A SCHEME OF WEAK INTERACTIONS WITH NEUTRAL CURRENTS

V. N. BAĬER and I. B. KHRIPLOVICH

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The cross sections for scattering and annihilation in the collision of light particles due to weak interaction are calculated. The degree of logitudinal polarization in such nucleon-nucleon scattering is estimated. Effects caused by weak interaction between the electrons in the medium are considered.

1. INTRODUCTION

It is well known that in the V – A scheme of weak interactions,[1] it is possible for charged particles to be scattered by neutral ones, along with decay processes. It is not excluded, however, that the weak interaction has a universal character not only in the sense of the coupling constant and the interaction structure, but is also universal in that it is realized between all the fermions. If this assumption is adopted, the following law results: the weaker the interaction (from strong to gravitational), the more universal it is in the sense of the particles participating in it.[2]

It must be considered, however, that many processes (for example, the decay $\mu^{\pm} \rightarrow 2e^{\pm} + e^{\mp}$) are experimentally forbidden. In order to circumvent the difficulty, it is necessary to introduce supplementary exclusions: thus, Feynman and Gell-Mann exclude the neutral current containing terms of the type $(\bar{e}e)$, $(\bar{\mu}e)$, $(\bar{n}n)$, etc.[1]

Certain interest therefore attaches to a scheme in which the class of possible weak interactions is broadened, and at the same time the forbidden processes are automatically excluded. Such a scheme was proposed, for example, by Bludman.[3] It contains many new processes, but this does not contradict the experimental data known at present. Although we adhere to this scheme in the article, it should be noted it is not the only one, and that the authors are primarily interested in the consequences of introducing neutral currents into the theory of weak interactions. For the sake of simplicity, we do not consider strange particles.

We introduce the charge space of weak interactions. We consider in this space the doublets $(\nu\mu)$, (νe), and (pn), and assume that the weak interaction is invariant with respect to rotations in this space. Then the weak-interaction Lagrangian can be represented in the form

$$L = \frac{1}{4}\frac{G}{\sqrt{2}}\sum_{ij}[\bar{\psi}_i\gamma_\mu(1 - i\gamma_5)\tau\psi_i][\bar{\psi}_j\gamma_\mu(1 - i\gamma_5)\tau\psi_j]$$
$$= \frac{G}{\sqrt{2}}\sum_{ij}\Big\{[\bar{\psi}_i\gamma_\mu(1 - i\gamma_5)\tau_+\psi_i][\bar{\psi}_j\gamma_\mu(1 - i\gamma_5)\tau_-\psi_j]$$
$$+ \frac{1}{4}[\bar{\psi}_i\gamma_\mu(1 - i\gamma_5)\tau_3\psi_i][\bar{\psi}_j\gamma_\mu(1 - i\gamma_5)\tau_3\psi_j]\Big\}. \quad (1)$$

In the usual notation, the Lagrangian (1) can be written as

$$L = L_{\pm} + L_3; \quad (2)$$

$$L_{\pm} = (\bar{p}n)(\bar{e}\nu) + (\bar{n}p)(\bar{\nu}e) + (\bar{p}n)(\bar{\mu}\nu)$$
$$+ (\bar{n}p)(\bar{\nu}\mu) + (\bar{\nu}\mu)(\bar{e}\nu) + (\bar{\mu}\nu)(\bar{\nu}e)$$
$$+ (\bar{\nu}e)(\bar{e}\nu) + (\bar{\nu}\mu)(\bar{\mu}\nu) + (\bar{p}n)(\bar{n}p), \quad (3)$$

$$L_3 = (\bar{p}p)(\bar{\nu}\nu) - (\bar{n}n)(\bar{\nu}\nu) - \frac{1}{2}(\bar{p}p)(\bar{e}e) + \frac{1}{2}(\bar{n}n)(\bar{e}e)$$
$$- \frac{1}{2}(\bar{p}p)(\bar{\mu}\mu) + \frac{1}{2}(\bar{n}n)(\bar{\mu}\mu) + \frac{1}{4}(\bar{p}p)(\bar{p}p)$$
$$+ \frac{1}{4}(\bar{n}n)(\bar{n}n) + (\bar{\nu}\nu)(\bar{\nu}\nu) + \frac{1}{4}(\bar{e}e)(\bar{e}e) + \frac{1}{4}(\bar{\mu}\mu)(\bar{\mu}\mu)$$
$$+ \frac{1}{2}(\bar{\mu}\mu)(\bar{e}e) - \frac{1}{2}(\bar{p}p)(\bar{n}n) - (\bar{\mu}\mu)(\bar{\nu}\nu) - (\bar{e}e)(\bar{\nu}\nu). \quad (4)$$

Here $L_{\pm}$ is the usual weak-interaction Lagrangian (1); the Lagrangian L_3 is new; it is seen to contain the interaction of the neutral currents.

