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A DOUBLET RESONANCE IN THE REACTION $^{32}S(p, \gamma)^{33}Cl$

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Synopsis

Gamma-ray spectra, yields, and angular distributions have been measured with scintillation spectrometers at two resonances in the reaction $^{32}S(p, \gamma)^{33}Cl$, at 579.8 ± 1.5 keV and 587.4 ± 1.5 keV. The 580 keV resonance corresponds to a 2.85 ± 0.02 MeV level in ^{33}Cl to which $J = 5/2^+$ is assigned. This level decays almost exclusively to the ground state. The 587 keV resonance corresponds to a 2.86 ± 0.02 MeV level in ^{33}Cl with spin $J = 3/2$, which decays with approximately equal intensities to the ground state and to the first excited state at 0.806 ± 0.004 MeV. A ^{33}Cl mass excess of − 11.244 ± 0.011 MeV results from these experiments. The resonance strengths amount to $\gamma = 4.5 \pm 1.5$ meV for the 580 keV resonance, and to $\gamma = 26 \pm 10$ meV for the 587 keV resonance. A search for the conjugate state of the 2.94 MeV level in ^{33}S, with $J = 7/2^-$, was unsuccesful.

1. *Introduction.* The $E_p = 594$ keV resonance in the reaction $^{32}S(p, \gamma)^{33}Cl$, which had been investigated about a year ago at this laboratory[1)2)], has proved to be a doublet. The resolution of this doublet was made possible by putting a new 90 degree analysing magnet into use. With a 20 cm orbit radius and with entrance and exit energy-defining slits of 2 mm, an energy spread of 3 keV is observed for protons of 600 keV. With a ZnS target of 10 $\mu g/cm^2$ the resonance peaks have a half-width of 5 keV. With the 30 degree magnet and the 100 $\mu g/cm^2$ target, used in the earlier experiment, the two resonances were not resolved. An investigation of gamma-ray spectra, yields, and angular distributions at the two resonances is reported in this paper.

2. *Resonances.* Use was made of a ZnS target of about 10 $\mu g/cm^2$, with sulphur of natural isotopic constitution. In the energy region from 300–830 keV, the only two resonances which could be ascribed to ^{32}S are those forming the doublet mentioned above. Other peaks in the yield curve originate from ^{33}S, ^{34}S, and from contaminants. The two resonances appear at proton energies of 579.8 ± 1.5 keV and 587.4 ± 1.5 keV (see Fig. 1). The proton energies are determined by measuring the magnetic field of the analyzing magnet with a magnetic resonance fluxmeter, calibrated at a number of $^{19}F(p, \alpha\gamma)^{16}O$, $^{24}Mg(p, \gamma)^{25}Al$, and $^{26}Mg(p, \gamma)^{27}Al$ resonances.

The resonance strengths can be calculated from the thick target yield [2], giving the sum of the two strengths, and from the relative strengths of the two resonances measured with a thin target. In this way $\omega\gamma = (2J + 1)\,\Gamma_p\Gamma_\gamma/(\Gamma_p + \Gamma_\gamma) = 0.027 \pm 0.010$ eV was found for the 580 keV resonance, and $\omega\gamma = 0.10 \pm 0.04$ eV for the 587 keV resonance.

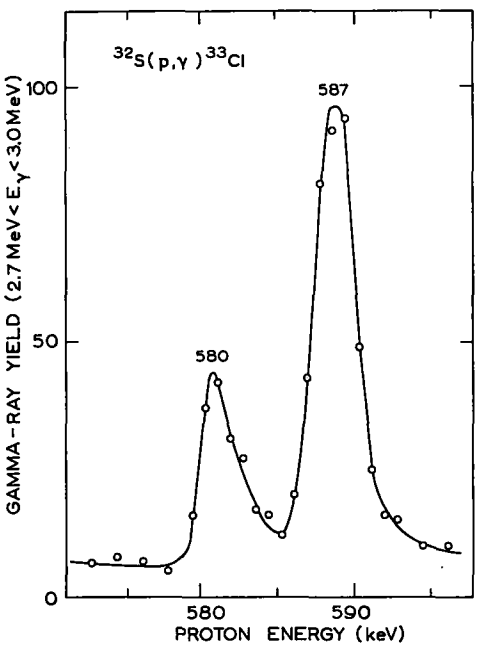

Fig. 1. Gamma-ray yield of the ground-state transitions from proton bombardment of ^{32}S.

