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GAMMA-RAY TRANSITIONS IN ^{32}S FOLLOWING PROTON CAPTURE BY ^{31}P

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Abstract: Gamma-ray spectra, angular distributions and coincidence spectra have been studied in the reaction $^{31}P(p, \gamma)\,^{32}S$ at bombarding energies of 355, 440 and 540 keV. Several cascades have been identified and branching ratios have been measured. The spins and parities of the 9.39, 9.29, 9.21 and 4.70 MeV levels in ^{32}S are found to be $2^{(-)}$, 1^+, (1^+) and 1^+, respectively.

1. Introduction

An extensive study of the reaction $^{31}P(p, \gamma)^{32}S$ at the two lowest proton resonance energies was recently published by Nelson, Carlson and Schlenker [1]). At about the same time, an oral report [2]) on the same reaction including the third resonance was given by the present authors. As the two accounts differed in several respects, we have extended our investigations with particular attention to the analysis of the gamma-ray spectra and to the elimination of systematic errors in the angular distribution measurements. We have verified the spin assignments of Nelson, Carlson and Schlenker for the 9.21 and 9.29 MeV levels, and made a new assignment for the 9.39 MeV level. The gamma-ray decay, particularly at the second proton resonance, is considerably more complex than previously reported. In particular, one of the angular correlation measurements made by Nelson, Carlson and Schlenker must be re-interpreted, such that the spin value of 1^+ which they reported for the 4.47 MeV state should instead be attributed to the 4.70 MeV state in ^{32}S.

S. L. Andersen [3]) has reported branching ratios in ^{32}S determined from measurements made at six higher-energy proton resonances. With some exceptions, these are in qualitative agreement with those given below.

Most of the available information concerning ^{32}S has been summarized by Endt and van der Leun [4]); the energy level values are for the most part those measured by Endt *et al.* [5]) and by Hinds and Middleton [6]).

2. The Resonances

Thick targets of P_4S_6 and of Zn_3P_2 evaporated on water-cooled copper backings were bombarded with 20 μA analysed proton beams. Three resonances in γ-ray yield

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at approximately 355, 440 and 540 keV laboratory kinetic energy were found, in agreement with the values of Kuperus *et al.* [7]) and corresponding to ^{32}S excited levels at 9.21, 9.29 and 9.39 MeV. No evidence was found for proton capture to the 9.23 MeV level (omitted, for clarity, from fig. 3). The total width of each resonance is less than 3 keV, and partial widths determined from the gamma-ray yields are given in table 1.

TABLE 1

Thick-target (Zn_3P_2) yields y and widths for the three resonances

	355			440			540	
E_p (keV, lab.)	355			440			540	
E_x (MeV)	9.21			9.29			9.39	
E_γ (MeV)	9.21	6.97	All	9.29	7.05	All	7.15	All
y (10^{-12} photon/proton)	0.40	0.34	0.80	4.0	1.8	7.2	12	15
$(2J+1)\ \Gamma_p\Gamma_\gamma/\Gamma$ (eV)	0.006	0.005	0.012	0.067	0.030	0.135	0.25	0.30
$\Gamma_p\ \Sigma\Gamma_\gamma/\Gamma$ (eV)			0.004			0.045		0.060

By the procedure outlined in ref. [9]) one readily obtains the quantity $(2J+1)\Sigma\Gamma_p\Gamma_\gamma/\Gamma$. in which Γ_p and Γ_γ are partial particle and radiation widths, the sum being taken over partial waves, channel spins and multipolarities contributing to each resonant capture and subsequent radiation process. The last line is calculated using the resonance spins found in this work. The yields, and consequently the widths, are uncertain to about $\pm$ 20 %.

Angular distributions of the ground-state gamma rays from the first two resonances and of the 7.15 MeV gamma ray from the third resonance were measured with a 5 cm × 5 cm NaI(Tl) scintillation counter. A second counter of the same dimensions was fixed in a direction perpendicular to the plane of rotation of the first, to monitor the reaction intensity. Pulses from both counters were accumulated simultaneously in two halves of a 256-channel pulse-height analyser. The intensity ratios were found to remain constant under interchange of the two counters or interchange of the electronic circuits. Measurements were made at forward and backward angles and on both sides of the proton beam direction.

