Neutrinoless Double Beta Decay for Particle Physicists

GK PhD Presentation

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About this talk

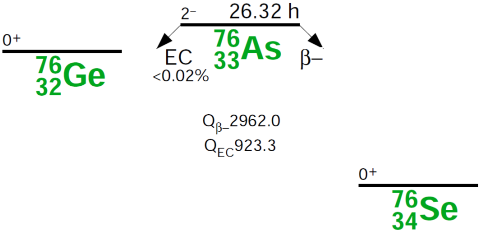
Double beta decay: Particle physics implications with nuclear physics methods

- Focus on implications, major challenges and the GERDA experiment
- No nuclear physics details (background nuclides, ...)

After the talk I hope you know

- Why is DBD research fundamental?
- Why are there so many different experiments?
- What is GERDA?
- What is my plan for the PhD?

Double Beta Decay - A Definition



Configuration where normal β-decay is forbidden:
35 nuclides (9 useful)

$2\nu\beta\beta$

$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$

- SM process
- Observed in 12 nuclides

$0\nu\beta\beta$

$(Z, A) \rightarrow (Z+2, A) + 2e^-$

- non SM process
- Debated claim of observation

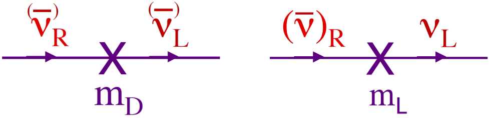
Implications

$$(Z, A) \rightarrow (Z+2, A) + 2e^-$$

- Lepton number violated ($\Delta L = 2$): Considered the most fundamental implication. Some theories assume B-L symmetry which could explain B-violation and baryogenesis via LNV processes
- Neutrino is a Majorana particle
- Coupling strength of Interaction: With $0\nu\beta\beta$ half-life measurement the coupling strength of the LNV process can be determined
  - In the standard interpretation: Determination of effective Majorana neutrino mass
  - ν-mass scale and mass hierarchy
- Determination of Majorana phases

Dirac and Majorana Mass Terms

$$\mathcal{L} \quad = \quad m_D \bar{\nu}_R \nu_L \quad + \quad m_M \bar{\nu}_L \nu_L^c$$



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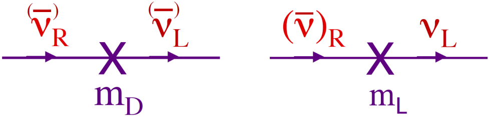
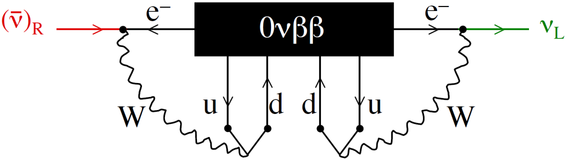


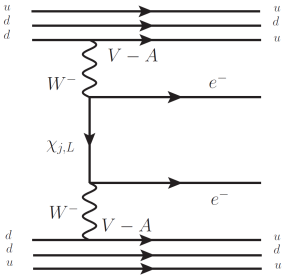
Quark level: $dd \rightarrow uu + ee$



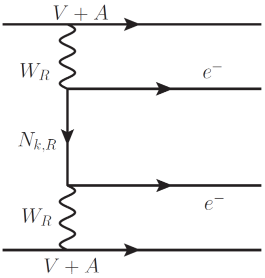
Schechter-Valle theorem: If $0\nu\beta\beta$ exists, it can always be interpreted as a Majorana mass term

Black box can be different processes - even more than one

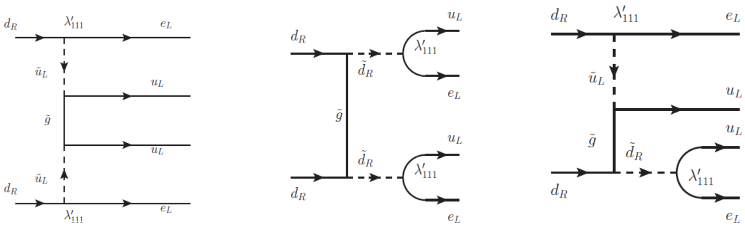
Different Mechanisms for the Black Box



Standard mechanism



Right handed currents



SUSY R-parity violation processes

Standard Mechanism: Light Majorana Neutrino Exchange

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(Q,Z) \cdot |\mathcal{M}^{0\nu}|^2 \cdot |m_{ee}|^2$$

