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THE $^{32}S(p,\gamma)^{33}Cl$ REACTION AT THE LOWEST T = 3/2 STATE OF ^{33}Cl

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1. - INTRODUCTION

The lowest $T = 3/2$ states in ($T_z = -1/2$, $A = 4n+1$, $Z = 2n-1$) nuclei, which are the third component of the $A = 4n+1$ isobaric quartets, have been identified both from the β-decay of their ($T_z = 3/2$, $Z = 2n+2$) analogues (1), and as compound nucleus resonances exhibited by the yield of the (p,p) reaction on nuclei having $T = 0$, $A = 4n$, $Z = 2n$, with n ranging from 2 to 10 (2). Proton decay of these resonances is allowed energetically only to $T = 0$ states of ($A = 4n$, $Z = 2n$) nuclei, but this decay is isospin forbidden and can compete with gamma decay. This fact makes it possible to observe these $T_>$ states as radiative capture resonances.

The $T_>$ states are expected to be single particle states and to have simple shell-model configurations. They have generally high excitation energies and are surrounded by $T_<$ states, with complicated configurations corresponding to many particle excitation.

Therefore the $T_>$ states will decay by strongly selective gamma transitions to the low-lying levels with simple shell-model configurations and not to higher excited states.

The three lowest $T = 3/2$ states in ^{33}Cl, which are the isobaric analogues of the ground, first and second excited states of ^{33}P, were found as compound nucleus resonances in the yield of the ^{32}S(p,p)^{32}S reaction (3). These levels are at an excitation energy, in the ^{33}Cl nucleus, of 5558±12, 6998±12, 7414±12 keV respectively, corresponding to an energy of the incident protons of 3370±1, 4855±3, 5284±3 keV (lab.syst.). Spin and parity $1/2^+$, $3/2^+$, $5/2^+$ respectively have been assigned to these levels from the analysis of the elastic and inelastic data. Recently, the yield curve of the β^+ rays following the ^{32}S(p,γ)^{33}Cl reaction has been studied by Eswaran, Ismail and Ragoowansi (4); these Authors report energy data in very good agreement with our previous results (3). The gamma-ray spectrum of the lowest $T = 3/2$ state decay in ^{33}Cl and the limit for the values of the branching ratios are also reported.

2. - EXPERIMENTAL PROCEDURE

The gamma-decay of the lowest T = 3/2 state in ^{33}Cl, reached through the $^{32}S(p,\gamma)^{33}Cl$ reaction, has been investigated. The measurements were performed by means of the proton beam of the 5.5 MeV Van de Graaff accelerator of the Laboratori Nazionali di Legnaro. Thin targets ($\sim 50 \mu g/cm^2$) of natural Sb_2S_3 (95% ^{32}S, 0.76% ^{33}S, 4.22% ^{34}S) on thick Au backings were used. The overall resolution, due to both the beam spread and the target thickness was (7.7±0.4) keV at E_p = 3374 keV. The target thickness was chosen to be as small as possible (taking obviously into account the necessary intensity of the gamma-rays yield) in order to reduce the large gamma-background due to both the impurities in the target evaporation and to the $(p,p'\gamma)$ reactions on the other sulphur isotopes. The gamma rays were detected by means of a 52 c.c. and a 70 c.c. Ge(Li) detectors with a resolution of 4.8 keV at E_γ = 1772 keV and the spectra were recorded with a 4096 and 1024 channel analyser.

Two sets of measurements were performed, the first devoted to the identification of the gamma rays and the second for measuring the gamma rays angular distribution. Relative efficiency was used in the first case; and the absolute one in the second case for the same angles used in the angular distribution measurements. The experimental points were obtained with a ^{56}Co calibrated source and by means of the $^{31}P(p,\gamma)^{32}S$ reaction ([5]). The experimental points were then fitted by means of the least-squares method, using the function $\ln \epsilon = a + b E_\gamma + c E_\gamma^2$. An example of absolute efficiency curve is shown in Fig. 1.

The energy of the resonance has been measured by the yield of the 2232 keV gamma-ray from the $^{32}S(p,p'\gamma)^{32}S$ reaction. Then gamma-ray spectra at E_p = 3367 keV (below the resonance energy), E_p = 3374 keV (the resonance energy has been modified in order to take into account the effects of the target thickness) and E_p = 3410 keV (above the resonance energy) and at an angle of 55° were performed. A 1024 channels spectrum taken at E_p = 3374 keV is reported in Fig. 2, and the most interesting parts of the spectra at the three energies are reported in Fig. 3.

