Search for New Physics with Neutrinoless Double Beta Decay

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Neutrinoless double beta decay ($0\nu\beta\beta$) is one of the most sensitive approaches to test particle physics beyond the standard model. During the last years, besides the most restrictive limit on the effective Majorana neutrino mass, the analysis of new contributions by the Heidelberg group led to bounds on left-right-symmetric models, leptoquarks and R-parity violating models competitive to recent accelerator limits, which are of special interest in view of the HERA anomaly at large $Q^2$ and $x$. These new results deduced from the Heidelberg-Moscow double beta decay experiment are reviewed. Also an outlook on the future of double beta decay, the GENIUS proposal, is given.

1. Introduction

Double beta decay corresponds to two single beta decays occurring in one nucleus and converts a nucleus ($Z,A$) into a nucleus ($Z+2,A$). While even the standard model allowed process emitting two antineutrinos

$$A^+_2 X \rightarrow A^+_{Z+2} X + 2e^- + 2\nu_e$$

is one of the rarest processes in nature with half lives in the region of $10^{21}-24$ years, more interesting is the search for the neutrinoless mode,

$$A^+_2 X \rightarrow A^+_{Z+2} X + 2e^-$$

which violates lepton number by two units and thus implies physics beyond the standard model.

2. The Heidelberg–Moscow Double Beta Decay Experiment

The Heidelberg–Moscow experiment is a second generation experiment searching for the $0\nu\beta\beta$ decay of $^{76}$Ge. Five crystals with an active mass of 10.96 kg, grown out of 19.2 kg of $^{76}$Ge, are in regular operation as $p$-type HPGe detectors in low level cryostats in the Gran Sasso laboratory, which provides a shielding of 3500 m of water equivalent (mwe). The high source strength of the experiment, the large size of the detectors concentrating the background in the peaks and the excellent energy resolution yield an outstanding position compared with other experiments. It has been described recently in detail in.

Fig. 1 shows the results after 31.8 kg y measuring time for all data corresponding to a half life limit of

$$T_{0\nu\beta\beta}^{1/2} > 1.2 \cdot 10^{25} y.$$  (3)

The limits from the pulse shape data with 15.3 kg y (filled histogram in Fig. 1), corresponding to $T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25} y$, are not yet competitive to the large data set without application of pulse shape analysis. However the background improvement will allow to test the half life region up to $6 \cdot 10^{25} y$, corresponding to a neutrino mass limit of 0.1–0.2 eV, during the next five years.

The standard model allowed $2\nu\beta\beta$ decay is measured with the highest statistics ever reached, containing 21115 events in the energy region of 500–2040 keV, and yields a half life of

$$T_{1/2}^{2\nu\beta\beta} = (1.77_{-0.01}^{+0.01}(\text{stat.)}^{+0.13}_{-0.11}(\text{syst.}) \cdot 10^{21} y.$$ (4)

This result, confirming the theoretical predictions of with an accuracy of a factor $\sim \sqrt{2}$, provides
3. Double Beta Decay and Physics Beyond the Standard Model

3.1. Neutrino Mass

The search for $0\nu\beta\beta$ decay exchanging a massive left–handed Majorana neutrino between two standard model vertices at present provides the most sensitive approach to determine the mass of the neutrino and also a unique possibility to distinguish between the Dirac or Majorana nature of the neutrino. With the recent half life limit of the Heidelberg–Moscow experiment the following limits on effective left–handed neutrino masses can be deduced:

$$\langle m_\nu \rangle \leq 0.45eV \quad (90\% C.L.)$$

$$\langle m_\nu \rangle \geq 7.5 \cdot 10^7GeV \quad (90\% C.L.)$$

Taking into account the uncertainties in the numerical values of nuclear matrix elements of about a factor of 2, the Heidelberg–Moscow experiment, improving its half life limit up to $6 \cdot 10^{25} y$, will test degenerate neutrino scenarios in the next five years.