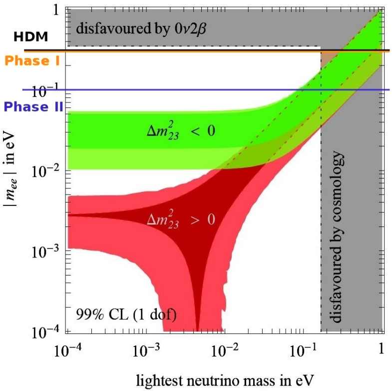
$T_{1/2}^{0\nu}$ $0\nu\beta\beta$ half-life (Observable)

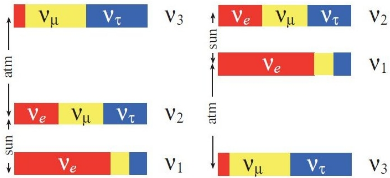
$G^{0\nu}(Q,Z)$ Phase Space Factor

$\mathcal{M}^{0\nu}$ Nuclear Matrix Element

$|m_{ee}|^2$ Effective Majorana neutrino mass (Neutrino property)

$$= \left| m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i(\alpha_2-\alpha_1)} + m_3 |U_{e3}|^2 e^{-i(\alpha_1+2\delta)} \right|^2$$





normal hierarchy

inverted hierarchy

What happens if more than one mechanism contributes?

If $0\nu\beta\beta$ is observed the question will be:

Which process is responsible?
How many processes are responsible?
Do they interfere?

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(Q,Z) \cdot \left| \sum_{\text{model } i} \mathcal{M}_i \cdot \eta_i \right|^2$$

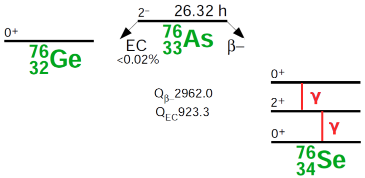
with $\eta_i \equiv m_{ee}$ in the standard scenario.

If more than one process is involved they can be disentangled by measuring half-lives of multiple nuclides.

First motivation for investigating more than one $0\nu\beta\beta$ nuclide

Nuclear Matrix Elements (NME):

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(Q,Z) \cdot |\mathcal{M}^{0\nu}|^2 \cdot |m_{ee}|^2$$



Difficulty:
76 nucleons in initial state, final state and intermediate states

- Different approaches (QRPA, IBM, SM, ...)
- Large uncertainties ($\approx$ factor 3)
- Use of different experimental input (excited state transitions)

Uncertain parameters in NME calculations can be constrained by measuring half-lifes of multiple nuclides and calculations can be cross checked.

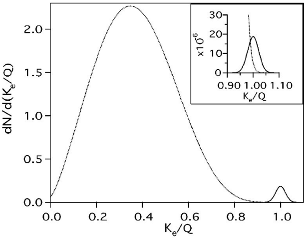
Second motivation for investigating more than one $0\nu\beta\beta$ nuclide

Experimental Signature and Background

Final state:

$2\nu\beta\beta$: 2 neutrinos and 2 electrons
$^{76}\mathrm{Ge}$: $T_{1/2} \approx 10^{21}$ yr

$0\nu\beta\beta$: 2 electrons
$^{76}\mathrm{Ge}$: $T_{1/2} > 10^{25}$ yr



Main Background:

All radionuclides with a Q-value large than that of the DBD nuclide

- Cosmic muons
- Cosmic activated nuclides
- Primordial decay chains in detectors and surrounding matter
- $2\nu\beta\beta$ of target nuclide

In principle, any unknown γ-line of any radionuclide could be mistaken for the $0\nu\beta\beta$ signal: Credibility only with observation in multiple nuclides

Third motivation for investigating more than one $0\nu\beta\beta$ nuclide

Which DBD Nuclide Makes Sense?

Simple sensitivity estimation: $$[T_{1/2}]^{-1} \propto \alpha \cdot \eta \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

(The calcutlated half-life if the signal counts hide in a 1σ background fluctuation)

- α Isotopic abundance: Natural abundance? Enrichment?
- η Detection efficiency: Possible detector technology? On-source / off-source approach
- M Target mass: Cheap and easy to procure
- t Measuring time
- B Background: Easy to purify? Q-value above 2.6 MeV? Other cosmic activated radioisotopes?
- ΔE Energy resolution: Possible detector technology?

