Nuclear emulsion with molybdenum filling for 2β -decay observation

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Application of the nuclear emulsion as a detector surrounding the 2β -decay target

- J.H.Fremlin et al. Pros.Phys.Soc. V.65, p.911 (1952) For 16 isotopes the lower limits were measured relative to (0ν) – mode ~10^{15} – 10^{17} years.

- A.S.Barabash et al. Preprint ITEP 104 – 88 (1988) The limit for $2\beta(2\nu)$ from ^{96}Zr > $0.7x10^{17}$ years was established.

Proposed method

- ✓ In the stage of production the nuclear emulsion is filled with fine powder of the required isotope.
- ✓ Thus, the nuclear emulsion is simultaneously target and detector
- ✓ The main advantage of this approach to the 2β-decay study is the visualization of events and the possibility of all the decay characteristics measurement:
  - the total energy,
  - the single electron energies
  - and their angle of divergence.

Testing of proposed method

R&D with use of molybdenum fine powder of industrial production were held**.**

There were made 10 plates (9x12x0.0075) cm^3, V_{em} =8.1cm^3 with 1.43 grams Mo (4.6% of the dry emulsion weight).

Testing of proposed method

ESTABLISHED

Molybdenum does not "spoil" of the nuclear emulsion properties and the powder does not interfere with scanning and measurements on microscope

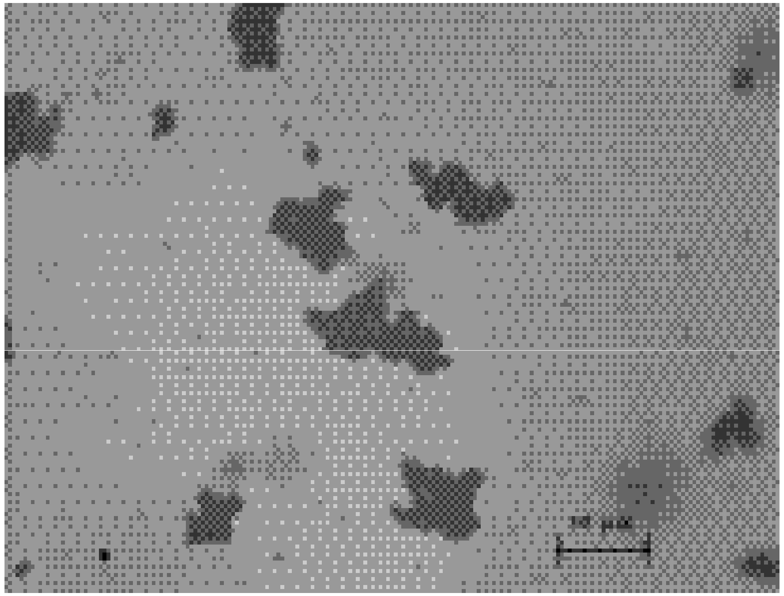


Fig.1. Emulsion image with different size of Mo grains

In the emulsion polymerization process, the partial deposition of large Mo grains take place in the field of gravity

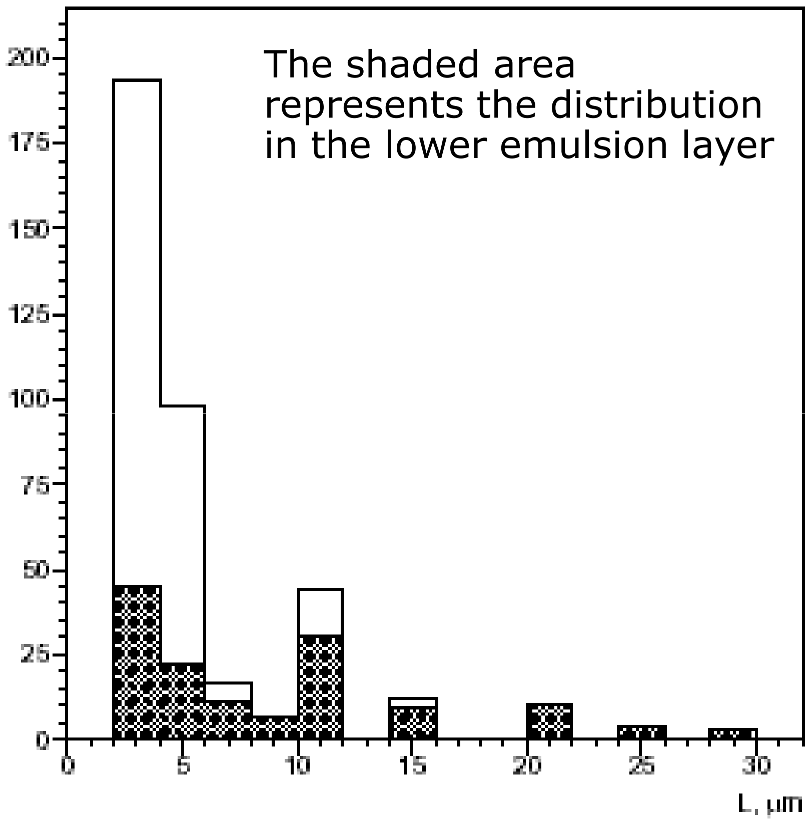


Fig.2. Grains size distribution.

