1000 and 10,000 ev for $\Gamma_n E^{-\frac{1}{2}}$ between 0.2 and 2. This is in rough agreement with the experimental results for the level spacing since this is the level spacing per isotope, for a given spin state.

We wish to thank Miss Miriam Levin who assisted with the numerous calculations involved in this paper and the members of the cyclotron staff who aided with these measurements. Thanks are also due to the United States Atomic Energy Commission for its support of this research.

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The Reaction $C^{14}(p,n)N^{14}$: Excited States in N^{15}

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The relative neutron yield from $C^{14}(p,n)N^{14}$ has been measured for proton energies of 1100 to 2600 kev. Resonances occur at nine proton energies: 1165, 1310, 1664, 1789, 1883, 2024, 2079, 2272, and 2451 kev. The form of the yield curve and the calculated energies of the resonance levels in N^{15} are in good agreement with the results of others on the inverse reaction, $N^{14}(n,p)C^{14}$.

I. INTRODUCTION

THE excited states of N^{15} have been studied extensively.[1] As indicated schematically in Fig. 1, the virtual levels in the region of excitation somewhat above the neutron binding energy can be excited by three bombardments: $B^{11}+\alpha$, $N^{14}+n$, and $C^{14}+p$. We are concerned here with two reactions which are inverse to each other: $N^{14}(n,p)C^{14}$ and $C^{14}(p,n)N^{14}$. Both (n,p) and (p,n) reactions on stable, light nuclei lead to residual nuclei which are unstable. The recent availability of radioactive C^{14} in reasonable concentration has made this the first case in which both reactions, leading to the same compound nucleus, can be investigated.

It is expected that the yield curve, number of protons *vs* neutron energy E_n from $N^{14}(n,p)C^{14}$, should be very similar to the yield of neutrons *vs* proton energy E_p from $C^{14}(p,n)N^{14}$. The same resonances should be observed, with identical half-widths, but at higher bombarding energies, in the (p,n) reaction, by an amount equal to the (p,n) threshold energy (see Fig. 1). The cross sections are related by the principle of detailed balance.[2]

The absolute cross section $\sigma_{n,p}$ for $N^{14}(n,p)C^{14}$ has been measured by Johnson and Barschall[3] with fairly good resolution. They found three strong resonances and indications of several weaker ones in the neutron energy range 0.2 to 2.0 Mev. The neutron yield from $C^{14}(p,n)N^{14}$ was investigated by Shoupp, Jennings, and Sun.[4] Three large peaks in the neutron yield were found at energies which correlate with the later results of Johnson and Barschall. Although they used a thin target (estimated thickness 3 kev at $E_p=1.14$ Mev), their beam energy control did not suffice to resolve weaker resonances, and a detailed comparison is not possible. Because of the general interest of the reaction and its connection with parallel work in this laboratory on the total neutron cross section of N^{14}, we decided to remeasure the $C^{14}(p,n)$ yield with the good energy resolution available with the Rockefeller electrostatic generator.[5]

II. EXPERIMENTAL METHOD

Barium carbonate was obtained from Oak Ridge National Laboratory with carbon enriched to about 1.6 percent of C^{14}. This was converted to HCN and then to NaCN in a solution of NaOH.[6] The final material

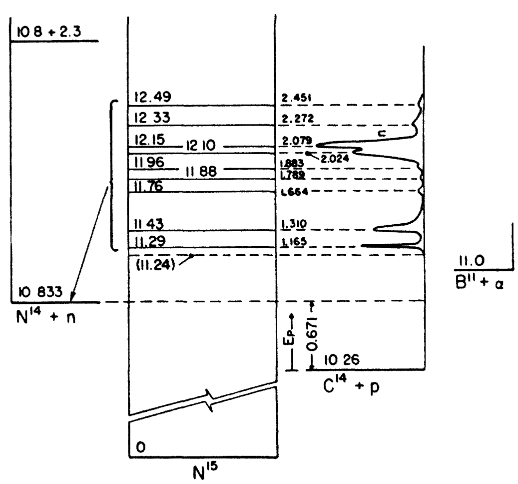

FIG. 1. Energy level diagram for N^{15} in the region somewhat above the neutron binding energy. The energies shown are computed from the results of this paper. *Note added in proof:* The energy of $C^{14}+p$ should read 10.207.

* This work was assisted by the BuShips and ONR.

[1] For a summary, see Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).

