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A mechanism for excitation of metastable levels by (γ, γ') reactions

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The analysis of the cross-section of ^{77}Se and ^{87}Sr isomeric states excitation in the (γ, γ') reaction, was carried out using neutron pick-up and stripping reaction results. It allows the shell configurations of the transitions to the activation states to be determined. To check thus obtained conclusions the energies of $J^\pi = 1^-$ excited states for ^{90}Zr and ^{138}Ba were calculated, which are in good agreement with the resonance structure at the γ-quanta elastic scattering in the 5 to 10 MeV energy range.

1. Introduction

Now, interest in the study on excitation of isomeric nuclei in the reaction of γ-quanta inelastically scattering by atomic nuclei has been resumed, mostly by studying the nuclei isomeric states excitation mechanism, which is to a certain degree related to the problem of γ-lasers [1].

The present report is aimed at attracting attention to the possibility of an atomic nucleus to be described by one-nucleon transitions, using the information from the one-nucleon transfer reactions.

We begin with the main regularities, which have been revealed by experimental studies of metastable states excitation in the reaction of γ-quanta inelastically scattering by atomic nuclei within the energy range below 25 MeV.

The study of nuclei isomeric states excitation at the reaction of γ-quanta inelastically scattering by nuclei has been carried out already for about 55 years since the pioneer papers [2,3], and a vast amount of experimental data has been accumulated. A review [4], containing more than 110 references, is devoted mainly to the investigation of the nuclei isomeric states excitation at a γ-quanta energy below 3 MeV. The $A(\gamma, \gamma')A^{\mathrm{m}}$ reaction in the energy range of 4 to 20 MeV was studied in refs. [5–12]. New results of the nuclei isomeric states excitation at the $A(\gamma, \gamma')A^{\mathrm{m}}$ reaction at an energy of 1.5 to 7 MeV in refs. [13–20] and the $A(\gamma, \gamma')A^{\mathrm{m}}$ reaction absolute cross-sections at energies of 4 to 14 MeV [21–27] have been obtained recently. A number of papers [28–31] is devoted to studies of short-lifetime isomeric states excitation at the $A(\gamma, \gamma')A^{\mathrm{m}}$ reaction in the range of energies from 3 to 6 MeV.

In nuclear reactions induced by photons with the energies below 30 MeV, the main role can be played only by E1, E2 and M1 transitions, while the isomeric transitions mostly belong to the E3, M4, M5 type, evidently implying the low probability of the nucleus isomeric state excitation by γ-quanta (the problem of the nuclei isomeric states direct excitation by the Mössbauer effect is discussed in ref. [32]). Therefore, nucleus isomeric state excitation occurs as follows. A level (usually called the activation level, energetically higher than the metastable one) is excited, for which the probability of the transition to the metastable level is comparable with that of the transition to the ground state. Thus the de-excitation of the activation level results in the isomeric state excitation.

The experimental studies of γ-quanta inelastic scattering by nuclei which have been carried out, can be classified into several groups:

- determination of the principal possibility of the isomers to be activated;
- determination of activation level energies, widths and the activation cross-sections;
- plotting the $A(\gamma, \gamma')A^{\mathrm{m}}$ absolute reaction cross-section versus the γ-quanta energy;
- plotting the $A(\gamma, \gamma')A^{\mathrm{m}}$ reaction integrated cross-section versus the γ-quanta energy;
- applications of the γ-quanta inelastic scattering in γ-activation analysis of materials and γ-radiation monitoring.

It should be noted that the data, obtained from the experiments on the γ-quanta inelastic scattering by nuclei, combined with the results obtained by other techniques for nuclei excitation (e.g. one-nucleon transfer reactions), can give important information on the nucleus energy level structure and the transition multipolarity.

The studies of the nuclei metastable states excitation in (γ, γ') reaction have revealed the metastable states to be populated via the separate activation levels of the nucleus [29–31,33–38], the metastable state excitation cross-sections within the energy range of 3 to 7 MeV being two to three orders of magnitude higher than those below 2.5 MeV. Besides, in ref. [27] the isomeric cross-section ratio in the (γ, γ') reaction (i.e. the ratio of the metastable state excitation cross section in the (γ, γ') reaction to the total photoabsorption cross-section) was noticed to be sensitive to the metastable state shell structure.

The present paper is aimed to perform an analysis of the data on ^{77}Se and ^{87}Sr nuclei metastable states excitation in the energy range below 3 MeV along with the results concerning the single-nucleon transfer reactions for the discussed nuclei.