3.2. Left–Right–Symmetric Models

In left–right symmetric models the left–handedness of weak interactions is explained as due to the effect of different symmetry breaking scales in the left– and in the right–handed sector. $0\nu\beta\beta$ decay proceeds through exchange of the heavy right–handed partner of the ordinary neutrino between right–handed W vertices, leading to a limit of

$$m_{WR} \geq 1.2 \left( \frac{m_N}{1TeV} \right)^{-(1/4)} TeV.$$  \hspace{1cm} (7)

Including a theoretical limit obtained from considerations of vacuum stability one can deduce an absolute lower limit on the right–handed W mass of

$$m_{WR} \geq 1.2 TeV.$$  \hspace{1cm} (8)

3.3. Supersymmetry

Supersymmetry (SUSY), providing a symmetry between fermions and bosons and thus doubling the particle spectrum of the SM, belongs to the most prominent extensions of the standard model. While in the minimal supersymmetric extension (MSSM) R–parity is assumed to be conserved, there are no theoretical reasons for R–parity violation in the low energy regime. Also recent reports concerning an anomaly at HERA in the inelastic $e^+p$ scattering at high $Q^2$ and $x$ renewed the interest in $R_P$–SUSY (see for example [14]). In this case $0\nu\beta\beta$ decay can occur through Feynman graphs involving the exchange of superpartners as well as $R_P$–couplings $\lambda^{111}$. The half–life limit of the Heidelberg–Moscow experiment leads to bounds in a multidimensional parameter space

$$\lambda^{111}_1 \leq 3.2 \times 10^{-4} \left( \frac{m_{\tilde{d}}} {100 GeV} \right)^2 \left( \frac{m_{\tilde{g}}} {100 GeV} \right)^{1/2}$$

(for $m_{\tilde{d}_R} = m_{\tilde{u}_L}$), which are the sharpest limits on $R_P$–SUSY. This limit also excludes the first generation squark interpretation of the HERA events. In the case of R–parity conserving SUSY, based on a theorem proven in [22], the $0\nu\beta\beta$ mass limits can be converted in sneutrino Majorana mass limits being more restrictive than
what could be obtained in inverse neutrinoless double beta decay and single sneutrino production at future linear colliders (NLC) [21].

3.4. Leptoquarks

Leptoquarks are scalar or vector particles coupling both to leptons and quarks, which appear naturally in GUT, extended Technicolor or Compositeness models containing leptons and quarks in the same multiplet. Also production of a scalar leptoquark with mass of $m_{LQ} \simeq 200 \text{GeV}$ has been considered as a solution to the HERA anomaly (see for example [14]). However, TEVATRON searches have set stringent limits of (combined with NLO cross section calculations [23]) $m_{LQ} > 240 \text{GeV}$ for scalar leptoquarks decaying with branching ratio 1 into electrons and quarks. One possibility to keep the leptoquark interpretation interesting is therefore to reduce the branching ratio due to the mixing of different multiplets leading to a significant weakening of the CDF/D0 limits [24]. This kind of mixing can be obtained by introducing a leptoquark–Higgs coupling – which would lead to a contribution to $0\nu\beta\beta$ decay [25]. Combined with the half–life limit of the Heidelberg–Moscow experiment bounds on effective couplings can be derived [26]. Assuming only one lepton number violating $\Delta L = 2$ LQ–Higgs coupling unequal to zero and the leptoquark masses not too different, one can derive from this limit either a bound on the LQ–Higgs coupling

$$Y_{LQ-Higgs} = (\text{few}) \cdot 10^{-6} \quad (10)$$

or a limit implying that HERA does not see Leptoquarks with masses in the range of $O(200\text{GeV})$. This excludes most of the possibilities to relax the TEVATRON bounds by introducing LQ–Higgs couplings to reduce the branching ratio [19].