With reference to the spectrum at E_p = 3374 keV, one can easily see peaks number 8, 8', 8" which are the full, first and double escape peaks (E_γ = 5558, 5047, 4536 keV), corresponding to the gamma-ray resulting from

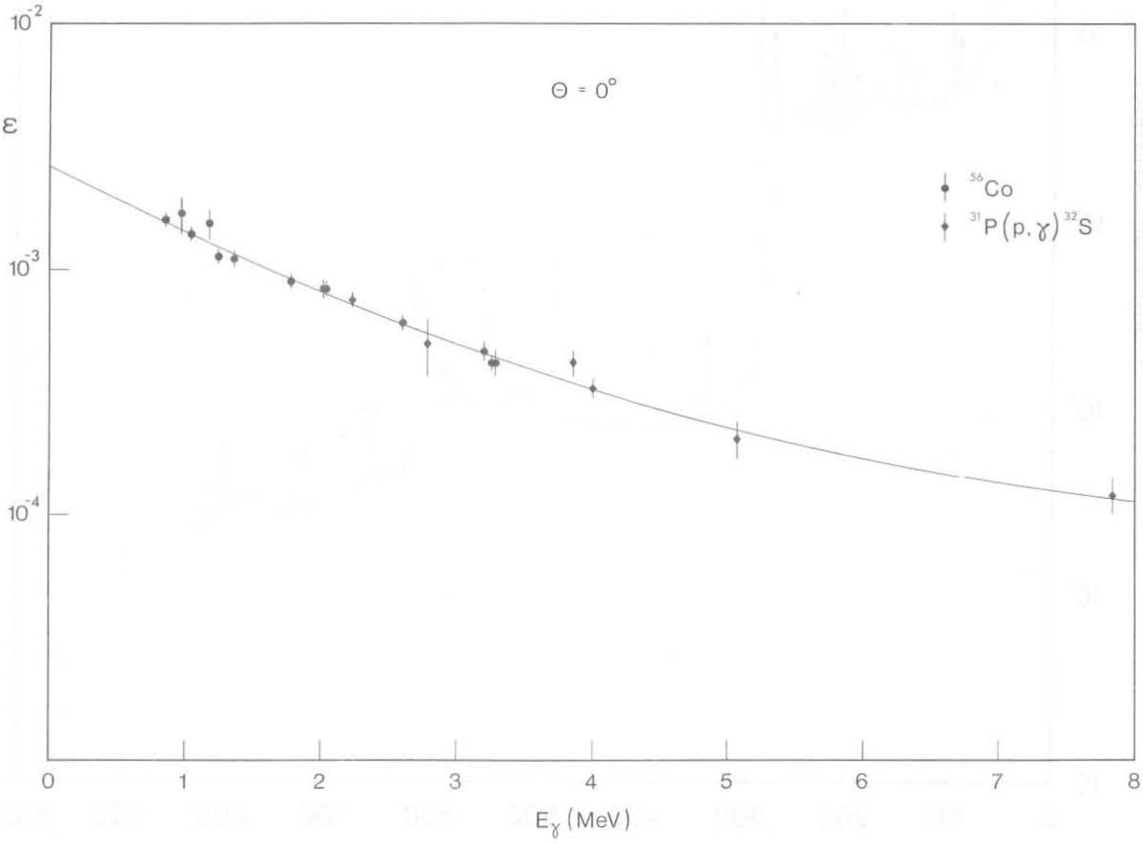

Fig. 1 - Absolute efficiency of the γ -rays detector measured at ϑ = 0°. The meaning of the solid line is explained in the text.

