INVESTIGATION OF GIANT RESONANCES WITH THE BIN MULTIPOLE ANALYSIS IN ^{6}Li AT MOMENTUM TRANSFERS RANGING FROM 0.75 TO 1.30 fm^{-1}

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The giant resonances in ^{6}Li nucleus were investigated basing on the electro-nuclear experimental data and by means of the bin multipole analysis. As a result the Coulomb excitation and the multipolarities of transitions in ^{6}Li at excitation energies $\varepsilon = 4.31$; 5.65; 15.80; 17.98 MeV and for sum of resonances at $\varepsilon = 24.78$, 24.89, 26.60 MeV were determined. Furthermore new resonance of the nucleus at $\varepsilon = 10.3 \pm 0.4\,MeV$ and with multipolarity $\lambda = 0$ or 2 was discovered.

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1. INTRODUCTION

The giant resonances (GR) in nuclei were actively investigated both by means inelastic electron scattering and using other probe particles. However, when the results of the investigations for $A > 90$ nuclei has systematical character, in the case of light nuclei the giant resonances experimental data are scarce (see, for instance, reviews [1, 2]). It's necessary to say, that the interpretation of GR as the collective excitation of nucleus becomes conditional in the case of light nuclei. Though, the usage of this term for light nuclei are proved to be correct, because above the nucleon threshold the excited levels of these nuclei have the energy width of order 1 MeV or more, as well as GR in the case of $A > 90$ nuclei.

As for nuclei close to the lightest, the investigations of excited states of these nuclei at energies above the nucleon or cluster threshold are of particular interest from the point of view of the astrophysical problems (the nucleosynthesis inside the stars) and for the theory of the controlled thermonuclear fusion. ^{6}Li nucleus is one of such nuclei.

According to paper [3], the excited levels of ^{6}Li nucleus are placed at excitation energies $\varepsilon = 2.0 \ldots 6.0\,MeV$ and form $18.0 \ldots 27.0\,MeV$. In modern database [4] GR at $\varepsilon = 15.80$ MeV and at $\varepsilon = 21.5$, $23.0\,MeV$ are present in the table of ^{6}Li nucleus "adopted levels". However, in the author's [4] opinion, the information about these levels is not reliable. It's necessary to say, that in the inelastic electron scattering experiment the ^{6}Li nucleus levels were investigated up to excitation energy $\varepsilon = 5.5$ MeV only. And the excitation nature (magnetic, transversal electric or Coulomb transitions) and the transition multipolarities (λ) are only known for first four excited levels of ^{6}Li nucleus [3, 4, 5].

The aim of the present paper is the investigation of GR properties of ^{6}Li nucleus in wide excitation energies region basing on the electron scattering experiment.

2. EXPERIMENT AND DATA PROCESSING

The experimental spectra of inelastically scattered by ^{6}Li electrons were obtained at the linear accelerator LUE-300 of NSC KIPT. The investigation of the quasi-elastic scattering (QES) of electrons was the primary goal of these measurements. Therefore the energy resolution of the equipment was chosen 1.4% for increasing of the count-rate statistic. The chemical purity of the lithium target was better than 99.9%, and the isotope composition was ^{6}Li - 90.5% and ^{7}Li - 9.5%. The details of the equipment and the experiment can be found elsewhere [7, 8].

Five spectra of scattered electrons were used for the investigation of GR in ^{6}Li at initial energy $E_0 = 259.0$ MeV and scattering angle $\theta = 34^\circ\,10'$, $40^\circ\,30'$, $47^\circ\,00'$, $53^\circ\,20'$, $60^\circ\,30'$.

Each measured spectrum have been corrected for the radiative effects according to formulas of the work [9]. At the same time we measured ^{6}Li(e, e')-spectra and elastic electron scattering by ^{12}C nuclei. These data and precise data of elastic electron scattering by ^{12}C nuclei from work [10] were used for the normalization procedure of measured spectra ^{6}Li(e, e'). As a result the scattered electron spectra were obtained in the excitation energies region $\varepsilon = 3 \ldots 38\,MeV$.

For the further analysis the spectra were divided into successive bins of equal excitation energy intervals and averaged. They were $0.5\,MeV$ in the range

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$\varepsilon = 3 \ldots 18\,MeV$ and $1.0\,MeV$ at $\varepsilon = 18 \ldots 38\,MeV$.

