conversion of the 496- and 372-kev lines is negligible[4,8]; and the conversion coefficient of the 214-kev line is about 0.24.[8] Similarly, the intensity of the 82-kev gamma-ray of Ba^{133}, corrected for internal conversion, is a good measure of the Ba^{133} activity[20,21]; the internal conversion coefficient has been reported to be 3.5.[20] Corrected to the end of the pile irradiation, the activities of Ba^{131} and Ba^{133} are in the ratio 130:1. Assuming a uniform irradiation of 28 days, a 12.0-day half-life for Ba^{131}, and a 7.5-year half-life for Ba^{133},[22] the ratio of the pile activation cross sections is $\sigma(Ba^{130})/\sigma(Ba^{132})=1.2\pm0.3$.

If one recalculates for a 7.5-year half-life of Ba^{133}, one finds that the ratio obtained by Katcoff[1] is ~2.2, while the ratio of the cross sections given in AECU-2040[14] is 0.002. Katcoff's results can be considered in fair agreement with the work reported here, but the Ba^{130} activation cross section appearing in AECU-2040 is certainly in error.

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[21] M. Langevin, Comp. rend. **240**, 289 (1955).
[22] S. Katcoff (private communication, 1955).

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Angular Distributions of Deuterons from (*p*,*d*) Reactions in Light Nuclei. I. Nitrogen*

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Deuterons have been observed from the reaction $N^{14}(p,d)N^{13}$, produced by 18.7-Mev protons. The deuterons were distinguished from proton background by a thin NaI crystal in a scintillation counter with the crystal thickness equal to the deuteron range. The angular distribution of deuterons to the N^{13} ground state was fitted by a curve calculated from Butler's theory for an angular momentum transfer $l_n=1$. This shows that the ground states of N^{13} and N^{14} have opposite parity and is consistent with the assignment of 1+ to the N^{14} ground state. The reduced width for the ground state transition is in qualitative agreement with that calculated using an independent-particle shell model with some indication that the N^{14} ground state is largely a *D* state. The transition $N^{14}(p,d)N^{13*}$ to the first excited state of N^{13} was not observed. The experimental upper limits on its cross section give upper limits of a few percent probability for admixtures of the configurations p^8s^2 and p^8sd in the N^{14} ground state. Application to the lifetime of C^{14} is discussed.

A. INTRODUCTION

A GREAT deal of recent work has been concerned with the angular distribution of the protons and neutrons from (*d*,*p*) and (*d*,*n*) stripping reactions.[1] Butler has shown[2] that the shape of the angular distribution in stripping determines the angular momentum carried into the target nucleus by the captured particle, e.g., by the captured neutron in a (*d*,*p*) reaction. By application of conservation laws for parity and angular momentum, this angular momentum transfer yields the change in parity and angular momentum between the initial state of the target nucleus and the final state of the residual nucleus. Thus if the parity and spin of the target nucleus are known, the parity and spin of the final state are determined (the latter with some ambiguity because of the vector addition rules for angular momentum). Because of this result, stripping reactions have given much information useful in nuclear spectroscopy.

With the present activity in the study of stripping reactions, it seems surprising at first that the inverse reactions (*p*,*d*) and (*n*,*d*) have been neglected, since, because of the reciprocity theorem,[3] Butler's results apply also to them. There is, however, an important practical reason for this neglect of "pick-up" reactions. The energy release Q in a ground-state stripping reaction is positive in almost every case, and is usually 5–10 Mev in magnitude. This means that low-energy deuterons will produce high-energy protons in a (*d*,*p*) reaction, while any background of scattered neutrons, etc., is at low energy and so is easily removed. For (*p*,*d*) reactions the situation is just the opposite; high-energy protons produce low-energy deuterons, which must be examined in the midst of a large background of protons of the same or higher energy. The interesting features of the angular distributions usually occur at small angles, where the background is particularly bad. Because of this difficulty, angular distributions from (*p*,*d*) reactions have been measured in a few favorable cases only.[4,5]

