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MUON CAPTURE BY COMPLEX NUCLEI

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When a μ^--meson passes through matter it is captured into atomic orbit and cascades down to the first Bohr orbit where it either decays or is captured by the nucleus. The fundamental process in muon capture is the weak interaction

$$\mu^- + p \rightarrow n + \nu \, . \qquad (1)$$

According to the Universal Fermi Interaction (UFI) theory the matrix element for the process (1) is

$$\sqrt{2}M = \{\bar{u}_\nu (1-\gamma_5) i\gamma_\lambda \gamma_5 u_\mu\}\{g_A(\bar{u}_n i\gamma_\lambda\gamma_5 u_p) - \frac{g_p}{m_\mu}(\bar{u}_n q_\lambda \gamma_5 u_p) + g_T(\bar{u}_n \sigma_{\lambda\rho} q_\rho \gamma_5 u_p)\} + \qquad (2)$$

$$+ \{\bar{u}_\nu(1-\gamma_5)\gamma_\lambda u_\mu\}\{g_V(\bar{u}_n \gamma_\lambda u_p) - i\frac{g_M}{M_p+M_n}(\bar{u}_n\sigma_{\lambda\rho} q_\rho u_p) + i\frac{g_s}{m_\mu}(\bar{u}_n q_\lambda u_p)\}.$$

The quantities g are form factors which depend on $q^2 = (p_\lambda - n_\lambda)^2$, and they are nearly constant if q^2 does not vary too much. They are real if T-invariance holds.

1. From the UFI theory it follows that $g_V(0) = g_V^\beta$ and $g_A(0) = g_A^\beta$. The values of the beta decay constants are given in Table 1.

2. From the Conserved Vector Current (CVC) hypothesis it follows that

$$g_M(0) = (\mu_p - \mu_n)\, g_V^{\beta}$$
$$g_S = 0 \qquad (3)$$

and that the functional dependence of g_V and g_M on q^2 is the same as that for the electromagnetic current.

3. In the one-pion pole diagram dominance, Partially Conserved Axial-Vector Current (PCAC) hypothesis leads to the relations

$$g_P(q^2) = \frac{(M_p + M_n)\, m_\mu}{q^2 + m_\pi^2}\, g_A(q^2) \approx 7\, g_A \quad . \qquad (4)$$

$$g_A(q^2) = g_A(0) \, .$$

4. There are general arguments for causing both the induced scalar and the induced tensor interaction to vanish. They follow from the hypothesis that the nucleon currents are G -invariant.

To obtain the effective Hamiltonian from expression (2) it is necessary to reduce the four-component spinors to the two-component ones.

The effective Hamiltonian embraces all the weak interaction hypotheses considered above. Thus, the fundamental question concerning the validity of such basic postulates as the UFI, CVC and PCAC and the assumption that the currents are G-invariant is reduced to the more concrete question of the numerical values of the constants.

The simplest process would be the muon capture by proton.

The hydrogen mesic atom (μp) can be formed in either singlet or triplet state. All originally formed triplet atoms are very quickly converted by collision into the singlet atoms. When muon capture takes place in gaseous hydrogen, reaction (1) proceeds from the (μp) mesoatomic singlet system. The experimental capture rate[1] for gaseous target is

$$\Lambda_0 = (640 \pm 70) \quad sec^{-1}$$

In liquid hydrogen most of the singlet atoms form the ortho $(p\mu p)$ molecules, from which muon capture takes place. The capture rate from ortho $(p\mu p)$ molecules is

$$\Lambda_{mol} = 2\gamma \left(\frac{3}{4}\Lambda_0 + \frac{1}{4}\Lambda_1\right). \qquad (5)$$

Here Λ_0 and Λ_1 are the capture rates for the singlet and triplet states of (μp) atoms, respectively; a γ is the ratio of the muon density at the position of either proton in the $(p\mu p)$ molecule to that in the (μp) atom. For calculating γ a detailed knowledge of the wave function of the $(p\mu p)$ system is required. Recent accurate calculation by Kabir[2] gives the value

$$2\gamma = 1.01 \pm 0.01. \qquad (6)$$

The experimental capture rate for the liquid target is

$$\Lambda_{mol} = (460 \pm 42) \quad sec^{-1}.$$

The ratio

$$\Lambda_{mol}/\Lambda_0 = 2\gamma \left(0.75 + \frac{\Lambda_1}{3\Lambda_0}\right) \qquad (7)$$

is about 0.75 because of a large hyperfine effect. Therefore comparing results of these two experiments one can make the conclusion only about the value of γ.

The precise calculation of the muon capture rate in hydrogen was performed by Ohtsubo and Fujii/3/. Basing on their results we compare the theoretical predictions with the measured value. The relations between the capture rate and g_P/g_A for the various values of g_A/g_V are shown in Fig.1. Table 2 shows the magnitude of g_P/g_A which fits the measured value in the both experiments mentioned. The range of the allowed values of g_P/g_A is fairly large. This is due to both the large experimental error and the fact that the capture rate does not depend on g_P/g_A very sensitively.

The information, obtained from experiments on hydrogen does not solve completely the problem of the determination of the fundamental constants. Therefore one is forced to study this process in nuclei too. This raises an important problem in muon capture theory, as to whether it is possible to use current concepts of nuclear properties in the interpretation of the relevant experiments.

Muon Capture by Complex Nuclei

There are some reasons for which nucleons in nuclear matter interact with lepton field in a manner which differs from that for free nucleons. 1) The constants of the effective Hamiltonian are in reality form factors dependent on the momentum transfer, which in the case of muon capture by a nucleus differ from those of hydrogen. 2)The weak interaction between nucleons within the nucleus can be described by special diagrams which do not exist for the single-nucleon problem. They occur when exchange meson currents whithin the nucleus are taken into account. 3) It is quite possible that the pion propagator is altered in nuclear matter leading the induced pseudoscalar value other than that in hydrogen.

