Suffert, M.
Endt, P. M.
Hoogenboom, A. M.
1959

Physica 25
659–670

POLARIZATION MEASUREMENTS OF PROTON CAPTURE GAMMA RAYS

by M. SUFFERT, P. M. ENDT and A. M. HOOGENBOOM

Fysisch Laboratorium der Rijksuniversiteit, Utrecht, Nederland

Synopsis

The linear polarization has been measured of eight different gamma rays of widely differing energies ($E_\gamma = 0.8 - 8.0$ MeV) emitted at resonances in the ^{24}Mg(p, γ)^{25}Al, ^{30}Si(p, γ)^{31}P, and ^{32}S(p, γ)^{33}Cl reactions. The gamma rays emitted at 90° to the proton beam were Compton scattered in a 2″ NaI scintillation crystal and then detected in two 4″ NaI scintillation counters.

For six of the eight gamma rays mentioned above previous angular distribution measurements had left just two alternatives for either the spin or the parity of the corresponding resonance level, or for the $E2/M1$ mixing ratio. The present polarization measurements have resolved these ambiguities with the following results:

a. the 2.85 and 2.86 MeV levels in ^{33}Cl have $J^\pi = 5/2^+$ and $3/2^-$, respectively;

b. the 2.69 and 2.24 MeV gamma rays observed at the 418 keV ^{24}Mg(p, γ)^{25}Al resonance, and the 2.85 MeV gamma ray at the 580 keV ^{32}S(p, γ)^{33}Cl resonance have predominantly $M1$ character, while the 8.04 MeV gamma ray at the 776 keV ^{30}Si(p, γ)^{31}P reaction has predominantly $E2$ character.

For the two remaining gamma rays the measured polarizations were in agreement with known nuclear data.

1. *Introduction.* Useful nuclear information has been obtained from angular distribution measurements of gamma rays produced in proton capture reactions. It is quite common, however, that two or more sets of nuclear data may agree with a given angular distribution measurement. In the following the types of ambiguities left open by angular distribution measurements will be discussed. The discussion is limited to E1, M1 or mixed M1 + E2 transitions, and to even-even initial nuclei, excluding channel-spin mixing and mixing of proton angular momenta.

We first consider the case where the measured angular distribution agrees within the experimental error with that predicted for pure dipole radiation. This leaves the parity of the resonance level in doubt, assuming that spin and parity of the lower state are known. An example is the 2.86 MeV level in ^{33}Cl[1]).

If the measured angular distribution is different from that predicted for pure dipole radiation the transition can only be of M1 + E2 character and thus the parity of the resonance level is determined. It may happen, however, that two values of the spin of the resonant state can be found, with corresponding values of the E2/M1 mixing ratio, both agreeing with the measured angular distribution. The 2.85 MeV level in ^{33}Cl [1]) is an example of this type of spin ambiguity.

Finally the angular distribution may uniquely determine spin and parity of the resonance level, leaving doubt, however, as to the value of the E2/M1 mixing ratio. E.g. for a $J = 3/2$ resonance level the angular distribution contains no $P_4(\cos\theta)$ term, and thus from experiment only the $P_2(\cos\theta)$ coefficient can be obtained. This coefficient is a quadratic function of x, the E2/M1 mixing amplitude, and thus generally two possible x-values are found. This x-ambiguity occurs e.g. for the 2.69 and 2.24 MeV gamma rays de-exciting the 2.69 MeV level in ^{25}Al [2])[3]) and for the 8.04 MeV ground-state transition in ^{31}P [4])[5]).

It will be shown below that a measurement of the sign and degree of the linear gamma-ray polarization can decide very effectively between the alternatives left open by an angular distribution measurement. The polarizations produced in proton capture reactions are often large, and for pure radiation the sign of the polarization is determined by the parities of the levels involved. If the degree of polarization can be measured accurately enough it can decide between alternative spin values or mixing ratios.

For low-energy gamma rays ($E_\gamma \lesssim mc^2$) Compton scattering has generally been used for the measurement of polarization (see e.g. ref. 11). The gamma rays are scattered from a scintillating crystal in coincidence with a second crystal detecting the scattered radiation, at azimuthal angles of either 0 or 90 degrees.

