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Study of the Level Structure of Ni^{60} from $(p,p'\gamma)$ Angular Distributions*

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Measurements of $Ni^{60}(p,p'\gamma)$ angular distributions have been made for incident proton energies of 5 to 7 MeV, using a 99.0% enriched Ni^{60} target 3.9 mg/cm² thick. The γ-ray spectra become quite complex at 7 MeV, with transitions from most of the Ni^{60} states up to 4-MeV excitation being present. The angular distributions remain essentially the same at various energies after correction for cascade feeding. The earlier tentative 0^+ assignment for the 2.29-MeV level now appears to be correct, since the angular distribution of the 0.95-MeV γ ray is isotropic ($\pm 4\%$) and the (p,p') cross section is in good agreement with Hauser-Feshbach theory. From its observed angular distribution, a 0.47-MeV cascade (2.63 → 2.16 MeV) has been identified as a $3^+(M1,E2)2^+$ transition essentially pure $E2$ in character. The angular distribution of the 1.79-MeV cascade from the 3.12-MeV level agrees with the prediction for a $2^+(M1,E2)2^+$ transition with a mixing ratio of $\delta = 0.24 \pm 0.06$, in accord with a previous determination from the decay of Cu^{60}. The present work indicates the following level scheme for Ni^{60}: $1.33(2^+)$, $2.16(2^+)$, $2.29(0^+)$, $2.50(4^+)$, $2.63(3^+)$, and $3.12(2^+)$; 3.19(1) and 3.39(3 or 2) MeV.

1. INTRODUCTION

In earlier publications,[1,2] it was shown that it is possible to excite readily the low-lying states of medium-weight even-even nuclei and study the properties of these states by measuring both the angular distributions of the $(p,p'\gamma)$ radiations and also the excitation cross sections for these states. This approach proved to be quite useful and a supplement to the radioactivity and (p,p') work in the cases of Ni^{60}, Ni^{62}, $Zn^{64,66}$, $Ge^{70,72}$, and $Se^{76,78}$. Available information on the structure of Ni^{60} includes the work of Broek[3] up to 9-MeV excitation by inelastic scattering of 43-MeV alphas, and of Matsuda[4] up to 5-MeV excitation by inelastic scattering of 14-MeV protons. The spin assignments and energy determinations by the various authors[5–8] have been tabulated by Broek.[3]

The present investigations of Ni^{60} have been undertaken at higher bombarding energies to get information about the higher levels. It has been possible to excite such levels using incident energies just below the (p,n) threshold for Ni^{60}. It seemed worthwhile to confirm the 0^+ assignment for the 2.29-MeV level and to attempt to determine the spin of the 2.63-MeV level, as well as to get information regarding γ-ray mixing and branching ratios.

These experiments may also help in understanding the reaction mechanism at bombarding energies of the order of the Coulomb barrier height. The dominant reaction process should be through compound-nucleus formation, and if the energy spread of the beam is sufficient to excite a large number of compound-nuclear levels, the reaction process should be understood within the framework of the statistical theory. Such calculations by Hauser and Feshbach[9] and by Satchler[10] have been carried out for inelastic scattering which are in excellent agreement with our previous experiments[2,11] and of various other workers.[12,13]

2. EXPERIMENTAL TECHNIQUE

For these measurements, protons of about 5- to 7-MeV energy were provided by the tandem Van de Graaff accelerator (supported by the National Science Foundation), of the University of Pennsylvania. The energy resolution of the incident beam was better than 10 keV. The self-supporting Ni^{60} target with 99.0% enrichment[14] and 3.9 mg/cm² thickness was kept oriented at an angle of 45° with respect to the incident proton beam. The average proton energies at the center of the target were $\bar{E}_p = 4.90$, 5.92, and 6.94 MeV in the laboratory system and the corresponding target thicknesses were 260, 230, and 200 keV, respectively.

The experimental geometry used is essentially the same as reported in an earlier publication.[2] The $(p,p'\gamma)$ radiations were detected with a 3×3-in. integral-line NaI detector, and recorded with an RIDL 400-channel analyzer. A similar 3×3-in. NaI detector located at 90° with respect to the incident beam was used as a monitor for the angular-distribution measurements. The angular distributions were studied at 0°, 30°, 55°, 78°, 90°, and also at 150° to verify the symmetry of angular distributions around 90°. A Pt foil 0.022-cm

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* Work supported by the U. S. Atomic Energy Commission.
[1] D. M. Van Patter, R. Rikmenspoel, and P. N. Trehan, Nucl. Phys. **27**, 467 (1961).
[2] A. K. Sen Gupta and D. M. Van Patter, Nucl. Phys. **50**, 17 (1964).
[3] H. W. Broek, Phys. Rev. **130**, 1914 (1963).
[4] K. Matsuda, Nucl. Phys. **33**, 536 (1962).
[5] R. R. Spencer, G. C. Phillips and T. E. Young, Phys. Rev. **108**, 69 (1957).
[6] C. H. Paris and W. W. Buechner, *Proceedings of the International Conference on Nuclear Physics, Paris, 1958* (Crosby Lockwood & Son, Ltd., London, 1959), p. 515.
[7] R. K. Jolly, E. K. Lin and B. L. Cohen, Phys. Rev. **128**, 2292 (1962).
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[9] H. W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).
[10] G. R. Satchler, Phys. Rev. **104**, 1198 (1956); **111**, 1747 (E) (1958).
[11] D. M. Van Patter, N. Nath, S. M. Shafroth, S. S. Malik, and M. A. Rothman, Phys. Rev. **128**, 1246 (1962).
[12] R. B. Day and M. Walt, Phys. Rev. **117**, 1330 (1960).
[13] F. D. Seward, Phys. Rev. **114**, 514 (1959).
[14] Supplied by Oak Ridge National Laboratory, Oak Ridge, Tennessee.

thick was placed immediately behind the Ni^{60} target to ensure complete stopping of the beam and enabling the angular distributions to be extended to 0° with respect to the incident proton beam. Two types of background spectra were recorded at 55° for each incident energy: (a) the effects of the beam and reaction chamber were measured by rotating the target through 180° so that the beam struck the Pt backing, and (b) effects due to time and room background were determined by switching off the beam. Background (a) was used for subtraction since it included the contribution due to time background.