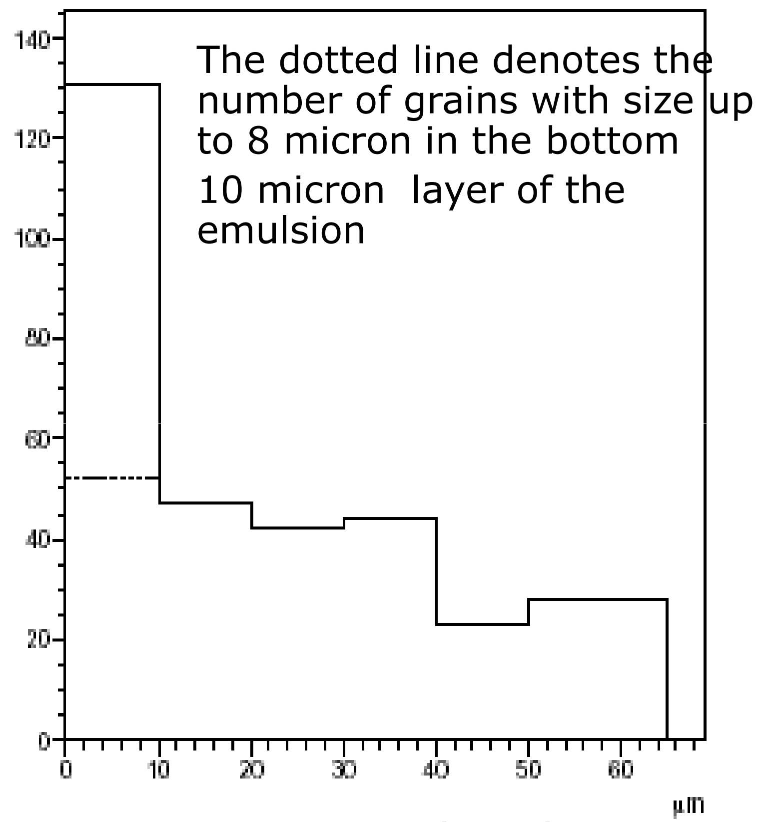


Fig.3. Grains distribution in the emulsion depth

Testing of proposed method

I. It is necessary to eliminate Mo grains larger than 6-8 microns and periodically turn over the emulsion layers while drying.

II. Visual evaluation shows that that the emulsion charge with molybdenum powder can be increased in 1.5-2 times.

Estimation for the experiment with 1 kg of Molybdenum

- For 1 gram of Mo it should be taken 5.6 cm^3 of dry emulsion;
- For 1 kg.→ 5.6 liters (21.3 kg. of dry emulsion).
- For 1 liter of dry emulsion→115 kg. of gel.
- For test with 1 кg of ^{100}Mo → 65.5 kg of gel.
- 860 emulsion layers (9x12x0.06) cm^3 with filling increased by factor of 1.5-2 give

  570 – 430 emulsion layers (10 -12 emulsion chambers).

- Measurements on three units with scanning speed 1 layer per day will take for about a year.

Background estimation

- With zero background and 70% detection efficiency for $0\nu\beta\beta$ ^{100}Mo during one year one can get result ~$1.5\text{x}10^{24}$ years. The first stage of the test: ~ 100 gr. ^{100}Mo for background estimation and measurement of ~10^3 $2\nu2\beta$-decays.
- Nuclear emulsion does not have temporal resolution. Consecutive, not simultaneous escape of 2 electrons from grain will simulate 2β decay of ^{100}Mo.

Background estimation

Bad purification of ^{100}Mo and two decays of ^{40}K in gelatin near the grain ($T_{1/2}$ = 1.28 x 10^9 years, E_β = 1.312 MeV)

^{90}Sr decay near the grain

$^{90}Sr_{38} \rightarrow {}^{90}Y_{39} + e^- + \nu_e$ ($T_{1/2}$ =28.8 years, E_e = 0.549 MeV)

$^{90}Y_{39} \rightarrow {}^{90}Zr_{40} + e^- + \nu_e$ (E_e = 2.28 MeV)

Total energy 2.829 MeV.

