# *ON THE COUPLING CONSTANTS IN $\mu$ CAPTURE*

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It is shown that within the framework of the theory of the universal Fermi interaction the best agreement with the available experimental data on the interaction of $\mu$ mesons with nucleons is obtained with a theory in which there is a conserved vector current and the effective pseudoscalar coupling constant $g_P^{(\mu)}$ is large. The sign of the ratio $g_P^{(\mu)}/g_A^{(\mu)}$ is positive, in agreement with the theory.

## 1. THE THEORETICAL PREDICTIONS

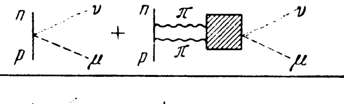
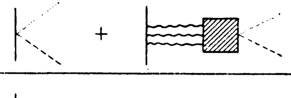
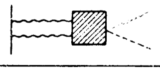
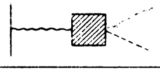
SINCE all known experimental facts about nuclear $\beta$ decay and about $\mu$ decay are in good agreement with the theory of the universal Fermi interaction (UFI),[1,2] it is natural to compare the experimental data so far accumulated on the interaction of $\mu$ mesons with nucleons with the predictions of this theory. In the case of $\mu$ decay the theory of the UFI describes the interaction of the four fermions by means of one coupling constant $G = (1.41 \pm 0.01) \times 10^{-49}$ erg cm$^3$ and the vector (V) and axial vector (A) types of interaction. When, however, weak-interaction processes involve nucleons, which have strong interactions, the effective Lagrangian for the processes $e^- + p \rightarrow n + \nu$ ($a \equiv \beta$, $l \equiv e$) and $\mu^- + p \rightarrow n + \nu$ ($a \equiv \mu$, $l \equiv \mu$) takes the more complicated form[3]:

$$L_{eff}^{(a)} = 2^{-1/2} [g_V^{(a)} (\bar{\psi}_\nu (1 - \gamma_5) \gamma_i \psi_l) (\bar{\psi}_n \gamma_i \psi_p) + g_A^{(a)} (\bar{\psi}_\nu (1 - \gamma_5) \times i\gamma_i\gamma_5\psi_l) (\bar{\psi}_n i\gamma_i\gamma_5\psi_p) + (1/2m)\, g_M^{(a)} (\bar{\psi}_\nu (1 - \gamma_5) \gamma_i \psi_l) \times (\bar{\psi}_n \sigma_{ik} (p_k - n_k) \psi_p) + g_P^{(a)} (\bar{\psi}_\nu (1 - \gamma_5) \gamma_5 \psi_l) (\bar{\psi}_n \gamma_5 \psi_p)]. \quad (1)$$

Here $\sigma_{ik} = (\gamma_i\gamma_k - \gamma_k\gamma_i)/2i$; $p_i$ and $n_i$ are the four-momenta of the proton and the neutron; m is the nucleon mass ($\hbar = c = 1$); and the form-factors $g_V^{(a)}, \ldots, g_P^{(a)}$ are functions of the square of the four-momentum transfer, $(p - n)^2$. When the strong interactions are "turned off" $g_V^{(a)}, g_A^{(a)} \rightarrow G$, $g_M^{(a)}, g_P^{(a)} \rightarrow 0$, and we get the Lagrangian for $\mu$ decay.

Table I summarizes the theoretical predictions regarding the values of the form-factors for $\mu$ capture that are given by the theory of the UFI with conserved vector current when strong interactions are taken into account.[3-6] The second column of the table shows the diagrams included in the theoretical estimate of the effects of the strong interactions. One-pion intermediate states lead to the appearance in the effective Lagrangian (1) of a term which imitates a pseudoscalar coupling. The value of the effective pseudoscalar coupling constant $g_P^{(\mu)}$ given in the third column is that calculated in [3,6] by using the renormalized pion-

**Table I.**

| Coupling constants in $\mu$ capture | Diagrams taken into account | Expressions in terms of coupling constants for $\beta$ decay of nucleons |
|---|---|---|
| $g_V^{(\mu)}$ |  | $0.97 \cdot g_V^{(\beta)}$ [6] |
| $g_A^{(\mu)}$ |  | $g_A^{(\beta)}$ [3] |
| $g_M^{(\mu)}$ |  | $0.97 \times 3.7\, g_V^{(\beta)}$ [6] |
| $g_P^{(\mu)}$ |  | $8 \cdot g_A^{(\beta)}$ [3] |

nucleon interaction constant and the experimental probability of the decay $\pi^- \to \mu^- + \bar{\nu}$.