The resonances correspond to excited states in ^{33}Cl at 2.85 and 2.86 MeV. The spins and parities of these two levels are $J = 5/2^+$ and $J = 3/2^\pm$, respectively (see below). One can then expect a third state in this region which is the analogue of the 2.94 MeV level in the mirror nucleus ^{33}S, and which probably has $J = 7/2^-$ [3]. If the resonance corresponding to this state were to occur at a proton energy of 600 keV, its strength would be smaller by a factor of about 20 to 100 than that of the 580 keV resonance. In this estimate the average values for the proton and radiative widths derived from a literature survey [2] were used, and the $J = 7/2^-$ level was supposed to decay by an $E1$ transition to a $J = 5/2^+$ level at 2 MeV (the conjugate state of the 1.96 or 2.31 MeV level in ^{33}S). Thus this resonance was expected to be too weak to be detected in the usual single-crystal measurement with a relatively high background. A search was made for it by measuring coincidences between gamma rays in a 0.45–1.30 MeV and in a 1.75–2.35 MeV channel. The results are shown in Fig. 2. Although the background re-

duction effected in this way is quite appreciable, it was impossible to detect the $f_{7/2}$ resonance. This means that its strength is at least 50 times smaller than that of the 580 keV resonance. The only resonance seen in Fig. 2 is that at 587 keV. The 580 keV resonance has disappeared completely, indicating that it decays by a pure ground-state transition (see below).

TABLE I

Gamma rays observed at the 580 and 587 keV resonances

E_p (keV)	E_γ (MeV)	Transition	Intensity	Anisotropy
580	2.85 ± 0.02	$(r_1) \rightarrow (0)$	100	−0.68 ± 0.02
587	2.86 ± 0.02	$(r_2) \rightarrow (0)$	50 ± 5	+0.77 ± 0.04
587	2.053 ± 0.015	$(r_2) \rightarrow (1)$	50 ± 5	−0.61 ± 0.03
587	0.806 ± 0.004	$(1) \rightarrow (0)$	50 ± 7	+0.03 ± 0.03

3. *Gamma rays.* The gamma rays measured at the 580 and 587 keV resonances are summarized in Table I, together with their intensities and

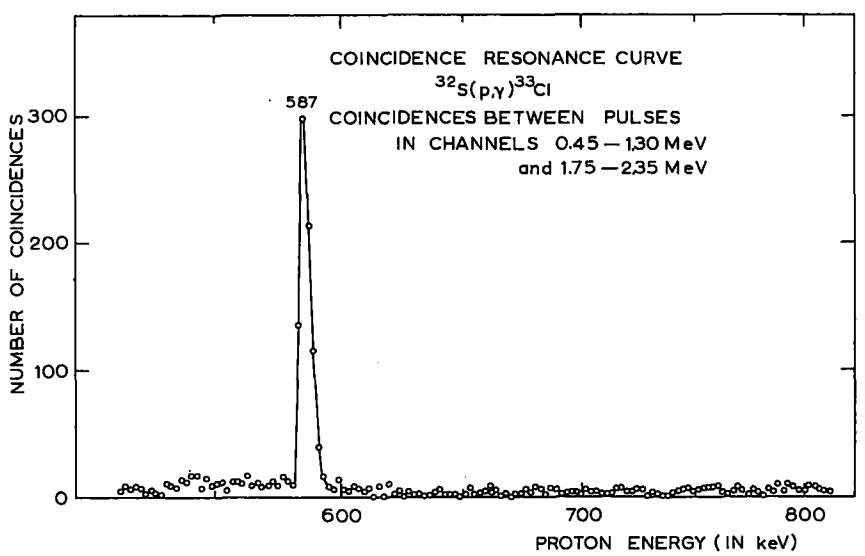

Fig. 2. Coincidence resonance curve from the bombardment of a ZnS target. Coincidences are counted between pulses in the channels 0.45–1.30 MeV and 1.75–2.35 MeV.

anisotropies. The gamma-ray intensities are expressed in percents of the number of proton captures at each resonance. The numbering of the levels in column 3 is given in Fig. 5. A sum-coincidence measurement [4]) at the 580 keV resonance showed that any cascade transition would have an intensity of less than 2 percent of the ground-state transition. The upper limit to be put on the intensity of a cascade through level (1) is still lower and amounts to $\frac{1}{2}$ percent. At the 587 keV resonance the 2.053 and 0.806 gamma rays form a cascade. Any other cascades have an intensity of at most 2 percent of the ground-state transition.

The reaction energy computed from these measurements amounts to 2.289 ± 0.011 MeV. From this Q value, the ^{33}Cl mass excess can be computed as −11.244 ± 0.011 MeV, taking a ^{32}S mass excess of −16.5396 ± 0.0010 MeV [5]).

