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ELECTROWEAK SIGNALS IN CIRCUITS

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To illustrate our general thesis that electronic circuits can probe electroweak interactions, it is shown that the decay rate of chiral anomaly induced spin waves into neutrinos depends crucially upon the number of generations, neutrino mass and macroscopic parameters (geometry, flux, voltage) of the circuit. Whether the electroweak vacuum is magnetoelectric can also be settled through circuits.

It has recently been observed [1] that the present microchip technology can be exploited with little effort to provide a beautiful probe into some non-perturbative, collective aspects of QED, which are unreachable by standard high-energy experiments or by low-energy atomic physics set-ups. This observation rests on the realization that there are certain electronic transport properties for which non-linear QED effects are large even though the (circuit) transition energies are miniscule (typically millielectronvolt to electronvolts) compared to the "threshold" energy $2m_ec^2$ ($\sim 10^6$ eV), traditionally considered necessary for appreciable QED effects. In the following, we discuss two interesting avenues to bypass the above "threshold barrier".

The first obvious path was to search out QED processes appropriate for a circuit, where quantum fluctuations do not involve the electron mass in an essential way. Such processes do exist. The Casimir effect, which can be substantial for microchips, has already been discussed in ref. [1]. Also, through the physical four-component massive Dirac equation, it has been shown [2] that the time rate of change of the electronic spin density is in fact independent of the electron mass. This leads to a polarization current (through the magnetoelectric effect) which also depends only upon the external EM fields and remains independent of the electron mass [2,3]. But more on this later on.

The second path, which will not be pursued in this paper, devolves upon isolating processes whose quantum fluctuations themselves dissolve the tunneling barrier. Such examples in field theory also exist. A purely scalar theory with $\lambda\phi^4$ interaction, for instance, after renormalization results in a free field theory. A more "practical example is provided by the RSJ (Resistively Shunted Josephson junction) model, where the critical current – which is a measure of the barrier height – is driven to zero through quantum fluctuations [4].

Since QED is but one facet of the unified electroweak interaction, it is reasonable to enquire whether circuits can be used to probe the "weak" part of the theory as well. Several new obstacles to such an endeavor arise immediately. Contrary to the photon which is massless and in addition is readily available as an external field or as part of the circuit itself, the weak bosons (W and Z) are immensely massive ($\sim 10^{11}$ eV), decay rapidly ($\sim 10^{-25}$ s) and appear to play a vanishingly small role in the workings of a circuit. However, the situation is not quite so grim. Granted that the weak gauge bosons are massive, the weak fermion (neutrino) is not, contrary to the electron which is massive. [All our considerations are made in the standard $SU(2) \times U(1)$ model.] It is obvious, therefore, what we must try first: investigate the production of massless neutrinos through the only massless EW gauge boson (i.e., the photon) which does couple to the circuit directly. Of course, the caveat we must bear in mind is that apart from the overall Fermi coupling constant G_F, such neutrino production must not involve "large masses" (even the electron mass is huge compared to the circuit frequencies). Luckily, such a mechanism exists by virtue of the axial anomaly [5,6]. Appropriate external EM fields applied to a circuit can induce vacuum spin waves [2] which then "decay" into a neutrino pair.

As discussed in ref. [2], the spin density

$$S^\mu = (\hbar/2c) J_5^\mu. \tag{1}$$

The neutrino source density K^μ, as given by the charged current alone (neutral currents are added suitably in the final result) reads

$$K^\mu = -\sqrt{2}\,(\hbar G_F/c^4)(J^\mu - J_5^\mu). \tag{2}$$

The anomaly equation $\partial_\mu J_5^\mu = -(e^2/2\pi^2\hbar^2 c) \times (\boldsymbol{E}\cdot\boldsymbol{B})$ and current conservation $\partial_\mu J^\mu = 0$, lead to

$$\partial_\mu K^\mu = -(e^2 G_F/\sqrt{2}\,\pi^2\hbar c^5)(\boldsymbol{E}\cdot\boldsymbol{B}). \tag{3}$$

