СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

ДУБНА

E1 - 9457

Yu.A.Batusov, R.A.Eramzhyan

CHARGED PARTICLE EMISSION IN MUON CAPTURE BY ATOMIC NUCLEI

1976

E1 - 9457

Yu.A.Batusov, R.A.Eramzhyan

CHARGED PARTICLE EMISSION IN MUON CAPTURE BY ATOMIC NUCLEI

I. Introduction

For a long time one of the most principal points in the problem of muon-nuclear interaction was the problem of muon capture mechanism. The experimental proof of the idea that the collective states are dominating in this prooess has made it possible to understand and interpret in a unique way main features of the process. At present the problem of the muon capture mechanism is not so critical. New problems raised due to experiments are brought now to the first place: these are the problems of description of energy spectra of outgoing particles (first of all, neutrons) and their angular distributions, the final states population in daughter nuclei and so on. Such a change of interest is not accidental. The description of the nucleus desintegration touches much upon many aspects of nuclear structure and the reaction mechanisms. That allows one the thorough test of many basic ideas of the theory of muon interaction with oomplex nuclei.

Among different channels of nucleus disintegration in muon capture, those with the charged particle emission are of a special interest. The emission of such particles is not directly due to the elementary process of muon capture and is a result of the correlations between nucleons in nucleus. On the one hand the nucleon correlations result in the generation of various collective states in nucleus. By those states of a giant resonance type the muon capture proceeds mainly. The decay of these states in some cases leads to the charged particle emission. Hence, immediately the question arises to what extent is the charged particle emission in muon capture due to the decay of resonance states? Or are they evaporating after establishing the statistical equilibrium?

On the other hand correlations of short-range type give rise to formation of some associations of nucleons in a nucleus. The muon interaction with such subsystems is more complicated and results in the appearance of specific channel with the emission of several correlated particles. This type of process would also contribute to charged particle emission.

The first information /1/ on observation of charged particle emission in muon capture has been published long ago. However, a systematical study of the process has started quite recently. At present quite various experimental and theoretical information is already available /2/ . On its basis the experimental results may be systematized and possibilities of their interpretation may be considered. It is just the problem this paper is devoted to.

II. Experimental data on charged particle emission in muon capture by complex nuclei

1. For investigation of charged particle emission in muon capture by complex nuclei one of the effective methods appears to be the method of nuclear emulsion. By such a method the yield

of charged particles has been determined /3-6/ and some features of this process have been established. The yield W_σ was measured by several experimental groups. The obtained results are given in Table I. On the whole they are consistent with each other and two of them /4,6/ are in close agreement.

Table 1. Charged particle yield from muon capture in nuclear emulsion

	Number of stopped muons	Charged particle yield in %
Morinaga and Fray /3/	$2.4\ 10^4$	2.4
Kotelchuck /4/	$9.3\ 10^4$	1.95 ± 0.07
Batusov et al. /6/	$\sim 1\ 10^6$	1.94 ± 0.11
Vaisenberg et al. /5/	$4.7\ 10^4$	3

According to these measurements the charged particle yield in muon capture in nuclear emulsion *) equals

$$W_\sigma = (1.95 \pm 0.06)\% \quad . \qquad (1)$$

Somewhat higher yields obtained in the other two measurements /3,5/ may be due to somewhat inaccurate consideration of the background. The latter is mainly due to the pion contamination in the muon beam. Such contaminations are usually very small. However, because of that about 70% of the pion stops in nuclear emulsion give rise to the charged particle emission /7/, the background can be sufficiently large.

*) The muon ending in a nuclear emulsion with its subsequent capture by atomic nuclei resulting in the charged particle emission is conventionally called the σ -star.

The observed distribution of σ - stars over the number of prongs is given in Table 2. The quantity N_n/N_{ch} is the ratio in per cent of the number of the n-prong stars to the total number N_{oh} of the observed ones.

Table 2. Prong number distribution of the σ -stars ($\frac{N_n}{N_{oh}}$ in %) from muon capture in nuclear emulsion

	Prong number distribution				
	n=1	2	3	4	5
Morinaga and Fray /3/	65.8±3.3	22.8±2.0	3.4±0.8	0.8±0.4	0.2±0.2
Kotelchuck/4/	86.5	10.3	2.8	0.3	0.06
Batusov et al./8/	78.5±1.6	14.8±0.7	5.2±0.4	1.5±0.2	0.03±0.03
Vaisenberg et al./5/	69.0±2.3	21.4±1.3	7.9±0.8	1.6±0.3	0.1±0.1

When a charged particle is emitted after muon capture by the light component of nuclear emulsion (C,N,O) one usually sees a two-prong star. Second prong is due to the recoil nucleus. Emission of one more heavy neutral particle may result in such a momentum distribution among outgoing particles that recoil nucleus turns out to be at rest. In such a case or in a similar one muon capture on light nuclei results in the one-prong star. However the probability of such events cannot be large. So the one-prong stars are mainly due to the process on the heavy component and in the first approximation the contribution to these events from the light component may be neglected. Such a criterion was used in papers /3,4/ . To determine the contribution of each component of nuclear emulsion in charge particle

yield one can use one of the standard criteria /9/ - either the Coulomb barrier criterion /5/ or the Auger electron criterion/6/. The results of the treatment of experimental data in terms of these criteria are given in Tables 3 and 4. The total yield

Table 3. The relative yield of n-prong σ -stars in muon capture by light and heavy nuclei of nuclear emulsion /6/

Prong number	1	2	3	4	All stars
Light nuclei	5.7±4.0	68.2±2.1	88.6±2.5	97.7±2.3	20.4±3.6
Heavy nuclei	94.3±4.0	31.8±2.7	11.4±2.5	2.3±2.3	79.6±3.6

Table 4. Muon capture rate with charged particle emission (in % to the total muon capture rate) in nuclear emulsion /6/

Prong number	Light nuclei	Heavy nuclei
1	1.5±1.1	2.7±0.2
2	3.7±0.3	0.17±0.02
3	1.7±0.1	0.02±0.005
4	0.5±0.08	≈ 0.001
Total	7.4±1.4	2.9±0.2

of charged particles from muon capture by heavy nuclei of emulsion agrees with each other in all experiments and it equals about 3%. It is not the case for the light component, and discrepancies here are rather essential (see Table 5).