The positive sign of the ratio $g_P^{(\mu)}/g_A^{(\mu)}$ is obtained on the assumption that the main contribution to $\pi$ decay comes from intermediate states with a nucleon-antinucleon pair. Two-pion intermediate states give the main contribution to the "weak magnetism" constant $g_M^{(\mu)}$ and represent the main dependence on the momentum transfer in $g_V^{(\mu)}$. In the theory of the UFI with conserved vector current the effect of the two-pion intermediate states is easily calculated[1,4,6] and leads to the values of $g_V^{(\mu)}$ and $g_M^{(\mu)}$ shown in the third column of the table. We note, however, that the hypothesis of the conserved vector current has not yet received direct experimental confirmation. The expected dependence on the momentum transfer in $g_A^{(\mu)}$ is extremely small, since its first contribution is from three-pion intermediate states.

Thus experiments to test the predictions of the theory of the UFI regarding the interaction of $\mu$ mesons with nucleons include the determination of four coupling constants. In this connection it must be emphasized that the least trivial questions are those of the magnitude and especially the sign of the constant $g_P^{(\mu)}$. The experimental determination of this constant is extremely important both to establish the accuracy of the pole approximation used in calculating it and to test the correctness of our ideas about the mechanism of $\pi$ decay.

## 2. ANALYSIS OF THE EXPERIMENTAL DATA

In this paper we do not give a review of all the existing experimental material on $\mu$ capture, but consider in detail those experiments that are accurate enough for quantitative comparison with the predictions of the theory.

A. Experiments on the probability of $\mu$ capture. Numerous measurements of the total probability of $\mu$ capture (cf., e.g., [7,8]) in various nuclei demonstrate convincingly that the coupling constants for the weak interactions of $\mu$ mesons and electrons with nucleons are of the same order of magnitude. Furthermore the ratio of the probabilities of $\mu$ capture in adjacent nuclei[7,9] evidently indicates that interactions of the Gamow-Teller type predominate to some extent over those of the Fermi type. One cannot, however, get from these experiments any exact information about the numerical values of the coupling constants.

The study of partial $\mu$ transitions which obey definite selection rules is more promising. Up to now the only experiments of this type are the measurements of the probability of the reaction[10,11]

$$\mu^- + C^{12} \to B^{12} + \nu \tag{2}$$

as a fraction of the probability of the $\beta$ decay

$$B^{12} \to C^{12} + e^- + \bar{\nu} \tag{2'}$$

Since in this reaction about 90 percent of the $B^{12}$ nuclei are produced in the ground state, the transitions (2) and (2′) are of the Gamow-Teller type ($\Delta J = 1$, no).

The probability of the reaction (2) with production of the $B^{12}$ nucleus in the ground state is proportional to the square of the effective Gamow-Teller coupling constant[6]:

$$\begin{aligned} (\Gamma_A^{(\mu)})^2 &= (G_A^{(\mu)})^2 + \tfrac{1}{3}\,[(G_P^{(\mu)})^2 - 2G_A^{(\mu)}G_P^{(\mu)}]; \\ G_A^{(\mu)} &= g_A^{(\mu)} - (g_V^{(\mu)} + g_M^{(\mu)})\,(E_\nu/2m), \\ G_P^{(\mu)} &= (g_P^{(\mu)} - g_A^{(\mu)} - g_V^{(\mu)} - g_M^{(\mu)})\,(E_\nu/2m). \end{aligned} \tag{3}$$

where $E_\nu$ is the energy of the neutrino in reaction (2). The most accurate experiment[10] leads to the following estimate for $\Gamma_A^{(\mu)}$:

$$\Gamma_A^{(\mu)} = (1.16 \pm 0.13)\, g_A^{(\beta)}. \tag{4}$$

The indicated error is mainly due to theoretical inaccuracies which arise in the calculation of the nuclear matrix element for reaction (2).[12]

