ELECTROEXCITATION OF GIANT RESONANCES IN ^{54}Fe AND ^{56}Fe NUCLEI

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The investigation of giant multipole resonances in ^{54}Fe and ^{56}Fe nuclei has been carried out. The resonance at excitation energy of~13 MeV ($51A^{1/3}$) is shown to be of *E2* type and to exist in both nuclei. In both nuclei the contribution of the *E3* multipole is very small, especially of the $1\hbar\omega$ branch of isovector resonance, and the *E4* resonance is absent completely. Small *E5* strength contribution is observed in both nuclei at excitation energy of 10 to 15 MeV.

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1. INTRODUCTION

The investigation of giant resonance (GR) electroexcitation in various nuclei with the help of the inelastic scattering of electrons was carried out intensively during the last decades. The big volume of information was accumulated about the excitation energy, width and energy weighted sum rule (EWSR) exhausting for nearly 40 nuclei. However, the giant resonances were studied and systematized well enough only in heavy nuclei (for A>90), where the results are in good agreement with the proton and α-particle scattering [1]. In the region of intermediate nuclei with 40≤A≤90 the agreement of the experimental results with different scattered particles is not good enough and still remains a number of unresolved fundamental questions.

During many years there is a problem with isoscalar giant monopole resonance (ISGMR) in nuclei with A≤ 90. The EWSR exhausting for these nuclei are significantly smaller 100 %. Recently for several nuclei there were obtained the α-scattering experimental results [2], that shows the existence of high energy "tail" up to excitation energy of 35 MeV in the ISGMR strength distribution. Taking into account this "tail" the EWSR exhausting should be increased up to 100 % for ^{90}Zr and up to 60 % for nuclei with smaller A – ^{28}Si, ^{40}Ca, ^{58}Ni. It is still unclear where the rest part of ISGMR might be located. From the theoretic point of view there is no obvious reason to suggest ISGMR vanishing in light nuclei. But it is known that in light nuclei the strengths of other GRs are spread over a large range of excitation energy. If such behavior is typical for ISGMR, this will cause a significant difficulties in observing the E0 strength localization.

The multipole resonance investigation in the mass region A~60 is of great interest also due to the discovery of additional *E2* GR. The distinct resonant excitations at 13 MeV ($51A^{-1/3}$) in ^{58}Ni, ^{60}Ni, and ^{64}Ni were first observed in Kharkov [3] in inelastic electron scattering and identified as *E2* resonance [4]. Other experiments, which found structure at this energy (~(50-53)$A^{-1/3}$ MeV) in nuclei with 56≤A≤60, partly support and partly disagree with the *E2* multipole assignment [5]. The discovered resonance is situated at lower excitation energy, than isoscalar *E2* GR ($63A^{-1/3}$). Besides, the EWSR nuclear mass dependence of this resonance differs significantly from the one of the main isoscalar *E2* GR [5,6]. The authors of [5,6] analyzed this situation and drew a conclusion that the resonance at the excitation energy $51A^{-1/3}$ is the isovector quadrupole resonance and perhaps it's manifestation depends on the neutron excess. This resonance is not observed in nuclei with lower A.

We have carried out the investigation of electric giant multipole resonance excitation in ^{54}Fe and ^{56}Fe nuclei. These nuclei are situated in the mass region where the ISGMR manifestation differs from the heavy nuclei systematic (A>90), and the additional *E2* resonance vanishes almost completely. The absence of information even about the electric dipole GR excitation [7] in spite of wide occurrence of these nuclei is another stimulus to choose them for study.

