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A ROLE OF DEEP SHELL NUCLEONS IN THE FORMATION OF GIANT DIPOLE RESONANCE

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1. INTRODUCTION

It is well known that the excitation of giant dipole resonance (GDR) is the universal process in a sense that it is excited in all the atomic nuclei. Less discussed is the other aspect of the universality of GDR, namely, its excitation in different processes, e.g., in photoabsorption, electroexcitation, and muon capture/1/. Dependence of the excitation probability on the process involved allows one to study the different components of GDR comparing several processes. On the other hand, the comparison of several excitation processes gives us a unified treatment of different phenomena.

The aim of the present paper is to demonstrate the usefulness of the above-mentioned aspect of universality of GDR in revelation of new regularities of the resonance. The high energy branch that is formed by the excitation of deeply bound nucleons is discussed. It has not yet been studied experimentally because it is weakly excited in photoabsorption and nothing new was expected in other processes in this energy region.

The consideration is carried out for ^{32}S, $^{58,60}Ni$ and ^{88}Sr nuclei. Due to the universality of GDR this choice enables us to cover rather large number of nuclei from (2s-1d), (2p-1f) and $1g_{9/2}$ shell region. Rather detailed calculations of excitation spectra in muon capture/2-4/ are available for these nuclei which serve us as a tool for consideration. The above choice is also connected with the aim to explain the following regularity in muon capture by nuclei with $A \leq 100$: in these nuclei appears a rather broad local maximum in spectra of neutrons following muon capture. This maximum lies at $E_n = (9-13)$ MeV and is shifted to the lower energy region with increasing A/5-7/.

The next section is devoted to the discussion of the gross structure of giant dipole resonances and the comparison of the excitation spectra in photoabsorption, electroexcitation, and muon capture. Than the decay of high energy branch of GDR excited in muon capture is considered and possible explanation of the above-mentioned regularity in neutron spectra is given.

2. GROSS STRUCTURE OF THE DIPOLE EXCITATION

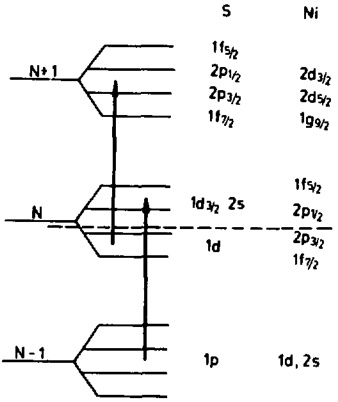

Fig.1. The schematic formation of the dipole states.

The dipole resonance is formed mainly by the transitions between neighbour shells. Two groups of transitions can be found in nonmagic nuclei. The first group corresponds to the excitations of deeply bound nucleons to the valence shell states while the second consists of those from valence shell to the states of next unfilled shell. As a result, two groups of resonance states arise in this approximation. Schematically transitions forming dipole resonance are shown in fig.1, where the corresponding shells and transitions for ^{32}S and Ni nuclei are also given.

The account of residual interaction results in the mixing of these (1p–1h) resonance states as well as in their fragmentation over more complex states. However, due to the large gap between the energies of the first and second groups of transitions (e.g., $E_{1p_{3/2}\to 1d_{3/2}} \approx 25$ MeV and $E_{1d_{5/2}-1f_{1/2}} \approx 15$ MeV in ^{32}S nucleus) there is no considerable mixing between the states belonging to the different groups. The fragmentation over the more complex states leads to the broadening of the resonance regions especially in the high energy part but does not affect the separation of two groups of states. Such an effect is known in photoabsorption reactions where it was called the configurational splitting of dipole resonance /8/.

The configurational splitting will take place in other processes too, where the resonance mechanism dominates - e.g. electroexcitation, muon capture, and radiative pion capture. However, the relation between the excitation probabilities for different groups of resonances depends significantly on the concrete process and on the filling of the valence shell.

The transitions from valence shell are most intensive in phoroabsorption reaction except for nuclei where the valence shell is almost empty, e.g ^{6}Li and ^{24}Mg. As a consequence, the high energy part of the resonance (N–1 → N transitions in notation of fig.1) is weakly excited in comparison with the medium energy part. On the other hand, the large excitation probability for the high energy $N-1 \to N$ transitions can be expected in muon capture. As was shown in ref./2/, this difference between muon capture and photoabsorption is due to the spin-flip transitions that are intensive in the former process.