The first difference can be very easily taken into account. But the properties of exchange currents in nuclei are not sufficiently known. Contrary to the form factor effects, where the form of the effective Hamiltonian remains unchanged, corrections for exchange currents result in changes in the structure of the Hamiltonian, giving rise to correlation two-particle terms.

When muon is captured by a nucleus many transitions are possible. For the description of the most of them it is necessary to known in details both nuclear structure and reaction mechanism, which is mostly unknown. This fact restricts very strongly the choice of useful reaction channels. The transitions to the definite bound state, namely transition in selected nuclei such as ^{3}He, ^{12}C and ^{16}O, satisfy first of all this requirement.

There are two methods for the partial transition description. The first one uses the model wave functions and impulse approximation for nuclear matrix element calculation. But the use of model wave functions is usually the principal source of trouble in the interpretation of muon of parameters fitted to explain a particular set of experimental data. Therefore there arises the question whether it is necessary to have nuclear models as intermediaries linking different experimental results. Can this not be achieved on a completely phenomenological basis, by introducing into the theory parameters of the form factor type that do not have an exact meaning associated with a model and satisfy more general requirements with regard to a rigorous approach? Such a method was developed by Kim and Primakoff. They treated the complex nuclei in muon capture theory as "elementary" particles/4/. We shall consider below both methods as applied to ^{3}He .

Muon Capture in ^{3}He

Except for a very small component of isospin $T=3/2$ in the ^{3}He wave function, the initial and final state wave function are identical and there are 10 possible components. The antisymmetric ^{2}S state and the P states are not thought to be present to any appreciable extent . Therefore only five components remain: the predominating symmetrical ^{2}S state, the ^{2}S state of mixed symmetry (S') and the three ^{4}D states. If one takes into account the term with $T=3/2$ as well, there is a number of additional states.

The most reliable information concerning the three-body wave function is obtained from the analysis of the elastic electron scattering form factors.

The result of the analysis is the following: 2% of S' , 6% of ^{4}D and 0.25% $T=3/2$ states (Gibson/5/ state) with Irving radial function are presented in the wave function. In calculating the axial matrix element in the beta decay of ^{3}H with this wave function one gets:

$$|M_A|^2 = 3(P_S - \frac{1}{3}P_{S'} + \frac{1}{3}P_S)^2 . \qquad (8)$$

In expression (8) any $T=3/2$ states are neglected and $P_S, P_{S'}$ and P_D are the probabilities of the states considered. From the neutron and triton ft values

$$\frac{(ft)_n}{(ft)_{^3H}} = \frac{1+g_A^2|M_A|^2}{1+g_A^2\,3} = \frac{1228 \pm 35}{1137 \pm 20} \quad \text{for the case}^{x/}$$

$$= \frac{1167}{1137 \pm 20} \quad \text{for the case}^{xx/}$$

x/ A.N.Sosnowsky et al. Nucl.Phys., 10, 595 (1959).

xx/ C.J.Christensen et al. Phys. Lett., 26B, 11 (1967).

it is seen that

$$|M_A|^2 = \begin{matrix} 3.3 \pm 0.2 & \text{for the case}^{x/} \\ 3. & \text{for the case}^{xx/}. \end{matrix}$$

In any case $|M_A|^2_{theor} \leq 3$; for the Gibson state $|M_A|^2_{theor} = 2.59$. The conclusion which may be drawn is that exchange effects are important in the $^3H - ^3He$ system.

Let us turn to the muon capture now. Detailed analysis of the muon capture rate shows that 6% D mixture lowers the rate by 120 sec^{-1} and 2% s' mixture by another 50 sec^{-1} as compared with the pure s state wave function /8,9/. The result of the capture rate calculation with the Gibson state with Irving - wave function is shown in Fig.2. In the same Fig. is shown also the result when axial matrix element in muon capture is corrected on the exchange effects by means of the relation

$$|\int \vec{\sigma}|^2_{\mu, corr} = (3.3 \pm 0.2) \frac{|\int \vec{\sigma}|^2_{\mu, uncorr.}}{|\int \vec{\sigma}|_{\beta, uncorr}}.$$

It is seen, that both in beta decay and in muon capture exchange effects are important and a calculations, in which they are ignored, are very likely to be incorrect.

From the comparison of the theoretical and experimental values of the capture rate $(1460 \leq \Lambda_{exp} \leq 1530)$ one can obtain the following relation for induced pseudoscalar $g_P/g_A = 0 \pm 3$ (without exchange currents) and $6 \leq g_P/g_A \leq 32$ (with exchange currents); $g = 1.403 \cdot 10^{-49}$ erg.cm^3 .

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x/ A.N.Sosnowsky et al. Nucl. Phys., 10, 595 (1959).

xx/ C.J.Christensen et al. Phys. Lett., 26B, 11(1967).

Thus even in such a simple case as the muon capture in three nucleon system we meet difficulties, when we try to obtain the precise value of the coupling constants.

Let us turn to the second method. We shall take as the starting point the general form (1) of the matrix element describing the process

$$\mu^- + {}^3He \rightarrow {}^3H + \nu .$$

From the CVC hypothesis it follows

$$F_V(q^2) = F_1^{{}^3He}(q^2) - F_1^{{}^3H}(q^2)$$
$$F_M(q^2) = F_2^{{}^3He}(q^2) - F_2^{{}^3H}(q^2), \qquad (9)$$

where $F_V(0)=1$ and $F_M(0) = -5.44/2M$. In order to establish such a relationship, we do not require either model functions or any other hypotheses such as the impulse approximation. However, the situation is more complicated in calculating the axial form factor. PCAC and one pion pole dominance hypothesis yields

$$F_P(q^2) = \frac{(M_i + M_f)\, m_\mu}{q^2 + m_\pi^2} F_A(q^2) \qquad (10)$$

UFI yields $F_A(0) = \pm (1.21 \pm 0.01)$. After some assumptions on $F_A(q^2)$ have been made, it is possible to relate $F_A(q^2)$ directly to the electron scattering data; however, this does not mean that the approach, is independent of a model- the assumptions themselves have to some extent the character of models. Under the assumptions

