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IMPLICATIONS OF RESULTS OF NEUTRINO MASS EXPERIMENTS

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The long standing negative (mass)² anomaly encountered in attempts to measure the mass of the electron neutrino may be an indication of physics beyond the standard model. It is demonstrated that an additional charged current interaction which is not of $V-A$ form, and which is at least an order of magnitude weaker than the standard model charged current interaction, will produce a spectrum, which, if fitted by the standard model, may give a negative value for m_ν^2 . A possible physical explanation of the time dependent effects seen by the Troitsk experiment is also provided.

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1 Introduction

Following the early reports of a non-zero mass of the electron neutrino in the 1970s, much effort has been devoted to attempts to measure the mass of the electron neutrino. In the 1980s the sensitivity was about 20eV; now it is an order of magnitude better. As the sensitivity improved, something very strange happened which we can trace from the 1998 PDG report¹. It is m_ν^2 , not m_ν , which appears in the expression fitted to the spectrum. We see that all experiments from 1990 to 1995 measuring m_ν^2 with errors of less than about 100eV² give negative values of m_ν^2 . The best result of this period (from Troitsk²) is

$$m_{\nu_e}^2 = -22 \pm 4.8 \text{ eV}^2 \quad (1)$$

One obvious interpretation of the anomalous value of $m_{\nu_e}^2$ is that there is an unexpected excess of counts near the endpoint of the electron spectrum.

In 1999 new data at higher precision were reported by the Troitsk³ and Mainz⁴ groups which, although presented differently, confirmed the existence of anomalous results. The Troitsk data show an enhancement about 15eV below the endpoint, with evidence that the position of the bump is varying with time. In 4 of the 5 runs, the Mainz group report values of $m_{\nu_e}^2$ which "are significantly negative". Note that the magnitude of $m_{\nu_e}^2$ observed by the Mainz group varied with the span of electron energies below the end point which were included in the analysis. The results were mutually consistent.

More surprising than the negative $m_{\nu_e}^2$ was the claim of the Troitsk group that the position and amplitude of the enhancement exhibited a period of approximately 6 months.

At the NU2000 conference the Troitsk group⁵ presented data consistent with their earlier results, with a slight variation in the periodicity of the position of the enhancement, and the Mainz group⁶ presented results which were consistent with a zero value of $m_{\nu_e}^2$.

There is still an anomaly in the data and so it is appropriate to ask "Is the end point anomaly in the beta spectrum for tritium decay a hint of physics beyond the standard model?"

One possibility is that the electron and neutrino interact with the up and down quarks with an interaction which is not of the pure $V - A$ type. It was once well known that the effect of a finite mass on the beta decay spectrum depends on the interactions⁷, but with the incorporation of $V - A$ in the standard model this observation has passed out of the folklore. We explore its consequences, emphasizing that new interactions can distort the spectrum near the end point, especially through interference with the dominant standard model interaction, that mixing in the lepton sector plays an important role in the interference⁸, and that a time dependence can be introduced by a non-uniform background density of neutrinos.

2 New Interactions

For low energy physics, like nuclear β -decay in general and Tritium β -decay in particular, any new interactions can only appear as effective currents in the four fermion formulation of the theory with the usual space time structures of S, P, T, V or A . Given the dominance of the SM, in which the interaction is $V - A = L$, it is reasonable to recast this as S_L, S_R, T, R or L , where $R \sim (V + A)$ etc, using the convention that L or R indicates the chirality of the *neutrino* which enters the interaction. The interesting effect on the spectrum

only occurs if the additional currents in the lepton sector are different from L .

We need to evaluate the effect on the Tritium beta spectrum of possible interferences between the SM left-chiral vector current and the various possible new currents, as well as the contribution of the new currents by themselves. Taking the no-recoil approximation for the nuclei, the leptonic currents which survive after contraction with the hadronic currents give contributions to the beta spectrum, examples of which are:

$$\begin{array}{llll}
 LL(SM) : & E_\nu E_\beta & RR : & E_\nu E_\beta \\
 S_L S_L : & E_\nu E_\beta & S_R S_R : & E_\nu E_\beta \\
 LR + RL : & -2m_\nu m_e & S_L S_R + S_R S_L : & -2m_\nu m_e \\
 LS_L + S_L L : & -2m_\nu E_\beta & LS_R + S_R L : & 2E_\nu m_e
 \end{array} \quad (2)$$

The negative sign of the terms with a factor of m_ν arises from the fact that the neutral lepton in Tritium beta decay is an anti-neutrino.

It is important to emphasize that most scenarios for "Physics beyond the standard model" include some of these interactions. For example, supersymmetric models give S_L and S_R interactions.

Thus the question which should be asked is not "Do non- L interactions exist?" — almost every attempt to generalize physics beyond the standard model will introduce such interactions. The question should instead be "How strong are the new interactions?", but before turning to that question, we explain the influence of neutrino mixing on the interaction Hamiltonian.

3 Lepton Mixing

The exciting results from SuperKamiokande show us that neutrino flavour eigenstates are not the same as the mass eigenstates, or that weak interactions can link leptons of different families, just as they link quarks of different families. This mixing has been omitted from previous discussions of interference of different currents.

To illustrate, assume an orthogonal Maki, Nakagawa, Sakata⁹ mixing matrix, neglecting CP violation, and restrict the discussion to Dirac neutrinos. The generalization to Majorana neutrinos is discussed in detail in ref¹⁰. In particular, we assume the existence of three massive Dirac neutrinos, ν_i^D , with Dirac masses m_i . The interaction eigenstates for SM interactions, ν_f , $f = (e, \mu, \tau)$ are expressed in terms of the mass eigenstates as

$$\nu_f = \sum_i \Lambda_f^i \nu_i \quad (3)$$

where the Λ_f^i are the MNS matrix elements.

