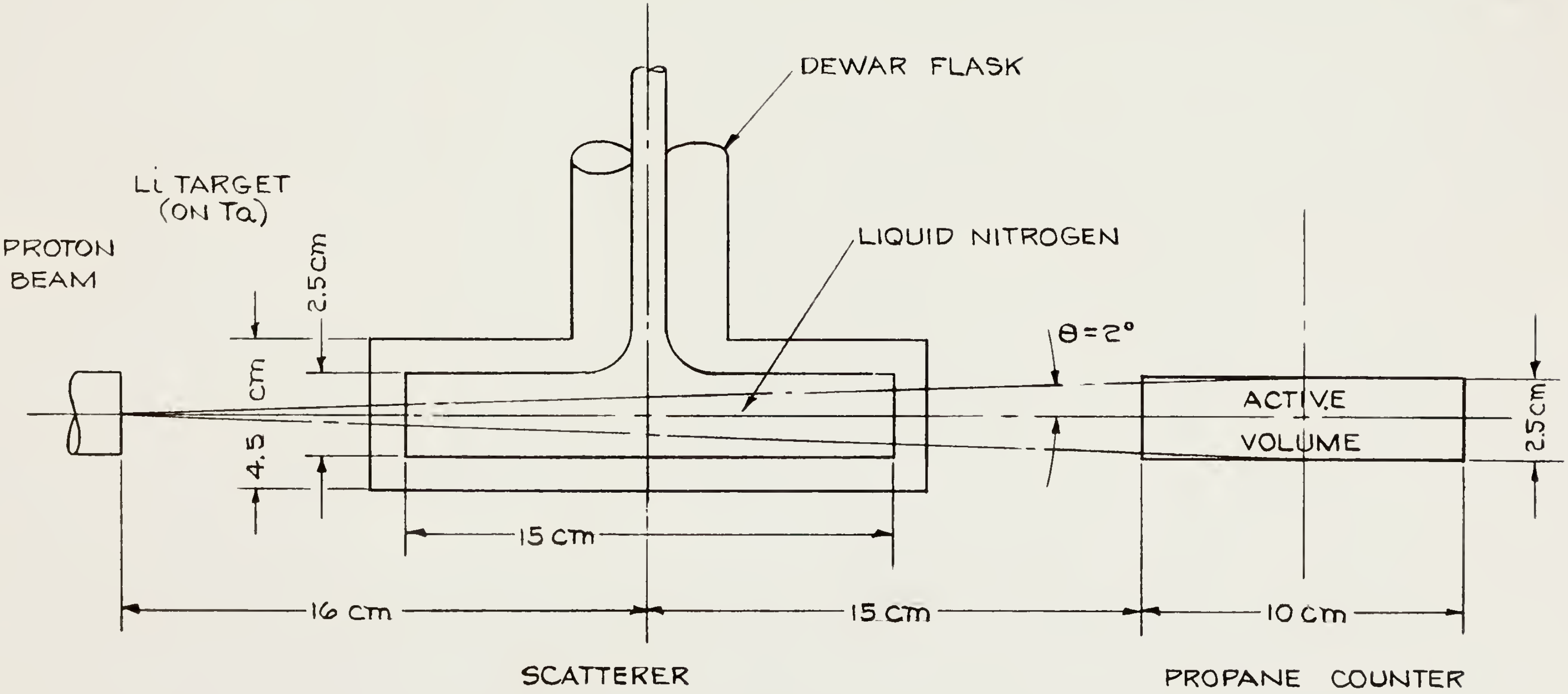
A propane counter, one inch in diameter and four inches long, was used to detect the neutrons transmitted through the scatterer. The advantages of this counter are discussed by Willard (W1) and the relative sensitivity of the particular counter used is shown in Figure 2. Although some experimenters

Figure 1

EXPERIMENTAL ARRANGEMENT OF

SOURCE, "SCATTERER," AND DETECTOR

Approximately half size.

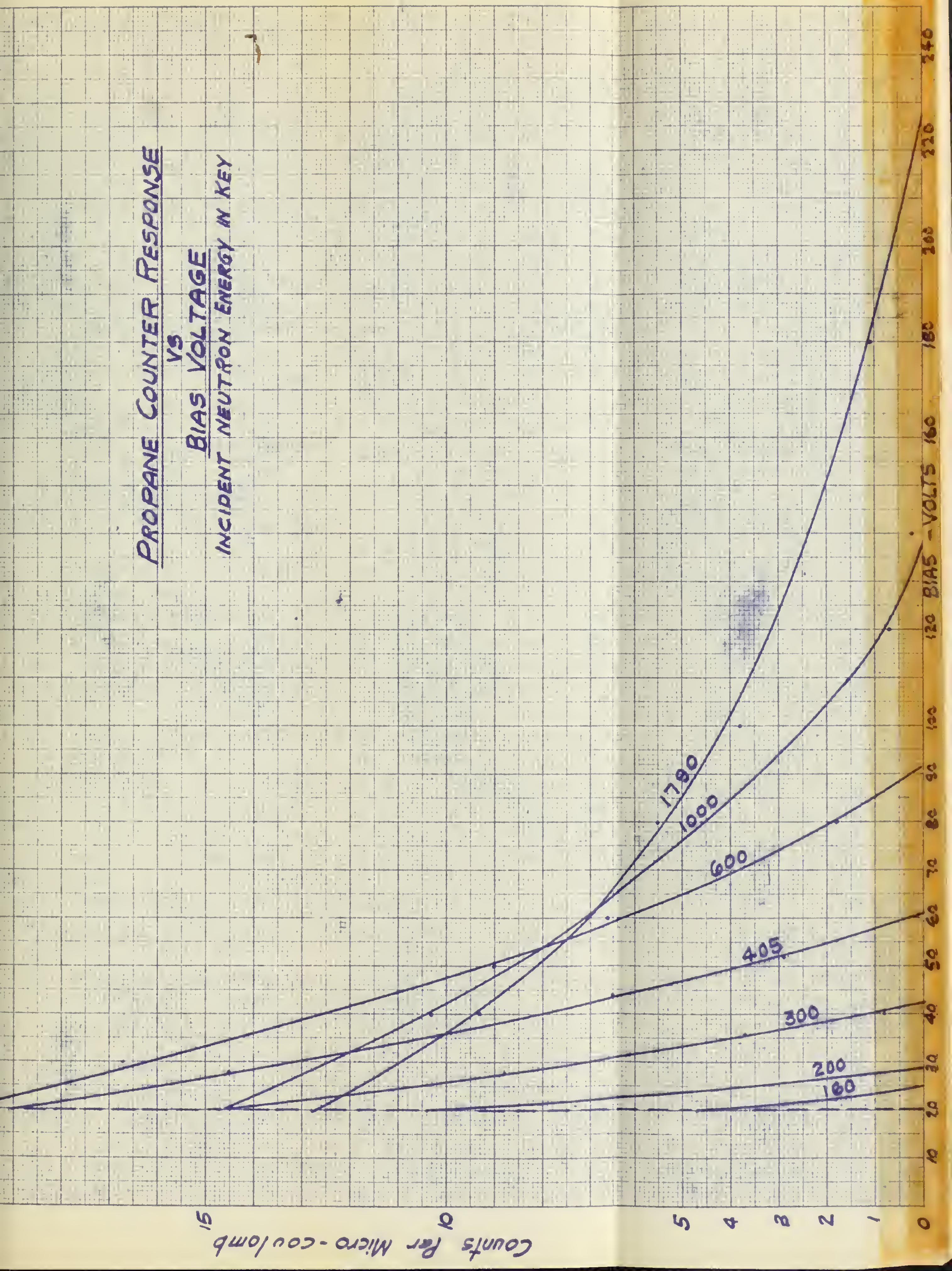


EXPERIMENTAL ARRANGEMENT - HALF SIZE

Figure 2

RELATIVE SENSITIVITY OF PROPANE
COUNTER AS FUNCTION OF BIAS VOLTAGE

Gamma-ray cutoff is bias voltage below which counter is insensitive to gamma rays from 1.0 milli-curie polonium-beryllium source.