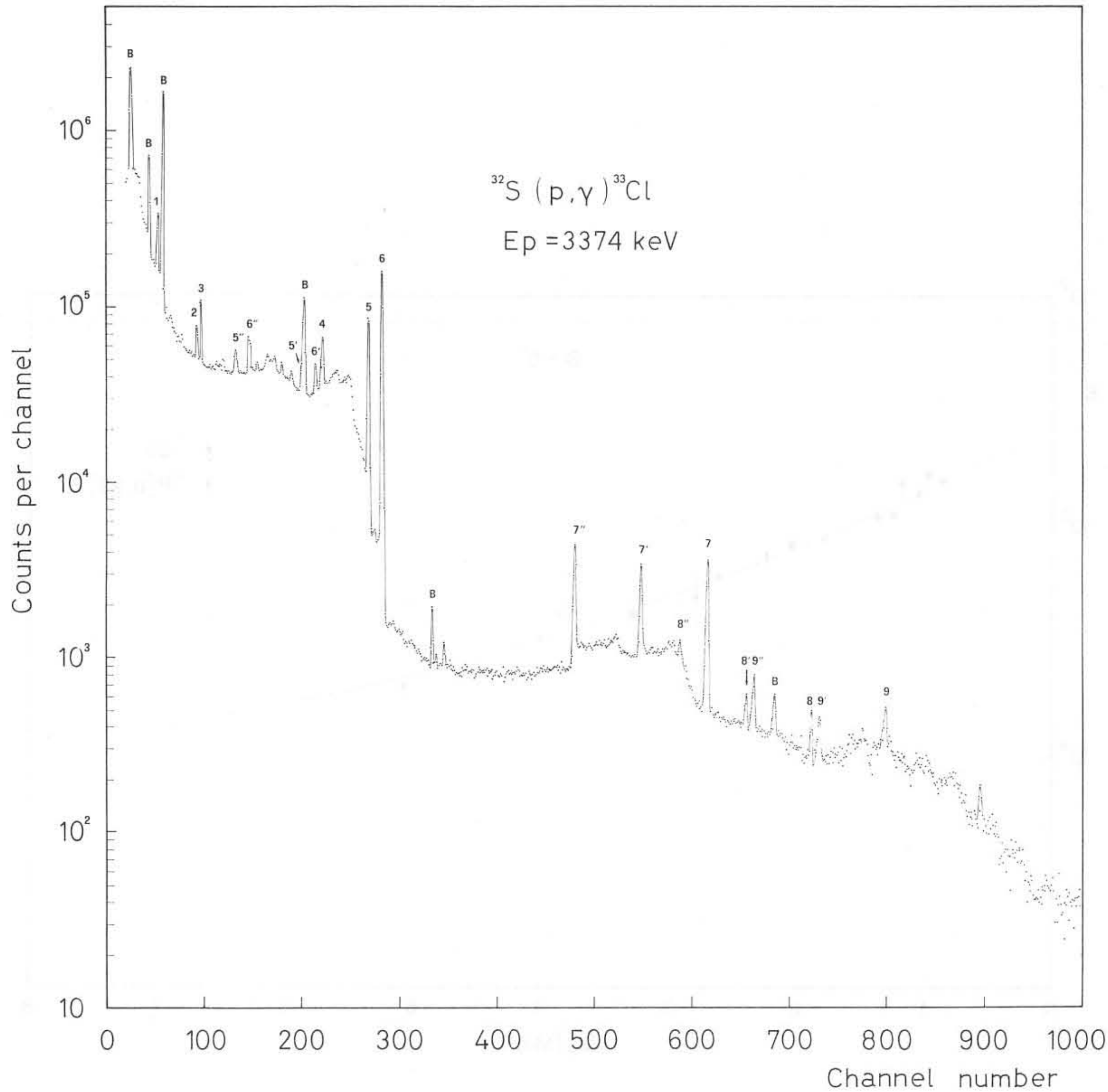

Fig. 2 - Gamma-ray spectrum measured at E_p = 3374 keV. The numbers on the peaks in this figure and in the following Fig. 3 refer to the identification of the various gamma rays, as shown in Table 1; the letter "B" refers to the Au backing and background structures, which have been seen during a background measurement performed at E_p = = 3374 keV with only the Au backing in the beam.

