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Introduction

Investigating muon capture on sulphur and calcium, Evseev et al.[1] have observed resonances (peaks) in the neutron spectrum. They conclude that this result is the first direct experimental confirmation of the idea of collective nuclear excitation in muon capture[2]. The predictions based on the resonance mechanism in muon capture were confirmed up to now only indirectly[3].

The idea of the resonance mechanism in muon capture (giant resonance) gives a general basis for further investigations of various aspects of the muon-nuclear interaction[4,5]. It forces one to concentrate attention on the manifestation of nuclear collective effects in muon capture and similar processes. In our paper we will discuss some of these problems.

It is known, that the experimental results on the neutron angular distribution[6] relative to the muon polarization vector have stimulated intensive investigations of muon capture processes. It is unknown, as yet, for what reason the neutron asymmetry is large, but now it is clear, that the extraordinary conclusions on muon-nucleon coupling constants, made[7] in the framework of the single particle model, are very relative. In recent experiments[8,9] one obtained the positive asymmetry rather than the negative[6] one.

When considering the neutron angular distribution it is necessary to bear in mind that the neutron asymmetry in a high energy ($E_n \gtrsim 20$ MeV) part of the spectrum is not related directly to the resonance mechanism. This part is discussed in connection with the determination of the coupling constants. However as was pointed out earlier[4] in this part of the spectrum one cannot but takes into account the short-range correlations between the nucleons in the nucleus (This leads us to the problrm of the cluster structure of nuclei). As to the asymmetry in the resonance region (up to the neutron energy of about 10 MeV) unfortunately there are there no direct measurements of the differential asymmetry. The latter means here the asymmetry in a narrow energy range. Undoubtedly, some direct measurements are needed.

Thus, the question arises as to whether it is possible in principle to make the resonance mechanism compatible with the presence of the neutron asymmetry in the soft part of the spectrum. Before discussing this problem let us consider how the peaks appear in the neutron spectrum.

1. Neutron Spectrum in Muon Capture by Complex Nuclei

The muon is captured by a proton from the K -orbit of the mesoatom. The most part of the energy is taken away by the neutrino. The remaining part is taken away by the neutron

$$\mu^- + p \rightarrow n + \nu .$$

As a result of muon capture a proton hole is created in one of the nuclear shells. Taking into consideration the proton hole, the final state of the nuclear system will be the three-body system: outgoing neutron, proton hole and core (vacuum). They are interacting with each other. The interaction of the outgoing neutron with the proton hole is of great importance. It causes the excitation of the residual nucleus and as a result the nuclear system goes over to other channel. Thus this interaction leads to the coupling of some various channels. When the neutron energy is about a few MeV the interaction is very strong. As a result the neutron spectrum has a very nonuniform structure. This effect is associated with the resonance behaviour of both the scattering matrices and the amplitudes of the nuclear disintegration by the external field (photoabsorption, inelastic electron and proton scattering and so on). The typical spectrum is shown (for muon capture/10/ in ^{16}O) on Fig. 1. It gives ones the idea about the disposition and width of the peaks.

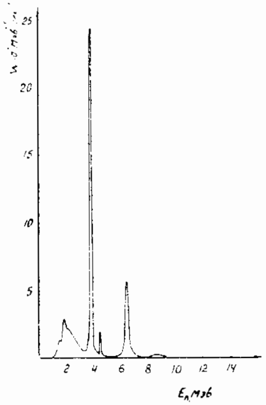

Fig. 1. The calculated /10/ neutron spectrum from muon capture in ^{16}O .

This spectrum was calculated using the unified theory of nuclear reactions, which takes into consideration both the direct and the resonance processes. The calculation has been done in the framework of the approximate method of this theory, developed by Balashov et al./10,11/. In such an approach the disintegration amplitude with a neutron in j -channel is given by

$$M_{0\to j}(E) = \langle \phi^{(-)}_{jE} | H_{\mu} | 0 \rangle + \sum_{\lambda} \frac{\langle \phi^{(-)}_{jE} | \hat{V} | \Psi_{\lambda} \rangle \langle \Psi_{\lambda} | \hat{H}_{\mu} | 0 \rangle}{E - \mathcal{E}_{\lambda}} \quad . \qquad (1)$$

This expression is quite simple. The first term is the direct transition amplitude into the particle-hole channel j . The distorted wave method is used for its calculation. The wave function $\phi^{(-)}_{jE}$ describes the final system in the j -channel when the coupling is absent. The second one is the amplitude of the resonance two-step transition into the same channel. The complex energy $\mathcal{E}_{\lambda} = E_{\lambda 0} - \frac{i}{2}\Gamma$ defines both the disposition and the width of the intermediate states. Their excitation probabilities are determined by the matrix elements $\langle \Psi_{\lambda} | \hat{H}_{\mu} | 0 \rangle$ and the decay probability by $\langle \phi^{(-)}_{jE} | V | \Psi_{\lambda} \rangle$. In the first approximation the wave functions Ψ_{λ} are the superposition of some particle-hole functions. Thus in a simple version of the particle-hole scheme it is possible to bring each resonance in correspondence with the definite quasistationary state of the intermediate nucleus. Knowing the excitation probabilities, the total and partial decay widths one calculates the spectrum of the outgoing neutrons.

