Hot Dark Matter and the Role of Neutrinoless Double Beta Decay

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Third Indication for BEYOND SM physics

NEUTRINOLESS DOUBLE BETA DECAY

Violation of TOTAL lepton number
Long Running Underground Experiments:

(more than 25 years!!)  (more than 20 years!!)  13 years!!

1990-2003

Chlor-Argon Experiment Prof. R. Davis
Baksan Underground Scintillation Telescope
Double Beta HEIDELBERG-MOSCOW Experiment in Gran-Sasso

(more than 7 years!!)

SAGE, Baksan
GALLEX, Gran Sasso
KAMIOKANDE and SuperK
DAMA, Gran Sasso

(more than 10 years!!)  (more than 15 years!!)
Development of sensitivity in double beta decay experiments in last 20 years

- 1987 discovery of $2\nu\beta\beta$ (for $^{82}$Se) with detectors (non-geochemical)
  
  \[(1.1 \pm 0.8) \times 10^{20} \text{ y} \quad (68\% \text{ c.l. } 2.2 \sigma)\]
  
  (35 events)
  
  M. Moe et al., PRL 59 (1987) 989

- 2003 $2\nu\beta\beta$ decay (for $^{76}$Ge)

  \[(1.74 \pm 0.18) \times 10^{21} \text{ y} \quad (160,000 \text{ events})\]

  First observation of $0\nu\beta\beta$ (76 Ge)

  \[(1.19 \pm 0.37) \times 10^{25} \text{ y} \quad (99.7\% \text{ c.l. } 4.2 \sigma)\]

  H.V. Klapdor-Kleingrothaus et al., PLB 586 (2004) 198-212

Heidelberg, 27.04.2004
DOUBLE-BETA Experiments yield contributions to New Physics in many fields

- Lepton Number Violation?
- Nature of $\nu'_s$ (Dirac - Majorana)
- Light $\nu$ Masses and Mixings
- Heavy $\nu$ Masses
- Compositeness
- Leptoquarks
- SUSY
  - $R$ - Parity Violation
  - $R$ - Parity Conserving Sneutrino Masses
- Superstrings (Lorentz Invariance, Equivalence Principle)

Sensitivity:
Unique, Better than High-Energy Colliders now:
LEP II HERA B TEVATRON NLC
Future (GENIUS):
LHC NLC

By Search for Cold Dark Matter
--- SUSY --- Neutralino Masses and Structure
**DOUBLE BETA DECAY**

\[ \begin{array}{c}
\text{Z} \ X \ N \rightarrow A \ X_{A-Z+2} \ N_{A-Z+2} + 2e^- (+2\nu)
\end{array} \]

35 potential \( \beta^-\beta^- \) emitters

- **2\( \nu \):**
  - allowed
  - 9 cases observed
  - \( \Delta l = 0 \)
  - \( ^{82}\text{Se}, ^{100}\text{Mo}, ^{76}\text{Ge}, \ldots \)\n
- **0\( \nu \):**
  - only allowed
  - if
  - a) \( V+A \)
  - or
  - b) \( m^M > 0 \)
  - \( \Delta l = 2 \)

\( W_{0\nu} \sim |M_{0\nu}|^2 < m_\nu >^2 \)

\( 0\nu\beta\beta \) beyond standard model!

(B−L) not conserved!

\[ < m_\nu > = |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 + |U_{e3}|^2 e^{-i2\beta} m_3 \]
What is double beta decay?

\[ 2\nu\beta\beta : \frac{A}{Z}X \rightarrow \frac{A}{Z+2} X + 2e^- + 2\bar{\nu}_e \]

- SM allowed: \( T_{1/2}^{2\nu} \approx 10^{19} - 10^{24} \text{y} \)
- Observed for 10 isotopes

\[ 0\nu\beta\beta : \frac{A}{Z}X \rightarrow \frac{A}{Z+2} X + 2e^- \]

- Physics beyond SM (\( L \) violation)

\[ \Delta L = 2; \quad B - L \text{ not conserved} \]

Sensitive on:

- Effective Neutrino–Majorana mass:
  \[ \langle m_\nu \rangle = \sum' U_{e j}^2 m_j \]
  \[ \omega_{00} \sim 1M_{0,0}^2 < m_\nu^2 \]

- \( L \)-violating parameters
  (SUSY, Leptoquarks, \( W_R \),...)
for $\phi\beta\beta$ decay within $R$-parity viol. superym.m.

$\bar{d} \rightarrow \bar{u}$
$\bar{d} \rightarrow \bar{u}$

$\bar{d} \rightarrow \bar{u}$
$\bar{d} \rightarrow \bar{u}$

$R_p$ conserving SUSY contributions to $\phi\beta\beta$-decay

Heavy neutrino exch.
Double Beta Decay - more general:

0νββ =
- ν = ν^C
- W^R, N_R
- Leptoquarks
- SUSY-particles
- Compositeness

Important theorem (Schechter & Valle 1981):
0νββ amplitude ≠ 0 ⇔ m^{(M)}_ν ≠ 0
(valid for any gauge model with spontaneously broken symmetry at weak scale)

Extension to SUSY (Hirsch, K.-K., Kovalenko 1997):
0νββ amplitude ≠ 0 ⇔ m^{(M)}_ν ≠ 0 ⇔ \tilde{m}^{M}_ν ≠ 0
Double Beta Observable:
\[ \langle m \rangle = \left| \sum U_{ei}^2 m_i \right| \]

\( U_{ei} \) elements of neutrino mixing matrix

For three-neutrino case
\[ \langle m \rangle = | m^{(1)}_{ee} | + e^{i\Phi_2} | m^{(2)}_{ee} | + e^{i\Phi_3} | m^{(3)}_{ee} | \]

where \( m^{(i)}_{ee} = | m^{(i)}_{ee} | e^{i\Phi_i} \) are the contributions to \( \langle m \rangle \) from the individual mass eigenstates, with \( \Phi_i \) relative Majorana phases. In terms of oscillation parameters
\[
\begin{align*}
| m^{(1)}_{ee} | &= | U_{e1} |^2 m_1 \\
| m^{(2)}_{ee} | &= | U_{e2} |^2 \sqrt{\Delta m_{21}^2 + m_1^2} \\
| m^{(3)}_{ee} | &= | U_{e3} |^2 \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2}
\end{align*}
\]

