Elastic Scattering and Capture of Protons by C^{14}†

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The reaction $C^{14}(p,p)$ has been investigated over the energy range from 340 to 690 kev. No wide anomalies are found, but a narrow anomaly at 527 kev has been attributed to *d*-wave protons forming a state of spin $\frac{3}{2}^+$. The reaction $C^{14}(p,\gamma)$, investigated over the range from 250 to 690 kev, shows a resonance at 261 kev in addition to the three previously known resonances at 351, 527, and 634 kev. Proton and radiative widths are obtained for all these resonances, and limits are placed on the spin assignments. From the data obtained, it is clear that the levels corresponding to the resonances at proton energies of 261, 351, and 527 kev cannot contribute significantly to the scattering or capture of low-energy neutrons by N^{14}. In addition, the level corresponding to the 634-kev resonance cannot be responsible for the whole of the $N^{14}+n$ cross section at low energies, but it may be responsible for part of this cross section. It is suggested that the level at 9.84 Mev is responsible for the remainder of this cross section. A good fit to the neutron elastic scattering cross section is obtained over the neutron energy range from 0 to 600 kev.

INTRODUCTION

THERE are four excited states of N^{15} known to occur between the $C^{14}+p$ threshold at 10.214 Mev and the $N^{14}+n$ threshold at 10.841 Mev.[1] These states are at energies of 10.457, 10.543, 10.706, and 10.806 Mev. All four levels, which decay only by proton emission or by gamma radiation, were first studied by Sperduto *et al.*[2] who observed proton groups in the $N^{14}(d,p)$ reaction. Bartholomew *et al.*[3] have observed all except the lowest of these four levels as gamma resonances in $C^{14}(p,\gamma)$, and have measured angular distributions of the ground-state gamma rays from the two highest levels. Ranken *et al.*[4] have found gamma radiation of 10.5 and 10.8 Mev following the reaction $N^{14}(d,p)$, but could not assign the radiation to particular levels.

The results reported here are measurements of the yield of gamma rays at all four resonances in the $C^{14}(p,\gamma)$ reaction, and a measurement of the elastic scattering of protons from C^{14} over an energy range including the three highest levels and the neutron threshold.

EXPERIMENTAL ARRANGEMENTS

The targets were prepared from acetylene enriched to 35% C^{14} supplied by The Radiochemical Centre, Amersham, England. This enriched acetylene was decomposed on red-hot tantalum target blanks that had previously been coated with natural carbon to provide a light-element backing for the elastic scattering experiments. The final target consisted of the tantalum with a layer of natural carbon approximately 300 μg cm^{-2} thick, on top of which was the layer of enriched carbon of thickness approximately 20 μg cm^{-2} (7 kev at $E_p=530$ kev).

The percentage of C^{14} in the targets was measured as $35\pm3\%$. A comparison was made between the maximum yields of protons elastically scattered from C^{12} both in the enriched material and in a carbon target of normal isotopic composition. The results were consistent for different proton energies, scattering angles, and for different targets.

The University of Melbourne 1-Mv electrostatic accelerator was used to bombard the targets for the elastic scattering experiments. The proton beam was magnetically analyzed, and the scattered protons detected in a double-focusing magnetic spectrometer stabilized by a fluxmeter. This spectrometer had an over-all momentum resolution of approximately 300, and a solid angle of acceptance such that $\Delta\theta\approx0.7°$ and $\Delta\phi\approx3°(\Delta\Omega=6.1\times10^{-4}$ sterad). Bombardments were made at a fixed beam energy and the profiles were obtained by varying the spectrometer field. First, the fluxmeter current at the foot and midpoint of the rise of the C^{12} profile were determined, using a target of normal isotopic composition. From this, the midpoint of the rise of the C^{14} profile for a clean target was calculated. The actual midpoint of the rise of the C^{14} profile was then determined. The difference between the calculated and experimental values of the fluxmeter current showed the amount of decomposed oil contamination on the C^{14} target surface. It also indicated the range of fluxmeter currents over which an acceptable measurement of the yield of elastically scattered protons from C^{14} could be made. After measurements were made over this range of fluxmeter currents, the beam energy was altered slightly, and the whole procedure was re-

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[1] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. (to be published).

[2] Sperduto, Buechner, Bockelman, and Browne, Phys. Rev. **96**, 1316 (1954).

[3] Bartholomew, Brown, Gove, Litherland, and Paul, Can. J. Phys. **33**, 441 (1955).

[4] Ranken, Bonner, McCrary, and Rabson, Phys. Rev. **109**, 917 (1958).

peated. As the target contamination increased, so the acceptable range of fluxmeter currents was decreased until a new target spot was used.

Most of the gamma-ray measurements were made at the Kellogg Radiation Laboratory, California Institute of Technology, using the 600-kv electrostatic accelerator as a source of protons, with electrostatic and magnetic analysis of the beam. The gamma rays were detected with a 4×4-inch sodium iodide crystal mounted on a Dumont 6364 photomultiplier. For the weakest gamma resonance, it was necessary for the crystal to be within 0.5 inch from the target, but for the other resonances, several different distances and angles were used. A 100-channel pulse-height analyzer was used to record the gamma spectra at each proton beam energy, and from these spectra, the yield curves were obtained.

RESULTS

A. Elastic Scattering

A preliminary survey of the yield of elastically scattered protons over the energy range from 340 to 690 kev disclosed no wide anomalies. The cross section agreed within 3% over the whole range of energy with the Rutherford cross section corrected for hard-sphere scattering. The only feature worthy of remark was a few low points on the yield curve at scattering angles of 70° and 90°, but not at 120°, the only other angle measured. These low points were localized at 529 kev, which did not correspond to any of the published resonances in $C^{14}(p,\gamma)$.

