NATURE OF ISOVECTOR *l*-FORBIDDEN *M*1 TRANSITIONS IN LIGHT NUCLEI

A.N. Vodin, I.V. Ushakov, L.P. Korda, O.A. Lepyoshkina, S.A. Trotsenko

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
e-mail: ushakov@kipt.kharkov.ua

Systematization of existing experimental data on probabilities of *l*-forbidden *M*1 transitions observed in the γ-decay of isobaric analogue resonances in odd-nuclei with $A < 52$ is carried out. The collective effects, connected with excitation of core-polarized states and the giant *M*1 resonance, are shown to contribute to the mechanism removing *l*-forbideness for the mentioned *M*1 transitions.

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1. INTRODUCTION

It is known that *M*1 transitions with $\Delta l = 2$ are strictly forbidden in the pure shell model [1]. Nevertheless, such transitions are experimentally observed in all mass regions that make them the good tool for checking the theoretical approaches in describing properties of the excited states of nuclei.

Till now the isoscalar *l*-forbidden *M*1 transitions between low excited states without isospin changing $\Delta T = 0$ represent special interest for researches [2]. However, the previous analysis of experimental data [3] allows to state that among *M*1 transitions the other group of the single particle *l*-forbidden *M*1 transitions at which isospin of initial state $T_> = T_0 + 1/2$ and isospin of final state $T_< = T_0 - 1/2$ change by one unit (T_0 – isospin of a nucleus core) is allocated also.

The present work is a part of investigations of the isovector *l*-forbidden *M*1 transitions which include the results of our experiments on research of the γ-decay of analogue resonances (AR) in nuclei of the 1*d*2*s*-shell [4, 5] and also searching of the systematic tendencies for all known data on the mentioned type of transitions in nuclei with $A < 52$.

2. SELECTION OF EXPERIMENTAL DATA

The feature of considered mass region is the presence both spherical and deformed nuclei [6]. This fact considerably complicates the problem of identification of the pure single particle *l*-forbidden *M*1 transitions, and especially in our case, when the transition goes between resonance and excited levels in a nucleus with the change of isobaric spin on unit. Therefore, the objective criteria of the selection of experimental data need to be established.

Identification of configurations was carried out on intensity of state population, measured in reactions with passing of one nucleon or out of experiments on scattering nucleons on nuclei. However, such information was missing for some analog levels. In this case the values of spectroscopic factor S_n of parent states [7] were used.

As an indirect way for the selection of the single particle *l*-forbidden *M*1 transitions with $\Delta T = 1$ the values of mixing ratios $\delta(E2/M1)$ were used. Unfortunately, the experimental data about these parameters are utterly fragmentary and it does not give an opportunity to estimate the contribution of collective components in the structure of AR. On the basis of the available data it is possible to note that impurities of the *E*2 components in the *l*-forbidden *M*1 transitions are insignificant. For cases when spin of AR is equal to 1/2, the assumption that parameter $\delta(E2/M1) = 0$ for transitions $s_{1/2} \rightarrow d_{3/2}$ was accepted.

3. DATA ANALYSIS

The rules, formulated in the previous section, were used for the data selection for discussions, which are listed in the Table. There are also a number of γ-transitions in this Table which do not answer strictly to the selection rules mentioned above, but they allow to reveal systematic tendencies for *l*-forbidden *M*1-transitions $T_> \rightarrow T_<$ in light nuclei with odd *A*.

The data on total radiation widths Γ_γ of AR decay are taken, mainly, from the data on integrated cross sections of (pγ)-reactions. In the case, if the proton width Γ_p of a resonant level is not known, it is supposed that $\Gamma_p >> \Gamma_\gamma$ and only the lower limit of the partial width Γ_γ (*M*1) value is given in the Table. For AR laying on excitation energy lower than the energy of bound proton, the evaluation of the *l*-forbidden *M*1 transitions velocity was carried out from the life time τ of the given states [7]. The inaccuracy in value $\Gamma_\gamma(M1)$ includes the determination errors of Γ_γ, values of branching ratio $b(\gamma)$ and parameter $\delta(E2/M1)$. At presence of several sets of experimental data for specific γ-transition the preference was given to results with the least inaccuracies.

