RICE UNIVERSITY

DETERMINATION OF THE ISOSPIN IMPURITY IN THE 11.50 MEV STATE OF ^{14}N*

by

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IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

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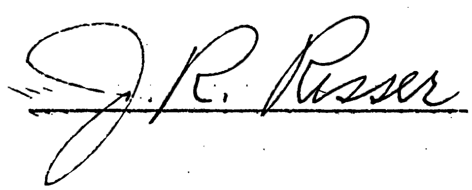


Houston, Texas

May 1971

ABSTRACT

Phillip Ritter LaRoe

In order to determine the characteristic of the 11.50 Mev excited state of $^{14}N^*$, the reactions $^{12}C(d,p_0)^{13}C$, $^{12}C(d,n_0)^{13}N$, $^{12}C(d,p_1)^{13}C^*$ (3.09 Mev state) and $^{12}C(d,d)^{12}C$ were investigated with deuteron energies in the neighborhood of the sharp proton resonance at 1.446 Mev. No corresponding resonance in neutrons was observed, and a lower limit on the ratio of ground state protons to ground state neutrons was found to be greater than twelve. Results indicate that this state in $^{14}N^*$ looks most like the first excited state of the A=13 system plus a nucleon.

<u>TABLE OF CONTENTS</u>

INTRODUCTION

The 1.446 Mev resonance of $^{12}C + d$, corresponding to the 11.50 Mev excited state of the self-conjugate ^{14}N nucleus, has a number of unusual properties. One of the most interesting of these properties is that while protons to the ground state of ^{13}C show a small but finite partial width, no neutron emission to the ground state of the mirror nucleus, ^{13}N, has been observed.

At this resonance, the nuclear reactions which can occur from deuteron bombardment of ^{12}C are

(1) $^{12}C(d,d)^{12}C$,

(2) $^{12}C(d,p_o)^{13}C$ $\quad Q=2.719$ Mev,

(3) $^{12}C(d,p_1)^{13}C^*$ (3.09 Mev state) $\quad Q=-0.371$ Mev,

(4) $^{12}C(d,n_o)^{13}N$ $\quad Q=-0.286$ Mev.

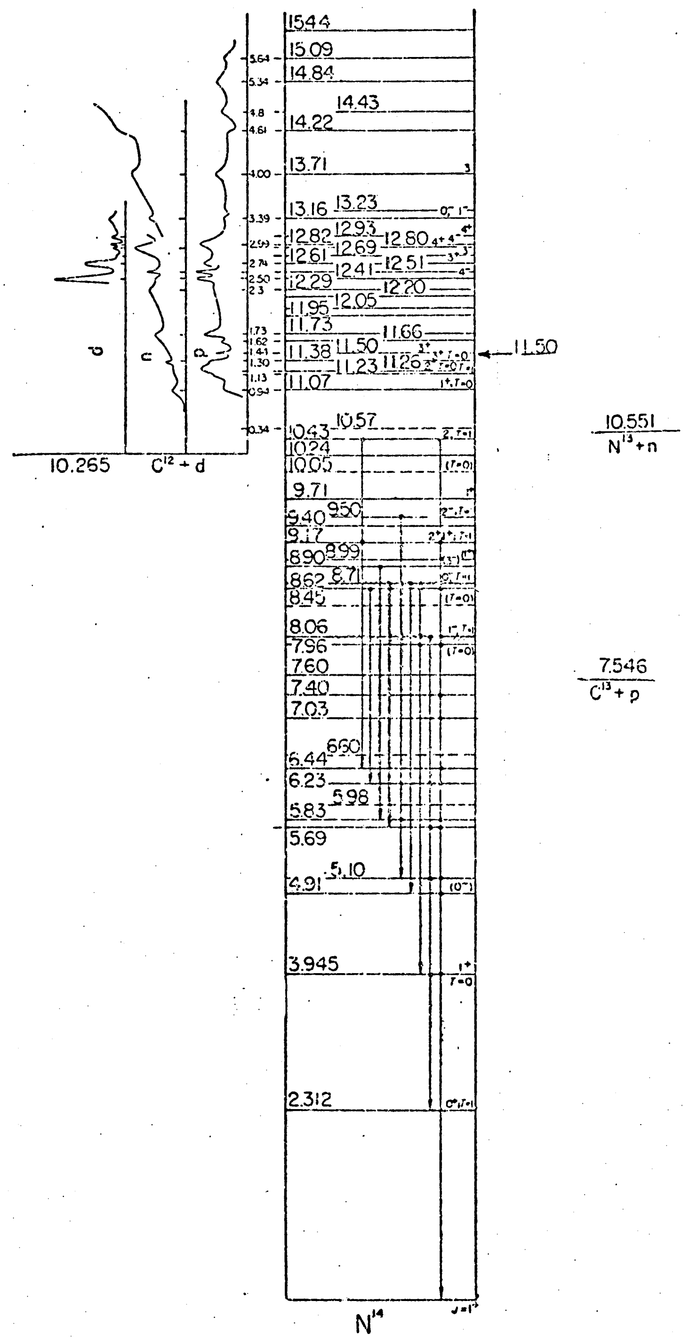
The energetics of these reactions are shown in figure 1.

Early work by Bonner, Evans, Harris, and Phillips [1] in 1949 was the first to search actively for the neutrons from reaction (4). The neutrons were monitored at several angles by the positron activity of ^{13}N as well as by a direct neutron-recoil counter method. No neutrons were observed, although a high cross section for 3.09 Mev γ rays associated with the de-excitation of $^{13}C^*$ produced from reaction (3) was found.

The ground state protons from reaction (2) were first observed

FIGURE 1 [2]

States in ^{14}N, with the energies of $^{13}N+n$, $^{13}C+p$, and $^{12}C+d$.



15.44
15.09
14.84
14.43
14.22
13.71
13.16
13.23
12.82
12.93
12.80
12.61
12.69
12.51
12.41
12.29
12.20
12.05
11.95
11.73
11.66
11.38
11.50
11.23
11.26
11.07
11.50
10.43
10.57
10.24
10.05
9.71
9.40
9.50
9.17
8.90
8.99
8.62
8.71
8.45
8.06
7.96
7.60
7.40
7.03
6.44
6.60
6.23
5.83
5.98
5.69
4.91
5.10
3.945
2.312
N14
d
n
p
10.265
C12 + d
10.551
N13 + n
7.546
C13 + p

by G. C. Phillips [3] in 1950, and were found to show a sharp resonance at backward angles.

In later work by E. Kashy, R. R. Perry, and J. R. Risser, [4] in 1959, the energy- and angular dependence of the differential cross section at this resonance were simultaneously observed in the elastic deuteron, p_o, and p_1 reactions; (1), (2), and (3) above.

T. A. Belote [5] found no resonance ground state protons or neutrons from the 11.50 Mev state in $^{14}N^*$ in the reaction of protons on ^{13}C, but this result would be expected for a small partial width for protons and neutrons, as the cross section for $^{13}C(p,p)^{13}C$ and $^{13}C(p,n)^{13}N$ would go as $(\Gamma_p)^2$ and $(\Gamma_p \Gamma_n)$. At this same energy, Belote observed a resonance in both deuterons and p_1 protons to the first excited state of $^{13}C^*$, in the reactions $^{13}C(p,p_1)^{13}C^*$ (3.09 Mev state) and $^{13}C(p,d)^{12}C$. This would indicate that Γ_d and Γ_{p_1} are both much greater than Γ_p or Γ_n.