$$\frac{F_M(q^2)}{F_M(0)} = \frac{F_A(q^2)}{F_A(0)} = \frac{m_\pi^2 + q^2}{m_\pi^2} \; \frac{F_P(q^2)}{F_P(0)}$$
$$F_P(0) = - F_A(0) \qquad (11)$$

one can obtain now all form factors from experimental data. Now the question is as to what is the accuracy of these relations. With the approach used it is not clear.Unfortunately most of the experimental data are at present available so no real test of the postulate could be made. Nevertheless the theoretical prediction $\Lambda_{\mu} = (1.51 \pm 0.04)\,10^{3}\ \mathrm{sec}^{-1}$ is in a very good agreement with the experimental results. Thus, finishing the discussion of the muon capture in ^{3}He one may conclude that experimental data are in agreement with the prediction of the theory. However, if one wants to know the coupling constants accurately, it is necessary even in a such simple case to have more detailed information on the structure of these nuclei.

Muon Capture in ^{12}C and ^{16}O

The particular attention paid to the reaction

$$\mu^{-} + {}^{12}C \to {}^{12}B_{gr.st.} + \nu \qquad (12)$$

is due to the fact that the transition rate is determined almost entirely by the Gamov-Teller constant. Comparison of the capture rate with that of the reverse beta transition is interesting from the point of view of comparing the axial constant in muon capture and beta decay.

Flamand and Ford/10/ have calculated directly the rate of beta decay Λ_{β} and of muon capture Λ_{μ} by means of the intermediate coupling shell model. With a model having the optimum parameters, Λ_{β} is in good agreement with experiment, while $\Lambda_{\mu} = 7300\ \mathrm{sec}^{-1}$. One can avoid cumbersome calculations in the intermediate coupling scheme, using calculations in the j-j scheme and the experimental value of Λ_{β} :

$$\Lambda_{\mu} = (\Lambda_{\mu})_{j-j} \frac{(\Lambda_{\beta})_{exp}}{(\Lambda_{\beta})_{j-j}} . \qquad (13)$$

The result by Gillet and Jenkins/11/ is given in Fig.3 which shows Λ_{μ} as a function of g_P/g_A and the experimental value of 6750^{+800}_{-750} sec^{-1} measured by Maier et al./12/.

Kim and Primakoff/4/ give the value

$$\Lambda_{\mu} = (6.6 \pm 1.0)\, 10^{8}\ \mathrm{sec}^{-1} .$$

Further attempt at a phenomenological approach in the reaction (12) was made by Foldy and Walecka/13/. Basing on the impulse approximation, they calculated the muon capture rate by extracting the main matrix element from experimental data on electron scattering and beta decay. Model wave functions were used directly only when calculating certain secondary terms in nuclear matrix elements. Fig.4 shows the final result of this calculation. From the comparison it follows that

$$g^{\mu}_{A}/g^{\beta}_{A} = 1.04^{+0.07}_{-0.10} . \qquad (14)$$

This result (which hardly differs from those obtained by /10,11,14/ and others) does not contradict the theoretical values of the constants.

The reaction

$$\mu^{-} + {}^{16}\mathrm{O} \rightarrow {}^{16}\mathrm{N} + \nu \qquad (15)$$

with excitation of the bound levels of ^{16}N(0^-,1^- and 2^-) is of considerable interest. Unfortunately, the experimental results obtained by different laboratories for the capture rates to these levels differ noticeably. The main reason for the investigation of this reaction is the fact that the study of partial transitions to ^{16}N bound states enables one to select effects produced by various terms of the weak interaction Hamiltonian. Muon capture rates in ^{16}O have been calculated by many authors. The results are the following. If the velocity terms in Hamiltonian are included the ratio $\Lambda(0^-)/\Lambda(1^-)$ is in agreement with the experimental data obtained by Columbia group, virtually irrespective of the choice of model parameters/15/. The explanation of the Berkeley group data requires negative rather than positive values of g_P/g_A (Fig.5). The absolute values of the capture rates are presented in Table 3. As seen the descrepancy between theory and experiment, except the Rho's/16/ method, is too high. The Rho's result based on the Migdal quasiparticle method agrees with the experiment. However, this problem can be hardly regarded to be solved. Indeed, the method used by Rho also allows the total capture rate to be calculated. In this case the agreement is satisfactory. But it is known that the calculated cross section of the dipole photoabsorption in ^{16}O closely related to the muon capture, exhausts the dipole sum rule below 30MeV contradicting the experimental observation. The Rho's method does not improve the situation. Therefore before making any conclusion about coupling constants from data on ^{16}O an additional investigation of this problem is required.

Let us come to some conclusions. The partial transitions give some additional information on muon-nucleon coupling constants. But, unfortunately, the accuracy of the calculation using model wave functions does not allow accurate quantitative values to be obtained. As to the phenomenological approach, there are also difficulties, due to the fact that not all relations used can be checked experimentally.

At the same time it would be very important to investigate other characteristics of the muon capture reaction, for example angular distribution of recoil nuclei, (γ,ν) correlation and so on. Such experiments are attractive because the interpretation of them is sometimes simpler from the theoretical point of view.

Concluding the discussion of partial transitions let us pass to another group of problems, namely to the investigation of the processes concerning neutron emission.

Asymmetry of Neutrons from Muon Capture. Mechanism of Neutron Emission.

The first neutron emission experiments were aimed at verifying the assumption of non-conservation of parity in weak interaction; a direct consequence of parity non-conservation is the asymmetry of the angular distribution of the neutrons in polarized muon capture. The general expression for the neutron angular distribution relative to the muon polarization vector has the form

$$\omega(\vartheta) \approx 1 + P_\mu a \cos\theta = 1 + A \cos\theta \qquad (16)$$

where P_μ is the residual polarization of the muon in the K-orbit and a is the asymmetry coefficient.