PROPANE COUNTER RESPONSE
VS
BIAS VOLTAGE

INCIDENT NEUTRON ENERGY IN KEY

(e.g. P1) state that the second group of neutrons from the $Li^7(p,n)Be^7$ reaction do not produce any observable effects in transmission experiments, it seemed advisable to "bias out" the second group of neutrons particularly since this is so readily accomplished with this type counter. Johnson and Barschall (J1) discuss the effect of the second group and show the apparent $N^{14}(n,p)$ cross sections observed.

The pulses produced by the proton recoils were amplified by a four-tube preamplifier, Model 204-B (A.I.C.) amplifier and recorded by an A.I.C. decimal scalar, model 105.

A "long counter" as described by Hanson and McKibben (H1) was used as a monitor for all transmission measurements. The counter was placed with its axis at 90° to the proton beam and at a distance which permitted feeding the pulses through a Model 101 preamplifier, and Model 100 amplifier into a single Atomic Instrument Company scalar.

The preliminary measurements were made using a Dewar flask which was made available by Professor D.H. Frisch. This flask was originally intended for use in an experiment of only qualitative nature. As a result, there was no information available regarding internal dimensions. Figure 3 shows X-radiographs made to determine the length and diameter of the effective scatterer. The thickness, T was determined to be 6.0 cm.

Although these preliminary measurements located most of

Figure 3

X-RADIOGRAPHS OF DEWAR FLASK

USED FOR PRELIMINARY MEASUREMENTS

Upper radiograph was made with axis of flask essentially parallel to x-ray beam. Lower was made with axis perpendicular to beam.

the resonances fairly well, it was felt that a thicker scatterer was desirable and a new flask was designed and constructed, see Figure 4. With this flask, transmission ratios were reduced considerably with an attendant increase in accuracy of the absolute values of σ_t (see Chapter IV on Statistical Error).

To check the accuracy of the results obtained with liquid nitrogen, similar transmission measurements were made with lithium azide (LiN_3). This is a resonably stable compound containing a high percentage of nitrogen together with a single element (Li) for which the total cross section is well-known and is fairly constant over the available neutron energy region.

It is unfortunate that circumstances did not permit extending this study to higher energies. It was hoped that the cross section could be measured for neutron energies up to about 2.3 Mev (4 Mev protons). However, the number of investigations being conducted by the MIT Shielding Group has been so great that the Rockefeller Generator has been in constant use to the extent that shut-down has been reduced to an absolute minimum. Time has not permitted modifications which would enable the generator to operate at these high energies.

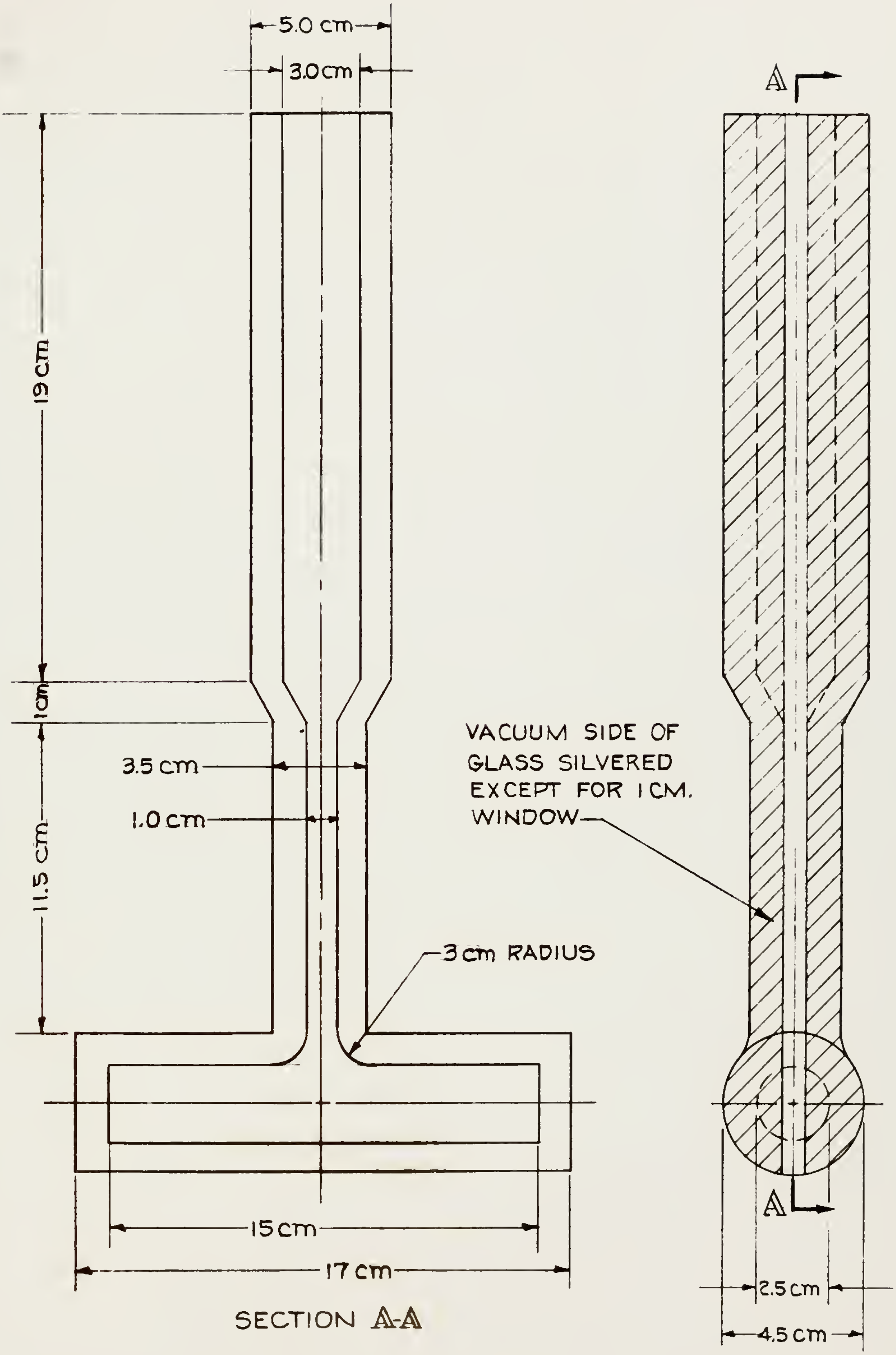
The liquid nitrogen used in this experiment was obtained from the Low Temperature Laboratory at M.I.T. The purity of the nitrogen is 99.8 per cent or greater, there being less than 0.1 per cent oxygen, still smaller amounts of argon and possibly traces of other gas impurities.

Figure 4

NEW DEWAR FLASK FOR LIQUID NITROGEN SCATTERER

(Thickness, T = 15 cm.)