Some of the parameters in (*) can be fixed or restricted from oscillation data:

**Normal hierarchy:** \( \Delta m_{21}^2, | U_{e1} |^2 = \cos^2 \Theta_s \) and \( | U_{e2} |^2 = \sin^2 \Theta_s \) fixed by solar neutrino (LMA or LOW solution); \( \Delta m_{32}^2 \) fixed by atmospheric neutrinos (Large Mixing)

**Inverse hierarchy:** exchange \( \nu_1 \leftrightarrow \nu_3 \) in equations (*)

\( m_1 \) free parameter, phases \( \Phi_i \) - connected with CP violation

\( 0\nu \beta\beta \) yields information on neutrino mass spectrum and absolute mass scale

Increase of \( m_1 \) level of degeneracy increases distinguish two extreme case

**Hierarchical Spectrum:** \( m_1^2 \ll \Delta m_{21}^2 \ll \Delta m_{31}^2 \ll m_1^2 \)

**Degenerate Spectrum:** \( \Delta m_{21}^2 \ll \Delta m_{31}^2 \ll m_1^2 \)
HEIDELBERG- MOSCOW, $0\nu\beta\beta$ Positive - Evidence

$\langle m_{ee} \rangle$ (eV)

- $WMAP'03$
- $0.9$ eV
- $0.4$ eV
- $0.12$ eV

BEST VALUE $4.2\sigma$

HEIDELBERG-2003 MOSCOW

CUORE 600kg project

MOON 3.3t project

GENIUS 1t, EXO 10t projects

GENIUS 10t project


HEIDELBERG-MOSCOW, FIRST $0\nu\beta\beta$ Positive - Evidence

Best Value
HEIDELBERG-2001
MOSCOW

CUORE 600kg project
MOON 3.3t project
GENIUS 1t, EXO 10t projects
GENIUS 10t project

Best Value of the Effective Neutrino Mass 0.39 eV
95% c.l. Range: ~ 0.05 - 0.84 eV Allowing Already for an Uncertainty of the Nuclear Matrix Element of a Factor of 2
The Present (2004) Most Sensitive $\beta\beta$ -Experiments:

Matrix elements from A. Staudt, K. Muto, H. V. Klapdor-Kleingrothaus, Europh. Lett. 13(1990)17

1. HEIDELBERG - MOSCOW  

$T_{1/2} = (0.69 - 4.18) \times 10^{25} \text{ y} \quad (3\sigma\text{ range})$

$m_\nu = (0.24 - 0.58) \text{ eV} \quad (99.7\%\text{ c.l.}), \quad 71.7 \text{ kg y} \quad !!!! \quad ^{76}\text{Ge}$

Best Values: $4.2\sigma \quad m_\nu = 0.4 \text{ eV} \quad T_{1/2} = 1.2 \times 10^{25} \text{ y}$


2. Level of $10^{24} \text{ y}$  

Geochemical Experiment - 

(68\% - 90\% c.l.)


DAMA Liquid Xenon -


Oroville, California, Dam; ITEP, Moscow -


IGEX, finished operation end 1999  


$m_\nu < 0.7 \text{ eV} \quad $\text{see hep-ph/0403056 and Phys. Rev. D 2004, H.V.K-K et al.}$

3. Level of $10^{23} \text{ y}$  

Gotthard- Time Projected Chamber

(90\% c.l.)


MIBETA-Cuoricino - Cryodet., finished in 2002, start in 2003


hep-ex/0302021

mistake in analysis
HEIDELBERG-MOSCOW \(\beta \beta\) -Experiment

H.V. Klapdor-Kleingrothaus,
\(^*\) Spokesman of HEIDELBERG-MOSCOW and GENIUS Collaborations

\[
T_{1/2} \sim a \sqrt{\frac{M}{\Delta E B}}
\]

a : isotopical abundance
M : active mass
t : measuring time
\(\Delta E\) : energy resolution
B : background count rate

http://www.mpi-hd.mpg.de/non_acc
HEIDELBERG - MOSCOW Experiment

1990 - 2003  11.5 kg of Enriched $^{76}$Ge (86%) in 5 High-Purity Ge Detectors in GRAN-SASSO

Runs Since 1990, in Final Form Since 1996, Reaches with 'a few kg Experiment' the Sensitivity of  a 'order of ton' Experiment.

( 10 kg $\approx= 1.2$ ton Natural Ge )

1. Largest Source Strength in Operation $\sim 11.0$ kg
2. Lowest Background in Operation $\sim 0.17c$/kgykeV
3. Highest Efficiency for Detection of a $\beta\beta$ events $\sim 100\%$
4. Highest Energy Resolution $\sim 3.5$ keV
5. Highest 'Duty Cycle' $\sim 80\%$
6. Highest Collected Statistics $\sim 65$ kg y

$\gg 10$ Years ahead of all running $\beta\beta$ experiments

$\uparrow$ Since 1992/93 Worldwide Best Value on $m_{\nu}$

(before that since $\sim 1985$ D. Caldwell and I. Kirpichnikov)
History of HEIDELBERG-MOSCOW

1995

Det. 1,2,3,5

1995

1995-Nov. 2003

Det. 1,2,3,5

after 30 Nov. 2003

Det. 1,2,3,5

Det. 4

Since 1995

Now, since December 2003

Det. 4

Det. 1,2,3,5
Most important block of data of the HEIDELBERG-MOSCOW experiment, 56.67 kg y 1995 - 2003

In 1995:
- installation of detectors 4,5
- neutron shield (boron-polyethylene, 10 cm)
- active anticoincidence shield against muons
- completely new electronics - 250MHz flash ADC’s for digital measurement of pulse shapes for 4 largest detectors (8 bit)
  - energy signals by 13 bit ADC’s

Data acquisition on VME basis


4.1 $\sigma$ signal (56.67 kg y)
in H.V. Klapdor-Kleingrothaus et al. NIM A 2004, in Press

