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# $E2/M1$ mixing ratio for the 1459→110 keV transition in $^{19}$F

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The unusually large $E2$ strength associated in the literature with the 1459→110 keV, $3/2^- \rightarrow 1/2^-$ transition in $^{19}$F is found to be due to unreliable measurements of the $E2/M1$ mixing ratio. The published values of the mixing ratio have been reexamined. New measurements of the angular distributions and linear polarizations of the 1459→110 keV and 1459 keV→g.s. $\gamma$ rays have been carried out, using the $^{19}F(p,p'\gamma)^{19}F$ reaction to populate the 1459 keV level. The best value of the mixing ratio from the former and present measurements is $\delta = 0.248 \pm 0.020$, corresponding to an $E2$ strength for the 1459→110 keV transition of $18.7 \pm 1.9$ Weisskopf units.

[NUCLEAR STRUCTURE $^{19}$F; measured $\gamma(\theta)$, $P(90°)$; deduced $\delta(E2/M1)$ for 1459→110.]

## I. INTRODUCTION

The 1459→110 keV transition in $^{19}$F connects the lowest $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states in $^{19}$F and has long been regarded as a test of the weak-coupling model in which these states are described as $p_{1/2}$ holes coupled, respectively, to the first $2^+$ and the ground state of $^{20}$Ne. The $E2$ strength for the $\frac{3}{2}^- \rightarrow \frac{1}{2}^-$ transition in $^{19}$F should then have the same value as the $2^+ \rightarrow 0^+$ transition in $^{20}$Ne, while the $M1$ strength is forbidden. In spite of the importance attached to this transition, the value of the $E2/M1$ mixing ratio is still in doubt. In what follows we shall first review the experimental measurements as reported in the literature, and then report on new measurements which we have made.

## II. ANALYSIS OF PREVIOUS MEASUREMENTS

The low lying states of $^{19}$F consist of two triplets of levels, with separations of about 100 keV between members of each triplet, and a separation of about 1.5 MeV between triplets. An energy level diagram is shown in Fig. 1. It is immediately apparent that studies of $^{19}$F using NaI(Tl) detectors may have problems arising from inadequate energy resolution, and early results on $^{19}$F obtained with such detectors should be carefully examined to see if they warrant consideration today.

The best measurements of the $E2/M1$ mixing ratio of the 1459→110 keV transition have been made using the $^{19}F(p,p'\gamma)^{19}F$ reaction. This is because of the high yield, which permits good statistics and good discrimination against room background, and because of the possibility of selectivity populating the 1459 keV level,[2] which minimizes unwanted contributions such as the 1554→197 keV transition. Compared with resonant alpha capture followed by known $\gamma$-ray decay cascades, the $^{19}F(p,p'\gamma)^{19}F$ reaction suffers from the disadvantage that the alignment tensor parameters are not known *a priori*. This means that in addition to the angular distribution of the 1459→110 keV $\gamma$ rays, it is necessary to measure at least one other independent quantity. This other measured quantity may for example be the angular distribution of the 1459 keV→g.s. transition, which, if assumed to be pure $E1$, yields the alignment parameter directly, or it may be the linear polarization of the 1459→110 keV $\gamma$ ray, which depends on both the alignment parameter and the mixing ratio.

The results of four previous measurements[3-6]

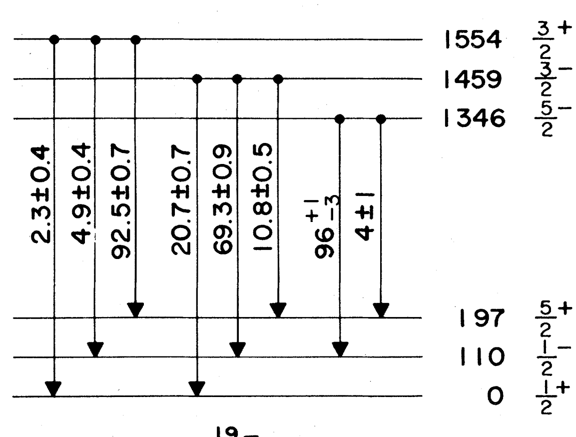


FIG. 1. The six lowest levels of $^{19}$F, from Ajzenberg-Selove (Ref. 1).

