SPIN–PARITY COMBINATIONS IN ^{32}S

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Abstract

Inelastically scattered α-particles from the reaction $^{32}S(\alpha,\alpha')^{32}S$ have been studied with solid state counters at extreme backward angles in order to determine spin–parity combinations for levels in ^{32}S at excitation energies E_x up to 7·15 MeV. The results confirm the well-established spin and parity values, show that the 5·798 MeV spin 1 state has negative parity, and provide narrow limits for the possible spin and parity values of the 6·410, 6·666, 6·762, and 6·854 MeV levels. A previously unreported natural parity level was found at $E_x = 6\cdot58$ MeV. Magnetic analysis of the reaction $^{32}S(p,p')^{32}S$ confirmed the existence of this level and established its excitation energy as $6\cdot581 \pm 0\cdot003$ MeV. Particle–γ-ray coincidence studies showed that this level decays predominantly by γ-ray transitions to the 2·23 MeV 2^+ state.

I. Introduction

Recently Moss *et al.* (1973) reviewed the experimental information concerning the characteristics of levels in ^{32}S within the range of excitation energies E_x from $\sim$5–8 MeV. They indicated where firm spin and parity assignments were needed to permit more rigorous evaluation of the various nuclear models applicable to levels in this region. For example, Castel *et al.* (1971) performed calculations in which vibrational excitations were coupled to $(s_{1/2})^{-1}(d_{3/2})$ and $(s_{1/2})^{-2}(d_{3/2})^2$ particle–hole excitations. In addition to obtaining good agreement with the experimental data for the E2 strengths in the decay of the low-lying one-phonon and two-phonon states, they were able to reproduce the level ordering up to $E_x = 6$ MeV. They tentatively identified a predicted 1^+ level at $E_x \approx 5\cdot8$ MeV with a level known to exist at $E_x = 5\cdot80$ MeV and to have a spin of 1 or 2, which has since been firmly established as 1 (Gardner *et al.* 1972). However, the parity of this level is believed to be negative because DWBA analyses of angular distribution data suggest that the level is populated with $l_p = 1$ in the reaction $^{31}P(^3He,d)^{32}S$ (Graue *et al.* 1968; Morrison 1970). Earlier inelastic electron scattering data had suggested the positive parity assignment (Barber *et al.* 1963; Lombard *et al.* 1964). A model-independent determination of the parity of this level was clearly desirable. Other relevant calculations for positive parity states include the shell model calculations of Wildenthal *et al.* (1971), who consider basis states with particles in the $d_{5/2}$, $s_{1/2}$, and $d_{3/2}$ orbits and the calculation of electromagnetic transition rates by Glaudemans *et al.* (1971), who also consider only excitations within the s–d shell.

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A model involving the coupling of a quadrupole phonon and an octupole phonon (corresponding to the 2^+ state at $2 \cdot 23$ MeV and the 3^- state at $5 \cdot 01$ MeV respectively) suggests the existence of five negative parity states of spins 1, 2, 3, 4, and 5 in the vicinity of $E_x = 7$ MeV (Mermaz *et al.* 1969). Gardner *et al.* (1972) have suggested that the 1^-, 2^-, and 4^- members of this multiplet might be identified with the states at $E_x = 5 \cdot 80$, $6 \cdot 22$, and $6 \cdot 62$ MeV respectively. The location and study of 3^- and 5^- states in the region was thus of considerable interest. Negative parity states in ^{32}S could also be interpreted in terms of the shell model by considering excitations to the $1f_{7/2}$ subshell or out of the 1p shell. It appears that no substantial shell model calculations involving these modes of excitation have yet been performed for ^{32}S.

The present paper describes the measurement of spin–parity combinations for levels in ^{32}S up to $E_x = 7 \cdot 15$ MeV, with the main interest centering on the region above 5 MeV. The technique used involved the study at extreme backward angles of inelastically scattered α-particles from the reaction $^{32}S(\alpha, \alpha')^{32}S$. Since the target and projectile in this reaction both have $J^\pi = 0^+$, α-particles scattered at 0° or 180° to the beam direction can populate only those states of the residual nucleus which have natural parity ($\pi = (-)^J$) (Litherland 1961). In cases where the level spin is known, this technique provides a model-independent determination of the parity.

II. Study of Reaction $^{32}S(\alpha, \alpha')^{32}S$

A difficulty which arises in studying inelastic α-particle scattering at 0° or 180° from $J^\pi = 0^+$ targets is that it is frequently impossible to place the detector exactly at 0° or 180° and, in addition, the finite solid angle subtended by the detector means that α-particles scattered at nearby angles are inevitably included. Consequently, if one uses only an annular detector encircling the incident beam (e.g. Ollerhead *et al.* 1971), it may be difficult to decide whether the observation of a small yield for the inelastic scattering to a particular state means that the state has natural parity but the integrated cross section is low, or that the state has unnatural parity but the detector is not precisely at 180°. In the present work this problem is avoided by measuring angular distributions of the scattered α-particles and noting the manner in which the cross section varies as the detection angle approaches 0° or 180°. If the cross section does not approach zero at 180°, the state has natural parity. If the cross section does tend to zero at 180°, then either the state has unnatural parity or the state has natural parity but the reaction mechanism at the chosen bombarding energy produces an angular distribution with a small cross section at 180°. In order to remove the latter possibility, data were obtained at a number of bombarding energies. A detailed excitation function over a small energy region showed structure of typical width $\sim$40 keV. Thus, by obtaining data at approximately 100 keV intervals and using energy-averaged angular distributions, firm spin–parity assignments could be made.