Table 5. Charged particle yield (in %) from muon capture by light and heavy nuclei of nuclear emulsion

	Light nuclei	Heavy nuclei
Morinaga and Fray /3/	12.9	2.7
Vaisenberg et al. /5/	15.6±2.3	3.1±0.4
Batusov et al. /6/	7.4±1.4	2.9±0.2

Table 6. Distribution of the single-charged particles over mass number in muon capture in nuclear emulsion /5/

	Light nuclei	Heavy nuclei	Total
Protons	0.44±0.15	0.86±0.06	0.79±0.06
Deuterons	0.56±0.15	0.14±0.06	0.21±0.06

The charged particles have a small range ever hardly exceeding 2-3 mm of the emulsion (see Fig.1). Therefore the identification of particles over masses is difficult to realize practically. It is somewhat easier to identify the particles over charge. However not in all the experiments this could be realized. By the results of paper /3/ the muon capture by heavy nuclei in emulsion leads mainly to the

emission of the single-charged particles (with the total yield of 2.2%). Other 0.5% are α - particles. In this experiments one has failed to identify the single-charged

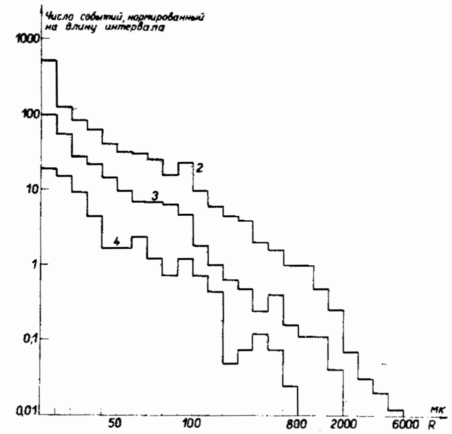

Fig.1. The distribution of charged particles over their range in the muon capture by atomic nuclei in photoemulsion.

particles over masses. As to the light component of nuclear emulsion the single charged particles yield is found to be equal to 9.5% and of α-particles - 3.4%.

The identification of single-charged particles over masses has been done only in one experiment. The results are given in Table 6. It is interesting to note that the yield of protons and deuterons from the muon capture by light nuclei of nuclear emulsion is practically the same.

Thus the nuclear emulsion method has allowed one to obtain various information, both of quantitative and qualitative type, on some features of muon capture process with charged particle emission. Unfortunately the information obtained concerns not an individual nucleus but a group of nuclei- either the light component (C,N,O) or the heavy one (Ag,Br). For the heavy nuclei this is not so important since in this region of nuclei their individual properties, as a rule, are less manifested. On the contrary, for the light nuclei the individual properties of their excitation in many cases determine the nature of the subsequent decay process. The accurate measurements of the angular distributions of the outgoing charged particles and their energies with the subsequent kinematical analysis have made it possible to identify a number of channels and estimate their probabilities /10,11/:

$$^{12}C\ (\mu^-,\nu)\ ^{8}Li + \begin{cases} ^{4}He & w < 2.6\ 10^{-2}\,\% \\ ^{3}He + n & (0.11 \pm 0{,}02)\% < w < (0.16 \pm 0{,}02)\,\% \end{cases}$$

$$^{12}C\ (\mu^-,\nu)\ 2\,^{4}He\,^{3}H\,n \qquad w \leq (2.0 \pm 0{,}2)\,\%$$

$$^{14}N\ (\mu^-,\nu)\ ^{8}Li\,^{6}Li \qquad w < 1.4\ 10^{-2}\,\%$$

$$^{16}O\ (\mu^-,\nu)\ ^{8}Li\,^{7}Be\,n \qquad w < 1.5\ 10^{-2}\,\%$$

The analysis of the angular correlations between the outgoing particles makes it possible, in some cases, to determine the reaction mechanism. Such examples are given on Figs.2 and 3.

From the angular correlation between ^{3}He and neutral particles in the reaction $^{12}C\ (\mu^-,\nu)\ ^{8}Li\,^{3}He\ n$ it follows that the neutron and ^{3}He are produced after decay of $^{4}He^{*}$(Fig.2).

The methods which allow one to investigate processes with charged particle emission from definite nucleus will complement significantly the information obtained by the nuclear emulsion method. Though there are no so far such systematical investigations, however, certain information does already exist.

2. There are two chamber experiments with neon as a target /12,13/ . In the first one /12/ there was measured only the fast charged particles and their yield appears to be equal to (3.2±0.5)%. If one does not put such a restriction and measures all charged particles, their yield becomes much higher and is equal /13/ to(20±4)%. It means, that in muon capture by neon the most part of the charged particles is low-energy one. Unfortunately it was impossible in that case to identify the outgoing particles.

3. In muon capture by ^{28}Si the charged particle yield is also large /14/: (15±2)%. The experimental identification of emitted particles has not been made. However, the authors suppose that they are mainly protons. Under such an assumption the spectrum has a form given in Fig.4. For its measurement with a high resolution a Li(Si) target detector was used. The spectrum has a maximum at about 2.5 MeV from which it decreases approximately exponentially.

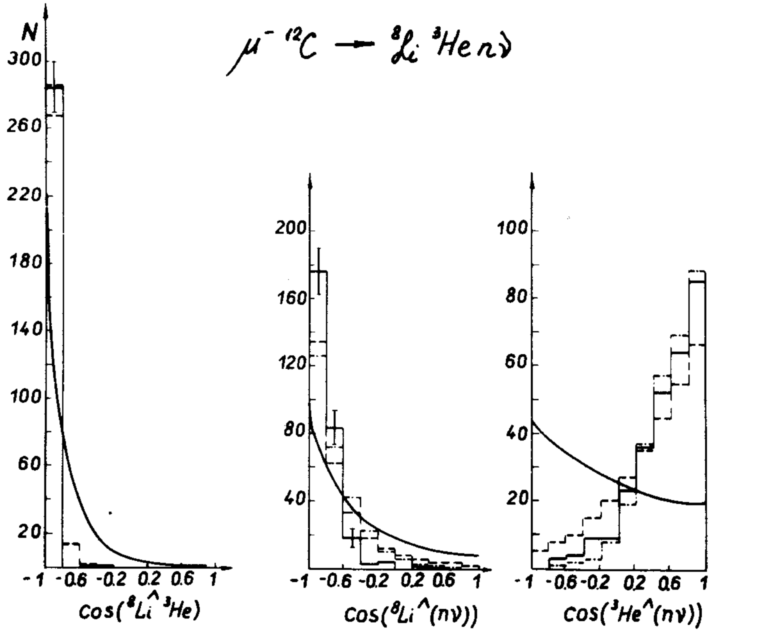

Fig.2. The angular correlations in the process $^{12}C\ (\mu^-, \nu)$ $^8Li^3He\ n$. The solid histogram is the measurement results, the solid curve is the phase volume, the dashed one–the result of the calculation aocording to the following soheme: $\mu^- {}^{12}C \to {}^{12}B^* \nu$; $^{12}B^* \to {}^8Li + {}^4He^*$; $^4He^* \to {}^3He + n$; the dash–dotted curve–the result of the calculation, based on the assumption of muon oapture by ^4Li cluster.