By virtue of the known symmetry property of the V – A interaction

$$(\bar{A}B)(\bar{C}D) = (\bar{C}B)(\bar{A}D),$$

the terms $(\bar{\nu}e)(\bar{e}\nu)$, $(\bar{\nu}\mu)(\bar{\mu}\nu)$, $-(\bar{\mu}\mu)(\bar{\nu}\nu)$, $-(\bar{e}e)(\bar{\nu}\nu)$ cancel out of the total Lagrangian. Thus, this scheme does not contain the interaction between the neutrino and electrons or muons,[4] which is so widely discussed at present.

The scattering of a proton by a neutron is described in the theory of weak interactions[1] by the term $(\bar{p}n)(\bar{n}p)$, and in the proposed scheme this process is described in addition by the term $-\frac{1}{2}(\bar{p}p)(\bar{n}n)$. These terms are not given here, since the nucleon currents cannot be written in the form of a pure V – A variant in view of the influence of the strong interactions.

We investigate below the processes brought about by the Lagrangian L_3.

2. LEPTON-LEPTON PROCESSES

Along with the decay $\mu \to e + \nu + \bar{\nu}$, and scattering $\mu + e \to \nu + \nu$, processes known from the usual theory of weak interactions, other lepton scattering processes are also possible in this scheme, viz: $e + e \to e + e$, $\mu + \mu \to \mu + \mu$, $\nu + \nu \to \nu + \nu$, $e + \mu \to e + \mu$, and also the weak annihilation $e + e \to \mu + \mu$. The total cross section for each of these processes can be written in the form

$$\sigma = \sigma_e + \sigma_i + \sigma_w, \tag{5}$$

where σ_e is the electromagnetic interaction cross section, σ_w the weak interaction cross section, and σ_i the term for the interference between the electromagnetic and weak interactions. In this section, all the cross sections are written out in the c.m.s. for ultrarelativistic particles.

In the case of scattering of identical leptons, the weak-interaction cross section is of the form

$$\sigma_w(\theta) = r_0^2\left(\frac{Gm^2}{e^2}\right)^2\left(\frac{\mathscr{E}}{m}\right)^2(5+\cos^2\theta), \tag{6}$$

and the interference term is of the form

$$\sigma_i(\theta) = \frac{1}{\sqrt{2}} r_0^2 \frac{Gm^2}{e^2}\frac{5+3\cos^2\theta}{\sin^2\theta}. \tag{7}$$

The following symbols are used here: r_0 is the classical radius of the electron, m is the electron mass, G is the weak-interaction constant, $\mathscr{E}$ is the particle energy, and θ is the scattering angle. In the case of the scattering of a neutrino, the weak interaction cross section has an additional factor 16, and there is no interference term.

The cross section for the scattering $e + \mu \to e + \mu$ has the form

$$\sigma_w(\theta) = 8r_0^2\left(\frac{Gm^2}{e^2}\right)^2\left(\frac{\mathscr{E}}{m}\right)^2\cos^4\frac{\theta}{2}, \tag{8}$$

$$\sigma_i(\theta) = \sqrt{2} r_0^2 \frac{Gm^2}{e^2}\frac{\cos^4(\theta/2)}{\sin^2(\theta/2)}. \tag{9}$$

For the cross sections of the weak annihilation $e + e \to \mu + \mu$ we obtain

$$\sigma_w(\theta) = 8r_0^2\left(\frac{Gm^2}{e^2}\right)^2\left(\frac{\mathscr{E}}{m}\right)^2\cos^4\frac{\theta}{2}, \tag{10}$$

$$\sigma_i(\theta) = \sqrt{2} r_0^2 \frac{Gm^2}{e^2}\cos^4\frac{\theta}{2}. \tag{11}$$

Comparing the energy dependence of different cross sections, we see that with increasing energy the electromagnetic cross section decreases as $\mathscr{E}^{-2}$, the interference cross section is independent of the energy, and the weak-interaction increases as $\mathscr{E}^2$. It is clear therefore that, starting with a certain energy, the contribution of the weak interaction to the cross section will exceed all others and will become decisive.

