Angular Distribution of Gamma-Rays and Short-Range Alpha-Particles from $N^{15}(p,\alpha\gamma)C^{12}$†

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Measurements of the angular distributions of gamma-rays and alpha-particles from the reaction $N^{15}(p,\alpha\gamma)C^{12}$ indicate that the 4.432-Mev excited state of C^{12} is 2^+ or >4, that the 12.51-Mev level of O^{16} is 2^- or >5, that the 12.95-Mev level is 2^- or >5, and that the 13.24-Mev level is 4^+ or >5.

THE reaction $N^{15}(p,\alpha\gamma)C^{12}$, in which the gamma-ray energy is 4.432 ± 0.010 Mev, exhibits strong resonances[1] at 429, 898, and 1210 kev, and we have measured the angular distribution of gamma-rays and alpha-particles relative to the protons at these resonances.

Protons from the 1.6-Mv electrostatic generator of the Kellogg Radiation Laboratory were magnetically analyzed and used to bombard a titanium nitride (TiN) target prepared using nitrogen enriched to 31 percent N^{15}. The emitted gamma-rays were detected by a scintillation counter consisting of a glass cell, containing about 100 cc of a solution of terphenyl in xylene, cemented to a 5819 photomultiplier tube. The center of the phosphor was 9.5 cm from the target. The amount of absorbing material between target and phosphor was small, and the symmetry of the arrangement was tested with natural sources of Co^{60} and ThC″ and with the isotropic gamma-rays from the 935-kev resonance in $F^{19}(p,\alpha\gamma)O^{16}$.

The angular distribution curves from gamma-rays from the 429- and the 898-kev resonances in $N^{15}(p,\alpha\gamma)C^{12}$ are shown in Figs. 1 and 2, respectively. The points plotted are the measured values corrected for background and absorption. The absorption corrections averaged about one percent and in no case exceeded four percent.

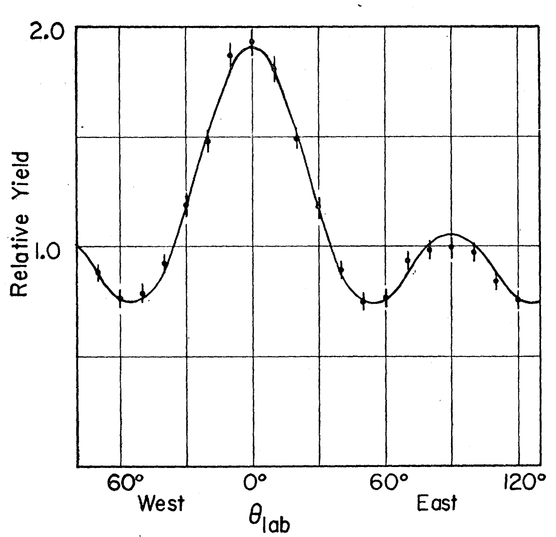

FIG. 1. Angular distribution of gamma-rays at the 429-kev resonance. The theoretical curve is for $x=0.82$.

It may be seen that the two angular distributions are very similar, and analysis shows that they may be accounted for under the following assumptions: (a) the ground state of N^{15} has spin $\frac{1}{2}$ and odd parity (denoted $\frac{1}{2}^-$), the proton being $\frac{1}{2}^+$; (b) the O^{16} compound states formed at 429 and 898 kev are both 2^- and are formed by d wave protons; (c) the O^{16*} breaks up by emission of p wave alpha-particles, leading to a 2^+ state of C^{12} which decays to the ground state 0^+ by emission of electric quadrupole gamma-rays.

