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MEASUREMENT OF THE GYROMAGNETIC RATIO OF THE 937-keV 3^+ STATE IN ^{18}F

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Abstract: The gyromagnetic ratio of the 3_1^+ state (937-keV excitation energy) in ^{18}F was measured by the time-integral IMPAC technique following implantation in a magnetically saturated Fe foil. The $^{16}O(^3He,p\gamma)$ reaction was employed using 3.75-MeV $^3He^+$ beams. Measurements of the angular distribution of the de-excitation γ ray from this level to the ground state and of its precession in the hyperfine field were carried out in coincidence with backward-emitted reaction protons. The sign and magnitude determined for the g-factor of this state is $g = +0.54 \pm 0.06$. Shell-model calculations of the g-factor of this level have been performed and are evaluatively compared with experiment.

[NUCLEAR REACTIONS $^{16}O(^3He,p\gamma)^{18}F$, E = 3.75 MeV; measured γ-ray ang. distr., particle-γ coin., ion implantation IMPAC technique perturbed ang. dist. 937-keV 3_1^+ ^{18}F level: deduced g-factor. Shell model calculation. Exp.-theor. comparison.]

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1. Introduction

As a facet of the continuing program of measurements in this laboratory of the gyromagnetic ratios of excited nuclear states utilizing both the enhanced transient hyperfine magnetic field[1] (manifest at the nuclei of ions rapidly recoiling through magnetized ferromagnet materials) and the static field (to which ions are subject at sites of implantation in such foils), and in view of the general interest in the structure characteristics of the levels in ^{18}F, we report on our recent measurement of the gyromagnetic ratio of the 3_1^+ state at 937-keV excitation energy.

The only extant published report of the measurement of the g-factor of this level in the literature appears to be that of Goldring <u>et al.</u>[2] who determined its <u>magnitude</u> to be $|g|=0.58\pm0.07$. While this value is in keeping with the expected shell-model configurations for this state, we considered it of value to determine experimentally the <u>sign</u> of the magnetic moment of this level (and to confirm the $|g|$ found earlier) in order to allow a more detailed and complete test of its shell-model description. To this end, we also present for comparison the results of our shell-model calculations of the g-factor of this 3_1^+ state.

2. Experimental procedures

The gyromagnetic ratio of the 937-keV 3_1^+ state in ^{18}F was determined experimentally utilizing the time-integral IMPAC technique.[3)]

The excited states in ^{18}F were populated via the reaction $^{16}O(^3He,p\gamma)^{18}F$ using beams of 3.75-MeV $^3He^+$ ions from the University of Melbourne 5U Pelletron accelerator. The target consisted of a thin layer ($\sim$ 180 μg cm^{-2}) of natural V_2O_5 [which evaporates predominantly as V_2O_3[4)]] evaporated onto a 3 μm thick Fe foil obtained from Goodfellows Metals. The Fe foil had been annealed by heating it to $\sim$ 800°C in vacuum prior to the evaporation. For added mechanical support, and to provide good heat conduction away from the beam spot, the target was pressed onto a 20 μm thick Cu backing using $\sim$ 1 mg cm^{-2} of evaporated In as adhesive.

The time-integral IMPAC technique used to measure the precession of the alignment of excited nuclei of ions under the influence of the static field at the site of their implantation in a magnetized ferromagnetic foil has been described in detail elsewhere.[3)] Two 12.5 cm x 15 cm NaI(Tl) detectors placed 25 cm from the target at ±55° to the incident beam direction were employed, as shown schematically in fig. 1. Each registered the γ-ray transitions in ^{18}F in coincidence with reaction protons detected in a common annular surface-barrier detector (3 cm upstream of the target) which subtended angles between 162^{o}-176^{o}. A Cu foil, 12.5 μm thick, placed over the particle detector served to stop ^{3}He particles backscattered from the target, while still allowing the reaction protons into the detector. The coincidence requirement resulted in events recorded for ^{18}F ions which recoiled into a narrow forward cone of half-angle $\sim 4^{o}$ with a mean recoil velocity $v/c = 1.3\%$.