In the experiments it is always the integral asymmetry with respect to the neutron spectrum $S(E_n)$ which is measured. This corresponds to recording all neutrons with an energy greater than a given value E_{min}:

$$a = \int_{E_{min}}^{E_{max}} a(E)S(E)dE \Big/ \int_{E_{min}}^{E_{max}} S(E)dE . \qquad (17)$$

The function a contains the weak interaction constants and all information concerning the neutron emission mechanism. After the nuclear matrix elements have been calculated, it is natural that an attempt should be made to use the asymmetry data to determine the constants of the effective Hamiltonian.

In a number of works/17,18/, the function $a(E)$ has been calculated under the assumption of a direct neutron emission mechanism in muon capture. As is seen from the comparison with experimental data /19/ (Fig.6) direct emission theory can not explain the measured value of neutron asymmetry. In the last experiment one obtained /20/ a positive asymmetry in ^{40}Ca rather than a negative one (Fig.7), but this fact does not saves the situation. Within the framework of the direct mechanism it is difficult, not to say impossible, to explain either the positive asymmetry or a large negative one. In order to explain the fact neutron asymmetry one must apparently go beyond the accepted ideas of direct mechanism.

The neutrons of the direct mechanism constitute only a small part of the total number of neutrons formed in muon capture; most of the neutrons are the results of the decay of the compound nucleus and in accordance with the traditional criteria of reactions involving compound nucleus, they must be concentrated in the soft part of the energy spectrum. A procedure including both the statistical and direct mechanisms when calculating the spectrum of neutrons in muon capture has been described in detail by Lubkin /21/.

The mechanism of direct neutron emission in muon capture is analogous to the well-known photoeffect mechanism, where the proton interacts with one of the protons or neutrons in the nucleus, transmits its energy to it and transfers it directly into a continium. The direct photoeffect idea was originally put forward as an alternative to the mechanism of collective excitation (and subsequent statistical decay) of a nucleus in gamma absorption. The aim is to explain the large proportion of fast particles in the photoproton spectrum. It was found subsequently that the direct photoeffect theory gives photoabsorption probability values that are much lower than those found experimentally. The use of the optical model to construct the wave functions of a nucleon in the final sates did not remove this shortcoming.

An important contribution to the over-all picture of nuclear photodisintegration is made bycorrelations between the nucleons in the nucleus which are neglected particularly in the direct photoeffect theory. They involve the coherent excitation of various degrees of freedom of the nucleus corresponding to individual particle-hole configurations; there arises a collective excited state of the nucleus (the giant resonance) which can decay along several channels.

Fundamentally, photodisintegration and muon capture are closely related problems. In both cases one is dealing with the disintegration of a nucleus by an external field, the effect of which can be calculated by means of perturbation theory. In practice, the problem is to construct the wave functions of the nucleus in its final state.

The theory of collective nuclear excitation in muon capture is completely analogous to the photoeffect theory /15/.

The quantitative estimates of the resonance mechanism of neutron emission in muon capture were performed in/15,25/

Figures 8 and 9 show the theoretical neutron spectrum in muon capture by ^{16}O . Even when the cut-off energies of the recorded neutron spectrum are very high (above 5-7 MeV), the resonance mechanism of neutron emission is predominant.

The problems of calculating the spectra are associated with the question of describing the continuous spectrum of a system of nucleons. We have mentioned two approaches underlying the problem: the approach based on the optical model and on the assumption of a direct mechanism; and the many particle approach, which takes into account only resonance processes. These two approaches reflect two sides of the muon -capture phenomenon.

The authors of paper/22/ have developed an approximate version of the unified theory of nuclear reactions with which it is possible to take into account simultaneously both the direct and the resonance processes in nuclear reactions. Fig.10 shows the spectrum of neutrons in the reaction $^{16}O(\mu,\nu n)^{15}N$. The resonance structure of the spectrum which usually results from the assumption of resonance excitation in muon capture, is a natural consequence of the mutual coupling of different channels and the collectivization of nuclear excitations in the continuum.

A profound analogy between the resonance mechanism of nuclear excitation in muon capture and the photoabsorption giant resonance has been demonstrated particularly well by Foldy and Walecka/23/, who have determined the quantitative relationship between the probabilities of these two processes.

The energy spectrum of neutrons emitted following the capture of negative muons in ^{40}Ca has been measured between 7.7 and 52.5 MeV in Carnegie/24/. (Fig.10). The spectrum was found to decrease exponentially with energy. All giant resonance peaks with significant amplitudes lie below the lowest threshold in experiment and it is natural that spectrum does not exhibit peaks.

The measured spectrum exceeds the direct spectrum predicted by Lubkin /21/ using a modified Fermi-gas model in magnitude and, above 7.7 MeV exceeds the direct spectrum magnitudes predicted using the single-particle shell model by about a factor of 30 /24/. This suggests that these models are not adequate for calculations of the spectrum and it is necessary to take into account other possibilities such as capture on the clusters and so on. So the problem is completely open.

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Table 1

The weak interaction constants from the beta-decay experiments

$g_V = (1.3986 \pm 0.0024) \cdot 10^{-49}$ erg.cm^3 x

$g_V = (1.4013 \pm 0.0022) \cdot 10^{-49}$ erg.cm^3 xx

Experiments	g_A/g_V
e–ν correlation in the beta-decay of free neutron [1]	-1.22 ± 0.08
electron asymmetry in decay of polarized neutron [2]	-1.25 ± 0.05
Sosnovsky + ft (^{14}O)[3]	-1.18 ± 0.02
Christensen + ft (^{14}O) [4]	-1.23 ± 0.01

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Table 2

Allowed values of g_p/g_A for various values of g_A/g_V from muon capture on hydrogen

$-g_A/g_V$	g_p/g_A
1.18	5.4 - 11.4
1.21	7.0 - 12.4
1.23	7.8 - 13.2
1.25	8.8 - 14.0

