Muon induced signals and isotope production in GERDA

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Low Radiation Techniques, Modane, October 1st 2006

GERDA experiment at Gran Sasso

The **GERmanium Detector Array** experiment will look for $0\nu 2\beta$ decay in ^{76}Ge using HP-Ge detectors enriched in ^{76}Ge

The experiment will be hosted in the Gran Sasso National Laboratory, under the Gran Sasso mountain (Italy), 3400 m w.e.

cosmic μ flux reduced by a factor 10^6

GERDA Collaboration

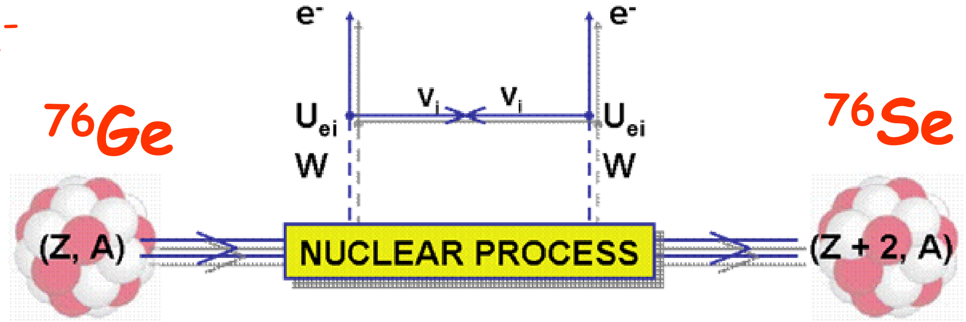
80 physicists

13 Institutions

Italy, Germany, Russia, Belgium, Poland

Gerda physics goals

$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$



Neutrinoless 2β-decay violates the lepton number conservation: $\Delta L=2$

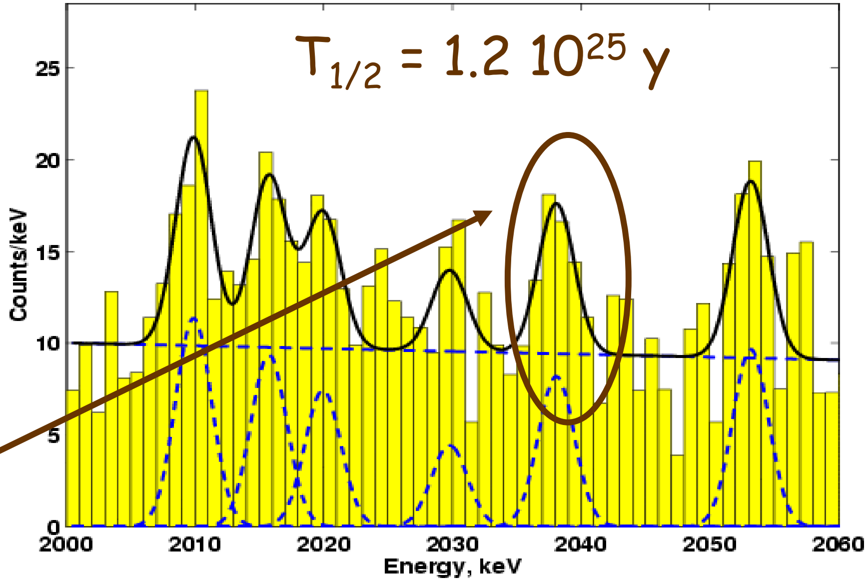
Explore the **Dirac/Majorana nature** of neutrino and the absolute **mass scale**

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

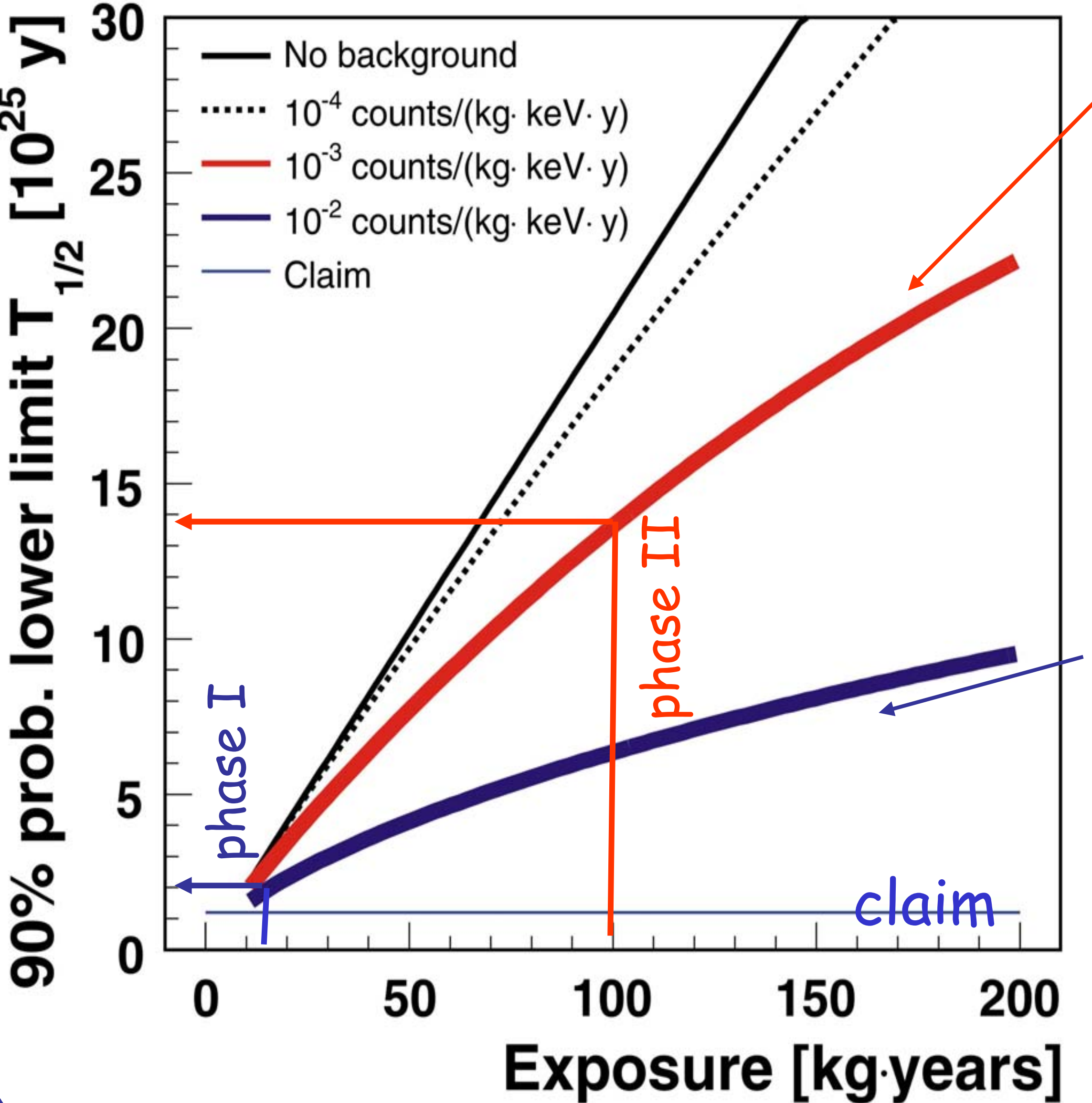
Very **rare process**: $T_{1/2} > 10^{25}$ y

