TRANSVERSE POLARIZATION AS A PROBE FOR
CP-VIOLATION FROM NEW PHYSICS

C.P. BURGESS and J.A. ROBINSON
Physics Department, McGill University, 3600 University Street
Montréal, Québec, H3A 2T8, Canada.

ABSTRACT

We use the effective-lagrangian formalism to examine the effects of CP-violation from outside the standard model at LEP and HERA. We then define a simple observable that may be defined when the initial electron beam is transversely polarized, and systematically determine which effective interactions can contribute to it. We find that for a wide class of theories, the observable only gets contributions from a single CP-violating electron-gauge boson coupling within the effective theory. We conclude that detectable CP-violation from this source may be observable at LEP or HERA.

I. INTRODUCTION

The spectacular success of the standard model suggests that the energy scale of the next level of new physics is likely to be high compared to those currently experimentally accessible. This invites the application of effective-lagrangian techniques to exploit this large ratio of scales. Since the standard model is itself the most general renormalizable theory consistent with its particle content and gauge symmetries, its success can be understood as simply being the consequence of the scale of this new physics being so large.

The biggest uncertainty faced when writing down a general effective lagrangian is the question of whether to include the Higgs particle. The least model-dependent attitude would be to not introduce an elementary Higgs particle, but to merely require that the effective theory include the Goldstone bosons associated with the spontaneous breaking of $SU_L(2) \times U_Y(1)$. In this case only the unbroken $SU_c(3) \times U_em(1)$ subgroup need be linearly realized. The alternative approach is to linearly realize the full standard-model gauge group, $SU_c(3) \times SU_L(2) \times U_Y(1)$, and include symmetry-breaking effects through the explicit dependence of the effective lagrangian on the Higgs field(s). This method has the advantage of incorporating the additional information that the order parameter of the electroweak symmetry breaking is one (or several) $SU_L(2)$-doublet(s).

The apparent reliance on the existence of a physical Higgs boson in the second of these techniques is illusory to the extent that propagating Higgs degrees of freedom are not important for the processes under consideration. In what follows the Higgs field only contributes through its vacuum-expectation-value (v.e.v.), and so just plays the role of order parameter for $SU_L(2) \times U_Y(1)$ breaking.

We ask here whether upcoming experiments at HERA or at LEP/SLC are likely to detect any of the CP-violating terms that can appear as dimension-five and -six effective interactions. The goal is to determine whether an visible signal (in as simple an observable as possible) can be consistent with other bounds, in particular those due to limits on electric dipole moments for elementary fermions. More details of the arguments and calculations described here may be found in Refs. [2] (HERA) and [3] (LEP/SLC). A summary of these results with a review of the effective-lagrangian formalism is given in Ref. [4]. Further applications to $W^\pm$ and $Z^0$ moments appear in Refs. [5].

In searching for signatures of CP violation, we take advantage of the fact that transversely polarized electron beams are expected to be available at both $ep$ and $e^+e^-$ machines in the near future. Consider, then, a two-body process such as pair production, $e^+e^- \rightarrow f\bar{f}$, at SLC or LEP, or deep-inelastic scattering, $e^+p \rightarrow tf$, at HERA. Given initially transversely polarized electrons or positrons a convenient observable consists of the asymmetry defined as the difference: $dA(p_l,s_l) = \ldots$
$d\sigma(p_1,s_1) - d\sigma(-p_1,-s_1)$, in the differential cross-section before and after reversing all momenta and spins. An integrated version of this observable is given in terms of the integrated luminosity, $L$, by: $A = L A$. It may be defined operationally as the difference between the number of final-state fermions, $f$, detected on either side of the plane defined by the initial transverse spin direction and the colliding-beam axis—or, equivalently the difference between the number of such fermions appearing out of one side of this plane as the initial electron polarization is reversed.