Table 3

Transition rates to ^{16}N bound states after muon capture in ^{16}O

1. Intermediate coupling shell model [11]

2. RPA [11]

3. Migdal's model [16]

g_p/g_A	0^-			1^-			2^-		
	1	2	3	1	2	3	1	2	3
0	3.01	3.10	2.12	2.53	2.36	1.94	20.0	17.6	7.87
8	1.68	1.76	1.21				16.0	14.1	6.19
16	0.735	0.795	0.548				13.7	12.0	5.28
x)	1.6 ± 0.2			1.4 ± 0.2					
xx)	1.1 ± 0.2			1.88 ± 0.10			6.3 ± 0.7		
xxx)	0.7 ± 0.15			0.9 ± 0.2			9.3 ± 0.8		

x) Berkeley

xx) Columbia

xxx) Louvain

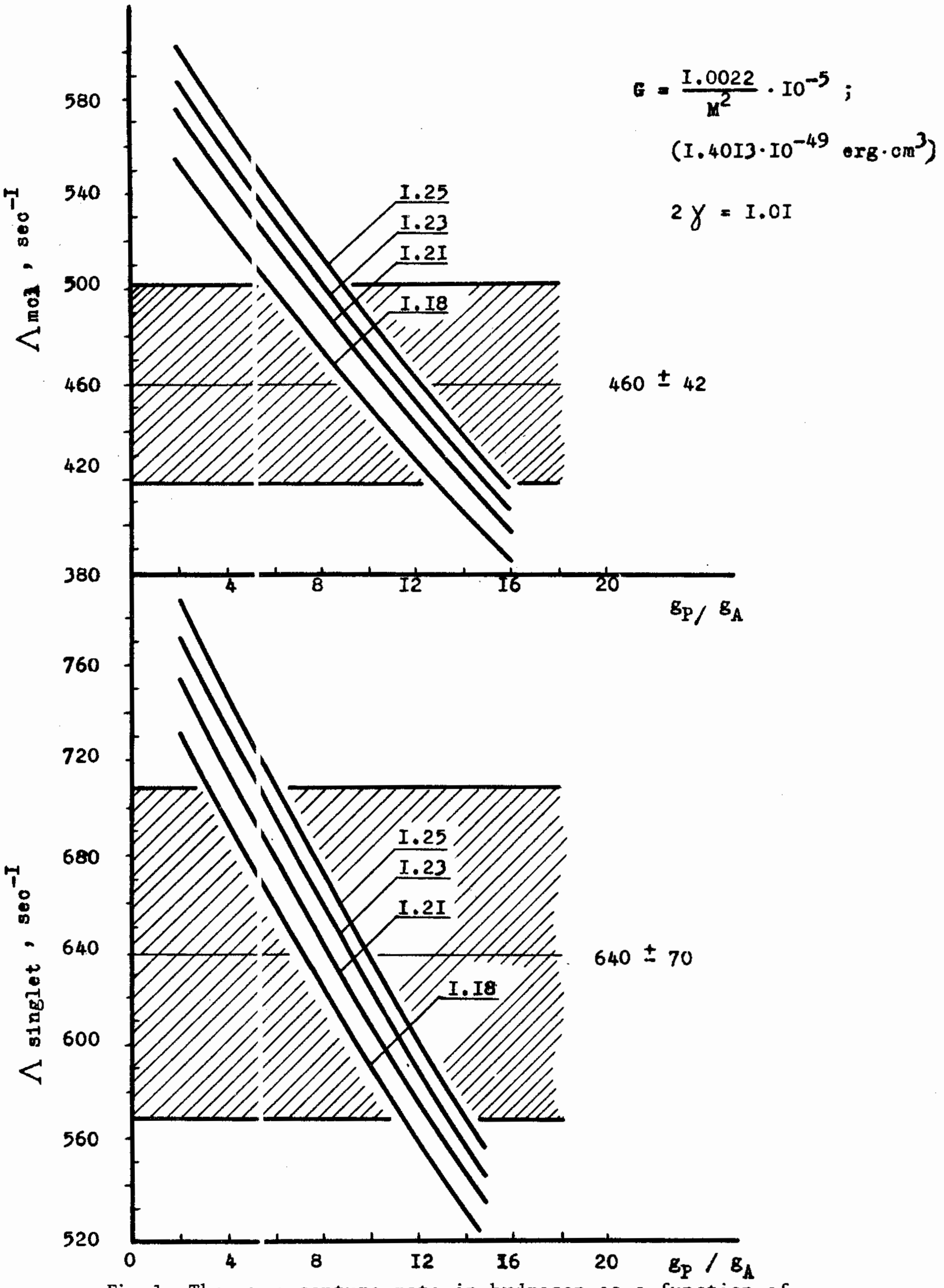

Fig.1. The muon capture rate in hydrogen as a function of g_P/g_A.