The analysis of the approximate method of channel coupling and the straightforward numerical calculations allow one to ground and to improve/10,11/ the traditional method/2,4 12/ of description of the nuclear disintegration. In the latter the direct transitions are not taken into account; the quasi stationary states are described by the shell model wave functions; the decay modes are calculated in the framework of the reduced width. The phases of the width, in general are dependent on the energy and associated with the phases of the potential scattering.

The above method, modified according to the more general theory was used for the muon capture calculation in calcium

$$\mu^- + {}^{40}\mathrm{Ca} \rightarrow {}^{39}\mathrm{K} + n + \nu \, . \qquad (2)$$

The calculation was performed in the particle-hole approximation without taking into account the spread of such states over more complicated ones. There were considered the following transitions: allowed, first and second forbidden ones. They correspond to the following states in the residual nucleus ${}^{40}\mathrm{K}: J^\pi = 1^+, 0^-, 1^-, 2^-$ and $2^+, 3^+$.

When calculating the neutron decay modes only the main channels were taken into account. They correspond to the transitions into the three hole $3/2^+$, $1/2^+$ and $5/2^+$ states of ${}^{39}\mathrm{K}$. The total neutron spectrum is shown in Fig. 2 Of course, such a method does not pretend to a precise quantitative description of the experimental data. The particle-hole states, considered in this calculation are spread over the more complicated ones (two-particle , two-hole, three-particle, three-hole ones and so on).