This observable is sensitive to time-reversal-odd interactions because time-reversal reverses all three-momenta, $p_i$, and spins, $s_i$. Strictly speaking, however, the observation of a nonzero $dA$ need not signal the presence of $T$-violation because the action of time reversal would run the reaction backwards as well as flipping all momenta and spins. As a result the potential effects of any $T$-preserving interactions must be carefully considered when considering such triple products. This type of background turns out to be negligibly small within the standard model.

A great simplification arises once we focus only on those terms in the effective lagrangian that can contribute to $dA$. In this case all but two of the many effective operators are suppressed in their tree-level contribution to $dA/d\theta d\phi$ by powers of light quark or lepton masses. This claim is justified in more detail in refs. [2] and [3]. The two effective interactions that can appear may be written (up to integrations by parts and field redefinitions) as a linear combination of:

$$\mathcal{L}_W = \lambda_W \left( [\bar{L} P_R \mu^\nu \not{E}] D_\mu \phi + \text{c.c.} \right) + \mathcal{L}_N = \frac{1}{2} \lambda \left( \not{g_1 B_{\mu\nu}} \left( \mathcal{L}_N^{\mu\nu} P_R \not{E} \right) \phi + \text{c.c..} \right)$$

In our conventions, the CP-odd part of these interactions is proportional to the imaginary part of the coefficients, $\lambda_W$ and $\lambda_N$.

Im $\lambda_N$ is strongly bounded by the electron e.d.m.(see below). The contribution of the remaining operator$^3$ to $dA$ (in the CM frame) are easily computed, and are summarized for LEP in the following table:

<table>
<thead>
<tr>
<th>Process</th>
<th>$\tau^+\tau^-$</th>
<th>$e^+e^-$</th>
<th>$b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Events, $(N \times 10^{-3})$</td>
<td>6.5</td>
<td>24</td>
<td>31</td>
</tr>
<tr>
<td>Asymmetry $(A/N \times 10^{-3})$</td>
<td>-6.1</td>
<td>-97</td>
<td>-170</td>
</tr>
<tr>
<td>$A/N \times 10^3$</td>
<td>0.94</td>
<td>4.0</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table (1): Integrated Asymmetries at LEP

This table assumes $\lambda_W = (400 \text{ GeV})^{-2}$ and an integrated luminosity of $^7 L = 4.8 \times 10^5 \text{ pb}^{-1}$ at LEP. The smaller luminosity at SLC makes it impossible to distinguish a signal from standard-model statistical fluctuations.

In order to quantitatively estimate how big $\lambda_W$ must be to be detectable at LEP let us assume that the systematic error in the measurement of the asymmetry, $A$, in the lepton- and heavy-quark-production cross-section can be reduced to 0.1% of the total cross-section. Systematic errors of roughly this size are expected$^8$ for LEP measurements of the forward-backward asymmetry, $A_{FB}$. In this case the two-jet asymmetry would be just visible at the 2-$\sigma$ level above background provided that: $\lambda_W > (570 \text{ GeV})^{-2}$, for up-type quarks; and $\lambda_W > (660 \text{ GeV})^{-2}$, for down-type quarks.

The tree-level expression for the asymmetry in $e^-p$ collisions may be similarly found$^2$. We have numerically integrated these expressions using $\lambda_W = (400 \text{ GeV})^{-2}$, and a HERA luminosity of 200 pb$^{-1}$. The charged-current signal is greater than twice the standard-model statistical background if: Im $\lambda_W > \left( \frac{400 \text{ GeV}}{E} \right)^2$ in $e^-p$ collisions and Im $\lambda_W > \left( \frac{330 \text{ GeV}}{E} \right)^2$ for $e^+p$.

