GIANT *M*1 RESONANCE ON THE GROUND AND EXCITED STATES IN 2*s*1*d*-SHELL NUCLEI

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The gamma decay of the resonance-like structures observed in the reaction of radiative capture of protons by the nuclei ^{22}Ne, ^{26}Mg, ^{30}Si, ^{34,36}S, and ^{38}Ar in the region of excitation energies of 7…12 MeV was studied. The excitation functions of this reaction were measured. The resonance strengths in the energy range of the accelerated protons E_p = 1.0…3.0 MeV were determined. The obtained discrete distributions of the magnetic dipole γ-transitions on the ground and excited states for the nuclei of the 2*s*1*d*-shell have resonance character. Giant *M*1 resonance on the ground and excited states in the ^{23}Na, ^{27}Al, ^{31}P, $^{35.37}$Cl, and ^{39}K nuclei has been identified. The position of the *M*1 resonance on excited states coincides with that predicted by the Brink-Axel hypothesis for nuclei that are at the beginning of the subshell.

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INTRODUCTION

In recent years, extensive theoretical and experimental studies of the properties of magnetic dipole resonance (MDR) have been carried out [1, 2]. Accumulative extensive information about the position and fine structure of the *M*1 resonance in even-clear 4*N*- and $4N + 2n$-cores of 2*s*1*d*-shells [3, 4]. Nielson's model, shell model with consistent mixing, Hartree-Fock method [3 - 5]. In addition, it was shown in [6, 7] that meson currents, isobar – hole excitations, and quartz degree of freedom.

For the odd and odd-nucleus nuclei of the 2*s*1*d* shell, magnetic dipole γ-transitions are obtained in the ground state [8, 9], which makes it possible to identify MDRs in the ground state. The position of the center of gravity of the MDR in oddly distinct nuclei differs from the position of the center of gravity of the MDR at 3 MeV [8]. At the same time, the maximum MDR in odd nuclei with a filled $d_{5/2}$ subshell (^{31}P, ^{35,37}Cl, ^{39}K) is at an excitation energy 3 MeV higher than in nuclei with an unfilled $d_{5/2}$ subshell (^{23}Na, ^{25}Mg, ^{27}Al) [9]. The behavior of the total MDR force in odd nuclei of the 2*s*1*d*-shell corresponds to the behavior of the total force obtained from the analysis of the Kurath sum rule [10].

According to the Brink-Axel hypothesis, in any excited state it is possible to construct a giant resonance (GR), similar to the giant resonance of the ground state. GRs in excited states were studied in [11 - 15]. In [11], all new data on the properties of GDRs in excited states show that the excitation energy, width, and cross sections for these resonances have a simple mass dependence of type $A^{-1/3}$ or $A^{-1/6}$. From the data obtained, it follows that the detected resonance is a common collective feature of all nuclei with $N - Z \geq 1$ and has a simple mass dependence, which assumes the presence of two fashionable resonances: isobaric analog resonance and giant dipole resonance. In [12, 13], the temperature change was studied. The considered fluctuation of the partial-hole (*ph*) energy, relative to its mean value as a perturbation, leads to simple width expressions and rules that are in good agreement with experimental data [14]. In [15], GRs were studied, built on excited states in nuclei and, in particular, the resonances $L = 0$, 2 ($T = 0$). It turned out that their maximum corresponds to the energy that corresponds to the resonance built in the ground state of the nucleus. Preliminary results of our research were published in [16].

1. EXPERIMENTAL RESULTS

To determine the position of the center of gravity (maximum)

$$E_{cg} = \sum_k E_k B_k(M1)\uparrow \Big/ \sum_k B_k(M1)\uparrow [\text{MeV}] \qquad (1)$$

and the total strength of the magnetic dipole resonance

$$S_{EW}^{M1} = \sum_k E_k B_k(M1)\uparrow [\text{MeV}\cdot\mu_N^2] \qquad (2)$$

observed in the radiative capture of protons by the nuclei, it is necessary to know the resonance forces of the corresponding reaction

$$S = (2J+1)\frac{\Gamma_p \Gamma_\gamma}{\Gamma}[\text{eV}]. \qquad (3)$$

The value of *S* is related to the probability of the *M*1 transition $B(M1)\uparrow$ by the relation:

$$B(M1)_{fi}\uparrow = \frac{86.6}{(2J+1)}\frac{b_{if}S_i}{(1+\delta_{if}^2)E_{\gamma_{if}}^3}[\mu_N^2], \qquad (4)$$