There is only one paper [8] in literature where the preliminary results of such type investigation are represented and only for ^{56}Fe. The excitation energy range has been extended in our experiment comparing with paper [8] to cover the energy region of quasielastic (QE) excitation. This allowed to account the QE process contribution more correctly. The transferred momentum range was extended up to 1,7 Fm^{-1} that made it possible to investigate resonances up to *E5*. The method of dividing the scattered electron spectra into successive bins ("bin method") with their subsequent analysis was used instead of separating the individual peak in the initial spectrum as it was done in paper [8]. The advantage of the "bin method" in comparison with individual peak adjustment is the possibility to reveal the contributions of different multipoles at the same excitation energy. This advantage can be clearly seen in paper [9] where the "bin" technique was first applied for treating spectra of inelastically scattered electrons in the range of discrete level energy excitation. The "bin" technique permitted to discover additional, weaker levels not observed earlier in (e,e′) experiments against the background of strongly excited levels and to determine their spins and parities. To understand the "bin method" influence on the final results of multipol analysis we have treated out the initial experimental

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data of the paper [8] with the help of this method and compared the results with those of paper [8].

2. THE EXPERIMENTAL TECHNIQUE AND DATA PROCESSING

The experiment was carried out at the LINAC-300 of NSC KIPT. Eight spectra were measured for each nucleus at electron initial energy of 225 MeV for the angles from 40° to 75° with a step of 5°. In the energy range of giant resonances excitation (up to 40 MeV) the measurements were carried out continuously, and in the range of QE scattering (~40 … 150 MeV) they were done by means of 3 MeV wide bunches with the spaces of the same width.

The description of the experimental equipment, methods of measuring spectra of scattered electrons and processing the data obtained may be found in [9] and references therein.

Besides operations described in [9], taking into account the QE processes plays a significant role while studying the giant resonances. Their contribution to scattered electron spectra depends on the excitation energy and amounts to dozens percents. The problem of correct spectrum splitting into QE and resonance cross sections remains to be unresolved up to now. The shape of the energy dependence of QE cross section at excitation energies lower than QE maximum is not known even qualitatively. In different papers the authors use various semi-empirical methods for giant resonances separation against the QE background. We have carried out two different data treatments with two shapes of QE background energy dependence to estimate the effect of this background extraction on the final result.

In the first case the QE spectrum was approximated by Gaussian and was fitted by least square method to experimental data in the excitation energy range equal to and higher than the QE maximum for each spectrum of scattered electrons. In addition it had to vanish at the QE threshold to the accuracy of experimental errors. Such approach gives good description of the cross section energy dependence higher the QE maximum.

In the second case the QE background was approximated with a straight line starting from the origin of coordinates and crossing the measured spectrum at the energy corresponding to the QE maximum. The QE cross section calculated on the ground of the Fermi-gas model possesses such a linear dependence. But it seems impossible to use the exact Fermi-gas calculations because their absolute values are in a poor agreement with measured data.

The example of the QE cross section energy dependence for both cases is represented in Fig.1. Further the QE cross section was subtracted from the experimental data, then spectra were divided into bins and form factor for each bin was a subject of multipol analysis.

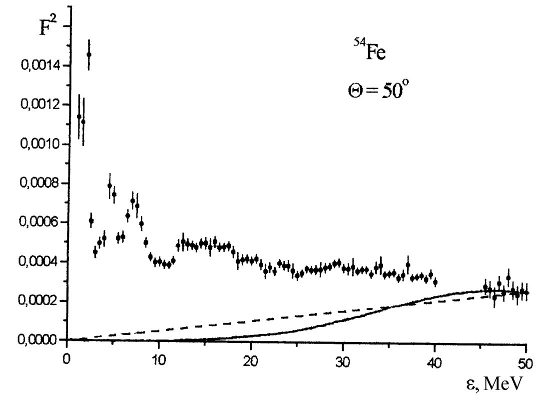

Fig. 1. *The scattered electron spectrum. The elastic peak is subtracted. The curves show two methods of QE cross section calculation: Gaussian – solid curve, straight line –dashed curve*

Besides, we have used the photo cross section [10] for more careful identification of the dipole strength. It's value was recalculated into the electric Coulomb form factor for small momentum transfer according to the equations of paper [11].

