SEARCHING THE ANALOGUE $2p_{3/2}$-RESONANCE IN THE $^{36}S(p,\gamma)^{37}Cl$ REACTION

A.N. Vodin, I.V. Ushakov, A.S. Kachan, L.P. Korda, V.M. Mischenko, B.A. Nemashkalo

National Scientific Centre "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
e-mail: vodin@kipt.kharkov.ua

Searching the analogue $2p_{3/2}$-resonance in ^{37}Cl, which is an isobaric analogue of the parent level with $E^* = 0.646$ MeV ($J^\pi = 3/2^-$) of ^{37}S was carried out. The excitation function for the $^{36}S(p,\gamma)^{37}Cl$ reaction was measured in the energy region $E_p = 2487 - 2680$ keV. Resonance strengths were determined for 44 resonances. The decay schemes and branching ratios of four resonances were investigated at $E_p = 2539$, 2599, 2659 and 2676 keV. Spins and parities of these resonances ($3/2^+$, $3/2^+$, $3/2^+$ and $5/2^+$, correspondingly) were established from angular distributions of γ-rays and measured intensities of γ-transitions.

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1. INTRODUCTION

The $^{36}S(p,\gamma)^{37}Cl$ reaction has been the subject of frequent investigation, almost exclusively at proton energies below $E_p = 2$ MeV. The exception is the work [1], performed with a NaJ-detector in the energy region $E_p = 2300 - 3200$ keV. The resonances up to $E_p = 2$ MeV have been investigated in detail in [2]. Decay schemes and lifetimes of a number of resonances and bound states of ^{37}Cl have been measured in those experiments. A substantial study of the analogue $1f_{7/2}$-resonance at $E_p = 1887$ keV have been made in [3,4].

The aim of the present work was to search the analogue $2p_{3/2}$-resonance in ^{37}Cl, which is an isobaric analog of the first excited level of the parent nucleus ^{37}S with $E^* = 0.646$ MeV ($J^\pi = 3/2^-$). In this connection a series of researches was carried out. The excitation function of the $^{36}S(p,\gamma)^{37}Cl$ reaction was studied in vicinity of the analogue $2p_{3/2}$-resonance ($E_p \approx 2.6$ MeV), γ-decay schemes of the most intensive resonances at $E_p = 2539$, 2599, 2659 and 2676 keV were defined and the angular distributions of the γ-rays were measured.

2. EXPERIMENTAL PROCEDURE

The experiments were performed with the proton beam from the 3 MeV Van de Graaf accelerator at the Nuclear Spectroscopy Laboratory of NSC "KhIPT". A target of approximately 2 keV thickness at $E_p = 2$ MeV consisting of Ag_2S (81.1 % ^{36}S) was used. A beam current of 20 μA was maintained during the experiments.

The γ-radiation was detected with a 70 cm^3 Ge(Li)-detector (full width at half maximum was equal to 3.1 keV at 1.332 MeV) coupled to a 4096 channel analyzer. The detector was at an angle $\theta_{lab} = 55°$ in relation to a proton beam. The Ge(Li)-detector efficiency was determined with calibrated standard sources and using relative γ-ray intensities in the $^{27}Al(p,\gamma)^{28}Si$ reaction [5].

The angular distributions of γ-rays, arising from the decay of resonance states in ^{37}Cl, were measured at angles 0°, 30°, 45°, 60° and 90° concerning a proton beam direction. As a radiation monitor a current integrator and additionally a spectrometer on the basis of a ∅ 150 × 100 mm NaJ(Tl) crystal were used. This detector was used to obtain a yield curve of the $^{36}S(p,\gamma)^{37}Cl$ reaction as a function of proton energy.

3. RESULTS OF MEASUREMENTS

3.1. EXCITATION FUNCTION

In the present investigations the excitation function of the $^{36}S(p,\gamma)^{37}Cl$ reaction was measured in the proton energy region $E_p = 2487 - 2680$ keV. Measurements were carried out with $\Delta E_p = 0.8$ keV. The yield curve of the $^{36}S(p,\gamma)^{37}Cl$ reaction registered by the NaJ(Tl)-detector at an angle $\theta_{lab} = 55°$ with respect to a proton beam direction is represented in fig. 1. Measurements were done with the $E_\gamma > 6.13$ MeV discrimination threshold for energy of γ-rays.

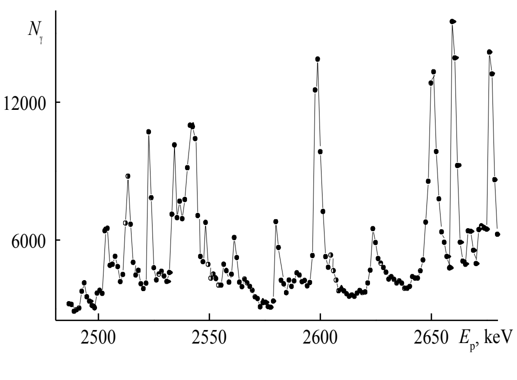

Fig.1. *The excitation function of the $^{36}S(p,\gamma)^{37}Cl$ reaction in the energy region $E_p = 2480 - 2680$ keV, $\theta_{lab} = 55°$*

The experimentally observable widths of resonances indicated in fig.1 are equal approximately to 2.8 keV and are stipulated by a final thickness of a target and energy scatter in a proton beam.

