THE 5·80 MeV STATE OF ^{32}S

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Abstract

Studies of the reaction ^{29}Si(α, nγ)^{32}S indicate that the 5·80 MeV state of ^{32}S has an excitation energy of $5798 \cdot 2 \pm 1 \cdot 0$ keV, a mean lifetime of 14 ± 7 fs, and a spin of 1. Particle–gamma coincidence studies of the reaction ^{32}S(p, p$'\gamma$)^{32}S indicate that the state decays 100% to the 0^+ ground state, with all other possible transitions having intensities $\lesssim 2\%$ of the ground state transition. The properties of the state are shown to be consistent with those expected for the 1^- member of the negative parity quintuplet predicted by the coupled quadrupole–octupole vibrator model.

I. Introduction

It has been suggested recently by Garvey *et al.* (1971) and by Ingebretsen *et al.* (1971) that the low-lying positive parity levels of ^{32}S can be interpreted as the one- and two-quadrupole phonon states of the vibrational model. Enhanced E2 transitions from negative parity levels in the 6–8 MeV region to the lowest 3^- state have been observed in ^{32}S by one of us (L.E.C.) and in ^{36}Ar by B. W. Sargent (personal communication), e.g. the E2 transition from the 6·62 MeV 4^- state of ^{32}S to the 5·01 MeV 3^- state has a strength of approximately 20 W.u. These enhanced E2 transitions may be explained by an extension of the vibrational model. The coupling of one quadrupole phonon and one octupole phonon produces five negative parity states of spins 1, 2, 3, 4, and 5. Each of these states will decay to the one-octupole phonon state (the lowest 3^- state) by an E2 transition, and to the one-quadrupole phonon state (the lowest 2^+ state) by an E3 transition. The E2 transition should have the same enhancement as the E2 transition from the one-quadrupole phonon state to the 0^+ ground state, and the E3 transition should have the same enhancement as the E3 transition from the one-octupole phonon state to the ground state. For ^{32}S the single-phonon states are identified with the levels at 2·23 MeV (2^+) and 5·01 MeV (3^-). The observed enhancements for the relevant transitions to the ground state are approximately 9 W.u. for the E2 transition (Ingebretsen *et al.* 1971) and 20 W.u. for the E3 transition (Ollerhead, Alexander, and Häusser 1970).

There is insufficient information available at present to permit identification of all members of the quadrupole–octupole quintuplet in ^{32}S. Possible candidates are the 2^- state at 6·23 MeV (Endt and Van der Leun 1967) and the 4^- state at 6·62 MeV (Dorum 1968). A possibility for the 1^- member of the quintuplet is a state listed by Endt and Van der Leun as having an excitation energy of 5799 ± 8 keV and a spin of 1 or 2. A mean lifetime τ of 14 ± 2 fs had been reported by Lombard, Kossanyi-Demay, and Bishop (1964) from measurements of inelastic electron scattering. The state was believed to decay 100% to the ground state. Since then it has been reported

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by Graue *et al.* (1968) and Morrison (1970) that the state is populated in the $^{31}P(^{3}He, d)^{32}S$ reaction via an $l_p = 1$ transition, indicating $J^\pi = 0^-$, 1^-, or 2^-. This information, taken in conjunction with the γ-decay characteristics of the state, suggests a $J^\pi = 1^-$ assignment.

The present work was undertaken with the specific aim of using γ-ray spectroscopic techniques to obtain more definite values for the parameters of the 5·80 MeV state in order that its identification as a member of the quadrupole–octupole quintuplet might be more rigorously evaluated. Doppler-shift attenuation measurements via the reaction $^{29}Si(\alpha, n\gamma)^{32}S$ were used to determine the mean lifetime (Section II), angular distribution studies of γ-rays from the same reaction were used to obtain a spin assignment (Section III), and particle–gamma coincidence studies of the reaction $^{32}S(p, p'\gamma)^{32}S$ were used to determine the decay scheme of the state (Section IV).