Further investigation confirmed the existence of an elastic scattering anomaly and a gamma resonance at 529 kev. At this energy, the yield of elastically scattered protons at laboratory angles of 70° and 90° shows a decrease, and there is a slight increase in yield at 120°. Figure 1 shows the yield of elastically scattered protons plotted as a function of the proton energy before scattering. The points on the top of the C^{14} profiles were plotted on a diagram at the energy appropriate to the depth in the target of the reactions causing the counts. Over a period of several days, sufficient of these points were accumulated to group them into 0.625-kev intervals in the region of the anomaly. The groups were then averaged and a probable error was assigned to the result. This probable error was obtained from the spread of the individual points in the cases where this was greater than to be expected of a Poisson distribution. Except at the anomaly, the spread of points was consistent with a Poisson distribution. At the anomaly, the spread was greater in the case of the measurements at 70° and 90°, because the anomaly showed up at these angles as a rounding-off of the top of the profiles. Figure 2 illustrates this by showing three C^{14} profiles superposed, one at the resonance energy with slight carbon contamination and the others at different energies with different amounts of contamination. The contamination displaces and rounds off the corners of the profiles, and this creates a danger of manufacturing an anomaly of this size by taking measurements on the sloping edge of a profile. It is believed that this error has been avoided by the measurement technique described in the previous section.

The gamma-ray yield also shown in Fig. 1 was obtained by lifting the elastic scattering target and allowing the beam to strike a second C^{14} target close to a 1×1-inch NaI crystal. The energy of the protons at resonance was measured by scattering them into the double-focusing magnetic spectrometer. In this way, all energies are referred to the spectrometer which was

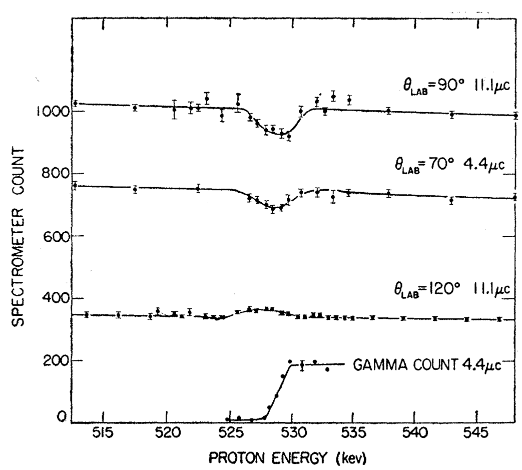

FIG. 1. $C^{14}+p$ elastic scattering anomaly. In the region of the anomaly, the original data have been grouped into 0.625-kev intervals with 5 to 10 points in each group. The probable errors shown are calculated from the spread of the points or from the Poisson distribution, whichever is the greater. Away from the anomaly, the data are grouped into intervals of 5 kev, and part of the smooth curve produced is shown. The gamma count was recorded when the proton beam was allowed to bombard a second C^{14} target near a small NaI crystal. The collected charge in microcoulomb is indicated in the figure.

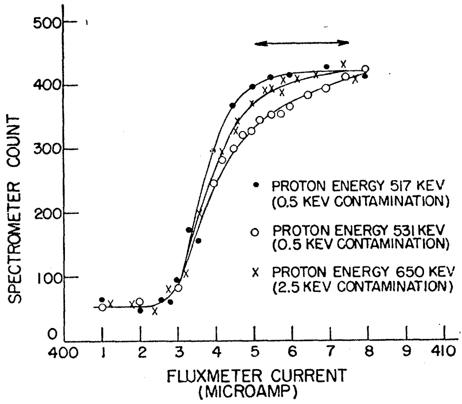

FIG. 2. C^{14} target profiles at a laboratory angle of 90°. The arrows show the range of fluxmeter currents for a clean target over which the count was recorded. The ordinate scales are normalized to give the same maximum count, and the abscissa scales are adjusted so that the feet of the three profiles are exactly superposed.

stabilized by a fluxmeter and was calibrated using the $F^{19}(p,\alpha\gamma)$ resonances[1] at 340, 483, and 669 kev.

A similar intensive scanning (0.3-kev intervals) of the energy region around a proton energy of 636 kev was carried out. At this energy another gamma resonance was found, but no elastic scattering anomaly was observed. The spread in counts, plotted as described for the 529-kev anomaly, was no greater than expected for a Poisson distribution and the mean count fell on a smooth curve, which extends over the whole energy range investigated. Part of this smooth curve is shown in Fig. 1.

At 529 kev, the elastic scattering measurements support an assignment $l_p=2$ for the orbital angular momentum of the incoming protons, rather than the value $l_p=1$ assigned by Bartholomew *et al.* The gamma-ray angular distributions[3] are consistent only with the spin assignment $\frac{3}{2}$. Figure 3 shows the expected elastic scattering anomaly shapes, at the scattering angles used, for p- and d-wave resonances with $J=\frac{3}{2}$. After allowance for the experimental resolution, a narrow p-wave resonance would produce an increase in the yield of elastically scattered protons at all scattering angles used, whereas a narrow d-wave resonance would produce a decrease in yield at scattering angles of 70° and 90°, and an increase in yield at 120°. The magnitude of the increase in yield at 120° is less than expected from the size of the anomaly at the other two angles. The measurements at 120° were taken at greater depths in the target, as this allowed the targets to last longer.