Inelastically scattered α-particles were detected at four angles. A 115 μm thick annular surface barrier detector was mounted 16 cm from the target so that it subtended detection angles in the laboratory coordinate system ranging from $177 \cdot 5°$ to $178 \cdot 9°$ relative to the incident beam direction. An energy resolution of 30 keV for scattered α-particles was achieved by cooling the detector and by mounting a permanent magnet near the detector to suppress secondary electrons from the target.

In addition, 100 μm thick surface barrier detectors were mounted 18 cm from the target at mean laboratory angles of 160°, 140°, and 120°. The dimensions of the collimators on these three detectors were chosen to maintain an energy resolution of about 30 keV in each case. To permit comparison of yields, the relative acceptance solid angles of the four detectors were measured using an α-particle source mounted in place of the target. Much care was taken to maintain good transmission through the annular detector in order to reduce X-ray background. Background due to backscattering of α-particles from the metal surfaces of the target chamber walls and the target frame was minimized by lining these surfaces with polythene sheet.

The target consisted of approximately 60 μg cm^{-2} of natural cadmium sulphide evaporated onto a thin carbon film. The $^4He^{2+}$ beams were obtained from the ANU EN tandem Van de Graaff accelerator. Spectra from the four detectors were collected simultaneously in 4×2048 channels of a pulse height analysis system for 500 μC of integrated beam at energies E_α ranging from 16·8 in steps of 0·1 to 17·6 MeV and thence in steps of 0·2 to 18·2 MeV. Typical spectra obtained at $E_\alpha = 17 \cdot 5$ MeV are shown in Figures 1(*a*) and 1(*b*). The statistical quality of the data was considerably better for the annular counter than for the other counters, with the improvement corresponding to the difference in acceptance solid angles. The excitation energies of ^{32}S levels adopted for Figure 1 and throughout this paper are as listed by Coetzee *et al.* (1972), except for the 6410 keV level, for which the excitation energy is taken from the work of Forsblom *et al.* (1970). In order to monitor possible contributions to the spectra from ^{34}S (natural abundance 4·2%), parallel spectra were taken at each bombarding energy using a target which was made in identical fashion to the natural cadmium sulphide target except that the sulphur was enriched to 85·6% ^{34}S.

After subtraction of linear backgrounds, peak areas were extracted for α-particle groups corresponding to particular levels in ^{32}S and were then summed over all bombarding energies. At some energies and angles certain groups were obscured by contaminant peaks from ^{12}C, ^{13}C, ^{14}N, and ^{16}O in the target. In these cases allowance was made in the summation over all incident energies by normalizing all the summed yields to the same total integrated beam. Contributions from ^{34}S were found to be negligible for all groups of interest. After correction for the different detector solid angles the data thus yielded energy-averaged four-point "angular distributions" for the inelastic α-particles leading to each of the ^{32}S states studied. These distributions are shown in Figure 2, in which spins and parities are indicated in all cases where they are well established (Coetzee *et al.* 1972). It can be clearly seen that levels known to have unnatural parity exhibit minima close to zero at 180°, while those with known natural parity do not. Figure 3, which shows the 180° yields normalized to the sum of the yields at the other three angles, reveals that the known natural and unnatural parity levels form two distinct bands. It is concluded from the results shown in Figures 2 and 3 that the 5798, 6410, 6666, 6762, 6854, and 7117 keV levels all have natural parity.

In addition to the observed α-particle groups leading to the previously known levels of ^{32}S, there was strong and consistent evidence in the 180° data for a group corresponding to a previously unreported level at $E_x = 6 \cdot 58 \pm 0 \cdot 01$ MeV. The group concerned could not be ascribed to any possible contaminant, and its energy varied with bombarding energy in such a way that it could correspond only to an atomic mass $A = 32 \pm 1$.