The 3.75-MeV beam energy employed ensured that (i) the threshold for the $^{16}O(^{3}He,n)$ reaction was not reached, (ii) the yield of the 937-keV γ ray of interest in this work was high,[5] and (iii) the recoil energy of the ^{18}F ions was sufficient to implant them within the 3 μm Fe foil (^{18}F range in Fe $\sim$ 0.9 μm).

Although magnetometer tests on randomly selected (but otherwise identical) unannealed Fe foils showed them to be fully saturated in an applied magnetic field of $\leq$ 400 Oe, we choose to be somewhat overly conservative and utilized an applied field of 800 Oe, to be certain that the annealed Fe foil employed in the present experiment was indeed completely saturated. This field, in the plane of the Fe foil and normal to the incident beam direction, was provided by a small electromagnet mounted inside the target chamber. Bending of the incident beam projectile ions in the fringing field of the magnet was estimated from measurement of the profile of that field along the incident beam axis; for the incident $^3He^+$ beam ions, this was calculated to be ≈ 0.4 mrad which, in the present experiment, was negligible. The entire magnet-target assembly was mounted on a cold finger cooled with liquid N_2 to dissipate the heat generated in the magnet coils. To minimize systematic errors and, at the same time, to provide appropriate normalization of the recorded field-up and field-down data, the applied field direction was reversed automatically at frequent intervals (∿ every 5 min.); the field flip mechanism being tripped after a preset number of singles proton counts were registered in the particle detector. Data collection was inhibited during the time the field direction was changing. Events recorded for the field-down (↓) and field-up (↑) directions were stored separately in the lower and upper half of the relevant pulse-height spectrum, respectively.

Proton-γ coincidence data were recorded between the proton detector and each γ-ray detector using standard coincidence electronics; the data being written event-by-event onto magnetic tape. With a typical beam current of ∿ 300 na (not electron-suppressed) on target, the singles counting rate in the proton detector was ∿ 8 kHz and that in each NaI(Tℓ) detector was ∿ 15 kHz. Because of the relatively high coincidence rates which pertained, a single-channel analyzer was set to exclude most other uninteresting proton groups. Even so, at these counting rates, a single 800 m magnetic tape was filled in about 2h.

Prior to these precession measurements, the angular distribution of the 937-keV γ ray depopulating the 3_1^+ state of interest was measured in coincidence with reaction protons emitted in the backward direction. The yield of the γ ray was measured by one of the NaI(Tl) detectors (at 25 cm from the target) at the angles -45°, 0°, 22.5°, 45°, and 65° to the beam direction and normalized to the integrated singles proton spectrum recorded during the coincidence measurement at each angle. The normalized yield data were least-squares fitted to the usual Legendre polynomial series in cos θ -

$$W(\theta) = 1 + a_2P_2(\cos\theta) + a_4P_4(\cos\theta)$$

with the result that $a_2 = 0.529\pm0.037$ and $a_4 = -0.126\pm0.029$. The measured angular distribution is displayed in fig. 2 together with the least-squares fit made to it. From this fit, the value of the logarithmic derivative of this distribution, $S(= \frac{1}{W(\theta)}\frac{dW(\theta)}{d\theta})$, was found at 55° (where the slope of the angular distribution was maximal) to be $S = -0.812\pm0.067$.

3. Analysis and results

The event-by-event data stored on magnetic tape was sorted off-line to obtain the randoms-subtracted coincidence γ-ray spectrum associated with the proton group corresponding to direct population of the 937-keV level for each field direction. The normalized recorded field-up (↑) and field-down (↓) intensities of the 937-keV γ ray were obtained after appropriate background subtraction. Resolution in the particle detector was not sufficient to separate completely the proton group corresponding to population of the 3_1^+ state from that associated with the 0_1^+ state at 1045 keV; consequently a small contribution of the $0_1^+ \to$ground state γ-ray transition was present in the coincidence γ-ray spectra which was not fully resolved [due to NaI(Tℓ) resolution limitations] from that of the 937-keV γ ray. As the $0_1^+ \to$g.s. 1045-keV transition is, of course, isotropic, and, further, as line-shape fitting to this region of the spectrum showed its contribution to be quite small, its effect on the extracted g-factor for the state of interest was found to be negligible.