The proton and N^{15} may collide with parallel or antiparallel spin orientations. If we suppose that in a fraction x of all cases the O^{16} is formed from the antiparallel configuration, the relative probability for emission of a gamma-ray at an angle θ to the proton beam is given by

$$W(\theta)=\left(\frac{1}{2}+\frac{5}{2}\cos^2\theta-\frac{8}{3}\cos^4\theta\right)+\frac{x}{1-x}(1-3\cos^2\theta+4\cos^4\theta).$$

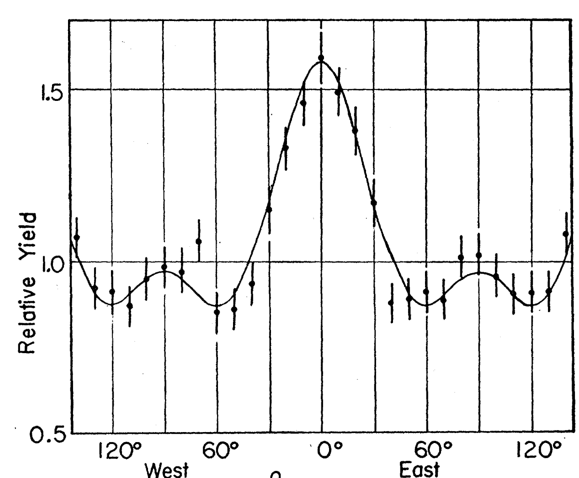

FIG. 2. Angular distribution of gamma-rays at the 898-kev resonance. The theoretical curve is for $x=0.58$.

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* On leave of absence from Cavendish Laboratory, Cambridge, England.
[1] Schardt, Fowler, and Lauritsen, Phys. Rev. 86, 527 (1952).

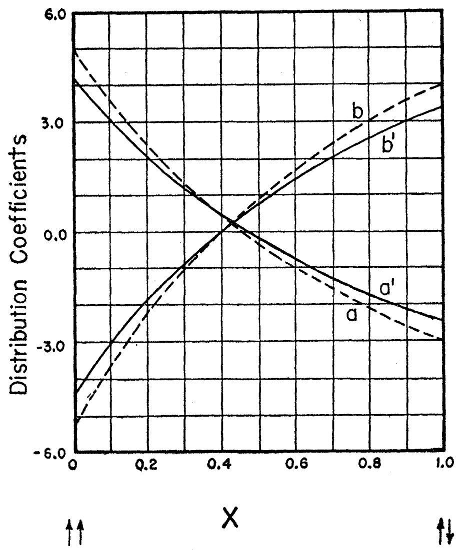

FIG. 3. Angular distribution coefficients for the assignment (2 2^- 1 2^+). The dashed curves are theoretical values. The solid curves are corrected for the gamma-ray detector solid angle.

In obtaining this expression we ignore any possible contribution from f wave alpha-particles in the breakup of the O^{16}, on the grounds that they are strongly discouraged by the potential barrier. If the theoretical distribution function is normalized to the form

$$W(\theta)=1+a(x)\cos^2\theta+b(x)\cos^4\theta,$$

a and b can be plotted as functions of x. These functions are shown as dashed curves in Fig. 3.

The finite solid angle subtended by the gamma-ray detector modifies the ideal pattern somewhat. Its effect is to replace a and b in the above formula by different values a' and b'. These are plotted as the solid curves in Fig. 3. The experimental data of Fig. 2 (898 kev) were analyzed by an approximate least squares method and gave $a'(x)\simeq -0.927$ and $b'(x)\simeq 1.471$. These correspond to $x\simeq 0.62$ and $x\simeq 0.60$, respectively. The actual least square error is obtained, however, with $x=0.58$; the estimated probable error on this value is ± 0.03. The theoretical distribution for $x=0.58$ is shown as the solid curve in Fig. 2, and it can be concluded that the experimental results conform to our initial assumptions about the spins and parities of the nuclear states involved. The result obtained at the 429-kev resonances can be fitted in a similar way by putting $x=0.82\pm 0.04$ (solid curve of Fig. 1).

Our assumption that the 4.432-Mev level of C^{12} is 2^+ is supported by studies[2] of the reaction $B^{11}(p,\gamma\gamma)C^{12}$ and is in agreement with nearly all theoretical models of this nucleus. The 898-kev gamma-ray distribution indicates that the 12.95-Mev level of O^{16} is 2^- or greater than five, and that the 4.432-Mev state of C^{12} is 2^+ or greater than four. The 429-kev distribution indicates that the 12.51-Mev level of O^{16} is 2^- or greater than five.

