Angular Correlation in the Reaction $F^{19}(p,\alpha)O^{16*}(\gamma)O^{16}$

WAYNE R. ARNOLD*
State University of Iowa, Iowa City, Iowa
(Received June 12, 1950)

The angular correlation of alpha-particles and gamma-rays from the 340-kev resonance in the reaction $F^{19}(p,\alpha)O^{16*}(\gamma)O^{16}$ has been observed. This correlation is very strong and allows a unique identification with a correlation calculated for this transition by the method of Hamilton. If we assume even parity and zero spin for the ground state of O^{16}, even parity and spin $\frac{1}{2}$ for the ground state of F^{19}, this experiment allows the following assignments of spin and parity: 13.24-Mev excited state of Ne^{20}, spin 1, even parity; 6.14-Mev excited state of O^{16}, spin 3, odd parity. Since no pairs have been observed from this resonance reaction, we can also assign even parity to the 6.0-Mev pair producing state of O^{16}.

I. INTRODUCTION

THE 340-kev resonance in the reaction $F^{19}(p,\alpha)O^{16*}$-$(\gamma)O^{16}$ has a high yield and a spherically symmetric angular distribution of the 1.8-Mev alpha-particles and 6.14-Mev gamma-rays.[1] There is also strong evidence that there is no branching in the decay of the excited state of Ne^{20} formed, so that each alpha-particle has an associated gamma-ray.[1,2] For these reasons R. E. Holland suggested that this would be a good reaction to use in an attempt to extend to nuclear reactions the theory which Hamilton[3] applied to gamma-gamma cascade transitions and Falkoff[4] to beta-gamma transitions. A similar application to nuclear reactions has been made by Feld[5] and by Rose and Wilson[6] on the reaction $B^{10}(n,\alpha)Li^{7*}(\gamma)Li^7$.

The measured angular correlation in the fluorine reaction was very strong, so the shape of the resulting intensity *vs.* angle curves were compared with the theoretically expected curves instead of the usual procedure of calculating coefficients of $\cos^n\theta$.

II. THEORY

The spherically symmetric angular distribution of both alpha- and gamma-particles with respect to the

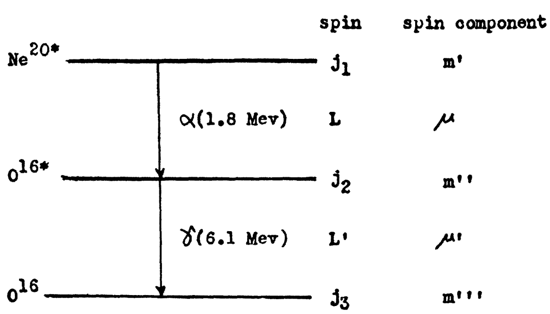

FIG. 1. Decay scheme of the excited state of Ne^{20} produced from F^{19} bombarded by 340-kev protons. The notations to the right are the ones used in the text.

* Now at Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
[1] Van Allen and Smith, Phys. Rev. **59**, 501 (1941).
[2] Bureham and Devons, Proc. Roy. Soc. **173**, 555 (1939).
[3] D. R. Hamilton, Phys. Rev. **58**, 122 (1940).
[4] D. L. Falkoff, Thesis, University of Michigan, April 1948.
[5] B. T. Feld, Phys. Rev. **75**, 1618 (1949).
[6] B. Rose and A. R. W. Wilson, Phys. Rev. **78**, 68 (1950).

beam means that one of the following possibilities is true: (1) the reaction proceeds with S-wave protons; (2) the compound nucleus Ne^{20*} has spin zero; (3) the alpha-particles are emitted with zero angular momentum. The last possibility is ruled out by the fact that the angular correlation of alpha-particles in coincidence with gamma-particles is not symmetric. Cases 1 and 2 are covered by the theory outlined below, which requires random orientation of the spin axes of the Ne^{20*}.

The decay scheme of the Ne^{20*} is shown in Fig. 1, with the notation to be used. It will also be convenient to define $\Delta j = j_1 - j_2$ and $\Delta j' = j_2 - j_3$.

