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NON-RADIATIVE TRANSFORMATION OF THE μ MESON INTO AN ELECTRON

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Submitted to JETP editor March 12, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 1646-1647 (May, 1960)

1. The process of non-radiative transformation of the μ meson into an electron in the Coulomb field of the nucleus,

$$\mu^- + A_Z \to A_Z^* + e^- \tag{1}$$

may occur with greater probability than the decay $\mu \to e + \gamma$, if the monopole form factor for the transition $\mu \to e$ is larger than the dipole form factor. Weinberg and Feinberg[1] quoted the example of the four-fermion interaction of the type $(\bar{e}\mu)(\bar{f}f)$ (where f is a charged particle) for which this situation may occur in principle. Steinberger and Wolfe[2] have made attempts to discover the process (1). According to their data the ratio of the probability of process (1) and the probability of the ordinary capture of μ mesons by the protons of the Cu^{64} nucleus is $\leq 5 \times 10^{-4}$. These experimenters searched for the reaction (1) by registering the electrons with energies of about 100 Mev.

In this note we discuss a different method for detecting the reaction (1). Let us consider a μ-mesic atom with a light even-even nucleus (for example, C^{12}, O^{16}, or Ne^{20}). In the 6 to 10 Mev region of the excitation energies these nuclei have excited states 0^+ from which decay with emission of α particles takes place.[3] Our proposed method for the detection of the process (1) consists of registering the α particles of known energy emitted by nuclei which have been excited to the 0^+ level as a consequence of reaction (1). The probability of this process can be calculated. It is equal to (in units where $\hbar = c = 1$)

$$W_{00}^{\mu e} = \frac{16}{9}\pi Z^3\alpha^5\mu^2(1-2\omega)\,|\,\mu^2 Q_0\,|^2\,|\,f_{E0}\,|^2. \tag{2}$$

Here ω is the excitation energy of the nucleus in units of the rest energy of the μ meson, μ (we assume that $\omega \ll 1$), Q_0 is the nuclear matrix element for the transition $0^+ \to 0^+$:

$$Q_0 = \langle A_Z^* 0^+ \left| r^2 - \tfrac{1}{6}(\mu r)^2 \right| A_Z 0^+ \rangle, \tag{3}$$

and f_{E0} is the electric monopole form factor for the transition $\mu \to e$, which depends on the momentum transfer $q = p_e - p_\mu$ (p_e and p_μ are the momenta of the electron and the μ meson) in the following fashion:

$$f_{E0}(q^2) = q^2 G(q^2), \quad \lim G(q^2) < \infty \quad \text{for } q^2 \to 0. \tag{4}$$

It is convenient to compare $W_{00}^{\mu e}$ with the probability for the ordinary capture of μ^- mesons,

$$\mu^- + A_Z \to A_{Z-1} + \nu \tag{5}$$

(this type of reaction has now been relatively well studied in the case of C^{12}). The probability $W_{if}^{\mu\nu}$ for the process (5) has been calculated by a number of authors.[4,5] Using their result and formulas (2) and (4), we obtain

$$W_{00}^{\mu e}/W_{if}^{\mu\nu} = \frac{32}{9}\pi^3\alpha^2\left[1 + 2(\omega' - \omega)\right]\eta\,|\,\mu^2 Q_0\,|^2/M_{if}. \tag{6}$$

Here ω' is the difference in energy of the nuclei $f(A_{Z-1})$ and $i(A_Z)$ (in the units μ, $\omega' \ll 1$),

$$\eta = G^2(\mu^2)/g^2, \quad M_{if} = \lambda_F^2\,|\,M_F^{if}\,|^2 + \lambda_{GT}^2\,|\,M_{GT}^{if}\,|^2, \tag{7}$$

where g is the universal constant of the weak four-fermion interaction as determined from the decay time of the μ meson; M_F^{if} and M_{GT}^{if} are the Fermi and Gamow-Teller matrix elements for the allowed transition $i \to f$ including meson corrections and corrections for the finite wave length of the neutrino (see reference 4). In particular, formula (6) gives for the ratio of the probabilities of processes (1) and (5) for the C^{12} nucleus

$$W(\mu^- + C^{12} \to C^{12*} + e)/W(\mu^- + C^{12} \to B^{12} + \nu) = 1.1 \cdot 10^{-2}\eta. \tag{8}$$

