Radiative Capture of Protons by C^{13}*

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The reaction $C^{13}(p,\gamma)N^{14}$ has been studied experimentally for proton bombarding energies between 0.4 and 2.7 Mev. Targets of carbon enriched in the isotope C^{13} were prepared, and thick and thin target excitation functions obtained. Five resonances were found, corresponding to excited states of N^{14} at 8.05, 8.62, 8.70, 9.18, and 9.49 Mev. The radiation spectrum from these levels was found to involve several branches of decay and transitions cascading through intermediate levels.

I. INTRODUCTION

THERE exists an important class of proton-induced reactions in light nuclei in which radiative capture is the only transmutation of the target nucleus energetically possible for proton energies up to several Mev. Three such (p,γ) reactions figure in the "carbon cycle" of energy production in the sun and hotter stars. Until quite recently, investigation of these reactions had been limited to proton energies between 0.2 and 1 Mev. Hornyak *et al.* give bibliography (to June, 1950) and energy level diagrams for these nuclei in their review article.[1] The nuclei N^{13} and O^{15} are positron emitters, and recent investigations[2,3] of proton capture by C^{12} and N^{14} have taken advantage of the β^+-activity produced in the targets to measure the small (p,γ) yield. In the case of the reaction $C^{13}(p,\gamma)N^{14}$, which is the principal subject of this paper, the residual nucleus is stable, and it is necessary to measure the gamma-radiation directly.

Unpublished work by Fowler and Lauritsen at this laboratory with a thick sample of C^{13}-enriched lampblack was continued above 1.3 Mev on the new electrostatic accelerator by Day and Perry, who discovered a very sharp resonance in the vicinity of 1.76 Mev, and a continuous increase in yield extending from the known resonance at 0.55 Mev. It was recognized that the sharp resonance should appear superimposed on the broader resonance at 1.7 Mev due to C^{12}, even in a target of normal carbon. This was found to be the case by Day, using a thin lampblack target. He was in fact able to obtain angular distributions for both resonances separately.[4]

The present work has involved preparation of thick and thin targets highly enriched in C^{13}, and an investigation of the energy levels and γ spectrum of N^{14} for proton energies from 0.4 to 2.7 Mev.

* This work was assisted by the joint program of the ONR and AEC.

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[1] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).
[2] J. D. Seagrave, Phys. Rev. **84**, 1219 (1951).
[3] D. B. Duncan and J. E. Perry, Phys. Rev. **82**, 809 (1951).
[4] R. B. Day and J. E. Perry, Phys. Rev. **81**, 662(A) (1951).

II. EXPERIMENTAL TECHNIQUES

The 3-Mev electrostatic accelerator recently constructed at the Kellogg Radiation Laboratory provided a steady source of protons, continuously variable in energy, and maintained homogeneous to better than 0.1 percent by a 90° magnetic analyzer of a double focusing design.[5] This equipment will be described in detail elsewhere.[6]

An auxiliary pump and cold trap between the analyzer and target chamber minimized contamination of the targets by normal carbon and oxygen from pump oil vapor.

The basic detection unit was a system of three Geiger tubes[7] of 30 mg/cm² glass wall and a sensitive region $\frac{3}{4}$ in. in diameter$\times 3\frac{1}{2}$ in. long. These were placed in a geometrical arrangement standardized at this laboratory.[8] Secondary electrons produced in a thick aluminum converter which pass through both the front counter and either one of the two rear counters are registered by standard coincidence circuits as coincidence counts. The spectrum of the radiation may be inferred by studying the reduction in coincidence rate as a function of the thickness of aluminum absorber placed directly in front of the rear counters. For the geometry employed, the ratio of coincidence counts to front counts with no absorber is 0.30 ± 0.03 for 3- to 9-Mev gamma-radiation. The counter system was enclosed in a lead shield, and receptacle for a standard ThC″ γ-source permitted periodic checks on counter operation.

The thick target was simply prepared by compressing C^{13}-enriched lampblack into a $\frac{3}{8}$-in. recess milled in a silver blank. It was found necessary to wet the lampblack with a dilute solution of shellac in alcohol. After evaporation of the solvent, the target material could be pressed into a pellet within the recess.

It was clear that thin lampblack targets were quite nonuniform and gave rise to nonuniformities in proton energy loss, and in addition could not be made thin enough for convenient investigation of narrow resonances. Preparation of very thin targets of high uni-

[5] D. B. Duncan, Phys. Rev. **76**, 587(A) (1949).
[6] J. E. Perry, Rev. Sci. Instr. (to be published).
[7] Made by Radiation Counter Laboratories.
[8] Fowler, Lauritsen, and Lauritsen, Revs. Modern Phys. **20**, 236 (1948).

