RESONANCE-LIKE STRUCTURE OBSERVED IN $^{25}Mg(p,\,\gamma)^{26}Al$ REACTION

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The γ decay of the resonance-like structure (RLS), observed in the $^{25}Mg(p,\,\gamma)^{26}Al$ in the region of excitation energies of 7...9 MeV was studied. The excitation function of the $^{25}Mg(p,\,\gamma)^{26}Al$ reaction was measured. The resonance strengths in the accelerated proton energy range of $E_p = 1.4...2.0\,MeV$ were determined. The obtained distributions of the strength of $M1$ transitions between the resonance states and the low-lying bound states in ^{26}Al have resonance character. The position of the center of gravity of the magnetic dipole resonance (MDR) on the ground state is equal to 7.92 MeV. Total strength MDR in ^{26}Al is equal to 5.7 MeV μ_N^2.

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1. INTRODUCTION

In recent years, reactions of inelastic scattering and radiative capture of protons have been actively used to study the giant multipole ($M1$, $E2$, octupole) resonances in the region of low excitation energies and, therefore, falling in the range of discrete nuclear states [1, 2]. Among the low-lying giant resonances, $M1$ is one of the most interesting because $M1$ transitions carry the most complete information about the spin and isospin dependences of nuclear forces [2]. In real nuclei, the $M1$ strength is distributed over neighboring states; this circumstance makes it possible to study the relationship between the single-particle and collective motion. For sd shell nuclei, the role of collective motion is insignificant; therefore, the $M1$ resonance clearly manifests itself in these nuclei. To date, the position and fine structure of the magnetic dipole resonance (MDR) in even-even ($4N$ and $4N + 2n$) sd shell nuclei have been sufficiently well studied [3, 4]. It has also been established that the main mechanism responsible for the MDR excitation is the transitions between spin-orbit partners [2]. To explain the reduction in the total strength and MDR fragmentation in these nuclei, the Nilsson model [4], the configuration- mixing shell model [3], and the Hartree-Fock method [5] were successfully used. Consideration of the effect of pairing correlations on the position and energy-weighted strength of giant multipole resonances leads to more complete agreement between the predictions of different theoretical models and experimental data [6, 7]. Behavior of the MDR total strength in odd sd shell nuclei corresponds to that of the total strength, which follows from the Kurath sum rule [8]. Analysis of the MDR total strength in even-even ($4N$ and $4N + 2n$) sd shell nuclei indicates that the valence nn and pp pairs play a key role in the MDR formation in this nuclei [9]. Analysis of the MDR total strength in odd-odd ($4N + np$) sd shell nuclei can also give information about the effect of pairing influence. on the MDR properties.

2. EXPERIMENTAL RESULTS AND DISCUSSION

For experimental determination the center of gravity ($E_{cog} = \sum_k E_k B_k(M1)/\sum_k B_k(M1)$ and the total strength ($S_{EW}^{M1} = \sum_k E_k B_k(M1)\uparrow$) of the MDR observed in the radiative proton capture reaction, it is necessary to know resonance strengths for the current reaction ($S = (2I + 1)\Gamma_p\Gamma_\gamma/\Gamma$), since

$$B(M1)_{fi}\uparrow = \frac{86.6}{2I_f + 1}\frac{b_{if}S_i[eV]}{(1 + \delta_{if}^2)E_{\gamma_{if}}^3}\,\mu_N^2\,, \qquad (1)$$

here i is the initial (resonance) state; f is the terminal state; b_{if} is the branching ratio for transition between the initial and the terminal states; S_i represents resonance state strengths; δ is the ratio of mixing by multipolarities for γ transitions between the initial and the terminal states; I is the state spin; is the energy of γ transition between the initial and the terminal states; E_{if} is the energy of γ transition between the initial and the terminal states; $B(M1)fi$ is the reduced probability of the $M1$ transition from the final to the initial state: ($B(M1)_{fi} = ((2I_i + 1)/(2I_f + 1))B(M1)_{if}$). K is of the MDR states. Expression (1) below the binding energy for proton as follows:

$$B(M1)_{fi}\uparrow = 14.2\frac{b_{if}(2I_f + 1)}{(1 + \delta_{if}^2)\tau_{m_i}[fs]E_{\gamma_{if}}^3[MeV]}\,\mu_N^2\,, \qquad (2)$$

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where $_{mi}$ is the average lifetime of the excited state.