While treating the experimental data of paper [8], the *E1-E5* multipoles were fitted in accordance with the range of momenta transferred in experiment. In this case we had not possibility to account the QE background correctly because the experimental spectra were measured not far enough over the excitation energy. That's why two methods were used for the data treatment. In the first case the QE background under the giant resonances was taken with the same way as it was in paper [8], i.e., it was constant and not depended on the excitation energy for each given spectrum. But such an approach gives the improbable result at small excitation energy. Namely, near the threshold, where the QE cross section has to vanish, it's value is still very big - 90 % and more of the total cross section. That's why in the second case the QE background was taken as a strait line that exhausts the cross section in the QE maximum and is equivalent to zero in the threshold. This make it possible to compare the QE background shape influence on the final result.

3. RESULTS AND DISCUSSION

Figs. 2,3 represent the reduced transition probability B($E\lambda$) for each multipolarity λ. The comparison of results obtained by us between themselves and with the results of work [8] is shown in Tables 1,2. The determination of the individual peak excitation energy, reduced transition probability and width was accomplished by least square fitting of Gaussian to the experimental data. The EWSR was taken to be isovector for E1 transitions and the general for other multipolarities.

3.1. The processing of data from paper [8] for ^{56}Fe

In the *E1* strength distribution one can see the first not big peak at low energy ~10 MeV and another broad one with the maximum at ~16 MeV. The broad peak increases sharply at low energy and decreases smoothly at high energy. This means that it consists at least of two peaks with different magnitude and width. So we approximated this broad peak with two Gaussians.

From Table 1 one can see that the excitation energy and reduced transition probability of the low-energy peak depend on the QE background. But this resonance exists in both cases, when the QE background near the 10 MeV is maximum (constant background) and when it is equivalent to zero (the background is falling down linearly at the low energies).

There is also the strong QE background dependence of the high-energy peak excitation energy. The characteristics of another resonance depend on QE background too little.

The both methods of QE background consideration give some strength in the energy range above 30 MeV. In the case of constant background it even looks like peak. But the existence of resonance at this range is doubtful. This might lead to the second peak with the approximately the same magnitude in the photo cross section. Such situation is not observed not only in ^{56}Fe but in all neighboring nuclei (see for example [7]). Besides, even without this peak the *E1* strength exhausts more than 100 % of the EWRS for isovector resonances. The existence of this peak most likely indicates that the QE background, which is dominant at high excitation energies, was not subtracted correctly in both cases.

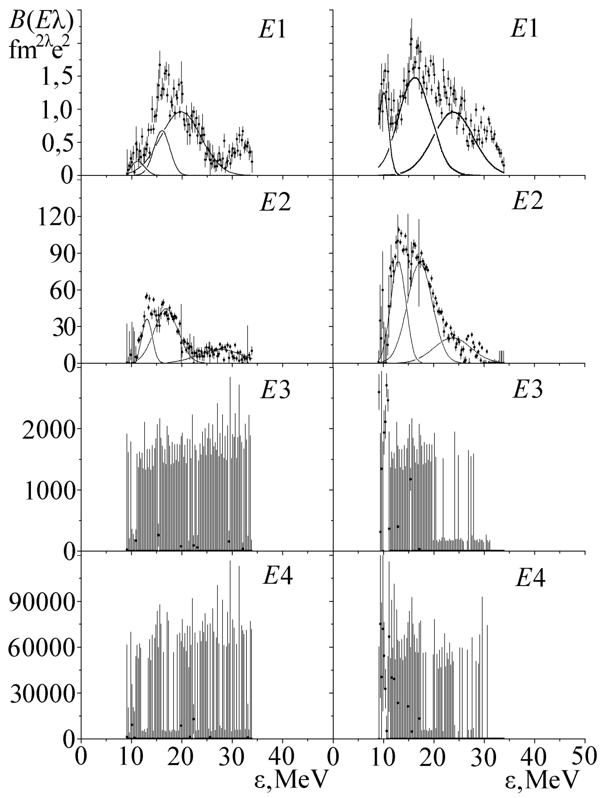

Fig. 2. *The reduced transition probability B(Eλ) for ^{56}Fe nuclei data from paper [8]. Left part – the background was subtracted as in paper [8], right part – as increasing straight line (see text above)*