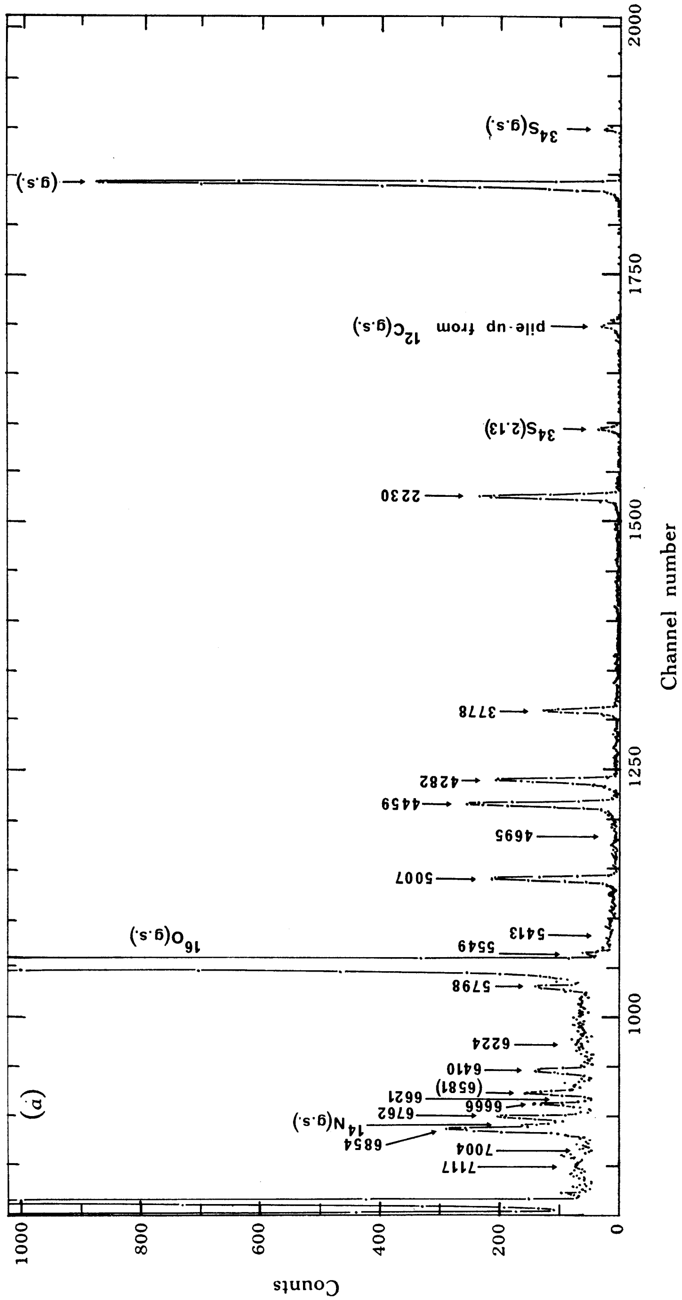

Fig. 1(*a*).—α-particle energy spectrum at 178° for the reaction $^{32}S(\alpha,\alpha')^{32}S$.

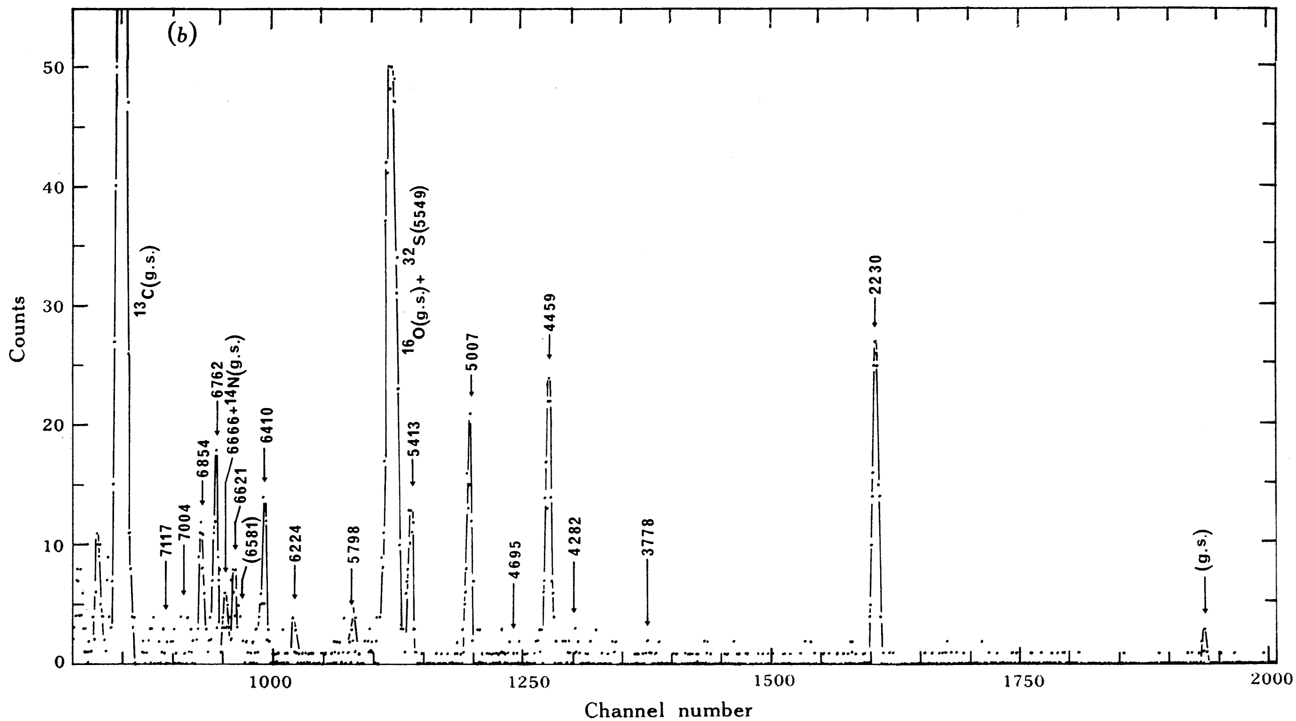

Fig. 1(*b*).—α-particle energy spectrum at 160° for the reaction $^{32}S(\alpha,\alpha')^{32}S$.

