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Beta spectrum of unique first-forbidden decays as a novel test for fundamental symmetries

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ABSTRACT

Within the Standard Model, the weak interaction of quarks and leptons is characterized by certain symmetry properties, such as maximal breaking of parity and favored helicity. These are related to the $V - A$ structure of the weak interaction. These characteristics were discovered by studying correlations in the directions of the outgoing leptons in nuclear beta decays. Presently, correlation measurements in nuclear beta decays are intensively studied to probe for signatures for deviations from these couplings, which are an indication of Beyond Standard Model physics. We show that the structure of the energy spectrum of emitted electrons in unique first-forbidden β-decays is sensitive to the symmetries of the weak interaction, and thus can be used as a novel probe of physics beyond the standard model. Furthermore, the energy spectrum gives constraints both in the case of right and left couplings of the new beyond standard model currents. We show that a measurement with modest energy resolution of ≈ 20 keV is expected to lead to new constraints on beyond the standard model interactions with tensor couplings.

Since their discovery, nuclear β decays have been used as heralds of new physics. The existence of the neutrino was conjectured by Pauli, using the continuous spectrum of the electron. Later, experiments emphasized the study of the kinematics of β decays, in particular the angular correlation between the directions of the emitted β particle, i.e., electron or positron, and the neutrino (ν) (or, equivalently, the recoiling nucleus) [1]. In particular, the famous Wu experiment [2] has proven the breaking of parity symmetry. In recent years, several experiments are using precision measurements of the β–ν angular correlation coefficient in the decay of the short-lived radio-nuclides (see e.g. [3–7] and references therein). These experiments search for the minute experimental signal that originates from possible tensor or scalar terms in the weak interaction. Such scalar or tensor terms modify the angular correlation between a neutrino and an electron in the beta-decay process, thus probing new physics of "beyond-the-standard-model" (BSM) nature [8,9]. Present limits on possible deviations from the standard model predictions are of the order of 0.1–1% [5,7,10], broadly yielding a limit on the scale of new physics of the order of $\sim$ 1–10 TeV [11,12]. The latter limits originate in analysis of β-decays, assuming BSM couplings to left handed neutrinos, and become significantly worse for right handed neutrinos.

Precision measurements which are based on correlations of the emitted leptons have several disadvantages. In particular, most modern experiments make use of trapped ions or atoms in order to characterize the kinematics. The use of traps allows a significant reduction in the systematic uncertainties enabling precise correlation experiments. This limits the number of possible radio isotopes, as trapping is efficient for relatively short times. Additionally, complex detection and analysis schemes are required for the extraction of the correlations [8,13]. Current experiments mostly study allowed β-decays, where constraining separately right handed and left handed couplings is currently out of reach, due to inconsistencies in the energy averaging (see Ref. [14] for details).

Here, we propose a novel probe for beyond the standard model couplings, the energy spectrum of β decays that are characterized by transitions in which the total angular momentum in the daughter and mother nuclei differ by $\Delta J = 2$ units, as well as by change in parity. These decays are commonly known as *unique first-forbidden decays*. Such measurements are potentially simpler

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than a precise determination of the β–ν correlation coefficient, demand neither trapping nor cooling, and require a single observable to characterize. Additionally, a measurement of the full β spectrum, is less amenable to detector calibration and resolution issues, which plague *beta* endpoint measurements. More importantly, they provide constraints on exotic couplings and thus allow identifying systematic errors, a valuable feature for precision studies.

In order to show the difference between allowed and unique first-forbidden decays, it is convenient to write the general differential distribution of β-electron (positron) of energy ϵ, momentum $\vec{k}$ and direction $\vec{\beta}=\frac{\vec{k}}{\epsilon}$, and neutrino $\bar{\nu}(\nu)$ of momentum $\vec{\nu}$ in a $\beta^{\mp}$ decay process, as follows:

$$\frac{d^5\omega_{\beta^{\mp}}}{d\Omega_k/4\pi\, d\Omega_\nu/4\pi\, d\epsilon}=\Sigma(\epsilon)\cdot\Theta(q,\vec{\beta}\cdot\hat{\nu}). \quad (1)$$

With $\vec{q}=\vec{k}+\vec{\nu}$ is the momentum transfer in the process.