In this present work we set out to investigate the characteristic of the 11.50 Mev excited state of $^{14}N^*$. The intent was to obtain an upper limit on the ratio of the cross section for the ground state neutrons of reaction (4) to the ground state protons of reaction (2), and if possible, to obtain a measure of the isospin mixing in this state of $^{14}N^*$.

It would also be of interest to compare the cross section for the protons from the reaction (3) with the cross section for the n_1 neutrons to the first excited state of $^{13}N^*$, but this state in $^{13}N^*$ is energetically forbidden at a deuteron bombarding energy of 1.446 Mev.

EXPERIMENTAL APPARATUS AND PROCEDURE

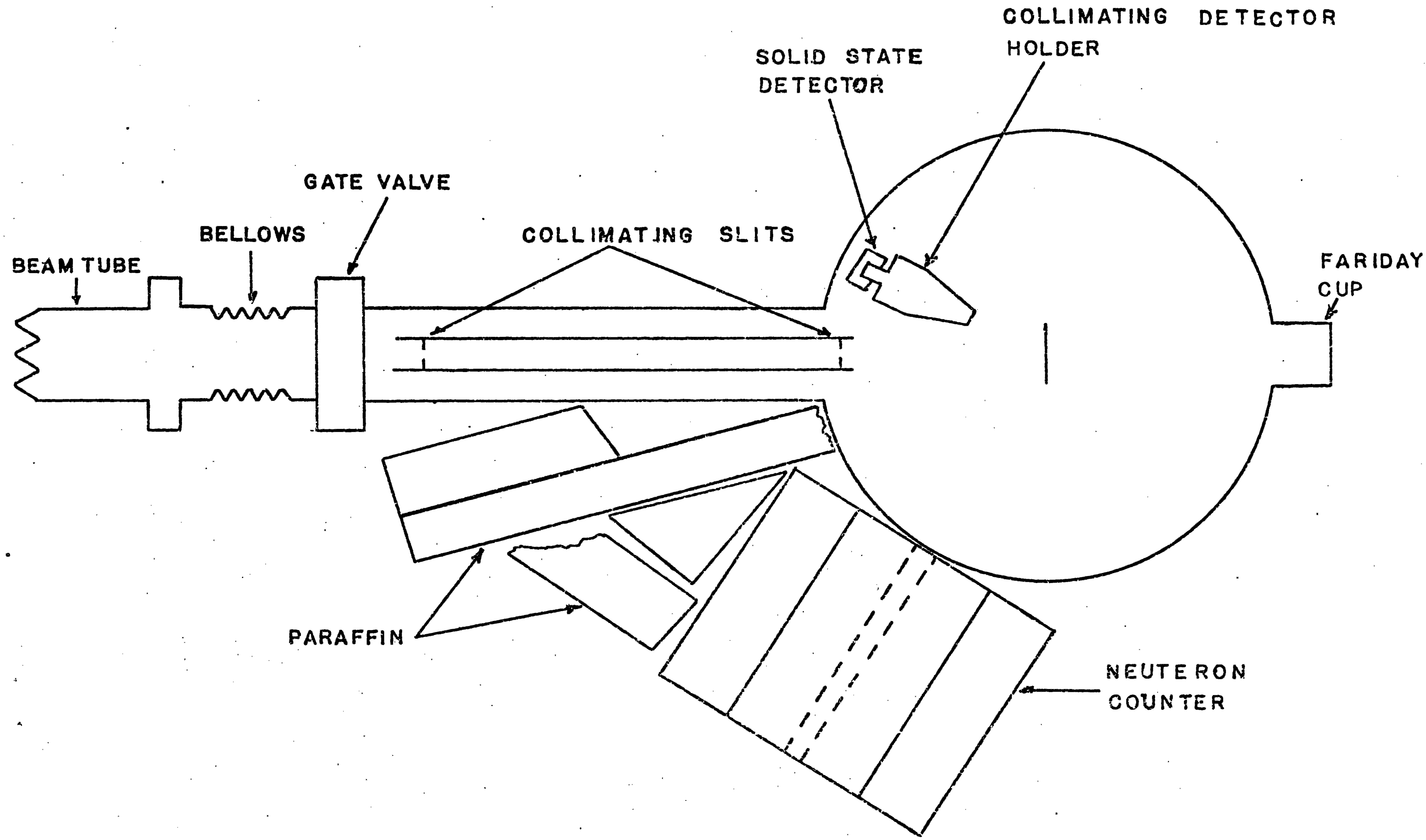
Apparatus. The Rice University Tandem Van de Graaff accelerator was used to supply an analyzed beam of deuterons. Since we sought only the neutron and proton counts from a resonance whose energy was previously well established, it was only necessary that the calibration of the 90^{o} analyzing magnet be good enough to allow us to locate the resonance without undue searching. We were able to confirm that we were on the 1.446 Mev resonance by observing the shape of the excitation verses energy curve, which is unique in this energy region. [(1) (4)]

The arrangement of the experimental apparatus is shown in figure 2. The two beam collimators are made of quartz in order to facilitate the alignment of the chamber, as the beam will cause the quartz to fluoresce unless it passes through the collimating hole in the center of the quartz. The target chamber is described in detail in reference 6, except that connections have been made through the bottom of the chamber to a unit which can support either a cell for a gas target (see appendix A), or a brass holder for a foil target. The detector mounts inside the chamber are designed to hold ORTEC A-series surface-barrier detectors, and to be positioned from 20^{o} foreward to 160^{o} backward angles. The mounts can be rotated from outside the chamber. The chamber is fitted with a Fariday cup so that the incident beam can be integrated. Secondary emission of electrons from the deuterons striking the cup were inhibited by a -70 volt bias on the suppressor ring.

Targets. Commercially prepared [(7)]self supporting ^{12}C targets

FIGURE 2

Arrangement of the experimental apparatus.


COLLIMATING DETECTOR HOLDER
SOLID STATE DETECTOR
GATE VALVE
BELLOWS
BEAM TUBE
COLLIMATING SLITS
FARIDAY CUP
PARAFFIN
NEUTERON COUNTER

were used. These targets come on a glass slide and are prepared for use by floating the target off the slide in water, and then lifting the target out of the water on an aluminum target blank so that the target is mounted over a 9 mm diameter hole in the center of the target blank. The target thickness was 10 $\mu gm/cm^2$ which corresponds to an energy loss of 2.4 kev for 1.446 Mev deuterons. The energy of the deuterons used in this experiment was from approximately 1.42 to 1.45 Mev.

