BRIEF REPORTS

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Anomalous neutrino reactions at DESY HERA

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We study the sensitivity of DESY HERA to new physics using the helicity suppressed reaction $e_R p \to \nu X$, where the final neutrino can be a standard model one or a heavy neutrino. The approach is model independent and is based on an effective Lagrangian parametrization. It is shown that HERA will put significant bounds on the scale of new physics, though, in general, these are more modest than previously thought. If deviations from the standard model are observed in the above processes, future colliders such as the SSC and CERN LHC will be able to directly probe the physics responsible for these discrepancies.

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The fact that the DESY ep collider HERA will provide a polarized electron beam opens the possibility of performing experiments which are sensitive to physics beyond the standard model [1]. In this report the reaction for which a right-handed electron scatters off a proton creating a neutrino will be studied, both for the standard model particle spectrum and when a right-handed massive neutrino is added to it. This reaction is enormously suppressed in the standard model[1] and is therefore a good process in which to look for new physics. The approach which we will use consists in parametrizing the effects of new interactions using an effective lagrangian. This has the advantage of preserving all symmetries of the standard model and is completely model independent with respect to the underlying physics. The approach also provides reliable estimates for the magnitudes of the coefficients of the effective operators.

The most important operators responsible for left-handed neutrino production were identified long ago in Ref. [2] where restrictions on these interactions stemming from low-energy meson physics were obtained and where the effects on the Callan-Gross relation were determined. In this report we will present a parallel study where the effects of these operators on polarized cross sections are considered.[2]

The processes under consideration have been identified before in [4,5], and in [5] it is claimed that HERA will be sensitive to new physics up to a scale of a few TeV. We will see that this result is strongly dependent on the assumptions regarding the physics underlying the standard model: If it is weakly coupled (such a situation is realized, for example, by supersymmetry), sensitivity to the scale of new physics, which we call Λ, is much weaker. (It must be emphasized that the meaning of Λ is very clear within this approach: It represents the mass of the lightest excitation in the underlying theory.)

We consider first the reaction $e_R p \to \nu_L X$, where p represents a proton and ν_L the electron's neutrino.[3] As mentioned above, the standard model cross section for this process is essentially zero; in contrast, physics underlying the standard model can generate effective interactions which contribute significantly to this reaction. The relevant operators are of two types and can be found in the complete compilation of Büchmuller and Wyler [6] (for an operator not included in this list, see Ref. [2]).

The contributing four Fermi operators are

$$\mathcal{O}_{lq} = (\bar{l}e)\epsilon(\bar{q}u) \ ,$$

$$\mathcal{O}_{qde} = (\bar{l}e)(\bar{d}q) \ , \tag{1}$$

$$\mathcal{O}'_{lq} = (\bar{l}u)\epsilon(\bar{q}e) \ ,$$

where we adopted the notation and conventions of Büchmuller and Wyler in Ref. [6]: l and q denote the left-handed lepton and quark doublets, respectively, e, u,

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[1]The standard model charged currents are left handed and a chirality flip must occur; thus, the corresponding cross section is proportional to $(m_e/E_e)^2 \sim 4 \times 10^{-10}$.

[2]These operators must violate chirality and are therefore *not* of the type current$\times$current which have been extensively studied [3].

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[3]We will ignore intergeneration mixing as the scale for the corresponding operators is presumably much larger than Λ; see Ref. [6].

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and d denote the right-handed electron, up and down quark fields, and $\epsilon = i\sigma_2$.

The remaining operators containing standard model (SM) fields which contribute to the process at hand are

$$\mathcal{O}_{De} = (\overline{l}D_\mu e)(D^\mu \phi) ,$$

$$\mathcal{O}_{\overline{D}e} = (\overline{D_\mu l}e)(D^\mu \phi) , \quad (2)$$

$$\mathcal{O}_{eW} = g\overline{l}\sigma^{\mu\nu}\tau^I e\phi W_{\mu\nu}^I ,$$

where ϕ denotes the scalar doublet, D_μ the covariant derivative, τ^I the usual Pauli matrices, and $W_{\mu\nu}^I$ the $SU(2)_L$ gauge field strength tensor with g the corresponding coupling constant. These operators contribute via t-channel W exchange.

The Lagrangian is therefore

$$\mathcal{L}_L = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i \lambda_i \mathcal{O}_i \quad (3)$$

(the sum over i runs over the above six terms; the subscript L refers to the neutrino's helicity). We have kept only the operators of lowest dimension contributing at the tree level, as they give the leading contributions.