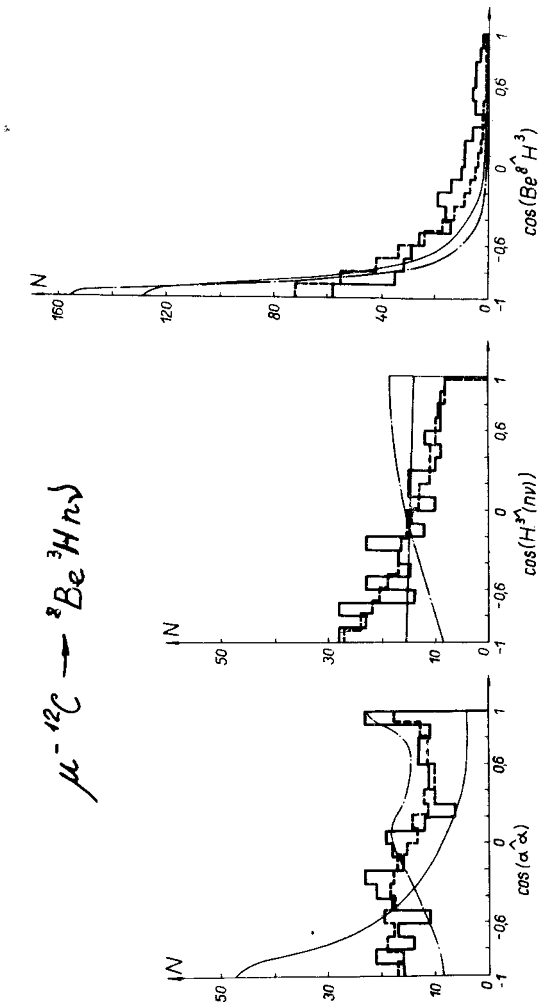

Fig.3. The angular correlations in the process $^{12}C\ (\mu^-, \nu)$ $^4He^4He^3Hn$. The solid histogram is the measurement results, the solid ourve is the phase volume, the dashed one–the result of the calculation according to the scheme: $\mu^- {}^{12}C \to {}^{12}B^* \nu$; $^{12}B^* \to {}^{11}B^* + n$; $^{11}B^* \to {}^8Be^* + {}^3H$; $^8Be^* \to {}^4He{}^4He$; the dashed–dotted one–the result of the calculation according the scheme $\mu^- {}^{12}C \to {}^{12}B^* \nu$; $^{12}B^* \to {}^8Be^* {}^4H^*$; $^4H^* \to {}^3Hn$; $^8Be^* \to {}^4He{}^4He$.

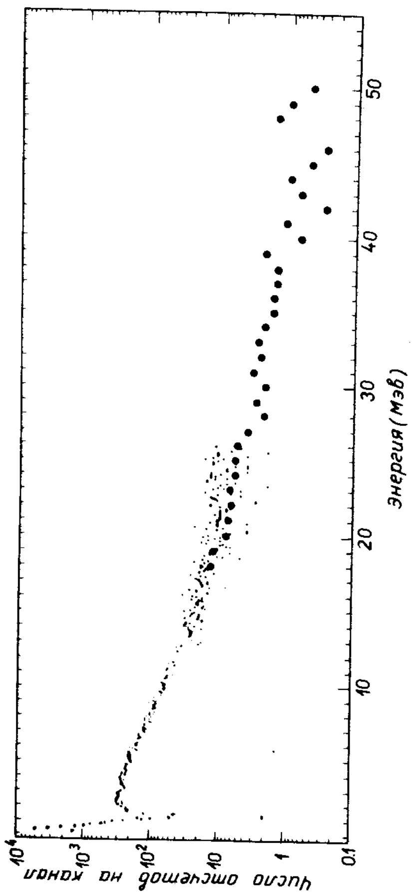

Fig.4. The energy spectrum of charged particles (presumable, protons) in the muon capture by ^{28}Si nucleus (from ref./14/ for E < 20 MeV and from ref./15/ for E > 20 MeV).

The high energy part of the charged particle spectrum was analysed in detail in paper /15/ . For the specific aims of separating the charge particles by masses and measuring their energy there was used the system of semiconductor counters. The targets used in the experiment were ^{28}Si, ^{32}S, ^{40}Ca and ^{64}Cu. The methods employed allowed one to measure only the high energy part of spectrum: for protons - from E_p =15 MeV, for deuterons - from E_d= 18 MeV, and for tritium - from E_t= 24 MeV. The measurements weremade for several values of the threshold energy E. The results are collected in Table 7 and are shown in Fig.5. From the experimental data it follows that

i) to the high energy tail of the spectrum there contribute practically only single charged particles;

ii)the larger the mass of the single-charged particles the smaller their yield;

iii) the deuteron fraction in the total yield decreases with increasing charge of the target nucleus;

iv) the proton spectra extend up to 60 MeV and those for deuterons up to 50 MeV;

v) within the experimental errors the proton spectra of ^{32}S and ^{40}Ca agrees with the neutron spectra measured by /16/ on the same targets, but differs rather strongly from the spectra measured by /17/ .

4. In some cases the daughter nucleus is a long-lived one. Using the radiochemical methods one can measure the yield of these nuclei and determine the intensity of muon capture process leading to these final nuclei. By such a manner there were studied the reactions

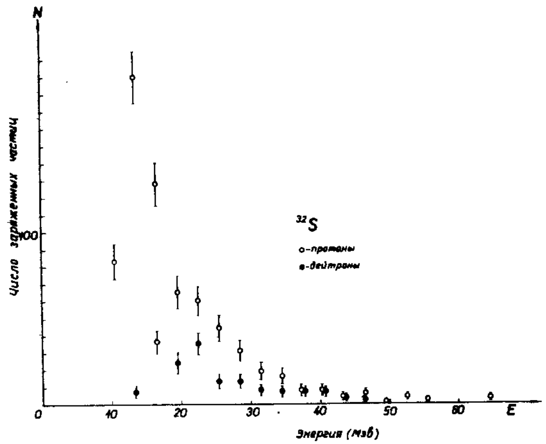

Fig.5. The energy spectra of protons (∘) and deuterons (•) in the muon capture by ^{32}S nucleus according to results of ref. /15/ .

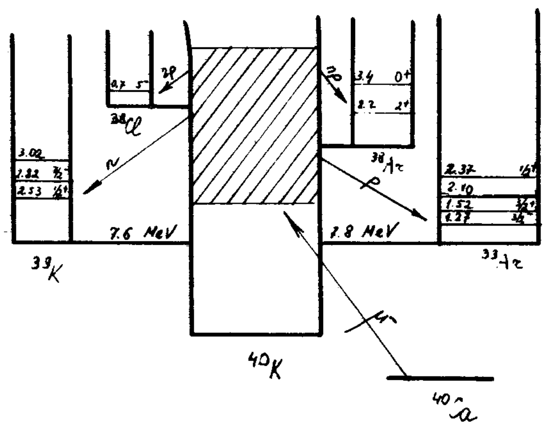

Fig.6. The scheme of levels of the daughter nuclei produced in the muon capture by ^{40}Ca nucleus.

$$\mu^- + {}^{28}Si \rightarrow p + \nu_\mu + {}^{27}Mg\,, \qquad (2a)$$

$$\mu^- + {}^{39}K \rightarrow p + \nu_\mu + {}^{38}Cl\,. \qquad (2b)$$

The intensity of the first reaction was (5.3±1.0)%, and the second one - (3.2±0.6)%. From comparison of these results for the reaction (2a) with the counter-experiment data /14/ it follows that if the main channel with the charged particles emission in muon capture by ^{28}Si is the proton one, it means that the most of protons are accompanied by neutrons. Such a channel was picked out /23/ by radiochemical method in muon capture in ^{27}Al: ^{27}Al (μ^-, ν p2n) ^{24}Na . The intensity of this reaction is (3.5±0.8)%.

The emission of composite systems has been found in the muon capture by Ni isotopes (the target consisted of the natural mixture of isotopes - 68% of ^{58}Ni and 26% of ^{60}Ni). For the total yield of charged particles of 5% (see Table 8) the main channel has been found to be

$$^{58}Ni\,(\mu^-, \nu\, x)\,^{54}Mn \qquad (1,9\pm0,2)\%$$

5. The daughter nuclei frequently left in muon capture processes in an excited state. Detection of the deexcitation γ rays and the subsequent interpretations of spectra allow one to identify the daughter nuclei. At the same time measuring the γ rays intensity one can extract the information on excited states population in a daughter nuclei. This method however does not allow one to obtain any information on ground state population.