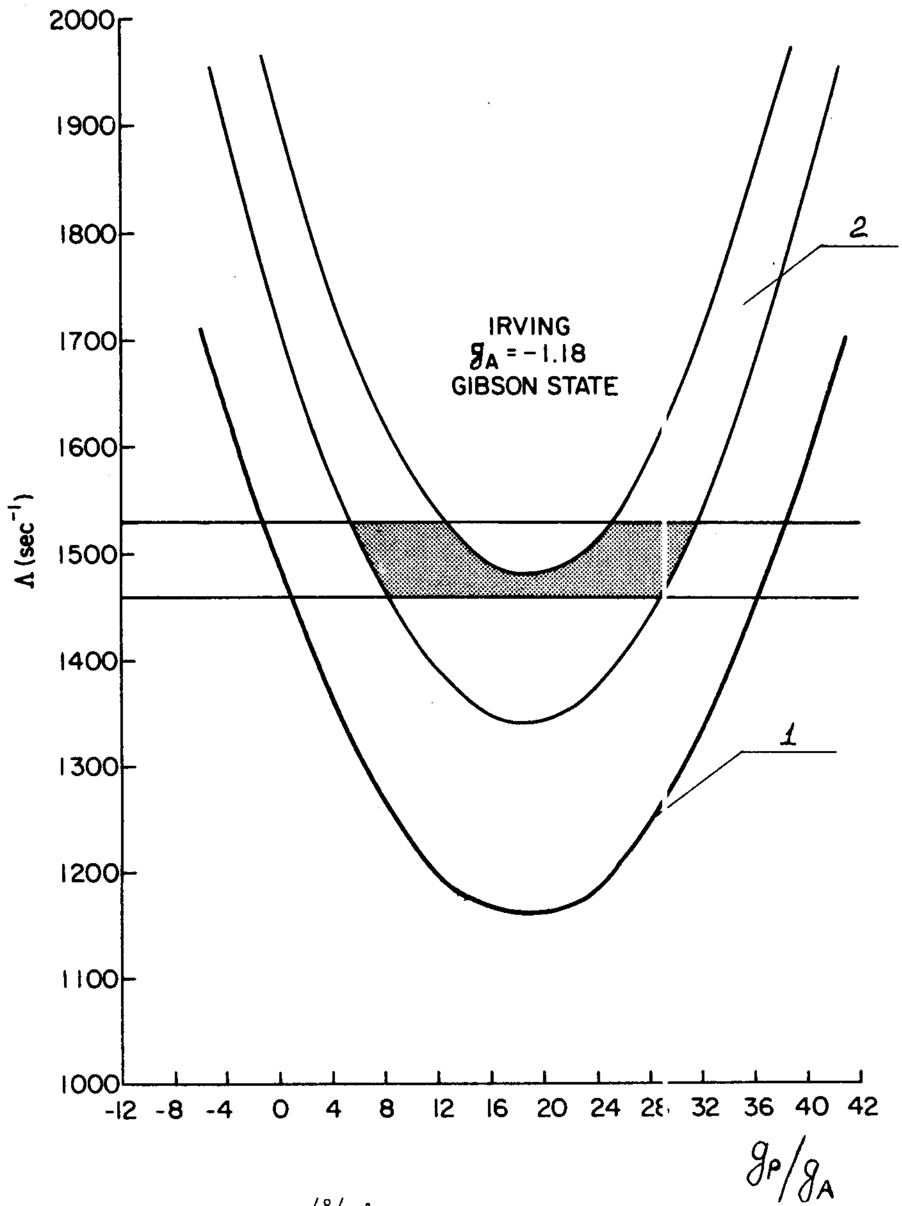

Fig.2. Calculated[8] ^3He muon capture rate for various values of g_P/g_A (Irving; Gibson state 6% ^4D, 2% S', 0.25% T=3/2; g_A/g_V=-1.18).
1 - no exchange correction;
2 - including exchange correction.

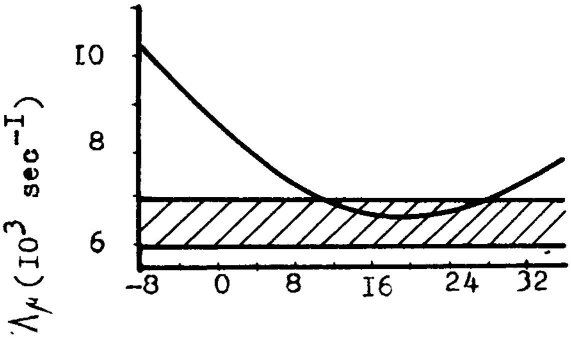

Fig.3. Muon capture rate[11] in ^{12}C .

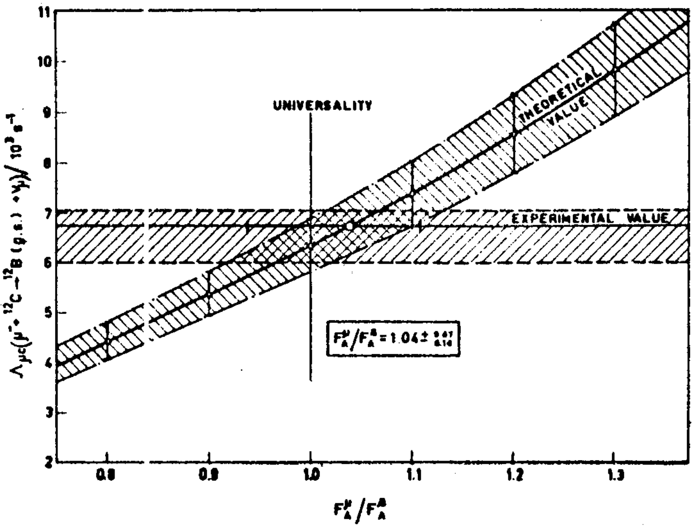

Fig.4. Muon capture rate[13] in ^{12}C .

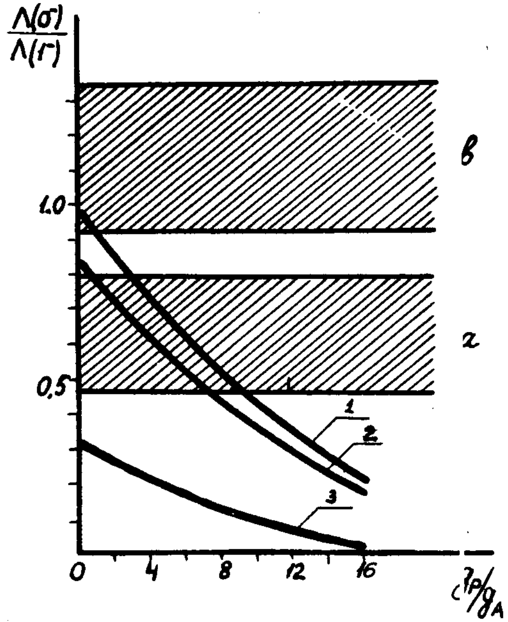

Fig.5. Transition rate ratio[15] $\Lambda(0^-)/\Lambda(1^-)$ as a function of g_P/g_A . 1. Elliott - Flowers function. 2. j-j coupling with velocity terms. 3. j-j coupling without velocity terms.