To estimate the orders of magnitude of the quantities, we consider the cross section for the scattering of an electron by an electron. At a scattering angle of 15° and an energy of 3 Bev, the contribution of the interference term amounts to 0.01% of the contribution of the electromagnetic term, and the contribution of the weak term is negligibly small. But even at 100 Bev both the interference and the weak scattering cross sections become greater than the electromagnetic cross-section. At a scattering angle of 90°, the effects are even more noticeable: at 3 Bev the contribution of the interference term is 0.2% of the contribution of the electromagnetic term, but even at 70 Bev the contribution of both the interference and the weak terms of the interactions become comparable with the contribution from the electromagnetic term.

Thus, in the local theory the cross section for the scattering of an electron by an electron has a minimum at an energy of several times 10 Bev, and the absolute magnitude of the cross section is very small ($\sim 10^{-34}$ cm^2). If, however, the interactions are "smeared out" then the cross sections are multiplied by the corresponding form factors, and the absolute values of the cross sections become even smaller. Unfortunately, nothing is known at present regarding either the form factors or in general regarding the applicability of the V − A variant at such high energies. We note that if the weak interaction is produced through an intermediate boson whose mass is usually assumed to be several Bev, this leads to an appreciable distortion of the angular cross sections given above; this circumstance could in principle permit the detection of this boson.

Along with the processes considered above, the weak interaction between electrons will naturally lead to new effects in optics and in solid state physics.

The parity nonconserving part of the weak interaction will contribute to the antisymmetrical part of the polarization tensor, the presence of which leads to natural optical activity.[5] It is clear that this effect will be of order v/c.

Calculation in first order in G yields the following expression for the angle of rotation of the plane of polarization

$$\theta = \frac{16}{9}\pi^2 N\frac{n^2+2}{\lambda}\operatorname{Im}\sum_{n,k}\frac{\hbar\omega}{(E_n-E_0)^2-\hbar^2\omega^2}$$
$$\times\left[\frac{\pi^*_{nk}\mathbf{p}_{0k}\mathbf{M}_{n0}+\pi_{nk}\mathbf{p}_{n0}\mathbf{M}_{k0}}{E_n-E_k}+\frac{\pi^*_{0k}\mathbf{p}_{0n}\mathbf{M}_{nk}+\pi_{0k}\mathbf{p}_{kn}\mathbf{M}_{n0}}{E_0-E_k}\right]. \tag{12}$$

Here N is the concentration, $\mathbf{p}_{0k}$, $\mathbf{M}_{n0}$, and π_{nk} are the matrix elements of the electric dipole moment, magnetic dipole moment, and weak interaction, respectively. For liquid helium $\theta \sim 10^{-15}$ rad/cm,

$$\frac{\pi_{kn}}{E_k - E_n} \sim 10^{-18},$$

$$\mathbf{p}_{0k}\mathbf{M}_{n0} \sim \left(\frac{v}{c}\right)\mathbf{p}_{0k}\mathbf{p}_{n0} \sim \left(\frac{v}{c}\right)|\mathbf{p}_{0k}|^2 \sim \frac{e\hbar^2}{2m(E_0 - E_k)}\frac{v}{c}f_{0k} \sim 10^{-36},$$

where f_{0k} is the oscillator strength.

In addition, weak interaction between electrons will lead (in first order in G) to a shift of the levels of the atomic electrons. Thus, for singlet levels of helium the shift will be of order 0.1 cps (in the nonrelativistic approximation the shift for triplet levels is equal to 0).

It is clear that the probability of forbidden transitions due to weak interactions will be of order G^2, although the corrections to the probabilities of the allowed transitions will be of order G.

Were the weak interaction between electrons capable of leading to bound states, this could lead to effects of the superconductivity type. Unfortunately, this effect cannot be estimated by virtue of the well known difficulties with higher approximations of the 4-fermion interaction.