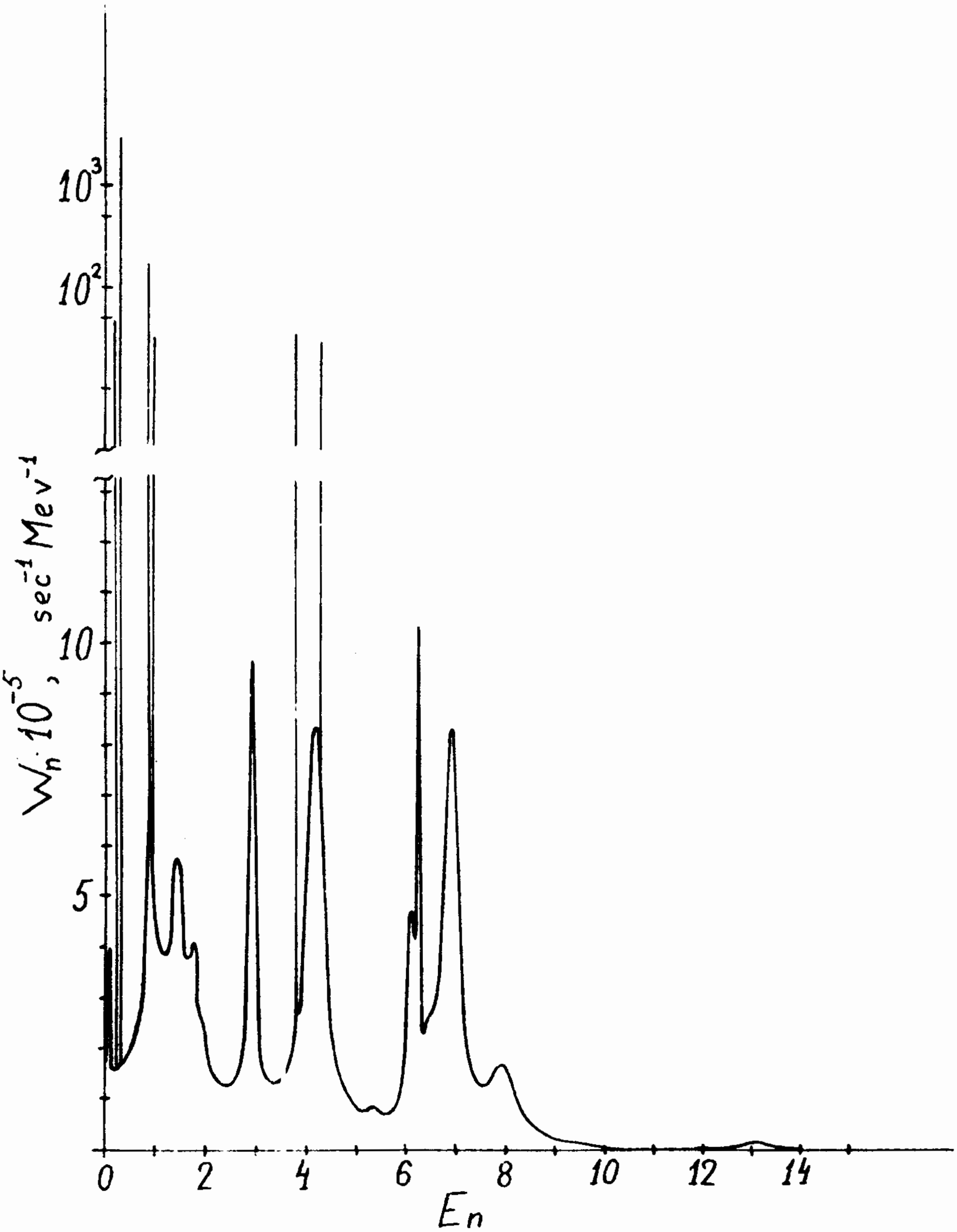

Fig. 2. The calculated neutron spectrum from muon capture in ^{40}Ca. The upper part of the figure (above the axis breaking has a semilogarithmical scale.

Such a spread leads to the increasing of the number of the peaks, the change of their intensities and dispositions [13]. As to the decay modes such a spread leads to the decrease of the high-energy part of the outgoing particle spectrum and to the increase of the soft part. Indeed, from the analysis of the photonuclear reactions [14,15] it is known that the photonucleon spectrum calculated without the account of such a spread disagree with the experimental data in their very soft part.

2. Asymmetry of the Angular Distribution of Neutrons from Polarized Muon Capture

The asymmetry of the neutron angular distribution from polarized muon capture is due to the interference between the waves of the opposite parity. A similar problem arises when investigating photoprotons and photoneutrons. It is clear, that in the region of the overlapping of dipole and quadrupole resonances the level density is very high. Therefore, one would expect , that the overlapping of the large number of the levels cancels the effect of the interference. However, it appears, that the interference between E1 and E2 transitions is coherent [11]. This means that the fluctuation of the angular distribution coefficient when passing through each the resonance does not cancel on the average over the region of the dipole and quadrupole giant resonances overlapping. Therefore it is quite reasonable to estimate the value of the asymmetry coefficient in the framework of the simple particle-hole model, which does not take into consideration the large number of other states.

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The neutron asymmetry coefficient $\alpha(E_n)$ calculated in the same approach, as the neutron spectrum in Fig. 2, is shown in Fig. 3. The result is given for reaction (2). The coefficient is defined by the following expression.

$$w(E_n, \theta_n) \approx 1 + \alpha(E_n) P_\mu \, \mathrm{Cos}\, \theta \ , \tag{3}$$

where P_μ is the residual muon polarization before capture.

The shape of the angular distribution both for the photonucleons and for the neutrons from muon capture is more sensitive to the parameters of the model than the rate of the total capture or even its shape. However, in general $\alpha(E_n)$ has a shape, as is shown in Fig. 3. It is important, that even if we do not take into account the spread of the states the overlapping of the levels with positive and negative parity is large enough.

3. Transitions to the Excited States of the Residual Nucleus

The results by Kaplan et al.[3] on ^{15}N yield in the $I^\pi = 1/2^-$ and $3/2^-$ states after muon capture by ^{16}O were considered as an indirect confirmation of the idea of the resonance mechanism in muon capture. The experimental value for the muon capture rate with ^{15}N in $3/2^-$ state is equal to $(2.50 \pm 0.23).10^4$ sec^{-1}. The diagonalization method gives $5.3.10^{+4}$ sec^{-1} (according to[2]) and $3.0.10^4$ sec^{-1} (according to[12]). The result, obtained in the framework of the unified reaction theory in surprisingly good[10] and is $(2.6-2.7).10^4$ sec^{-1}.

