POLARIZATION STUDIES OF GROUND-STATE RADIATION FROM THE 2·21 AND 2·73 MeV LEVELS OF ^{27}Al

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Abstract

The E2/M1 mixing ratios of the ground-state γ-ray transitions from the 2·21 and 2·73 MeV levels of ^{27}Al have been measured using a three-crystal Compton polarimeter in order to resolve discrepancies between previous experimental results for the 2·73 MeV transition.

I. Introduction

Among the properties of states of ^{27}Al below 3·0 MeV excitation only the mixing ratio of the 2·73 MeV to ground-state transition remains seriously uncertain. Ophel and Lawergren (1964) reported a value of $-0\cdot04\pm0\cdot06$ from a triple correlation measurement of the $2\cdot73 \to 1\cdot01 \to 0$ MeV cascade combined with a measurement of the linear polarization of the 2·73 MeV transition using the reaction ^{27}Al(p, p$'$)^{27}Al. The latter measurement was made with a sum-coincidence Compton polarimeter consisting of two NaI(Tl) crystals. Subsequently, Van der Leun *et al.* (1967) obtained a value of $-0\cdot09\pm0\cdot03$ from angular correlation studies of the reaction ^{26}Mg(p, γ)^{27}Al, in agreement with the result of Ophel and Lawergren. However, Lumpkin *et al.* (1971) have recently reported a value of $+0\cdot22\pm0\cdot09$ obtained from linear polarization studies of the reaction ^{27}Al(p, p$'$) with a Compton polarimeter comprising two Ge(Li) crystals. All these values of the mixing ratio have signs in accordance with the convention of Rose and Brink (1967). The value obtained by Lumpkin *et al.* is in serious disagreement with the previous measurements, and this discrepancy is important in the application of various models to the nucleus ^{27}Al, which lies in the transition region between prolate ($A \approx 25$) and oblate ($A \approx 28$) nuclear shapes. In an attempt to resolve the discrepancy for the 2·73 MeV transition and thus make comparisons with present and future model predictions more meaningful, we report here on measurements of the mixing ratios for the ground-state transitions from the 2·21 and 2·73 MeV levels using a Ge(Li)/NaI(Tl) Compton polarimeter.

II. Experimental Procedure

The states of interest in ^{27}Al were populated via the reaction ^{27}Al(p, p$'$)^{27}Al using a beam of 4·41 MeV protons from the EN tandem accelerator at the Australian National University. The bombarding energy was chosen from an excitation function