This conclusion is illustrated in figs.2 and 3 where the calculated excitation spectra in different processes are given for ^{32}S and ^{58}Ni nuclei. The excitation spectrum in muon capture by ^{88}Sr nucleus is calculated in ref./4/ As can be seen from figs.2 and 3 the high energy part of the dipole resonance excited in muon capture is expected to be the most intensive one. Moreover, the calculations also show that this part of the resonance must be intensively excited in certain (e,e′) reactions - namely at 180° and small q when only E1 and M2 transitions occur.

Let us now briefly discuss some particular features of the high energy branch of the resonance in the nuclei under consideration. The J^π , $T=1^-$, T_0+1 resonance is connected with spin-flip transitions of nucleons from inner shells - $1p_{3/2} \to 1d_{3/2}$ in ^{32}S , $1d_{5/2} \to 1f_{5/2}$ in Ni nuclei and $1f_{7/2} \to 1g_{7/2}$ in ^{88}Sr nucleus. Let us note that $1d_{5/2} \to 1f_{5/2}$ transition which forms a resonance in Ni is found in ^{32}S nucleus too, but at lower energy. Analogically $1p_{3/2} \to 1d_{3/2}$ transition forms resonance in ^{16}O nucleus though the excitation energy is smaller than in ^{32}S due to the fact that 1p shell is the last filled one in this magic nucleus. This is seen from fig.4 where the calculated excitation spectra/11/ of ^{16}O nucleus in (e,e′) reaction and muon capture are given. There are experimental data on ^{16}O(e,e′) reaction/12/ and the resonances are indeed seen in the energy region predicted by the theory. Particularly the J^π , $T=1$ 1 resonance lies at ~25 MeV. However, more detailed analysis of the spectrum in this region is needed.

For several (2s-1d) shell nuclei, particularly for ^{32}S nucleus/12,13/ the (e,e′) reaction cross section was measured but at smaller angles and with high energy electrons. Such measurements with separation of the transversal E1 transition can be used also to study the high energy resonance. However, up to now the high energy region of excitation has not been investigated.

Thus, based on the results of calculations and available experimental data one can expect the concentration of the transition strength in some (e,e′) reactions and muon capture at high energy excitation region. But due to the fragmentation the width of the peaks will be larger than that in low energy branch of the resonance.

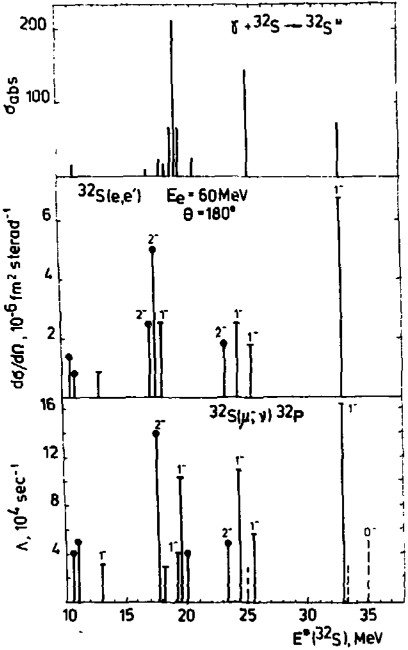

Fig.2. The calculated excitation spectra of ^{32}S. a) Photoabsorption[10]. b) Muon capture[2]. c) Backward (e,e') reaction[9].

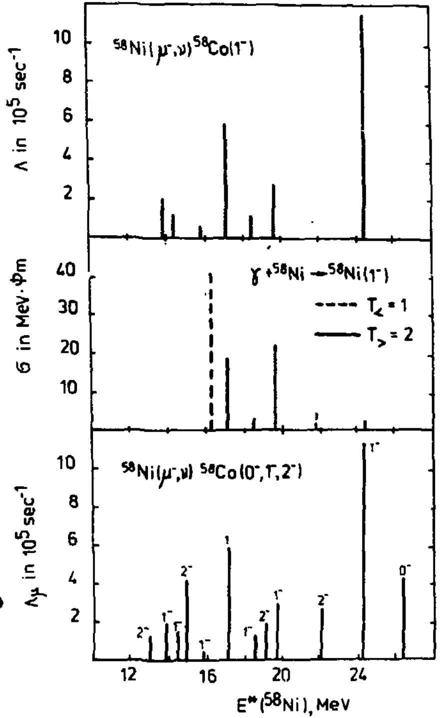

Fig.3. The calculated[8] excitation spectra of ^{58}Ni. a) Photoabsorption, b) Muon capture.