Table 1. Parameters of the giant resonances in ^{56}Fe

Eλ	E_{res}, MeV	*ΔE*, MeV	*B(Eλ)*, fm$^{2\lambda}$ e^2	EWRS, %
E1	10.1±0.1	0.9±0.1	2.96±0.39	14±2 [1)]
	11.3±0.5	1.4±0.6	0.73±0.24	4±1 [2)]
	10.3±0.3	0.2±0.1	0.05±0.03	<1 [3)]
	10.3±0.3	0.2±0.1	0.05±0.03	<1 [4)]
	16.3±0.1	3.2±0.2	11.89±0.79	93±6 [1)]
	16.0±0.2	1.6±0.2	2.65±0.55	21±4 [2)]
	14.6±0.3	1.3±0.2	1.00±0.14	7±1 [3)]
	15.0±0.4	1.5±0.3	1.00±0.14	7±3 [4)]
	23.9±0.3	4.0±0.5	9.55±0.59	110±7 [1)]
	19.8±0.3	4.0±0.1	9.61±0.52	92±6 [2)]
	18.3±0.1	2.3±0.1	6.71±0.36	59±3 [3)]
	18.2±0.1	2.5±0.1	6.68±0.36	59±3 [4)]
	19.0±.05			[5)]
				217±9 [1,6)]
				117±7 [2,6)]
				66±3 [3,6)]
				66±4 [4,6)]
E2	1-8		917±42	13±1 [3)]
or			892±42	13±1 [4)]
E0	9.5±0.1	0.7±0.1	137±23	4±1 [3)]
	9.5±0.1	0.7±0.1	130±41	4±1 [4)]
	13.0±0.3	1.5±0.6	312±6	13±3 [1)]
	13.1±0.1	1.0±0.1	92±5	4±1 [2)]
	13.0±0.9	2.5±0.2	642±59	27±3 [3)]
	11.9±0.9	1.5±0.6	205±93	8±3 [4)]
	17.3±0.1	2.5±0.1	510±12	28±1 [1)]
	16.9±0.1	2.4±0.3	266±6	14±3 [2)]
	17.9±0.2	2.4±0.2	343±41	20±2 [3)]
	15.6±1.2	2.6±0.7	401±181	20±9 [4)]
	16.1±.05		672	34 [5)]
	23.8±0.4	3.7±0.3	192±15	15±1 [1)]
	27.7±0.3	4.3±0.4	121±10	11±1 [2)]
	25.0±0.3	6.0±0.5	1004±23	80±2 [3)]
	22.8±0.5	7.7±0.3	1099±62	73±4 [4)]
	32.0±.05			[5)]
				56±3 [1,6)]
				29±3 [2,6)]
				144±4 [3,6)]
				118±10 [4,6)]
E3	4-9		32463±898	10±1 [3)]
			31488±898	10±1 [4)]
	13.3±.05			[5)]
	35.8±0.9	4.7±0.9	4157±694	8±1 [3)]
	38.2±0.6	6.4±0.9	9601±1069	19±2 [4)]
E5	12.4±0.3	3.8±0.5	(33±3)10^6	5±1 [3)]
	11.5±0.4	3.7±0.6	(26±3)10^6	4±1 [4)]

[1,2)] The data of work [8] treatment. [1)] The QE background was subtracted as increasing strait line (see text above). [2)] The QE background was subtracted as in [8].

[3,4)] Our experiment. [3)] The QE background was approximated by Gaussian.. [4)] The QE background - straight line (see text above).

[5)] Results of paper [8].

[6)] *The total EWSR exhausting for resonances with this multipolarity.*

In the *E2(E0)* strength distribution there are two strongly overlapping peaks and one very week peak at high excitation energies. The magnitude of the low-energy peak depends strongly on the QE background. In the paper [8] this peak was identified as the *E3* resonance.

The energy position of the resonance at the highest energy we have obtained is lower than in [8]. But, as can be seen in Table 1, the QE background influences on it's position strongly. Besides, the cross section higher than 30 MeV was included in [8] in this resonance while in our treatment it manifests partly as *E1* strength. Such difference leads to the shift of the peak maximum to higher excitation energies.