II. Lifetime Measurement

The 5·80 MeV state was populated via the reaction $^{29}Si(\alpha, n)^{32}S$ using a 250 nA beam of 9·8 MeV $^{4}He^{2+}$ ions from the A.N.U. EN tandem accelerator. Targets of thickness approximately 200 $\mu g\,cm^{-2}$ were prepared by vacuum evaporation of SiO_2 from a tantalum boat onto a 0·051 cm thick tantalum backing. The silicon of the target material was enriched to 92% in ^{29}Si. Gamma ray spectra were taken at angles θ to the beam direction of 0°, 55°, 90°, and 135° with a 40 cm^3 Ortec Ge(Li) detector 9 cm from the target. The detector resolution was 3·5 keV FWHM at 1332 keV. At the bombarding energy used, the 6131 keV state of ^{16}O was populated by inelastic α-particle scattering. The full-energy and escape peaks of the γ-rays resulting from the ground state transition from this level were used in conjunction with the 2614 keV γ-rays from Tl^{208} to provide an energy calibration.

Centroids of the full-energy and escape peaks of the 5·80 MeV γ-radiation were determined after subtraction of an exponential background. Figure 1 shows sections of the spectra containing the 5·80 MeV γ-ray peaks for the four angles involved. The excitation energy of the state was determined from the unshifted 90° data as $5798 \cdot 2 \pm 1 \cdot 0$ keV, which agrees well with the value of $5797 \cdot 6 \pm 1 \cdot 0$ keV reported recently by Coetzee, Meyer, and Reitmann (1972).

The centroid positions were fitted with the expression

$$E(\theta) = E_0\{1 + F(\tau)\,(V_{cm}/c)\cos\theta\}, \tag{1}$$

where $E(\theta)$ is the energy of the γ-ray emitted at angle θ, E_0 is the unshifted γ-ray energy, V_{cm} is the velocity of the centre of mass in the laboratory frame, and $F(\tau)$ is the ratio of attenuated to full Doppler shift. At 9·8 MeV bombarding energy $V_{cm}/c = 0 \cdot 0088$. This formula is based on the assumption that the angular distribution of the recoiling nuclei is symmetrical about 90° in the centre-of-mass system. The effect of any asymmetry has been investigated by Ingebretsen *et al.* (1969). For their work using the reaction $^{32}S(\alpha, p)^{35}Cl$ they estimate that the effective forward velocity may be increased over V_{cm} by up to 5%. This effect is estimated to be less than 1% for the present measurements using the $^{29}Si(\alpha, n)^{32}S$ reaction and has therefore been neglected. The smaller value arises because it is possible to work closer to the threshold energy for the state under study with the (α, n) reaction than with