where the subscripts *i* and *f* denote the initial E_i^* and the final E_f^* state of the nucleus, respectively; b_{if} is the branching coefficient for the transition $E_i^* \to E_f^*$; S_i is the strength of resonant states; δ_{if} is the mixing coefficient by multipolarities for γ-transitions $E_i^* \to E_f^*$; *J* is the spin of the resonance state; $E_{\gamma_{if}}$ [MeV] is the energy of the transition $E_i^* \to E_f^*$. The value $B(M1)_{fi}\uparrow$ is related to the probability $B(M1)_{if}\downarrow$ of the $M1$ transition $E_i^* \to E_f^*$ by the relation:

$$B(M1)_{fi}\uparrow = \frac{2J_i+1}{2J_f+1} B(M1)_{fi}\downarrow. \qquad (5)$$

Below the threshold (pγ)-reaction, expression (4) takes the form:

$$B(M1)_{fi}\uparrow = 14.2\frac{b_{if}(2J_f+1)}{(1+\delta_{if}^2)\tau_{m_i} E^3_{\gamma_{if}}}, \qquad (6)$$

where τ_{mi} [fs] is the average lifetime of the excited state.

Usually, the forces of resonances in the energy region of accelerated protons with E_p <1 MeV are well known, so it is convenient to determine the forces of the first studied resonances from relative measurements. Comparing the yield of γ-lines in the spectrum of the resonance under study with γ-lines in the spectrum of a known resonance (the force and decay scheme of which are well known), one can find the strength of the resonance under investigation. A detailed method for determining the strength of resonances for a thin target is described in [17, 18].

The strength of the resonances in (pγ) reactions is defined as [16]:

$$S = \frac{(2J+1)\varepsilon N_\gamma}{\pi\lambda^2 \xi N_p b\eta W(\theta)}, \qquad (7)$$

where ε is the stopping power of the target in terms of energy multiplied by cm²·atom⁻¹; N_γ – gamma-quanta output of a given energy; ξ is the target thickness in energy units; N_p is the number of protons that hit the target; b is the branching ratio; η – absolute detector efficiency; W(θ) – coefficient taking into account the effect of the angular distribution. The target thickness ξ can be expressed through ε:

$$\xi = nt_M \varepsilon, \qquad (8)$$

where n is the number of atoms per 1 g of the target substance, t_M is the thickness of the target in g·cm^{-2}. Measurements in the entire energy range are carried out under the same experimental conditions, which makes it possible to exclude the dependence on the number of protons hit the target and on the target thickness. As a result, we have:

$$\frac{S_1}{S_2} = \frac{N_{\gamma_1} E_{r_1} b_2 \eta_2}{N_{\gamma_2} E_{r_2} b_1 \eta_1}, \qquad (9)$$

where N_{γ_1}, N_{γ_2} is the output of γ-quanta (area under the γ-line) for the first and second resonances, respectively; E_{r_1}, E_{r_2} – resonant proton energies in the laboratory system; b_1, b_2 are the branching coefficients of the studied transitions; η_1, η_2 is the absolute efficiency of the detector with respect to the γ-quanta recorded in the first and second resonances, respectively.

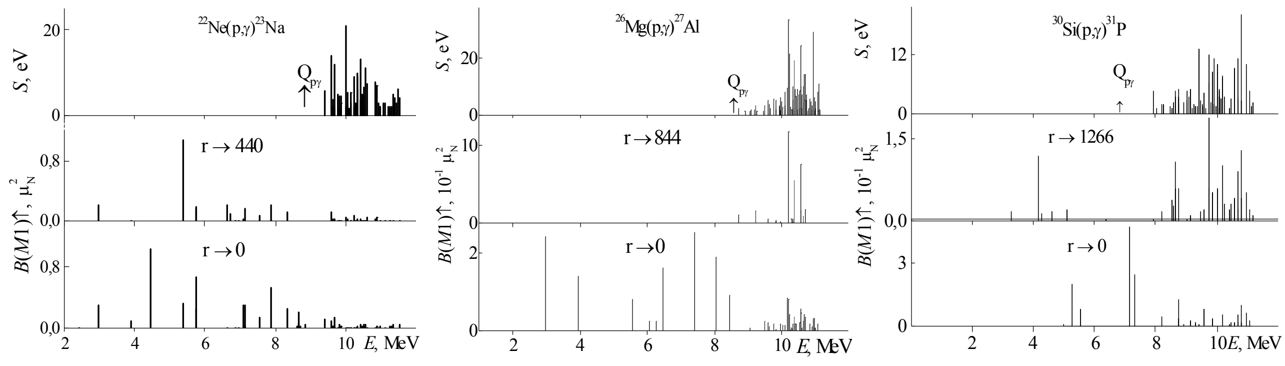
The resonance forces constituting the resonance-like structures (RLS) observed in the radiative capture of protons by the ^{22}Ne, ^{26}Mg, ^{30}Si, $^{34.36}$S, and ^{38}Ar nuclei were determined by comparing the intensities of the γ-lines formed during the decay of the studied resonant levels with the intensity of the known γ-lines resulting from the decay of calibration resonances (Table 1).