A method for hard radiation is the use of the $D(\gamma, n)H$ reaction with deuterium-loaded nuclear emulsions (see e.g. refs. 6 and 7). This method entails long exposures and tedious plate reading. The energy resolution is low and the statistics obtained are generally so bad that at best the sign of the polarization can be determined.

These disadvantages of the emulsion method led to the decision to use Compton scattering, although for high-energy radiation the Compton cross section is small, as is the relative difference in counting rates of the 0- and 90-degree counters, even for completely polarized incoming radiation.

2. *Theoretical remarks on polarization and Compton scattering.* The direction-polarization correlation (DPC) of two successive gamma rays is treated e.g. in the survey paper by Biedenharn and Rose [8]). They also remark briefly on the changes necessary to extend the theory to (α, γ) and (p, γ) DPC's. From their remarks the following simple way may be deduced to obtain the (p, γ) DPC.

For any (p, γ) reaction with a 0^+ initial nucleus in which the gamma transition is of mixed dipole-quadrupole character the gamma-ray angular distribution can be written as:

$$W(\theta) = 1 + x^2 + (a + bx + cx^2)\, P_2(\cos\theta) + dx^2 P_4(\cos\theta), \qquad (1)$$

where x is the amplitude mixing ratio, and where a, b, c, and d are constants depending only on the spins of the resonant state and of the final state, to be found e.g. in the tables of Sharp *e.a.* [9]).

The (p, γ) DPC is then given by:

$$W(\theta, \varphi) = W(\theta) \pm \{(\tfrac{1}{2}a - \tfrac{1}{6}bx + \tfrac{1}{2}cx^2)\, P_2{}^2(\cos\theta) - \\ - \tfrac{1}{12}dx^2\, P_4{}^2(\cos\theta)\} \cos 2\varphi; \qquad (2)$$

in which φ is the angle between the polarization vector and the normal to the plane through the proton and gamma-ray momentum vectors, and where $P_2{}^2(\cos\theta)$ and $P_4{}^2(\cos\theta)$ are associated Legendre polynomials. The plus sign in front of the $\cos 2\varphi$ term should be taken for a E1—M2 mixture, the minus sign for a M1—E2 mixture.

In the present investigation gamma rays were only observed at 90 degrees to the proton beam ($\theta = \pi/2$). The degree of polarization P is then defined as:

$$P = \frac{W(\pi/2, 0) - W(\pi/2, \pi/2)}{W(\pi/2, 0) + W(\pi/2, \pi/2)} = \frac{\pm\, (\tfrac{3}{2}a - \tfrac{1}{2}bx + \tfrac{3}{2}cx^2 + \tfrac{5}{8}dx^2)}{1 + x^2 - \tfrac{1}{2}(a + bx + cx^2) + \tfrac{3}{8}dx^2}. \qquad (3)$$

For pure dipole radiation ($x = 0$) one may write the angular distribution as:

$$W(\theta) = 1 + A_2 \cos^2\theta,$$

with $A_2 = \tfrac{3}{2}/(1 - 1/2a)$, which yields the following particularly simple relation for the dipole polarization:

$$P = \pm\, A_2, \qquad (4)$$

with the plus sign relating to E1, the minus sign to M1 radiation.

In the remaining half of this section the efficiency of Compton scattering for the measurement of gamma-ray polarization will be discussed (see also e.g. ref. 10). For plane polarized incoming radiation the differential cross section for Compton scattering is given by the Klein-Nishina formula:

$$\sigma_C\,(\vartheta, \psi) = \tfrac{1}{4} r_0{}^2 \frac{k^2}{k_0{}^2} \left(\frac{k_0}{k} + \frac{k}{k_0} - 2 \sin^2\vartheta \cos^2\psi \right), \qquad (5)$$

where k_0 and k are the wave numbers of the incoming and scattered radiation, respectively, ϑ the scattering angle, ψ the angle between the (k_0, k) plane and the polarization plane of the incoming radiation, and $r_0 = e^2/mc^2$ the classical radius of the electron; k and k_0 are connected by the relation $k = k_0/\{1 + k_0(1 - \cos\vartheta)\}$. The efficiency for the polarization measurement