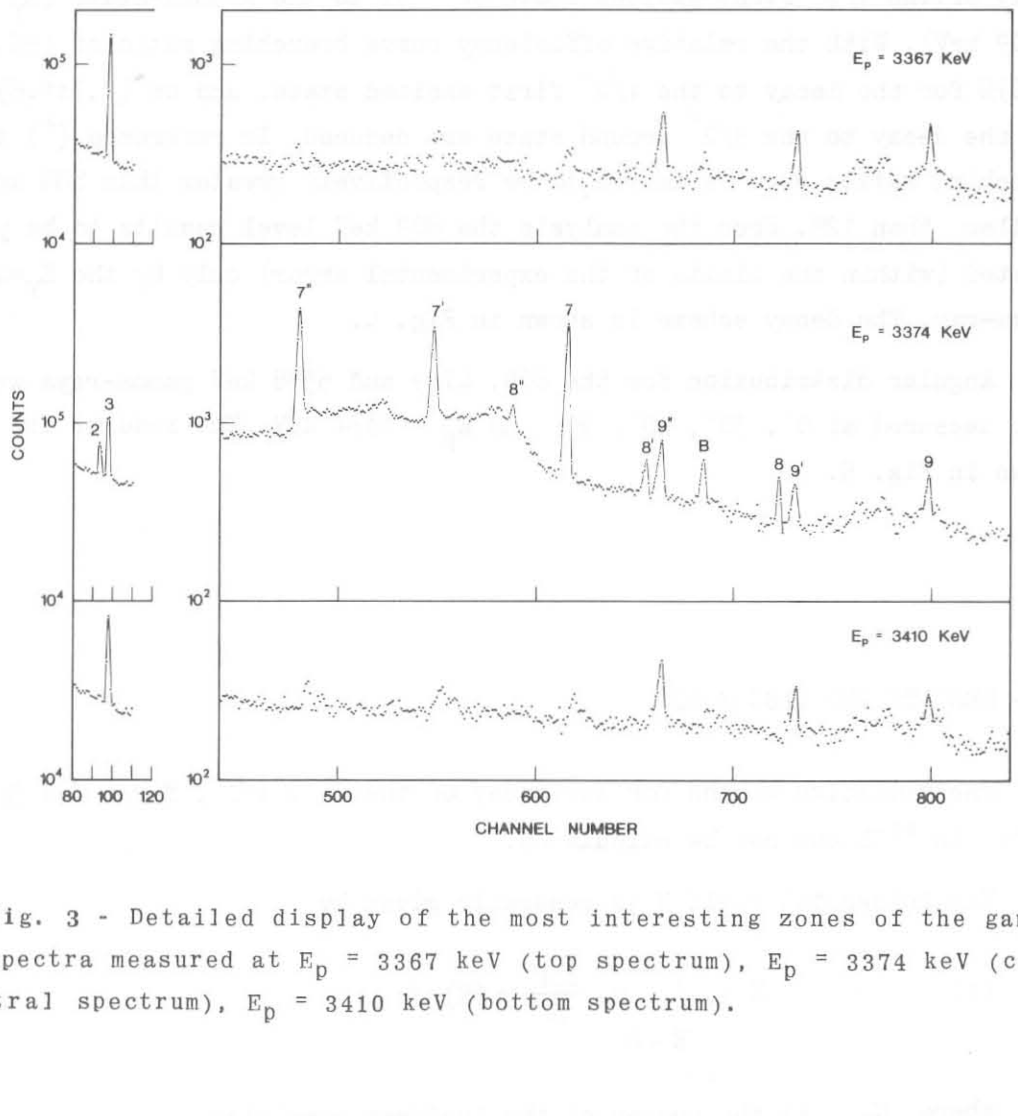

Fig. 3 - Detailed display of the most interesting zones of the gamma spectra measured at E_p = 3367 keV (top spectrum), E_p = 3374 keV (central spectrum), E_p = 3410 keV (bottom spectrum).

the decay of the $J^{\pi} = 1/2^{+}$, $T = 3/2$ state to the $3/2^{+}$ ground state of ^{33}Cl. Peaks number 7, 7', 7" are the full, first and second escape peaks ($E_{\gamma} = 4749, 4238, 3727$ keV respectively) corresponding to the gamma-ray resulting from the decay of the same level to the ^{33}Cl first-excited ($J^{\pi} = 1/2^{+}$) level. Peak number 2, corresponds to the gamma ray from the decay of the $1/2^{+}$ first-excited state of ^{33}Cl to the ground-state ($E_{\gamma} =$ $= 809$ keV). With the relative efficiency curve branching ratio of $(92.3\pm$ $\pm1.6)\%$ for the decay to the $1/2^{+}$ first excited state, and of $(7.7\pm1.6)\%$ for the decay to the $3/2^{+}$ ground state are deduced. In reference ([4]) these branching ratios were estimated to be respectively greater than 88% and smaller than 12%. From the analysis the 809 keV level results to be populated (within the limits of the experimental error) only by the E_{γ}=4749 gamma-ray. The decay scheme is shown in Fig. 4.

Angular distribution for the 809, 4749 and 5558 keV gamma-rays were also measured at 0°, 30°, 60°, 90° and $E_p = 3374$ keV. The results are shown in Fig. 5.

3. - RESULTS AND DISCUSSION

The radiative widths for the decay of the $J^{\pi} = 1/2^{+}$, first $T = 3/2$ state in ^{33}Cl can now be calculated.