New generation experiments require unprecedented low-background conditions!

Claim from Klapdor-Kleingrothaus et al., NIM A 522 (2004) 371



Goals of the GERDA experiment



GERDA goal:
10^{-3} count/(keV kg y)

improvement of a factor 100 with respect of H-M

Phase I: **test claim**

crystals from HM and IGEX

exposure: 15 kg·y

bck: **10^{-2}** cnt/(keV kg y)
(^{60}Co contamination)

Phase II:

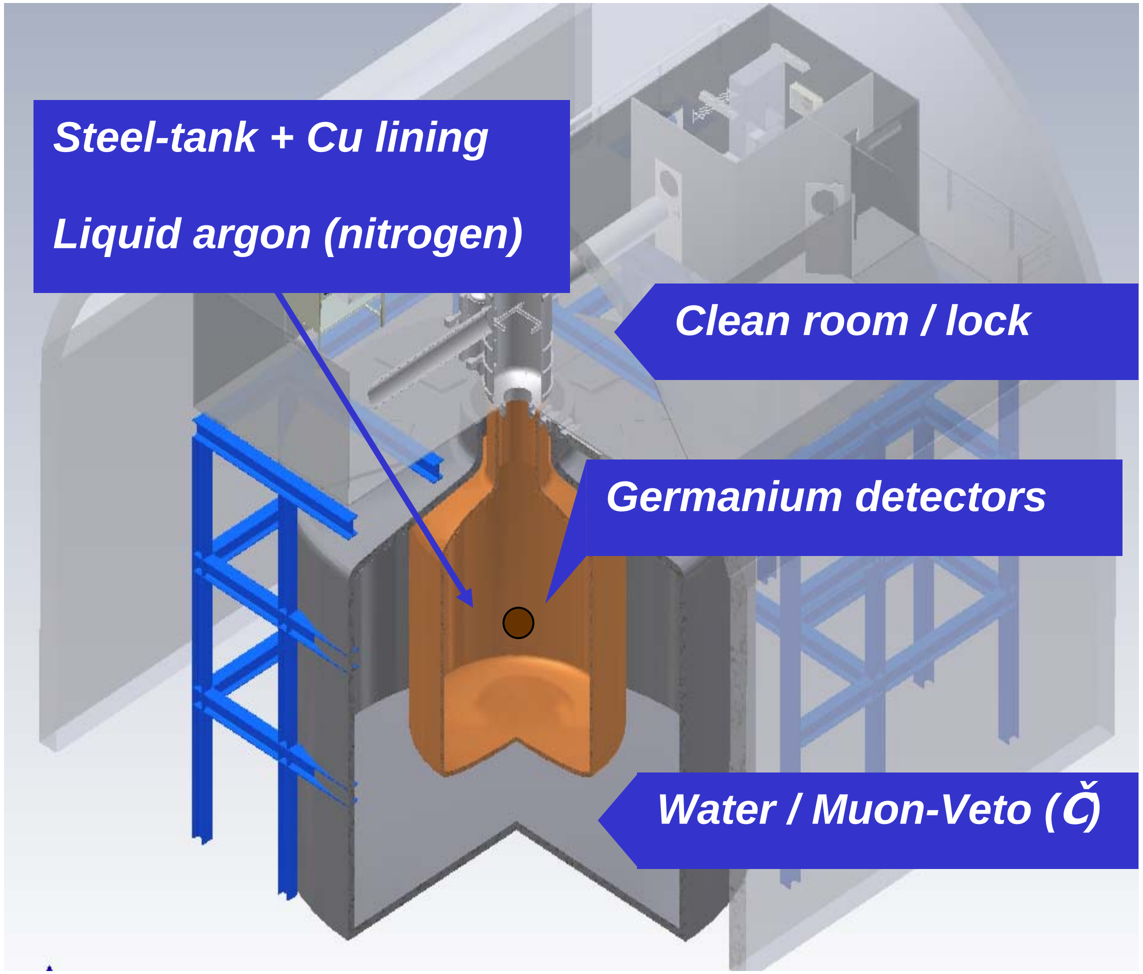
new **segmented** detectors

exposure: 100 kg·y
(it was 71 kg·y in HM)

bck: 10^{-3} count/(keV kg y)