TABLE I. Published values of the $E2/M1$ mixing ratio for the 1459 → 110 keV transition in $^{19}$F. The $E2$ strengths are calculated using a lifetime of 130 ± 20 fs and a branching ratio of 69.3 ± 0.9%. Error limits are calculated from the limits on δ. None of these $E2$ values should be accepted without further examination of the data.

| Reference | $\delta(E2/M1)$ | $\|M\|^2(E2)$ (W.u.) |
|---|---|---|
| Prentice *et al.* (Ref. 3) | 0.23 ± 0.10 | $16^{+16}_{-11}$ |
| Poletti *et al.* (Ref. 4) | 0.21 → 0.50 | 14 → 64 |
| Lam *et al.* (Ref. 5) | $0.17^{+0.13}_{-0.06}$ | $9^{+18}_{-5}$ |
| Hardy *et al.* (Ref. 6) | 0.30 → 0.38 | 27 → 41 |
| Endt (Ref. 8) (adopted) | 0.36 ± 0.07 | $37^{+13}_{-12}$ |

of the $E2/M1$ mixing ratio for the 1459 → 110 keV transition are listed in Table I, together with the $E2$ strengths calculated assuming a lifetime of 130 ± 20 fs for the 1459 keV state,[7] and a branching ratio of 69.3 ± 0.9% for the 1459 → 110 keV transition.[1] (By comparison, the $2^+ \to 0^+$ strength in $^{20}$Ne is 20.5 ± 1.2 Weisskopf units (W.u.), using a lifetime[1] of 1.05 ± 0.06 ps for the 1.63 MeV state.)

There are important caveats to be attached to each of the entries in Table I. Prentice *et al.*[3] used a Compton polarimeter with NaI(Tl) detectors which did not have sufficient energy resolution to resolve all of the possible γ-ray transitions in $^{19}$F, but they nevertheless achieved most impressive results. The experiment of Poletti *et al.*[4] did not produce a theoretically possible ratio of $a_2$ coefficients for the angular distributions of the 1459 → 110 and the 1459 keV → g.s. transitions; this deficiency will be dealt with below. The experiment of Lam *et al.*[5] gave a result which we believe to be correct within the errors quoted, but a more accurate result could have been obtained from their data by ignoring the polarization measurements, which were of low accuracy because of the low sensitivity of their single-detector polarimeter. The experiment of Hardy *et al.*[6] does not yield consistent values for the alignment tensor parameter of the 1459 keV state when the 1459 → 110 keV and the 1459 keV → g.s. transitions are analyzed separately.

In order to clarify these experimental measurements we have first used the measured angular distribution data of the various authors to derive the $E2/M1$ mixing ratio for the 1459 → 110 keV transition, without regard to the polarization measurements. This analysis is possible because the 1459 keV → g.s., $\frac{3}{2}^- \to \frac{1}{2}^+$ transition is nearly pure $E1$. If we take the lifetime[7] of the 1459 keV state to be 130 ± 20 fs, the branching ratio[1] of the 1459 keV → g.s. transition to be 20.7 ± 0.7%, and the upper limit for possible $M2$ strength to be 0.1 W.u. (from Endt and van der Leun[8]), then it follows that the magnitude of the $M2/E1$ mixing ratio for the 1459 keV → g.s. transition is less than 0.008. For a $\frac{3}{2} \to \frac{1}{2}$ transition, the $a_2$ coefficient in the angular distribution $1 + a_2 P_2(\cos\theta)$ can be written in the convenient form[9]

$$a_2 = B_2 \sin 2(\rho + 15^\circ)\,,$$

where $B_2$ is the alignment tensor parameter and $\delta = \tan\rho$. For the 1459 keV → g.s. transition we then have

$$a_2(1459 \to \text{g.s.}) = (0.500 \pm 0.014) B_2\,.$$

Hence simultaneous measurement of the two $a_2$ coefficients yields directly $B_2$, and $\delta(E2/M1)$ for the 1459 → 110 transition. Experimentally it is necessary to ensure that the 1459 keV → g.s. γ ray is much stronger than the $^{40}$K background γ ray of 1461 keV, and this is easily achieved using the prolific $^{19}$F$(p, p'\gamma)$ reaction.