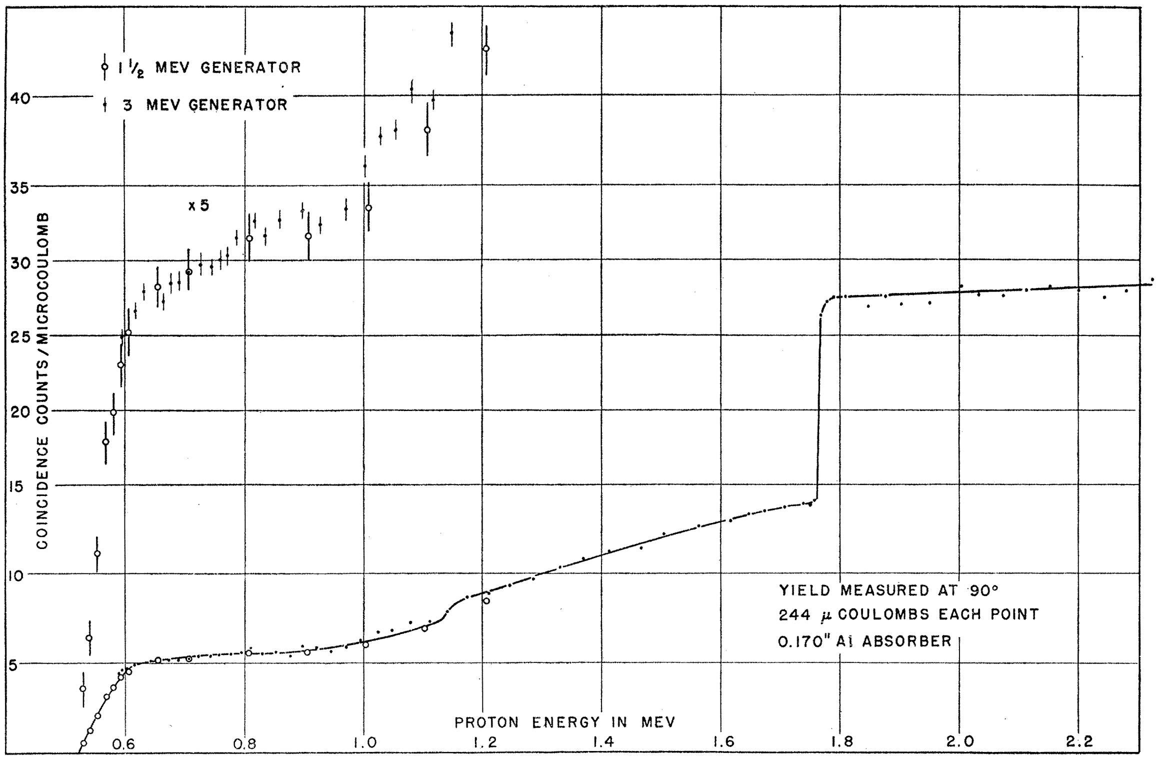

FIG. 1. Thick target yield of high energy radiation from $C^{13}(p,\gamma)N^{14}$ measured at 90° to the axis of the proton beam.

formity was achieved by "cracking" a hydrocarbon vapor or gas on a heated metal surface, leaving an adherent film of carbon. Phillips and Richardson have reported[9] two techniques, using a high temperature oven for cracking benzene on silver foils and later an induction heater to crack C^{13}-enriched CH_3I on nickel disks. The targets used at this laboratory were prepared simply by passing current through a thin tantalum strip suspended in a chamber filled to about $\frac{1}{10}$ atmosphere with CH_4, or (normal or enriched) CH_3I. Cracking proceeds satisfactorily at a temperature corresponding to a bright red color of the tantalum. On the polished Ta surface a thin film was quite invisible, but was detected and measured by the gamma-yield at the 1.76-Mev proton resonance as a result of C^{13}. By comparison with lampblack and graphite targets, these films were shown to be nearly pure carbon. The 1.76-Mev resonance was very convenient to use for the examination of the targets, since the coincidence counting rate from the 3.5-Mev radiation from N^{13} could be attenuated markedly compared to the 9.2-Mev radiation from N^{14} by the use of an appropriate absorber.

Trouble with "blistering" of the film was greatly reduced by the use of a sliding vacuum-fitting in the cracking chamber which maintained the Ta strips in tension during heating, to prevent buckling. It was also necessary to use vapor pressures less than 10 cm Hg, and to reduce temperature slowly. However, by encouraging blistering, it was found possible to remove sections intact as large as 5×5 mm, which should be of interest when an unsupported target is desired. In appearance these "foils" greatly resemble thin beryllium foils. The irregularities of thickness observed with the first films made were greatly reduced by careful polishing and cleaning of the tantalum. It was found unnecessary to outgas the Ta in a high vacuum, and it was merely exposed to a glow discharge while the chamber was being evacuated with the forepump alone (to about 5 microns). Although the voluminous production of I_2 vapor was a nuisance in the cracking chamber, it served as an index of the cracking process and targets made from normal CH_3I showed no detectable difference from those made from methane. Methyl iodide enriched to an absolute concentration of 61 atom percent C^{13} was obtained,[10] and a series of thin targets made from both normal and enriched methyl iodide. The three most satisfactory "C^{13}" targets were 16, 8, and <1 kev thick.

