The GERDA experiment and the search for $0\nu\beta\beta$ decay: first results and future perspectives

Carla Macolino on behalf of the GERDA collaboration

INFN, Laboratori Nazionali del Gran Sasso

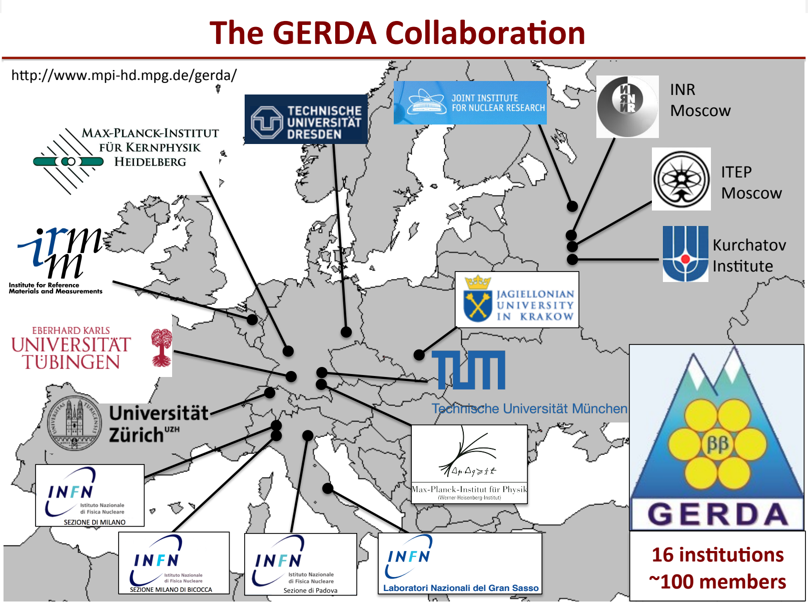
The Us-Italy Physics Program at Laboratori Nazionali del Gran Sasso

Princeton, 10.15.2013

Outline

- probing the nature of neutrino with neutrinoless double-beta decay
- the GERDA experiment: design and detection principle
- GERDA performances w.r.t. to other experiments
- GERDA physics results:
  - measurement of two-neutrino double beta decay half-life
  - the background models for GERDA Phase I
  - the Pulse Shape Discrimination of GERDA events
  - **GERDA result on $0\nu\beta\beta$ half-life**
- on the way to Gerda Phase II
- GERDA and Majorana

The GERDA collaboration



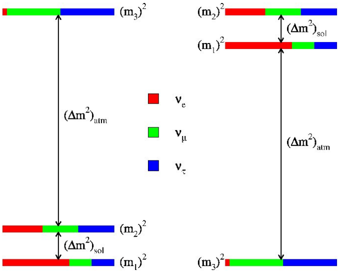
112 physicists, 16 institutions, 7 countries

The GERDA collaboration

GERDA Collaboration Meeting in Dubna, Russia
June 2013

Investigate existence of $0\nu\beta\beta$

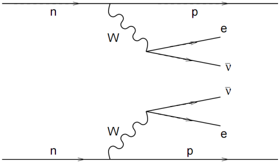
- $0\nu\beta\beta \rightarrow$ Majorana nature of neutrino
- lepton number violation
- physics beyond Standard Model
- shed lights on absolute neutrino mass
- shed lights on neutrino mass hierarchy



Search for $0\nu\beta\beta$ decay

$2\nu\beta\beta$

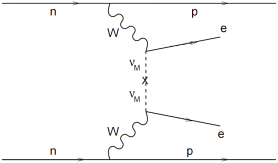
$$(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\overline{\nu}_e$$



$\Delta L = 0 \Longrightarrow$ Predicted by SM

$0\nu\beta\beta$

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



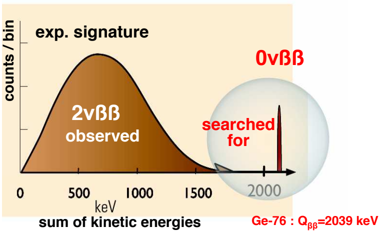
$\Delta L = 2 \Longrightarrow$ Prohibited by SM

Light Majorana neutrino exchange

$$Q = M_i - M_f - 2m_e$$

The GERmanium Detector Array

experiment is an ultra-low background experiment designed to search for ^{76}Ge $0\nu\beta\beta$ decay.