The Gerda design

Use cryogenic liquid (liquid argon) as cooling medium and shield simultaneously → array of naked detectors



Additional water shielding:

- cheap
- safe
- neutron moderator
- Cerenkov medium for 4π muon veto

LAr required to shield γ **radiation** from the **stainless steel cryostat** and from the rock

Background components

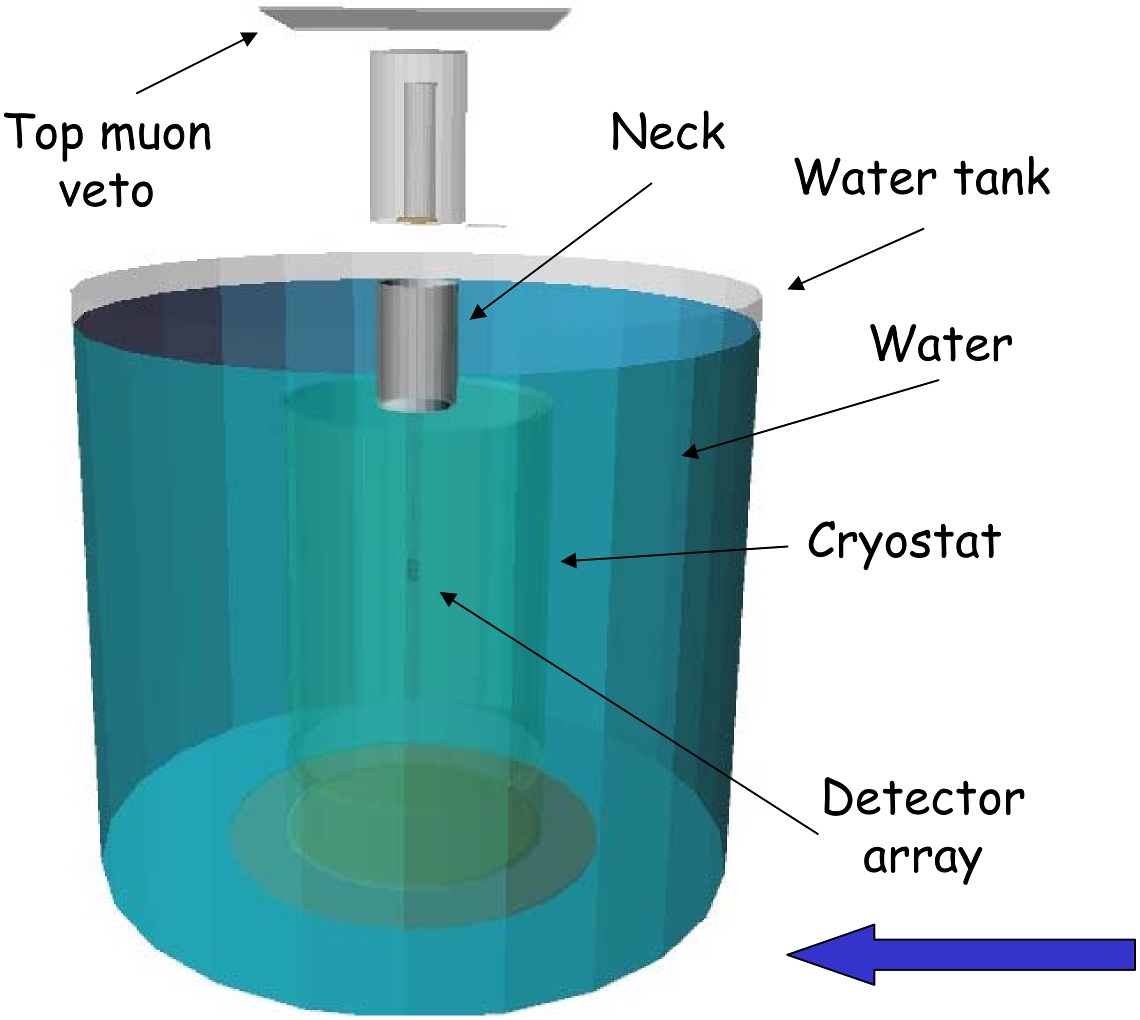
Background source	Possible tools for reduction
External γ-rays (rock)	Multiplicity, passive shielding
Internal contamination	Multiplicity (for γ-rays), delayed coincidences (e.g. ^{68}Ge)
Radioactive **contamination** of the **setup materials** (cryostat, holders, etc.)	Multiplicity, reduction of total mass, radiopurity, passive/active shielding
Muon and neutron induced events	Muon veto, multiplicity, (active shielding)
Unstable isotopes produced by muons	Multiplicity (for γ-rays), delayed coincidence with muon veto
2ν2β decay	Energy resolution

This talk

To meet conservatively the background specification of 10^{-3} counts/(keV·kg·y) **each single component** should be **smaller than 10^{-4} counts/(keV·kg·y)** (goal) at $Q_{\beta\beta}$