III. THE EXCITATION FUNCTIONS

The excitation function obtained with the C^{13}-enriched lampblack target is shown in Fig. 1. Since N^{14} produced is excited to about 9 Mev while N^{13} is excited

[9] G. C. Phillips and J. E. Richardson, Rev. Sci. Instr. 21, 885 (1950).

[10] From Distillation Products Industries, Eastman Kodak Company. With conservative handling, a large number of targets can be made from 0.1 g of C^{13} in this form.

to about 3 Mev, an 0.150-inch aluminum absorber[11] was employed in the coincidence set-up described previously. This thickness of absorber reduced coincidence counts from N^{13} radiation to a negligible level, while attenuating those from 9-Mev radiation only about 50 percent. The coincidence excitation function shown is thus a measure of the high energy yield only. The bombardment was carried down to 600 kev, as low as it was convenient to operate the accelerator. The low energy data was in agreement with the data obtained by Fowler and Lauritsen on the $1\frac{1}{2}$-Mev accelerator for proton energies of 400 to 1200 kev. The two sets of data were adjusted in scale to match at 700 kev, as shown.

The strong sharp resonance at 1.76 Mev manifests itself as an abrupt "step." The "rise above resonance" observed in the low energy data is seen to exhibit the general features of an extremely broad resonance centered near 1.3 Mev, and extending over several Mev. A small bump appears at 1.16 Mev, and is more marked in the front counter data (not shown), as is a similar bump at 2.1 Mev which is not resolved in the coincidence curve at all. These weak resonances thus give much softer radiation than do the principal resonances.

With the original thick target, Day and Perry determined the location of the sharp resonance as 1754 ± 3 kev and its width as 2.5 ± 0.5 kev. A later value of 1757 ± 3 kev on the same target may have been shifted up by a layer of contamination deposited by the beam. It was hoped to obtain more precise values with the more highly enriched and uniform thin targets, but difficulties with regulation of the magnetic analyzer arose and made it difficult to validate a more precise determination of the energy. A sharper value for the width will be discussed below. It is planned to carry out this important experiment as soon as the electrostatic analyzer now being tested can be calibrated. Indeed, the resonance should prove very useful as a standard itself, as it is believed to be the sharpest proton resonance now known in the light nuclei ($Z\leq10$), and its high energy radiation makes detection convenient. We shall continue to refer to it here as the "1.76-Mev resonance."

Sections of several C^{13}-coated tantalum strips were selected and their "profiles" examined by means of the sharp resonance. A target 16 kev thick at 1.76 Mev which was particularly uniform was used in most of the following work.

Preliminary thin target data confirmed the existence of resonances at 1.16 and 2.10 Mev and a broad maximum at about 1.3 Mev. With 0.030-in. added absorber to suppress only the annihilation quanta from the N^{13} positron decay, a complete excitation curve was run. As is seen in Fig. 2, a good deal of structure was revealed. Attention is called to the scale, on which the yield at 1.76 Mev is 16 times the portion shown. The broad resonance is clearly shown. Its asymmetry is readily accounted for by the energy dependence of factors in the dispersion formula. $E_R=1.25$ Mev and