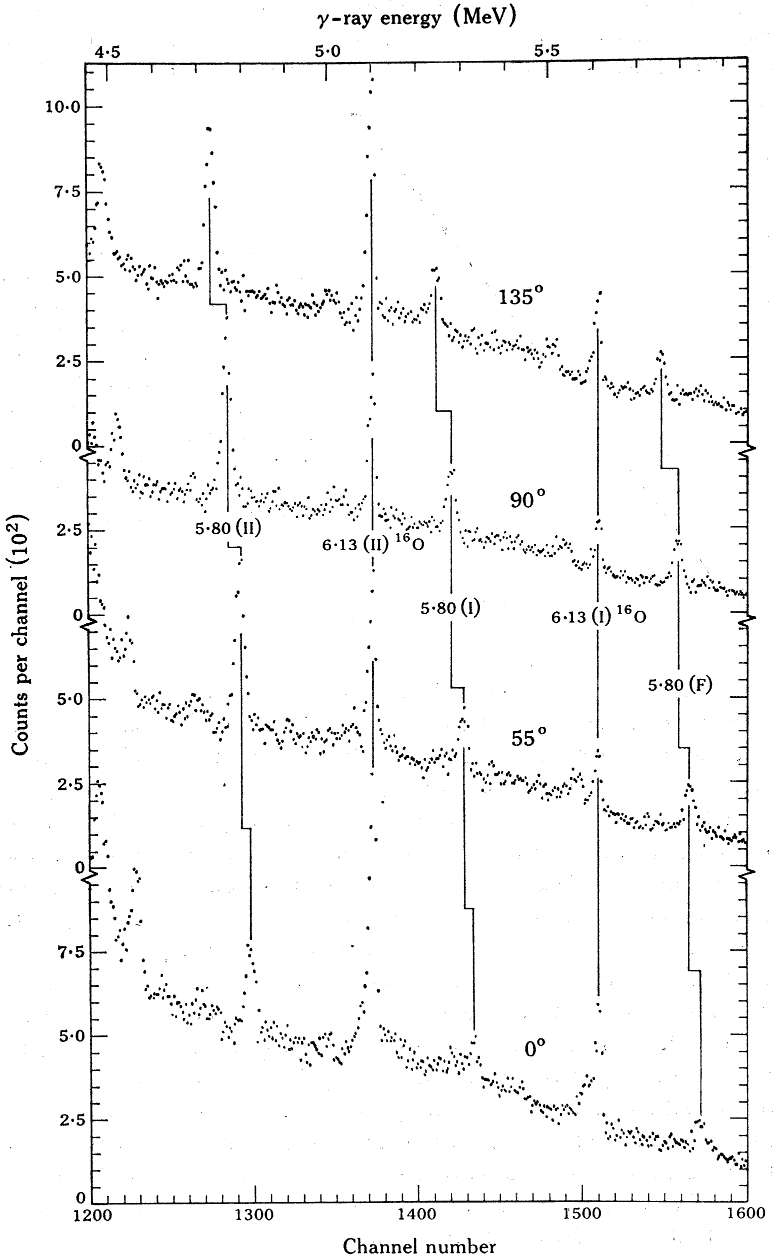

Fig. 1.—Sections of spectra containing the 5·80 MeV γ-ray peaks taken at $\theta = 0°$, 55°, 90°, and 135° at 9·8 MeV bombarding energy.

the (α, p) reaction. Figure 2 shows a least squares fit to the data of the above expression for $E(\theta)$, together with the calculated line corresponding to full shifts. For the sake of simplicity the diagram shows a combination of the data for the full-energy and escape peaks, although in the analysis each peak was treated separately. The weighted mean value of $F(\tau)$ derived from this analysis is $0\cdot 980 \pm 0\cdot 011$.

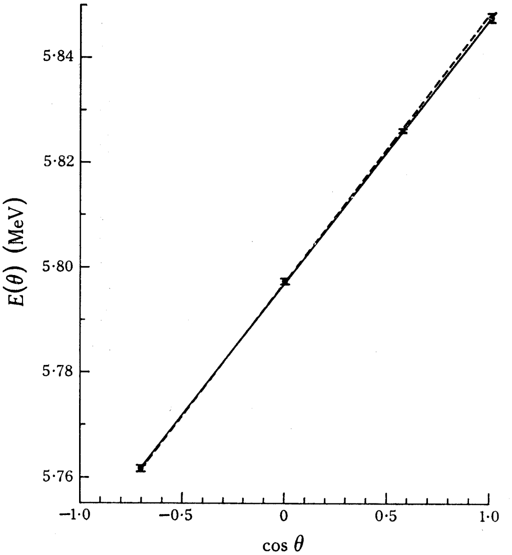

Fig. 2.—Least squares fit of expression (1) to the energies of the $5\cdot 80$ MeV γ-ray peaks shown in Figure 1. The values $F(\tau) = 0\cdot 980 \pm 0\cdot 011$ and $\tau = 14 \pm 7$ fs were obtained. For the sake of simplicity the diagram shows a combination of the data for the full-energy and escape peaks, although in the analysis each peak was treated separately. The dashed line represents the calculated full shifts.

The relationship between $F(\tau)$ and τ for the experimental situation was evaluated using the stopping theory of Lindhard, Scharff, and Schiott (1963) and includes the effects of nuclear scattering as discussed by Blaugrund (1966). This yielded a value for the mean lifetime of the $5\cdot 80$ MeV state of 14 ± 7 fs, where the quoted error arises predominantly from the uncertainty in the experimental value for $F(\tau)$. Errors due to uncertainty in the electronic stopping power derived from the theory of Lindhard, Scharff, and Schiott are $\sim 15\%$ and those due to the uncertainty in the density of the target material are $\sim 5\%$. In the process of vacuum evaporation from tantalum, the SiO_2 was reduced to some degree but the exact proportions of Si, SiO, and SiO_2 in the target were not known, although measurements of inelastic scattering of α-particles have confirmed that the target was not completely SiO_2. In the analysis it was assumed that the target contained equal proportions of Si, SiO, and SiO_2, and the 5% uncertainty used in the error analysis corresponds to the variation in density which could arise from uncertainty in the target composition.

The present result of $\tau = 14 \pm 7$ fs is in good agreement with the earlier result of 14 ± 2 fs obtained by Lombard, Kossanyi-Demay, and Bishop (1964) from inelastic electron scattering and with the value of 8 ± 5 fs obtained recently by Coetzee, Meyer, and Reitmann (1972) from Doppler-shift attenuation studies of the $^{31}P(p,\gamma)^{32}S$ reaction.