[2] Hubbard, Nelson, and Jacobs, Phys. Rev. **87**, 378 (1952).

Figure 4 shows the angular distribution of alpha-particles at the 898-kev resonances as measured by the $10\frac{1}{2}$-inch variable angle (0°–160°) proton spectrometer of the Kellogg Radiation Laboratory. The target was evaporated KNO_3 (enriched to 61 percent N^{15}). The points plotted are the measured points corrected for a small background, for the fact that some of the alpha-particles leave the target singly charged, for the change in solid angle due to the motion of the center of mass, and for the fact that some of the particles are slowed down by irregularities in the target. The theoretical curve shown in Fig. 4 is

$$W(\theta)\sim 7-6\cos^2\theta,$$

obtained from the assignment (2 2^- 1 2^+) with $x=0.60$.[3] The agreement with the experimental points is considered satisfactory in view of the number of corrections applied to the original data. The point at 117° is high, because near this angle the scattered protons have the same energy as the alpha-particles and were not separated from the alpha-particles by the spectrometer. This distribution is in agreement with the assignments made on the basis of the gamma-ray distribution.

We have also measured the gamma-ray distribution at the 1210-kev resonance, but in preliminary measure-

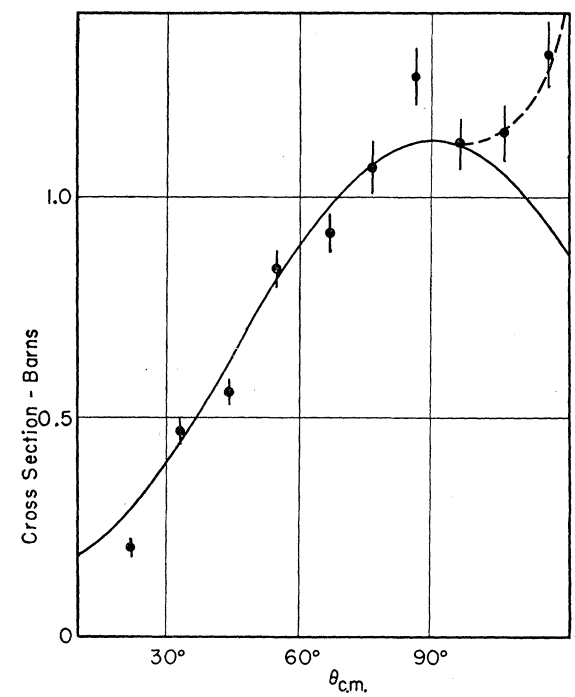

FIG. 4. Angular distribution of short-range alphas from the 898-kev resonance. The solid curve represents $W(\theta)\sim 7-6\cos^2\theta$. The dashed line indicates the scattered protons. The probable error of the cross section is ± 20 percent.

[3] In the assignment $(lJ^{\pm}l'J'^{\pm})$, the first number describes the angular momentum of the proton wave; the second, the spin and parity of the state in O^{16}; the third, the relative angular momentum of the emitted alpha-particles; and the fourth, the spin and parity of the 4.432-Mev excited state of C^{12}.

ments we were unable to determine uniquely the spin and parity of the excited state of O^{16} since the theoretical distributions for the assignments 3^-, 4^+, and 5^- differ only by small amounts. The short-range alpha-particle distribution was then measured at this resonance. The

