# Gamma Rays from $N^{15}(p,\alpha\gamma)C^{12}$ and $N^{15}(p,\gamma)O^{16}$†

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A new resonance in the reaction $N^{15}(p,\alpha\gamma)C^{12}$ giving the 4.43-Mev $\gamma$ ray from the first excited state of $C^{12}$ has been found at a proton energy of 1.64±0.03 Mev. The angular distribution of the $\gamma$ rays indicates that the resonant state in the compound nucleus $O^{16}$ at an excitation energy of 13.65 Mev has spin and parity equal to $1^+$ or $2^-$. The resonance at 1.05-Mev proton energy has been reinvestigated. At this resonance the capture $\gamma$ rays from the reaction $N^{15}(p,\gamma)O^{16}$ are found to be isotropic, which indicates that this 13.09-Mev level of $O^{16}$ has spin equal to 1. A search was made for capture $\gamma$ rays at the 0.340-Mev resonance of $N^{15}(p,\alpha)C^{12}$ but there were less than 1 percent of the number at the 1.05-Mev resonance. Therefore, it seems that these two levels do not have identical spin, parity, and isotopic spin values.

THE reaction $N^{15}(p,\alpha\gamma)C^{12}$ has been studied by Schardt, Fowler, and Lauritsen,[1] by Kraus, French, Fowler, and Lauritsen,[2] and by Barnes, Neilson, and James.[3] In the work herein reported the excitation function for this reaction has been extended to a proton energy of nearly 2 Mev. Protons from the 2-Mv electrostatic accelerator of the Kellogg Radiation Laboratory were magnetically analyzed and used to bombard a titanium nitride (TiN) target enriched to 31 percent $N^{15}$. The detector was a $1\frac{1}{2}$-in. diameter by 2-in. long Na(Tl) crystal which was cemented to a 5819 photomultiplier tube. The tube was surrounded by three magnetic shields. The output was fed through a conventional pulse amplifier, a single channel differential discriminator, and then to decade scalers. The channel was set to select pulses only in the region of the pair and Compton electron peaks of the 4.43-Mev $\gamma$ rays. The measured excitation curve corrected for a small background is shown in Fig. 1. The resonance at 1.21-Mev bombarding energy is known from the work of Schardt *et al.*[1] A new resonance is observed at 1.64±0.03 Mev with a width of half-maximum of approximately 150 kev. The asymmetrical shape of the resonances shows that the distribution of $N^{15}$ atoms in the target was not uniform, as to be expected from the mode of chemical preparation. The excitation function rises again above 1.9 Mev. Preliminary investigations up to 2.4 Mev indicated a broad resonance somewhat above 2.4-Mev proton energy.

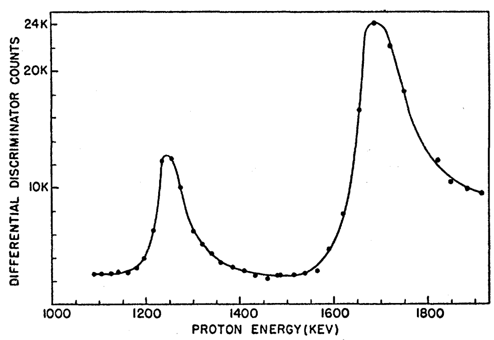


FIG. 1. Excitation function for the reaction $N^{15}(p,\alpha\gamma)C^{12}$.

The angular distribution of the 4.43-Mev $\gamma$ rays from the 1.64-Mev resonance is shown in Fig. 2. The points have been corrected for background and absorption. The curve shown is given by $1+a\cos^2\theta$ with $a=0.30\pm0.04$. The errors are statistical errors compounded with a 1 percent error of the absorption corrections. If the coefficient of $\cos^2\theta$ is corrected for the finite solid angle of the detector, the corrected value is $a=0.32\pm0.04$.

Since there are no significant $\cos^4\theta$ terms in the angular distribution, it seems likely that the compound nucleus is formed by $p$-wave protons. $N^{15}$ and the proton are assumed to have spin and parity equal to $\frac{1}{2}^-$ and $\frac{1}{2}^+$, respectively. The excited state of $C^{12}$ is known[2] to be $2^+$, its ground state, $0^+$. If one specifies the compound state of $O^{16}$ at this point the relevant proton and $\alpha$-particle waves are then determined.

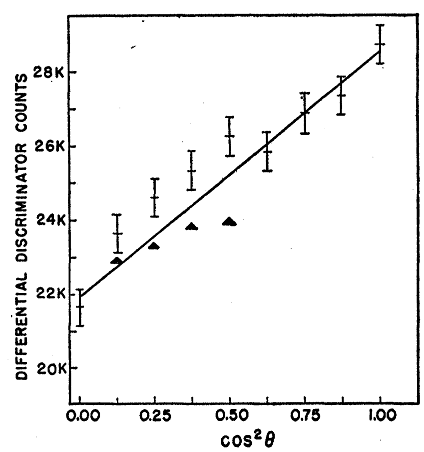


FIG. 2. Angular distribution of the 4.43-Mev $\gamma$ rays from the 1.64-Mev resonance in $N^{15}(p,\alpha\gamma)C^{12}$. The triangles are the measured points for $\theta>90°$.