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† Now at the Department of Physics, University of Manitoba, Winnipeg, Canada.
[1] For a review of experimental and theoretical information, see R. Huby in *Progress in Nuclear Physics* (Pergamon Press, London, 1953), Vol. 3, pp. 177–218.
[2] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[3] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), pp. 336, 528.
[4] $Be^9(p,d)Be^8$, $Q=559$ kev: J. A. Harvey, Phys. Rev. **82**, 298 (1951), and Massachusetts Institute of Technology Progress Report NP-3434, October 1, 1950 (unpublished); Cohen, Newman, Handley, and Timnick, Phys. Rev. **90**, 323 (1953).
[5] $He^4(p,d)He^3$, $Q=-18.3$ Mev: J. Benveniste and B. Cork, Phys. Rev. **89**, 422 (1953). Here no measurements were reported for angles smaller than 22.5°.

The absolute cross section for a stripping or pick-up reaction is also of interest. Perhaps the most satisfactory way of expressing such a measurement is in terms of "reduced width."[6] It has been shown[1,7,8] that the cross section for a (p,d) reaction is proportional to the "partial width" for the disintegration of the target nucleus into a neutron + the final state of the residual nucleus. The partial width may be factored into a quantity called the "reduced width" γ^2, which expresses the intrinsic nuclear probability of the disintegration, and a penetration factor which takes into account effects outside the nucleus (Coulomb and angular momentum barriers, etc.). It is convenient to use a dimensionless reduced width θ^2 as a fraction of the "sum rule limit"[6] $\theta^2=2Mr_0\gamma^2/3\hbar^2$.

Unfortunately, reduced widths calculated from stripping are subject to corrections which are not completely understood. Thomas[9] found that, in the few cases where reduced widths determined from stripping could be compared with those determined for the same disintegration from resonance reactions, the reduced widths from stripping were smaller by factors up to $\sim$5 than those from resonance reactions. Horowitz and Messiah[10] and Tobocman and Kalos[11] have made numerical calculations in special cases to allow for various factors neglected in the Butler theory (Coulomb effects and the interaction between the deuteron and the target nucleus and between the proton and the residual nucleus in stripping). Their corrections are of the right order of magnitude to explain the discrepancies, but the exact correction to be applied is uncertain.

Prediction of the reduced width on theoretical grounds depends on the choice of a specific nuclear model. Recently the independent-particle shell model[12,13] has had considerable success in explaining the properties of light nuclei. In the nuclear p-shell the interaction of a particle with angular momentum 0 or 2 may be represented on a "single-particle model," i.e., the interaction is treated as a simple potential well. On the other hand, for reactions of particles with angular momentum one, the reacting particle is the same as those already in the p-shell, and the mode of coupling becomes the most important factor. Lane[12] has given formulas for the reduced width in the extreme cases of L–S and j–j coupling, and has found that in most cases experimental reduced widths lie between those calculated on the opposite extremes. This, along with evidence from the level positions,[14] seems to indicate that an intermediate coupling between the two extremes gives a fairly adequate description of the properties of nuclei in the p-shell.

This paper and the one following[15] describe a method of observing (p,d) reactions and its application to the study of light nuclei. The present paper is concerned with the method and with the (p,d) reaction in nitrogen; the following paper considers other light elements.

B. EXPERIMENTAL METHOD AND APPARATUS

In order to measure the angular distribution of deuterons from (p,d) reactions it is clearly necessary to distinguish them from proton background. Here this was done by use of a thin NaI crystal ($\sim$0.01 in.) in a scintillation counter. When a particle passes into such a crystal, the pulse-height output from the scintillation counter is proportional to the energy loss of the particle in the crystal, and so is proportional to the incident particle energy as long as it is entirely dissipated in the crystal. Thus pulse height increases proportionally with incident particle energy until the particle has a range equal to the crystal thickness. For energies larger than this critical value, the particle will pass through the crystal and lose only part of its energy; the energy loss in the crystal will decrease since the energy loss per unit distance decreases with increasing energy.