If, as well as the $W^\pm$ and Z , additional charged bosons couple to both the quarks and the leptons, we may define neutral leptons, denoted by $\hat{\nu}_{X,f}$, $f = (e, \mu, \tau)$, $X = R, S_L, \dots$ which are current eigenstates of this new interaction. This introduces a new, and *different* mixing matrix, $\hat{\nu}_{X,f} = \sum_i \hat{\Lambda}_{X,f}^i \nu_i$.

The effective coupling, ρ_X , of the interaction X relative to the $L-L$ interaction of the SM, is dependent on the intrinsic coupling constant, the relative mass of the W and X and the elements of each of the mixing matrices:

$$\rho_X = (g_X/g)^2 (M_W/M_X)^2 (\hat{\Lambda}_{X,e}^1/\Lambda_e^1). \quad (4)$$

The sign of ρ_X is not determined *a priori*, allowing for both destructive and constructive interference. Data from beta spectra and angular correlations show that the ρ_X cannot exceed the 10% level in general, but that $\rho_{S_L} \leq 0.01$. It may be possible to improve these independent limits by application of appropriate cuts to the electron energy in the correlation measurements¹¹.

4 The spectrum near the end point

Near the end point, we note that $E_e \approx m_e$, so we obtain a convenient approximate spectrum by putting m_e/E_e equal to some constant average value, which can be absorbed into new parameters¹⁰, K' , ε_i and ϕ_i .

$$\begin{aligned} \frac{dN}{dE_\beta}(\mathcal{E}_0^k) &\cong K' \sum_i (1 + \varepsilon_i) |\Lambda_{ei}|^2 (\mathcal{E}_0^k - E_\beta)^2 \\ &\left[1 + \frac{\phi_i}{(\mathcal{E}_0^k - E_\beta)} \right] \sqrt{1 - \frac{m_i^2}{(\mathcal{E}_0^k - E_\beta)^2}} \Theta(\mathcal{E}_0^k - E_\beta - m_i), \end{aligned} \quad (5)$$

This approximate formula is valid for all of the interactions, the differences being hidden in the relationship of the parameters in Eq. (5) with the underlying ρ_X and for each endpoint energy $\mathcal{E}_0^k$.

Modern experiments do not measure the differential spectrum; instead the spectrum integrated from a lower cut-off electron energy E_e^C to above the end point is measured. To understand how the neglect of the additional interactions can produce a negative (mass)², use an approximate form of the integral spectrum, making some additional approximations to make the formulae easier to interpret. When this is fitted to the standard model spectrum (obtained by setting $\varepsilon_k = \phi_k = 0$ and $|\Lambda_{ek}|^2 = \delta_{k,e}$ in Eq. (5)) the fitted $m_{\nu_e}^2 \sim m_1^2 (1 - \phi_1/(3(\mathcal{E}_0^0 - E_e^C)))$. In this approximation, negative values of

$m_{\nu_e}^2$ occur naturally. Moreover, were one to fit data using m_i and ϕ_i as parameters, there are likely to be significant correlations. These observations are confirmed by detailed numerical studies¹⁰.

5 Right-handed neutrinos

All of the new interactions introduced, except the S_L interaction, involve right-handed neutrinos. It has become traditional to regard right-handed neutrinos as having masses at the 100GeV weak scale or larger and interacting very weakly. But in the absence of a real understanding of the source of the neutrino mass, one should keep an open mind on this matter, being guided by experimental constraints, rather than theoretical expectations. In our case the right-handed neutrinos are light, and almost the same mass as the left-handed neutrinos. This is consistent with the limits on neutrinoless double beta decay, which constrain the CP weighted sum of the masses of the neutrinos emitted in double beta decay to be less than 0.3eV.

As discussed in detail elsewhere¹², one expects the SNO neutral current results not to make up the deficiency in the charged current events, because of the oscillations to right-handed neutrinos with milli-weak interactions.

It is worth emphasising that these right-handed neutrinos interact at the milli-weak level. They are not strictly sterile, and one of the goals of experimental neutrino physics should be to measure the strength of "sterile" neutrino interactions.

6 The Lobashev time variation

The standard model can be extended to include a very light scalar particle interacting with a very small coupling constant with neutrinos only¹³. In this model, a high density of neutrinos will act as a source of the scalar, producing a classical scalar field, which, in turn, interacts with the neutrinos to reduce the effective neutrino mass¹⁴. Thus a dense system of neutrinos is bound.

In the early universe, neutrinos are born bound. As the density of the universe decreases, lacking sufficient separation energy, the neutrinos form into clouds. It may be the clouds act as seeds for structure on the stellar or stellar cluster scale. This forces the question, "Do we live in a neutrino cloud?". If we do, density variations in the vicinity of the earth's orbit would mean that $m_{i,\text{eff}}$ could vary, varying the parameters in the beta decay spectrum, and producing Lobashev variations in the beta spectrum.

7 The NU2000 results

It is clear that there is now a discrepancy between the results of the Moscow and Mainz groups. Of course the discrepancy will be resolved by careful attention to experimental detail, and perhaps by new, improved experiments. Whatever the outcome, at the least these sensitive and precise measurements of the beta spectrum near the end point will provide more accurate limits on the non-SM interactions involving charged currents. They should therefore be analysed with this in mind, using the spectrum of Eq. (5), or the unapproximated version of it. Then these delicate experiments will be able to give reliable values for, or limits on, the neutrino mass.

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