Background simulations with MaGe

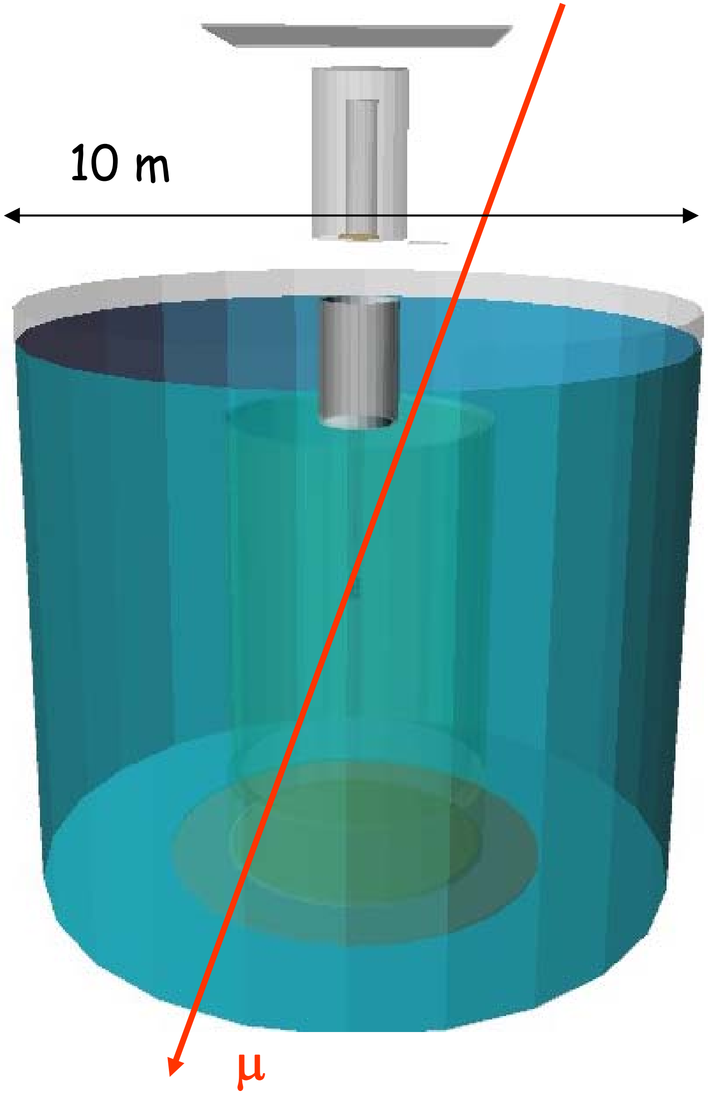
(common Majorana-Gerda Geant4 MC framework)



MaGe includes the whole simulation chain (generator, physics processes, material, management, etc.) and is runnable by script

Description of the **Gerda setup** including shielding (water tank, stainless steel cryostat, copper lining, cryogenic liquid), crystals array and suspension system

Muon-induced background



Prompt background:

$e^{\pm}$ and γ-rays from electromagnetic showers, γ-rays from neutron inelastic interactions or captures

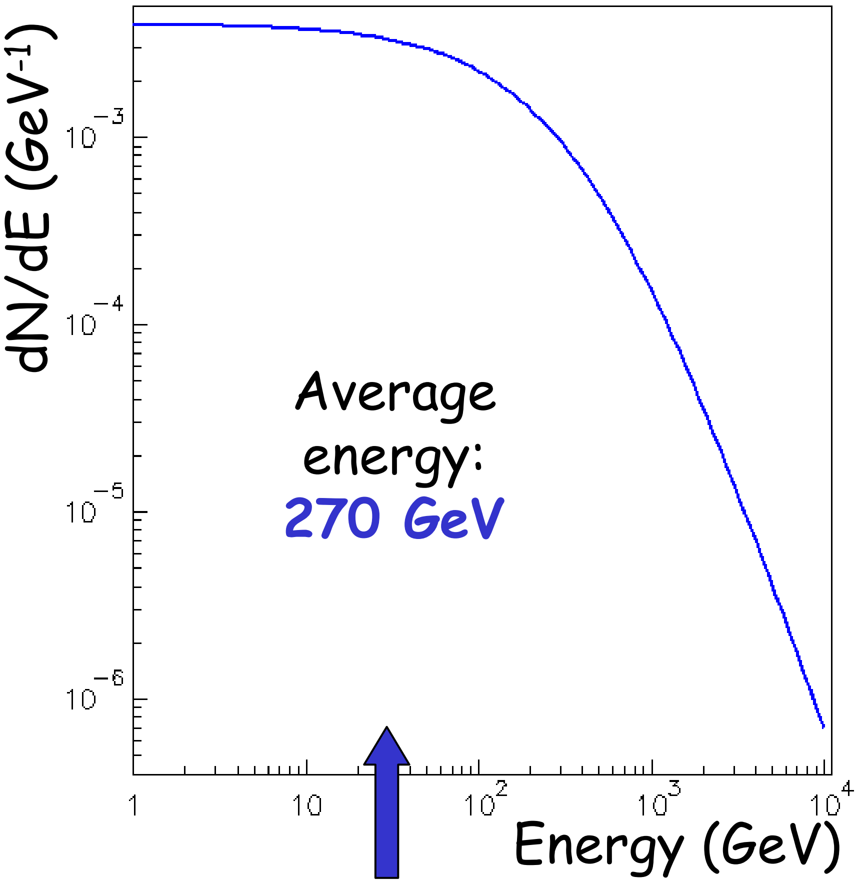
Reduced by anticoincidence or segmentation (Phase II) and **muon veto**. Background reduction depends essentially on the **veto efficiency** only