[2] H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York, 1947).

[3] C. H. Johnson and H. H. Barschall, Phys. Rev. **80**, 818 (1950).

[4] Shoupp, Jennings, and Sun, Phys. Rev. **75**, 1 (1949).

[5] W. M. Preston and C. Goodman, Phys. Rev. **82**, 316 (1951).

[6] The chemical conversion was performed by Tracerlab, Inc., Cambridge, Massachusetts.

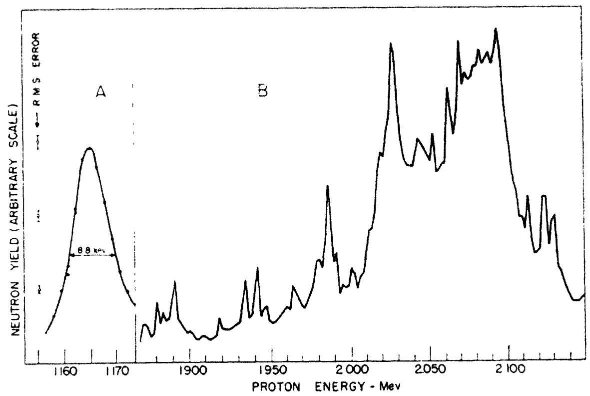

FIG. 2. Neutron yield *vs* proton energy, target No. 1, (A) the $C^{14}(p,n)$ resonance at 1.165 Mev; (B) narrow, closely spaced peaks due to a contaminant, Cl^{37}, superimposed on C^{14} resonances at 2.024 and 2.079 Mev.

consisted of about equal parts NaCN and NaOH, with 0.25 atom-percent C^{14}. It was evaporated[7] onto 10-mil tantalum disks, 6.2 cm in diameter, which fit with rubber gaskets on a rotating target assembly, eccentric to the axis of the proton beam. With a 3-μa beam in a spot about 2×2 mm, the targets lasted many hours with little evaporation, provided a strong air jet was directed on the back face of the target. The (p,n) thresholds of C^{12}, C^{13}, N^{14}, N^{15}, O^{16}, O^{17}, O^{18}, and Na^{23} are all higher than the proton energies used in this experiment.

The neutrons were detected by a 1-inch diameter counter with an active volume 12 inches long, filled to a pressure of 55 cm with enriched BF_3 (95 percent B^{10}). The counter was embedded in a cadmium-covered cylinder of paraffin, 12 inches long and 8 inches in diameter. The latter was mounted with its axis perpendicular to the beam and its side almost touching the target in order to get maximum counting rates. We cannot assume that its efficiency in this position is as independent of neutron energy as that of the "long counter" of Hanson and McKibben.[8]

The ion beam of the Rockefeller generator is bent through 90 degrees, on a 38-cm radius, by a magnetic analyzer whose field is stabilized by a proton magnetic moment resonance control. The field B at the point of measurement is proportional to the resonant frequency f, which can be measured to about one part in 10^5 by comparison with a standard oscillator. The proton energy is then given by $E=E'(1-E'/M_pc^2)$ to a sufficient approximation, where $E'=kf^2$ is the energy computed without the relativity correction. The constant k is determined by the $Li^7(p,n)$ threshold energy, which is taken as 1882.2 kev.[9] The constancy of k has been checked, for fields well below saturation, by measurements of a sharp resonance with the H^+ and the H_2^+ beams. Drifts in the calibration constant, amounting to 0.1 percent over periods of a few weeks, appear to be the largest source of instrumental error in energy measurements.

The energy resolution of the proton beam is set by the defining slits at the object and image planes of the magnetic analyzer. In the present work, the slit widths were 1 mm, corresponding to a possible energy spread of 0.15 percent. The voltage stabilizer keeps the beam fairly well centered on the slits, and tests on narrow resonances indicate that the effective half-width of the energy distribution is not over 0.075 percent with 1-mm slits.