("Compton polarization efficiency") can then be defined as follows:

$$p(\vartheta) = \frac{\sigma_C(\vartheta, \pi/2) - \sigma_C(\vartheta, 0)}{\sigma_C(\vartheta, \pi/2) + \sigma_C(\vartheta, 0)} = \frac{\sin^2\vartheta}{k_0/k + k/k_0 - \sin^2\vartheta}. \tag{6}$$

If the incoming radiation is incompletely polarized ($|P| < 1$) the numbers of scattered quanta N_0 and N_{90} detected by counters at azimuth angles of $\psi = 0$ and 90 degrees are related by the expression:

$$\frac{N_{90} - N_0}{N_{90} + N_0} = p(\vartheta)P. \tag{7}$$

As a function of ϑ $p(\vartheta)$ shows a maximum at some forward angle, the maximum shifting to smaller angles with increasing k_0. However, this is not the most advantageous position for the counter detecting the scattered radiation. It will be shown below that for (p, γ) polarization measurements in which the accuracy obtainable is largely determined by counting statistics, the optimum value of ϑ maximizes $\bar{\sigma}_C(\vartheta)p^2(\vartheta)$, where $\bar{\sigma}_C(\vartheta)$ is the Compton cross section averaged over ψ.

From the rules for the propagation of errors the statistical error ΔP in P is found from (7) as:

$$\Delta P = \frac{1}{p(\vartheta)} \Delta \left(\frac{N_{90} - N_0}{N_{90} + N_0}\right) = \frac{1}{p(\vartheta)} \sqrt{\frac{4N_0N_{90}}{(N_{90} + N_0)^3}} \approx \frac{1}{p(\vartheta)} \frac{1}{\sqrt{2\bar{N}}},$$

where $\bar{N}$ is the average number of scattered quanta detected in the two counter positions. Use has been made of $\Delta N_{90} = (N_{90})^{\frac{1}{2}}$ and $\Delta N_0 = (N_0)^{\frac{1}{2}}$. Of course $\bar{N}$ is a.o. proportional to the measuring time t, to the relative resonance strength $\omega\gamma$, and to the average Compton cross section $\bar{\sigma}_C(\vartheta)$. One thus finds:

$$t (:) \{\bar{\sigma}_C(\vartheta)\, p^2(\vartheta)\, \omega\gamma(\Delta P)^2\}^{-1}, \tag{8}$$

which proves that the shortest measuring time to yield a given error ΔP is obtained for the maximum value of $\bar{\sigma}_C(\vartheta)\, p^2(\vartheta)$.

It can also be seen from (8) that it must be possible to extend the Compton scattering technique to high gamma-ray energies. Both $\bar{\sigma}_C(\vartheta)$ and $p(\vartheta)$ are then approximately proportional to E_γ^{-1}. The measuring time given by (8) remains approximately independent of E_γ, however, because for most resonances γ is equal to the radiation width Γ_γ which for dipole radiation varies with E_γ^3. The high-energy limit of the method is determined by instrumental errors.

3. *Experimental technique.* The proton beam was provided by the 850 kV Utrecht Cockcroft-Walton generator, yielding a proton current of up to 30 μA and a H_2-current of up to 150 μA after magnetic deflection (see e.g. ref. 4). The high voltage is stabilized with a signal from the exit slits of the magnet. The magnetic field is determined accurately with a magnetic resonance gaussmeter[12]).

For the $^{24}Mg(p, \gamma)^{25}Al$ measurements a copper target backing was coated with MgO smoke, producing a relatively thick target layer, which, however, could dissipate a large beam power without deterioration. The magnesium was of natural isotopic composition. The $^{30}Si(p, \gamma)^{31}P$ measurements were performed with an enriched 60 $\mu g/cm^2$ $^{30}SiO_2$ target obtained from the Atomic Energy Research Establishment, Harwell. For the measurements on the $^{32}S(p, \gamma)^{33}Cl$ reaction use was made of a ZnS target of about 10 $\mu g/cm^2$ with sulphur of natural isotopic constitution, evaporated in vacuo onto a copper backing. For eccentricity determinations also a carbon target was used, made by blackening with pencil a slightly roughened copper surface.

