Violation of *CP* Invariance in the Dyon Model*

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The *CP*-violation mechanism proposed by Schwinger in the dyon model is discussed. It is pointed out that, once dual-charged particles are introduced, we have *two* kinds of smallest units of electric charge for magnetically neutral particles: one for purely electrically charged particles, the other for the magnetically neutral composites of the dyons. These two units, which, *a priori*, could be different, are assumed to be the charges carried by the lectron and the proton, respectively. Schwinger's mechanism can then be understood as a self-consistent condition that ensures the equality of these two units of electric charge. The analogy between this mechanism and that proposed by Bernstein, Feinberg, and Lee is discussed. The case of neutral-*K* decay is briefly analyzed. The magnitude of the *CP*-violation parameter in different processes is estimated.

Several years ago Schwinger proposed[1] a mechanism for *CP* violation[2] in his dyon model. It is based on the observation that "if the dual-charged particles (dyons), and their antiparticles, realize a certain ratio between electric and magnetic charge (e/g ratio), but *not its negative value*, the rule of *CP* invariance is broken." But is there any other argument (besides *CP* violation) to support this idea that particles (which will be called anomalous dyons in the following) whose e/g ratios are of opposite sign to those of the dyons do not exist? The qualitative symmetry between electric and magnetic charge does not demand their nonexistence. And clearly we do not have any experimental argument against their existence, since the dyons themselves have not been observed experimentally either. To use a crude analogy, one would not have insisted on *CPT* invariance being violated before positrons or antiprotons were discovered. Therefore we would like to have an independent argument to support the idea that the electromagnetic interaction violates *CP* invariance. Otherwise we shall always have the doubt that perhaps the electromagnetic interaction conserves *CP*, while it is the superweak interaction[3] that violates *CP*.

In this note we would like to present such an argument. The idea is the following. In the original discussion of charge quantization by Dirac, without the dual-charged particles, there is only *one* smallest unit of electric charge, which is assumed to be that carried by the "elementary" particles, in particular, the electrons *and* the protons. Once dual-charged particles are introduced we have in principle *two* kinds of smallest units of electric charge for magnetically neutral particles: one for purely electrically charged (elementary) particles and the other for the magnetically neutral composites of the dyons. Since electrons are (presumably) elementary and protons are magnetically neutral composites of the dyons in the dyon model, it seems natural to assume their charges are equal to these two units respectively. The experimental fact that no fractionally charged (and magnetically neutral) particles have been found is consistent with this assumption. On the other hand, once we make this assumption, we are faced with the question why these two units of electric charge turn out to be the *same*; *a priori* they could just as well be different from each other. We shall show in the following that these two units will be the same in the dyon model only if we assume that the anomalous dyons do not exist. Therefore, Schwinger's mechanism for *CP* violation can be understood as a kind of self-consistent relation in the dyon model.

We now turn to the details of this argument. Let us begin by listing in Table I the electric and magnetic charge assignment of the nine dyons. As we see, there are only the following e/g ratios: e_0/g_0, $-2e_0/g_0$, and $-e_0/2g_0$. The antidyons realize the same ratios. Schwinger's proposal is that there are no anomalous dyons with e/g ratios equal to $-e_0/g_0$, $2e_0/g_0$, and $e_0/2g_0$. As pointed out by him, one of the consequences of this proposal is the weakening of the charge quantization condition[4] between two dual-charged particles (e_1, g_1) and (e_2, g_2),

$$e_1 g_2 - e_2 g_1 = \nu ,$$

where ν is an even integer.[1] One can easily check that the charge quantization condition is satisfied by the above assignments if

$$e_0 g_0 = \tfrac{1}{3}\nu .$$

From this it follows that the *smallest* charge units (namely for the case $\nu = 2$) for *both* the magnetic

TABLE I. Electric and magnetic charge assignment of the nine dyons.

Strangeness S \ $S_M=$	Magnetic counterpart of strangeness 0	0	-1
0	$d_{11}(2e_0, 2g_0)$	$d_{12}(2e_0, -g_0)$	$d_{13}(2e_0, -g_0)$
0	$d_{21}(-e_0, 2g_0)$	$d_{22}(-e_0, -g_0)$	$d_{23}(-e_0, -g_0)$
-1	$d_{31}(-e_0, 2g_0)$	$d_{32}(-e_0, -g_0)$	$d_{33}(-e_0, -g_0)$

neutral composite (hadrons), e_H, *and* for the pure electric charge particles (leptons), e_L, have to satisfy the condition

$$e_H = e_L \ (=3e_0).$$

Thus, dyons are fractionally charged.[5] However, if there were anomalous dyons, the charged quantization condition between, for example, the anomalous dyon $(-2e_0, -g_0)$ and the dyon $(-e_0, -g_0)$ would demand

$$2e_0 g_0 - e_0 g_0 = e_0 g_0 = \nu$$

instead of $e_0 g_0 = \frac{1}{3}\nu$. It then follows that $e_H = 3e_L$ $(=3e_0)$. If we assume that the electric charges carried by the electron and the proton are equal to $-e_L$ and e_H, respectively, then experimentally $e_H = e_L$. Therefore we have to assume that the anomalous dyons do not exist and we have the CP-violation mechanism proposed by Schwinger.[6]