In the conventional manner, the double ratio

$$\rho = \left[\frac{N_1(\uparrow)}{N_1(\downarrow)} \, \frac{N_2(\downarrow)}{N_2(\uparrow)} \right]^{\frac{1}{2}}$$

was formed, where $N_{1(2)}(\uparrow)$ and $N_{1(2)}(\downarrow)$ are the recorded normalized counts in the 937-keV full-energy peak registered in the $+55^{o}(-55^{o})$ detectors for field-up and field-down directions, respectively. The precession angle, $\Delta\theta$, was extracted using the governing relation

$$\Delta\theta = \frac{1}{S}\left(\frac{1-\rho}{1+\rho}\right)\Bigg|_{\theta=55^{o}} ,$$

where S is the logarithmic derivative of the measured $W(\theta)$ (evaluated above). Furthermore, when the mean life, τ, of the state of interest is much greater than the time taken for the recoiling ion to come to rest in the Fe foil, T, then

$$\Delta\theta = -g\left(\frac{\mu_N}{\hbar}\right)\left(\int_0^T B_{tr}\,dt + B_s\tau\right) , \qquad (1)$$

where μ_N is the nuclear magneton, B_{tr} is the velocity-dependent transient field experienced by the nucleus of the recoiling ion during the time T, B_s is the static hyperfine field manifest at the nucleus at the implantation site in the Fe foil, and g is the gyromagnetic ratio of the state.

The measured mean life, τ, for the 937-keV 3_1^+ state in ^{18}F has been determined to be[6] 67.6±2.5 psec. For B_s, the static field experienced by the implanted ^{18}F in the polarized Fe foil, we adopted the measured value +95.7±0.5 kOe of Braunsfurth et al.[7] The stopping time of the ^{18}F ion in iron,

$T(\sim 0.6$ psec), was calculated from the known kinematics employing the stopping powers of Zeigler.[8] To evaluate the contribution of the velocity-dependent transient field to the precession while the ^{18}F ions recoiled through Fe, we employed the "universal" parameterization of the field obtained by the Rutgers group[9]

$$B_{tr}(v,Z) = (96.7\pm1.6)\left(\frac{v}{v_0}\right)^{0.45\pm0.18} Z^{1.1\pm0.2}$$

[where $v_0 = (c/137)$ and Z is the atomic number of the nucleus of the recoiling ion]; from it the precession due to the transient field was calculated in the present case to be $(\Delta\theta/g) = -3.9\pm2.0$ mrad. This value is consistent with the precession in the transient field experimentally measured[10] for the short-lived 1.7 MeV 1^+ state of ^{18}F for the same recoil velocity as pertained in our investigation: $(\Delta\theta/g) = -4.2\pm1.9$ mrad. Despite the large fractional uncertainty in the contribution due to the transient field, that contribution is quite small compared with the presently measured overall $(\Delta\theta/g) = -34.8\pm3.3$ mrad which is almost completely governed by the precession in the static field, and does not materially effect the experimental uncertainty in the measured value of g extracted for the 3_1^+ level.

Table I lists the data of the present precession measurements for each numbered run of our experiment. The weighted average value of the precession angle, $\langle\Delta\theta\rangle$, measured was $\langle\Delta\theta\rangle = -18.8\pm1.8$ mrad. Using the parameters specified above and this measured value of $\langle\Delta\theta\rangle$, the gyromagnetic ratio of the 3_1^+

state in ^{18}F extracted using eq. 1 is: $g = +0.54 \pm 0.06$. This value is in excellent agreement with the magnitude of the g-factor, $|g| = 0.58 \pm 0.07$, reported by Goldring *et al.*[2]

4. Shell-model calculations for levels in ^{18}F

Shell-model calculations were performed to obtain the g-factors and quadrupole moments of the 1_1^+(ground state), 3_1^+, and 5_1^+ states in $^{18}_{9}F_{9}$, in addition to the mean lives of the latter two excited levels. Two sets of basis states were employed; those which would be reasonably expected to describe well these states of interest.