Table 7. High energy charged particle yields in muon capture by $^{28}_{14}Si$, $^{32}_{16}S$, $^{40}_{20}Ca$ and $^{64}_{29}Cu$ (in %)

Threshold energy, MeV	^{28}Si p	^{28}Si d	^{28}Si t	^{32}S p	^{32}S d	^{32}S t
15	0.875±0.064			1.149±0.088		
18	0.635±0.050	0.334±0.032		0.781±0.067	0.343±0.040	
24	0.330±0.032	0.148±0.018	0.020±0.07	0.421±0.045	0.173±0.027	0.037±0.013
42	0.035±0.009	0.020±0.007		0.058±0.014	0.014±0.007	

Thresdold energy, MeV	^{40}Ca p	^{40}Ca d	^{40}Ca t	^{64}Cu p	^{64}Cu d	^{64}Cu t
15	1.304±0.105			0.600±0.072		
18	0.942±0.084	0.259±0.040		0.456±0.061	0.096±0.032	
24	0.484±0.055	0.187±0.030	0.019±0.010	0.274±0.050	0.082±0.026	0.005±0.005
42	0.061±0.017	0.019±0.010		0.038±0.015	0.019±0.011	

Table 8. Charged particle yield in muon capture by Ni (the natural isotopic distribution) and Fe with the formation of daughter nuclei in the excited states

Final nuclei	Excitation energy E* MeV	Yield in %	Experimental method
$^{58}Ni\ (\mu^-, \nu pn)^{56}Fe^*$	0.847	9.3±1.1	γ- spectrometry/22/
$^{58}Ni\ (\mu^-, \nu\alpha)\ ^{54}Mn^*$		1.9±0.2	
$^{58}Ni\ (\mu^-, \nu\alpha 2n)^{52}Mn^*$		0.56±0.06	radiochemistry/23/
$^{60}Ni\ (\mu^-, \nu p)^{59}Fe^*$		0.12±0.01	
Other channels		1.5	
$^{56}Fe\ (\mu^-, \nu pn)^{54}Cr^*$	0.835	2.9±0.6	γ- spectrometry/22/

As an example, in Fig.6, the level scheme is shown of the daughter nuclei produced in the muon capture by ^{40}Ca. The main channel of muon capture by ^{40}Ca is the channel with ^{39}K production in different states. At the same time in experiments/19,20/ there are observed the γ -lines corresponding to transitions in ^{39}Ar, ^{38}Ar and ^{38}Cl. These nuclei can be produced if in the muon capture the charged particle is emitted. The probabilities of excitation of the definite states in these nuclei are given in Table 9.

Table 9. Relative population of excited states in daughter nuclei ^{39}K, ^{39}Ar, ^{38}Ar and ^{38}Cl in muon capture by ^{40}Ca

Daughter nuclei	Excitation Energy E* in MeV	J^{π}	Relative population in % /20/	Relative population in % /19/
$^{39}Ar^*$	1.27	3/2$^-$	1.0 ± 0.3	2.2 ± 0.9
	1.52	3/2$^+$	2.6 ± 0.6	0.4 ± 0.3
	2.10		0.7 ± 0.2	
	2.37	1/2$^+$	0.5 ± 0.2	
	2.43		0.76 ± 0.13	
	3.26		0.32± 0.19	
Total yield			5.9	2.3
$^{38}Ar^*$	2.17	2$^+$	3.1± 0.4	6.0 ± 3.0
	3.38	0$^+$	0.94±0.16	
	3.81	3$^-$	1.52±0.15	
	3.94	2$^+$	$1.2^{+0.3}_{-0.7}$	
Total yield			6.8	
$^{38}Cl^*$	1.31	4$^-$	1.05± 0.17	
Total yield of ^{39}K in excited states			13	20

Table 10. Charged particles yield in muon capture by ^{24}Mg and ^{28}Si with the formation of daughter nuclei in the excited states

Final nuclei	Excitation Energy E* in MeV	Yield in % /21/	Yield in % /19/
1. $^{24}Mg(\mu^-, \nu p)^{23}N^*$		0.7	
2. $^{24}Mg(\mu^-, \nu pn)^{22}N^*$	1.247	4.4±0.6	
3. $^{24}Mg(\mu^-, \nu p2n)^{21}Ne^*$	0.350 ($5/2^+$)	2.5±0.3	
4. Total yield of ^{19}F		3.4	
5. $^{24}Mg(\mu^-, \nu 3p3n)^{18}F$	1.979	1.9±1.0	
1. $^{28}Si(\mu^-, \nu p)^{27}Mg^*$	0.984 ($3/2^+$)	1.9±0.2	0.4±1.0
2. Total yield of $^{26}Mg^*$		10± 1	
3. $^{28}Si(\mu^-, \nu pn)^{26}Mg^*$	2.940	3.2±0.5	2.7±1.8

A great amount of γ-transitions and their cascade character leads, in many cases, to the overlapping of lines. That complicates considerably the analysis of the spectra. It is one of the main reasons for discrepancy of the final results given by different experimental groups, for one and the same nucleus (this is already seen from Table 9).

The γ-yield from Ar and Cl (Table 9) testifies to a considerable contribution of the channel with the charged particle emission in muon capture by ^{40}Ca. As it is impossible to determine the contribution of transitions to the ground state of Ar and Cl the obtained value should be treated as a lower limit of the total yield of charged particles.

Analogous results have been obtained for the muon capture by ^{24}Mg, ^{28}Si, ^{32}S, ^{56}Fe, ^{58}Ni (Tables 8 and 10). It should be noted that the probability of the emission of one proton only is equal to or even smaller than that for proton with one or several neutrons.

For some odd nuclei in the region of atomic numbers A=45-93 the γ- spectrometry /24/ gives the intensity of the channel with the charged particle production not larger than 1% (^{45}Sc, ^{55}Mn, ^{59}Co and ^{93}Nb). For heavier nuclei the charged particles are either not observed /25/ (^{151}Eu, ^{153}Eu) or their yield does not exceed /24,26/ (1-2)% (^{127}I, ^{209}Bi, ^{142}Ce, ^{140}Ce, ^{138}Ba, ^{120}Sn).

III. Some general features of muon capture with charged particle emission

The foregoing experimental data allow one to establish a number of general features of the muon capture with the charged particle production:

i. The total yield of the charged particles from the 1p - shell nuclei (^{12}C-^{16}O) is about 10%. In the (2s-1d) shell nuclei (^{20}Ne - ^{40}Ca) the contribution of this channel increases up to (15-20)% . The yield of charged particles is almost the same also for heavier even-even nucleus ^{58}Ni. However, for odd nuclei in this region of atomic number A the yield strongly decreases. In the nuclei Br and Ag the yield is 2.9% and does not exceed (1-2)% in nuclei with A > 100.

The maximum yield of the charged particles is in nuclei near ^{40}Ca.

ii. The charged particle spectrum is mainly the low-energy one. Most likely this evidences that the charged particle emission is due to the secondary processes which take place in the excited intermediate nucleus.