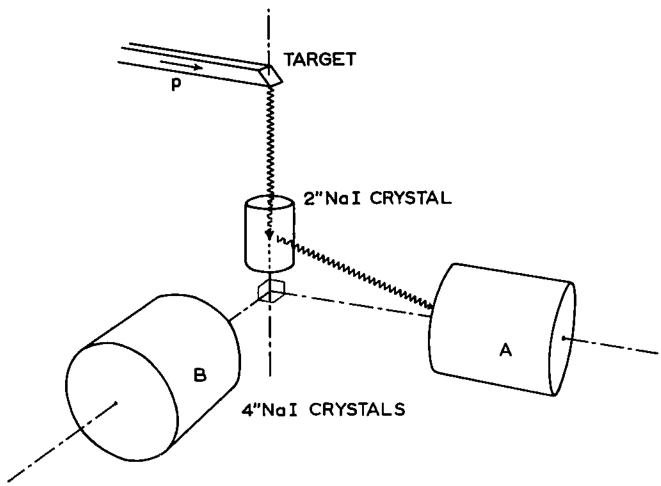

Fig. 1. Perspective drawing of the arrangement of scintillation counters.

A perspective drawing of the arrangement ot scintillation counters is shown in Fig. 1. The gamma radiation emitted vertically downwards at 90° to the proton beam is scattered and detected by NaI crystals. The center of the scattering crystal ($1\frac{5}{8}''$ in diameter and 2″ long) is at 11.5 cm from the target. The crystal is mounted on a Dumont 6292 photomultiplier with its axis coinciding with that of a large turntable [4]). On this table the two 4″ detecting crystals and their Dumont 6364 photomultipliers, which are mounted in heavy lead cylinders (not shown in Fig. 1), can be turned around the centre crystal. The centre of the 4″ crystals is at 14.6 cm from the axis of the 2″ crystal. The vertical distance between the centres of the 4″ and 2″ crystals can be adjusted so as to optimize the average scattering angle (see section 2).

The lead shielding is shown in Fig. 2. The rather large distance of the 2″ crystal from the target is determined by the requirement that the 4″ crystals be properly shielded from direct target radiation. A wall of lead bricks (not shown in Fig. 2) was used to shield the counter from radiation produced at the beam defining slits.

The use of two 4″ crystals offers several advantages. The counters, designated by A and B, were used alternately in two positions 1 and 2, respectively, as shown in Fig. 3. The "counter ratio" R was then defined as $\{(N_{B1}/N_{A1})/(N_{B2}/N_{A2})\}^{\frac{1}{2}}$, where N_{A1} etc. are the numbers of 4″ — 2″ coincidences for the same number of counts registered by the 2″ counter in the

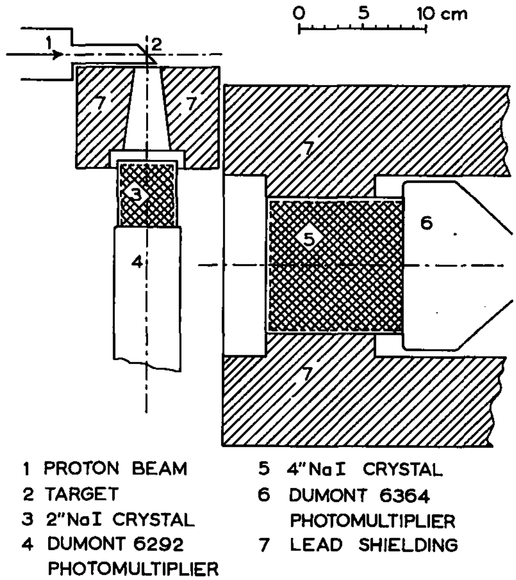

Fig. 2. Scale drawing of scattering and detecting crystals with lead shielding.

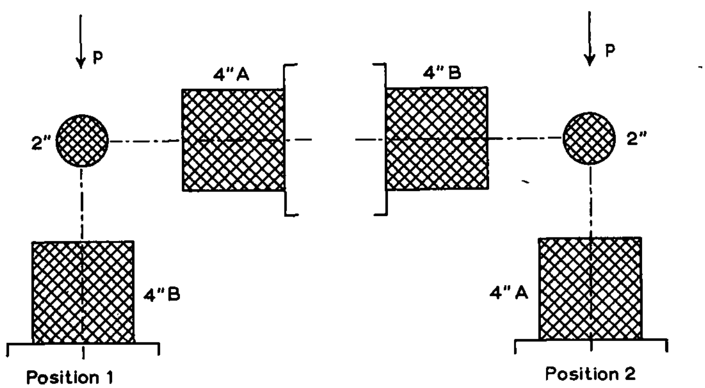

Fig. 3. Upper view of counter arrangement with detecting crystals in two alternative positions.

