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NEUTRAL CURRENTS AND THE CIRCULAR POLARIZATION OF BREMSSTRAHLUNG *)

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ABSTRACT

Bremsstrahlung from lepton-nucleus scattering has a tiny circular polarization if the weak neutral currents are vector and axial vector. The magnitude of the effect is calculated for low incident lepton energies where the nuclear excitation may be neglected.

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1. INTRODUCTION

A central issue in particle physics is the nature of the weak neutral currents and whether or not the weak and electromagnetic interactions are unified ¹⁾. The test of the unification hypothesis and the unravelling of the underlying theory requires the knowledge of several types of neutral currents.

At present the weak neutral currents have been established only in muon-neutrino (and antineutrino) experiments, where the measured cross-sections ^{2),3)} are in agreement with the predictions of the most popular unified model proposed by Weinberg ⁴⁾. The knowledge of the differential cross-sections in the near future should supply a far better source of information.

Regardless of what we may learn from neutrino experiments, an essential question is whether there are neutral currents not involving neutrinos. In this paper we shall focus our attention on neutral current interactions between a charged lepton (in our case, an electron) and a nucleon. In order to study this sector of neutral current interactions, several possibilities have been advocated by various authors. These suggestions concern:

- (a) e^+e^- colliding beam experiments ⁵⁾;
- (b) lepton-nucleon (or nucleus) scattering ⁶⁾;
- (c) parity violation effects in atoms ⁷⁾;
- (d) decay of Σ^0 ⁸⁾;
- (e) weak spin rotation in neutron optics ⁹⁾.

A common feature of all of these experiments (some of which are in progress) is their being very difficult. In this paper we investigate another (again most probably very difficult) possibility, i.e., looking for the weak neutral current effects in bremsstrahlung (emitted in lepton-nucleus scattering) by measuring the circular polarization of the photon.

Our motivation has been twofold: first, we have been inspired by experiments on parity violation in nuclei where photon circular polarizations as small as a few parts in 10^7 have been reported ¹⁰⁾. Our second source of inspiration was a recent article by Fleischmann ¹¹⁾ in which the tremendous development in the technology of high current linear accelerators is reviewed. The currents involved are far bigger than what one is accustomed to in particle physics. Availability of a high current linear accelerator is a prerequisite for measuring the effect to be discussed here.

We expect the neutral current effects in bremsstrahlung processes to be very tiny. A quick order of magnitude estimate for the circular polarization of the photon, p_{γ}^c , gives $p_{\gamma}^c \approx GE^2/\alpha$ (where G and α are, respectively, the Fermi and the fine structure constants; E is the incoming electron energy). For $E \approx 10$ MeV we obtain the estimate $p_{\gamma}^c \approx 10^{-7}$, which is not far from the measured value quoted in Ref. 10).

The plan of the paper is as follows. We begin by giving our notations and assumptions. In Section 3 simple expressions are obtained for the differential cross-section and the photon circular polarization by neglecting the electron mass and the nuclear form factor. The effects due to the mass and the form factor are taken into account in Section 4. Finally, our conclusions are presented in Section 5.

2. BREMSSTRAHLUNG WITH NEUTRAL CURRENTS

The process of bremsstrahlung has been studied for over half a century ¹²⁾ and its various aspects have been recorded in a monumental literature in books and journals ¹³⁾. Here we wish to examine the effects due to the weak neutral currents. The only hope of seeing an effect is that the relevant neutral current violates parity.

A rather model-independent description of the lepton-nucleon sector of the neutral current interactions is given by the pointlike four-fermion interaction Lagrangian density

$$\mathcal{L} = \frac{G}{\sqrt{2}} \sum_i \bar{\Psi}_e \Gamma^i \Psi_e \sum_{j=p,n} \bar{\Psi}_j \Gamma^i (c_j^i - c_j^{i'} \gamma_5) \Psi_j \quad (1)$$

+ muonic terms

Here G is the Fermi constant. The sum i goes over the five possible interactions (scalar, pseudoscalar, tensor, vector, and axial vector). The c_j^i and $c_j^{i'}$ are constants, and our notation for the fields, etc., is as in Ref. 14).