$Q_{\beta\beta} = 2039$ keV

Search for $0\nu\beta\beta$ decay

In the hypothesis of light Majorana neutrino exchange:

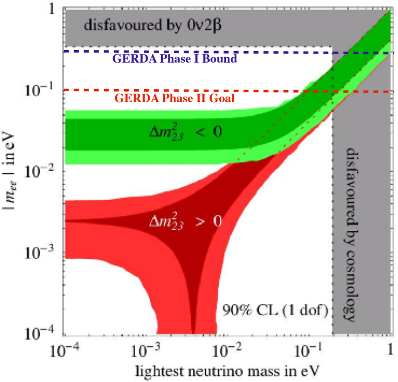
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}|M^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

with $\langle m_{\beta\beta}\rangle$ = effective electron neutrino mass

$$\langle m_{\beta\beta}\rangle \equiv |U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i\phi_2} + |U_{e3}|^2 m_3 e^{i\phi_3}$$

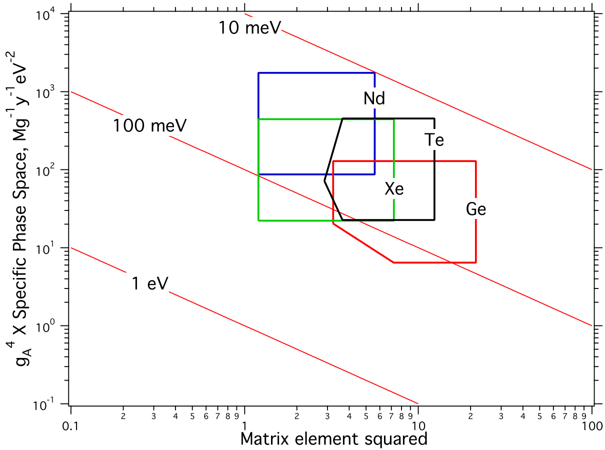
m_i=masses of the neutrino mass eigenstates
U_{ei}=elements of the neutrino mixing matrix
$e^{i\phi_2}$ and $e^{i\phi_3}$=Majorana CP phases

→ information on the absolute mass scale!



- **Phase I result**: BI ∼ 10^{-2} cts/(keV kg yr) and ∼ 20 kg yr exposure
  → limit on $\langle m_{ee}\rangle$ between 0.2 and 0.4 eV
- **Phase II goal**: BI ∼ 10^{-3} cts/(keV kg yr) and 100 kg yr exposure
  → sensitivity on $\langle m_{ee}\rangle$ ∼ 100 meV

Ge detectors w.r.t. other isotopes



Plot by R. G. H. Robertson, arXiv:1301.1323v1

- plot corresponding to $0\nu\beta\beta$ rate of 1 count/(ton·yr)
- no clear golden candidate
- similar specific rates within a factor of 2
- ^{76}Ge important for historical reasons too

Ge detectors

Sensitivity $T_{1/2} \propto \epsilon \cdot \frac{f_A}{m_A} \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

ϵ	detection efficiency	$\gtrsim$ 85%
f_A	enrichment fraction	high natural or enrichment
M	active target mass	increase mass
T	measuring time	
b	background rate (cts/(keV kg yr))	minimize & select radio-pure material
ΔE	energy resolution	use high resolution spectroscopy

Ge semiconductor detectors

Advantages:

- well established enrichment technique
  $f_A = f_{76} = 86\%$ for ^{76}Ge
- M and T expandable
- very good energy resolution
  $\Delta E \sim 0.1\%$ - 0.2%
- very good detection efficiency $\epsilon \sim 1$
  (Ge as source and detector)
- high-purity detectors → low background b

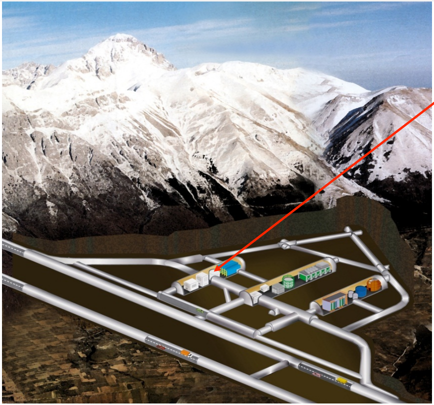
Disadvantages:

- low $Q_{\beta\beta}$ value
  (lower than ^{208}Tl 2614 keV)
  → background
- need enrichment from 7% to 86%
  → it is expensive

GERDA @ LNGS

Construction completed in 2009 - Inauguration 9 Nov. 2010

GERDA @ LNGS



- Hall A of Gran Sasso Laboratory (INFN)
- 3800 m.w.e.

Background from:

External:

- γ's from Th and Ra chain
- neutrons
- cosmic-ray muons

Internal:

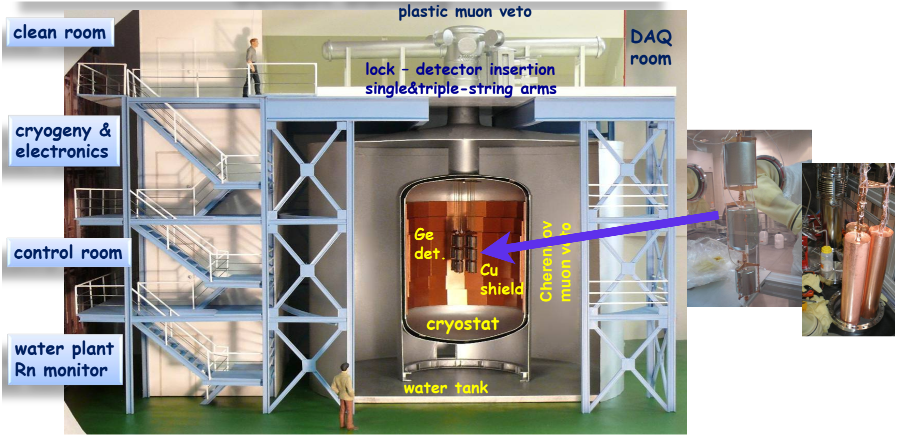
- cosmogenic ^{60}Co ($T_{1/2}$=5.3 yr)
- cosmogenic ^{68}Ge ($T_{1/2}$=271 d)
- radioactive surface contaminations

Background reduction and events identification

- Gran Sasso suppression of μ flux (10^6)
- material selection
- passive shields (H_2O - LAr - Cu)
- muon veto
- detector anticoincidence
- pulse shape analysis (PSD)

GERDA @ LNGS

GERDA Building

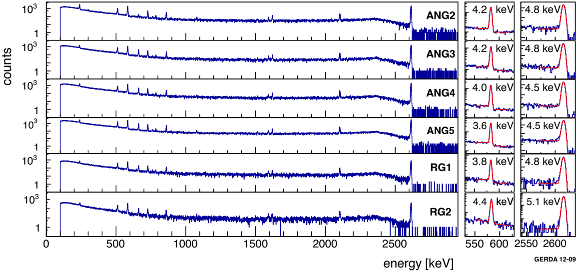


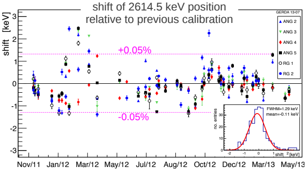
The GERDA collaboration, Eur. Phys. J. C 73 (2013)

- 3 + 1 strings
- 8 enriched Coaxial detectors: total mass 17.7 kg (6 out of 8 detectors working)
- GTF112 natural Ge: 3.0 kg
- 5 enriched BEGe: total mass 3.6 kg (4 out of 5 working)

Energy calibrations and data processing

- weekly calibrated spectra with ^{228}Th sources and pulser with 0.05 Hz frequency
- data useful for monitoring of resolution and stability over time
- FWHM at $Q_{\beta\beta}$ is about 4.8 keV for Coaxials (0.23%) and 3.2 keV (0.16%) for BEGes



