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$N^{15}(p,n)O^{15}$ Reaction Study*

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The excitation curve for the $N^{15}(p,n)O^{15}$ reaction at zero degrees has been measured from threshold at 3.78 Mev to 6.38 Mev bombarding energy. Resonances corresponding to excited states in O^{16} at 16.21, ~16.3, ~17.0, 17.13, 17.29, ~17.5, 17.63, 17.84, 17.97, and 18.05 Mev were observed. The 16.21-Mev state is $J^\pi=1^+$ and the 16.3-Mev state is $J^\pi=0^-$. The energy difference between the $N^{15}(p,n)O^{15}$ threshold energy and the $Li^7(p,n)Be^7$ H_2^+ beam thick-target threshold was found to be 17.6±0.5 kev. A threshold energy for $N^{15}(p,n)O^{15}$ of 3.7808±0.0011 Mev is implied if possible differences in the extrapolated end points of the $Li^7(p,n)Be^7$ thresholds with H^+ and H_2^+ beams are ignored.

I. INTRODUCTION

A STUDY of the $N^{15}(p,n)O^{15}$ reaction is of interest since it gives information on the location and spin of excited states in O^{16} above 15.66 Mev. This region has previously been studied through the use of the O^{16} photodisintegration reactions,[1] but the results from these reactions are difficult to analyze and suffer from possible large systematic errors in the energy measurement of the γ rays. An independent method for studying this region and checking the photodisintegration work is thus clearly useful. Measurements of the angular distributions of the neutrons from (p,n) reactions can give the J value of the resonances and in some cases their parity. In the present case the existence of rather broad, overlapping resonances makes it difficult to do more than place a limit on the possible spin values for most of the levels observed.

A precision measurement of the $N^{15}(p,n)O^{15}$ threshold is of value not only for the aid that it gives in determining the O^{15}-N^{15} mass difference and O^{15} ft value, but also for its convenience as a calibration point in magnetic analysis of charged particles from Van de Graaff accelerators.

II. EXCITATION CURVE

The excitation curve was measured at zero degrees with a thin (≤10 kev) gas target of N^{15} ($N^{15}\geq 75\%$, balance N^{14}) and a conventional long counter.[2] The long counter could be used since the $N^{15}(p,n)O^{15}$ ground-state reaction is the only neutron producing reaction energetically possible in the energy region covered for the target nucleus N^{15} or for the possible contaminants C^{12}, N^{14}, or O^{16}. Absolute cross sections were estimated by calibrating the long counter with a Ra-Be neutron source of known strength. Backgrounds were measured with the target filled with helium. Most of the background was probably due to neutrons originating from (p,n) reactions in the nickel entrance foil of the gas target.[3] Background was relatively small (10%) below 4.5 Mev but increased rapidly and averaged about 50% above 5 Mev. It was not determined above 6 Mev because of difficulties in machine operation. The correction above 6 Mev was made from a smooth extrapolation of the lower energy background data. Errors on the absolute cross sections are estimated at ±50%. The excitation curve obtained for the $N^{15}(p,n)O^{15}$ reaction at 0° is shown in Fig. 1.

III. ANGULAR DISTRIBUTIONS

The angular distributions were measured with the same experimental equipment as that used for the excitation curve. In this case the front face of the long counter subtended an angle of 20° at the target. The results obtained are shown in Fig. 2.

An IBM 650 computer was used to calculate a least-squares fit to the experimental angular distributions of the form

$$\sigma(\theta)=\text{const}[1+\sum_{\nu>0} b_\nu P_\nu(\cos\theta)].$$

The values of b_ν obtained are tabulated in Table I. The values given are for the smallest values of $\nu_{\max}$ which give a good fit to the experimental data. The effect of the finite angular resolution is to decrease the values of the coefficients of the higher order Legendre polynomials, that is, to make the angular distributions more isotropic. For the geometry used it was estimated that the attenuation would be approximately 15% for a sixth-order Legendre polynomial.[4] The curves through the experimental points in Fig. 2 were calculated using the coefficients given in Table I.

