Cross Sections for Elastic Scattering and Reactions Due to Protons on N^{15}†

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Absolute differential cross sections were measured for the reactions $N^{15}(p,p)N^{15}$, $N^{15}(p,\alpha_0)C^{12}$ (ground state), and $N^{15}(p,\alpha_1)$-C^{12*} (first excited state). Thin gas targets, enriched up to 98% in N^{15}, and a 6-mil CsI(Tl) crystal detector were used. Numerous angles were studied for bombarding energies between 1 Mev and 3.6 Mev. Spins and parities are discussed where resonances suggest the existence of excited states in O^{16}. Results are as follows:

E_p (kev)	Resonant mode	Spin, parity
1028	$p\alpha_0\alpha_1\gamma$	1^-
1210	$p\alpha_0\alpha_1$	3^-
1640	$p\ \ \alpha_1$	1^+
1890	α_0	
1985	α_1	2^-
3000	$p\alpha_0\alpha_1$	4^+
3300	$p\ \ \alpha_1$	2^-
3350	α_0	2^+
3520	$p\alpha_0\alpha_1$	1^-, 2^+, 3^-, 4^+

At the 1210-kev resonance, the incident energy for which the α_0 yield is maximum depends on the angle of observation. This is probably the result of interference and has bearing on the spin and parity assignment of this level. The anomaly at 1890 kev cannot be positively identified as due to resonance.

INTRODUCTION

IN previous work at this laboratory,[1] the level structure of the O^{16} nucleus has been studied by observation of the gamma rays resulting from the proton bombardment of N^{15}. Bombarding energies from 800 kev to 4020 kev were used, covering the excitation range from 12.9 Mev to 15.9 Mev in O^{16}. A number of new states were observed. Spin and parity assignments and limitations were made on the basis of yield and angular distribution measurements. In the present work, the absolute differential cross sections and angular distributions of the reactions:

$$N^{15}+p\rightarrow N^{15}+p,$$
$$\rightarrow C^{12}(\text{ground state})+\alpha_0,$$
$$\rightarrow C^{12*}(4.43\text{-Mev excited state})+\alpha_1,$$

were studied by observation of the particles.[2] Essentially the same energy range was covered. It was hoped that further limitations could be placed on the character of the states of O^{16} in this energy region.

METHOD

The proton beam from an electrostatic generator was collimated and allowed to enter the target chamber (see Fig. 1) through a nickel foil, 1000 A thick. Scattered and reaction particles were detected by a 6-mil thick CsI(Tl) crystal cemented to a Dumont 6291 photomultiplier tube.[3] The beam and detector collimators defined a reaction volume which varied with the angle of observation. An angular spread of $\pm 4°$ was accepted by the detector. Graphical calculation was used to obtain the effective solid angle of the detector. The error which the uncertainty in solid angle contributed to the final measured cross section is listed in Table I.

Figure 2(a) shows the electronic circuitry used with the particle detector. The pulses from the particle detector were sorted by the 256-channel pulse-height analyzer. Figure 3 shows a pulse-height distribution obtained at 1210-kev bombarding energy with a thin target of N^{15} gas. The peaks result from the different reaction particles and elastically scattered protons. Pulse-height distributions such as that shown in Fig. 3 were recorded at a large number of bombarding energies, including all resonance energies, and numerous observation angles. The variation of pulse height with bombarding energy and observation angle was one means of identifying the source of each peak. Another means was the resonant behavior of the peaks.

The yield of a particular process was obtained by adding the number of counts under a peak. Some background, partly due to 4.43-Mev gamma rays, underlay the α_1 and C^{12} peaks. By rotating a 5-mil thick tantalum shutter in front of the CsI(Tl) crystal, the charged particles were excluded from the detector, allowing a direct measurement of the background. A background correction, which was less than 10% at resonance but larger off resonance, has been applied to the α_1 and C^{12} yields. The C^{12} yield agreed with that of the α_0 particles at corresponding center-of-mass angles.

In addition to taking complete pulse-height spectra at many energies, the yields of the various particles were measured with scalers which responded to pulses above appropriately chosen discriminator levels. The discriminators were set by requiring them to gate the 256-channel analyzer at the valleys in the pulse-height distribution, so that a given particle yield was simply the difference between two scaler readings. This technique facilitated the taking and reduction of data

† Supported in part by the U. S. Atomic Energy Commission.
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[1] S. Bashkin and R. R. Carlson, Phys. Rev. **106**, 261 (1957).
[2] Preliminary reports of the present work have been given: Jacobs, Bashkin, and Carlson, Bull. Am. Phys. Soc. Ser. II, **1**, 212 (1956); Carlson, Douglas, Bashkin, and Broude, Bull. Am. Phys. Soc. Ser. II, **3**, 199 (1958).
[3] Bashkin, Carlson, Douglas, and Jacobs, Phys. Rev. **109**, 344 (1958).