Table 1

Calibration resonances in (pγ) reactions on light nuclei

Reaction	E_p, keV	S, eV	Ref.
^{22}Ne(pγ)^{23}Na	1278	21±2	[19, 20]
^{26}Mg(pγ)^{27}Al	1966	9.5±0.9	[21, 22]
^{30}Si(pγ)^{31}P	1880	4.8±0.9	[23-25]
^{34}S(pγ)^{35}Cl	1212	9.7±0.7	[9, 26]
^{36}S(pγ)^{37}Cl	1887	32±3	[27, 28]
^{38}Ar(pγ)^{39}K	1394	2.7±0.8	[25, 27, 29]

As a result of the measurements carried out in odd nuclei, RLS were found, similar to those observed for even nuclei that we studied earlier [8, 30, 31]. In the case of even nuclei, the RLS had a complex structure, i.e. consisted of states belonging to both the $M1$ resonance of the ground state and the $M1$ resonance "built" in excited states. The final conclusion on the nature of the observed RLS in the case of odd nuclei can be made after establishing all the quantum characteristics of the resonant states that make up these RLS, and studying their γ-decay. To this end, we have measured the spectra and angular distributions of γ-quanta, which are formed during the decay of the most intense resonances that make up the RLS data. From the analysis of experimental data, discrete distributions of magnetic dipole γ-transitions at the ground and first excited states, which are resonant in nature, were obtained (Fig. 1).



^{22}Ne(p,γ)^{23}Na ^{26}Mg(p,γ)^{27}Al ^{30}Si(p,γ)^{31}P

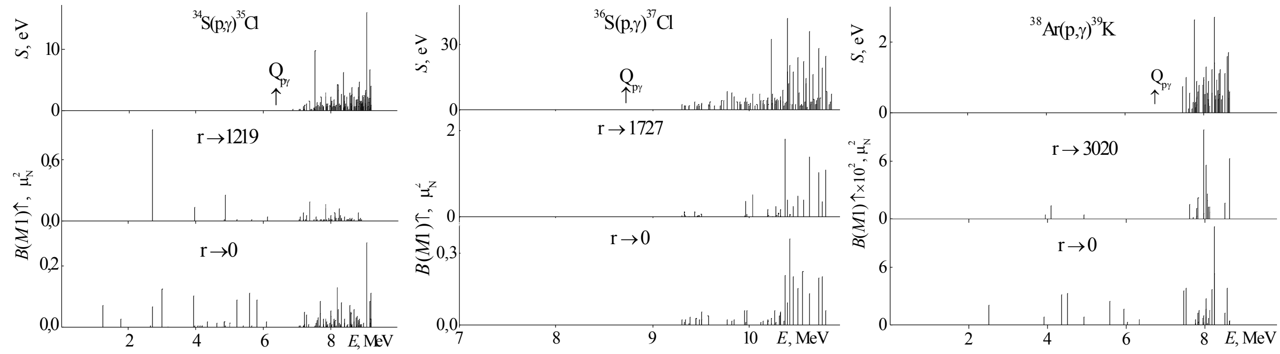


Fig. 1. Gamma-decay of a resonance-like structure observed in reactions. S – resonance strength, B(M1) – reduced probabilities of γ-transitions from the ground and first excited states in the ^{23}Na, ^{27}Al, ^{31}P, $^{35,37}Cl$, and ^{39}K nucleus

The measurements were carried out on the ESU-5 accelerator of the NSC KIPT. To measure the γ-spectra, a Ge(Li) detector with a volume of 60 cm^3 and a resolution of 3.2 keV was used for E_γ = 1332 keV ^{60}Co. The detector was located at a distance of 2 cm from the target at an angle of 55°. The targets were prepared by driving the corresponding ions of the highly enriched isotope into the tantalum substrate directly in an electromagnetic separator. Targets prepared in this way are convenient for long-term experiments, since they withstand high proton beam current densities for many hours of operation.