The energy dependence of the long counter used in this experiment was investigated for neutron energies below 1 Mev by measuring the yield from the $Li^7(p,n)Be^7$ reaction. An increase in the sensitivity was found for neutrons with an energy of a few hundred

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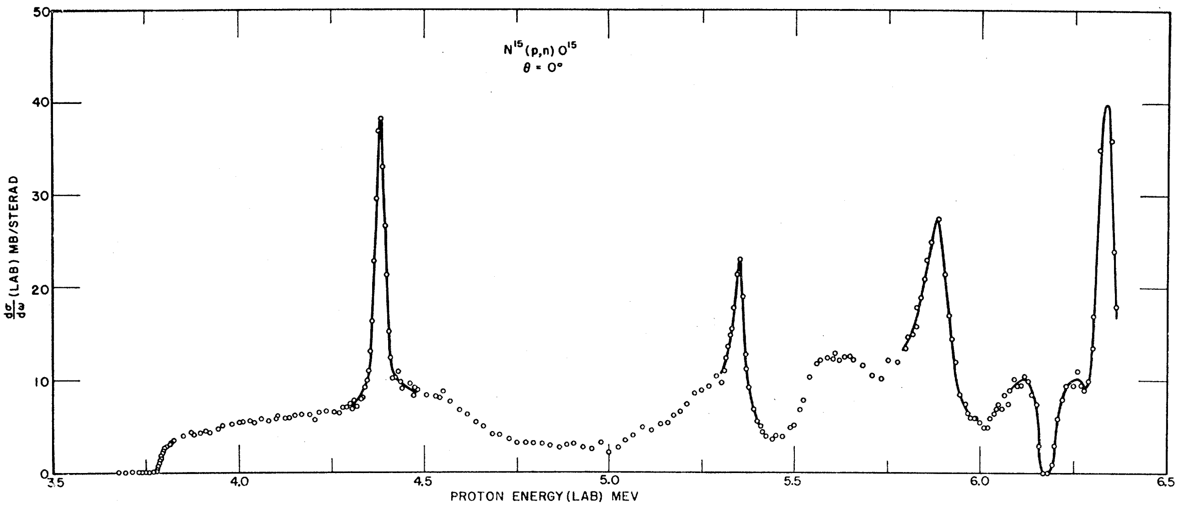

FIG. 1. Yield curve for the $N^{15}(p,n)O^{15}$ reaction taken at a laboratory angle of 0°. Statistical errors are generally smaller than the size of the data points.

kev. It is therefore possible that the rise at the back angles in the 3.948-Mev angular distribution is due to the increase in counter sensitivity for the lower energy neutrons emitted at those angles and that the angular distribution is actually much more isotropic.

IV. THRESHOLD MEASUREMENT

The $N^{15}(p,n)O^{15}$ threshold energy has been measured previously by Kington *et al.*,[5] who obtained a value of 3.776±0.008 Mev. Kistner *et al.*[6] used both an intermediate-image spectrometer and a thin-lens spectrometer to measure the end point of the O^{15} positron spectrum. Their results implied values for the $N^{15}(p,n)O^{15}$ threshold of 3.765±0.006 Mev and 3.779±0.011 Mev, respectively.

The experimental arrangement used in making the threshold measurement is shown in Fig. 3. The protons deflected through ~90° are twice the energy of the protons in the H_2^+ beam deflected through ~60°. Fortuitously, the $N^{15}(p,n)O^{15}$ threshold energy is also very closely twice the energy of the $Li^7(p,n)Be^7$ threshold. Therefore, if the $Li^7(p,n)Be^7$ threshold is measured at 60° with the H_2^+ beam, only a small (~0.25%) change in the magnetic field is needed for measurement of the $N^{15}(p,n)O^{15}$ threshold at 90° with the H^+ beam. Errors which result from the energy dependence of the magnet calibration constant are negligible, and a very accurate measurement of the energy difference between the two thresholds can be made.