The integrated yield N is generally given by

$$N = \int_{E-\Delta}^{E} N_0 \frac{\rho \mathcal{N}}{A} \sigma(E)\, ds \qquad (1)$$

where N_0 is the number of the incident particles

$\sigma(E)$ is the integral cross section

ρ is the density of the target material

$\mathcal{N}$ is the Avogadro's number

Δ is the thickness of the target

ds is the range of the incident particle in the target

This formula can be written as

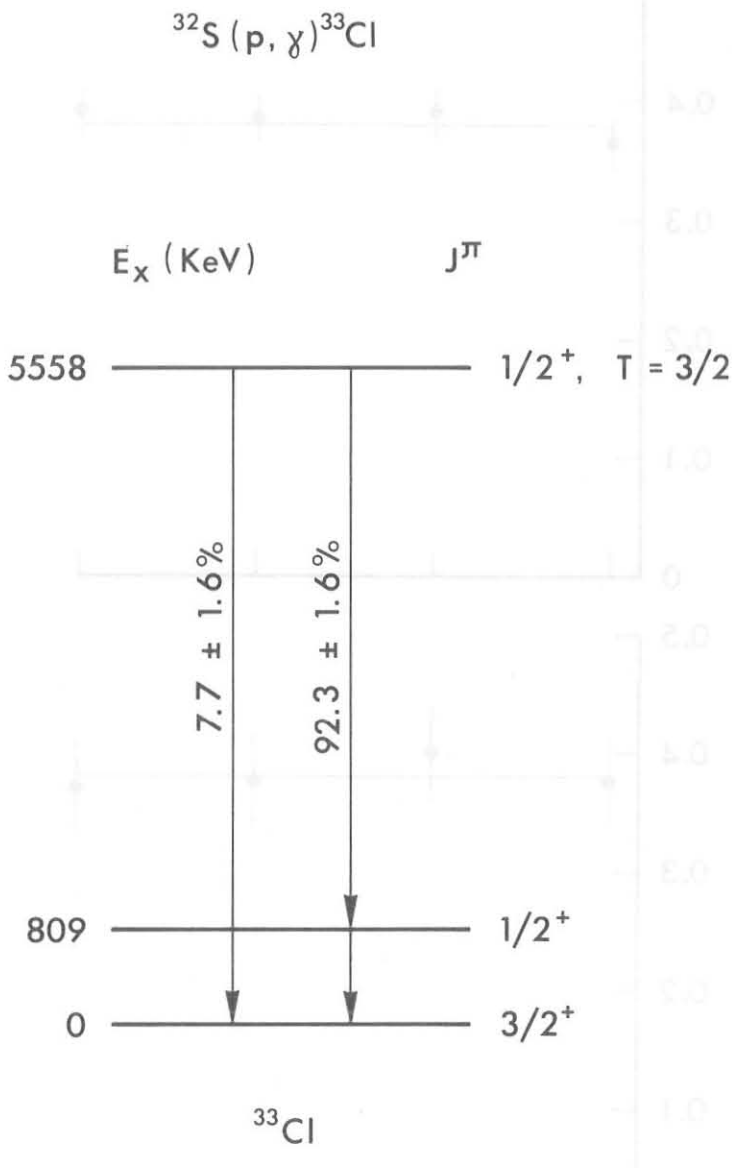

Fig. 4 - Decay scheme of the $J^{\pi} = 1/2^{+}$ lowest T = 3/2 state of ^{33}Cl.