The problem of the second maximum in $A(\gamma, \gamma')A^{\mathrm{m}}$ reaction cross-sections for ^{89}Y, ^{103}Rh, ^{107}Ag, ^{197}Au, revealed in refs. [6–9] at energies near 20–22 MeV, at present still remains open. The nature of the maximum was discussed in refs. [39,40] in the framevork of the shell model of nuclei and is supposed to be related to the isobar-analog resonances, in particular, with 2p–2h excitations.

As noted above, the metastable states in the (γ, γ') reaction are populated via the higher energy excited levels of the nucleus, therefore, the issue on the metastable state population mechanism is reduced to the nuclear levels excitation mechanism.

At the interaction of γ-quanta with atomic nuclei the nuclear level excitation occurs either due to photoabsorption (i.e. via the giant dipole resonance states), or at the γ-quanta inelastic scattering.

Within the discussed range of the excitation energies below 3 MeV there is a discrete spectrum of excited nuclear levels. In this case the γ-quanta inelastic scattering is the main channel of the nucleus excitation.

In the approximation of one resonance level the probability P of exciting an isomeric level is determined by

$$P = \Phi(E_{\mathrm{r}})\sigma_{\mathrm{r}}\,, \tag{1}$$

where

$$\sigma_{\mathrm{r}} = g(\lambda^2/4\pi)\Gamma_0\Gamma_{\mathrm{iso}}/\Gamma\,.$$

The parameters g, Γ_0, Γ_{iso}, and Γ are, respectively, the statistical weight, the ground state transition width of the resonance level, the partial width for the decay to the isomeric level, and the total width of the resonance level. λ is the wavelength of the γ-quanta which excite the resonance level at the energy E_{r}. $\Phi(E_{\mathrm{r}})$ is the flux of photons per unit energy interval.

The analysis of the experimental studies of metastable states excitation in the range of isolated levels, i.e. via the activation states, is based on eq. (1).

At present there are some indications [41–43] of the presence of nonresonant processes at the nuclei metastable states excitation by isotopic sources of γ-quanta. The same issue was discussed in ref. [44].

In this view ref. [45] should be mentioned. Evidently it seems to be a single paper where are the mechanism of the nuclear levels non-resonant excitation is proposed. This mechanism is similar to the Compton effect, only instead of the γ-quantum scattering the nucleus excitation occurs. In ref. [45] such a process is called the nucleus Compton excitation.

2. Analysis of isomers excitation data

The analysis of photonucleon reactions, performed in refs. [46–48], indicated a correlation of partial photoproton cross-sections of the population of finite nuclei lower excited states with the pick-up reactions data. In refs. [49,50] a correlation of (e,e′p) and (d,τ) reactions for closed-shell nuclei was also indicated. The correlation of fpg-shell nuclei isomeric states excitation cross-sections in (γ,n) reaction is also indicated in ref. [51]. Such a correlation probably enables to make the choice in favour of the one-nucleon mechanism of the γ-quanta interaction with the atomic nucleus, at least for the near-magic nuclei. Recently in ref. [52] a positive correlation between the excitation of ^{15}N and ^{39}K nuclei hole states, excited in (γ,γ') and (d,τ) reactions was found. This part of the report will be devoted to the analysis of (γ,γ') reactions with the excitation of ^{77m}Se and ^{87m}Sr nuclei and the data from the (p,d) reactions for ^{78}Se and ^{88}Sr nuclei.

These nuclei are chosen due to the necessary information for them being available from the one-nucleon transfer reaction [53–58] and (γ,γ') reactions [35,36].

Using the spin-dependent sum rule [59] for the spectroscopic factors from the one-nucleon transfer reaction for ^{78}Se and ^{88}Sr nuclei, one can conclude the 1f2p1g shell in ^{88}Sr nucleus to be completely filled with neutrons and $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$ subshells in the ^{78}Se nucleus to be completely filled with neutrons, and the $1g_{9/2}$ subshell to contain only four neutrons.

In table 1 the ^{77}Se and ^{87}Sr nuclei levels with excitation energy below 1.7 MeV for ^{77}Se and below 2.7 MeV for ^{87}Sr are listed.

Only the levels, via which the metastable states can be populated, are included, i.e. those pretending for the activation levels. For the levels, observed in pick-up reactions, the spectroscopic factors C^2S^- are listed. For comparison, the activation level energies, detected in the (γ,γ') reaction in refs. [35,36], are also enumerated.

It is seen that for ^{77}Se nucleus in the (γ,γ') reaction mainly the same levels are observed, as those observed in (p,d) reactions, except the 950 keV level, observed in the (d,p) reaction [54].