3. DATA ANALYSIS

The method of analysis and reduction of the data along with the various sources of error has been described previously.[2] The level energies resulting from the magnetic-spectrographic measurements of Paris and Buechner[6] have been adopted for this experiment. The method of self-calibration of γ-ray energies has been used, utilizing the known energies of prominent $Ni^{60}(p,p'\gamma)$ rays of 0.826, 1.332, 1.787 (3.120 → 1.333), 2.159, 2.40 (3.73 → 1.33), and 4.01 MeV. Also, the 4.43-MeV $C^{12}(p,p')$ γ ray arising from carbon contamination on the target has been used to check the energy calibration.

The γ rays up to 4.01 MeV have been analyzed by the conventional peeling-off technique from the composite spectrum as shown in Fig. 1. In the spectra above 1.5 MeV, background contributions [these included γ rays identified from Th^{232} (2.62 MeV), K^{40} (1.46 MeV), $Al^{27}(p,p'\gamma)$ (2.21 and 2.73 MeV), and $Si^{28}(p,p'\gamma)$ (1.78 MeV)] were found to be sufficiently significant to merit subtraction from each observed spectrum. For analysis, a smoothly varying background was assumed; its contribution was estimated by inspection of the valley heights and adjusted to get the best fit with the expected γ-ray shapes. These shapes were obtained by interpolation of the measured response functions of 3×3-in. NaI crystal using various calibration sources. At $E_p = 6$ and 7 MeV, there is considerable overlapping of the two or more γ rays in certain regions (see Fig. 1). The spectral decomposition then involves an iterative procedure for the balancing of counts between two adjacent γ rays, which naturally gives rise to substantial uncertainty.

The photopeak counts of the γ rays for a given observation angle, after being corrected for dead time losses of the analyzer, were normalized to the observed monitor counts. This procedure eliminates uncertainties in the angular distribution measurements such as due to target nonuniformities. By a computer program, the least-squares-fit analysis of these numbers to the angular distribution function[15] $W(\theta) = A_0 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$ gave values of A_0, A_2, and A_4 together with their rms deviations. The values of A_2 and A_4 were corrected for the finite solid angle of the detector using the tables given by Davisson and Gossett.[15,16] No correction was necessary due to the finite dimensions (about 2 mm diam) of the source.

The photopeak yields at various angles were corrected for the absorption in the target backing and the chamber. For obtaining the intensities, the values of the photofractions and the absolute total efficiencies for a 3×3-in. NaI crystal were taken from Heath.[17] For angular distribution measurements, the errors in

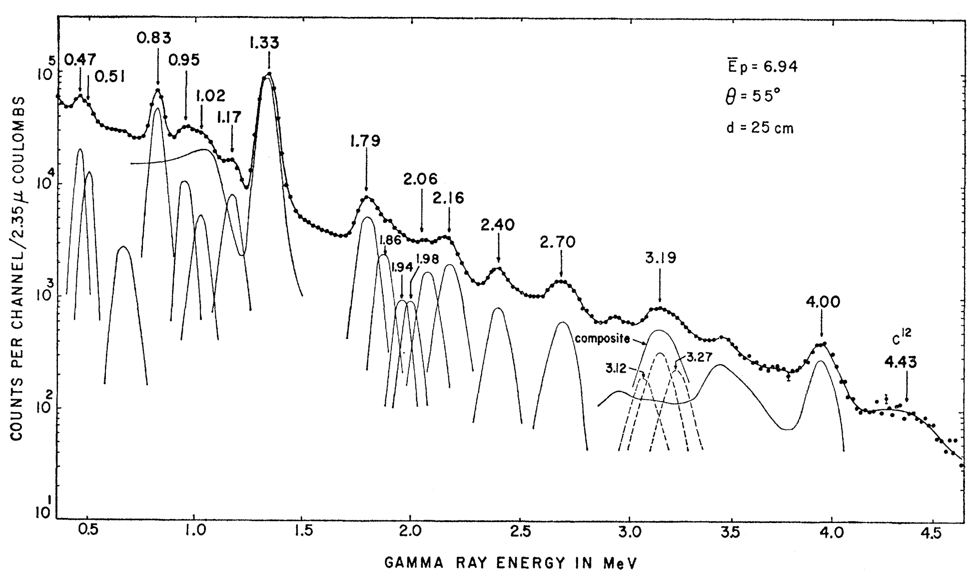

FIG. 1. Gamma-ray spectrum at $\theta = 55°$ from a 99.0% enriched Ni^{60} target bombarded by 6.94-MeV protons. All γ rays except the 0.51-MeV annihilation and the 4.43-MeV $C^{12}(p,p'\gamma)$ radiation are assigned to the $Ni^{60}(p,p'\gamma)$ reaction. Spectral decomposition indicates a possible weak group at 0.66 MeV as well as a broad composite peak centered at 3.19 MeV.

[15] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[16] C. R. Gossett and C. M. Davisson, Bull. Am. Phys. Soc. **7**, 9 (1962); C. M. Davisson (private communication).
[17] R. L. Heath, Phillips Petroleum Report I.D.O. 16408, 1957 (unpublished).

the yield are mainly due to the statistical error, the error in estimating the background, and the systematic error of the analysis due to overlapping peaks. The values of A_0 as obtained from the least-squares-fit analysis, give the total cross section for the production of the particular γ ray. Absolute cross sections are subject to possible systematic errors, such as uncertainties due to target nonuniformities. The average ratio of monitor counts per microCoulomb of beam charge remained fairly constant (±1 to 3%) during the angular distribution measurements. This observation still does not eliminate the possibility that the part of the target exposed to the beam might not equal the average target thickness determined from weighing the Ni^{60} foil.