III. EXPERIMENTAL RESULTS

Figure 2 shows two sections of the neutron yield curve obtained with our first C^{14} target. Two strong resonances appeared, at 1165 and 1309 kev; the first of these is shown on an enlarged scale in Fig. 2A. The background in this region was small, since the proton energy is below the (p,n) threshold of all likely contaminants. Above 1680 kev, however, a spectrum appeared consisting of narrow and closely spaced resonances characteristic of an element heavier than C^{14}. Some of these are shown in Fig. 2B, superimposed on two broader C^{14} peaks. Investigation with targets of NaCl showed that the impurity was C^{37}, which has its threshold at 1640 kev.[10]

Since the Cl^{37} spectrum obscured any weak resonances of C^{14}, the enriched material was processed chemically to remove chlorine.[11] A run with a second target then showed that nearly all of the chlorine had been removed successfully, but that the neutron background from

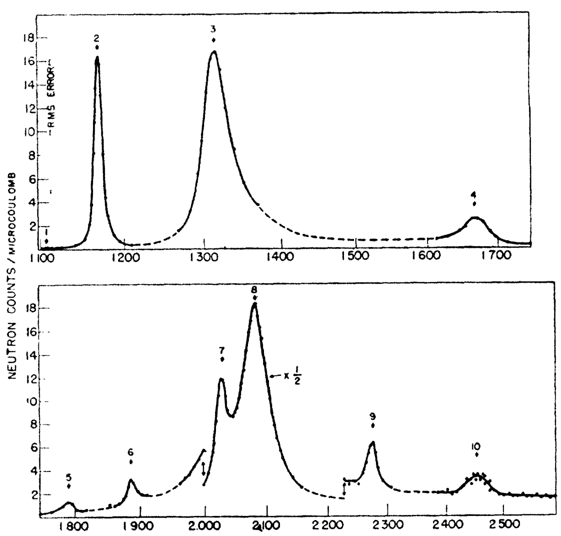

FIG. 3. Neutron yield from $C^{14}(p,n)$ *vs* proton energy, target No. 3 (about 8 kev thick at 1.165 Mev).

[7] The evaporation was carried out by Mr. Edward Barr of Baird Associates, Cambridge, Massachusetts.

[8] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[9] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).
[10] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[11] The purification was performed by Tracerlab, Inc.

TABLE I. The $C^{14}(p,n)$ resonance at 1165 kev. Γ' = observed half-width of resonance, kev. T = target thickness, kev. Γ = calculated natural half-width, kev. Y_{max} = maximum yield at resonance. E_r = proton energy at resonance, kev. $E_{rt} = E_r - \frac{1}{2}T$ = resonance energy corrected for target thickness.

Date of run	Target No.	Γ'	T	Γ	Y_{max}	E_r	E_{rt}
2/8/51	1	8.8	4	7.8	···	1165.5	1163.5
4/17/51	2	8.2	3.0	7.6	7.1	1165.5	1164.0
5/3/51	3	11.3	8.4		16.3	1169.4	1165.2

parts of the machine other than the target was unusually high. This background was reduced by cleaning the slits and shielding with paraffin. Data taken with a third target are shown in Fig. 3, over the energy range 1100 to 2600 kev.

Nine resonances were found in this range. The dashed portions of the yield curve in Fig. 3, up to 1700 kev, were covered with targets No. 1 or 2 and no resonances found above background. A major portion of the yield between resonances is still due to a background from the generator which increases smoothly with energy, as shown by runs with a blank target. This background was somewhat variable, and we did not feel justified in subtracting it from the total yield. The scatter in points in the region of resonance No. 10, which is larger than the expected statistical variations, may be due to background fluctuations. At still higher energies, indications of additional resonances were so masked by the same effect that we have not included the data.

Table I summarizes data taken with all three targets on resonance No. 2 at 1165 kev, from which we can calculate the natural width and the thickness of the targets. The natural width of the chlorine resonances in Fig. 2B is small compared with the target thickness, and from several of the more isolated peaks we can estimate the thickness of target No. 1 as 4 kev at 1165 kev. This gives $\Gamma = 7.8$ kev for the natural half-width of resonance No. 2. The neutron counter was in the same position during the runs with targets 2 and 3, so we can use the observed half-widths of the resonance and the ratio of the peak yields to calculate the natural half-widths and the target thicknesses. The value obtained is $\Gamma = 7.6$ kev, in good agreement with the first estimate. The spread in values of E_{rt}, the resonance energy corrected for target thickness, may be caused by: (a) target contamination, (b) errors in estimating the position of the maxima, (c) long term shifts in the energy calibration of the generator (the same calibration constant has been used for all three runs).