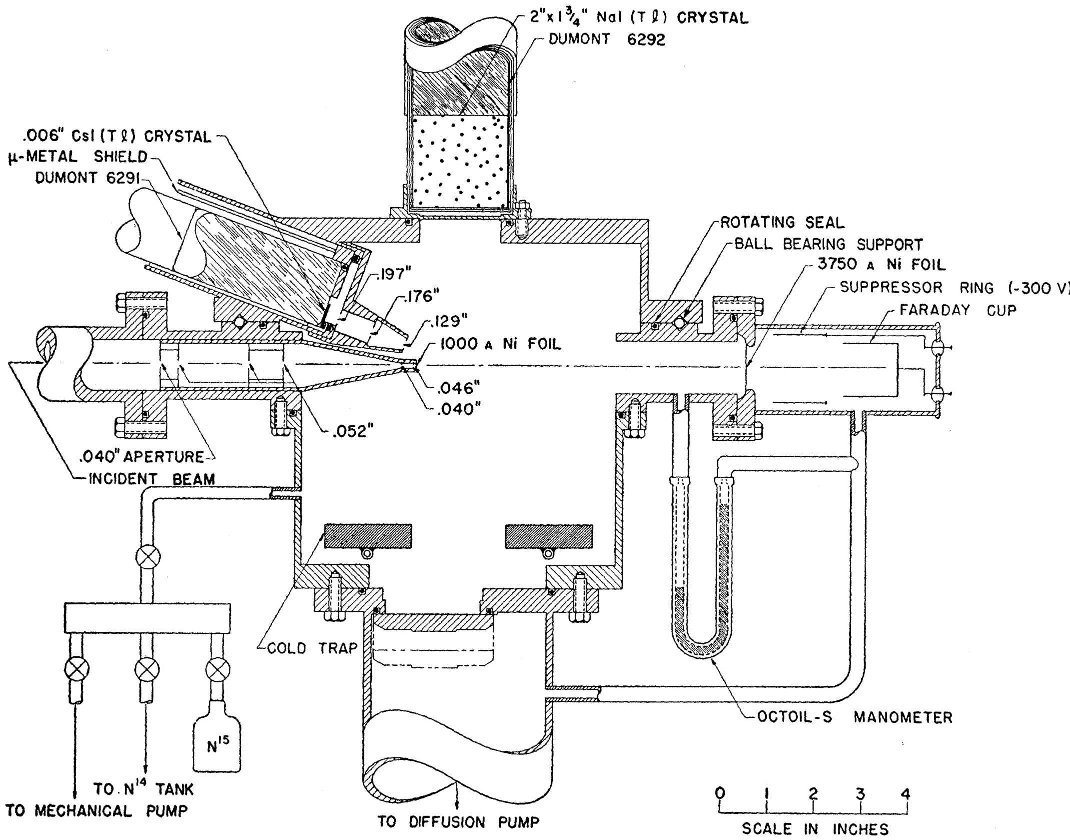

FIG. 1. Gas target chamber.

for regions where the yield was almost entirely due to elastically scattered protons.

Reaction gamma rays were detected with a fixed, conventional NaI(Tl) crystal detector (see Fig. 1). The associated electronics is illustrated in Fig. 2(b). The 10-channel analyzer was set to count 4.43-Mev gamma rays and high-energy capture gamma rays. Since a 4.43-Mev gamma ray appears for every α_1 particle, the gamma-ray yield was a convenient monitor on the incident proton energy. Maxima in the gamma-ray yields were located to an absolute accuracy of $\pm 1\%$ by the beam deflecting magnet.[1] These resonance energies are well known.[1,4,5] The bombarding energy

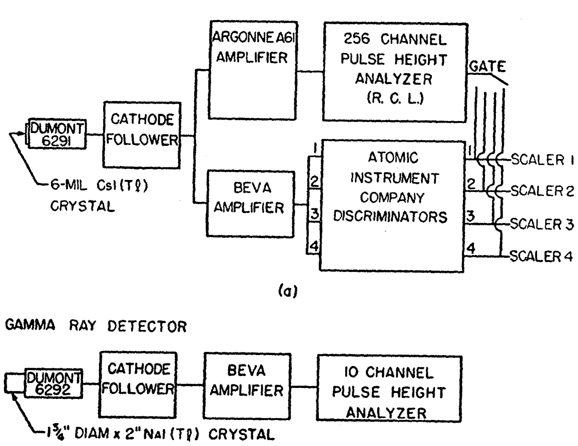

FIG. 2. Block diagram of electronic circuits. (a) Particle detector; (b) gamma-ray detector.

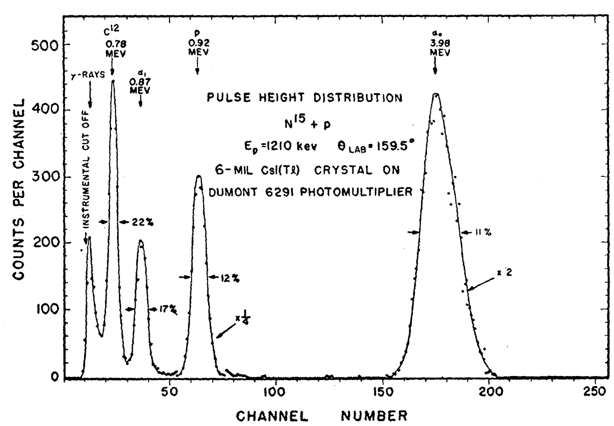

FIG. 3. Pulse-height distribution.

[4] Lidofsky, Jones, Bent, Weil, Kruse, Bardon, and Havens, Bull. Am. Phys. Soc. Ser. II, 1, 212 (1956).
[5] F. B. Hagedorn, Phys. Rev. 108, 735 (1957).