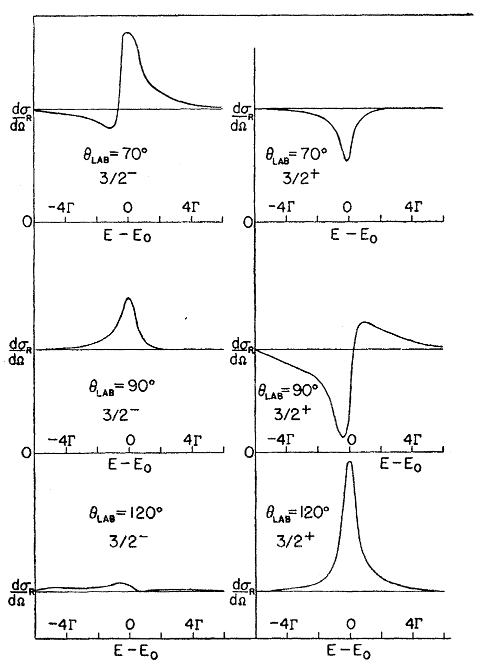

FIG. 3. The expected anomaly shapes for p- and d-wave protons forming states in N^{15} with spins $\frac{3}{2}^-$ and $\frac{3}{2}^+$, respectively. To give the observed anomalies, the d-wave curves must be averaged over an energy range greater than the width of the diagrams.

Because of this increased depth, the straggling of energy loss in the target is responsible for a larger effective spectrometer window. The larger window at 120° then reduces the apparent size of the anomaly. In addition there is a tendency at all angles to produce low yields by moving off the edge of the profile. The estimated proton width of 200 ev makes an allowance of about 30% for the latter effect.

The angular distribution of gamma rays measured by Bartholomew *et al.* eliminates all spin possibilities except $\frac{3}{2}$, but cannot readily distinguish between positive and negative parity. The observation of a d-wave anomaly gives $\frac{3}{2}^+$ as the spin and parity assignment. For d-wave protons, the width of 200 ev corresponds to a reduced width of 20% of $3\hbar^2/2Ma^2$. The normal definition of a reduced width, $\gamma^2=\Gamma(F_l^2+G_l^2)(2ka)^{-1}$, is used.

No elastic scattering anomaly was observed at the neutron threshold at 671.5-kev proton energy.[5] Wigner

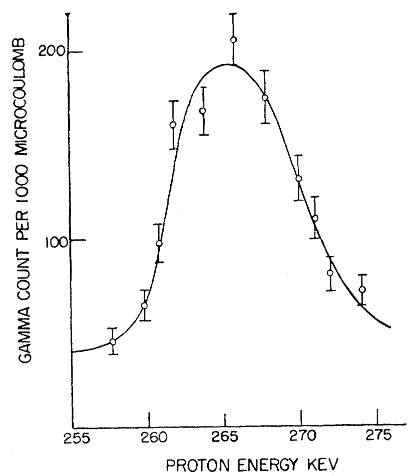

FIG. 4. Gamma pulses in the energy range 3.6 to 5.7 Mev observed at the 261-kev resonance in $C^{14}(p,\gamma)$.

predicts that a cusp[6] may occur in the elastic scattering cross section at a threshold for outgoing s-wave neutrons, but this will only be appreciable if, at the threshold, there is a relatively large amplitude compound nucleus wave function. This is not the case for C^{14} plus protons.

B. Gamma Measurements

The three gamma resonances found by Bartholomew *et al.* and attributed to $C^{14}(p,\gamma)$ have been re-investigated. In addition, a fourth resonance at a proton energy of 261 kev, corresponding to a level in N^{15} at an excitation of 10.457 Mev, has been found. This resonance gives radiation of about 5, 7, and 10 Mev, but the yield is so low that accurate measurement of the gamma energies is extremely difficult. No angular dis-

[5] R. Sanders, Phys. Rev. **104**, 1434 (1956).
[6] E. Wigner, Phys. Rev. **73**, 1002 (1948).

tribution measurements have been made, because of the low yield. The gamma resonance observed is attributed to $C^{14}(p,\gamma)$ because of the close agreement of the excitation energy with that measured by Sperduto *et al.* The yield curve is shown in Fig. 4. The steep rise and fall in the yield shows that the target nuclei are located in a layer in the first ten kev of the target, which is the region occupied by C^{14}. The proton energy at which the resonance is observed does not correspond to a known resonance of any impurity that might be present in the enriched carbon layer in a small proportion. In addition, the energies of the gamma rays observed are consistent with emission from N^{15}. The gamma-ray yields of the 10.457-Mev level for the observed gamma rays are all in the region of $10^{-13}\gamma/p$ and are given in Table I.

The lowest-energy gamma resonance previously known was found by Bartholomew *et al.* to have 5.4- and 7.1-Mev gammas resonant at a proton energy of 361 kev. Figure 5 shows the gamma spectrum due to the resonance obtained here at a proton energy of 351 kev, corresponding to an excitation of 10.543 Mev. Figure 5 is actually the difference of two spectra taken only a few hundred electron volts apart. This subtraction eliminates the 2.37-Mev gamma rays due to $C^{12}(p,\gamma)$ which tend to obscure the low-energy gamma spectrum. From time coincidence measurements, the decay scheme shown in Fig. 6 was constructed.

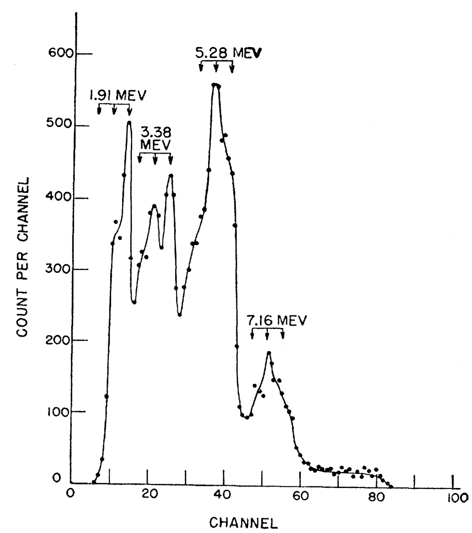

FIG. 5. The gamma spectrum due to the 351-kev resonance in $C^{14}(p,\gamma)$. This spectrum is the difference of two spectra taken with proton energies less than 500 ev apart.