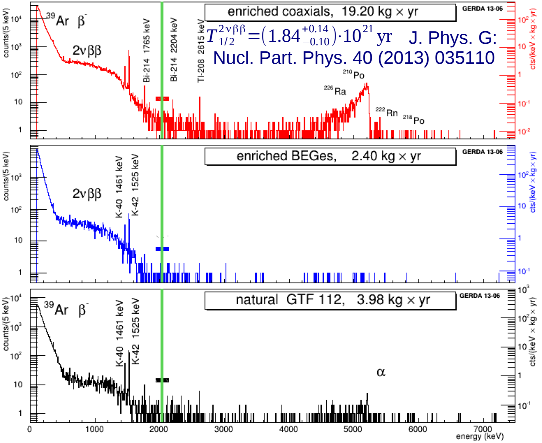


shifts are small compared to FWHM ~ 0.2% $Q_{\beta\beta}$

Data processing: diode→amplifier→FADC→digital filter →energy, pulse shape,...

Data selection: anti coincidence + quality cuts + pulse shape discrimination (total fraction of accepted events = 65%)

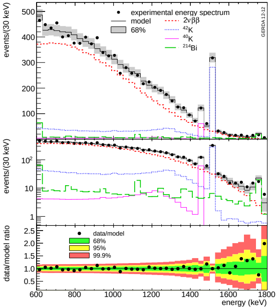
Energy spectra

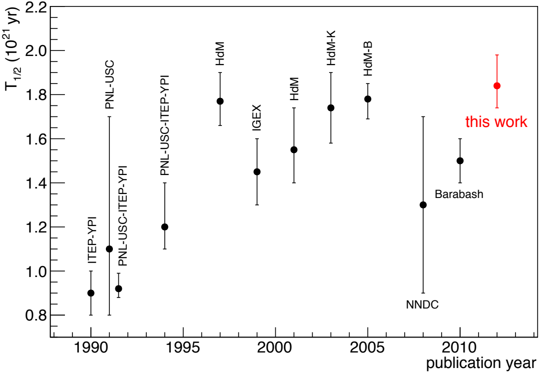


- Measurement of $2\nu\beta\beta$ decay half-life published
- events in $Q_{\beta\beta} \pm$ 20 keV kept BLINDED to not bias analysis and cuts
- total exposure for enriched detectors: 21.6 kg·yr

Average background level @$Q_{\beta\beta}$ before PSD:
0.018±0.002 cts/(keV kg yr)
Background 10x lower than previous Ge experiments!!

Half-life of $2\nu\beta\beta$ decay of ^{76}Ge



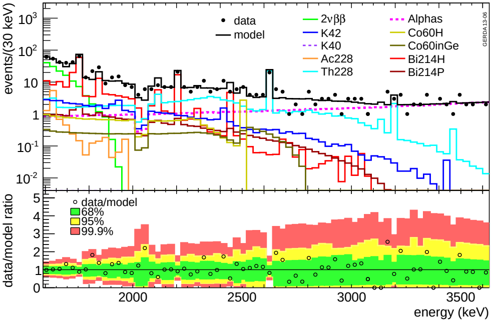


The GERDA collaboration J. Phys. G: Nucl. Part. Phys. 40 (2013) 035110

- $\mathbf{T^{2\nu}_{1/2} = (1.84^{+0.09+0.11 syst}_{-0.08-0.06 syst}) \cdot 10^{21}}$ **yr**
- Uncertainty comparable to best previous experiment (even with lower exposure).
- Such a careful systematic error analysis never done in the past.
- Good agreement with re-analysis of HdM data
  HdM-K: *Nucl. Instr. Meth. A 513, 596 (2003)*
  HdM-B: *Phys. Part. Nucl. Lett. 2, 77/ Pisma Fiz. Elem. Chast. Atom. Yadra 2, 21 (2005)*

The Background Model of GERDA Phase I

The GERDA collaboration, submitted to Eur. Phys. J. C



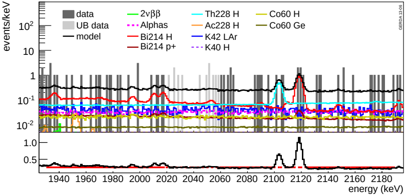
- simulation of known and observed background
- fit combination of MC spectra to data from 570 keV to 7500 keV
- different combinations of positions and contributions tested