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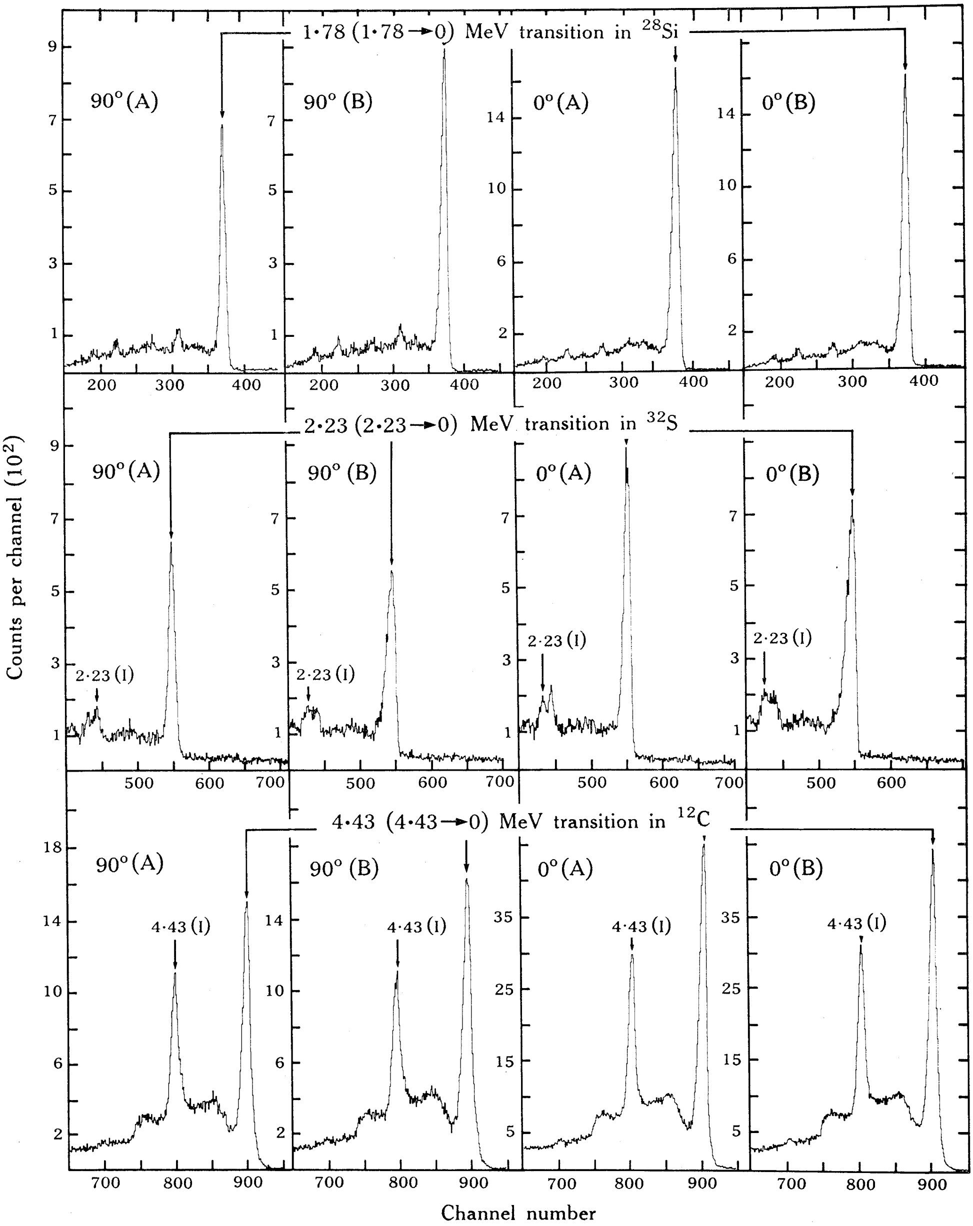

Fig. 1.—Relevant regions of the sum-coincidence spectra for the polarimeter calibration with pure E2 γ-rays scattered in directions (A) parallel and (B) perpendicular to the reaction plane with the polarimeter set at 90° and 0° to the proton beam direction. (I) denotes the first escape peaks.

measured over a limited range for the 2·73 MeV γ-rays. The target was 0·6 μm aluminium foil. The linear polarizations of the 2·21 and 2·73 MeV γ-rays were measured using a three-crystal sum-coincidence Compton polarimeter of the type described by Twin *et al.* (1970). This instrument consists of a 60 cm^3 coaxial Ge(Li) crystal as a Compton scatterer and two 7·62 × 7·62 cm NaI(Tl) crystals mounted to detect γ-rays scattered through mean angles of about 75°. The scatterer was set 16·5 cm from the target spot on a rotatable table. Beam currents were limited to 40 nA to render contributions from random coincidences negligible.

Sum-coincidence spectra for the two Ge(Li)/NaI(Tl) detector combinations were collected simultaneously in 2 × 1024 channels in an IBM 1800 computer. The polarimeter was set with the Ge(Li) detector axis alternately at angles of 90° and 0° to the proton beam direction (at 0° the γ-rays are unpolarized thus enabling the instrumental asymmetry to be measured) and three runs were made at each angle. Angular distributions were also measured for the 2·21 and 2·73 MeV γ-rays using the Ge(Li) detector alone. The instrumental anisotropy was determined using the isotropic 3·56 MeV ground-state γ-rays from the first $J^\pi = 0^+$ state in ^{6}Li which was populated via the reaction ^{9}Be(p, α)^{6}Li at a bombarding energy of 4·5 MeV. Reaction yields were monitored by a 40 cm^3 Ge(Li) detector set at 90° to the beam direction.