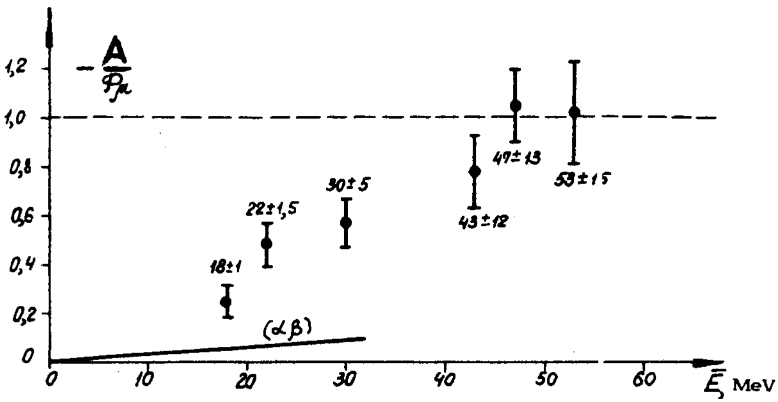

Fig.6. The asymmetry coefficient in muon capture in ^{40}Ca as a function of mean neutron energy[19].

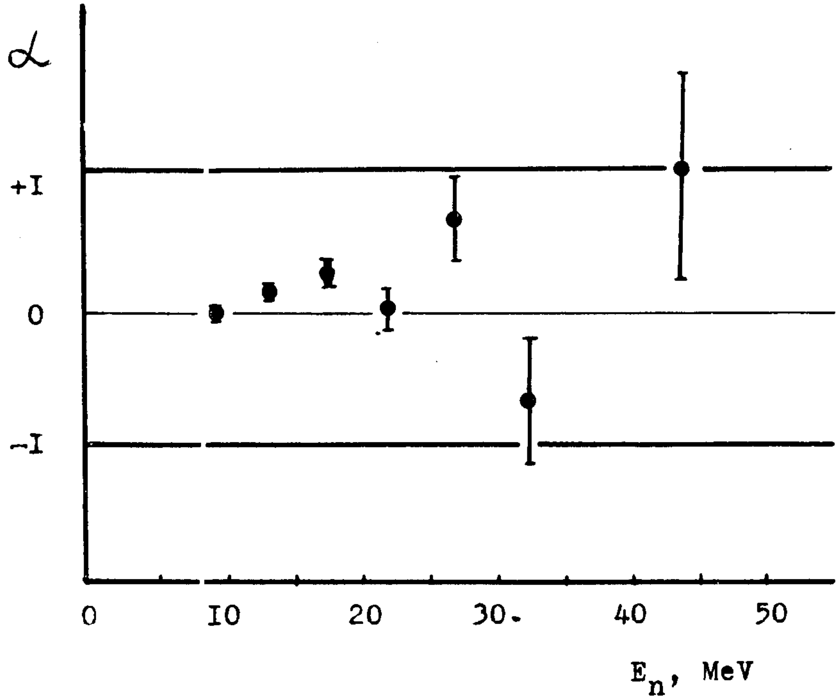

Fig.7. The asymmetry coefficient in muon capture in ^{40}Ca as a function of neutron energy /20/.

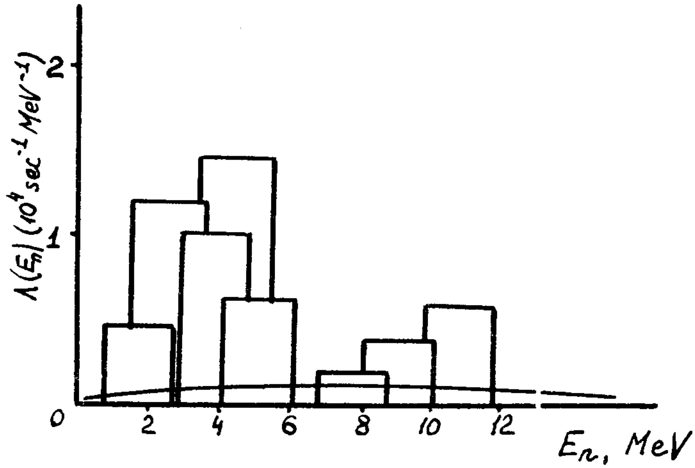

Fig.8. Theoretical spectrum[15] of neutrons from muon capture in ^{16}O .

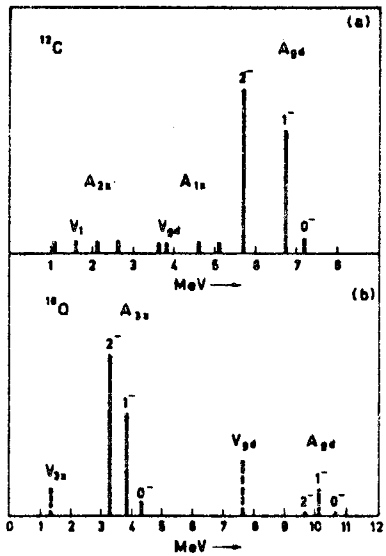

Fig.9. Theoretical spectrum of neutrons[25] from muon capture in ^{16}O and ^{12}C .