In the first calculation (denoted Theory I), one proton and one neutron were constrained to occupy the valence s-d shell, while the $(0s)^4(0p)^{12}$ core remained closed. The Chung-Wildenthal[11] interaction was employed. The second calculation (labelled Theory II) allowed for three valence protons and three valence neutrons in the $(p_{1/2}, s_{1/2}, d_{5/2})$ shells; the interaction taken here was that of Reehal and Wildenthal,[12] which has been referenced as F-pds in the paper of McGrory and Wildenthal.[13] In both sets of calculations, the effective charges used to obtain the transition rates and quadrupole moments were $e_p = 1.5$ and $e_n = 0.5$; while the bare nucleon magnetic moments were employed in the calculations of the g-factors. The results of these calculations are presented in table II where they are compared with experiment.

From these, it is noted that both sets of calculations yield predicted g-factors and quadrupole moments for the 5_1^+ level which are in excellent agreement with experiment, while the measured mean life of this state appears to be in closer accord with that calculated using Theory I. However, in the case of the 3_1^+ state, the simpler sd-shell calculation (Theory I) is seen to overestimate its gyromagnetic ratio by about 30% (compared with our experimental value), while the more elaborate basis calculation (Theory II) predicted it to be in good agreement with our measured value (again, in this case, Theory I gives a mean life for this state which agrees better with experiment).

Of particular relevance to the present experimental g-factor determination of the 3_1^+ level is that both basis sets employed predict its sign to be positive. This is in accord with expectations, as it is difficult to presume reasonable configurations for this level which do not lead to positive g-factors.

5. Summary and conclusion

We have calculated the g-factors and static quadrupole moments of the 1_1^+(g.s.), 3_1^+, and 5_1^+ levels (as well as the lifetimes of the two latter states) using two different shell-model basis sets. These calculated predictions are found to be in good accord with prior measurements and with both the sign and magnitude of the gyromagnetic ratio of the 3_1^+ level determined in the present work.

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ished).

Table I. Measured precession data for the 3_1^+ level in ^{18}F

Run	$\epsilon(55^o)(x10^3)$[a]
1	13.6±1.7
2	15.4±1.7
3	15.9±1.8
4	14.2±1.7
5	18.9±2.2
	<15.3±0.8>[b]

a $\epsilon(55^o) = (1-\rho)/(1+\rho)$ measured at 55^o to the incident beam direction (see text). These listed values have been multiplied by 10^3.

b <...> denotes the weighted average value; the resultant $\langle\Delta\theta\rangle$ obtained using $\Delta\theta = \epsilon/S$, with $S = -0.812\pm0.067$, is $\langle\Delta\theta\rangle = -18.8\pm1.8$ mrad (see text).

Table II. Comparisons of calculated and measured gyromagnetic ratios, static quadrupole moments, and mean lives of designated states in ^{18}F.

Level (J^{π})	Quantity	Calculated values Theory I	Calculated values Theory II	Measured values[a]
1_1^+	Q(efm^2)	-1.34	-1.34	-
	g	+0.57	+0.72	-
3_1^+	Q(efm^2)	-9.53	-6.6	-
	g	+0.72	+0.60	+(0.54±0.06)[b]; ±(0.58±0.07)[c]
	τ(psec)	59	101	67.6±2.5
5_1^+	Q(efm^2)	-12.4	-10.7	±(13±3)
	g	+0.57	+0.58	+0.571±0.006
	τ(psec)	207	270	218±8

a Apart from the experimental values listed for $g(3_1^+)$, these measured values were taken from ref. 6.

b Present measurement.

c Ref. 2.

Figure Captions

Figure 1: Schematic plan view (not to scale) of experimental set-up of the precession measurement. The polarizing field was oriented in the plane of the target-Fe foil normal to the incident beam direction. The field up (↑) direction is also normal to the beam and is directed out of the page. The annular detector registered the reaction protons from the target.

