Energy Levels in N^{14} and C^{14} from Deuteron Bombardment of C^{13}†

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An approximately 50-kev thick carbon target enriched to 61 percent C^{13} was bombarded by 3.89-Mev deuterons. The neutrons resulting from the $C^{13}(d,n)N^{14}$ and $C^{12}(d,n)N^{13}$ reactions were detected in photographic emulsions placed at angles of 0°, 20°, 45°, and 80° with respect to the incident beam. It was possible to examine the energy level scheme of N^{14} up to 8.1-Mev excitation and by means of Butler's stripping theory to assign parities to the first three excited states.

Energy levels of N^{14} are located in this experiment at 2.23±0.10, 3.85±0.08, 4.80±0.07, 4.97±0.07, 5.76±0.05, 6.23±0.05, 6.43±0.04, 7.00±0.04, 7.72±0.04, and 8.08±0.06 Mev excitation with possible levels at 5.5±0.1, 6.1±0.1, and 7.50±0.04 Mev excitation. The parities of the 2.23- and 3.85-Mev levels are found to be even with $J\leq 2$ while that of the 4.8-Mev level is found to be odd with $J=0$ or 1.

As an auxiliary experiment, the $C^{13}(d,p)C^{14}$ reaction was investigated at six angles of observation again by use of photographic emulsions. No levels clearly ascribable to C^{14} were observed below the known 6.1-Mev excited state. This state appears to have odd parity, $J=0$ or 1.

I. INTRODUCTION

THE energy level scheme of N^{14} has always been of considerable interest in the study of light nuclei because it affords an insight into the coupling rules for two unpaired nucleons. For N^{14} the possible configurations of these nucleons are expected to be of sufficient simplicity to lend themselves very well to theoretical analysis of the level structure. In addition, renewed interest in the hypothesis of charge independence of nuclear forces has once again focused attention on the concept of isobaric spin; this concept seems to take on a particular interest in the level scheme to be discussed.

Each state of a nucleus is presumed to be characterized, at least partially, by three quantum-mechanical properties; the total angular momentum or J value; parity; and the total isobaric spin quantum number T. The Butler theory of the stripping process[1] has provided a powerful method for obtaining both the parity and upper and lower limits to the J value of a nuclear energy level. This method has been applied to N^{14} by measuring the intensities of neutron groups from the $C^{13}(d,n)N^{14}$ reaction at four different angles of observation.

The principal results obtained for this nucleus from the Butler analysis have been the assignment of parities to the first three excited states of N^{14}. By combining information from this and other experiments it has also proved possible to make what is believed to be a self-consistent assignment of J values to these same three excited states.

When nuclear states are identified by means of energy measurements made on the outgoing particles from a nuclear reaction, there is a chance that a state may be overlooked if observations are made at only one angle. That is to say, the differential cross section for production of particles which leave a nucleus in a particular energy level may be very low at that particular angle. The data at several angles necessary for the Butler analysis permit in addition a better investigation of the level scheme of a given nucleus. It has been possible to examine the excited states of N^{14} up to 8.1 Mev, including a previously unexplored region of excitation lying between 6.5 and 8.1 Mev.

An auxiliary experiment was performed in order to assign the total isobaric spin quantum number T to the levels of N^{14}. If a level in N^{14} has no analog in C^{14} it may be assigned the value $T=0$; otherwise it must be assumed to be a member of an isobaric spin one triplet. The $C^{13}(d,p)C^{14}$ reaction was examined at six angles of observation in order to check once again into whether any level in C^{14} lies below the one known to exist at 6.1 Mev and to assign parities wherever possible. A level in C^{14} at 4.1 Mev had been suggested.[2]

The parities of the ground states of N^{14} and C^{14} are of considerable interest in any attempt to explain the unusually long lifetime of the C^{14} beta-decay. Bromley and Goldman report that the parities of both ground states are even.[3] This has also served to fill an important gap in the present N^{14} parity assignments since the results from the present experiment were inconclusive for the ground state.

II. EXPERIMENTAL PROCEDURE FOR THE $C^{13}(d,n)N^{14}$ EXPOSURE

3.89-Mev deuterons from the Wisconsin electrostatic generator passed through a 90° cylindrical electrostatic analyzer and a $\frac{1}{8}$-inch defining aperture in 0.01-inch tantalum and then struck an approximately 50-kev thick carbon target. The target consisted of 61 percent C^{13} and 39 percent C^{12} placed on a 0.005-inch tantalum backing. The neutrons from the $C^{13}(d,n)N^{14}$ and $C^{12}(d,n)N^{13}$ reactions were detected by means of Eastman NTA 200-micron emulsions placed at angles of 0°,

† Work supported by the U. S. Atomic Energy Commission and the Wisconsin Alumni Research Foundation.

[1] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).

[2] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952).

[3] D. A. Bromley and L. M. Goldman, Phys. Rev. **86**, 790 (1952).

10°, 20°, 30°, 45°, 60°, and 80° with respect to the incident beam. The front edge of each emulsion was 10 cm from the target.

The processing technique for the Eastman emulsions, the range-energy curve used for converting the lengths of the recoil proton tracks to energy, and the method of measuring tracks and acceptance criteria all appear in previous papers.[4–6]

The carbon target was prepared by cracking enriched methyl iodide obtained from the Eastman Kodak Company on a 5-mil tantalum backing. The technique was quite similar to that discussed by Seagrave[7] except that the backing was heated in an induction heater and blistering of the carbon deposit was reduced by producing it as a sandwich layer. First, a small square of tantalum was outgassed in a vacuum of better than 10^{-5} mm Hg. Following this, it was placed on a carbon coated lavite block in a system which was then sealed and evacuated to a pressure of approximately 10^{-2} mm Hg. The tantalum was heated to redness and cracking took place as methyl iodide vapor was slowly admitted to the system. A final pressure of half an atmosphere of the vapor was attained. In order to obtain the thickness of the target the carbon deposit appearing on the upper surface of the tantalum was removed and the remaining carbon plus backing were weighed.