Table II summarizes the data for all resonances observed, taken from Fig. 3. The column headed E_r gives the proton energy at the observed resonance peaks. The target thickness, T, is taken as 8.4 kev for resonance No. 2 (from Table I) and adjusted for higher energy values. Under E_{rt} are given the proton resonance energies corrected for target thickness, based on the $Li(p,n)$ threshold 1882.2 kev. The errors given are estimates; except for the sharp resonance No. 2, instrumental errors should be smaller than the uncertainty in locating graphically the position of a peak. Γ is the width of a resonance at half maximum; its measurement is uncertain in cases of small peaks with large background.

IV. DISCUSSION

Resonance Energies

In order to compare our resonance energies with the results of Johnson and Barschall, we must subtract from the former the threshold energy E_t for the $C^{14}(p,n)$ reaction. For this quantity, we have taken the value $E_t = 671$ kev, from Tollestrup, Fowler, and Lauritsen.[12] It is based on a weighted mean value of 782 ± 1 kev for the $n-H'$ difference and 156 ± 1 kev for the end point of the C^{14} beta-spectrum, giving a Q-value for $N^{14}(n,p)$ of 626 kev. This value agrees, within stated errors, with the direct determination of Johnson and Barschall[3]

TABLE II. Resonances in $C^{14}(p,n)N^{14}$. E_r = proton energy at peak of resonance, measured. T = calculated target thickness. E_{rt} = resonance energy corrected for target thickness. Γ = natural half-width of resonance. $E_n = E_{rt} - 671$, neutron resonance energy, this paper. E_n(JB) = neutron resonance energy, Johnson and Barschall.[a] E_n(SJS) = neutron resonance energy, computed from data of Shoupp, Jennings, and Sun.[b] Y_{max} = observed relative yield at maximum. Y_n = normalized yield (see text). $\sigma_{n,p}$(JB) of $N^{14}(n,p)C^{14}$ reaction, in millibarns, observed by Johnson and Barschall. $E_x(N^{15})$ = excitation energy of level in N^{15}. Quantities in brackets are our own estimates, from Fig. 3 of the paper of Johnson and Barschall.[a]

No.	E_r(kev)	T(kev)	E_{rt}(kev)	Γ(kev)	This paper E_n(kev)	JB E_n	SJS E_n	Y_{max}	Y_n	JB $\sigma_{n,p}$	$E_x(N^{15})$ (Mev)
1			(1105)		(434)			<0.1			(11.238)
2	1169.4	8.4	1165±2	8±1	494±2	499±5	469±20	21	280	125	11.294
3	1313.5	7.4	1310±3	43±5	639±3	640±7	629±20	17	200	200	11.429
4	1667.0	6.2	1664±4	38±10	993±4	993±12	(800±50)	2.0	19	20	11.759
5	1791.9	5.8	1789±4	18±5	1118±4	[1120]	···	0.9	9	[5]	11.876
6	1885.9	5.6	1883±4	15±5	1212±4	[1220]	···	2.0	18	[5]	11.964
7	2026.8	5.4	2024±4	18±5	1353±4	···	···	16	140	···	12.095
8	2081.9	5.2	2079±4	55±10	1408±4	1415±15	1379±20	36	300	190	12.146
9	2274.7	4.8	2272±4	22±5	1601±4	[1610]	1539±50	~4	~33	[5]	12.326
10	2453.6	4.6	2451±10	45±20	1780±10	1800±15	···	~1.6	~13	[5]	12.493

[a] See reference 3.
[b] See reference 4.

[12] Tollestrup, Fowler, and Lauritsen, Phys. Rev. 78, 372 (1950).

(630±50 kev); with that of Franzen, Halpern, and Stephens[13] (630±6 kev); and with the Q-value for the $C^{14}(p,n)$ reaction obtained by Shoupp, Jennings, and Sun[4] (−620±9 kev). In Table II we list our values for $E_n=E_{rt}-671$. The agreement with the results of Johnson and Barschall, in the next column, is quite satisfactory.[14] (The values enclosed in brackets are our own estimates of the positions of weak peaks in Fig. 3 of their article, not mentioned in their text.) The results in the column headed E_n(SJS) are computed from data of Shoupp, Jennings, and Sun.[4] The agreement is almost within their stated error, except for their resonance at 800 kev, which they list as doubtful.