3. LEPTON-NUCLEON PROCESSES

The scheme which we consider contains additional processes of scattering of leptons by nucleons, such as $p(n) + e(\mu, \nu) \to p(n) + e(\mu, \nu)$ (their probability was previously estimated by Zel'dovich[6]), and annihilation processes such as $e(\mu, \nu) + e(\mu, \nu) \to p(n) + p(n)$. We shall again write the cross sections in the form (5).

The electromagnetic nucleon current can be represented in the form

$$j_\mu = \bar{\psi}'\left[\gamma_\mu F_1^{p(n)} - \frac{\mu^{p(n)}}{4M}(\gamma_\mu\hat{q} - \hat{q}\gamma_\mu)F_2^{p(n)}\right]\psi, \quad (13)$$

where $F_1^{p(n)}$, $F_2^{p(n)}$ are the electric and magnetic form factors of the proton (neutron), $\mu^{p(n)}$ is the anomalous magnetic moment of the proton (neutron), M is the nucleon mass, and $q = p' - p$ the momentum transfered.

Allowing for G invariance,[7] we obtain for the weak nucleon current the expression

$$V_\mu + A_\mu = \bar{\psi}'\Big[\gamma_\mu F_1 - \frac{\mu}{4M}(\gamma_\mu\hat{q} - \hat{q}\gamma_\mu)F_2 - i\gamma_\mu\gamma_5 g_1 - i\gamma_5 q_\mu g_3\Big]\psi, \quad (14)$$

where F_1 and F_2 are the isovector parts of the corresponding electromagnetic nucleon form factors, $\mu = \mu_p - \mu_n$, and g_1 is the axial form factor. The terms proportional to g_3 make a contribution $\sim m^2/M^2$ (and are neglected).

For the scattering of an electron by a nucleon at rest, we obtain

$$\sigma_w(\theta) = 4r_0^2\left(\frac{Gm^2}{e^2}\right)^2\left(\frac{\mathcal{E}}{m}\right)^2\frac{\cos^2(\theta/2)}{[1+2(\mathcal{E}/M)\sin^2(\theta/2)]^3}\Big\{F_1^2 - \frac{q^2}{4M^2}\Big[2(F_1+\mu F_2)^2\tan^2\frac{\theta}{2} + \mu^2F_1^2 + 2g_1^2\tan^2\frac{\theta}{2} - 4g_1(F_1+\mu F_2)\left(\frac{M}{\mathcal{E}}\sec^2\frac{\theta}{2} + \tan^2\frac{\theta}{2}\right)\Big]\Big\}, \quad (15)$$

$$\sigma_i(\theta) = \sqrt{2}r_0^2\frac{Gm^2}{e^2}\frac{\cot^2(\theta/2)}{[1+2(\mathcal{E}/M)\sin^2(\theta/2)]^2}\Big\{F_1F_1^{p(n)} - \frac{q^2}{4M}\Big[2(F_1+\mu F_2)(F_1^{p(n)} + \mu^{p(n)}F_2^{p(n)})\tan^2\frac{\theta}{2} + \mu\mu^{p(n)}F_2F_2^{p(n)} - 2g_1(F_1^{p(n)} + \mu^{p(n)}F_2^{p(n)})\left(\frac{M}{\mathcal{E}}\sec^2\frac{\theta}{2} + \tan^2\frac{\theta}{2}\right)\Big]\Big\}. \quad (16)$$

In the derivation of (15) and (16) we neglected m^2 compared with M^2 and q^2. Neglect of the latter limits the applicability of these formulas in the small angle region. Comparison with the formula of Rosenbluth[8] shows that the ratio of the interference cross section to the electromagnetic cross section amounts to $\sim 0.003\%$ for the proton, and $\sim 0.006\%$ for the neutron in backward scattering of 1-Bev electrons.