The lithium targets were prepared by evaporating lithium on a tantalum backing. The N^{15} targets were in the form of $Pb(N^{15}O_3)_2$ and were prepared by adding a few drops of $HN^{15}O_3$ (99% N^{15}) to a thick lead backing. The nitrate target was stable provided the beam currents were kept below ~0.6 $\mu a/cm^2$. A number of different lithium and nitrogen targets were used in order to reduce the effect of carbon buildup. No systematic shifts in the thresholds due to such a buildup were observed. The neutrons were detected with paraffin moderated BF_3 counters.

A typical pair of Li^7 and N^{15} threshold measurements are shown in Fig. 4. A proton resonance magnetometer was used to measure the magnetic field of the deflecting magnet. The fast energy stabilization for the Van de Graaff accelerator was controlled from the H^+ beam at 90°. The 60° defining slits were set so that most of the H_2^+ beam would strike the target. To ascertain that the threshold did not depend on the position of the 60° slits, the variation of the threshold energy was investigated as a function of the slit position. The variation in the threshold was no more than would be

TABLE I. Table of coefficients for least-squares Legendre polynomial fits to the angular distributions. The differential cross section is expressed in the form

$$\sigma(\theta) = \text{const}[1+\sum_{\nu>0} b_\nu P_\nu(\cos\theta)].$$

E_p (Mev)	b_1	b_2	b_3	b_4
3.948	−0.0916			
4.250	+0.0663			
4.372	+0.891	+0.531		
4.508	+0.042	−0.011	−0.087	
5.202	−0.100	+0.122	−0.156	−0.209
5.351	+0.321	+0.175	−0.180	−0.226
5.411	−0.428	+0.387	−0.150	−0.363
5.530	−0.102	+0.114	−0.072	−0.240
5.614	−0.223	+0.916	−0.041	−0.361
5.751	−0.402	+1.182		
5.887	−0.023	+0.750	+0.919	
5.987	−0.218	+0.993	−0.361	

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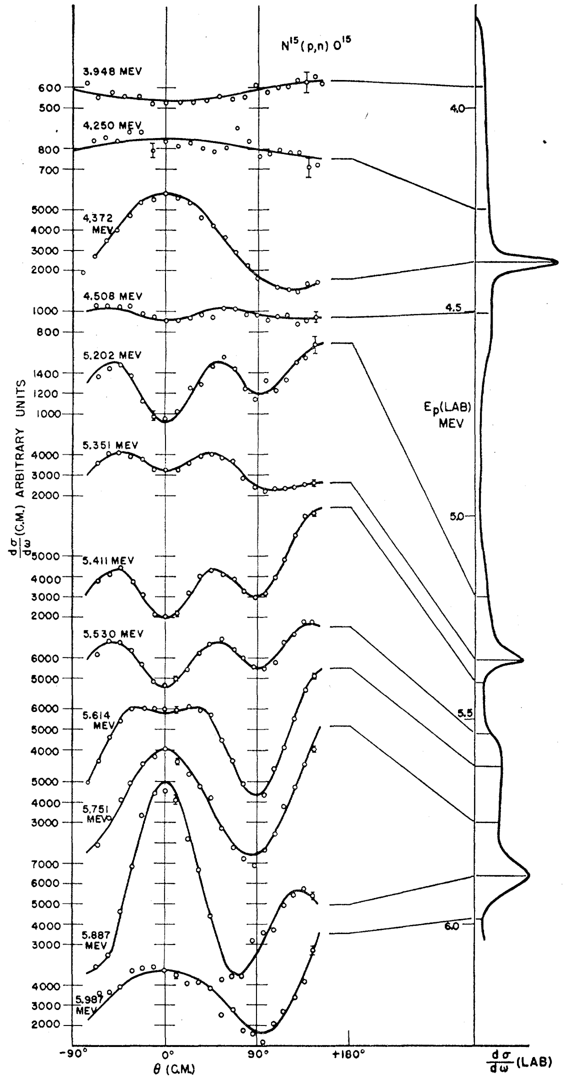