Figure 2: Measured angular distribution of the 937-keV to ground-state γ ray ($3_1^+ \to 1_1^+$) transition. The solid curve is the least-squares fit to these data; the 55° degree position at which the detectors were placed in the precession measurement is denoted by the arrows.

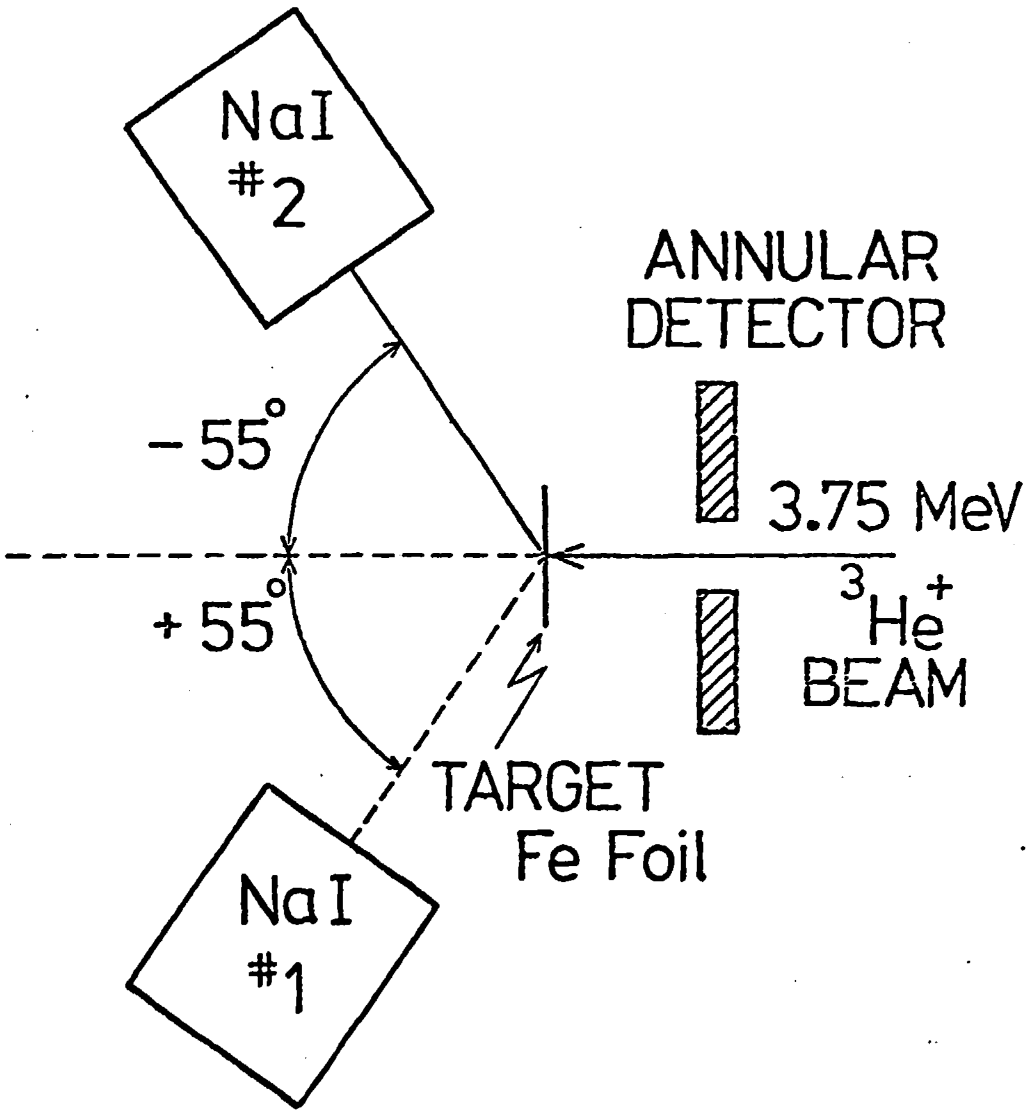
NaI
#2
ANNULAR
DETECTOR
−55°
3.75 MeV
+55°
$^3He^+$
BEAM
TARGET
Fe Foil
NaI
#1

Figure 1.