Both the first and second resonances appear to have isotropic angular distributions†. The very low yield at the 355 keV resonance allows us only to estimate the anisotropy as less than 20 %, while at 440 keV it is less than 10 %. Isotropy implies s-wave proton entry; and since for both resonances a radiative transition proceeds to the 0^+ ground state of ^{32}S, a spin assignment of 1^+ is obtained for both the 9.21 and 9.29 MeV levels. Considering all possible spins and parities corresponding to proton partial waves with l = 0, 1 or 2, the choice $J = 1^-$ can give "accidental" isotropy, if initial state channel spins 0 and 1 occur in the ratio 1 : 2; no other choice can give accidental isotropy. Nelson, Carlson and Schlenker [1]) have already presented ancillary arguments for the 1^+ assignment to the 9.29 MeV level.

† An earlier report of anisotropy at the 440 keV resonance [2]) is in error, due to contamination of the beam-defining slits.

There being no observable ground-state transition at 540 keV bombarding energy, the angular distribution measured in this case was that of the 7.15 MeV gamma ray leading to the 2^+ first excited state in ^{32}S. The experimental points are shown in fig. 1, together with calculated angular distributions for several assumed spin and parity assignments. Particular assumptions were made in calculating some of the curves: the $J = 1^-$ curve is for equal parts of channel spin 0 and 1: at most the anisotropy could be twice the value for this mixture. For $J = 2^+$ the assumptions were equal contributions of channel spins and pure M1 radiation, while for the choice $J = 3^+$, all possible M1/E2 mixing ratios were taken into account, the case illustrated being that approaching most nearly to the experimental data. From fig. 1 it is clear that the

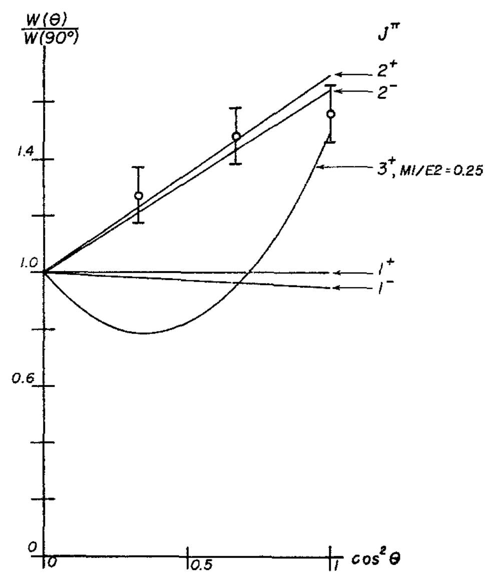

Fig. 1. Angular distribution of 7.15 MeV gamma rays at the 540 keV resonance. The solid lines are calculated for various possible spins and parities of the 9.39 MeV state.

9.39 MeV level can only have spin 2. The choice 2^+ seems improbable as the intensity of this resonance is inconsistent with d-wave proton entry at such a low kinetic energy. Furthermore if this level were 2^+, an E2 transition to the ground state should compete favourably with the transitions observed. Hence the 9.39 MeV level has spin 2 and, very probably, negative parity.

The angular distribution of the 4.38 MeV gamma ray leading from the same capture state to the 5.01 MeV level was also measured. As the latter is already known [4]) to have spin 3, this transition must be either E1 or M1+E2. The experimental angular distribution is inconsistent with the calculated E1 angular distribution but is compatible with an M1+E2 mixture. Hence the 5.01 MeV level must have negative parity, if the assignment of 2^- for the 9.39 MeV level is correct.