TABLE 1

POLARIMETER CALIBRATION DATA FOR PURE E2 γ-RAYS

Target	E_p (MeV)	E_γ (MeV)	Angular distribution coeffs. a_2	a_4	Polarization P(E2)	Asymmetry A*	Polarimeter sensitivity R
^{28}Si	3·10	1·78	0·45±0·02	−0·12±0·02	0·81±0·04	−0·17±0·01	0·21±0·01
^{32}S	4·10	2·23	0·10±0·01	0·28±0·01	0·31±0·01	−0·06±0·01	0·19±0·02
^{12}C	5·37	4·43	0·50±0·02	−0·15±0·02	0·93±0·04	−0·06±0·01	0·07±0·01

* Corrected for instrumental effects using measurements taken at 0° to the beam direction.

The polarimeter was calibrated using pure E2 γ-rays whose polarizations at 90° to the beam direction could be readily calculated in terms of the a_2 and a_4 angular distribution coefficients (Fagg and Hanna 1959). These γ-rays were obtained from the decay of the first excited states of three even–even nuclei populated by inelastic proton scattering, namely ^{28}Si(E_γ = 1·78 MeV), ^{32}S(2·23 MeV), and ^{12}C(4·43 MeV). Bombarding energies were chosen from brief excitation functions to coincide with the well-known resonances at 3·10, 4·10, and 5·37 MeV respectively. Relevant regions of the spectra obtained from the above reactions are shown in Figure 1.

III. Results

Table 1 shows the angular distribution coefficients a_2 and a_4, corrected for finite detector solid angle, obtained for the 1·78, 2·23, and 4·43 MeV calibration γ-rays. The resulting polarizations P measured at 90° to the beam direction are given by the formula (Twin *et al.* 1970)

$$P(\mathrm{E2}) = \frac{n(0^\circ)-n(90^\circ)}{n(0^\circ)+n(90^\circ)} = \frac{3a_2+(5/4)a_4}{2-a_2+(3/4)a_4},$$

where $n(0^\circ)$ and $n(90^\circ)$ are the numbers of γ-rays with their electric vectors parallel and perpendicular to the reaction plane respectively. The measured asymmetry A for a particular γ-ray, after corrections for instrumental effects, is defined here as

$$A = \{N(0°)-N(90°)\}/\{N(0°)+N(90°)\},$$

where $N(0°)$ and $N(90°)$ are the numbers of counts in the full energy peaks of the sum-coincidence spectra for γ-rays scattered parallel and perpendicular to the reaction plane respectively. It is possible to define a sensitivity factor R for the polarimeter as

$$R = -A/P.$$

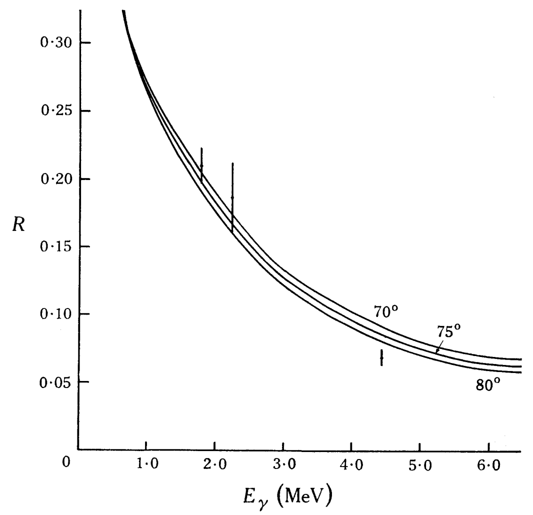

Fig. 2.–Polarimeter sensitivities R determined for the 1·78, 2·23, and 4·43 MeV pure E2 calibration γ-rays. The curves were calculated for mean Compton scattering angles of 70°, 75°, and 80° using a computer program adapted from that of Taras (1968) for the experimental arrangement used here.

Figure 2 shows the derived polarimeter sensitivities for the 1·78, 2·23, and 4·43 MeV γ-rays. The areas of the full energy peaks were determined using a simple exponential background subtraction. The solid curves were calculated for mean Compton scattering angles of 70°, 75°, and 80° using a computer program adapted from the one described by Taras (1968) for the particular detector arrangement used here. The calculation uses the Klein–Nishina formula for Compton scattering and divides the detectors into small radial and axial elements to determine the probability of absorption by an NaI(Tl) detector of a γ-ray scattered from the Ge(Li) detector. The fact that the 4·43 MeV point falls slightly below the curves can be explained by a contribution of about 25% to be expected from pair production events in the full energy peak (Marion and Young 1968). Because of the generally good agreement between the calculated curves and the experimental points, polarimeter sensitivities for the 2·21 and 2·73 MeV γ-rays were determined from the curves assuming a mean scattering angle of $75° \pm 5°$.