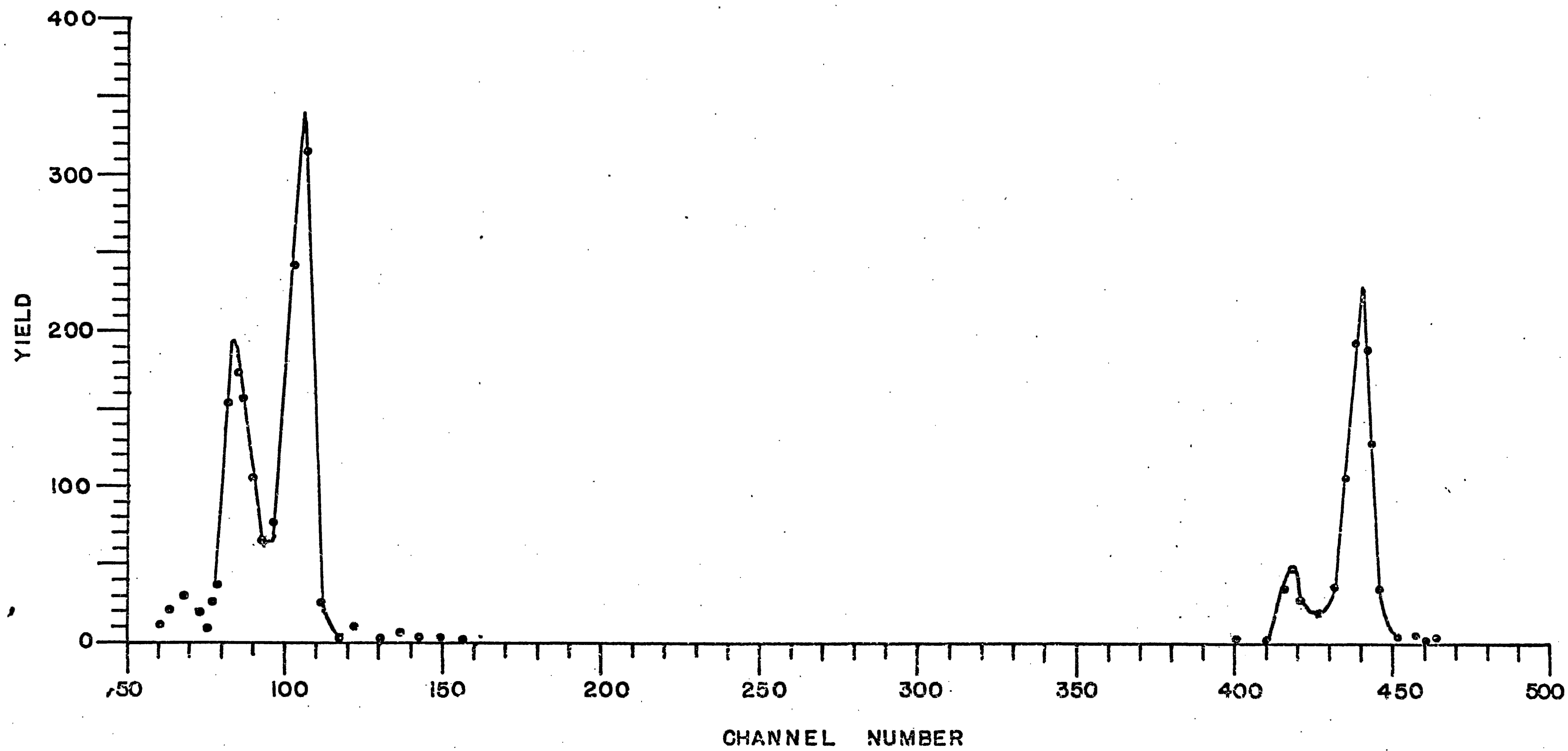
In order to minimize carbon deposits on the target, all runs were of short duration (on the order of 90 sec.) and the beam was kept at relatively low intensity (~100 nanoamps) and was kept off the target except while actively accumulating data.

Detectors. The charged particle detector was an ORTEC A-series surface-barrier detector with 50 mm^2 total active area. The resistivity was 14,000 ohm-cm with a depletion depth of 2000 μ, and bias voltage of 525 volts supplied by an ORTEC detector control unit (Model #210). A sample charged particle spectrum for a ^{12}C target, for deuteron energy of 1.446 Mev is shown in figure 3. The peaks corresponding to the elastic deuterons, the ground and first excited state protons have been labeled. This detector was positioned at a backward angle of 156.6° where a sharp resonance peak is known to exist, (3) (4) and at a distance of three and one-eighth inches from the target, subtending a solid angle of 5.19×10^{-3} steradians. The efficiency of this detector is 100%.

The neutrons were counted with a paraffin moderated "long counter"

FIGURE 3

Sample charged particle spectrum for a ^{12}C target, for deuteron energy of 1.446 Mev.



400
300
200
100
0
YIELD
50
100
150
200
250
300
350
400
450
500
CHANNEL NUMBER

of standard geometry, operating with boron-tri-floride gas. This proportional neutron counter was operated with a bias of 2000 volts supplied by an Atomic Instruments high voltage power supply. The detector was placed outside the scattering chamber at an angle of about 30° above the horizontal and collected neutrons from a backward angle of 101° to 140° at a distance of 11 inches from the target. The solid angle subtended was 3.78×10^{-1} steradians. The counter was shielded on all sides by at least four inches of paraffin and by as much as 10 inches of paraffin between the side of the counter and the quartz collimators. The positioning and shielding of the counter was chosen to yield the best ratio of target counts to background counts. The counter was calibrated by replacing the target with a standard Pu-Be neutron source, emitting 1.44×10^6 neutrons per second.

The bias of the counter and the discriminator in the electronics circuitry were chosen so that gamma rays would not be counted. The counter was checked for sensitivity to gamma rays by exposing it to a 1 mc ^{137}Cs source. No response to gamma rays was detected.

Electronics. After preamplification with Tennelec FET preamplifiers (Model #TC133) the output of both detectors were fed into ORTEC selectable active filter amplifiers (Model #440A). The delayed output of the amplifier became the input to the 1024 channel analog-to-digital converter (ADC). The prompt output of the amplifier was fed into a multiple coincidence unit which is used in this experiment only to provide a discriminator on the signal which serves as the gate for the ADC. Unwanted low level noise, and in the case of the neutron counter, gamma ray counts, were eliminated by adjusting the fast discriminator bias voltage on the gat signal which prepares the ADC to analyze a count.

All data was accumulated, stored, displayed, and printed by the BONER system. BONER is a programmed on-line multi-laboratory data acquisition system implemented on the Rice University IBM 1800 computer. This system allowed us to take data from both neutron and proton counters simultaneously.

