RESONANCE-LIKE STRUCTURE IN $^{36}S(p\gamma)^{37}Cl$ REACTION

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The γ-decay of resonances forming resonance-like structure have been investigated in the $^{36}S(p\gamma)^{37}Cl$ reaction. The decay schemes have been established for the first time. The branching ratios and probabilities of direct γ-transitions have been determined. The assumption that these resonances belong basically to the states of the $M1$ resonance on the first excited state in ^{37}Cl has been stated. Position of the $M1$ resonance has been explained with the account of pairing forces.

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1. INTRODUCTION

In our previous works [1-3], studying the γ-decay of resonance-like structures (RLS) in the proton radiation capture reaction by ^{21}Ne, ^{25}Mg, ^{29}Si and ^{34}S, we have found out the new phenomenon connected with existence of triplet pairing between odd neutron and proton taking place on the same orbit. The position of the centre of gravity (c.g.) of the magnetic dipole resonance (MDR) in odd-odd nuclei $4N + np$ was found to be on 3 MeV below on excitation energy than in even-even nuclei $4N$. In the same works a model for explanation of this fact was offered. From the model it follows that odd nuclei of *sd*-shell can be divided into two groups depending on in what sub-shell there is an odd particle – in $d_{5/2}$-or $d_{3/2}$-state. In the first case the position of c.g. of MDR will be in the range of excitation energy about 5 …6 MeV since it is determined only by energy of spin-orbital splitting. In the second case – at excitation energy approximately 9-10 MeV since in this case (*nn*)- or (*pp*)- pairs from $d_{5/2}$-subshell will be involved in formation of MDR.

New experimental data on position, fine structure and total strength of MDR in odd nuclei are necessary for confirmation and the further development of model approximations of the nature of MDR and mechanisms of its excitation. In the present work the cycle of measurements connected with identification and determination of RLS position, observed in the $^{36}S(p\gamma)^{37}Cl$ reaction is described.

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 [4]. A beam current of 15 μA was maintained during the experiments.

The γ-radiation was detected with a 70 cm³ Ge(Li)-detector (total 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 $E_p = 2000…2400$ 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.

The experimentally observable widths of resonances indicated in Fig. 1 are equal approximately to 2.1 keV and are limited by a finite 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 detail in [6].

3.2. 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 [7]:

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

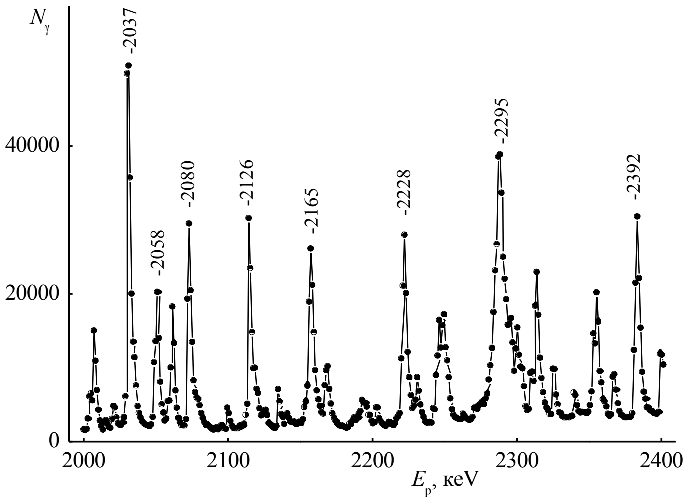

***Fig. 1**. The excitation function of the $^{36}S(p\gamma)^{37}Cl$ reaction in the energy region E_p = 2000…2400 keV*

Spectroscopic data on resonance levels and probabilities of M1 transitions in ^{37}Cl