The resonance strengths within the accelerated proton energy range with $E_p < 1\,MeV$ are generally well known, and it is therefore convenient to determine the resonance strengths being investigated for the first time on the basis of relative measurements. If we compare the yield of γ lines within the spectrum of the resonance investigated to the ones within a spectrum of known resonance (with well - known strength and decay patterns), we can obtain the strength value for the investigated resonance. The method for determining resonance strength for thin targets is described in detail in [10, 11]. We measured the excitation function for the $^{25}Mg(p,\gamma)^{26}Al$ reaction in the range of proton energies $E_p = 1.4...2.0\,MeV$ (Fig.1). The measurements were performed on the ESU-5 accelerator at the National Scientific Center Kharkov Institute of Physics and Technology. A $Ge(Li)$ detector with volume of $60\,cm^3$ and resolution of $3.2\,keV$ for $E_\gamma = 1332\,keV$ was used to measure the γ spectra. The detector was placed at a distance of 2 cm from the target at an angle of 55°. The target was prepared by knocking ions directly into a tantalum substrate in the electromagnetic separator. A target prepared in this manner is convenient for long-lasting experiments, since it is capable of sustaining high current densities for many hours of operation.

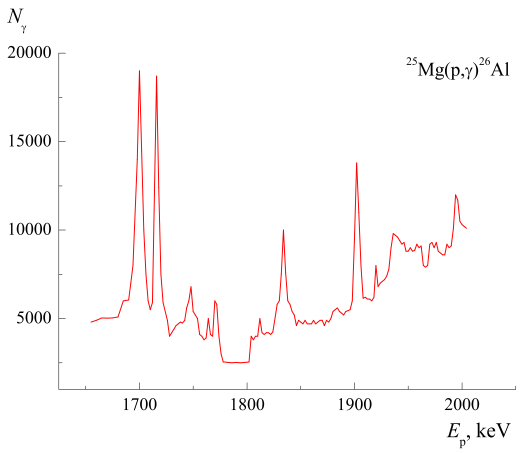

Fig.1. *Excitation function of the $^{25}Mg(p,\gamma)^{26}Al$ reaction. γ photons with $E_\gamma > 2.6\,MeV$ was detected*

The resonance strengths in the (p,γ) reactions are determined as in [10]:

$$S = \frac{(2I+1)\varepsilon N_\gamma}{4\pi^3\lambda^2\xi N_p b\eta W(\theta)}\,, \tag{3}$$

where ε is the target's deceleration capability measured in energy units and multiplied by $cm^2/atom$; N_γ is the γ quantum yield for the current energy; ξ is the target thickness measured in energy units; N_p is the number of protons that fell on the target; b is the branching ratio; η is the detector's absolute efficiency; and $W(\theta)$ is a coefficient used to consider the angular distribution effect. The target thickness ξ may be expressed through deceleration capability of the target substance

$$\xi = nt_M\varepsilon\,, \tag{4}$$

where n is the number of atoms per $1\,g$ of the target substance and t_M is the target thickness measured in gcm^{-2}. Measurements over the energy range were performed under the same experimental conditions, making it possible to exclude the dependence on the number of protons that fall on the target and target thickness:

$$\frac{S_1}{S_2} = \frac{N_{\gamma_1}E_{r_1}b_2\eta_2}{N_{\gamma_2}E_{r_2}b_1\eta_1}\,, \tag{5}$$

where and are $N_{\gamma_1}, N_{\gamma_2}$ quantum yields (the area under the γ line) for the first and the second resonances respectively; and are the resonance energies of protons in the laboratory system; b_1 and b_2 are branching ratios of the γ transitions under study; η_1 and η_2 represent the detector's absolute efficiency with respect to γ quanta detected in the first and in the second resonances, respectively. The results of these measurements are listed in the Table 1.

