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ABSTRACT

The higher, T = 3/2, analogue resonances in ^{33}Cl have been searched for, using the experimental procedure of the elastic scattering of protons of suitable energy on ^{32}S nuclei, that is via an isospin-forbidden way. A sound evidence has been obtained on the location of the second analogue resonance in ^{33}Cl, at an incident proton energy of E_p = 4855 ± 3 keV, with $J^{\pi} = 3/2^{+}$, and also of a third resonance at an incident proton energy E_p = 5285 ± 5 keV, with $J^{\pi} = 5/2^{+}$. Details are given on the computation method used for the search.

1. - INTRODUCTION

In the context of the studies relevant to the isobaric quartet with A = 33 (^{33}P, ^{33}S, ^{33}Cl, ^{33}Ar)(1), the first T = 3/2 level in ^{33}Cl has been reached via isospin allowed reactions (2) but also by means of an isospin forbidden reaction consisting in a (p,p) elastic scattering on a ^{32}S target nucleus (3,4). In the excitation curve the resonance appeared as a noticeable anomaly at an excitation energy of (5558 ± 1) keV in ^{33}Cl, corresponding to an energy of the incident proton (lab. syst.) of (3370 ± 1) keV. The resonance, which is the isobaric analogue of the ground state in ^{33}P ($J^{\pi}=1/2^{+}$), has been analyzed with an R-matrix formalism revealing momentum and parity equal to $1/2^{+}$, a total width Γ equal to the proton width $\Gamma = \Gamma_p$ = (100 ± 25) eV.

In this paper the subsequent work carried out to search for the higher isobaric resonances in ^{33}Cl, that is the second and third level with T = 3/2, is reported.

Useful previsions in energy, spin and parity of these resonances can be obtained from existing experimental data regarding the ^{33}P nucleus. These indications have been derived by studying the reactions ^{30}Si(α,p)^{33}P (5,6), ^{30}Si(α,pγ)^{33}P (7) and ^{31}P(t,p)^{33}P (8). All measurements agree in assigning to the fundamental and to the first and second excited levels of ^{33}P the spin and parity sequence of $1/2^{+}$, $3/2^{+}$, $5/2^{+}$. The determination of the energy of the levels was obtained by taking the mean value, weighted on the errors, of the results given in (5,6,7,8). The derived level scheme is indicated in Fig. 1. By its examination one can derive that the higher T = 3/2 levels in ^{33}Cl can be searched for at the energy of incident protons of E_p= (4851±3)keV and E_p= (5275±5) keV respectively; they will look like resonances in the excitation curve of the compound nucleus ^{32}S + p and will present angular momentum and parity equal to $J^{\pi} = 3/2^{+}$ and $5/2^{+}$ respectively.