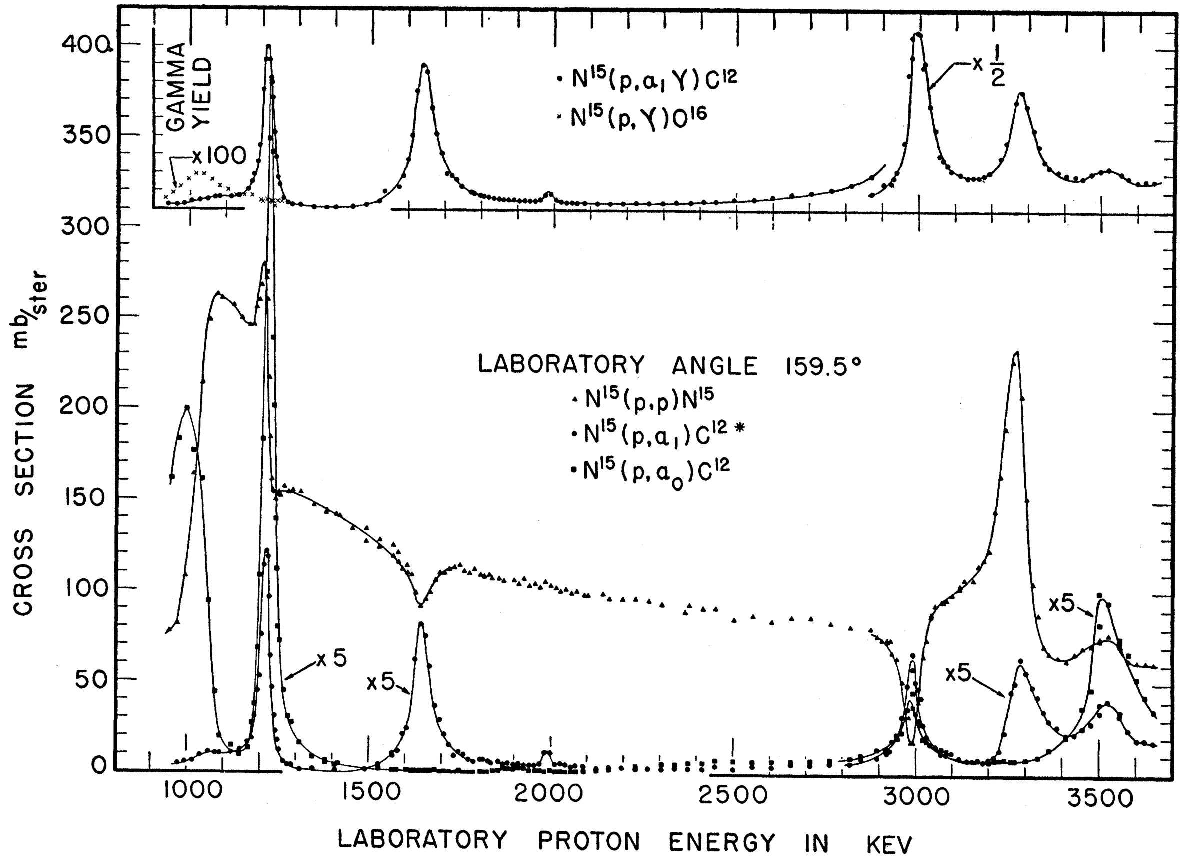

FIG. 4. Cross sections for elastic scattering and (p,α) reactions on N^{15} at backward angles. The former is in the center-of-mass system and the latter are in the laboratory system. The center-of-mass angle for elastic scattering is 160.8°.

was known to $\pm 0.2\%$ or better, *relative to these known gamma-ray resonances*. The center of the reaction volume as seen by the gamma-ray detector differed from that seen by the particle counter, so that the particle yields are displaced from the gamma-ray yields. This displacement is less than 5 kev. Since the particle angular distributions were monitored with the 4.43-Mev gamma-ray yield at its maxima, the distributions were obtained at energies slightly off resonance.

Pressure in the target chamber was measured with an oil manometer. The chamber wall temperature was measured frequently; however, during most of the runs the operation of a cold trap made the gas temperature in the reaction volume lower than that at the walls. This was determined by means of a direct thermocouple measurement and by comparison of yields with and without the cold trap in operation. A correction of $(8.0 \pm 0.5)\%$ was applied for this effect. The cold trap was initially used to eliminate condensable

TABLE I. Sources of error.

	Relative cross sections	Absolute cross sections
Pressure	0.5%	1.0%
Temperature	0.5%	1.0%
Beam integration	0.5%	2.0%
Slit geometry	0.5%	1.5%
Total rms error excluding counting statistics and background subtraction	1.0%	3.0%
Typical total rms error for		
$N^{15}(p,p)N^{15}$	2.0%	3.5%
$N^{15}(p,\alpha_0)C^{12}$	5.0%	5.0%
$N^{15}(p,\alpha_1)C^{12*}$	8.0%	8.0%

TABLE II. Absolute laboratory cross sections in mb/sterad.

	E_p (Mev)	Lab angle (°)	Iowa	Minnesota	Wisconsin	
$H^1(p,p)H^1$	2.00	35.0	535 ± 16		535 ± 0.5[a]	+0.0%
	2.00	40.0	497 ± 15		508 ± 0.5[a]	−2.2%
$He^4(p,p)He^4$	2.22	100.0	165 ± 5	162 ± 5[b]		+1.8%
$C^{12}(p,p)C^{12}$	2.20	101.5	148 ± 5		143 ± 7[c]	+3.5%
	2.20	122.0	120 ± 4		121 ± 6[c]	−0.8%
$O^{16}(p,p)O^{16}$	2.20	131.7	93 ± 3		94 ± 3[d]	−1.1%
	2.20	113.3	110 ± 3		113 ± 3[d]	−3.0%
	2.20	86.8	144 ± 4		147 ± 5[d]	−2.1%
				Rutherford scattering		
$A^{40}(p,p)A^{40}$	0.98	159.5	478 ± 15	467 ± 9[e]		+2.4%
				Root-mean-square deviation		2.2%

[a] H. R. Worthington *et al.*, Phys. Rev. **90**, 899 (1953).
[b] G. Freier *et al.*, Phys. Rev. **75**, 1345 (1949).
[c] H. L. Jackson *et al.*, Phys. Rev. **89**, 365 (1953).
[d] F. Eppling unpublished data, University of Wisconsin, reported in Los Alamos Scientific Laboratory Report, LA-2014 (unpublished).
[e] Rutherford scattering cross section has error resulting from energy uncertainty.