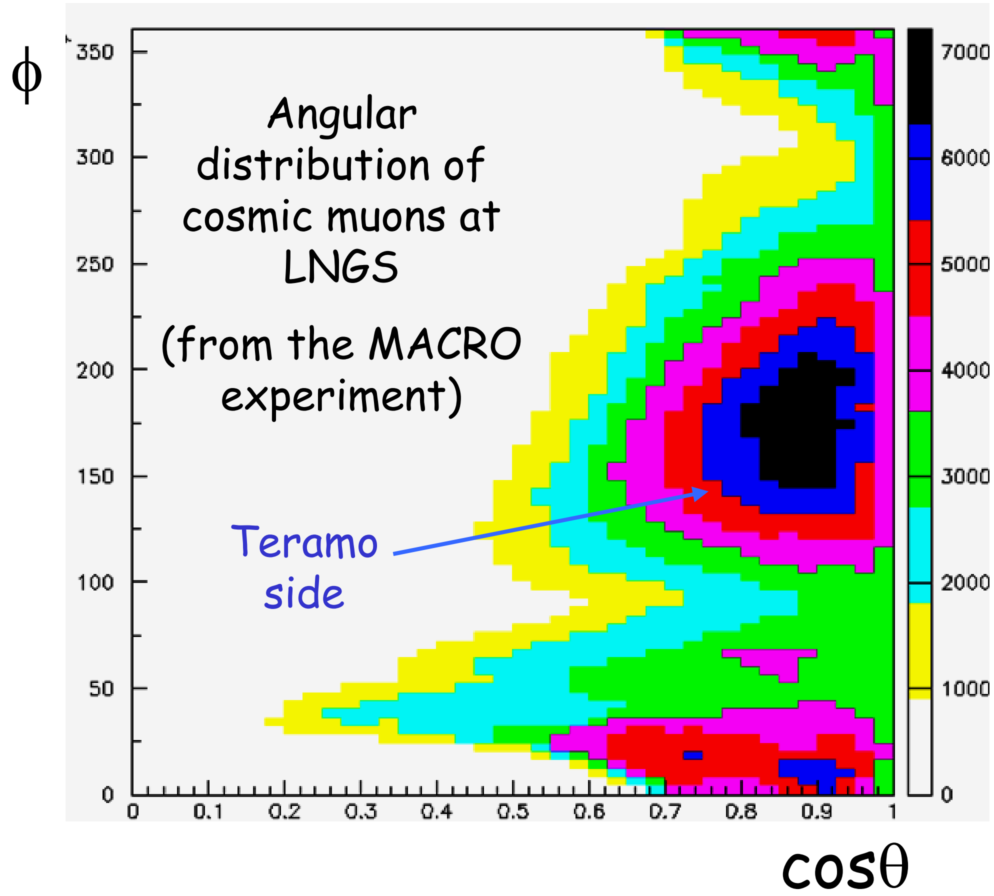
Delayed background:

Production of long-lived **unstable isotopes** in the crystals or in the surrounding material → veto **not effective**

Reduced by multiplicity or segmentation. **Delayed coincidence cuts**

Muon simulations

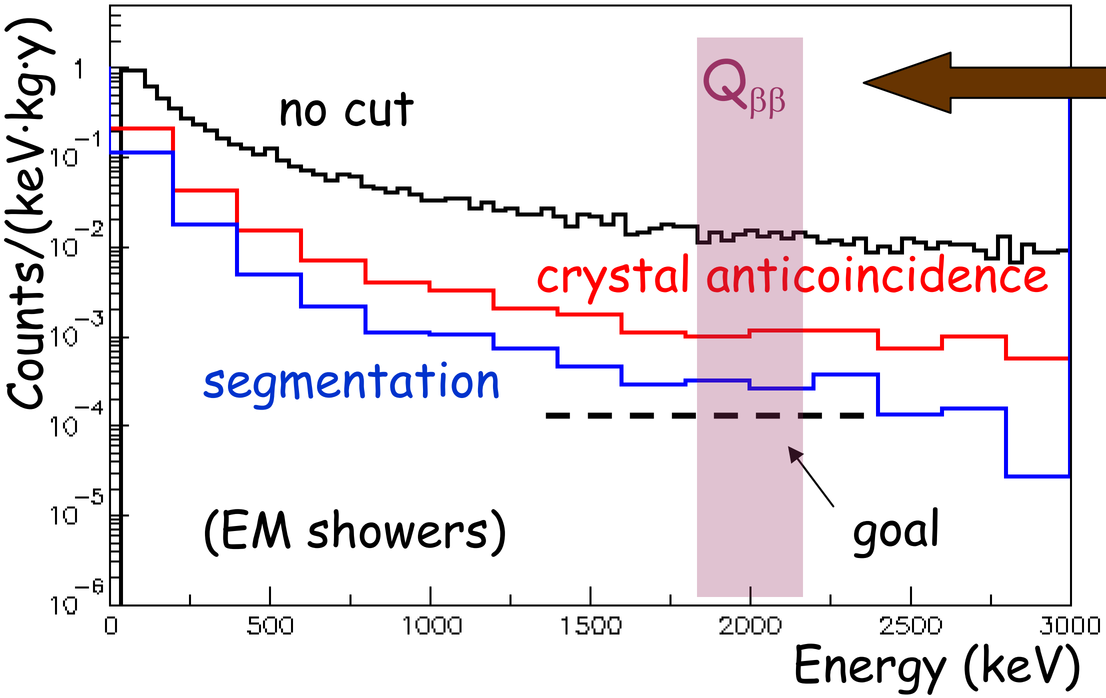




Energy spectrum sampled according to the parametrization of Lipari and Stanev, Phys. Rev. D 44 (1991) 3543

Energy and direction are **sampled independently** → checked with the MUSUN code that simplification does not affect results

Prompt muon-induced background



Energy spectrum in the detectors

Anti-coincidence: factor from 15 (Phase I) to 25 (Phase II)

Segmentation: extra factor of two (Phase II)

This is not enough!