- $G^{0\nu}(Q, Z)$ Large phase space factor?
- $\mathcal{M}^{0\nu}$ Large nuclear matrix element?

Main examples: $^{76}\mathrm{Ge}$, $^{130}\mathrm{Te}$, $^{136}\mathrm{Xe}$, $^{150}\mathrm{Nd}$, $^{116}\mathrm{Cd}$, $^{82}\mathrm{Se}$, $^{100}\mathrm{Mo}$

Taxonomy of DBD Experiments

Source = detector? ΔE? Event topology?

Class 1: Source = detector, good Δ E, no event topology

- Background rejection with good Δ E
- GERDA (^{76}Ge), Majorana (^{76}Ge), CUORE (^{130}Te)

Class 2: Source = detector, bad Δ E, no event topology

- Easy to scale to very large dimensions and reduce outside background with fiducial volumes
- SNO+ (^{150}Nd), KamLAND-ZEN (^{136}Xe)

Class 3: Source = detector, medium Δ E, event topology

- Background rejection with event topology
- EXO (^{136}Xe), NEXT (^{136}Xe), C0BRA (^{116}Cd)

Class 4: Source $\neq$ detector, medium Δ E, event topology

- Difficult to scale but best event reconstruction. Possibility to measure angular correlations
- SuperNemo (^{82}Se, ^{150}Nd), MOON (^{100}Mo)

The GERDA Collaboration

Institute for Reference Materials and Measurements
Geel, Belgium

INFN-Padova
Università di Padova
Padova, Italy

Max-Planck-Institut für Kernphysik
Heidelberg, Germany

Eberhard Karls Universität Tübingen
Tübingen, Germany

INFN-Milano
Università di Milano
Milan, Italy

Universität Zürich
Zurich, Switzerland

INFN-Milano Bicocca
Università di Milano Bicocca
Milan, Italy

Gran Sasso National Laboratory
Assergi, Italy

Institute for Nuclear Research
Moscow, Russia

Jagellonian University
Cracow, Poland

Institute for Theoretical and Experimental Physics
Moscow, Russia

Technische Universität Dresden
Dresden, Germany

Kurchatov Institute
Moscow, Russia

Joint Institute for Nuclear Research
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Max-Planck-Institut für Physik
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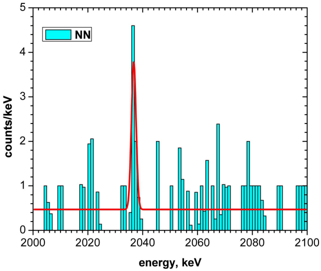
GERDAs First Mission

Test the $0\nu\beta\beta$ claim by subset of Heidelberg-Moscow experiment (2002)

$$T^{0\nu}_{1/2} = 2.23^{+0.44}_{-0.31} \cdot 10^{25}\,\mathrm{yr} \qquad \rightarrow \qquad |m_{ee}| = (0.11..0.56)\,\mathrm{eV}$$

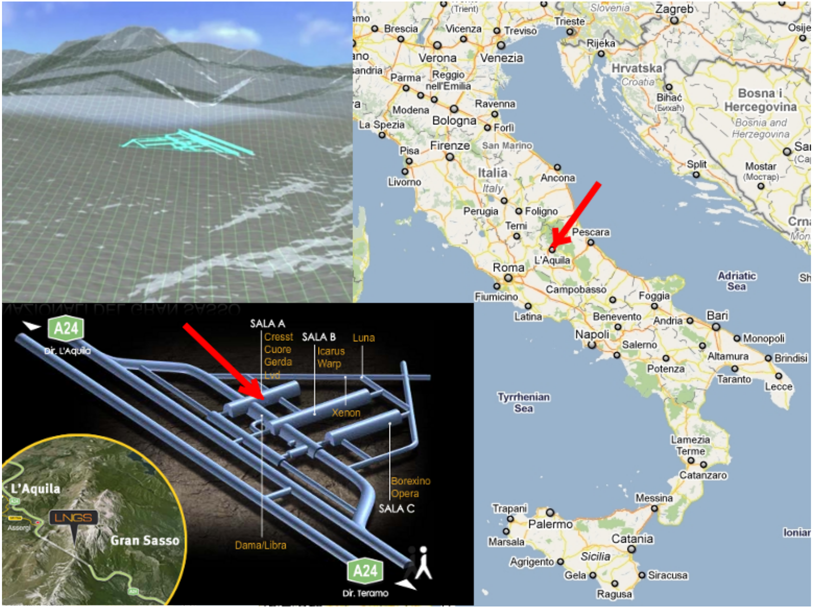
Mod. Phys. Let. A, Vol.21, 1547 (2006)