E_p, keV	$E_i^* \to E_f^*$, MeV	$J_i^\pi \to J_f^\pi$	S, eV	b, %	$a_2 \pm \Delta a_2$	$a_4 \pm \Delta a_4$	$a_6 \pm \Delta a_6$	δ(Δδ)	$B(M1)\uparrow$, μ_N^2
2037	10.368 → 0	$3/2^+ \to 3/2^+$	40(2)	25	0.25±0.12	-0.14±0.12	-0.01±0.13	0.0(1)	0.21(4)
	→ 1.727	$\to 1/2^+$		65	-0.40±0.10	0.05±0.10	-0.11±0.09	0.26(15)	1.7(5)
2080	10.410 → 0	$3/2^+ \to 3/2^+$	20(2)	93	0.38±0.09	-0.05±0.08	0.06±0.09	-0.17(15)	0.36(1)
	→ 1.727	$\to 1/2^+$		3	-	-	-	(0)	0.04(1)
2126	10.455 → 0	$3/2^+ \to 3/2^+$	23(3)	61	0.42±0.15	0.41±0.15	0.14±0.17	-0.7(5)	0.13(4)
	→ 1.727	$\to 1/2^+$		21	-0.32±0.12	-0.11±0.12	-0.03±0.10	0.3(2)	0.21(6)
2165	10.492 → 0	$3/2^+ \to 3/2^+$	23(3)	34	0.01±0.11	-0.04±0.12	0.08±0.13	0.26(15)	0.14(4)
	→ 1.727	$\to 1/2^+$		31	-0.12±0.12	0.09±0.13	0.07±0.12	-0.28(20)	0.44(12)
2228	10.554 → 0	$3/2^+ \to 3/2^+$	22(2)	55	0.09±0.11	0.12±0.13	0.15±0.14	0.0(1)	0.22(2)
	→ 1.727	$\to 1/2^+$		28	-0.35±0.13	0.12±0.12	-0.11±0.12	0.0(1)	0.39(4)
2392	10.713 → 0	$3/2^+ \to 3/2^+$	27(3)	39	-0.09±0.14	-0.09±0.15	0.12±0.16	0.46(20)	0.16(4)
	→ 1.727	$\to 1/2^+$		61	-0.39±0.14	0.04±0.13	0.010.14	0.27(20)	0.95(28)
2428	10.745 → 0	$3/2^+ \to 3/2^+$	19(2)	70	0.29±0.12	0.07±0.12	0.13±0.14	-0.21(15)	0.18(3)
	→ 1.727	$\to 1/2^+$		20	-0.23±0.26	0.24±0.28	-0.21±0.30	0.57(30)	0.26(5)
2459	10.780 → 0	$3/2^+ \to 3/2^+$	25(3)	15	-0.04±0.11	0.35±0.13	-0.10±0.12	-0.07(10)	0.06(1)
	→ 1.727	$\to 1/2^+$		75	-0.44±0.12	0.02±0.11	-0.02±0.11	0.52(30)	0.87(16)

where J – a spin of a resonance state, Γ_p, Γ_γ and Γ – proton, radiation and total widths of a resonance. The S values received for researched resonances are listed in the Table (4 column). The evaluation of values of a radiation resonance width was carried out in assumption that $\Gamma_p >> \Gamma_\gamma$.

3.3. 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 for researched resonance levels are presented in the Table (5 column).

3.4. ANGULAR DISTRIBUTIONS OF γ-RAYS

The angular distributions of γ-rays were measured for determination of quantum characteristics of the resonances forming RLS. The function of angular correlation $W(\theta)$ was searched as an expansion on even polynomials of Legendre:

$$W(\theta) = A_0(1 + a_2P_2(\cos\theta) + a_4P_4(\cos\theta) + a_6P_6(\cos\theta)), \qquad (2)$$

where A_0 is the normalization constant, 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 the Table (6-9 columns). 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.

Probable values of J^π for the most intensive resonances forming RLS are given in the Table (3 column). The values of parity are attributed to a state on the basis of comparison of probabilities of electromagnetic transitions with various multipolarities taking in consideration recommended upper limits for probabilities of electromagnetic γ-transitions in nuclei with $A < 44$ [9].

The experimental values of probabilities of γ-transitions $B(M1)\uparrow$ between resonances and bound states of ^{37}Cl based on obtained data were determined. Values of $B(M1)\uparrow$ were calculated by the formula:

$$B(M1)\uparrow = 21{,}65\frac{b \cdot S}{E_\gamma^3}\mu_N^2, \qquad (3)$$

where E_γ – energy of γ-transition.

4. DISCUSSION

The joint analysis of data in [6, 8, 9] and experimental results received has allowed to identify resonance-like structure in ^{37}Cl (Fig. 2), similar to that observed in ^{35}Cl [2]. The estimation of the upper limit of $B(M1)$ is given on Figs. 2 *a, b* for states at which all quantum characteristics are not known. These values do not exceed 0,05 μ_N^2 (a "background" level for transitions to the ground state) and 0,5 μ_N^2 (a "background" level for transitions to the first excited state).

