Physics

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1957

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Abstract

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On the Question of the Interaction of μ-Mesons with Nucleons

(Presented by Academician D. V. Skobeltsyn, 27 V 1957)

At present there is very little experimental information on the non-electromagnetic interactions of μ-mesons with nucleons; from it there follows only the fact that this interaction belongs to the class of "weak" ones. Meanwhile, a more detailed investigation of the μ-meson—nucleon interaction is of great interest from the standpoint of clarifying the nature of the μ-meson —one of the most mysterious among the elementary particles known to us (the same types of interactions are characteristic of the μ-meson and the electron —weak and electromagnetic; both particles have the same spin, but the mass of the μ-meson is 206.7 times greater than the mass of the electron). In particular, determining the type of interaction of μ-mesons with nucleons may prove decisive in understanding why, despite the existence of decays of π- and K-mesons into μ and ν*, there are no decays of these particles into e and ν. Indeed, if the decays of π- and K-mesons proceed through the baryon vacuum, then, regarding π- and K-mesons as pseudoscalar particles, it is easy to show that the decay process is forbidden for the scalar, vector, and tensor variants of the four-fermion interaction, but allowed for the pseudoscalar and pseudovector variants. Since only the scalar and tensor variants** are apparently responsible for the interaction of electrons with nucleons, as follows from β-decay, the decay of π- and K-mesons into e and ν will therefore be forbidden. The presence, however, of decays into μ and ν would indicate the presence (of at least one of the two) pseudoscalar and pseudovector variants in the interaction of μ-mesons with nucleons.

If, on the other hand, the decay of π- and K-mesons occurs, at least in part, through the direct interaction of a π- or K-meson with a μ-meson and a neutrino, then the Hamiltonian of the interaction of μ-mesons with nucleons must contain a pseudoscalar interaction.

It is well known that negative μ-mesons, when slowed down in matter, undergo nuclear absorption, this process passing through an intermediate stage with the formation of a mesoatom. It is generally assumed that the process of absorption of μ^--mesons proceeds by means of the reaction

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

In the present work the angular distribution of neutrons obtained as a result of the capture of a μ^--meson by a proton in μ-mesohydrogen is considered. It is assumed that the μ^--meson is polarized***. In this case, by virtue of noncon–

* The symbol ν denotes the neutrino.
** At present, in light of new experimental data, the question of the choice of variants of the interaction in β-decay has become more complicated.
*** μ^--mesons are produced in the decay of π^--mesons polarized in a direction parallel to their motion ([1]). Upon slowing down and formation of the μ-mesoatom, depolarization is possible, although it is not complete ([2]). It is understood that an experiment to study the angular distribution in reaction (1) must be preceded by a measurement of the polarization of μ^--mesons in the mesoatom (for example, by measuring the anisotropy in the angular distribution of decay electrons).

conservation of parity in weak interactions, the angular distribution of neutrons will, generally speaking, be anisotropic, with the sign and magnitude of the anisotropy depending on the type of interaction.

The interaction energy of the μ-meson with nucleons, taking into account non-conservation of parity, can be written in the form

$$H = \sum_k (\bar{\psi}_n O_k \psi_p)(\bar{\psi}_\nu [g_k - g'_k \gamma_5] O_k \psi_\mu) + \text{c.c.},$$

where O_k are the operators known from the theory of β-decay, composed of the Dirac matrices γ_μ; $k = s, p, v, a, t$, where s, p, v, a, t denote, respectively, the scalar, pseudoscalar, vector, pseudovector, and tensor variants of the interaction. In the case when $g_k = -g'_k$, we obtain the variant of the theory with a longitudinally polarized neutrino proposed by L. D. Landau ([1]).

The angular distribution of neutrons is described by the formula

$$W(\theta) = 1 + \alpha \cos\theta,$$

where θ is the angle between the direction of emission of the neutron and the direction of polarization of the μ^--meson.

In the general case of the presence of all variants of the interaction, α has the form

$$\alpha = A/B,$$

where

$$A = (E+M)h_{ss} + (E-M)h_{pp} + 2(M+\varepsilon)h_{vv} - 2(M-\varepsilon)h_{aa} -$$
$$- 8(E+2\varepsilon)h_{tt} + 2(E+M+\varepsilon)\operatorname{Re} h_{sv} + 4\varepsilon \operatorname{Re} h_{st} + 2(E-M+\varepsilon)\operatorname{Re} h_{ap} +$$
$$+ 4\varepsilon \operatorname{Re} h_{tp} - 4\varepsilon \operatorname{Re} h_{va} - 4(E-M+\varepsilon)\operatorname{Re} h_{vt} - 4(E+M+\varepsilon)\operatorname{Re} h_{at},$$