To estimate the magnitude of the λ_i, we note first that the operators (1) can be generated at the tree level by the underlying particles, while (2) can appear only at one loop [7]. This, together with the assumption that the underlying physics is weakly coupled, implies that $\lambda_i \lesssim 1$ for (1), while $\lambda_i \lesssim 1/16\pi^2$ for (2). The λ's will also contain some coupling constants from the underlying theory; we will assume that these are of the same order as the weak gauge coupling. Then $\lambda_i \sim 0.44$ for (1) and $\lambda_i \sim 2\times10^{-3}$ for (2). With these estimates Λ will correspond to the mass of a low-lying excitation in the underlying physics.

There are some experimental constraints on the coefficients λ_i: From K and π decays it is known that [2]

$$\lambda_{qde} \simeq 0 \quad \text{and} \quad \lambda_{lq}' \simeq 2\lambda_{lq} , \quad (4)$$

which we will henceforth adopt. Within the framework of this work, these conditions are assumed to be the result of some (unknown) constraint stemming from the underlying physics.

While we have assumed that the physics at scale Λ will generate all operators in (1) and (2), this may not be the case: One could imagine situations where (1) are generated at a scale Λ while (2) are produced at a different scale[4] $\Lambda' \ll \Lambda$; if this is the case, HERA will be insensitive to the physics responsible for (1) and (2) for any interesting (i.e., $\gtrsim 100$ GeV) value of Λ.

With (3) we can calculate the cross section for the process at hand. Note that the two types of operators (1) and (2) will not interfere due to helicity conservation at the quark vertex (provided we ignore quark masses, as we will). The result is

$$\frac{d\sigma_L}{dx\,dy} = \frac{s}{32\pi\tilde{\Lambda}^4}x[(2-3y)^2 U+(2-y)^2\overline{D}]$$

$$+ \frac{g^4v^2}{64\pi\Lambda_1^4}\left[\frac{x^2y(1-y)}{(xy+m_W^2/s)^2}(U+\overline{D})\right], \quad (5)$$

where x and y are the usual scaling variables, $v = \sqrt{2}\langle\phi\rangle \simeq 250$ GeV, and U and $\overline{D}$ are the (x- and y-dependent) quark distribution functions; we also defined

$$\tilde{\Lambda} = \Lambda/|\lambda_{lq}|^{1/2} ,$$
$$\tilde{\Lambda}_1 = \Lambda/|\lambda_{De} - \lambda_{\overline{D}e} + 8\lambda_{eW}|^{1/2} . \quad (6)$$

The result of a numerical integration using the Eichten-Hinchliffe-Lane-Quigg (EHLQ) type-II distribution functions [8] is (for $\sqrt{s} = 292$ GeV with no cuts imposed)

$$\frac{1}{s}\sigma_L = 0.0021\frac{1}{\tilde{\Lambda}^4} + 0.00013\frac{1}{\tilde{\Lambda}_1^4} . \quad (7)$$

From the previous discussion, we expect $\tilde{\Lambda} \sim 1.5\Lambda$ and $\tilde{\Lambda} \ll \tilde{\Lambda}_1$; we will therefore ignore the contributions from the operators (2).

Using (7), we can estimate the sensitivity of HERA to the scale Λ: The above cross section will generate 15 events per year at HERA provided $\Lambda \lesssim 315$ GeV.

This result will be weakened for polarizations below 92%; in this case, the statistical significance of the right-handed electron signal must be considered. Suppose that we have a beam of polarization $\mathcal{P}$, where $\mathcal{P}=1$ implies pure right-handed electrons. Let σ_{SM} be the standard model contribution to $e_L p \to \nu_L X$ via t-channel W exchange; a simple calculation shows that[5]

$$\sigma_{\text{SM}} = \frac{g^4}{8\pi s}\int_0^1 dx\,dy\frac{xU+x(1-y)^2\overline{D}}{(xy+m_W^2/s)^2}$$

$$\simeq 5.67\times10^{-7} \text{ GeV}^{-2} \quad (\sqrt{s}=292 \text{ GeV}) . \quad (8)$$

The number of signal events is $N_{\text{signal}} = \mathcal{P}\sigma_L\mathbb{L}$, where $\mathbb{L}$ is the luminosity ($\mathbb{L}=4\times10^9$ GeV^2/yr for HERA), the number of background events is $N_{\text{bcgd}} = (1-\mathcal{P})\sigma_{\text{SM}}\mathbb{L}$, and the condition for the signal to be statistically significant is

$$N_{\text{signal}} > \sqrt{N_{\text{bcgd}} + N_{\text{signal}}} , \quad (9)$$

which determines the sensitivity to Λ given $\mathcal{P}$. The corresponding graph is presented in Fig. 1. Note that for realistic values of $\mathcal{P}$ the process is no longer rate dominated: Once the signal is statistically significant, there will be more than 15 events per year.