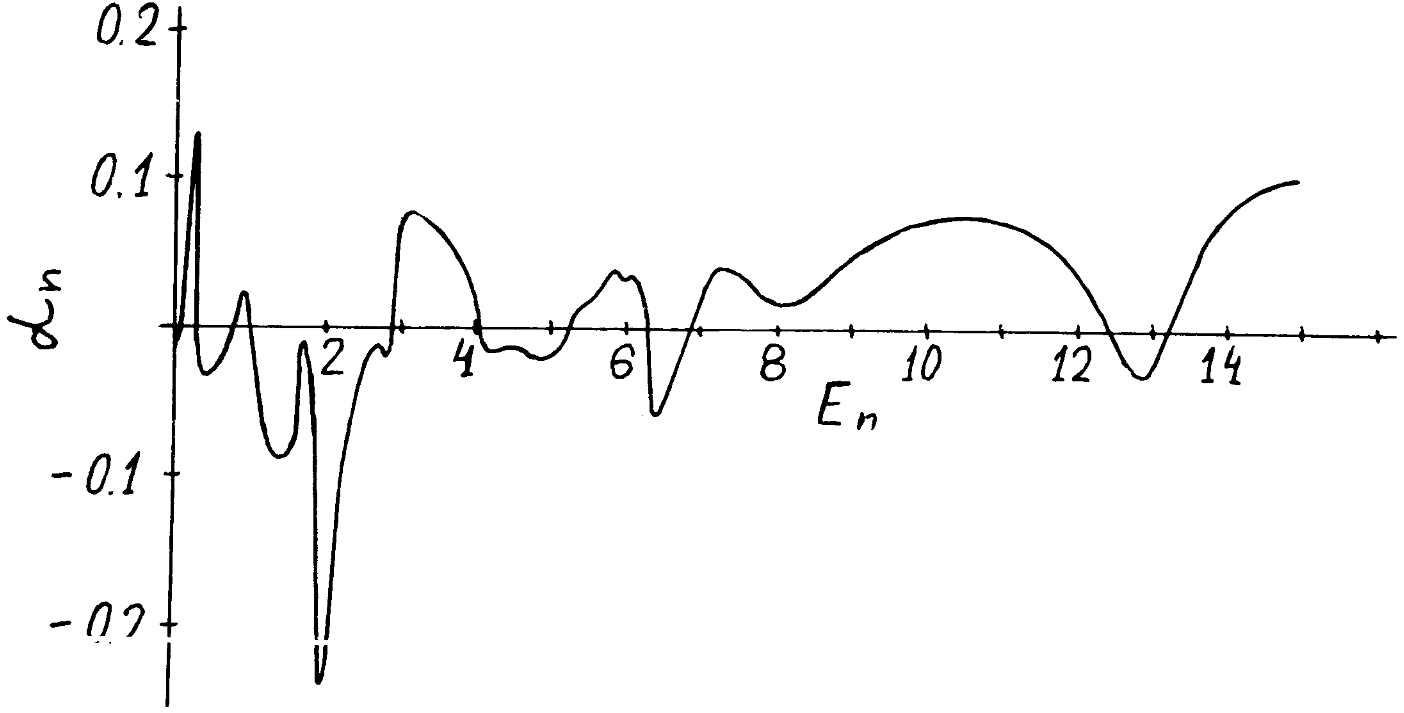

Fig. 3. The neutron asymmetry coefficient in muon capture from ^{40}Ca .

The development of the coincidence method in nuclear experiments would give the possibility for measuring the outgoing neutron in coincidence with γ -quanta, emitted by the residual nucleus. Therefore we have calculated the partial neutron spectra (when the residual nucleus is in a given state) and the corresponding asymmetry coefficient from muon capture on ^{40}Ca. The results are shown in Figs. 4,5 and 6. The total yield is given in Table 1.

It is clear , that if in coincidence experiments one defined the γ -lines one would be able to bring into correspondence each peak of the neutron spectrum with the peaks in excitation spectrum of the intermediate nucleus. Such information would give the possibility for investigating together with photonuclear reactions and inelastic electron scattering the analog states in nuclei. Up to now the analogy between photonuclear process and muon capture/16/ is used either qualitatively or for the comparison of the total capture rate with the photoabsorption cross sections.

Another problem, which can be investigated by means of the coincidence method, is associated with the study of the neutron asymmetry mechanism in the resonance region. It is clear that the neutron yield corresponding to the definite state of residual nucleus (measured in coincidence with γ -quanta) would be less sensitive to a possible spread of the particle-hole states. Therefore such calculations performed in the framework of the particle-hole model would give a larger possibility for investigating the problem than the total neutron spectrum calculations.