The energies of the observed gamma rays are 7.15 ±0.20, 3.38$\pm$0.05, and 1.91$\pm$0.05 Mev. The 5.28-Mev gamma ray [actually a mixture of (5.27+5.28)-Mev cascades or (5.31+5.24)-Mev cascades or both] is used for calibration. The 2.37-Mev $C^{12}(p,\gamma)$ radiation and the 0.51-Mev annihilation radiation observed in the coincidence experiments are also used for calibration.

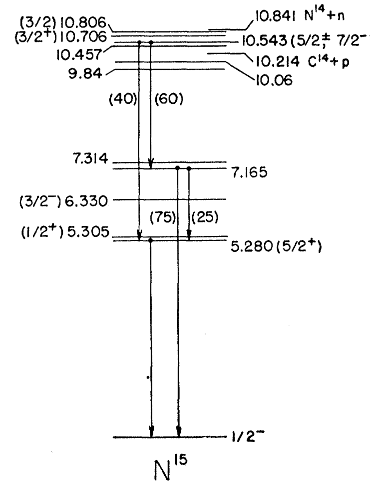

FIG. 6. Relevant energy levels of N^{15}. The cascades from the 10.543-Mev level are indicated, together with their branching ratios in parentheses. Some of the spin assignments shown are supported by experimental evidence but others are based on shell model predictions.

The coincidence spectra, rather than Fig. 5, are used to measure the low gamma-ray energies because for these spectra, there is less uncertainty in eliminating the effects of the high-energy gamma rays. The 7.15-Mev gamma ray in one 4$\times$4-inch NaI crystal is in coincidence with only the 3.38-Mev radiation in a second 4$\times$4-inch crystal. This limits the excition of the level near 7 Mev involved in the cascade to 7.16$\pm$0.05 Mev. The 5.28-Mev radiation is in coincidence with the 1.91, 3.38, and 5.28-Mev radiation, and this means that the level near 7.16 Mev has a further cascade through either the 5.28- or 5.31-Mev level. If the 5.28-Mev level is involved, then the level near 7.16 Mev has an excitation of 7.17$\pm$0.05 Mev, while if the 5.31-Mev level is involved, the excitation is 7.22$\pm$0.05 Mev. It is clear from these measurements that the level at 7.32 Mev cannot be involved in the cascades. There is a level already known at 7.165 Mev, and if the level involved in the cascade from the 10.543-Mev state is identified with this, the measurement of the 1.91$\pm$0.05-Mev transition indicates that the 7.165-Mev level decays through the 5.280-Mev level rather than through the 5.305-Mev level. Thompson[7] has observed a 1.88-Mev gamma ray following the reaction $N^{14}(d,p)$ which is probably the same transition. However, no direct transition to the ground state from the 7.165-Mev level is observed to follow the $N^{14}(d,p)$ reaction, and only a weak 7.16-Mev transition is observed to follow the $N^{14}(n,\gamma)$ reaction where the first member of the cascade is very strong. This contradictory evidence suggests that two levels may be involved, both close to 7.16 Mev. If this is so, then the argument that the 1.91-Mev gamma ray is a transition to the 5.28-Mev level and not to the 5.31-Mev level is invalid. However the 5.28-Mev level is still preferred in the present experiment, because the absence of a ground state transition from the 10.543-Mev level suggests it has a high spin, and would therefore cascade through levels of high spin.

[7] L. Thompson, Phys. Rev. **96**, 369 (1954).

TABLE I. Thick-target gamma-ray yields from four C^{14} (p,γ) resonances.[a]

Gamma energy Mev	Gamma yield $\times 10^{13}(\gamma/p)$ 261-kev resonance	351-kev resonance	527-kev resonance	634-kev resonance
1.91	b	30	b	b
3.38	b	125	b	b
5.28	0.5	200	1600	270
7.16	~0.05	95	b	b
10.5	~0.05	<1.5	1600	370

[a] The percentage of C^{14} in the target is 35%. The gamma-ray energies quoted are those observed at the 351-kev resonance, and do not necessarily imply cascades to the same levels from the other resonances.
[b] Radiation not observed.

The high-energy pulses observed from 8 to 10.5 Mev (channels 60 to 80 in Fig. 5) can all be explained as being due to the detection in the one crystal of both members of a cascade. Allowing an error of 25% in the calculation of the number of these double pulses, an upper limit of $1.5\times10^{-13}\gamma/p$ is obtained for the ground-state gamma-ray yield of the 10.543-Mev level. The gamma-ray yields for the cascade radiations are shown in Table I.

Because of the disagreement between the resonance energies determined by Bartholomew *et al.*[3] and the energies found during the elastic scattering experiments, the positions of the two highest resonances were determined using an electrostatic analyzer calibrated at the 340-kev $F^{19}(p,\alpha\gamma)$ resonance. The results (527±1 and 634±1 kev) agree excellently with those determined with the magnetic spectrometer (529±2 and 636±2 kev), and also agree within 1 and 5 kev, respectively, with the excitations given by Sperduto.[2] For both the 527- and 634-kev resonances, measurements were made on the strength of the cascade radiation through the levels near 5.3 Mev, as well as measurements of the strength of the ground-state radiation. No information was obtained on any 7-Mev radiation, as this was partly obscured by 8-Mev radiation from $C^{13}(p,\gamma)$ in the natural carbon backing for the target. The spectra obtained agree with those of Bartholomew *et al.*, and the ratio of the yields of the different resonances, as given in Fig. 3 of the paper by Bartholomew *et al.*,[3] is also consistent with the measurements reported here in Table I. A revision of the radiative widths measured by Bartholomew *et al.* has recently been made by Bartholomew and Gove.[8] The resultant widths for ground state radiation from the 527- and 634-kev resonances are $\omega\Gamma_p\Gamma_{\gamma0}/\Gamma=0.34$ and 0.087 ev, respectively. These are in excellent agreement with the comparable figures from Table II, namely 0.36 and 0.080 ev, respectively. The measurements reported here were made with the sodium iodide crystal at several different distances and angles for both the 527- and 634-kev resonances, and are consistent with one another, using the angular distributions measured by Bartholomew *et al.* The crystal efficiencies used in this experiment were computed at the California Institute of Technology and have been checked experimentally on several reactions of known cross section.