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[1] Schardt, Fowler, and Lauritsen, Phys. Rev. **86**, 527 (1952).
[2] Kraus, French, Fowler, and Lauritsen, Phys. Rev. **89**, 299 (1953).
[3] Barnes, Neilson, and James, Can. J. Phys. **30**, 717 (1952).

TABLE I. Theoretical angular distributions of the 4.43-Mev $\gamma$ rays.

| Spin of the $O^{16}$ state | Lowest $l_p$ | Lowest $l_\alpha$ | Angular distribution |
|---|---|---|---|
| $0^+$ | 1 | 2 | 1 |
| $0^-$ | 0 | Forbidden | None |
| $1^+$ | 1 | 2 | $(7+3\cos^2\theta)+2A(5-3\cos^2\theta)$ |
| $1^-$ | 0 | 1 | 1 |
| $2^+$ | 1 | 0 | $1+\cos^2\theta$ |
| $2^-$ | 2 | 1 | $(3+15\cos^2\theta-16\cos^4\theta)+6A(1-3\cos^2\theta+4\cos^4\theta)$ |
| $3^+$ | 3 | 2 | $(8-3\cos^2\theta+5\cos^4\theta)+2A(5-12\cos^2\theta+15\cos^4\theta)$ |
| $3^-$ | 2 | 1 | $27+78\cos^2\theta-55\cos^4\theta$ |

Since no information is available about the emission of long-range $\alpha$ particles from this state to the ground state of $C^{12}$, all possible compound states must be considered. As an additional complication, the proton and $N^{15}$ can come together to form compound systems of channel spin 0 to 1. The channel spin 0 will contribute only if the parity of the $O^{16}$ state is $(-1)^{J+1}$, where $J$ is its spin. Table I gives a summary of the relevant orbital angular momenta and the theoretical angular distributions. The angular distributions were calculated assuming only the lowest possible values of $l_p$ and $l_\alpha$, the relative angular momenta of the proton and $\alpha$ particle, respectively, in units of $\hbar$. The quantity $A$ is the amount of channel spin 0 compared to unity for channel spin 1. A reasonable fit is obtained by assigning $1^+$ as the spin and parity of the $O^{16}$ state and choosing $A\approx 1/14$. However, this fit is not unique. An assignment of $2^-$ for the $0^{16}$ state will also fit with $A\approx\frac{2}{3}$ when it is considered that some protons of higher $l$ waves probably contribute to the reaction and the effect of the resonance at a higher energy ($\gtrsim 2.4$ Mev) is not known. This resonance could conceivably cause a change of 0.05 in the coefficient of $\cos^2\theta$ at 1.64 Mev. Therefore the spin and parity of the state of $O^{16}$ at 13.65-Mev excitation are either $1^+$ or $2^-$.

Considerable discussion has been centered on the 1.05-Mev resonance in the reactions[4] $N^{15}(p,\gamma)O^{16}$ and $N^{15}(p,\alpha)C^{12}$. In order to obtain more information about this level, the angular distribution of the $\gamma$ rays from the reaction $N^{15}(p,\gamma)O^{16}$ was measured. The measured distribution is isotropic to about 7 percent (statistical error). It is assumed that all the $\gamma$ rays represent direct transitions ($\sim$13 Mev) to the ground state of $O^{16}$ as indicated by their energy as measured with the scintillation counter. Table II gives a list of the theoretical angular distributions of these $\gamma$ rays. The only isotropic distributions are from spin 1 states and the spin and parity of this state of $O^{16}$ at 13.09-Mev excitation are either $1^-$ with $A=0$ or $1^+$ with $A=\frac{1}{2}$.

TABLE II. Theoretical angular distributions of the capture $\gamma$ rays.

| Spin of the $O^{16}$ state | Lowest proton wave | Angular distribution |
|---|---|---|
| $0^+$ | $p$ | Forbidden |
| $0^-$ | $s$ | Forbidden |
| $1^+$ | $p$ | $(1+\cos^2\theta)+2A(1-\cos^2\theta)$ |
| $1^-$ | $s$ | 1 |
| $2^+$ | $p$ | $1+\cos^2\theta$ |
| $2^-$ | $d$ | $(1-3\cos^2\theta+4\cos^4\theta)+6A(\cos^2\theta-\cos^4\theta)$ |

A search was made for capture $\gamma$ rays at the 0.340-Mev resonance of the reaction $N^{15}(p,\alpha)C^{12}$. Less than 1 percent of the number at the 1.05-Mev resonance were found. This result means that quite probably the two states have a different set of spin, parity, and isotopic spin values.

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