This flask was designed and constructed after preliminary measurements had been made using the 6 cm. scatterer. The flask was made of No. 774 Pyrex glass of about 1 mm. thickness. In addition to being of greater thickness, this flask has the following advantages over the original flask: (1) ease of supporting due to decrease in size and weight and (2) more accurate alignment possible because outer shell is of same shape as inner shell and because 1 cm. sight window is parallel to scatterer. Upper reservoir holds sufficient liquid nitrogen to permit taking data for approximately two hours without replenishing.



VACUUM SIDE OF GLASS SILVERED EXCEPT FOR 1 CM. WINDOW

DEWAR FLASK FOR LIQUID NITROGEN SCATTERER

CHAPTER III

THEORETICAL CONSIDERATIONS

The previously mentioned Breit-Wigner single level resonance formula and the more recent developments by Feshbach, Peaslee and Weisskopf concern the theoretical aspects of resonance reactions and are discussed thoroughly in the literature of the past few years (B4, F1, A1, B2, and W1).

The derivation and discussion of formulae used in this work can be found in any of the above referenced papers as well as elsewhere in recent literature. Only those necessary to the calculations at hand are listed below:

$$(1) \quad \sigma_{n,n} = (2\ell' + 1)\, G_{J\ell'}\, 4\pi ƛ^2 \left[\frac{\Gamma n/2}{E - E_r + i\frac{\Gamma}{2}} - e^{-i\delta_{\ell'}} \sin \delta_{\ell'} \right]^2 + (2\ell' + 1)(1 - G_{J\ell'})\, 4\pi ƛ^2 \sin^2 \delta_{\ell'} + \sum_{\ell \neq \ell'} (2\ell + 1)\, 4\pi ƛ^2 \sin^2 \delta_\ell$$

$$(2) \quad \sigma_{n,p} = (2\ell' + 1)\, G_{J\ell'}\, 4\pi ƛ^2 \frac{\Gamma n\, \Gamma p}{(E - E_r)^2 + \frac{\Gamma^2}{4}}$$

$$(3) \quad \sigma_{n,n'} = (2\ell' + 1)\, G_{J\ell'}\, 4\pi ƛ^2 \frac{\Gamma n\, \Gamma n'}{(E - E_r)^2 + \frac{\Gamma^2}{4}}$$

$$(4) \quad \sigma_t = \sigma_{n,n} + \sum \sigma_{n,n'} \pm \sum \sigma_{n,p(\alpha)}$$

(5) $\Gamma_{n_\ell} = 2(1/\lambda)\,\gamma_n^2\,T_{n_\ell}$ and $\Gamma_{p_\ell} = 2(\frac{1}{\lambda})\,\gamma_p^2\,T_{p_\ell}$

(6) $\Gamma_{n_\ell} = \frac{2k}{K}\,T_{n_\ell}\,\frac{\overset{D}{2\pi J}}{\pi}$

(7) $\delta_0 = -X$

$\delta_1 = -X + \pi/2 - \cot^{-1} X$

$\delta_2 = -X + \pi/2 - \cot^{-1}(\frac{X^2 - 3}{3X})$

(8) <u>for neutrons only</u>

$T_0 = 1$

$T_1 = X^2/1 + X^2$

$T_2 = \frac{X^4}{X^4 + 3X^2 + 9}$

Where:

σ_t = total neutron cross section

σ_{nn} = elastic scattering cross section

σ_{nX} = charged particle cross section (X = proton or α-particle)

$\sigma_{n,n'}$ = inelastic scattering cross section

ℓ' = angular momentum of incident neutron causing resonance

J = spin of excited level of compound nucleus

Γ = total level width, the sum of the partial widths of all processes by which the level can be excited

$\delta_{\ell'}$ = phase shift caused by scattering from a rigid sphere

$D_{\pi J}$ = average energy separation of levels of the same J value and same parity

E_r = resonance energy

E = energy near resonance

$\bar{\lambda}$ = wave length of incident neutron = $\lambda/2\pi = 1/k$

$G_{J\ell'}$ = statistical weighting factor (discussed below)

γ^2 = reduced width, considered to be a constant with maximum value of $3\hbar^2/2mR$

T_{n_ℓ} = centrifugal barrier penetration factor

T_{p_ℓ} = proton barrier penetration factor

K = wave number of neutron inside nucleus

X = $\dfrac{R}{\bar{\lambda}}$.

The following parameters of these equations are experimentally observable quantities:

$$\sigma_t\ ,\ \sigma_{n,p}\ ,\ \sigma_{n,\alpha}\ ,\ \Gamma\ ,\ \Gamma_p\ ,\ \Gamma_\alpha\ ,\ \text{and}\ \Gamma_{n'}\quad .$$

$\bar{\lambda}$ and $\delta_{\ell'}$ are readily determined from the energy of the incident particle and Γ_n can be calculated from formula 5 or 6, so that the only unknown factors remaining are ℓ' and J.

The problem of selecting consistent values for these two parameters such that the resulting calculations agree with the observed experimental data is indeed complex and tedious. Considerable work is being done by the theoreticians at present in an effort to determine reliable barrier penetration factors for protons and α particles. The values used in this study have

been obtained from calculations made at M.I.T. using Breit's coulomb wave functions.

When the incident particle is a neutron (or proton) the number of possible vectorial combinations of I, spin of the target nucleus, and ℓ' is $2(2I + 1)(2\ell' + 1)$ and there are $(2J + 1)$ combinations which lead to the same value of J. Since the bombarding particle has no preferred direction (spin "up" or "down") the fraction of ℓ' neutrons affected by a level of spin J is:

$$G_{J\ell'} = \frac{2J + 1}{2(2I + 1)(2\ell' + 1)}$$

It is reported (H2) that the lowest excited level in N^{14} is at about 2.3 Mev, so that inelastic scattering does not become a problem in the energy region of interest. However, it has been shown (J1 and R2) that the $N^{14}(n,p)$ and (n,α) reactions exhibit appreciable resonance cross sections in this same region. Consequently, any attempt to assign possible quantum numbers must include the total cross section data and (n,p), (n,α) data.

The formula (1) above for the scattering cross section is seen to consist of the partial cross section, for ℓ' neutrons forming a state of spin J, which is affected by the resonance, plus a potential scattering cross section, a non-resonant phenomena. In the analysis of the nitrogen cross section, the potential scattering cross section was not obtained through

the use of this formula. Rather, it was considered more realistic to subtract the background, or "effective" potential scattering cross section, from the observed maximal value and treat the difference as the resonance scattering cross section. This would appear to be more proper in case the resonances are fairly closely spaced, as is true for nitrogen, since the theory treats an isolated resonance. If one resonance should be superposed on another, such as the nitrogen resonance observed at 1405 Kev, the background is determined in the following manner: A Breit-Wigner curve is fitted to the leading resonance; this curve is subtracted from the observed values in the region of the second resonance; and the resulting curve is considered to be an isolated resonance.