From eq. (3), it is straightforward to compute the neutrino production rate. Let us perform this computation for the general case of n generations belonging to $SU(2) \times U(1)$ so that there are n types of massless neutrinos (ν_e, ν_μ, ν_τ, ...). The transition probability (Γ) per unit volume per unit time for the production of all types of neutrino pairs is given by

$$\Gamma(\text{electronic spin waves into all } \nu\bar{\nu}) = (\alpha^2 c/96\pi^5)\Lambda_F^4(\boldsymbol{E}\cdot\boldsymbol{B}/\hbar c)^2 \times (n/4)(8n/3-2)^2, \tag{4}$$

where $\Lambda_F^2 = (\hbar G_F/c^3)$, relates the Fermi length Λ_F ($> 10^{-16}$ cm) to the Fermi coupling constant G_F in the same way the Planck length Λ_P ($\sim 10^{-32}$ cm) is related to the Newton constant G_N. (It is possible to do a similar calculation for the production of graviton pairs through the decay of vacuum spin waves.) For a stacked sandwich of r capacitors each of volume Ω containing magnetic flux Φ and with an impressed voltage V, the number of $(\nu\nu)$ events/time is given by eq. (4) to be

$$\dot{N}_{\nu\bar{\nu}} = (r/24\pi^3)\left[n/4(8n/3-2)^2\right] \times (\Lambda_F/c)(\Lambda_F^3/\Omega)(\Phi/\Phi_0)^2\,[\text{eV}/\hbar]^2, \tag{5}$$

where $\Phi_0 = (2\pi\hbar c/e)$ is one flux quantum. An alternative form of eq. (5), which leads to a simple physical picture is

$$\dot{N}_{\nu\bar{\nu}} = r(\alpha/6\pi^2)\left[n/4(8n/3-2)^2\right] \times (\Phi_F/\Phi_0)^2[E_{\text{coulomb}}/\hbar], \tag{6}$$

where E_{coulomb} is the (classical) capacitor energy and $\Phi_F = (B\Lambda_F^2)$. Thus, the neutrino production rate from each capacitor is given by (i) the square of the number of flux quanta in the Fermi interaction region, (ii) the Coulomb energy stored in the capacitor, and (iii) the multiplicity factor which depends rather sensitively on the number of generations n.

In eq. (6), the electrostatic Coulomb energy enters extensively whereas the magnetic flux quanta contained in the weak interaction length Λ_F enters in an intensive way. The total rate can be enhanced by stacking a large number of capacitors as well as by increasing the electromatic field strengths.

The expression in eq. (6) is changed drastically if a given neutrino has a non-vanishing mass m_ν. For such a neutrino, the result is multiplied by a suppression factor $s_\nu = \exp(-Y_\nu)$, where

$$Y_\nu = \left[\sqrt{2}\,\pi^2/(8n/3-2)\right](\Phi_0/\Phi_F) \times \left[(m_\nu c^2)^2/(eE)(\hbar c)\right], \tag{7}$$

and E denotes the electric field. The corresponding suppression factor for the production of an (e^+e^-) pair in a similar set-up ($B/E \gg 1$) in QED is given by [3]

$$Y_e = \pi\left[(m_e c^2)^2/(eE)(\hbar c)\right]. \tag{8}$$

Apart from a multiplicity factor (depending on n), eq. (7) contains an extra large factor (Φ_0/Φ_F) which does not occur in eq. (8). This signifies that the production of massive particles (at low energies) is severely inhibited due to the short range of weak interactions. Such a sensitive dependence on the neutrino mass may be used to probe for very small neutrino masses such as $m(\nu_e) = 2 \times 10^{-7}$eV estimated by Bethe [7] from an analysis of the MS mechanism [8] for the solar neutrino puzzle.