For the quantitative determination of the decay probability of the *l*-forbidden *M*1 transitions in comparison with single-particle evaluations, the factor of forbideness F_M was used:

$$F_M = \frac{B(M1)^{th}}{B(M1)^{exp}} . \qquad (1)$$

The evaluation of the $B(M1)^{th}$ value was taken from Moszkowski estimate [8] with the statistical factor $S(J_i, L, J_f) = 1$ as the γ-transitions forbidden on *l* in the single-particle shell model are considered. In such approximation we have [1]:

Spectroscopic data on l-forbidden M1 transitions $T_> \to T_<$ in light nuclei

Nucleus	$E_i^* \to E_f^*$, keV	$(lj)_i \to (lj)_f$	Γ_γ, 10^2·eV	δ(Δδ)	$B(M1)$, $10^2 \cdot \mu_N^2$	F_M	Ref.
^{9}Be	14392→2429	$p_{3/2}\to f_{5/2}$	762(38)		38.9	4.6	[9]
^{9}B	14655→2361	$p_{3/2}\to f_{5/2}$	762(76)		34.9	5.1	[9]
^{19}F	7540→4378	$d_{5/2}\to g_{7/2}$	151(24)	0.042(30)	407	0.44	[10]
	7661→ 0	$d_{3/2}\to s_{1/2}$	71(18)	0.06(2)	13.5	13.3	
	8793→1554	$s_{1/2}\to d_{3/2}$	5.6(9)	(0)	1.26	142	
	→3908	$\to d_{3/2}$	15.4(23)	(0)	11.3	15.9	
	→6497	$\to d_{3/2}$	4.2(6)	(0)	29.6	6.1	
	→6528	$\to d_{3/2}$	1.4(2)	(0)	10.3	17.4	
	→7262	$\to d_{3/2}$	1.2(2)	(0)	28.5	6.3	
^{21}Na	8973→1716	$d_{5/2}\to g_{7/2}$	67(13)	0.02(2)	17.2(33)	9.7(20)	[7]
	9220→ 0	$s_{1/2}\to d_{3/2}$	435(85)	(0)	55	3.0	
^{23}Na	7891→2076	$d_{5/2}\to g_{7/2}$	295(19)	0.01(4)	128(8)	1.4	[4,11]
	8664→ 0	$s_{1/2}\to d_{3/2}$	329(82)	(0)	49(7)	3.4	
	→2982	$\to d_{3/2}$	15.3(9)	(0)	8	20	
	9608→2391	$d_{3/2}\to s_{1/2}$	3(1)	-0.20(2)	0.78	213	
	→4430	$\to s_{1/2}$	1.1(3)	0.01(3)	0.78	213	
	9700→2391	$d_{3/2}\to s_{1/2}$	45	0.04(7)	5.5	45	
	9732→ 440	$g_{7/2}\to d_{5/2}$	≥2.2(6)	-0.033(7)	>0.27	<620	
	→3914	$\to d_{5/2}$	≥0.5(1)	0.12(5)	>0.25	<670	
	→5379	$\to d_{5/2}$	≥0.4(1)	-0.02(3)	>0.48	<350	
	→5742	$\to d_{5/2}$	≥0.5(1)	0.00(3)	>0.77	<216	
	10016→2076	$d_{5/2}\to g_{7/2}$	≥17.2(2)	0.276(14)	>3.3	<50	
	10169→2076	$d_{5/2}\to g_{7/2}$	1.44(4)	-0.11(3)	0.27	626	
	→4775	$\to g_{7/2}$	90(2)	-0.30(2)	56	3.0	
	→5927	$\to g_{7/2}$	1.44(4)	-0.18(4)	1.9	90	
	10231→2076	$d_{5/2}\to g_{7/2}$	≥3	0.01(5)	>0.54	<307	
	→5927	$\to g_{7/2}$	≥8.3	-0.04(2)	>10.2	<16.3	
	10346→2076	$d_{5/2}\to g_{7/2}$	2.3	0.06(2)	4.5	45	
	10440→2076	$d_{5/2}\to g_{7/2}$	2.4	-0.09(3)	5.6	56	
^{25}Mg	10549→2076	$d_{5/2}\to g_{7/2}$	3.4	0.07(6)	3.5	65	[7]
^{25}Al	7901→1613	$d_{5/2}\to g_{7/2}$	3.7(7)	-0.07(6)	1.5(4)	114(45)	[7,12]
	7970→ 452	$d_{3/2}\to s_{1/2}$	2.0(2)		0.46	361	
^{27}Al	6814→1014	$s_{1/2}\to d_{3/2}$	<1	(0)	>0.49	<342	[13]
	→3680	$\to d_{3/2}$	<0.3	(0)	>0.99	<169	
^{31}P	6381→ 0	$d_{3/2}\to s_{1/2}$	>2	(0)	>0.4	<500	[7]
	7141→1266	$s_{1/2}\to d_{3/2}$	46(5)	(0)	20(2)	8.8(9)	[14,15]
	8033→3415	$d_{5/2}\to g_{7/2}$	≥0.3	0.10(8)	>0.3	<650	
	→4634	$\to g_{7/2}$	≥0.1	0.03(8)	>0.3	<600	
	→5529	$\to g_{7/2}$	≥0.1	0.17(15)	>0.4	<400	
	8738→ 0	$d_{3/2}\to s_{1/2}$	2.0(5)	0.20(7)	0.29(7)	567(140)	
	→3134	$\to s_{1/2}$	4.6(11)	-20(14)	2.6(5)	65(13)	
	→5256	$\to s_{1/2}$	0.5(1)	0.15(10)	1.1(3)	150(40)	
	9241→ 0	$d_{3/2}\to s_{1/2}$	17(3)	0.04(3)	2.1(4)	79(16)	[16]
	→3134	$\to s_{1/2}$	3(1)	0.7(5)	1.3(3)	129(26)	
^{33}S	5480→ 0	$s_{1/2}\to d_{3/2}$	(3.2)	(0)	1.9	87	[12]
^{33}Cl	5544→ 0	$s_{1/2}\to d_{3/2}$	3.2	(0)	1.8	90	[12]
^{35}Cl	5654→1219	$d_{3/2}\to s_{1/2}$	0.2(80)		0.2	742	[17,18]
	7179→ 0	$s_{1/2}\to d_{3/2}$	2.7(8)	(0)	0.7	232	
	→2694	$\to d_{3/2}$	0.28(8)	(0)	0.3	548	
	→3918	$\to d_{3/2}$	0.21(6)	(0)	0.6	280	
	8381→2646	$s_{1/2}\to d_{3/2}$	5(1)	(0)	2.6	64	
	→2694	$\to d_{3/2}$	7(1)	(0)	8.8	19	