Then the double-differential cross-sections of inelastic electron scattering $(\frac{d^2\sigma}{d\Omega dE})_{inel}$ were used for calculation of differential form factors:

$$F^2_{dif}(q,\varepsilon) = (\frac{d^2\sigma}{d\Omega dE})_{inel}/\sigma_{Mott}\,. \quad (1)$$

Here σ_{Mott} is the electron scattering cross-section by point nucleus with nuclear charge Z.

$$\sigma_{Mott} = \left(\frac{Ze^2}{2E_0}\right)^2 \cdot \frac{cos^2(\theta/2)}{sin^4(\theta/2)} \cdot \frac{1}{\eta}\,, \quad (2)$$

where e is the electron charge, $\eta = 1 + 2E_0 sin^2(\theta/2)/M$ is the kinematical correction, M is the nucleus mass. The effective 3-momentum transferred to nucleus is written as

$$q = [4 \cdot E_0 \cdot (E_0 - \omega) \cdot sin^2\frac{\theta}{2} + \omega^2]^{1/2} \cdot \xi,$$

where ω is the transferred to nucleus energy, ξ takes into account the distortion of the electron wave by the electrostatic field of nucleus. Note that the formula shown here is from ref.[11]

$$\xi = 1 + \frac{4}{3} \cdot \frac{Ze^2}{E_0 \cdot < r^2 >^{1/2}},$$

and $< r^2 >^{1/2}$ is the root mean square radius.

The obtained differential form factors of ^{6}Li nucleus are shown in Fig.1.

3. DIFFERENTIAL FORM FACTOR ANALYSIS

The obtained differential form factors of ^{6}Li nucleus contain the information both about excited levels and QES of electrons by nucleon of nucleus. In the case of levels characteristics study the QES continuum is background. One of the correct methods of taking into account of this background is the bin multipole analysis, modernized in the work [6]. This approach is used by us for data analysis.

Within Helm framework the squared form factor $F^2_\lambda(q)$ for Coulomb transition with multipolarity λ is

$$F^2_\lambda(q) = j^2_\lambda(qR) \cdot exp(-q^2 g^2), \quad (3)$$

where $j_\lambda(qR)$ is Bessel spherical function of order λ, and model parameters R and g correspond to nucleus under study.

The only Coulomb transition in ^{6}Li nucleus, for which form factor was measured, is the excited level at $\varepsilon = 2.18\,MeV$ and $\lambda = 2$. To obtain the R and g values the approximation of this ^{6}Li excited level data from [12, 13] by expression (3) was made. The derived parameters are $R = 0.43\,fm^{-1}$ and $g = 1.35\,fm^{-1}$, and the fitting result is shown in Fig.2.

Then differential form factors $F^2_{dif}(q,\varepsilon_i)$ for each bin corresponding to the same excitation energy ε_i is assumed to be the sum

$$F^2_{dif}(q,\varepsilon_i) = \sum_{\lambda=1}^{3} \beta_\lambda F^2_\lambda(q), \quad (4)$$

where β_λ are determined by least-square fitting and correspond to transitions of multipolarity λ.

The highest multipole term in the sum (4) was $\lambda = 3$, as the multipolarities $\lambda > 3$ give small contribution to the form factor in the region under study $q = 0.75 \ldots 1.30\,fm^{-1}$. The example of the bin multipole analysis of differential form factor for $\varepsilon_i = 18\,MeV$ is shown in Fig.3.

As a result of the approximation of experimental values of $F^2_{dif}(q,\varepsilon)$ by expression (4) we obtained the dependences $\beta_{\lambda=1,2,3}(\varepsilon)$ in the range $\varepsilon = 3 \ldots 38\,MeV$ (Fig.4). Then these β_λ-dependences were analysed by Gaussian sum fitting. Let us consider in detail the β_λ-dependences analysis.

There are two well-visible picks at $\varepsilon = 4.5\,MeV$ and $\varepsilon = 18.8\,MeV$ in the β_1-dependence. They were fitted by Gaussians with all free parameters. Notice, the experimental energy resolution was taken into consideration in the width parameter, as here and below. The obtained at $\varepsilon = 18.8 \pm 0.8\,MeV$ pick corresponds with the known level at $\varepsilon = 17.98\,MeV$ within the limits of experimental errors (see the schema of ^{6}Li nucleus levels from [4] in the left part of table).