In particular, the maximum pulse in a crystal of thickness T from a deuteron passing normally through it, will come from a deuteron of the critical energy $E_d(T)$. Deuterons of energy $E_d(T)$ have a range T in NaI and hence *just* stop in the crystal. Deuterons of both lower and higher energies will give smaller pulses. The same relations hold for other types of particles, protons for example, except that their maximum energy loss is different from that for deuterons. Since the maximum energy loss in a given crystal is characteristic of the type of particle a measurement of its value for a group of particles determines the type of particle as well as its energy. Particles heavier than deuterons will in general have larger maximum energy losses, but a study of the range-energy curves[16] shows that for protons, the most important background, the maximum energy loss is $\sim\frac{3}{4}$ the maximum deuteron energy loss for a given range, i.e., $E_p(T)\sim\frac{3}{4}E_d(T)$. Therefore a deuteron of the critical energy $E_d(T)$ will give a larger pulse out of the crystal than will any other deuteron or *any* proton.

In order to observe a deuteron group of energy E a crystal of thickness T should be used such that $E_d(T)=E$. The deuterons will then give output pulses corresponding to their full energy, while all proton background will be at lower pulse heights. It was found

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[7] S. Yoshida, Progr. Theoret. Phys. (Japan) **10**, 1 (1953); **10**, 370 (1953).
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[9] R. G. Thomas, Phys. Rev. **91**, 453 (1953), and private communication.
[10] J. Horowitz and A. M. L. Messiah, J. phys. radium **14**, 695 (1953).
[11] W. Tobocman and M. H. Kalos, Phys. Rev. **97**, 132 (1955).
[12] A. M. Lane, Proc. Phys. Soc. (London) **A66**, 977 (1953); **68**, 189 (1955); **68**, 197 (1955); Atomic Energy Research Establishment (Harwell) Report T/R 1289, 1954 (unpublished).
[13] A. M. Lane and L. A. Radicati, Proc. Phys. Soc. (London) **A67**, 167 (1954).
[14] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).
[15] J. B. Reynolds and K. G. Standing, following paper [Phys. Rev. **101**, 158 (1955)], hereafter referred to as II.
[16] Aron, Hoffman, and Williams, U. S. Atomic Energy Commission Report AECU-663 (unpublished).

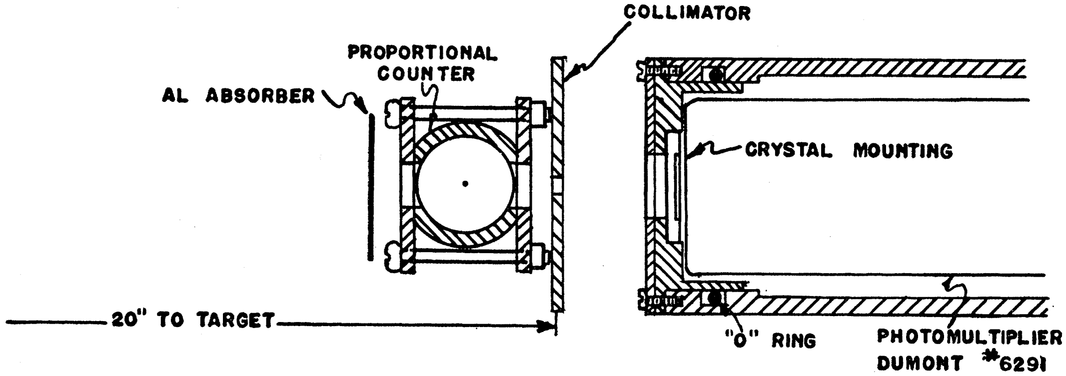

FIG. 1. Counter geometry. Particles from the target at the center of the scattering chamber passed through the variable Al absorber, then through the proportional counter, and finally through a collimator into the scintillation counter. The path of particles passing through the proportional counter was $\approx\frac{3}{4}$ in. and the counter was filled with argon at a pressure of 32 cm Hg. The scintillation counter was kept at atmospheric pressure for convenient operation in the vacuum system. The proportional counter, the scintillation counter, and the crystal mounting were sealed by ≈ 2 mg/cm^2 mica windows.