Comparison of Cross Sections

For the purpose of comparing the cross sections for the inverse reactions, $C^{14}(p,n)N^{14}$ and $N^{14}(n,p)C^{14}$, we can use the single-level Breit-Wigner resonance formula:

$$\sigma_J{}^l(E_p)=(C/E_p)(2l+1)\times G_J{}^l\{\Gamma_p{}^l\Gamma_n{}^{l'}/[(E_p-E_{rp})^2+\tfrac{1}{4}\Gamma^2]\}, \quad (1)$$

$$\sigma_J{}^{l'}(E_n)=(C/E_n)(2l'+1)\times G_J{}^{l'}[\Gamma_p{}^l\Gamma_n{}^{l'}/(E_n-E_{rn})^2+\tfrac{1}{4}\Gamma^2], \quad (2)$$

where $\sigma_J{}^l(E_p)$ is the cross section for the reaction: C^{14} (spin $I=0$)+proton (spin $\frac{1}{2}$, angular momentum l)→N^{15} (in a state of spin J, appropriate parity, resonant at $E_p=E_{rp}$)→N^{14} (spin $I'=1$)+neutron (spin $\frac{1}{2}$, angular momentum l'); $\sigma_J{}^{l'}(E_n)$ is the cross section for the inverse reaction; $C=h^2/8\pi m$, where m is the mass of the proton or neutron; E_p and E_n are the proton and neutron energies; $\Gamma_p{}^l$ and $\Gamma_n{}^{l'}$ are the half-widths for proton and neutron emission; Γ is the total half-width of the level. The lowest reported excited states of N^{14} and C^{14} are at 2.3 and 5.6 Mev, respectively,[1] so in the energy range covered in this paper the compound nucleus must decay to the ground states.

The statistical weight factors are, respectively,

$$(2l+1)G_J{}^l=(2J+1)/2(2I+1)=(2J+1)/2$$

and

$$(2l'+1)G_J{}^{l'}=(2J+1)/2(2I'+1)=(2J+1)/6.$$

Substituting in Eqs. (1) and (2), we obtain, for the ratio of the cross sections at the peak of the same resonance,

$$\sigma(E_{rp})/\sigma(E_{rn})=3E_{rn}/E_{rp}. \quad (3)$$

In Table II, we list under the heading Y_{max} the observed relative maximum yields, taken from Fig. 3. The target thickness T is considerably less than the natural width Γ for all resonances except No. 2; in this case, a correction has been applied to give the correct relative yield for a thin target.

Resonance No. 1 appears strongly in measurements of the total cross section of N^{14} for fast neutrons.[15] The background in this region is very low, and it is possible to set an upper limit of 1 percent for the ratio of the peak yield at this resonance to that at No. 2, in the $C^{14}(p,n)$ reaction.

In order to compare roughly our relative yields with the (n,p) cross sections of Johnson and Barschall, in the column under σ_{np} in Table II, we have divided our peak yields Y_{max} by the value of $\sigma(E_{rp})/\sigma(E_{np})$ from Eq. (3), and normalized to 200 millibarns at resonance No. 3. The results are in the column headed Y_n. (It must be emphasized that (a) the efficiency of our neutron detector was probably not independent of energy and that (b) we measured yields in a large forward angle, whereas Barschall and Johnson measured the integrated yield over all angles.) Resonances 3 and 4 are broad and known to be formed on N^{14} by s neutrons,[15] so their yields should be almost isotropic; the agreement for No. 4 is seen to be good. It seems probable that Johnson and Barschall somewhat underestimated the cross section for the narrow resonance No. 2. Our higher values for No. 5, 6, and 9 may be due partly to better resolution, to an increase in our counter's efficiency at higher energies, and to preferred yield in the forward direction.

Levels in N^{15}

In the last column of Table II we list the computed energies of the levels in N^{15}, where the excitation energy $E_x=[10.833+(14.0076/15.0166)E_n]$ Mev. We have used the adjusted value[16] 10.833±0.007 Mev for the neutron binding energy in N^{15}. The levels are also plotted in Fig. 1.

In conclusion, we wish to express our sincere appreciation to the maintenance staff of the Rockefeller generator: Mr. Donald Thompson, Mr. Gene Slawson, Mr. Richard Spencer, and Mr. John Adams.

[13] Franzen, Halpern, and Stephens, Phys. Rev. 77, 641 (1950).

[14] Our values average slightly higher. We believe these authors somewhat underestimated the energy spread of their neutron source, as evidenced by their failure to resolve resonances No. 7 and 8; this may make their resonance energies too high.

[15] Measurements made in this laboratory, to be published.

[16] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951), see Table I; private communication to W. Buechner.