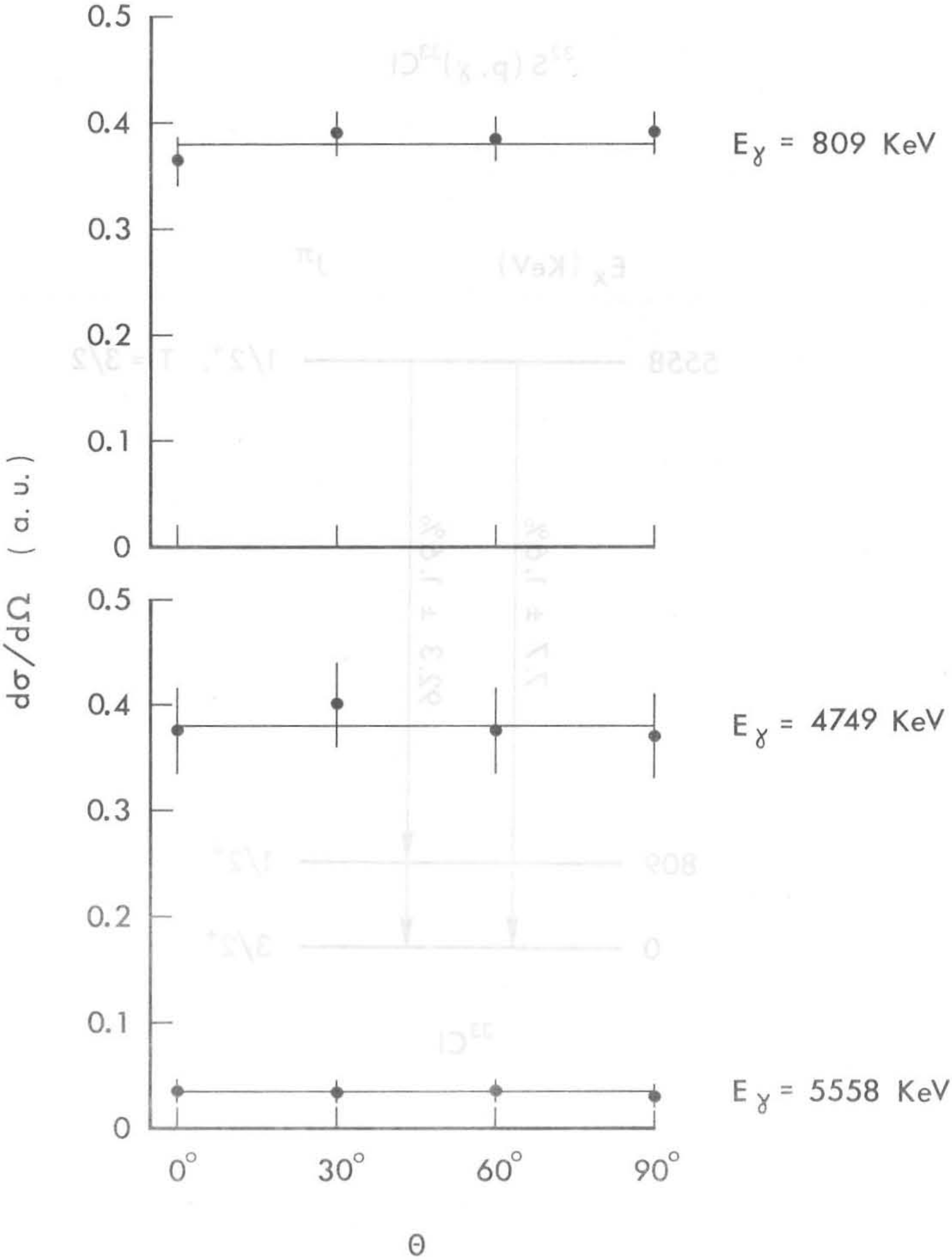

Fig. 5 - Angular distributions of the E_γ = 809, 4749 and 5558 keV gamma-rays in ^{33}Cl.

$$N = N_0 \frac{\rho \mathcal{N}}{A} \frac{ds}{dE} \int_{E-\Delta}^{E} \sigma(E)\, dE \tag{2}$$

If the resonance occurs in a (p,γ) type reaction, $\sigma(E)$ is proportional to the widths Γ_p and Γ_γ in the entrance and exit channels and is related to the spins of the resonant state (J), of the incident particle (s) and of the target nucleus (I) by the formula [6]

$$\sigma_{p\gamma}(E) = \pi \lambda\!\!\!^{-2} \frac{(2J+1)}{(2s+1)(2I+1)} \cdot \frac{\Gamma_p \Gamma_\gamma}{(E-E_0)^2 + \frac{1}{4}\Gamma^2} \tag{3}$$

with Γ total width of the resonance, and $\lambda\!\!\!^{-}$ the reduced wavelength of the incoming particle.

By using the relation (3) the formula (2) can be written:

$$N = N_0 \frac{\rho \mathcal{N}}{A} \frac{ds}{dE} \pi \lambda\!\!\!^{-2} \frac{(2J+1)}{(2s+1)(2I+1)} \int_{E-\Delta}^{E} \frac{\Gamma_p \Gamma_\gamma}{(E-E_0)^2 + \frac{1}{4}\Gamma^2}\, dE \tag{4}$$

