γ-DECAY OF RESONANCE-LIKE STRUCTURE OBSERVED IN $^{30}Si(p,\gamma)^{31}P$ REACTION

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γ-Decay of a resonance-like structure observed in the reaction $^{30}Si(p,\gamma)^{31}P$ in the energy region E_p=1.4-2.7 MeV of accelerated protons is studied. The M1 resonance built on the ground state of ^{31}P is identified. The position of the M1 resonance is explained taking into account pairing forces.

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1. INTRODUCTION

Later [1,2], having studied γ-decays of the resonance-like structures (RLS) observed in the reactions of radiative capture of protons by ^{21}Ne, ^{25}Mg, ^{29}Si and ^{33}S nuclei, we identified the magnetic dipole resonance (MDR) built on the ground states of the odd-odd 4N+np ^{22}Na, ^{26}Al and ^{30}P nuclei and performed the search for MDR in ^{34}Cl nuclei. The position of the centre-of-gravity (COG) of MDR ($E_0=\Sigma_k E_k B_k(M1)/\Sigma_k B_k(M1)$) in these nuclei differs from that in 4N-nuclei by 3 MeV, on average, and, in fact, does not depend on mass number A (it is usually thought that this dependence must be of the form $E_{c.g}=40\cdot A^{-1/3}$). We explained this new fact by assuming the existence of the triplet neutron-proton pairing. The joint analysis of the MDR total strength and position in 4N, 4N+2n and 4N+np nuclei shows that the formation of MDR in these nuclei is strongly influenced by the valence nucleons and that the MDR COG is determined not only by the energy of spin-orbit splitting but also by the strengths of both the nn(pp)-pairing and the np-pairing as well. The similar analysis for odd nuclei shows that the position of MDR COG in these nuclei depends on the state of odd particle: $d_{5/2}$ or $d_{3/2}$. The position of MDR COG in the first case must be in the region of excitation energies of 5-6 MeV. In the second case, the nn- or pp-pairs from $d_{5/2}$-subshell can participate in the formation of MDR and the position of MDR COG in odd nucleus will then slightly differ from that position in even nuclei. Up to now, this conclusion is confirmed by our studies [3-6] (MDR COG in ^{35}Cl and ^{37}Cl are situated in the region of excitation energies of 9-10 MeV, while the same region for ^{23}Na and ^{27}Al is 5-6 MeV). With the aim of confirming and further developing the model vision of the nature of MDR and its mechanisms, we need new experimental data on the position, fine structure and total strength of MDR in those even and odd nuclei where MDR is not observed yet.

2. EXPERIMENTAL DATA AND DISCUSSION

Up to date, wide experimental information on resonance states in ^{31}P is collected via the reaction of radiative capture of 0.5-4.0 MeV protons by ^{30}Si [7-10]. But the data for several resonance states are insufficient. For instance, the angular distributions of the radiatively captured protons were not measured for the resonance states having intensive transitions into ground state with E_p=1482, 2350 and 2505 keV. Thus, the multipole mixing coefficients of γ-radiation are unknown for γ-transitions from these states. In the context, we have carried out the set of experiments associated with identification and determination of the COG position, fine structure and total strength of MDR in ^{31}P via measuring the excitation function of $^{30}Si(p,\gamma)\ ^{31}P$ reaction in the proton energy region of E_p=1.4-2.7 MeV (Fig. 1). The measurements were held on the electrostatic accelerator of National Scientific Centre "Kharkov Institute of Physics and Technology". The γ-output with E_γ>2.6 MeV were measured via the 150× 100 mm^2 NaI(Tl) detector positioned at a distance of 5 cm from the target at an angle of 55° with respect to the proton beam direction (to remove the dependence of γ-output on angle). The resonance strength ($S=(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$) were determined by comparing the square under the resonance curve for the resonances under study with the same square for the resonance at E_p=1880 keV. The strength of the latter is well known and equal to 4.8±0.7 eV [7]. We found RLS (Fig. 2a) similar to those ones we observed later in ^{23}Na, ^{27}Al, ^{35}Cl and ^{37}Cl [3-6]. However, COG ($E_0=\Sigma_k E_k S_k/\Sigma_k S_k$) of this RLS being equal to 10.4±0.5 MeV were situated in the same region of excitation energy as for ^{37}Cl and 1 MeV higher the excitation energy for ^{35}Cl. In all preceding cases [1-6] RLS had complicated structures, comprising the states belonged both to the M1-resonance on the ground state and to the one built on the excited states.

