ELECTRON ANGULAR CORRELATION IN NEUTRINOLESS DOUBLE BETA DECAY AND NEW PHYSICS

A. Ali
Deutsches Elektronen-Synchrotron, DESY, 22607 Hamburg, Germany
A.V. Borisov, D.V. Zhuridov
Faculty of Physics, Moscow State University, 119991 Moscow, Russia

Abstract. The angular correlation of the electrons in the neutrinoless double beta decay ($0\nu2\beta$) is calculated taking into account the nucleon recoil, the $S$ and $P$-waves for the electrons and the electron mass using a general Lorentz invariant effective Lagrangian. We show that the angular coefficient is essentially independent of the nuclear matrix element models. We work out the angular coefficient in several scenarios for new physics, in particular, in the left-right symmetric models.

1 Introduction

It is now established that the observed neutrinos have tiny masses and they mix with each other [1]. Theoretically, it is largely anticipated that the neutrinos are Majorana particles. Experimental evidence for $0\nu2\beta$ decay would deliver a conclusive confirmation of the Majorana nature of neutrinos, establishing the existence of physics beyond the standard model (SM) [2]. An extended version of the SM could contain tiny nonrenormalizable terms that violate lepton number (LN) and allow the $0\nu2\beta$ decay. Probable mechanisms of LN violation may include exchanges by: Majorana neutrinos $\nu_{MS}$ [3,4] (the preferred mechanism after the observation of neutrino oscillations [1]), SUSY particles [5,6], scalar bilinears (SBs) [7], e.g. doubly charged dileptons (the component of the $SU(2)_L$ triplet Higgs etc.), leptoquarks (LQs) [8], right-handed $W_R$ bosons [4,9] etc. From these particles light $\nu$s are much lighter than the electron and others are much heavier than the proton that gives two possible classes of mechanisms for the $0\nu2\beta$ decay: long range (with the light $\nu$s in the intermediate state) and short range mechanism. Our aim was to examine the possibility to discriminate among the various possible mechanisms contributing to the $0\nu2\beta$-decays and the various sources of LN violation using the information on the angular correlation of the final electrons. We published a preliminary study along these lines in Ref. [10] and a more detailed study in Ref. [11]. Here, we summarize the main results of Ref. [11].

2 Angular correlation for the long range mechanism of $0\nu2\beta$ decay

For the decay mediated by light $\nu_{MS}$, the most general effective Lagrangian is the Lorentz invariant combination of the leptonic $j_\alpha$ and the hadronic $J_\alpha$ currents of definite tensor structure and chirality [12,13]

$$\mathcal{L} = \frac{G_F V_{ud}}{\sqrt{2}} \left[ (U_{ei} + \epsilon_{V-A,i}) V^{\mu}_i V^{\mu}_j \tilde{J}^+_{\alpha i} J^+_{\alpha j} + \sum_{\alpha,\beta} \epsilon^{\beta}_{\alpha i} j^i_{\beta} J^+_{\alpha} + \text{H.c.} \right], \quad (1)$$

where the hadronic and leptonic currents are defined as: $J^+_{\alpha} = \tilde{u}_\alpha d$ and $j^i_{\beta} = \tilde{e}_\beta \nu_i$; the leptonic currents contain neutrino mass eigenstates, and the
index $i$ runs over the light eigenstates. Here and thereafter, a summation over the repeated indices is assumed; $\alpha, \beta = V + A, S \mp P, T_{L,R}$ ($O_{T_{\rho}} = 2\sigma^{\mu\nu} P_{\rho}$, $\sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$), $P_{\rho} = (1 \mp \gamma_5)/2$ is the projector, $\rho = L, R$; the prime indicates the summation over all the Lorentz invariant contributions, except for $\alpha = \beta = V - A$, $U_{ei}$ is the PMNS mixing matrix. The coefficients $\epsilon_{\alpha i}^\beta$ encode new physics, parametrizing deviations of the Lagrangian from the standard $V - A$ current-current form and mixing of the non-SM neutrinos.