If the $5\cdot 80$ MeV state is assumed to decay 100% to the 0^+ ground state (see Section IV), a lifetime of 14 ± 7 fs implies γ-ray transition strengths which are unreasonably large for all spin–parity combinations except 1^+, 1^-, and 2^+; for example, $J^\pi = 2^-$ would require an M2 transition of 47^{+50}_{-15} W.u.

III. Angular Distribution Measurements

Angular distributions of 5·80 MeV γ-rays from the reaction ^{29}Si(α, nγ)^{32}S were measured at bombarding energies of 8·7 and 8·8 MeV using ^{4}He^{2+} beams of approximately 250 nA. The threshold for population of the 5·80 MeV state is 8·34 MeV. Hence, at the bombarding energies used, the emission of s-wave neutrons will predominate and the interpretation of the angular distributions will be correspondingly simplified. The target was the same one used for the lifetime measurement (Section II). Gamma ray spectra were recorded at $\theta = 0°$, 15°, 30°, 45°, 60°, 75°, and 90° (in random order) with a 40 cm^3 Ortec Ge(Li) detector located 10 cm from the target. Repeat measurements were made at 0°, 45°, and 90°. A 40 cm^3 Nuclear Diodes Ge(Li) detector set 6 cm from the target at $\theta = 270°$ served as a monitor.

The asymmetry of the moving-detector system was measured using the isotropic 2·31 MeV γ-rays resulting from the decay of the first excited state of ^{14}N ($J^\pi = 0^+$). This state was populated by bombarding a 100 μg cm^{-2} ^{11}B target on a 0·051 cm thick tantalum backing with 8·0 MeV ^{4}He^{2+} ions.

At each angle the number of counts observed in the second escape peak of the 5·80 MeV γ-ray was normalized to the number recorded simultaneously in the second escape peak of the 5·80 MeV γ-ray in the monitor detector spectrum. Corrections were applied for instrumental asymmetry ($\sim 4\%$) and for absorption in the target backing ($\sim 2\%$). The angular distributions so obtained (Fig. 3) were fitted with the expression

$$W(\theta) = A_0 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)\,. \tag{2}$$

The normalized experimental angular distribution coefficients, corrected for solid angle effects, were:

E_α	8·8 MeV	8·7 MeV
A_2	$-0·38 \pm 0·06$	$-0·31 \pm 0·06$
A_4	$0·06 \pm 0·06$	$-0·10 \pm 0·06$

An attempt was made to distinguish between spin assignments of 1 and 2 for the 5·80 MeV state by fitting the formulae of Rose and Brink (1967) to the data. For $J = 1$ a best fit (well within the 0·1% confidence limit) was obtained with the physically reasonable population parameters $P(0) = 0·56$ and $P(\pm 1) = 0·44$ at 8·8 MeV and $P(0) = 0·58$ and $P(\pm 1) = 0·42$ at 8·7 MeV (see Fig. 3). Population parameters to be expected for $J = 2$ were estimated by using neutron penetrabilities and the appropriate Clebsch–Gordan coefficients for weighting the production of the final magnetic substates by neutrons with $l = 0$, 1, and 2. The results obtained, essentially the same for both bombarding energies, indicated that $P(\pm 2) = 0·05$. The best fit to the data for $J = 2$ using this value of $P(\pm 2)$ yielded a value of χ^2 well outside the 0·1% confidence limit (see Fig. 3). In fact, fits to the data for $J = 2$ produced values of χ^2 below the 0·1% confidence limit only for values of $P(\pm 2)$ greater than about 0·50 (see Fig. 4). Assuming that this is physically unreasonable, it is concluded that $J(5·80) = 1$.

The angular distribution data were also compared with calculations made with the statistical compound nucleus program MANDY of Sheldon and van Patter (1966).

The normalized angular distribution coefficients calculated using MANDY, for a bombarding energy E_α of 8·8 MeV, were:

$J\pi$	2^+	2^-	1^+	1^-
A_2	0·43	0·39	−0·20	−0·20
A_4	−0·21	−0·13		

Comparison with the experimentally determined coefficients tabulated above shows that a $J = 1$ assignment is very strongly favoured. An assignment of $J = 1$ is consistent with the conclusion reached by Poletti and Grace (1966) from particle–gamma correlation studies of the reaction $^{32}S(p, p'\gamma)^{32}S$.