<table>
<thead>
<tr>
<th>Detector Number</th>
<th>Life Time (days)</th>
<th>Date Start - End</th>
<th>Life Time accepted for Analysis</th>
<th>Background* (counts/keV y kg)</th>
<th>2000-2100 keV</th>
<th>PSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>1237.0</td>
<td>8/90 - 8/95</td>
<td>930.9</td>
<td>856.43</td>
<td>0.31</td>
<td>no</td>
</tr>
<tr>
<td>No. 2</td>
<td>1070.0</td>
<td>9/91 - 8/95</td>
<td>977.2</td>
<td>2750.28</td>
<td>0.21</td>
<td>no</td>
</tr>
<tr>
<td>No. 3</td>
<td>834.7</td>
<td>9/92 - 8/95</td>
<td>753.1</td>
<td>1750.2</td>
<td>0.20</td>
<td>no</td>
</tr>
<tr>
<td>No. 4</td>
<td>147.6</td>
<td>1/95 - 8/95</td>
<td>61.0</td>
<td>139.99</td>
<td>0.43</td>
<td>no</td>
</tr>
<tr>
<td>No. 5</td>
<td>48.0</td>
<td>12/94 - 8/95</td>
<td>—</td>
<td>—</td>
<td>0.23</td>
<td>no</td>
</tr>
</tbody>
</table>

After summing of all 5 detectors over period 1990 - 1995
Accepted life time = 15.05 kg y

<table>
<thead>
<tr>
<th>Detector Number</th>
<th>Life Time (days)</th>
<th>Date Start - End</th>
<th>Life Time accepted for Analysis</th>
<th>Background* (counts/keV y kg)</th>
<th>2000-2100 keV</th>
<th>PSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>2123.90</td>
<td>11/95 - 5/03</td>
<td>2090.61</td>
<td>1923.36</td>
<td>0.20</td>
<td>no</td>
</tr>
<tr>
<td>No. 2</td>
<td>1953.65</td>
<td>11/95 - 5/03</td>
<td>1894.11</td>
<td>5223.96</td>
<td>0.11</td>
<td>yes</td>
</tr>
<tr>
<td>No. 3</td>
<td>2120.22</td>
<td>11/95 - 5/03</td>
<td>2079.46</td>
<td>4832.67</td>
<td>0.17</td>
<td>yes</td>
</tr>
<tr>
<td>No. 4</td>
<td>2123.90</td>
<td>11/95 - 5/03</td>
<td>1384.69</td>
<td>3177.86</td>
<td>0.21</td>
<td>yes</td>
</tr>
<tr>
<td>No. 5</td>
<td>2110.66</td>
<td>11/95 - 5/03</td>
<td>2076.34</td>
<td>5535.52</td>
<td>0.17</td>
<td>yes</td>
</tr>
</tbody>
</table>

After summing of all 5 detectors over period 1995 - 2003
Accepted life time = 56.655 kg y
Background = 0.113 + 0.007 events keV y kg **
or 0.16 events keV y kg according to*

Collected statistics and background numbers in the different data acquisition periods for the enriched detectors of the HEIDELBERG-MOSCOW experiment.
for the period 1990 - 2003. The life times of the experiment given in the second column the data sets rejected. *) - Without PSA method; background determined by averaging rate in intervall 2000-2100 keV.

**)From 11.1995 till 05.2003, background determined at Q_{BB} from fit of spectrum in range 2000-2060 keV.
HEIDELBERG-MOSCOW Data
Period: August 1995 - May 2003
Reliability of Data Acquisition and Data

The strong Bi lines at 609.31 (left), 1764.5 and 2204.2 keV (right)

H.V. Klapdor-Kleingrothaus et al., NIM A (2004), in Press
HEIDELBERG-MOSCOW EXPERIMENT
Total Spectrum (low-energy part) of all 5 Detectors
(2003 kgy)
H. V. Klapdor-Kleingrothaus et al.
NIM A 2004, in Press
vol. A 522
P. 341-
406
HEIDELBERG-MOSCOW EXPERIMENT
Total Spectrum (higher-energy part) of all 5 Detectors
(Feb 1995 - May 2003) 40 kg
H.V. Klapdor-Kleingrothaus et al.
NIM A 2004, in Press. vol. A522,
pp. 371-406
Sum spectrum of the $^{76}$ Ge detectors Nr. 1,2,3,4,5

HEIDELBERG-MOSCOW, 2004

Period: August 1990 - May 2003

$T^{0\nu}_{1/2} = (0.69 - 4.18) \times 10^{-25}$ y

$m_\nu = (0.24 - 0.58)$ eV

4.2 $\sigma$

Counts/keV

Energy, keV

G. Doussset et al., PRL 86 (2001) 4259

$Q=2039.006(50)$ keV

H.V. Klapdor-Kleingrothaus et al. NIM A 2004, in Press
The probability that the four Bi lines, and the line at $Q_{\beta\beta}$, are produced by fluctuations, is $< 10^{-20}$
natural Germanium detectors

High-purity Germanium detectors

Maximum Likelihood Method  Bayes method

UCBS/LBL,

ITEP/YePI spectrum,
A.A. Vasenko et al., Mod.Phys.Lett. A 5 (1990) 1299,
I. Kirpichnikov,
Preprint ITEP (1991)

IGEX,
C.E. Aalseth et al.,
Yad. Fiz. 63 (2000) 1298

H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Klevshchinskaya, Tomoei
NIM A 510 (2003) 281 - 289
Earlier criticism **strongly rejected:**

- Extra measurement with $^{226}$Rn ( $^{214}$Bi) source
  Published in NIM A511 (2003) 335 - 340, H.V. Klapdor-Kleingrothaus et al.
  and hep-ex/0202018 (first version)

- Simulations of dependence of size of energy interval of analysis
  Published in NIM A510 (2003) 281 - 289, H.V. Klapdor-Kleingrothaus et al.

and hep-ex/0202018 (first version)
H.L. Harney, hep-ph/0205293
A. Ianni., in Press NIM A (2004?)