In this study, the strengths of the resonances forming the resonance-like structure observed in the reaction of proton radiative capture $^{25}Mg(p,\gamma)^{26}Al$ were determined from comparison of the intensities of the γ lines formed during decay of the resonance levels under study with the intensity of the γ line at $E_\gamma = 5153\,keV$, corresponding to the transition from the resonance level with $E_p = 953\,keV$ (whose strength and decay scheme are well known) to the state at $2069\,keV$.

We also measured the spectra and angular distributions of γ rays formed at the decay of the most intensive resonances with $E_p = 953, 1375, 1587, 1649, 1699, 1714\,keV$. The $Ge(Li)$ detector was located at a distance of $7\,cm$ from the target. The target was situated in the rotation center at an angle of 45° to the proton beam direction. Measurements were performed at angles of 0°, 30°, 45°, 60° and 90°. Corrections taking into account the finite dimensions of the detector were chosen from the tables. A scintillation detector with a $NaI(Tl)$ crystal served as a monitor. The same detector was used to measure the excitation function of the $^{25}Mg(p,\gamma)^{26}Al$ reaction. The measurement results as the expansion coefficients (a_k) in Legendre polynomials are given in Table 2.

The coefficients a_k were determined by least-squares fitting of the experimental data and using the expression:

$$W(\theta) = A_0[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)+a_6P_6(\cos\theta)]\,.$$

Table 1. *Resonance strengths in the* $^{25}Mg(p,\gamma)^{26}Al$ *reaction*

E_p, *keV*	E_x *keV*	*S, eV*	*S, eV* [12]	*S, eV* [13]	$< S >$, *eV*
1375	7628	21±7	14.6±1.2	9±2	
1587	7832	6.3±1.5	8.2±1.0	6.6±1.0	7.2±0.5
1649	7891	30±9	35.±3	32.±6	34±0.5
1699	7939	18±5	11±2	20±4	13.4±1.5
1714	1953	42±9	38±5	57±	43.1±2.6
1744	7982	2.7±1	14.8±1.5	-	6.4±3.1
1748	7987	1.7±0.7	-	-	-
1763	8001	1.5±0.6	1.1±0.2	-	1.14±0.11
1771	8008	-	2.3±0.4	-	-
1774	8011	3.6±1.2	2.4±0.8	-	2.77±0.46
1776	8013	0.8±0.3	-	-	-
1800	8036	-	0.18±0.03	-	-
1811	8047	0.3±0.2	0.9±0.2	-	0.6±0.2
1829	8064	0.6±0.3	7.6±0.5	-	2.45±1.59
1833	8067	1.8±0.7	2.7±0.7	-	20.5±0.7
1899	8131	2.2±0.9	-	-	-
1998	8227	3.8±1.5	-	-	-

Table 2. *Results of the measurements of* γ *ray angular distributions in the* $^{25}Mg(p,\gamma)^{26}Al$ *reaction*

E_p, *keV*	$E_i^* \to E_f^*$ *keV*	a_2	a_4	a_6	χ^2_{min}	δ
953	722→2069	-0.21±0.03	-0.11±0.03	0.03±0.04	0.7	0.24±0.02
1375	7628→4205	-0.03±0.03	-0.08±0.04	0.03±0.05	0.5	0.22±0.05
1587	7832→0	0.28±0.08	-0.24±0.09	0.07±0.09	0.6	-0.39±0.07
1649	7891→0	-0.13±0.03	-0.05±0.04	0.01±0.04	1.2	0.38±0.08
1699	7939→2069	0.28±0.05	-0.16±0.05	-0.01±0.05	0.4	-0.40±0.07
1714	7953→0	-0.11±0.01	-0.04±0.01	0.02±0.02	0.6	0.21±0.05

Further analysis of the angular distributions was to find the spins of resonant states and γ ray multipolarity mixing ratios δ by minimizing the quantity χ^2:

$$\chi^2 = \sum_n \left[\frac{A_0 W^{theor}(\theta_n) - W^{exp}(\theta_n)}{\Delta W^{exp}(\theta_n)} \right]^2 , \quad (6)$$

where $W^{theor}(\theta) = \sum_k Q_k \rho_{k_0} F_k(J_1, J_2, L, \delta) P_k$ is the theoretical angular distribution of γ rays 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 experimental data with the corresponding statistical errors, A_0 is a normalization constant, Q_k is the coefficient taking into account the finite size of the detector were chosen from the tables, ρ_{k_0} is the element of the statistical tensor, and n is the number of experimental points (angles).