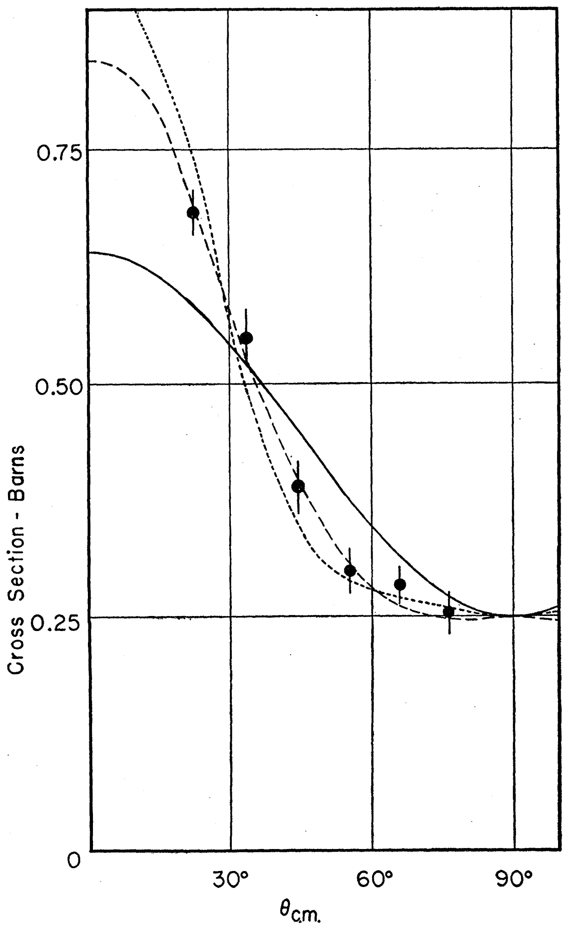

FIG. 5. Angular distribution of short-range alphas from the 1210-kev resonance. The solid curve is for ($2\ 3^-\ 1\ 2^+$), the curve of long dashes is for ($3\ 4^+\ 2\ 2^+$), and the dotted curve is for ($4\ 5^-\ 3\ 2^+$).

points are plotted in Fig. 5. The solid curve is for ($2\ 3^-\ 1\ 2^+$); the dashed curve is for ($3\ 4^+\ 2\ 2^+$); and the dotted curve is for ($4\ 5^-\ 3\ 2^+$). From this distribution we can conclude that the state is not 3^-. The final measurement was a more accurate gamma-ray distribution.

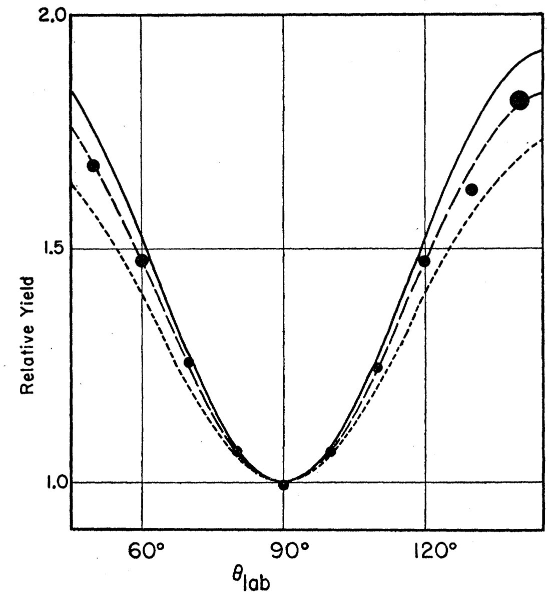

FIG. 6. Angular distribution of gamma-rays at the 1210-kev resonance. The curves correspond to the assignments in Fig. 5.

During this experiment the target was set at 45° with respect to the proton beam. The gamma-rays were measured at angles such that they did not pass through the target material, so there were no absorption corrections. Statistical errors were minimized by taking on the order of 10^4 counts at each point. The results are shown in Fig. 6. From this curve we conclude that the excited state is 4^+. The gamma-ray distribution at this resonance enables one to show, independently of the results at the other resonances, that the excited state of C^{12} is 2^+ or greater than four.

In each case for an assignment in O^{16}, states of spin up to but not always including six were considered in the theoretical calculations. States with such high angular momentum would require proton waves of orbital angular momentum greater than five, and the barrier factors for such waves make the formation of such states highly improbable. In all cases we have considered only the minimum allowed l values for the incoming protons and outgoing alpha-particles.

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