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Electroweak tests at beta-beams

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Abstract

We explore the possibility of measuring the Weinberg angle from (anti)neutrino–electron scattering using low energy beta-beams, a method that produces single flavour neutrino beams from the beta-decay of boosted radioactive ions. We study how the sensitivity of a possible measurement depends on the intensity of the ion beam and on a combination of different Lorentz boosts of the ions.

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1. Introduction

Soon after electroweak theory was introduced, 't Hooft pointed out that low energy neutrino–electron scattering experiments can be used to test the Standard Model [1]. This purely leptonic process measures $\sin^2\theta_W$ ($Q^2 \sim 0$). The first such measurement was reported in Ref. [2], yielding $\sin^2\theta_W = 0.29 \pm 0.05$. Two subsequent low Q^2 experiments were performed, namely the atomic parity violation at $Q^2 \sim 10^{-10}$ GeV^2 [3] and the Møller scattering at $Q^2 = 0.026$ GeV^2 [4], with a precision of 1% and 1.3%, respectively. These experiments, combined with the measurements of $\sin^2\theta_W$ at the Z^0 pole [5], are consistent with the expected running of the weak mixing angle. However, a recent measurement, with a precision of 0.7%, of the neutral- to charged-current ratio in muon antineutrino–nucleon scattering at the NuTeV experiment, disagrees with these results by about 3σ [6]. A number of ideas were put forward to explain the so-called NuTeV anomaly, including QCD and nuclear physics effects, extra U(1) gauge bosons, dimension six-operators [7]; universal suppression of Z-neutrino couplings [8]; higher twist effects arising from nuclear shadowing [9]; and sterile neutrino mixing [10]. However, a complete understanding of the physics behind the NuTeV anomaly is still lacking. Probing the Weinberg angle through additional experiments with different systematic errors would be very useful.

The precision tests of the electroweak theory, in principle, can help determine possible "oblique corrections" arising from vacuum polarization corrections with the new particles in the loops and suppressed vertex corrections. Such corrections can be characterized with two parameters, named S and T [11]. It was recently stressed that a measurement of the electron antineutrino–electron elastic scattering count rates at 1 or 2% level would restrict the parameter S more closely than measurements of atomic parity violation [12].

Motivated in part by the NuTeV result, a strategy was presented in Ref. [13] for measuring $\sin^2\theta_W$ to about one percent at a reactor-based experiment. In this Letter we explore an alternative scenario, namely using low energy beta-beams. These are pure beams of electron neutrinos or antineutrinos produced through the decay of radioactive ions circulating in a storage ring [14,15]. In our analysis, we investigate the possibility of using a low energy beta-beam facility [16] to carry out such a test, through scattering on electrons at $Q^2 \sim 10^{-4}$ GeV^2.

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We should point out that several other measurements of the Weinberg angle using neutrino–electron scattering already exist. These use either conventional muon neutrino beams ($Q^2 \sim 0.01\ \mathrm{GeV}^2$) [17,18] or electron neutrinos coming from muon decay at rest [19]. These experiments typically determine $\sin^2\theta_W$ to an accuracy of five to twenty percent.

In Section 2 we present the calculations and describe the advantages of using beta-beams. In Section 3, the selection of the events is presented, as well as the results for the $\Delta\chi^2$ fits and for the 1σ uncertainty on the Weinberg angle, including both statistical and systematic errors. The sensitivity of these results to the intensity of the ions in the storage ring is also discussed. Finally, conclusions are drawn in Section 4.

2. Calculations

The differential cross section for $\nu_e(\bar\nu_e)e^- \to \nu_e(\bar\nu_e)e^-$ in units of $\hbar c = 1$ is [20]

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(\mathrm{g}_V + \mathrm{g}_A)^2 + (\mathrm{g}_V - \mathrm{g}_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + \left(\mathrm{g}_A^2 - \mathrm{g}_V^2\right)\frac{m_e T}{E_\nu^2}\right], \tag{1}$$

where[1] $\mathrm{g}_V = 1/2 + 2\sin^2\theta_W$, and $\mathrm{g}_A = \pm 1/2$ for ν_e ($\bar\nu_e$), m_e is the electron mass, G_F is the Fermi weak coupling constant, E_ν is the impinging (anti)neutrino energy and T is the electron (positron) recoil energy. By integrating Eq. (1) over the electron recoil energy and averaging over the neutrino flux one gets the flux-averaged cross section