If we start with a given state of Ne^{20*}, i.e. given j_1 and m' values, and go by alpha-emission to a particular state of O^{16*} with given j_2 and m'', then the probability function $f_\mu{}^L(\theta_1)$ for finding an alpha-particle at an angle θ_1 with respect to the direction of m' and m'' will be given by the spherical harmonic $|Y_\mu{}^L|^2$. If we now have a transition by photon emission from the j_2, m'' state to the O^{16} state with j_3 and m''', the probability of finding the photon at an angle θ_2 with respect to the m', m'' direction can be shown from Hamilton's work[3] to be given by $F_\mu{}^{L'}(\theta_2)$ defined by

$$F_\mu{}^{L'}(\theta) = \left|\frac{\partial}{\partial\theta} Y_\mu{}^{L'}(\theta,\varphi)\right|^2 + \left|\frac{1}{\sin\theta}\frac{\partial}{\partial\varphi} Y_\mu{}^{L'}(\theta,\varphi)\right|^2.$$

(This function is denoted by f in Hamilton's paper.) The functions F for L' up to 5 are given in Table I. The probability function, W, for the transition involving only the particular m values, and for the alpha- and gamma-particles being found at θ_1 and θ_2 will be the product of the individual probabilities. If we now take into account the fact that the Ne state may have several values of m' possible, and each may decay to one or more states with different m'', the probability functions, f, for the alpha-particle to be found at a particular angle must be multiplied by weighting factors, g, corresponding to the relative probabilities of decay from and to the states involved and then summed over all m-values. The same will be true of the gamma-ray transition. Because there is no preferred direction in the laboratory for the orientation of the Ne spin axes, and

TABLE I. Coefficients of powers of $\cos\theta$ for the functions $F_\mu{}^L(\theta)$.

$F_\mu{}^L$	const.	$\cos^2\theta$	$\cos^4\theta$	$\cos^6\theta$	$\cos^8\theta$	$\cos^{10}\theta$
1/0	2	−2				
1/1	1	1				
2/0	0	6	−6			
2/1	1	−3	4			
2/2	1	0	−1			
3/0	12	−132	420	−300		
3/1	1	111	−305	225		
3/2	10	−30	110	−90		
3/3	15	−15	−15	15		
4/0	0	180	−1020	1820	−980	
4/1	9	−153	885	−1463	784	
4/2	2	98	−450	742	−392	
4/3	7	−7	105	−217	112	
4/4	14	−28	0	28	−14	
5/0	180	−5220	47880	−148680	185220	−79380
5/1	6	4878	−42420	128268	−156114	66150
5/2	168	−3528	28560	−79632	92232	−37800
5/3	63	1827	−11970	32382	−36477	14175
5/4	126	378	1260	−7308	8694	−3150
5/5	315	−945	630	630	−945	315

These unnormalized functions have the proper relative weights within each L group.

because the same state m'' is involved in both transitions, we can simplify the expression for W by choosing either θ_1 or θ_2 as the preferred direction and expressing W as a function of $\theta=|\theta_1-\theta_2|$. This will eliminate interference terms, and give us the two expressions:

$$W(\theta)=\sum_{m''}\Big(\sum_{m'} \overset{\Delta jL}{g_{m'm''}} f_\mu{}^L(0)\Big)\Big(\sum_{m'''} \overset{\Delta j'L'}{G_{m''m'''}} F_{\mu'}{}^{L'}(\theta)\Big), \quad (1)$$

$$W(\theta)=\sum_{m''}\Big(\sum_{m'} \overset{\Delta jL}{g_{m'm''}} f_\mu{}^L(\theta)\Big)\Big(\sum_{m'''} \overset{\Delta j'L'}{G_{m''m'''}} F_{\mu'}{}^{L'}(0)\Big), \quad (2)$$

where the functions g and G are weighting factors for transitions between different m values and are given by

$$\overset{\Delta jL}{g_{m'm''}}=|(\psi_{m'}{}^{j_1}|\psi_\mu{}^L\psi_{m''}{}^{j_2})|^2,$$
$$\overset{\Delta j'L'}{G_{m''m'''}}=|(\psi_{m''}{}^{j_2}|\psi_{\mu'}{}^{L'}\psi_{m'''}{}^{j_3})|^2.$$

Limited tables of these matrix elements g and G can be found in books on atomic spectra[7] but those for high L values must be calculated.