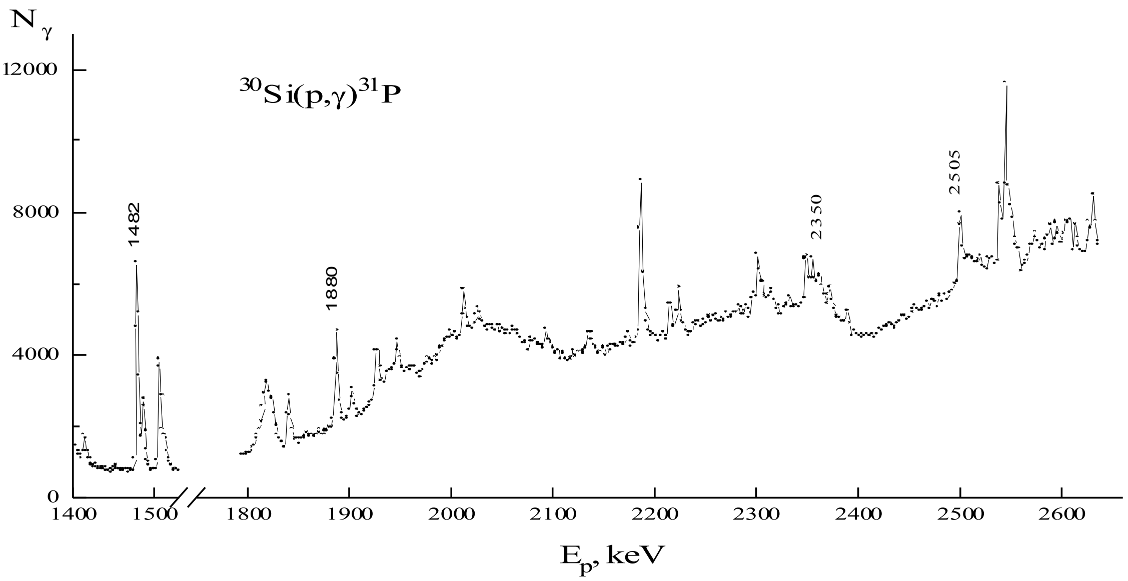

Fig. 1. *Excitation function of the reaction* $^{30}Si(p,\gamma)\,^{31}P$ *in the region of proton energies* E_p*=1400-2700 keV*

Only in the case of ^{34}Cl RLS COG was determined by the states of M1-resonance on the excited state.

The final conclusion on the nature of RLS observed in ^{31}P can be made after the determination of all quantum characteristics of the resonance states comprising this RLS and the study of their γ-decays.

The spectra of photons were measured with a Ge(Li) detector of the volume of 60 cm^3. The resolution of the detector for E_γ=1332 keV was 4 keV. The detector was positioned at a distance of 7 cm from a 20 μg/cm^2-thick target (^{30}Si).

Experimental angular distributions of photons from the reaction $^{30}Si(p,\gamma)^{31}P$

№	E_p, кeV	E_f-E_i, кeV	$a_2 \pm \Delta a_2$	$a_4 \pm \Delta a_4$	$a_6 \pm \Delta a_6$	χ^2_{min}
1	1482	8730 → 0	0.25±0.12	-0.14±0.12	-0.009±0.13	0.003
2		→ 2234	-0.40±0.10	0.05 ±0.10	-0.11 ±0.09	1.2
3		→ 3134	0.38±0.09	-0.05±0.08	0.06 ±0.09	0.27
4		→ 3295	0.42±0.15	0.41 ±0.15	0.14 ±0.17	0.15
5		→ 5015	-0.32±0.12	-0.11±0.12	-0.03 ±0.10	0.07
6	2350	9571 → 0	0.01 ±0.11	-0.04±0.12	0.08 ±0.13	1.9
7		→ 1266	-0.12±0.12	0.09 ±0.13	0.07 ±0.12	0.0005
8		→ 3134	0.09 ±0.11	0.12 ±0.13	0.15 ±0.14	0.0003
9		→ 1727	-0.35±0.13	0.12 ±0.12	-0.11±0.12	0.01
10	2505	9721 → 0	-0.09±0.14	-0.09±0.15	0.12 ±0.16	0.04
11		→ 1266	-0.39±0.14	0.04 ±0.13	0.005±0.14	0.21
12		→ 2234	0.29 ±0.12	0.07 ±0.12	0.13 ±0.14	1.1
13		→ 3506	-0.23±0.26	0.24 ±0.28	-0.21±0.30	1.45
14		→ 4261	-0.04 ±0.11	0.35 ±0.13	-0.10±0.12	0.38