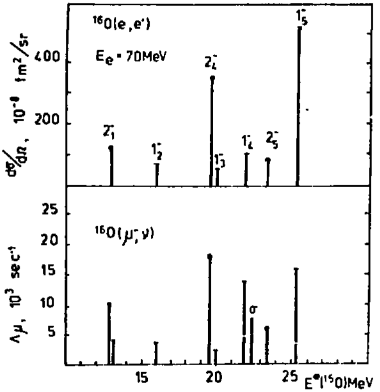

Fig.4. The calculated /11/ excitation spectra of ^{16}O a) Backward electron scattering, b) muon capture.

Note that $T_>$ branch of the resonance in nuclei with large neutron excess cannot be studied via (e,e′) reactions because it is hindered with respect to $T_<$ one. The $T_>$ resonance is purely excited in the processes where the transition proton-neutron takes place. It means that, for example, muon capture is well suited to study this branch of the resonance. However the excitation spectrum cannot be observed directly in muon capture and the information has to be obtained from the spectra of emitted particles. In the next part we will discuss the manifestation of high energy $T_>$ branch of the resonance in the neutron decay channel characteristics.

3. *THE DECAY OF HIGH ENERGY BRANCH OF DIPOLE RESONANCE IN MUON CAPTURE*

The neutron decay channel is the main one in muon capture. Because of weak mixing between different transitions connected with the excitation of a nucleon from different shells (configurational splitting) the neutron emission will be accompanied by the excitation of corresponding hole states in the daughter nucleus. This means that the decay of high energy part of the resonance excited in muon capture by ^{32}S nucleus is connected with $1p^{-1}_{3/2}$ states in ^{31}P nucleus and in the case of $^{58,60}Ni$ nuclei with $1d^{-1}_{5/2}$ states in $^{57,59}Co$.

From pick up and quasielastic knock-out reactions it follows that these hole states are spread over rather broad energy region in corresponding (A-1) nuclei. At the same time the centre of mass of the hole distribution lies at considerably high energy. For example it is known that $1p^{-1}$ hole state in ^{31}P is distributed over the 20 MeV interval and that considerable part of its strength is at ~14 MeV excitation enerhy /14-16/.

If only the centre of mass is taken into account, the decay to the corresponding hole states of daughter nucleus is forbidden. In such a case the calculated neutron spectrum turns out to be too hard, the peaks arise in the high energy region contrary to the experimental data.

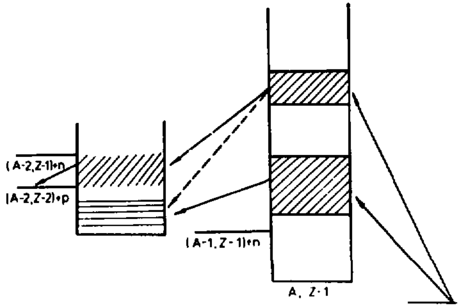

Fig.5. The scheme of the decay of high energy branch of GDR.

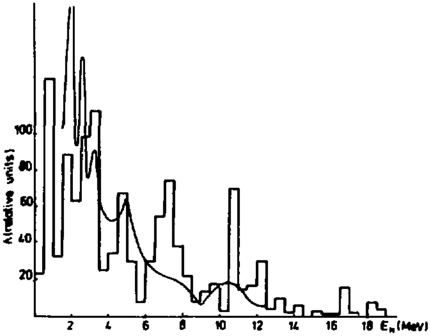

Fig.6. Comparison of the calculated (histogram) and measured /5,6/ spectra of neutrons from $^{32}S(\mu^-,\nu_\mu n)$ reaction.