possible to cleave crystals of the required thickness ($\sim$0.01 in.) and $\sim\frac{1}{2}$ in. square from a block of NaI by use of a sharp razor blade. As it was inconvenient to change crystals for every change in deuteron energy, (i.e., at every change of angle of observation for a given group), a variable aluminum absorber was placed in front of the counter system. In practice a crystal somewhat thinner than the deuteron range was used, then the absorber thickness was increased until the deuterons had the critical energy $E_d(T)$ on leaving the absorber and entering the crystal. Pulses from the scintillation counter were amplified and fed into a 20-channel pulse-height analyzer.[17] Typical pulse-height distributions are shown in Fig. 2. Here the deuterons appear as a peak at about channel 53, and it is apparent that there is little significant background present. The dashed lines show background as estimated from the general shape of the curves. To obtain more information, runs were taken with extra Al absorber in front of the counters, so as to depress the deuteron peak to a smaller pulse height. The background which then appears should be a good approximation to the background present initially, since it is expected to vary slowly with energy.

At very small angles the background became more serious, and was found to consist partly of protons, presumably a small proportion of high-energy protons which had been scattered through large angles in the crystal. To remove these, a thin proportional counter was inserted in front of the scintillation counter. Because of the "Landau effect" the pulse-height distribution from such a counter is broad, with a large high-energy tail. The low-energy cutoff is sharp, however, so that all deuterons of the group being examined will give pulses above a certain height. Because of their lower rate of energy loss, most of the high-energy protons will give smaller pulses. The output of the proportional counter was applied as a coincidence gate to the pulse-height analyzer so that a scintillation counter pulse was recorded only when the proportional counter gave a pulse large enough to be caused by a deuteron of the group being observed. This system gave some reduction of background as a rule, so was used as an addition to the scintillation counter for all measurements except those on Li and the B^9 ground state (see II). Measurements with and without the proportional counter gave the same results except for some reduction in background with its use. The geometry of the counting system is shown in Fig. 1.

This work was done in the 60-in. diameter Princeton scattering chamber.[18] A beam of protons of energy ≈ 18 Mev from the cyclotron was collimated at the entrance to the scattering chamber and gave a beam $\approx\frac{3}{8}$-in. diameter at the target. After hitting the target and passing through the chamber, the undeflected beam was collected in a graphite cup connected to a current integrator.[19] A scintillation counter was used as a monitor at 30° to the incident beam. Since the monitor counter took account of any variations in target position, etc., it was used to normalize the angular distributions. The current integrator was used to determine absolute cross sections.

In all cases described in this paper and the following one, the measured energy of the particles agreed with that expected for deuterons from the known level positions.[20] Definite identification of the particles as deuterons was provided by their maximum energy loss in the known crystal thickness. The critical energy at which the pulse height reached its maximum value agreed with that expected from deuterons, and disagreed with that expected from protons or tritons by $\sim$25%.

[17] Bell and Kelley model—described by A. B. Van Rennes, Nucleonics **10**, No. 10, 50 (1952).

[18] J. L. Yntema and M. G. White, Phys. Rev. **95**, 1226 (1954).

[19] W. Higinbotham and S. Rankowitz, Rev. Sci. Instr. **22**, 688 (1951).

[20] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

For the experiments on nitrogen a melamine foil was used as a target. Melamine ($\sim C_5H_7N_6$) is a plastic which contains a large proportion of nitrogen and no elements (except C^{13}, $\sim 1\%$ of natural carbon) which give deuteron background for ~18-Mev protons. Foils were made of Melmac 404*T*[21] by sprinkling a thin layer of finely-ground material between a pair of glass plates in a hydraulic press heated to ~400°F and applying ~4500 lb/in.^{2} pressure for 2 minutes. This procedure gave uniform foils down to ~0.001 in. thick with an area ~1 in.^{2} Analysis of the foils gave $\approx 45\%$ nitrogen by weight.