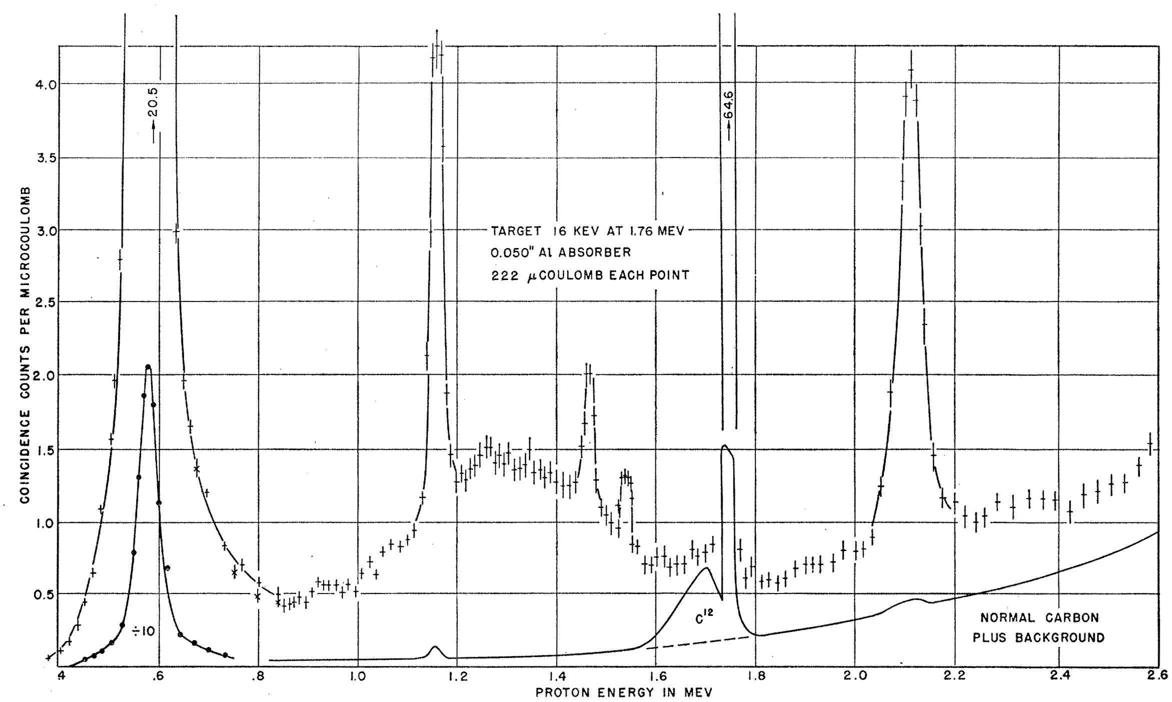

FIG. 2. Detailed thin target yield from $C^{13}(p,\gamma)N^{14}$ measured at 90° to the axis of the proton beam, showing resonances due to C^{13} at 0.55 1.16, 1.25, 1.76, and 2.10 Mev, the 1.70-Mev resonance due to C^{12}, and unidentified weak resonances at 1.47 and 1.55 Mev.

[11] Absorption in the counter walls, equivalent to 0.020 in. of aluminum, has been included in labeling the drawing "0.170 in. Al absorber."

TABLE I. Resonance energies and widths for $C^{13}(p,\gamma)N^{14}$ (in the laboratory system).

E_R (Mev)	0.55	1.16	1.25	1.76	2.10
Γ_R (kev)	32.5	6	500	2.1	45
Error (kev)	±1	±2	——	±0.2	±3

$\Gamma_R=500$ kev are satisfactory parameters when used with the s-wave penetration factor.

The smoothed coincidence background curve is also shown in Fig. 2. Background readings were taken by bombarding a 20-kev normal carbon film on tantalum. The two targets were mounted on opposite sides of the target support, which could be rotated, so that background checks were made without delay or other changes in the system. The 1.70-Mev resonance due to C^{12} is clearly shown in the "background" curve.[12] Because the target is both thick for the C^{13} resonance and thin for the C^{12} resonance, the sharp C^{13} peak stands out clearly and indicates the width and uniformity of the target. The target enrichments were checked by the yield at 1.76 Mev, and it was found acceptable to take the manufacturer's value of 61 percent as exact. Statistically indistinguishable yields were obtained from normal films, normal lampblack, and graphite, so the stopping power of the target may safely be taken as that for pure carbon. The 0.55-Mev resonance was examined using the "Mass Two" (H_2^+) component of the beam, and the data overlapped with the Mass One data for 200 kev. Deuterium contamination of the beam was judged to be negligible.[13]

Because of their very small yield, the resonances at 1.47 and 1.55 Mev could not be definitely assigned to C^{13} by comparison with normal carbon. The region was examined with a target half as thick and the reductions in yield and observed width favor values of about 16 and 6 kev for the widths if that assignment is correct.

An unsuccessful attempt was made to identify possible impurities. The light nuclei are ruled out by their well-known excitation functions, as is phosphorus,[14] the only impurity anticipated from the chemistry of preparing the enriched material.[15] Iodine would hardly be expected to admit proton resonances, because of the forbidding barrier factor for $Z=53$. It would not be surprising to find a "trace" of iodine trapped in the target, however. One of these targets was used in scattering experiments[16] and a small unidentified bump appeared in the analyzer spectrum just before the strong Ta rise. Interpretation as scattering caused by $_{53}I^{127}$ is plausible, in which case the intensity relative to carbon scattering would imply an iodine contamination of not more than 0.5 percent.[17]

In order to obtain the true widths, the principal resonances were examined with several targets and the resonance widths calculated from the yields and observed widths. The most probable values are tabulated in Table I. In the case of the 1.76-Mev resonance, a target was prepared for which the width (from integration) was 0.5 kev. The lowest resonance was examined in somewhat greater detail, to find $Y_{\max}(\xi)/Y_{\max}(\infty)$, and to pursue preliminary evidence that the width was rather less than the 40 kev previously reported.[18] The resonance is also somewhat unsymmetrical, so that interpretation plays a part in the value given for Γ. The excitation function for this resonance was studied with the same target at three angles to the beam, and the target profiles were measured at 1.76 Mev for each position, so that knowledge of the target thicknesses was not dependent on accurate measurement of the target angle. The thickest target used was sufficiently thicker than the resonance width that advantage could be taken of the "infinitely" thick target yield function, Fig. 1, which was normalized in magnitude to fit the thickest "thin" target data at the point of inflection and below. $Y_{\max}(\infty)$ was taken as the value at 700 kev. The internal consistency of these procedures was quite satisfactory, and led to a width $\Gamma=32.5\pm1$ kev, some 20 percent lower than Fowler and Lauritsen's value[18] of 40 kev, but a resonance energy entirely in agreement with their value of 554 ± 2 kev.