Let us introduce the notations

$$-g_A^{(\mu)}/g_V^{(\mu)} = \lambda, \quad g_P^{(\mu)}/g_A^{(\mu)} = \varkappa, \quad g_M^{(\mu)}/g_V^{(\mu)} = \mu - 1 \tag{5}$$

which will be convenient in what follows. If we fix the value of the ratio $g_A^{(\beta)}/g_A^{(\mu)}$, then Eq. (4) gives a connection between the three quantities $\lambda$, $\kappa$, and $\mu$. When we take into account the weak dependence of $g_A^{(\mu)}$ on the four-momentum transfer (see Sec. 1), the latest measurements of the branching ratio $(\pi \to e + \nu)/(\pi \to \mu + \nu)$ of $\pi$-meson decay[13] give the result $g_A^{(\mu)} = g_A^{(\beta)}$ to an accuracy of the order of 10 to 15 percent. Furthermore, according to calculations of Goldberger and Treiman,[3] $g_M^{(\mu)}$ is very small in the theory of the UFI without a conserved vector current, so that $\mu \approx 1$. In the theory with conserved vector current, according to Table I, $\mu \approx 4.7$. In comparing theory with experiment we shall consider only these two values of $\mu$.

Figure 1 shows the dependences of $\kappa$ on $\lambda$ for $\mu = 4.7$ and for $\mu = 1$. In these diagrams curve 1 corresponds to the values $\Gamma_A^{(\mu)} = (1.16 + 0.13)$, $g_A^{(\beta)} = 1.29\ g_A^{(\beta)}$ and $g_A^{(\mu)} = (1 - 0.15)\, g_A^{(\beta)} = 0.85\ g_A^{(\beta)}$, and curve 2 to the values $\Gamma_A^{(\mu)}$

