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Levels in N^{16} from the Total Neutron Cross Section of N^{15}†

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The total neutron cross section of N^{15} has been measured for energies from 0.45 to 2.20 MeV. Neutrons with energy spreads between 15 and 30 keV were produced by the $Li^7(p,n)Be^7$ or $T(p,n)He^3$ reaction with protons from a Van de Graaff accelerator. Resonances were observed in the total cross section at laboratory energies of 0.93, 1.11, 1.57, 1.92, and 2.02 MeV with widths of 30, 20, ≤ 10, ≤ 15, and 55 keV, respectively. The excitation energies, spins, and parities for the corresponding N^{16} levels deduced from this experiment are, respectively, 3.37, 1^+; 3.54, (0^+); 3.97, (1^-); 4.30, (1^+); and 4.39, 1^-; where the energies are in MeV.

INTRODUCTION

THE N^{16} nucleus has three excited states below a few hundred keV. Above these low-lying levels, an energy gap of several MeV exists. This level arrangement is established both experimentally and theoretically.[1,2] The three low-lying levels plus the ground state form a quartet with spins and parities of 2^-, 0^-, 3^-, and 1^- in order of increasing energy which are predominantly the result of $(1p_{1/2})^{-1}(1d_{5/2})$ and $(1p_{1/2})^{-1}(2s_{1/2})$ configurations. Above the energy gap, three levels between excitation energies of 3 and 4 MeV have been found from work by Silbert *et al.*[3] with the $N^{14}(t,p)N^{16}$ reaction and Warburton *et al.*[4] with the $N^{15}(d,p)N^{16}$ reaction. A further study has been performed in this region of excitation by Donoghue *et al.*[5] with angular distributions of neutrons scattered by N^{15}. The nature of these first few levels above the gap is not as well understood. Sikkema[6] has carefully studied a region at higher excitation in N^{16}, 4.3–5.8 MeV, by measuring the angular distribution of neutrons elastically scattered from N^{15}. A number of states were found in this energy region and, in particular, two broad states associated with the $(1p_{1/2})^{-1}(1d_{3/2})$ configuration.

In an attempt to add experimental information to the N^{16} levels, the N^{15} total neutron cross section was measured from 0.45- to 2.20-MeV neutron energy, which corresponds to an excitation energy of 2.92–4.56 MeV in the compound nucleus N^{16}. This experiment was also designed to check the feasibility of total neutron cross-section measurements with well-collimated neutron beams and small quantities of the scattering materials. With the present experimental arrangement and with the assumption that cross sections are about 2 b, the amount of material required for total cross-section measurements is one-tenth of a gram atomic weight of the scattering material.

EXPERIMENTAL TECHNIQUE

Neutron Source

Neutrons between 0.45- and 1.65-MeV energy were produced with the $Li^7(p,n)Be^7$ reaction, and above 1.65 MeV with the $T(p,n)He^3$ reaction. A Van de Graaff accelerator was used as the source of protons.

For the $Li^7(p,n)Be^7$ reaction, a thin target of lithium was evaporated onto a 0.010-in. pure gold backing. The neutron energy spread for this reaction varied from 10 to 20 keV over the appropriate energy region. The contributions from the second group neutrons appearing above 650 keV were kept to less than 5% by an adjustment of the energy bias on the neutron detector.

A tritium gas target with a 5×10^{-5}-in. nickel foil and a 0.010-in. pure gold backing was used for the $T(p,n)He^3$ reaction. The gas pressure was varied such that the neutron energy spread resulting from proton energy loss and straggling was about 30 keV.

Neutron Collimator

Neutrons produced in the target were collimated to less than 0.200 in. at the transmission sample. The collimator, consisting of a series of polyethylene cylinders 2 in. in diameter by 1.5 in. in length, was about 20 in. long. Drilled through the cylinders were center holes of varying diameters; these aligned holes formed the throat and the collimating taper, which had a minimum diameter of 0.120 in. and a maximum of 0.200 in. The target, collimator, and sample were accurately aligned in a 2-in.-diam tube, which was surrounded with borated paraffin. (See Fig. 1.) In Fig. 2,

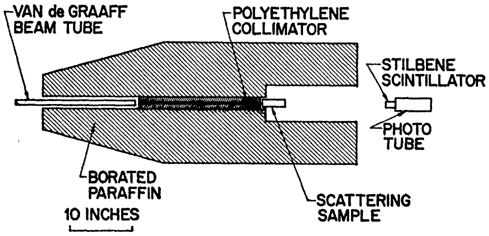

FIG. 1. A schematic diagram of the experimental geometry.