The analysis of the EWSR magnitude shows, that there is a systematic error in the results obtained. The *E1* isovector strength exhausts more than 100 % but the *E2* strength is very week. This conclusion does not depend on the QE background shape and on the low energy *E2* transition contribution, not measured in [8]. Most likely it should be a big contribution of background not connected with the QE scattering in spectra of paper [8].

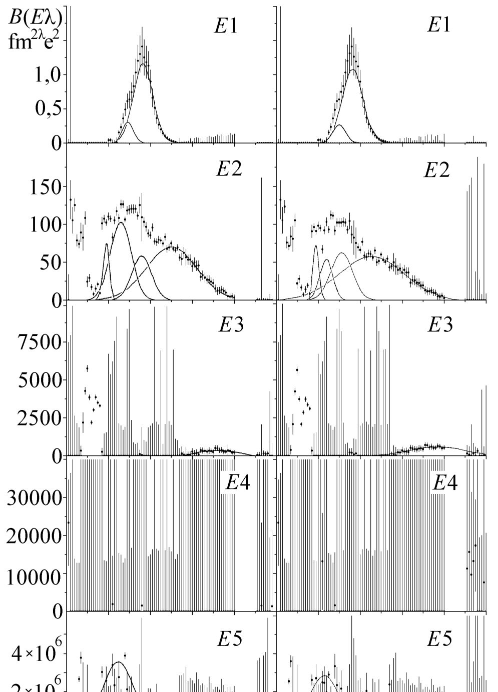

Fig. 3. *The reduced transition probability for ^{56}Fe nuclei obtained in our experiment. Left part – the QE background was approximated by Gaussian, right part – by straight line (see text above)*

3.2. Results of our experiment

The magnitude and shape of *E1* resonance obtained by us is under the strong influence of photo cross section. It has to be mentioned that the photo cross section used by us is the theoretic one from the paper [10], because the experimental data for ^{56}Fe is completely absent. We used three Gaussians for fitting to compare with the results of previous section.

As it is seen in Table 1, the difference in the excitation energy is 1…2 MeV while the difference in the reduced transition probability is several times. The biggest difference is for the low energy resonance. This is not the result of our experiment but due to the usage of photon cross section which is almost equivalent to zero at 10…11 MeV.

Table 2. *Parameters of the giant resonances in ^{54}Fe*

E_{res}, MeV	ΔE, MeV	$B(E\lambda)$, fm$^{2\lambda}$ e^2	EWRS, %
E1			
15.0±1.3 15.0±0.9	1.4±0.2 1.4±0.2	0.79±0.17 0.81±0.17	6±1 [1)] 6±1 [2)]
19.2±0.1 19.2±0.1	2.4±0.1 2.4±0.1	10.0±0.2 10.0±0.2	96±2 [1)] 96±2 [2)]
			112±2 [1,3)] 112±2 [2,3)]
E2			
1-8		1742±43 1707±43	26±1 [1)] 26±1 [2)]
9.7±0.1 9.7±0.1	0.7±0.1 0.7±0.1	175±25 151±19	6±1 [1)] 5±1 [2)]
13.4±0.2 13.8±0.2	2.4±0.2 2.7±0.2	764±89 859±66	35±4 [1)] 41±3 [2)]
17.5±0.2 17.9±0.2	1.3±0.2 1.1±0.2	175±54 126±43	10±3 [1)] 8±3 [2)]
23.9±0.3 25.4±0.4	6.8±0.2 6.2±0.3	1459±60 1016±50	119±5 [1)] 88±5 [2)]
			196±7 [1,3)] 168±7 [2,3)]
E3			
4-9		30082±605 28765±605	12±1 [1)] 11±1 [2)]
20.3±0.1 20.2±0.1	0.6±0.2 0.6±0.1	1480±341 1529±323	2±1 [1)] 2±1 [2)]
36.2±0.5 38.3±0.4	4.7±0.6 5.3±0.5	6628±670 10871±802	14±1 [1)] 25±2 [2)]
E5			
12.4±0.5 12.6±0.4	2.0±0.4 2.1±0.5	(12±2)10^6 (12±2)10^6	2±1 [1)] 3±1 [2)]

