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THE REACTION ^{33}S(p, p′γ)^{33}S

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Abstract: In the energy range E_p = 1.2-3.2 MeV forty-four resonances were found in inelastic proton scattering from ^{33}S. The energies, widths and relative strengths are reported. No indication was found at these resonances for the existence of a 1.4 MeV level of ^{33}S, suggested by shell-model calculations.

The 1.96 MeV level of ^{33}S predominantly (> 97%) decays to the ground state; its spin is $\geq \frac{5}{2}$.

1. Introduction

The excitation energies of levels of A = 28-40 nuclei, resulting from a recent shell-model calculation [1]) are generally in fair agreement with the experimental values. One notable exception is the $J^\pi = \frac{5}{2}^+$ second excited state of ^{33}S and ^{33}Cl. The calculation yields E_x = 1.38 MeV, whereas experimentally the second excited states in ^{33}S and ^{33}Cl are found at E_x = 1.965 and 2.1 MeV, respectively [2]). This discrepancy leads to the suggestion that a 1.4 MeV level in the A = 33 nuclei might have been missed in earlier experiments. Confining the attention to ^{33}S, the level structure of which is better known than that of ^{33}Cl, this suggestion is strengthened by the fact that the same calculations indicate that in the ^{32}S(d, p)^{33}S reaction (the main source of information concerning ^{33}S levels) the cross section for the proton group to this calculated 1.4 MeV level in ^{33}S should be relatively small [1]). Other reactions leading to ^{33}S levels are not conclusive as to the existence or non-existence of a 1.4 MeV level. So, for instance, in the ^{32}S(n, γ)^{33}S reaction weak γ rays were observed [3,4]) of 7.19±0.03 and 1.52±0.05 MeV, which could possibly form a cascade through a 1.5 MeV level.

For these reasons the ^{33}S(p, p′γ)^{33}S reaction was investigated, with the attention focussed on the possibility of inelastic proton scattering to a ^{33}S level at $E_x \approx$ 1.4 MeV. Though the search for this level had a negative result, some information was obtained on the ^{33}S* = 1.96 MeV level and on ^{34}Cl resonance levels. These results are reported in this note.

2. Experimental

The proton beam of the Utrecht 3 MV Van de Graaff accelerator was magnetically deflected over 90° before hitting the target. Targets were prepared from CdS enriched in ^{33}S(22% ^{33}S; 74% ^{32}S; 4% ^{34}S), obtained from Oak Ridge National Laboratory, U.S.A., by evaporation onto 0.3 mm tantalum backing. The energy dissipation in the target was limited to 3 W.

The γ rays were detected in a cylindrical NaI crystal, 10 cm in diameter and 10 cm long, surrounded by 10 cm of lead. It was placed at 2 cm from the target and its front was shielded with 0.5 cm of lead. During the angular distribution measurements the distance between the target and the crystal front was 10 cm.

3. Results

Yield curves were measured with the following four discriminator settings

(a) E_γ = 0.81-0.87 MeV, to detect the 0.84 MeV γ ray de-exciting the ^{33}S first excited state. About forty resonances were found in the energy range E_p = 1.2-3.2 MeV; see fig. 1 (circles);