Fig. 1.—α-particle energy spectra obtained at angles of (*a*) 178° (annular counter) and (*b*) 160° by bombarding a target of natural cadmium sulphide with 17·5 MeV $^4He^{2+}$ ions. The indicated excitation energies are in keV, while the symbol g.s. denotes a ground state.

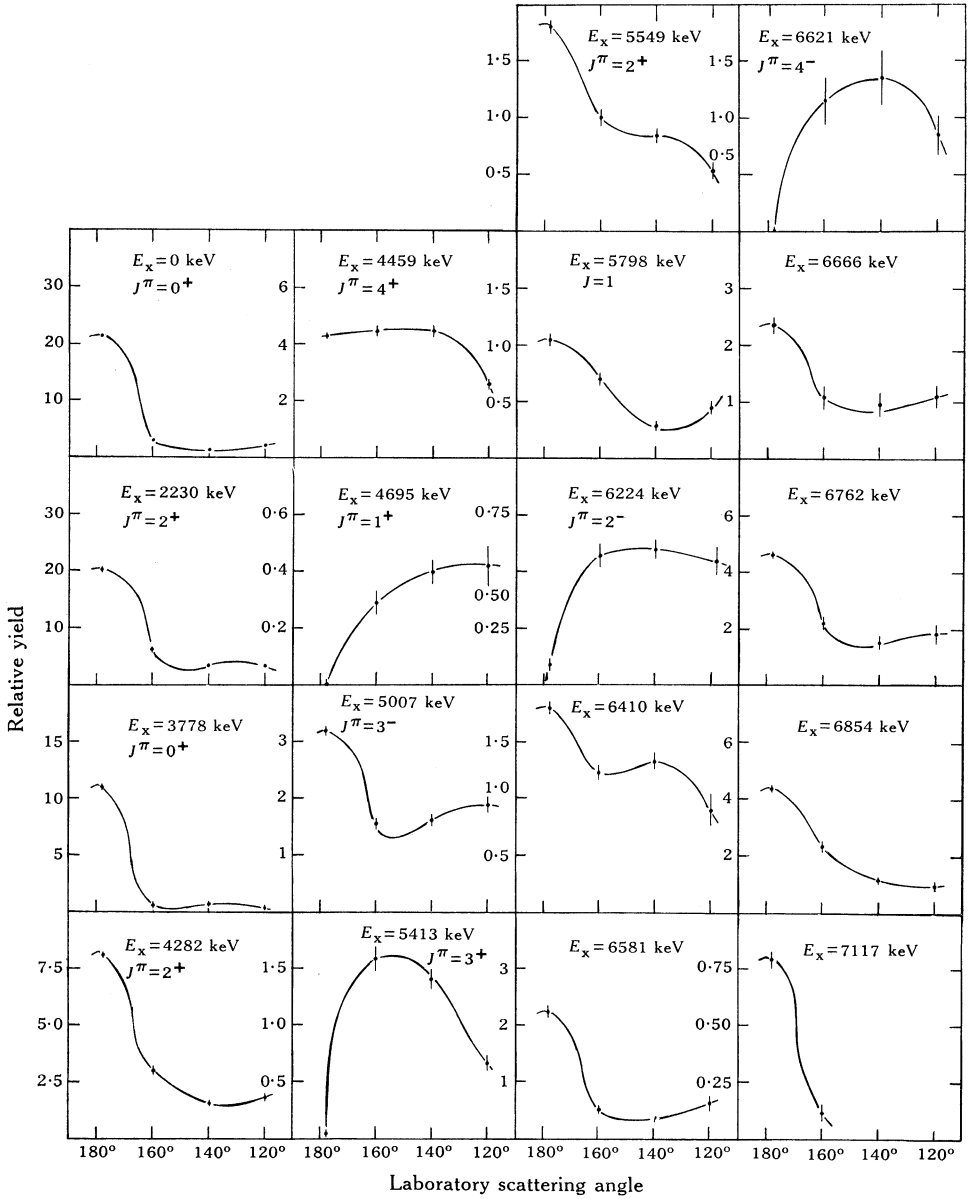

Fig. 2.—Energy averaged four-point angular distributions for inelastically scattered α-particles from the reaction $^{32}S(\alpha,\alpha')^{32}S$. Full curves are included as a visual guide.

III. Magnetic Analysis of Reaction $^{32}S(p, p')^{32}S$

Energy spectra of protons inelastically scattered from ^{32}S were studied with a high-resolution magnetic spectrometer in order to confirm the existence of the 6·58 MeV level observed in the $^{32}S(\alpha, \alpha')^{32}S$ data, to measure the excitation energy of the 6·58 MeV level more accurately, and to investigate the possible existence of other previously unreported levels in the region $6 \cdot 4 < E_x < 7 \cdot 1$ MeV.