The average energy of produced neutrinos is too small (typically $\langle E_\nu \rangle \sim 10^{-9}$ eV) to be measurable directly by standard neutrino detection techniques. Thus, we must turn to other, indirect ways to infer about this process. (Just as Pound and Rebka [9] had to, when dealing with a change in energy $(\Delta E/E) \sim 10^{-15}$ of a falling photon under the gravitational potential.) One possible method consists in a careful analysis of the decay spectrum of vortices which are formed under an intense magnetic field on the surface of a capacitor. An average neutrino energy of 10^{-9} eV can be converted into a temperature $T_\nu \cong 10^{-5}$ K. Observation of such a characteristically low temperature scale in surface transport phenomena on a FET for example would be significant as a signal for neutrino production, since such low temperatures would be difficult to understand otherwise. A more direct method consists in monitoring the correlation between flux and voltage noise $\langle \Delta\Phi\Delta V \rangle$ as a function of the frequency ω. The neutrino production signal should appear at about (10–100) megacycles which corresponds to about 10^{-9} eV. The normalized distribution of the pulse shape can be written as

$$\mathrm{d}P(\omega)/\mathrm{d}\omega = (-12/\pi c^2\gamma)\,\omega \times \ln[1 - \exp(-\pi\omega^2/c^2\gamma)], \qquad (9)$$

where

$$\gamma = (G_F/\sqrt{2})(\alpha/\pi^2 c^4)(\boldsymbol{E}\cdot\boldsymbol{B})(n/4)^{1/2} \times (8n/3 - 2). \qquad (10)$$

A detailed qualitative analysis shall be presented elsewhere.

We now turn to another fundamental aspect of the EW theory – alluded to earlier – which can be resolved through circuits. The question we pose is whether the EW vacuum is magnetoelectric. That is, is there a non-zero coefficient G in the effective Lagrange density

$$L_{\mathrm{eff}} = G(\boldsymbol{E}\cdot\boldsymbol{B}), \qquad (11)$$

for the electroweak vacuum under an external EM field? Since eq. (11) is a surface term, high-energy experiments (done in the large volume limit) tell us nothing about this term directly. The relevance of a finite size circuit to reveal eq. (11) becomes evident.

To appreciate better the implications of eq. (11), let us recall what is known about *materials* containing such a term. Magnetic materials do exist for which an external electric field causes magnetization and an external magnetic field produces electrical polarization. It is a sobering thought that while Curie [10] made the original suggestion in 1894 that such substances might exist, for half a century, illustrious theorists convinced the rest why *no* such materials could possibly exist in nature (for reasons of parity, time-reversal invariance, microscopic reversibility etc. etc.). It was in 1960 that Astrov was able to show experimentally that the magnetic crystal Cr_2O_3 was indeed magnetoelectric [11]. (For an excellent review, see ref. [10].) It has only very recently been realized that on the surface of such substances, the photon acquires a mass and that we have superconducting surface currents [12]. It is the last discovery which makes it so tantalizing to enquire experimentally whether the EW vacuum posesses similar properties. A two-port network with a ferromagnet providing the flux through a capacitor to measure G experimentally has been discussed in refs. [13,14].

A first principle computation of G in the Fermi theory encounters a divergence almost identical to that found for the Schwinger term in the free fermion case [15]. On the other hand, for the charged scalar case, the Schwinger term is proportional to the condensate, $e^2\langle \phi^+\phi \rangle$. In high-energy physics, the Schwinger term has been considered irrelevant [16], renormalized to zero [17], or else made finite [18], because it is not measured directly. On the contrary, in condensed-matter physics, the Schwinger term in the commutator

$$[J_i(\boldsymbol{r}), \rho(\boldsymbol{r}')] = -(\mathrm{i}\hbar/4\pi)\omega_\mathrm{p}^2\,\partial_i\delta^3(\boldsymbol{r}-\boldsymbol{r}') \quad (12)$$

appears as the plasma frequency

$$\omega_\mathrm{p} = \left(4\pi n_\mathrm{s} q^2/m\right)^{1/2}, \quad (13)$$

where $n_\mathrm{s} = \langle \Psi^+ \Psi \rangle$ is the density and q the charge. ω_p is a measured quantity.

Since the EW theory does contain the Higgs condensate, it is not unreasonable to conjecture that the latter provides a cutoff. Also, since G is dimensionless, if non-vanishing, it should be of the order of the fine structure constant. We shall return to this interesting theoretical problem in another work. Here we only wish to underline the necessity and the possibility of its experimental measurement through circuits.

To conclude, we have advocated investigating properties of the EW theory through circuits, which should complement the usual methods of blasting the vacuum degrees of freedom above energy gaps (due to masses) with high-energy particle beams. We hope that the two examples which have been worked out here will spur further activity in a rich and fertile field yet to be explored.

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