Main contribution from close background sources:
^{228}Th and ^{226}Ra in holders, ^{42}Ar
α on detector surface

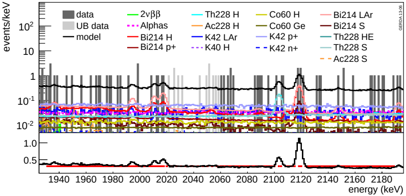
The Background Model of GERDA Phase I

The GERDA collaboration, submitted to Eur. Phys. J. C

Minimum model fit



Maximum model fit



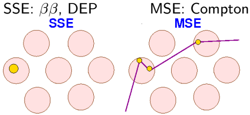
- no line expected in the blinded window
- background flat between 1930 and 2190 keV

8.6 (minimum) or 10.3 (maximum) expected events while
13 observed in 30 keV window

Golden coax:
BI $= 1.75^{+0.26}_{-0.24} \cdot 10^{-2}$ cts/(keV kg yr)

BEGe:
BI $= 3.6^{+1.3}_{-1.0} \cdot 10^{-2}$ cts/(keV kg yr)

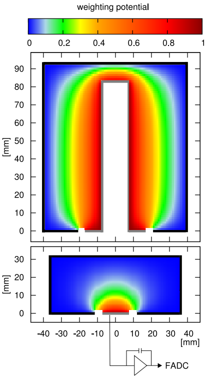
Pulse shape discrimination of GERDA Phase I data

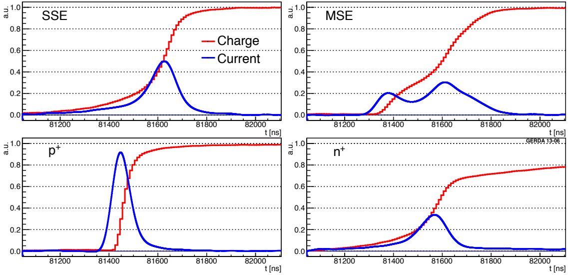


Pulse-shape analysis

e signal: single site energy deposition

γ signal: multiple site energy deposition





Current signal = q · v · ΔΦ

q=charge, v=velocity

(Schockley-Ramo theorem)

$0\nu\beta\beta$ events: 1 MeV electrons in Ge ∼ 1mm
one drift of electrons and holes SINGLE SITE EVENTS (SSE)

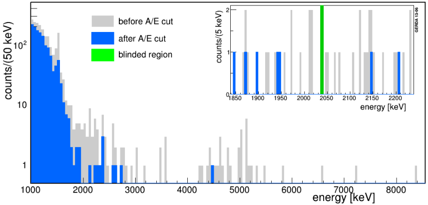
background from γ's: MeV γ in Ge ∼ cm
several electron/holes drifts MULTI SITE EVENTS (MSE)

surface events: only electron or hole drift

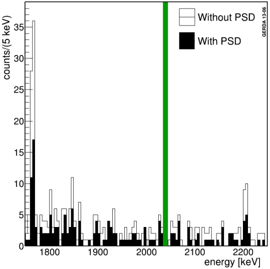
Pulse shape discrimination of GERDA Phase I data

The GERDA collaboration, Eur. Phys. J. C 73, 2583 (2013)

PSD for BEGe: A over E parameter (A/E) - 92% eff.



PSD for Coaxials: Artificial Neural Network **A**NN - 90% eff.

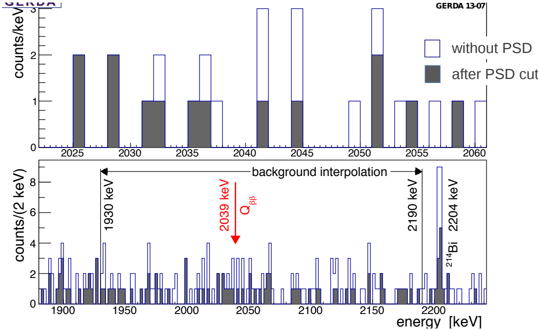


Both methods give high bkg rejection + high signal efficiency

Results on $0\nu\beta\beta$ decay

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503

- sum spectrum **21.6 kg yr**
- unblinding after calibration finished, data selection frozen, analysis method fixed and PSD selection fixed
- 7 events observed in 10(8) keV window - 5.1 expected
- 3 events observed after PSD - 2.5 expected
- No events in $\pm 1\sigma_E$ after PSD



No peak in spectrum observed, number of events consistent with expectation from background

→ GERDA sets a limit on the half-life of the decay!