Shortly after the $C^{13}(d,n)N^{14}$ exposure a background determination was performed by exposing plates at 0° and 90° to a target of bare tantalum. The background exposure was unsatisfactory in that because of generator trouble it had to be performed at almost 0.5 Mev lower deuteron energy than the actual $C^{13}(d,n)N^{14}$ experiment.

III. EXPERIMENTAL PROCEDURE FOR THE $C^{13}(d,p)C^{14}$ EXPOSURE

The target used for this experiment was obtained by peeling a carbon flake from its backing following a suggestion of Seagrave[7] and placing the flake in a tantalum frame. Otherwise, the method of producing the target was as described above. The thickness was estimated to be between 50 and 100 kev for 4.00-Mev deuterons.

An analyzed 4.06-Mev deuteron beam passed through a $\frac{3}{32}$-inch defining aperture in 5-mil tantalum into an evacuated box containing the plate camera. The plate camera is shown in Fig. 1. The beam passed through the carbon target and was stopped by a system of nickel absorbers mounted between the target and the emulsions. Six 100-micron Eastman NTA emulsions were placed in slots in the plate camera oriented so that protons entering the center of each emulsion made an angle of 8° with the plane of the surface. Measurements of track lengths were confined to within 5 millimeters of these centers, and except that all tracks were assumed to have a dip angle of 8° the same techniques as discussed for the (d,n) experiment were used. The following nickel absorber thicknesses were used: for the −5° and 10° plates, 1.75 mils; for the 25° and 40° plates, 1.50 mils; for the 55° plate, 1.25 mils; and for the 85° plate, 1.05 mils. The absorber thicknesses were chosen to stop elastically scattered deuterons and tritons and alpha-particles from all possible deuteron induced reactions taking place at the target. For the portions of the plates which were located at 7.3 cm from the target approximately 1.5 microcoulombs of deuteron charge resulted in the maximum density of tracks per microscope field of view which could be read at the small angles.

A background run was made by removing the target with other conditions being kept the same. Only the plates at −5° and 10° had an appreciable number of tracks which were acceptable for measurement (i.e., dip angle ~8°).

The angle measurement is uncertain by ±3°. Placement of the plate camera, Rutherford scattering in the absorbers, finite extension of the target area and position in the plate at which the tracks were measured are the factors contributing to this uncertainty. An error of 3° would be of importance as regards the positions of the −5° and 10° plates relative to each other, but the third angular distribution of Fig. 6 suggests this difficulty was not present.

IV. EXPERIMENTAL RESULTS—$C^{13}(d,n)N^{14}$ EXPOSURE

Recoil proton tracks were measured only in the 0°, 20°, 45°, and 80° plates since it was felt that these would be sufficient to define peaks in the Butler theoretical curves. The neutron spectra for these plates are shown in Fig. 2. These spectra represent the number of acceptable recoil proton tracks per 50-kev interval after corrections have been applied for the variation of n-p cross section with neutron energy[8] and for the

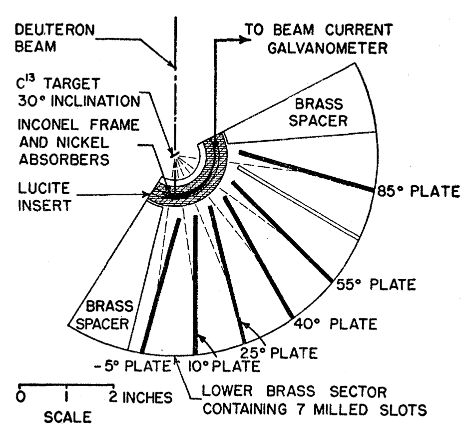


FIG. 1. Plate camera at midsection showing arrangement of the photographic emulsions for the $C^{13}(d,p)C^{14}$ exposure.

[4] F. Ajzenberg, Phys. Rev. **88**, 298 (1952).
[5] Richards, Johnson, Ajzenberg, and Laubenstein, Phys. Rev. **83**, 994 (1951).
[6] Johnson, Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).
[7] J. D. Seagrave, Phys. Rev. **85**, 197 (1952).
[8] R. K. Adair, Revs. Modern Phys. **22**, 249 (1950).