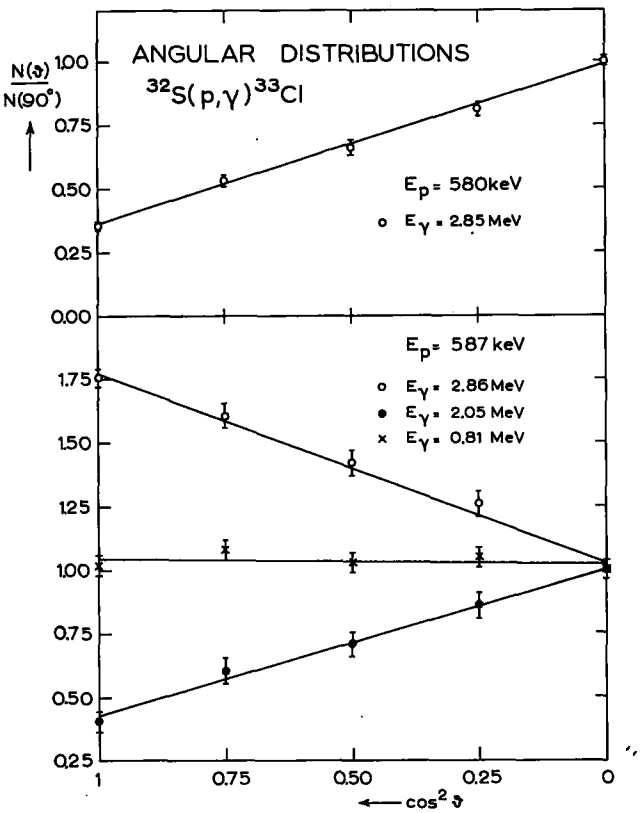

Fig. 3. Angular distributions of the four gamma rays observed at the 580 and 587 keV resonances in ^{32}S(p, γ)^{33}Cl.

The angular distributions of the four gamma rays were determined from pulse spectra taken at 0, 30, 45, 60, and 90 degrees to the proton beam. Within the experimental error (Fig. 3) they are all of the form $1 + A \cos^2\vartheta$. The observed values of A are given in Table I, fifth column. The effect of the great differences in the anisotropies of the 2.86 and 2.05 MeV gamma rays ($A = +0.77$ and -0.61, respectively) on the gamma ray spectra at 0 and 90 degrees, is shown in Fig. 4.

4. *Discussion.* The spin and parity of the ^{33}Cl ground state and first excited state are safely established as $3/2^+$ and $1/2^+$, respectively [6]). Both resonance levels have as possible spins and parities $J = 3/2^\pm$ and $5/2^+$,

since $J = 1/2^{\pm}$ is excluded by the measured anisotropies, and since $J = 5/2^{-}$, $7/2^{\pm}$, or higher, requires capture of protons with orbital momentum $l_p \geq 3$, which would result in resonance strengths much lower than the observed ones.

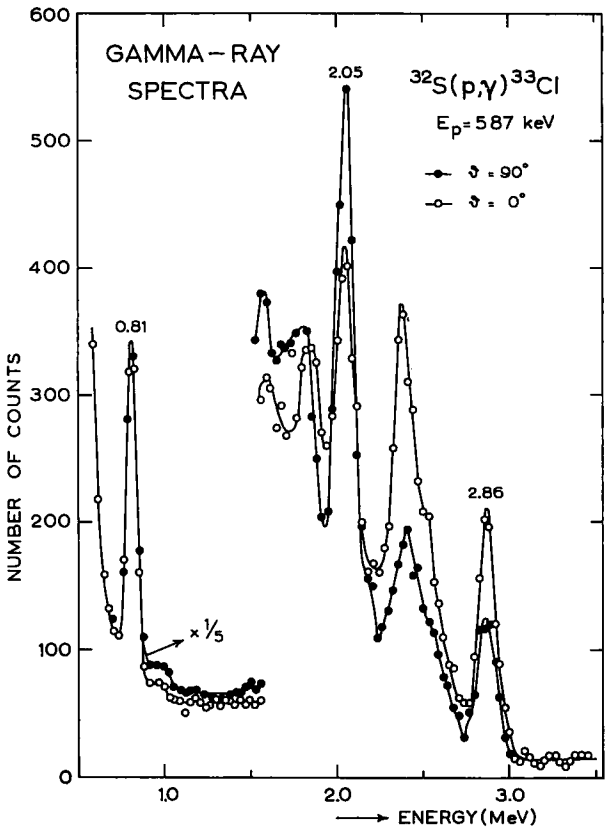

Fig. 4. Scintillation spectra taken at the 587 keV resonance at 0 and 90 degrees to the proton beam, showing the strong anisotropies of the 2.86 and 2.05 MeV gamma rays.