We are interested in the parity violating terms in (1). For the scalar, pseudoscalar and tensor interactions, the parity violating terms automatically violate time-reversal invariance ¹⁵⁾. Stringent limits are available ¹⁶⁾ for such couplings from the experimental information on the electric dipole moments of atoms. Thus, in the following we restrict ourselves to the vector and axial vector interactions. It is convenient to describe these interactions by the form

$$\mathcal{L} = \sum_{j=e,\mu,\tau,n} \bar{\Psi}_j \gamma_\lambda (a_j^i - b_j^i \gamma_5) \Psi_j Z_i^\lambda \quad (2)$$

where a_j^i, b_j^i are constants, and Z_i denotes one or more heavy spin one-neutral bosons. Since Z_i are assumed to be heavy, the form (2) is equivalent to the vector and axial vector terms in (1).

We now consider the bremsstrahlung process

$$e(p) + N(P) \rightarrow e(p') + N(P') + \gamma(k) \quad (3)$$

where $e(p)$ denotes an electron with four-momentum p , etc. The symbol N stands for a nucleus. We shall assume that the initial state is unpolarized. Then the circular polarization of the photon is a measure of parity violation to be attributed to the weak neutral currents, provided that in the final state only the photon is observed. This is because the circular polarization changes sign under reflection in the plane spanned by $\vec{p}$ and $\vec{k}$, and thus vanishes if parity is good ¹⁷⁾.

The point here is that we shall be using the first Born approximation and must make sure that the higher order Born terms and electromagnetic corrections do not give circularly polarized photons. If, however, one considers the process (3) with polarized beam or target, the photon will generally be produced with some circular polarization, even if parity is not violated. Muons are usually polarized. Because of this phenomenon, and by far lower intensity of the muon beams, we restrict our attention to bremsstrahlung in electron scattering. However, our results in Section 4 are also valid for muons.

Next we restrict ourselves to low energies (below 50 MeV incoming energy) where the static approximation is expected to be valid and the theoretical interpretation is not marred by complications due to the nuclear form factor (the effects due to the form factor are discussed in Section 4). Putting the form factor equal to unity, process (3), in the static approximation is described by the coherent matrix element (see Fig. 1)

$$\begin{aligned} \mathcal{M} = & Z e^3 \bar{u}(p') \left[\not{\epsilon}^* \frac{1}{\not{p}' - m} \gamma_0 \left(-\frac{1}{q^2} + \xi \gamma_5 \right) + \right. \\ & \left. + \gamma_0 \left(-\frac{1}{q^2} + \xi \gamma_5 \right) \frac{1}{\not{p} - m} \not{\epsilon}^* \right] u(p), \end{aligned} \quad (4)$$

$$f = p - k, \quad f' = p' + k, \quad q = p - p' \quad (5)$$

Here Z is the nuclear charge; m denotes the electron mass, and ϵ^* is the polarization vector of the photon. Our notations for the γ matrices and the spinors are as in Ref. 14). Finally, the quantity ξ , which is due to the parity violation in Z_i exchange, is given by

$$\xi = \frac{1}{Ze^2} \sum_i b_e^i [Z \alpha_p^i + N \alpha_n^i] / M_{Z_i}^2. \quad (6)$$

In (6) the a 's and b 's are as defined in (2). N denotes the number of neutrons, and M_{Z_i} is the mass of the Z_i boson. Note that in the static limit in the expression for ξ , the axial vector leptonic and the vector nucleonic neutral currents enter.

In the Weinberg model, ξ is given by

$$\xi^{\text{Weinberg}} = \frac{\sqrt{2} G}{4\pi\alpha} \left\{ \sin^2 \theta_w + \frac{N-Z}{4Z} \right\}, \quad (7)$$

where θ_w is the Weinberg angle.