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[1] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1 (1959).

[2] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) 242, 57 (1957).

[3] M. G. Silbert, N. Jarmie, and D. B. Smith, Nucl. Phys. 25, 438 (1961).

[4] E. K. Warburton and J. N. McGruer, Phys. Rev. 105, 639 (1957).

[5] T. R. Donoghue, A. F. Behof, and S. E. Darden, Nucl. Phys. (to be published).

[6] C. P. Sikkema, Nucl. Phys. 32, 470 (1962).

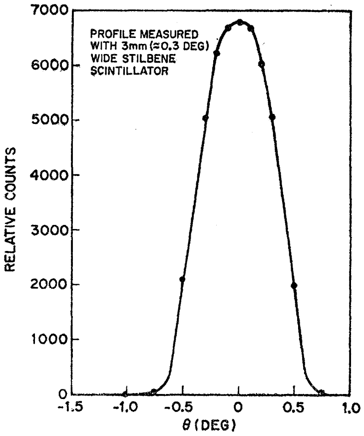

FIG. 2. The neutron beam profile at the position of the detector which was measured with a 0.12-in.-wide stilbene scintillator.

a profile of the neutron beam 20 in. from the collimator is shown.

N^{15} Sample

The characteristics of the neutron collimator permitted the use of a sample geometry 0.250 in. in diameter and 4 in. long. This small diameter allowed a transmission of ~65% to be achieved with 1.5 liters (NTP) of gas. The cell was constructed of stainless steel with blind, flat-bottomed holes in two pieces which were welded together mouth to mouth. End windows were 0.062 in. thick. A 4-in. length of 0.062-in. stainless-steel tubing connected the cell to a high-pressure stainless-steel valve whose internal volume was minimized with an insert.

The gas was transferred by immersion of the cell in liquid nitrogen over which a rough vacuum was pumped. A small Bourdon gage monitored the pressure drop in the storage vessel. A stable residual pressure of about 0.12 atm was reached in a few minutes, and the system was sealed by the closing of the valve. On warming to room temperature, the pressure within the cell was estimated to reach 10 000 psi.

The gas purity was stated by the supplier[7] to be 96.7%; the remainder was presumably N^{14}. No other significant contamination was believed to have been introduced in the filling procedure.

Detector

Neutrons were detected with a stilbene scintillator, 1 in. in diameter and 1.5 in. long, which served as a biased proton recoil detector. Gamma-ray discrimination was achieved by space-charge techniques for the last dynode of the phototube which utilizes the difference in pulse shape between electron- and proton-induced scintillations. The discrimination circuit was checked with a time-of-flight system where γ rays are easily isolated and identified. At 20 in. from the transmission sample, the detector was aligned with the collimator; the neutron profile diameter at the detector was smaller than the scintillator diameter.

Experimental Procedure

The total cross sections were measured by a transmission experiment with the N^{15} sample and a similar empty cell. The samples were aligned immediately after the collimator, about 20 in. from both the source and the detector. Figure 1 shows the geometry used in the experiment.

Data were taken at intervals of the target thickness, except at resonances, where more closely spaced points were taken. Sufficient data were collected at each energy to keep statistical errors in the cross section to less than 5%.

By shadow-cone measurements, contributions from background neutrons were determined to be negligible. In-scattering corrections were also negligible—less than 0.2%.

EXPERIMENTAL RESULTS

Absolute values of the total cross section as a function of neutron energy are shown in Fig. 3. The normalization is based on pressure measurements obtained during the gas transfer process and is believed good to ±10%. The error bars show the statistical errors only. The energy scale has been corrected for target thickness and is believed correct to ±10 keV.