For weak annihilation of an electron-positron pair and a pair of nucleons we obtain in the c.m.s.

$$\sigma_w(\theta) = 2r_0^2\left(\frac{Gm^2}{e^2}\right)^2\left(\frac{\mathcal{E}}{m}\right)^2 v\Big\{(F_1^2+g_1^2)(1+v^2\cos^2\theta) + \frac{M^2}{\mathcal{E}^2}(F_1^2-g_1^2) + 4\mu F_1F_2 + \mu^2F_2^2\Big[\frac{\mathcal{E}^2}{M^2}(1-v^2\cos^2\theta)+1\Big] + 4g_1(F_1+\mu F_2)v\cos\theta\Big\}, \quad (17)$$

$$\sigma_i(\theta) = \frac{1}{\sqrt{2}}r_0^2\frac{Gm^2}{e^2}v\Big\{F_1F_1^{p(n)}\left(1+v^2\cos^2\theta + \frac{M^2}{\mathcal{E}^2}\right) + 2(\mu^{p(n)}F_2^{p(n)}F_1 + \mu F_2F_1^{p(n)}) + \mu\mu^{p(n)}F_2F_2^{p(n)}\Big[\frac{\mathcal{E}^2}{M^2}(1-v^2\cos^2\theta)+1\Big] + 2g_1(F_1^{p(n)} + \mu^{p(n)}F_2^{p(n)})v\cos\theta\Big\}, \quad (18)$$

where v is the velocity of the nucleon. Near the threshold, σ_i amounts to 0.1% of σ_e.

All the foregoing pertains also to processes in which muons participate, the only difference being that the neglect of m_μ^2 can result in an error of several percent. For processes in which neutrinos participate, obviously $\sigma_i = 0$ and σ_w must, according to (4), be multiplied by 4.

4. SCATTERING OF NUCLEONS BY NUCLEONS

To describe the scattering of nucleons by nucleons, we use the phenomenological transition matrix in the c.m.s.:[9]

$$M_0 = \alpha + \beta(\sigma_1 \mathbf{n})(\sigma_2 \mathbf{n}) + \gamma_1(\sigma_1 \mathbf{n}) + \gamma_2(\sigma_2 \mathbf{n})$$
$$+ \delta(\sigma_1 \mathbf{m})(\sigma_2 \mathbf{m}) + \varepsilon(\sigma_1 \mathbf{l})(\sigma_2 \mathbf{l}), \qquad (19)$$

where α, β, $\gamma_{1,2}$, δ, ϵ are functions of the energy and the transferred momentum; σ_1 and σ_2 are the spin operators of particles 1 and 2, **l**, **m**, and **n** are the unit vectors in the directions $\mathbf{p}_1' + \mathbf{p}_1$, $\mathbf{p}_1' - \mathbf{p}_1$ and $(\mathbf{p}_1' + \mathbf{p}_1) \times (\mathbf{p}_1' - \mathbf{p}_1)$. This matrix includes all the interactions which are invariant under space reflection, including electromagnetic interactions, and the parity-conserving part of the weak interactions. Thus, considering weak interaction between nucleons we should take additional account only of the parity nonconserving part of the Lagrangian

$$L_{\text{nc}} = a\frac{G}{\sqrt{2}}\Big\{\Big[\bar{u}_2'\Big(\gamma_\mu F_1 - \frac{\mu}{4M}(\gamma_\mu \hat{q} - \hat{q}\gamma_\mu)$$
$$\times F_2\Big)u_2\Big][\bar{u}_1'(-i\gamma_\mu\gamma_5 g_1)u_1] + [\bar{u}_2'(-i\gamma_\mu\gamma_5 g_1)u_2]$$
$$\times\Big[\bar{u}_1'(\gamma_\mu F_1 + \frac{\mu}{4M}(\gamma_\mu \hat{q} - \hat{q}\gamma_\mu)F_2)u_1\Big]\Big\}, \qquad (20)$$

where a = 1/4 for pp and nn scattering; a = 1/2 for pn scattering.*

We note that the interference contribution from (19) and (20) to the cross section averaged over the spins is 0. Actually, this contribution should be a pseudo-scalar, and after averaging over the spins the scattering process is characterized by 2 vectors, from which a pseudo-scalar cannot be constructed.

Weak interaction between nucleons is apparently simplest to observe in polarization experiments. The interference term between (19) and (20) leads to the occurrence of longitudinal polarization. Since the dominating contribution to (19) is made by strong interactions, we shall assume M_0 invariant in isotopic space, that is, $\gamma_1 = \gamma_2 = \gamma$.