C. RESULTS

18.7-Mev protons struck a melamine foil of thickness 3.09 ± 0.06 mg/cm^2. Figure 2 shows scintillation counter spectra of deuterons leaving N^{13} in its ground state in the reaction $N^{14}(p,d)N^{13}$ ($Q=-8.3$ Mev). The total number of counts in the peak less background was determined at each angle, and the results [converted to the center-of-mass (c.m.) system] gave the angular distribution shown in Fig. 3. It is clear from comparison with the theoretical curves that the angular momentum transfer l_n in this reaction is one. We estimate the value of the nuclear radius (the only adjustable parameter in the theory) as $r_0=(5.4\pm0.3)\times10^{-13}$ cm. The absolute cross section at the maximum of the angular distribution (~18° c.m. system) was calculated from the target thickness and the integrated current to be $d\sigma/d\Omega=(5.0\pm0.6)$ millibarns/steradian in the c.m. system.

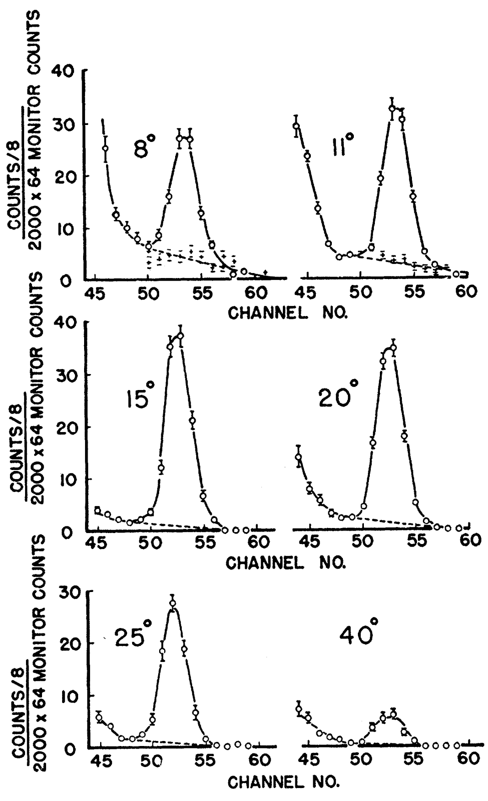

FIG. 2. Scintillation counter spectra from $N^{14}(p,d)N^{13}$ (ground state) at angles as indicated in the laboratory system. Estimated background is indicated by the dotted lines. Circles indicate experimental points, and bars standard deviations. On the first two curves the crosses show spectra taken with larger absorber thicknesses for estimation of background.

[21] American Cyanamid Company, which kindly supplied the Melmac 404*T*.