Where more than one point was obtained for a given energy, the results shown represent averages. In several regions away from resonances, adjacent points at energy intervals less than the target thickness have been averaged in energy as well as in cross section. At 1.41 MeV, several points have been corrected for the effect of the second group neutrons from the Li source going through the 0.93-MeV resonance.

The curve in Fig. 3 is intended only to show the fit of the data to a monotonically decreasing function and the five obvious peaks in this energy region. All five peaks occur at energies corresponding to known levels in the N^{16} nucleus. The resonance energies and widths from this experiment are shown in Table I, along with a comparison with previous work. Slight departures of the data from the monotonically decreasing trend are also seen at 0.82, 1.35, and 1.8 MeV. None of these energies corresponds to known energy levels in either N^{16} or other nuclei expected from contaminants. However, in none of these instances does more than one data point lie outside the statistical limit of one standard deviation.

The energy region above 1.9 MeV was included largely for comparison with Sikkema's total cross sections obtained by integration over angular distributions. There is good agreement with the exceptions that Sikkema's 1.92-MeV peak is higher and the minimum at 2.02 MeV from this experiment is deeper. The com-

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[7] Isomet Corporation, Palisades Park, New Jersey.

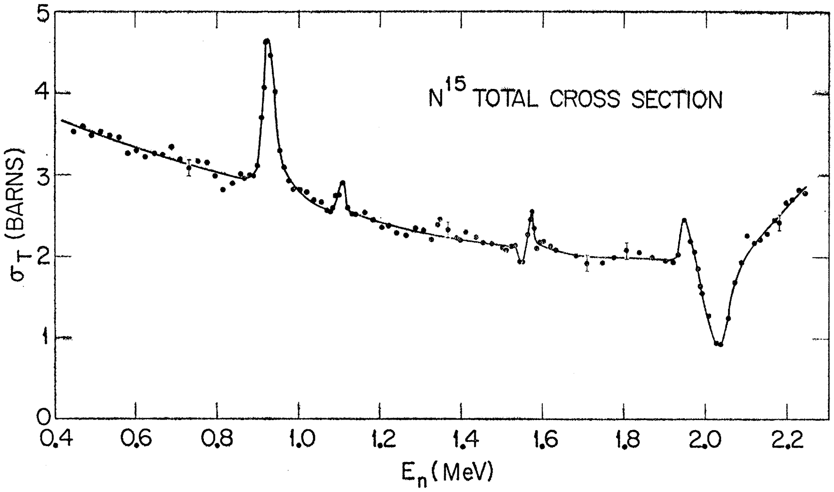

FIG. 3. The total neutron cross section of N^{15}. Statistical uncertainties are less than ±5% and the absolute value is believed accurate to within ±10%. The neutron energy spread is about 15 keV up to 1.65 MeV and about 30 keV above this energy.

parative heights of the two extremes are consistent with the fact that the energy resolution in Sikkema's experiment was better than in this work on the positive peak, and worse on the negative peak.

ANALYSIS AND DISCUSSION

Level parameter information for excited states in N^{16} can be deduced from the peaks observed in N^{15} total neutron cross sections. Since the (n,γ) channel, whose width is small relative to that for elastic scattering, is the only other competing reaction at these neutron energies, the maximum variation in the cross section $\Delta\sigma$ for an isolated level in N^{16} is given by $\Delta\sigma = (0.74/E_{\text{lab}}) \times (2J+1)$, where E_{lab} is the energy in MeV of the incident neutron in the lab system, and J is the angular momentum of the compound state. From the measured $\Delta\sigma$, the J of the observed levels can then be deduced, or at least a lower limit on J if the resonance is not completely resolved.

Information on the parity π of these levels can also be obtained from the observation of interference effects with the potential scattering background, which is dependent on the orbital angular momentum l of the incident neutron.

With a knowledge of the experimental resonance parameters and the available channel spins 0 or 1, which are the vector sum possibilities of the $\frac{1}{2}^-$ N^{15} ground state and the neutron spin, attempts are made to determine the J, l, and π of each level.

From the measured widths Γ of the resonances, reduced widths and their ratio θ^2 to the Wigner limit $3\hbar^2/2\mu a^2$ are also calculated.

