NEW PHYSICS POTENTIAL OF DOUBLE BETA DECAY AND DARK MATTER SEARCH *

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The search for neutrinoless double beta decay and WIMP dark matter has a broad potential to test particle physics beyond the standard model. During the last years, the analysis of various contributions to the double beta decay rate by the Heidelberg group led, besides the most restrictive limit on the effective Majorana neutrino mass, to bounds on left-right-symmetric models, leptoquarks and supersymmetry. In a general framework bounds on arbitrary lepton number violating theories can be derived. Using double beta technology for direct dark matter detection, stringent limits on the spin-independent WIMP–nucleon interaction have been obtained. These results deduced from the Heidelberg-Moscow double beta decay experiment are reviewed. Also an outlook on the future of double beta decay and dark matter search, the GENIUS proposal, is given.

1 Double Beta Decay – the basic mechanism

Double beta decay ($0\nu\beta\beta$) 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 (SM) allowed process emitting two antineutrinos

$$\frac{2}{2}X \rightarrow \frac{2}{2}Z + 2e^- + 2\bar{\nu}_e$$

(1)

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,

$$\frac{2}{2}X \rightarrow \frac{2}{2}Z + 2e^-$$

(2)

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

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 86% enriched $^{76}$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

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Figure 1: Comparison of running and proposed double beta experiments. Shown is the sensitivity on the effective neutrino Majorana mass. The filled bars correspond to the present status, open bars correspond to ‘safe’ expectations for the year 2003 and dashed lines correspond to long-term planned or hypothetical experiments.

the background in the peaks and the excellent energy resolution yield an outstanding position compared with other experiments (see Fig. 1). It has been described recently in detail in 1,3,4.

Fig. 2 shows the results after 35 kg y measuring time for all data corresponding to a half life limit of $T_{1/2}^{0\nu\beta\beta} > 1.2 \cdot 10^{25} y$. (3)
The limits from the pulse shape data with 18 kg y (filled histogram in Fig. 2), are just becoming competitive to the large data set without application of pulse shape analysis. 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 SM allowed $2\nu\beta\beta$ decay is measured with high statistics, containing 21115 events in the energy region of 500-2040 keV, and yields a half life of $T_{1/2}^{2\nu\beta\beta} = (1.77^{+0.01}_{-0.01} (\text{stat.}) \times 0.13 (\text{syst.})) \cdot 10^{23} y$. (4)

This result, confirming the theoretical predictions of $\nu$, with an accuracy of a factor $\sim \sqrt{2}$, provides a consistency check of nuclear matrix element calculations. It also for the first time opens up the possibility to search for deviations of the $2\nu\beta\beta$ spectrum such as those due to emission of exotic scalars.

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 SM vertices at present provides the most sensitive approach to determine an absolute neutrino mass 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\cite{4}, the following limits on effective left–handed neutrino masses can be deduced:

\[
\langle m_\nu \rangle \leq 0.44\,eV \quad (90\%\ C.L.) \tag{5}
\]
\[
\langle m_\nu \rangle \geq 7.5 \cdot 10^7\,GeV \quad (90\%\ C.L.) \tag{6}
\]

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\cite{8} 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

\[
m_{WR} \geq 1.2 \left( \frac{m_N}{1\,TeV} \right)^{-\frac{1}{4}} \, TeV. \tag{7}
\]
Including a theoretical limit obtained from considerations of vacuum stability one can deduce an absolute lower limit on the right–handed W mass of

\[ m_{W_R} \geq 1.2 \text{TeV}. \]  

(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 SM. While in the minimal supersymmetric extension (MSSM) R–parity is assumed to be conserved, there are no theoretical reasons for R_p conservation and several GUT and Superstring models require R–parity violation in the low energy regime. Also the reports concerning an anomaly at HERA have renewed the interest in R_P–SUSY (see for example ). In this case 0νββ 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

\[ \lambda'_{111} \leq 3.2 \times 10^{-4} \left( \frac{m_{\tilde{q}}}{100 \text{GeV}} \right)^2 \left( \frac{m_{\tilde{g}}}{100 \text{GeV}} \right)^{1/2} \]  

(9)

(for \( m_{\tilde{d}_R} = m_{\tilde{u}_L} \)), which are the sharpest limits on R_P–SUSY (see Fig. 3).