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*Heidelberg, 27.04.2004*
Simulated background components of the $^{76}$ Ge detectors Nr. 1,2,3,4,5
HEIDELBERG-MOSCOW, 2004

20.11.1995 - 16.04.2002 49.59 kg y

A bin width of 2 keV was chosen. The simulated spectrum is not folded with the energy resolution of the detectors.

H.V. Klapdor-Kleingrothaus et al., NIM A 2004, in Press.
Background components

- Natural decay-chain of $^{232}$Th and $^{238}$U
- Natural radioactivity of $^{40}$K
- Anthropogenic radionuclides
  $^{125}$Sb, $^{134}$Cs, $^{137}$Cs, $^{207}$Bi
- Cosmogenic produced radionuclides
  $^{54}$Mn, $^{57}$Co, $^{58}$Co, $^{60}$Co, $^{65}$Zn
- Bremsstrahlung of $\beta$-electrons from $^{210}$Bi-decay
- Myons
- Neutrons

Building the background-model:

→ determine the activity of the components
→ determine the localisation of the components

→ Simulate the background components in their localisation
Simulated geometry of the detector chamber inside the lead shield in setup. The colours indicate different materials: green = vespel, yellow = teflon, magenta = iron, red (transparent) = copper

(see Ch. Doerr and H.V. Klapdor-Kleingrothaus, NIM A 513 (2003) 596-621)
HEIDELBERG-MOSCOW EXPERIMENT

Total Spectrum of all 5 Detectors  (Nov. 1995 - June 2002) 49.59 kgy
HEIDELBERG-MOSCOW EXPERIMENT

Total Spectrum of all 5 Detectors  
(Dec. 1995-June 2002) 49.59 kgy
HEIDELBERG-MOSCOW EXPERIMENT
Total Spectrum of all 5 Detectors
(Nov. 1995 - June 2002) 49.59 kg y

Counts per 20 keV

E [keV]

Counts per 20 keV

E [keV]

57 Co
58 Co
65 Zn
54 Mn
60 Co
134 Cs
207 Bi
125 Sb
137 Cs
Neutron capture:

\[ {}^{76}\text{Ge} (n, \gamma) {}^{76}\text{Ge} \rightarrow \beta^- \rightarrow \gamma \]

Simulation yields, for neutron background in Gran Sasso, 0.15 counts in the range 1990-2110 keV.

2037.8 keV transition not visible

If large neutron flux assumed, then important check (see Table of Isotopes):

<table>
<thead>
<tr>
<th>relative intensities of</th>
<th>2037.8</th>
<th>0.061</th>
</tr>
</thead>
<tbody>
<tr>
<td>relative intensities of</td>
<td>2000.1</td>
<td>0.56</td>
</tr>
</tbody>
</table>

So 2000.1 keV line is factor 10 stronger than 2037.8 keV.

But: no 2000.1 keV line in spectrum!

Others: \[ {}^{74}\text{Ga} (\mu - \text{capture}) \]

\{ 2036.2 \text{ keV} 0.17 \]
\{ 1999.3 \text{ keV} 0.4 \]
\{ 2353.5 \text{ keV} 45\% \]
Simulated contribution to the measured spectrum of the radioactive decays of the isotopes $^{75}$Ge and $^{77}$Ge produced via neutron capture in the detectors. The most prominent line in the simulated spectrum results from the emission with 264.7 keV $^{77}$Ge, intensity 11\% and 264.4 keV (~$^{77}$Ge, 54\%). Further lines in the simulation are located at 211.0 (30.8\%), 215.5 (28.6\%) and 416.3 (21.8\%) keV, they all come from $^{77}$Ge.

Simulated contribution to the measured spectrum of the radioactive decay of the isotope $^{77}$Ge in the energy range between 1990 and 2110 keV. The line at 2000.4 keV results from $\gamma$-emission with an intensity of 0.561\%. The $\gamma$ emission at 2037.8 keV with an intensity of 0.061 keV is hidden in the Compton continuum.
Vergleich des aus der Addition aller simulierten Komponenten resultierenden Untergrundspektrums mit dem Meß spektrum des Experiments.

(see Ch. Doerr 2003 )
\[
T_{1/2}^{2v} = (1.74 \pm 0.01 \text{ (stat)} \pm \frac{0.04}{0.04} \text{ (norm)} \pm \frac{0.14}{0.12} \text{ (syst.)}) \times 10^{21} \ y
\]

\[
= (1.74 \pm 0.18) \times 10^{21} \ y
\]
Conclusion at this point:

assuming, that NO unknown gamma-line

we have a 4.2σ ββ- signal
$\beta\beta$ events should be **SINGLE SITE EVENTS**, i.e. located to a small area in the detector (emitted electrons run less than one mm).

in contrast to, e.g., **MULTIPLE SITE EVENTS**, corresponding to multiple Compton-scattered $\gamma$ rays.

We have developed methods for pulse shape discrimination between these different types of signals:

J.Hellmig, F.Petry and H.V.Klapdor-Kleingrothaus, Patent DE19721323A
J. Hellmig and H.V. Klapdor-Kleingrothaus, NIM A 455 (2000) 638-644
Shapes of candidates for $0\nu\beta\beta$ decay

HEIDELBERG-MOSCOW 1990-2003

Dependence on $R$

Bazzacco et al., 2003

L. Mihaiescu et al.

H.V. Klapdor-Kleingrothaus
MPI, Heidelberg, GERMANY
27.04.2004

NIM A447 (2000) 350
Calibration of Pulse Shape Method, with

\[ \beta \] - sources:  \[ ^{207} \text{Bi} \] conversion line (SSE)  
(source inside detector)

\[ ^{90} \text{Sr} \]  \[ \beta \] - spectrum (SSE)  
(collimated source outside detector, Be window)

\[ \gamma \] - sources:  \[ ^{228} \text{Th} \]  
(collimated source outside enriched detectors)

- 2614 keV line MSE
- 2103 keV line MSE
- 1592 keV line SSE
The Single Site Selected Spectrum of the $^{76}$Ge detectors Nr. 2,3,4,5

HEIDELBERG-MOSCOW, 2004

Energy Range 100 - 3000 keV

H.V. Klapdor-Kleingrothaus et al.