The Coulomb barrier for nuclei with A around A=60 increases to 8 MeV that makes the yield of secondaries, if charged, almost impossible. It is therefore natural that the yield of the charged particles in the muon capture by the heavy nuclei is small.

iii. The yield of the high energy charged particles ($E \geqslant 15$ MeV) is small (about 1%). The yield of these particles also has a maximum for nuclei with Z near Z=20.

The high-energy particles can be either due to the cluster mechanism of capture (quasideuteron, biproton, α-particle, etc.) or due to the subsequent rescattering of fast neutrons produced in the direct process of capture.

4. In light and medium nuclei the emission of the charged particle is rather frequently accompanied by the emission of one or several neutrons. Such a situation is specific for the cluster mechanism but in this case at least one particle should be fast. The secondary processes in the intermediate nucleus also can result in the emission of several particles most likely, the low-energy ones. Therefore, to establish the mechanism of such a process it is necessary to examine the energy and angular characteristics of the emitted particles.

IV. Theoretical analysis of muon capture with charged particle emission

The muon capture by atomic nuclei proceeds mainly through the excitation of collective states of a giant resonance type. The main part of the neutron spectrum is due to the decay of these states. The theory suggested for the desoription of the giant resonance phenomenon in muon capture allows one to cover a wide range of the problems on the deoay of colleotive states with the neutron emission: the shape of the neutron spectrum, total neutron yield, population of different states in daughter nuclei. Therefore it is natural to try to relate the charged particle emission with the decay mode of the giant resonance states [27]. In this case the process of a disintegration of atomic nuclei in muon capture will be two-step: the nucleus first is excited to the giant resonance levels and subsequently decays in a variety of ways permitted energetically.

1. The giant resonance is produoed from several groups of transitions. This is shown in Figs. 7 and 8. One of these is due to exoitation of the outer nucleons and forms the main branch of the exoitation (except for some cases when the outer shell only starts to fill). Another group is due to the excitation of deeply bounded nuoleons whioh form the high-energy branch of the spectrum. The energy gap between two branohes is due to large difference in the energy of transition from the inner and outer shells. Such a property of the giant resonance in the photonuolear reactions has been observed long ago and called a configurational splitting [28] (see also ref.[29]).

The configurational splitting should appear also in the

muon capture. However, as compared to the photonuclear reactions in muon capture processes the energy dependence of the capture rate on the definite state of an intermediate nucleus is quite different. In the photonuclear reactions the cross seotion of the dipole photoabsorption to the definite level is proportional to its excitation energy E^*. In muon capture the rate of the first forbidden transition to the same analog state (such transitions form the main part of the excitation spectrum in light and medium nuolei) is practioally proportional to the quantity $E_\nu^4 = \{m_\mu - (E^* - E_0)\}^4$. This quantity rapidly decreases with growing E^*. That means that the high-energy branch of the excitation spectrum will be sufficiently weak if in the muon capture there is no enhancement of its excitation due to the axial ourrent. In the nuclei in the middle and end of 1p-shell there is no suoh enhancement and the intesity of the high energy branch of the spectrum is rather small ($\sim$3%) [30]. In the nuclei of 2s-1d shell suoh an enhancement occurs due to the transition $p_{3/2}-d_{3/2}$ caused mainly by the axial current [31]. As a result, the high energy part of speotrum has 15% of the intensity.

In the framework of the microscopic approach based on the shell model to such a qualitative description the following scheme is adequate (Fig.7). We consider the nuclei with Z=N as the main experimental information concerns such nuclei. Let ($n_1 j_1$) be the latest closed shell with the number of particles K_1, and ($n_2 j_2$) be the outer shell where there are K of particles. More deep closed shells are denoted by (0). Then the structure of the ground state of an initial nucleus can be represented as $\{(0)(n_1 j_1)^{K_1}(n_2 j_2)^{K_2}\}$. The low-energy

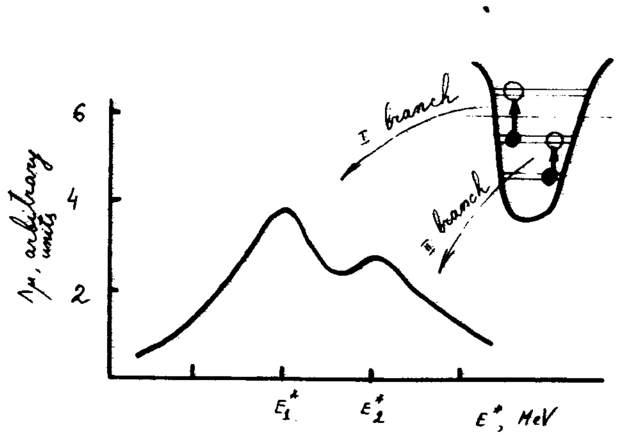

Fig.7. The scheme of forming of the giant resonance states.

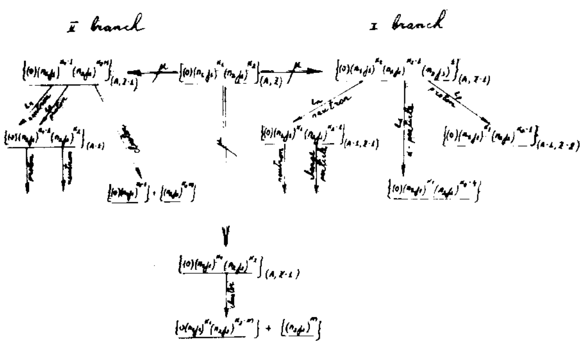

Fig.8. The structure of the giant resonance states.

branch of the giant resonance is formed mainly by transitions to the states $\{(0)(n_1 j_1)^{K_1}(n_2 j_2)^{K_2-1}(n_3 j_3)\}$ and it is in the energy region $E^* = 12$–20 MeV. The high-energy branch is formed by transitions to the states $\{(0)(n_1 j_1)^{K_1-1}(n_2 j_2)^{K_2+1}\}$ and it is in the region of energies higher than $E_2 = 20$ MeV. In the muon capture by light and medium nuclei transitions of the dipole type (the first-forbidden ones) are dominating. Therefore we restrict ourselves only to these transitions and to these nuclei.

A subsequent process of the decay of the giant resonance states depends on the structure both of the resonance itself and of the daughter nucleus states and on the energy factors determined by the thresholds $\mathcal{E}$ of the emission of particles of a definite kind.

The thresholds $\mathcal{E}$ of emission of various particles from the intermediate nucleus (A,Z-1) depend on the atomic number A. These are for

i) the nuclei in the middle and end of 1p-shell	ii) the nuclei of (2d-1d) shell
$\mathcal{E}_n = 4$–7 MeV	$\mathcal{E}_n = 8$ MeV
$\mathcal{E}_p = 15$–20 MeV	$\mathcal{E}_p = 8$–10 MeV
$\mathcal{E}_\alpha = 10$–12 MeV	$\mathcal{E}_\alpha = 6$–10 MeV

Strong difference between the thresholds of emission of different type particles is due to violation of the number of protons and neutrons in the intermediate nucleus. From the above values it follows immediately that due to the high threshold of proton emission in the 1p-shell nuclei such a channel is weak. Indeed, a detailed calculation /30/, within the considered scheme for the ^{14}N nucleus shows that the contribution from the channel $^{14}N(\mu^-, \nu)p\,^{13}B$ does not exceed 1%.