2. DISCUSSION

The discrete distributions of magnetic dipole γ transitions in the ground and excited states obtained in [9, 19 - 29] are resonant in nature. We found that for odd nuclei, as well as for even nuclei, RLSs have a complex structure, i.e. consist of states belonging to both the *M*1 resonance of the ground state and the *M*1 resonance "built" in excited states. The position of the center of gravity of the MDR on excited states, as determined from experimental data, is given in Table 2.

Table 2

The position of the center of gravity of the MDR on excited states in odd 2s1d-shell nuclei

Nucleus	E_i^*, MeV	E_{cg}, MeV	ΔE_{cg}, MeV	ΔE_{BA}, MeV
^{23}Na	0	5.6(2)	-	-
	0.440	6.0(3)	0.4	0.04
	2.982	10.2(3)	4.6	1.6
^{27}Al	0	6.1(6)	-	-
	0.844	10.3(1.0)	4.2	3.3
	1.014	10.3(1.0)	4.2	3.2
^{31}P	0	8.5(3)	-	-
	1.266	9.2(3)	0.7	0.6
^{35}Cl	0	8.5(6)	-	-
	1.219	5.7(4)	-2.8	1.6
	1.763	7.3(5)	-1.2	0.6
^{37}Cl	0	10.4(3)	-	-
	1.727	10.4(3)	0.01	1.7
^{39}K	0	8.5(9)	-	-
	3.020	7.9(9)	0.4	2.6
	3.944	7.4(8)	0.9	3.1

The difference in the position of the MDR predicted by the Brink-Axel hypothesis from the experimental value of the center of gravity of the MDR is:

$$\Delta E_{BA} = \Delta E_{cg} - E_i^*, \qquad (10)$$

where $\Delta E_{cg} = \Delta E_{cg}^* - E_{cg}^0$; E_{cg}^* is the position of the center of gravity of the MDR on the excited state; E_{cg}^0 – the position of the center of gravity of the MDR on the ground state; E_i^* is the energy level of the excited state at which the MDR is observed.

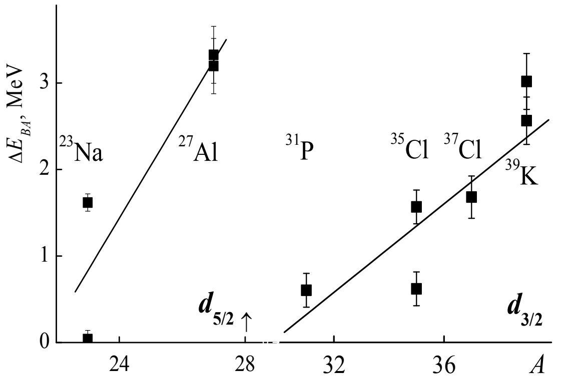


Fig. 2. Testing the Brink-Axel hypothesis for M1 resonance in odd 2s1d-shell nuclei

As can be seen from Fig. 2, the position of the MDR on excited states coincides with that predicted by the Brink-Axel hypothesis for nuclei that are at the beginning of the subshell (^{23}Na – $d_{5/2}$-subshell; ^{31}P – $d_{3/2}$-subshell) and differs by 3 MeV for nuclei with almost full subshell (^{27}Al – $d_{5/2}$-subshell; ^{39}K – $d_{5/2}$-subshell).

This is due to the influence of the pairing energy of nucleons on the properties of MDRs in the 2*s*1*d*-shell nuclei. In other words, for the nuclei in the beginning of the subshell, an odd particle takes part in the formation of the MDR. And for nuclei with an almost filled subshell, the role of *nn* or *pp* pairs increases. The behavior of the total MDR force on the ground state for odd nuclei of the 2*s*1*d* shell corresponds to that obtained from the Kurath sum rule in the framework of the single-particle shell model [9]. At the same time, the full strength of the MDR in excited states does not correspond to that obtained from the Kurath sum rule (Fig. 3). This may be due to the increasing role of collective movement in the structure of excited states.