There aren't Coulomb transitions with multipolarities $\lambda = 1$ near the excitation energy $4.5\,MeV$, and magnetic transitions are suppressed under our experimental conditions. Hence, it may be assumed, that the obtained at $\varepsilon = 4.5\,MeV$ pick can be explained by electrons QES on α-cluster of ^{6}Li (in this excitation energy region the same process was observed in works [12, 14]).

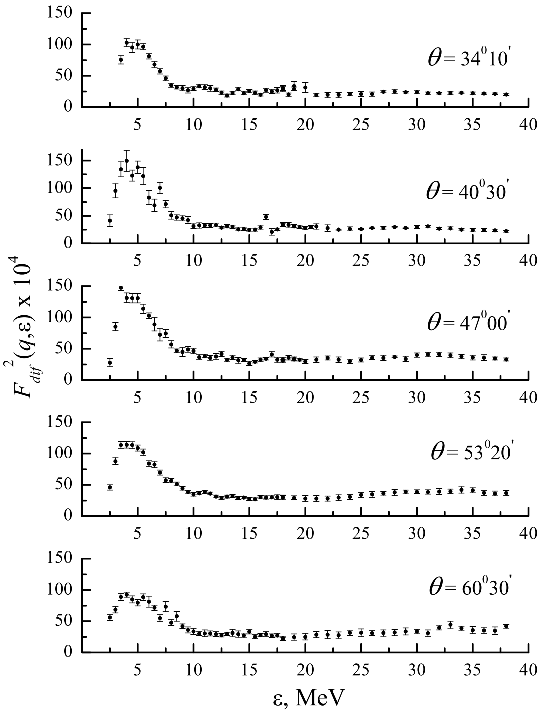

Fig.1. *The differential form factors of ^6Li nucleus obtained for initial energy of electrons* $E_0 = 259.0\,MeV$

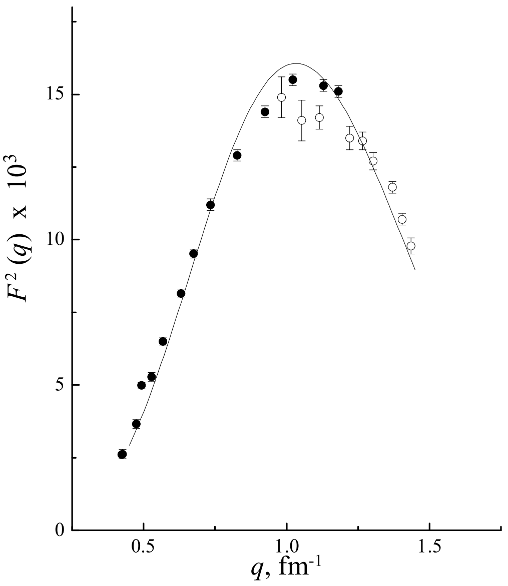

Fig.2. *The form factor of* ^6Li *nucleus excited state at* $\varepsilon = 2.18\,MeV$ *and* $\lambda = 2$. *The data of work [12] are shown as full circles, and data of [13] are open circles. The solid line shows the fitting result by expression (3) of these data*

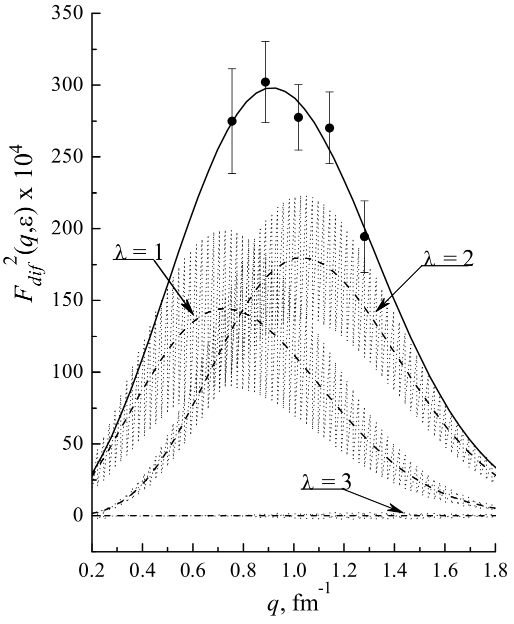

Fig.3. *The bin multipole analysis of differential form factor for* $\varepsilon_i = 18\,MeV$. *The experimental data are shown by points, the contributions of particular multipolarities are dashed lines, their sum is solid line, the confidence intervals of each multipolarities* λ *are shaded areas*

The most rich structure is in the $\beta_{\lambda=2}$– dependence. To analyse this dependence we fix the energy position of Gaussian maxima at: $\varepsilon = 4.31\,MeV$ (well known C2 transition); $\varepsilon = 5.65,\ 15.80\,MeV$ (levels for which C2 transitions are possible). The height was the only fitting parameter in each Gaussian function, while values of energy position and width are taken according to [4].