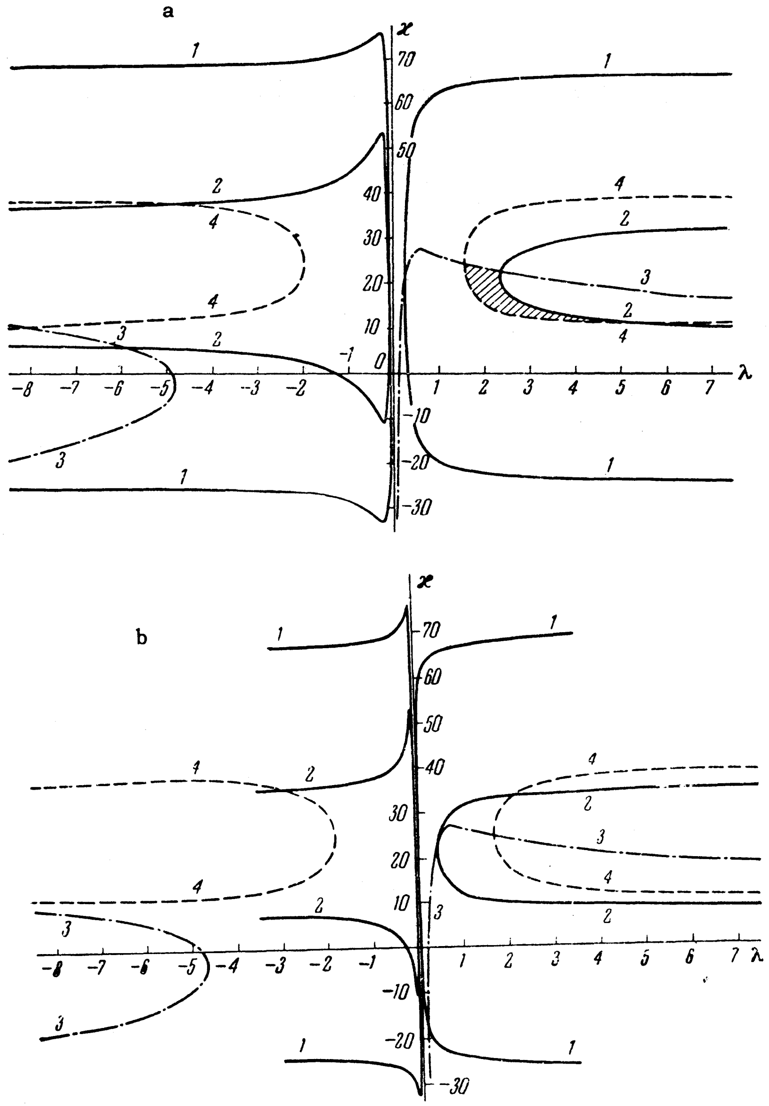



FIG. 1

$= (1.16 - 0.13)$, $g_A^{(\beta)} = 1.03\ g_A^{(\beta)}$ and $g_A^{(\mu)} = (1 + 0.15)\, g_A^{(\beta)} = 1.15\ g_A^{(\beta)}$. The region of allowed values of $\kappa$ and $\lambda$ lies between curves 1 and 2. The choice of the values of $\Gamma_A^{(\mu)}$ and $g_A^{(\mu)}$ for curves 1 and 2 has been made so as to obtain the maximum range of admissible values of $\kappa$ and $\lambda$ compatible with the existing experimental and theoretical uncertainties in $\Gamma_A^{(\mu)}$ and $g_A^{(\mu)}$. As can be seen from the diagrams of Fig. 1, within the allowed region the values of $\kappa$ and $\lambda$ can vary over wide ranges.

Let us now turn to the measurements of the difference of the probabilities of nuclear absorption of $\mu^-$ mesons from two states of the hyperfine structure of a mesic atom.[14] So far there have been two experiments of this type.[15,16] Telegdi[15] has studied capture from the states of the hyperfine structure of the mesic atom $Al^{27}$. The results of this work confirm that terms of the Gamow-Teller type are present in the interaction between $\mu$ mesons and nucleons, but a more detailed interpretation of the results is difficult. A paper by Egorov and others[16] describes a measurement of the difference of the probabilities of $\mu$ capture from the states of the mesic atom $P^{31}$ with spins F = 0 and F = 1. The estimate obtained as a lower limit on the quantity

$$\Delta W/W = (W_0 - W_1)/(W_0/4 + 3W_1/4),$$

where $W_0$ and $W_1$ are the probabilities of $\mu$ capture from the states of the mesic atom with F = 0 and F = 1, is

$$(\Delta W/W)_{\text{lower}} = 0.29 \pm 0.04 \qquad (6)$$

(the indicated error is the statistical error).

Using the results of the calculation of the value of $\Delta W = W_0 - W_1$ for phosphorus in a paper by Überall[17] and taking into account only the main dependence on the coupling constants in Primakoff's formula for the $\mu$-capture probability W,[18] we get an expression for $\Delta W/W$ as a function of $\kappa$, $\lambda$, and $\mu$:

$$\Delta W/W = 0.324 \{\lambda^2 (3 + 2\gamma - 2\gamma\varkappa) + \lambda [2\mu\gamma (2 + \gamma) + (3 + \gamma)(1 + \gamma) - (1 + \gamma + 2\mu\gamma)\gamma\varkappa] + (2 + 2\gamma + \mu\gamma)\mu\gamma\} \{\lambda^2 (3 + 2\gamma + \gamma^2 - 2\gamma\varkappa - 2\gamma^2\varkappa + \gamma^2\varkappa^2) + 4\mu\gamma\lambda + 2\mu^2\gamma^2 + (1 + \gamma)^2\}^{-1}, \quad (7)$$

where $\gamma = \bar{E}_\nu/2m$, and $\bar{E}_\nu$ is the average energy of the neutrinos emitted in $\mu$ capture in $P^{31}$. In Eq. (7) we have adopted the value $\gamma = 0.048$, which corresponds to a mean excitation energy of the $P^{31}$ nucleus of the order of 15 Mev.