For a resonance narrow compared with the thickness of the target as in this case, one can write:

$$\int_{E-\Delta}^{E} \frac{\Gamma_p \Gamma_\gamma}{(E-E_0)^2 + \frac{1}{4}\Gamma^2}\, dE = \int_{-\infty}^{+\infty} \frac{\Gamma_p \Gamma_\gamma}{(E-E_0)^2 + \frac{1}{4}\Gamma^2}\, dE = \Gamma_p \Gamma_\gamma \frac{2\pi}{\Gamma} \tag{5}$$

and by putting this result in the expression (4) one can obtain

$$N = N_0 \frac{\rho \mathcal{N}}{A} \frac{ds}{dE} 2\pi^2 \lambda\!\!\!^{-2} \frac{(2J+1)}{(2s+1)(2I+1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma} \tag{5}$$

In the present case $J = 1/2$, $I = 0$, $s = 1/2$, $\Gamma_p = \Gamma$ and then

$$N = N_0 \frac{\rho \mathcal{N}}{A} \frac{ds}{dE} 2\pi^2 \lambda\!\!\!^{-2} \Gamma_\gamma \tag{6}$$

or

$$\Gamma_\gamma = \frac{N}{N_0 2\pi^2 \lambda\!\!\!^{-2} \frac{\rho \mathcal{N}}{A} \frac{ds}{dE}} \tag{7}$$

By using in the formula (7) the experimental values of N and N_0 and the value of $\frac{ds}{dE}$ obtained from the tables of Northcliffe and Schilling[7], a value of Γ_γ = (695±70) meV for the $1/2^+$, T = 3/2 → $1/2^+$, T = 1/2(E_γ = = 4749 keV) decay and a value of Γ_γ = (58±10) meV for the $1/2^+$, T = 3/2→ → $3/2^+$, T = 1/2 (E_γ = 5558 keV) decay can be obtained. In Table 2 the strengths obtained following Skorka, Hertel and Retz-Schmidt (8) are also reported.

The only theoretical prediction with which the experimental value can be compared is the one reported by Glaudemans et al. (9): 9.2×10^{-2}W.u. However it is to be emphazised that this value is obtained with one of the three temtative fitting procedures, whose character is more adherent to a single particle model. With another procedure, in which effective g-factors and charges obtained from a least-square fit to experimental data were used, a value for the analogue transition in the ^{33}S mirror nucleus is presented (32×10^{-2} W.u.), which is nearer to the one extracted in the present experiment.

To reach a deeper insight into this argument, a comparison between the strengths of the M1 gamma transition and of the analogue β -decay from the ^{33}Ar g.s. ($1/2^+$, 3/2) to the 809 keV first excited level in ^{33}Cl ($1/2^+$, 1/2) could be profitable.

Under the assumption of good isospin symmetry the relation between the two strengths is reported by Hanna (10) in the form:

$$(8) \qquad \Lambda(M1) = 11.1 \, \frac{(CG)^2_\gamma}{(CG)^2_\beta} \left[1 + 0.11 \, \frac{\langle f | \ell\tau | i \rangle}{\langle f | \sigma\tau | i \rangle} \right]^2 \Lambda\,(GT)$$

where the Λ are the two strengths, (CG) are the isospin coupling coefficients and $\langle f|\ \ |i\rangle$ are the orbital and spin part of the transition matrix element. The strength of the beta transition can be calculated with the expression (10):

$$(9) \qquad \Lambda(GT) = \frac{4390}{ft}$$

Due to the small coefficient in the second term of the bracket if the orbital matrix element is not large compared to the spin matrix element, in a first approximation we can ignore this second term. Moreover the second term would vanish exactly if the configuration of the T = 3/2 and T = 1/2 states were:

TABLE 1

Gamma rays observed in the $^{32}S(p,\gamma)^{33}Cl$ reaction at E_p = 3374 keV

Peak number	E_γ(keV)	Assignment
1	511	Annihilation peak
2	809	$^{32}S(p,\gamma)^{33}Cl$ = $1/2^+$ first-excited → $3/2^+$ ground state
3	842	$^{33}S(pp'\gamma)^{33}S$ = $1/2^+$ first-excited → $3/2^+$ ground state
4	1778	$^{28}Si(pp'\gamma)^{28}Si$ = 2^+ first-excited → 0^+ ground state
5	2127	$^{34}S(pp'\gamma)^{34}S$ = 2^+ first-excited → 0^+ ground state
6	2232	$^{32}S(pp'\gamma)^{32}S$ = 2^+ first-excited → 0^+ ground state
7	4747	$^{32}S(p,\gamma)^{33}Cl$ = $1/2^+$, T = 3/2 → $1/2^+$ first excited
8	5558	$^{32}S(p,\gamma)^{33}Cl$ = $1/2^+$, T = 3/2 → $3/2^+$ ground state
9	6144	$^{19}F(p,\alpha\gamma)^{16}O$ = 3^- second excited → 0^+ ground state