4. CALCULATIONS FOR ANGULAR DISTRIBUTIONS

Angular distributions have been calculated using Satchler's theory which requires statistical averaging over many compound states.[10] Transmission coefficients up to 5 MeV for incident and outgoing protons were available.[18] For 6-MeV incident particles, extrapolated values based on comparison with the available values for Ni^{58} for $E_p \leqslant 7$ MeV have been used. [*Note added in proof*. Recent computations of these T_l values for Ni^{60} using the ABACUS-2 code show that errors due to this extrapolation procedure were negligible.] The optical-model potential that has been used in the present work was of the form

$$V=-V_0/(e^x+1)+iW(d/dx')1/(e^{x'}+1),$$

where $x=(r-r_0A^{1/3})/a$ and $x'=(r'-r_0A^{1/3})/a'$. The proton transmission coefficients are based on the following parameters:

$$V_0=52\text{ MeV},\quad W'=44\text{ MeV},\quad r_0=r_0'=1.25\text{ f},$$
$$a=0.65\text{ f}\quad\text{and}\quad a'=0.47\text{ f}.$$

For evaluating the angular distributions of mixed transitions, various values of the mixing parameter $\delta=(E2/M1)^{1/2}$, have been used.

5. RESULTS

In Fig. 1 is presented a typical γ-ray spectrum observed at $\bar{E}_p=6.94$ MeV at an angle of 55° with respect to the incident beam, and with a distance between target and crystal face of 25 cm. It was found that at this large distance contributions due to γ-ray summing could be disregarded. The more prominent γ rays are due to transitions from the lower levels. The yields of 1.86-, 1.94-, and 1.98-MeV γ rays are uncertain because of considerable overlapping in this region. Our recent

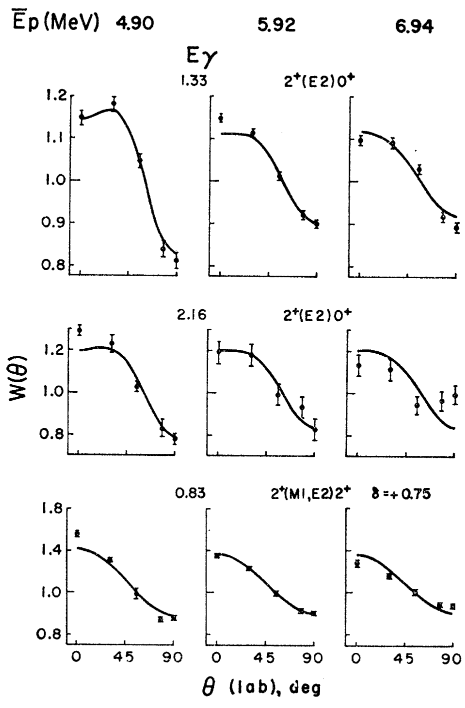

FIG. 2. Angular distributions of $Ni^{60}(p,p'\gamma)$ radiations from the 1.33 (2^+)- and 2.16 (2^+)-MeV levels for three bombarding energies. The experimental points are compared with theoretical calculations using Satchler's statistical-reaction theory (solid curves) which include the contributions of cascade fractions from higher levels up to 3.12-MeV excitation.

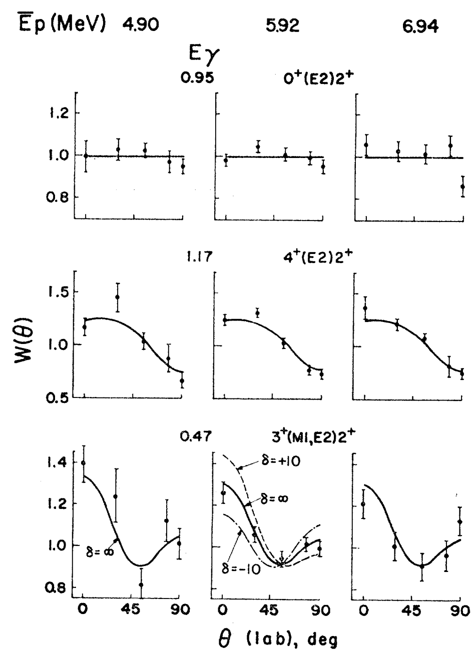

FIG. 3. Angular distributions of $Ni^{60}(p,p'\gamma)$ radiations from the 2.29 (0^+)-, 2.50 (4^+)-, and 2.63 (3^+)-MeV levels for three bombarding energies. The solid lines represent theoretical calculations for the indicated transition types, with those for $E_p=5.92$ MeV being repeated at $E_p=6.94$ MeV. In the case of the 0.47-MeV γ ray, identified as a 2.63 → 2.16-MeV transition, predicted curves for pure $E2$ transitions ($\delta=\infty$) as well as predominantly $E2$ transitions ($\delta=\pm10$) are shown.

[18] The authors are indebted to Dr. G. R. Satchler and Dr. E. Sheldon for providing these proton transmission coefficients.

TABLE I. Angular distribution results for the $Ni^{60}(p,p'\gamma)$ reaction, with values of α_2 and α_4 as described by $W(\theta)=1+\alpha_2 P_2(\cos\theta)+\alpha_4 P_4(\cos\theta)$.

