$NiCl_2$. In the spectrum of negative ions, the lines Cl^-, Cl_2^-, $NiCl^-$, $NiCl_2^-$ and also weak Ni^- lines (masses 58 and 60) were observed. With forced operation of the ion source, the intensity of the Ni_{58}^- and Ni_{60}^- lines substantially increased and a Ni_{62}^- line became noticeable. The current of Ni_{58}^- ions was successfully raised to 1×10^{-12} amp.

We have thus discovered the existence of Fe^- and Co^- ions and have confirmed the existence of Ni^- ions.

One can make two different hypotheses about the electronic structure of the Fe^-, Co^- and Ni^- ions. Either the additional electron starts a new 4p group in these ions, or, upon its penetration, a rearrangement of the electronic shell proceeds which results in one of the electrons going into the 3d group. The second hypothesis seems to us the more probable. If it is correct, then the Fe^- ion should have the structure $1s^2 \ldots 3d^7\,4s^2$, differing from the structure of the Fe atom ($1s^2 \ldots 3d^6\,4s^2$) by an odd electron in the 3d group. Analogously, a Co^- ion must have the structure $1s^2 \ldots 3d^8\,4s^2$, and a Ni^- ion the structure $1s^2 \ldots 3d^9\,4s^2$. In connection with this, one should note that according to spectroscopic data,[2] upon the removal of one of the outer 4s electrons from atoms of Co and Ni the second 4s electron goes over into the 3d group.

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THE UNIVERSAL FERMI INTERACTION AND THE CAPTURE OF THE μ MESON BY THE PROTON

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GELL-MANN and Feynman,[1] and independently Suderman and Marshak,[2] proposed principles leading to a definite form of the interaction between four fermions. Depending on whether the A, B, C, D are "particles" or "antiparticles," these principles yield two distinct possibilities: the interaction (V − A), which is invariant under different pairings of the particles,

$$H_1 = 8^{1/2} G\,(\overline{\Psi}_A \gamma_\mu a \Psi_B)(\overline{\Psi}_C \gamma_\mu a \Psi_D) \qquad (1)$$

[where Ψ_A, Ψ_B, Ψ_C, Ψ_D are the wave functions of the "particles," $a = (1 + \gamma_5)/2$], or the interaction (V + A),

$$H_2 = 8^{1/2} G\,(\overline{\Psi}_A \gamma_\mu \bar{a} \Psi_B)(\overline{\Psi}_C \gamma_\mu a \Psi_D) \qquad (2)$$

[where Ψ_A, Ψ_B are the wave functions of the "antiparticles," $\bar{a} = (1 - \gamma_5)/2$], which for a different pairing of the particles[3] has the form (S − P):

$$H_2 = 2 \cdot 8^{1/2} G\,(\Psi_A a \Psi_D)(\overline{\Psi}_C \bar{a} \Psi_B). \qquad (2')$$

In all formulas we consider here one and the same process A + C = B + D and, by convention, call "particles" all those particles which have a left longitudinal polarization for $v/c = 1$; their antiparticles have the opposite sign of polarization.

The difference between the interactions (1) and (2) is particularly clear when we look at the formula (2′). Gell-Mann and Feynman note the extremal properties of (V − A) and (V + A) from the point of view of the asymmetry of the decay of the polarized neutron. We note that even before the discovery of parity non-conservation one of us has shown[4] that the difference of the Fermi and Gamow-Teller interactions with equal coefficients of (S − T) and (V − A) (which does not satisfy the Tolhoek-de Groot symmetry[5]) yields full polarization of the slow electron, whereas the sum yields complete depolarization of the slow electron in the β decay of the polarized neutron. The capture of the μ meson by a proton from a definite state of the hyperfine structure is evidently the reverse process to the emission of a slow particle. Expressions for the capture probability of the μ meson in different states of the hyperfine structure are given in reference 6. It follows from these expressions that in the variant (V + A), which goes over into (S − P) when written as $(\overline{P}0\nu)\,(\bar{\mu}^-0N)$, the (S − P) probabilities for the capture in the states F = 0 and F = 1 (F is the combined spin of the proton and μ meson) are exactly the same, while in the variant (V − A) the probability for capture from F = 1 is zero, and the probability for capture from $F = 0$ is four times larger than the value averaged over the spins. This result can be obtained immediately, when we write the interactions $(\mu\nu PN)$ (1) and (2) in spinor components for the case when the neutron, proton, and μ meson are described by nonrelativistic wave functions:

$$H_1 = -2G\,(N_1^*\nu_2^* - N_2^*\nu_1^*)\,(P_1\mu_2 - P_2\mu_1); \quad (3)$$

$$H_2 = -2G\Big\{N_1^*\nu_1^*P_1\mu_1 + N_2^*\nu_2^*P_2\mu_2 + \frac{1}{2}(N_1^*\nu_2^* + N_2^*\nu_1^*)(P_1\mu_2 + P_2\mu_1) - \frac{1}{2}(N_1^*\nu_2^* - N_2^*\nu_1^*)(P_1\mu_2 - P_2\mu_1)\Big\}, \quad (4)$$

where the wave functions of the neutron (N), proton (P), μ meson (μ), and neutrino (ν) have the form (we use a representation in which γ_4 is diagonal):*

$$N = \begin{pmatrix} N_1 \\ N_2 \\ 0 \\ 0 \end{pmatrix}; \qquad P = \begin{pmatrix} P_1 \\ P_2 \\ 0 \\ 0 \end{pmatrix}; \qquad \mu = \begin{pmatrix} \mu_1 \\ \mu_2 \\ 0 \\ 0 \end{pmatrix};$$

$$\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} \nu_1 \\ \nu_2 \\ -\nu_1 \\ -\nu_2 \end{pmatrix}.$$