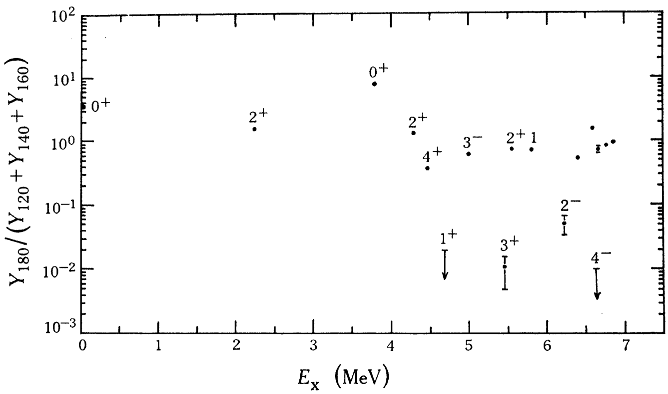

Fig. 3.—Energy averaged ratio of the 180° yield Y_{180} to the sum of the yields at other angles for α-particles scattered from ^{32}S. Barred arrows are used to indicate upper limits for the 4695 and 6621 keV levels.

A target consisting of $\sim 100\ \mu g\, cm^{-2}$ of lead sulphide (sulphur enriched to 99·9% ^{32}S) was mounted in the target chamber of the double-focusing magnetic spectrometer described by Elliott *et al.* (1968*a*) and bombarded with protons of energy $E_p = 11 \cdot 2$ MeV. The entrance slits of the spectrometer were set to produce acceptance angles of $\pm 1°$ in the horizontal plane and $\pm 3°$ in the vertical plane. Inelastically scattered protons were detected by a 500 μm surface barrier detector mounted behind a 1·6 mm slit at the focal point of the spectrometer. Aluminium foil of thickness 0·001 cm was placed in front of the detector to separate protons from α-particles.

Figure 4 shows proton spectra obtained by varying the magnetic field of the spectrometer at laboratory angles of 30° and 150°. The arrows indicate previously known levels of ^{32}S. In each case, the excitation energy scale was obtained by least squares fitting to the data of an expression of the form $E_x = a + bf + cf^2$, where f is the n.m.r. frequency corresponding to the half-height of the high-energy edge of the group from a ^{32}S level of excitation energy E_x, and a, b, and c are fitted parameters. All ^{32}S groups shown in Figure 4 were used in the fitting procedure. The 6·58 MeV level is clearly evident at both laboratory angles. The least squares analysis gives its excitation energy as 6582 ± 4 keV at 30° and 6579 ± 6 keV at 150°, or a mean excitation energy of 6581 ± 3 keV. The variation of group energy with angle is consistent only with $A = 32$. There is no indication in either spectrum of any other previously unreported levels in ^{32}S.