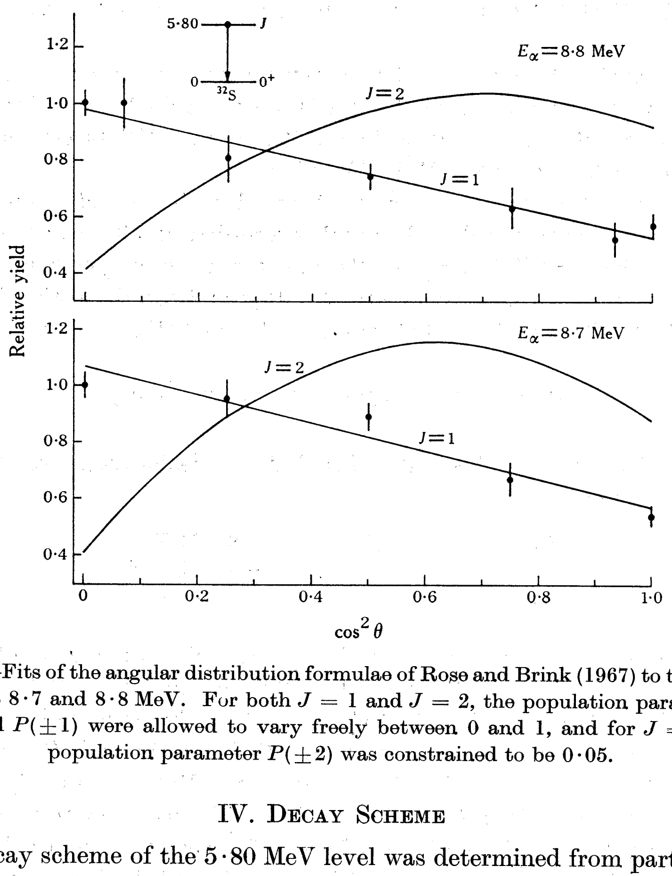

Fig. 3.—Fits of the angular distribution formulae of Rose and Brink (1967) to the data taken at 8·7 and 8·8 MeV. For both $J = 1$ and $J = 2$, the population parameters $P(0)$ and $P(\pm 1)$ were allowed to vary freely between 0 and 1, and for $J = 2$ the population parameter $P(\pm 2)$ was constrained to be 0·05.

IV. Decay Scheme

The decay scheme of the 5·80 MeV level was determined from particle–gamma coincidence studies of the reaction $^{32}S(p, p'\gamma)^{32}S$ at a bombarding energy of 8·63 MeV. The target consisted of 100 $\mu g\ cm^{-2}$ of natural cadmium sulphide deposited by vacuum evaporation onto a thin gold backing. Protons populating the 5·80 MeV level were detected at $\theta = 90°$ by a 5 cm (long) × 6 mm (wide) position-sensitive detector at the focal plane of the 61 cm double-focusing magnetic spectrometer described by Elliott, Carter, and Spear (1968). A 12·7 cm × 10·2 cm NaI(Tl) crystal was mounted with its axis vertical and its front face 4·1 cm above the target spot. The crystal was supported in the top of the target chamber by a 1·6 mm thick steel plate. Pulses from the NaI(Tl) detector were recorded in a 512-channel pulse height analyser gated by coincidences between NaI(Tl) and position-sensitive detector pulses. Conventional crossover timing techniques were employed. The ratio of real to random coincidences was determined using a time to pulse height converter. Gamma ray singles spectra

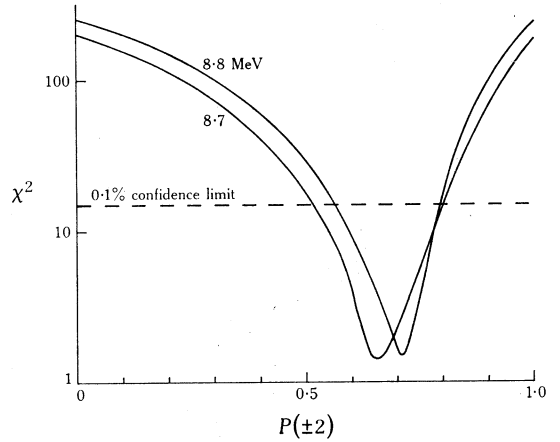

Fig. 4.—Plots of χ^2 versus $P(\pm 2)$ for the best fits with $J = 2$ to the data shown in Figure 3.

were also recorded for use in correcting for random coincidences. The resolution of the magnetic spectrometer was sufficient to ensure that contributions to the coincident γ-ray spectrum from levels other than the 5·80 MeV level or from contaminant reactions were negligible.