The yield of gamma rays between the known resonances has also been measured. No further resonances have been found, but there was a yield, steadily increasing with energy, probably due to the broad resonance at a proton energy of 1.50 Mev. At the 634-kev resonance, this nonresonant background corresponds to a cross section of 8 μb. Between 610- and 690-kev proton energy, there is no resonance with a ground-state gamma-ray yield greater than 1% of the γ_0 yield at the 634-kev resonance. The resonant yield of any cascade radiation of energy between 3.0 and 7 Mev is less than 5% of the γ_0 yield at the 634-kev resonance. The presence of $C^{13}(p,\gamma)$ radiation prohibited any smaller limit being placed on the strength of this cascade radiation.

DISCUSSION

The gamma rays of 10.5 and 10.8 Mev observed by Ranken can now be assigned to particular levels. A requirement for these levels is that $\Gamma_{\gamma0}/\Gamma$ shall not be small. In particular, Ranken's experiment[4] shows that for the 10.5-Mev radiation, $\Gamma_{\gamma0}/\Gamma$ is of the order of 0.1, and for the 10.8-Mev radiation, $\Gamma_{\gamma0}/\Gamma$ is the order of 0.2, assuming that only two levels are involved. We assume further that the bound and unbound levels are populated approximately equally, and that the bound states decay mainly by ground-state radiation. The measurements just presented show that for the 10.543-Mev level, $\Gamma_{\gamma0}/\Gamma<0.007$, and for the 10.706-Mev level, $\Gamma_{\gamma0}/\Gamma<0.002$. This means that these two levels make a negligible contribution to the radiation observed by Ranken. This radiation must then be assigned to the 10.457- and 10.806-Mev levels. This is the basis for the estimate of the proton widths for these levels given in Table II.

For the 10.457-Mev level, the estimate of the proton width puts an upper limit of $l_p=4$ on the angular momentum of the incident proton. This upper limit should be good, because a change of one unit of orbital angular momentum changes the proton reduced width by a factor much larger than the uncertainty in the proton width. The lower limit to the proton width of the 10.543-Mev level, obtained directly from the gamma-ray yield, is used in the same way to limit the spin and parity assignment of this level. The spin and parity are further restricted because of the lack of ground-state radiation from the 10.543-Mev level. The upper limit to the strength of this radiation in Weisskopf[9] units is $4\times10^{-7}|M|^2$ and $1\times10^{-5}|M|^2$ for electric and magnetic dipole radiation, respectively. This is considerably smaller than the weakest dipole radiation so far identified, except for the $E1$ ground-state radiation from the

[8] H. Gove and G. Bartholomew (private communication).

[9] V. Weisskopf, Phys. Rev. 83, 1073 (1951).

TABLE II. Partial widths for four levels in N^{15}.[a]

Proton energy kev	N^{15*} Mev	$\omega\Gamma_p$ ev	$\omega\Gamma_{\gamma 0}$ ev	$\omega\Gamma_\gamma$(5 Mev) ev	$\omega\Gamma_\gamma$(3.4 Mev) ev	l_p, J^π
261	10.457	$\sim$0.0005[b]	$\sim$0.0001	0.0004	$\sim$0.0001	$l_p \leqslant 4$,
351	10.543	$\geqslant$0.04	$\leqslant$0.0003	0.018	0.025	$l_p \leqslant 3$, $(\frac{5}{2}^\pm, \frac{7}{2}^-)$
527	10.706	$\sim$200[c]	0.36	0.18	?	$l_p = 2$, $\frac{3}{2}^+$ [c,d]
634	10.806	$\sim$0.4[b]	0.11	0.04	?	$\frac{3}{2}$[d]

[a] The gamma-ray energies shown apply only to the 351-kev resonance and are approximate for the other resonances.
[b] From gamma rays following $N^{14}(d,p)$.
[c] From $C^{14}(p,p)$.
[d] From angular distributions in $C^{14}(p,\gamma)$.

7.56-Mev level in O^{15}, for which only an upper limit[10] of $1\times10^{-5}|M|^2$ is given. If we assume that the 10.543-Mev radiation is not electric or magnetic dipole, we are left with the spin assignments listed in Table II.

The 10.706- and 10.806-Mev levels are both given the assignment $J=\frac{3}{2}^-$ by Bartholomew *et al.*[3] For the assignment $J=\frac{3}{2}^+$, the theoretical angular distribution of ground-state gamma radiation (assuming pure $E1$ radiation) differs from the experimental distributions by slightly more than the quoted experimental error. The experimental distributions may however be fitted exactly if the assignment $\frac{3}{2}^-$ is made, and a suitable mixture of $M1$ and $E2$ radiation is assumed. The observed radiative widths are consistent with either parity, but the elastic scattering data for the 10.706-Mev level support a positive-parity assignment. This suggests that the angular distributions may have a larger error than was realized, so that considerable doubt is cast on the negative-parity assignment of the 10.806-Mev level. In a recent publication,[11] Bartholomew and Campion withdraw the negative-parity assignment of the 10.806-Mev level.

If we assume that the 10.806-Mev level is $\frac{3}{2}^-$ formed by p-wave protons, we obtain the extremely small proton reduced width of 1×10^{-3}% of $3\hbar^2/2Ma^2$. Protons with $l_p=2$ forming a $\frac{3}{2}^+$ level would give a reduced width of a size more usually encountered, namely 0.02% of the same limit. This is weak evidence in favor of a positive-parity assignment to the 10.806-Mev level.