$$B = (E+M)f_{ss} + (E-M)f_{pp} + 2(2E-M+\varepsilon)f_{vv} +$$
$$+ 2(2E+M+\varepsilon)f_{aa} + 8(3E+2\varepsilon)f_{tt} + 2(E+M+\varepsilon)\operatorname{Re} f_{sv} +$$
$$+ 4\varepsilon \operatorname{Re} f_{st} + 2(E-M+\varepsilon)\operatorname{Re} f_{ap} + 4\varepsilon \operatorname{Re} f_{tp} + 4\varepsilon \operatorname{Re} f_{va} +$$
$$+ 12(E-M+\varepsilon)\operatorname{Re} f_{vt} + 12(E+M+\varepsilon)\operatorname{Re} f_{at}.$$

Here

$$f_{ik} = g_i^* g_k + g_i'^* g_k', \qquad h_{ik} = g_i^* g_k' + g_i'^* g_k;$$

E, M are, respectively, the total energy and rest energy of the neutron; ε is the energy of the neutrino ($E = 944.7$ MeV, $M = 939.5$ MeV, $\varepsilon = 99.1$ MeV).

The values of the coefficient α for various variants of the interaction (2), under the assumption of a longitudinal neutrino, are given in Table 1*.

Table 1

Variant	s	p	v	a	t
α	−1	−1	−0.99	+0.29	+0.38
P	0	0	0.095	0.64	0.72

In view of the special significance of the combinations of variants $s+t$ and $p+a$, we give separately the value of α for these cases. If the constants of the scalar and tensor interactions are taken, in accordance with the hypothesis of conservation of combined parity, to be real and one uses their

* In accordance with experimental data ([3]), the antineutrino emitted in β-decay of nucleons is polarized opposite to the direction of its motion. The form of the interaction Hamiltonian chosen by us corresponds to the emission in process (1), as also in the case of electron capture by nuclei, of a neutrino, i.e., a particle polarized along the direction of motion. If, in the capture of μ^--mesons, an antineutrino is emitted, then the sign of the coefficient α changes to the opposite one.

values known from β-decay (see, for example, (4)) of nucleons: $g_s = (+1.4$ or $-1.4) \cdot 10^{-49}$ erg $\cdot$ cm^3, $g_t = +1.8 \cdot 10^{-49}$ erg $\cdot$ cm^3, then in the case of a longitudinal neutrino we obtain $\alpha^{s+t} = +0.30$ or $+0.32$. Similarly, in the case of a longitudinal neutrino, for the combination $p+a$ we obtain

Fig. 1

Figure 1: Fig. 1

$$\alpha^{p+a} = \frac{1.78\,|g_a|^2 - 0.0055\,|g_p|^2 - 0.22\ \mathrm{Re}\, g_a^* g_p}{6.20\,|g_a|^2 + 0.0055\,|g_p|^2 + 0.22\ \mathrm{Re}\, g_a^* g_p}.$$

The values of α^{p+a} as a function of $x = g_a/g_p$, in the case of a real ratio of the constants x, are shown in Fig. 1. It should be noted that the values of the coefficient α, for comparable values of the constants g_p and g_a, will be very close to α^a, since the pseudoscalar constant is always accompanied by the small factor v/c (v is the neutron velocity). Conversely, if the experimentally measured α turns out to be close to α^p, then one may state with confidence that the admixture of the pseudovector and tensor variants is negligibly small.

Fig. 1

Let us note that formulas of the same kind can also be obtained for the capture of μ^--mesons by protons bound in nuclei. In this case, generally speaking, the coefficient α will depend on nuclear matrix elements, which will complicate the interpretation of experimental data. For some light nuclei these matrix elements can be estimated if the final state of the residual nucleus formed as a result of process (1) is known.

In addition to the anisotropy of the angular distribution of neutrons, the fact that the neutrons produced in process (1) are, generally speaking, polarized may also be used to determine the type of interaction. This polarization may be both transverse and longitudinal, and part of the latter is due to nonconservation of parity and will occur even when the captured μ^--mesons are unpolarized. Table 1 gives the magnitudes of the longitudinal polarization of P-neutrons produced in the capture of unpolarized μ^--mesons by free protons in the case of a longitudinal neutrino.

These same data are also approximately valid for the capture of μ-mesons by nuclei, since the nuclear spin-orbit interaction changes the longitudinal polarization of the neutron only little, and its depolarization in the Coulomb field of the residual nucleus is negligibly small.

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named after M. V. Lomonosov

Received
18 V 1957

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Note: Figure translations are in progress. See original paper for figures.