- **profile likelihood result**: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr at 90% C.L.
- **Bayesian analysis result**: $T^{0\nu}_{1/2} > 1.9 \cdot 10^{25}$ yr at 90% C.I.
- best fit: $N^{0\nu}=0$

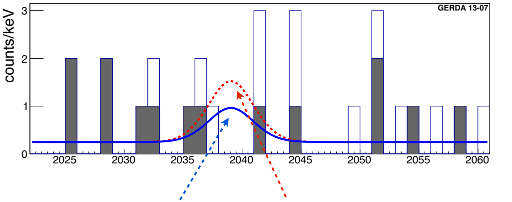
Results on $0\nu\beta\beta$ decay

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503
Comparison with Phys. Lett. B 586 198 (2004) claim

Compare two hypotheses:

- H_1: $T^{0\nu}_{1/2} = 1.19^{+0.37}_{-0.23} \cdot 10^{25}$ yr
- H_0: background only

- **GERDA only**:
  Profile likelihood
  $P(N^{0\nu}=0|H_1) = 0.01$
  Bayes factor
  $P(H_1)/P(H_0) = 0.024$



Compatible with no signal events
$T^{0\nu}_{1/2} = 2.1 \cdot 10^{25}$ yr

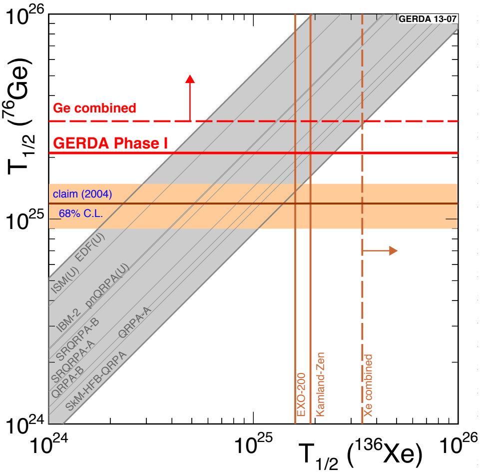
Claim strongly disfavoured!

N.B.: $T^{0\nu}_{1/2}$ from Mod. Phys. Lett. A 21 (2005) 157 not considered because of inconsistencies (missing efficiency factors) pointed out in Ann. Phys. 525 (2013) 259 by B. Schwingenheuer.

Combining Ge and Xe

The GERDA collaboration, Phys. Rev. Lett. 111 (2013) 122503

Comparison with previous half-life limits from Ge and Xe experiments



- **GERDA+HdM+IGEX:**
  - Bayes factor $P(H_1)/P(H_0) = 0.0002$
  - $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr at 90% C.I.
  - best fit: $N^{0\nu}=0$
- **GERDA+KamLAND+EX0**:
  - Bayes factor $P(H_1)/P(H_0) = 0.0022$

On the way to GERDA Phase II

How to get a higher sensitivity for the Phase II:

- reduce radiation sources and understand background sources
- improve background rejection
- increase mass and improve energy resolution

Strategy:

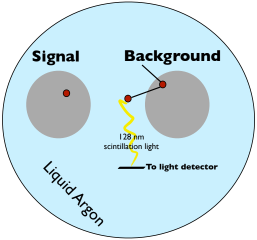
- transition currently ongoing at LNGS
- increase mass: additional 30 enriched BEGe detectors (about 20 kg)
- **suppress background contamination** by a factor of 10 w.r.t. GERDA Phase I:
  1. make things clearer:
     - use lower background Very Front End electronics w.r.t. Phase I
     - use lower background Signal and HV cables w.r.t. Phase I
     - minimize material around sources and special care in crystal production
  2. reject *a posteriori* residual radiation:
     - use BEGes with Pulse Shape Analysis for high background recognition efficiency
     - use LAr scintillation light for background recognition and rejection
- start commissioning in Autumn 2013-Spring 2014