THE SHELL MODEL

The shell-model calculations of Halbert and French[12] for N^{15} assume positive-parity configurations only of the forms $(1s)^4(1p)^{10}(2s)$, $(1s)^4(1p)^{10}(1d)$, and $(1s)^3(1p)^{12}$. The 10.706-Mev level, identified as $\frac{3}{2}^+$ by the elastic scattering results, has a large d-wave proton reduced width. This suggests a substantial amplitude of the configuration with a C^{14} core in its ground state and a $d_{3/2}$ proton. No corresponding level appears near this energy in the shell model calculations. There is a gap in the calculated $\frac{3}{2}^+$ level energies from 9 to 12 Mev. However, the shell model calculations are less trustworthy in this energy region than for lower energies.

NEUTRON CROSS SECTION OF N^{14}

The problem of the large scattering and radiative capture cross sections[13,14] for low-energy neutrons on N^{14} has received much attention[3,4] recently. The $N^{14}(n,p)$ cross section can be explained satisfactorily by means of known levels above the neutron threshold of N^{15}. The shape of the total cross section curve of N^{14} for neutrons of energies from 0.2 to 1.0 Mev[15,16] requires a $\frac{1}{2}^+$ or $\frac{3}{2}^+$ level in the range of excitation from 9.8 to 10.7 Mev, as already noticed by Bartholomew *et al.* The shape of the total cross section curve in the range from 0 to 2.5-kev neutron energy, measured by Melkonian,[13] implies that a level exists between 2 and 5 kev below the neutron threshold. However, more recent measurements by Bilpuch *et al.*[17] show that the cross section does not decrease as rapidly as Melkonian's measurements suggest. The cross section measured by Bilpuch in the energy range from 3 kev to 200 kev joins smoothly onto Melkonian's measurements below 500 ev, and also joins smoothly onto the results of Hinchey *et al.*[15] and Johnson *et al.*[16] above 200-kev neutron energy. The revised shape of the total cross section curve implies the existence of a level approximately 40 kev below the neutron threshold, rather than the 3 kev required by Melkonian's results.

The cross section up to a neutron energy of 1 Mev cannot be fitted by means of a single level, but apparently needs at least two levels below the neutron threshold. A comparison of the coherent[18] and total[13] cross sections of N^{14} for thermal neutrons shows that the scattering lengths for both channel spins $\frac{1}{2}^+$ and $\frac{3}{2}$ are positive and are of the same order of magnitude. Since the ground-state radiation from either a $\frac{1}{2}^+$ or $\frac{3}{2}^+$ level is electric dipole, it is probable that both the needed levels contribute to the $N^{14}(n,\gamma)$ cross section. Neither level may contribute much more to the $N^{14}(n,p)$

[10] R. Pixley, Ph.D. thesis, California Institute of Technology, 1957 (unpublished).
[11] G. Bartholomew and P. Campion, Can. J. Phys. **35**, 1347 (1957).
[12] E. Halbert and J. French, Phys. Rev. **105**, 1563 (1957).
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[15] Hinchey, Stelson, and Preston, Phys. Rev. **86**, 483 (1952).
[16] Johnson, Petree, and Adair, Phys. Rev. **84**, 775 (1951).
[17] Bilpuch, Weston, Bowman, and Newson, Bull. Am. Phys. Soc. Ser. II, **4**, 42 (1959), and private communication.
[18] S. Peterson and H. Levy, Phys. Rev. **87**, 462 (1952).

cross section than the levels above the neutron threshold, which already explain this cross section satisfactorily.[3] The possibility of destructive interference between levels of the same spin and parity allows a greater contribution to the $N^{14}(n,p)$ cross section from the postulated bound levels than would otherwise be the case.

An attempt has been described to find another resonance in $C^{14}(p,\gamma)$ besides the 634-kev resonance in the region from 60 kev below the neutron threshold to 20 kev above the threshold. The observed upper limit to the resonant yield of gamma rays puts an upper limit of 0.001 ev on the product $\omega\Gamma_p\Gamma_\gamma/\Gamma$ for ground-state radiation from such a level. For cascade radiation, the product has an upper limit of 0.005 ev. Since several $E1$ or $M1$ transitions are possible to levels between 5 and 7 Mev from a $\frac{1}{2}^+$ or $\frac{3}{2}^+$ level near 10.8-Mev excitation, it would be rather surprising not to observe such radiation if a level with $J^\pi=\frac{1}{2}$, $\frac{3}{2}^+$ existed in this energy region. If we assume that the level escaped detection because of a small proton width, then the proton reduced width would have to be less than 5×10^{-7} of the Wigner limit for d-wave protons forming a $\frac{3}{2}^+$ level, or less than 5×10^{-9} of the Wigner limit for s-wave protons forming a $\frac{1}{2}^+$ level. These would be abnormally small proton reduced widths. On the other hand, if we assume that the level escaped detection because of small radiative widths, the problem arises of explaining a ground-state radiative width less than 2×10^{-6} of the Weisskopf estimate, and simultaneously explaining cascade radiative widths less than 10^{-4} and 2×10^{-3} of the Weisskopf estimates for electric dipole and magnetic dipole radiation, respectively.

In order to give the observed (n,n), (n,p), and (n,γ) thermal neutron cross sections for N^{14}, a level 5 kev below the threshold would require a radiative width of the order of 0.008 ev for ground-state radiation and 0.06 ev for cascade radiations. If the level were further below the threshold, the required widths would be larger, in proportion to the binding energy of the level (for neutron emission). A level with these parameters would have been detected unless $\omega\Gamma_p\Gamma_{\gamma0}/\Gamma$ were of the order of 0.001 ev or less, and the previous paragraph shows that this is unlikely for a level with $J^\pi=\frac{1}{2}^+$ or $\frac{3}{2}^+$.