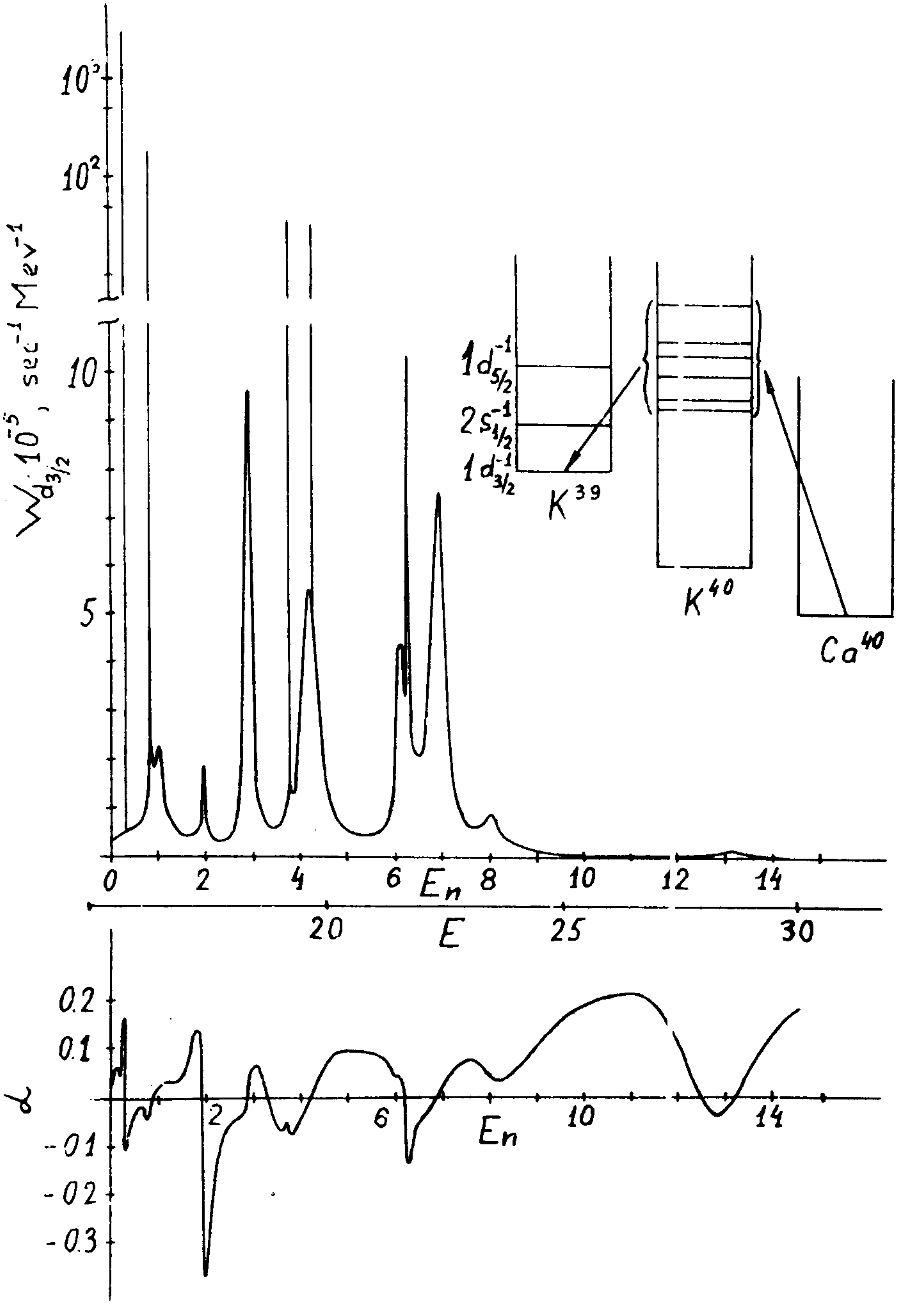

Fig. 4. The partial neutron spectrum and the corresponding asymmetry coefficient, when the daughter nucleus ^{39}K is in the $3/2^+$ state.