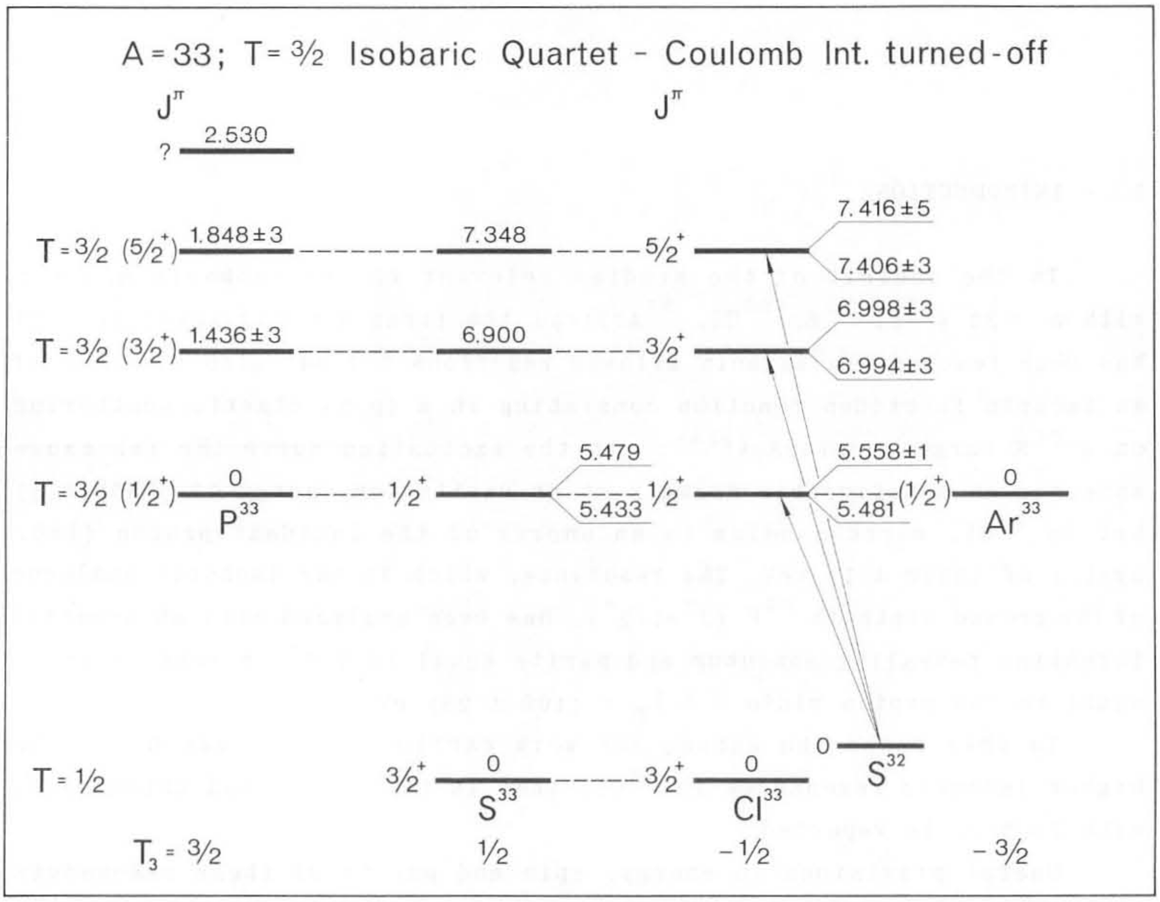

Fig. 1 - Level scheme of the isobaric A = 33, T = 3/2 quartet with Coulomb interactions turned off. Only levels pertinent to the isobaric configuration are shown.

2. - EXPERIMENTAL DETAILS

The experimental set-up, used for the measurements, has already been described (3). We shall only remember that the proton beam provided by the 5.5 MeV Van de Graaf C.N. of the Laboratori Nazionali di Legnaro, had an energetic spread of about 0.5 keV; the targets were formed by evaporating CdS or Sb_2S_3 on carbon backings of 20 $\mu g/cm^2$. The total, beam plus target, energy spread could be estimated of the order of 1.2 ÷ 1.5 keV at an incident proton energy of 4.8 MeV.

The detectors were placed in a 25 cm diameter scattering chamber, and were situated at the angles of 92°, 123°, 165° or 172° in respect of the direction of the incident beam. They were surface barrier silicon detectors, with a depletion depth of 700 or 1000 μm. Their typical energetic resolution was about 40 keV at 4.8 MeV.

3. - EXPERIMENTAL RESULTS

Different measurements were performed during the search.

I. The excitation curve for the elastic scattering of protons from ^{32}S on a CdS target, in the energetic interval 4000 ÷ 5400 keV, with 5 keV steps, at an angle θ_L = 172°, was detected and is reported in Fig. 2. The points on the curves were obtained as a ratio of the proton yield from sulphur to that from cadmium which, in this energy region, can be regarded as completely devoided of resonances.

The aim of this measurement was to extend the knowledge of the ^{33}Cl excitation function beyond the energy value reached by Olness et al. (9) and to compare this result with the preliminary data obtained by R. Van Bree at Rutgers University (10). The accurate examination of the excitation curve allows one to single out the two anomalies, located at an energy of the incoming proton of E_p = 4855 keV and E_p = 5285 keV, respectively, whose angular momentum can be l = 2.

II. Having obtained a general view of the behaviour of the excitation function, a repeated measurement was performed over the incident proton energies between 4750 and 5000 keV, in 2-keV steps, that is around the region where the expected second T = 3/2 isobaric resonance had to be found. The target was always the same and the selected laboratory angles were θ_L = 92° and 172°. In this connection and within the same limits, the excitation function of the inelastic proton scattering to the first ^{32}S excited state ($J^\pi = 2^+$ at 2240 keV) was also determined.