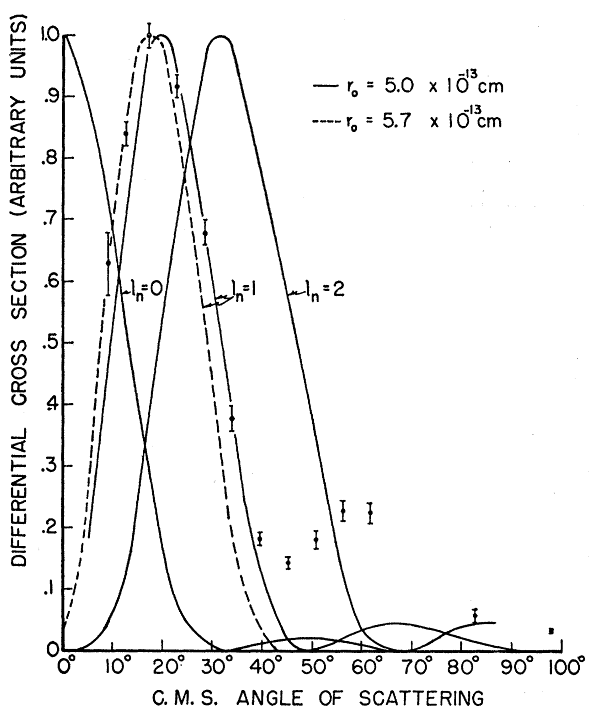

FIG. 3. Angular distribution of deuterons from $N^{14}(p,d)N^{13}$ (ground state) in the center-of-mass system. The circles are experimental points with bars indicating standard deviations. The curves are theoretical curves calculated from Butler's formula for the angular momentum transfers l_n and radii r_0 indicated.

Deuterons from transitions to the first excited state in N^{13} ($N^{14}(p,d)N^{13*}$, $Q=-10.7$ Mev) were searched for and none were found above background. This gave upper limits on the cross section for the excited state transition in the c.m. system as $d\sigma/d\Omega\lesssim0.4$ mb/sterad at 14°, $d\sigma/d\Omega\lesssim0.2$ mb/sterad at 23° and $d\sigma/d\Omega\lesssim0.1$ mb/sterad at 35°.

D. DISCUSSION

(1) Angular Momentum Transfer and Nuclear Radius

The foregoing result shows that the angular momentum transfer in the reaction $N^{14}(p,d)N^{13}$ is one, and therefore that the ground states of N^{13} and N^{14} must have opposite parity. Since N^{13} is known to have odd parity,[20] the parity of the N^{14} ground state must be even. This agrees with the result obtained by Bromley[22] from a measurement of the $C^{13}(d,n)N^{14}$ angular distribution, a result which was in some doubt because of a

[22] D. A. Bromley, Phys. Rev. 88, 565 (1952).

contradictory result obtained by Benenson[23] from the same reaction. An angular momentum transfer of one is also consistent with the known spins,[20] $\frac{1}{2}$ for N^{13} and 1 for N^{14}. The nuclear radius required to fit the angular distribution $r_0=(5.4\pm0.3)\times10^{-13}$ cm agrees with the value obtained for nitrogen by stripping measurements[24] when analyzed by the Butler theory (see II).

(2) Reduced Width for the Ground-State Transition

The reduced width calculated from the absolute cross section for the $N^{14}(p,d)N^{13}$ ground-state transition is $\theta^2=0.021$. The corrections to this reduced width should be of the same order of magnitude as those for the reaction $F^{19}(d,p)F^{20}$, since the energies involved are comparable. For the fluorine reaction Tobocman and Kalos[11] have computed a correction factor between 2 and 6 depending on the particular nuclear interactions assumed. Thus we expect the corrected reduced width for the reaction $N^{14}(p,d)N^{13}$ to lie in the range 0.04 to 0.12.

Lane's theoretical expression for the reduced width[12] gives the ratio of reduced width θ^2 to the "single-particle" reduced width θ_0^2, where θ_0^2 is the reduced width for a single nucleon in the potential well of the shell model. The value of θ^2/θ_0^2 depends on the character of the nuclear states involved. In L–S coupling N^{14} is normally considered[14] to be an S-state, but it has been suggested that it may be a D-state[25] or a P-state.[26] In j–j coupling the ratio θ^2/θ_0^2 is 1; in L–S coupling θ^2/θ_0^2 is 5/9 if N^{14} is an S-state, 2/9 if N^{14} is a D-state and 0 if N^{14} is a P-state. The single-particle reduced width depends somewhat on the well shape chosen, but should be about 0.25 for this energy,[12] so in j–j coupling the reduced width θ^2 is ≈0.25; in L–S coupling θ^2 is ≈0.14 if N^{14} is an S-state, ≈0.056 if N^{14} is a D-state and 0 if N^{14} is a P-state. Thus we see that these theoretical values of reduced width lie in the same range as the corrected experimental values given in the last paragraph, a result which is interesting in view of the disagreement by one or two orders of magnitude between experimental cross sections and previous calculations (for Be and Si) based on "single-particle" models.[27,28] The result also contradicts the suggestion that N^{14} is a P state in L–S coupling,[26] but beyond that it is difficult to say much about the character of the N^{14} ground state from this comparison.