IV. THE RADIATION SPECTRUM

a. Absorption of Secondary Electrons

A study of the radiation from each of the principal resonances was undertaken by measuring the coincidence counts/microcoulomb as a function of thickness of absorber placed between the counters. These "absorption curves" were carried below 1 percent transmission until background, accidental coincidences, and statistical fluctuations became serious. Background readings were measured with 0.700-in. aluminum absorber in place and the radiation present, to include the effects of accidental coincidences. The data was corrected for this background and normalized to unit transmission at zero absorber. It was analyzed with

TABLE II. Approximate composition of the $C^{13}(p,\gamma)N^{14}$ spectrum, from scintillation counter integral-bias curves.

E_R(Mev)	Character of the spectrum (γ's)		
0.55	70% 8 Mev,	30% $2\frac{1}{2}$ Mev	
1.16	40% $\sim$4 Mev,	60% $\sim2\frac{1}{2}$ Mev	
1.25	75% $8\frac{1}{2}$ Mev,	15% $\sim3\frac{1}{2}$ Mev,	10%<1 Mev
1.76	85% 9 Mev,	15% $2\frac{1}{2}$ Mev	
2.10	all 4 or 5 Mev.		

[12] The enriched (61 percent) C^{13} target is of course impoverished (39 percent) in C^{12}, while the "background" is taken with a normal (98.9 percent C^{12}) fraction.

[13] The gamma-yield following (d,p) and (d,n) reactions in carbon would be at most only a few percent of the (p,γ) yield if the beam had a normal isotopic content of deuterium.

[14] Grove, Cooper, and Harris, Phys. Rev. **80**, 107 (1950).

[15] D. W. Stewart (Eastman Kodak Company), private communication. I also understand that our "normal methyl iodide," although also made by DPI, is made by a different process than the enriched material.

[16] C. W. Li and W. Whaling, Phys. Rev. **82**, 122 (1951).

[17] Ward Whaling, private communication.

[18] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **76**, 314 (1949).

the aid of semi-empirical "master-curves" applicable to the geometrical arrangement used, which were prepared by interpolation[8] from the results of a study of several well-known gamma-rays. A plot of the logarithm of transmission against absorber thickness gives a family of characteristic curves of small curvature. Unfortunately, if proper account is taken of the probable errors of the data and those errors inherent in graphical solutions, this analysis cannot be carried very far. In addition, the linear dependence of detection efficiency on energy causes the high energy quanta to mask the low, and in the case of complex radiation the above method does not yield very satisfactory results. This appears to be the case for $C^{13}(p,\gamma)N^{14}$: both branching and cascades occur. However, considerable qualitative information has been obtained in this manner. Absorption curves were obtained at each of the five principal resonances, using the same target employed for the thin target yield (Fig. 2). The data at 0.55 and 1.76 Mev is very well fitted in each case by the master curve for the corresponding energy of excitation, and it is clear that the ground-state transition predominates.

In the case of the broad resonance, the tail of the absorption curve again exhibits the shape characteristic of the energy of excitation (8.7 Mev), but about 20 percent of the counts at zero absorber appear to be due to radiation of about 3 Mev, which suggests strong competition, perhaps by a branch in triple cascade.

The radiations from the 1.16- and 2.10-Mev resonances seem to be entirely of quanta less than 5 or 6 Mev, but their analysis is complicated by their weak intensity and location (see Fig. 2) astride the broad resonance.

b. Scintillation Spectrometry

Considerable interest has been aroused by this complex spectrum, but its low intensity makes conventional spectrometer techniques difficult to apply. Preliminary examination[19] of the stronger resonances by a scintillation spectrometer indicated much more sensitive detection of softer components.

E. J. Woodbury at this laboratory has used some of the C^{13}-enriched targets in an investigation[20] of the $C^{13}(p,\gamma)N^{14}$ reaction at 130 kev, in connection with the extrapolation to stellar energies. To calibrate his NaI crystal and associated equipment, we examined the $C^{13}(p,\gamma)N^{14}$ resonances and obtained integral bias curves in each case which give information to supplement that from the absorption curves. Table II gives the composition of the N^{14} radiation as determined from the integral bias curves.[20] The fractions and energies indicated are subject to systematic uncertainties similar to those involved in interpretation of the absorption curves, but with the important difference that here the soft components are not resolved less well than the hard. The results are consistent with the Geiger tube

[19] R. L. Walker and R. B. Day, Phys. Rev. **83**, 203 (A) (1951).
[20] E. J. Woodbury and W. A. Fowler, Phys. Rev. **85**, 51 (1952).