The same approach can be used to investigate the sensitivity to Λ when a massive neutrino is included in the low-energy spectrum. In this case the characteristics of the above reaction (large missing transverse momentum)

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[4]For the reaction under study, the contributions from (1) and (2) are comparable when $\Lambda \sim 25\Lambda'$.

[5]There is a large class of operators which also modifies the coupling of the W to the left-handed weak currents, as well as shifting the W mass from its standard model value [6]. We have not included these contributions in σ_{SM} since they represent but small corrections and we are interested only in a sensitivity estimate for Λ.
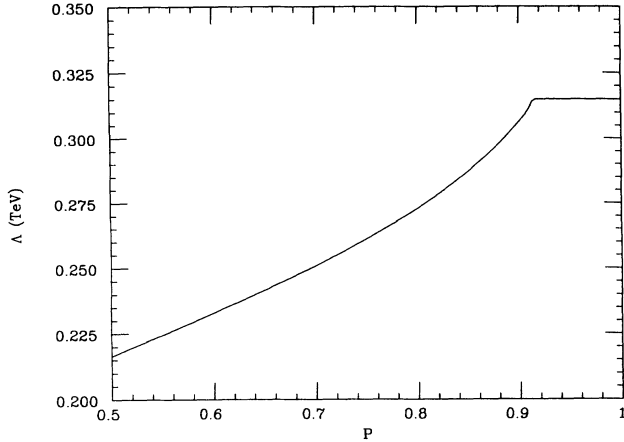
FIG. 1. Sensitivity to Λ in the reaction $e_R p \to \nu_L X$ as a function of the polarization $\mathcal{P}$, assuming $|\lambda_{lq}| = 0.44$. For $\mathcal{P} \leq 0.9$, the curve is generated by (9); for $\mathcal{P} > 0.9$, the curve corresponds to 15 events per year at HERA.

can be also realized by the process $e_R p \to \nu_R X$, where ν_R represents the right-handed polarized massive neutrino. We will not deal here with the problem of including ν_R in a consistent model; we merely note that if its left-handed partner (if present) couples as an ordinary neutrino to the W and Z bosons, collider experiments require the heavy neutrino to have a mass $m_\nu > 50$ GeV [9]. It must also be

mentioned that this type of object, if it exists, is probably not the right-handed partner of a known neutrino, as the corresponding models which satisfy all constraints of flavor-changing neutral currents and neutrinoless double-β decay, together with a reasonable leptonic phenomenology, are difficult to construct without endowing the right-handed neutrinos with an enormous mass [10]. Here we will take a purely phenomenological approach adding such a particle to the standard model without reference to any specific model. We will assume that this massive neutrino lies in the low-energy spectrum of the model, but that its interactions are generated by the physics underlying the standard model. Aside from a mass term of the type $\bar{l}\nu_R \phi$, there are two independent dimension-6 operators which contribute to the reaction under consideration:

$$\mathcal{O}_R^{(1)} = (\bar{d}\gamma^\mu u)(\bar{\nu}_R \gamma_\mu e) ,$$

$$\mathcal{O}_R^{(2)} = i(\phi^T \epsilon D_\mu \phi)(\bar{\nu}_R \gamma^\mu e) . \qquad (10)$$