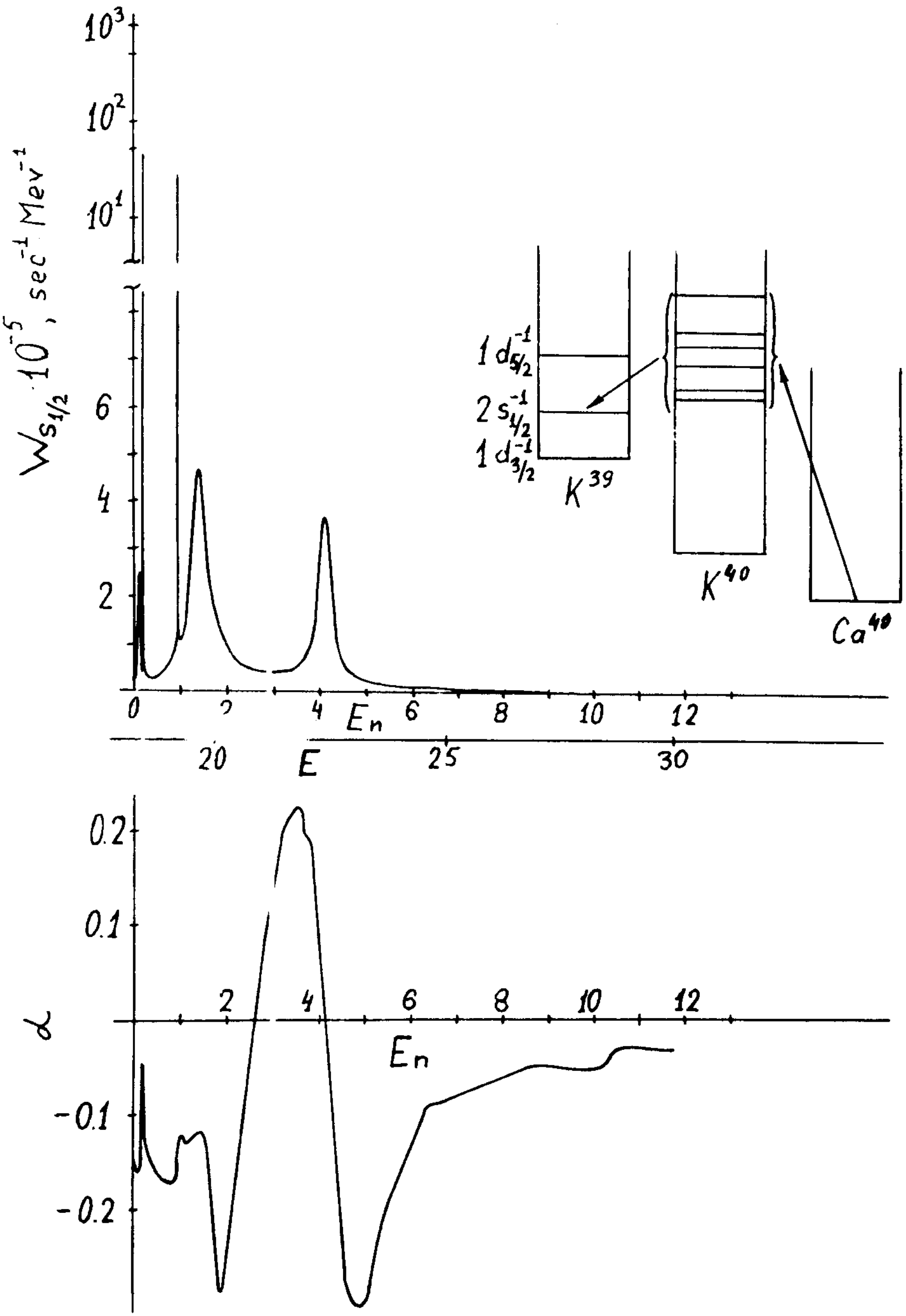

Fig. 5. The same as in Fig. 4 however ^{39}K is in the $1/2^+$ state.

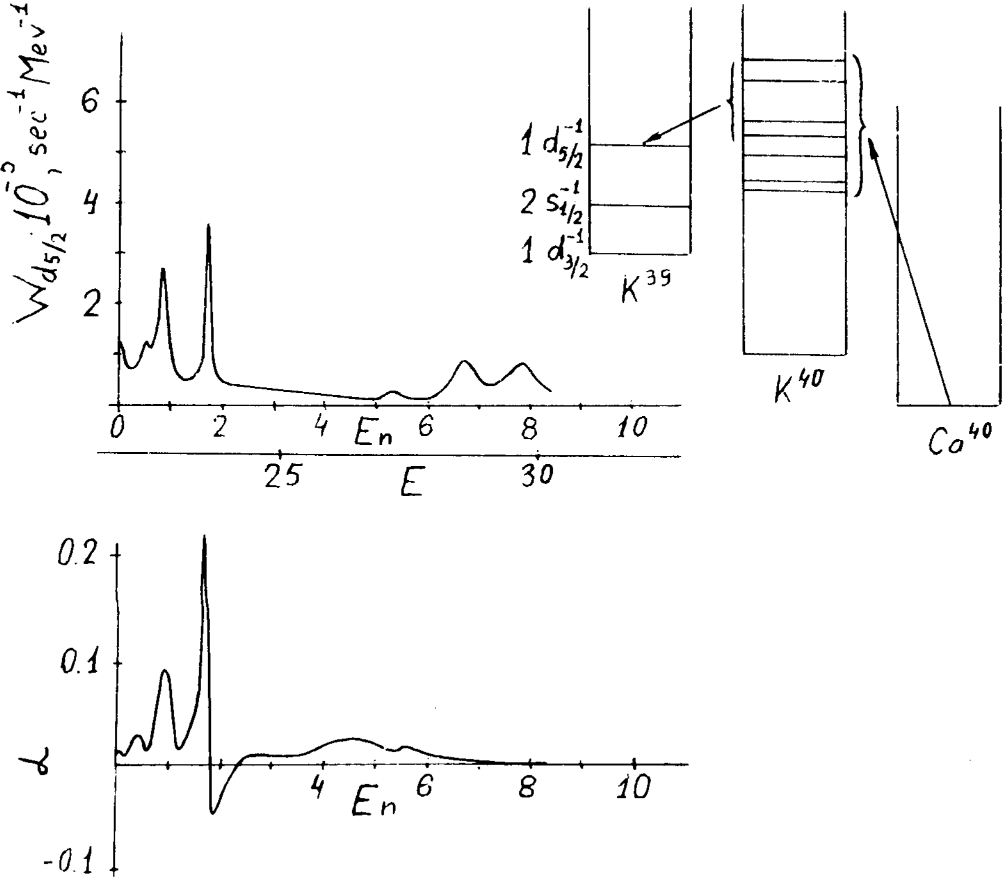

Fig. 6. The same as in Fig. 4 however ^{39}K is in the $5/2^+$ state.