The curves 3 in Fig. 1 a and b represent the functions $\kappa = \kappa(\lambda)$ obtained from Eq. (7) for $\mu = 4.7$ and $\mu = 1$, respectively, with $\Delta W/W = +0.25$, which corresponds to subtraction of one standard deviation from the lower limit. The region of allowed values of $\kappa$ and $\lambda$ is inside each of the indicated curves. As can be seen from the diagrams, the shape of the curves is not very sensitive to the value of $\mu$. Practically all positive values of $\lambda$ are allowed, but the allowed negative values begin at large magnitudes $|\lambda| \approx 5$. For positive $\lambda$ the values of $\kappa$ are bounded above: $\kappa \leq 27$.

B. Experiments on the angular distribution of the neutrons. When averaged over energy the angular distribution of the neutrons emitted on the absorption of polarized $\mu^-$ mesons by nuclei of spin zero is of the form[19,20]

$$1 + a\cos\theta, \quad (8)$$

where $\theta$ is the angle between the direction of emission of the neutron and the polarization of the $\mu^-$ meson, and the asymmetry coefficient a is given by the formula

$$a = P_\mu P_n \tilde{\beta}\tilde{\alpha}. \quad (9)$$

Here $P_\mu$ is the degree of polarization of the $\mu^-$ meson in the K shell of the mesic atom at the instant of capture; $P_n$ is a factor that allows for the background of isotropically distributed evaporated neutrons which are products of the decay of the compound nucleus which can be produced by the $\mu$-capture process; $\tilde{\beta}$ is a factor that allows for the decrease of the asymmetry in the angular distribution of the neutrons of the direct process* on account of the motion of the protons in the original nucleus and the interaction of the emerging neutron with the residual nucleus; and $\tilde{\alpha}$ is the "internal" asymmetry coefficient, which depends on the coupling constants of the interaction of $\mu$ mesons with nucleons. $\tilde{\alpha}$ differs by only a few percent from the value of the asymmetry coefficient $\alpha_H$ for mesic hydrogen, calculated with neglect of the hyperfine structure of the mesic atom[20] (this difference is due to the smaller value of the mean energy of the neutrinos emitted in $\mu$ capture by the nuclei, as compared with that of the neutrinos from $\mu$ capture by free protons). The expression for $\tilde{\alpha}$ is given in [20]. Thus to obtain information about the coupling constants from the experimental asymmetry coefficient a it is necessary to get from it the "internal" asymmetry coefficient $\tilde{\alpha}$, i.e., it is necessary to know the values of $P_\mu$, $P_n$, and $\tilde{\beta}$.

The polarization $P_\mu$ of the $\mu^-$ mesons is measured directly by an experiment on the amount of asymmetry in the angular distribution of the electrons from $\mu^-$ decay, and can be obtained with high accuracy.

The quantity $P_n$ is given by the formula[21]

$$P_n = (gW)/[gW + \tau(\nu W_{exp} - W)], \quad (10)$$

where W is the probability of emission of a direct-process neutron on $\mu$ capture; $W_{exp}$ is the total probability of $\mu$ capture in the given nucleus; $\nu$ is the average multiplicity of neutron emission in a single act of $\mu$ capture; g is the fraction of direct-process neutrons with energy $E_N$ above the threshold energy $E_0$ of the neutron detector; and $\tau$ is the fraction of evaporation neutrons with energy $E_N > E_0$. In principle the quantities g, $\tau$, and W can be determined directly from experiment by measuring the spectrum of the neutrons from $\mu$ capture and separating out from it the Maxwell spectrum of evaporation neutrons and the spectrum of direct-process neutrons with $E_N > E_0$. Because of great experimental difficulties, however, these measurements have not yet been made, and for the calculation of $P_n$ one uses theoretical values of g, $\tau$, and W and experimental values of the quantities $W_{exp}$ and $\nu$.[21] The result is that the values of $P_n$ shown in Table II and used in going from a to $\tilde{\alpha}$ contain inaccuracies which can arise from the use of the ideas of particular models of nuclear structure in the theoretical calculations. It must be emphasized, however, that if the neutron-registration threshold $E_0$ is high enough large errors in the theoretical values of the quantities g and W lead to very small errors in $P_n$.[21]

*Neutrons of the direct process are neutrons emitted from the nucleus immediately after the absorption of the $\mu^-$ meson, with omission of the stage of the compound nucleus.