Equations (1) and (2) can be simplified further for the special conditions of the $Ne^{20*}-O^{16*}-O^{16}$ transitions. For Eq. (1): $f_\mu{}^L(0)=\delta_{m'm''}$; j_3 is assumed to be zero, so $m'''=0$ and the factors $G=1$. This gives

$$W(\theta)=\sum_{m'} \overset{\Delta jL}{g_{m'm'}} F_{m'}{}^{L'}(\theta). \quad (1a)$$

The simplification for Eq. (2) arises because $F_{\mu'}{}^{L'}(0)$ $=\delta_{m'',\pm1}$ for $m'''=0$ and the factors G are again equal to unity. This gives

TABLE II. Unnormalized correlation coefficients for $W(\theta)$.

$j_1-j_2-j_3$	L	const.	$\cos^2\theta$	$\cos^4\theta$	$\cos^6\theta$	$\cos^8\theta$	$\cos^{10}\theta$
0−1−0	1	1	−1				
0−2−0	2	0	1	−1			
0−3−0	3	1	−11	35	−25		
0−4−0	4	0	9	−51	91	−49	
0−5−0	5	1	−29	266	−826	1029	−441
1−1−0	0	1					
	1	1	1				
1−2−0	1	1	1				
	2	1	−3	4			
1−3−0	2	5	6	5			
	3	1	111	−305	225		
1−4−0	3	9	−9	39	−7		
	4	9	−153	855	−1463	784	
1−5−0	4	13	44	−210	364	−147	
	5	1	813	−7070	21378	−26019	11025

$$W(\theta)=\sum_{m'}\big(\overset{\Delta jL}{g_{m',+1}} \overset{L}{f_{m'-1}}(\theta)+\overset{\Delta jL}{g_{m',-1}} \overset{L}{f_{m'+1}}(\theta)\big). \quad (2a)$$

Since Eqs. (1a) and (2a) involve different g values and different functions f and F, the correlations $W(\theta)$ were calculated both ways as a check on the numerical computations. In the calculations constant factors in $W(\theta)$ were neglected since they do not affect the usefulness of the results and the final functions may be normalized, if desired, by integration. The unnormalized coefficients of the various powers of $\cos\theta$ for the different $W(\theta)$ are given in Table II, and the corresponding normalized curves in Figs. 5–7, where they are compared with the experimental results. There is a separate $W(\theta)$ for each value of the angular momentum L possible in a transition between states of given j values, however parity considerations separate these L values into even and odd groups, and rapidly decreasing barrier penetrabilities for higher annular momenta means that only the lowest even and odd angular momenta need be considered. The different $W(\theta)$ curves are distinguished by the notation $j_1-j_2-j_3$. The transitions for $j_1=0$ have only one value of L possible for each value of j_2 and are plotted together in Fig. 5. Transitions for $j_1=1$ have both even and odd values of L possible, and are separated into two groups in Figs. 6 and 7 corresponding to even and odd L. Only values of j_1 equal to 0 or 1 were used since the spin of F^{19} is $\frac{1}{2}$, the spin of the proton is $\frac{1}{2}$, and as has been indicated, the symmetric angular distribution means that $j_1=0$ or only S-wave protons are involved.

III. APPARATUS

The 350-kev protons used were obtained from the 500-kev Cockcroft-Walton linear accelerator recently constructed at the University of Iowa and described

[7] E. U. Condon and G. H. Shortley, *The Theory of Atomic Spectra* (Macmillan Company, New York, 1935), p. 76.

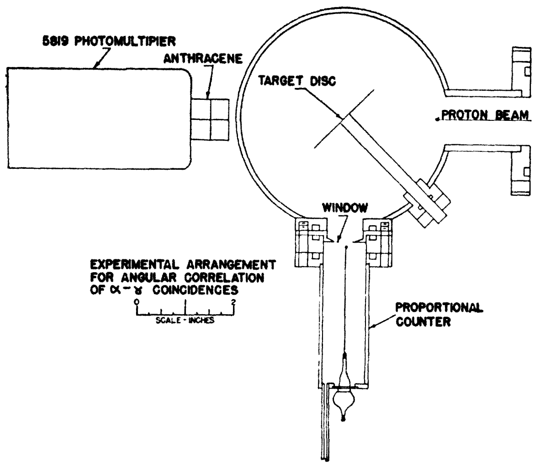

FIG. 2. Experimental arrangement for counting alpha-gamma coincidences. The angle θ is the angle between the proportional counter and the photo-multiplier tube. The target support is $\frac{3}{4}$ inch below the beam.