E_γ (MeV)	$\bar{E}_p$ (MeV)	Experimental[a] α_2	Experimental[a] α_4	Theoretical[b] α_2	Theoretical[b] α_4	Assigned transition[c]
1.33	4.90	0.293 ± 0.012	-0.143 ± 0.016	0.267	-0.124	$2^+(E2)0^+$
	5.92	0.180 ± 0.006	-0.034 ± 0.009	0.164	-0.054	
	6.94	0.162 ± 0.008	-0.068 ± 0.010	0.143	-0.024	
2.16	4.90	0.388 ± 0.025	-0.093 ± 0.030	0.327	-0.133	$2^+(E2)0^+$
	5.92	0.251 ± 0.042	-0.055 ± 0.056	0.286	-0.088	
	6.94	0.096 ± 0.041	$+0.066\pm0.054$	0.281	-0.080	
0.83	4.90	0.532 ± 0.017	$+0.035\pm0.021$	0.442	-0.014	$2^+(M1,E2)2^+$
	5.92	0.384 ± 0.013	-0.021 ± 0.018	0.387	-0.009	$\delta=+0.75$
	6.94	0.299 ± 0.014	-0.019 ± 0.019	0.380	-0.008	
0.95	4.90	0.053 ± 0.036	-0.060 ± 0.044	0	0	$0^+(E2)2^+$
	5.92	0.041 ± 0.028	-0.060 ± 0.037			
	6.94	0.080 ± 0.039	-0.034 ± 0.052			
1.17	4.90	0.447 ± 0.079	-0.253 ± 0.096	0.393	-0.153	$4^+(E2)2^+$
	5.92	0.439 ± 0.045	-0.179 ± 0.060	0.366	-0.120	
	6.94	0.430 ± 0.039	-0.080 ± 0.053			
0.47	4.90	0.118 ± 0.079	0.325 ± 0.100	0.097	0.254	$3^+(E2)2^+$
	5.92	0.095 ± 0.029	0.163 ± 0.041	0.092	0.225	
	6.94	0.024 ± 0.056	0.210 ± 0.075			
1.79	5.92	0.054 ± 0.061	-0.028 ± 0.082	0.071	-0.003	$2^+(M1,E2)2^+$
	6.94	0.086 ± 0.060	-0.038 ± 0.081			$\delta=-0.24$

[a] The least-squares fits to the experimental data which are listed have been corrected for the finite solid angle of the NaI detector.
[b] The calculated angular distributions for the 1.33-, 2.16-, and 0.83-MeV γ rays include contributions of cascade fractions (based on experimental relative intensities) originating from levels up to 3.12-MeV excitation. The multipolarities of the various transitions are known except for the $2.63\rightarrow1.33$-MeV transition which is assumed to be $M1$. The angular distributions calculated for $\bar{E}_p=5.92$ have also been assumed for $\bar{E}_p=6.94$ MeV, with only the relative contributions of the cascade fractions being different.
[c] The theoretical values of α_2 and α_4 listed for $2^+(M1,E2)2^+$ transitions correspond to the values chosen for the mixing ratio δ.

investigations[19] of $(p'\text{-}\gamma)$ coincidences confirm that all the observed γ rays are from the known levels of Ni^{60} up to about 4-MeV excitation.

Figure 2 shows the angular distribution of γ rays from the first two excited levels of Ni^{60} at $\bar{E}_p=4.90$, 5.92, and 6.94 MeV. The solid lines represent the theoretical angular distributions. At $\bar{E}_p=4.90$ MeV, there is a remarkable agreement between theory and experiment for the 1.33-MeV $2^+(E2)0^+$ transition. It should be noted that corrections for cascade feeding have been applied to the theoretical predictions which change the angular distribution calculated for direct excitation of the level. For example, inclusion of the predicted cascade contributions from the 2.16-, 2.29-, 2.50-, 2.63-, and 3.12-MeV levels has reduced the A_2 coefficients for 1.33-MeV radiation by a factor of 0.78 and 0.55 at $\bar{E}_p=4.90$ and 5.92 MeV, respectively, yielding the values listed in Table I. The angular distributions due to direct excitation remain essentially constant with bombarding energy while the flattening of the 1.33-MeV γ-ray angular distributions with increasing energy is due to feeding from higher excited levels.

2.16-MeV Level

At $\bar{E}_p=4.90$ and 5.92 MeV, a comparison between the experimental and theoretical distributions is shown for the 2.16-MeV pure $E2$ transition. As was determined previously from $(p,p'\gamma)$ angular distributions,[20] the 0.83-MeV γ ray is a mixed $2^+(M1,E2)2^+$ transition with a value of $\delta\approx0.75$ which has been adopted for the calculation of its theoretical angular distribution. The possible $(3.12\rightarrow2.29)$ transition could also contribute to the yield of the above 0.83-MeV γ ray. Its contribution was estimated to be less than 3% of the 0.83-MeV yield by noting that the relative intensities of the 0.83- and 2.16-MeV γ rays remained constant within $\pm3\%$ at $\bar{E}_p=4.90$, 5.92, and 6.94 MeV, while the 3.12-MeV level is hardly excited at 4.90 MeV. The branching of the 2.16-MeV level (crossover/cascade) was determined to be 0.166 ± 0.005. The best angular-distribution data for the 2.16-MeV γ ray were obtained at $\bar{E}_p=4.90$ MeV, since at this bombarding energy the yield of 2.06-MeV radiation is negligible. The results of least-squares fits to the angular distribution data for the 0.83- and 2.16-MeV γ rays are listed in Table I. For $\bar{E}_p=4.90$ MeV, the ratio of $\alpha_2(0.83)/a_2(2.16)=1.37\pm0.10$ can be used to evaluate the mixing ratio $\delta=0.7\pm0.3$ for the 0.83-MeV transition. Combining this with our measured branching of the 2.16-MeV level, we obtain a value for the $B(E2)$ ratio of $B(E2;2_2^+\rightarrow2_1^+)/B(E2;2_2^+\rightarrow0_1^+)=250\pm140$.

2.29- and 2.50-MeV Levels

The angular distributions of 0.95-, 1.17-, and 0.47-MeV γ rays from higher levels are shown in Fig. 3. The theoretical predictions calculated for $E_p=5.92$ MeV are repeated at 6.94 MeV since little change with bombarding energy is anticipated.

The 0.95-MeV γ ray shows an isotropic angular distribution at variouse nergies within $\pm4\%$. Such a

[19] D. M. Van Patter, R. K. Mohindra, G. T. Wood, and P. F. Hinrichsen, Bull. Am. Phys. Soc. 10, 38 (1965).
[20] A. K. Sen Gupta and D. M. Van Patter, Phys. Letters 3, 355 (1963).