The nonzero $\epsilon_{\alpha}^\beta$ for the particular SM extensions are collected in Table 1.

| Model                  | Nonzero $\epsilon$s |
|------------------------|----------------------|
| with $W_{RS}$          | $\epsilon_{V+}^{+A}$ |
| RPV SUSY               | $\epsilon_{S+P}, \epsilon_{V-}^{-A}, \epsilon_{T_{L,R}}$ |
| with LQs               | $\epsilon_{S+P}, \epsilon_{V+}^{+A}$ |

We have calculated the leading order in the Fermi constant and the leading contribution of the parameters $\epsilon_{\alpha i}^\beta$ using the approximation of the relativistic electrons and nonrelativistic nucleons. We take into account the $S_1/2$ and the $P_1/2$ waves for the outgoing electrons and include the finite de Broglie wave length correction for the $S_1/2$ wave. Taking into account the nucleon recoil terms including the terms due to the pseudoscalar form factor we obtain the differential width in $\cos \theta$ for the $0^+(A, Z) \rightarrow 0^+(A, Z+2)e^-e^-$ transitions:

$$
\frac{d\Gamma}{d\cos \theta} = \frac{\ln 2}{2} |M_{GT}|^2 A(1 - K \cos \theta),
$$

(2)

where $\theta$ is the angle between the electron momenta in the rest frame of the parent nucleus, $M_{GT}$ is the Gamow–Teller nuclear matrix element and the angular correlation coefficient is

$$
K = B/A, \quad -1 < K < 1.
$$

(3)

Expressions for $A$ and $B$ are given in Ref. [11]. The analytic expressions associated with the coefficients $\epsilon_{V+}^{+A}$ confirm the results of Ref. [4], while the expressions associated with $\epsilon_{V-}^{-A}, \epsilon_{S+P}, \epsilon_{T_{L,R}}$ transcend the earlier work.

3 Analysis of the electron angular correlation

Consider the case of zero effects of all the interactions beyond the SM extended by the $\nu_{MS}$ (i.e., all $\epsilon_{\alpha}^\beta = 0$), which we call the “nonstandard” effects. The values of $K = K_0 = K(\epsilon_{\alpha}^\beta = 0)$ for various decaying nuclei are given in Table 2.

| Model          | $K$ (GeV) | $K$ (Se) | $K$ (Mo) | $K$ (Te) | $K$ (Xe) |
|----------------|-----------|----------|----------|----------|----------|
| $^{76}$Ge       | 0.81      | 0.88     | 0.88     | 0.85     | 0.84     |

We will concentrate on the case of $^{76}$Ge nucleus in the following. The non-standard terms with $\epsilon_{V+}^{+A}, \epsilon_{T_{L,R}}$ do not change the angular correlation (the value of $K$) and the terms with $\epsilon_{S+P}$ give small corrections to $K_0$. The terms with any other parameters $\epsilon_{\alpha}^\beta$ do change this correlation.
Using Table 1 and taking into account the fact that $|\mu^2|$ are suppressed in comparison with $|\epsilon^2|$ by the factor $m_\ell/m_e$ (the chiral suppression), we find the coefficient $K$ and the set {\epsilon} of nonzero $\epsilon^2$s that change the $1 - 0.81 \cos \theta$ form of the correlation for the SM plus $\nu_{MS}$, see Table 3 (the lower two entries).

| SM extension | {\epsilon} | K         |
|--------------|-----------|-----------|
| $\nu_{MS}$   | $\epsilon_{T_0}$   | $|K| < 1$  |
| $\nu_{MS} + \text{RPV SUSY}$ | $\epsilon_{V_{TA}}$ | $-1 < K < 1$ |
| $\nu_{MS} + \text{RC}$   | $\epsilon_{V_{TA}}$ | $-1 < K < 1$ |

They correspond to the following extensions of the SM: $\nu_{MS}$ plus RPV SUSY [6], $\nu_{MS}$ plus right-handed currents (RC) (connected with right-handed $W$ bosons [4] or LQs [8]). Hence, $K$ can signal the presence of this new physics.

Let us now consider some particular cases for the parameter space. We will analyze only the terms with $\epsilon = 0$ for the fixed value of $\epsilon = 0$. In the model $SU(2) \times SU(2) \times U(1)$ we have

$$\left|\frac{m_W}{m_{W_L}}\right| \left(\frac{\epsilon}{|\epsilon_{V_{TA}}|}\right)^{1/2}, \quad \zeta = -\arctan\left(\frac{|\epsilon_{V_{TA}}|}{\epsilon}\right)$$

for the mass of the right-handed $W$ boson and its mixing angle $\zeta$ with the left-handed one. The correlation among $m_{W_R}$ ($\zeta$), $K$, and $T_{1/2}$ is shown in Fig. 1 left (right) for conservative value $\epsilon = 10^{-6}$ for the mixing parameter $\epsilon = |U_{eR}V_{e\ell}|$. It is clear that the closer is $K$ to 1 for the fixed value of $T_{1/2}$ the stronger is the lower bound on $m_{W_R}$ (the upper bound on $\zeta$). We have also shown that the sensitivity of the angular correlation to the $W_R$ mass increases with decreasing values of the effective Majorana neutrino mass $|\langle m\rangle|$ [11].