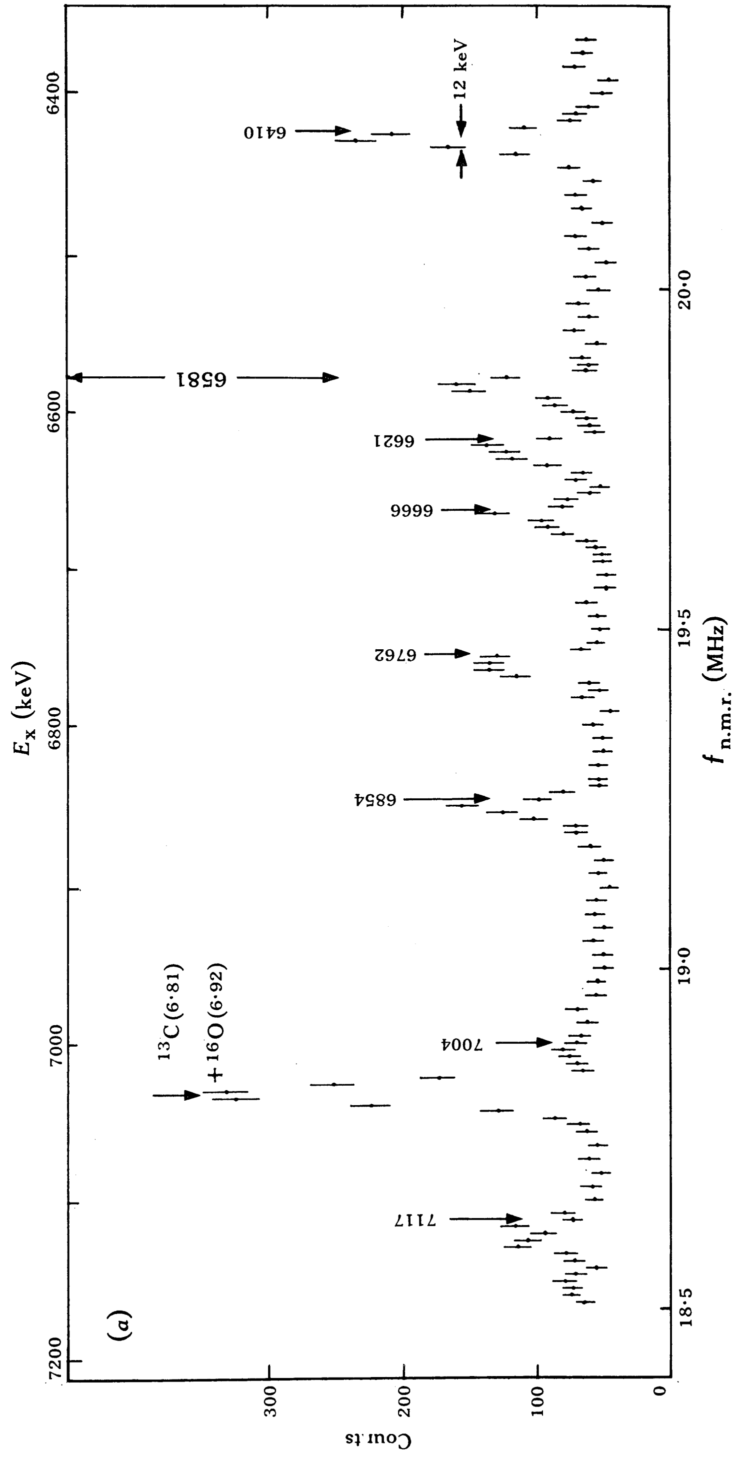

Fig. 4(*a*).—Proton spectra at 30° for the reaction $^{32}S(p, p')^{32}S$.

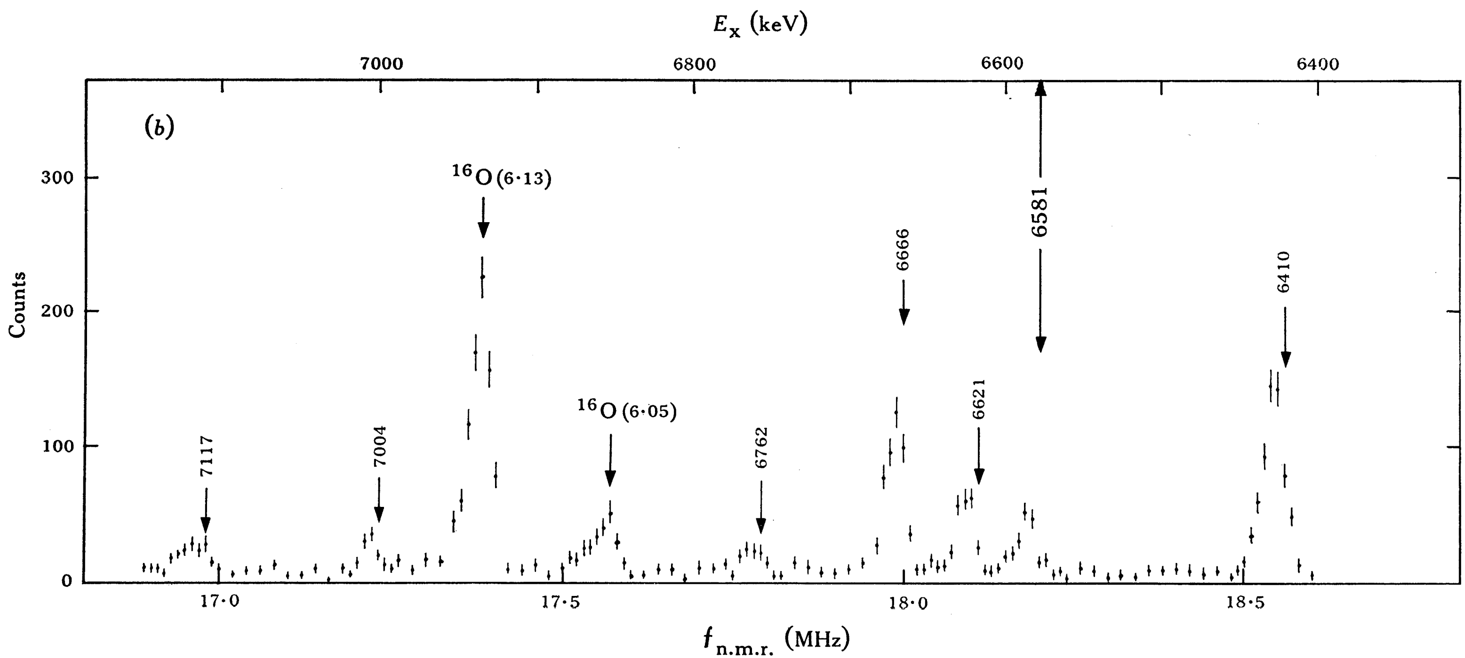

Fig. 4(*b*).—Proton spectra at 150° for the reaction $^{32}S(p,p')^{32}S$.

