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Reaction $N^{15}(p,\gamma)O^{16}$†

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The reaction $N^{15}(p,\gamma)O^{16}$ has been studied up to a proton energy of 4 Mev by using a gas target and NaI(Tl) detectors. Above the well-known resonance at a proton energy of 1.05 Mev where the peak cross section is 1 mb, the cross section drops to a minimum of about 8 μb around a proton energy of 3 Mev and then increases slightly towards the higher energies. There are no pronounced new resonances and in particular the cross section up to a proton energy of about 3 Mev can be largely accounted for in terms of the high-energy tail of the 1.05-Mev resonance. There is no sign of the very strong quadrupole emission which earlier results on the inverse photodisintegration reaction had led one to expect near a proton energy of 2.8 Mev with a peak cross section of about 90 μb. Over the whole range of proton energy the gamma-ray emission is isotropic to within about 10%, and this suggests that the 13.09-Mev state of O^{16} (the 1.05-Mev resonance) is well described as $p^{-1}2s$ and probably contains less than 3% in intensity of $p^{-1}d$.

INTRODUCTION

THE radiative capture of protons by N^{15} has been investigated over the range of proton energy below 1.4 Mev.[1] Within this interval, only one resonance has been discovered, but it was a rather interesting one at a proton energy of 1.05 Mev corresponding to an excitation in the O^{16} nucleus of 13.09 Mev. This level is of width 150 kev and, from the great strength ($\Gamma_\gamma = 150$ ev, $|M|^2 = 0.10$ Weisskopf unit) of its radiative transition to the ground state, must be 1− and chiefly $T=1$.[2] It has a large proton width consistent only with its chief formation by *s*-wave protons for which its reduced width is the greater part of a single-particle unit.[3] This is confirmed[1] by the isotropy of the gamma-ray emission. Both proton and gamma-ray widths are quantitatively consistent with a description of the state as $p^{-1}2s$ in which the ground state of N^{15} is the unique parent. Although this extreme description seems to be quite satisfactory, we must inquire whether or not the admixture of $p^{-1}d$ may not be considerable. The 2*s* and 1*d* shells lie rather close together and, for the nuclei just above $A=16$ at any rate, are rather well mixed up,[4] although that case is different from the present one because there the particle-particle interactions outside the closed shell are of great importance. Even if $p^{-1}d$ figured quite largely in the *description* of the 13.09-Mev state, we should be ignorant of it from work performed so far because the importance of *d* waves in the *formation* of the state would be greatly diminished relative to that of *s* waves by the angular momentum barrier. The relative penetrabilities stand in the ratio 40:1 for protons of 1.05 Mev. It is also of some importance to locate the states containing a large proportion of $p^{-1}d$, if they exist, because such states are held by the shell model[5] to be chiefly responsible for the giant resonance seen[6] in the photodisintegration of O^{16} and this is found at an excitation of about 22.5 Mev. An approach to both these problems is obviously to carry investigation of the reaction $N^{15}(p,\gamma)O^{16}$ to higher energies and this we have done. The importance of $p^{-1}d$ in the make-up of the 13.09-Mev state should become clearer in the high-energy tail of this resonance as the relative penetrability of *d*-wave protons improves. Again, new states described chiefly as $p^{-1}d$ may be found with strong radiative capture to the ground state. Ideally this investigation should be carried through the region of the giant resonance, but this is to be found at a proton energy of about 11 Mev and was not attainable in the present investigation.

A further reason for the present work is the possibility of finding strong *E*2 transitions. There has been reported[7] a resonance in the inverse reaction $O^{16}(\gamma,p)N^{15}$ at a gamma-ray energy of 14.7 Mev of characteristics which seemed to require[8] an exceptionally strong *E*2 nature for the photon absorption and suggested a state of collective motion. This resonance would be found at a proton energy of about 2.8 Mev in the present investigation, with a peak cross section of about 90 μb.

EXPERIMENTAL METHOD

Gaseous N^{15} of 99% purity[9] at a pressure of 157 mm Hg at 21°C was contained in a thin-walled brass cylinder of length 5 cm and diameter 1 cm sealed at one end by a thin brass plate and at the other by a nickel

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[1] Schardt, Fowler, and Lauritsen, Phys. Rev. **86**, 527 (1952); A. Kraus, Phys. Rev. **94**, 975 (1954).

[2] D. H. Wilkinson, Phys. Rev. **90**, 721 (1953).

[3] A. M. Lane, Atomic Energy Research Establishment Report T/R 1289, 1954 (unpublished).

[4] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955); M. G. Redlich, Phys. Rev. **99**, 1427 (1955).

[5] D. H. Wilkinson, *Proceedings of the 1954 Glasgow Conference on Nuclear and Meson Physics* (Pergamon Press, London, 1955), p. 161.