In addition 0νββ decay is not only sensitive to \( \lambda'_{111} \). Taking into account the fact that the SUSY partners of the left and right–handed quark states can mix with each other, new diagrams appear in which the neutrino mediated double beta decay is accompanied by SUSY exchange in the vertices . A calculation of previously neglected tensor contributions to the decay rate allows to derive improved limits on different combinations of \( \lambda' \). Assuming the supersymmetric mass parameters of order 100 GeV, the half life limit of the Heidelberg–Moscow Experiment implies:

\[ \lambda'_{113} \lambda'_{131} \leq 5.8 \times 10^{-8}, \quad \lambda'_{112} \lambda'_{121} \leq 1.7 \times 10^{-6} \]

In the case of R–parity conserving SUSY, based on a theorem proven in , the 0νββ mass limits can be converted in sneutrino Majorana mass term limits being more restrictive than what could be obtained in inverse neutrinoless double beta decay and single sneutrino production at future linear colliders (NLC).

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 the production
of a scalar leptoquark with mass of $m_{LQ} \simeq 200\,\text{GeV}$ has been discussed as possible effect in recent accelerator experiments such as HERA (see for example [14]). To keep the leptoquark option interesting in view of stringent TEVATRON limits ($m_{LQ} > 240\,\text{GeV}$ for scalar leptoquarks decaying with branching ratio 1 into electrons and quarks [25]), possibilities to reduce the branching ratio due to the mixing of different multiplets [26] have been examined. 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 [27]. Combined with the half-life limit of the Heidelberg–Moscow experiment bounds on effective couplings can be derived [28]. 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

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

(10)

or a limit excluding Leptoquarks with masses in the range of $\mathcal{O}(200\,\text{GeV})$. This excludes most of the possibilities to relax the TEVATRON bounds by introducing LQ–Higgs couplings to reduce the branching ratio [22].
3.5 A general context for the double beta decay rate

The variety of non–SM couplings appearing in different contributions to $0\nu\beta\beta$ decay led to the idea to construct the general double beta decay rate allowed by Lorentz–invariance\textsuperscript{29,30}. This approach allows to constrain lepton number violating parameters in arbitrary models.

For the long range part of the decay rate with two separable vertices and light neutrino exchange in between, one has to consider the Lorentz-invariant contractions of six projections with defined helicity both for the leptonic and hadronic current. The general Lagrangian can be written in terms of effective couplings $\epsilon_{\alpha}^{\beta}$, which correspond to the pointlike vertices at the Fermi scale so that Fierz rearrangement is applicable:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \left\{ j_{V-A}^{\nu} j_{V-A,\mu}^T + \sum_{\alpha,\beta} \epsilon_{\alpha}^{\beta} j_{\alpha}^T j_{\beta}^T \right\}$$

with the combinations of hadronic and leptonic Lorentz currents of defined helicity $\alpha, \beta = V - A, V + A, S - P, S + P, T_L, T_R$. The prime indicates the sum runs over all contractions allowed by Lorentz–invariance, except for $\alpha = \beta = V - A$. Here $\epsilon_{\alpha}^{\beta}$ denotes the strength of the non–SM couplings. For the helicity suppressed terms proportional to the (from below) unconstrained neutrino mass no limit can be derived and terms proportional $(\epsilon_{\alpha}^{\beta})^2$ can be neglected. The limits on the remaining non–SM couplings derived in in $s$-wave approximation and evaluated “on axis” are\textsuperscript{29,30}: $\epsilon_{V+A}^{V+A} < 7.0 \cdot 10^{-7}$, $\epsilon_{V-A}^{V-A} < 4.4 \cdot 10^{-9}$, $\epsilon_{S+P}^{S+P} < 1.1 \cdot 10^{-8}$, $\epsilon_{S-P}^{S-P} < 1.1 \cdot 10^{-8}$, $\epsilon_{T_R}^{T_R} < 2 \cdot 10^{-9}$, $\epsilon_{T_L}^{T_L} < 7 \cdot 10^{-10}$. A further step will consider the short range part of the general decay rate.