Should a nonzero asymmetry be observed there are several ways to determine whether the effective interaction, $\mathcal{L}_W$, is responsible: (a) The angular ($\theta$- and $\phi$-) dependence of the asymmetry at LEP, or the x- and $Q^2$-dependence at HERA, must be as predicted since the only unknown parameter, $\lambda_W$, enter into these expressions through an overall multiplicative factor. (b) If both the electron and positron beams at LEP are transversely polarized then the asymmetry must be proportional to the difference between electron and positron polarization, $s_e - s_p$. At both HERA and LEP $A$ must change sign with the initial polarization. (c) $SU_L(2) \times U_Y(1)$-invariance implies that the effective interaction, $\mathcal{L}_W$, also predicts a CP-violating electron-photon-Z vertex which might be detectable through asymmetries in the process $e^-e^+ \to f\overline{f} \gamma$ or $e^-p \to f\overline{f}\gamma$.

The main question is whether Im $\lambda_W$ of this size is consistent with other experimental bounds. By far the most restrictive bound is the present limit on the intrinsic electric dipole moment of the electron: $d_e < 1.5 \times 10^{-26}$ (Berkeley$^9$), $d_e < 1.2 \times 10^{-26}$ (Amherst$^{10}$). Other observables, such as limits on
triple-product correlations in $\mu$-decays, or limits on deviations from standard-model predictions of $Z^0$-partial widths, $\Gamma(Z \rightarrow ff)$, are not sufficiently sensitive to significantly constrain $\lambda_W$.

The e.d.m.-bound completely eliminates the coupling $\text{Im} \lambda_7$. This is because although many effective operators can contribute to the electron e.d.m., they cannot cancel the effect due to $\text{Im} \lambda_7$ without undermining perturbation theory in our small expansion parameters—the small gauge and Yukawa couplings. Since $\text{Im} \lambda_7$ is the coefficient of the sole operator that contributes to $d_e$ at tree level and to leading order in $m_e/v$ it must be bounded to be smaller than: $\text{Im} \lambda_7 < (10^3 \text{TeV})^{-2}$.

The remaining coupling, $\text{Im} \lambda_W$, is only one of several interactions that contribute to $d_e$ at one-loop and at leading order in $m_e/v$ so its contribution to the electron e.d.m. could potentially cancel with others in at this order. If we assume that each of these operators is separately bounded by its individual contribution to the electron e.d.m. we derive a bound of: $\text{Im} \lambda_W < (10 \text{ TeV})^{-2}$. This would be sufficiently strong to rule out any observable asymmetry at all at either LEP or HERA.

It should be borne in mind, however, that this bound would not apply if the contribution of $\text{Im} \lambda_W$ to $d_e$ should cancel with that of another operator of the effective lagrangian. Indeed, the occurrence of such cancellations tell us a great deal about the symmetries and selection rules of the underlying theory. In the present instance this would require a cancellation of the contribution to within a little better than the percent level. Although a cancellation to this accuracy appears unnatural in the effective lagrangian approach, it need not be within the context of a specific model where the effective couplings are all determined in terms of a small number of underlying parameters. The most famous example in which this occurs is the standard model itself where the cancellation reflects the GIM mechanism of the underlying theory. The observation of the asymmetry described here would point to similar cancellations at work at the scale of new physics.

**ACKNOWLEDGEMENTS**

We acknowledge with thanks J. Anglin, D. Atwood, M. Frank, H. deGuise, C. Hamzaoui, B. Irwin, and C. Mangin for their collaboration on various aspects of the work reported on here, and A. Soni and G. Valencia for helpful discussions.

**REFERENCES**

DISCUSSION

Q. Kam-Biu Luk (UC, Berkeley, LBL): If I understand you correctly, you are using triple-product to look for CP violation. If so, how will you compare your approach with semi-leptonic decays, for instance, beta decay of kaon?

A. C. P. Burgess: Yes, it is a triple-product test for CP violation. Semi-leptonic decay of kaon involves light masses that do not give good limit on the parameters in the lagrangian. Other decays like $Z^0$ decay give comparable constraints on the parameters as from the electric dipole moment of the electron.