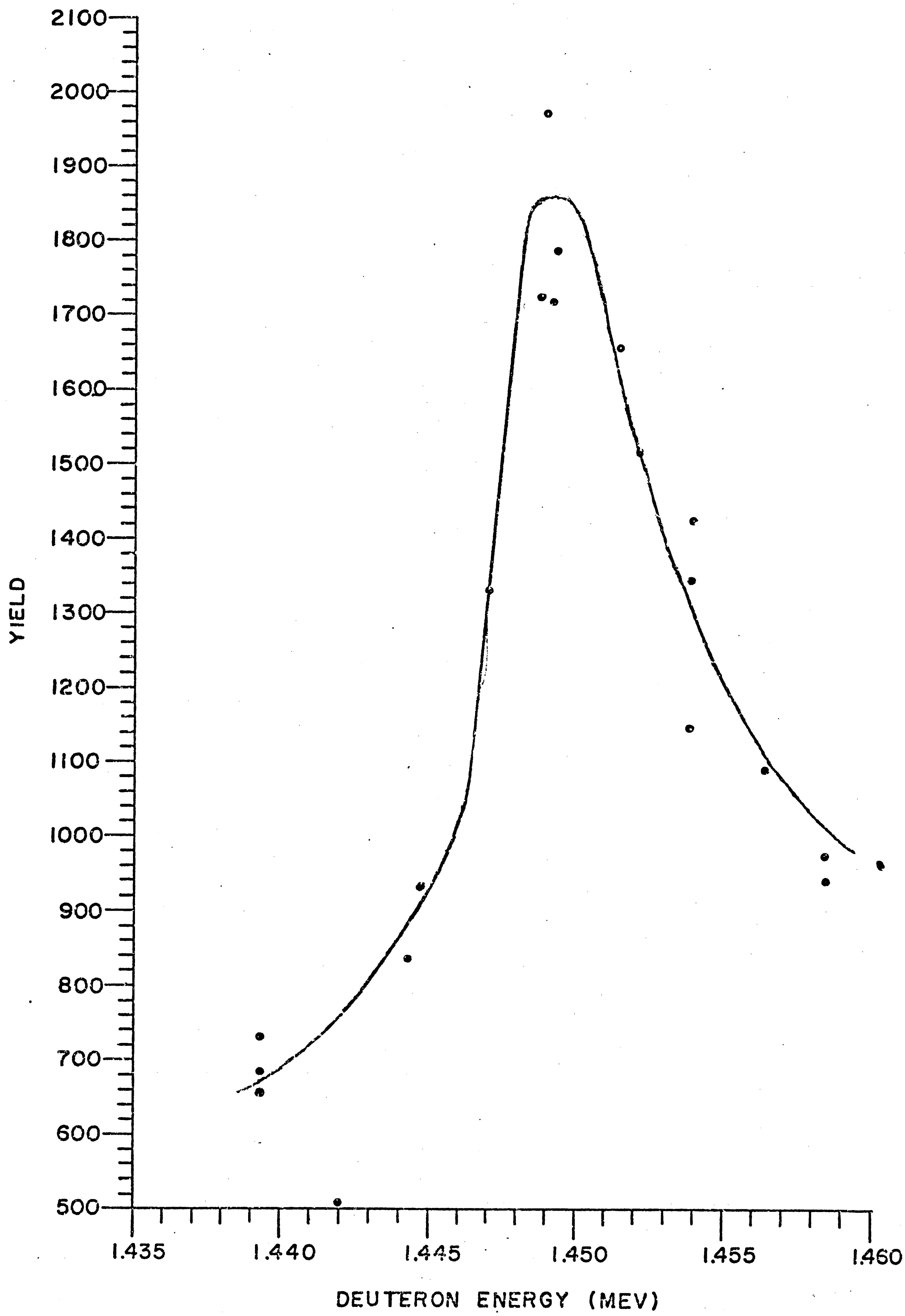
Procedure. The target chamber was aligned optically before the experiment in order to minimize final adjustments necessary to make the beam enter the collimating slits. Once the tandem was tuned up successfully, we were able to produce and maintain a very good low energy deuteron beam necessary for the experiment. The beam was tuned as well as possible on the 90° quartz, and then the image and object slits on the 90° magnet were narrowed to an estimated gap of 5 mills, and 50 mills respectively, in order to yield a beam resolution on the order of a few kev. Final adjustments to the beam intensity were made by adjusting the stripper gas so that the target current was on the order of 100 nanoamps during the runs. This current produced typical neutron counting rates of 3 counts/sec. and charged particle counting rates of 34 counts/sec. off resonance. The runs were all made for an integrated charge of 9 coulombs.

We began the search for the resonance at 1.439 Mev, as determined by the 90° analyzing magnet, and went up in energy in 4 kev steps. The neutron counter and shielding was arranged during these runs to obtain the best ratio of target to background counts. The resonance was found at 1.448 Mev as determined by the analyzing magnet, and identified by the shape of the excitation versus energy curves (4) for the ground state protons. The excitation curves for p_0, n_0, d, and p_1, are presented in figures 4,5, and 6. "Off-resonance" points were several times the FWHM-plus-target-thickness in kev from the resonance energy.

Once the resonance was located, many data points were taken; first below resonance, on resonance, then above resonance, alternately repeating the sequence in reverse order. Since no resonance associated neutrons were observed, it was hoped that a large number of points could statistically reduce the experimental error in order to set more accurate limits on the number of neutrons produced on resonance.

FIGURE 4

Excitation curve for ground state protons from the reaction $^{12}C(d,p)^{13}C$.



2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
YIELD
1.435
1.440
1.445
1.450
1.455
1.460
DEUTERON ENERGY (MEV)

FIGURE 5

Excitation curve for elastic deuteron from reaction $^{12}C(d,d)^{12}C$.

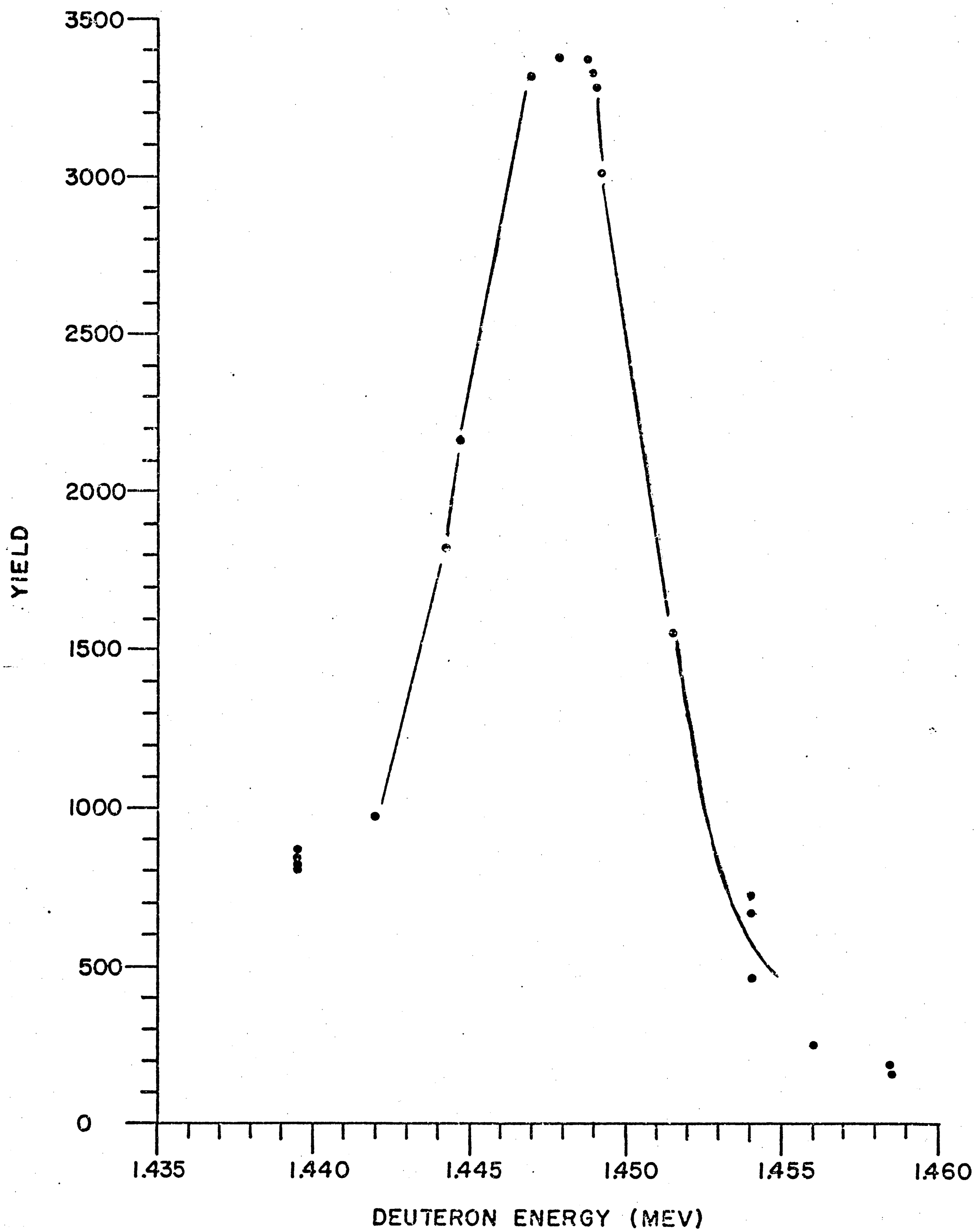
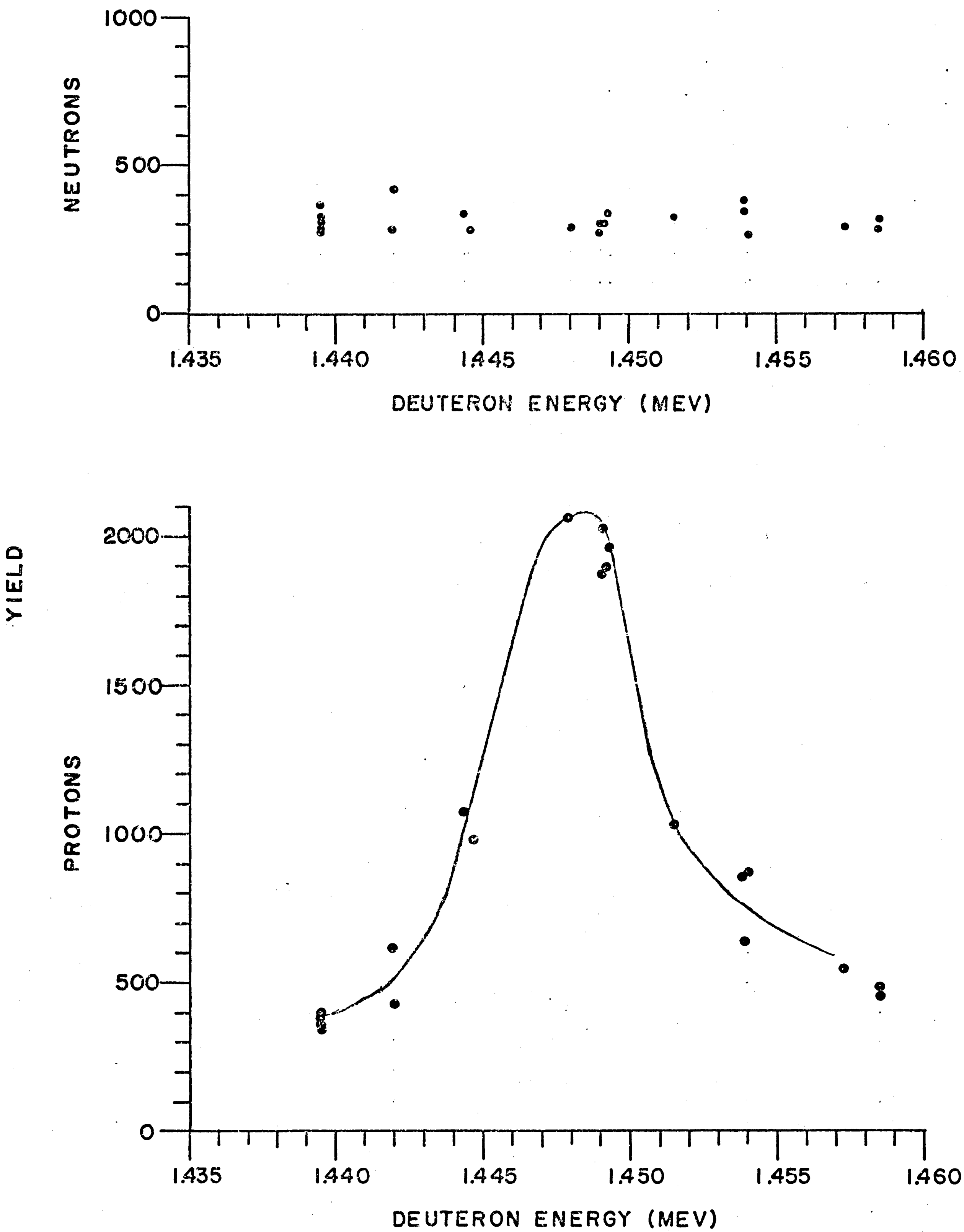