The threshold of α-emission is far lower than that of protons that, in principle, should favour such a decay channel. However, as follows from the scheme, the α-particle should be composed of nucleons from different shells that results in the smallness of the corresponding spectroscopic factors. No numerical estimates were made for intensity of such a channel. Nevertheless, for the nucleus ^{12}C the required information may be obtained directly from the photoemulsion data on the muon capture when in the final state there is the nucleus ^{8}Li. The intensity of the channels $^{12}C(\mu^-,\nu)^{8}Li\,\alpha$ and $^{12}C(\mu^-,\nu)^{8}Li\,^{3}He\,n$ appears to be small and not higher than 0.16% /10/. It may be expected that in the nuclei of (2s-1d) shell the intensity of such a channel will be almost the same. In these nuclei the proton channel becomes more important because the corresponding threshold is considerably lowered. However there also are no calculations, nevertheless, the experimental data available allow one to estimate the lower limit of intensity. If the emitted nucleon ($n_3 j_3$) is proton the daughter nucleus (A-1,Z-2) is produced in the ground or excited states with the parity equal to $(-1)^{\kappa_1 \ell_1 + (\kappa_2 - 1)\ell_2}$. The γ-spectrometry gives the required information. As follows from the results given in Table 10, in the muon capture by ^{28}Si this probability is about 2%.

The dominating decay channel of the low-energy branch of the giant resonance is that with the neutron emission. In this case excited states of daughter nucleus (A-1,Z-1) are populated very often. Some of these states are above the threshold of the subsequent neutron or charged particle

emission. In the nucleus (A-1,Z-1) the decay thresholds with emission of different particles are of the same magnitude. That allows the competition of different channels. Such a chain of transitions has been calculated /30/ for the muon capture by ^{14}N and it has turned out that the intensity of the process

$$^{14}N(\mu^-, \nu)np\,^{12}B$$

is smaller than 1% and for the process

$$^{14}N(\mu^-, \nu)\,2n3\alpha$$

it is about 1%.

For the nuclei of $(2S\text{-}1d)$ shell such a calculation has been carried out /31/ for the muon capture by ^{32}S. The probability of population of the states of ^{31}P which are above the threshold of the subsequent proton emission, i.e., of the channel

$$^{32}S(\mu^-, \nu)\,np\,^{30}Si$$

appears to be about 2%.

Consider next the decay of the high energy branch of the resonance. In this case the dominating channel is the decay with emission of a nucleon ($n_2 j_2$), (proton or neutron) with production of the daughter nucleus (A-1) in the hole state. The center of gravity of the hole component in the daughter nucleus (A-1) lies very high and the direct decay of the giant resonance states to it is energetically forbidden. A small admixture of that component into the low-lying states of the daughter nucleus (A-1) opens the channel. However, in nuclei in the middle and end of 1p shell the intensity of excitation of the high-energy branch of the resonance is not large (only $\sim$ 3%). Therefore the charged particle emission in this case is very small /30,32/:

$^{14}N\ (\mu^-, \nu)\ n^{13}C^*$

$\quad \hookrightarrow$ charged particles $\qquad W_{th} < 0.1\%$

$^{12}C\ (\mu^-, \nu)\ n\ ^{11}B^*$

$\quad \hookrightarrow \begin{cases} ^8Be + {}^3H & W_{th} \sim 1\%;\ W_{exp.} = (1.1 \pm 0.1)\% \\ ^8Li + {}^3He & W_{th} < 0.2\%; \text{ in the experiment was not observed.} \end{cases}$

A different matter is with the nuclei in the beginning of 1p shell (nuclei ^{6}Li and ^{7}Li). The intensity of excitation of the high-energy branch of resonance is large in that case. Detailed calculations for ^{6}Li show that due to peculiarities of the giant resonance structure in intermediate nuclei ^{6}He the decay channel

$$^6Li\ (\mu^-, \nu)\ ^3H^3H$$

has the probability $\sim$ 10% and for the channel

$$^6Li\ (\mu^-, \nu)\ nd^3H$$

it is (20÷25)%.

The spectrum of tritium nuclei in channel $^6Li\ (\mu^-, \nu)^3H^3H$ is shown in Fig.9. Since the states decaying by such a channel mainly lie not high above threshold, the spectrum of emitted tritium nuclei appears to be very low-energy. The tritium spectrum calculated in the framework of the resonance mechanism of muon capture is similar to the spectrum calculated in the framework of direct mechanism. However, in the latter case the spectrum is smooth while the resonance mechanism predicts the presence of structure for the spectrum.

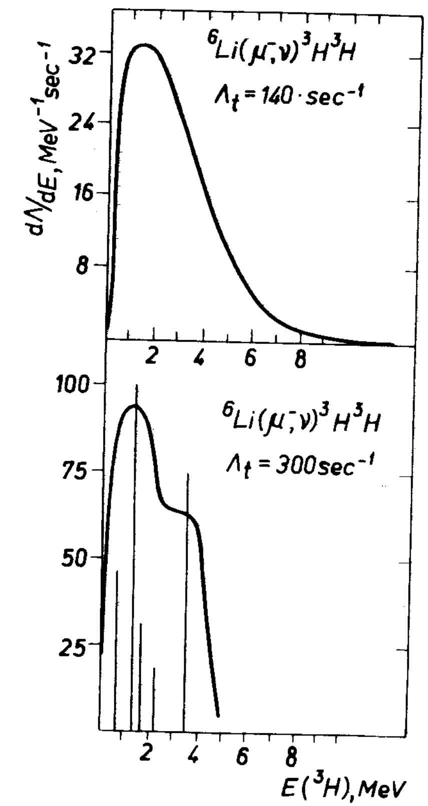

Fig.9. The calculated spectrum of tritium nuclei in the process $\mu^-\ ^6Li \to {}^3H^3H\ \nu$; a) calculation in the framework of the direct mechanism /34/ , b) calculation in the framework of giant resonance mechanism /32,33/ .

A different situation occurs in the nuclei of $(2s-1d)$ shell. First, the high-energy branch of the resonance has a maximum at rather high energies. The calculation for ^{32}S indicates the energy region 25–28 MeV. The intensity of its excitation is also large: about 15%. If the admixture of the 1p-hole component into the low-lying states of the daughter nucleus ^{31}P is considered to be 5%, it appears to be sufficient for the decay proceeds completely through these components /36/. The calculations here give the proton yield about 3% and the other 12% for the neutron channel with the dominating population of ^{31}P states above the threshold of the subsequent proton emission.

Thus, the probability of the process

$$^{32}S\ (\mu^-, \nu)\ np\ ^{30}Si$$

developing through the hole components is about 12%. Summing up over all the channels we obtain from calculations that the charged particle yield in the muon capture by ^{32}S equals 15–20%. Such a picture should be observed practically for all the nuclei of the $(2s-1d)$ shell since their individual properties (except for nuclei which shell only starts to populate) are of little importance in the given case. So in most cases the resonance decays with a subsequent emission of neutron and proton. Though for ^{32}S the yield of this channel has not as yet been measured, for other nuclei of $(2s-1d)$ shell such a regularity has been observed (see Tables 9 and 10).