The results obtained at the analysis of the excitation function of the $^{36}S(p,\gamma)^{37}Cl$ reaction are represented in Table 1, in which the data from [1] are also introduced.

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***Table 1**. Strengths of resonances in the $^{36}S(p,\gamma)^{37}Cl$ reaction*

E_p, keV	E^*, MeV	S, eV	$E_p^{a)}$, keV	E_p, keV	E^*, MeV	S, eV	$E_p^{a)}$, keV	E_p, keV	E^*, MeV	S, eV	$E_p^{a)}$, keV
2489.0	10.8081	0.03		2547.1	10.8646	2.2		2613.0	10.9287	0.09	
2491.3	10.8103	0.05		2551.8	10.8692	0.18		2617.7	10.9333	0.17	
2494.8	10.8137	0.01	2493	2555.3	10.8726	0.52		2622.5	10.9380	1.9	
2498.3	10.8171	0.57		2561.2	10.8783	1.3		2627.2	10.9425	0.15	
2502.9	10.8216	2.2	2502	2565.8	10.8828	0.32		2630.8	10.9460	0.04	
2508.7	10.8272	1.0	2510	2569.4	10.8863	0.09		2634.3	10.9494	0.21	
2512.2	10.8306	3.2		2574.1	10.8909	0.16	2572	2639.1	10.9541	0.32	
2514.5	10.8329	0.83		2577.6	10.8943	1.8		2642.7	10.9576	0.16	
2518.0	10.8363	0.07	2520	2579.9	10.8965	0.10		2646.8	10.9616	8.3	
2522.6	10.8408	0.02		2583.5	10.9000	0.63		2651.0	10.9657	0.43	
2525.0	10.8431	6.7		2588.2	10.9046	0.28		2658.8	10.9733	7.4	2657
2529.6	10.8476	2.3		2592.9	10.9092	0.07	2593	2662.9	10.9773	1.2	
2531.9	10.8498	4.5		2598.8	10.9149	9.1		2667.7	10.9819	1.1	
2538.9	10.8566	4.0	2541	2605.3	10.9212	1.3		2676.1	10.9901	6.0	
2543.6	10.8612	5.0		2608.3	10.9241	0.11					

***Note:** the values E_p are indicated with an error $\pm$ 0.8 keV, $^{a)}$ - data from [1]*

3.2. RESONANCE DECAY SCHEMES

Based on balance of energy values and intensities of observed γ-transitions the γ-decay schemes of investigated resonances were defined in view of all known data on levels of the ^{37}Cl nucleus. The branching ratios $b(\gamma)$ for resonances at E_p = 2539, 2599, 2659 and 2676 keV are represented in Table 2.

3.3. ANGULAR DISTRIBUTIONS OF γ-RAYS

The data on parameters of mixing ratios δ are necessary for account of probabilities of direct γ-transitions. In this connection the angular distributions of γ-rays were measured and on the basis of their analysis the δ values were determined. The function of angular correlation was searched as expansion on even polynomials of Legendre:

$$W(\theta) = 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)\,, \qquad (1)$$

where the coefficients a_2 and a_4 depend on an angular moment of initial and final states and a parameter δ. The a_2 and a_4 coefficients, found using the method of least squares, were compared to their theoretical values for various hypotheses about a spin J of a resonance level and appropriate δ value with the help of criterion χ^2.

The combination of J and δ was rejected, if the obtained value $\chi^2 \equiv \chi^2_{min}$ exceeded probable 0.1%-limit. The defined thus a_2 and a_4 coefficients in the function of angular distribution of γ-rays and δ values, appropriate to them, are represented in tab. 2. The corrections which take into account a final solid angle of the Ge(Li)-detector are brought into results of measurements. The indicated errors are standard deviations.

3.4. RESONANCE STRENGTHS AND γ-WIDTHS

For determination of the absolute yield of γ-rays from the $^{36}S(p,\gamma)^{37}Cl$ reaction the comparison of researched resonances with the resonance at E_p = 1887 keV was carried out. The strength for the last one was equal to [4]:

$$S = (2J+1)\frac{\Gamma_p \Gamma_\gamma}{\Gamma} = 31 \pm 3 \text{ eV}\,, \qquad (2)$$

where J - a spin of a resonance state, Γ_p, Γ_γ and Γ - proton, radiation and total widths of a resonance. The evaluation of values of a radiation resonance width was carried out in assumption that $\Gamma_p >> \Gamma_\gamma$.

The experimental values of probabilities of γ-transitions between resonances and bound states of ^{37}Cl based on obtained data were determined. It allowed to determinate the parities of resonance states taking in consideration recommended upper limits (RUL's) for probabilities of electromagnetic γ-transitions in nuclei with $A < 44$ [6].