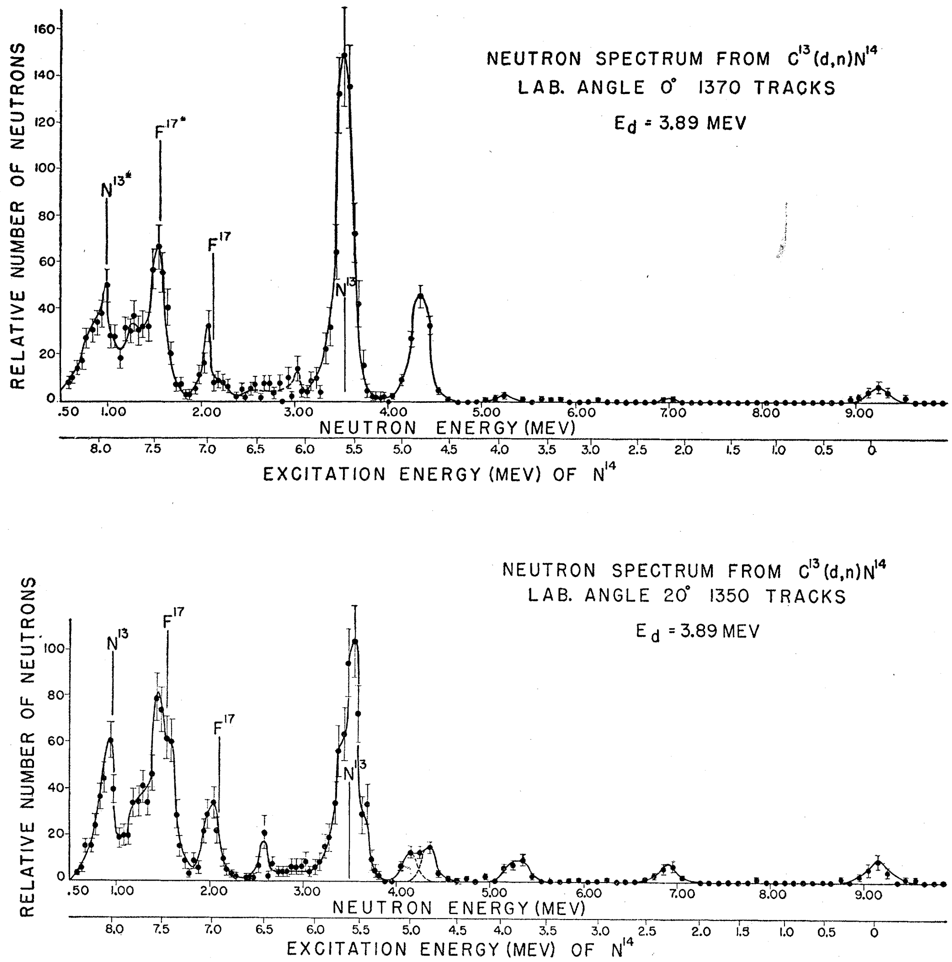


FIG. 2. Neutron spectra at the four angles of observation for the $C^{13}(d,n)N^{14}$ exposure. The relative number of energy the spacing is 50 kev between

probability of tracks leaving the emulsion.[9] Each of the four spectra shown in Fig. 2 was obtained from a certain area scanned on the 0°, 20°, 45°, and 80° plates. These areas are in the ratios 1:1.39:2.59:4.73. Where tracks of special lengths are measured on a plate to improve statistics, the number of tracks in the energy intervals involved are scaled down appropriately on the plot. In a few cases it was also necessary to apply an inverse square law correction when calculating the relative area scanned because the strips swept across began at a distance further from the target than usual. For neutron energies below 4.00 Mev the experimental points are plotted in 50-kev intervals; above 4.00 Mev they are plotted in 100-kev intervals since the width of recoil proton groups from monoenergetic neutrons becomes greater for high neutron energies.

In the case of the 0°, 20°, and 45° plates extra tracks were measured corresponding to neutron energies greater than 3.75 Mev in order to improve statistics for these long-range tracks. An additional 153 tracks corresponding to neutron energies between 2.05 and 3.60 Mev were measured on the 45° plate in order to help resolve a possible level at 6.1-Mev excitation.

Since C^{12} is 39 percent of the target and there is the possibility of oxygen contamination being present, the lines marked N^{13}, N^{13*}, F^{17}, and F^{17*} in Fig. 2 represent the positions at which neutron groups from the $C^{12}(d,n)N^{13}$ and $O^{16}(d,n)F^{17}$ reactions would be expected. Allowance was made for target thickness. The Q values used in the calculations were obtained from the "Table of Atomic Masses" given by Li, Whaling, Fowler, and Lauritsen,[10] and the first excited states of N^{13} and F^{17} were taken to lie, respectively, 2.37 Mev and 536 kev above the ground states.[11,12]

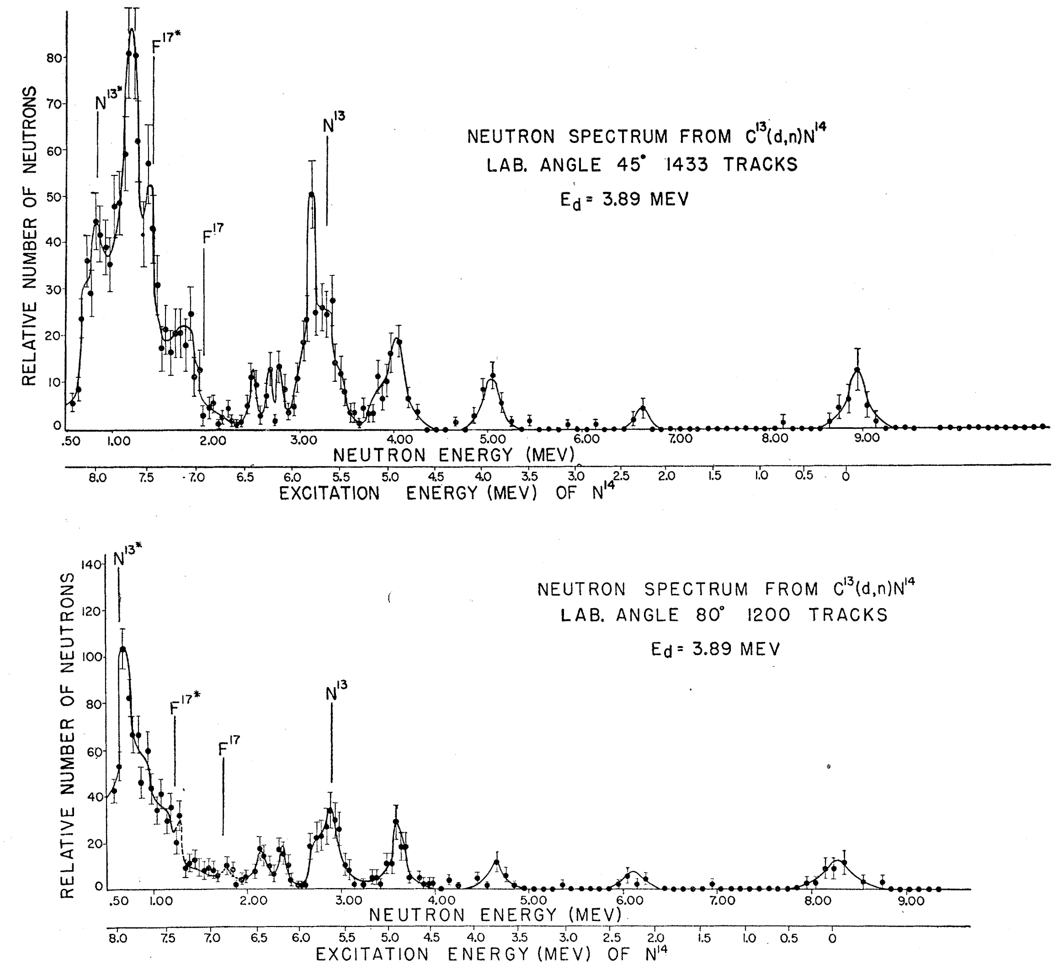
The experimental angular distributions of the neutron groups and the theoretical Butler curves with which

[9] H. T. Richards, Phys. Rev. **59**, 796 (1941).