What about the magnitude of this violation of CP invariance? As an illustration, consider the electromagnetic interaction between the dyons in the conventional field theory:

$$\mathcal{L}_{\rm int}^{eg} = iA_\mu^e j_\mu^e + iA_\mu^g j_\mu^g ,$$

where the electric and magnetic currents are given by

$$j_\mu^e = 2e_0 \bar{d}_{1i}\gamma_\mu d_{1i} - e_0 \bar{d}_{2i}\gamma_\mu d_{2i} - e_0 \bar{d}_{3i}\gamma_\mu d_{3i}$$

and

$$j_\mu^g = 2g_0 \bar{d}_{i1}\gamma_5\gamma_\mu d_{i1} - g_0 \bar{d}_{i2}\gamma_5\gamma_\mu d_{i2} - g_0 \bar{d}_{i3}\gamma_5\gamma_\mu d_{i3} ,$$

respectively. The d's are the corresponding Dirac fields for dyons, the repeated indices are summed from 1 to 3, and the γ_5 is inserted because j_μ^e and j_μ^g behave oppositely under parity. The symmetry between the electric and magnetic charge is expressed by the possibility of performing the rotation,[1]

$$j_\mu^{e\prime} = j_\mu^e \cos\theta + j_\mu^g \sin\theta ,$$

$$j_\mu^{g\prime} = -j_\mu^e \sin\theta + j_\mu^g \cos\theta ,$$

with a corresponding rotation for A_μ^e and A_μ^g. Since $e_0/g_0 \sim e_0^2$ is of the order of the fine-structure constant[1] α, we denote

$$\mathcal{L}_{\rm int}^{eg} = \mathcal{L}^{\rm st} + \mathcal{L}^{\gamma} ,$$

where we have the "strong"-interaction part

$$\mathcal{L}^{\rm st} = iA_\mu^g j_\mu^g ,$$

and the (usual) "electromagnetic"-interaction part

$$\mathcal{L}^{\gamma} = iA_\mu^e j_\mu^e ,$$

and $\mathcal{L}^{\rm st}$ *is SU(3)-invariant*. The CP-violation results from the mismatch between $C_{\rm st}P_{\rm st}$ and $C_\gamma P_\gamma$. To show this explicitly, let us separate the electric charge conjugation C_e and magnetic charge conjugation C_g. We then have

$$P_{\rm st} = P_\gamma = P ,$$

$$C_e C_g = C ,$$

$$C_{\rm st} = C_g \neq C_\gamma = C_e .$$

The analogy between this CP-violation mechanism and the scheme proposed by Bernstein, Feinberg, and Lee[7] becomes more apparent if we *assume* that the weak-interaction Lagrangian conserves $C_{\rm st}P_{\rm st}$, namely,

$$C_{\rm wk}P_{\rm wk} = C_{\rm st}P_{\rm st} \neq C_\gamma P_\gamma ,$$

but violates $C_{\rm st}$ and $P_{\rm st}$ separately: $C_{\rm wk} \neq C_{\rm st} \neq C_\gamma$, $P_{\rm wk} \neq P$. From CPT invariance,[8] i.e., $C_{\rm st}P_{\rm st}T_{\rm st} = C_\gamma P_\gamma T_\gamma = C_{\rm wk}P_{\rm wk}T_{\rm wk} = C_e C_g PT$, we have $TC_e = T_{\rm wk} = T_{\rm st} \neq T_\gamma = TC_g$. The order of magnitude of the CP-violation parameter is then given by

$$\epsilon \sim \frac{e_0}{g_0} \sim e_0^2 \sim \alpha .$$

In the case of neutral-K decay[9] the 2π state $|\pi^+\pi^-\rangle$ is an eigenstate of $C_e C_g P$ with eigenvalue $+1$. The state $|K^0\rangle$ is an eigenstate of $H^{\rm st} + H^\gamma$. The states

$$|\bar{K}^0\rangle = CPT\,|K^0\rangle$$

and

$$|K_2^0\rangle = \frac{1}{\sqrt{2}}(|\bar{K}^0\rangle - |K^0\rangle)$$

are also eigenstates of $H^{\rm st} + H^\gamma$. Since $H^{\rm st} + H^\gamma$ does not commute with $C_e C_g P$, $|K_2^0\rangle$ is not an eigenstate of $C_e C_g P$. On the other hand $H^{\rm st} + H^\gamma$ differs from a $C_e C_g P$-conserving Hamiltonian only by a term of the order of e_0/g_0. If the perturbation approach is applicable, then $|K_2^0\rangle$ will differ from a $C_eC_gP=-1$ eigenstate also only by a term of the order of e_0/g_0. Therefore $\epsilon \sim e_0/g_0$.