TABLE II. Comparison of $Ni^{60}(p,p'\gamma)$ cross sections with theoretical predictions using Hauser-Feshbach theory. The experimental cross sections include corrections for γ-ray branching and cascade feeding from higher levels.

Level (MeV)	J^π	$\bar{E}_p=4.90$ σ_{exp}(mb)	σ_{exp}/σ_{th}	$\bar{E}_p=5.92$ σ_{exp}(mb)	σ_{exp}/σ_{th}
1.33	2^+	73	0.84	95	0.56
2.16	2^+	16	1.17	43	0.77
2.29	0^+	4.5	1.14	20	1.03
	1^+		0.55		0.50
	2^+		0.49		0.45
	3^+		0.72		0.63
2.50	4^+	2.0	1.35	9.5	1.04
2.63	3^+	3.0	1.47	16.5	1.03
3.12	2^+	0.5	1.6	8.3	1.20

distribution may be expected from $0^+(E2)2^+$, as well as for $J(D,Q)2$ transitions with $J=1$, 2, or 3 and certain $E2/M1$ mixing ratios. To help to ascertain the spin of the 2.29-MeV level, Hauser-Feshbach calculations were carried out to find the cross section for this level for various spin values. As shown in Table II only the assignment of 0^+ yields good agreement with the experimental level cross section, while the theoretical cross sections for spin values of 1^+, 2^+, or 3^+ are 60 to 100% too high. This confirms the earlier tentative assignment of 0^+ for this level.[21] It should be noted that these theoretical cross sections have not been corrected for the effect of fluctuating level widths.

A small contribution to the 0.95-MeV γ ray could arise from a $3.12\rightarrow 2.16$-MeV transition. The isotropy of the 0.95-MeV distribution is an indication that this contribution should be small. More recently, a study of $Ni^{60}(p'\text{-}\gamma)$ coincidences has revealed[19] that the branching of the 3.12-MeV level by this mode is less than 4%, which means that this possible contribution to the 0.95-MeV γ-ray yield is of no consequence. The agreement between the theoretical and observed distribution at $\bar{E}_p=4.90$ and 5.92 MeV for the 1.17-MeV $4^+(E2)2^+$ transition is fairly good within statistics.

2.63-MeV Level

The present investigation has revealed the presence of a prominent γ ray of 0.47 ± 0.01 MeV, which has been assigned to a $2.63\rightarrow 2.16$ MeV transition from measurements of $(\gamma\text{-}\gamma)$ and $(p'\text{-}\gamma)$ coincidences.[19] In an earlier $Ni^{60}(p,p'\gamma)$ investigation[22] this γ ray was not observed because of the presence of annihilation radiation which was substantially reduced for the present target by eliminating copper contamination. The three experimental angular distributions for this 0.47-MeV transition have a minimum near 55° (Fig. 3), requiring a large positive A_4 term. As we have pointed out,[23] this evidence suffices for a unique identification of this γ ray as a $3(D,Q)2$ transition. As indicated in Fig. 3, excellent agreement with theory is obtained for each angular distribution if a multipole mixing ratio of $|\delta|>30$ is assumed, corresponding to an essentially pure (>99.9%) quadrupole transition. This result appears to rule out a 3^- assignment for the 2.63-MeV level since such an admixture of $E1$ and $M2$ radiation is highly unlikely. Therefore the 3^+ assignment seems to be unambiguous.

The large ellipse in Fig. 4 demonstrates the sensitivity of a $3^+(M1,E2)2^+$ $(p,p'\gamma)$ angular distribution to the multipole admixture. This ellipse may be generated from the theoretical $3^+(E2)2^+$ angular distribution by multiplying its A_2 and A_4 coefficients by

$$C_2=(-2.8+15.336\delta+\delta^2)/(1+\delta^2) \quad C_4=\delta^2/(1+\delta^2).$$

The large interference term in C_2 is the source of this sensitivity to δ. This term was given incorrectly in our previous publication,[23] which in turn affected the shape of $3^+(M1,E2)2^+$ ellipse shown. The result of this correction is a much larger ellipse, and an improved limit of $|\delta|>30$, which supercedes our previous estimate $(-6>\delta>1.6)$. No correction for the effects of cascades from higher levels to the 2.63-MeV level has been made. It is now known that such cascades amount to about 2% of the 0.47-MeV yield at $\bar{E}_p=4.90$ MeV, and about 10% at $\bar{E}_p=5.92$ MeV.[19]

Studies of $(p'\text{-}\gamma)$ coincidences have shown that the 2.63-MeV level has another mode of decay (35%) by a 1.29-MeV transition to the 1.33-MeV level.[19] In the

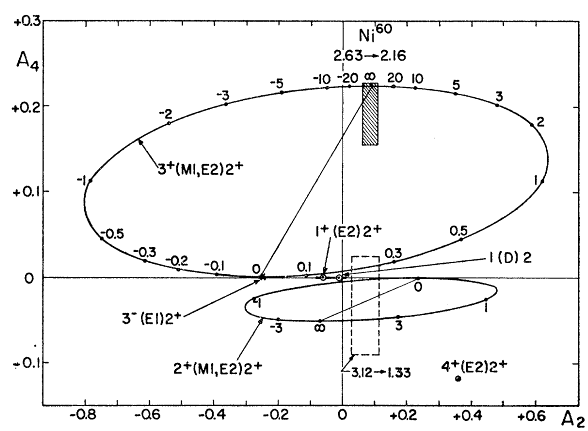

FIG. 4. The experimental results for the averaged $(p,p'\gamma)$ angular distribution (crosshatched area) for the $2.63\rightarrow 2.16$-MeV transition in Ni^{60} are compared with theoretical predictions for various transition types for $E_p=5.92$ MeV. By plotting A_4 versus A_2 (assuming $A_0=1$), the predictions for the mixed transitions $2^+(M1,E2)2^+$ and $3^+(M1,E2)2^+$ are represented by ellipses, which are a function of the mixing parameter $\delta=(E2/M1)^{1/2}$. The dashed rectangle represents the averaged results of the experimental distributions for the $3.12\rightarrow 1.33$-MeV transition.