TABLE 2

γ-decay widths for the decays of the $1/2^+$,T=3/2,E_x=5558 keV level of ^{33}Cl

Transition	$1/2^+$,T=3/2→$1/2^+$ 1° excited	$1/2^+$,T=3/2→$3/2^+$ g.s.
Energy (keV)	5558→809	5558→0
E_γ (keV)	4749	5558
Branching ratio % (present work)	93.3±1.6	7.7±1.6
Branching ratio % (ref.(4))	> 88	< 12
Γ_γ (present work) meV	695±70	58±10
Γ_γ (ref.(4)) meV	340±90	50
M1 strength (w.u.) (present work)	$(31\pm3)\times10^{-2}$	$<(16\pm3)\times10^{-3}$

$$(10)\qquad \left[(d_{3/2})^{2}_{0\,1}\;\; s^{-1}_{1/2\,1/2}\right]_{1/2\,3/2} \quad \text{and} \quad \left[(d_{3/2})^{2}_{0\,1}\;\; s^{-1}_{1/2\,1/2}\right]_{1/2\,1/2}$$

If we use the log ft value measured by Hardy et al.[11], 4.44±0.03, we obtain for Λ (M1) a value which is about half of the one derived by our experiment.

It is in order then to test if the examined levels actually have this dominant configuration. For that purpose we have compared the spectroscopic factors experimentally obtained to those theoretically computed for the simple configuration supposed. Table 3 shows this comparison for selected levels of ^{33}S and ^{33}P nuclei, analogues to the ^{33}Cl and ^{33}Ar states, in which we are interested. It appears from this data that the experimental spectroscopic factor from the g.s. in ^{33}P, $1/2^+$, $3/2$, and the analogue in ^{33}S, E_x = 5479 keV, $1/2^+$, $3/2$, are compatible with the theoretical ones. However for the 842 keV level in ^{33}S, the experimental value is much lower compared to the theoretical one, indicating for this level, and presumably for the 809 keV analogue in ^{33}Cl, a more complicated structure. Therefore these levels cannot be thought of as entirely antianalogues of the $1/2^+$, $3/2$ analogue levels. To support this conclusion we have compared the reduced matrix element for the Gamow-Teller transition from the ^{33}Ar ground state to the 809 KeV ^{33}Cl level, computed for the simple configuration supposed and the corresponding one deduced from the experimental log ft value. The theoretical and experimental obtained values are the following:

$$< \left[(J=0,T=1)\, j=1/2, t=1/2\right]_{1/2\,1/2} \| | \sigma\tau | \| \left[(J=0,T=1)\, j=1/2, t=1/2\right]_{1/2\,3/2} >=5.65 \text{ theor.}$$

$$=1.59 \text{ exp.}$$

The disagreement suggests a more involved configuration for at least one of the two states. If we now use the value deduced experimentally for the Gamow-Teller transition $<\||\sigma\tau|\|>$, and the Γ (M1) value obtained in the present work for the 5558→809 KeV gamma transition, we can deduce from (8) the $<|\ell\tau|>$ matrix element for this transition. The value is 4.8±0.5. In deriving at this figure we made the assumption that there existed good isospin symmetry among the different numbers of the multiplet and we have used the free particle values for the magnetic moments of the proton and of the neutron.

TABLE 3

Reaction	Final State E_x J^{π} T	$c^2 s$ Exp	$c^2 s$ $[(d_{3/2})^2_{01}\ s^{-1}_{1/2\,1/2}]\ \mathrm{conf}^{\ 1/2\ 3/2}_{\ 1/2\ 1/2}$	$\frac{c^2 s\ \mathrm{exp}}{c^2 s\ \mathrm{theo}}$
$^{34}S(d,{}^3He)^{33}P^{(a)}$	g.s. $1/2^+$ $3/2$	1.8±0.4	2	0.9
$^{34}S({}^3He,\alpha)^{33}S^{(b)}$	g.s. $3/2^+$ $1/2$	1.9±0.4		
	842 $1/2^+$ $1/2$	0.65±0.2	1.33	0.49
	5479 $1/2^+$ $3/2$	0.47±0.1	0.67	0.7

(a) ref.[12]
(b) ref.[13]

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More detailed calculations on the structure of the 809 keV level would be useful at this point, in order to proceed to a sounder comparison with the experimental M1 and Gamow-Teller strengths.

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