elsewhere.[8] They are resolved from other beam components by a 90° deflecting magnet whose one-dimensional focusing action allows one to obtain a beam which is either a horizontal or vertical line of about 1 mm width. The length of this line was defined by a 0.250-in. diameter aperture located at the entrance to the target chamber. A vertical line beam was used for measurements in the horizontal plane in an effort to increase the intensity of the reaction without decreasing the resolution.

The target chamber and counters are shown in Fig. 2, which, as drawn, is a horizontal section. The target consists of a 0.030-in. brass disk in a vertical plane at 45° to the beam with a coating of calcium fluoride on the face toward the beam. A piece of quartz was placed on one sector to allow a check on proton scattering. The target is mounted on a rod whose axis is 0.750 in. below the beam, and is rotated by means of this rod to expose a new area of calcium fluoride whenever the carbon deposited by the beam action becomes thick enough to interfere with alpha-particles escaping from the target. The walls of the chamber are of 0.125-in. brass which scatters about 15 percent of the 6.14-Mev gamma-rays. The top of the chamber is made of Lucite. The alpha-detector is a proportional counter with a 0.005-in. tungsten wire in the center of a 0.874-in. I.D. brass tube. It was operated using Iowa City illuminating gas (which is 80 percent methane, nine percent nitrogen, six percent ethane, and the rest are hydrocarbons of higher molecular weight) at a pressure of 2.6 cm of mercury, and with a voltage of 1050 volts positive on the center wire.

Between the proportional counter and the target chamber, and 6.2 cm from the target, is a 1.12-cm diameter window covered with cast films of Formvar lacquer. This window was made of such a thickness that the alpha-particles from the reaction could penetrate it while the scattered protons were for the most part excluded. Two films whose thickness was tested by use of polonium alphas were used in the window, as it was easier to find a combination of two films which would have the proper stopping power. These films were slightly irregular in thickness, and allowed a few protons to get into the propertional counter; however it was possible to discriminate electrically against almost all of the proton pulses.

The gamma-ray detector used was an RCA 5819 photo-multiplier tube with a 2-cm cube of anthracene taped to the front surface. Aluminum foil was used to shield the tube from room light. This detector is capable of rotation in two planes. In Fig. 2 it is rotating in a horizontal plane by means of a support pivoted on an axis on the bottom of the target chamber. An auxiliary bracket mounts on the bottom of the chamber and provides an axis of rotation coaxial with the beam. This allows an angular correlation to be taken in a plane through the target and proportional chamber, and perpendicular to the beam. When rotated in the horizontal plane the anthracene is 5.6 cm from the beam spot on the target, and when rotated in the vertical plane it is 7.2 cm away.

The photo-multiplier tube is in the stray field from the 90° magnet and its gain is sensitive to small magnetic fields. This change in gain is different for different orientations of the tube with respect to the stray field. For a constant pulse height discriminator setting this leads to an over-all efficiency for the gamma counter, ϵ_γ, which is a function of angle. This effect was reduced by magnetic shielding around the photo-multiplier tube, and between the tube and the magnet. In an attempt to keep ϵ_γ independent of angle the discriminator bias was set at different values for the different angles. The values used for the discriminator setting were obtained by the following procedure: for each setting of θ a Co^{60} source was placed in front of the counter and the change in discriminator bias found which would give the same counting rate with the magnet on as was obtained with the magnet off. The final results were then calculated so that the effect of efficiency changes in the gamma-counter were eliminated.

Pulses from each of the detectors were fed through cathode-follower circuits into amplifiers which give output pulses of uniform height and shape. These output pulses were used to drive a scaling circuit for each amplifier, and also to drive a channel in the coincidence circuit.

The coincidence circuit is similar to Atomic Instrument Model 502 Coincidence Analyzer, except that it has only two channels. The output of the coincidence circuit drives a third scalar. Since the alpha-particle pulses come at varying times after the alpha-particle has entered the proportional counter (due to varying collection times for the electrons formed in the ion's path) the formed pulse for the gamma-ray (in the coin-

[8] Submitted to Rev. Sci. Inst.