two positions. This counter ratio is independent of discriminator settings and of the solid angles subtended by the 4″ counters. The gamma-ray polarization is then obtained from the following relation:

$$P = \frac{1}{p} \frac{R-1}{R+1}, \tag{9}$$

if eccentricity, background, and solid angle corrections (see below) are neglected. This follows immediately from equation (7).

An eccentricity occurs if either the target spot or the centre of the 2″ crystal are not situated exactly on the axis of the turntable. The counter ratio is independent of an eccentricity perpendicular to the proton beam. The eccentricity in the direction of the beam could also have been eliminated if the 4″ counter structure could have been rotated over a further 90 degrees,

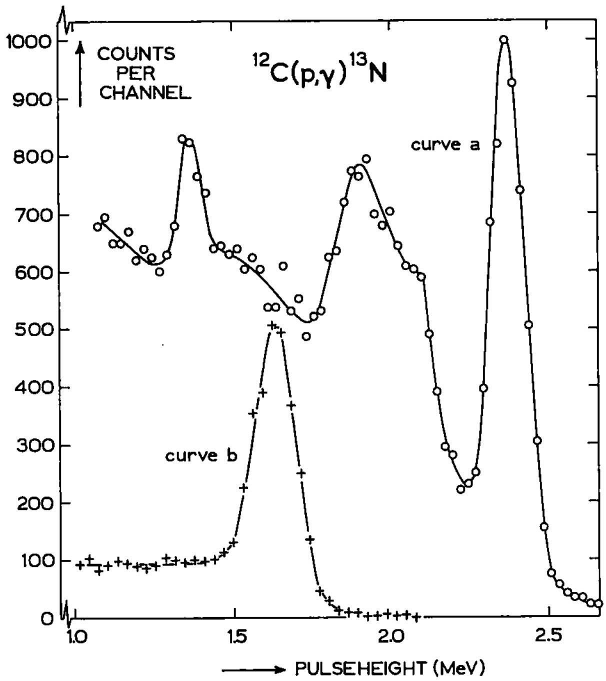

Fig. 4. Pulse spectra observed at the 461 keV $^{12}C(p, \gamma)^{13}N$ resonance.
a. Single spectrum of 2″ counter showing 2.37 MeV gamma ray.
b. Coincidence spectrum of 2″ counter gated with 0.60–0.76 MeV pulses from one of the 4″ counters.

thus bringing one of the 4″ counters directly below the proton beam. This, however, was impossible because of the voluminous counter lead shielding. In the present investigation this remaining eccentricity was corrected for by determining the counter ratio for gamma rays which are known to be unpolarized.

Before discussing the other corrections the electronic arrangement has to be mentioned briefly. After amplification the pulses of all three counters were fed through differential discriminators to two coincidence circuits with a resolving time of 1 μs, measuring the number of coincidences of each of the 4″ counters with the 2″ counter. The correct setting of the differential discriminators was arrived at as follows.

For a given geometrical arrangement (chosen to maximize $\bar{\sigma}_C(\vartheta)\, p^2(\vartheta)$, see section 2) one can easily find the minimum and maximum scattering angles from Fig. 2. The corresponding energies of scattered quanta then determine the setting and width of the 4″ differential discriminators. Actually, the width of the discriminator windows was chosen somewhat narrower than that determined by the scattering angle limits. Once the 4″ discriminators are set the 2″ window is determined by the requirement that the pulse heights in the 2″ and 4″ counters add up to that corresponding to the primary gamma-ray energy. A 100-channel Hutchinson-Scarrott pulse-height analyzer was used to check the correctness of the settings. First the 2″ single spectrum is registered. Then this spectrum is recorded again, but now "self-gated" with a pulse from the 2″ discriminator. Finally 2″ spectra are taken gated, respectively, by each of the 4″ disrciminators. This procedure is partly illustrated in Fig. 4 where the 2.37 MeV gamma ray observed at the 461 keV $^{12}C(p, \gamma)^{13}N$ resonance has been taken as an example. The tail observed in curve b (2″ spectrum gated by 4″ discriminator) probably originates from double scattering in the 2″ crystal or from scattering in the lead shielding. If two or more gamma rays are emitted at one resonance the polarization measurement of a low-energy gamma ray has to be corrected for the tail contributions of all higher-energy ones. The tail contributions were treated as background, i.e. they were assumed to be equal for the two 4″ counters, irrespective of position.