In order to obtain more information about the character of the states involved, the experimental reduced width may be compared with the reduced width for another reaction, provided one can be found for which the corrections should be about the same (see II). We might expect this to be the case for the reaction[8,29] $N^{14}(d,p)N^{15}$, since the energies involved are comparable. The ratio of experimental reduced width for the reaction $N^{14}(d,p)N^{15}$ to that for the reaction $N^{14}(p,d)N^{13}$ is $6\pm\sim2$. In j–j coupling this ratio has the value 1.5; in L–S coupling its value is 0.9 if N^{14} is an S state, and 5.6 if N^{14} is a D-state. This would seem to indicate that the N^{14} ground state is mostly D, in agreement with recent suggestions.[14,25,30,31]

Since a straightforward calculation[14] taking into account central and spin-orbit forces indicates that the N^{14} ground state is an S-state in L–S coupling but becomes $\sim85\%$ D-state a short distance into intermediate coupling, it might be thought that agreement between the above calculated and experimental ratios of reduced widths would be obtained in intermediate coupling. However, an intermediate coupling calculation using Lane's wave functions[12,32] for N^{13} and wave functions calculated for N^{14} using the same force mixture as Lane[33] gave a ratio which remained between 0.9 and 2.2 for all points in intermediate coupling, in contradiction to the above experimental ratio ~6. This discrepancy should probably not be taken too seriously: on the one hand the experimental ratio of reduced widths may be in error because of differences in the corrections for the two reactions; on the other hand, the theoretical ratio may be rather sensitive to the exact force mixture used, and it may be necessary to introduce tensor forces as has been proposed[30,31] to explain the C^{14} beta decay.

We conclude that the ground-state reduced width is in qualitative agreement with that calculated on an independent-particle shell model. Our results contradict the suggestion[26] that the N^{14} ground state is a P-state, and they tend to support the state being largely D.

(3) Reduced Width for the Excited State Transition

It is known from measurements on $C^{12}(d,p)C^{13}$ and $C^{12}(p,p)C^{12}$ that the first excited state of N^{13} has the configuration p^8s and even parity (see Thomas,[34] Inglis,[14] and Lane[12] for discussions). If N^{14} has the configuration p^{10} (in agreement with the ground-state data presented above), then the transition to the first excited state of N^{13} involves a change in orbit for two particles $p^{10}\rightarrow p^8s$, and thus is forbidden. We expect the reduced width for the excited state transition to be zero in any coupling.

If N^{14} is not a pure p^{10} configuration, but has a small admixture of other configurations p^8s^2, p^8sd, etc., then one expects to find some transitions to the N^{13} excited

[23] R. E. Benenson, Phys. Rev. **90**, 420 (1953).
[24] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 1032 (1953).
[25] A. M. L. Messiah, Phys. Rev. **88**, 151 (1952).
[26] A. M. Feingold, Phys. Rev. **89**, 318 (1953).
[27] G. Abraham, Proc. Phys. Soc. (London) **A67**, 273 (1954).
[28] J. Dabrowski and J. Sawicki, Nuovo cimento **12**, 293 (1954).
[29] W. M. Gibson and E. E. Thomas, Proc. Roy. Soc. (London) **A210**, 543 (1952).
[30] B. Jancovici and I. Talmi, Phys. Rev. **95**, 289 (1954).
[31] W. M. Visscher and R. A. Ferrell, Phys. Rev. **99**, 649(A) (1955).
[32] A. M. Lane (private communication).
[33] With results close to those obtained by Inglis,[14] who used a slightly different force mixture.
[34] R. G. Thomas, Phys. Rev. **88**, 1109 (1952).

state because of this configuration mixing. The reduced widths for the transitions $p^8s^2 \to p^8s$ and $p^8sd \to p^8s$ may be calculated as before. The ratio of reduced width to single-particle reduced width for either transition is calculated as 0.5 in any coupling. The single-particle reduced width should be ~ 0.4 for s and ≈ 0.3 for d, giving a theoretical reduced width ≈ 0.2 for $p^8s^2 \to p^8s$ and ≈ 0.15 for $p^8sd \to p^8s$.