Table 1

The total neutron yield with excitation of daughter nucleus ^{39}K in a given state. $W_j^{(-)}$ and $W_j^{(+)}$ are the capture rates (in 10^5 sec^{-1}) through the negative and positive parity intermediate states respectively. $\bar{a}_j$ and $\bar{a}$ are partial and total neutron asymmetry averaged over the giant resonance region

Channel , j	$W_j^{(-)}$	$W_j^{(+)}$	$W_j = W_j^{(-)} + W_j^{(+)}$	$\bar{a}_j$
$3/2^+$	11.7	6.3	18.0	0.019
$1/2^+$	6.5	1.6	8.1	-0.082
$5/2^+$	0.3	3.8	4.1	0.042
Σ	18.5	11.7	30.2	$\bar{a}$ =-0.005

4. Emission of Charged Particles in Muon Capture by Complex Nuclei

Emission of charged particles in muon capture testifies directly the presence of the correlations between the nucleons in nuclei. Though the experiments on charged particles detection are carried out during the long time[17-21] they are associated insufficiently directly with the basic problem of muon capture mechanism. Basing on the resonance mechanism idea in muon capture we are able to give some predictions about the charged particles emission. The direct calculations of the charged particles emission in muon capture in the framework of the resonance mechanism are only in their initial stage[22]. Nevertheless using the results, obtained when investigating the same problem in photonuclear reactions[14,23,24] it is possible to formulate the statements about their yield.

The gross structure of the cross section for the dipole photoabsorption in double magic nuclei (^{16}O, ^{40}Ca) is very simple. The same process in nuclei with infilled shell shows that in this case the excitation mechanism is more complicated. First of all the giant resonance in nuclei with unfilled shell is very broad. It is formed out of the two groups of the nucleon transitions, i.e. transition from the last, unfilled shell and from the next to last, filled shell. As a result one has two energy regions in the excitation (configurational splitting of the giant resonance[24]) spectrum. The connection between these two groups of transitions is weak. Therefore each group decays through its own channels. The low energy part of the giant resonance decays mostly by the single nucleon emission into the ground and low lying states of the residual nucleus (A−1). The high energy part decays into the high excited states of the final nucleus. Such states contain a hole into the next to last shell and generally are lying above the nucleon threshold. Therefore it appears that one of the main decay channels of the upper group of the giant resonance is two-particle one. Fig. 7 illustrate schematically such a situation. In the case of 1p -shell nuclei the nucleon channel in daughter nucleus A−1 is supressed very often as compared with the emission of more complex particles.

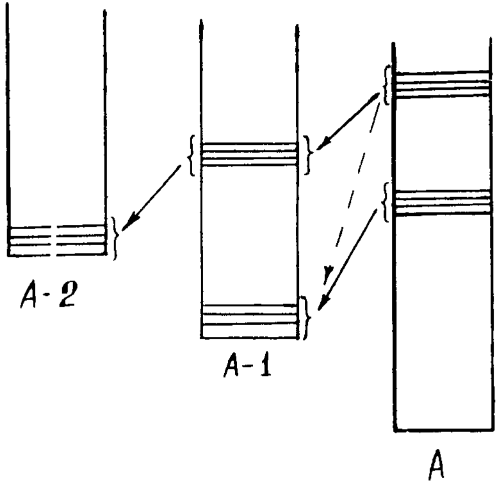

Fig. 7. The splitting of the giant resonance and its decay mode.

Extending this picture to muon capture[25] it is necessary to take into account the following. Contrary to photoabsorption the number of protons and neutrons change after muon capture. In the case of 1p shell nuclei in an intermediate nucleus (A, Z−1) the thresholds for the decays with charged particles emission are much more higher, than the neutron one. For example, in ^{12}B formed in muon capture by ^{12}C, the neutron threshold is 3.4 MeV and the proton one is 11.2 MeV. With increasing atomic number the proton and neutron threshold difference decreases. In $(2s-1d)$ shell nuclei this difference is small. In ^{28}Al formed in muon capture by ^{28}Si the neutron threshold is 7.7. MeV and the proton one is 9.6 MeV, for example. However, when the atomic number A increases, the Coulomb barrier also increases and prevents from emission of the charged particles if it is allowed from the energetic point of view. Therefore unlike photoabsorption in muon capture the neutron channel must be the predominant one. After the intermediate nucleus have emitted the neutron it restores the neutron-proton balance. The charged particle threshold in the daughter nucleus $(A-1, Z-1)$ lies at the same energy or sometimes even lower, than the neutron one (in ^{11}Be the neutron threshold is 11.5 MeV and the proton is 11.2 MeV). For the high-lying states of the daughter nucleus $(A-1, Z-1)$ with a hole in the filled shell the charged particle emission may compete with the neutron one. Consequently, according to the resonance model the yield of the charged particle x in muon capture must be necessarily associated not only with the $(\mu^-, \nu x)$ channel, but also (and, probably mainly) with the $(\mu^-, \nu n x)$ channel. Therefore the total charged particle yield must increase as the nucleons occupy the shell, achieve the maximum, when the shell is semifilled (between neighbouring magic nuclei) and decrease with approaching to the nearest magic nuclei. The main part of the spectrum of charged particles must be soft. With increasing atomic number, the charged particle yield decreases. For nuclei with $A > 40$ the charged particle yield would be small.

Such a mechanism will give a negligible yield in the high energy part of the spectrum. One may expect, that high energy particles are due to the other mechanism of muon capture. At such energies the role of the short-range correlations becomes important. Muons may be captured directly by some clusters/26/. However, the total yield of the charged particles due to cluster absorption is not expected to be large. Comparing these two mechanisms we may conclude that basing only on the detection of the two outgoing particles in coincidence it is impossible to distinguish between these two mechanisms.