A different situation occurs in the nuclei in the midele and end of 1p-shell. The total charged particles yield predicted by theory is several times smaller than the experimental one. Recent measurements /6/ make almost twice decrease the value, nevertheless, the discrepancy is still large enough. The consideration of the monopole branch (the allowed transitions) helps little. To that branch there correspond states of the type $\{(0)(n_1 j_1)^{\kappa_1}(n_2 j_2)^{\kappa_2}\}$ (Fig.8). Their contribution has been calculated for ^{12}C and it is as follows /32/

$$^{12}C\ (\mu^-, \nu)\ ^{12}B^* \rightarrow \begin{cases} ^{10}B + d & w_{th} \sim 0.4\,\% \\ ^{8}Li + \alpha & w_{th} \sim 0.1\,\% \end{cases}$$

Partly, the discrepancy of theory with experiment for the 1p-shell nuclei may be related to the fact that in these nuclei, according to the photonuclear experiments, half dipole sum is distributed over the region above 30 MeV. By allowing for a specific character of the energy dependence of the muon capture rate this value decreases. But undoubtedly this value is higher than 3% resulting from calculations which take into account only the states corresponding to the $1\hbar\omega$ excitations. The inclusion of more complicated components may result not only in the intensity increase of population of the high-energy region but also in the appearance of new decay channels, that, in the end, may raise the charged particle yield. Such calculations, however, are not yet performed. Thus, for the present time the question on the mechanism of charged particle emission in 1p-shell nuclei is still open. To solve it one needs more detailed experimental data on main decay channels.

2. The microscopical approach based on the shell model gives a detailed description of structure of the giat resonance states. However, such a description makes the calculations very cumbersome. To perform them one should employ various simplifications. It concerns especially the calculations of the decay channels. Therefore, at a definite step in the medium and,

especially, in the heavy nuclei where individual properties are little important it makes sense to reject such a detailed description of the giant resonance states and retain only its gross structure. The latter may be calculated either within simple models, or by sum rules.

The simplest way to construct the excitation spectrum of an intermediate nucleus is to neglect the dynamics of a process. In this case the muon-nuclear interaction Hamiltonian is put constant. If now in the wave function of a produced particle-hole system $|1p1h\rangle$ one changes the one-particle functions of neutron in the potential well by the plane wave, the squared matrix element for transition from the ground state $|0\rangle$ to the excited one $|ph\rangle$

$$|\langle ph|H_\mu|0\rangle|^2 \sim \rho(P_p)$$

becomes proportional to the momentum distribution of protons in the initial nucleus, and the distribution of the capture probability over the excitation spectrum of the intermediate nucleus becomes of the form:

$$d\Lambda = \rho(P_p)\,\delta(\varepsilon - E_\nu - E)\,\delta(\vec{P}_n + \vec{P}_\nu - \vec{P}_p)\,d^3P_p\,d^3P_n\,d^3P_\nu$$

Taking a definite momentum distribution (the Fermi distribution at kT =0 or kT > 0, the Gaussian one, etc) one can easily calculate (following papers /37/) the excitation spectrum of the intermediate nucleus. Assuming that the decay of the excited nucleus has the statistical character the spectrum /37/ and yield of protons and α-particles were calculated. The nuclei Ag and Br were investigated. The agreement with experiment has been achieved for α-particles

whereas the proton yield has been found to be by an order of magnitude lower.

3. To explain the large experimental yield of protons it has been proposed /38/ to take into account the direct muon capture by the correlated pair of protons in the nucleus:

$$\mu^- + (pp) \rightarrow n + p + \nu$$

that is analogous to the known "quasideuteron" mechanism of high energy γ-quantum absorption. The calculation shows that the proton yield in such a process may equal about 2% that, in principle, explains the experimental yield. However, one should bear in mind that the reliability of such results is difficult to determine as in the calculations a great number of different approximations is used. Most of them can hardly be tested experimentally or grounded theoretically.

4. The above presented calculation scheme of the excitation spectrum of the intermediate system and the statistical character of the decay are very crude. Such a scheme may hardly pretend to the reliable description of the process. The scheme may be made far better by allowing for both the dynamics of the muon capture and the possibility of particle emission from the preequilibrium stage. Estimates /39/ made within such a scheme indicate that if one takes into account the preequilibrium stage of the decay the agreement of theory with experiment becomes better in describing spectra of emitted particles. A consistent analysis, by such a scheme, both of spectra and multiplicity of emitted neutrons, as well as of spectrum and yield of charged particles in principle can allow one to gain an important information on the distribution of atomic nuclei excitation after the muon capture.

5. The calculation of direct reactions by the distorted wave method gives two terms in the transition amplitude. To the first of them there corresponds the so-called direct diagram (Fig.11a) which usually is taken in the calculations. To the second one there corresponds the exchange diagram (Fig.11b) which is as a rule, neglected, as it gives small contribution. The latter diagram is partly responsible for the proton emission. Treating the reaction

$$\mu^- + {}^{16}O \rightarrow {}^{15}C\ (5/2^+) + p + \nu$$

on the basis of the exchange diagram the authors of ref./40/ have found its probability to be about 0.1%. For polarized muon the mechanism under consideration leads to asymmetry of protons relative to the muon spin. The results are shown in Fig.10.

The proton yield can be also due to the charge exchange of the neutron produced in the muon capture by proton. Such a process could be described by the diagram drawn in Fig.11c.

The observation of γ - line from the de-excitation of $J^{\pi} = 5/2^+$ level in ^{15}C and determination of its intensity would allow one to obtain information on the reaction

$$\mu^- + {}^{16}O \rightarrow {}^{15}C\ (5/2) + p + \nu$$

V. CONCLUSION

We have studied a wide range problems concerning the charged particle emission in the muon capture by atomic nuclei. At present some features of the process become to be visible. It seems to be that some of them can be understood in the framework of the giant resonance excitations and its subsequent decay. In the first place, this concerns the nuclei of (2s-1d) shell. The feature of the process for the nuclei in the middle and end of 1p shell cannot be described as yet. These nuclei have pronounced

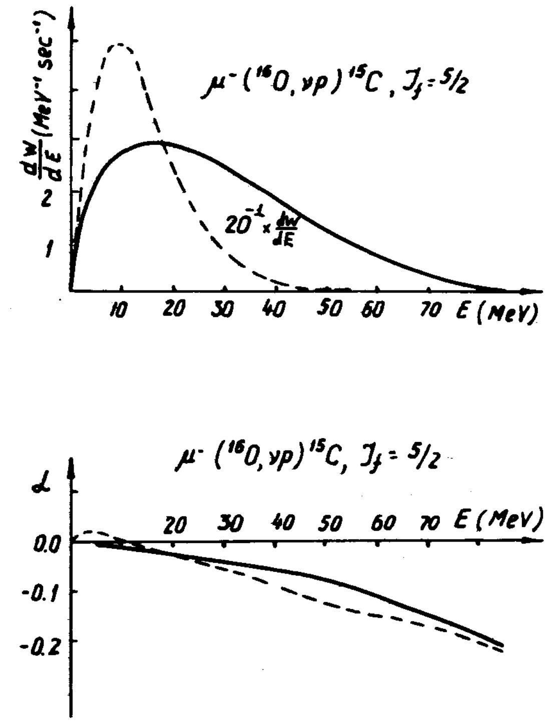

Fig.10. The spectrum of protons and asymmetry of their angular distribution with respect to the muon spin in the process $\mu^- {}^{16}O \rightarrow {}^{15}C\ (5/2^+) p \nu$. The dashed curve is the plane wave calculation, the solid one - with the final state interaction.

individual properties and it is most likely therefore that a detailed analysis of all main channels in necessary. In this view it seems important to obtain an additional experimental information. Due to the mainly low-energy character of the spectrum the emulsion methods may be believed to be most appropriate. However, it is also necessary, at the same time, to perform a consistent kinematical analysis of reactions that may allow one to single out the main channels of charged particles emission. Exmaples of such an analysis have been discussed above. The result of measurements in emulsions, with changing the ratio between the component introduced, may appear to be of interest.