Table II displays values of $\delta(E2/M1)$ for the 1459 → 110 keV transition as calculated from the published angular distribution data. It is immediately seen that the measurements of Poletti *et al.*[4] are not self-consistent, since there is no solution for δ within limits of one standard deviation in the $a_2$ coefficients. The value of δ calculated from the data of Lam *et al.*[5] agrees with their published

TABLE II. Angular distribution coefficients for the 1459 → 110 keV and 1459 keV → g.s. transitions excited in the $^{19}$F$(p, p'\gamma)$ reaction at $E_p = 2.78$ MeV, and the derived mixing ratio for the 1459 → 110 transition.

| Author | $a_2$(1459 → 110) | $a_2$(1459 → g.s.) | (1459 → 110) transition $\sin 2(\rho + 15^\circ)$ | δ |
|---|---|---|---|---|
| Prentice *et al.* | not published | | | |
| Poletti *et al.* | −0.396 ± 0.013 | −0.167 ± 0.019 | 1.19 ± 0.14 | |
| Lam *et al.* | −0.48 ± 0.01 | −0.30 ± 0.03 | 0.800 ± 0.085 | 0.205 ± 0.074 |
| Hardy *et al.* | −0.438 ± 0.004 | −0.256 ± 0.005 | 0.855 ± 0.030 | 0.257 ± 0.031 |

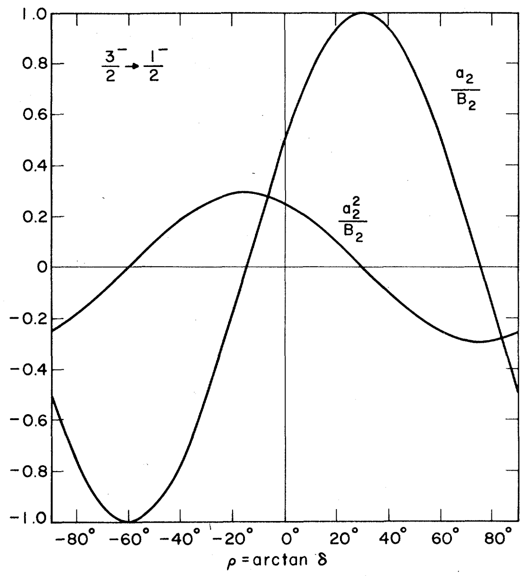


FIG. 2. Coefficients $a_2/B_2$ for the angular distribution and $a_2^2/B_2$ for the linear polarization of a $\frac{3}{2}^- \to \frac{1}{2}^-$ transition, as a function of the $E2/M1$ mixing ratio $\delta$.

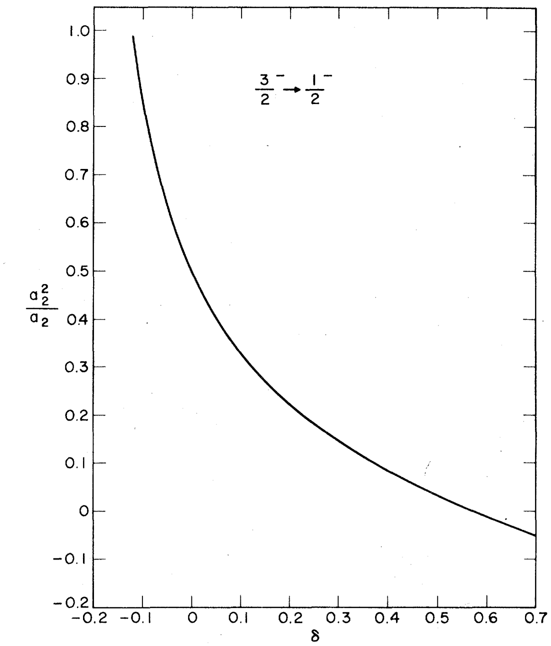


FIG. 3. The ratio $a_2^2/a_2$ for a $\frac{3}{2}^- \to \frac{1}{2}^-$ transition as a function of the $E2/M1$ mixing ratio $\delta$.