(Reduction by PS discrimination not considered!)

Čerenkov muon veto required !

To get **below 10^{-4} counts/(keV kg y)** it is required a veto **efficiency > 75%** above 120 MeV (> 65% for liquid nitrogen)

Feasible with 0.5% photocatode coverage and VM2000 foils → **80 8" PMT**. Placement of the PMTs optimized with a dedicated simulation of the Cherenkov light

High-energy neutrons from the rock

High-energy neutrons produced in the surrounding rock by cosmic ray muons are a background source → they can enter in the experimental setup. **Veto is uneffective**

Major background source indicated by Mei & Hime, Phys. Rev. D 73 (2006) 053004, for a Majorana-like experiment (= compact experiment with high-Z passive shielding)

→ $(n,n'\gamma)$ interactions on Pb, Cu and Ge

Simulated with spectrum and total flux (~ 300 n/(m^2·y)) from hep-ph/0401032 (2004). Typical energy ≈ 100 MeV

Background: ~ $6 \cdot 10^{-5}$ counts/(keV kg y) ✓

Reduced below 10^{-5} **counts/(keV kg y)** by segment anti-coincidence

Different design with thick low-Z shielding: **water** (3 m) and the **cryogenic liquid** (2 m) are **effective neutron moderators**

Delayed background

Muon-induced interactions can create long-lived unstable isotopes in the setup materials with **$Q > Q_{\beta\beta}$**

veto rate: 2.5 ev/minute

cannot be vetoed if $T_{1/2}$ > 100's ms

Isotopes in the crystals are the most relevant (also β-rays detected with high-efficiency).

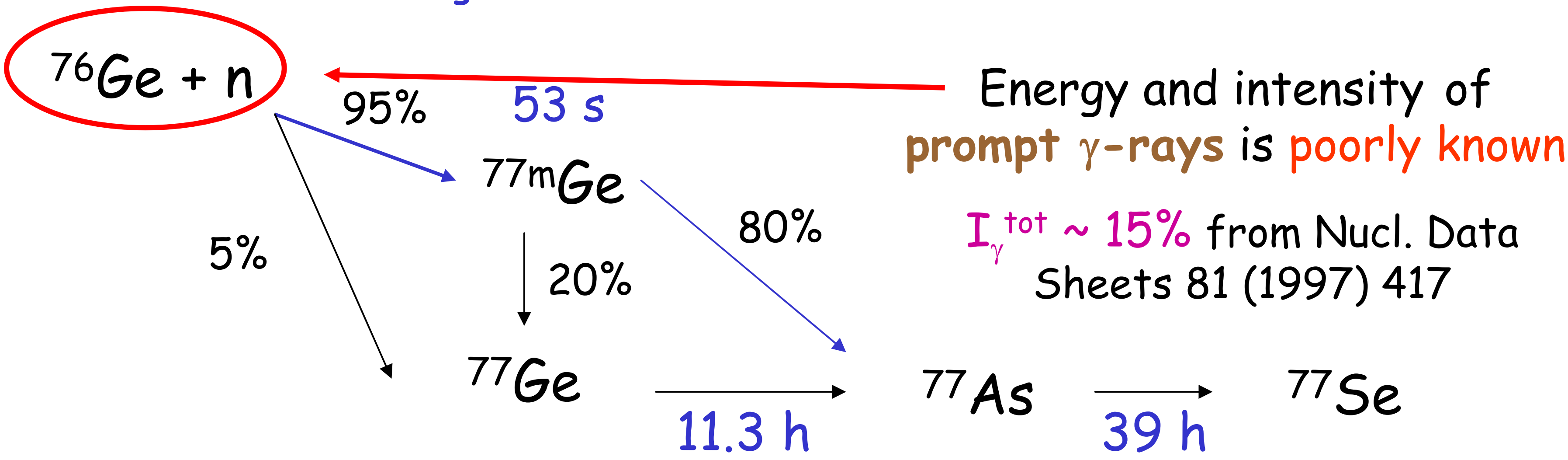
In crystals: ^{74}Ga, ^{75}Ga, ^{76}Ga, ^{68}Ge, ^{69}Ge, ^{77}Ge, ^{71}Zn
In cryoliquid: ^{13}N, ^{11}C, ^{12}B, ^{38}Cl, ^{39}Cl, ^{40}Cl
In water: ^{16}N, ^{14}O, ^{12}B, ^{6}He, ^{13}B

Red → isotopes > 10^{-6} counts/(keV·kg·y)

Most dangerous is ^{77}Ge from **thermal neutrons**: no threshold, high cross section (0.14 b), high decay Q-value (2.7 MeV), **scales with enrichment**

Thermal neutron capture in ^{enr}Ge

Neutron capture in ^{76}Ge (0^+) can eventually populate $^{77}Ge_{g.s.}$($7/2^+$) or ^{77m}Ge ($1/2^-$, 159 keV)



PHYSICAL REVIEW VOLUME 107, NUMBER 4 AUGUST 15, 1957

Radioactive Ge^{77} and Ge^{77m}

W. S. Lyon and J. S. Eldridge
Oak Ridge National Laboratory, Oak Ridge, Tennessee*
(Received February 25, 1957)

Pile neutron activation cross sections for production of Ge^{77} and Ge^{77m} have been obtained. In addition, the half-lives of Ge^{77} and Ge^{77m} have been measured as well as the γ/β^- branching in the beta decay of Ge^{77m}.