Results of the angular distribution and polarization measurements for the 2·21 and 2·73 MeV transitions in ^{27}Al are given in Table 2; the probable errors quoted represent the statistical uncertainties in the analysis. Sum-coincidence spectra are shown in Figure 3. Because the polarimeter resolution was about 40 keV, the 2·98 and 3·00 MeV peaks are not resolved. However, the 2·21 MeV peak is well isolated, and its area was determined using a simple exponential background subtraction.

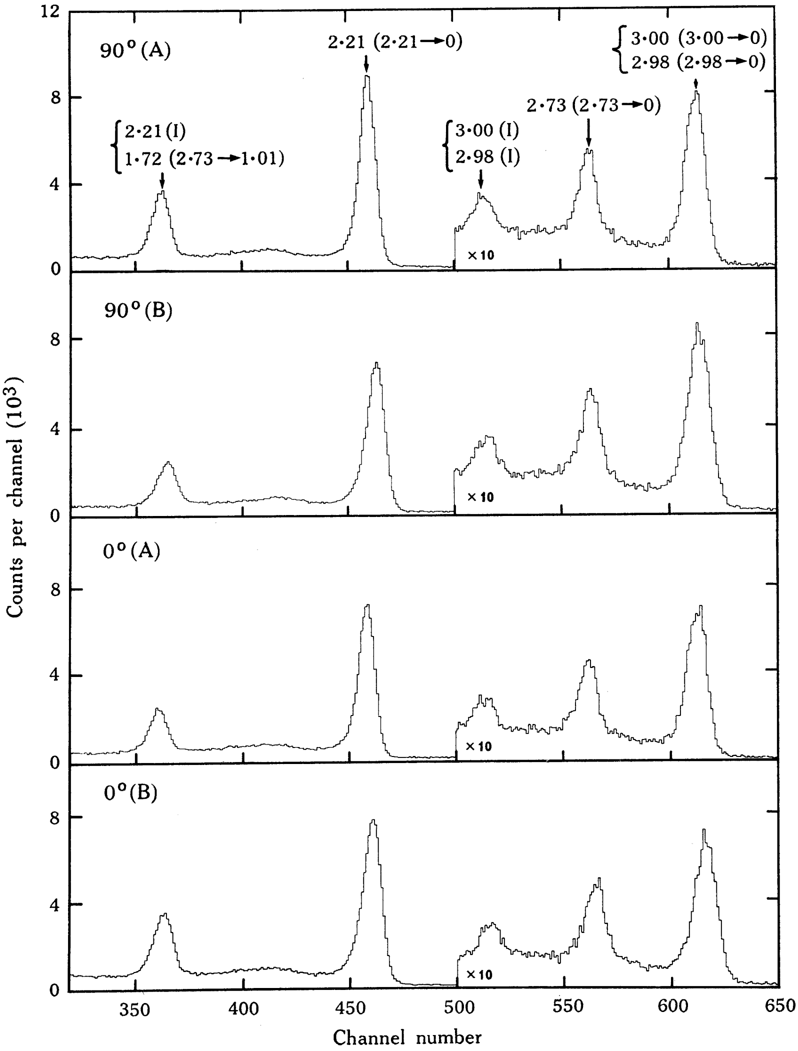

Fig. 3.—Relevant regions of the sum-coincidence spectra obtained from the reaction ^{27}Al(p,p′γ)^{27}Al showing the 2·21, 2·73, and 3·00 MeV full energy and first escape (I) peaks for γ-rays scattered in directions (A) parallel and (B) perpendicular to the reaction plane with the polarimeter set at 90° and 0° to the proton beam direction.