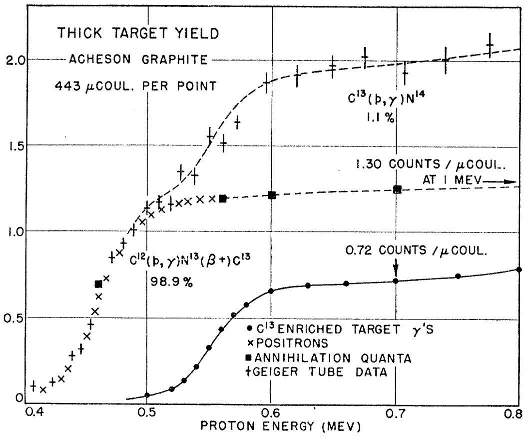

FIG. 3. Analysis of the (p,γ) yield near 0.5 Mev from a thick target of normal graphite. More accurate information on the shapes of the separate resonances has been used to disentangle the observed gamma-yield. The positron data is from reference 8 and the annihilation quanta from an entirely different measurement of the N^{13} yield, reference 2.

results, which were (linearly) weighted in favor of the hard component. It is not yet possible to make definite assignments of levels and transitions, beyond the strong suggestion that the "$2\frac{1}{2}$-Mev" line is the transition to the ground state from the well-known first excited state at 2.32 Mev. A very low energy contribution appears only in the broad resonance. It is to be noted that the soft components do not add up to the excitation energy unless the data represents the average energy of a complex cascade process. Additional work on this spectrum is in progress at this laboratory.‡

V. THE ABSOLUTE YIELDS

The absolute yields are based on the yield from the 0.55-Mev resonance with the thin target of Fig. 2, for which $Y_{\max}=0.50Y_{\max}(\infty)$, as determined during the investigation of the resonance width. The detector for this measurement was a single counter with its axis 10 cm from the target at 90° to the beam axis, surrounded by an aluminum sleeve 1.51-cm thick (to give saturation intensity of secondaries). In addition to making a direct calculation of the detection efficiency,[8] a comparison was made with the yield from a thick CaF_2 target at 1.00 Mev. For the latter we obtained 1940 counts/microcoulomb, and calculated a yield of 6.9×10^{-7} γ/p, which is in excellent agreement with the recent results of Chao *et al.*[21] The corresponding result for the C^{13} target was 8.70 counts/microcoulomb (of protons). By a similar calculation, we find a yield of 4.9×10^{-9} for a thick target taken to be 61 percent C^{13}. The yield for pure C^{13} would then be 8.0×10^{-9}, and 0.9×10^{-10} for a normal (1.12 percent C^{13}) target. It must be recognized in quoting "absolute" figures and applying small "cor-

‡ *Note added in proof:* Woodbury, Day, and Tollestrup, Bull. Am. Phys. Soc. **26**, No. 8, paper J2, report more precise measurements of these γ-ray energies.
[21] Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).

TABLE III. Resonance characteristics for carbon (p,γ) reactions.[a]

Reaction	E_R (Mev)	γ_p (kev)	G (kev) s-wave	G (kev) p-wave	G (kev) d-wave	$Y_{max}(\infty)$ disint./proton	$\omega\Gamma_\gamma$ (ev)	σ_R (millibarns)
$C^{12}(p,\gamma)N^{13}$	0.45	35	>1750	—	—	7.6×10^{-10}	0.67	0.127
	1.70	70	117	230	1900	1.1×10^{-9}	1.39	0.035
$C^{13}(p,\gamma)N^{14}$	0.55	32.5	880	>4500	—	0.9×10^{-8}	8.6	1.44
	1.16	6	18	60	670	0.12×10^{-8}	1.3	0.56
	1.25	500	>1400	>4000	—	1.13×10^{-8}	12.8	0.062
	1.76	2.1	3.2	7.2	42	1.15×10^{-8}	14.8	12.0
	2.10	45	60	150	560	0.48×10^{-8}	6.15	1.96

[a] All energies and widths are given for the laboratory frame of reference. Yields are given for thick targets of pure isotope. Values at 1.16 and 2.10 Mev calculated from 4π times the differential yield at 90°; all others are total yields.

rections" that it is very difficult to make the calculation of absolute gamma-yields much more precise than 10 percent. The value used for the standard fluorine yield may not be much more precise.