$\Sigma(\epsilon)$ is a nuclear independent part, related to the electrostatic interaction between the β particle and the decaying nucleus,

$$\Sigma(\epsilon)=\frac{2G^2}{\pi^2}\frac{2\Delta J+1}{\Delta J(2J_i+1)}(\epsilon_0-\epsilon)^2 k\epsilon\, F^{(\pm)}(Z_f,\epsilon), \quad (2)$$

with G the Fermi constant, J_i is the total angular momentum of the decaying (mother) nucleus, ΔJ is the difference between the angular momenta of the mother and daughter nuclei, Z_f is the charge of the daughter nucleus, and $\epsilon_0=\frac{2Q+Q^2+m_e^2}{2Q+2m_r}$ [15] is the maximum electron energy (m_e and m_r are electron and daughter nucleus masses, respectively, Q is the decay Q-value). The deformation of the lepton wave function due to the long-range electromagnetic interaction with the nucleus is taken into account in the Fermi function $F^{(\pm)}$ for a $\beta^{(\pm)}$ decay [16,17],

$$F^{(\pm)}(Z_f,\epsilon)=2(1+\gamma_0)(2\epsilon R_f)^{2(\gamma_0-1)}\frac{|\Gamma(\gamma_0+i\rho)|^2}{|\Gamma(2\gamma_0+1)|^2}e^{\pi\rho} \quad (3)$$

with $\alpha\approx 1/137$ the fine structure constant, R_f the radius of the final nucleus, $\rho=\mp\alpha Z_f/\beta_f$ (β_f is the momentum to energy ratio of the β particle), and $\gamma_0=\sqrt{1-(\alpha Z_f)^2}$ ($\Gamma(x)$ is the Gamma function).

Assuming the Standard Model $(V-A)$ coupling, the second term in Eq. (1), i.e., the function $\Theta(q,\vec{\beta}\cdot\hat{\nu})$, depends on the nuclear wave functions, and is usually written using a multipole expansion [18],

$$\begin{aligned}
&\Theta(q,\vec{\beta}\cdot\hat{\nu})\\
&=\frac{\Delta J}{2\Delta J+1}\Bigg\{\Big[1-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]\sum_{J\geq 1}\big(|\langle\|\hat{E}_J\|\rangle|^2+|\langle\|\hat{M}_J\|\rangle|^2\big)\\
&\pm\hat{q}\cdot\Big(\hat{\nu}-\vec{\beta}\Big)\sum_{J\geq 1}2\Re\langle\|\hat{E}_J\|\rangle\langle\|\hat{M}_J\|\rangle^*\\
&+\sum_{J\geq 0}\Big[\Big[1-\hat{\nu}\cdot\vec{\beta}+2(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\Big]|\langle\|\hat{L}_J\|\rangle|^2\\
&+\Big(1+\hat{\nu}\cdot\vec{\beta}\Big)|\langle\|\hat{C}_J\|\rangle|^2\\
&-2\hat{q}\cdot\Big(\hat{\nu}+\vec{\beta}\Big)\Re\langle\|\hat{C}_J\|\rangle\langle\|\hat{L}_J\|\rangle^*\Big]\Bigg\}, \quad (4)
\end{aligned}$$

where, $\langle\|\hat{O}_J\|\rangle$, is the reduced matrix element of a rank J spherical tensor operator $\hat{O}_J$, between the daughter and mother wave functions.