FIG. 2. Angular distributions measured for the $N^{15}(p,n)O^{15}$ reaction. The points shown are the experimental points. The curves drawn through the points were calculated from the data given in Table I. The errors shown are the statistical errors only.

expected from the estimated energy spread of the analyzed beam. The targets used were thick compared to the energy spread of the incident beam. The extrapolated end point of the yield curve was used as a measure of the threshold energy. The weighted mean of fifteen measurements of the difference in proton resonance frequency for the two thresholds was 68.9±1.9 kc/sec. The $Li^7(p,n)Be^7$ H_2^+ threshold gives an energy calibration and the energy difference is then found to be 17.6±0.5 kev.

At this point it should be emphasized that the energy difference is in terms of the thick target extrapolated end points for the $N^{15}(p,n)O^{15}$ threshold with the H^+ beam and the $Li^7(p,n)Be^7$ threshold with the H_2^+ beam. In order to obtain an accurate value for the $N^{15}(p,n)O^{15}$ threshold, the energy of the $Li^7(p,n)Be^7$ threshold must be known. This energy has been measured accurately by a number of workers using H^+ beams; a weighted mean of these measurements is 1.8811±0.0005 Mev for the extrapolated end point of the thick target curve.[7] It has been pointed out by Herring *et al.*, Bondelid *et al.*, and Newson *et al.*[8] that the internal energy of the H_2^+ molecule is large enough to increase appreciably the energy spread of the H_2^+ beam. Bondelid *et al.* also found that the midpoint of the $Al^{27}(p,\gamma)Si^{27}$ resonance at 993 kev measured with a thick target and the H_2^+ beam was too low by ~0.05%.[8] No data are available on the difference of extrapolated end points for (p,n) thresholds with H^+ and H_2^+ beams. If such an effect should be present in (p,n) thresholds, our measured energy difference, which is based on the extrapolated end point for the $Li^7(p,n)Be^7$ threshold with the H_2^+ beam, would be too large by about 0.05% or approximately 1.9 kev. A precision measurement of the difference in end points for the $Li^7(p,n)Be^7$ reaction with H^+ and H_2^+ beams would remove this possible source of error.

At the present time it seems most reasonable to ignore this possible systematic error and to calculate the $N^{15}(p,n)O^{15}$-threshold energy by assuming that there is no difference for (p,n) thresholds taken with H^+ and H_2^+ beams. The energy of the H_2^+ molecule at the $Li^7(p,n)Be^7$ threshold is 3.7632±0.0010 Mev, where the effect of the single electron in the H_2^+ molecule has been taken into account. The $N^{15}(p,n)O^{15}$-threshold energy is therefore 3.7808±0.0011 kev. (The possible systematic error discussed in the foregoing is *not* included in the estimate of the probable error.)

This result is in good agreement with the value of Kington *et al.*[5] It also agrees with the thin-lens spectrometer value of Kistner *et al.*,[6] but it does not agree with their value obtained with the intermediate-image spectrometer.

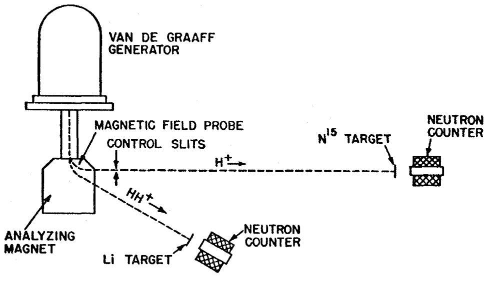

FIG. 3. Schematic diagram of the experimental arrangement for the $N^{15}(p,n)O^{15}$ threshold measurement.

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V. DISCUSSION OF RESULTS

The 0° excitation curve indicates the presence of a number of excited states of O^{16}. The bombarding energies at which these states were observed, the corresponding excitations in O^{16}, and the approximate level widths are tabulated in Table II.