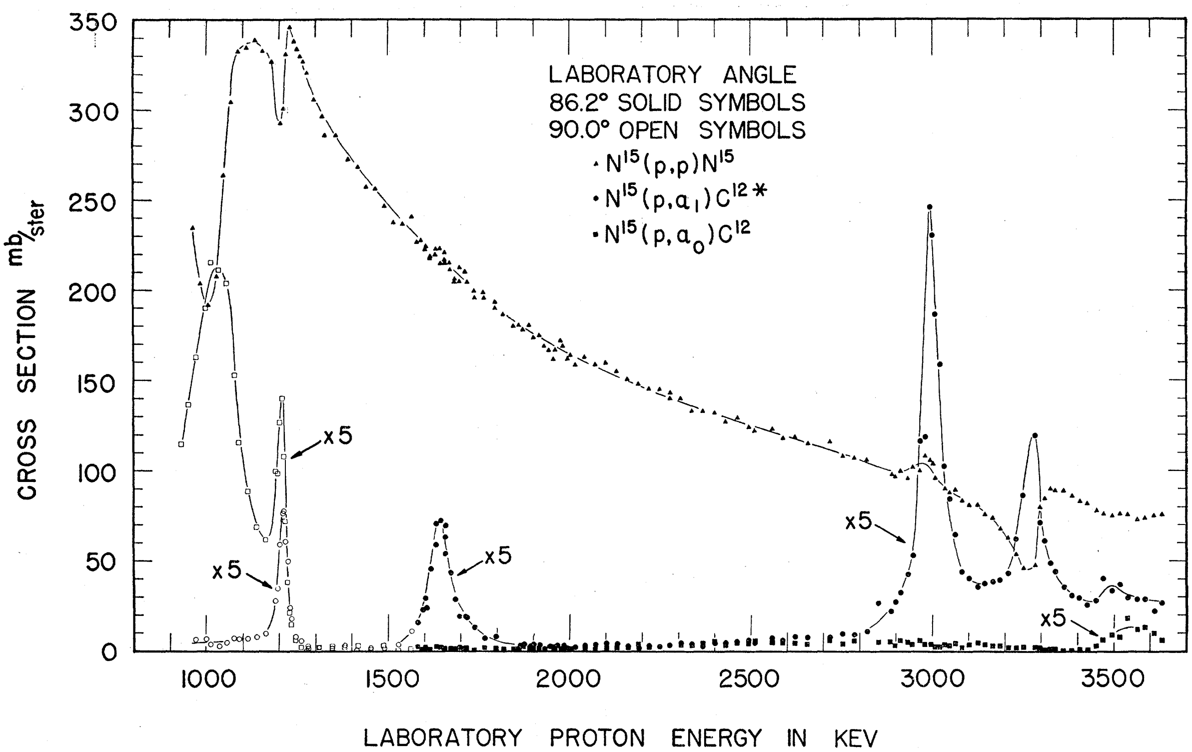

FIG. 5. Cross section for elastic scattering and (p,α) reactions on N^{15} near 90°. The former is in the center-of-mass system and the latter are in the laboratory system. The center-of-mass angle for elastic scattering is 90.0° for a laboratory angle of 86.2°.

vapors but was abandoned when the chamber was found to be essentially vapor free. In order to investigate any localized beam-heating effects, measurements were made as a function of beam current. Beam currents typically used were about 0.05 microampere. This was varied over two orders of magnitude without showing any effect as large as 1%.

The target gas was nitrogen, enriched to either 95% or 98% in N^{15}. Cross sections were corrected for the residual N^{14} content. The chamber pressure was typically 2.5 mm of Hg, although pressures from 0.4 mm to 6 mm of Hg were tried while searching for any apparent dependence of cross section on chamber pressure. There was no effect greater than 1%. At 1.2-Mev bombarding energy, 2.5-mm pressure gave a calculated effective target thickness of 2 kev for the detector at 90°.

We measured[6] the width of the sharp 1.7-Mev anomaly in the elastic scattering from N^{14} to be 6.5 kev. It has been reported[7] to be 4 kev wide. The possible additional width in our measurement may be attributed primarily to variations in entrance foil thickness. The resulting beam spread is considerably less than the width of any of the resonances considered in the present work.

[6] See Bashkin, Carlson, and Douglas, Phys. Rev. **114**, 1552 (1959), following paper.

[7] Hagedorn, Mozer, Webb, Fowler, and Lauritsen, Phys. Rev. **105**, 219 (1957).

The beam left the target chamber through 3750 A nickel foil and was collected in a Faraday cage in which a high vacuum was maintained. Secondary electron suppression was provided by the repeller biased at 300 volts below ground. A magnetic field of about 100 gauss was also found necessary to ensure secondary electron suppression. The collector cup was connected to a standard, condenser-discharge type current integrator. A summary of the sources of error is given in Table I.

Differential elastic scattering cross sections for protons on hydrogen, helium, carbon, and oxygen were measured at a number of angles and energies chosen to correspond to previous measurements by others. The cross sections at these chosen angles and energies are very slowly varying quantities. Elastic scattering from argon was also measured. In Table II, the present results are compared with the results of other laboratories and with the Rutherford value.

The angular variation of the calculated effective solid angle of the detector was checked by measuring the cross section for the elastic scattering of protons by argon at 980-kev bombarding energy and for fourteen laboratory angles from 44° to 159.5°. In this range the measured cross section followed a $\csc^4(\theta/2)$ angular variation to within $\pm 1\%$, θ being the center-of-mass angle of observation.