[1)] *The QE background was approximated by Gaussian.*
[2)] *The QE background - as straight line (see text above).*
[3)] *The total EWSR exhausting for resonances with this multipolarity.*

In the *E2* strength distribution we found four resonances. The low energy resonance was not observed in the treatment of paper [8] because of the excitation energy was too low. The rather big magnitude of this resonance depends strongly on the photon cross section magnitude. The additional test fittings show that a not big increase of the photo cross section at this excitation energy leads to a significant increase in the low energy *E1* resonance strength and to the decrease of the corresponding *E2* resonance. The significant difference in *B(E2)* for the high energy resonance is due to the QE background.

There is *E3* resonance in our results at excitation energy 35,8 MeV that corresponds to 3¬ω branch of the *E3* resonance. In the results of paper [8] this resonance could not be separated from the high energy *E2* resonance due to the lack of the data treatment method. In our treatment this resonance is also not observed. But there is unlikely big *E1* strength at this energy. Probably the reason of this "transfer" of *E3* strength to the *E1* strength is the impossibility to subtract correctly the QE background from the data of paper [8].

The results obtained for ^{54}Fe are very similar to results for ^{56}Fe (see Table 2). In addition in ^{54}Fe there is the *E3* resonance at ~20 MeV, corresponding to the 1¬ω branch of E3 resonance.

4. CONCLUSIONS

The investigation of the multipole giant resonances in ^{54}Fe and ^{56}Fe accomplished allows to make a number of conclusions:

1. The resonance at excitation energy 13 MeV(51A$^{1/3}$) is not *E3* one but *E2* resonance and it exists in both nuclei.
2. In both nuclei the cross section is exhausted mainly by *E1* and *E2* multipoles. The contribution of the *E3* multipole is very small, especially of the 1¬ω branch of isovector resonance, and the *E4* resonance is absent completely. This differ them greatly from the nearest neighbors – ^{65}Cu [12], ^{58}Ni [5].
3. The small contribution of the *E5* strength was found in both nuclei in the energy excitation range 10…15 MeV.

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ЭЛЕКТРОВОЗБУЖДЕНИЕ ГИГАНТСКИХ РЕЗОНАНСОВ В ЯДРАХ ^{54}Fe И ^{56}Fe

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Исследованы мультипольные гигантские резонансы в ядрах ^{54}Fe и ^{56}Fe. Получено, что резонанс при энергии ~13 МэВ (51A$^{-1/3}$) является *E2* переходом и существует в обоих ядрах. В обоих ядрах вклад *E3* переходов очень мал, особенно 1¬ω ветви изовекторного резонанса, а *E4* переходы вообще отсутствуют. Это сильно отличает ^{54}Fe и ^{56}Fe от ближайших исследованных соседей ^{58}Ni и ^{65}Cu. В обоих ядрах обнаружен небольшой вклад *E5* силы в области энергий возбуждения 10…15 МэВ.

ЕЛЕКТРОЗБУДЖЕННЯ ГИГАНТСЬКИХ РЕЗОНАНСІВ У ЯДРАХ ^{54}Fe И ^{56}Fe

В.М. Хвастунов, В.В. Деняк, Ю.М. Ранюк

Досліджено мультипольні гігантські резонанси у ядрах ^{54}Fe і ^{56}Fe. Отримано, що резонанс при енергії ~13 МеВ (51A$^{-1/3}$) є *E2* переходом і існує в обох ядрах. В обох ядрах внесок *E3* переходів дуже малий, особливо 1¬ω гілки ізовекторного резонансу, а *E4* переходи взагалі відсутні. Це дуже відрізняє ^{54}Fe і ^{56}Fe від найближчих досліджених сусідів ^{58}Ni і ^{65}Cu . В обох ядрах виявлено невеликий внесок *E5* сили при енергіях збудження 10…15 МеВ.