[6] A. S. Penfold and B. M. Spicer, Phys. Rev. **100**, 1377 (1955); Stephens, Mann, Patton, and Winhold, Phys. Rev. **98**, 839 (1955).

[7] B. M. Spicer, Phys. Rev. **99**, 33 (1955).

[8] D. H. Wilkinson, Phys. Rev. **99**, 1347 (1955).

[9] This N^{15} was supplied by Professor T. I. Taylor of Columbia University, to whom our very best thanks are given.

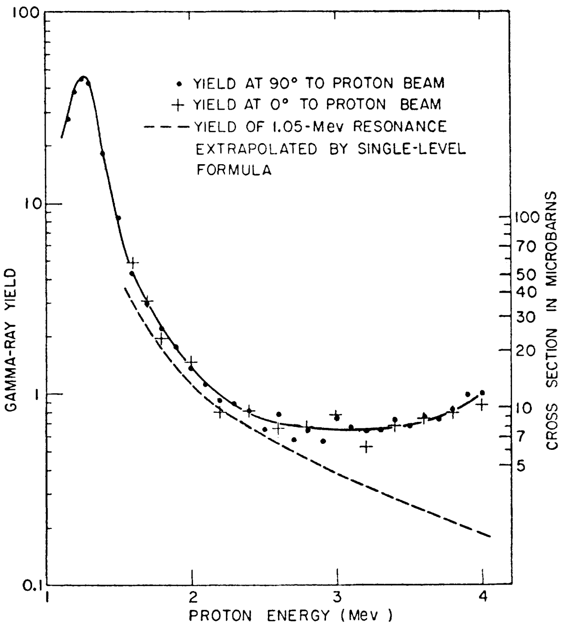

Fig. 1. The gamma-ray yield as a function of proton energy in the reaction $N^{15}(p,\gamma)O^{16}$ taken with a target semithick at the lowest proton energies and thin at the high. The energy shown is that of the protons incident upon the nickel foil of thickness 50 micro-inches which sealed the gas target. The energy of the protons entering the gas is therefore less than that shown here by about 120 kev at 1.25 Mev, 90 kev at 2.5 Mev, and 50 kev at 4 Mev. The (total) cross section scale has been corrected for the target thickness and applies only over the higher proton energies. Yields at both 0° and 90° are shown. The dashed curve gives the simple theoretical extrapolation of the *s*-wave resonance at a proton energy of 1.05 Mev (1.25-Mev incident proton energy under our conditions).

foil of thickness 50 micro-inches. The inside of the gas target was coated with gold to minimize unwanted reactions. Proton currents of from 0.02 to 1 μa were used depending on the conditions. Gamma rays were detected in a cylindrical NaI(Tl) crystal of length 5 cm and diameter 4 cm. The crystal was placed at a distance of about 7 cm from the target in the 90° position with its axis parallel to that of the target tube for the greater part of the measurements. The measurements at 0° were made with the crystal at the same distance from the center of the target tube and again in the "broadside" position.

Over the whole range of bombarding energy used here, namely up to 4.0 Mev, the overwhelming majority of the gamma rays observed by the crystal came from the N^{15} as was checked by replacing the nitrogen by 300 mm Hg of hydrogen and repeating the observations.

The response of the crystal to high-energy gamma rays was determined in bombardments in the region of the 1.05-Mev resonance where the yield of capture gamma rays is great. At higher proton energies the high-energy spectrum observed with a 20-channel kicksorter was generally clearly that of a high-energy gamma ray and showed a well-defined peak which enabled the intensity to be estimated with accuracy. In the region of resonances in the much more prolific reaction $N^{15}(p,\alpha)C^{12*}$, the great intensity of 4.4-Mev gamma rays from the first excited state of C^{12} caused some trouble as their piling-up tended to interfere with clear definition of the spectrum of capture radiation. In such cases the proton current was lowered until the spectrum of the capture radiation showed either a peak or at least a plateau over several channels of the kicksorter, from which the intensity could again be accurately found.

An absolute measurement was not attempted but rather the results were reduced in terms of the already-determined parameters[1] of the 1.05-Mev resonance. Because of the protons' energy loss in the nickel foil and of the considerable thickness of the target, the 1.05-Mev resonance did not appear at that energy but rather at about 1.25 Mev. This accorded well with calculations. Again, because of the thickness of the target the relative yields at the resonance and at a high proton energy could not be taken as a direct measure of the relative cross sections. The cross section for a low proton bombarding energy varied considerably from point to point within the target as the proton energy changed on passing through the gas, whereas at the higher proton energies the cross section was effectively constant within the target tube. The correction on this account was again computed by using the published constants for the resonance.

Corrections for the background above the spectrum due to the capture radiation were always carefully determined. They varied from negligible proportions at the lower proton energies to as much as 15% at those higher proton energies which were in the region of resonances in the $N^{15}(p,\alpha)C^{12*}$ reaction. This background correction was due in part to cosmic rays, the irradiation being naturally longer when the competing reaction necessitated the use of very small currents. It was also due in part to addition pulses between the capture radiation and the 4.4-Mev radiation from C^{12}. The current was always lowered until this latter source was very small.