The measurement results are illustrated in

Fig.2,a

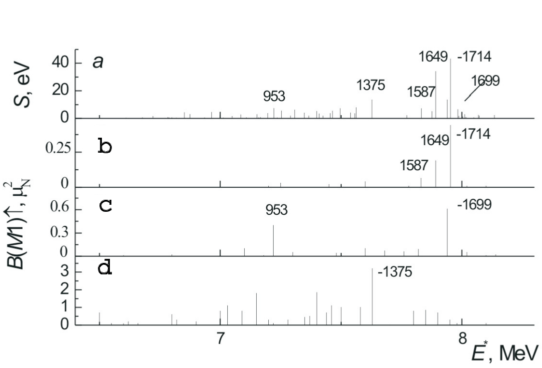

Fig.2. *Decay of the resonance-like structure from the* $^{25}Mg(p,\gamma)^{26}Al$ *reaction: a – resonance strengths, b – reduced probabilities of* γ *transitions to the ground state of* ^{26}Al*, c – reduced probabilities of* γ *transitions to the* 2069 *keV state, d – sum of reduced transition probabilities to the states of energies* 3963...5726 *keV*

The obtained distribution of resonance strengths made it easier to identify a resonance-like structure (RLS) similar to those investigated earlier for the nuclei of the sd shell [8, 9]. This the resonance-like structures is of a complex structure; i.e, they consisted of states belonging both to the $M1$ resonance of the ground state and to the $M1$ resonance of excited states [8, 9]. The obtained probability distributions of magnetic dipole γ transitions have a resonance character and allow us to conclude that the resonances that form the RLS belong to states of the $M1$ resonance on the ground and excited states of the $26Al$ nucleus (Figs.2,b, c, d).

The position of the center of gravity of the MDR on the ground state in $26Al$ is equal to $7.92\,MeV$. Total strength MDR in ^{26}Al is equal to $5.7\,MeV\ \mu_N^2$. The center of gravity of the MDR in $4N + np$ nuclei lies on the average $3\,MeV$ lower in the excitation energy than that in $4N$ nuclei.

This difference can be explained by assuming the existence of the neutron-proton pairing between the odd neutron and proton being in the same orbit [9].

The analysis of the experimental data [9-17] allowed us to obtain distributions of the $M1$-transition probabilities for the ground state in the ^{22}Na, ^{30}P, ^{34}Cl nuclei (Fig.3).

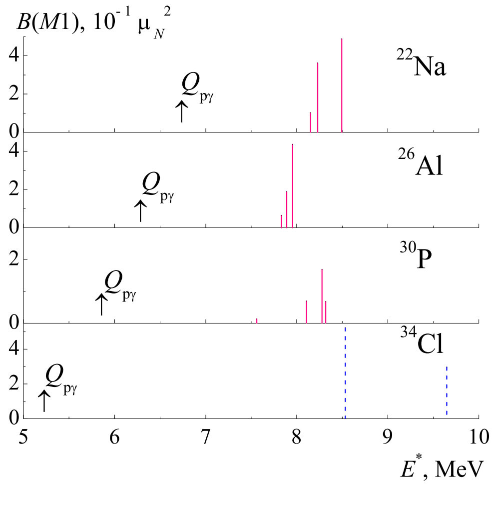

Fig.3. *Magnetic dipole resonance in odd-odd* $(4N + np)$ *sd-shell nuclei*

The behavior of the MDR total strength in odd-odd $(4N + np)$ sd shell nuclei (Fig.4) differs from that of the following from the Kurath sum rule. To elucidate the reasons for this behavior of the total strength of MDR in odd-odd nuclei of the sd shell, further investigations are required.