[10] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).

[11] H. L. Jackson and A. I. Galonsky, Phys. Rev. **84**, 401 (1951).

[12] Fay Ajzenberg, Phys. Rev. **83**, 693 (1951).



neutrons per 50-kev interval is plotted against neutron energy for each spectrum. Below 4.00-Mev neutron points; above 4.00 Mev it is 100 kev.

they are to be compared are shown in Fig. 3 for the cases of N^{14} left in its ground state and each of its first three excited states. The experimental points are plotted in center-of-mass coordinates; the change of differential cross section in transforming from the laboratory to the center-of-mass system has been taken into account at each angle.

The angular distribution for the 4.8-Mev level shown in Fig. 3 has an uncertainty not related to the standard deviation indicated at each point. This uncertainty results from the existence of neutron groups from an adjacent state of N^{14}. Slight errors made in the somewhat arbitrary assignment of tracks to the two sets of groups at each angle should not affect the interpretation in terms of the Butler theory of the strong forward maximum of neutrons from the 4.8-Mev level.

The L_p value associated with each of the theoretical curves in Fig. 3 identifies the angular distribution to be expected according to the units of angular momentum transferred by the captured proton to the capturing nucleus. Taking the ground state of C^{13} to have odd parity,[13] even values of L_p signify odd-parity levels of N^{14}, and vice versa. Computations of these Butler curves were carried out for N^{14} left in its ground state, a 3.9-Mev level, and a hypothetical level at 6.0 Mev. Because the calculations are lengthy and the shapes of the curves vary slowly with increasing excitation, the experimental points from the 2.23-Mev level are compared with the ground state Butler curves; those from the 4.8-Mev level are compared with the 3.9-Mev curves. The interaction radius used in the calculations was taken as 4.8×10^{-13} cm. The L_p value is assigned to a level by noting with which theoretical curve the experimental points most nearly coincide. For the excited states the scale of the plots is chosen so that the highest experimental point coincides with the peak of the appropriate Butler curve.

Table I summarizes the information obtained from

[13] C. J. Rotblat, Nature **167**, 1027 (1951) has shown that the parities of the C^{12} and C^{13} ground states differ.

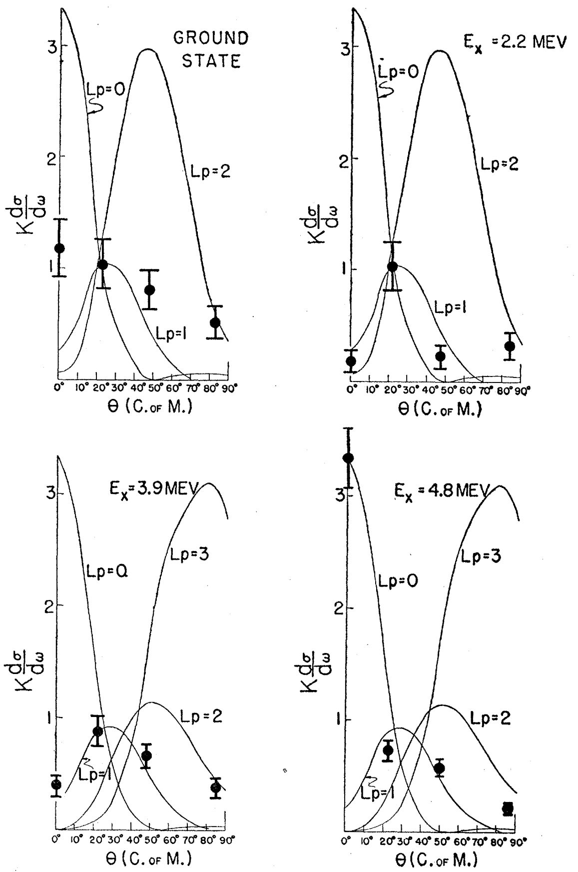


FIG. 3. Angular distributions of neutrons from the lowest four states of N^{14}. Center-of-mass coordinates. Solid curves are calculated from Butler theory.

this $C^{13}(d,n)N^{14}$ experiment, and Fig. 4 shows the energy level scheme deduced from the average energies of neutron groups. The excitation energy of a level was obtained by subtracting its weighted mean Q value from the Q value for the ground state. However, the ground state value was taken from the "Table of Atomic Masses"[10] and not from this experiment. The Q value from mass measurements is expected to be considerably more precise than that which is obtained by converting the long recoil proton track lengths to energy; by this choice all excitation energies are not subject to a fixed error. The excitation energy for each level now depends only on the accuracy of the conversion of range to energy for the relevant recoil proton track lengths.

Energy levels in N^{14} which are considered uncertain are shown dotted in the diagram of Fig. 4 and are listed with question marks in Table I. The 6.1-Mev level is suggested by weak groups at 0° and 45°; the 5.5-Mev level evidences itself only as asymmetries in two N^{13} peaks. The 7.50-Mev level will be discussed later.

V. EXPERIMENTAL RESULTS—ENERGY LEVELS IN C^{14}

The proton spectra from the $C^{13}(d,p)C^{14}$ exposure at each of the six angles of observation are shown in Fig. 5. The number of proton tracks per 50-kev interval is plotted against the proton energy. Below 4.00 Mev proton energy points are plotted in 50-kev intervals; above 4.00 Mev in 100-kev intervals. Shown below each spectrum is a scale of excitation energy of C^{14} based on the ground-state Q value[10] and the absorber thickness at each angle. Also indicated on each plot are the energies at which proton groups from the $C^{12}(d,p)C^{13}$ and $O^{16}(d,p)O^{17}$ reaction are to be expected after the protons pass through the nickel foils. All Q values used in the calculation were obtained from the "Table of Atomic Masses,"[10] and the first excited states of C^{13} and O^{17} were taken to lie, respectively, 3.10 Mev and 0.87 Mev above the ground states.[14] The areas scanned in the −5°, 10°, 25°, 40°, 55°, and 85° plates are, respectively, in the ratios 1:1.07:2.44:5.40:3.10:2.77. The absorber thicknesses were chosen to stop particles from all (d,t) and (d,α) reactions. The Bethe range-

TABLE I. Summary of results on $C^{13}(d,n)N^{14}$.