At the 580 keV resonance, the observed A value fixes the resonance level as $J = 5/2^{+}$, since $J = 3/2^{-}$ (with an unmixed $E1$ transition) would give $A = +0.75$, and since a $J = 3/2^{+}$ assignment requires the improbably high $E2/M1$ intensity mixing ratio of 2.1 ± 1.3. The only remaining possibility is $J = 5/2^{+}$, with an $E2/M1$ mixing of 0.014 ± 0.008 (or 5.0 ± 0.5). The large value of the mixing parameter can be excluded since it would entail a strong $\cos^4\vartheta$ term, which is not observed. The theoretical anisotropies and mixing parameters used in these considerations are calculated from the tables of Ferguson and Rutledge [7]).

The strength of this resonance yields only lower limits for the proton and

radiative widths. These are lower (by factors of 10 and 2, respectively) than the average values derived for these widths [2]).

At the 587 keV resonance a $J = 5/2^+$ assignment can be excluded since in this case the 2.05 MeV gamma ray would have to be pure $E2$ radiation with a corresponding strong $\cos^4\vartheta$ term in the angular distribution. Moreover, an explanation of the observed anisotropy of the ground-state transition would require an $E2/M1$ intensity mixing of at least 0.7 which would also lead to an observable $\cos^4\vartheta$ term. A choice between the two remaining possibilities $J=3/2^{\pm}$ is impossible, since the measured anisotropies of the 2.86 and 2.05 MeV transitions are equal (within the experimental errors) to the values ($A = +0.75$ and $A = -0.60$, respectively) calculated for unmixed dipole radiation.

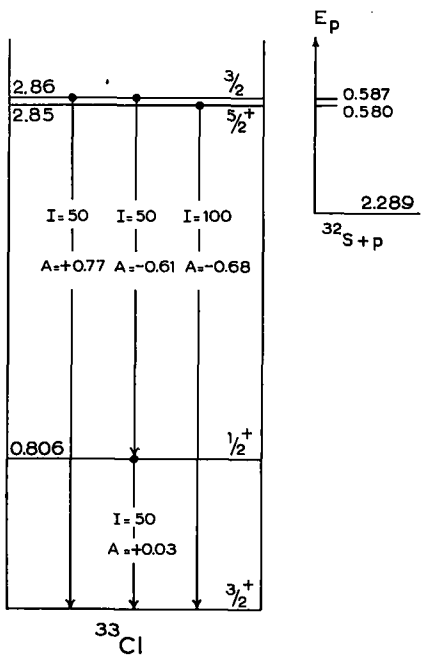

Fig. 5. Level scheme of ^{33}Cl, with gamma-ray transitions and their intensity (I) and anisotropy (A).

From the measurement of the resonance strength a decision as to the parity of the 2.86 MeV level is also impossible. In the case of p-capture ($J = 3/2^-$) the resonance strength is limited by the radiative width, and yields $|M|^2 = 0.0005$ and 0.0014 for the transitions to the ground state and the first excited state, respectively, where $|M|^2$ is the radiative width in Weisskopf units. These values are in good agreement with the average value of $|M|^2 = 0.0017$ found for $E1$ transitions in this mass region [2]). If d-capture occurs ($J = 3/2^+$), the resonance strength is limited either by the proton width or by the radiative width. Calculation of lower limits yields a reduced

proton width $\theta_p^2 < 0.03$ and radiative widths $|M|^2 < 0.027$ and < 0.07 for the $(r) \rightarrow (0)$ and $(r) \rightarrow (1)$ transitions, respectively, to be compared with the average values $\theta_p^2 = 0.07$ and $|M|^2 = 0.025$ (for $M1$ transitions). Thus $J = 3/2^+$ cannot be excluded as the spread around the average values is rather large [2]).

If the 2.86 level indeed has $J = 3/2^-$, it might be the conjugate state of the 3.22 MeV level in ^{33}S. The large energy displacement (360 keV) could be accounted for as the sum of the "boundary-condition displacement" and of the "displacement due to the electromagnetic spin-orbit interaction" [8]), if the reduced particle width of the level is large ($\theta^2 \geq 0.5$), which is not quite impossible for a pronounced single particle state. The ^{33}Cl level scheme as resulting from the present measurement is given in Fig. 5.

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REFERENCES

1) Van der Leun, C. and Endt, P. M., Physica **22** (1956) 1234.
2) Van der Leun, C., Thesis Utrecht (1958).
3) Endt, P. M. and Paris, C. H., Phys. Rev. **110** (1958) 89.
4) Hoogenboom, A. M., Nucl. Instr. **3** (1958) 57.
5) Quisenberry, Giessen, and Benson, Bull. Am. phys. Soc. Ser. II, **2** (1957) 223.
6) Endt, P. M. and Braams, C. M., Revs. mod. Phys. **29** (1957) 683.
7) Ferguson, A. J. and Rutledge, A. R., "Coefficients for triple angular correlation analysis in nuclear bombardment experiments", A.E.C.L. no. 420, Chalk River (1957).
8) Thomas, R., Phys. Rev. **88** (1952) 1109.