Sum spectrum of the $^{76}$ Ge detectors Nr. 1,2,3,4,5

HEIDELBERG-MOSCOW, 2004

$T^{0v}_{1/2} = (0.69 - 4.18) \times 10^{-25}$ y

$m_\nu = (0.24 - 0.58)$ eV

71.7 kg y

Period: August 1990 - May 2003

4.2 $\sigma$

G. Douyss et al., PRL 86(2001)4259

Q = 2039.006(50) keV

H.V. Klapdor-Kleingrothaus et al. NIM A 2004, in Press
<table>
<thead>
<tr>
<th>Period</th>
<th>Detectors</th>
<th>$T_{1/2}^{0\nu}$ (1σ error)</th>
<th>$&lt;m&gt;$ eV (1σ error)</th>
<th>Conf. level σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period 1990 - 71.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>1, 2, 3, 4, 5</td>
<td>$(1.19 \pm 0.37) \times 10^{25}$</td>
<td>$0.44 \pm 0.05$</td>
<td>4.2</td>
</tr>
<tr>
<td>Period 1990 - 50.57</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>1, 2, 3, 4, 5</td>
<td>$(1.24 \pm 0.59) \times 10^{25}$</td>
<td>$0.43 \pm 0.07$</td>
<td>3.1</td>
</tr>
<tr>
<td>Period 1995 - 2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56.66</td>
<td>1, 2, 3, 4, 5</td>
<td>$(1.17 \pm 0.38) \times 10^{25}$</td>
<td>$0.45 \pm 0.06$</td>
<td>4.1</td>
</tr>
<tr>
<td>51.39</td>
<td>2, 3, 4, 5</td>
<td>$(1.25 \pm 0.48) \times 10^{25}$</td>
<td>$0.43 \pm 0.06$</td>
<td>3.6</td>
</tr>
<tr>
<td>42.69</td>
<td>2, 3, 5</td>
<td>$(1.49 \pm 0.79) \times 10^{25}$</td>
<td>$0.40 \pm 0.06$</td>
<td>2.9</td>
</tr>
<tr>
<td>51.39</td>
<td>2, 3, 5 SSE</td>
<td>$(1.98 \pm 0.85) \times 10^{25}$</td>
<td>$0.34 \pm 0.05$</td>
<td>3.3</td>
</tr>
<tr>
<td>28.21</td>
<td>1, 2, 4</td>
<td>$(1.22 \pm 0.84) \times 10^{25}$</td>
<td>$0.44 \pm 0.08$</td>
<td>2.5</td>
</tr>
<tr>
<td>28.35</td>
<td>3, 5</td>
<td>$(1.03 \pm 0.63) \times 10^{25}$</td>
<td>$0.48 \pm 0.08$</td>
<td>2.6</td>
</tr>
<tr>
<td>Period 1995 - 09.1999</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.59</td>
<td>1, 2, 3, 4, 5</td>
<td>$(0.84 \pm 0.38) \times 10^{25}$</td>
<td>$0.53 \pm 0.08$</td>
<td>3.2</td>
</tr>
<tr>
<td>Period 09.1999 - 05.2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30.0</td>
<td>1, 2, 3, 4, 5</td>
<td>$(1.12 \pm 0.45) \times 10^{25}$</td>
<td>$0.46 \pm 0.06$</td>
<td>3.5</td>
</tr>
</tbody>
</table>


Half-Life for the Neutrinoless Decay Mode and deduced effective Neutrino Mass from the HEIDELBERG-MOSCOW experiment.
Matrix element:

Prediction given by
(basing on fit of \( g_{pp} \) in QRPA by experimental \( \beta^+ \) decays)

for \( 2\nu\beta\beta \):
\[
T_{1/2} = 2.99 \times 10^{21} \text{ y}
\]

● Later, experiment gave
\[
T_{1/2} = 1.74 \times 10^{21} \text{ y}
\]

calculation underestimates \( 2\nu \) matrix element by
only 29% and thus overestimates \(<m>\) by \(<29\%\)

Heidelberg, 27.04.2004
CONSEQUENCES:

- Lepton Number not Conserved
- Neutrino is Majorana Particle
- Neutrino Mass Models: Degenerate
- Neutrino Mass
- Cosmology (Dark Matter)
- Other Beyond Standard Model Physics
HEIDELBERG- MOSCOW, 0νββ Positive Evidence

BEST VALUE 4.2 σ
HEIDELBERG-2003 MOSCOW

CUORE 600kg project
MOON 3.3t project
GENIUS 1t, EXO 10t projects
GENIUS 10t project

After we published these results in December 2001
(see NEW RESULTS in H.V. Klapdor-Kleingrothaus et al., NIM A 2004)

\[0_{\nu}\beta\beta \quad 0.1 \text{ eV} < \sum m_j < 3.5 \text{ eV}\]

many informations came in 2002-2003 which supported our result

- Oscillations
  \[m > 0.04 \text{ eV}\] (SuperKamiokande)
  \[\sum m_j < 2.2 \text{ eV}\] (J.E. Ruhl, et al., astro-ph/0212229)
  \[\sum m_j < (2.2 - 2.8) \text{ eV}\] (C. Weinheimer, Appec, Karlsruhe, Sept. 2003)

- SDSS+WMAP
  \[\sum m_j < 0.69 \text{ eV}\] (M. Tegmark et al., astro-ph/0310723)
  \[\sum m_j < 1.0 \text{ eV}\] (D.N. Spergel et al., astro-ph/0302209)
  \[\sum m_j < 1.38 \text{ eV}\] (H. Hannestad, astro-ph/0303076)

- MAP
  \[\sum m_j < 0.66 \text{ eV}\] (Z. Fodor, S.D. Katz, A. Ringwald)
  \[0.01 - 1.3 \text{ eV}\] (JHEP 0206:046,2002, hep-ph/0203198)
  \[0.4 \text{ eV}\] (D. Fargion, DARK2000, Heidelberg)
  (Springer, eds.HVKK, 2001, 455-468)

- CMB

- 'preferred value'

- Z-burst

- g-2

- Theory

\[m_{\text{com}} > 0.2 \text{ eV}\] (E. Ma, M. Raidal, Phys.Rev.Lett.87(2001)011802)
\[m_{\text{com}} > 0.2 \text{ eV}\] (K.S. Babu, E. Ma, J. W. F. Valle, hep-ph/0206292)
\[m_{\text{com}} > 0.1 \text{ eV}\] (R.N. Mohapatra et al., hep-ph/0301234)
identical quark and neutrino mixing at GUT scale

Status: March 2004
So far for light neutrinos.