It probably should be emphasized that the above discussions of the magnitude of the CP-violation parameter imply that additional evidence for the CP violation will be quite difficult to obtain. The argument presented only depends on the validity of the estimates based on the perturbation approach. We therefore expect the CP-violation parameter in general for *all* other processes to be of the same order of magnitude as that of the K-decay processes. The accuracy[10] in the η-decay asymmetry experiments (0.5% to 1.3%), for this reason, is not enough to decide the issue. Similarly, assuming CPT invariance, the existing tests of T invariance by measuring the phase of g_A^β/g_V^β ($181°\pm1.3°$), the relative phase between the S-wave and P-wave amplitudes of the $p+\pi^-$ system in Λ decay, and the reciprocal relation of $\gamma+d \rightarrow p+n$ reactions are not decisive. As an alternative to decay processes, the CP-forbidden process S-wave $\bar{p}p$ annihilation at rest into $K_1^0K_1^0$ might be considered, if the background of P-wave capture (~1%) (Ref. 11) can be controlled.

A few brief comments about the weak interaction are in order. Let us take the point of view as expressed by Schwinger,[1] that the weak interaction can be viewed as a mechanism of electric charge exchange between particles of the *same* magnetic charge, and we have a corresponding magnetic-charge-exchange interaction between particles of the *same* electric charge. The $V-A$ form of weak interaction means the angle (in the e-g plane) between $j_\mu^{\text{wk}}, j_\mu^e$ and $j_\mu^{\text{wk}}, j_\mu^g$ is equal to $\frac{1}{4}\pi$. The e-g symmetry would suggest the magnetic-charge-exchange current to be of the form $V+A$. For the two interactions to single out two specific (mutually perpendicular) directions in the e-g plane, thereby establishing the distinction between the electric and magnetic charge, it seems natural to take the strength of the two interactions as proportional to the electric (magnetic) charge difference between the two particles involved. The proportionality constants can be fixed by Lee's K-triplet current hypothesis.[12] We then have, for these two interactions between the dyons,

$$\mathcal{L}_{\text{int}}^{w} = \frac{W^-}{2\sqrt{2}} 3e_0[\cos\theta \bar{d}_{1i}\gamma_\mu(1+\gamma_5)d_{2i} + \sin\theta \bar{d}_{1i}\gamma_\mu(1+\gamma_5)d_{3i}] + \text{H.c.},$$

$$\mathcal{L}_{\text{int}}^{m} = \frac{{}^-S}{2\sqrt{2}} 3g_0[\cos\theta' \bar{d}_{i1}\gamma_\mu(1-\gamma_5)d_{i2} + \sin\theta' \bar{d}_{i1}\gamma_\mu(1-\gamma_5)d_{i3}] + \text{H.c.},$$

where W^- and ${}^-S$ are the corresponding vector boson fields, and θ is the Cabibbo angle.[13] Is this an acceptable form? We note that conservation of vector current (CVC) is built in. But partial conservation of axial-vector current (PCAC) would require careful justification in view of the fact that g_0 is so large. If the magnetic-charge-exchange interaction is responsible for the breaking of SU(3) into SU(2)×U(1) as proposed by Schwinger,[1] would not this suggest that the leptons might also have this interaction? Otherwise, why is the μ-e mass difference of the same order of magnitude as the mass difference within a SU(3) multiplet? Would this lead to the possibility that leptons belong to some kind of "lepton" family, with $e_L=3e_0$ and $g_L=3g_0$ as the electric and magnetic charge units?[14] One would then consider θ and θ' to be such mixing angles as were suggested by Cabibbo,[15] and speculate that $\theta=\theta'$. Perhaps the most important question is whether there is any connection with the weak-interaction model proposed by Weinberg.[16] In particular, is there any connection between the coupling constants g and g' in his scheme and the coupling constants e_0 and g_0 in the dyon model? We shall discuss the details of these questions in future papers.

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[1]J. Schwinger, Science 165, 757 (1969). It should be pointed out that one can construct C- and P-conserving theory involving magnetic charges. [A. O. Barut, Phys. Letters 38B, 97 (1972); Rutherford Centenary Symposium Lecture given at the University of Canterbury, Christchurch, N. Z., 1971 (unpublished), and earlier references cited therein.] The mechanism proposed by Schwinger as quoted in the text is the crucial assumption that leads to CP violation.