The essential feature of expression (4) is the $1/q^2$ fall of the electromagnetic interaction, as compared to the weak interactions. Thus, it is desirable to consider kinematical configurations where the magnitude of q^2 is as large as possible. We use the notations

$$p_\mu = (E, \vec{p}), \quad p'_\mu = (E', \vec{p}'), \quad k_\mu = (\omega, \vec{k}), \quad p = |\vec{p}|. \quad (8)$$

It is convenient to introduce the dimensionless quantities

$$\mu = -q^2/p^2, \quad (9)$$

$$w = \omega/p, \quad \eta = |\vec{p}'|/p, \quad \tilde{E} = E/p, \quad (10)$$

where p is the incoming momentum. For a fixed angle, θ , between the incoming electron and the outgoing photon, the quantity u is restricted to the region

$$u_- \leq u \leq u_+ \quad (11)$$

$$u_{\pm} = 2 \left\{ 1 + W^2 - W(\tilde{E} + \cos\theta) \pm \sqrt{W^2 - 2W\cos\theta + 1} \right\}^{\frac{1}{2}} \quad (12)$$

The quantity u_- varies rapidly with θ and W . We have displayed u_- for $p = 10$ MeV, and $\theta = 30, 90$ and 180 degrees. For this energy and range of θ the quantity u_+ is in the range 0.3 to 4. The quantities $u_{\pm}$, to within a few percent, are independent of the incoming momentum p , provided that $p \gtrsim 5$ MeV. This is because the $u_{\pm}$ are completely independent of p if the electron mass could be neglected, which is a good approximation for $p \gtrsim 5$ MeV.

From Fig. 2 and relation (9) we conclude that it is appropriate to study bremsstrahlung emitted at large angles with respect to the beam and to go to moderately large incoming energies, so that the factor Gp^2 is as large as possible without getting involved in complications due to the nuclear form factor and excitation. Therefore, in the following we shall be interested mainly in large angle bremsstrahlung.

3. DIFFERENTIAL CROSS-SECTIONS; CIRCULAR POLARIZATION

The matrix element (4) for the process (3) leads to the differential cross-sections

$$d\sigma^R + d\sigma^L = \frac{Z^2 \alpha^3}{4\pi p^2} \frac{d\omega}{\omega} d\Omega \cdot I_+, \quad (13)$$

$$d\sigma^R - d\sigma^L = \frac{Z^2 \alpha^3}{4\pi p^2} \frac{d\omega}{\omega} d\Omega \cdot I_-, \quad (14)$$

where R and L refer to the right- and left-circularly polarized photons. Ω is the photon solid angle. Furthermore, our notation is as in (8). The quantities $I_{\pm}$ are given by

$$I_+ = \int \frac{d\Omega'}{2\pi} \frac{E_+}{(q^2)^2}, \quad (15)$$

$$I_- = \int \frac{d\Omega'}{2\pi} \frac{E_-}{(q^2)^2} \quad (16)$$

Here Ω' denotes the solid angle of the outgoing electron, and

$$\begin{aligned} E_+ = 8 \eta \omega^2 p^2 \{ & -m^2 c'^{-2} (q^2 + 4E^2) - m^2 c^{-2} (q^2 + 4E'^2) \\ & + c^{-1} c'^{-1} [(q^2)^2 + 2q^2 (p^2 + E'^2) - 8m^2 E E'] \\ & + c^{-1} (c/2 - q^2) + c'^{-1} (c/2 - q^2) \}, \end{aligned} \quad (17)$$

$$\begin{aligned} E_- = -8 \eta \omega^2 p^2 \xi q^2 \{ & -2m^2 (c - c') (c'^{-1} + c^{-1})^2 \\ & - 8m^2 \omega (c'^{-1} + c^{-1}) (E c'^{-1} + E' c^{-1}) \\ & + 2q^2 (cc')^{-1} [c - c' + 2(E^2 - E'^2)] \\ & - (cc')^{-1} (c^2 - c'^2) \}, \end{aligned} \quad (18)$$