[21] A. K. Sen Gupta and D. M. Van Patter, Program for the Topical Conference on Compound Nuclear States, Gatlinburg, Tennessee, 1963 (unpublished), p. 70.

[22] A. K. Sen Gupta, P. N. Trehan, and D. M. Van Patter, Bull. Am. Phys. Soc. 7, 81 (1962).

[23] D. M. Van Patter and R. K. Mohindra, Phys. Letters 12, 223 (1964).

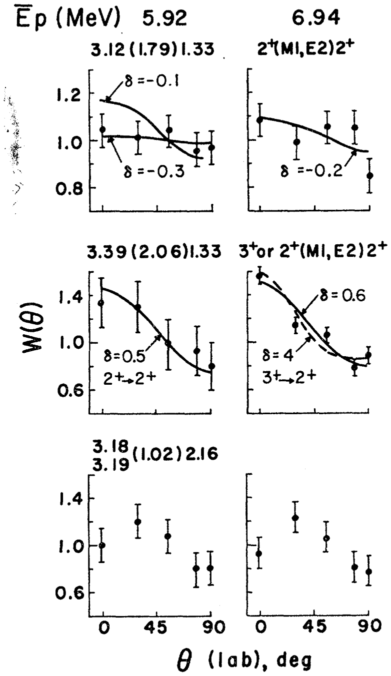

FIG. 5. Angular distribution data for the 1.02-, 1.79-, and 2.06-MeV γ rays observed from the Ni^{60} $(p,p'\gamma)$ reaction for $\bar{E}_p=5.92$ and 6.94 MeV. Theoretical calculations ($E_p=5.92$ MeV) for various transition types and multipole admixtures are indicated by solid lines.

singles γ-ray spectra observed in this investigation, the 1.29- and 1.33-MeV γ rays were not resolved.

3.12-MeV Level

Figure 5 shows the angular distribution data for transitions from levels near 3 MeV at $\bar{E}_p=5.92$ and 6.94 MeV, which are barely excited at 4.90 MeV. The 1.79-MeV γ ray from the 3.12-MeV level has been uniquely identified as a $2^+(M1,E2)2^+$ transition by Levine *et al.*[24] from a measurement of a (γ-γ) correlation in the decay of Cu^{60}. The present results are compared with theoretical predictions for a mixing ratio δ in the range of -0.1 to -0.3. Since there is no known feeding of the 3.12-MeV level from higher states,[19] it is expected that the 1.79-MeV angular distribution should remain essentially independent of bombarding energy, particularly since it is nearly isotropic. It is then reasonable to take a weighted average of the results at $\bar{E}_p=5.92$ and 6.94 MeV, which yields a value of $\delta=-0.24\pm0.06$. This value agrees with the radioactivity value of $\delta=0.15\pm0.09$ obtained by Levine *et al.*,[24] since the sign of δ from this $(p,p'\gamma)$ study should be reversed due to the reversal in order of the $2^+\rightarrow2^+$ mixed transition. Taking an average value for $\delta=0.20\pm0.05$ and the branching measured by Nussbaum *et al.*,[25] then a value for the ratio

$$B(E2;2_3^+\rightarrow2_1^+)/B(E2;2_3^+\rightarrow0_1^+)=8\pm5$$

is calculated.

[24] N. Levine, H. Frauenfelder, and A. Rossi, Z. Physik **151**, 241 (1958).

[25] R. H. Nussbaum, R. Van Lieshout, A. H. Wapstra, N. F. Verster, F. E. L. Ten Haaf, G. J. Nijgh, and L. T. M. Ornstein, Physica **20**, 555 (1954).

3.19-MeV Doublet

Analysis of the γ-ray spectrum shown in Fig. 1 indicated a composite peak centered at 3.19 MeV. A study of (p'-γ) coincidences has revealed that this peak includes ground-state transitions from levels at 3.12, 3.19 (doublet), and 3.27 MeV.[19] The usual decomposition of such a composite group is subject to considerable uncertainty. Since the main contribution was due to 3.19-MeV radiation, it was possible to adopt a different method of analysis to obtain its angular distribution. A three-channel strip centered at 3.19 MeV was taken, which maximized the relative yield of 3.19-MeV radiation. The yield in this region was then corrected for the contributions of the 3.12- and 3.27-MeV satellites, after taking into account the underlying continuous background. The resulting angular distribution data is shown in the upper left diagram of Fig. 6. Theoretical predictions for $1^+(M1)0^+$ or $2^+(E2)0^+$ transitions are shown as well, It seems clear that the data obtained by this procedure are sufficiently accurate to show that one of the members of the 3.19-MeV doublet has a spin of 1. A positive parity assignment cannot be made from this experiment; it originates from recent evidence for the population of this 3.19-MeV state in the decay of Cu^{60}.[26]

It was not possible to obtain meaningful angular distribution data for the 1.86-MeV transition to the first 2^+ state because of its proximity to the more intense 1.79-MeV γ ray shown in Fig. 1. The unusual form of the angular distribution of the 1.02-MeV γ-ray transition to the second 2^+ level suggests that it is a composite peak with contributions from both the 3.18- and 3.19-MeV levels. Proton-gamma coincidence