The only known level in the energy region close below the neutron threshold is the 10.806-Mev level, observed both in $N^{14}(d,p)$ and in $C^{14}(p,\gamma)$. It must now be investigated to see if its characteristics are suitable to explain the $N^{14}+n$ cross sections. The 10.806-Mev level is 37 kev below the neutron threshold, and this is in a satisfactory position to explain the results of Bilpuch *et al.* It has spin $\frac{3}{2}$ but the parity is unknown. There is weak evidence of positive parity. The ground-state radiative width is rather small for electric dipole radiation, but is not inconsistent with a $\frac{3}{2}^+$ assignment. The ground-state radiative width is of the same order of magnitude as the width required to explain the $N^{14}(n,\gamma_0)$ cross section. The radiation spectrum of the 10.806-Mev level is unlike that of $N^{14}(n,\gamma)$, but this may be due to the $N^{14}(n,\gamma)$ spectrum being the contribution of two levels. The second level would then have to contribute most of the cascade radiation. The proton width of the 10.806-Mev level is well within the limit imposed by the size of the $N^{14}(n,p)$ cross section. Before a detailed fitting of the $N^{14}(n,n)$ cross section is attempted, the $\frac{1}{2}^+$ level also required must be investigated.

We turn to the other known levels, bound for neutrons, to see if their characteristics are compatible with those required of the proposed level in the range of excitation from 9.8 to 10.7 Mev. The proton width of the 10.706-Mev level is a factor of 10 too large, and the radiative widths of the 10.457-Mev level are too small by a factor of 10^4. The $\frac{1}{2}^+$ or $\frac{3}{2}^+$ spin and parity assignment of the 10.543-Mev level have already been shown to be unlikely.

Further evidence against the suitability of these three levels is available from the $N^{14}(d,p)$ angular distributions of Sharp and Sperduto.[19] None of these levels shows a stripping pattern.[20] The 10.457-, 10.543-, and 10.706-Mev levels are sufficiently far below the neutron threshold to expect a stripping pattern if any of them were the required level. As before, the neutron reduced width needed is of the order of the binding energy (for neutrons) of the level influencing the $N^{14}+n$ cross section.

The level at 10.06 Mev shows a p-wave stripping pattern, and so is of the wrong parity, while all other known levels except that at 9.84 Mev are too far away from the neutron threshold. In addition, the levels below 9.84 Mev are populated by $N^{14}(n,\gamma)$.[11,14] The matrix element for a gamma transition from the level causing capture to itself at another energy is likely to be small.[21] The levels populated by $N^{14}(n,\gamma)$ are therefore unlikely to be causing the capture of neutrons, as the transitions observed experimentally appear to have normal matrix elements, after allowance is made for the differences in energy of the various gamma rays.

The level at 9.84 Mev is the only known level not eliminated so far. It is observed as a strong proton group in $N^{14}(d,p)$ but no strong gamma transition to the ground state is observed to follow this reaction.[4] It is therefore a level that cascades freely, agreeing with the requirement of the $N^{14}(n,\gamma)$ spectrum, since the 10.806-Mev level can explain most of the ground state transitions but only a fraction of the cascades. Unfortunately, nothing more can be said about this level at present, as it is obscured[20] at many angles in the

[19] R. Sharp and A. Sperduto (to be published).

[20] A. Sperduto (private communication).

[21] In Wigner's supermultiplet "approximation one," which neglects spin-dependent forces, the matrix element for this type of magnetic dipole transition is zero. A similar matrix element occurs in β decay, where the supermultiplet "approximation one" accounts for superallowed β transitions and would make the nonsuperallowed transitions zero. This encourages the opinion that in actual nuclei, this magnetic dipole gamma transition will behave like the nonsuperallowed β transition and will be small.

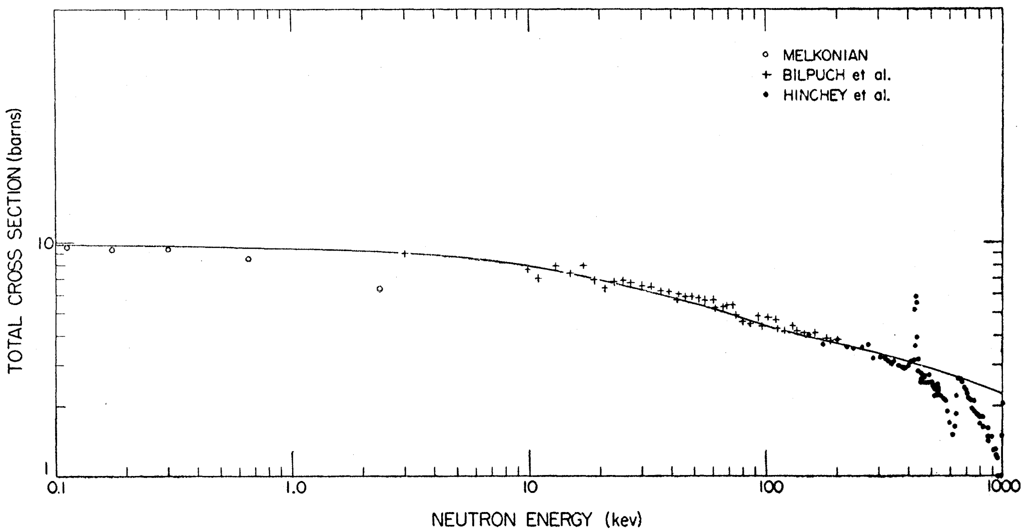

FIG. 7. The elastic scattering cross section for neutrons on N^{14}. The curve drawn is the expected cross section for *s*-wave neutrons forming a $\frac{3}{2}^+$ level bound by 36 kev ($\gamma_n^2=39$ kev), and a $\frac{1}{2}^+$ level bound by 1 Mev ($\gamma_n^2=290$ kev). A hard-sphere radius $a=4.80\times10^{-13}$ cm is assumed for each channel spin. Above 600 kev neutron energy, this leads to an *s*-wave scattering cross section larger than the experimental value. Disagreement is not unexpected at these energies because higher order partial waves are becoming important, and all levels above the neutron threshold of N^{15} have been neglected. The experimental points are total cross sections, which, for the present purpose, are identical with the elastic scattering cross sections.