III. The previous measurements revealed a slight erratic behaviour of the sulphur target, in spite of the low beam intensity adopted, so

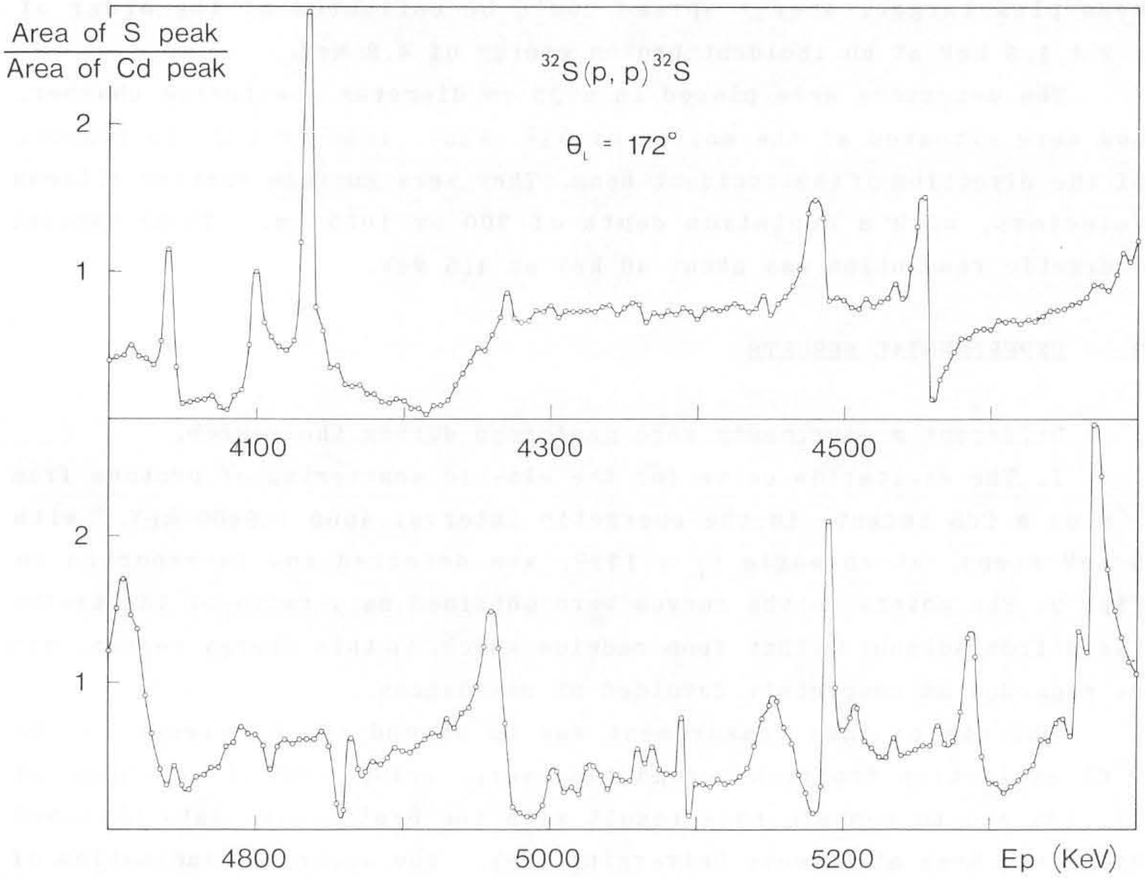

Fig. 2 - Excitation curve for the elastic p + ^{32}S scattering in the energy interval 4000 ÷ 5400 keV, lab. syst., at an angle θ_L = 172°, with ΔE = 5 keV.

that a new measurement, with a Sb_2S_3 target, was performed. The corresponding excitation function, determined in the energy interval 4650 ÷ 5000 keV, in 2-keV steps and at the laboratory angles $\theta_L = 95°$, 123°, 165° is shown in Fig. 3.

IV. A subsequent investigation was performed in the region where the third isobaric analogue resonance was expected. A CdS target was used, and the energetic interval 5200 ÷ 5400 keV, in 2-keV steps, was examined at the lab. angles $\theta_L = 92°$ and 172°. The corresponding excitation curve is shown in Fig. 5.