For the resonances observed in this experiment, the neutron energy resolution ΔE_n is not small compared with the widths Γ of the resonances. Where $\Gamma > \Delta E_n$, the Γ's and $\Delta\sigma$'s have been corrected for the finite resolution by the assumption of a Gaussian shape for ΔE_n. The Γ's are reduced from the observed values and the $\Delta\sigma$'s increased. Where $\Gamma \leq \Delta E_n$, the upper limits on Γ and lower limits on $\Delta\sigma$ are similarly corrected. In the text, all references are made to these corrected values.

0.93 MeV

The variation in the cross section for this resonance is about 80% of that expected for a $J=1$ level in N^{16}. With a consideration of statistical uncertainties and the neutron resolution, this slight difference can be understood; furthermore, it is unlikely that higher J values would be allowed. From the angular distributions of neutrons of N^{15}, Donoghue *et al.*[5] have found this state to be formed by $l=1$ neutrons. With this result and the

TABLE I. Experimental resonance parameters from the N^{15} total cross section and comparisons.

This experiment			Silbert *et al.*[b]		Sikkema[c]	
E_n(MeV)[a]	E_{ex}(MeV)	Γ(keV)[a]	E_{ex}(MeV)	Γ(keV)	E_{ex}(MeV)	Γ(keV)
0.93±0.02	3.37±0.02	30±10	3.340±0.025	≤25	...	...
1.11±0.02	3.54±0.02	20±10	3.506±0.025	≤25	...	...
1.57±0.02	3.97±0.02	≤10	3.956±0.025	≤25	...	...
1.92±0.02	4.30±0.02	≤15	4.318±0.025	≤25	4.33±0.02	≤15
2.02±0.02	4.39±0.02	55±20	4.392±0.025	110±31	4.42±0.02	70±10

[a] Laboratory energy.
[b] M. G. Silbert, N. Jarmie, and D. B. Smith, Nucl. Phys. 25, 438 (1961).
[c] C. P. Sikkema, Nucl. Phys. 32, 470 (1962).

results of the present experiment, an assignment of $J=1^+$, $l=1$, can be made to this resonance. Since the resonance is parity-unfavored, the theoretical $\Delta\sigma$ might be slightly reduced because of the two available channel spins, giving better agreement with the peak height. The measured width of the resonance is 30±10 keV, which results in $\theta^2=0.011$.

1.11 MeV

A small peak of $\Gamma=20\pm10$ keV at this energy has a variation in cross section which is about 65% of the value calculated with the assumption that $J=0$. Even though the measurements indicate $J=0$, higher J values cannot be eliminated because of possible resolution difficulties. If $J=0$ is assumed to be correct, the measurements would imply $l=1$ because of the lack of s-wave interference effects, although this is statistically not very certain. The assignment suggested by this experiment is thus $J=0^+$, $l=1$. With the assumption that $l=1$, the resonance width implies $\theta^2=0.008$.

1.57 MeV

At this energy, an unresolved peak preceded by a small minimum was observed. The corrected lower limit on the variation in cross section is about 75% of that expected for $J=1$; however, because the resonance was not completely resolved with a 15-keV energy spread, this variation would imply $J\geq1$. If the observed minimum before the peak is statistically significant, the resonance is formed by $l=0$ neutrons since only the s-wave phase shift for potential scattering is sufficiently large to cause this destructive interference. As $J=0$ is not allowed by the variation in the cross section, an $l=0$ would require the $s=1$ channel spin and $J=1$. From calculations based on $\delta_0\approx-90$ deg at 2.02 MeV and hard-sphere scattering considerations, the s-wave phase shift δ_0 at this energy should be about -50 to -70 deg. With estimates for the level width, this region of δ_0 could produce an interference minimum before the peak with the measured energy separation of about 25 keV. More detailed fitting is difficult and inaccurate with the resonance being unresolved. If the level is assumed to be $J=1$ and formed by $l=0$, the total variation in cross section, if completely resolved, would be about 1.4 b; this would leave a reasonable value for the nonresonant residual cross section at the minimum. The width of this resonance is relatively small for $l=0$ from estimates of level spacings. A tentative assignment for this level based on the above assumptions is $J=1^-$, $l=0$; however, if the minimum is not real, the $\Delta\sigma$ would only imply a $J\geq1$. The width $\Gamma\leq10$ keV for $l=0$ results in $\theta^2\leq0.002$.