$N^{14}(d,p)$ angular distributions by a proton group from $C^{12}(d,p)$. However, it is the level most likely to be causing the rise in the $N^{14}(n,n)$ cross section below 1-Mev neutron energy. For this reason it would be very desirable to observe the angular distribution of the proton group leading to the 9.84-Mev level.

An attempt was made to fit the $N^{14}(n,n)$ cross section at low energies by assuming that the levels responsible were the 10.806-Mev level ($\frac{3}{2}^+$) and the 9.84-Mev level ($\frac{1}{2}^+$). The neutron reduced widths chosen were $\gamma_n^2=39$ kev for the 10.806-Mev level and $\gamma_n^2=290$ kev for the 9.84-Mev level. The radius for potential scattering was taken as $a=4.80\times10^{-13}$ cm for both channel spins. These parameters give an elastic scattering cross section at thermal energies of 10 barn, and a coherent scattering cross section smaller by 0.5 barn, as observed experimentally. The elastic scattering cross section was calculated as a function of energy from the expression

$$\sigma=4\pi\lambda\!\!\!^{-2}(\tfrac{1}{3}\sin^2\delta_{\frac{1}{2}}+\tfrac{2}{3}\sin^2\delta_{\frac{3}{2}}),$$

where $\delta_{\frac{1}{2}}$ and $\delta_{\frac{3}{2}}$ are the phase shifts for channel spins $\frac{1}{2}$ and $\frac{3}{2}$, respectively. The phase shifts for each channel spin may be written

$$\delta=ka+\arctan[ka\gamma_n^2/(E-E_0)].$$

Because of the uncertainty in the difference between the total and coherent cross sections, there is some latitude in the choice of γ_n^2 for the two levels. However, the choice given above leads to a predicted elastic scattering cross section that agrees well with the experimental results over an energy range from 0 to 600 kev neutron energy and then begins to deviate from experiment. Where Melkonian and Bilpuch *et al.* disagree, the predictions are in accord with the latter, and up to 600 kev, the predictions lie within the spread of the experimental results. The theoretical curve and experimental results are shown in Fig. 7.

With the same parameters used to calculate the elastic scattering cross section, the contribution of the 10.806-Mev level to the $N^{14}(n,\gamma)$ thermal neutron cross section has been calculated from the formula

$$\sigma(n,\gamma)=\pi\lambda\!\!\!^{-2}\omega\Gamma_n\Gamma_\gamma/[(E-E_0)^2+\tfrac{1}{4}\Gamma^2]$$
$$=2\pi\lambda\!\!\!^{-}a\gamma_n^2\Gamma_\gamma/(E-E_0)^2.$$

The contribution to the ground-state gamma transition is 20 millibarn, which is to be compared with the experimental value of 9 millibarn. The difference is not thought to be significant as the radiative width of the 10.806-Mev level is uncertain by a factor of two, partly because of the uncertainty in the experimental value of the yield of gamma rays at the 634-kev resonance, and partly because of the uncertainty in the estimate of the Γ_p/Γ. In addition, there is the possibility of destructive interference (from the $\frac{3}{2}^+$ levels above the neutron threshold) reducing considerably the effect of the 10.806-Mev level. There is also latitude in the choice of γ_n^2 for the 10.806- and 9.84-Mev levels, and in the choice of the hard sphere radius a for each channel spin. This increases the uncertainty of the predicted $N^{14}(n,\gamma)$ cross section.

The estimated contribution of the 10.806-Mev level to the cascade radiation is 7 millibarn. The $\frac{3}{2}^+$ and $\frac{1}{2}^+$ levels above the neutron threshold contribute an unknown amount, but this can be appreciable if we allow for interference. Therefore, the cross section to be attributed to the 9.84-Mev level is not well defined, but it must be of the order of tens of millibarn for the cascade radiation, and of the order of a few millibarn for ground-state radiation. When these estimates are combined with the adjustable γ_n^2 for the 9.84-Mev level, the result is that radiative widths between 1 and 10 ev are expected for the individual transitions from the 9.84-Mev level. These estimates are of the expected order of magnitude.

A comment must be made on the observed lack of a stripping pattern[20] in the $N^{14}(d,p)$ reaction leading to the 10.806-Mev level. The neutron reduced width required to explain the $N^{14}(n,n)$ cross section is of the order of 40 kev. This is sufficiently small that no stripping would be observed for this level.

CONCLUSION

The exact binding energy for neutrons of the 10.806-level is of great importance in estimating the effect on the shape of the $N^{14}(n,n)$ cross section. This binding energy is believed to be 37 kev, as a result of two independent determinations of the gamma resonance energy and a comparison with the published neutron threshold measurement.

It is now possible to give a satisfactory account of the low-energy neutron cross section of N^{14}, by ascribing to the 10.806-Mev and 9.84-Mev levels properties in addition to those observed experimentally. None of these additional properties are in conflict with experiment or our expectations, but further work is necessary to test the predicted characteristics. The 10.806- and the 9.84-Mev levels are the only known levels not definitely eliminated from consideration, and it has been shown that there is only a small probability that an undetected level within 60 kev of the neutron threshold is partly responsible for the $N^{14}+n$ cross sections.

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