result, but has a smaller error. The value of $\delta$ calculated from the data of Hardy *et al.*[6] is significantly smaller than their published result, showing a lack of self-consistency in their data; the $\delta$ from their angular distribution data now agrees with the result of Lam *et al.*[5] If this analysis is accepted, there is no longer any case for the large $E2$ strength claimed to be necessary by Hardy *et al.*[6] and accepted by Endt.[8]

The values of $\delta(E2/M1)$ published by Lam *et al.*[5] and by Hardy *et al.*[6] are basically derived from measurements of the angular distribution and the linear polarization of the 1459→110 keV $\gamma$ rays; at least initially in the analysis the 1459 keV →g.s. transition is not used. The data may be simply analyzed as follows. The polarization at 90° is written as

$$P(90°) = \frac{3a_2^2}{1-0.5a_2},$$

where the polarization coefficient $a_2^2$ is given by[9]

$$a_2^2 = -0.2887 B_2 \sin 2(\rho - 30°)$$

for a $\frac{3}{2}^- \to \frac{1}{2}^-$ transition. The ratio $a_2^2/a_2$ is independent of $B_2$, and hence serves to determine $\rho$; next $B_2$ is found from $a_2$ and $\rho$. Figure 2 shows $a_2/B_2$ and $a_2^2/B_2$ as a function of $\rho$, while Fig. 3 shows the ratio $a_2^2/a_2$ plotted against $\delta$ in the region of interest for the 1459→110 keV transition. In Table III the data of Lam *et al.*[5] and of Hardy *et al.*[6] are analyzed for each of the 1459→110 keV and the 1459 keV→g.s. transitions. It is seen that the data of Lam *et al.*[5] are self-consistent, leading to an essentially zero mixing ratio for the 1459 keV→g.s. transition, and to the same value of $B_2$ from each transition. On the other hand the data of Hardy *et al.*[6] lead to a mixing ratio for

TABLE III. Analysis of published polarization measurements for the 1459→110 keV and 1459 keV→g.s. transitions excited in the $^{19}$F$(p,p'\gamma)$ reaction at $E_p$ = 2.78 keV.

| Quantity | Lam *et al.* (Ref. 5) (1459→110) | (1459→g.s.) | Hardy *et al.* (Ref. 6) (1459→110) | (1459→g.s.) |
|---|---|---|---|---|
| $a_2$ | −0.48 ± 0.01 | −0.30 ± 0.03 | −0.438 ± 0.004 | −0.256 ± 0.005 |
| $P(90°)$ | −0.30 ± 0.13 | 0.39 ± 0.19 | −0.130 ± 0.027 | 0.54 ± 0.08 |
| $a_2^2/a_2$ | 0.26 ± 0.11 | −0.50 ± 0.24 | 0.121 ± 0.025 | −0.79 ± 0.12 |
| $\delta$ | $0.16^{+0.13}_{-0.09}$ | $0^{+0.16}_{-0.08}$ | 0.34 ± 0.04 | $-0.09^{+0.03}_{-0.02}$ |
| $B_2$ | $-0.64^{+0.10}_{-0.14}$ | $-0.60^{+0.20}_{-0.24}$ | −0.47 ± 0.02 | −0.75 ± 0.10 |

the 1459 keV→g.s. transition which is significantly different than zero, and to $B_2$ parameters which do not agree. Since the analysis of Table II does show agreement between Lam *et al.*[5] and Hardy *et al.*,[6] it seems likely that the latter's lack of self-consistency can be traced to their polarization measurements.