TABLE III. Experimental data.

Angle	N_α $\times 10^{-2}$	N_γ $\times 10^{-2}$	N_γ/N_α	N_c	N_a	N_{ct}	N_{ct}/N_γ $\times 10^4$
			Horizontal plane				
220	1923	499	0.259	140	34	106	21
210	1692	487	0.288	143	29	114	23
200	1586	456	0.288	160	25	135	30
190	1966	552	0.282	300	38	262	47
180	4545	1543	0.339	779	85	694	45
170	2845	880	0.309	462	53	409	46
165	1444	434	0.303	209	22	187	43
160	1996	627	0.314	214	26	188	30
150	5324	1664	0.313	377	72	305	18
145	1476	415	0.281	109	21	88	21
140	3765	1065	0.283	273	70	203	19
135	3787	1113	0.294	271	62	209	18
130	5626	1671	0.297	415	100	315	19
120	6822	2153	0.316	537	108	429	20
110	4387	1364	0.312	322	70	252	18
105	1271	424	0.333	74	19	55	13
100	3184	1009	0.317	154	57	97	10
90	6492	1998	0.308	211	101	110	6
			Vertical plane				
180	4248	732	0.172	438	109	329	45
170	4037	668	0.165	429	94	335	50
160	4037	711	0.176	357	100	257	36
150	4009	626	0.156	211	88	123	20
140	3659	552	0.151	168	71	97	18
130	4027	636	0.158	216	90	126	20
120	4210	698	0.166	266	103	163	23
110	3801	662	0.174	228	88	140	21
100	3633	640	0.176	187	81	106	17
90	2734	475	0.174	82	45	37	8

cidence circuit) was made almost three times as long as that for the alpha-particle so that true coincidences would be sure to overlap in time. The resolving time of the coincidence circuit was measured by counting accidental coincidences between gamma-rays from a Co^{60} source and pulses from the alpha-counter amplifier driven by a pulse generator.

IV. PROCEDURE

The energy of the proton beam was set by slowly increasing the high voltage until it was just above the value for which gamma-rays appeared from the 340-kev resonance. The target was then rotated until the small quartz plate was in the path of the beam. The bias on the alpha-counter amplifier was then set so that pulses from the scattered protons entering the chamber were almost entirely discriminated against. The beam was then allowed to strike the calcium floride. The intensity of the beam was adjusted so that the alpha-counting rate was 500–700 counts/sec. The discriminator on the photo-multiplier tube amplifier was set at the predetermined value for the angle being used, and a run of 200–300 sec. made. The angle θ, the time, and the total number of alpha-, gamma-, and coincidence counts were recorded. Runs were made at 5° to 10° intervals, and measurements between 90° and 180° in the horizontal plane of Fig. 2 were repeated several times. A single set of runs was made in the plane perpendicular to the beam. Since the theory predicts only even powers of $\cos\theta$, one quadrant is sufficient to determine the shape of the curve. Runs were made for angles up to 220° in the horizontal plane to check the predicted symmetry of the curve about 180°.

V. RESULTS

The measured value of the resolving time (0.52 μsec.) for the coincidence circuit was used to calculate the number of random coincidences that would be expected in each individual run. The value obtained for these random coincidences is too low as they depend upon the instantaneous product of the counting rates in the two counters and these counting rates varied with time due to changes in beam strength and beam location on the defining aperture. However, the ratio of true to accidental coincidences was greater than unity for all angles except 90° and the uncertainty due to fluctuations up to a factor of two in beam intensity will be less than the statistical probable error.

The number of scattered protons counted as alpha-particles was about one percent of the alpha-particles counted, and this percentage was almost a constant for all runs. Since this, in effect, gives a small and almost constant factor in the efficiency of the alpha-counter, the effect it has upon the shape of the correlation curve was negligible.