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[3]L. Wolfenstein, Phys. Rev. Letters 13, 562 (1964); T. D. Lee and L. Wolfenstein, Phys. Rev. 138, B1490 (1965).

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[6]The other alternative will be making the leptons composites.

[7]J. Bernstein, G. Feinberg, and T. D. Lee, Phys. Rev.

139, B1650 (1965); T. D. Lee, *ibid.* 140, B959 (1965).

[8]When magnetic charges are present the *CPT* theorem corresponds to a $C_e C_g PT$ theorem, see N. F. Ramsey, Phys. Rev. 109, 225 (1958).

[9]We would like to thank Professor L. Schulman for clarifying comments on this point.

[10]Numerical values are taken from Particle Data Group, Rev. Mod. Phys. 43, S1 (1971).

[11]C. Baltay *et al.* (Columbia-Rutgers Collaboration), Phys. Rev. Letters 15, 532 (1965).

[12]T. D. Lee, Phys. Rev. Letters 26, 801 (1971).

[13]N. Cabibbo, Phys. Letters 10, 513 (1963).

[14]For example, one might consider the following "lepton" family:

$$\nu = l_{11}(0,0),\ l_{12}=(0,-g_L),\ l_{13}=(0,g_L),$$
$$e^- = l_{21}(-e_L,0),\ l_{22}=(-e_L,-g_L),\ l_{23}=(-e_L,g_L),$$
$$\mu^+ = l_{31}(+e_L,0),\ l_{32}=(e_L,-g_L),\ l_{33}=(e_L,g_L).$$

Here to preserve the analogy with the dyons, we adopt the lepton number assignments first proposed by E. J. Konopinski [Phys. Rev. 92, 1045 (1953)].

[15]N. Cabibbo, in *Hadrons and Their Interactions*, 1967 International School of Physics "Ettore Majorana," Erice, Italy, 1968, edited by A. Zichichi (Academic, New York, 1968), p. 381.

[16]S. Weinberg, Phys. Rev. Letters 19, 1264 (1967); 27, 1688 (1971).

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Bounds on Pomeranchukon Amplitudes and the Positions of Their Zeros*

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Rigorous lower bounds on the imaginary part of helicity-nonflip elastic amplitudes are derived under the assumption that their impact-parameter representations are monotonically decreasing functions of b (central profiles). One result of these bounds is that at intermediate to high energies, typical Pomeranchukon-dominated elastic helicity-nonflip amplitudes must not have zeros for $|t| \lesssim 0.6\ \text{BeV}^2$. A connection between the phenomenological absence of zeros in these Pomeranchukon amplitudes at small $|t|$ and the conjectured central behavior of the profile is thus established.

I. INTRODUCTION

Ever since the geometrical-absorptive picture was first applied to high-energy two-body scattering processes,[1] the impact-parameter profile of elastic helicity-nonflip amplitudes has been viewed as a monotonically decreasing function in impact-parameter (b) space. This profile is often referred to as a "central" profile. Such forms have been used extensively to calculate the effects of absorption on various "basic" exchanges, as well as to phenomenologically describe elastic amplitudes at high energies.

One of the more successful phenomenological models which uses geometrical language, and which has been applied with considerable success to two-body processes at intermediate and high energies, is the dual absorptive model.[2] This model utilizes two-component duality. The diffractive or Pomeranchukon-exchange part of any given amplitude is assumed to be central in b space *and* to have no zeros in t space for $|t| \leq 1\ \text{BeV}^2$. This last assumption is of a crucial importance in the phenomenological analyses to which the model has been applied, where it has become a common practice to parametrize Pomeranchukon-exchange amplitudes by simple exponentials e^{St}.

It has already been shown[3] that the two above assumptions – "centrality" in b and "no zeros" in t – are in some sense independent. Slight modifications of the profile can effortlessly generate or eliminate zeros in the amplitude. In fact, it is quite possible that the structure observed in $pp \to pp$ at[4] $|t| \simeq 1.2\ \text{BeV}^2$ is caused by a zero in a Pomeranchukon-exchange amplitude. It is, however, a remarkable phenomenological observation that Pomeranchukon-exchange amplitudes do not exhibit zeros or dips at values of $|t|$ smaller than ~$0.8\ \text{BeV}^2$. We face therefore the interesting problem: What exactly is the relation between the property of "centrality" in b, and the location of the zeros in t? A precise answer to this question will, of course, provide tests for monotonicity of the Pomeranchukon-exchange profile. Some interest was recently added to this problem by conjectures that Pomeranchukon profiles may possess a pe-