Our conclusion in this survey is that of the four published values of $\delta(E2/M1)$ for the 1459→110 keV transition listed in Table I, only that of Prentice *et al.*[3] should be accepted without modification. The value of Poletti *et al.*[4] has a large uncertainty, compounded by a lack of internal consistency, and the values published by Lam *et al.*[5] and by Hardy *et al.*[6] should be replaced by the values listed in Table II.

## III. NEW MEASUREMENTS

In view of the unsatisfactory nature of the existing data on the $E2/M1$ mixing ratio for the 1459 →110 keV transition, we have undertaken new measurements of the angular distributions and linear polarizations. The NRC 4 MV Van de Graaff accelerator provided a proton beam of 2.78 MeV energy to excite a resonance in the $^{19}F(p,p'\gamma)$ reaction which is known to populate the 1459 keV level selectively. $CaF_2$ targets of thickness corresponding to a proton energy loss of about 5 keV were used.

Angular distributions were measured in a straightforward manner with two Ge(Li) detectors, one rotating and one fixed to serve as a monitor. The moving detector was placed about 30 cm from the target, and at that distance no correction for the finite size of the detector was necessary. Because of the high yield of the reaction the beam current had to be restricted to about 0.5 $\mu$A. Corrections were applied for analyzer deadtime and for self-absorption in the target backing, the latter correction amounting in the worst case at the 90° position to 6%. The peak shapes due to the combined 1459→110 keV and 1554→197 keV transitions were fitted with double Gaussians; the ratio of the intensity of the former to that of the latter varied from about 6 at 0° to about 13 at 90°. For the 1459 keV→g.s. transition it was necessary to make a correction to each peak area for the 1461 keV peak from $^{40}K$ background. Data were taken for nine angles spaced in equal intervals of $\cos^2\theta$, and the coefficients $a_2$ found by a least squares fit. The results for the 1459→110 keV and 1459 kev →g.s. transitions are shown in Table V, and are in substantial agreement with the values found by previous investigators and listed in Table II. Using the fact that the 1459 keV→g.s. transition is pure $E1$, the $\delta$ calculated for the 1459→110 keV transition from our angular distribution data is 0.224 ±0.040.

The polarization measurements were carried out with a Compton polarimeter consisting of two coaxial Ge(Li) detectors each of volume about 30 cm$^3$. The front faces of the detectors were separated by 3.2 cm and they were placed about 25 cm beneath the beam target, as shown in the inset of Fig. 4. Either detector served as a scatterer, the $\gamma$ rays scattered through about 90° being detected in the other counter. Scattering events were selected by a conventional fast coincidence system which gave a time resolution of 15 ns (full width at half maximum); a coincidence resolving time of 60 ns was used. The coincidence events were also restricted to those in which more than 200 keV were expended in each detector. This restriction eliminated true $\gamma$-$\gamma$ coincidences involving the 110 and 197 keV $\gamma$ rays of $^{19}F$ without affecting the overall detection efficiency of the polarimeter for 1 MeV $\gamma$ rays. The pulses from the two detectors were summed and fed through a linear gate controlled by the coincidence circuits to a pulse-height analyzer. The energy resolution of the sum peak was 4→5 keV for the 1332 keV $\gamma$ ray of $^{60}Co$. The singles spectra for each detector were also analyzed and recorded. Each polarization measurement involved four orientations: two with the symmetry axis of the polarimeter in the plane of polarization of the photons, and two with the symmetry axis perpendicular to this.

Choosing the alignment axis as the accelerator beam direction, the linear polarization $P(\theta)$ is given by

$$P(\theta)=\frac{W(\theta,\psi=0°)-W(\theta,\psi=90°)}{W(\theta,\psi=0°)+W(\theta,\psi=90°)},$$

where $W(\theta,\psi)$ is the intensity of the $\gamma$ rays emitted at an angle $\theta$ to the beam direction with the electric vector at an angle $\psi$ to the plane defined by

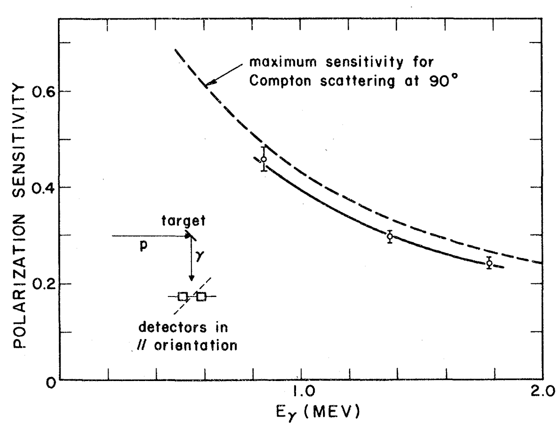


FIG. 4. Polarization sensitivity of the two-crystal Ge(Li) Compton polarimeter.