When the resonance part of the scattering cross section is written as:

$$\sigma_{res,sc} = (2\ell' + 1)G_{J\ell'}\, 4\pi\lambda^2 \sin^2\phi$$

where

$$\phi = \tan^{-1} \Gamma n/2(E - E_r) + \delta_{\ell'}$$

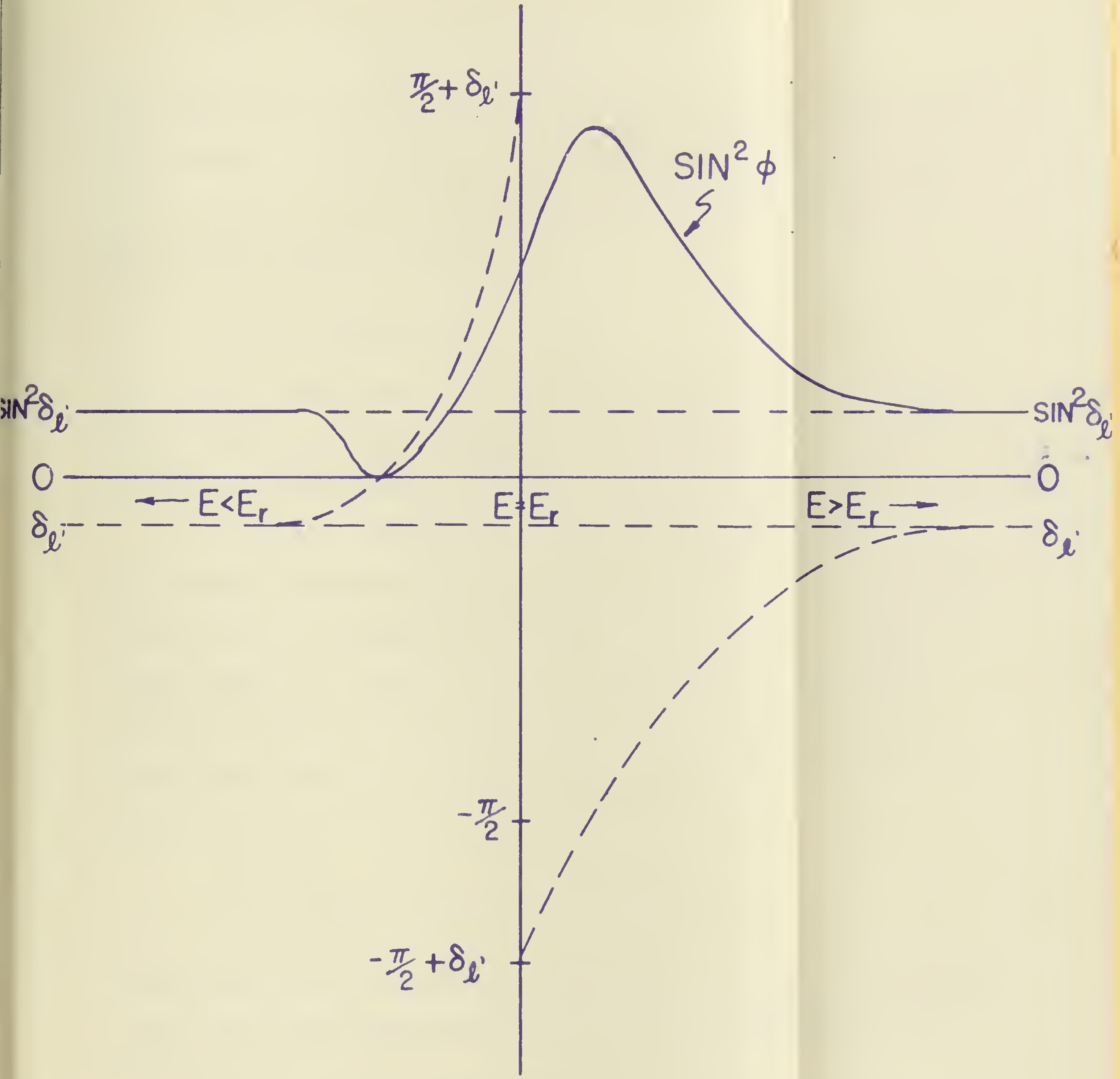
it is seen that there will be a minimum at ϕ equal 0° and a maximum at ϕ equal 90°. Inspection of ϕ and $\sin^2\phi$ as a function of E (refer to figure 5) shows that ϕ goes from $\delta_{\ell'}$ at $E < E_r$, to $\pi/2 + \delta_{\ell'}$ at $E = E_r$, then to $-\pi/2 + \delta_{\ell'}$ for $E > E_r$ and approaches $\delta_{\ell'}$ at $E \gg E_r$. $\delta_{\ell'}$ is negative; therefore the total cross section will exhibit a dip as ϕ goes from $\delta_{\ell'}$ through zero

Figure 5

ϕ AND $\sin^2\phi$ AS FUNCTION OF E

$$\phi = \mathrm{Tan}^{-1} \frac{\Gamma_n}{2(E - E_r)} + \delta_\ell,$$

A study of this sketch shows that the cross -section has a dip preceeding the peak of the resonance and indicates the position of the minimum and maximum.



ϕ AND $\sin^2\phi$ VS E
WHERE $\phi = \tan^{-1}\dfrac{\Gamma_n}{2(E-E_r)}+\delta_{\ell'}$

(or as E goes from $E < E_r$ to $E = E_r$). The depth of the dip will be given by

$$(2\ell' + 1)G_{J\ell'}\ 4\pi\lambda^2 \sin^2\delta_{\ell'}$$

and since only $\sin^2\delta_0$ will be important for the energy region of interest, a dip before a peak is indicative of excitation by S neutrons ($\ell' = 0$). The difference between the maximal and minimal values is given by

$$(2\ell' + 1)G_{J\ell'}\ 4\pi\lambda^2 \ .$$

The maximal and minimal values will occur at $E_{max} = E_r - \frac{\Gamma_n}{2} \tan\delta_{\ell'}$ and $E_{min} = E_r + \frac{\Gamma_n}{2\tan\delta_{\ell'}}$, whereas the peak of an absorption cross section for the same resonance occurs at $E = E_r$.

If elastic scattering is the only contributing factor, the maximal value of the observed resonance in the total cross section would be expected to be equal to the value calculated using formula (1) with $\Gamma_n = \Gamma$. However, when the cross sections for the (n,p), (n,α), and (n,n') reactions are of significant value, the total cross section observed should be equal to

$$\sigma_t = \sigma_{n,n} + \sigma_{n,p} + \sigma_{n,\alpha} + \sigma_{n,n'} \ .$$

The problem thus becomes more complicated in that the selected values of ℓ' and J must be consistent with observed σ_t, $\sigma_{n,p}$, and $\sigma_{n,\alpha}$.

A further consideration is the important selection rule

regarding parity: the parity of the reacting system does not change. If the parity of the target (scatterer) nucleus is π (may be odd or even) then the parity of the excited level in the compound nucleus is π if $\ell' = 0,2,4,---$ and π' (opposite parity) if $\ell' = 1,3,5,---$. Thus the parity of the compound nucleus will be π (or π') if the angular momentum of the incident neutron (proton) $\ell' = 0,2,4,---$ (or $= 1,3,5$)

Consideration of parity is particularly interesting in the study of the compound nucleus, N^{15}. It is generally accepted that the parity of C^{14} (even, even) is even (G1) and since the angular momentum of both the proton and neutron enter into the calculations of total cross section, the parity of N^{14} can be determined. Although the shell model predicts that the parity of N^{14} is even, β-decay studies (G1) suggest that this model fails to predict the correct parity of N^{14} and that it is odd. As will be discussed in Chapter IV, the results of this investigation tend to confirm the shell model prediction but an unambiguous assignment of parity cannot be made at this time. Taking the parity of C^{14} as even the parity of N^{14} is determined as follows:

ℓ_n	ℓ_p	N^{15} parity	N^{14} parity
even	even	even	even
even	odd	odd	odd
odd	even	even	odd
odd	odd	odd	even

CHAPTER IV

EXPERIMENTAL RESULTS

Preliminary measurements using the 6 cm. liquid nitrogen scatterer indicated the presence of eight resonances in the neutron energy region of 160-1600 Kev. However the transmission ratios were quite high (of the order of 0.6 to 0.7) and the poor resolution resulting from the thick lithium targets required gave inadequate definition of some resonances. Figure 6 shows the results of the preliminary study.