The experimental reduced widths, calculated from the upper limits on the cross section given above, are $\lesssim 0.001$ for $l_n = 0(p^8s^2 \to p^8s)$ and $\lesssim 0.0013$ for $l_n = 2(p^8sd \to p^8s)$. To allow for Coulomb effects and nuclear interactions, these values should be multiplied by correction factors, which we estimate as ~ 2 in the first case and ~ 3 in the second case from the measurements on the ground state and the calculations of Tobocman and Kalos.[11] Thus we get a ratio of experimental reduced width to calculated reduced width $\lesssim 0.01$ for the transition $p^8s^2 \to p^8s$ and a ratio $\lesssim 0.03$ for the transition $p^8sd \to p^8s$.

This ratio is a direct measure of the probability with which the configuration appears in the nuclear wave function. Therefore, we conclude that the N^{14} ground state contains a mixture of the configuration p^8s^2 with a probability less than $\sim 1\%$, and a mixture of the configuration p^8sd with a probability less than $\sim 3\%$. These figures are probably only good to a factor of 2, since the theoretical estimates are rough, but they provide a useful limit as to order of magnitude. This absence of any appreciable configuration mixing is a direct indication that the individual particle model gives a rather good approximation to the nuclear wave function here.

(4) Application to the C^{14} Beta Decay

The anomalously long lifetime of C^{14} (by a factor $\sim 10^6$) has been for some time one of the chief problems in the theory of beta decay.[35] Several suggestions have been offered for its solution:

The long lifetime could be explained if C^{14} and N^{14} had opposite parities.[36] Bromley's measurement[22] indicated that the parities were the same, and our result on the ground state transition, supporting Bromley, seems to dispose of this explanation conclusively.

The long lifetime might be explained if N^{14} were an almost pure D-state or a P-state in L–S coupling.[25,26] Our ground-state data contradict the suggestion that the N^{14} ground state is a P-state, but are quite consistent with it being a D-state. However, there are various arguments against a sufficiently pure D-state: (a) the absence of companion D-states,[14] (b) inversion of the level order from that calculated,[14] (c) the perturbation introduced by the tensor force, which should mix in enough S state to destroy the required purity of the D-state,[26] (d) the evidence that simple L–S coupling fails to give an adequate description of nuclei in the p-shell, but that at least the complication of intermediate coupling is required.[12–14] Although none of these arguments is flawless, the combination seems to make this explanation unlikely.

The other suggested possibility has been simply an accidental cancellation of terms in the matrix element for the transition $C^{14} \to N^{14} + \beta$. Inglis[14] has shown that this will not occur in a pure p^{10} configuration if only central forces and spin-orbit forces are assumed, but that it is possible with a fairly small amount of mixing of higher configurations. Our results for the excited state transition mean that any mixture of configurations p^8s^2 or p^8sd must occur with a probability less than a few percent. This certainly does not disprove Inglis' hypothesis, but seems to make it somewhat less plausible, since at least for these configurations the admixture is probably less than would be required for cancellation of the matrix element.

Jancovici and Talmi have shown[30] that it is possible to obtain cancellation of the matrix element within the ground state configuration by the inclusion of tensor forces. They used a particular mixture of tensor and central forces, and Visscher and Ferrell have found[31] that their result may be generalized to give cancellation for a wide range of values of the nuclear force parameters. This explanation has (in common with all the others) the disadvantage of being an *ad hoc* theory, but it appears to have no evidence against it, and at present would seem to be the most likely possibility that has been suggested.

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