The observed intensities of the capture radiation were finally corrected for the change of gamma-ray energy with proton energy which was observed to take place in the expected manner and also for the change in the pair-production cross section in sodium iodide with gamma-ray energy.

The final results of the investigation are shown in Fig. 1. The 1.05-Mev resonance is seen at higher energy for the reason given; its width is also greater than 150 kev because the target is semithick at these low energies. The right-hand ordinate, the cross-section scale, has been corrected for the target thickness and should not be extrapolated for measurements at the lower proton energies. For a direct cross-section comparison rather than the displayed comparison of yields, it should be remarked that the cross section on the 1.05-Mev resonance has been taken[1] as 1 mb. It is seen then from the figure that the correction applied in deducing the absolute cross sections at the higher energies on account of the target thickness for protons in the neighborhood of the resonance is roughly a factor of two.

The figure also shows the results obtained at 0° in the region of higher energies, corrected for the differing geometry in the two positions of irradiation.

DISCUSSION

The results displayed in Fig. 1 demonstrate at once that no resonance of height within an order of magnitude of 90 μb is present anywhere near a proton energy of 2.8 Mev. The photodisintegration results[7] must therefore contain some misinterpretation and we need have no further concern with the possibility of strong collective quadrupole oscillations in this present region of excitation in O^{16}.

No other strong resonance than that at 1.05 Mev is manifest in these results.[10]

The dashed line of Fig. 1 is obtained simply by extrapolating the 1.05-Mev resonance to higher energies assuming that the reduced proton and gamma-ray widths are energy-independent, *viz.*, increasing the proton width proportionally to the product of the proton's momentum and s-wave penetrability and the gamma-ray width proportionally to the cube of its energy. This simple procedure is incorrect over so wide an energy range but the agreement to within 50% between the dashed line and the experimental points, which persists as high as a proton energy of 3 Mev by which time the cross section has fallen to less than 1% of its peak value, shows that the s-wave resonance at 1.05 Mev dominates the cross section over a wide range of proton energy. The increase in cross section towards 4 Mev shows the effect of resonances at higher energy.

From the 0° results it can be seen that the emission is isotropic to 10% or better over the whole range investigated. As we mentioned in the Introduction, we may use this fact to make some remarks about the possible admixture of $p^{-1}d$ in the predominantly $p^{-1}s$ state at 13.09 Mev since we have just seen that this state seems to be responsible for most of the yield even as high as a proton energy of 3 Mev. For formation of the 1− intermediate state by both s-wave and d-wave protons, only channel spin 1 can be used and so the theoretical angular distribution due to interference between the s- and d-wave effects is unambiguous, at least when the admixture of d wave remains small. The result is that, at 3 Mev, an admixture of 5% of d wave in *amplitude* in the formation of the compound state would give rise to a 10% anisotropy in the gamma-ray emission. This, together with the remark that the relative penetrabilities of s and d waves at 3 Mev are about 6:1 suggests that the 13.09-Mev state probably contains less than about 3% in *intensity* of $p^{-1}d$. In making this estimate we assume that the s- and d-wave reduced widths are simply proportional to the intensities of the $p^{-1}s$ and $p^{-1}d$ components. This small admixture of d state may be a little surprising and suggests that the center-of-gravity of the $T=1$ $p^{-1}d$ may indeed be rather far away as would be desired according to the shell model of the giant resonance.[5]

The observed isotropy of emission allows a stronger remark to be made about possible quadrupole transitions in this region because such emission is proportional to $1+\cos^2\theta$. The observed isotropy therefore excludes the cross section containing very much more than 10% of quadrupole state and this corresponds to a peak cross section of about 1 μb.

More recent work[11] on the inverse $O^{16}(\gamma,p)N^{15}$ reaction has failed to reproduce the earlier results[7] near a gamma-ray energy of 15 Mev. However, a group of low-energy protons is found which, if they represent transitions to the ground state of N^{15}, would imply for the (p,γ) reaction here studied a resonance at a proton energy of about 2.6 Mev with a peak cross section of about 30 μb. This does not appear in these present results and so the alternative interpretation, that the photoproton peak represents resonant absorption at a gamma-ray energy of about 20 Mev with transitions to the N^{15} states at 5.3 Mev, must be correct.

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[10] Similar work to that reported here has been carried out at Columbia University [R. D. Bent (private communication)]. The same general trend is shown in that work which, however, indicates a broad feeble resonance centered on a proton energy of about 3 Mev. Such a resonance cannot be excluded by the present work although it does not seem comparable in strength with the nonresonant background.

[11] S. A. E. Johnasson and B. Forkman (unpublished).