The errors reported in Figs. 3, 4 and 5 include, besides the statistical error which generally is low, the error due to the measurement reproducibility, which is derived both by repeating many times the same measurement with the same target, and by comparing the data obtained with different targets. A systematic error depending on the normalization of the data in mb/sr is also inserted. In fact the targets used in the measurements show some inhomogeneity in the sulphur distribution, and as a consequence the proton yield presents some fluctuations along the survey of the excitation curve. In order to overcome this difficulty a normalization of the proton yield from sulphur to that from the component of higher Z in the target, was performed. Regarding the data reported in Figs. 3 and 4 it should be noticed that the yields from sulphur and from antimony were simultaneously measured at different angles and normalized to the Sb Coulomb cross-section at 90°. The same thing was done in preparing Fig. 5 by comparing the yield from S with that from Cd. The normalization error, introduced in this way, operates a shift in the measured excitation functions, which is of the order of ~5% at 4650 keV, rises to ~12% in the energy region of ~5000 keV and can reach the value of ~25% in the interval between 5200 and 5400 keV. This indicates the convenience of adopting as target materials sulphides with metals of higher Z.

3. - ANALYSIS AND DISCUSSION

The data analysis has been carried out in much the same way as that used for the treatment of the first forbidden analogue resonance, that is by means of an ANSPEC computing program [11,12]. This program calculates the excitation functions for spin-1/2 particles elastically scattered from spin-0 nuclei, when a maximum number of five different spin and parity resonances are present.

The background scattering is described by a spherical optical model potential:

$$V(r) = - (V + iW)\ f(r) - iW'g(r) - V_s h(r)\bar{\sigma}.\bar{l} + V_c(r)$$

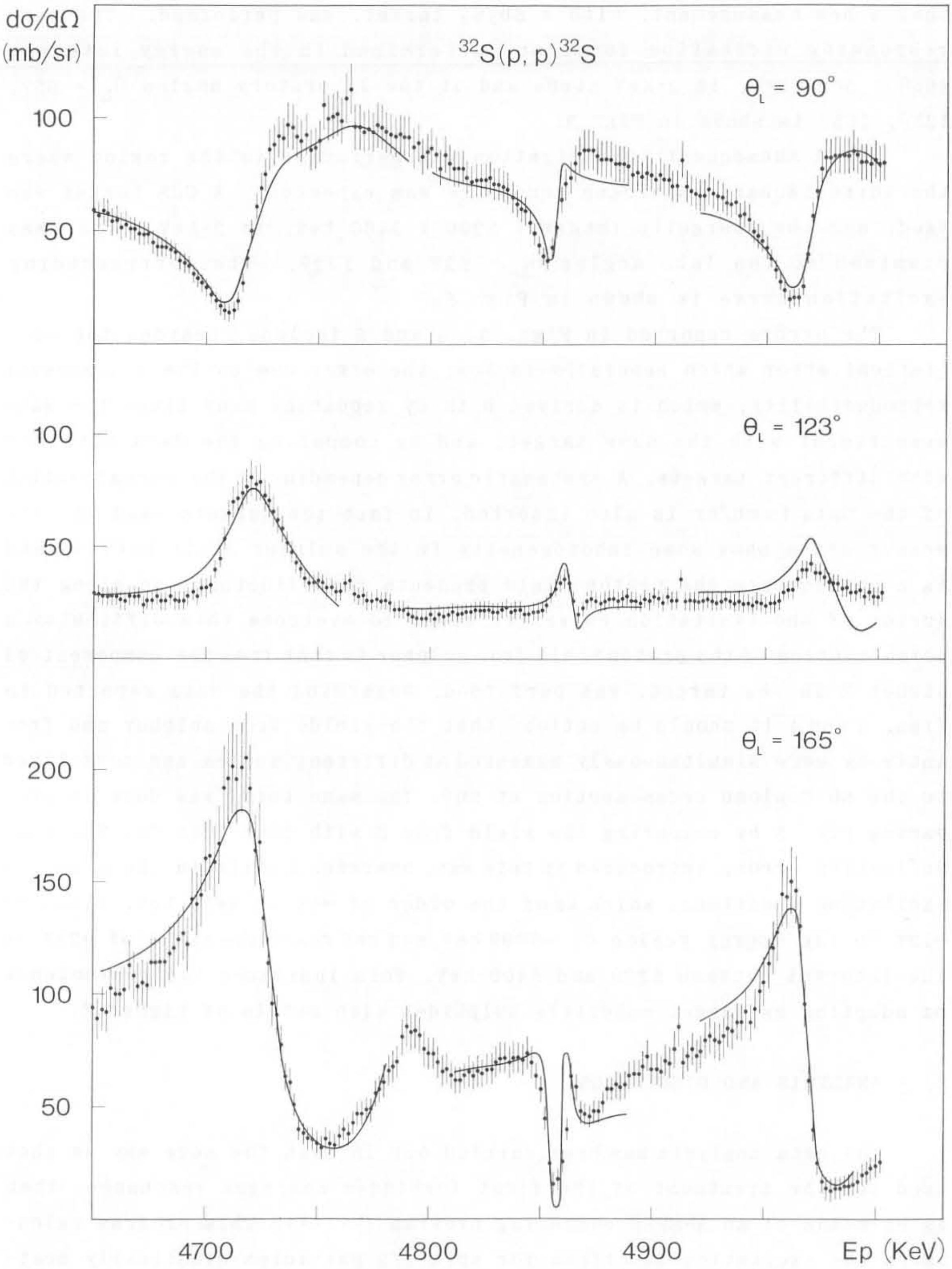

Fig. 3 - Excitation curves for the elastic scattering p + ^{32}S in the energy interval 4650 ÷ 5000 keV, with ΔE = 2 keV, taken at the lab. angles 90°, 123°, 165°. The full-line represents the calculation with an ANSPEC program.

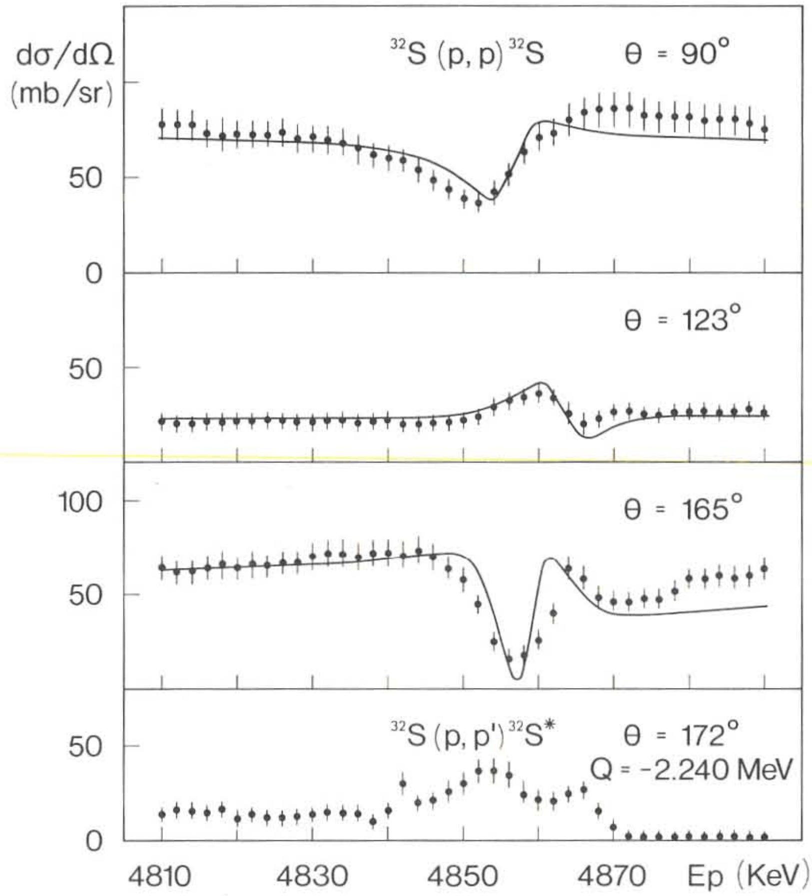

Fig. 4 - Picture of the second T = 3/2 resonance in ^{33}Cl, as revealed by the excitation curves relevant to the three lab. angles: 90°, 123°, 165° (points: experiment; full-line: calculation). The bottom yield is the inelastic scattering (p,p') relevant to the first excited state in ^{32}S, taken at θ_L = 172°.