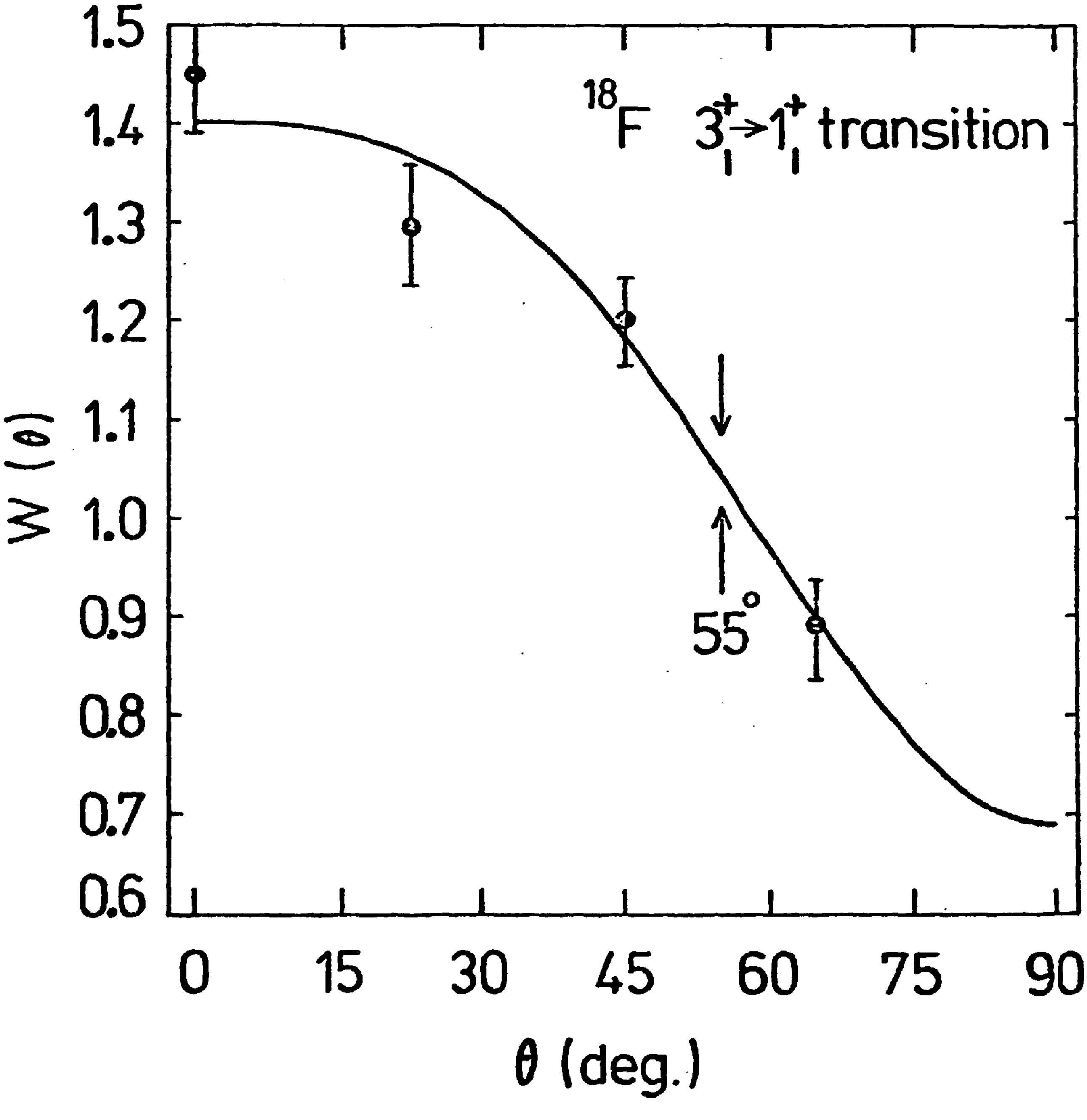
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
W (θ)
^{18}F $3_1^+ \rightarrow 1_1^+$ transition
55°
0
15
30
45
60
75
90
θ (deg.)

Figure 2.