3500
3000
2500
2000
1500
1000
500
0
YIELD
1.435
1.440
1.445
1.450
1.455
1.460
DEUTERON ENERGY (MEV)

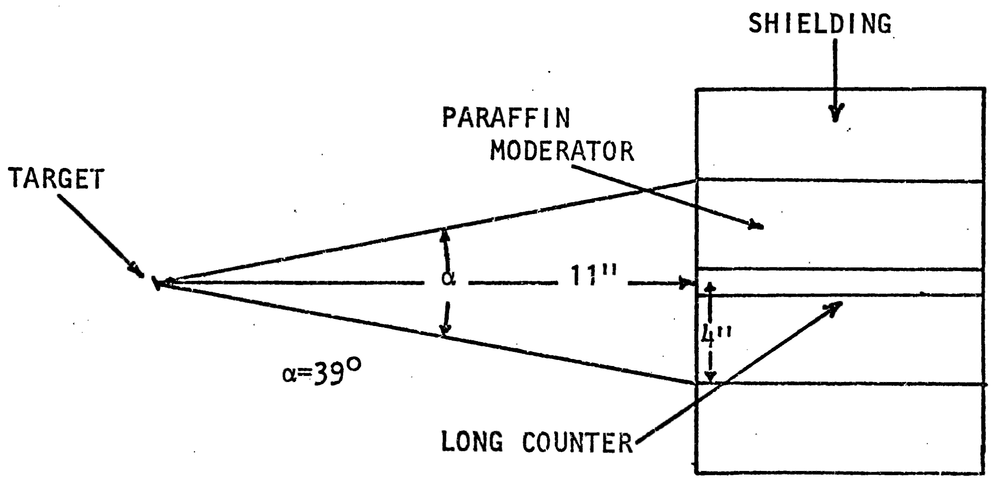
FIGURE 6

Excitation curves for protons to the first excited state of $^{13}C^*$ (3.09 Mev state), and ground state neutrons, from the reactions $^{12}C(d,p_1)^{13}C$ and $^{12}C(d,n_o)^{13}N$.


YIELD
NEUTRONS
1000
500
0
1.435
1.440
1.445
1.450
1.455
1.460
DEUTERON ENERGY (MEV)
PROTONS
2000
1500
1000
500
0
1.435
1.440
1.445
1.450
1.455
1.460
DEUTERON ENERGY (MEV)

CALCULATIONS

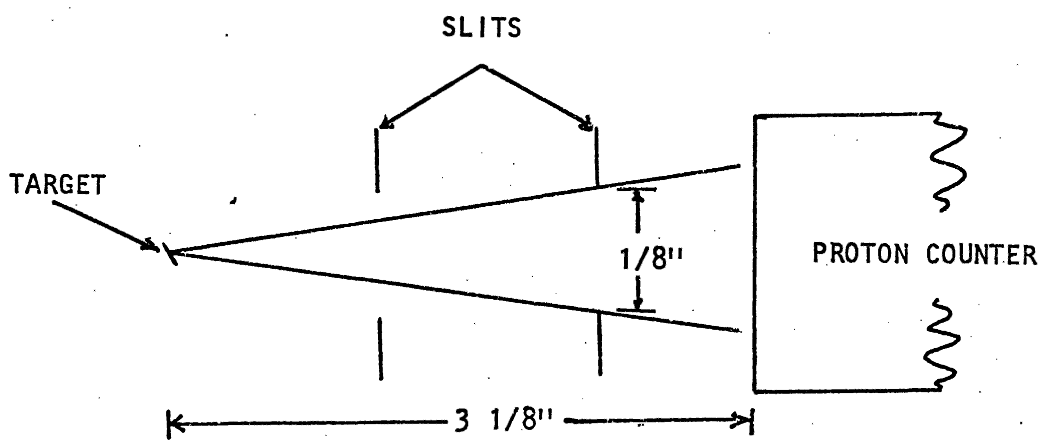
Neutron counter solid angle.