$$c = -2k p = -2(E\omega - \vec{k} \cdot \vec{p}), \quad (19)$$

$$c' = 2k p' = 2(E'\omega - \vec{k} \cdot \vec{p}'). \quad (20)$$

Taking $\vec{k}$ along the z axis, the integrations in (15) and (16) over the angle φ' may be performed easily. The subsequent integrations over the azimuthal angle θ' are rather complicated. However, the formulae simplify considerably by letting $m \rightarrow 0$ in every term, which after integration vanishes in this limit. The simplifications are largely due to the fact that we have restricted ourselves to the large angle bremsstrahlung. We find ¹⁸⁾

$$\begin{aligned}
 I_+ = & -\eta (2\eta + 5 - 2\eta y) / y^2 - 2 (1 + \eta^2)(2 - y) / y^2 \\
 & \times \ln \left[\frac{m(1-\eta)}{2p\eta} \right] - \frac{y}{y} \ln(1-\eta) - \frac{(2-\eta)\eta^2}{y^2 R^2} - \\
 & - \frac{(1-\eta)}{y R^3} (2\eta - \eta^2 + 3R^2) \ln \left[\frac{R+\eta}{R-\eta} \right]
 \end{aligned}
 \tag{21}$$

and

$$\begin{aligned}
 I_- = & -8 \xi p^2 W \left\{ \eta \frac{7-2y}{2y} + \frac{(2-y)}{y} (1+\eta) \ln \left[\frac{m(1-\eta)}{2p\eta} \right] \right. \\
 & - \frac{2}{y} (1+\eta-y) \ln(1-\eta) + \frac{\eta^2(2-\eta)}{2y R^2} \\
 & \left. + \frac{(1-\eta)}{2R^3} (2\eta - \eta^2 + R^2) \ln \left[\frac{R+\eta}{R-\eta} \right] \right\} ;
 \end{aligned}
 \tag{22}$$

where

$$R^2 = \eta^2 + 2(1-\eta)y, \quad y = 1 - \cos\theta, \quad \eta = p'_p = 1 - W.
 \tag{23}$$

We have checked (by numerical integration) that our approximation is good to within a few percent. We defer the discussion of the results (21) and (22) to the next Section where the effects of the lepton mass and nuclear form factor are taken into account.

4. THE EFFECTS DUE TO THE LEPTON MASS AND
THE NUCLEAR FORM FACTOR

The expressions (15) and (16) are exact within the context of the static approximation. In order to investigate the effects due to the nuclear form factor, we must multiply the integrands with the appropriate nuclear form factor. First we consider the quantity I_+ which becomes

$$I_+ = \int \frac{d\Omega'}{2\pi} \frac{E_+}{(q^2)^2} F(q^2) \quad (24)$$

where $F(q^2)$ is the nuclear charge form factor. Next we rewrite I_+ in the form

$$I_+ = \int dq^2 \frac{F(q^2)}{(q^2)^2} \int \frac{d\Omega'}{2\pi} E_+ \cdot \delta(q^2 - (k + p' - p)^2). \quad (25)$$

Performing the angular integrations leaves us with the integration over q^2 , or equivalently the variable u introduced in (9). The result reads

$$I_+ = \frac{W^2}{R} \int_{u_-}^{u_+} \frac{du}{u^2} F(u) \sum_{n=1}^4 A_n \cdot J_n \quad (26)$$

where the terms in the sum originate from the different powers of the quantity c' occurring in E_+ ; $u_{\pm}$ are given in (12); we have replaced $F(q^2)$ by $F(u)$ and

$$R = [W^2 - 2W \cos \theta + 1]^{\frac{1}{2}}. \quad (27)$$

The A 's are given by

$$A_1 = -2 \tilde{E}'/D ,$$

$$A_2 = \frac{-\delta}{W^2 D^2} (4 \tilde{E}'^2 - u) - \frac{2u}{WD} ,$$

$$A_3 = - \left\{ u^2 - 2u(1 + \tilde{E}'^2) - 8 \delta \tilde{E} \tilde{E}' \right\} \frac{1}{W^2 \tilde{E}' D} \\ + 2(u - WD) \frac{1}{W \tilde{E}'}$$

$$A_4 = - \delta \cdot \frac{(4 \tilde{E}'^2 - u)}{\tilde{E}'^2 W^2} . \quad (28)$$