The analogy between photoabsorption (dipole) and muon capture holds when one considers only the first forbidden transitions. Though they give the main contribution (in the case of light nuclei) to the total capture rate, the allowed and second forbidden transitions may lead ,in principle, to specific decay channels.

The allowed transitions in muon capture/22/ are very similar to the transitions in inelastic M1 electron scattering/27/. The strongly excited levels, are in general, either the bound or the low lying ones and therefore decaying mostly through the neutron channel. The yield of the charged particles due to the allowed transitions is small.

Below we apply the formulated general principles for the description of the disintegration of some of light nuclei in 1p and (2s − 1d) shells. However, sometimes the general principles are not enough for understanding the decay modes and we will take into account the particular features of the nuclei considered.

^{6}Li . In the intermediate nucleus ^{6}He three groups of the levels are excited/28/ by analogy with the dipole giant resonance of photoabsorption/29,30/. The first group is in the energy region of about 8 MeV. It is formed from the transitions of the external 1p -nucleon to the neighbouring (2s− 1d) shell. The main decay mode is the neutron one to ^{5}He with a subsequent decay of ^{5}He to ^{4}He + n. The second and third groups are in the energy region of 10–20 MeV and of about 30 MeV, respectively. They are formed from the transitions of the internal 1s-nucleon to 1p shell. These level groups decay mostly to the high excited states of ^{5}He. These decay mainly to ^{3}H + ^{2}H

^{7}Li. The same features characterize muon capture in ^{7}Li. The low lying states would apparently decay to ^{4}He + n and ^{4}He + 3n, and the high excited ones ^{3}H + ^{2}H + 2n.

^{9}Be. The decay of the intermediate nucleus ^{9}Li is very peculiar. Decay with neutron emission leads to ^{8}Li. After beta decay ^{8}Be is formed which is unstable. As a result one has two α-particles in the final state. The neutron threshold in ^{8}Li is very low (2MeV). Therefore one would have particles from the subsequent decay of ^{8}Li to ^{7}Li + n. It seems that the intensity of this channel is of the same order (or somewhat higher) as ^{8}Li in the bound states. It is also expected that ^{8}Li would decay to ^{5}He(^{4}He + n) + ^{3}H with a smaller probability.

Note that the analysis/31/ of photodisintegration of ^{9}Be, based on the same principles have given good results.

^{10}B. After the decay of the intermediate nucleus ^{10}B through the neutron channel ^{9}Be is formed. Because the neutron threshold in ^{9}Be is very low it would emit a second neutron. As a result we would have the following channel

$$\mu^{-} + {}^{10}\mathrm{B} \to 2\alpha + 2n + \nu$$

as the main one.

^{11}B, ^{12}C and ^{13}C. In this case it is impossible to add anything more to the general principles formulated without making any calculation.

^{14}C . This is a neutron-rich nucleus. Therefore after muon capture the intermediate nuclei would emit subsequently some neutrons. Probably the yield of the charged particles is unlike.

^{14}N . According to the analogy with photoabsorption/32/ in ^{14}C the intermediate states of this nucleus will decay mainly with emission of two neutrons. The experimental data/33/ on photoabsorption in ^{14}N confirm indirectly such a conclusion: the main channel of the photodisintegration is the (α ,np) one. The channel (γ,np 3α) is also of importance/34/. In muon capture this channel corresponds to the (μ^-, ν 2n 3α) one.

^{15}N. This nucleus is the nearest one to the double magic ^{16}O . Therefore the process of capture will be quite similar to muon capture in ^{16}O , i.e. the main channel is the single neutron emission. The yield of the charged particles would be singificantly smaller as compared with nuclei having smaller atomic numbers.

The considered specific features of disintegration of the 1p shell nuclei, were associated with the fact that the Young scheme for them is a good quantum number. For the (2s – 1d) shell nuclei such specific features are not manifested. However, the general regularity associated with the presence of two groups of nucleon transitions in the muon capture giant resonance must hold. Let us consider, as an example, the nucleus ^{20}Ne .

The neutron (6.6 MeV) and α -particle (8.1 MeV) thresholds for the intermediate nucleus ^{20}F decay are very close to one another. The upper states of the giant resonance may decay directly on ^{16}N with α - particle emission. However, because of high Coulomb barrier and the decrease of the structural factors of the decay width it is unlikely that the α - particle channel will dominate the neutron one. The decay of ^{20}F on the ^{19}F

excited states in energy region of 4–8 MeV leads also to α-particle decay. (α - decay is the single decay channel in this energy region). Komarov et al.[36] observed the high yield of the soft charged particles after muon capture in ^{20}Ne. However, they did not identify them.

The experimental check of the formulated predictions would give the possibility for better understanding of the muon capture mechanism and would stimulate more detailed calculations.

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