As in the case for the left-handed neutrinos, the above two operators do not interfere due to helicity conservation at the quark vertex (we again assume massless quarks) irrespective of the neutrino mass. The cross section obtained from the Lagrangian

$$\mathcal{L}_R = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_{i=1,2} \lambda_R^{(i)} \mathcal{O}_R^{(i)} \qquad (11)$$

is

$$\frac{d\sigma_R}{dx\,dy} = \frac{s}{8\pi\Lambda_{R1}^4} \left\{ \left[x - \frac{m_\nu^2}{s} \right] U + (1-y) \left[x(1-y) + \frac{m_\nu^2}{s} \right] \bar{D} \right\}$$

$$+ \frac{s}{8\pi\Lambda_{R2}^4} \left\{ \left[x - \frac{m_\nu^2}{s} \right] \bar{D} + (1-y) \left[x(1-y) + \frac{m_\nu^2}{s} \right] U \right\} \left[\frac{m_W^2}{xys + m_W^2} \right]^2 , \qquad (12)$$

where

$$\Lambda_{R1,R2}^2 = \Lambda^2 / |\lambda_R^{(1,2)}| \qquad (13)$$

and where $x \geq m_\nu^2/s$. As before, we take $\lambda_R^{(1)} \sim 0.44$ and expect (with the previously mentioned caveats) $\lambda_R^{(2)} \ll \lambda_R^{(1)}$, whence the contributions from $\mathcal{O}_R^{(2)}$ will be ignored.

If ν_R exists, then a given experiment will not differentiate between the reactions $e_R p \to \nu_{L,R} X$ and will actually measure the "total" cross section $\sigma = \sigma_L + \sigma_R$. Using this, we can obtain a sensitivity plot for Λ by requiring the signal to be statistically significant; as mentioned previously, this is the relevant condition for polarizations below 92%. Applying (9) to the sum of the above contributions [i.e., using $N_{\text{signal}} = \mathcal{P}(\sigma_R + \sigma_L)\mathbb{L}$], we obtain the expected sensitivity to Λ as a function of the right-handed neutrino mass and the polarization. The results are presented in Fig. 2.

The effects of the massive neutrino are significant for $m_\nu \lesssim 130$ GeV (for this range of masses $\sigma_R > \sigma_L$). This can be traced back to the fact that the main contributions
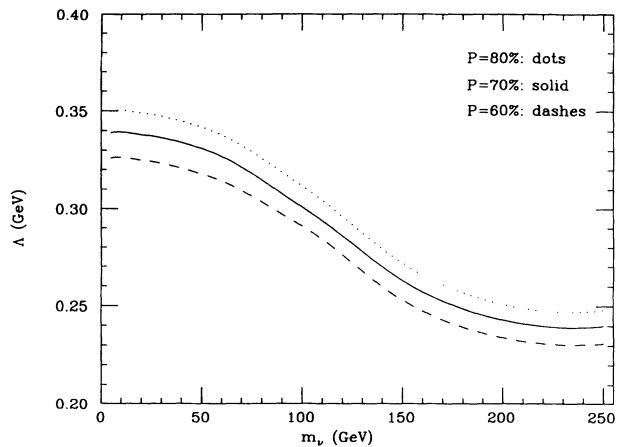

FIG. 2. Sensitivity to Λ (assuming $|\lambda_{lq}| = |\lambda_R^{(1)}| = 0.44$) for 80% (dashed curve), 70% (solid curve), and 60% (dotted curve) polarization, as a function of the right-handed neutrino mass. This indicates the contributions from both the ν_L and ν_R processes.

to σ_L can be interpreted as a heavy scalar exchange, while for σ_R it corresponds to a heavy vector exchange; this leads to a factor of 4 in σ_R, which is compensated by decreasing phase space only for $m_\nu \gtrsim 130$ GeV.

From the above we conclude that the polarized experiment described in this paper can be used to generate interesting bounds on the scale of the physics underlying the standard model, even when it is assumed to be weakly coupled. If such an effect is found, the corresponding interactions will certainly be observable in their full glory at the next colliders such as the Superconducting Super Collider (SSC) and CERN Large Hadron Collider (LHC). These bounds, though weaker than those obtained in other experiments such as the muon's anomalous magnetic moment [11], are of interest since they probe the helicity violating processes which generate (1).

The sensitivity to Λ (understood to be the mass of a low-lying resonance) depends crucially on the estimates on the coefficients λ_i: If the effective operators are assumed to be generated by weakly interacting physics, HERA's sensitivity drops by one order of magnitude compared to the results in Refs. [1,5,2].

Of course, it is certainly possible that the operators considered here are generated at a scale much larger than the ones of the type studied in [3], so that the nonobservability of helicity-violating processes does not necessarily constrain other types of beyond the standard model effects. It is also true that the approach followed here cannot determine the specific type of new physics which generates the effective operators responsible for a nonzero effect; this necessarily must await a collider that can reach the scale Λ.

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