As noted above, the $2p_{1/2}$, $2p_{3/2}$ and $1f_{5/2}$ subshells in the ^{78}Se nucleus are completely filled, and the $1g_{9/2}$ subshell contains four neutrons, which means that the ^{77}Se levels, observed in the (p,d) reaction, are the holes in the corresponding subshells. The ^{77}Se nucleus subshell ground state is the hole state of the $2p_{1/2}$ subshell. In this case in order to excite the level with energy 250 keV and spin $J^\pi = 5/2^-$, being the $1f^{-1}_{5/2}$ hole state (as observed in the (p,d) reaction), one should transfer a neutron from the filled $1f_{5/2}$ subshell to the unfilled $2p_{1/2}$ subshell, i.e. the $1f_{5/2}$–$2p_{1/2}$ transition should be realized.

A similar pattern is observed for the rest of the activation levels. The configurations of the transitions, occurring at the activation levels excitation for ^{77}Se, are listed in table 1. The activation level with an energy of 950 keV should, probably, be assigned to the $2p_{1/2}$–$3s_{1/2}$ transition. The transition type for the activation level with an energy of 1600 ± 10 keV, coresponding most likely to the 1623 keV level from the (p,d) reaction [53], cannot be determined, since its structure is undetermined. In the case of the ^{87}Sr nucleus four activation levels with energies below 1220, 1220, 1880 and 2660 keV have been experimentally observed. We assign the activation level with the energy below 1220 keV to the level with an energy of 873 keV. Since the ^{87}Sr isomer was excited by γ-quanta from the isotopic source ^{46m}Sc [4], emitting γ-quanta with the energies of 890 and 1170 keV. The activation level with the energy 1220 keV may correspond to the level with the energy 1228 or 1254 keV, usually the former being chosen as the activation level. The activation level with an energy of 1880 keV most likely corresponds to the level with an energy of 1920 keV and spin $7/2^+$, which agrees with the fracture at the ^{87}Sr isomer efficiency curve depending on the electron

Table 1

E (keV) [58]	J^π	P [58]	nlj	C^2S^-(p, d) [53]	E_a (keV) [36]	Transition configuration	Type
				^{77}Se			
0	$1/2^-$		$2p^{-1}_{3/2}$	0.35			
168	$7/2^+$						
175	$9/2^+$		$1g^{-1}_{9/2}$	2.54			
239	$3/2^-$						
250	$5/2^-$	0.32	$1f^{-1}_{5/2}$	2.38	250±10	$1f_{5/2} \longrightarrow 2p_{1/2}$	E2
300	$5/2^+$	–	$2d_{5/2}$	0.09			
439	$5/2^-$	0.012	$1f^{-1}_{5/2}$	0.37	440±10	$1f_{5/2} \longrightarrow 2p_{1/2}$	E2
521	$3/2^-$	0.004	$2p^{-1}_{3/2}$	0.98	520±10	$2p_{3/2} \longrightarrow 2p_{1/2}$	M1
581	$7/2^-$	0.034					
680	$5/2^+$	0.9	$2d_{5/2}$	0.097			
818	$1/2^-$	$< 10^{-4}$	$2p^{-1}_{1/2}$				
824	$3/2^-$	0.08	$2p^{-1}_{3/2}$	0.26	825±10	$2p_{3/2} \longrightarrow 2p_{1/2}$	M1
950	$1/2^+$		$3s_{1/2}$	0.36 [54]	932±10	$2p_{1/2} \longrightarrow 3s_{1/2}$	E1
1005	$3/2^-$	0.12	$2p^{-1}_{3/2}$	0.15	1000±10	$2p_{3/2} \longrightarrow 2p_{1/2}$	M1
1186	$5/2^-$	–	$1f^{-1}_{5/2}$	0.25	1190±10	$1f_{5/2} \longrightarrow 2p_{1/2}$	E2
1231	$5/2^-$	0.03	$1f^{-1}_{5/2}$	0.54			
1623	(p,d)		–	–	1600±10		
				^{87}Sr			
0	$9/2^+$	[55]	$1g^{-1}_{9/2}$	5.4 [56]	[35]		
388	$1/2^-$		$2p^{-1}_{1/2}$	2.42			
873	$3/2^-$	1	$2p^{-1}_{3/2}$	3.91	< 1220	$2p_{3/2} \longrightarrow 1g_{9/2}$	E3
1228	$5/2^+$	0.11		0.43			
1254	$5/2^-$	1	$1f^{-1}_{5/2}$	4.19	1220	$1f_{5/2} \longrightarrow 1g_{9/2}$	M2
1770	$5/2$	0.04					
1920	$7/2^+$				1880		
2116	$5/2^-$	1					
2169	$1/2^+$	1					
2414	$5/2^-$	0.82	$1f^{-1}_{5/2}$	0.715			
2660	$5/2^-$	1	$1f^{-1}_{5/2}$	0.57	2660	$1f_{5/2} \longrightarrow 1g_{9/2}$	M2