4 WIMP Dark Matter Search with Double Beta Experiments

Weakly interacting massive particles (WIMPs) such as the lightest supersymmetric particle (LSP) are major candidates for the cold component of nonbaryonic dark matter in the universe. Due to its low background properties double beta technology can also find applications in the search for direct detection of WIMPs. The Heidelberg–Moscow Experiment, without being specially designed for this purpose, gave the most stringent limits on WIMPs for several years\textsuperscript{32}. New results with 0.69 kg y of measurement reached a background level of 0.042 cts/(kg d keV) in the region between 15 keV and 40 keV. The derived limit excludes WIMPS with masses greater than 13 GeV and cross sections as low as $1.12 \cdot 10^{-5}$ pb (see Fig. 4). These are the most stringent limits on spin-independent interactions using only raw data\textsuperscript{33}. 
5 Outlook on the future: GENIUS

To render possible a further breakthrough in search for neutrino masses and physics beyond the SM, recently GENIUS, an experiment operating a large amount of naked Ge–detectors in a liquid nitrogen shielding, has been proposed \cite{1}, and studied in detail in \cite{34,35}. The possibility to operate Ge detectors inside liquid nitrogen has already been demonstrated by the Heidelberg group. An excellent energy resolution and threshold is obtained.

Operating 288 enriched \(^{76}\text{Ge}\) detectors with a total mass of 1 ton inside a nitrogen tank of 11-12 m height and diameter, improves the sensitivity to neutrino masses down to 0.01 eV. This allows to definitely exclude \(\nu_e \leftrightarrow \nu_\mu\) oscillations as solution for the atmospheric neutrino problem (already disfavored
Figure 5: Sensitivity of the GENIUS proposal on the parameters $\Delta m^2$ and $\sin^2 2\theta$, compared with various hints and bounds from neutrino oscillation experiments. The solid lines indicate the sensitivity of the 1 ton version, the dashed lines for the 10 ton version, both for different hierarchical models with neutrino mass ratios of (from top to bottom) $m_1/m_2 = 0, 0.01, 0.1, 0.5$ (from [31]).
from the recent CHOOZ and Super-K results, 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.

The required purity levels for the liquid nitrogen are (except for $^{222}$Rn and $^{40}$K) less stringent than already obtained by the Borexino Collaboration for the liquid scintillator. A ten ton version would probe neutrino masses even down to $10^{-3}$ eV. This way it tests the large angle MSW solution – and in less hierarchical scenarios even the small angle solution – of the solar neutrino problem for all oscillation channels (see Fig. 5). As direct dark matter detection experiment it would allow to test almost the entire MSSM parameter space (see Fig. 4) already in a first step using only 100 kg of enriched or even natural Ge.

6 Conclusions

Neutrinoless double beta decay and dark matter search belong to the most sensitive approaches with great perspectives to test particle physics beyond the SM.

The possibilities to use $0\nu\beta\beta$ decay for constraining neutrino masses, left–right–symmetric models, SUSY and leptoquark scenarios, as well as effective lepton number violating couplings, 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 yields results in the sub–eV range for the neutrino mass.

Direct WIMP detection experiments can compete with recent and future accelerator experiments in the search for SUSY and experiments using double beta technology belong to the most promising approaches in this field of research. Here the Heidelberg–Moscow experiment yields the most stringent limits on spin–independent WIMP interactions using only raw data.

A further large breakthrough, both for double beta decay and dark matter search, will be possible realizing the GENIUS proposal.

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