Before enriched material was available, the thick target yield from C^{13} was estimated from the excitation function by an attempt to disentangle the "doublestep." This is a very difficult experiment. With the aid of coincidence counting of the high energy radiation and positron counting of the N^{13} yield, Fowler and Lauritsen[22] were able to study the shapes of the two excitation functions separately. Both yields were found to continue to rise well "beyond" the resonance. The yields reported were 7.2×10^{-10} for C^{12} and 1.8×10^{-10} for C^{13}. The latter is twice that calculated above for the most reliable enriched target data. In view of this discrepancy, it was thought of interest to repeat the above experiment on the 3-Mev accelerator. By the use of the copious H_2^+ components of the beam, equivalent to 4 microamperes of protons, it was possible to obtain data with a 3 percent standard deviation in bombardments lasting only 2 minutes, permitting the contribution of annihilation quanta to be included in background measurements alternating with bombardment. The results are shown in Fig. 3. In view of the serious statistical scatter of the earlier data (not shown), it is in agreement with the present excitation function. The double excitation curve was analyzed with the use of Fowler and Lauritsen's positron curve, and the gamma-curve (Fig. 1) obtained with enriched material. Detailed interpretation of the curve with the advantage of improved hindsight about the separate shapes gives considerably different results. CaF_2 was again used as an independent check on efficiency calculations, and the yields calculated are 7.0×10^{-10} for C^{12} (at 1.00 Mev) and 1.1×10^{-10} for C^{13} (at 700 kev), in normal graphite.

The data obtained in calibrating Woodbury's counter on CaF_2 and carbon targets permits calculation[23] of the yield from C^{13} in normal graphite as $0.9\times10^{-10}\ \gamma/p$ for the hard component, and a total yield of 1.0×10^{-10} N^{14}/p if the soft components are regarded as three equal quanta in cascade.

An additional check on the ratio of yields due to C^{12} and C^{13} near 0.5 Mev is available from the ratio near 1.7 Mev, but at present it offers no increase in precision. We conclude that the yield at 700 kev for a thick target of pure C^{13} is 0.9×10^{-8} disintegration/proton. This value supersedes earlier measurements made at this laboratory and has a probable error about 10 percent in excess of that of the fluorine yield used as a reference.

[22] This data is presented in Fig. 1 of reference 8.

[23] E. J. Woodbury (private communication). See reference 20.

VI. WIDTHS AND CROSS SECTIONS

From the measured proton widths Γ_p and the value of $Y_{\max}(\infty)$ for the 0.55-Mev resonance, the values of $Y_{\max}(\infty)$ have been calculated for each of the other resonances using the data of Fig. 2 and the absorption curves. The width for gamma-emission cannot be obtained directly, but the product $\omega\Gamma_\gamma$ can readily be calculated, where ω is a statistical factor. For a target of C^{13}, $\omega=(2J+1)/4$, where $\hbar J$ is the total angular momentum of the compound state. The cross sections at resonance are on the order of millibarns, and are numerically related to the widths and resonance energies (in the laboratory frame of reference) by the expression

$$\sigma_R=0.301(1\,\text{Mev}/E_R)(\omega\Gamma_\gamma/1\,\text{ev})(10\,\text{kev}/\Gamma_p)\ \text{millibarns}.$$

Table III gives the resonance characteristics for each of the resonances studied and the two resonances in $C^{12}(p,\gamma)N^{13}$. Also tabulated are the "nuclear widths without barrier." G_l calculated from the curves of Christy and Latter[24] for s-, p-, and d-wave protons, which give a measure of the dependence of widths on intrinsically nuclear factors. R. G. Thomas has shown[25] that estimation of the nuclear width in this manner may be in error for broad resonances, so that the larger values (over 1 Mev) in the table should be somewhat larger.

VII. DISCUSSION

Without better information on the spectrum very few unequivocal conclusions can be drawn about the structure of the nuclear states involved. It appears that the 0.45-Mev resonance with C^{12} and the 0.55- and 1.25-Mev resonances with C^{13} are formed by capture of s-wave protons, since a nuclear width of a few Mev corresponds

[24] R. F. Christy and R. Latter, Revs. Modern Phys. **20**, 185 (1948).

[25] R. G. Thomas, Phys. Rev. **80**, 136 (A) (1950), and Ph.D. thesis, California Institute of Technology (1951). A paper on this subject is forthcoming.

to decay in a time comparable to the time of formation of the compound state. More refined calculations of "reduced widths" for the broad resonances, based on a modified dispersion theory[25] indicate that this is indeed so. Moreover, the two resonances in N^{14} have nearly equal reduced widths, and the large level spacing predicted for such levels requires that these two have different "spin,"[26] i.e., $J=0$, or $J=1$. The ground state of N^{14} has $J=1$, and presumably even parity.[27] For both of these resonances, the observed radiation widths correspond to reasonable electric dipole matrix elements for either $J=0$, or $J=1$.