**Table II.**

| Nucleus | Neutron-registration threshold $E_0$, Mev | $a = P_\mu P_n P_\gamma \tilde{\beta}\,\tilde{\alpha}$* | $P_\mu$ | $P_n$ | $\tilde{\beta}$ | $\tilde{\alpha}$ |
|---|---|---|---|---|---|---|
| S[27] | 3 | −(0.045±0.015) | 0.126±0.018 | (0.7)** <br> 0.28 | 0.59 | (−0.86±0.31) <br> −2.16±0.78 |
| S[28] | 5 | −(0.019±0.007) | 0.084±0.015 | 0.53 | 0.62 | −0.69±0.28 |
| Mg[28] | 5 | −(0.020±0.005) | 0.066±0.012 | 0.43 | 0.62 | −1.14±0.36 |
| Ca[21] | 7 | −(0.066±0.022) | 0.135±0.0194 | 0.96 | 0.58 | −0.93±0.33 |

*$P_\gamma$ allows for registration of the isotropic $\gamma$-ray background by the neutron detector. In [21] $P_\gamma = 0.96$; in the other cases, in obtaining $\tilde{\alpha}$ it has been assumed that $P_\gamma = 1$.

**The value $P_n = 0.7$ is given in [27].

The factor $\tilde{\beta}$ has been calculated in a number of papers.[19,20,22,23] Calculations made with the Fermi-gas model[22] for an unbounded nucleus, which give a crude correction for the decrease of the asymmetry of the neutrons only on account of the motion of the protons in the original nucleus, give $\tilde{\beta} \approx 0.8$. A modified Fermi-gas model,[23] which takes into account the refraction and reflection of the neutrons at the boundary of the nucleus, gives $\tilde{\beta} \approx 0.7$. More realistic calculations by the use of the shell model and the optical model,[19,20] which have been made for the nuclei $C^{12}$, $O^{16}$, $Ne^{20}$, $Si^{28}$, $S^{32}$, and $Ca^{40}$, lead to values $\tilde{\beta} \approx 0.5 - 0.6$.

In the discussion of the accuracy of the theoretical calculations of the quantity $\tilde{\beta}$ two questions arise at once. The first is the question of the legitimacy of using the ideas of a definite model of nuclear structure in the calculations. An answer to this question can be obtained by an experimental test of the theoretically calculated probabilities and spectra of direct-process neutrons, of the ratios of the asymmetry coefficients a for different nuclei, of the dependence of the amount of asymmetry on the energy of the neutrons, and so on. The second question is that of the degree of accuracy of the calculations when one uses the "method of distorted waves" to take account of the interaction between the emitted neutron and the nucleus. As is shown in a paper by Shapiro,[24] the treatment of the interaction by the method of distorted waves correspond to only the first iteration in the integral equation for the amplitude for $\mu$ capture with the emission of a direct-process neutron. The "small parameter" that characterizes the convergence of the iteration procedure is the quantity $\delta = k\sigma_s^{1/2}/8\pi^{3/2}$, where $\sigma_s$ is the cross section for elastic scattering of neutrons by the given nucleus at the energy $E_N = \hbar^2 k^2/2m$. For light nuclei and neutron energies of the order of $5 - 10$ Mev we have $\delta \sim 0.1$; obviously this favors the method of distorted waves, but more exact quantitative conclusions can be reached only through an investigation of the exact solution of the equation for the amplitude for $\mu$ capture.

It must be pointed out that in the calculations of $\tilde{\beta}$ in [19,20] the potentials used in the shell and optical models were rectangular wells, which of course is a rather crude approximation. More accurate determination of the quantity $\tilde{\beta}$ within the framework of these models will have to include the making of calculations with better potentials.