With the aid of several cumbersome transformations we can obtain from (20) the parity nonconserving scattering matrix, written in the two-component form in the c.m.s.

*In the examination of scattering of neutrons by protons, we shall take into account only the term $-\frac{1}{2}(\bar{p}p)(\bar{n}n)$ in the Lagrangian, and disregard the term $(\bar{p}n)(\bar{n}p)$, although they are of the same order, since lack of experimental information enables us to obtain only rough estimates for the matrix M_0.

$$M_1 = a\frac{Gg_1}{2\pi}p\cos\frac{\theta}{2}\Big\{\Big[F_1 - \frac{\mathscr{E}-M}{M}\mu F_2\sin^2\frac{\theta}{2}\Big](\sigma_1 - \sigma_2)\mathbf{l}$$
$$+ i\frac{\mathscr{E}-M}{2\mathscr{E}}\sin\theta\Big[F_1 + \frac{\mathscr{E}+M}{M}\mu F_2\Big][(\sigma_2\mathbf{l})(\sigma_1\mathbf{n})$$
$$-(\sigma_2\mathbf{n})(\sigma_1\mathbf{l})]\Big\}. \qquad (21)$$

The total transition matrix is of the form

$$M = M_0 + M_1. \qquad (22)$$

Let us calculate, in first order in G, the polarization of the scattered nucleons, brought about in the scattering of unpolarized particles. The polarization vector will be represented in form

$$\mathbf{P} = \mathbf{P}_\perp + \mathbf{P}_\parallel. \qquad (23)$$

The longitudinal-polarization vector, in the scattering of protons by protons or of neutrons by neutrons, is

$$\mathbf{P}_\parallel = \frac{Gg_1 p\cos(\theta/2)}{4\pi(|\alpha|^2 + |\beta|^2 + 2|\gamma|^2 + |\delta|^2 + |\varepsilon|^2)}$$
$$\times\Big\{\Big(F_1 - \frac{\mathscr{E}-M}{M}\sin^2\frac{\theta}{2}\mu F_2\Big)[\mathbf{l}\,\mathrm{Re}(\alpha + \beta + \delta - \varepsilon)$$
$$- 2\mathbf{m}\,\mathrm{Im}\gamma] - \frac{\mathscr{E}-M}{2\mathscr{E}}\sin\theta\Big(F_1 + \frac{\mathscr{E}+M}{M}\mu F_2\Big)$$
$$\times[2\mathbf{l}\,\mathrm{Im}\gamma + \mathbf{m}\,\mathrm{Re}(\alpha + \beta - \delta - \varepsilon)]\Big\}, \qquad (24)$$

and in the scattering of neutrons by protons

$$\mathbf{P}_\parallel = \frac{Gg_1 p\cos(\theta/2)}{2\pi(|\alpha|^2 + |\beta|^2 + 2|\gamma|^2 + |\delta|^2 + |\varepsilon|^2)}$$
$$\times\Big\{\Big(F_1 - \frac{\mathscr{E}-M}{M}\sin^2\frac{\theta}{2}\mu F_2\Big)[\mathbf{l}\,\mathrm{Re}(\alpha - \varepsilon) - \mathbf{m}\,\mathrm{Im}\gamma]$$
$$- \frac{\mathscr{E}-M}{2\mathscr{E}}\sin\theta\Big(F_1 + \frac{\mathscr{E}+M}{M}\Big)\mu F_2[\mathbf{l}\,\mathrm{Im}\gamma + \mathbf{m}\,\mathrm{Re}(\beta - \varepsilon)]\Big\}. \qquad (25)$$

Here p is the momentum of the scattered nucleon.

The up-down asymmetry coefficient can be written in the form

$$\varkappa = (1 - P_\parallel)/(1 + P_\parallel) \approx 1 - 2P_\parallel. \qquad (26)$$

Unfortunately, the moduli and phases of the coefficients α, β, γ, δ, and ϵ are still unknown. We can therefore only make a rough estimate of the longitudinal polarization. It is found to be $10^{-6} - 10^{-7}$ at 200 – 300 Mev.

It is clear that an analogous calculation can also be made for the lepton and the lepton-nucleon scattering, in which case the coefficient of longitudinal polarization will be of order $10^{-3} - 10^{-4}$ at an energy of several Bev.

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