Acknowledgments

We thank Alexander Barabash and Fedor Šimkovic for helpful discussions. One of us (DVZ) would like to thank DESY for the hospitality in Hamburg where a good part of this work was done.
Figure 1: Correlation between the right-handed W-boson mass $m_{W^R}$ (left) or the mixing $\zeta$ (right), the angular coefficient, and the half-life $T_{1/2}$ for the $0\nu2\beta$ decay of $^{76}\text{Ge}$.

References

[1] Particle Data Group: W.-M. Yao et al., J. Phys. G33, 1 (2006).
[2] S.R. Elliot, P. Vogel, Ann. Rev. Nucl. Part. Sci. 52, 115 (2002); P. Vogel, arXiv:hep-ph/0611243.
[3] Ya.B. Zel’dovich, M.Yu. Khlopov, JETP Lett. 34, 141 (1981); Sov. Phys. Usp. 24, 755 (1981); M.G. Shchepkin, Sov. Phys. Usp. 27, 555 (1984).
[4] M. Doi, T. Kotani, E. Takasugi, Prog. Theor. Phys. Suppl. 83, 1 (1985).
[5] R.N. Mohapatra, Phys. Rev. D34, 3457 (1986); J.D. Vergados, Phys. Lett. B184, 55 (1987); M. Hirsch, H.V. Klapdor-Kleingrothaus, S.G. Kovalenko, Phys. Rev. Lett. 75, 17 (1995); Phys. Lett. B352, 1 (1995); Phys. Lett. B403, 291 (1997); Nucl. Phys. Proc. Suppl. B52, 257 (1997); Phys. Rev. D57, 1947 (1998); K.S. Babu, R.N. Mohapatra, Phys. Rev. Lett. 75, 2276 (1995); A. Faessler, S.G. Kovalenko, F. Šimkovic, J. Schwieger, Phys. Rev. Lett. 78, 183 (1997).
[6] M. Hirsch, H.V. Klapdor-Kleingrothaus, S.G. Kovalenko, Phys. Lett. B372, 181 (1996); B381, 488 (Erratum) (1996); H. Päs, M. Hirsch, H.V. Klapdor-Kleingrothaus, Phys. Lett. B459, 450 (1999).
[7] H.V. Klapdor-Kleingrothaus, U. Sarkar, Phys. Lett. B554, 45 (2003).
[8] M. Hirsch, H.V. Klapdor-Kleingrothaus, S.G. Kovalenko, Phys. Rev. D54, 4207 (1996).
[9] M. Hirsch, H.V. Klapdor-Kleingrothaus, O. Panelia, Phys. Lett. B374, 7 (1996).
[10] A. Ali, A.V. Borisov, D.V. Zhuridov, arXiv:hep-ph/0606072.
[11] A. Ali, A.V. Borisov, D.V. Zhuridov, Phys. Rev. D 76, 093009 (2007).
[12] H. Päs, M. Hirsch, H.V. Klapdor-Kleingrothaus, S.G. Kovalenko, Phys. Lett. B453, 194 (1999).
[13] G. Gamov, E. Teller, Phys. Rev. 49, 895 (1936); S.F. Novaes, in “Particle and Fields”, Proc. 10th J.A. Swica Summer School, São Paulo, Brazil, 31 Jan – 12 Feb 1999 (World Scientific, Singapore, 2000) [arXiv:hep-ph/0001283].
[14] G. Pantis, F. Šimkovic, J.D. Vergados, A. Faessler, Phys. Rev. C53, 695 (1996).
[15] M. Kortelainen, J. Suhonen, Phys. Rev. C75, 051303 (2007).
[16] C.E. Aalseth et al., Phys. Rev. D70, 078302 (2004).
[17] J.C. Pati, A. Salam, Phys. Rev. D10, 275 (1974); R.N. Mohapatra, J.C. Pati, Phys. Rev. D11, 566, 2558 (1975); G. Senjanovic, R.N. Mohapatra, Phys. Rev. D12, 1502 (1975); R.N. Mohapatra, G. Senjanovic, Phys. Rev. D23, 165 (1981).