The improved total neutron cross section obtained with the 15 cm. liquid nitrogen scatterer is shown in Figure 7. It is seen that peak values occur at 434, 494, 663, 1020, 1120, 1212, 1349, 1405, 1597, and 1782 Kev. It is also noted that minimal values occur at 623 and 972 which are the dips preceding the resonances caused by s-wave neutrons ($\ell = 0$) at 649 and 997 Kev. It should also be noted that a small peak is suggested at 1182. This peak appeared on two or more separate sets of measurements. However, it was not until the LiN_3 scatterer was used that this peak was definitely established as a true resonance beyond the range of statistical error.

Table I lists the resonances observed in this experiment, their half-widths, and the ℓ_n and J values assigned on the basis of calculations[1] using the Breit-Wigner formula (A1) and the

---

[1] The calculations were made in collaboration with members of the M.I.T. Shielding Group who are engaged in a very extensive study of the experimental results of this thesis and that of CDR. W.D. Roseborough (R1).

Figure 6

PRELIMINARY MEASUREMENTS OF THE TOTAL
NEUTRON CROSS SECTION OF NITROGEN USING 6 cm.
LIQUID NITROGEN SCATTERER

These measurements were made for preliminary study only. Results are plotted as function of frequency of analyzing magnet.

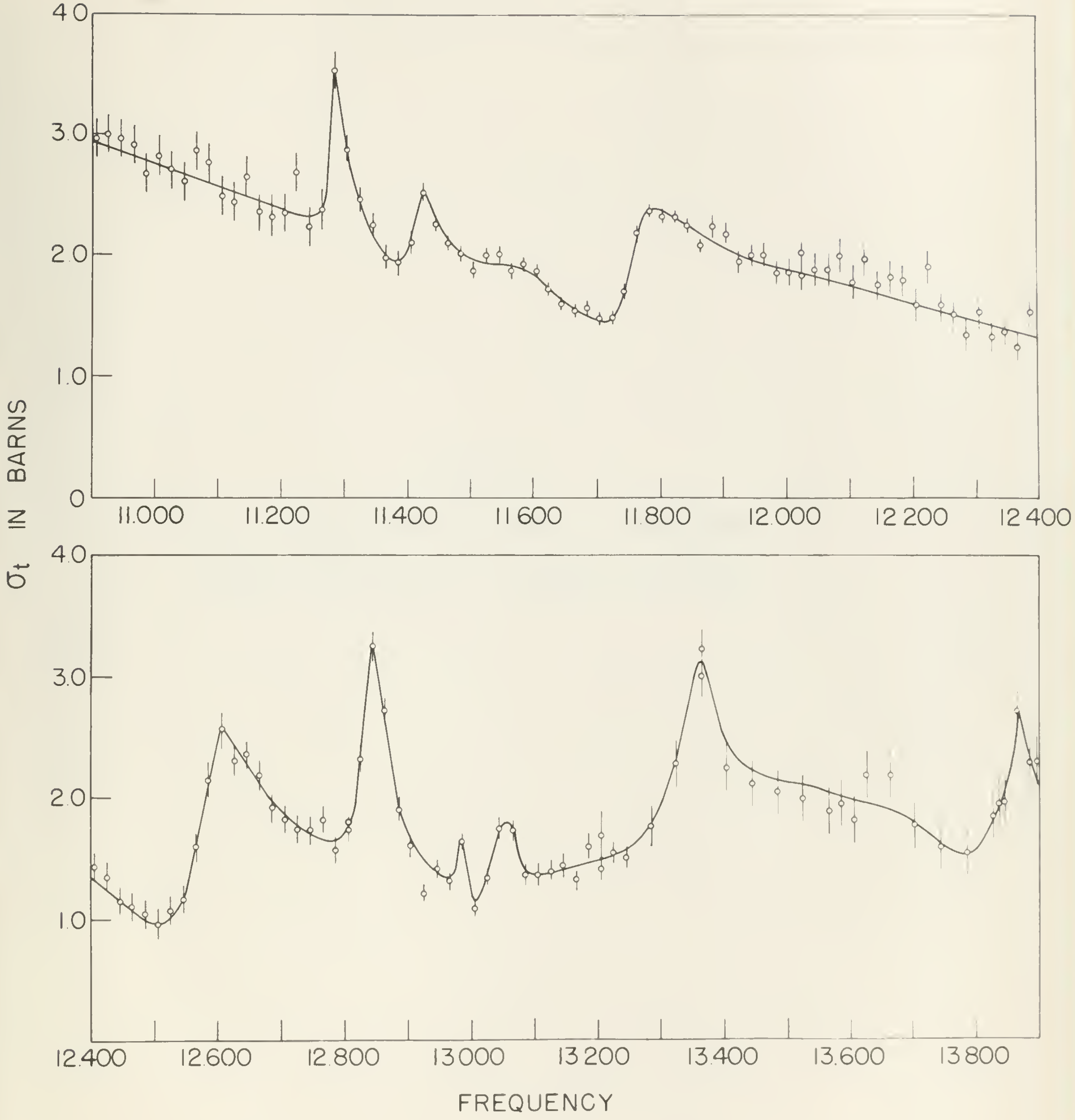
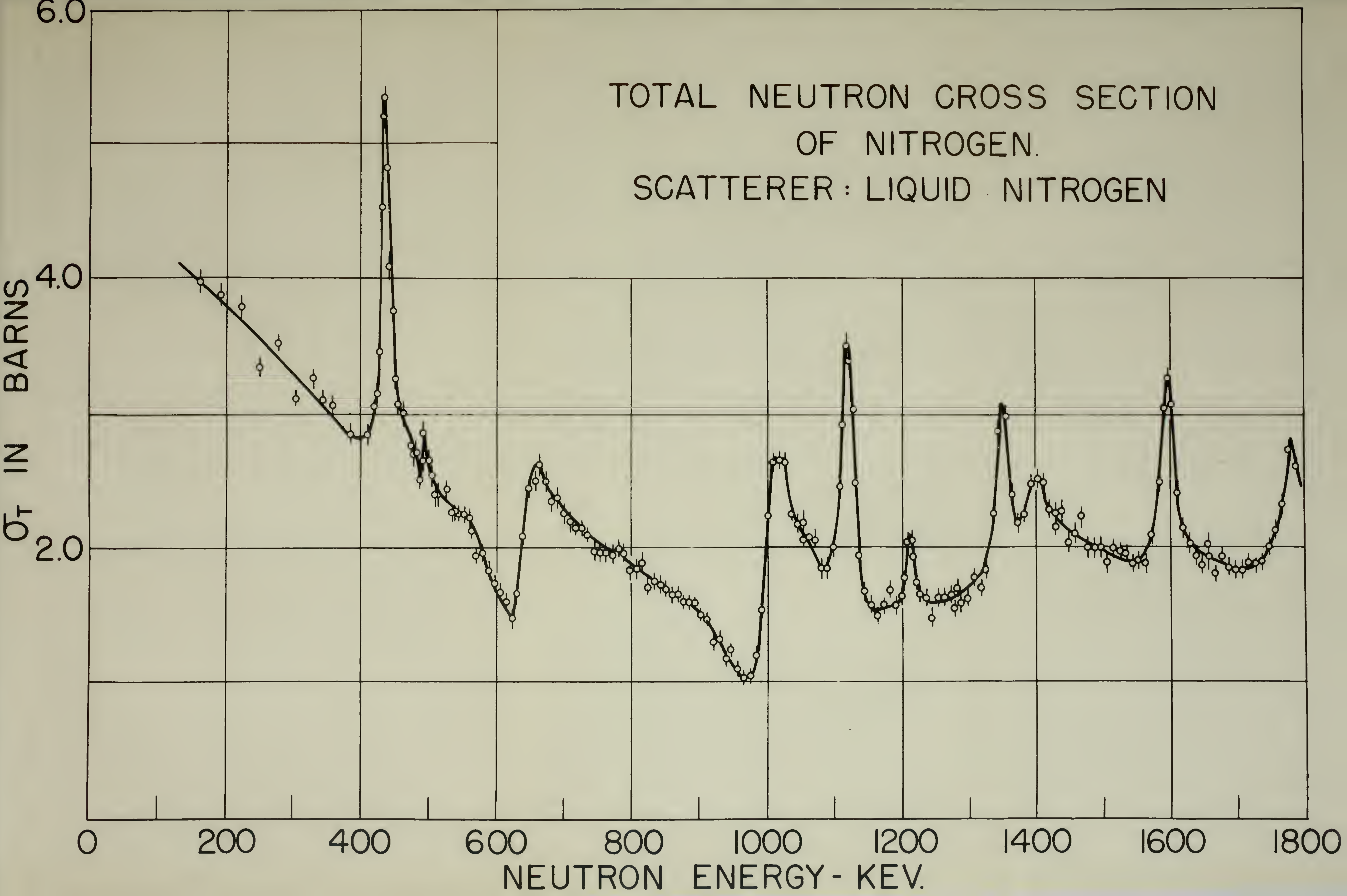