TABLE II. N^{16} level parameters.

E_n(MeV)[a]	E_{ex}(MeV)	Γ(keV)[a]	J	π	l	θ^2 [b]
0.93±0.02	3.37±0.02	30±10	1	+	1	0.011
1.11±0.02	3.54±0.02	20±10	(0)	(+)	(1)	(0.008)
1.57±0.02	3.97±0.02	≤10	(1)	(−)	(0)	≤(0.002)
1.92±0.02	4.30±0.02	≤15	(1)	(+)	(1)	≤(0.003)
2.02±0.02	4.39±0.02	55±20	1	−	0	0.005

[a] Laboratory energy.

[b] Ratio of reduced width to Wigner limit as calculated in H. E. Gove, *Nuclear Reactions*, edited by P. M. Endt and M. Demeur (North-Holland Publishing Company, Amsterdam, 1959), p. 259.

1.92 MeV

A maximum in the total cross section was observed at this energy with a height of about 80% of the theoretical value for $J=1$. With a tritium gas target used in this energy region, the neutron energy spread was approximately 30 keV; thus, the resonance was not completely resolved. Sikkema reported a tentative assignment of $J=1^+$, $l=1$, from neutron angular distribution data which is compatible with our measurements. A $\theta^2\leq0.003$ is deduced from this assignment and the measured width.

2.02 MeV

The large minimum in the cross section at this energy results from s-wave potential scattering interference with a phase shift of $\delta_0\approx-90$ deg. The variation in cross section within uncertainties equals the value theoretically expected for $J=1$. This assignment of $J=1^-$, $l=0$, is the same as previously reported by Sikkema. A $\Gamma=55$ keV implies $\theta^2=0.005$. The residual cross section at the corrected minimum $\sigma_T\approx0.8$ b indicates the contribution from higher orbital angular momentum and capture.

To summarize the level assignments for the resonances observed, Table II contains a list of E_n, E_{ex}, Γ, J, π, l, and θ^2. Parentheses are placed around assignments of a tentative nature.

CONCLUSIONS

The calculations of Elliott and Flowers[2] accurately predict the negative parity, shell-model-like states in N^{16}. These states include the quartet of levels around the ground state formed by the coupling of the $(1p_{1/2})^{-1}$ configuration with $(1d_{5/2})$ and $(2s_{1/2})$ configurations, and two levels near 5 MeV which are formed from the $(1p_{1/2})^{-1}$ and the widely split $(1d_{3/2})$ configurations. This coupling can be easily visualized from the level schemes of N^{15} and O^{17} (see Fig. 4). The proton shell structure of N^{16} is similar to that of N^{15} since both lack one of being a closed shell. Similarly, the extra neutron in N^{16} above the closed core of eight neutrons is like that in O^{17}. The ground state of N^{15} $(1p_{1/2})^{-1}$, being well isolated from its first excited state by over 5 MeV, couples to the O^{17}-like neutron particle states. Elliott and Flowers' calculations were based on the $(1d_{5/2})$, $(2s_{1/2})$, and $(1d_{3/2})$ particle states which correspond to levels in O^{17} at 0, 0.871, and 5.08 MeV.