TABLE 2

SUMMARY OF RESULTS FOR 2·21 AND 2·73 MeV TRANSITIONS

Transition	Asymmetry A*	Polarimeter sensitivity R†	Polarization P	Angular distribution coeffs. a_2	a_4	Mixing ratio δ
2·21 → 0 MeV ($7/2^+ \to 5/2^+$)	0·057±0·002	0·170±0·005	−0·33±0·01	0·19±0·02	0·00±0·02	−0·46±0·02
2·73 → 0 MeV ($5/2^+ \to 5/2^+$)	−0·036±0·011	0·140±0·005	0·26±0·08	0·20±0·03	0·04±0·04	$-0\cdot13^{+0\cdot17}_{-0\cdot26}$

* Corrected for instrumental effects using measurements taken at 0° to the beam direction.
† Deduced from Figure 2.

Since the 2·73 MeV peak is superposed on a complex background arising from the 3 MeV γ-rays, several different background subtraction techniques were investigated. The results presented in Table 2 were obtained by subtracting a cubic polynomial background; other techniques gave results which differed from these by amounts that were insignificant in comparison with the statistical errors.

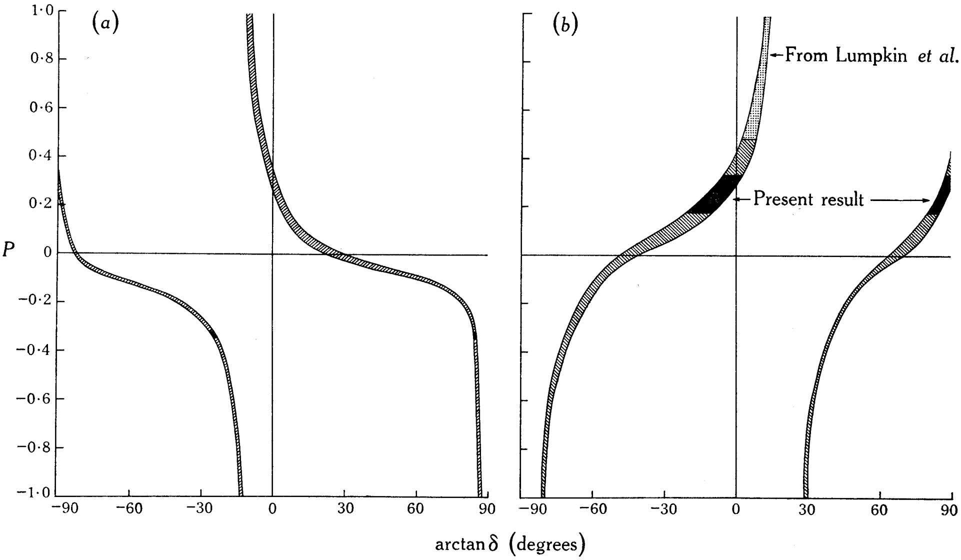

Fig. 4.—Plots of the polarization P versus the E2/M1 mixing ratio δ for the (*a*) 2·21 MeV and (*b*) 2·73 MeV transitions in ^{27}Al. The shaded areas show the values that are consistent with the angular distribution data while the solid areas represent the measured polarizations and errors. The dotted area in (*b*) corresponds to the range of values required by the mixing ratio given by Lumpkin *et al.* (1971).

Table 3

COMPARISON OF EXPERIMENTAL RESULTS FOR MIXING RATIO WITH THEORETICAL CALCULATIONS USING EXCITED CORE AND SHELL MODELS

Transition (MeV)	Experiment* Present work	(OL)	(VL)	(L)	Theory† (E)	(T)	(DV)
$2\cdot21 \rightarrow 0$	$-0\cdot46\pm0\cdot02$	$-0\cdot46\pm0\cdot04$	$-0\cdot40\pm0\cdot02$	$-0\cdot57\pm0\cdot08$	0·406	0·496	−0·50
$2\cdot73 \rightarrow 0$	$-0\cdot13^{+0\cdot17}_{-0\cdot26}$	$-0\cdot04\pm0\cdot06$	$-0\cdot09\pm0\cdot03$	$+0\cdot22\pm0\cdot09$	−0·821	−0·503	−0·62

* Previous experimental results by: (OL) Ophel and Lawergren (1964), (VL) Van der Leun *et al.* (1967), and (L) Lumpkin *et al.* (1971).

† Excited core model calculations by: (E) Evers *et al.* (1967) and (T) Thankappan (1966); shell model calculations by (DV) De Voigt *et al.* (1972).