Another background correction stems from contaminants on the target. It can be measured in an off-resonance run, with the proton energy slightly below or above the resonance energy. Generator-off background was always negligible, while single counting rates were mostly so low that also random coincidences could be neglected.

In the computation of the polarization from the counter ratio (corrected for background and eccentricity) corrections have to be applied for the solid angles subtended by the counters. Of course, all solid angle effects tend to bring the measured counting ratio nearer to unity. It is useful to treat separately the corrections introduced by the finite ranges of ψ-, ϑ-, and θ-values (see section 2 for definitions) accepted by the counters. The ψ-correction can be obtained from (5) by averaging this expression over a suitable region $\Delta\psi$. The correct value of $\Delta\psi$ was arrived at by computing it for different volume elements of the 2″ crystal and then taking a weighted average. In the geometry used in the present experiments the ψ-correction lowers $p(\vartheta)$ by about 12%. The ϑ-correction is found by averaging (6) numerically over the ϑ-region defined by the discriminator settings; it lowers $p(\vartheta)$ by at most 3%. In this averaging procedure the factor $\sin\vartheta\bar{\sigma}_C(\vartheta)$ was taken as a weight; actually, also the efficiency of the 4″ crystal depends on the angle of incidence but this variation may be neglected. Finally, the θ-correction can be obtained from expression (2). Because the distance of

TABLE I

Experimental results for the polarization compared with values computed from angular distribution data

1	2	3	4	5	6	7	8	9			
	Reaction; E_p	E_γ (MeV)	Transition; Intensity	R measured	R [a] corrected	p [b] corrected	P [c] experimental	P computed from angular distribution data [2)4)1)]			
1	$^{24}Mg(p, \gamma)^{25}Al$ 418 keV	2.69	$(r) \rightarrow (0)$ 30%	1.057 ±0.036	1.045 ±0.06	0.209	0.11 ±0.14	$3/2^+ \rightarrow 5/2^+$ $x = 0.35 \pm 0.10$	0.01 ±0.02	$3/2^+ \rightarrow 5/2^+$ $x = 11 \pm 6$	0.39 ±0.05
2	$^{24}Mg(p, \gamma)^{25}Al$ 418 keV	2.24	$(r) \rightarrow (1)$ 30%	1.263 ±0.063	1.40 ±0.12	0.239	0.71 ±0.17	$3/2^+ \rightarrow 1/2^+$ $x = 0.06 \pm 0.06$	0.67 ±0.07	$3/2^+ \rightarrow 1/2^+$ $x = -2.2 \pm 0.5$	−0.70 ±0.09
3	$^{24}Mg(p, \gamma)^{25}Al$ 823 keV	2.63	$(r) \rightarrow (1)$ 70%	0.813 ±0.040	0.774 ±0.046	0.215	−0.60 ±0.14	$3/2^- \rightarrow 1/2^+$ $x = 0$	−0.60		
4	$^{30}Si(p, \gamma)^{31}P$ 776 keV	8.04	$(r) \rightarrow (0)$ 66%	0.967 ±0.023	0.940 ±0.028	0.082	−0.38 ±0.18	$3/2^+ \rightarrow 1/2^+$ $x = 0.06 \pm 0.02$	0.67 ±0.02	$3/2^+ \rightarrow 1/2^+$ $x = -2.2 \pm 0.2$	−0.70 ±0.03
5	$^{32}S(p, \gamma)^{33}Cl$ 580 keV	2.85	$(r) \rightarrow (0)$ 100%	1.28 ±0.11	1.24 ±0.11	0.198	0.55 ±0.22	$5/2^+ \rightarrow 3/2^+$ $x = -0.09 \pm 0.03$	0.39 ±0.01	$3/2^+ \rightarrow 3/2^+$ $x = -1.4 \pm 0.6$	−0.45 ±0.14
6	$^{32}S(p, \gamma)^{33}Cl$ 587 keV	2.86	$(r) \rightarrow (0)$ 50%	1.51 ±0.15	1.46 ±0.15	0.198	0.96 ±0.25	$3/2^- \rightarrow 3/2^+$ $x = 0$	0.75	$3/2^+ \rightarrow 3/2^+$ $x = 0.006 \pm 0.011$	−0.75 ±0.01
7	$^{32}S(p, \gamma)^{33}Cl$ 587 keV	2.05	$(r) \rightarrow (1)$ 50%	0.835 ±0.07	0.74 ±0.10	0.252	−0.59 ±0.26	$3/2^- \rightarrow 1/2^+$ $x = 0$	−0.60	$3/2^+ \rightarrow 1/2^+$ $x = -0.007 \pm 0.02$	0.60 ±0.02
8	$^{32}S(p, \gamma)^{33}Cl$ 587 keV	0.81	$(1) \rightarrow (0)$ 50%	1.01 ±0.07	0.96 ±0.10	0.50	−0.04 ±0.10	$1/2^+ \rightarrow 3/2^+$	0.00		