4. DISCUSSION

4.1. RESONANCE STATES

Col.3 of table 2 shows the spins and parities of the resonance and bound levels of ^{37}Cl. The RUL's used were 0.1 W.u. for $E1$, 100 W.u. for $E2$, 10 W.u. for $M1$ and 3 W.u. for $M2$-transitions [6].

The E_p = 2539 keV resonance. Results of the angular distribution measurements revealed that $J = 3/2$ gives the χ^2 value below the 0.1% confidence limit for the $r \to 0$ and $r \to 1.727$ MeV transitions. Both transitions exclude $J = 1/2$, whereas $J = 5/2$ is excluded by the $r \to 1.727$ MeV transition. The probable value $J_r^\pi = 3/2^-$ for the $r \to 0$ MeV transition can lead to the $M2$-strength of 19.2 W.u., that considerably exceeds the RUL's value. Conclusion: $J_r^\pi = 3/2^+$

The E_p = 2599 keV resonance. The $r \to 0$ and $r \to 1.727$ MeV angular distributions together allow only $J = 3/2$ for the resonance spin. The value $J_r^\pi = 3/2^-$ should be eliminated, sins in this case for the $r \to 0$ MeV transition the magnitude of $B(M2)$ = 18.6 W.u. is significant more than the RUL's value. Conclusion: $J_r^\pi = 3/2^+$.

The E_p = 2659 keV resonance. The measured angular distributions of the primary γ-transitions to the g.s., 3086 and 3707 keV levels show that the spin $J = 1/2$ can be excluded, but allow $J = 3/2$ and 5/2. Only the $r \to 1727$ keV transition limits the resonance spin to 3/2. The probable value $J_r^\pi = 3/2^-$ for the resonance at the E_p = 2659 keV resonance can lead to $B(M2)$ = 24.1 W.u. for the $r \to 1.727$ MeV transition, that considerably exceeds the RUL's value. Conclusion: $J_r^\pi = 3/2^+$.

***Table 2**. Results of the angular distributions for the dominant primary transitions*

E_p, keV	$E_i^* \to E_f^*$, MeV	$J_i^\pi \to J_f^\pi$	$b(\gamma)$, %	$a_2 \pm \Delta a_2$	$a_4 \pm \Delta a_4$	$\delta \pm \Delta\delta$
2539	10.857→ 0	$3/2^+ \to 3/2^+$	67	0.40±0.08	0.03±0.08	-1.6±0.3
		$5/2 \to 3/2^+$				-0.8±0.1
	→1.727	$3/2^+ \to 1/2^+$	33	-0.40±0.15	-0.09±0.15	0.20±0.13 or 1.2±0.4
2599	10.915→ 0	$3/2^+ \to 3/2^+$	54	0.61±0.08	-0.01±0.06	-0.8±0.6
	→1.727	$3/2^+ \to 1/2^+$	46	-0.33±0.08	0.07±0.07	0.10±0.06 or 1.4±0.4
2659	10.973→ 0	$3/2^+ \to 3/2^+$	55	-0.27±0.05	-0.06±0.05	1.3±0.1
		$5/2 \to 3/2^+$				0.2±0.05
	→1.727	$3/2^+ \to 1/2^+$	13	-0.47±0.16	0.01±0.14	1.3±0.1
	→3.086	$3/2^+ \to 5/2^+$	17	0.09±0.15	0.00±0.17	0.4±0.3 or 1.7±0.4
		$5/2 \to 5/2^+$				0.1±0.2
	→3.707	$3/2^+ \to 3/2^+$	15	0.36±0.21	-0.02±0.23	-0.19±0.02
		$5/2 \to 3/2^+$				-0.65±0.27
2676	10.990→ 0	$5/2^+ \to 3/2^+$	100	-0.42±0.02	-0.00±0.02	0.44±0.05

The E_p = 2676 keV resonance. The χ^2 value for the $r \to 0$ MeV angular distribution allows only $J = 5/2$. The spins $J = 1/2$ and 3/2 were rejected because the minimum χ^2 exceed the 0.1% confidence limit. Assuming that $J_r^\pi = 5/2^-$ for this resonance, in this case the value $B(M2)$ = 7.5 W.u., that is more than the RUL's value. Conclusion: $J_r^\pi = 5/2^+$.

4.2. SEARCHING ANALOGUE STATE

The identification of analogue states in the (p,γ) reaction requires prior knowledge of the proton width Γ_p, the Coulomb displacement energy ΔE_C, spins and parities and the spacing between strong resonances in the yield curve. Simple calculations based on the Coulomb displacement energy lead to the conclusion that the analogue of the 0.646 MeV ($J^\pi = 3/2^-$) state of the parent nucleus ^{37}S should lie at $E^* \approx 10.9$ MeV ($E_p \approx 2.6$ MeV) in ^{37}Cl.

The results, obtained in the present work, show, that among the investigated resonance levels of ^{37}Cl there is no state, which can be considered as a $2p_{3/2}$ state. Moreover, at decays of researched resonances an intensive $M1$-transition on an antianalog level (states with 4.176 MeV), expected from accounts on the shell model [7] with the surface δ-interaction was not observed.

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