Level of N^{14} shown in Fig. 4[a]	Q value (Mev) 0°	Q value (Mev) 20°	Q value (Mev) 45°	Q value (Mev) 80°	Weighted mean Q value[a] (Mev)	L_p	Parity
Ground state	5.44	5.37	5.40	5.38	5.40±0.10	See ref. 3	Even
2.23±0.10	3.17	3.09	3.08	3.07	3.09±0.10	1	Even
3.85±0.08	1.41	1.49	1.45	1.52	1.47±0.09	1	Even
4.80±0.07	0.54	0.54	0.45	0.48	0.52±0.08	0	Odd
4.97±0.07	0.34	0.40	0.29	0.32	0.35±0.08	1?	Even?
5.5 ±0.1?	···	−0.10	0.18	···	−0.14±0.08	0?	Odd?
5.76±0.05	···	−0.40	−0.46	−0.45	−0.44±0.05	···	
6.1 ±0.1?	−0.76	···	0.79	···	−0.78±0.06	···	
6.23±0.05	···	···	−0.92	−0.89	−0.91±0.05	···	
6.43±0.04	···	−1.13	−1.16	−1.07	−1.11±0.04	···	
7.00±0.04	−1.65	−1.70	−1.73	···	−1.68±0.04	1?	Even?
7.50±0.04?	−2.16	−2.20	−2.16	−2.23	−2.18±0.04	0?	Odd?
7.72±0.04	−2.43	−2.41	−2.33	−2.51	−2.40±0.04	···	
8.08±0.06	−2.76	···	−2.76	···	−2.76±0.06	···	

[a] In order to account for a possible systematic error in the range-energy conversion, an arbitrary uncertainty of 1 percent of the recoil proton energy has been added to the estimated probable error of the weighted mean.

[14] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. 22, 291 (1950).

energy curves for copper[15] were used for all absorber calculations, copper having very nearly the same stopping power as nickel.

Included in Fig. 5 is a histogram of tracks measured in the $-5°$ background plate. The exposure and area scanned were approximately the same as for the $-5°$ plate of the $C^{13}(d,p)C^{14}$ run.

The angular distributions which may be obtained from this experiment are shown in Fig. 6. Those for the $C^{12}(d,p)C^{13}$ and $C^{13}(d,p)C^{14}$ ground-state reactions are in agreement with ones reported previously.[13,3] The shape which these angular distributions exhibit agrees very well with the shape expected for the Butler curve for $L_n=1$, i.e., unit angular momentum transferred by the captured neutron to the C^{13} nucleus. The theoretical curves shown in Fig. 3 may be used for comparison since the masses and Q values involved are quite similar and the formula from which the curves were calculated does not distinguish between (d,n) and (d,p) reactions. The fourth angular distribution of Fig. 6 refers to C^{14} left in its 6.1-Mev level; also plotted are two Butler curves calculated for this case.

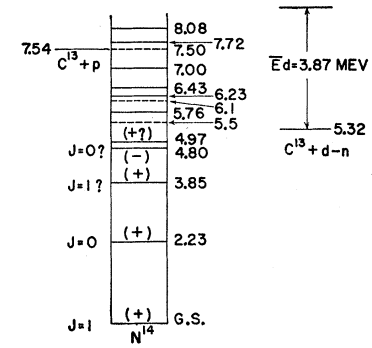


FIG. 4. Energy levels of N^{14} deduced from the $C^{13}(d,n)N^{14}$ reaction.

VI. DISCUSSION OF THE ENERGY LEVELS OF N^{14}

The $C^{13}(d,n)N^{14}$ experiment has resulted in an assignment of parities to the first three excited states of N^{14} and has provided an opportunity to examine the energy levels of this nucleus up to 8.1-Mev excitation. Some further inferences about the level scheme may be made by drawing on outside information, particularly the