3. CONCLUSIONS

In this paper, we studied the decay of the resonance-like structure observed in the $^{25}Mg(p,\gamma)^{26}Al$ reaction in the accelerated proton energy range $E_p = 1.4...2.0\,MeV$. We also measured the excitation function, spectra and angular distributions of γ rays formed at the decay of the most intensive resonances with E_p = 953, 1375, 1587, 1649, 1699 and $1714\,keV$. From the analysis of the excitation function of this reaction and the angular distributions of γ quanta, the resonance forces and the mixing coefficients for the multipolarities of the γ radiation are determined. The obtained probability distributions of magnetic dipole transitions on the ground and excited states of the ^{26}Al nucleus, which have a resonance character. The MDR was identified on the ground state in ^{26}Al. The position of the center of gravity of the MDR was found to be $7.92\,MeV$. The total strength of the MDR is found to be $5.7\,MeV$ μ_N^2.

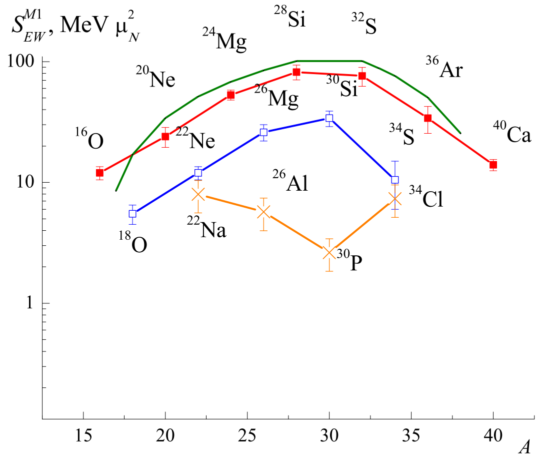

Fig.4. *Dependence of the total MDR strength of A for sd shell nuclei. The solid line is the Kurath sum rule [6, 16]. Blacksquare – 4N nuclei (*^{16}O*,* ^{22}Ne*,* ^{24}Mg*,* ^{28}Si*,* ^{32}S*,* ^{36}Ar*,* ^{40}Ca*) [3, 4, 14, 15];* □ *–* $4N + 2n$ *nuclei (*^{18}O*,* ^{22}Ne*,* ^{26}Mg*,* ^{30}Si*,* ^{34}S*) [3, 4, 15];* × *–* $4N + np$ *nuclei (*^{22}Na*,* ^{26}Al*,* ^{30}P*,* ^{34}Cl*) – our results*

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РЕЗОНАНСНОПОДОБНАЯ СТРУКТУРА, НАБЛЮДАЕМАЯ В РЕАКЦИИ $^{25}Mg(p,\,\gamma)^{26}Al$

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Изучен γ-распад резонансноподобной структуры (РПС), наблюдаемой в реакции $^{25}Mg(p,\,\gamma)^{26}Al$ в районе энергий возбуждения 7...9 МэВ. Проведены измерения функции возбуждения данной реакции. Силы резонансных состояний определены в интервале энергий ускоренных протонов $E_p = 1,4...2,0$ МэВ. Полученные распределения силы $M1$ переходов между резонансными состояниями и низколежащими связанными в ^{26}Al имеют резонансный характер. Положение центра тяжести магнитного дипольного резонанса (МДР) на основном состоянии равно 7,92 МэВ. Полная сила МДР равна 5,7 МэВ μ_N^2.

РЕЗОНАНСНОПОДІБНА СТРУКТУРА, ЩО СПОСТЕРІГАЄТЬСЯ В РЕАКЦІЇ $^{25}Mg(p,\,\gamma)^{26}Al$

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Вивчено γ-розпад резонансноподібної структури (РПС), що спостерігається в реакції $^{25}Mg(p,\,\gamma)^{26}Al$ в районі енергій збудження 7...9 МеВ. Проведено вимірювання функції збудження даної реакції. Сили резонансних станів визначені в інтервалі енергій прискорених протонів $E_p = 1,4...2,0$ МеВ. Отримані розподіли сили $M1$ переходів між резонансними станами і низьколежачими пов'язаними в ^{26}Al мають резонансний характер. Положення центра ваги магнітного дипольного резонансу (МДР) на основному стані дорівнює 7,92 МеВ. Повна сила МДР дорівнює 5,7 МеВ μ_N^2.