Figures 4(*a*) and 4(*b*) show plots of polarization versus the E2/M1 mixing ratio for the 2·21 and 2·73 MeV transitions calculated using the formulae of Rose and Brink (1967). The shaded areas show the values that are consistent with the angular distribution data while the solid areas represent the measured polarizations. The positive solution for the 2·21 MeV transition mixing ratio has been excluded on the basis of angular correlation work by Van der Leun *et al.* (1967), while that for the 2·73 MeV transition has been excluded by the angular correlation results of Ophel and Lawergren (1964). The negative solutions are in agreement with those of the above authors for both transitions. The dotted area in Figure 4(*b*) corresponds to the range of values of polarization for the 2·73 MeV transition required to reproduce the mixing ratio given by Lumpkin *et al.* (1971). The value of polarization obtained in the present work is significantly different from this range. The error associated with the present result for the mixing ratio of the 2·73 MeV transition is larger than those given by Ophel and Lawergren and Van der Leun *et al.*, who used angular correlation techniques. The result of Lumpkin *et al.* also has a smaller error than the present result but corresponds to a value of polarization where the mixing ratio does not vary rapidly with polarization.

TABLE 4

E2 AND M1 STRENGTHS OF $2\cdot73 \rightarrow 0$ ($5/2^+ \rightarrow 5/2^+$) TRANSITION IN ^{27}Al

The calculated experimental strengths are compared with model predictions from (DV) De Voigt *et al.* (1972), (D) Dehnhard (1972), (T) Thankappan (1966), (E) Evers *et al.* (1967), and (R) Ropke *et al.* (1970). All values are in W.u.

Experimental strengths	Shell model (DV)	Oblate band-mixing model (D)	Weak coupling model (T)	Weak coupling model (E)	Rotation–vibration interaction model (R)
E2: $0\cdot13 \pm 0\cdot08$	$1\cdot6$	$1\cdot5$	$3\cdot6$	$2\cdot6$	$0\cdot2$
M1: $(2\cdot7 \pm 0\cdot8) \times 10^{-2}$	$0\cdot6 \times 10^{-2}$	—	$2\cdot0 \times 10^{-2}$	$0\cdot6 \times 10^{-2}$	—

IV. DISCUSSION

Table 3 summarizes the present and previous experimental results for the mixing ratios of the 2·21 and 2·73 MeV transitions in ^{27}Al together with values predicted from calculations using the excited core model (Thankappan 1966; Evers *et al.* 1967) and the shell model (De Voigt *et al.* 1972). It is not clear whether the sign conventions used by Thankappan and by Evers *et al.* are in accord with the convention of Rose and Brink (1967). The present results confirm all previous measurements of the E2/M1 mixing ratio for the 2·21 MeV transition. In the case of the 2·73 MeV transition, the present result is in agreement with those of Ophel and Lawergren (1964) and Van der Leun *et al.* (1967) within the stated errors, but the polarization obtained here is several standard deviations from that required by the mixing ratio of Lumpkin *et al.* (1971).

Excluding the result of Lumpkin *et al.* (1971), the weighted mean of all experimental values for the mixing ratio of the 2·73 MeV ($5/2^+ \rightarrow 5/2^+$) transition in ^{27}Al is $-0\cdot08 \pm 0\cdot03$. This value differs in magnitude from that of the corresponding transition in ^{27}Si, namely $+0\cdot40 \pm 0\cdot07$ (Main *et al.* 1971). The implications of this difference have been discussed by Main *et al.* in the context of the general observation that E2/M1 mixing ratios of corresponding transitions in mirror nuclei in the 2s–1d shell are usually equal in magnitude but opposite in sign.

Using a value of 12 ± 3 fs for the lifetime of the 2·73 MeV level (Schaller and Miller 1964; Smulders *et al.* 1968) and the branching ratio measurement of Smulders *et al.*, the experimental E2 and M1 widths for the 2·73 MeV transition can be calculated, and the results are shown in Table 4, together with values predicted by various models for ^{27}Al. It may be seen that the obvious discrepancy between the experimental and theoretical mixing ratio values of Table 3 occurs because the theoretical calculations overestimate the E2 strength by more than a factor of 10, while better agreement is obtained for M1 strengths. Only the rotation–vibration interaction model of Ropke *et al.* (1970) reproduces the observed E2 strength of the 2·73 MeV transition.

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