3. Gamma-Ray Spectra

Gamma-ray spectra from each of the three resonances were observed with either of two 7.6 cm × 7.6 cm NaI(Tl) scintillation counters. These counters have energy resolution of less than 3 % at 4 MeV, allowing the energies of all resolved gamma rays to be determined to an accuracy not worse than ± 0.05 MeV over the range from 1 to 10 MeV. Energy calibrations were based on known lines from radioactive sources ^{24}Na and ThC″ and the reactions $^{11}B(p, \gamma)^{12}C$ and $^{19}F(p, \alpha\gamma)^{16}O$. All of the lines represented in fig. 3 were resolved, either in the singles spectra or in appropriate coincidence spectra, with the exception of the 2.18 MeV line occurring at the second resonance. Existence of the 2.18 MeV line can be inferred from shifting of the "2.2" MeV peak toward 2.18 or 2.24 depending upon the coincidence window settings and from the intensity of this peak when observed in coincidence with the 4.87 MeV line. All of the measured gamma ray energies agree within ± 0.03 MeV with energy differences between known levels [4]) when assigned the positions shown in fig. 3. To avoid possible confusion, each gamma-ray energy quoted is that deduced from these energy differences, rather than the directly measured value.

Coincidence spectra were measured on one of the 7.6 cm × 7.6 cm counters in coincidence with selected pulse-height windows on a 12.7 cm × 10.2 cm NaI(Tl) counter of somewhat poorer resolution. The two counters were placed on opposite sides of the target and 4 cm from its centre, at 90° to the beam axis. In interpreting the spectra, due allowance was made for summing in the crystals. During each coincidence experiment, coincident and non-coincident pulses from the same (7.6 cm × 7.6 cm) counter were recorded in the two halves of the 256-channel analyser so that any drift could be immediately detected.

Fig. 2 illustrates one series of experiments carried out at the 440 keV proton resonance. In the singles spectrum (a) the region between 4 and 5 MeV is difficult to interpret. In the coincidence spectra (c, d and e) separate components at 4.87, 4.70 and 4.59 MeV appear. With other coincidence settings, not illustrated, the 4.59 MeV line was isolated from the others when viewed in coincidence with a 2.46 MeV window, the 4.29 in coincidence with 2.82, while a weak component at 3.99 MeV was found to be in coincidence with the 3.06 MeV line. Fig. 2 has been prepared especially to illustrate the point that the 4.59 and 4.70 MeV gamma rays are in coincidence with each other, while the 4.87 MeV line is coincident only with the "2.2" MeV transitions. Special care was taken to obtain good energy calibrations in measuring the energies of the lines in this group.

4. Decay Scheme

Sufficient coincidence experiments were carried out to verify all of the cascades indicated in the decay scheme (fig. 3) and to allow branching ratios to be determined for all of the levels involved. In determining intensities of lines above 4 MeV, total areas were estimated through the use of known line shapes. For lines below 4 MeV, only the total-energy peak was used. The efficiencies and peak-to-total ratios used were those compiled by J. B. Marion [8]).