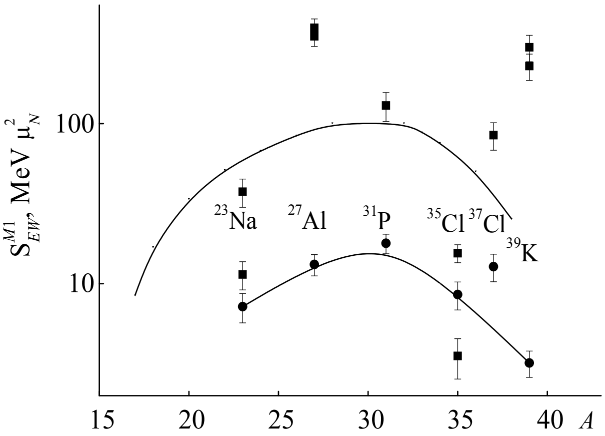


Fig. 3. The solid curve is the Kurath sum rule [10]. ■ *is the dependence of the total MDR force on A for the excited states in odd 2s1d-shell nuclei.* • *– data from [9, 18 - 28] for the ground state*

CONCLUSIONS

In this work, the γ-decay of resonant-like structures observed in the radiative capture of protons by ^{22}Ne, ^{26}Mg, ^{30}Si, ^{34,36}S, and ^{38}Ar nuclei in the region of excitation energies of 7…12 MeV was studied. Measurements were made of the excitation functions of these reactions and the forces of the resonances were determined in the energy range of accelerated protons E_p = 1.0…3.0 MeV.

The MDR was identified on excited states in ^{23}Na, ^{27}Al, ^{31}P, ^{35,37}Cl, and ^{39}K nuclei. The position of the magnetic dipole resonance in the excited states coincides with that predicted by the Brink-Axel hypothesis for nuclei that are at the beginning of the subshell and differs by 3 MeV for nuclei with an almost filled subshell. For nuclei located at the beginning of the subshell, an odd particle mainly takes part, and for nuclei with an almost filled subshell, the role of *nn*- or *pp*-pairs increases. The total strength of the MDR on excited states does not correspond to that obtained from the Kurath sum rule, which may be due to the increasing role of collective movement in the structure of excited states.

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ГИГАНТСКИЙ *М*1-РЕЗОНАНС НА ОСНОВНЫХ И ВОЗБУЖДЕННЫХ СОСТОЯНИЯХ В ЯДРАХ 2*s*1*d*-ОБОЛОЧКИ

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Исследован гамма-распад резонансоподобных структур, наблюдаемых в реакции радиационного захвата протонов ядрами ^{22}Ne, ^{26}Mg, ^{30}Si, $^{34,36}S$ и ^{38}Ar в области энергий возбуждения 7…12 МэВ. Измерены функции возбуждения этих реакций и определены силы резонансов в области энергий ускоренных протонов E_p = 1,0…3,0 МэВ. Полученные дискретные распределения магнитных дипольных γ-переходов на основные и возбужденные состояния ядер 2*s*1*d*-оболочки имеют резонансный характер. Идентифицирован гигантский *M*1-резонанс на основных и возбужденных состояниях в ядрах ^{23}Na, ^{27}Al, ^{31}P, $^{35,37}Cl$ и ^{39}K. Положение *M*1-резонанса на возбужденных состояниях для ядер, находящихся в начале подоболочки, совпадает с ее значением, предсказанным гипотезой Бринка-Акселя.

ГІГАНТСЬКИЙ *М*1-РЕЗОНАНС НА ОСНОВНИХ І ЗБУДЖЕНИХ СТАНАХ В ЯДРАХ 2*s*1*d*-ОБОЛОНКИ

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Досліджено гамма-розпад резонансоподібних структур, які спостерігаються в реакції радіаційного захоплення протонів ядрами ^{22}Ne, ^{26}Mg, ^{30}Si, $^{34,36}S$ і ^{38}Ar в області енергій збудження 7…12 МеВ. Виміряно функції збудження цих реакцій та визначено сили резонансів в області енергій прискорених протонів E_p = 1,0…3,0 МеВ. Отримані дискретні розподіли магнітних дипольних γ-переходів на основні та збуджені стани ядер 2*s*1*d*-оболонки мають резонансний характер. Ідентифіковано гігантський *M*1-резонанс на основних і збуджених станах в ядрах ^{23}Na, ^{27}Al, ^{31}P, $^{35,37}Cl$ і ^{39}K. Положення *M*1-резонансу на збуджених станах для ядер, що знаходяться на початку підоболонки, збігається з її значенням, передбаченим гіпотезою Брінка-Акселя.