Ω_n = solid angle subtended by neutron counter

$$\Omega_n = 2\pi(1-\cos\alpha) = 3.78 \times 10^{-1} \text{ steradians}$$

Proton counter solid angle.



Ω_s = solid angle subtended by solid state counter

$$\frac{\pi r^2}{4\pi R^2} = \frac{\text{surface area subtended by solid angle}}{\text{total surface area in } 4\pi \text{ steradians}} = \frac{\Omega_s}{4\pi \text{ steradians}}$$

$$\Omega_s = \frac{\pi r^2}{R^2} = 5.19 \times 10^{-3} \text{ steradians}$$

Efficiency of neutron counter. In order to calibrate the neutron detector, a Pu Be neutron source with a flux of 1.44×10^6 neutrons/second was placed in the position of the carbon target, and the counter was run for 500 seconds. The number of neutrons detected was then compared with the number of neutrons emitted by the source in 500 seconds through the solid angle subtended by the detector.

$$1.44 \times 10^6 \text{ neutrons/second} \times 500 \text{ seconds} \times \frac{.378 \text{ steradians}}{4\pi \text{ steradians}}$$

$= 0.214 \times 10^8$ neutrons through the neutron counter in 500 seconds

Efficiency = # neutrons detected/# neutrons through detector

$= 53.3 \times 10^3 / 24.4 \times 10^6 = 2.49 \times 10^{-3}$

The neutrons detected in this experiment were analyzed by comparing the average of neutrons detected per run on resonance to the average number of neutrons detected per run off resonance. These values were found to agree well within one standard deviation. The averages obtained were:

Average # of neutrons per run on resonance = 303

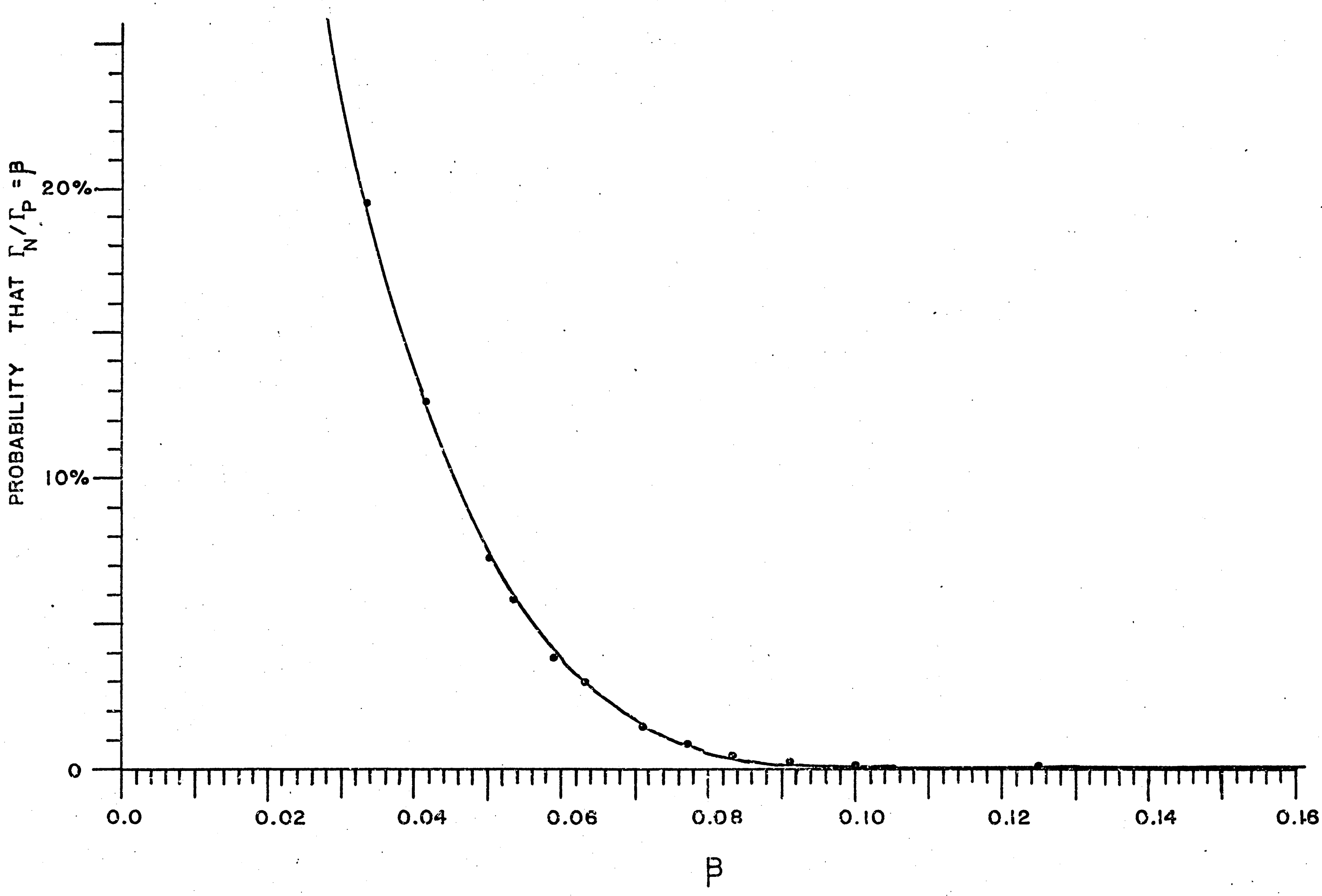
Average # of neutrons per run off resonance = 319 with standard deviations of 25 and 41 respectively.

In order to obtain a lower limit on Γ_p/Γ_n, we first assume that Γ_n is equal to a variable parameter, β^{-1}, multiplied by Γ_p. The ratio of Γ_n/Γ_p will then be equal to β. The expected distribution of resonant neutrons is then calculated from the distribution of the neutrons found off resonance. From this expected distribution, we calculate the probability of finding the number of resonance neutrons observed in the experiment. The resultant plot of the probability of obtaining the experimental result versus β is shown in figure 7.

A practical upper limit on β is certainly the point on the graph for which the probability of obtaining the experimental result falls to 0.01. From the graph in figure 7, we find that this reasonable lower limit on β^{-1} is 12. Thus we can conclude that $\Gamma_p/\Gamma_n > 12$.

FIGURE 7

Probability of finding Γ_n/Γ_p equal to β versus β.


PROBABILITY THAT $\Gamma_N/\Gamma_P = \beta$
20%
10%
0
0.0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
β

THEORY AND RESULTS

Theory. Since the protons to the ground state of ^{13}C have angular distributions peaked at large backward angles at this 1.446 Mev resonance,[4] we would expect neutrons to the ground state of ^{13}N to show resonance at these backward angles. This is because the proton and neutron emissions are to the ground states of mirror nucleii with definite angular momentum and parity ($P_{\frac{1}{2}}-$). Thus with the exception of the Coulomb field differences, the ground state of ^{13}C and ^{13}N have identical wave functions, and one would expect the same angular distribution for the emission of neutrons as for protons. The validity of this argument is supported in general by the available data showing the angular dependence of the cross section of the ground state neutrons and protons: for deuterons of nearly the same bombarding energy, the curves for protons and neutrons show a marked similarity in shape.[1] [4]

At first consideration, one might present a similar argument to show that the reduced width for neutron production should be comparable to the reduced width for proton production, and hence a neutron resonance should be expected to occur along with the proton resonance. In fact, this is the case for proton resonances at 0.91, 1.16, 1.30 and 1.73 Mev.[2] A quantum mechanical isotopic spin argument however, can be made to show how the differences in widths can come about. We consider the neutrons and protons as identical particles, with isotopic spin $\frac{1}{2}$, in different states. The neutron is in a state where the z component of the isotopic spin is $\frac{1}{2}$, and the proton is in a state where the z component of the isotopic spin is $-\frac{1}{2}$. The excited state of $^{14}N^*$ can be thought to exist as a combination of two states, one of which consists of ^{13}N plus a neutron, and the other of which consists of ^{13}C plus a proton.