The coincident-γ-ray spectrum was analysed using the lineshape fitting program described by Elliott, Ophel, and Spear (1968). The result obtained by fitting a 5·80 MeV lineshape to the data is shown in Figure 5. Upper limits for the intensities of possible weak transitions were estimated by adding lineshapes of the appropriate

Table 1

DECAY SCHEME OF 5·80 MeV STATE OF ^{32}S

The spin and parity assignments listed are taken from Endt and Van der Leun (1967) and Ollerhead, Alexander, and Häusser (1970)

Final state E_x (MeV)	J^π	Intensity of transition (%)	Final state E_x (MeV)	J^π	Intensity of transition (%)
0	0^+	100	4·69	1^+	<2
2·23	2^+	<1	5·01	3^-	<1
3·78	0^+	<1	5·41	3^+	<1
4·28	2^+	<2	5·54	2^+	<2
4·46	4^+	<1			

energies to the fitted spectrum and noting the intensities at which these extra components changed the fit significantly. The results are summarized in Table 1. The only previous attempt to set limits on the strengths of weak transitions is that of Coetzee, Meyer, and Reitmann (1972) who reported an upper limit of 5% for a branch to the 2·23 MeV level.

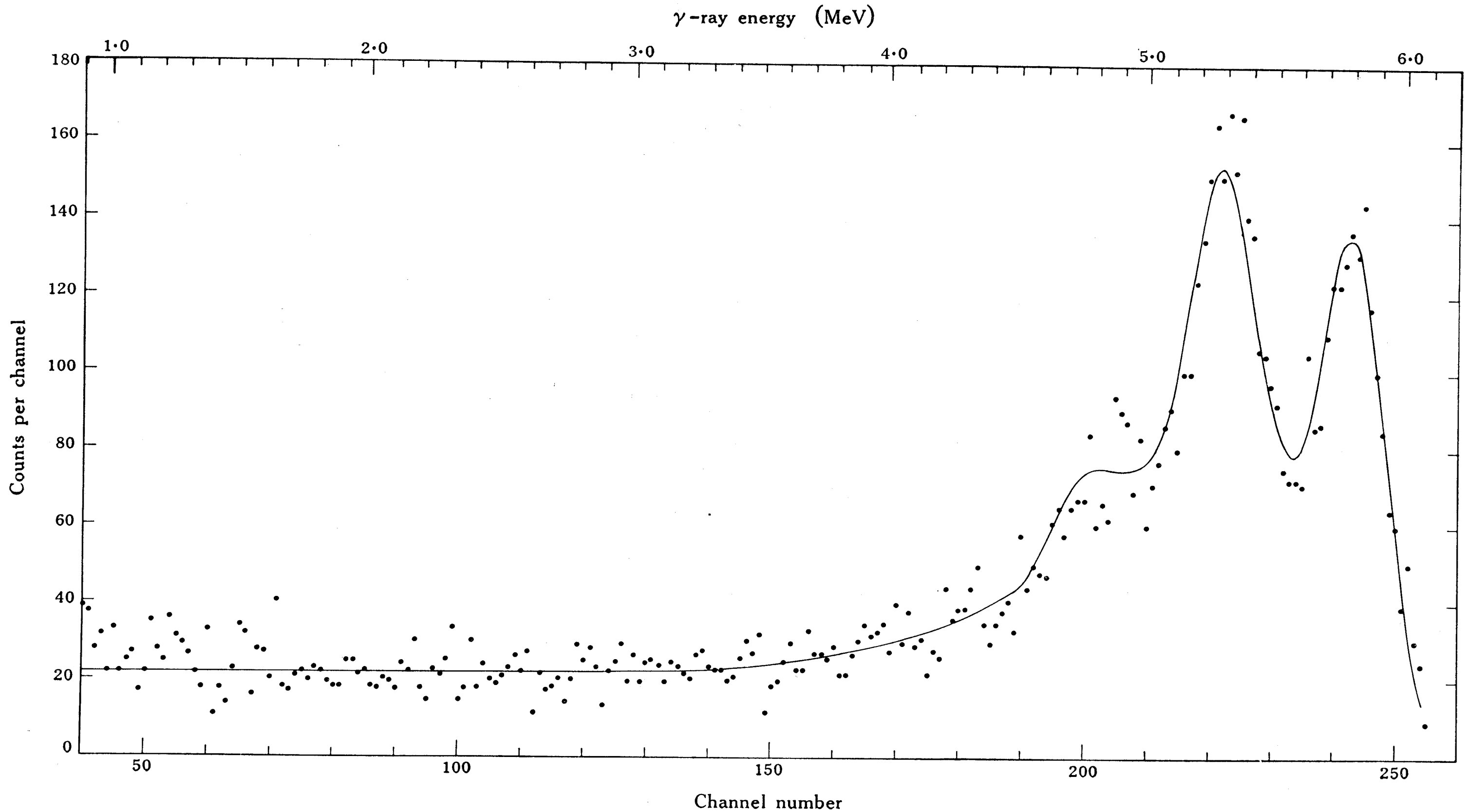

Fig. 5.—Gamma ray spectrum taken in coincidence with protons populating the 5·80 MeV level in ^{32}S. A 5% random coincidence background has been subtracted. The full line shows the 5·80 MeV lineshape fit to the data.

V. Discussion

The present work indicates that the 5·80 MeV state of ^{32}S has an excitation energy of $5798 \cdot 2 \pm 1 \cdot 0$ keV, a mean lifetime of 14 ± 7 fs, a spin of 1, and a 100% decay to the 0^+ ground state, with all other possible transitions having intensities less than 2% of the ground state transition. It is not possible to determine the parity of the level from these results alone; negative parity implies an E1 transition of approximately 4×10^{-4} W.u. and positive parity implies an M1 transition of approximately 0·01 W.u., neither of which values is physically unreasonable. For the purposes of the present discussion, it will be assumed that the 5·80 MeV state has negative parity. The strongest evidence for this comes from DWBA analyses of angular distribution data from the reaction ^{31}P(^{3}He, d)^{32}S; both Graue *et al.* (1968) and Morrison (1970) report $l_p = 1$ and hence negative parity.