The following were each totaled for all the runs at a given angle: N_α, the total number of alpha-counts; N_γ, total gamma-counts; N_c, total coincidence counts; and N_a, total calculated accidental coincidences for each individual run. These totals, and values obtained from

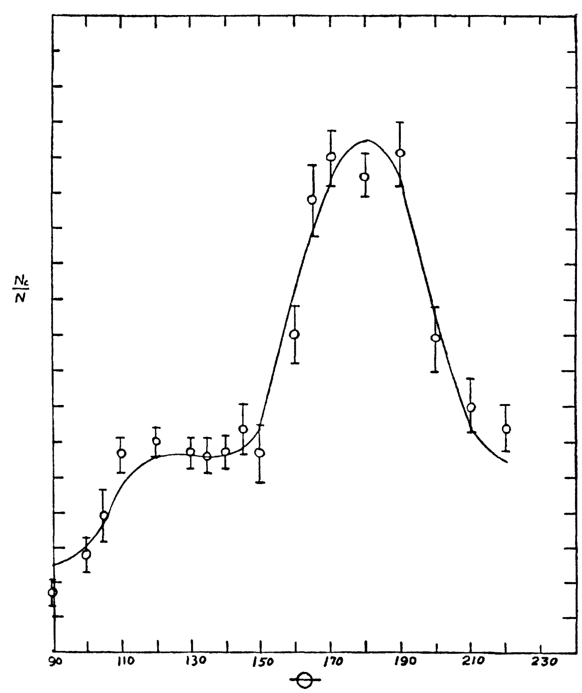

FIG. 3. Observed angular correlation for θ, the angle between alpha and gamma counted in coincidence, lying in a plane containing the beam. The solid line is the curve 1—3—0 from Fig. 7 modified for 40° resolution.

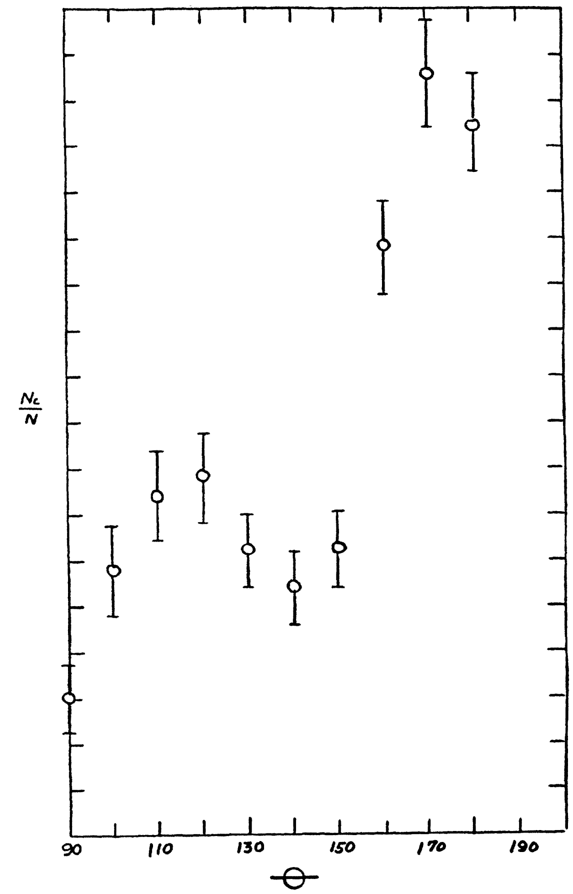

FIG. 4. Observed angular correlation for θ in a plane perpendicular to the proton beam. The low point at 180° is due to finite resolution in the dimension perpendicular to the plane of θ.

them are shown in Table III. The total number of coincidences minus the total number of accidental coincidences gives the number of true coincidences N_{ct}. If ϵ_α and ϵ_γ are the over-all efficiencies of the two counters, and N is the total number of disintegrations in the target in the time interval considered, then:

$$N_{ct}=N\epsilon_\alpha\epsilon_\gamma W(\theta)=N_\alpha\epsilon_\gamma W(\theta)=N_\gamma\epsilon_\alpha W(\theta).$$

The ratio N_{ct}/N_γ will then give a number proportional to the desired $W(\theta)$ regardless of changes in ϵ_γ provided only that ϵ_α remains constant. A constant ϵ_α was assumed in the calculation of the data. An indication of the changes in efficiencies is obtained from the ratio of $N_\gamma/N_\alpha=\epsilon_\gamma/\epsilon_\alpha$. With the exception of the data for angles of 220°, 105°, and 180° this ratio did not differ by more than six percent from the average and even if the change had been due partly to a change in the shape of the curve obtained (Fig. 3) would not have been radically different from the curve that would have resulted if the proper correction for efficiencies could have been made. Six runs were taken at 180° and the r.m.s. deviations in the values of N_{ct}/N_γ for the individual runs was 0.0006 compared to the expected statistical deviations of 0.0002.