4. Outlook on the future of double beta decay: The Heidelberg project GENIUS

To render possible a further breakthrough in search for neutrino masses and physics beyond the standard model, recently GENIUS, an experiment operating a large amount of naked Ge–detectors in a liquid nitrogen shielding, has been proposed (and studied in detail in [27]). The possibility to operate Ge detectors inside liquid nitrogen has already been demonstrated by the Heidelberg group and yield an excellent energy resolution and threshold.

Operating 288 enriched $^{76}$Ge detectors with a total mass of 1 ton inside a nitrogen tank of 9 m height and diameter, improves the sensitivity to neutrino masses down to 0.01 eV. This allows to solve the atmospheric neutrino problem, if it is due to $\nu_e \leftrightarrow \nu_\mu$ oscillations, confirm or exclude Majorana neutrinos as hot dark matter in the universe as well as to test SUSY models, leptoquarks and right–handed W–masses comparable to the LHC [27], requiring purity levels less stringent (except for $^{222}$Rn) as already obtained by the CTF (Counting Test Facility) of the Borexino experiment. A ten ton version would probe neutrino masses even down to $10^{-3}$ eV, which would allow to test the large angle MSW solution of the solar neutrino problem. As direct dark matter detection experiment it would allow to test almost the entire MSSM parameter space already in a first step using only 100 kg of enriched or even natural Ge [1,27].

5. Conclusions

Neutrinoless double beta decay has a broad potential to test physics beyond the standard model. The possibilities to constrain neutrino masses, left–right–symmetric models, SUSY and leptoquark scenarios have been reviewed. Experimental limits on $0\nu\beta\beta$ decay are not only complementary to accelerator experiments but at least in some cases competitive or superior to the best existing direct search limits. The Heidelberg–Moscow experiment has reached the leading position among double beta decay experiments and as the first of them now yields results in the sub–eV range for the neutrino mass. A further breakthrough will be possible realizing the GENIUS proposal. For the application of double beta technology in WIMP dark matter search we refer to [28].
REFERENCES