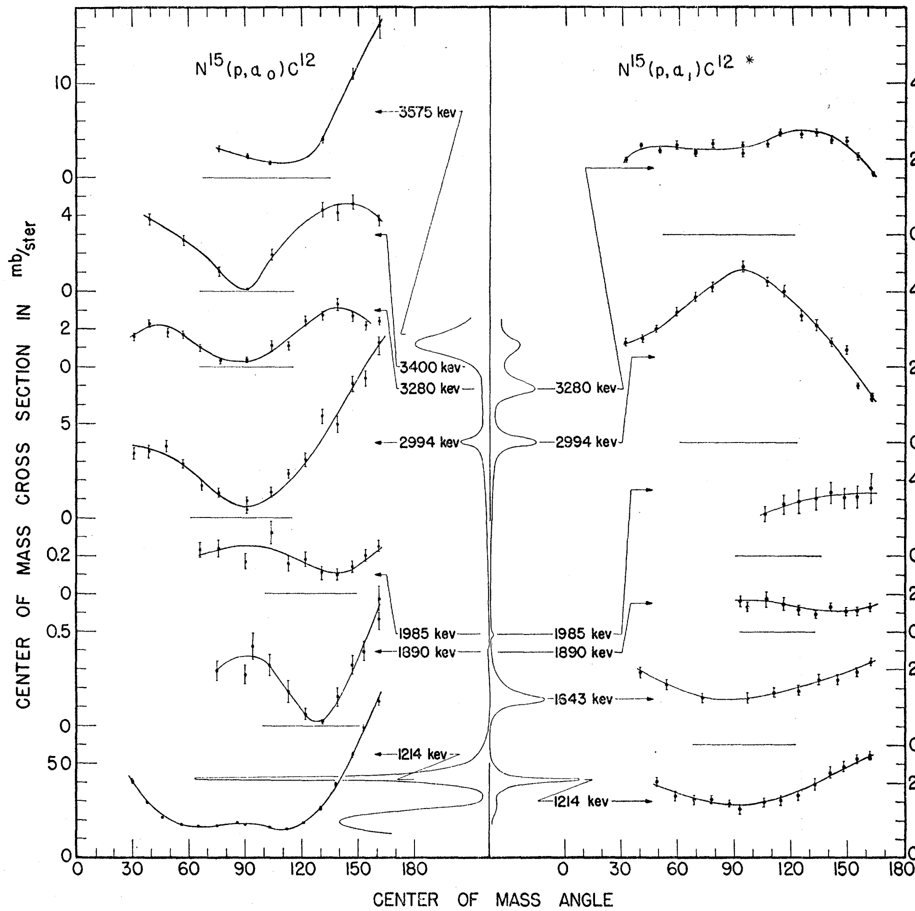

FIG. 6. Angular distributions of alpha particles resulting from proton bombardment of N^{15}. The bars indicate the uncertainty due to counting statistics and background subtraction. The curves are experimental. Schematic cross-section curves are drawn in the center as guides. Indicated energies are correct to ±0.2% assuming the resonance energies given in Table IV. See text.

RESULTS

Figure 4 shows the differential cross sections for the reactions and elastic scattering at backward angles. Inset are the yields of 4.43-Mev and capture gamma rays which were measured simultaneously with the particles. The gamma-ray yield curve is displaced in energy by an amount less than 5 kev to take account of the different reaction centers of the gamma detector and particle detector. The counting statistics contributed less than ±3% to the uncertainty in the cross section for elastic scattering, and the over-all uncertainty in the absolute differential cross section for elastic scattering is ±3.5%. For the reactions, the absolute differential cross sections at resonance are believed known to ±5% for the α_0 particles, and to ±8% for the α_1 particles. The latter includes a contribution due to background subtraction. The uncertainty in the relative differential cross section for any of the above processes is due almost entirely to counting statistics and background subtraction. These errors are point size or smaller for the elastically scattered protons and α_0 particles shown in Fig. 4.

Figure 5 shows corresponding results for lab angles near 90° (90° in the center-of-mass system for the elastic scattering curve). The same errors apply. In addition to the results shown in Fig. 4 and Fig. 5, data were taken at lab angles of 66.7°, 131.0°, 140.1°, and 151.7°. The same general structure shown in Fig. 4 and Fig. 5 appeared at the other angles.

Angular distributions of the alpha particles and scattered protons were measured at or near the peaks of resonances. The gamma-ray yield was used to monitor the energy. The results are shown in Fig. 6 for the alpha-particle groups and in Fig. 7 for the elastically scattered protons.

The present data on the elastic scattering of protons are in good agreement with the findings of Hagedorn[5] in the energy range (E_p<1800 kev) common to the two experiments. Typical numerical comparisons of the two sets of data appear in Table III.

At the 1028-kev resonance, Schardt, Fowler, and Lauritsen[8] measured a differential (p,α_0) cross section of 35±5 mb/sterad at 137.8° (lab), whereas we obtain 46±3 mb/sterad at that resonance at 134.5° (lab). At the 1210-kev resonance, our relative angular distribution of the α_0 particles is in very good agreement

[8] Schardt, Fowler, and Lauritsen, Phys. Rev. **86**, 527 (1952); referred to as SFL.

with that reported by Hagedorn and Marion.[9] However, Hagedorn and Marion, who normalized their data to the absolute measurements of SFL, found an integrated (p,α_0) cross section of 300 mb at this resonance; we find 380±50 mb (see Table IV). It thus appears that our absolute (p,α_0) yield differs from that given by SFL.

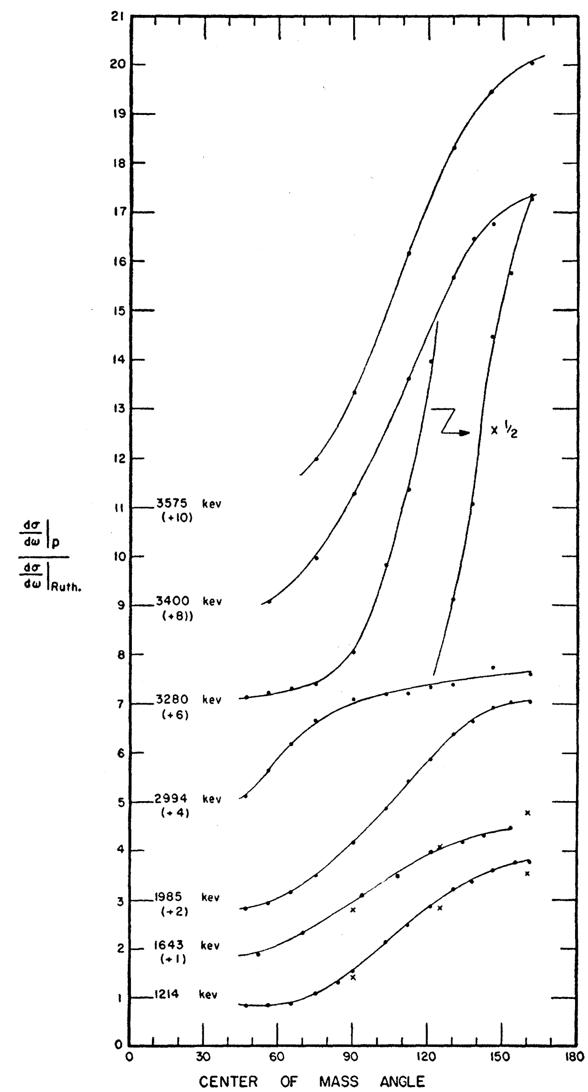

FIG. 7. Ratio of cross section for elastic scattering of protons by N^{15} to cross section for Rutherford scattering as a function of center-of-mass angle. The curves are labeled with the laboratory proton energy at which they were obtained. Crosses on the two lower curves are from reference 5. For clarity of presentation, the curves have been displaced upward from their proper positions by adding to the cross-section ratios the arbitrary numbers given in brackets.