Now some other Beyond Standard Model Physics.
Half-life for SUSY $0\nu\beta\beta$ decay

From the SUSY Feynman graphs one finds:

$$\left[ T_{1/2}^{0\nu\beta\beta}(0^+ \rightarrow 0^+) \right]^{-1} \sim G_{01} \left\{ \frac{\lambda_{111}^2}{m_\eta^4 \varepsilon m_\eta \chi} \right\}^2$$

Abbildung 5.6: $\beta\beta$-Zerfallsamplituden aufgrund des Austausches supersymmetrischer Teilchen.
Superpotential

The superpotential can be written as:

\[ W = W_{R_p} + W_{R_p} \]

The R-parity violating part has the form:

\[ W_{R_p} = \lambda_{ijk} L_i L_j \tilde{E}_k + \lambda'_{ijk} L_i Q_j \tilde{D}_k + \lambda''_{ijk} \tilde{U}_i \tilde{D}_j \tilde{D}_k \]

\( \lambda_{ijk}, \lambda'_{ijk} \) - lepton number violating terms

\( \lambda''_{ijk} \) - baryon number violating terms

\( L, Q \) - lepton and quark doublet superfields

\( \tilde{L}, \tilde{U}, \tilde{D} \) - lepton and up, down quark singlet superfields

\( i, j, k \) : generation indices \((1,2,3)\)

\( \lambda'_{ijk} \) : no symmetry

\( \lambda''_{ijk} \) : antisymmetric in \((i \Theta j)\)

\( \lambda''_{ijk} \) : symmetric in \((j \Theta k)\)
Hirsch, Klapdor-Kleingrothaus, Kovalenko

1. Low energy constraint: Charged-current universality


3. Possible limits from HERA, assuming 200 pb$^{-1}$ of data = 1 year (J. Butterworth and H. Dreiner, Nucl. Phys. B 397 (1993) 3

4. Absence of $0\nu\beta\beta$ decay - $^{76}$Ge limit from HEIDELBERG-MOSCOW assuming $m_{\tilde{g}} = 100$ GeV, 1 TeV (M. Hirsch et al. Phys. Rev. D 53 (1996) 1329)
For other Beyond SM Physics from $0 \nu \beta \beta$

I refer to our recent PAPERS and our BOOK

60 Years of Double Beta Decay - From Nuclear Physics to Beyond Standard Model Particle Physics - H.V. Klapdor-Kleingrothaus

World Scientific, Singapore, 2001
With the HEIDELBERG-MOSCOW experiment, the era of the small smart experiments is over.

New approaches and considerably enlarged experiments will be required in future to fix the $0\nu\beta\beta$ half life of $^{76}$Ge with higher accuracy.

This will, however, because of the uncertainties in the nuclear matrix elements, which probably hardly can be reduced to less than 50 %, only marginally reduce the precision of the deduced neutrino mass.

(See H.V. Klapdor-Kleingrothaus et al., Gran Sasso Reports 2003) hep-ph/0404062
What did we learn from $^{76}$Ge $\nu\nu\beta\beta$ in Gran Sasso 1990-2003:

- (total) Lepton Number is Violated
- Neutrino is Majorana Particle
  \[ \rightarrow \text{space-time structure} \rightarrow \text{SUSY} \]
- $\nu$ mass models: $\nu$'s are degenerate (excluded 10(3) models)

Other Beyond Standard Model Physics:
- SUSY (R violating): \[ \lambda^{\text{III}}_{111} < 3.9 \times 10^{-4} \]
  \[ \lambda^{\text{I}}_{112} \lambda^{\text{II}}_{121} < 3.2 \times 10^{-6} \]
  \[ \lambda^{\text{II}}_{113} \lambda^{\text{I}}_{131} < 1.1 \times 10^{-7} \]
- SUSY (R conserving): sneutrino (Majorana) Mass \[ \tilde{m}_M < 2 (m_{\text{SUSY}}/100\text{GeV})^{3/2} \text{ GeV} \]
  \[ \chi \approx \tilde{B} \]
- Left-right Symmetric Models: \[ m_{W_R} > 1.2 \text{ TeV} \]
  (Sharper than future NLR)
- Compositeness: Sharper than LEP II
- Superheavy Neutrinos: Sharper Lower Limits than future NLR
- Leptoquarks: Leptoquark-Higgs coupling \[ < 10^{-4.5} \]
- Violation of Lorentz Invariance in Neutrino Sector:
  Limits in otherwise unaccessible Regions

Reached essentially what we wanted to learn from our large GENIUS project, proposed in 1997, namely observation of $\nu\nu\beta\beta$ decay. June 2004
What **can we learn** in **FUTURE** from more sensitive experiments (if any):

- **independent** **confirmation** of **HEIDELBERG** result

**BUT:**

- **NO MORE** about neutrino properties (mass, ...)
  (because of Matrix Elements)

- **NO MORE** about Other Beyond Standard Model Physics: **from Half-Life**

- Only with **HUGE Experiments**, out of reach -
  like **GENIUS** - 10 tons, or **NEMO** - like observing tracks (not **EXO**) -
  **possibly** information about **SUSY contribution to** $\nu\beta\beta$
  (from branchings and angular correlation)
GENIUS-TF experiment at LNGS

Since 5 May 2003

Since 1 December 2003

The successful team after installation of the first four detectors on May 5, 2003.

The first four contacted naked Ge detector before installation into the GENIUS-TF setup.

A first spectrum measured, det.1.