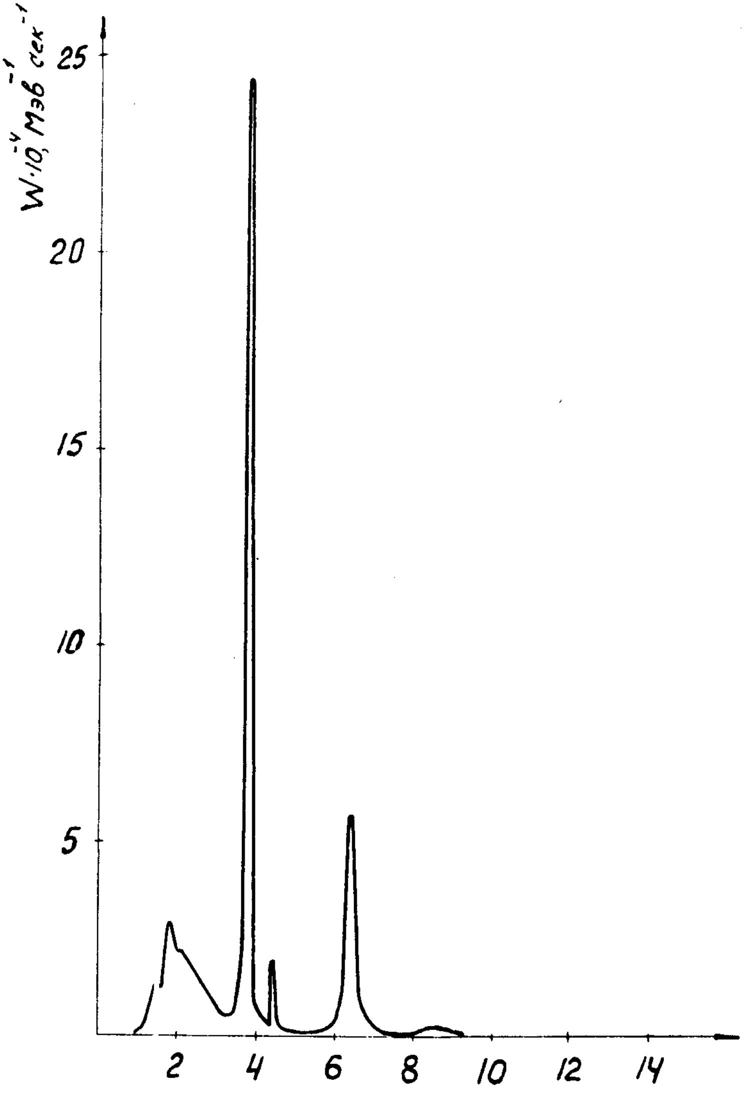

Fig.10. Spectrum of neutrons in the reaction $^{16}O(\mu^-, n\nu)^{15}N$ (based on calculations by Balashov et al. /22/*).

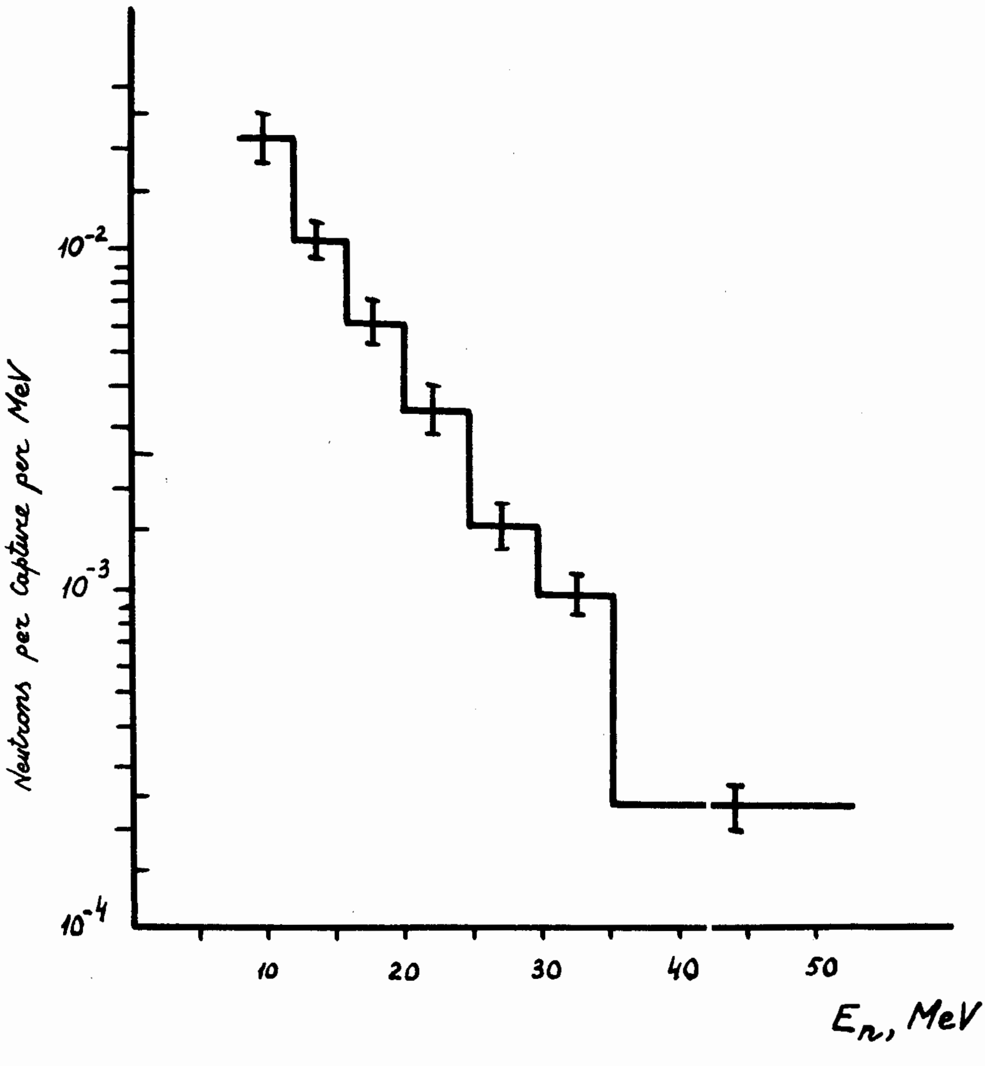

Fig.11. Experimental spectrum [24] of neutrons in ^{40}Ca .