$$\langle\sigma\rangle = \frac{G_F^2 m_e}{2\pi}\left[\frac{4}{3}\left(\mathrm{g}_V^2 + \mathrm{g}_A^2 + \mathrm{g}_V \mathrm{g}_A\right)\langle E_\nu\rangle - \mathrm{g}_V(\mathrm{g}_V + \mathrm{g}_A)m_e\langle\phi\rangle\right], \tag{2}$$

where we defined

$$\langle E_\nu\rangle = \int dE_\nu\, \phi(E_\nu) E_\nu, \tag{3}$$

and

$$\langle\phi\rangle = \int dE_\nu\, \phi(E_\nu). \tag{4}$$

We consider a scenario where the (anti)neutrinos are produced by low energy beta-beams. The (anti)neutrino flux $\phi(E_\nu)$ is then the one associated to the decay of boosted radioactive ions. The details of the formalism used, including the calculation of the flux, can be found in [21]. Since the work in [21] has shown that a small storage ring is more appropriate, we consider such a ring, the actual dimensions being determined according to [22]. We assume that a detector of cylindrical shape, having radius R and depth h, is located at a distance d from the storage ring. Therefore, the count rate is given by

$$\frac{dN(\gamma)}{dt} = f\tau n h\langle\sigma\rangle. \tag{5}$$

Here γ is the Lorentz boost of the ions, $\tau = t_{1/2}/\ln 2$ is the lifetime of the parent nuclei, n is the number of target particles per unit volume, and f is the number of injected ions per unit time. Note that the mean number of ions in the storage ring is $\gamma\tau f$. Combining Eqs. (2) and (5), one gets

$$N(\gamma)E_0(\gamma) = -\mathrm{g}_V(\mathrm{g}_V + \mathrm{g}_A)m_e + \frac{4}{3}\left(\mathrm{g}_V^2 + \mathrm{g}_A^2 + \mathrm{g}_V \mathrm{g}_A\right)\frac{\langle E_\nu(\gamma)\rangle}{\langle\phi(\gamma)\rangle}, \tag{6}$$

where $E_0(\gamma)$ is a quantity with units of energy defined as

$$E_0(\gamma) = \left[\Delta t f\tau n h\left(\frac{G_F^2 m_e}{2\pi}\right)\langle\phi(\gamma)\rangle\right]^{-1}, \tag{7}$$

with Δt being the duration of the measurement at each γ.

Eq. (6) can be rewritten as

$$N(\gamma)E_0(\gamma) - \mathrm{g}_A^2 m_e = \frac{4}{3}\left(\mathrm{g}_V^2 + \mathrm{g}_A^2 + \mathrm{g}_V \mathrm{g}_A\right)\left[\frac{\langle E_\nu(\gamma)\rangle}{\langle\phi(\gamma)\rangle} - \frac{3}{4}m_e\right]. \tag{8}$$

If one neglects oblique corrections then $\mathrm{g}_A^2 = 1/2$; in that limit, Eq. (8) represents a linear relationship between the number of counts $N(\gamma)$ and the (anti)neutrinos average energy $\langle E(\gamma)\rangle$. This relationship is depicted in Fig. 1. The phase difference

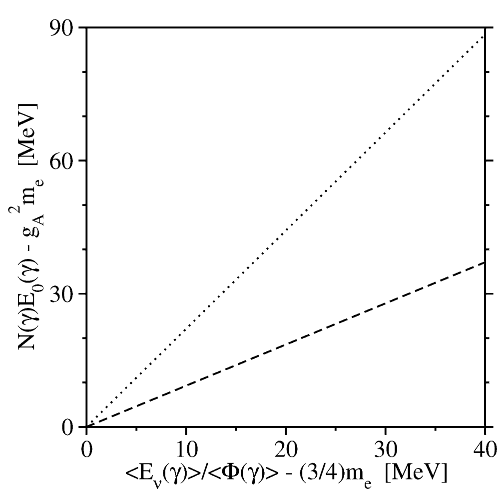

Fig. 1. Representation of the linear behavior expressed in Eq. (8) for electron neutrinos (dotted line) and electron antineutrinos (broken line). The slope is proportional to $(\mathrm{g}_V^2 + \mathrm{g}_A^2 + \mathrm{g}_V \mathrm{g}_A)$, being different for neutrinos and antineutrinos because of the relative phase in g_A. One measurement of the count number at a particular γ for either (ν_e, e^-) or $(\bar\nu_e, e^-)$ scattering is sufficient to determine the Weinberg angle since the y-intercept is zero.

[1] When considering oblique corrections, g_V and g_A include terms that depend on the parameters S and T [11].