The target oriented at an angle of 45° with respect to the proton-beam direction was at the centre of rotation. The measurements were carried out at angles of 0°, 60°, 30°, 90° and 45°. Corrections taking into account finite dimensions of the detector were borrowed from the tables presented in [11]. A scintillation detector involving a NaI(Tl) crystal of dimensions 150×100 mm^2 served as a monitor. The same detector was also used to measure the excitation function of the reaction ^{30}Si(p,γ) ^{31}P. The results represented as the coefficients (a_k) in the expansion in Legendre polynomials are displayed in the Table. To find the coefficients a_k, we constructed the least-square fit to the experimental data proceeding from the expression $W(\theta)=A_0[1+\ a_2P_2(\cos\theta)+a_4P_4(\cos\theta)+a_6P_6(\cos\theta)]$. A further analysis of the angular distributions involved determining the spins of resonance states and the multipole-mixing coefficients for γ-rays (δ) by minimizing the quantity

$$\chi^2 = \sum_n \left[\frac{A_0 W^{theor}(\theta_n) - W^{exp}(\theta_n)}{\Delta W^{exp}(\theta_n)} \right]^2 . \qquad (1)$$

where $W^{theor}(\theta) = \Sigma_k Q_k \rho_{k0} F_k(J_1,J_2,L,\delta) P_k$ is the theoretical angular distribution of photons for the transition between the initial and final states with spins J_1 and J_2, $W^{exp}(\theta)$ and $\Delta W^{exp}(\theta)$ are the experimental data and the corresponding statistical uncertainty, A_0 is the normalization constant, $Q_к$ is a coefficient accounting finite dimensions of the detector, ρ_{k0} is an element of the statistical tensor, n is the number of experimental points (angles). The quantity χ^2 was minimized with the help of the software created on the basis of refined genetic algorithm [12]. The fitting procedure for odd nuclei differed from that for even nuclei: for odd nuclei the parameters of the statistical tensor were calculated and the multipole-mixing coefficient (δ) remained the only fitting parameter. The spin values of resonances at hand were defined, in general, via analysis of transitions to the ^{31}P ground state ($J^{\pi}=1/2^{+}$). The parities were defined based on the comparison of probabilities of electromagnetic transitions of different multipolarity with recommended upper limits of the given values [7]. The reduced probability of γ-transition B(M1) was calculated using the expression

$$B(M1)\uparrow=86{,}6bS(eV)/((2J+1)E^3_\gamma\,(MeV)), \qquad (2)$$

where b is the branching coefficient of γ-transition, J is the spin of initial state, E_γ is the energy of γ-transition.

Figs. 2b and 2c show estimate of the upper limit of B(M1) for the states for which not all quantum characteristics are known.

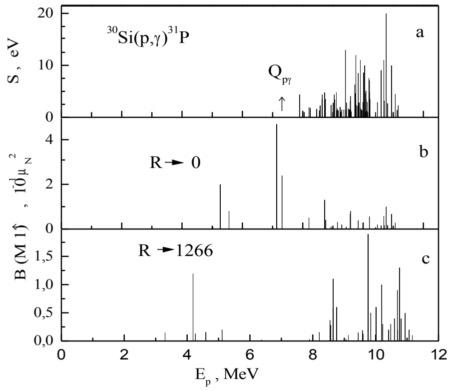

Fig. 2. *γ-decay of a resonance-like structure from the reaction $^{30}Si(p,\gamma)^{31}P$: a - resonance strength; b - reduced probabilities of the γ-transitions from the ^{31}P ground state; c - reduced probabilities of the γ-transitions from the ^{31}P first excited state ($E^*=1266$ keV). For the sake of convenience only those resonance states for which S > 1 eV are presented*

These values do not exceed 0,1 μ^2_N (background level for transitions to the ground state) and 0,05 μ^2_N (background level for transitions to the first excited state). Derived probability distributions for magnetic dipole γ-transitions allow concluding that the resonances comprising RLS belong to the states of M1-resonance built on the first excited state of ^{31}P (Fig. 2c). The greatest probability of M1-transition from the bound state 7141 keV ($J^{\pi}=1/2^{+}$) to the ground one is equal to 0,47 μ^2_N. This value is found accounting for the mean half-time of the state 7141 keV [9]. The COG position of MDR on ^{31}P ground state (Fig. 2b) is equal to 8.5± 0.3 MeV and is situated in the region of excitation energies which is expected for nuclei with closed $d_{5/2}$-subshell. This experimental fact confirms that the formation of M1-resonance in ^{31}P is affected by the magnitude of nn(pp)-pairing in $d_{5/2}$-subshell. The total strength of MDR ($S^{M1}_{EW}=\Sigma_k E_к B_к(M1)$) on the ground state being equal to 8 MeVμ^2_N substantially differs from that value for ^{35}Cl. This fact is probably due to different numbers of particles participating in the transition between the spin-orbit partners. Our investigations show that we have identified M1-resonance on the ground and first excited states in ^{31}P.

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