GERDA or other $^{76}\mathrm{Ge}$ experiments (Majorana) can test the claim directly via $T^{0\nu}_{1/2}$ (no NME uncertainties)

GERDA reaches sensitivity within one year of data taking - soon to start

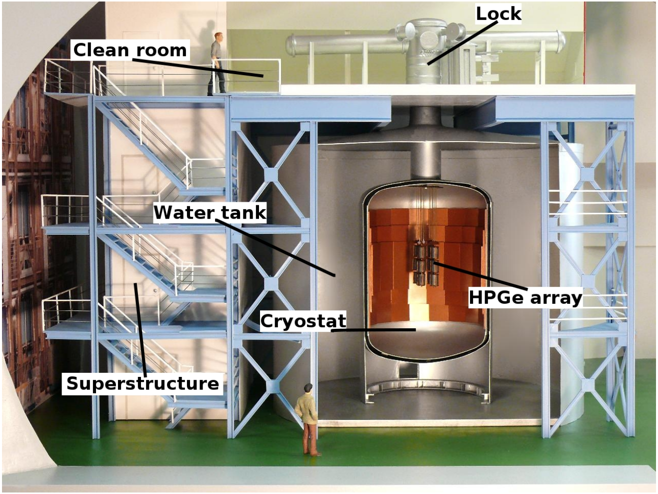
LNGS - Laboratori Nazionali del Gran Sasso



GERDA - GERmanium Detector Array

Novel idea: Operate germanium detectors naked in liquid argon

- Serving as cooling
- Serving as shielding
- Possible to implement as active veto



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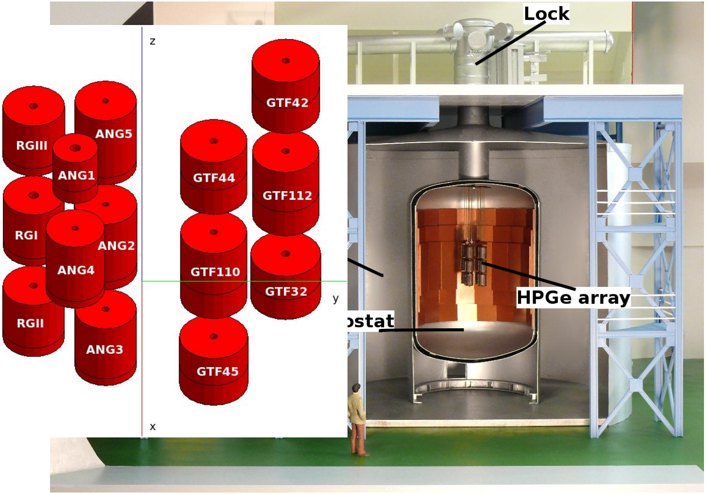
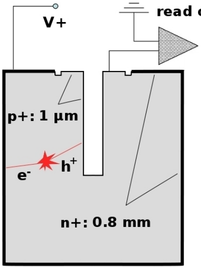
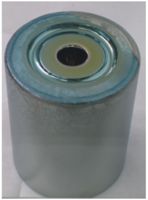


Detectors and Background Rejection





HPGe detectors

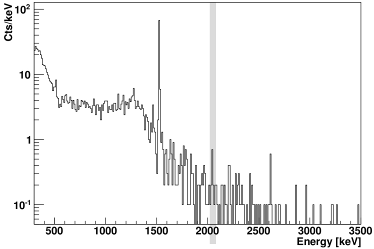
- Commissioning:
  3 Detectors (4 kg · yr)
- Phase I:
  12 Detectors (15 kg · yr)
- Phase II:
  25 BEGe + PI detectors (100 kg · yr)