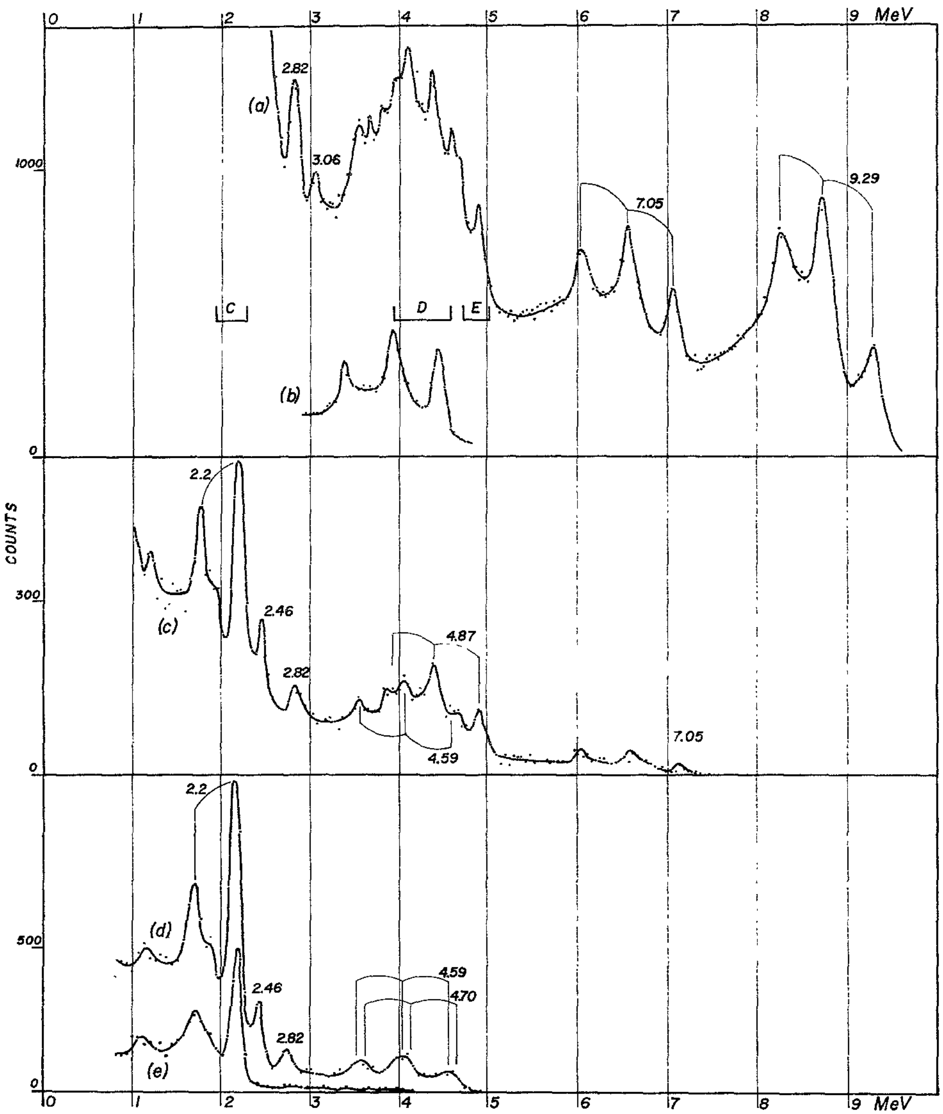

Fig. 2. (a) Gamma-ray spectrum of the reaction $^{31}P(p, \gamma)$ ^{32}S at 440 keV proton energy, taken with a 7.6 cm × 7.6 cm detector. (b) The 4.43 MeV line from the reaction $^{11}B(p, \gamma)^{12}C$, shown to indicate the line shape for this detector. (c) Spectrum in coincidence with window C, i.e. in coincidence with the 2.24 and 2.18 MeV gamma rays. Note especially the absence of the 4.70 MeV and reduced intensity of the 4.59 MeV lines. (d) Spectrum in coincidence with window D, i.e. with all gamma rays between 3.9 and 5.1 MeV. Here the 4.59 and 4.70 MeV lines have equal intensities while the 4.87 is absent. (e) Coincidences with window E, showing the 4.87 MeV line to be in coincidence only with the 2.18 and 2.24 MeV transitions.

Line intensities so determined were self-consistent within 20%, and often much better, with the exception noted below. Nevertheless it is not unlikely that some weak transitions have been overlooked, in view of the low intensity of the reaction. At the 540 keV resonance there is one discrepancy among the intensity measurements, in that the intensity of the 2.77 MeV line is almost twice as great as that of the 4.38 MeV transition which ostensibly precedes it. Also the 2.77 MeV peak appears to be slightly broader than normal, so there may be another line of about the same energy present.