To describe the dependence $\beta_2(\varepsilon)$ in the range $\varepsilon \approx 25\ldots40\,MeV$ Gaussian function with all free parameters was used. This peak gives us energy dependence of the electron QES by nucleons of nucleus as in works [6, 15] in the same energy region.

Such sum of Gaussian functions can't describe data near $\varepsilon = 10\,MeV$. Therefore one more Gaussian with all free parameters was added to sum used for approximation of energy dependence $\beta_2(\varepsilon)$.

To analyse dependence $\beta_3(\varepsilon)$ three Gaussians with all free parameters are sufficient. The maximum at $\varepsilon = 8.3\,MeV$ reflects the electron QES by α-cluster as maximum at $\varepsilon = 4.5\,MeV$ in dependence $\beta_1(\varepsilon)$. Maximum at $\varepsilon = 33.8\,MeV$ can be considered as electron QES by nucleons of nucleus. Near excitation energy $\varepsilon = 24.9\,MeV$ three levels with the possible $\lambda = 3$ multipolarity of Coulomb transitions are: at $\varepsilon = 24.78$; 24.89 and $26.60\,MeV$ and with energy width $\Gamma = 5\ldots9\,MeV$. Therefore obtained at these excitation energy maximum can be one of them or their sum.

There are results of our analysis of $\beta_{1,\,2,\,3}(\varepsilon)$-dependences in table.

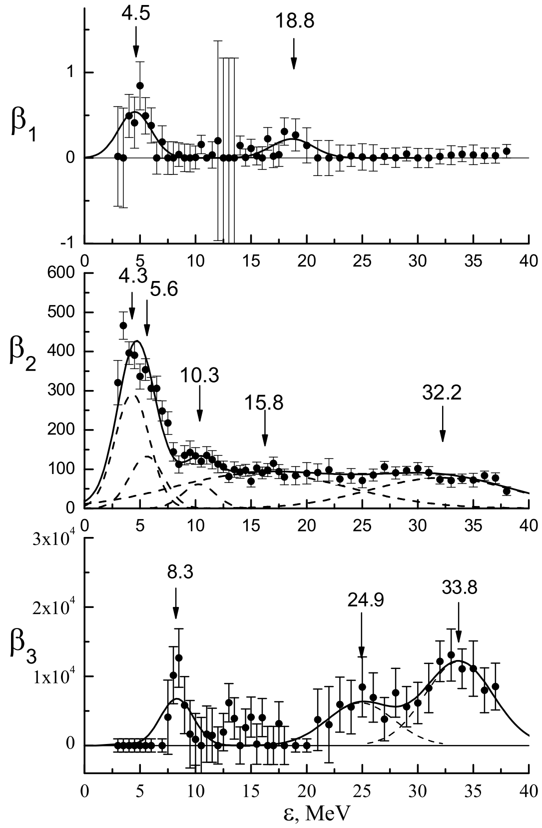

Fig.4. *The* ε *dependence of adjustable parameters* β_λ *for* $\lambda = 1$, 2 *and* 3. *The experimental data are shown by points, the contributions of particular picks are dashed lines, their sums are solid lines*

4. CONCLUSION

The excitation energy range above 5.5 MeV wasn't investigated earlier in (e, e')−experiment. The multipolarities and transition types of ^{6}Li levels at $\varepsilon = 15.80, 17.98\,MeV$ were determined in this energy range (see table). The multipolarity of level at $\varepsilon = 5.65\,MeV$ can be $\lambda = 0$ or 2 (though we observe this maximum in the energy dependence $\beta_2(\varepsilon)$, but we can't unambiguously identify its multipolarity. This is the weakness of the (e, e')−experiment method.) The maximum at $\varepsilon = 24.9\,MeV$ represents transition with $\lambda = 3$ to one of the levels $\varepsilon = 24.78, 24.89, 26.60\,MeV$ or is their sum.