The development of scheme which takes into account the preequilibrium stage of particle emission makes it possible to analyse also the disintegration of intermediate and heavy nuclei. In this case an effective tool may be an approach based on the use of combined methods: the resonance one for description of the intermediate nuclei excitation and preequilibrium decay method for description of particle emission.

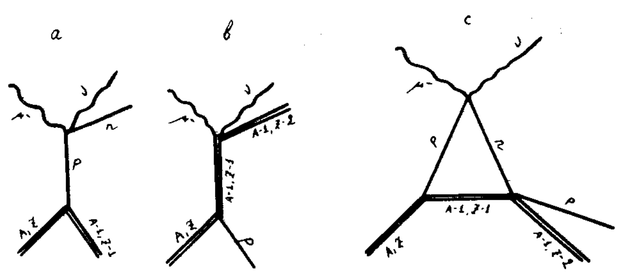

Fig. 11

References:

1. E.P.George, J.Evans. Proc.Phys.Soc.A64, 193 (1951).
2. P.Singer. Springer Tracts in Modern Physics, v.71,p.39 (1974);
H.Uberall.ibid. p.1.
3. W.F.Fray. Phys.Rev. 85, 676 (1952);
H.Morinaga, W.F.Fray. Nuovo Cim. 10, 308 (1953).
4. D.Kotelchuck. Nuovo Cim. 34, 27 (1964).
D.Kotelchuck, J.V.Tyler. Phys.Rev. 165, 1190 (1968).
5. А.О.Вайсенберг, Э.Д.Колганова, Н.В.Рабин. Ядерная физика 1,652 (1965); 11,830 (1970).
6. Ю.А.Батусов, С.А.Бунятов, Л.Визирева и др. Ядерная физика 2I, I2I5 (1975).
7. A.Alumkal, A.G.Barkow et al. Nuovo Cimento 1, 316 (1960).
E.Marshak. Meson Theory, p.182, New-York, 1952.
8. Ю.А.Батусов, С.А.Бунятов, Л.Визирева и др. Ядерная физика I8, 962 (1973).
9. G.Vanderhaeghe, M.Demeur. Nuovo Cim.Suppl. 2, 938 (1956).
10. Ю.А.Батусов, С.А.Бунятов,В.А.Вартанян и др. ЯФ I4,I206(I97I).
11. Ю.А.Батусов , С.А.Бунятов, Л.Визирева и др. ЯФ 22,320 (1975).
12. M.Schiff. Nuovo Cimento 22, 66 (1961).
13. В.И.Комаров, О.В.Савченко. ЯФ 8, 4I5 (I968).
14. S.E.Sobottka, E.L.Wills. Phys.Rev.Lett. 20, 596 (1968).
15. Ю.Г.Будяшов, В.Г.Зинов, А.Д.Конин и др. ЖЭТФ 60, I9 (I97I), А.М.Чатрчян. Автореферат диссертации, I-6I79,Дубна, I97I.
16. R.M.Sundelin, R.M.Edelstein, A.Suzuku, K.Takahashi. Phys.Rev.Lett. 20, 1198 (1968).

17. В.С.Евсеев, В.С.Роганов и др. ЯФ 4, 342 (1965), M.Krieger. Preprint Columbia Univ.NEVIS-172 (1969).
18. Л.Вильгельмова, В.С.Евсеев, Л.Н.Никитюк и др. Ядерная физика I3, 55I (I97I).
19. T.Pratt. Nuovo Cimento 61B, 119 (1969).
20. P.Igo-Kemenes, J.P.Deutsch, D.Favart et al. Phys.Lett. 34B, 286 (1971).
21. G.H.Miller, M.Eokhause, P.Martin, R.E.Welsh. Phys.Rev. C6, 487 (1972).
22. H.J.Evans. Nucl.Phys. A207, 379 (1973).
23. G.Heusser, T.Kitsten. Nucl.Phys. A195, 369 (1972).
24. G.Backenstoss, S.Charalambus, H.Daniel et al. Nucl.Phys. A162, 541 (1971).
25. C.Petitjean, H.Backe, R.Engfer et al. Nucl.Phys.A178,193 (1971).
26. G.R.Lucas, P.Martin, G.H.Miller et al. Phys.Rev.C7,1678(1973).
27. V.V.Balashov, R.A.Eramzhyan, N.M.Kabachnik et al. JINR E4-4601, Dubna, 1969. Proc.III Int.Conf.on High Energy Physics and Nuclear Structure, Plenum Press. New York-London, 1970, p.174.
28. В.Г.Неудачин, В.Г.Шевченко, Н.П.Юдин. Phys.Lett. 10, 180 (1964).
29. Г.-У.Егер, Г.Р.Киссенер, Р.А.Эрамжян. Труды семинара "Электромагнитные взаимодействия ядер при малых и средних энергиях", Изд."Наука", Москва, 1973, стр.63; препринт ОИЯИ Р4-694I (I973).
30. H.R.Kissener, A.Aswad, H.U.Jager, R.A.Eramzhyan. Nucl.Phys. A215, 424 (1973).
31. Yu.I.Bely, R.A.Eramzhyan, L.Majling et al. Nucl.Phys.A204, 357 (1973).

32. В.А.Вартанян. Материалы Всесоюзной конференции "Ядерные реакции при высоких энергиях. Тбилиси, I972.
33. В.А.Вартанян, Р.А.Эрамжян. Вопросы атомной науки и техники, ХФТИ 73-9, стр.25 (I973).
34. B.R.Wienke, S.L.Meyer. Phys.Rev. C3, 2179 (1971); C9, 943 (1974).
35. R.A.Eramzhyan, L.Majling, J.Řizek. Nucl.Phys. A247,411 (1975).
36. В.А.Вартанян, М.А.Жусупов, Р.А.Эрамжян. Изв.АН СССР 33, 2087 (I969).
37. C.Ishii. Prog.Theor.Phys. 21, 663 (1959).
38. P.Singer. Phys.Rev. 124, 1602 (1961).
39. T.Kozlowski, A.Zglinski. Phys.Lett. 50B, 222 (1974); Nucleonika, 19, 72 (1974).
40. R.A.Eramzhyan, Yu.A.Salganic. Nucl.Phys. A207, 609 (1973); Г.Е.Доготарь, Ю.А.Салганик, Р.А.Эрамжян. Сообщение ОИЯИ Р4-5997, Дубна, I97I.

Received by Publishing Department
on January 15, 1976.