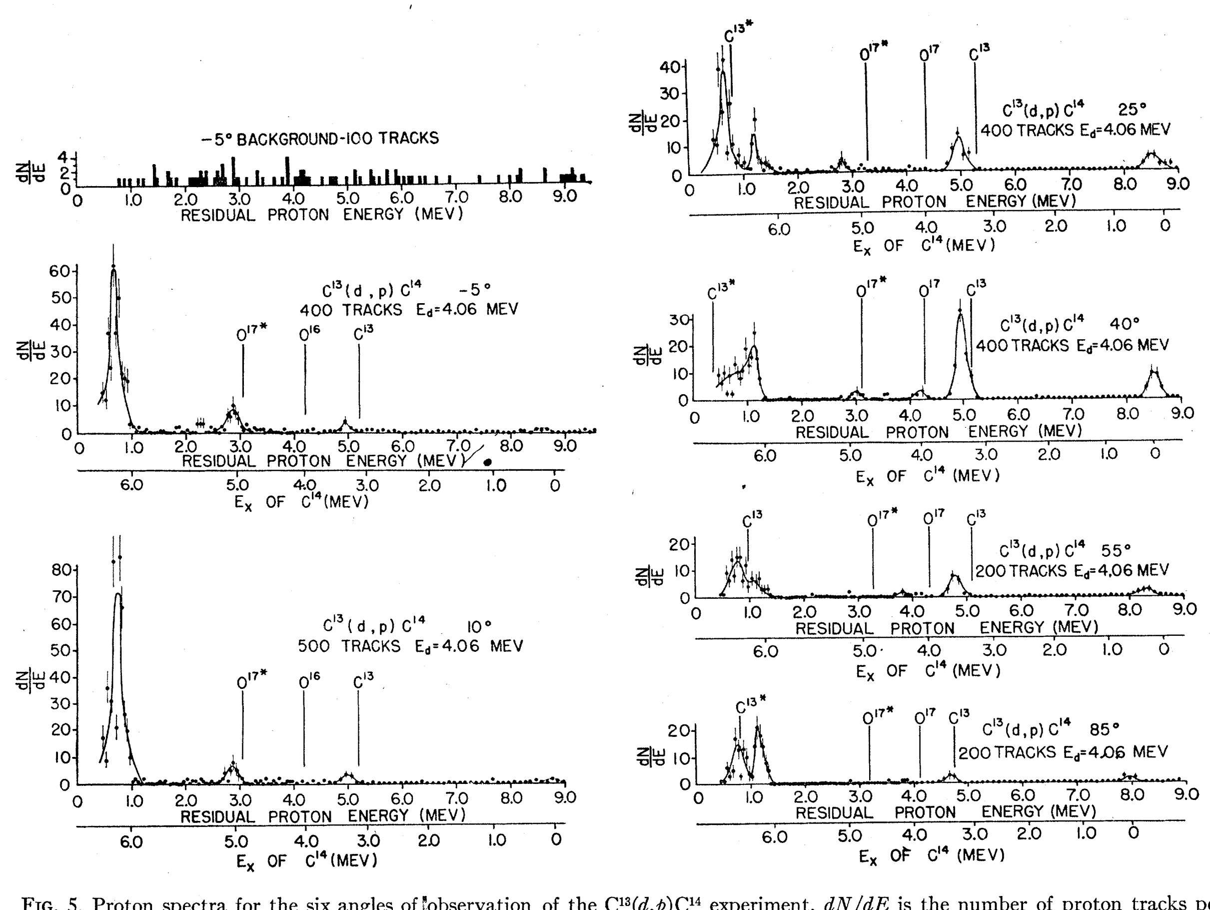


FIG. 5. Proton spectra for the six angles of observation of the $C^{13}(d,p)C^{14}$ experiment. dN/dE is the number of proton tracks per 50-kev interval. Points are plotted in 50-kev intervals below 4.00-Mev residual proton energy; in 100-kev intervals above 4.00 Mev. Deviation of peaks from calculated positons is not taken to be significant, no correction having been made for use of the emulsions in vacuum and because there is some uncertainty in the absorber thicknesses.

[15] H. A. Bethe, Brookhaven National Laboratory Report BNL-T-7 (1949).

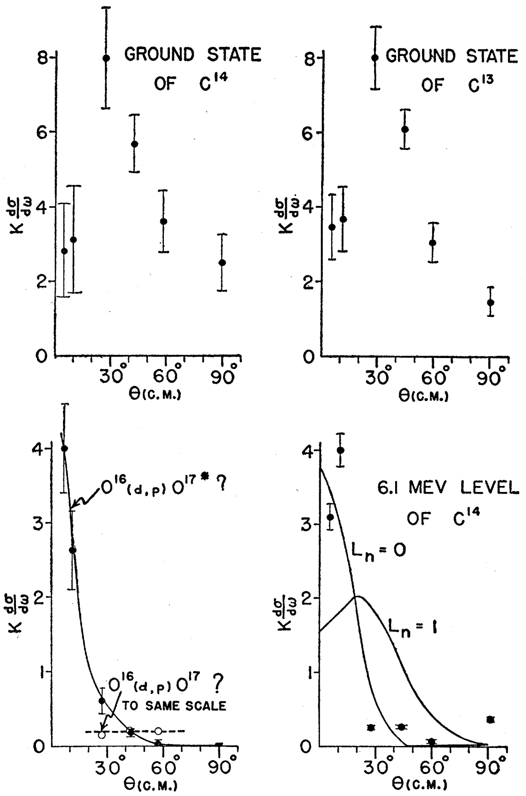


FIG. 6. Angular distributions for all groups in the $C^{13}(d,p)C^{14}$ experiment. Center-of-mass coordinates.

gamma-ray work of Thomas and Lauritsen[2] and Woodbury, Day, and Tollestrup.[16] In general it appears that there are more excited states in N^{14} below 8.1-Mev excitation energy than a level scheme based on observed gamma-ray energies would indicate.

The average energies of the neutron groups associated with the ground state, first, second, and fourth excited states are consistently very nearly 80 kev higher than the values required to give good agreement with the known ground-state Q value[8] and with the positions of the first three excited states in the level scheme deduced from gamma-ray energies.[2] A similar upward shift may be expected to apply also to the 4.80-Mev level shown in Fig. 4 which would bring it into better agreement with the level previously observed to lie at 4.9-Mev excitation.[17,18] Since this shift does not appear to apply to the higher energy levels, the explanation is believed to be in the uncertainties in applying range-energy relation to the longer recoil proton tracks involved. It is possible that the humidity conditions under which the emulsions were used differs from the conditions at the time the range-energy curve was obtained, or that a small error in self-calibration for the microscope shows up more seriously at the higher neutron energies.

The angular distribution for neutrons which leave N^{14} in its ground state obtained in this experiment does not appear to agree with the results of Bromley and Greenman who also studied the $C^{13}(d,n)N^{14}$ reaction.[3] They find a clear-cut $L_p=1$ angular distribution for neutrons which leave N^{14} in its ground state requiring this state to have even parity. The results here suggest the superposition of $L_p=0$ and $L_p=2$ curves; however, the statistics are poor. In what follows the results of Bromley and Greenman will be accepted; it is hoped to check the ground-state results in this laboratory later on.

The first excited state of N^{14} listed in Table I at 2.23-Mev excitation energy gives rise to an $L_p=1$ angular distribution. For the C^{13} nucleus having spin $\frac{1}{2}$ and odd parity the Butler theory requires that a state of N^{14} corresponding to an $L_p=1$ angular distribution have even parity with $J\leq 2$. These results are consistent with the usual assumption[19] that this level is a member of the same isobaric spin triplet as the ground states of O^{14} and C^{14}. With the exception of one component of the isobaric spin vector, the members of an isobaric spin triplet must have the same quantum-mechanical properties. Hence, since C^{14} and O^{14} are even-even nuclei with C^{14} known and O^{14} expected to have zero-spin states, the first excited state of N^{14} will also have $J=0$.

Mandeville and Swann have reported a 3.47-Mev level in N^{14}.[18] From two to four tracks at each of three angles correspond approximately to the correct excitation energy but statistics are far too poor to make any further statement.