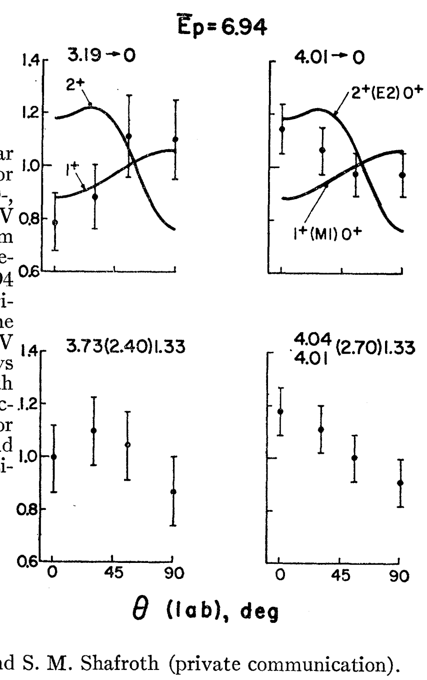

FIG. 6. Angular distribution data for the 2.40-, 2.70-, 3.19-, and 4.01-MeV γ rays observed from the $Ni^{60}(p,p'\gamma)$ reaction for $\bar{E}_p=6.94$ MeV. The experimental points for the 3.19- and 4.01-MeV ground-state γ rays are compared with theoretical predictions (solid lines) for $1^+(M1)0^+$ and $2^+(E2)0^+$ transitions.

[26] G. T. Wood and S. M. Shafroth (private communication).

studies[19] have revealed that the weak 0.66-MeV γ ray seen in the singles spectrum originates from a combination of $3.19 \rightarrow 2.50$- and $3.27 \rightarrow 2.63$-MeV transitions.

3.39- and 3.73-MeV Levels

The angular distributions of the 2.06-MeV γ ray (Fig. 5) show a strong forward peaking. As is indicated in Fig. 4, large A_2 values can be accounted for by either $2(D,Q)2$ or $3(D,Q)2$ transitions. It can be seen that the experimental data for this γ ray are well fitted by theoretical predictions for either a $2^+ \rightarrow 2^+(\delta \approx 0.5)$ or a $3^+ \rightarrow 2^+(\delta \approx 0.6$ or $4)$ transition, although a parity assignment cannot be made on the basis of these results. The (p,p') cross sections for this level are consistent with either choice.

Another prominent γ ray arises from the decay of the 3.73-MeV level whose (p,p') cross section is consistent with a spin assignment of 1, 2, or 3. Unfortunately, the angular distribution of this 2.40-MeV γ ray is isotropic within errors. In this instance, it is not possible to distinguish between these spin possibilities, since according to Fig. 4, a nearly isotropic distribution is predicted for some range of δ values in each case.

4.01- and 4.04-MeV Levels

It is known from studies of the γ spectrum of Cu^{60} that the 4.01-MeV level is either 1^+ or 2^+.[25] A sufficiently accurate $(p,p'\gamma)$ angular distribution of the 4.01-MeV ground-state transition should be able to distinguish between these two possibilities. In our initial studies, the yield of 4.01-MeV radiation was too weak at $\bar{E}_p = 5.92$ MeV, and was obscured by the presence of the one-escape peak of 4.43-MeV $C^{12}(p,p'\gamma)$ radiation from carbon contamination of the target. A substantial reduction of this carbon contribution was achieved in repeat runs, as illustrated by the spectrum shown in Fig. 1 for $E_\gamma > 2.1$ MeV. Nevertheless, the data failed to yield an unambiguous assignment for the 4.01-MeV level, as indicated in Fig. 6. Without such a unique determination, it was not possible to analyze reliably the angular distribution for the composite 2.70-MeV γ ray, which contains contributions from the decays of both the 4.01 and 4.04 (3^-) levels.

It is evident from the relative γ-ray intensities listed in Table III that the branching of the 4.01-MeV level [(2.68-MeV cascade)/(4.01-MeV crossover)] is at least a factor of 4 lower than the value of 5 ± 3 determined by Nussbaum *et al.*[25] in their study of the Cu^{60} decay. In addition, they assumed that a 3.52 ± 0.05-MeV γ ray was a ground-state transition. Since we have found no evidence from these $(p,p'\gamma)$ studies for such a ground-state decay, it is more likely that this γ ray should be identified as a $4.85 \rightarrow 1.33$ MeV transition, although no state has yet been established near this excitation energy.[3]

TABLE III. Relative production cross sections in mb for gamma rays from the $Ni^{60}(p,p'\gamma)$ reaction.

Parent level (MeV)	E_γ (MeV)	Cross sections[a] for values of $\bar{E}_p$ [b] (in MeV) =		
		4.90	5.92	6.94
1.332	1.33	97	207	398
2.159	2.16	2.5 ± 0.1	8.2 ± 0.3	17.2 ± 0.6
	0.83	15.2 ± 0.4	50.6 ± 1.2	103 ± 3
2.286	0.95	4.5 ± 0.2	20.3 ± 0.7	30.9 ± 1.3
2.505	1.17	2.0 ± 0.2	9.5 ± 0.4	29.6 ± 1.1
2.625	0.47	1.9 ± 0.2	11.7 ± 0.4	24.8 ± 1.5
3.120	1.79	0.4 ± 0.1	7.4 ± 0.4	31 ± 2
3.19 (doublet)	1.86	...	3.4 ± 0.6	16 ± 2
	1.02	...	4.3 ± 0.5	14 ± 1
3.27	1.94	...	2.0 ± 0.5	6.7 ± 0.8
3.12, 3.19, 3.27	3.19 (broad)	...	1.6 ± 0.3	11.4 ± 1.3
3.316	1.98	...	1.5 ± 0.5	6.7 ± 0.8
3.391	2.06	...	2.4 ± 0.5	12.2 ± 0.6
3.732	2.40	...	0.7 ± 0.2	6.5 ± 0.6
4.005	4.01	...	...	5.6 ± 0.5
4.038, 4.005	2.70	...	0.6 ± 0.2	7.5 ± 0.6

[a] These values were calculated after taking into account (i) the isotopic enrichment of the target and (ii) the γ-ray absorption in the target chamber and target backing. The errors listed apply to the yields of the various γ rays relative to that of the 1.33-MeV γ ray, and include an estimate of $\pm 2\%$ for the uncertainty in the relative photopeak efficiencies for the NaI detector. Systematic errors such as arising from possible target nonuniformities or incorrect beam charge collection have not been included, but they could contribute to uncertainties in absolute cross sections.
[b] $\bar{E}_p$ is the average bombarding energy corrected for half of the target thickness.