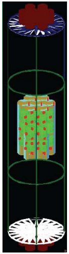
Liquid Argon instrumentation for Phase II

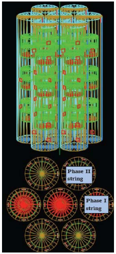
PMT LAr instrumentation studies for Phase II in LArGe (a smaller GERDA facility)

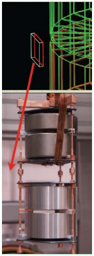
Different possible hardware configurations:

- SiPM fiber curtain
- PMTs on top and bottom of the array
- hybrid solution
- meshed copper shroud around strings
- transparent mini-shroud
- VM2000 coated mini-shroud with large area SiPMs between detectors









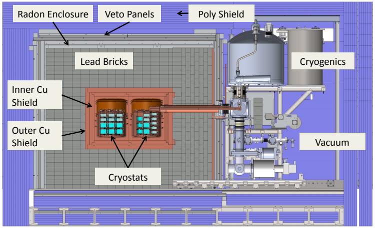
High bkg suppression factors!⟶

Experimental condition	1540-3000 keV[1] cts/(kg d)	Suppression to bare BEGe
Bare BEGe, PMTs off	514(18)	1
MMS, HV = 0, PMTs off	552(16)	0.9
MMS, HV = 0, PMTs on	154(9)	3.3
MMS, HV = +4kV, PMTs on	58(8)	8.9
Nylon MS, PMTs off	203(10)	2.5
Nylon MS, PMTs on	64(3)	8.0
Nylon MS, PMTs on[2]	60(6)	8.6
Nylon MS, PMTs off	58(4)	8.9
Foil MS + SiPM, PMTs off	69(4)	7.5
Foil MS + SiPM, PMTs off	61(3)	8.4
Foil MS + SiPM, PMTs on	49(4)	10.5
LAr refilling		
Foil MS + SiPM, PMTs off	k*81(4)	~ 5.8
Glued Nylon MS, PMTs off	K*28(2)	~ 17

GERDA and Majorana

- water buffer + LAr shield
- active muon veto
- low Z material around detectors
- LNGS ~3800 m.w.e.
- **Phase II goal**: $\frac{10^{-3}\ \text{cts}}{\text{keV kg yr}}$
- commissioning now
- start data taking in 2014
- ~40 kg Ge detectors

Same bkg goal for Gerda and Majorana



Talk by M. Green TAUP '13

- compact Cu+Pb shield
- active muon veto
- high Z material around detectors
- SURF (Sanford) ~4200 m.w.e.
- **Demonstrator goal**: $\frac{3\ \text{cts}}{(4\ \text{keV})\ \text{ton yr}}$
- commissioning in 3 fases:
  - 2 ^{nat}Ge strings now
  - 3 ^{enr}Ge + 4 ^{nat}Ge strings Early 2014
  - 7 ^{enr}Ge strings Late 2014
- ~40 kg of Ge detectors

GERDA and Majorana

- GERDA and Majorana already cooperate for:
  - MC simulations: shared framework
  - detector properties study
  - annual meetings to discuss ongoing results
- last joined GERDA-Majorana meeting in Santa Fe in Sept. 2013
- next meeting in Munich in July 2014
- on the way to a Letter Of Intent to define shared data, shared detectors, intercalibrations, etc.
- to abate costs learn how to grow Ge crystals in view of possible increase of mass: MPI Munich cooperates with IKZ (Leibniz Institut für Kristallzüchtung)
- if the scientific case will remain, a possible Phase III with GERDA+Majorana detectors
- best detection technique for Phase III depends on the future results

Conclusions

- Phase I data taking successful!!
- **5 publications in the first 9 months of 2013**
- total exposure of GERDA Phase I is 21.6 kg yr
- very low background 0.01 cts/(keV kg yr) after PSD
- 3 events observed while 2.5±0.3 expected in $Q_{\beta\beta}$±5 keV
- **half-life of $0\nu\beta\beta$: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.) for ^{76}Ge**
- previous claim signal refuted by GERDA at 99%
- ready to start with Phase II and improve sensitivity
- **GERDA+Majorana** possible joined experiment at the ton scale

Thanks

Thank you for your attention!