^{77}Ge → β-decay, Q = 2.7 MeV

^{77m}Ge → β-decay, Q = 2.8 MeV

Isotopes production rate

Isotope	Liquid Nitrogen		Liquid Argon	
	nucl/(kg·y)	cts/(keV·kg·y)	nucl/(kg·y)	cts/(keV·kg·y)
^{74}Ga/^{75}Ga/^{76}Ga	< 0.08	< $3\cdot10^{-5}$	< 0.1	< $4\cdot10^{-5}$
^{68}Ge	0.07	$4\cdot10^{-6}$	0.08	$5\cdot10^{-6}$
^{69}Ge	0.38	$1\cdot10^{-6}$	1.8	$5\cdot10^{-6}$
^{77}Ge/^{77m}Ge	0.05	$1\cdot10^{-5}$	**0.51**	**$1.1\cdot10^{-4}$**
^{38}Cl	-	-	46 day^{-1}	$3.3\cdot10^{-5}$
^{40}Cl	-	-	2.7 day^{-1}	$4\cdot10^{-6}$

Actual background depends on: production rate, location and decay scheme. Isotopes produced in water and cryostat < 10^{-6} cts/(keV·kg·y)

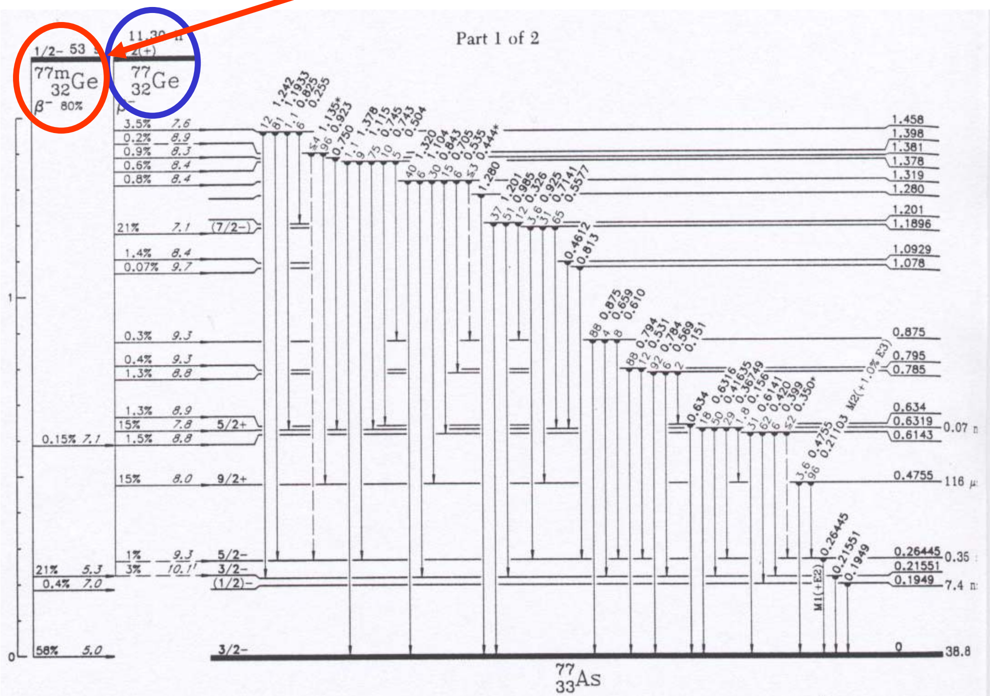
^{38}Cl and ^{40}Cl reduced below 10^{-5} cts/(keV·kg·y) by segmentation cuts

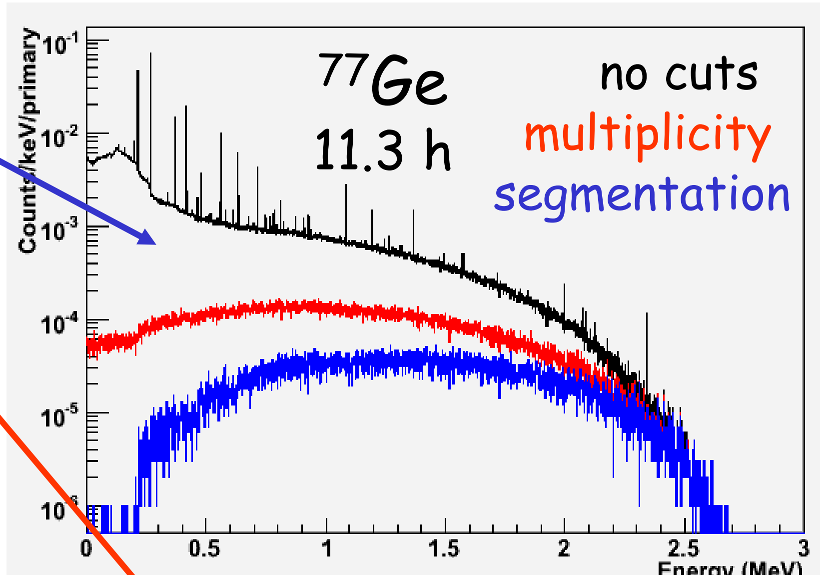
Main contribution (for LAr) from ^{77}Ge/^{77m}Ge → 10^{-4} cts/(keV·kg·y) **= goal!**