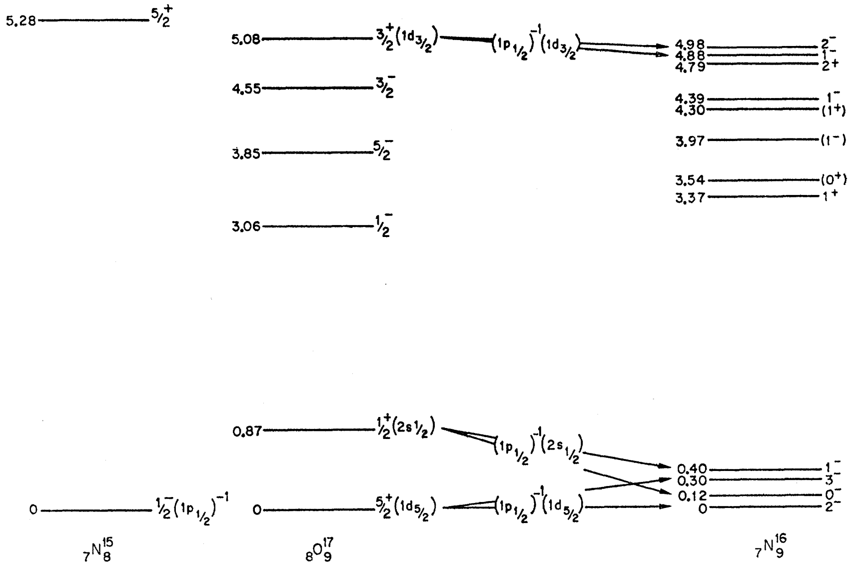

FIG. 4. Energy level schemes for N^{15}, O^{17}, and N^{16}. Solid arrows indicate states formed by coupling a $(1p_{1/2})^{-1}$ proton configuration with various neutron single-particle states from calculations of Elliott and Flowers.

Because of the success of these calculations for the negative-parity states in N^{16}, it would be interesting to compare the positive-parity levels experimentally observed in N^{16} with those which might be formed by the coupling again of the $(1p_{1/2})^{-1}$ configuration to the three negative-parity levels below 5 MeV in O^{17}. Whether these three states in O^{17} are predominantly excitations of the neutron into shell states above the core or include excitations within the core is not fully understood. A coupling of the $(1p_{1/2})^{-1}$ configuration to these O^{17}-like states ($\frac{1}{2}^-$ at 3.06 MeV, $\frac{5}{2}^-$ at 3.85 MeV, and $\frac{3}{2}^-$ at 4.55 MeV) would result in a 0^+ level, two 1^+ and 2^+ levels, and a 3^+ level in N^{16}. The observed positive-parity levels in this region of excitation of N^{16} have spin assignments which are not inconsistent with this simple coupling.

A comparison of reduced widths θ^2 for the corresponding levels in O^{17} and N^{16} adds further consistency to this coupling. Bockelman *et al.*[8] have found a reduced width θ^2 for the 5.08-MeV level in O^{17} from total neutron cross-section measurements of O^{16}. Their results for the $\frac{3}{2}^+$ $(1d_{3/2})$ level at 5.08 MeV varied between $\theta^2=0.75$ and 0.26 depending upon the nuclear radius. Sikkema's results[6] for the 1^- and 2^- levels near 5 MeV in N^{16} formed by coupling to this $(1d_{3/2})$ O^{17}-like level are $\theta^2=0.44$ and 0.55, respectively, in agreement with Bockelman's measurement. Warburton and McGruer[4] have also observed that the stripping reduced widths from the $N^{15}(d,p)N^{16}$ reaction to the four low-lying levels are similar to those of the two associated states from the $O^{16}(d,p)O^{17}$ reaction. Reduced widths of the three negative parity states in O^{17} below 5 MeV are small fractions of the Wigner limit as obtained from the O^{16} total neutron cross-section measurements[8] and from $O^{16}(p,p)O^{16}$ reaction measurements for F^{17} mirror levels.[9] The positive-parity levels in N^{16} associated with these O^{17} levels by the suggested coupling, have similarly small reduced widths as measured in the present experiment.

The six shell-model-like states of negative parity in N^{16} seem well understood from Elliott and Flowers' calculations; however, the other states require both theoretical consideration and more experimental work in order to clarify their nature.

Due to similarities in the level structure of N^{15} and O^{15} and of O^{17} and F^{17}, the level structure of F^{16} formed by the coupling of the $(1p_{1/2})^{-1}$ ground state of O^{15} with F^{17}-like proton states, should be very similar to that of N^{16}. Further experimental studies of the F^{16} nucleus would add to the understanding of this type of nuclear structure.

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[8] C. K. Bockelman, D. W. Miller, R. K. Adair, and H. H. Barschall, Phys. Rev. 84, 69 (1951).

[9] S. R. Salisbury and H. T. Richards, Phys. Rev. 126, 2147 (1962).