The angular correlation was measured again in a plane perpendicular to the beam, and is shown in Fig. 4. This curve was taken with about 5° better resolution than the curve of Fig. 3, and the presence of a minimum at around 140° is a little more apparent.

Comparison of the experimental results as shown in Figs. 3 and 4 with the theoretical correlations as shown in Figs. 5–7 shows that only one theoretical curve (1−3−0, odd L, Fig. 7) corresponding to Ne^{20*} having spin 1, O^{16*} spin 3, the ground state of O^{16} spin zero, with odd angular momentum L for the alpha-particles, has the same shape as the experimental curves. Since the shape of the theoretical curves is modified by the finite resolution of the apparatus, the curve 1−3−0, odd L, modified for 40° resolution, is drawn in on Fig. 3

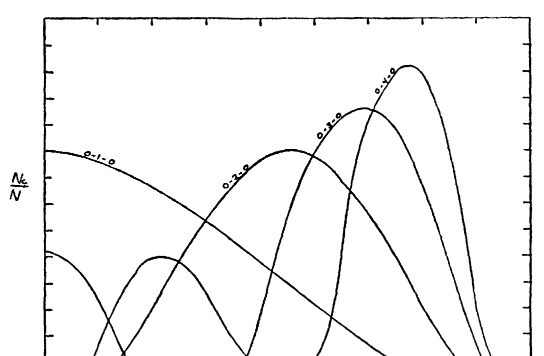

FIG. 5. Calculated angular correlations for the spin of Ne^{20*} equal to 0. The curves are labeled $j_1-j_2-j_3$ corresponding to the spins of $Ne^{20*}-O^{16*}-O^{16}$. Since only even powers of $\cos\theta$ are involved the correlation for θ between 90° and 180° is sufficient for identification. Note the value of zero for N_c/N at 180° for all of these curves.

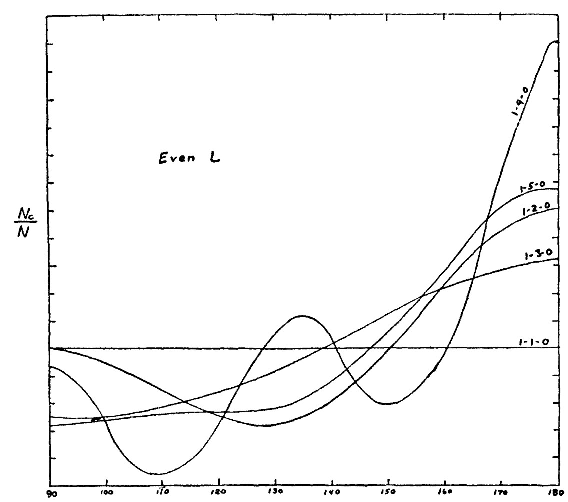

FIG. 6. Calculated angular correlations for the spin of Ne^{20*} equal to unity, and for the alpha-particle being emitted with even angular momentum L. Curves are labeled $j_1-j_2-j_3$ corresponding to the spins of $Ne^{20*}-O^{16*}-O^{16}$

for comparison. A $2\frac{1}{2}$ degree center of mass correction on θ was neglected.

VI. CONCLUSIONS

From the unique correlation between the experimental data and the one theoretical curve it appears that the spin of Ne^{20*} is unity, the spin of O^{16*} (6.14 Mev) is 3, and that the alpha-particles are emitted with angular momentum 3 (the only odd value of L possible in this transition). The spin of O^{16*} is thought not to be 6 or greater (for which theoretical curves were not calculated) because of general trends in the shape of the curves for spins below 6, and also because higher values for the spin of the excited state would lead to a lifetime for this state, which should be long enough to observe experimentally.