<table>
<thead>
<tr>
<th>Co source outside, and the</th>
<th>Ba source inside the setup</th>
</tr>
</thead>
</table>

The first background spectrum (det.2)
Status and Perspectives of Direct Dark Matter Search

V. Bednyakov, H. V. Klapdor-Kleingrothaus, and E. Zaiti (2002)
APPROACHING AREAS

BEYOND THE DESERT

LHC

DESY

TEVATRON

GENIUS

IMAB

SUPERSTINGS

SUGRA

SuSy

GUTS

AMS

MAP PLANCK

BEPPO SAX

HERA-B

LEPI, II

Heid.-Mos.
Revolution in particle physics
HEIDELBERG-MOSCOW Data
Period: August 1995 - May 2003
Reliability of Data Acquisition and Data

Spectra for all five detectors in energy interval 500 - 600\text{keV}.

Low- and High-energy measurements of the full spectrum.

Threshold ranges for detectors 4 and 5

URANIUM - 238
4 Million Years

THORIUM - 234
24 Days

PROTACTINIUM - 234
70 Seconds

URANIUM-234
250 000 Years

THORIUM-230
75 000 Years

RADIIUM-226
1 600 Years

RADON-222
3.8 Days

POLONIUM-218
187 Seconds

Important Daughters of Radon-222
POLONIUM-218 and POLONIUM-214

The Time Under the Name
Is the Atomic Half Life

Alpha Particles: $\alpha$
Beta Particles: $\beta$

POLONIUM-214
2000 Micro-sec

LEAD - 210
22 Years

BISMUTH - 214
20 Minutes

LEAD-214
27 Minutes

BISMUTH - 210
5 Days

BISMUTH - 210
138 Days

POLONIUM-210
Stable
HEIDELBERG-MOSCOW Data
Period: August 1995 - May 2003

H.V. Klapdor-Kleingrothaus et al., NIM A (2004),
in Press

Left: arrival time for all events in the interval 2035.5 - 2042.5 keV as function of time after the calibrations for the period 1995 - 2003.

Right: the corresponding cumulative distribution analyzed by the Kolmogorov-Smirnov test.
Alexander Newski said:

Не в силе Бог - а в правде.

Nicht in Kraft ist Gott – sondern in der Wahrheit.

Not in force is God – but in truth.
Dr. Chandrasekhar: "...An important result of the work is that the life of a star of small mass must be essentially different from that of a star of large mass. ..."

Sir Arthur Eddington: "... Dr. Chandrasekhar has been referring to degeneracy. ... the point of my paper is that there is no such thing as relativistic degeneracy! ... I left driven to the conclusion that this was almost a reductio ad absurdum of the relativistic degener. formula. Various accidents may intervene to save the star, but I want more protection than that. I think there should be a Law of nature to prevent a star from behaving in this absurd way!"

"EDDINGTON" (The most distinguished astrophysicist of his time)
S. Chandrasekhar (University of Chicago) Cambridge Univ. Press., p.50-53
"... But he (A. Eddington) was unwilling to accept a conclusion that he so presciently drew; and he CONVINCED HIMSELF that 'there should be a law of nature to prevent a star from behaving in this absurd way!"
"...For my part I shall only say that I find it hard to understand why Eddington..... should found the conclusions that black holes could form during the natural course of the evolution of the stars, so unacceptable. ..."
High Scale Mixing Unification and Large Neutrino Mixing Angles

R. N. Mohapatra  
Department of Physics, University of Maryland, College Park, MD 20742, USA.

M. K. Parida  
Department of Physics, North Eastern Hill University, Shillong 793022, India.

G. Rajasekaran  
Institute of Mathematical Sciences, Chennai 600 113, India.  
(Dated: January 27, 2003)

Starting with the hypothesis that quark and lepton mixings are identical at or near the GUT scale, we show that the large solar and atmospheric neutrino mixing angles together with the small reactor angle \( \theta_{13} \) can be understood purely as a result of renormalization group evolution. The only requirement is that the three neutrino masses must be nearly degenerate in mass and have some CP parity. It predicts that the common Majorana mass for the neutrinos must be larger than \( 0.1 \text{ eV} \), making the idea testable in the currently planned or ongoing experiments searching for neutrinoless double beta decay.

PACS numbers: 14.60.Pq, 11.30.Hv, 12.15.Lk

The idea that disparate physical parameters describing forces and matter at low energies may unify at very short distances (or high mass scales) has been a very helpful tool in seeking a unified understanding of apparently unrelated phenomena [1]. In the context of supersymmetric grand unified theories, such an approach explains the weak mixing angle \( \sin^2 \theta_W \) and thereby the difference strengths of the weak, electromagnetic and strong forces.

One of the key ingredients of the unified theories is the unification between quarks and leptons. One may, therefore, hope that in a quark-lepton unified theory, the weak interaction properties of quarks and leptons parameterized by means of the flavor mixing matrices will become identical at high energies.

On the experimental side, recent measurements on atmospheric and solar neutrino fluxes and those at K2K and KamLAND which are a manifestation of the phenomenon of neutrino oscillations suggest that two of the neutrino mixings i.e. the mixings between \( \nu_e - \nu_\mu \) and \( \nu_\mu - \nu_\tau \) (to be denoted by \( \theta_{12} \) and \( \theta_{23} \), respectively) are large [2, 3, 4, 5, 6] while the third mixing between the \( \nu_\mu - \nu_\tau \) is bounded to be very small by the CHOOZ-Palo Verde reactor experiments i.e. \( \sin^2 2\theta_{13} < 0.15 \) [7]. On the other hand, it is now quite well established that all observed quark mixing angles are very small. One may therefore ask whether there is any trace of quark lepton unification in the mixing angles as we move to higher scales.

The first question in this connection is whether high scales have anything to do with neutrino masses or it is purely a weak scale phenomenon. One of the simplest ways to understand small neutrino masses is via the seesaw mechanism [8] according to which the neutrino mixing is indeed a high scale phenomenon, the new high scale being that of the right handed neutrino masses \( M_R \) in an appropriate extension of the standard model. Present data put the seesaw scale \( M_R \) very close to the conventional GUT scales. It is therefore tempting to speculate whether quark and lepton mixing angles are indeed unified at the GUT-seesaw scale. This would of course imply that all neutrino mixing angles at the high scale \( M_R \) are very small whereas at the weak scale two of them are known to be large. In this letter we show that simple radiative correction effects embodied in the renormalization group evolution of parameters from seesaw scale to the weak scale can indeed provide a complete understanding of all neutrino mixings at the weak scale, starting with very small mixings at the GUT-seesaw scale.