The neutrons which leave N^{14} in 3.85-Mev level again exhibit an $L_p=1$ angular distribution requiring that this be an even parity state with $J\leq 2$. If the level here reported at 3.85 Mev is the same as the 3.96-Mev level of Woodbury, Day, and Tollestrup,[16] and Ashmore and Raffle,[20] then the fact that the gamma-ray emission occurs with equal probability to the ground and first excited states[16] excludes $J=0$. Furthermore the argument of Austern and Sachs that magnetic dipole radiation is much more probable than electric quadrupole radiation for light nuclei[21] suggests the assignment of $J=1$ as being more consistent with the equal probability of decay to the two lower states.

There is a bare possibility that two levels in N^{14} are present in the vicinity of 3.85-Mev excitation energy. one level lying above, and one below this value. Such a possibility is suggested by the shape of the neutron groups in the 20° and 80° spectra. An attempt to separate these tracks into two groups implied two even parity $L_p=1$ levels.

Strong evidence for an energy level in N^{14} at about

[16] Woodbury, Day, and Tollestrup, Phys. Rev. **85**, 760 (1952) and private communication.

[17] Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).

[18] C. E. Mandeville and C. P. Swann, Phys. Rev. **79**, 787 (1950).

[19] R. K. Adair, Phys. Rev. **87**, 1041 (1952).

[20] A. Ashmore and J. R. Raffle, Proc. Phys. Soc. (London) A64, 754 (1951).

[21] N. Austern and R. G. Sachs, Phys. Rev. **81**, 710 (1951).

4.8-Mev excitation energy is presented in this experiment. It clearly corresponds to an $L_p=0$ angular distribution and therefore is assigned odd parity with $J=0$ or 1. Neutron groups from the $C^{13}(d,n)N^{14}$ reaction which correspond to this level have been observed previously.[17,18] Although a 4.8-Mev gamma-ray has not been reported, it is felt that Fig. 7 of the article by Thomas and Lauritsen[2] indicates the presence of such radiation. Since there is no evidence whatever for a gamma-transition between this 4.8-Mev level and the first excited state of N^{14}, it must be a $J=0$ level.

The assignment $J=0$, odd parity to the 4.80-Mev level of N^{14} fulfills the conditions for electric dipole transitions to the ground state and the 3.9-Mev level. L. E. H. Trainor has introduced a new gamma-ray selection rule which says, in part: electric dipole transitions between states of a nucleus having equal numbers of protons and neutrons are forbidden if the states have the same isobaric spin multiplicity.[22] The ground state, 3.9- and 4.8-Mev levels of N^{14} have no analogs in the C^{14} level scheme and hence are $T=0$ states. Electric dipole radiation is now forbidden; however magnetic quadrupole radiation is allowed. A check on the selection rule might be provided by a careful measurement of the internal pair coefficient for the 4.8-Mev transition. According to the calculations of Rose[23] the internal pair coefficient for a 4.8-Mev transition is a factor of two greater for an electric dipole than for a magnetic quadrupole transition.[24]

There is slender evidence which should perhaps be mentioned that the 4.97-Mev level is an even parity, $L_p=1$ state. At each angle tracks from this level and those from the 4.8-Mev level form overlapping groups. An attempt may be made to separate these groups by considering the shapes of the peaks and the position on the N^{14} excitation energy scale at which they occur. Taking the group centered about 4.30-Mev neutron energy in the 0° data to belong almost entirely to the 4.8-Mev state and observing that the intensity for the groups corresponding to the 4.97-Mev level is higher at 20° than at 45° suggests an $L_p=1$ angular distribution. It is believed that this 4.97-Mev level is the same level reported as the 5.05-Mev state from the gamma-ray measurements.[2,16]

The large fraction of C^{12} in the target gives rise to neutrons from the $C^{12}(d,n)N^{13}$ reaction. The highest peaks in the 0° and 20° data are located at a neutron energy which agrees very well with that calculated for neutrons which leave N^{13} in its ground state. However, the group at 0° is of considerably greater intensity than the group at 20°, a fact at variance with the $L_p=1$ angular distribution known to correspond to this N^{13}

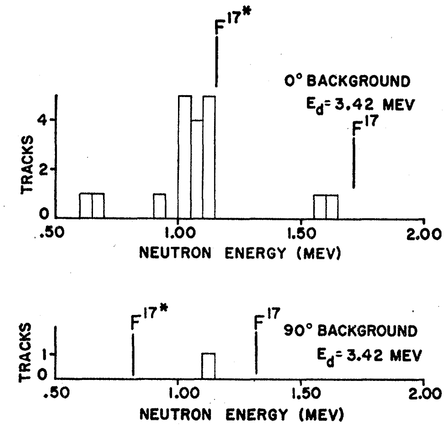


FIG. 7. Histograms of 0° and 90° background plates for the (d,n) exposure. The 90° histogram represents a plate area one-half that for the 0° histogram. Also indicated are the calculated positions for neutrons from the $O^{16}(d,n)F^{17}$, F^{17*} reactions.

ground state.[25] This is suggestive that one or more levels in N^{14} are contributing to these peaks. The asymmetry to the right of the peak in the 20° data and the width of the corresponding group at 45° suggests a possible level at 5.5-Mev excitation energy. Such a level has been reported earlier.[26] The asymmetry on the left side of the N^{13} peak in the 20° data is assumed to be due to a 5.76-Mev level in N^{14}; evidence for such a level is quite strong at 45°. This 5.76-Mev level most likely is the same as the 5.7-Mev level reported from the $O^{16}(d,\alpha)N^{14}$ reaction[20] and is perhaps the source of the 5.7-Mev gammas.[16]

A 6.1- or 6.2-Mev level in N^{14} is here believed to exist; the evidence favors the latter, but a sharp cleavage in the spectra at 0° and 45° suggests the possibility of both states being present. A 6.1-Mev level had been reported earlier by Stühlinger.[26] The 6.43-Mev excited state corresponds very well to a known gamma-ray.

Both the 7.00-Mev and the questionable 7.50-Mev level are identified by neutron groups having very nearly the calculated energies for F^{17} left, respectively, in its ground and first excited states by the $O^{16}(d,n)F^{17}$ reaction. However the small relative intensity for neutrons of the correct energy for F^{17} left in its ground state is in disagreement with the known angular distribution for this state.[12,27] This disagreement is taken to demonstrate the existence of a 7.00-Mev level in N^{14}. It is also considered to place an upper limit on the amount of oxygen contamination on the target, which limit opens the possibility of a 7.50-Mev excited state of N^{14}.