The most detailed previous study of this region of excitation in O^{16} was made by Penfold and Spicer[1] from a study of breaks in the $O^{16}(\gamma,n)O^{15}$ activation curve. A summary of the levels they observed is also given in Table II. The results of Katz,[1] who has also observed this energy region, are in good agreement with Penfold and Spicer. From analysis of their data, Penfold and Spicer conclude that the bulk of the cross section for the $O^{16}(\gamma,n)O^{15}$ reaction is contributed by narrow levels and that the widths of the levels are less than 40 kev. They place an upper limit of 70 kev on the level widths which their technique can detect. The radiation widths for the levels observed were also deduced and indicate that the levels are reached by $M1$ or $E2$ radiation. They rule out $M1$ radiation on the basis of a shell model argument, but this is probably not a very stringent requirement at these energies. Spicer,[1] from a study of the angular distribution of protons, emitted in the $O^{16}(\gamma,p)N^{15}$ reaction, also concludes that the levels in this energy region are reached predominantly by $M1$ or $E2$ radiation. This implies that the levels in this region are predominantly $J^\pi = 1^+$ or 2^+.

The present experiment shows ten levels in the region covered compared to twelve reported by Penfold and Spicer. Our results, however, show only four levels with widths of ~40 kev or less. It is not clear why fewer narrow levels should be observed in the $N^{15}(p,n)O^{15}$ experiment, unless Penfold and Spicer have underestimated the widths of the levels which they can detect. In Table II this is assumed to be the case, and in some cases the levels are matched when the energies correspond even though the widths estimated from the $N^{15}(p,n)O^{15}$ reaction are somewhat too large.

The angular distribution coefficients given in Table I show large values for the P_1 and P_3 terms at many of the energies, which implies interference between levels of opposite parity. The odd terms would not be expected if the levels were reached only by $M1$ or $E2$ radiation as stated by Penfold and Spicer. The broad levels observed in the present experiment, but not by Penfold and Spicer, may therefore have negative parity.

TABLE II. Summary of levels observed in the present experiment and in the $O^{16}(\gamma,n)O^{15}$ experiment of Penfold and Spicer.

E_p (Mev)	Γ_{lab} (kev)	O^{16*a} (Mev)	O^{16*b} (Mev)
...	...	...	15.85
...	...	...	16.03
4.372	24	16.21	...
~4.5	~250	~16.3	...
...	...	...	16.47
...	...	...	16.75
...	...	...	16.95
~5.3	~200	~17.0	...
...	...	...	17.02
5.35	44	17.13	17.13
...	...	...	17.18
5.52[c]	90	17.29	...
...	...	...	17.55
~5.8	~250	~17.5	...
5.88	70	17.63	17.68
6.12	105	17.84	17.84
6.24	52	17.97	...
6.33	40	18.05	18.04

[a] Present experiment.
[b] Penfold and Spicer, reference 1.
[c] This energy assignment is based on incomplete data taken at 90°.

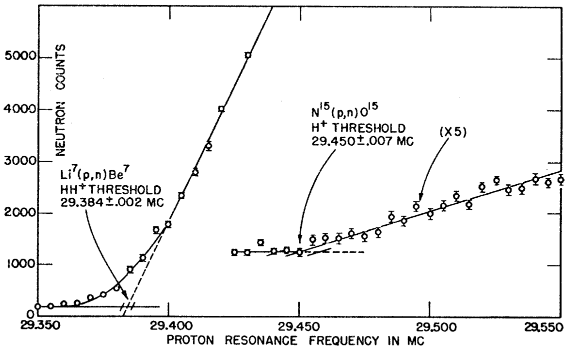

FIG. 4. Typical pair of threshold runs. The proton resonance frequency is proportional to the magnetic field of the deflecting magnet. At this field 1 kc/sec≅0.26 kev.

Some information about the spins of the levels may be obtained from the angular distributions. In particular, the narrow resonance at 4.372 Mev and the broad resonance at ~4.5 Mev are sufficiently isolated from other levels that it should be possible to make reasonable inferences about their spin and parity assignments.