A discrepancy is also seen on consideration of the (p,α_1) data. Of course, the integrated cross section for the (p,α_1) reaction should agree with that obtained

[9] F. B. Hagedorn and J. B. Marion, Phys. Rev. **108**, 1015 (1957).

TABLE III. Comparison of $N^{15}(p,p)N^{15}$ cross sections.[a]

Bombarding energy (kev)	90.0° Iowa	90.0° Cal. tech.[b]	160.8° Iowa	160.1° Cal. tech.[b]
1100	334±11	310±34	259±9	245±24
1450	257± 9	235±26	134±5	150±16
1800	188± 7	180±20	109±4	120±13

[a] Cross section given in mb/sterad in the center-of-mass system at the center-of-mass angle.
[b] See reference 4.

from the yield of the 4.43-Mev gamma rays. It does not. The values listed in Table IV are consistently 0.58±0.02 times those in Table I of our previous paper.[1] Those earlier absolute values were themselves based on a normalization to the gamma-ray measurements of SFL. Finally, Kraus, French, Fowler, and Lauritsen[10] have measured the α_1 distribution at the 1210-kev resonance, and while our relative distribution is in excellent agreement with their distribution, a total cross section of 380 mb may be deduced from their paper, in contrast to our result of 250 mb.

In view of these disagreements, we have put our previous gamma-ray yields on an absolute basis. Using the (now available) calculated efficiencies of NaI(Tl) crystals,[11] our data yield a total cross section of 290±60 mb for the emission of 4.43-Mev gamma rays at the 1210-kev resonance. This value agrees with our particle measurements. In passing, it may be worth mentioning that the particle work of references 5, 8, 9, and 10 was carried out with N^{15} imbedded in solid targets and a magnetic analyzer. The gamma-ray data of SFL were obtained with Geiger counters.

Evidence in favor of the lower value for the (p,α_1) cross section appears in Hagedorn's analysis[5] of his elastic scattering work. At the 1640-kev (p,α_1) resonance, he extracted a total reaction cross section of 170 mb and commented that he could not explain the

TABLE IV. Characteristics of states in O^{16} formed by proton bombardment of N^{15}.

Bombarding energy (kev)	Width (kev)	Excitation energy in O^{16} (Mev)	Measured[a] total cross section for (p,α_0) (mb)	Measured[a] total cross section for (p,α_1) (mb)	Spin and parity
1210±3[b]	22.5±1[b]	13.24	380±50	250±35	3−[b]
1640±3[b]	68 ±3[b]	13.66	nonresonant	190±15	1+[b]
1890±20[c]	90 ±20	13.88	3±1	~20	
1985±20	25 ±5	13.97	nonresonant	28±6[d]	2−
3000±30	45 ±10	14.92	38±4	435±40	4+
3300±35	75 ±15	15.20	nonresonant	290±25[e]	2−
3350±50	750 ±100	15.25	18±2		2+
3520±40	100 ±25	15.41	125±20	140±30[d]	1−2+ 3−4+

[a] Angular distributions were integrated and corrected to resonance energy. Errors are rms and include contribution from correction to resonance energy.
[b] From reference 5.
[c] It is not clear that this anomaly is due to an excited state of O^{16} at this excitation energy. See text and reference 9.
[d] Gamma-ray cross section from reference 1 multiplied by 0.58 correction factor.
[e] Combined effects of 3300-kev and 3350-kev states.

[10] Kraus, French, Fowler, and Lauritsen, Phys. Rev. **89**, 299 (1953).
[11] Wolicki, Jastrow, and Brooks, Naval Research Laboratory Report, NRL-4883 (unpublished).

difference from our previous value of 340 mb.[1] Now, however, we have a total reaction cross section of 190 mb at that resonance, in good agreement with Hagedorn. Hagedorn reports a total reaction cross section of 630 mb at the 1210-kev resonance, as do we. The later experiments, therefore, are in satisfactory absolute agreement.

The differential cross section for the α_0 particles has been replotted on a log scale in Fig. 8 for an angle of observation of 159.5° (lab). The bars indicate the standard deviation due to counting statistics. An anomaly is evident at a bombarding energy of 1890 kev. A similar anomaly has been reported by Hagedorn and Marion[9] at 1870 kev. In Fig. 6, one sees that the α_0

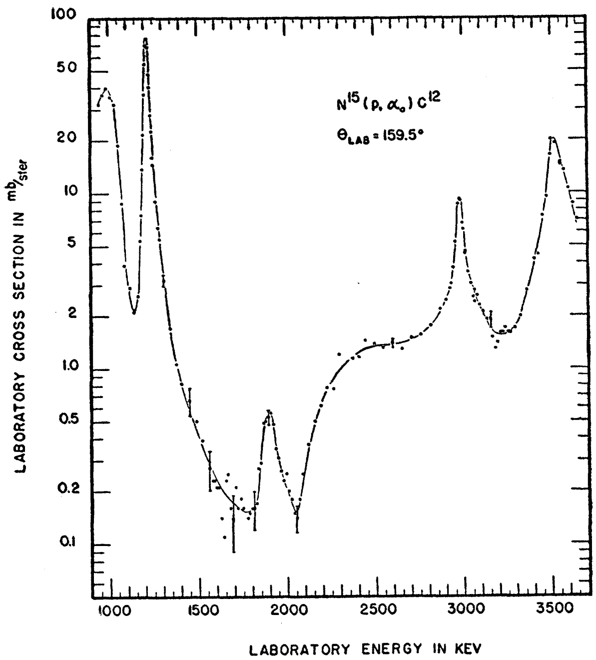

FIG. 8. Logarithmic plot of cross section for $N^{15}(p,\alpha_0)C^{12}$ reaction. Bars on points indicate counting statistics (rms). The background was negligible.

particles exhibit a very strong angular dependence at 1890 kev.