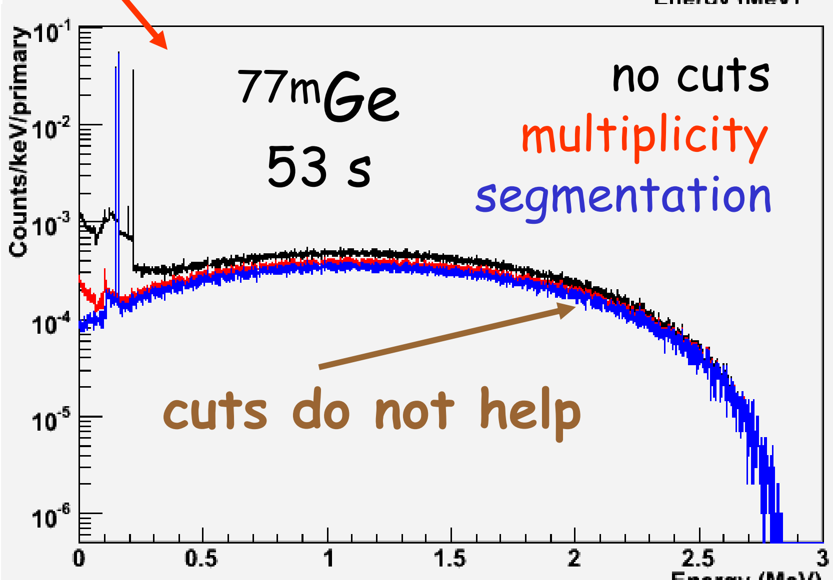
Rejection strategies for ^{77m}Ge

^{77}Ge(7/2)$^+$ → ^{77}As(3/2)$^-$ has a lot of **associated γ-rays**. Anticoincidence and segmentation very effective

^{77m}Ge(1/2)$^-$ → ^{77}As(3/2)$^-$ is dominantly a **pure β-decay** (215 keV γ-ray with 25% BR)







Rejection strategies for ^{77m}Ge

A 4-minutes long (=4 $T_{1/2}$) dead-time after each muon veto trigger is not feasible (2.5 events/minute)

Possibility: **dead time** after each coincidence between **muon veto** (primary μ) and **Ge crystals** (prompt γ-rays)

The cut efficiency depends on the probability to observe the capture γ-rays: 6 MeV released after neutron capture in ^{76}Ge. Intensities and energies are very poorly known

The **efficiency** is **> 50%** in the most pessimistic case (energy released in a single photon) → ^{77m}Ge background can be **reduced** by **at least** a factor of **two**

Conclusions

Prompt μ-induced background can be kept **under control**, provided the **veto** is **efficient**

Isotope production (delayed background) is more relevant for **LAr** (required for shielding γ-rays from cryostat)

Background rate from all isotopes (^{68}Ge, ^{69}Ge, ...) can be kept below 10^{-5} counts/(keV·kg·y) (possibly with segment coincidence), **except ^{77m}Ge**

^{77m}Ge gives mostly **single-site events**. Rejection strategies based on delayed coincidence between muon, prompt γ-rays and β-decay

The background from muons is **< 10^{-4}** counts/(keV·kg·y) **for LAr → within specifications** ✓

Backup slides

Muon-induced fluxes

Muon-induced **flux** of **secondary particles** (γ-rays and neutrons) in the detector region → possible background sources

Cryoliquid:	Flux of **γ-rays** above $Q_{\beta\beta}$ (2039 keV) particles/($m^2 \cdot h$)	Integral **neutron** flux particles/($m^2 \cdot h$)
Liquid nitrogen	5.4	0.72
Liquid argon	9.8	5.7

Fluxes **depend** on the **cryogenic liquid** → different A, Z and density (= different x_0 and E_c) affect **propagation** of **neutrons** and **γ-rays**

Neutron flux is increased by a factor of 8 in liquid argon:

- larger neutron yield from muons ($\propto A^{0.8}\,\rho$)
- smaller efficiency in neutron moderation and absorption

Prompt muon-induced background

Prompt energy deposition at $Q_{\beta\beta}$ is **dominated** (> 95%) **by γ-rays** from muon-induced electromagnetic showers

(n,n'γ) on ^{74}Ge and ^{76}Ge mainly produce **γ-rays below $Q_{\beta\beta}$** (not a background!). Radiative capture in Ge less likely than inelastic

If the muon passes through the detector → large energy deposition (**tens of MeV**). **Far from $Q_{\beta\beta}$!**

Systematic uncertainty on the prompt background:

Item	Uncertainty
Primary muon spectrum	10%
e± and γ-ray tracking in Geant4	< 5%
EM interactions of HE muons	< 5%
Total	**≈ 11%**

Med Phys. 32 (2005) 1696; IEEE TNS 52 (2005) 910 (→ e± and γ-ray tracking in Geant4)

IEEE TNS 53 (2006) 513 (→ EM interactions of HE muons)

Neutrons & isotopes in the setup

Neutrons are produced by muon-induced interactions (e.g. photo-nuclear reaction) → sources of prompt and delayed background

Simulation of muon-induced neutron yield → **"hot" topic** in Monte Carlo, mainly in DM experiments. Data are scarce (and sometimes inconsistent) → comparison between different codes (Fluka, MCNPX)

Systematic uncertainty on the neutron flux:

Item	Uncertainty
Primary muon spectrum	10%
Neutron yield from muons (Z < 35)	40%
Neutron tracking in Geant4 (thermal to hundreds of MeV)	20%
Total	**≈ 45%**

From NIM A 545 (2005) 398 (40%)

From NIM A 560 (2006) 454 (20%)

Uncertainty for isotopes produced directly by neutrons (e.g. via capture) → same order of magnitude. **Uncertainty** of a **factor 2-4** for **other isotopes** (e.g. photo-nuclear)

Rejection strategies for ^{77m}Ge

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Production rate of $^{77(m)}Ge$ depends on the **specific isotopic composition** of the enriched detectors

^{73}Ge has a capture cross section 100 times larger than ^{76}Ge → it absorbs neutrons and produces ^{74}Ge (stable). The capture γ-rays are prompt (→ muon veto)