TABLE IV. Calibration data for the Compton polarimeter.

| Reaction | $E_p$ (MeV) | $E_\gamma$ (keV) | $P(90°)$ | Measured asymmetry $A$ | Polarization sensitivity $Q$ |
|---|---|---|---|---|---|
| $^{56}Fe(p,p'\gamma)$ | 3.43 | 847 | $0.54 \pm 0.02$ | $0.248 \pm 0.011$ | $0.459 \pm 0.026$ |
| $^{24}Mg(p,p'\gamma)$ | 3.07 | 1368 | $0.71 \pm 0.03$ | $0.212 \pm 0.009$ | $0.299 \pm 0.013$ |
| $^{28}Si(p,p'\gamma)$ | 3.10 | 1778 | $0.86 \pm 0.02$ | $0.211 \pm 0.010$ | $0.245 \pm 0.013$ |

the beam direction and the emitted $\gamma$ ray.

Experimentally, the sum coincidence counting rates $N_\parallel$ and $N_\perp$ were measured, where $N_\parallel$ is the sum coincidence counting rate for the polarimeter symmetry axis in the plane defined by the accelerator beam and the emitted $\gamma$ ray, and $N_\perp$ is the sum coincidence counting rate when the polarimeter symmetry axis is perpendicular to this plane. An asymmetry $A$ is defined by

$$A(\theta) = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} .$$

A measured asymmetry yields the polarization $P$ through the relation $A = QP$, where $Q$ is defined to be the polarization sensitivity of the polarimeter.

The polarization sensitivity was measured with linearly polarized $E2$ $\gamma$ rays from the $^{56}Fe(p,p'\gamma)^{56}Fe$, $^{24}Mg(p,p'\gamma)^{24}Mg$, and $^{28}Si(p,p'\gamma)^{28}Si$ reactions. The polarization of these $\gamma$ rays can be determined from angular distribution measurements. The values for the 847 keV $\gamma$ rays from $^{56}Fe(p,p'\gamma)^{56}Fe$ and the 1368 keV $\gamma$ rays from $^{24}Mg(p,p'\gamma)^{24}Mg$, for targets of thicknesses greater than the range of the protons, were taken from measurements made previously.[10] In the case of the 1778 keV $\gamma$ rays from $^{28}Si(p,p'\gamma)^{28}Si$ existing data for the 3.1 MeV resonance are in some disagreement, and we have remeasured the angular distribution for a target thickness of about 11 keV. We find $a_2 = 0.464 \pm 0.004$, $a_4 = -0.107 \pm 0.004$, and calculate $P(90°)$ $0.86 \pm 0.02$. Calibration data for the polarimeter are given in Table IV and a plot of $Q$ as a function of $\gamma$ ray energy is shown in Fig. 4. The maximum sensitivity for point detectors at a scattering angle at 90°, calculated from the intrinsic polarization sensitivity of the Compton cross section, is also shown in Fig. 4. By way of contrast, the polarization sensitivity of a single planar Ge(Li) polarimeter for 1 MeV $\gamma$ rays is only about 0.06.