Assignment at $J=0$ to the $E_p=0.55$-Mev level would forbid the 5.8-Mev direct transition to the first excited state of 2.3 Mev, which is taken to have $J=0$ and even parity, as it is presumably the analog of the C^{14} and O^{14} ground states (see below). The corresponding transition from the broad level ($J=1$) should then be allowed, but the present evidence seems to indicate that the branch competing with the ground-state transition consists of quanta of lower energy.

Another competing mechanism which may be suggested is the possibility of magnetic radiation between the two broad resonances, followed by ejection of a proton from the lower state, since the proton width is several thousand times the radiation width. Inelastically scattered protons should be observable.

For the 1.16-, 1.76-, and 2.10-Mev resonances, the observed widths correspond to reasonable matrix elements for electric dipole radiation of the energy observed, but very little more can be said. The very small width and anisotropic radiation observed by Day exclude s-wave formation of the resonance at 1.76 Mev, and an assignment of $J=2$, odd parity is consistent with all results, but the assignment is not unique.

Figure 4 is an energy-level diagram for N^{14}, showing the levels now known and the regions explored by this and other work. The reader is referred to reference 1, page 335 for a complete diagram, including the levels above 11 Mev. It is clear that our cascades could take place in a number of ways. The region of excitation between 9.5 and 10.5 Mev remains unexplored and requires energies up to 3.2 Mev for the (p,γ) reaction. Also the region between 6.7 and 7.7 Mev is inadequately explored. With the advent of thin C^{13} targets, the $C^{13}(d,n)N^{14}$ reaction may be used, and the yield of slow (threshold) neutrons investigated. An investigation of proton scattering by C^{13} is being undertaken at this laboratory and is expected to give information on the values of J for the levels found in the (p,γ) reaction.

Also shown in Fig. 4 are the ground states of O^{14} and C^{14}. These occur at the energies shown in parentheses, but when the Coulomb energy and n^1-H^1 differences are removed, they correspond very well to the first excited state of N^{14}. A level at 6.11 Mev in C^{14} has been found in the $C^{13}(d,p)C^{14}$ reaction.[28] This state must have

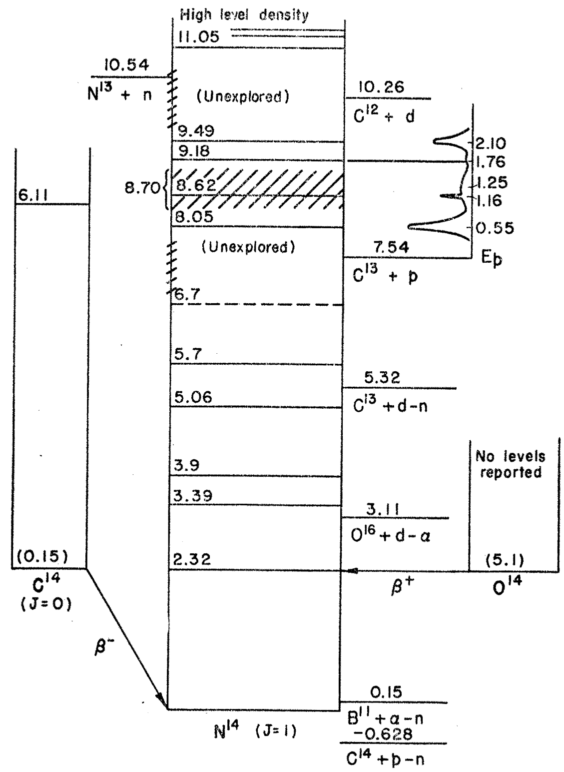

FIG. 4. Energy-level diagram for N^{14} and related nuclei. The Q-values given are based on the recent results of Li, Whaling, Fowler, and Lauritsen, Phys. Rev. 83, 512 (1951).

$J\neq 0$ to radiate as observed to the ground state ($J=0$), and has presumably $J=1$ and odd parity. This state may be the analog of the level in N^{14} at 8.05 Mev.[29] If this is correct, the 8.05-Mev level in N^{14} must (also) have $J=1$, odd parity, and the 8.70-Mev level have $J=0$, odd parity, but a more complex explanation is required for the apparent failure of the 8.05-Mev level to radiate to the 2.3-Mev level.

VIII. CONCLUSION

Five states in N^{14} have been investigated, and shown to emit a complex radiation spectrum, suggesting and challenging further experimental and theoretical work. The next important step should be an intensive attack on the energies, intensities, and branching ratios of the spectrum. It is hoped that the new techniques of scintillation spectroscopy may prove a useful tool in that investigation. The properties of more levels in regions of excitation not yet investigated may supply additional information.

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[26] R. G. Thomas (private communication).
[27] S. T. Butler, Phys. Rev. 80, 1095 (1950).
[28] R. G. Thomas and T. Lauritsen, Phys. Rev. 78, 88 (1950).

[29] R. G. Thomas (private communication).