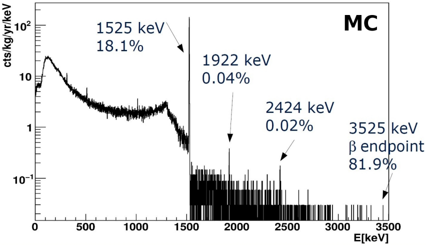
Background rejection techniques

- Anti-coincidence between detectors
- Pulse-shape discrimination against multi-site events
- * LAr Veto against outside events
- Background goal:
  $10^{-2(3)}\ \mathrm{cts}/(\mathrm{kg}\cdot\mathrm{yr}\cdot\mathrm{keV})$

The GERDA Commissioning Phase

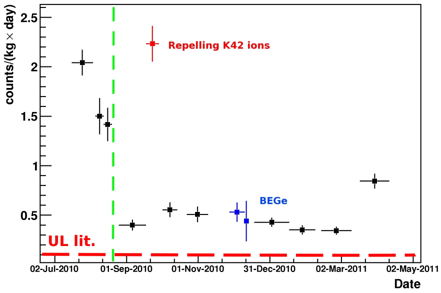
- Start data taking: July 2010





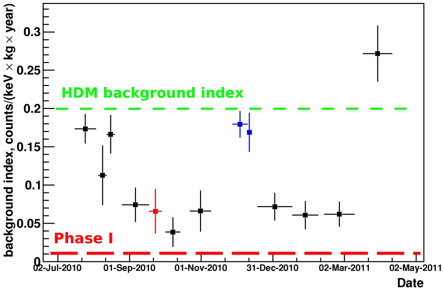
- Decay chain: ${}^{42}\mathrm{Ar} \rightarrow {}^{42}\mathrm{K} \rightarrow {}^{42}\mathrm{Ca}$
- Main issue: 3.5 MeV β's penetrating from LAr into detectors
- More than one year investigation of ${}^{42}\mathrm{Ar}$ - ongoing
  Larger concentration than previously measured? Charge collection of ${}^{42}\mathrm{K}^{+}$? Does a shroud installation help? Or an encapsulation of the detectors? Or a field free operation?

Evolution of Observables



Observables:

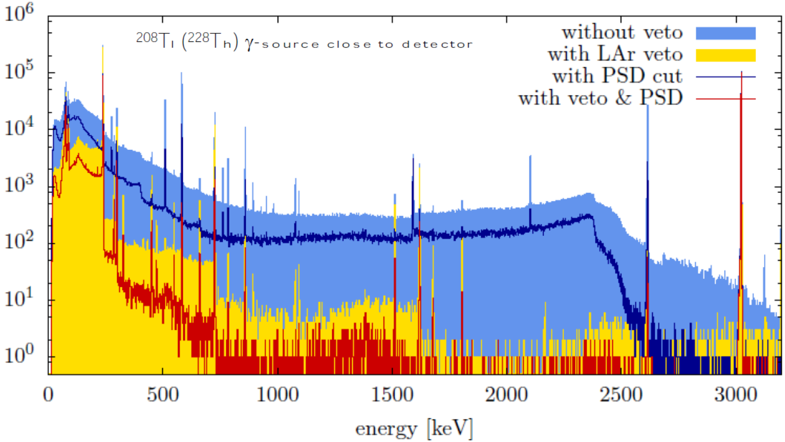
^{42}K 1524 keV peak count [cts/(kg · day)]



Background Index $\pm$200 keV [cts/(kg · keV · yr)]

LAr Veto

Power of LAr veto already tested in our R&D facility LArGe:



Possibilities for LAr instrumentation in GERDA are developed right now.
They need to be tested for veto efficiency, radiopurity, cost and installation time

Conclusions

What I wanted to convey...

- Why is DBD research fundamental?
  - Lepton violation, Majorana nature of ν, strength of LNV process (neutrino mass), Majorana phases
- Why are there so many different experiments?
  - Credibility against false signal, improve and constrain NME calculations, disentangle LNV processes
- What is GERDA?
  - Recently finished and soon to test claim of $0\nu\beta\beta$ in $^{76}\mathrm{Ge}$
- What is my plan for the PhD?
  - Help to develop a LAr veto for GERDA, ...