The existence of a strong P_1 term in the angular distribution taken at the peak of the 4.372-Mev resonance shows that the levels are of opposite parity and the strong P_2 term rules out $J^\pi = 0^\pm$ for the sharp resonance. The only levels which can give P_2 terms, and none higher, are $J^\pi = 1^\pm$. Another possibility is 2^+, which can give a P_4 term only if formation and decay with $l=3$ is appreciable. 1^- is unlikely since the calculated coefficient for the P_2 term is not big enough to explain the measured value. Therefore, the narrow level is 1^+ or 2^+. The angular distribution measured at 4.51 Mev is nearly isotropic and hence the broad level is probably $J^\pi = 0^-$. (The weak P_1, P_2, and P_3 terms are presumably effects due to the 4.372-Mev resonance and the tails of other resonances.) A 2^+-0^- combination cannot give the P_1 interference term at $E_p = 4.37$ Mev since these angular momentum states are formed by different channel spins. Therefore, it is concluded that the two levels are 1^+ and 0^-, respectively.

Additional support for this assignment comes from the $N^{15}(p,\gamma)O^{16}$ ground-state reaction.[9] The 4.372-Mev resonance is observed, but the broad resonance at ~4.5 Mev is not. The intensity of the 4.372-Mev resonance is much less than the $E1$ transition seen at 1.05 Mev.[10] On the basis of the relative intensity an assignment of $J^\pi=1^+$ ($M1$) or $J^\pi=2^+$ ($E2$) can be made to the narrow resonance. The broad resonance at 4.5 Mev is not observed at all, which indicates an assignment of $J=0^\pm$ or a high J. The $N^{15}(p,n)O^{15}$ angular distribution measurements rule out the high J assignment and require that the levels show a large P_1 interference term. A $J^\pi=2^+-0^-$ combination does not give an interference term, as noted above. A $J^\pi=2^+-0^+$ combination does not give the P_1 term because the levels have the same parity. Therefore, it is again concluded that the 4.372-Mev resonance is $J^\pi=1^+$ and the 4.5-Mev broad resonance is $J^\pi=0^-$.

The $N^{15}(p,\alpha\gamma)C^{12}$ reaction has also been observed in this energy region[9] and neither level was found. This mode of decay for the 0^- level is forbidden by conservation of parity. There is no obvious reason why the 1^+ level should not have been observed unless the alpha-particle width is very small, due to a low penetrability for the outgoing d-wave alpha particles, for example.

At higher energies it becomes more difficult to make spin assignments, although a rather weak limit may be set. As can be seen from the Legendre polynomial coefficients given in Table I, no more than a fourth-order Legendre polynomial is required to fit the measured angular distributions. Theoretical Legendre polynomial coefficients were calculated for $J\leq 4$.[11] A fourth-order Legendre polynomial is the highest needed to fit angular distributions for $J\leq 2$. A 3^- state is formed with incoming and outgoing channel spins of one and with various combinations of incoming and outgoing orbital angular momentum values, namely, (2,2), (2,4), (4,2), and (4,4). Only the last combination gives a P_6 term in the angular distribution. However, the penetrabilities for $l=4$ neutrons and protons are small at the energies used in this experiment and the intensity contribution from the (4,4) combination should be negligible. The angular distribution for a 3^- state should then contain no Legendre polynomial higher than fourth order. All other spin values give Legendre polynomials of order higher than four. The possible spin values for the excited states observed below 6-Mev bombarding energy are therefore restricted to $J\leq 2$ and 3^-. A more detailed analysis of the angular distribution does not appear to be profitable for the following reasons: (1) Interference between levels is required because of the odd Ledengre polynomials present; thus, a two- or even three-level formula may be necessary; (2) A level may be formed with two incoming and outgoing channel spins or with two incoming and outgoing l values; (3) the neutron and proton partial widths are not known.

Further study of the $N^{15}(p,\alpha\gamma)C^{12}$ and $N^{15}(p,\gamma)O^{16}$ reactions is planned in order to restrict the spin values of the various levels to a greater degree than can be attained from the $N^{15}(p,n)O^{15}$ reaction alone, as well as to locate levels not observed in the $N^{15}(p,n)O^{15}$ reaction.

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