4.0
3.0
2.0
1.0
0
11.000
11.200
11.400
11.600
11.800
12.000
12.200
12.400
σ_t IN BARNS
4.0
3.0
2.0
1.0
12.400
12.600
12.800
13.000
13.200
13.400
13.600
13.800
FREQUENCY

Figure 7

TOTAL NEUTRON CROSS SECTION OF NITROGEN

USING 15 cm. LIQUID NITROGEN SCATTERER



TOTAL NEUTRON CROSS SECTION OF NITROGEN.
SCATTERER : LIQUID NITROGEN

Table I

SUMMARY OF DATA CONCERNING RESONANCES IN N^{15} NUCLEI

Resonance energy (E_r) tabulated for Preston et al. (R2) based on $C^{14}(p,n)$ threshold of 0.671 Mev reported therein. E_r values tabulated in parenthesis for Johnson and Barschall were estimated from Figure 3 of their paper (J1) and in view of this present work are considered to be $N^{14}(n,p)$ resonances although Johnson and Barschall did not report them as such. Γ_n tabulated is the observed value corrected for thickness of Li target. The resonance energies tabulated for Nos. 3 and 4 were calculated using $E_r = E_{max} + \frac{\Gamma_n}{2} \tan\delta_\ell$; similar calculations using $E_r = E_{min} - \frac{\Gamma_n}{2 \tan\delta_\ell}$ agree within less than 1.0 Kev.

Note: More rigorous calculations, which include the effect of Γ_p, completed after this table had been compiled, give 0.644 and 0.997 Mev respectively for the resonance energies of these two s-wave resonances.

TABLE I

SUMMARY OF DATA CONCERNING RESONANCES IN N^{15} NUCLEI

	TOTAL CROSS SECTION STUDY					PRESTON et al			JOHNSON & BARSCHALL	
#	E_R (Mev)	σ (barns)	Γ(Kev)	ℓ_n	J	E_R (Mev)	$\sigma_{(n,p)}$	Γ(Kev)	E_R (Mev)	$\sigma_{(n,p)}$
1	0.434	$\sigma_{max.}$ = 5.37 σ_0 = 2.62 $\Delta\sigma$ = 2.75	15	1	5/2	-	<0.002	-	-	-
2	0.494	$\sigma_{max.}$ = 2.84 σ_0 = 2.35 $\Delta\sigma$ = 0.49	11	1	1/2	0.494	0.280	8 ± 1	0.499	0.120
3	0.649 $E_{min.}$ = 0.623 $E_{max.}$ = 0.663	$\sigma_{max.}$ = 2.62 $\sigma_{min.}$ = 1.52 $\Delta\sigma$ = 1.10	40	0	1/2	0.639	0.200	43 ± 5	0.640	0.200
4	0.997 $E_{min.}$ = 0.972 $E_{max.}$ = 1.020	$\sigma_{max.}$ = 2.65 $\sigma_{min.}$ = 1.06 $\Delta\sigma$ = 1.59	48	0	3/2	0.993	0.019	38 ± 10	0.993	0.018
5	1.120	$\sigma_{max.}$ = 3.56 σ_0 = 1.60 $\Delta\sigma$ = 1.96	20	1	5/2	1.118	0.009	18 ± 5	(1.118)	0.008
6	1.212	$\sigma_{max.}$ = 2.16 σ_0 = 1.50 $\Delta\sigma$ = 0.66	14	No Agreement with Theory		1.212	0.018	15 ± 5	(1.215)	0.016
7	1.349	$\sigma_{max.}$ = 3.18 σ_0 = 1.45 $\Delta\sigma$ = 1.73	24	1	5/2	1.353	0.140	18 ± 5	-	-
8	1.405	$\sigma_{max.}$ = 2.43 σ_0 = 1.45 $\Delta\sigma$ = 0.98	51	1	3/2	1.408	0.300	55 ± 10	1.415	0.195 0.035 (n,α)
9	1.597	$\sigma_{max.}$ = 3.30 σ_0 = 1.80 $\Delta\sigma$ = 1.50	21	1	5/2	1.601	0.033	22 ± 5	(1.600)	0.022
10	1.782	$\sigma_{max.}$ = 2.80 σ_0 = 1.80 $\Delta\sigma$ = 1.00	28 (Estim.)	*	*	1.780	0.013	45 ± 20	1.800	0.150 (n,α)
5a	1.182	$\sigma_{max.}$ = 1.78 σ_0 = 1.34 $\Delta\sigma$ = 0.44	12	No Agreement with Theory		-	-	-	-	-

* * This resonance has not been analyzed because of insufficient data and lack of reliable α particle penetration factors.

(p,n) data of Roseborough et al. (R2). Also listed in this table are the resonances observed by other investigators of the compound nucleus, N^{15}. The agreement with Roseborough et al. and with Johnson and Barschall is seen to be excellent. It was hoped that results of this experiment would give an indication of the parity of N^{14}. However, an unambiguous assignment of parity cannot be made until further study of the total cross section is completed. Of the eight resonances to which ℓ_n and J values are assigned, all but the 1.349 Mev resonance agree best with theoretical calculations using values of ℓ_p (angular momentum of the proton) such that the parity is the same as C^{14}.

Figure 8 is a plot of total neutron cross section of nitrogen using (LiN_3) lithium azide as a scatterer. While this plot covers only a portion of the energy region under study, it is sufficient to show the excellent agreement with that obtained using the liquid scatterer. This agreement between the two completely separate experiments is the best evidence as to the accuracy of the assumptions made in calculations, the adequacy of the experimental arrangement, and the purity of the liquid nitrogen.

The energy level diagram, Figure 9, similar to those of Hornyak et al. (H2) shows the excited levels of N^{15}. The results of this experiment indicate the existence of three energy levels not previously reported. It should be noted that there is a slight discrepancy in the assigned values of energy be-

Figure 8

TOTAL NEUTRON CROSS SECTION OF NITROGEN

USING LITHIUM AZIDE (LiN_3) SCATTERER

Note agreement with Figure 5 and the additional resonance resolved at 1182 Kev.