2. An effect which hinders the observation of reaction (1) (if the α particles are registered) is the Coulomb excitation of the nucleus of the μ-mesic atom by the decay electrons from the μ^- meson. This effect, however, occurs relatively seldom owing to the smallness of the phase volume. The calculation leads to the following formula for

the probability of this effect:

$$W_{00}^{ee'} = \frac{2}{9}\frac{1}{192\pi^3} Z^3\alpha^5\mu^5\left(\frac{7}{20} - \omega\right)|\mu^2 Q_0'|^2 g^2. \quad (9)$$

The ratio of the probabilities for the two effects is

$$W_{00}^{ee'}/W_{00}^{\mu e} = 2.36\cdot 10^{-3}\left(1 - \frac{6}{7}\omega\right)/\eta. \quad (10)$$

(Here we neglected the small difference between Q_0 and Q_0'.) It is seen from (10) that this ratio becomes comparable to unity for $\eta \approx 3 \times 10^{-6}$, which is about 10^3 times smaller than the upper limit for η calculated by Weinberg and Feinberg from the data of Steinberger and Wolfe ($\eta \leq 4 \times 10^{-3}$).

I express my gratitude to M. Ya. Balats and Ya. B. Zel'dovich for an interesting discussion.

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Translated by R. Lipperheide
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POLARIZATION OF NUCLEI IN NONMETALLIC FERROMAGNETIC SUBSTANCES

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Submitted to JETP editor March 13, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 1647-1649 (May, 1960)

IN 1955 a method for polarizing the nuclei of ferromagnetic atoms was proposed by us[1] and simultaneously by Kurti and his co-workers.[2] The corresponding experiments on the anisotropy of γ radiation have been made by a number of authors.[1-4] All of these experiments were made on ferromagnetic metals.

It would be interesting to make experiments of this type also in the case of nonmetallic ferromagnetic substances. As an example let us consider the case of a ferrite, i.e., a compound of the type $XO \cdot Fe_2O_3$, where X is a divalent metal ion. The ferrite is ferromagnetic if X is the ion of a divalent metal of the iron transition group (Fe, Co, Ni, Mn, Ti, Cu).* These ferrites have the reciprocal spinel structure. It is well known that in the spinel lattice there are one tetrahedral cation position A and two octahedral cation positions B for each molecule. In the case of the reciprocal spinel structure the X^{++} ions occupy half the positions B, and the Fe^{+++} ions occupy all the positions A and half the positions B.

We assume that the external magnetic field is larger than the saturation field. Then the specimen is a single domain. If furthermore the temperature is sufficiently low, the state will be close to the state of absolute saturation. We proceed further to apply the Néel model,[5] according to which each of the sublattices A and B is magnetized to saturation, with their magnetizations oppositely directed. Therefore the resultant magnetization is determined by the X^{++} ions whose magnetic moments are directed along the external field. It follows that the fields exerted by the shells of X^{++} ions on their nuclei will all have the same direction (parallel or antiparallel to the external field, depending on the sign of the hyperfine structure constant). At an extremely low temperature we get a considerable polarization of the X nuclei. The limiting degree of polarization (obtained if the Zeeman energy of the nuclear spin in the internal field caused by the ion shell is much larger than kT) will be equal to unity.

These considerations apply to the ferrites of Co, Ni, Mn, Ti, and Cu. It is easy to see that in these ferrites the iron nuclei will not be polarized, but only aligned. It is also obvious that in the ferrite of iron (i.e., in magnetite, Fe_3O_4) the limiting degree of polarization of the iron nuclei will be $\frac{1}{3}$.

As a second example let us consider the case of a ferromagnetic garnet, i.e., a compound of the type $3X_2O_3 \cdot 5Fe_2O_3$, where X is the trivalent ion of a rare-earth element. A model analogous to the Néel model has been proposed to explain the properties of garnets[6,7] (cf. also reference 8). According to this model there are three types of positions for cations in a garnet, namely, in each molecule there are six so-called d positions, four a positions, and six c positions. The d and a positions are occupied by Fe^{+++} ions, and the c positions by X^{+++} ions. At low temperatures all the sublattices are magnetized to saturation, with the c and a sublattices magnetized