The multipole operator decomposition of the nuclear current, viz. the Coulomb, electric, magnetic, and longitudinal operators:

$$\hat{C}_{JM}(q)=\int d\vec{x}\, j_J(qx)Y_{JM}(\hat{x})\hat{\mathcal{J}}_0(\vec{x}) \quad (5)$$

$$\hat{E}_{JM}(q)=\frac{1}{q}\int d\vec{x}\,\vec{\nabla}\times[j_J(qx)\vec{Y}_{JJM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \quad (6)$$

$$\hat{M}_{JM}(q)=\int d\vec{x}\, j_J(qx)\vec{Y}_{JJM}(\hat{x})\cdot\hat{\vec{\mathcal{J}}}(\vec{x}) \quad (7)$$

$$\hat{L}_{JM}(q)=\frac{i}{q}\int d\vec{x}\,\vec{\nabla}[j_J(qx)Y_{JM}(\hat{x})]\cdot\hat{\vec{\mathcal{J}}}(\vec{x}), \quad (8)$$

where $\hat{\mathcal{J}}^\mu(\vec{x})$ is the nuclear current coupling to the probe. For β-decays, which are characterized by a low-energy transfer $qR\ll 1$, further simplification is possible expanding in this small parameter. For example, for allowed β-decays with $\Delta J^\pi=1^+$ (Gamow–Teller decays),

$$\Theta\propto(1+b\frac{m_e}{\epsilon}+a_{\beta\nu}\vec{\beta}\cdot\hat{\nu})\langle\|\hat{L}_1\|\rangle^2, \quad (9)$$

where m_e is the electron mass. This is accurate up to (recoil) corrections of order qR. The $V-A$ structure of the weak interaction entails $a_{\beta\nu}=-\frac{1}{3}$ and $b=0$. In the presence of beyond standard model interaction with tensor symmetry $a_{\beta\nu}\approx-\frac{1}{3}\big(1-\frac{|C_T|^2+|C_T'|^2}{|C_A|^2}\big)$, and $b=2\frac{C_T+C_T'}{C_A}$ [1], where C_T/C_A (C_T'/C_A) is the relative strength of the tensor (pseudo-tensor) and the axial-vector interactions.[1] Thus, β–ν correlation measurements are sensitive to interactions of exotic, e.g., tensor, symmetries. However, the β energy spectrum form shows sensitivity only to the Fierz interference term b, since

$$\frac{d\omega_{\beta^{\mp}}}{d\epsilon}(allowed)\propto\Sigma(\epsilon)\big(1+b\frac{m_e}{\epsilon}\big). \quad (10)$$

The Fierz term is linear in the exotic couplings, while $a_{\beta\nu}$ is quadratic. In addition, the Fierz term vanishes for right-handed neutrinos, for which $C_T=-C_T'$. As a result, allowed β decay measurements are better able to constrain the combination C_T+C_T'. Moreover, current experiments cannot fit separately both $a_{\beta\nu}$ and the Fierz term (even when including a non-zero Fierz term in the analysis) [14], due to the fact that the correlation and Fierz terms have different recoil momentum dependence. This, however, is not the case for a first forbidden unique transition, where a different result is obtained (see, e.g., [19]),

$$\begin{aligned}
\Theta(q,\vec{\beta}\cdot\hat{\nu})\propto\ &1\pm 2\gamma_0\frac{C_T+C_T'}{C_A}\frac{m_e}{\epsilon}\\
&-\frac{1}{5}\big(2(\hat{\nu}\cdot\vec{\beta})-(\hat{\nu}\cdot\hat{q})(\vec{\beta}\cdot\hat{q})\big)\big(1-\frac{|C_T|^2+|C_T'|^2}{|C_A|^2}\big).
\end{aligned} \quad (11)$$

The last term linearly depends on $(\hat{\nu}\cdot\hat{k})^2$. As a result, integration over angles, i.e., the energy spectrum of the decay, is sensitive to beyond the standard model tensor interactions, and can be used to probe them. Moreover, a full spectrum measurement enables a simultaneous extraction of C_T+C_T' and C_T-C_T' is possible, allowing studies of right and left handed neutrino couplings.

Theory related systematic corrections In the derivation of Eq. (11), we have used an expansion in qR. The neglected recoil corrections terms compete with signatures of tensor and/or other beyond the standard model contributions. In order to estimate the recoil corrections, let us write the decay rate of a unique first-forbidden decay up to the next-to-leading order in the parameter qR (assuming no tensor terms):

[1] For simplicity, we assume here real couplings, i.e., time reversal symmetry.