As was shown in reference 7, the capture of a μ meson by a proton occurs, because of the possibility of the "jumping" of the μ meson from one proton to another, from the hyperfine structure state $F = 0$, i.e., from the state in which the μ meson and the proton have opposite spins. The probability for the capture of the μ meson by the proton is four times greater for $(V - A)$ than for $(V + A)$. Hence, it is possible to determine the relative sign of V and A in the fundamental interaction law $(\mu\nu PN)$ by a measurement of the absolute yield of the reaction $\bar{\mu} + P \rightarrow N + \nu$ in hydrogen for capture from the state $F = 0$.

Allowing for the possibility that strong interaction corrections may change the value of the axial vector constant, we may write the Hamiltonian for the interaction of the real nucleons with $(\mu\nu)$ in the form

$$H = \frac{1+\lambda}{2}H_1 + \frac{1-\lambda}{2}H_2$$

(where $\lambda = C_A/C_V$). The absolute yield of the reaction $\mu^- + P \rightarrow N + \nu$ from the state $F = 0$ is then equal to

$$W = \frac{8}{\pi^2}\left(\frac{e^2}{\hbar c}\right)^3\left(\frac{\hbar q_{\nu\,\max}}{m_\mu c}\right)^2\frac{G^2 m_\mu^5 c^4}{\hbar^7} \times \frac{1}{(1 + v_N/c)(1 + m\ \ /M_p)^3}\left(\frac{1+3\lambda}{4}\right)^2;$$

its ratio with the decay probability for $\mu \rightarrow e + \nu + \tilde{\nu}$ ($W_{\text{decay}} = G^2 m_\mu^5 c^4/192\pi^3\hbar^7 = 1/2.2 \times 10^{-6}$ sec^{-1}) is

$$W/W_{\text{decay}} \approx 1.1\cdot 10^{-3}\left(\frac{1+3\lambda}{4}\right)^2.$$

For $(V - A)$ $(\lambda = 1)$ $W/W_{\text{decay}} \approx 11 \times 10^{-4}$, while for $(V + A)$ $(\lambda = -1)$ $W/W_{\text{decay}} \approx 2.7 \times 10^{-4}$. If $|\lambda| = 1.13$, as in β decay,† $W/W_{\text{decay}} \approx 13 \times 10^{-4}$ (for $\lambda = +1.13$) and $W/W_{\text{decay}} \approx 4 \times 10^{-4}$ (for $\lambda = -1.13$).

Since the formation of the meson molecular ions $(pp)_\mu^+$ in liquid hydrogen complicates the picture of the capture of μ mesons by protons,[8] the experiments have to be carried out with hydrogen of a density $1/_{20}$ or $1/_{30}$ of the density of liquid hydrogen at 20°K. It is also necessary to use hydrogen purified from deuterium, since in natural hydrogen 25% of the mesons manage to "jump" to the deuterons.[9]

In conclusion we note that the spin correlations of the μ meson (or the electron) with the proton are easily obtained under the assumption that the β decay (or the μ decay) goes through a heavy intermediate particle with spin zero.[10,11] The interaction $(V - A)$ corresponds to a neutral particle (ζ): $N \rightarrow \zeta + \tilde{\nu}$; $\zeta \rightarrow p + e^-$, and the interaction $(V + A)$ corresponds to a charged particle (ζ'): $N \rightarrow \zeta' + e^-$; $\zeta' \rightarrow p + \tilde{\nu}$.

*The neutrino is described by the two-component function $\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$; $|\nu_1|^2 + |\nu_2|^2 = 1$.

†If C_A is renormalized owing to strong interactions, C_A/C_V for the $(\mu\nu PN)$ interaction may, of course, be different from C_A/C_V for the $(e\nu PN)$ interaction (through the influence of the direct decay $\pi \rightarrow \mu + \nu$ alone).