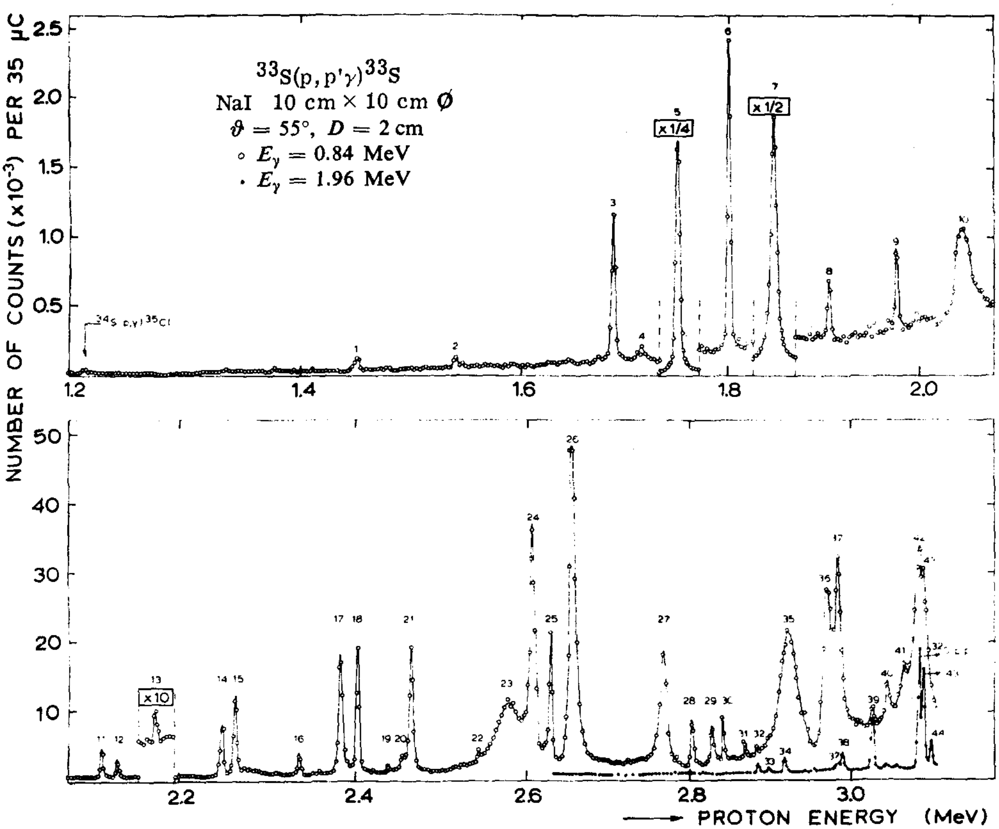

Fig. 1. Gamma-ray yield from inelastic proton scattering at ^{33}S. The circles and dots represent the yield of 0.84 and 1.96 MeV γ rays de-exciting the ^{33}S first and second excited states, respectively.

(b) E_γ = 1.3-1.6 MeV, corresponding to a possible ground-state decay of the calculated ≈ 1.4 MeV level. This curve exhibits no resonances, which cannot be attributed to Compton tails of resonating γ rays of higher energy.

(c) E_γ = 1.89-2.03 MeV, to detect the 1.96 MeV γ ray de-exciting the ^{33}S second excited state. The result for E_p = 2.5-3.2 MeV is given in fig. 1 (dots). Some of the eight observed resonances coincide with resonances in the 0.84 MeV yield curve.

(d) E_γ = 2.24-2.38 MeV, to detect a possible ground-state decay of the third ^{33}S level at E_x = 2.31 MeV. The curve shows four resonances, but these were proven to be due to 2.24 MeV γ rays from the ^{32}S(p, p')^{32}S(2.24) reaction, which is known [5]) to show resonances at E_p = 2810, 2902, 2917 and 3094 keV (all ±2 keV) in the proton energy region of the present work. The relative intensities agree with those given in ref [5]).

(e) E_γ = 2.5-6.5 MeV, to detect capture γ rays. This curve was measured up to E_p = 1.9 MeV; at higher energies the background increases rapidly. Besides all but a few of the weakest ^{34}S(p, γ)^{35}Cl resonances [6]) the curve exhibits about ten resonances. Though the nature of these resonances was not investigated, it can be stated that the strength of any ^{33}S(p, γ)^{34}Cl resonance in the E_p = 1.2-1.9 MeV region is at most of the same order of magnitude as that of known [7]) resonances in this reaction at lower proton energy.

The inelastic proton scattering resonances thus found, are listed in table 1. The numbers given in column 1 correspond to those of fig. 1. The resonance energies listed in column 2 were calculated using the four above-mentioned ^{32}S(p, p'γ)^{32}S resonances for calibration. The third column lists the corresponding ^{34}Cl excitation energies, calculated using a proton binding energy of E_b = 5119 keV [2]).

At most resonances the width of the peak is instrumental, mostly due to target thickness. For resonances where the measured width Γ_m exceeds the instrumental width Γ_i(≈ 4 keV), an approximate measure of the natural width Γ was found using the relation $\Gamma = \sqrt{\Gamma_m^2 - \Gamma_i^2}$; these values of Γ are listed in column 4. For resonances that have no entry in this column, the width is less than 4 keV.

The relative strengths of the resonances were calculated from the areas of the peaks in the resonance curves. The relative strengths were converted to absolute strengths by measuring the thick-target yield at the E_p = 1685 keV resonance; the result was $(2J+1)\gamma$ = 2.5 eV. The strength of this resonance was also calculated by comparing its yield with that of the E_p = 1214 keV † ^{34}S(p, γ)^{35}Cl resonance, the strength of which was measured recently [8]). This method yields $(2J+1)\gamma$ = 2.1 eV. The strengths thus found, listed in columns 5 and 6 of table 1, are considered to be correct within a factor of two; the relative strengths within a factor of 1.5.

The analysis of a single spectrum measured at the E_p = 3029 keV resonance indicates that the ^{33}S* = 1.96 MeV level decays mainly (> 97%) to the ground state. The 2.31 MeV level is probably not excited at any of the resonances observed in this

† The present experiment yields a resonant energy E_p = 1211.5±1.5 keV.