Near 1870 kev, Hagedorn and Marion[9] also noted a small anomaly in the 0° yield of 4.43-Mev gamma rays. We have looked for signs of this anomaly with the crystal arrangement of Fig. 1, the results being shown in Fig. 9. The simultaneously measured α_0 yield is included for comparison. Statistics are smaller than the point size for the gamma-ray yield. No anomalous behavior is seen in the 1800–1900 kev energy region, and if an anomaly exists at our angle of observation (110°±30°) it is less than 3% of the yield.

The α_1-particle yield is extremely small in the 1800–1900 kev energy interval, and is also subject to a large background correction due to scattered protons. Hence a large error (a factor of 2) applies to these data.

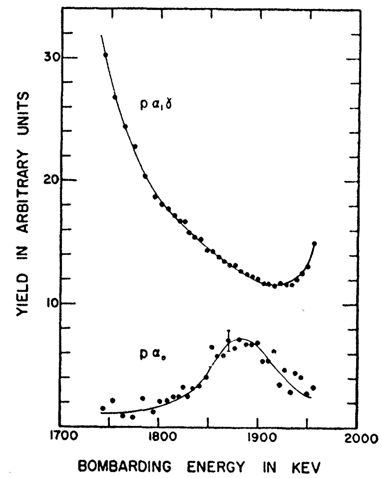

FIG. 9. Yield of 4.43-Mev gamma rays and α_0 particles in arbitrary units. Statistical uncertainty is less than point size for gamma rays. The background was negligible.

Within this error, Fig. 6 indicates that the α_1-particle yield is a weak function of angle.

The elastic scattering of protons by N^{15} has also been carefully surveyed in the interesting energy region from 1750 kev to 2000 kev (see Fig. 10). No anomaly is seen, and if such exists it is less than 5% of the yield, in agreement with the finding of Hagedorn and Marion.[9]

The energy region between approximately 1000 kev and 1250 kev contains structure in the reaction particle yields which has previously been studied only in a fragmentary manner. We have made simultaneous measurements of protons, α_0 and α_1 groups, and gamma rays. The reaction results are shown in Fig. 11. A

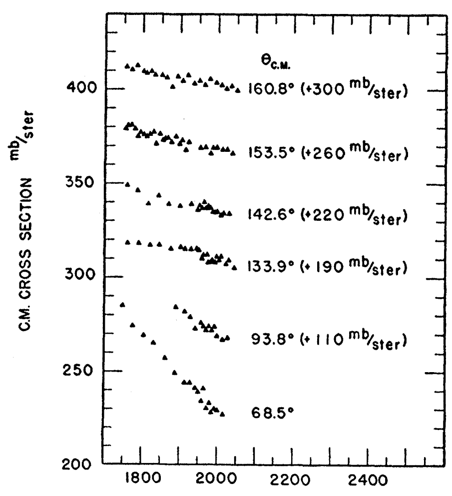

FIG. 10. Elastic scattering cross section between 1750 kev and 2000 kev. For clearity of presentation the curves have been displaced upward from their proper position by adding to the cross section the arbitrary numbers given in brackets. Note, also, the false zero to the ordinate scale.

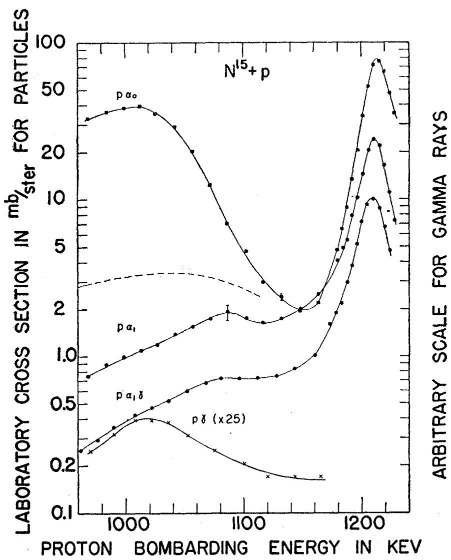

FIG. 11. Logarithmic plot of the yields of the reactions $N^{15}(p,\alpha\gamma)C^{12}$, $N^{15}(p,\alpha_1)C^{12*}$, $N^{15}(p,\alpha_0)C^{12}$, and $N^{15}(p,\gamma)O^{16}$. The laboratory angle was 159.5°. The dotted curve shows the (p,α_1) yield corrected for penetrability. The same arbitrary ordinate is used for both gamma-ray yields.

1.0-mil thick CsI(Tl) crystal was used here. The capture gamma rays show the well-known resonance at 1028 kev, $\Gamma=125$ kev. The α_1 particles associated with this resonance show a peak of sorts at 1085 kev and the 4.43-Mev gamma rays show a ledge at about the same energy. The difference between the peak positions of the (p,α_0) and (p,α_1) reactions can be accounted for by the variation in penetrability across the resonance. The (p,α_1) yield, corrected for penetrability, is shown as the dotted curve in Fig. 11. The particles show a peak at about 1000 kev. This peak energy was found to depend on the angle of observation, as reported earlier by Hagedorn and Marion.[9] However, the (p,α_0) cross section integrated over angle peaks at about the same energy as the capture gamma-ray yield.

A similar effect occurs at 1210 kev where it was noticed that the peak yields of the α_0 and α_1 groups usually did not occur at exactly the same bombarding energy. The peaks were no more than 6 kev apart at any angle of observation, however. Such small shifts were quite obvious in the present work because all groups of particles were observed at the same time at a given bombarding energy. Figure 12 shows a logarithmic plot of the cross sections observed at 159.5° around the 1210-kev resonance. By plotting these data on three separate sheets and superimposing the curves, the shifts indicated were obtained. The C^{12} curve gives information about α_0 particles emitted in the forward direction. In Fig. 13 these shifts, i.e., the α_0 peak yield energy minus the α_1 peak yield energy, are plotted as a function of the α_0 center-of-mass angle. The energy differences are believed known to ± 1 kev. By comparison with the gamma-ray monitor the peak yield energy of the α_1 group was shown to remain fixed to within ± 2 kev. Most of the variation must therefore be ascribed to the α_0 group. SFL observed this difference in peak yield energies at one angle of observation. Their measurement is included as the square in Fig. 13.