The linear polarization of the various $\gamma$ rays emitted in the $^{19}F(p,p'\gamma)^{19}F$ reaction were measured using a proton energy of 2.78 MeV. All measurements were done "on resonance" in order to avoid possible shifts in the population parameters of the states of interest in $^{19}F$. A typical gated sum coincidence spectrum is shown in Fig. 5. Several of the $\gamma$ rays are Doppler broadened and a general background from the high energy $\gamma$ rays of the $^{19}F(p,\alpha\gamma)^{16}O$ reaction is also present. The corresponding sum coincidence spectrum gated by random coincidences was found to be negligible. The areas of the peaks in the sum spectra were normalized to the sum of the two singles rates for the same peak, after correction of the latter for analyzer deadtime. This normalization introduced a correction of at most 3% to the unnormalized data, but was considered necessary to correct for slight angular distribution effects when the polarimeter was rotated from one orientation to another.

The results of the present measurements of the linear polarization for the 1459 → 110 and 1459 keV → g.s. transitions are shown in Table V. The values

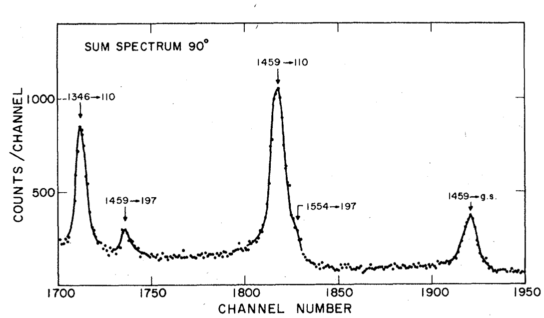


FIG. 5. A typical sum coincidence spectrum for observation of the $^{19}F$ $\gamma$ rays at 90°, with the polarimeter symmetry axis perpendicular to the reaction plane.

TABLE V. Analysis of present polarization measurements for the 1459 → 110 keV and 1459 keV → g.s. transitions excited in the $^{19}F(p,p'\gamma)$ reaction at $E_p = 2.78$ MeV.

| Quantity | (1459 → 110) | (1459 → g.s.) |
|---|---|---|
| $a_2$ | $-0.452 \pm 0.008$ | $-0.275 \pm 0.011$ |
| $P(90°)$ | $-0.182 \pm 0.027$ | $0.349 \pm 0.047$ |
| $a_2^2/a_2$ | $0.165 \pm 0.024$ | $-0.48 \pm 0.07$ |
| $\delta$ | $0.27 \pm 0.04$ | $0.01 \pm 0.03$ |
| $B_2$ | $-0.52 \pm 0.02$ | $-0.53 \pm 0.06$ |

TABLE VI. Experimental values of $\delta(E2/M1)$ for the 1459→110 keV transition which should be considered in choosing the best value.

| Author | Method | $\delta(E2/M1)$ |
|---|---|---|
| Prentice *et al.* (Ref. 3) | Polarization | 0.23 ± 0.10 |
| Lam *et al.* (Ref. 5) | 2 ang. dist. | 0.205 ± 0.074 |
| Hardy *et al.* (Ref. 6) | 2 ang. dist. | 0.257 ± 0.031 |
| Present work | 2 ang. dist. | 0.224 ± 0.040 |
| Present work | Polarization | 0.27 ± 0.04 |
| | Average | 0.248 ± 0.020 |

of δ are obtained analytically using the derived values of $a_2{}^2$ and $a_2{}^2/a_2$ (see Fig. 3). The δ for 1459→g.s. is found to be 0.01 ± 0.03, as required for a pure $E1$ transition, while the δ for the 1459→110 keV transition is found to be 0.27 ± 0.04. The values of the alignment parameter $B_2$, derived from $a_2$ and δ for each transition separately, are in agreement.

## CONCLUSIONS

Experimental values of δ which should be considered in choosing the best value are listed in Table VI. The reasons for accepting only certain values from the previously published results have been given in Sec. II above. The average value from Table VI is δ = 0.248 ± 0.020, corresponding to an $E2$ strength for the 1459→110 keV transition of 18.7 ± 1.9 W.u. This strength is in substantial agreement with the $E2$ strength of the 1.63 MeV $2^+ \rightarrow 0^+$ transition in $^{20}$Ne (20.5 ± 1.2 W.u.), and removes a perceived discrepancy in the weak-coupling model for the $K=\frac{1}{2}^-$ band in $^{19}$F.

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