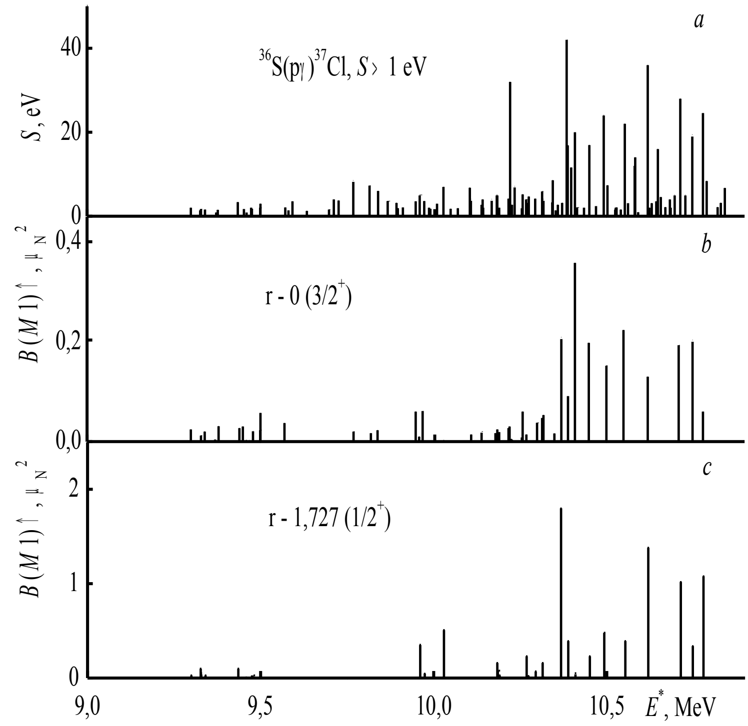

Fig. 2. *The γ-decay of resonance-like structure in the ^{36}S(pγ)^{37}Cl reaction: a - strengths of resonances; b - reduced probabilities of γ-transitions from the ground state of ^{37}Cl; c - reduced probabilities of γ-transitions from the first excited state*

The received distributions of probabilities for magnetic dipole γ-transitions allow to conclude that resonances forming RLS concern to the states of the $M1$-resonance on the ground states (Fig. 2 *a*) and first excited (Fig. 2 *b*) in ^{37}Cl. The centre of gravity for MDR on the ground state in ^{37}Cl

$$E_0 = \sum_k E_k B_k(M1) / \sum_k B_k(M1) \quad (4)$$

is equal to 12.8 MeV and it is located on energy of excitation above on 1 MeV relative to ^{35}Cl. It is possible to explain the difference found in position of c.g. for MDR in ^{35}Cl and ^{37}Cl nuclei by different connection of valence particles in these nuclei.

The total strength of MDR on the ground state

$$S_{EW}^{M1} = \sum_k E_k B_k(M1) \quad (5)$$

is equal to 12,8 MeV and it is also considerably differ from that in ^{35}Cl. It is connected with different number of particles that take part in transition between spin - orbital partners. As a result of the carried out researches MDR is identified on the ground and the first excited states for the first time in ^{37}Cl. Position of c.g., the total strength and fine structure of MDR on the ground state are determined. It is found to be in the excitation energy expected for nuclei with closed $d_{5/2}$-subshell.

This experimental fact is evidence of that *nn* or *pp*-pair from $d_{5/2}$-subshell in ^{37}Cl takes part in formation of the $M1$-resonance, therefore position of the centre of the $M1$-resonance in this nucleus is influenced with value of *nn* (*pp*) pairing in this sub-shell. The discrepancy in position of c.g and the total strength of the $M1$-resonance is found in ^{35}Cl and ^{37}Cl nuclei and for explanation of that the further researches are required.

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РЕЗОНАНСНО-ПОДОБНАЯ СТРУКТУРА В РЕАКЦИИ $^{36}S(p\gamma)^{37}Cl$

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В реакции $^{36}S(p\gamma)^{37}Cl$ исследован γ-распад резонансов, образующих резонансно-подобную структуру. Впервые установлены схемы распада, определены коэффициенты ветвления и вероятности первичных γ-переходов. Высказано предположение о том, что эти резонансы принадлежат в основном состояниям $M1$-резонанса на первом возбужденном состоянии ядра ^{37}Cl. Положение $M1$-резонанса объясняется с учетом сил спаривания.

РЕЗОНАНСНО-ПОДОБНА СТРУКТУРА В РЕАКЦІЇ $^{36}S(p\gamma)^{37}Cl$

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У реакції $^{36}S(p\gamma)^{37}Cl$ досліджено γ- розпад резонансів, що утворюють резонансноподібну структуру. Уперше побудовано схеми розпаду, встановлено коефіцієнти гілкування та імовірності прямих γ-переходів. Висловлено припущення про те, що ці резонанси належать в основному станам $M1$-резонансу на першому збудженому стані ядра ^{37}Cl. Положення $M1$-резонанса пояснюється з урахуванням сил спарювання.