We point out that in [19,20] the factor $\tilde{\beta}$ has been calculated for direct-process neutrons that have undergone elastic interaction with the nucleus. Along with these neutrons an experiment will register the direct-process neutrons that have undergone inelastic interactions with the nucleus but have energies above the registration threshold $E_0$. Since as a rule the angular distribution of the elastically scattered neutrons protrudes forward more than that of the inelastically scattered neutrons,[25] inclusion of the latter can only decrease the value calculated in [19,20]. The relative contributions to $\beta$ from inelastically and elastically scattered neutrons is determined in first approximation by the ratio of the cross sections for inelastic and elastic scattering ($\sigma_{nn'}$ and $\sigma_s$) of neutrons by the given nucleus. Since in the range of energies in which we are interested ($E_N \sim 5 - 20$ Mev) $\sigma_{nn'}/\sigma_s \sim 0.1 - 0.2$,[25] it is to be expected that the contribution to $\tilde{\beta}$ from inelastic processes will be very small.

Let us now consider the experimental data. Table II, which is taken from [21], shows a collection of the experimental data on the asymmetry of the neutrons emitted in $\mu$ capture in the nuclei of Mg, S, and Ca.* The values of $P_n$ and $\tilde{\beta}$ are calculated on the basis of the results obtained in [19,20]. Since, as noted above, the quantity $P_n$ can be calculated more reliably for higher values of the reg-

*We note that in the work of Baker and Rubbia [26] no asymmetry was found for Mg. Unfortunately the brevity of the exposition in [26] does not allow us to judge the reasons for the absence of an asymmetry.

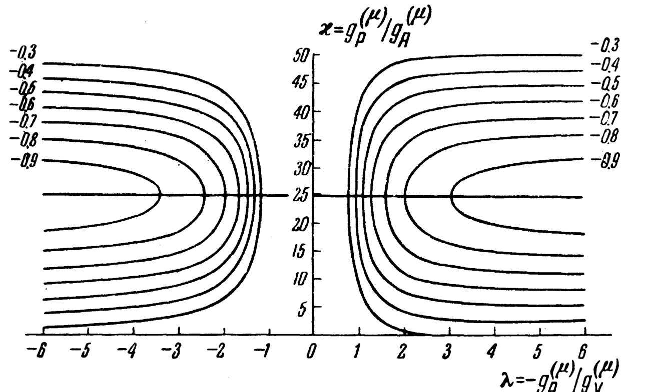



FIG. 2

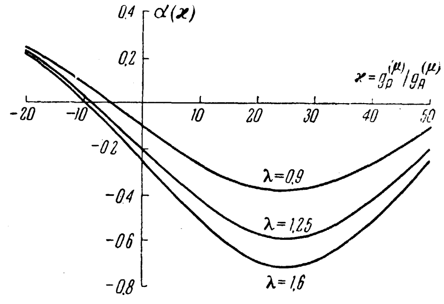



FIG. 3

istration threshold $E_0$, we shall confine ourselves to a discussion of the asymmetry coefficients for magnesium, sulfur, and calcium obtained in [21,28] and shown in the second, third, and fourth lines of Table II. From these papers we find as the average value of $\tilde{\alpha}$ (treating the experimental errors as standard deviations)

$$\tilde{\alpha}_{av} = -0.92 \pm 0.19. \quad (11)$$

This value differs by more than twice the error from the value $\tilde{\alpha} \approx -0.4$ predicted by the theory of the UFI for the coupling constants of Table I. The curves 4 in Fig. 1, a and b are those obtained for $\mu = 4.7$ and $\mu = 1$, respectively, from Eq. (19) of [20] for $\tilde{\alpha} = -0.7$ ($\alpha_{av}$ plus one standard error).* The allowed region of values of $\kappa$ and $\lambda$ is inside the curves 4. As can be seen from the diagrams, the positive values of $\lambda$ are bounded from below and the negative values from above. The values of $\kappa$ in the allowed region are positive and lie in the range $10 \leq \kappa \leq 40$.