The maximum at $\varepsilon = 10.3 \pm 0.4\ MeV$ was observed and its statistical error is 18%. We interpret this pick as excited state in ^{6}Li nucleus with transition multipolarity $\lambda = 0$ or 2 (ambiguity of multipolarity determination as in the case of level at $\varepsilon = 5.65\,MeV$).

Reasoning from our experimental conditions the observed levels has Coulomb nature of excitation.

In future the investigation of GR of ^{6}Li nucleus will be carried out basing on spectra measured in wider range of scattering angles.

Levels of nucleus ^6Li

ε, MeV	Γ, MeV	J^π	Possible		Observed		Observed in present work			
			$M\lambda$	$E_{T/L}\lambda$	M	E	ε, MeV	Γ, MeV	$E_L\lambda$	$\delta S, \%$
3.56	8E-6	0^+	1		1					
4.31	1.3	2^+	1, 3	2		2_L	4.3	1.3	2	9
5.37	0.54	2^+	1, 3	2	1					
5.65	1.5	1^+	1	0, 2			5.6	1.5	**0, 2**	18
							10.3± 0.4	**≤1.0**	**0, 2**	18
15.80	17.8	3^+	3	2, 4			15.80	17.8	**2**	7
17.98	3.0	2^-	2	1, 3			18.8 ± 0.8	3.0	**1**	43
21.5		0^-		1						
23.0	12.0	4^+	3, 5	4						
24.78	6.8	3^-	2, 4	3			24.9 ± 1.0	6	**3**	29
24.89	5.3	4^-	4	3, 5						
26.60	8.7	2^-	2	1, 3						

The spin and parity of the ^{6}Li nucleus ground state are $J^\pi = 1^+$. The possible multipolarities (λ) and transition types (M – magnetic and $E_{T/L}$ – electricals transverse or longitudinal) are determined from spins and parities of ground and excit ed states of the nucleus. The levels positioned above $\varepsilon = 5.5\,MeV$ weren't earlier investigated in (e, e')-experiment. In the present work first determined the characteristics are printed in bold type. The δS is the relative error of picks square in the energy dependences $\beta_\lambda(\varepsilon)$.

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ИССЛЕДОВАНИЕ ГИГАНТСКИХ РЕЗОНАНСОВ ЯДРА ^{6}Li В ДИАПАЗОНЕ ПЕРЕДАННЫХ ИМПУЛЬСОВ $q = 0,75 - 1,30$ фм$^{-1}$ С ПОМОЩЬЮ ПОЛОСКОВОГО МУЛЬТИПОЛЬНОГО АНАЛИЗА

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Используя данные электроядерного эксперимента и применяя методику полоскового мультипольного анализа, были исследованы гигантские резонансы ядра ^{6}Li. В результате определены кулоновская природа и мультипольности переходов в ядре ^{6}Li при энергиях возбуждения $\varepsilon = 4.31$; 5.65; 15.80; 17.98 МэВ и для суммы резонансов при $\varepsilon = 24.78$, 24.89,26.60 МэВ. Кроме того, был обнаружен новый уровень при $\varepsilon = 10.3 \pm 0.4$ МэВ с мультипольностью $\lambda = 0$ или 2.

ДОСЛІДЖЕННЯ ГІГАНТСЬКИХ РЕЗОНАНСІВ ЯДРА ^{6}Li В ДІАПАЗОНІ ПЕРЕДАНИХ ІМПУЛЬСІВ $q = 0,75 - 1,30$ фм$^{-1}$ ЗА ДОПОМОГОЮ ПОЛОСКОВОГО МУЛЬТИПОЛЬНОГО АНАЛІЗУ

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В роботі, використовуючи дані електроядерного експерименту та за допомогою полоскового мультипольного аналізу, проведено дослідження гігантських резонансів ядра ^{6}Li. Як результат знайдено кулонівську природу та мультипольності переходів в ядрі ^{6}Li, що розташовані при енергіях збудження $\varepsilon = 4.31$; 5.65; 15.80; 17.98 МеВ та для суми резонансів при $\varepsilon = 24.78$, 24.89, 26.60 МеВ. Крім того, було виявлено новий рівень при $\varepsilon = 10.3 \pm 0.4$ МеВ з мультипольністю $\lambda = 0$ або 2.