The spherically symmetric angular distribution of alpha-particles, combined with the measured spin of unity for Ne^{20*}, and a measured $L=3$ for the alpha-particle means that only S-wave protons are involved in the reaction. Therefore Ne^{20*} has the same parity as F^{19}, since the protons have even parity. The odd angular momentum of the alpha-particle means that O^{16*} has opposite parity from Ne^{20*} and hence opposite parity from F^{19}. Since F^{19} and O^{16} are both thought to have even parity[9] the parity of the 6.14-Mev excited state of O^{16} is probably odd. This would lead to electric octopole radiation for the γ-ray. This assumption of even parities for F^{19} and O^{16} is consistent with the fact that all of the atoms of Ne^{20*} formed in the 340-kev resonance decay by short range alpha-particles to the 6.14-Mev excited state of O^{16*} instead of emitting long range alphas and going directly to the ground state. The latter transition would be between states of even parity with a spin difference of unity, however, alpha-particles with angular momentum unity would require odd parity for either Ne^{20*} or O^{16}.†

Just below the 6.14-Mev excited state of O^{16} is a 6.0-Mev excited state which decays by pair emission,[10] and is therefore thought to have a spin of zero. The absence of pair production in the $F^{19}(p,\alpha)$ reaction at the 340-kev resonance, combined with the fact that the pair producing level is lower than the gamma-level involved, indicates even parity for this 6.0-Mev pair producing state. This spin and parity would indicate that, in the absence of any other selection rules, any state which decays by particle emission to the ground state of O^{16} would also decay to the pair level, although perhaps by a low branching ratio. One such case is N^{16} which decays by beta-emission to the ground state of O^{16} and also to the 6.14- and 7.0-Mev excited state of O^{16}. This radioactive isotope was studied by Sommers and Sherr[11] whose data on the presence or absence of pairs is somewhat inconclusive. They suggest that N^{16} has a high spin value which makes it prefer the transition to the 6.14-Mev level of O^{16} in preference to transitions to states with zero spin, although the higher energy involved allows transitions to the ground state of O^{16} to compete. The gamma-rays from N^{16} have also recently been measured by Millar, Cameron, and Glicksman,[12] whose experiments were such that pairs would not have been observed.

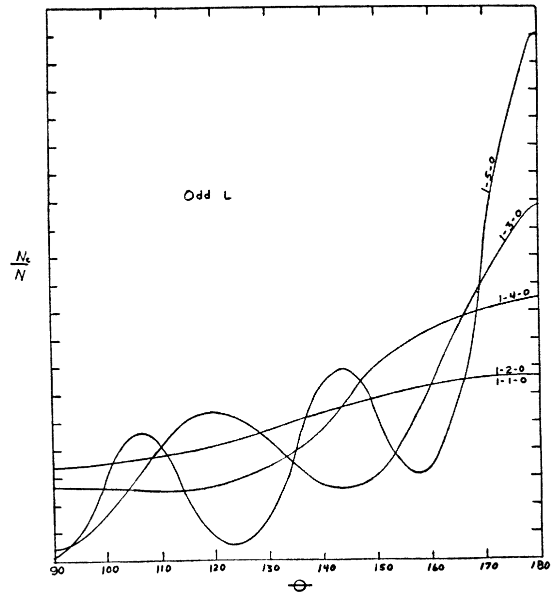

FIG. 7. Calculated angular correlations for the spin of Ne^{20*} equal to unity, and for the alpha-particle being emitted with odd angular momentum L. Curves are labeled $j_1-j_2-j_3$ corresponding to the spins of $Ne^{20*}-O^{16*}-O^{16}$.

This work was done as part of the research program at the University of Iowa under the direction of Professor James A. Jacobs. Dr. R. E. Holland, who suggested this problem, had previously modified the theory of Hamilton and Falkoff for use on alpha-gamma-transitions. Mr. J. Zijacek helped with the apparatus and the operation of the generator.

[9] Table VI of E. Feenberg and K. Hammack, Phys. Rev. **75**, 1877 (1949).

† *Note added in proof:* Identical conclusions as to the spin and parity of this O^{16*} state were obtained from a similar experiment reported by Barnes, French, and Devons [Nature **166**, 145 (1950)].

[10] V. K. Rasmussen *et al.*, Phys. Rev. **77**, 617 (1950).

[11] H. S. Sommers, Jr., and R. Sherr, Phys. Rev. **69**, 21 (1946).

[12] Millar, Cameron, and Glicksman, Phys. Rev. **77**, 742 (1950).