TABLE 1

Resonances in the reaction $^{33}S(p, p'\gamma)^{33}S$

Resonance number	E_p (keV)	$^{34}Cl^*$ (MeV)	Γ (keV)	$(2J+1)\Gamma_{p_0}\Gamma_{p_1}/\Gamma$ (eV)	$(2J+1)\Gamma_{p_0}\Gamma_{p_2}/\Gamma$ (eV)
1	1445±2	6.522		0.19	
2	1535±2	6.609		0.15	
3	1685±2	6.754		2.3	
4	1713±3	6.782	6±2	0.6	
5	1748±2	6.816		17	
6	1799±2	6.865		5	
7	1845±2	6.910		21	
8	1902±2	6.965	5±2	1.0	
9	1973±2	7.034		1.4	
10	2044±3	7.103	18±3	11	
11	2114±2	7.171		10	
12	2131±2	7.187		7	
13	2172±2	7.227		1.3	
14	2245±2	7.298		23	
15	2260±2	7.313		33	
16	2334±2	7.384		9	
17	2379±2	7.428		60	
18	2399±2	7.447		55	
19	2435±3	7.483		3.0	
20	2450±4	7.497		6	
21	2460±3	7.507		60	
22	2541±3	7.585		3.1	
23	2578±4	7.621	39±5	460	
24	2604±3	7.646	6±2	280	
25	2626±3	7.668		60	
26	2652±3	7.693	7±2	490	
27	2763±4	7.801	8±2	210	
28	2799±3	7.836		24	
29	2824±3	7.860		23	
30	2838±3	7.874		24	
31	2865±3	7.900		9	
32	2883±3	7.917		3.6	6
33	2896±3	7.930		<3.6	3.5
34	2915±3	7.948			10
35	2921±4	7.954	24±4	600	
36	2969±4	8.001	14±3	450	
37	2984±4	8.015	6±2	270	18
38	2988±3	8.019			10
39	3029±3	8.059	4±2	<25	100
40	3048±4	8.077		16	
41	3070±4	8.099		7	
42	3093±4	8.121	18±3	700	
43	3100±3	8.128			50
44	3109±3	8.137			14

work. It was already noted above that a search for a possible 2.31 MeV γ ray was unsuccessful. The possibility of de-excitation through an E_γ = 1.53-0.84 MeV cascade was also considered, but at none of the resonances exciting the 1.96 MeV level any sign could be found for a 1.53 MeV γ ray in the measured γ-ray spectra.

Angular distributions of the 1.96 MeV γ rays at the E_p = 2883 and 3029 keV resonances, were analysed in terms of Legendre polynomials P_2 and P_4:

$$W(\vartheta) \propto 1+A_2P_2(\cos\vartheta)+A_4P_4(\cos\vartheta).$$

The A_2 coefficients are -0.42 ± 0.04 and -0.49 ± 0.01, respectively. These values exclude $J = \frac{1}{2}$ for the 1.96 MeV level. The A_4 coefficients, -0.03 ± 0.06 and -0.04 ± 0.03, respectively, could indicate $J_{1.96} \geqq \frac{5}{2}$, but since the deviation from zero is so small it can only be concluded with certainty that $J_{1.96} \geqq \frac{3}{2}$.

4. Discussion

The lowest observed resonance for inelastic scattering to $^{33}S^*$ = 0.84 MeV occurs at E_p = 1448 keV; for scattering to $^{33}S^*$ = 1.96 MeV at E_p = 2888 keV. Thus, if a ^{33}S level with an excitation energy of about 1.4 MeV exists, inelastic scattering to this level might be expected at proton energies of 2 MeV and upward. Though the resonance curve for E_γ = 1.3-1.6 MeV γ rays did not give any positive indication as to the existence of the calculated level at $E_x \approx$ 1.4 MeV, γ-ray spectra were measured at all resonances with E_p > 2 MeV listed in table 1. However, no indication was found at these resonances for either a direct ground-state transition from a 1.4 MeV level or a cascade through the 0.84 MeV level.

These results favour the conclusion that the suggested level at about 1.4 MeV does not exist. Possibly it should be identified with the 1.96 MeV level. For some unidentified reason the calculations then yield an unusually large error in this particular case.

A definite conclusion that a 1.4 MeV $\frac{5}{2}^+$ level does not exist, however, cannot be drawn from this work. A possible 0.51-0.84 MeV cascade, for instance, would easily escape detection. But such a cascade de-excitation seems improbable, because a $\frac{5}{2}^+$ 1.4 MeV state would rather de-excite with an M1 transition to the $\frac{3}{2}^+$ ground state than with an E2 transition to the $\frac{1}{2}^+$ first excited state.

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