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NUCLEONIC INTERACTION WHICH PRODUCES A SUPERFLUID STATE OF THE NUCLEUS

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WE shall consider the possible appearance of superfluid states among medium and heavy nuclei, i.e., states which are energy wise more advantageous than the state of completely degenerate Fermi gas (normal state). In order to do this we shall apply the variational principle of Bogoliubov[1] as it arises from generalizing the method of Fock,[2] and mathematical techniques developed in the theory of superconductivity.[3]

Basing ourselves on the shell model of the nucleus, we shall examine the weak interaction[4] existing among protons (or neutrons) of the same shell with equal and opposite values of the projection of their angular momenta upon the axis of symmetry of the nucleus. Assuming that the shell is characterized by a set of quantum numbers s, the model Hamiltonian may be written in the following form:

$$H = \sum_{s,m} \{[E(s,m) - E_F]\, a^+_{m+}(s)\, a_{m+}(s) + [E(s,-m) - E_F]\, a^{\pm}_{-m-}(s)\, a_{-m-}(s)\} + \frac{1}{N} \sum_{\substack{s,m,m' \\ m \neq m'}} J_0(s\,|\,m,m')\, a^+_{m+}(s)\, a^{\pm}_{-m-}(s)\, a_{-m'-}(s)\, a_{m'+}(s), \tag{1}$$

where N is the number of levels and the other quantities are described in reference 4. Let us make the following canonical transformations.

$$a_{m+}(s) = u_m(s)\,\alpha_{m0}(s) + v_m(s)\,\alpha^+_{m1}(s), \tag{2}$$

$$a_{-m-}(s) = u_m(s)\,\alpha_{m1}(s) - v_m(s)\,\alpha^+_{m0}(s),$$

$$\eta_m(s) = u_m(s)^2 + v_m(s)^2 - 1 = 0. \tag{3}$$

We shall find the average value of $\overline{H} = \langle C_0^* H C_0 \rangle$ in the new vacuum $\alpha_{m_1} C_0 = \alpha_{m_0} C_0 = 0$. We then find the functions $u_m(s)$, $v_m(s)$ from the requirement that $\overline{H}$ have a minimum value with the additional condition (3). As a result we obtain the following equation for the new unknown function $C_m(s)$:

$$C_m(s) = -\frac{\frac{1}{2N} \sum_{m'} J_0(s\,|\,m,m')\, C_{m'}(s)}{\sqrt{\{\overline{E}(s,m) - E_F\}^2 + C_{m'}(s)^2}}, \tag{4}$$

thus

$$u_m(s)^2 = \frac{1}{2}\left[1 + \frac{\overline{E}(s,m) - E_F}{\varepsilon_m(s)}\right]$$

$$v_m(s)^2 = \frac{1}{2}\left[1 - \frac{\overline{E}(s,m) - E_F}{\varepsilon_m(s)}\right], \tag{5}$$

$$\varepsilon_m(s) = \sqrt{\{\overline{E}(s,m) - E_F\}^2 + C_m(s)^2},$$

$$\overline{E}(s,m) = \frac{1}{2}\{E(s,m) + E(s,-m)\}.$$

When the energy is close to the Fermi surface energy we obtain the following approximate solution to Eq. (4) for small values of J

$$C_m(s_0) = \omega \frac{J_0(s_0\,|\,m,m_0)}{J_0(s_0\,|\,m_0,m_0)} \exp\left\{\frac{(m_2 - m_1)\, d\overline{E}(s_0,m_0)/dm_0}{J_0(s_0\,|\,m_0,m_0)}\right\},$$

$$\ln\frac{\omega}{\mu} = \frac{1}{2}\int_{m_1}^{m_2} dm' \frac{d\overline{E}(s_0,m_0)}{dm_0} \ln\frac{|\overline{E}(s_0,m') - E_F|}{\mu} \times \frac{d}{dm'}\left[\frac{J_0(s_0\,|\,m_0,m')}{J_0(s_0\,|\,m_0,m_0)}\, \frac{1}{d\overline{E}(s,m')/dm'}\right], \tag{6}$$

where $\overline{E}(s_0, m_0) = E_F$. The functions $u_m(s)$ and $v_m(s)$ of the superfluid state are obtained from Eq. (5) and (6), while for the normal state $u_m(s) = 1 - \theta_F(s,m)$, $v_m(s) = \theta_F(s,m)$ where $\theta_F(s,m) = 1$ if $\overline{E}(s,m) < E_F$, and $\theta_F(s,m) = 0$ if $\overline{E}(s,m) > E_F$.

We shall now compute the difference ΔE^I between the ground and the first excited superfluid states in such a way as to avoid departing from even-even nuclei to odd ones, and we find

$$\Delta E^I_m(s) = \langle C_s^* \alpha_{m0}(s)\, \alpha_{m1}(s)\, H \alpha^+_{m1}(s)\, \alpha^+_{m0}(s)\, C_s \rangle - \langle C_s^* H C_s \rangle = 2\varepsilon_m(s), \tag{7}$$

and for $s = s_0$, $m = m_0$

$$\Delta E^I_{m_0}(s_0) \approx 2\omega \exp\left\{\frac{(m_2 - m_1)\, d\overline{E}(s_0 m_0)/dm_0}{J_0(s_0/m_0, m_0)}\right\}. \tag{7'}$$

It can be seen from this that the first excited state is separated from the ground state by a gap (7'). Note that there is no energy splitting when the normal state is perturbed.

We can find the difference ΔE between the superfluid and normal states in the form