The fact that renormalization group evolution from the seesaw scale to the weak scale [9, 10] can lead to drastic changes in the magnitudes of the mixing angles was pointed out in several papers [9, 11, 12, 13, 14, 15]. In particular, it was shown in [11] that this dependence on renormalization group evolution can be exploited in simple seesaw extensions of the minimal supersymmetric standard model (MSSM) to explain the large value of the atmospheric mixing angle starting with a small mixing at the seesaw scale, provided two conditions are satisfied: (i) the two neutrino-mass eigen states have same CP and (ii) they are very nearly degenerate in mass. In general, in gauge models that attempt to explain the large neutrino mixings [16], one needs to make many assumptions to constrain the parameters. In contrast, in this class of "radiative magnification" models [11], there is a need to invoke special constraints on the parameters at high scales beyond those needed to guarantee the
\[ \nu^C = \nu^C_L + \nu^C_R \]
\[ \nu = \nu^L + \nu^R \]

**Dirac Neutrino**

**Majorana Neutrino**

Possible assignment of the experimentally known (in boxes) neutrino states (of one family) in the theoretical description for Dirac and Majorana fields.
Degenerate case: \( m_1 \sim m_2 \sim m_3 \geq 0.1 \text{ eV} \)

Hierarchical case: \( m_1 \ll m_2 \ll m_3 \)

Inverse Hierarchy: \( m_1 \sim m_2 \gg m_3 \)

Motivated by analogies with quark sector and simplest see-saw models.

Now the heaviest state with mass \( m_3 \) is mainly electron neutrino.
Table 1

Technical parameters of the five enriched $^{76}\text{Ge}$ detectors.

<table>
<thead>
<tr>
<th>Detector Number</th>
<th>Total Mass [kg]</th>
<th>Active Mass [kg]</th>
<th>Enrichment in $^{76}\text{Ge}$ [%]</th>
<th>PSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>0.980</td>
<td>0.920</td>
<td>85.9 ± 1.3</td>
<td>no</td>
</tr>
<tr>
<td>No. 2</td>
<td>2.906</td>
<td>2.758</td>
<td>86.6 ± 2.5</td>
<td>yes</td>
</tr>
<tr>
<td>No. 3</td>
<td>2.446</td>
<td>2.324</td>
<td>88.3 ± 2.6</td>
<td>yes</td>
</tr>
<tr>
<td>No. 4</td>
<td>2.400</td>
<td>2.295</td>
<td>86.3 ± 1.3</td>
<td>yes</td>
</tr>
<tr>
<td>No. 5</td>
<td>2.781</td>
<td>2.666</td>
<td>85.6 ± 1.3</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 2


*) events show up partly in $\mu$ and Ge-Ge coincidence, therefore in total 25 470 events.

<table>
<thead>
<tr>
<th>Data Sets</th>
<th>Data Sets</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full measurement</td>
<td>10 513</td>
<td>951 044</td>
</tr>
<tr>
<td>Corrupted data sets</td>
<td>792</td>
<td>92 553</td>
</tr>
<tr>
<td>Rate $&gt;\pm5\sigma$</td>
<td>151</td>
<td>32 922</td>
</tr>
<tr>
<td>Muon coincidence *</td>
<td></td>
<td>3 672</td>
</tr>
<tr>
<td>Ge - Ge coincidence *</td>
<td></td>
<td>23 563</td>
</tr>
<tr>
<td>EoI selection</td>
<td></td>
<td>13 158</td>
</tr>
<tr>
<td>Data used</td>
<td>9 570</td>
<td>786 941</td>
</tr>
</tbody>
</table>

$^{56}Co$ counts in range 2000-2660 keV
HEIDELBERG-MOSCOW EXPERIMENT
Spectra of Detectors Number 1,2,3,5  (Nov. 1995 - June 2002) 49.59 kgy

GEANT 4

NIM 513A
(2003)
596-621
HERA  High $Q^2$ events:

**Interpretations:**

1. $e^+ S(2/3) e^+$
   - $\lambda$
   - $d$ ~ $d$
   - Amplit. $\sim \frac{\lambda^2}{m_{\lambda}^2}$
   - **Scalar Leptoquark formation**

2. $e^+ \tilde{u}_k e^+$
   - $\lambda'_{11k}$
   - $\lambda'_{11k}$
   - Amplit. $\sim \frac{\lambda'_{11k}}{m_{\tilde{u}}^2}$
   - **SUSY (squark formation)**

$m_{\tilde{u}} \approx 200$ GeV $\Rightarrow \lambda'_{11k} \approx 0.04 \pm 30\%$

$\Rightarrow$ **Squarks of 1 generation** excluded by $\nu\nu\bar{\nu}\bar{\nu}$
Underlying $A_4$ Symmetry for the Neutrino Mass Matrix and the Quark Mixing Matrix

K. S. Babu$^1$, Ernest Ma$^2$, and J. W. F. Valle$^3$

$^1$ Physics Department, Oklahoma State University, Stillwater, Oklahoma 74078, USA
$^2$ Physics Department, University of California, Riverside, California 92521, USA
$^3$ Instituto de Física Corpuscular – C.S.I.C., Universitat de València, Edificio Institutos, Aptdo. 22085, E-46071 València, Spain

Abstract

The discrete non-Abelian symmetry $A_4$, valid at some high-energy scale, naturally leads to degenerate neutrino masses, without spoiling the hierarchy of charged-lepton masses. Realistic neutrino mass splittings and mixing angles (one of which is necessarily maximal and the other large) are then induced radiatively in the context of softly broken supersymmetry. The quark mixing matrix is also calculable in a similar way. The mixing parameter $U_{e3}$ is predicted to be imaginary, leading to maximal CP violation in neutrino oscillations. Neutrinoless double beta decay and $\tau \rightarrow \mu \gamma$ should be in the experimentally accessible range.