energy in ref. [35]. The level with an energy of 1920 keV is observed in the (p,d) reaction [56], being a multiplet $2^+ \oplus 1g^{-1}_{1/2}$. The activation level with the energy 2660 keV corresponds to the level with the energy 2660 keV, being the hole state in the $1f_{5/2}$ subshell. The ground state of the ^{87}Sr nucleus is the hole state of the $1g_{9/2}$ subshell. By using the same procedure, as the above one for the ^{77}Se nucleus, the transition configurations for the excitation of the activation levels with energies below 1220 and 2660 keV could be determined and are listed in table 1. The level with an energy of 1880 keV falls out of this scheme. The accuracy of the 1220 keV activation level energy measurement is not sufficient for one of the ^{87}Sr levels – 1228 or 1254 keV is to be identified unambiguously.

Thus, the above speculations enable us to conclude the activation level in the range of the excitation energies below 2.7 MeV to be formed due to the one-nucleon transition in the framework of one upper unfilled nuclear shell, for the nuclei in question this being the 1f2p1g shell. These transitions will be referred to as those of type A.

Besides the transitions between the subshells of the same upper nuclear shell being filled to the neighbouring free nuclear shell (the energetic superimposement of whose subshells can be determined from the stripping reactions), are possible. We refer to these transitions as type B. In our case of ^{77}Se, ^{87}Sr nuclei these will be the transitions from the 1f2p1g shell to the 3s2d1g1h shell. Such transitions will result in the formation of a hole state at one of the subshells of the 1f2p1g shell, corresponding to the hole state in an $A-1$ nucleus, being revealed in the pick-up reaction for the A nucleus, while at one of the subshells of the 3s2d1g1h shell a particle state is formed, corresponding to the particle state of an $A+1$ nucleus, being revealed in the stripping reaction for the A nucleus. The energy of such a particle–hole state (1p–1h state) can be determined from refs. [60,61] by means of the expression

$$E_{\mathrm{ph}} = \varepsilon_{\mathrm{p}} + \varepsilon_{\mathrm{h}} + E^{\mathrm{c}}_{A} - E^{\mathrm{c}}_{A+1}\,, \tag{2}$$

where ε_{p} is the particle state energy determined in the stripping reaction for the A nucleus; ε_{h} is the hole state energy, determined in the pick-up reaction for the A nucleus; E^{c}_{A}, E^{c}_{A+1} are the binding energies of one nucleon (neutron) in the A or $A+1$ nucleus, respectively.

Using eq. (2), we have estimated E_{ph} energies for the states being formed due to E1 transitions for ^{90}Zr and ^{138}Ba nuclei, since for these nuclei the cross-sections of γ-quanta elastic scattering are available [62,63], while the particle ε_{p} and ε_{h} hole state energies are taken from refs. [57,64–66]. In the estimations only the levels possessing the highest spectroscopic factor in the one-neutron transfer reactions, were taken into account. The estimated energies E_{ph} and the energies E_{r}, corresponding to the observed maxima in the elastic scattering cross-section, are listed in table 2. They are seen to correlate, which means that the observed structure can be explained by the neutron transitions of type B. The transition configurations for the corresponding energies E_{ph} are also listed in table 2.

Thus, in the model of one-nucleon transitions between the subshells along with the one-nucleon transfer reactions data, the resonance structure in the cross-section of γ-quanta elastic scattering by ^{90}Zr and ^{138}Ba nuclei can be explained.

It should be noted that the obtained integrated cross-sections for $^{123\mathrm{m}}$Te and $^{135\mathrm{m}}$Ba isomers excitation are higher than those for $^{125\mathrm{m}}$Te and $^{137\mathrm{m}}$Ba isomers, respectively, the integrated cross-section value for the isomer excitation decreasing with the mass number of these nuclei.

The analysis of the one-nucleon transfer reactions shows the metastable states of ^{123,125}Te, ^{135,137}Ba nuclei to be formed by the $1\mathrm{h}_{11/2}$ subshell. Besides, in these nuclei the $1\mathrm{h}_{11/2}$ subshell is filled with neutrons with the increase of the mass number A. The difference between ^{123}Te and ^{125}Te or ^{135}Ba and ^{137}Ba nuclei consists in the $1\mathrm{h}_{11/2}$ subshell for ^{123}Te and ^{135}Ba being more filled then for ^{123}Te and ^{135}Ba, respectively.