Nucleus	$E_i^* \to E_f^*$, кeV	$(lj)_i \to (lj)_f$	Γ_γ, 10^2·eV	δ(Δδ)	$B(M1)$, $10^2 \cdot \mu_N^2$	F_M	Ref.
^{41}Ca	5819→3400	$d_{3/2} \to s_{1/2}$	<0.3	0.03(2)	>1.8	<93	[19]
	6822→4417 →4728	$s_{1/2} \to d_{3/2}$ $\to d_{3/2}$	<0.1 <0.4	(0) (0)	>0.7 >2.0	<237 <82	
^{41}Sc	5939→3411	$d_{3/2} \to s_{1/2}$	2.3(6)	0.05(4)	14.0(35)	11.9	[7]
^{47}Sc	10310→1297	$p_{3/2} \to f_{5/2}$	5.4(6)		0.63	285	[20]
^{49}Sc	15555→3084	$f_{5/2} \to p_{3/2}$	>170		7.5	24	[21]
^{49}V	7745→ 91 →4085 →4122 →4631	$p_{3/2} \to f_{5/2}$ $\to f_{5/2}$ $\to f_{5/2}$ $\to f_{5/2}$	32 21 6 5		6.1 36.5 10.8 14.1	29 4.9 16.6 12.7	[21]
^{51}V	9390→ 319 →3082	$p_{3/2} \to f_{5/2}$ $\to f_{5/2}$	73.6 11.5		8.4 3.9	21 46	[22]

$$B(M1)^{\text{th}} = \frac{1}{\pi} M_\mu \, \mu_N^2 , \qquad (2)$$

where for transitions such as $l \pm 1/2 \leftrightarrow l \mp 1/2$.

$$M_\mu = (\mu - \frac{1}{2} g_l)^2 . \qquad (3)$$

Here μ – the magnetic moment of a nucleon; g_l – the orbital gyromagnetic ratio.

4. DISCUSSION

The analysis of the collected experimental data on the given $M1$ transitions in considered nuclei allows formulating some general conclusions. It is established that l-forbidden $M1$ transitions with $\Delta T = 1$ are observed in all region of odd nuclei with $A < 52$. There are two types of isovector l-forbidden $M1$ transitions. Their intensity, in some cases, is comparable with the intensity of the single-particle $M1$ transitions between the analog and antianalog states ($B(M1) \sim 1$ W.u.).