6. CONCLUSIONS

New nuclear-spectroscopic information obtained in this experiment is included in the level scheme of Fig. 7. Those γ-ray transitions shown by dashed lines have not been definitely established from singles γ-ray spectra alone, but are known to exist on the basis of $(p'$-$\gamma)$ coincidence data.[19]

An unusual feature of the Ni^{60} level structure is the close proximity of the collective 2.63-MeV 3^+ state to the "two-phonon" triplet at 2.16, 2.29, and 2.50 MeV, together with the large 0.50-MeV gap immediately above this 3^+ state. It is noted that none of the currently available nuclear models give a satisfactory account of these features.

Arvieu *et al.*[27] have given a microscopic description of the Ni^{60} nuclear structure in terms of linear combinations of two quasiparticle states. On the basis of their present calculations, a clustering of levels in the excitation region of 2.3 to 3.0 MeV is expected, including four 2^+ states, in contradiction to the experimental situation. These calculations have been recently extended by Arvieu and Salusti[28] to include estimates of quadrupole transition rates. Their prediction for the $B(E2)$ ratio involving the transitions $(2_2 \rightarrow 2_1)/(2_2 \rightarrow 0_1)$ is nearly 400 times smaller than the experi-

[27] R. Arvieu, E. Salusti, and M. Veneroni, Phys. Letters **5**, 334 (1964).
[28] R. Arvieu and E. Salusti (to be published).

mental $B(E2)$ ratio of 250 ± 140 for the 2.16-MeV state. However, their predicted value of 41 for the $B(E2)$ ratio involving transitions $(2_3\rightarrow 2_1)/(2_3\rightarrow 0_1)$ is much closer to the approximate experimental value of 8 ± 5 for the 3.12-MeV state. Their calculations thus far have not included estimates for the energies of 3^+ states; however, a 3^+ state based on a $2p1/2$, $1f5/2$ configuration would be expected to be near 2.65 MeV.[29]

Kerman and Shakin[30] have considered a collective model with quadrupole oscillations which included cubic terms in the nuclear Hamiltonian. This model is being extended by Brink *et al.*[31] to include quartic terms. Energy spectra are given in terms of four parameters which are fixed by the experimental energies for the first four levels. Application of this model to Ni^{60} results in explicit predictions for the energies of each member of the three-phonon quintet. The 3^+ member has a predicted energy of 2.78 MeV, in reasonable agreement with the observed collective 3^+ state at 2.63 MeV. Unfortunately, the lowest lying three-phonon member is predicted to be a 0^+ state at 2.48-MeV excitation, in distinct disagreement with experiment.

In a recent preliminary report, Jolly[32] has claimed that the spin of the 3.12-MeV level of Ni^{60} has been "corrected" from 2^+ to 3^-, on the basis of applying the Blair phase rule to (d,d') angular distributions measured at 15-MeV bombarding energy. We note that, if this is a single level, the possibility of 3^- is completely ruled out by the $(\gamma\text{-}\gamma)$ angular correlation result of Levine *et al.*[24] for the Cu^{60} decay. Since a 3^- state should be observable in (p,p') studies, it would have to lie within about 5 keV of the 3.12-MeV 2^+ state in order not to be detected in the high resolution studies of Paris and Buechner.[6] A strong argument against the possibility of an unresolved 2^+, 3^- doublet can be advanced on the basis of the (p,p') cross section which we have measured for the 3.12-MeV level. We note that at $\bar{E}_p=5.92$ MeV, the experimental cross section agrees within 20% with theory, (Table II), while the presence of an unresolved 3^- level should increase the cross section by about 70%. A similar argument could be advanced in the case of the 3.31-MeV level whose (p,p') cross section is distinctly too low for the 2^+ assignment which has been tentatively made by Jolly.[32] We conclude that such applications of the Blair phase rule to weaker (d,d') groups are subject to uncertainty at the present time.

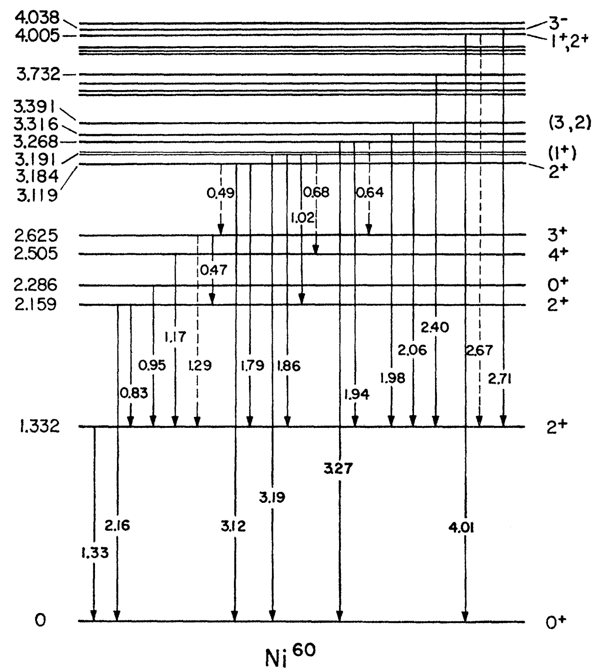

FIG. 7. Level scheme for Ni^{60}, indicating γ-ray transitions of interest in this experiment.

ACKNOWLEDGMENTS

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[29] R. Arvieu (private communication).
[30] A. K. Kerman and C. M. Shakin, Phys. Letters **1**, 151 (1962).
[31] D. M. Brink, A. F. R. de Toledo Piza, and A. K. Kerman (private communication).
[32] R. K. Jolly, Bull. Am. Phys. Soc. **10**, 122 (1965).