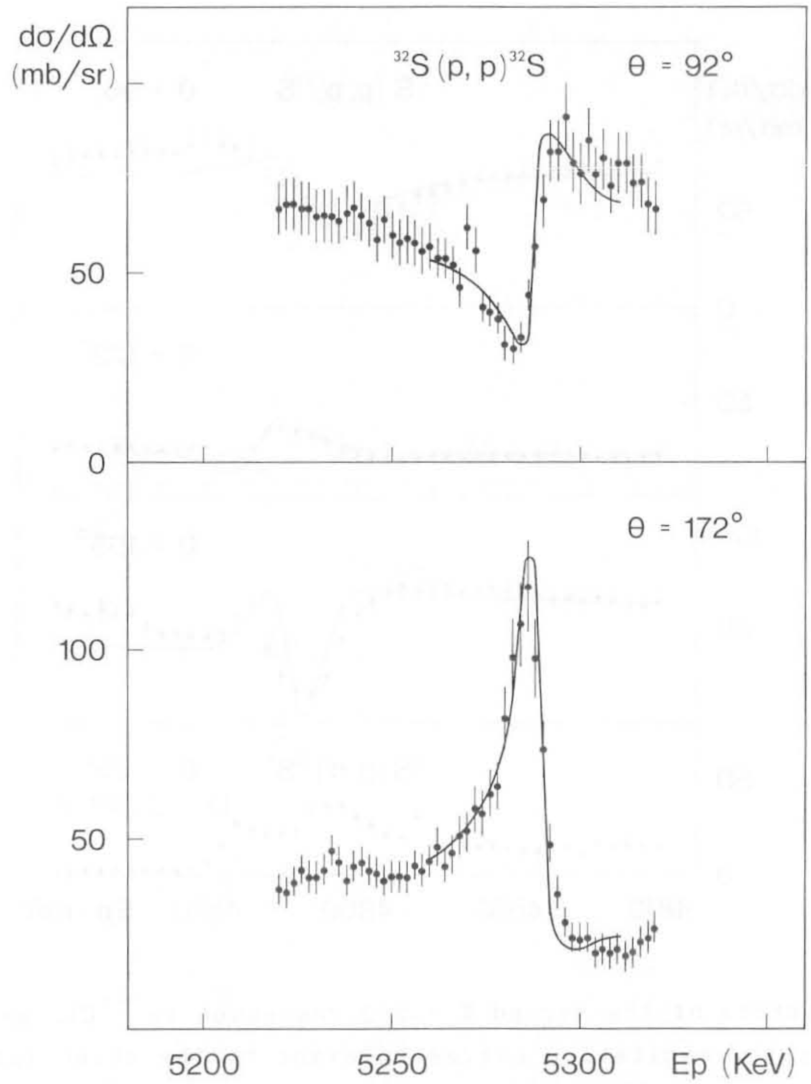

Fig. 5 - Picture of the third T = 3/2 presumed resonance in ^{33}Cl (points: experiment; full-line: calculation).

with

$$f(r) = [1 + \exp(\frac{r-R}{a})]^{-1}$$

$$g(r) = 4 \exp(\frac{r-R}{a'}) \; [1 + \exp(\frac{r-R}{a'})]^{-2}$$

$$h(r) = -\frac{2}{r} \frac{df(r)}{dr}$$

$$V_c(r) = \frac{ZpZre^2}{2R} [3-(\frac{r}{R})^2] \qquad r \leqslant R$$

$$R = r_o A^{1/3}$$

$$= \frac{ZpZre^2}{r} \qquad r > R$$

where Z_p and Z_r are the charge numbers of the incident particle and of the target respectively, and A is the atomic number of the target. The cross-section is given by the expression

$$\sigma_e(\theta) = |a(\theta)|^2 + |b(\theta)|^2$$

with

$$a(\theta) = \frac{-\eta \exp[-i\eta \ln(\sin^2\frac{\theta}{2})]}{2K \sin^2\frac{\theta}{2}} + \frac{1}{K} \sum_{j=1+\frac{1}{2}} 1 \; (j+\tfrac{1}{2}) \alpha^1_{j-1} \exp(2i\omega_1) P_1 (\cos\theta)$$