There are now three measurements of the lifetime of the 5·80 MeV level: 14 ± 2 fs by Lombard, Kossanyi-Demay, and Bishop (1964), 8 ± 5 fs by Coetzee, Meyer, and Reitmann (1972), and 14 ± 7 fs from the present work. On the basis of these results it will be assumed that the lifetime of the level is 12 ± 3 fs. This implies that the E1 transition to the ground state has a strength of $(4 \cdot 1 \pm 1 \cdot 0) \times 10^{-4}$ W.u.; the weakness of this $\Delta T = 0$ transition is consistent with the operation of the isospin selection rule for E1 transitions in self-conjugate nuclei. The same is true for the E1 transitions to the 2·23(2^+), 3·78(0^+), and 4·28(2^+) MeV states, which have strengths of less than $2 \cdot 3 \times 10^{-5}$, $1 \cdot 3 \times 10^{-4}$, and $5 \cdot 4 \times 10^{-4}$ W.u. respectively.

The $J^\pi = 1^-$ assignment is consistent with the identification of the 5·80 MeV level as a member of the quintuplet of states predicted by the coupled quadrupole–octupole vibrator model. This model predicts an enhanced E2 transition to the 5·01 MeV 3^- state and an enhanced E3 transition to the 2·23 MeV 2^+ state. Although the upper limits imposed for these branches by the present results are very small (1%), they correspond to absolute strengths of 470 and 4200 W.u. respectively, so that the failure to observe these transitions is not in itself inconsistent with the model. However, in order to explain the observed E1 transition to the ground state ($|M|^2 \simeq 4 \times 10^{-4}$ W.u.) it is necessary to introduce a noncollective component into the wavefunction. This is also true for the 5·01 MeV 3^- one-phonon state, which has an E1 transition of approximately 10^{-4} W.u. to the 2·23 MeV 2^+ state in addition to the E3 transition of approximately 20 W.u. to the ground state (Ollerhead, Alexander, and Häusser 1970). Thus, the noncollective component required for the 5·80 MeV two-phonon state is similar to that required for the one-phonon 3^- state itself. In summary, the present results strengthen the view that the 5·80 MeV level has properties consistent with those expected for the 1^- member of the quintuplet of negative parity states predicted by the coupled quadrupole–octupole vibrator model. However, the crucial test of the applicability of the model itself awaits the identification of all members of the quintuplet.

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