Since eigenkets for a two body system have only two eigenvalues for the isospin operator (T=1 and T=0) we can say that the ket representing ^{14}N can be composed of two kets, which can be represented in Dirac notation as: $|T\ T_z> = |0\ 0>$ and $|T\ T_z> = |1\ 0>$. This can be written:

(1) $|^{14}N> = a|T=1\ T_z=0> + b|T=0\ T_z=0>$

We have also shown, however, that ^{14}N can be thought of as $^{13}C(T_z=\frac{1}{2})$ plus a proton $(T_z=-\frac{1}{2})$, or as ^{13}N $(T_z=-\frac{1}{2})$ plus a neutron $(T_z=\frac{1}{2})$. We will represent these states as follows:

(2) $|^{13}C{+}p> = |^{13}C, T_z=\frac{1}{2}>|p, T_z=-\frac{1}{2}>$

(3) $|^{13}N{+}n> = |^{13}N, T_z=-\frac{1}{2}>|n, T_z=\frac{1}{2}>$

If we then expand equation (1) in terms of the states (2) and (3) we can discover how much the state $|^{14}N>$ looks like $|^{13}C{+}p>$, which will emit a proton, and how much the state $|^{14}N>$ looks like $|^{13}N{+}n>$, which will emit a neutron. This expansion can be done using Clebsch-Gordan coefficients for two spin $\frac{1}{2}$ particles.

$$|T=1\ T_z=0> = \frac{1}{\sqrt{2}}\,|^{13}N,-\tfrac{1}{2}>|n,\tfrac{1}{2}> + \frac{1}{\sqrt{2}}\,|^{13}C,\tfrac{1}{2}>|p,-\tfrac{1}{2}>$$

$$|T=0\ T_z=0> = -\frac{1}{\sqrt{2}}\,|^{13}N,-\tfrac{1}{2}>|n,\tfrac{1}{2}> + \frac{1}{\sqrt{2}}\,|^{13}C,\tfrac{1}{2}>|p,-\tfrac{1}{2}>$$

Thus: $|^{14}N> = \left(\frac{a+b}{\sqrt{2}}\right)|^{13}C{+}p> + \left(\frac{a-b}{\sqrt{2}}\right)|^{13}N{+}n>$

This is interpreted as meaning that we only find equal widths for the neutron and proton when either a≃0 or b≃0, that is, when the decaying excited state of ^{14}N is in a pure isospin state of either T=0 or T=1. A null count of neutrons must be interpreted as meaning that the excited state of ^{14}N must be an isospin mixed state of equal components of T=1 and T=0. One must be careful, however, that this null count of neutrons is not due to an unfavorable penetrability factor for the neutrons versus protons in this reaction.

It could be noted in support of this argument, that the states in $^{14}N^*$ excited by deuterons on ^{12}C which produce both neutrons and proton resonances at 0.91, 1.16, 130, and 1.73 Mev are all states in $^{14}N^*$ which have been assigned a definite isotopic spin.[(2)]

Results. The ratio of $\sigma_{p_0}/\sigma_{n_0}$ obtained in this experiment is on the same order of magnitude as the ratio of the penetrability for the ground state protons (p_o) to the penetrability for the ground state neutrons (n_o), and therefore no conclusion can yet be drawn regarding the isospin of this 11.50 Mev state of $^{14}N^*$, since we cannot claim that the absence of neutrons is due to isospin arguments rather than penetrabilities.

Penetrability factors for the deuterons, ground state protons, first excited state protons, and ground state neutrons have been calculated on the Rice University IBM 1800 computer using a Coulomb wave function penetrability program developed by Dr. Foster Rich. This method calculates the penetrabilities as:

$$P = \frac{kr}{F_l^2 + G_l^2} \Bigg|_{r = a_l = \text{channel radius}}$$

The Wigner limit for each channel was calculated from the relation:

$$W.L. = \frac{h^2}{2\mu a_1^2},$$

and was compared to the reduced width calculated from the experimental data. Values of penetrability, reduced width, and ratio of the reduced width to the Wigner Limit are given for P_o, p_1, d, and n_o in Table 1.

TABLE I

Particle	Penetrability Factor	γ^2 (kev)	γ^2/W.L.
d	0.035	55.6	0.04
p_o	0.001	16.24	0.012
p_1	0.017	257.6	0.182
n_o	0.002	---	---

The most surprising result from this experiment is the fact that such a large resonance in p_1 protons is observed. This resonance in p_1 protons is greater than the resonance in p_o protons. This high yield of protons from the reaction $^{12}C(d,p_1)^{13}C^*$ (3.09 Mev state) compared to the reaction $^{12}C(d,p_o)^{13}C$, despite the highly unfavorable ratio of penetrabilities for these two particles, must be interpreted as indicating that the 11.50 Mev excited state of the $^{14}N^*$ nucleus is mainly composed of the first excited state of the A=13 system plus a nucleon.

APPENDIX A

The early portion of this work included the construction of a gas target cell and windows for this cell. The gas cell is shown in figure A-1. This cell fits in an adaptation on the bottom of the scattering chamber discussed in reference (6) to which the exterior gas pumping connections are made. The gas target can be rotated periodically by a few degrees about a vertical axis, so that the beam does not destroy the windows during extended runs.

The windows were made by following the general procedure outlined in reference (8). A two percent, by weight, solution of 7/95E Formvar[(9)] dichloroethane was floated on a quiescent surface of distilled water, and a continuous formvar foil could be drawn from the evaporating solvent. This foil was wound onto the cell as discussed in reference (8). Figure A-2 shows the apparatus used for this procedure. It was found convenient to this author to float the solution by dropping a few drops of it into a small reservoir in an aluminum plate which was just barely submerged in the water (see figure A-2). If too much of the solution is dropped at one time, it will roll off the edge of the plate and sink to the bottom of the pan. A few drops of the solution on the aluminum plate is more than enough to form a satisfactory window.

The most successful windows obtained were formed by eight to twelve layers of formvar. After the windows had dried throughly, they were cut within one quarter of an inch from the opening in the cell, and the excess foil removed. This cut was then sealed with a thin coating of Glyptol. A typically good window could withstand a pressure of greater than fifteen inches of water, with a leak rate less than one third inch per hour.

FIGURE A-1

Diagram of gas cell.