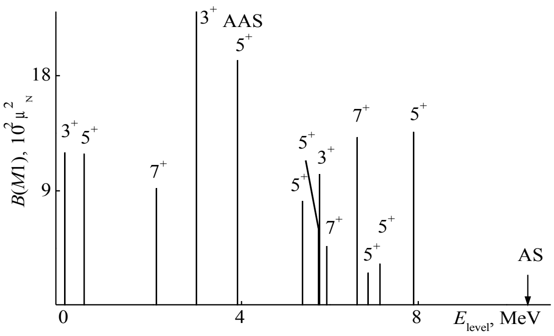
Transitions such as AR → 0 are concerned to the first type of the investigated ones. The nature of such transitions is caused by that the giant $M1$-resonance, which centre of gravity, is placed in the region of excitation energy of analogue states in light nuclei, takes part in formation of total radiation width of AR.

To the second type – $M1$ transitions from AR on the low-excited states in nuclei related to the core-polarized. Really, γ-transitions to these states are possible.

For example, the distribution of $B(M1)$ values for direct transitions from an analog $d_{5/2}$-state on low-lying levels in ^{23}Na is shown at the Figure. It is visible from distribution of $B(M1)$ that excited states with $J^\pi = 3/2^+$, $5/2^+$ and $7/2^+$ are most intensively populated. Its centre of gravity lays at $E^* \approx 4{,}93$ MeV. This maximum in distribution is caused by population of core-polarized states (CPS), which are fragmented on a spectrum of the ^{23}Na nucleus, and it lies in region of excitation energy expected from microscopic calculations [23]:

$$E_{\text{AR}} - E_{\text{CPS}} = \frac{V_1}{A}(T_0 + 1/2) + P_n , \qquad (4)$$

where P_n – pairing energy of a neutron.



Distribution of probabilities B(M1) for direct transitions from an analog $d_{5/2}$ state to levels of ^{23}Na

In fact the given analogue state has a configuration $\left|(d_{5/2}^2)^n_{J_0T_0} d_{5/2}\right\rangle_{J=5/2,T=3/2}$, i.e. it may be considered as one $1d_{5/2}$ nucleon connected with two $d_{5/2}$ neutrons, coupled in $(J_0T_0) = (01)$ over an inert core of ^{20}Ne (^{20}Ne is possible to consider as twice magic core ^{16}O + α-cluster). Then the transition of the core from $(d_{5/2}^2)^n_{01}$ to $(d_{5/2}^2)^n_{10}$ is possible, and in this case the probability of $M1$ transition is large according to [24] since transition includes a $d_{5/2}$-particle. It should be noticed that there is the core-core $M1$ transition without changing state of a valent $d_{5/2}$-particle. Thus, it is necessary to conclude, that the mechanism removing l-forbideness for the mentioned $M1$ transitions occurs due to the collective effects connected with the excitation of core-polarized states and the giant $M1$ resonance.

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ПРИРОДА ИЗОВЕКТОРНЫХ *l*-ЗАПРЕЩЕННЫХ *M*1-ПЕРЕХОДОВ В ЛЕГКИХ ЯДРАХ

А.Н. Водин, И.В. Ушаков, Л.П. Корда, О.А. Лепешкина, С.А. Троценко

Проведена систематика экспериментальных данных о вероятностях изовекторных *l*-запрещенных *M*1-переходов, наблюдающихся при распаде изобар-аналоговых состояний в легких ядрах с нечетным *A*. Показано, что заметный вклад в механизм снятия *l*-запрета для указанных *M*1-переходов дают коллективные эффекты, обусловленные возбуждением состояний типа поляризации остова и гигантского *M*1-резонанса.

ПРИРОДА ІЗОВЕКТОРНИХ *l*-ЗАБОРОНЕНИХ *M*1-ПЕРЕХОДІВ У ЛЕГКИХ ЯДРАХ

О.М. Водін, І.В. Ушаков, Л.П. Корда, О.О. Лепешкіна, С.О. Троценко

Проведено систематику експериментальних даних про ймовірності ізовекторних *l*-заборонених *M*1-переходів, що спостерігаються при розпаді ізобар-аналогових станів у легких ядрах із непарним *A*. Показано, що помітний внесок у механізм зняття *l*-заборони для зазначених *M*1-переходів дають колективні ефекти, пов'язані зі збудженням станів типу поляризації остова та гігантського *M*1-резонансу.