DISCUSSION

The above cross sections and their energy dependence may be expressed in terms of such parameters as the angular momenta, parities, and reduced widths of excited states of O^{16}. A complete treatment would also include interference effects involving several levels. Here we shall discuss those conclusions which can be drawn from the qualitative behavior of the cross sections. They supplement previous conclusions[1] and are summarized in Table IV.

As noted above, the present results for bombarding energies below 1.8 Mev are generally in good agreement with those of Hagedorn.[5] In the neighborhood of 1028 kev, the present data indicate that a single state is involved in the (p,γ), (p,α_0), and (p,α_1) processes. The α_1 particles seem not to show the large shift of peak position with observation angle that is noticed in the α_0 yield.

There is still some uncertainty in connection with the spin and parity of the 1210-kev resonance. Hagedorn[5] finds that the elastic scattering, the α_0 angular distribution, and the angular correlation of the α_1 particles and the 4.43-Mev gamma rays all indicate 3−. The 4.43-Mev gamma-ray angular distribution is consistent with either 3− or 4+. The α_1 angular distribution is consistent only with 4+. The shifts in Fig. 13 also have bearing on this question. Such shifts are due to interference terms in the differential cross section.[12] In the present case, interference between the

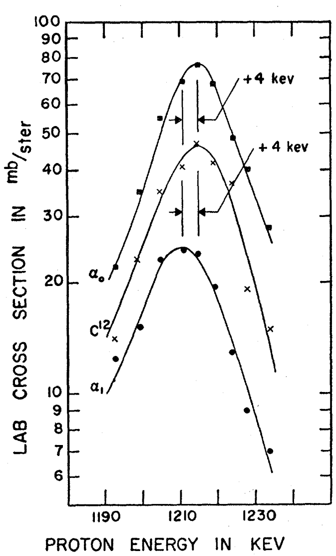

FIG. 12. Logarithmic plot of the cross sections for $N^{15}(p,\alpha_0)C^{12}$, $N^{15}(p,C^{12})\alpha_0$, and $N^{15}(p,\alpha_1)C^{12*}$ reactions around 1210-kev proton energy at 159.5° lab angle. Center-of-mass angle of α_1 is 162°; that of α_0 associated with observed C^{12} is 17°; that of observed α_0 is 161°. Curves are labeled with observed particle.

[12] J. M. Blatt and L. C. Biedenharn, Revs. Modern Phys. 21, 258 (1952).

1− state at 1028 kev, which has an appreciable amplitude at 1210 kev, and a 1210-kev state with spin and parity 3− would give shifts symmetric about 90°. If the 1210-kev state had spin and parity 4+, the shifts would be antisymmetric about 90°. The single-level approximation[13] is used for the elements of the collision matrix for the interfering levels. The curve of Fig. 13 is almost symmetric about 90°, adding weight to the choice of 3− for the 1210-kev resonance. The slight indication of asymmetry could arise from a broad 0+ level at 11.25 Mev[14] in O^{16}, which is below threshold for the $N^{15}+p$ system. It should be mentioned that the shifts cannot influence the total cross sections since the postulated interference terms integrate to zero.

At 1640 kev, the present results on proton scattering reinforce the assignment[5] of 1+. The present value obtained for the cross section clears up a disagreement between the results of Hagedorn's analysis[5] and the previous work.[1]

The anomalus behavior of the α_0 yield at 1890 kev (see Fig. 8) may arise from a level in O^{16}, but a possible alternative explanation, already suggested,[9] is interference between other states in O^{16}. Detailed calculation is necessary to decide between these alternatives.

The spin-parity assignment[1] at the 1985-kev state depended primarily on the angular distribution of the 4.43-Mev gamma rays, and this is unchanged. The failure to observe this state in the proton scattering (see Figs. 4, 5, and 10) indicate a small value of Γ_p/Γ.[9] In fact, our re-evaluation of the absolute gamma-ray yield leads to a value of 0.01 for the ratio.

Limitations on spin and parity assignments for the higher resonances can be made from the total reaction cross sections and the total width using the single level approximation and the Wigner limit. Allowed spins and parities are

3000 kev	3300 kev	3350 kev	3520 kev
3−, 4+	1+, 2−, 3+	1−, 2+, 3−	1−, 2+, 3−, 4+

[13] A. M. Lane and R. G. Thomas, Revs. Modern Phys. **30**, 257 (1958).
[14] J. W. Bittner and R. D. Moffat, Phys. Rev. **96**, 374 (1954).

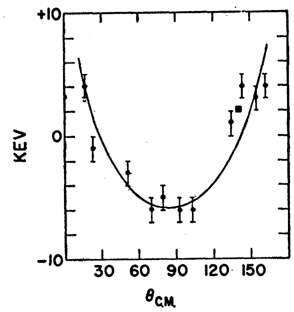

FIG. 13. α_0 peak-yield energy minus α_1 peak-yield energy in kev near 1210-kev resonance as a function of center-of-mass angle of α_0. The circular points are the present data. The square is from reference 8.

As compared with previous considerations[1] the increased number of possibilities results from the reduced (p,α_1) cross section.

For the 3000-kev resonance the near absence of any effect in the elastic scattering at 90° in the center of mass argues for formation with an odd orbital angular momentum. Since all states which decay by α_0 emission are formed with channel spin 1−, the 3000-kev state must be 4+. It then follows[1] that the broad 3350-kev state is 2+.

For the 3300-kev resonance there is a pronounced dip in the elastic scattering at 90°. This can only occur if the state is formed with even angular momenta. Of the three possibilities above, only the 2− case satisfies all requirements.

The 3520-kev resonance does not show in the elastic scattering at 90°; however, this resonance is relatively weak at the backward angle so the apparent absence at 90° is not conclusive. If one takes the absence at 90° as due to odd angular momenta formation, the 3520-kev state is restricted to 2+ and 4+. This conclusion must be bolstered by a detailed fitting, however.

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