1. H.V. Klapdor–Kleingrothaus, in [20]
2. W.C. Haxton, G.J. Stephenson, Progr. Part. Nucl. Phys. 12 (1984) 409; M. Moe, P. Vogel, Annual Review of Nucl. Part. Science 44 (1994) 247; M. Doi, T. Kotani, E. Takasugi, Progr. Theor. Phys. Suppl. 83 (1985) 1
3. HEIDELBERG–MOSCOW collab., Phys. Rev. D 55 (1997) 54
4. HEIDELBERG–MOSCOW collab., Phys. Lett. B 407 (1997) 219
5. J. Hellmig, PhD thesis, University of Heidelberg, 1996 J. Hellmig, H.V. Klapdor–Kleingrothaus, to be published
6. A. Staudt, K. Muto, H.V. Klapdor–Kleingrothaus, Europhys. Lett. 13 (1990) 31
7. M. Hirsch, H.V. Klapdor–Kleingrothaus, S. G. Kovalenko, H. Päs, Phys. Lett. B 372 (1996) 8; H. Päs et al., in: Proc. Int. Workshop on Double Beta Decay and Related Topics, Trento, 24.4.–5.5.95, World Scientific Singapore; HEIDELBERG–MOSCOW collab., Phys. Rev. D 54 (1996) 3641
8. A.Y. Smirnov, in Proc. of the Internation Conference on High Energy Physics (ICHEP), Warsaw, 1996; D.G. Lee, R.N. Mohapatra, Phys. Lett. B 329 (1994) 463; S.T. Petcov, A.Y. Smirnov, Phys. Lett. B 322 (1994) 109; A. Ioannisyan, J. Valle, Phys. Lett. B 332 (1994) 93; H. Fritzsch, Z.Z. Xing, Phys. Lett. B 372 (1996) 265 R.N. Mohapatra, S. Nussinov Phys. Lett. B 346 (1995) 75
9. R.N. Mohapatra, Phys. Rev D 34 (1986) 3457
10. M. Hirsch, H.V. Klapdor–Kleingrothaus, O. Panella, Phys. Lett. B 374 (1996) 7
11. L. Hall, M. Suzuki, Nucl. Phys. B 231 (1984) 419; D. Brahm, L. Hall, Phys Rev D 40 (1989) 2449; K. Tavvakis Phys. Lett. B 382 (1996) 251; G.F. Guidice, R. Rattazzi, hep-ph/9604339 R. Barbieri, A. Strumia, Z. Berezhiani, hep-ph/9704273 K. Tavvakis, Phys. Lett B 383 (1996) 307; R. Hempfling, Nucl. Phys. B 478 (1996) 3: A. Y. Smirnov, F. Vissani, Nucl. Phys. B 460 (1996) 37
12. M.C. Bento, L. Hall, G.G. Ross, Nucl. Phys. B 292 (1987) 400; N. Ganoulis, G. Lazarides, Q. Shafi, Nucl. Phys. B 323 (1989) 374; A. Faraggi, Phys. Lett B 398 (1997) 95; A. Faraggi, in: [20]
13. C. Adloff et al. (H1 collab.), Z.Phys. C 74 (1997) 191; J. Breitweg et al. (ZEUS collab.) Z.Phys. C 74 (1997) 207
14. J. Kalinowski, R. Rueckl, H. Spiesberger, P. M. Zerwas, Z.Phys. C 74 (1997) 595
15. M. Hirsch, H.V. Klapdor–Kleingrothaus, S.G. Kovalenko, Phys. Rev. Lett. 75 (1995) 17
16. M. Hirsch, H.V. Klapdor–Kleingrothaus, S. Kovalenko, Phys. Lett. B 352 (1995) 1
17. M. Hirsch, H.V. Klapdor–Kleingrothaus, S. Kovalenko, Phys. Rev. D 53 (1996) 1329
18. M. Hirsch, H.V. Klapdor–Kleingrothaus, S.G. Kovalenko, Phys. Lett. B 372 (1996) 181
19. M. Hirsch et al., in [20]
20. H.V. Klapdor–Kleingrothaus, H. Päs (Eds.): Beyond the Desert – Accelerator and Non-Accelerator Approaches, Proc. Int. Workshop on Particle Physics beyond the Standard Model, Castle Ringberg, June 8-14, 1997, IOP Publ., Bristol, Philadelphia
21. M. Hirsch, H.V. Klapdor–Kleingrothaus, S.G. Kovalenko, Phys. Lett. B 398 (1997) 311 and 403 (1997) 291; M. Hirsch, H.V. Klapdor–Kleingrothaus, S.G. Kovalenko, Phys. Rev. D in press, 1997; S. Kolb, M. Hirsch, H.V. Klapdor–Kleingrothaus, S. Kovalenko, in [20]
22. J. Conway, in [20]; S. Eno, in [20]
23. M. Krämer, T. Plehn, M. Spira, P. M. Zerwas Phys. Rev. Lett. 79 (1997) 341; M. Krämer, in [20]
24. K. S. Babu, C. Kolda, J. March-Russell, hep-ph/9705414
25. M. Hirsch, H.V. Klapdor–Kleingrothaus, S.G. Kovalenko, Phys. Lett. B 378 (1996) 17
26. M. Hirsch, H.V. Klapdor–Kleingrothaus, S.G. Kovalenko Phys. Rev. D 54 (1996) R4207
27. J. Hellmig, H.V. Klapdor–Kleingrothaus, Z. Phys. A, in press 1997; H.V. Klapdor–Kleingrothaus, M. Hirsch, Z. Phys. A, in press 1997; H.V. Klapdor–Kleingrothaus, Y. Ramachers, in [20]
28. L. Baudis et al., these proceedings