Histograms of the 0° and 90° background plates are shown in Fig. 7. It was mentioned before that the

[22] L. E. H. Trainor, Phys. Rev. **85**, 962 (1952).
[23] M. E. Rose, Phys. Rev. **76**, 678 (1949).
[24] Acceptance of the assignments made here to the first three excited states of N^{14} and of the new selection rule means that any $J=0$, $T=0$, odd parity state can at best decay to the lowest four states of N^{14} by magnetic quadrupole radiation.

[25] El Bedewi, Middleton, and Tai, Proc. Phys. Soc. (London) **A64**, 1055 (1951).
[26] E. Stühlinger, Z. Physik **114**, 185 (1939).
[27] E. Goldberg, Phys. Rev. **89**, 760 (1953), and private communication.

background exposure was made with about 0.5 Mev less energetic deuterons than used for the $C^{13}(d,n)N^{14}$ exposure. The tracks shown are believed to arise primarily from oxygen contamination on the bare tantalum which would not affect the above discussion. If some unknown contaminant were present and all neutron energies in the background exposure were increased by approximately 0.5 Mev, the 7.50-Mev level in N^{14} would be even more doubtful and some uncertainty could be attached to the 7.00-Mev level.

The 7.72-Mev level shown in the level diagram of Fig. 4 gives rise to a strong neutron group at 45° and also evidences itself in the 0° and 20° data. Since it is an unbound state, the Butler theory does not apply. This level may help account for the large cross section for radiative capture of 129-kev protons by C^{13} observed by Woodbury and Fowler.[28]

The well-known 8.1-Mev level of N^{14} appears as an asymmetry in the N^{13*} peak at two of the angles of observation. This state was earlier assigned odd parity, $J=0$ or 1.[7] The suggestion has been made that the 8.1-Mev level in N^{14} is the analog[2,7] of the 6.1-Mev level in C^{14} making both $J=1$, $T=1$ states. The 8.1-Mev level has been reported as not radiating to the N^{14} first excited state,[7] this behavior is consistent with the isobaric spin assignments since such an elective dipole transition would again be prohibited by Trainor's selection rule,[22] and gamma-decay to other states would be favored.[29]

No satisfactory explanation for the 725-kev gamma-ray attributed to N^{14} has yet been found. If the transition were to occur between the uncertain 5.5-Mev level and the 4.8-Mev level, the 5.5-Mev level should have been observed to radiate to lower states.

DISCUSSION OF THE $C^{13}(d,p)C^{14}$ RESULTS

The investigation of the $C^{13}(d,p)C^{14}$ reaction at several angles is not believed to have located any new levels in C^{14} below the one excited state known to be at 6.1 Mev. This would imply, therefore, that all the excited states of N^{14} between the first and the one at 8.1 Mev have $T=0$. However the possibility of a 4.1-Mev level[2] in C^{14} may not be completely ruled out. Despite this possibility the most reasonable explanation for the presence of the weak proton groups occurring at 4.0 and 5.0 Mev on the C^{14} excitation energy scale is that they arise from O^{17} being left in its ground and first excited states as a result of oxygen contamination absorbed in the target. The 40° and 55° data indicate that the position and spacing of such groups is very nearly correct for the O^{17} states; the angular distribution of the protons which would leave O^{17} in its first excited state has the correct $L_n=0$ shape.[30] What is perhaps surprising is the over-all low intensity of the O^{17} ground-state groups compared to the strong forward maximum for the excited state.

It will be noted that in several of the proton spectra the identifiable groups occur at a lower energy than would be predicted from calculations which make use of the range-energy curves for emulsions in air and for the absorbers. The data is presented as shown since it was not known what correction could be applied which would be consistent for all plates. Two factors could enter in: a one to three percent correction to the emulsion range-energy curve because the plates were exposed in an evacuated system[31] and, secondly, a greater than anticipated thickness for the absorbers at some angles.

An angular distribution of protons which leave C^{14} in its 6.1-Mev level is shown in the fourth diagram of Fig. 5. There is some uncertainty present in that protons which leave C^{13} in its 3.1-Mev excited state from the $C^{12}(d,p)C^{13*}$ reaction differ in energy by only a little over 200 kev with those which leave C^{14} in its 6.1-Mev level. Calculation indicates, however, that the C^{13*} tracks are too short to have been measured in the $-5°$ and 10° plates. Therefore, it has been assumed that the entire group at the low proton energy end of the $-5°$ and 10° spectra correspond to the C^{14} level. The points of discontinuity in these peaks are not believed to demonstrate the presence of two proton groups since this would indicate a better than the 100-kev resolution expected. A check made with a second microscope tended to confirm this.

Taking the angular distribution of protons from the 6.1-Mev level as it stands, the shape agrees most nearly with that of the Butler $L_n=0$ theoretical curve. Since C^{13} is again the target nucleus, an $L_n=0$ angular distribution implies that the 6.1-Mev level is an odd parity state with $J=0$ or 1. This is consistent with the view that this C^{14} level is the analog of the 8.1-Mev level in N^{14}. The 6.1-Mev level of C^{14} is observed to decay to the zero spin ground state[32] and hence a $J=0$ assignment is ruled out. It is hoped that a parity determination of the C^{14} excited state will be repeated with an instrument of higher energy resolution.

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[28] E. J. Woodbury and W. A. Fowler, Phys. Rev. **85**, 51 (1952).

[29] Woodbury, Day, and Tollestrup (see reference 16) have reported a weak 5.7-Mev gamma-ray which they ascribe to a transition from the 8.1-Mev level to the first excited state. As an alternative explanation, one might consider excitation and decay of the 5.7-Mev level.

[30] Burrow, Gibson, and Rotblat, Phys. Rev. **80**, 1095 (1950).

[31] J. Rotblat, Nature **165**, 387 (1950).

[32] F. Jenkins, Phys. Rev. **74**, 355 (1948).