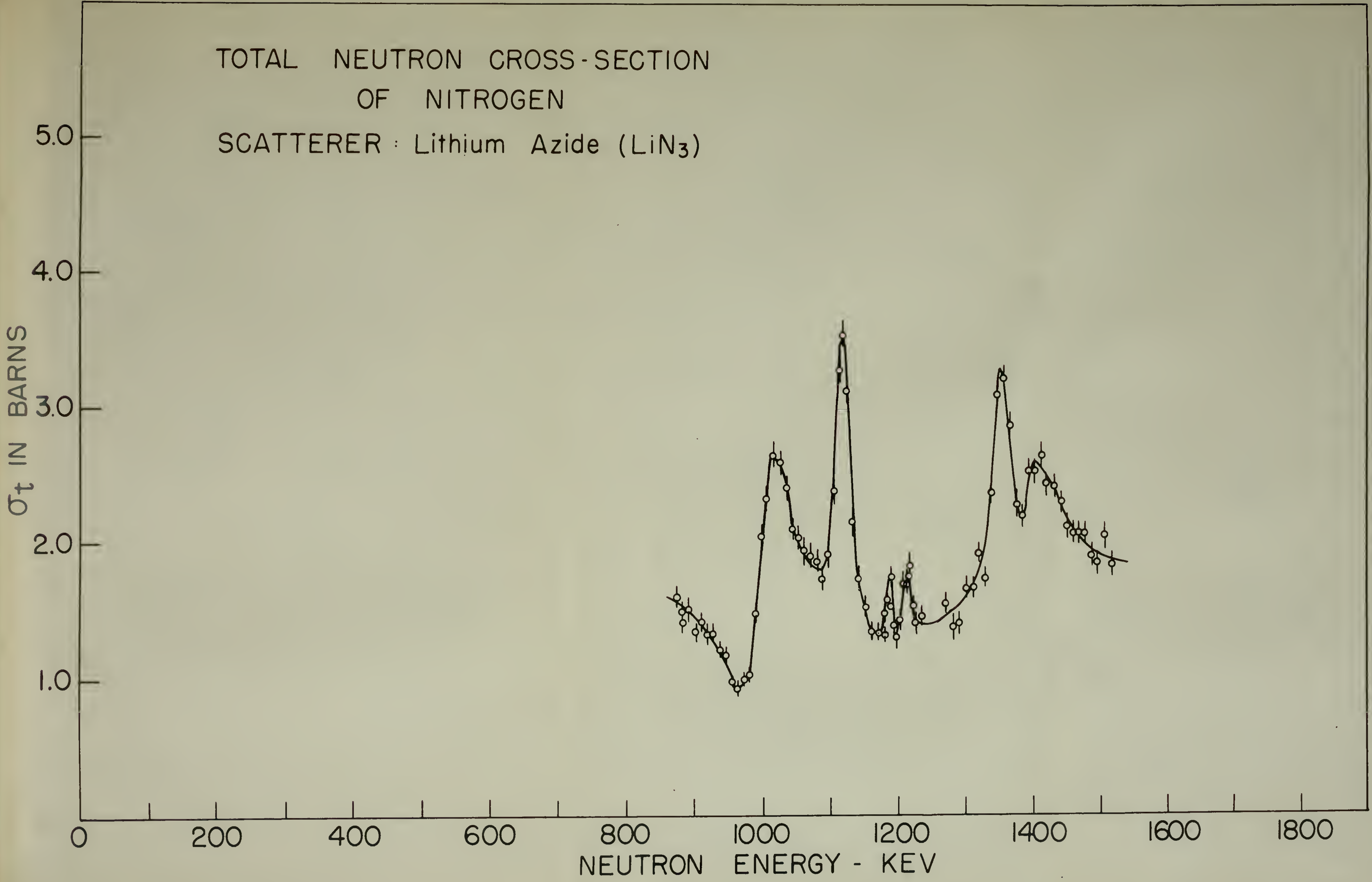
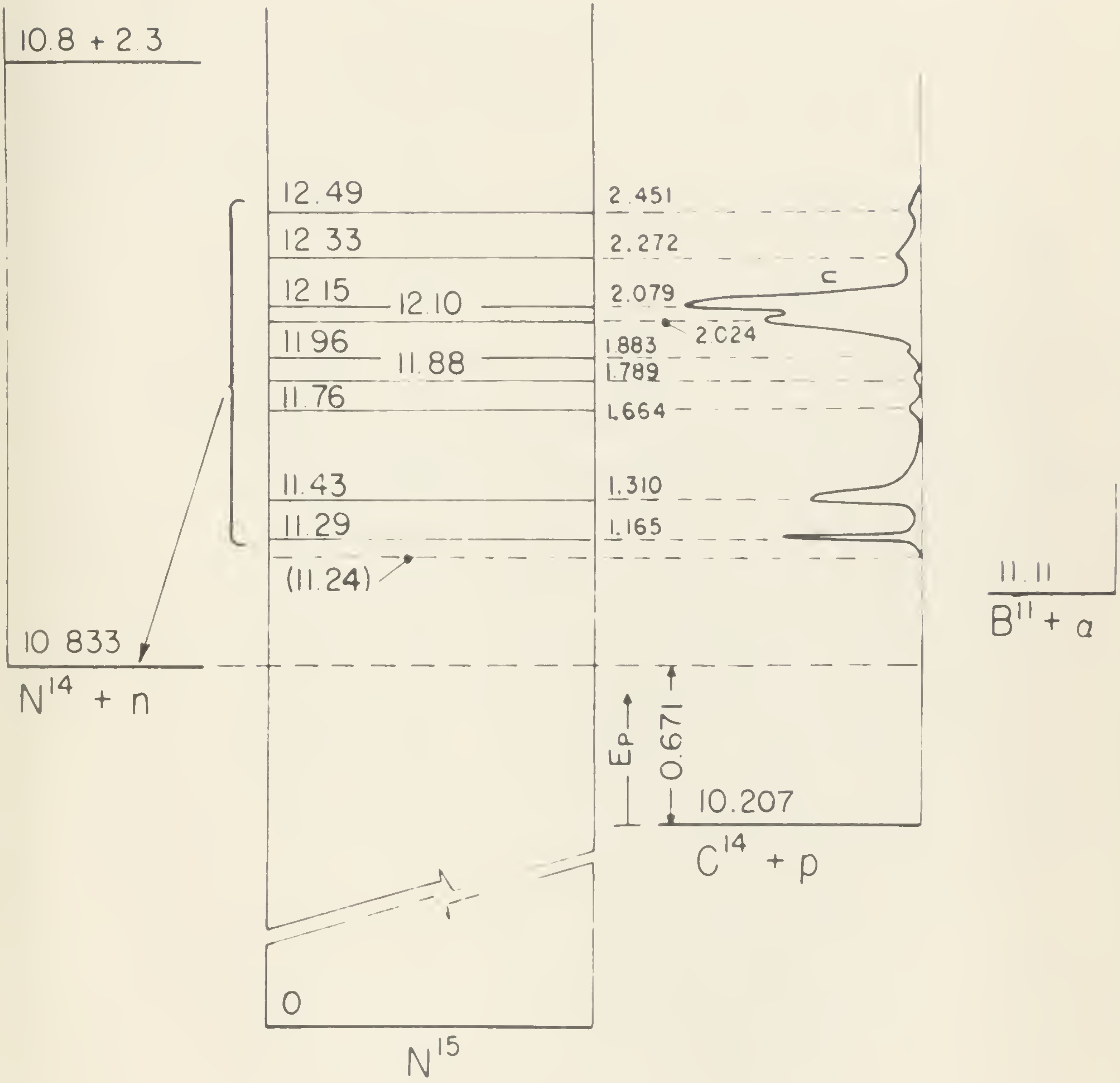

TOTAL NEUTRON CROSS-SECTION
OF NITROGEN
SCATTERER : Lithium Azide (LiN_3)
σ_t IN BARNS
5.0
4.0
3.0
2.0
1.0
0
200
400
600
800
1000
1200
1400
1600
1800
NEUTRON ENERGY - KEV

Figure 9

ENERGY LEVEL DIAGRAM FOR N^{15}

This diagram, similar to those of Hornyak *et al.*, (H2) includes the data of this investigation and that of Roseborough (R1).