$$b(\theta) = \frac{1}{K} \sum_{j=1+\frac{1}{2}} 1 \; (-1)^{j-1-\frac{1}{2}} \alpha^1_{j-1} \exp(2i\omega_1) P^1_1 (\cos\theta)$$

where ω_1 are the Coulomb phase shifts and the α^1_{j-1} are the scattering collision amplitudes, including the resonant terms. They have the following form:

$$\alpha^1_{j-1} = \alpha^{o1}_{j-1} \left[1+i \exp(2i\Phi^R_{1j}) \frac{\Gamma_{\lambda 1j}}{E_R-E-\frac{i}{2}\Gamma_\lambda}\right] + \frac{1}{2} \exp(2i\Phi^R_{1j}) \frac{\Gamma_{\lambda 1j}}{E_R-E-\frac{i}{2}\Gamma_\lambda}$$

where the α^{o1}_{j-1} are the optical scattering amplitudes, given by:

$$\alpha^{o1}_{j-1} = \frac{1}{2i} [\exp(2i\delta_{1j})-1]$$

and δ_{lj} is the optical phase shift.

The main problem in the analysis consists in the finding of a set of optical parameters which properly describe the non resonant scattering. This set cannot be usually extracted in a simple way from the systematic examination of the optical model parameters, but has to be determined for every nucleus and when the nucleus is fixed for every energetic interval.

The method suggested by Thompson and Adams (12) is to best fit the optical model parameters to an angular distribution obtained in an energetic zone which is not too far from the energetic range influenced by the resonance (that is an interval about 10 Γ wide) and to use the obtained parameters in fitting the resonant structures. This method has given good results (13) but it is not applicable to our case. In fact, by considering Fig. 3 one derives that in an energetic interval of 350 keV three resonances, whose width is of the order $\Gamma = 20 \div 40$ keV, at least are present; the condition for reaching an off-resonance zone is clearly not feasible.

Another influence on the definition of the parameter values could derive from the fact that a spherical optical model may be inadequate to describe even-even deformed nuclei, whose first 2^+ excited level is of collective character.

In the case under examination this could lead to an under-estimation of the coupling between the ground state and the first excited state, both because the ^{32}S nucleus has a large deformation parameter ($\beta \simeq 0.35$ (14,15)) and because it is likely that the sufficiently high energy of the incident particle may cause an appreciable contribution to the direct excitation to the 2^+ level at 2240 keV (16). It is clear for all these reasons that a particular choice of the optical parameters may introduce some ambiguities in the evaluation of the resonance parameters, particularly in what concerns the proton width.

The one-level formula was used in the present case and adapted to each resonance in the examined zone and the parameters were extracted by a trial and error method by using the computing program prepared by Thompson and Adams (12). The obtained values for the parameters are reported in Table I; in Table II instead the data relevant to the examined resonances are given.

The examination of the curve in Fig. 3 clearly shows the limitation imposed on the calculation by the necessity of considering resonances with different spin and parity. The analysis has been carried out by examining three distinct zones. In the first zone the presence of the resonance no. 1 with $J^{\pi} = 3/2^+$, and that of the resonance no. 2 with

$J^{\pi} = 3/2^-$, has been taken into account; the same has been done for the second zone, where the resonance no. 2, with $J^{\pi} = 3/2^-$, the resonance no. 3, with $J^{\pi} = 3/2^+$, and the resonance no. 4, with $J^{\pi} = 5/2^-$ were considered. In the third zone, the resonance no. 4, the resonance no. 5, with $J^{\pi} = 3/2^+$, were handled together, by adding, however, the contribution from the resonance no. 6, whose parameters ($l = 1$, $J^{\pi} = (3/2^-)$) were approximately evaluated from Fig. 2, in that it is situated out of the detailed zone of measurement. Let us examine now, angle by angle, the effect of the subdivision in the region of the second analogue state.

At 90° the three zones connect generally pretty well.

At 123° there is a trend in the calculation to lower too much the values of the cross-section around E_P = 4775 keV. This is probably due to the fact that, having analyzed the large $3/2^+$ resonance at 4720 keV, one cannot rely on the $3/2^+$ resonance at 4855 keV. The calculation made by taking into consideration the resonances nos. 2, 3, and 4 clearly gives a better agreement with the experimental curve.