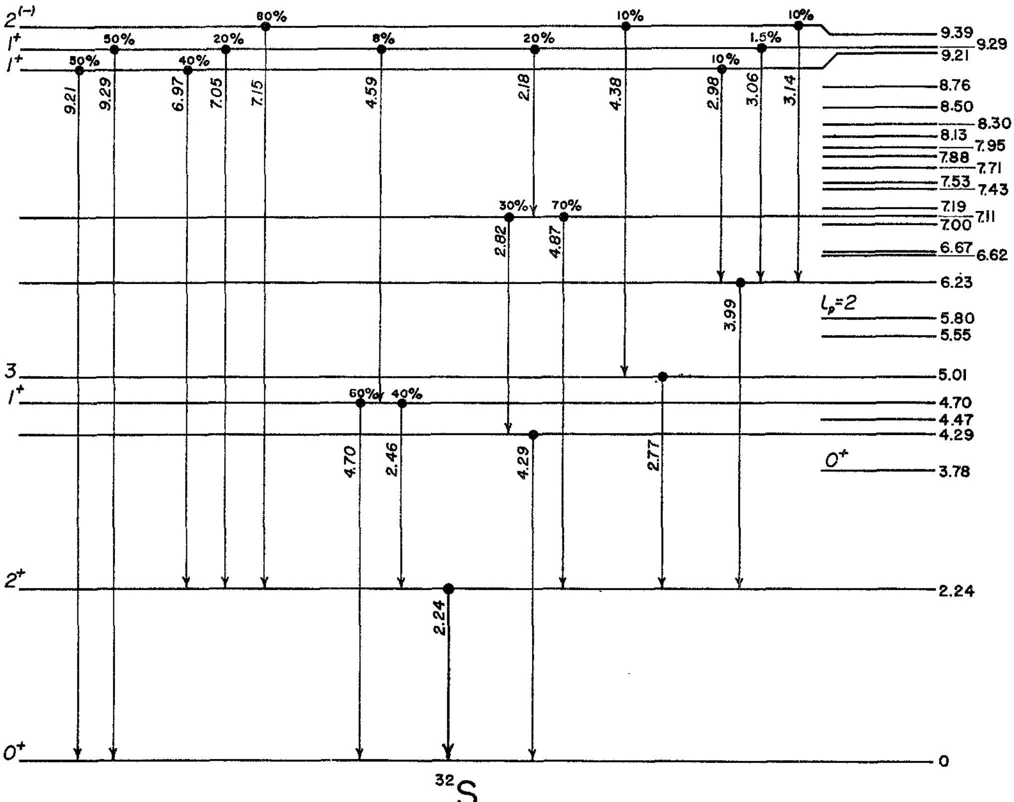

Fig. 3. Decay scheme for the 9.21, 9.29 and 9.39 MeV levels of ^{32}S. Known levels, which do not appear to participate in these cascades, are shown only at the right-hand edge. The spin assignments for the 2.24, 3.78, 5.01 and 5.80 MeV levels are taken from ref. [4]). Branching ratios are accurate to not worse than a factor of two. Some weak branches may have been missed.

The spin assignment of 1^+ for the 4.70 MeV level comes about in the following way: bombarding ^{31}P with protons at the 440 keV resonance, Nelson, Carlson and Schlenker [1]) investigated the gamma-ray spectrum with a three-crystal pair spectrometer. With good resolution but poor statistics, they found only two lines between 4 and 5 MeV, which they measured as 4.82 and 4.54 MeV. Then with larger counters but poorer resolution, they found two lines of about these energies to be in coincidence with each other, which they believed to be the same lines, forming a cascade through the 4.47 MeV level. They measured the angular correlation between the coincident gamma rays with wide discriminator windows and concluded that the spin and parity of the intermediate state must be 1^+.

We have full confidence in the angular correlation measurement itself; however, in the light of the present work it is clear that the cascade involved was the 4.59-4.70 MeV one through the 4.70 MeV level. We conclude that the assignment 1^+ must be attributed to the 4.70 MeV level, while that of the 4.47 MeV level is yet to be determined.

The branching ratios determined in this work and given in fig. 3 are in general agreement with those of Andersen [3]) for the 4.29, 4.70 and 5.01 MeV levels. We have not observed the transitions to the ground state from the 6.23 and 7.11 MeV levels as reported by Andersen.

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