10.8 + 2.3
12.49
12 33
12 15
12.10
11 96
11.88
11.76
11.43
11.29
(11.24)
10 833
N^{14} + n
2.451
2.272
2.079
2.024
1.883
1.789
1.664
1.310
1.165
c
11.11
B^{11} + α
E_p
0.671
10.207
C^{14} + p
0
N^{15}

tween those listed here and those by Hornyak. The difference is explained by the fact that more recent mass values (12) were used in this work.

The following corrections must be made to the observed counting rates, transmission ratios, neutron energies and calculated cross sections:

(a) Counting rates, both with and without scatterer, must be corrected for background which in the case of the liquid scatterer includes neutrons scattered into the counter by the surrounding glass of the Dewar Flask. This correction was made in the following manner: the counting rate was observed with the flask empty and again when filled with water. Since a water scatterer 15 cm. thick transmits essentially no neutrons, the observed counting rate is a good measure of background plus the number scattered into the detector by the glass. When this correction is applied to both, N_o, the counting rate without scatterer and, N, the counting rate with scatterer in the beam, the resulting transmission ratio is a true measure of the total cross section. This correction amounted to an almost constant value of 3 per cent of N_o except in the region of the oxygen resonance at 440 Kev where it reached a maximum of 5.2 per cent.

(b) Neutron energy must be corrected for: (1) spread

in energy due to finite angle subtended by counter. For the geometry used here, this angle is about 2° and therefore the spread in energy is so small that it was neglected. (2) spread in energy due to finite thickness of lithium target. The thicknesses of targets used in this experiment were determined by comparing their neutron yields (at proton energy of ~3.0 Mev) to the yield of a 9 Kev target whose thickness had previously been determined by the rise method (B1 and C1). The neutron energies were corrected by subtracting half the target thickness in Kev. Targets used in this experiment were two, four and ten Kev in thickness. (3) spread in energy due to spread in proton energy. This variation is so small that it can be neglected (see C1), since proton energies are considered to be accurate to better than 0.1 per cent. Proton energies were corrected for relativity effects in accordance with the following formula (P2),

$$\Delta E = 0.00053\ (E_0 - E)\ E$$

in which ΔE is the correction to the energy E (= kf^2 where f is the measured proton resonance frequency) and E_0 is the threshold energy of the Li(p,n) reaction. The maximum correction was about 2 Kev.

(c) The observed counting rate (W1) or the calculated cross section σ_t (A1) should be corrected for neutrons scattered into the detector. Approximate calculations based on the assumption of isotropic distribution of both the source and scattered neutrons, show that this correction, which is a function of the geometry, length of scatterer, and magnitude of the cross section, is about 0.2 barn for the 5.3 barn resonance at 434 Kev and correspondingly less for other values of the cross section. Since the maximum correction is of the same order of magnitude as the statistical error, scattering in corrections were not applied to any observed values.

In order to keep the statistical error (RMS error) in cross sections to a minimum, sufficient counts were taken for all points to ensure that the standard deviation in total cross section was less than 3 per cent as obtained from the following relation:

$$\frac{\Delta\sigma_t}{\sigma_t} = \frac{N}{N_o} \; \frac{\Delta(N_o/N)}{\ln N_o/N} .$$

CHAPTER V

CONCLUSIONS

The observed cross sections in the energy region below 485 Kev indicate that additional resonances may exist. In three separate sets of data taken over this region the same general trend was exhibited. It would seem profitable to make a further careful study of this region with a thin lithium target making observations at rather close intervals.

The measurement of the total neutron cross sections of other liquifiable gases, particularly the noble gases, by the techniques followed in this investigation would seem highly feasible and the results of this experiment indicate that the observations made would compare favorably with those obtained in more tedious experiments using solid compounded scatterers of two or more elements.

The results of this investigation together with the available (n,p) and (n,α) data should prove to be very valuable in further pursuit of the theory of resonance reactions. Very few compound nuclei that have been studied exhibit such a yield of resonances which have been established through (n,p), (n,α) and total cross section measurements.

BIBLIOGRAPHY

A1 Adair, Rev. Mod. Phys. 22, 249 (1950).

B1 Barschall, Bockelman, Peterson and Adair, Phy. Rev. 76, 1146 (1949).

B2 Blatt and Weisskopf, Tech. Rept. No. 42, LNSE, M.I.T. (1950).

B3 Bockelman, Adair, Barschall and Sala, Phy. Rev. 75, 336, (1949).

B4 Breit and Wigner, Phy. Rev. 49, 519 (1936).

F1 Feshbach, Peaslee and Weisskopf, Phy. Rev. 71, 145 (1947).

G1 Gerjuoy, Phy. Rev. 81, 62 (1951).

H1 Hanson and McKibben, Phy. Rev. 72, 673 (1947).

H2 Hornyak, Lauritsen, Morrison and Fowler, Rev. Mod. Phy. 22, 291 (1950).

J1 Johnson and Barschall, Phy. Rev. 80, 818 (1950).

L1 Lovington, M.I.T. Masters Thesis, 1951.

L2 Li, Whaling, Fowler and Lauritsen, to be published in Phy. Rev.

P1 Petersen, Barschall and Bockelman, Phy. Rev. 79, 593 (1950).

P2 Preston, "Reduction of Proton Resonance Frequency Scale to an Energy Scale," unpublished.

R1 Roseborough, M.I.T. Masters Thesis, 1951.

R2 Roseborough, Preston, McCue and Goodman, Phy. Rev. (to be published).

BIBLIOGRAPHY (continued)

S1 Schoenfeld and Duborg, M.I.T. Masters Thesis, 1951.

T1 Taschek and Hemmendinger, Phy. Rev. 74, 373 (1948).

W1 Willard, Preston and Goodman, Tech. Rept. No. 45, LNSE, M.I.T. (1950).

ACKNOWLEDGMENTS

The graduate study of the author was sponsored by the U.S. Naval Postgraduate School and the Bureau of Ships, Department of the Navy. The work reported herein was undertaken in conjunction with the Nuclear Shielding Project of the Laboratory of Nuclear Science and Engineering, M.I.T., which project was sponsored by the Bureau of Ships and the Office of Naval Research.

The author wishes to express his appreciation to Professor Clark Goodman for his guidance and forbearance as thesis supervisor, to Dr. P.H. Stelson with whose invaluable assistance the experimental data was obtained and who, with Dr. W.M. Preston, gave freely of his time in discussion of the related theory, to Dr. J.J.G. McCue who suggested the use of liquid nitrogen scatterer, and to the crew of the Rockefeller Generator. Also the author desires to express his gratitude to Dr. T.T. Magel of the M.I.T. Metallurgical Laboratories who made the lithium azide.

DATE DUE	BORROWER'S NAME