Figure 2 shows curves $\tilde{\alpha}$ = const in the plane of $\kappa$ and $\lambda$ for $\mu = 4.7$ (cf. the last footnote). The curves that correspond to the predictions of the theory of the UFI with the constants of Table I are those for values $\tilde{\alpha} \approx -(0.40 - 0.45)$. Figure 3 shows the dependence of the asymmetry coefficient $\tilde{\alpha}$ on $\kappa$ for three values of $\lambda$ with $\mu \sim 4.7$ (cf. the last footnote). For $\lambda$ = const $\tilde{\alpha}$ has its maximum absolute value at $\kappa \sim 25$. We note that with the value $\lambda = 1.25$ predicted by the theory of the UFI (see Table I) the minimum possible value of $\tilde{\alpha}$ (for $\kappa \sim 25$) differs from the experimental value of $\tilde{\alpha}_{av}$ given by Eq. (11) by one and one-half times the experimental error.

## CONCLUSION

Let us summarize the conclusions to be drawn from the preceding section. It follows from Fig. 1 that for negative $\lambda$ with $\mu = 4.7$ and $\mu = 1$ and for positive $\lambda$ with $\mu = 1$ there are no values of $\kappa$ and $\lambda$ that simultaneously agree with the three types of experiments we have considered—experiments on the capture probabilities in $C^{12}$ and $P^{31}$ and on the angular distributions of the neutrons. For positive $\lambda$ and $\mu = 4.7$, however, the three regions of allowed values of $\kappa$ and $\lambda$ overlap (shaded region in Fig. 1, a); the values of $\kappa$ and $\lambda$ consistent with all of the experimental data considered lie in the ranges $10 \lesssim \kappa \lesssim 25$ and $1.6 \lesssim \lambda \leq 6$.

When we compare these results with the predictions of the theory of the UFI, we come to the following conclusions.

1) Within the framework of the theory of the UFI the best agreement with the present experimental data on $\mu$ capture is obtained with the type of theory which has a conserved vector current.

2) The vector coupling constant $g_V^{(\mu)}$ and the axial-vector constant $g_A^{(\mu)}$ have opposite signs, which is evidence in favor of the idea of the (V − A) interaction.

3) The axial-vector interaction predominates over the vector interaction:

$$|g_A^{(\mu)}| > |g_V^{(\mu)}|.$$

4) The coupling constant $g_P^{(\mu)}$ of the induced pseudoscalar interaction is large, and the ratio $g_P^{(\mu)}/g_A^{(\mu)}$ is positive, in agreement with the predictions of the theory.

The third and fourth assertions are mainly based on the results of the experiments on the angular distribution of the neutrons.[21,28] The second assertion is based on experiments on the absorption of $\mu^-$ mesons from various states of the hyperfine structure of the mesic atom.[15,16] Finally, the first assertion follows from a combined consideration of all three types of experiments analyzed above.

We may also note some tendency toward values of the ratios $|g_A^{(\mu)}/g_V^{(\mu)}|$ and $g_P^{(\mu)}/g_A^{(\mu)}$ that are large in comparison with those predicted by the

*The quantity $\gamma = \bar{E}_\gamma/2m$ is assumed to have the value $\gamma = 0.042$.

theory (Table I). It is not excluded, however, that greater accuracy in the experimental data and the theoretical calculations will not confirm this tendency and will lead to agreement with the predictions of the theory. We also emphasize that whereas the experimental data on $\mu$ capture in $C^{12}$ and on the branching ratio in $\pi$ decay indicate the presence of an axial-vector interaction in $\mu$ capture, the experiments do not give any direct proof that there is a vector interaction in $\mu$ capture.

We express our sincere appreciation to I. S. Shapiro for a discussion of this work and to V. S. Evseev and A. E. Ignatenko for acquainting us with the results of their work before the appearance of their papers.[21,16]

Note added in proof (November 21, 1961). New experimental data have recently appeared. The probability of the process (2) has been found with good accuracy [29] and differs by a factor of one and one-half from the value from [10] used in the present paper. The probability of $\mu$ capture in $He^3$ has been measured.[30] The Liverpool group has obtained [31] for $\mu$ capture in sulfur the value $P_n\widetilde{\beta}\widetilde{\alpha} = -0.22 \pm 0.07$ (for $E_0 = 5$ Mev), which agrees well with the data of [28] (cf. Table II). These new results do not change the conclusions of the present paper.

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