Fig. 4.—Spectra obtained by magnetic analysis of protons scattered at (*a*) 30° and (*b*) 150° from a target of lead sulphide (sulphur enriched to 99·9% ^{32}S) for a bombarding energy of 11·2 MeV. The horizontal scales show the ^{32}S excitation energy E_x and the n.m.r. frequency $f_{n.m.r.}$.

IV. γ-Ray Decay Scheme of 6·58 MeV Level of ^{32}S

Moss *et al.* (1973) have studied the γ-ray decay schemes of ^{32}S levels in the region of excitation under consideration here, and it was considered desirable to determine the decay scheme of the newly discovered 6·58 MeV level. This was done using the technique described by Moss *et al.*

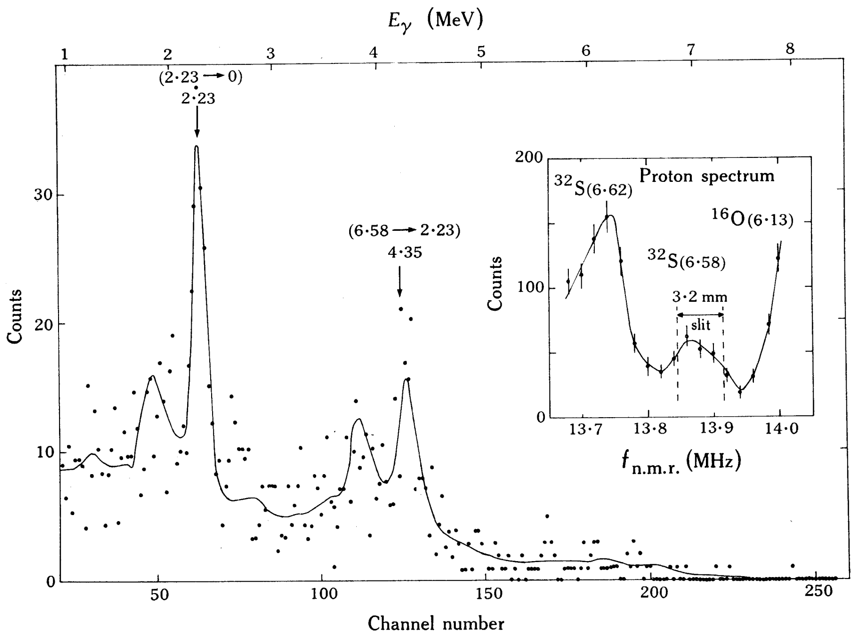

Fig. 5.—γ-ray spectrum taken in coincidence with protons populating the 6·58 MeV level of ^{32}S via the reaction ^{32}S(p,p′γ)^{32}S. Random coincidences have been subtracted from the data. The full line shows a lineshape fit obtained on the assumption that the level decays solely to the 2·23 MeV level and includes a calculated contribution from summing. The insert shows the proton spectrum obtained by sweeping the magnetic field of the spectrometer, with the effective window imposed by the 3·2 mm detector slit indicated.

A target consisting of approximately 200 μg cm^{-2} of lead sulphide (sulphur enriched to 99·9% ^{32}S) evaporated onto a thin carbon backing was bombarded with 9·16 MeV protons, and inelastically scattered protons populating the 6·58 MeV level were detected at the focal plane of the double-focusing spectrometer. The entrance slits of the spectrometer were set at $\pm 2{\cdot}5°$ (horizontal) and $\pm 5{\cdot}5°$ (vertical), the focal plane slit was 3·2 mm wide, the spectrometer was set at 90° to the beam direction, and the proton beam was stopped in a beam dump 3 m from the target. The focal plane detector and absorber foil were as described in Section III above. The γ-rays in coincidence with protons populating the 6·58 MeV level were detected at 90° in a 12·7 cm (diameter) × 10·2 cm (length) NaI(Tl) crystal mounted with its axis vertical and its front face 4·4 cm above the target spot. A 1·6 mm thick steel plate supported the crystal in the top of the target chamber, and sheets of 2·5 mm lead and 0·4 mm copper were inserted between the steel plate and the crystal face to attenuate low energy background radiation. The beam energy of 9·16 MeV was chosen to optimize the yield to the 6·58 MeV level while keeping the energy low enough that beam induced background radiation remained tolerable. Beam currents were limited to 40 nA so that pile-up in the γ-ray spectrum remained within acceptable limits.

Due to the weak population of the 6·58 MeV level, the coincidence count rate was extremely low. Figure 5 shows the spectrum obtained after running for 43 hours, while the insert shows the particle spectrum obtained by sweeping the magnetic field of the spectrometer and also the effective window imposed by the 3·2 mm detector slit.

The coincidence γ-ray spectrum was analysed using the line-shape fitting program previously described by Elliott *et al.* (1968*b*) and Ophel (1971). The spectra were corrected for random coincidences (13%) by subtracting a singles spectrum with an intensity normalization deduced from the measured ratio of real to random coincidences. The results of the line-shape analysis are consistent with there being no decay mode of the 6·58 MeV level other than via the 2·23 MeV first excited state. The counts in the high energy region of the spectrum can be wholly accounted for by summing of the cascade γ-rays, assuming that these have an isotropic angular correlation. If it is assumed that the summing contribution may be overestimated by a factor of two due to possible anisotropy of the angular correlation of the cascade γ-rays, an upper limit of 3% can be placed on the direct branching to the ground state. It is noteworthy that the coincidence γ-ray spectrum is characteristic of ^{32}S, which further supports the validity of the assignment of peaks in the charged particle spectra to a level at $E_x = 6 \cdot 58$ MeV in ^{32}S.