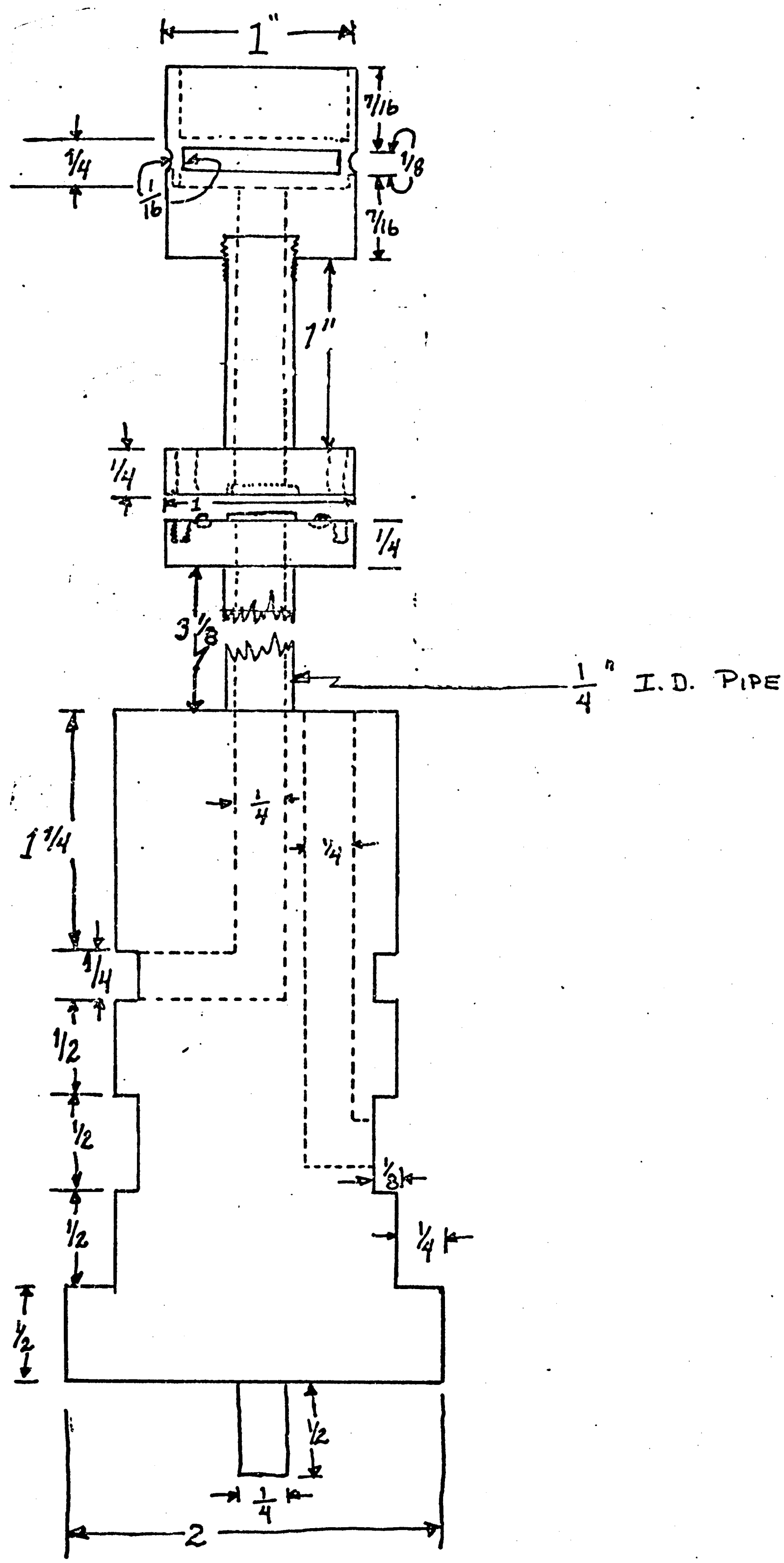
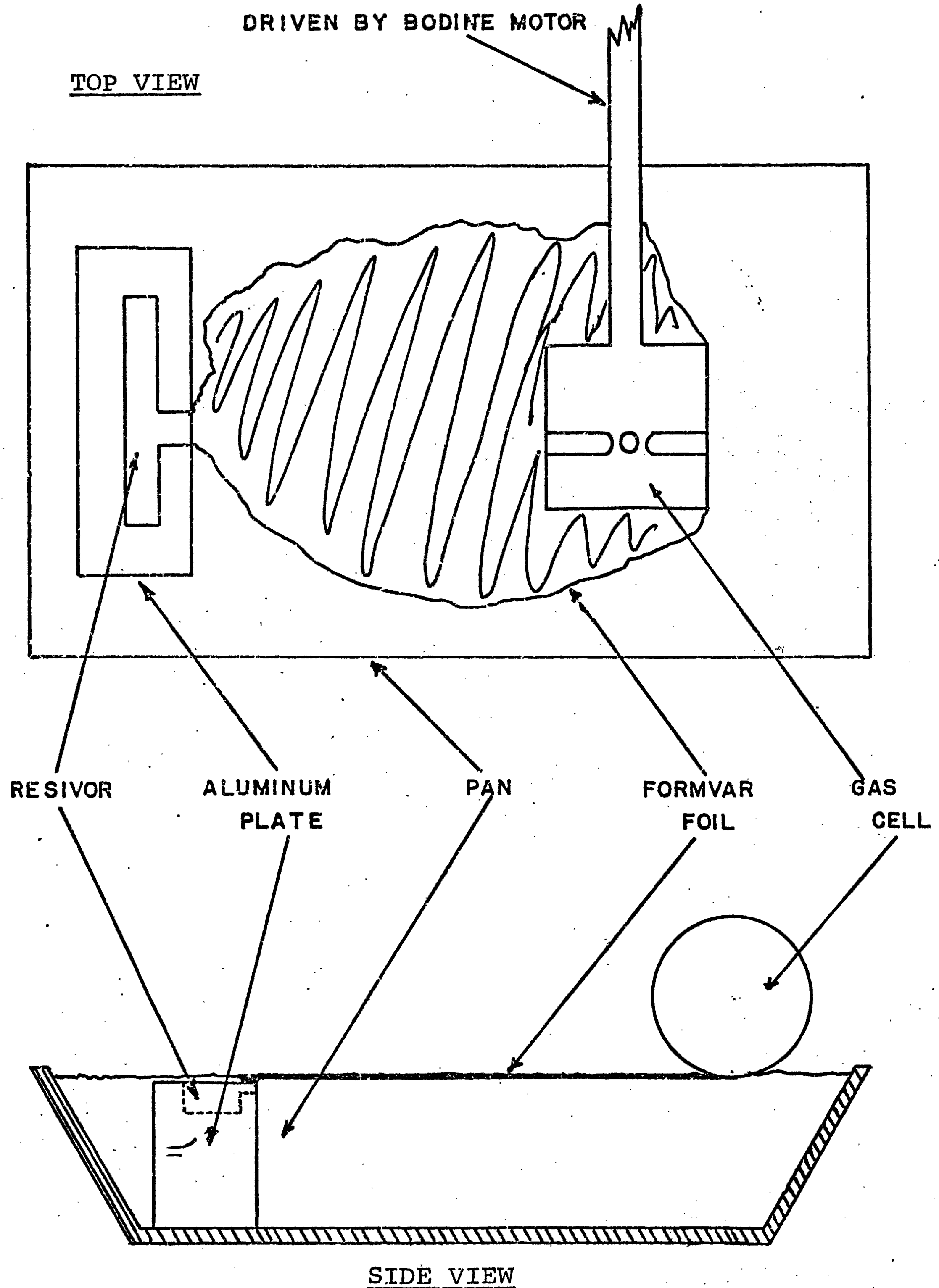

1"
7/16
1/8
7/16
1/4
1/16
7"
1/4
1
1/4
3 1/8
1/4" I.D. PIPE
1 1/4
1/4
1/4
1/4
1/2
1/2
1/2
1/8
1/4
1/2
1/2
1/4
2

FIGURE A-2

Apparatus used to form cell windows.


DRIVEN BY BODINE MOTOR
TOP VIEW
RESIVOR
ALUMINUM PLATE
PAN
FORMVAR FOIL
GAS CELL
SIDE VIEW

ACKNOWLEDGMENTS

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