Note the other fact concerning the daughter nuclei under consideration. Namely the proton threshold lies at ~6-8 MeV while the neutron one is situated approximately 4 MeV higher. Only few levels /17/ with admixture of corresponding $1p_{3/2}$ or $1d_{5/2}$ hole states are near the proton threshold (the proper levels both in ^{31}P and ^{57}Co arise at ~6 MeV excitation energy). On the other hand, there are more than ten levels with the admixture of the abovemensioned hole states between proton and neutron thresholds.

General situation in the neutron decay of high energy branch of the resonance is schematically depicted in fig.5. It can be expected that the decay with neutron emission proceeds mainly to the group of levels between proton and neutron thresholds. As a consequence, the local maximum in neutron spectrum appears. Moreover, due to the decay to the levels above the proton threshold the subsequent emission of proton from daughter nucleus can be expected.

More detailed consideration will be carrued out for ^{32}S nucleus where the corresponding calculations were done elsewhere /18/. It was supposed that the $1p^{-1}_{3/2}$ hole admixture in the wave function of ^{31}P levels lying between proton and neutron threshold is of the form

$$\alpha|1p_{3/2}^{-1}(2s_{1/2}-1d_{3/2})^4>+\beta_n|1d_{5/2}^{-n}(2s_{1/2}-1d_{3/2})^{n+2}(1f-2p)>.$$

Even small value $\alpha=\sqrt{0.05}$ changes the calculated neutron spectrum considerably and satisfactory agreement with experiment is obtained. This is demonstrated in fig.6 where the experimental and calculated neutron specıra are depicted.

The excited states of ^{31}P nucleus will decay further with the proton emission to the ^{30}Si levels of $|1d_{5/2}^{-n}(2s_{1/2}-1d_{3/2})^{n+2}>$ configuration. The excitation of the positive parity level was indeed observed experimentally/19-21/. Thus, the final product of the decay of high energy J^{π}, $T=1^-$, 1 resonance will be neutron, proton, and ^{30}Si nucleus. The calculated probability of this channel in the muon capture by ^{32}S nucleus is ~10%. Direct measurements of the (np) channel in muon capture were done for ^{28}Si /19/, ^{40}Ca /20/ and ^{58}Ni /22/ nuclei. The measured intensity is ~10% in ^{28}Si and (9.3±1.1)% in ^{58}Ni, in agreement with theoretical estimate.

The question arises about the contribution of the other than dipole excitation. The shell model estimation shows that they amount of ~10% of the dipole ones, the quadrupole excitations giving the main contribution. But the quadrupole excitations are considerably fragmented in (2s–1d) shell nuclei and their influence will result in broadening the local maximum in neutron spectrum not changing the picture based on the consideration of dipole type excitations only.

4. CONCLUSION

The excitation of high energy part of $T_>$ dipole resonance was analysed in (2s–1d) and (1f–2p) shell nuclei. This part of the resonance is intensively excited in muon capture and certain (e,e′) reactions. It is formed by spin flip transitions of deeply bound nucleons - $1p_{3/2}$ in (2s–1d) and $1d_{5/2}$ in (2p–1f) shell region. Its decay results in the formation of the local maximum in neutron spectra from the $(\mu^-, \nu_\mu n)$ reaction. The subsequent proton emission can be expected.

The proposed mechanism enables one to explain the appearance of local maximum in neutron spectra from $(\mu^-, \nu_\mu n)$ reaction and the fact that rather large contribution of channel is observed. It is pointed out that the above-mentioned resonance can be observed in (e,e′) reaction.

The proposed scheme allows one to connect several phenomena on the unified basis of specific structure of giant dipole resonances. To manifest this connection experimentally, it is necessary to measure the cross section of (e,e′) reaction at 180° and $E_e \sim 40$-80 MeV and at $E_e \sim 200$ MeV and smaller angles with separation of high energy transversal E1 resonance for ^{16}O , ^{28}Si , ^{32}S and ^{58}Ni nuclei. The simultaneous emission of two nucleons after the electroexcitation can be expected.

The study of (μ^-,ν_μ np) channel with the registration of neutron-proton coincidences and the measurement of their energy allows one to determine the energy region of the excitation of intermediate nuclear system in muon capture. Comparison of such a spectrum with the excitation spectrum from (e,e′) reaction will give us information about the reliability of the proposed mechanism.

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