TABLE 1

SPIN–PARITY COMBINATIONS IN ^{32}S

The J^π assignments are taken from Coetzee *et al.* (1972), with not well-established values given in parentheses. The parity from the present work is listed alongside as N (natural) or U (unnatural). Excitation energies are taken from Forsblom *et al.* (1970), Coetzee *et al.* (1972), and the present work.

E_x (keV)	J^π		E_x (keV)	J^π		E_x (keV)	J^π		E_x (keV)	J^π	
0	0^+	N	4695	1^+	U	6224	2^-	U	6762	$(2^-,3)$	N
2230	2^+	N	5007	3^-	N	6410		N	6854		N
3778	0^+	N	5413	3^+	U	6581		N	7004	$1^+, T=1$	—
4282	2^+	N	5549	2^+	N	6621	4^-	U	7117	$(2^+, T=1)$	N
4459	4^+	N	5798	$1^{(-)}$	N	6666		N			

V. Discussion

The results of the present work are summarized in Table 1. The spin–parity combinations obtained are consistent with those spins and parities that are well established. The newly discovered 6581 keV state decays predominantly by γ-ray transitions to the 2230 keV 2^+ state, while decay schemes for the other states have been discussed in detail by Moss *et al.* (1973). The 7004 keV level was not observed in any of the inelastic α-particle data, which is consistent with a $T = 1$ assignment for the level and the effective operation of isospin selection rules.

The unambiguous assignment of natural parity to the $J = 1$ state at $E_x = 5798$ keV provides a model-independent confirmation of the negative parity assignment previously made from DWBA analysis of angular distributions from the reaction $^{31}P(^{3}He,d)^{32}S$ (Graue *et al.* 1968; Morrison 1970). This result is in disagreement with the predictions of Castel *et al.* (1971) whose calculations, which involve the coupling of vibrational excitations to particle–hole excitations, require that the 5·80 MeV state have $J^{\pi} = 1^{+}$.

One of the primary motivations of the present work was to obtain further evidence concerning the possible existence of a 5^{-} state in the vicinity of $E_x = 7$ MeV. Apart from the predictions of the quadrupole–octupole coupling scheme discussed in Section I, the systematic variation of excitation energies of the lowest 5^{-} states in even nuclei in the mass region $A = 28$–40 strongly suggests that the first 5^{-} state in ^{32}S should occur at an excitation energy within about 500 keV of 6·2 MeV (Greene *et al.* 1972). Consideration of the known properties of levels in this region suggests that the 6762 keV state is the most likely candidate for a $J^{\pi} = 5^{-}$ assignment. The only states in the region whose spins and parities are not well established are at $E_x = 6410$, 6581, 6666, 6762, 6854, and 7117 keV. The 6410, 6581, 6666, 6854, and 7117 keV states all display strong γ-ray transitions to 2^{+} states, which renders a $J^{\pi} = 5^{-}$ assignment most unlikely for any of them. Coetzee *et al.* (1972) argue that the 6762 keV state has $J^{\pi} = 2^{-}$ or $3^{\pm}$. They report that the level was excited at two resonances in the $^{31}P(p,\gamma)^{32}S$ reaction, and that a ground state branch of $3\% \pm 2\%$ from the 6762 keV state was observed at one of the resonances. This resonance had $J^{\pi} = 4^{-}$ and, using transition strength arguments for the primary transitions, they concluded that J^{π} (6762) $= 2^{-}$ or $3^{\pm}$. Clearly the existence of a ground state transition would be inconsistent with a 5^{-} assignment. Moss *et al.* (1973) found that the 6762 keV level decays 100% to the 5007 keV 3^{-} state and $<26\%$ to the 4459 keV 4^{+} state. However, their upper limit of 5% for a ground state branch is not inconsistent with the result of Coetzee *et al.* It is highly desirable that the possible existence of this ground-state branch should be clarified. The decay scheme results of Moss *et al.* and the natural parity assignment from the present work are both consistent with a 5^{-} assignment for the 6762 keV state. The quadrupole–octupole coupling scheme also suggests the existence of a 3^{-} state in the region under consideration. The 6410, 6581, 6762, and 6854 keV states all have parities and decay schemes which would be consistent with $J^{\pi} = 3^{-}$.

The outstanding experimental information now required to permit evaluation of all the models which have been applied to this region of ^{32}S is: firm spin assignments for the levels at 6410, 6581, 6666, 6762, 6854, and 7117 keV and lifetime determinations for the levels at 6410, 6581, and 6762 keV (existing lifetime data for the other states are summarized by Coetzee *et al.* 1970).

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