The quantities J are defined by

$$J_1 = 1 - \frac{(\cos \theta - W)}{2 \tilde{E}' R^2} [2 - 2W(\tilde{E}' + \cos \theta) - u] ,$$

$$J_2 = 1 , \quad J_3 = 2 \tilde{E}' R \left\{ [2(1 - \tilde{E} \cos \theta) - u]^2 + \right. \\ \left. + 4 \delta (1 - \cos^2 \theta) \right\}^{-1/2}$$

$$J_4 = J_1 (J_3)^3 . \quad (29)$$

Furthermore,

$$\tilde{E}' = E'/p , \quad \delta = \frac{m^2}{p^2} , \quad D = \tilde{E} - \cos \theta \quad (30)$$

where p is again the incoming momentum and our notations are as in relations (8)-(10).

The parity violating contribution, I_- , may be calculated exactly in the same fashion, provided we assume that the neutron distribution function inside the nucleus is approximately the same as that of the proton. Then

$$I_- = 4 \xi P^2 \frac{W^2}{R} \int_{u_-}^{u_+} \frac{du}{u} F(u) \sum_{n=1}^4 B_n J_n, \quad (31)$$

where

$$B_1 = \tilde{E}'(-1 + \frac{\delta}{WD})/D,$$

$$B_2 = -\frac{1}{WD} (\delta + u + 2\delta \tilde{E}'/D),$$

$$B_3 = \frac{1}{\tilde{E}'W} \left[-\delta + 2\delta \frac{(\tilde{E} + \tilde{E}')}{D} - u(1 - \frac{\tilde{E} + \tilde{E}'}{D}) + WD \right],$$

$$B_4 = \frac{\delta}{W\tilde{E}'^2} (D - 2\tilde{E}). \quad (32)$$

All the other quantities occurring in (31) have been defined before [see Eqs. (6)-(12), (27), (29), and (30)].

5. RESULTS AND CONCLUSIONS

The expressions (13) and (14) with $I_{\pm}$ given by (26) and (31) constitute our final result. The circular polarization of a photon with energy ω emerging at an angle θ with respect to the beam is given by

$$P_{\gamma}^C = (d\sigma^R - d\sigma^L)/(d\sigma^R + d\sigma^L) = I_-/I_+. \quad (33)$$

Note that the expressions (26) and (31) for I_+ and I_- , respectively, include the effects of the nuclear form factor and lepton mass, i.e., they are just as well applicable to the muons as to the electrons. However, we have neglected the screening effect due to the atomic electrons, since it is expected to be small ¹⁹⁾.

For large angle bremsstrahlung from electrons, I_+ and I_- are given by the analytic expressions (21) and (22), provided that the incoming energy is above a few MeV (so that the electron mass does not play an important role) and provided also that the nuclear form factor may be approximated by unity. We now investigate some of the features of our results.

5.1 Dependence on the momentum transfer

In Fig. 3 we plot the functions A and B defined by [see Eqs. (26) and (31)]

$$A = \frac{W^2}{2Ru^2} F(u) \sum A_n J_n, \quad I_+ = 2 \int du A \quad (34)$$

$$B = \frac{W^2}{2Ru} F(u) \sum B_n J_n, \quad I_- = 8 \xi p^2 \int du B \quad (35)$$

for $F = 1$ and taking $p = 5$ MeV, $\theta = \pi/2$ and $W = 0.1$ (solid lines) and $W = 0.5$ (broken lines). The same quantities are plotted for $\theta = \pi$ in Fig. 4. Some onset of structure near $u = 2$ is seen for the $\theta = \pi/2$ case. This structure, which is more pronounced for higher energies (see Fig. 5 where $p = 20$ MeV), is due to the fact that J_3 [Eq. (29)] becomes large as $u = 2$. Physically this means that the outgoing electron tends to emerge along the direction of the emitted photon.