[a]) Counter ratio R corrected for background and eccentricity.

[b]) Compton polarization efficiency corrected for solid angle of the 4″ crystals.

[c]) Experimental value of the polarization P computed from columns 6 and 7 with

$$P = \frac{1}{p}\frac{R-1}{R+1}$$ and corrected for solid angle of the 2″ scattering crystal.

the target to the 2″ crystal is relatively large the corresponding correction in P is small, amounting to at most 1.5%.

4. *Results.* Measurements have been performed on four gamma rays observed from the $^{32}S(p, \gamma)^{33}Cl$ reaction, three gamma rays from the $^{24}Mg(p, \gamma)^{25}Al$ reaction, and one gamma ray from the $^{30}Si(p, \gamma)^{31}P$ reaction. The results are presented in Table I. In column 4 the resonance level is indicated by (r); the intensity of the transition is given as a percentage of the total gamma deexcitation of the resonance level. Columns 5 and 6 give the counting ratio R as measured, and after correction for background and eccentricity, respectively. Column 7 indicates the value taken for the Compton polarization efficiency p, averaged over φ and ϑ, while column 8 presents the final experimental value of the polarization P computed from (9) and corrected for the 2″ solid angle (θ-correction). These experimental values of P can be compared to the P-values (given in column 9) which can be computed from expressions (3) or (4) for the spins, parities, and mixing ratios following from angular distribution measurements[2]) [1]) [4]). All errors given are purely statistical and have to be interpreted as standard errors.

Four runs were performed to determine the correction for eccentricity. Two runs on the 2.37 MeV gamma ray observed at the 416 keV $^{12}C(p, \gamma)^{13}N$ reaction gave an average value of the counter ratio of $R = 1.032 \pm 0.023$, while two runs on the 7.89 MeV gamma ray at the 619 keV $^{30}Si(p, \gamma)^{31}P$ reaction yielded an average of $R = 1.029 \pm 0.016$. The average of these two values $R = 1.030 \pm 0.013$ was finally used for the eccentricity corrections.

The measurements at the 418 keV $^{24}Mg(p, \gamma)^{25}Al$ resonance were performed with the H_2^+ beam.

The coincidence rates obtained varied from 0.3–1.0 per minute for the sulphur runs to 25 per minute for the 619 keV ^{30}Si resonance used for the eccentricity measurements. The longest runs (e.g. run 7) took about 12 hours, not counting the time necessary for background and eccentricity runs and for the setting of the discriminators.

5. *Discussion and conclusions.* Runs 1 and 2. The polarization measurements prove conclusively that the 2.69 and 2.24 MeV gamma rays deexciting the 2.69 MeV ^{25}Al level have small E2/M1 mixing ratios. This would support the assumption[2]) that collective motion occurs in ^{25}Al. On this basis the initial and final states of the transitions investigated here belong to different bands, between which no strong E2 transitions are expected.