At 165°, in the same zone, the excitation function calculated as in the first case, tends to overestimate the experimental data, and also in the energetic interval between 4980 and 4930 keV the function cannot be calculated because the simultaneous effect of the resonances no. 3 at 4855 keV and no. 5 at 4965 keV, both with $J^{\pi} = 3/2^+$, ought to be considered.

TABLE 1

Optical model parameters used in the analysis.

	2^{nd} analogue resonance		3^{rd} analogue resonance	
V =	58.92	MeV	55	MeV
W =	0	"	0	"
W' =	1.70	"	10	"
V_S =	6.20	"	5.5	"
r =	1.26	fm	1.25	fm
a =	0.600	"	0.650	"
a' =	0.700	"	0.650	"

TABLE 2

Resonances examined from the study of the excitation function relevant to the reaction $^{32}S(p,p)\ ^{32}S$

n.	E_R(CM)(kev)	E_p(lab)(keV)	E_R in ^{33}Cl(keV)	l	J	Γ(keV)	Γ_p(keV)	Γ(keV)	Γ_p(keV)
						adopted value in the fit		acceptable values	
1	4577 ± 5	4720 ± 5	6867 ± 5	2	$3/2^+$	30	28	28 ÷ 32	26 ÷ 30
2	4630 ± 5	4774 ± 5	6920 ± 5	1	$3/2^-$	40	30	35 ÷ 45	25 ÷ 35
3	4708 ± 3	4855 ± 3	6998 ± 3	2	$3/2^+$	7	4	6 ÷ 8	3.5 ÷ 4.5
4	4713 ± 2	4860 ± 2	7003 ± 2	3	$5/2^-$	7	2.2	6 ÷ 8	1.5 ÷ 2.5
5	4815 ± 5	4965 ± 5	7105 ± 5	2	$3/2^+$	18	15	17 ÷ 19	15 ÷ 17
6	4840 ± 15	4991 ± 15	7130 ± 15	1	$(3/2)^-$	30	20		
7	5126 ± 5	5285 ± 5	7415 ± 5	2	$5/2^+$	7	5	6 ÷ 8	4 ÷ 6

The analysis shows that the structure observed at 4855 keV has $J^{\pi} = 3/2^{+}$. In this way, location spin and parity lead one to believe that this structure could represent the searched resonance, that is the second T = 3/2 excited state in ^{33}Cl. The analysis of this resonance and in general of the whole contiguous zone is made more difficult by the presence of the large resonance no. 2 with angular momentum $l = 1$, and of the resonance no. 4, with $l = 3$, which is located closer to the found structure, and which considerably can influence its form.

An additional reason which strengthens this opinion is derived by the presence of the $3/2^{+}$ resonances at 4720 and 4965 keV, whose total and partial proton widths are higher than those of the proposed analogue resonance. Their spin, parity and intensity put them in the condition to be the T < levels that "pump" the forbidden analogue resonance as is discussed in reference (1). One can object that the total width $\Gamma = 6 \div 8$ keV and the proton width $\Gamma_p = 3.5 \div 4.5$ keV are rather unusual in a forbidden analogue resonance; nevertheless similar values are already found, as in the case of the forbidden analogue resonance in ^{41}Sc with $\Gamma = \Gamma_p = 2.6$ keV at $E_p = 4899$ keV (17), and in the case of the second T = 3/2 state in ^{29}P, which is the analogue of the first excited level of ^{29}Al ($\Gamma = 7 \pm 3$ keV) (18).

In a similar way a tentative analysis has been carried out in the energetic interval 5200 ÷ 5400 keV, where the third analogue resonance is to be expected, and the result is given in Fig. 5. The optical model parameters used are reported in Table 1. As the figure shows, the calculated curves fit pretty well to the experimental points, so that it is not too unreasonable to consider this structure as the third analogue resonance in ^{33}Cl, with T = 3/2. The examination of the data indicate that its energy location is $E_P = 5285 \pm 5$ keV, its angular momentum and parity are $J^{\pi} = 5/2^{+}$, the total width is $\Gamma = 7$ keV and the proton width is $\Gamma_p = 5$ keV.

This indication however has yet to be confirmed by further experimental work, which is now in progress.

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