Another important feature of the results displayed in Figs. 3 to 5 is that the typical u (or the momentum transfer) is large and therefore the nuclear form factor may play an important role. To estimate the effect, we may take a Gaussian form factor $F(q^2) = \exp [-(1/6)q^2 \langle r^2 \rangle]$, where $\langle r^2 \rangle^{1/2}$ is the r.m.s. nuclear radius. We find that for a nucleus with r.m.s. radius about 4 fm the effect of the form factor is negligible for $p \lesssim 20$ MeV. For $p = 40$ MeV the effects become noticeable (at the level of about 20%). Note that in the circular polarization, Eq. (33), the corrections due to the form factor tend to drop out.

5.2 The magnitude of p_γ^c

We now integrate the quantities A and B [see Eqs. (34) and (35)] by numerical methods. The result is largely independent of the incoming energy for $p \gtrsim 5$ MeV. In Fig. 6 the integrals are shown for $p = 5$ MeV and $\theta = \pi$. For example, the corresponding distributions for $p = 30$ MeV

follow the displayed curves up to $W \sim 0.4$ and from there on they tend to be slightly higher. We also find that the analytic expressions (21) and (22) (in which the electron mass was neglected) are, to within a couple of percent, identical to the exact results except at the limit of the spectrum (i.e., $W \gtrsim 0.1$ and $W \gtrsim 0.9$) and particularly at low energies, $p \lesssim 5$ MeV.

The effect of the form factor on the circular polarization is found to be small (typically less than 10%) for energies up to 30 MeV and $\langle r^2 \rangle^{\frac{1}{2}} \lesssim 4$ fm. The magnitude of the circular polarization is obtained from relations (33)-(35) and (6). In Fig. 7 we have plotted the ratio $r \equiv \int B \, du / \int A \, du$ for six values of θ and $p = 10, 20$, and 30 MeV. The circular polarization is $p_Y^c = 4\xi p^2 r$, where ξ is defined as in relation (7). As is seen from Fig. 7, the circular polarization is largest in magnitude in the backward hemisphere (where it also changes sign!). In the Weinberg model ⁴⁾ we find

$$p_Y^c = 7.2 (10^{-5} p/\text{MeV})^2 \cdot r \cdot \left[\sin^2 \theta_W + \frac{N-Z}{4Z} \right].$$

Thus for an isoscalar nucleus ($N=Z$) and taking $p = 30$ MeV, $W = 0.2$ and $\theta = 90^\circ$, we find $p_Y^c \approx 7 \sin^2 \theta_W \times 10^{-8}$, where the current value of $\sin^2 \theta_W$ is about 0.4 ²⁰⁾. This number is about an order of magnitude below the limit reached by experiments up to now.

The circular polarization of the bremsstrahlung grows rapidly with increasing incoming momentum and photon energy. Measurement of the circular polarization of energetic photons is, in principle, possible ²¹⁾; at present, such a measurement ²²⁾ has been reported for photons up to 9 MeV. Furthermore, the beam luminosity does not seem to be a problem ¹¹⁾. It remains to be seen whether such a measurement is feasible for the tiny effects predicted here.

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FIGURE CAPTIONS

- Fig. 1 : The diagrams for bremsstrahlung [Eq. (3)] in the static approximation.
- Fig. 2 : The function u_- , defined in (12), versus W for $p = 10$ MeV and $\theta = 30, 90$, and 180 degrees.
- Fig. 3 : The functions A and B , defined in (34) and (35), versus u , for $p = 5$ MeV, $\theta = \pi/2$ and $W = 0.1$ and 0.5 . The curves are for a pointlike nucleus.
- Fig. 4 : Same as in Fig. 3, but for $\theta = \pi$.
- Fig. 5 : Same as in Fig. 3; $\theta = \pi/2$ and π ; $W = 0.1$.
- Fig. 6 : Integrals defined in (34) and (35) versus W ; $\theta = \pi$.
- Fig. 7 : The ratio $\int B du / \int A du$ for six different angles and p and W as indicated.

FIG.1

FIG.2

FIG.3

FIG. 4

FIG. 5

FIG. 6

FIG.7