In column 9 of Table I the angular distribution measurements of Litherland et al.[2]) have been used yielding $P_2(\cos\theta)$ coefficients of -0.5 ± 0.1 and -0.4 ± 0.1, respectively. By Varma and Jack[3]) slightly larger (in absolute value) coefficients have been measured, of -0.75 ± 0.04 and -0.56 ± 0.04, respectively. For the 2.69 MeV gamma ray this would lead to possible mixing ratios of $x = 0.72$ and 2.3 with predicted polarizations of $P = 0.00$ and 0.19, respectively. For the 2.24 MeV gamma ray the possible x-values are -0.04 and -1.7 leading to polarizations of 0.56 and -0.58, respectively. If the latter measurements are assumed as correct one has to conclude that run 1 has yielded no decision as to the mixing ratio of the 2.69 MeV gamma ray.

Run 3. The $3/2^-$ assignment [13]) [2]) to the 3.08 MeV ^{25}Al level leads to a unique prediction of the polarization of the 2.63 MeV gamma ray in perfect agreement with the present experiment.

Run 4. The polarization values given in column 9 are based on the value of -0.37 ± 0.03 measured by Hoogenboom [4]) for the $P_2(\cos\theta)$ coefficient in the angular distribution of the 8.04 MeV gamma ray. The value of -0.31 ± 0.01 measured by Broude et al.[5]) would lead to mixing ratios of 0.11 and -2.3 and to predicted polarizations of 0.74 and -0.72.

The measured polarization is nearest to the polarization predicted for the large value of the mixing ratio although the difference is almost twice the standard error. It is impossible to say whether this difference is just caused by statistics, or whether the measured polarization of this high energy gamma ray has been attenuated by processes like the production of pairs and of attendant bremsstrahlung.

Run 5. In this case the angular distribution data [1]) left the spin of the resonance level in doubt. The polarization measurement decides that the spin of the 2.85 MeV ^{33}Cl level is 5/2 and that the gamma ray deexciting this level has a small mixing ratio ($x = -0.09 \pm 0.03$).

Runs 6 and 7. Separately and combined these two runs determine the parity of the 2.86 MeV ^{33}Cl level as odd. It is then highly probable that this level is the conjugate state of the $p_{3/2}$ single-particle level at 3.22 MeV in ^{33}S, a possibility already suggested by Van der Leun and Endt [1]).

Run 8. The 0.81 MeV gamma ray is unpolarized (within the experimental error) in agreement with the $1/2^+$ assignment [1]) to the first excited state in ^{33}Cl.

Acknowledgements. This investigation is partly supported by the joint program of the „Stichting voor Fundamenteel Onderzoek der Materie", and the „Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek".

One of the authors (M.S.) would like to thank Prof. P. Cüer for granting a leave of absence from the Laboratoire de Physique Corpusculaire de Strasbourg, and he also wishes to express his gratitude to all those making possible his stay in Utrecht.

We much appreciate the active help of Dr. P. B. Smith in all stages of the present investigation.

Received 28-4-59

REFERENCES

1) Van der Leun, C., and Endt, P. M., Physica **24** (1958) 1095.
2) Litherland, Paul, Bartholomew, and Gove, Phys. Rev. **102** (1956) 208.
3) Varma, J., and Jack, W., Physica **22** (1956) 1139 (A).
4) Hoogenboom, A. M., thesis Utrecht (1958).
5) Broude, Green, and Willmott, Proc. phys. Soc. (London) **72** (1958) 1097, 1115, and 1122.
6) Fagg, L. W., and Hanna, S. S., Phys. Rev. **92** (1953) 372.
7) Hughes, I. S., and Sinclair, D., Proc. phys. Soc. (London) **A69** (1956) 125.
8) Biedenharn, L. C., and Rose, M. E., Revs. mod. Phys. **25** (1953) 729.
9) Sharp, Kennedy, Sears, and Hoyle, "Tables of coefficients for angular distribution analysis" A.E.C.L. no .97, Chalk River (1953).
10) Diddens, A. N., thesis Groningen (1957).
11) Siegbahn, K., "Beta- and gamma-ray spectroscopy", North-Holland Publ. Cy. Amsterdam (1955).
12) Kuperus, J., Smulders, P. J. M., and Endt, P. M., Physica **25** (1959) 600.
13) Koester, L. J., Phys. Rev. **85** (1952) 643.