Table 2

Transition configuration		ε_h (MeV)	ε_p (MeV)	E_{ph} (MeV)	E_r (MeV)	Transition configuration		ε_h (MeV)	ε_p (MeV)	E_{ph} (MeV)	E_r (MeV)
^{90}Zr $E_A^c - E_{A+1}^c = 4.8$ MeV						^{138}Ba $E_A^c - E_{A+1}^c = 3.86$ MeV					
$2p_{3/2}^{-1}$	$2d_{3/2}$	1.09	2.04	7.9	8.25	$2d_{3/2}^{-1}$	$3p_{1/2}$	0.0	1.09	4.95	4.8
$1f_{5/2}^{-1}$	$2d_{3/2}$	1.45	2.04	8.3	8.5	$2d_{5/2}^{-1}$	$2f_{7/2}$	1.29	0.0	5.15	5.1
$1f_{5/2}^{-1}$	$1g_{7/2}$	1.45	2.20	8.45	8.75	$2d_{3/2}^{-1}$	$2f_{5/2}$	0.0	1.42	5.28	5.3
$1f_{5/2}^{-1}$	$2d_{3/2}$	2.1	2.04	9.0	9.0	$2d_{5/2}^{-1}$	$2f_{7/2}$	2.0	0.0	5.86	5.8
$1f_{5/2}^{-1}$	$2d_{3/2}$	2.1	2.2	9.1	9.2	$1g_{7/2}^{-1}$	$1f_{7/2}$	2.23	0.0	6.09	6.2
$1f_{5/2}^{-1}$	$2d_{3/2}$	1.45	3.08	9.3	9.35	$1g_{7/2}^{-1}$	$1f_{7/2}$	2.54	0.0	6.4	6.4
$1f_{5/2}^{-1}$	$1g_{7/2}$	1.45	3.47	9.7	9.5	$1g_{7/2}^{-1}$	$1f_{7/2}$	2.99	0.0	6.85	6.8
$1f_{5/2}^{-1}$	$2d_{3/2}$	2.1	3.08	10.0	10.0	$1g_{7/2}^{-1}$	$1h_{9/2}$	2.23	1.28	7.4	7.4
$1f_{5/2}^{-1}$	$2d_{3/2}$	2.1	3.47	10.4	10.4	$1g_{7/2}^{-1}$	$1h_{9/2}$	3.0	1.28	8.1	8.1
						$1g_{7/2}^{-1}$	$1h_{9/2}$	3.0	1.6	8.45	8.4

Therefore, the population of the $1h_{11/2}$ subshell by the one nucleon transition via the higher subshell is more probable for ^{123}Te and ^{135}Ba nuclei. This results in the probability of ^{123}Te and ^{135}Ba metastable states population being higher than for ^{125}Te and ^{137}Ba. The difference by one or two orders of magnitude in the integrated cross-sections [16–20] of metastable states excitation within the energy ranges below 3 and above 5 MeV can be explained by the fact that in the first range the isomers are excited via the activation levels being formed due to the type A transitions, while in the second range due to those of type B.

3. Conclusions

The above analysis of the (γ, γ') reaction with the excitation of ^{77}Se and ^{87}Sr nuclei isomeric states within the γ-quanta energy range below 3 MeV along with the one-nucleon transfer reactions data enabled to conclude the activation states, via which the nuclei metastable states are populated, to be excited due to the one-nucleon transitions from the filled subshells to the unfilled one within the same nuclear shell.

Based on this conclusion, we have estimated the energies of ^{90}Zr and ^{138}Ba nuclei 1p–1h states, excited due to the one-nucleon transitions from their upper unfilled subshell to the neighbouring empty shell. The thus obtained 1p–1h state energies correspond to the resonance structure in the cross-section of γ-quanta elastically scattering by these nuclei.

Within the one-nuclear transitions assumption the nature of the difference in the integrated cross-sections of ^{123}Te and ^{125}Te, ^{135}Ba and ^{137}Ba isomers excitation can be explained.

Thus, the approximation of the one-nucleon transitions between the nuclear subshells along with the data from the one-nucleon transfer reactions, proves to be efficient for the analysis of the experiments on the metastable nuclear states excitation in the reaction of γ-quanta inelastic scattering in order to elucidate the mechanism of such reactions.

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