Background estimation

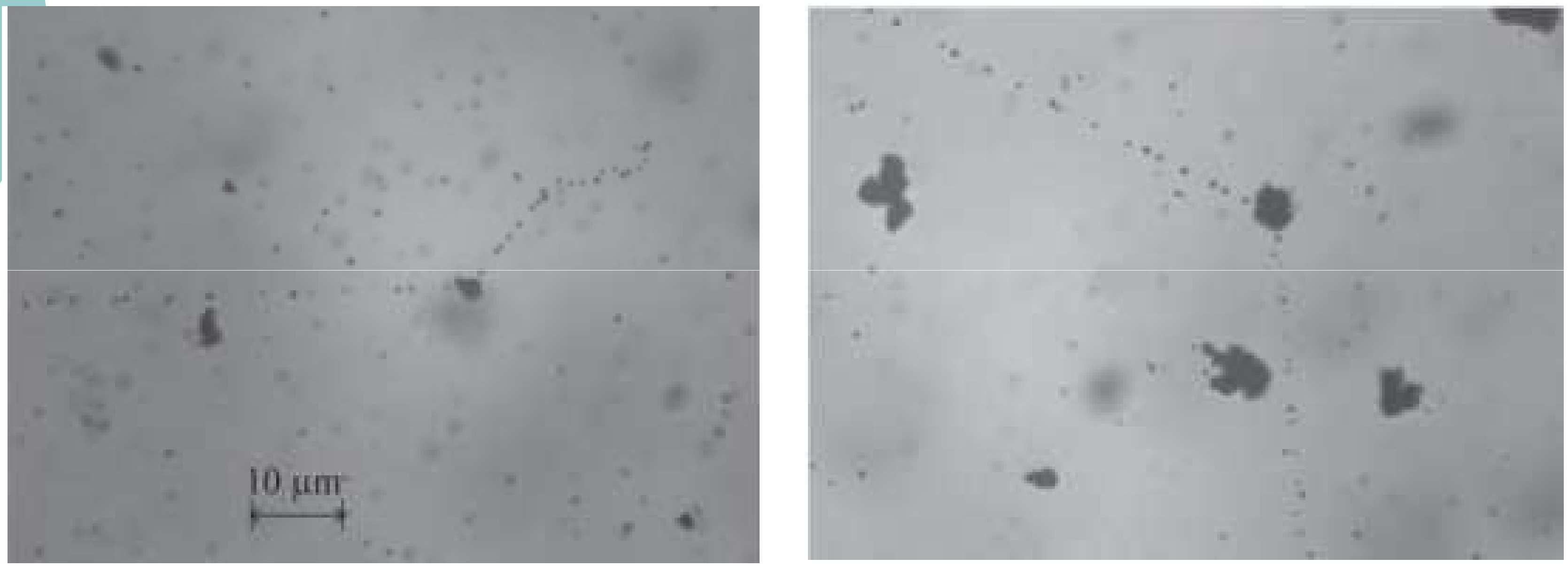


Fig.4. Image of real emulsion with Mo-conglomerates and simulation of flight two electrons with different energy value

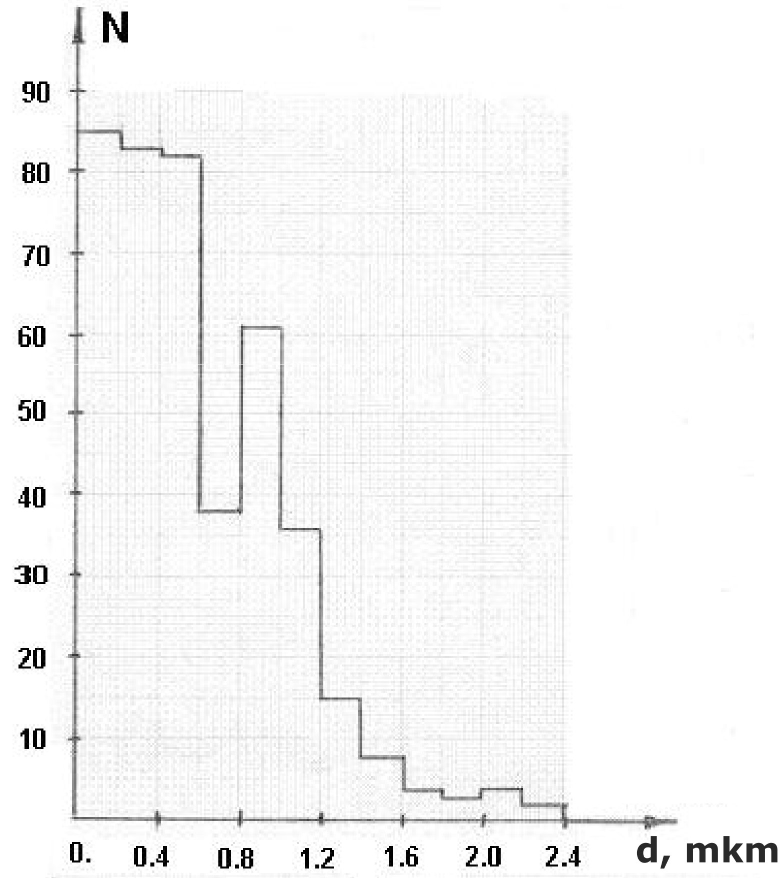
Possibility of exclusion of events imitating 2β- decay

There were considered positron-nuclear interactions in which produced relativistic particles are escaping from the interaction point with various angles. The pairs of particles with a divergence angle **φ** were selected and precision of their trajectory convergence to the interaction point were determined (schematically looks as intersecting straight lines). As the intersection point "**d**" the minimum distance between them is taken.

Position of "d" within the angle φ does not exceed the limits of conglomerate (grain of Mo) and 80% of "d" is concentrated in the area of ~1micron. $\langle d \rangle = (0.60 \pm 0.03)$ micron is about the emulsion grain size, and no correlations between d and φ are found.

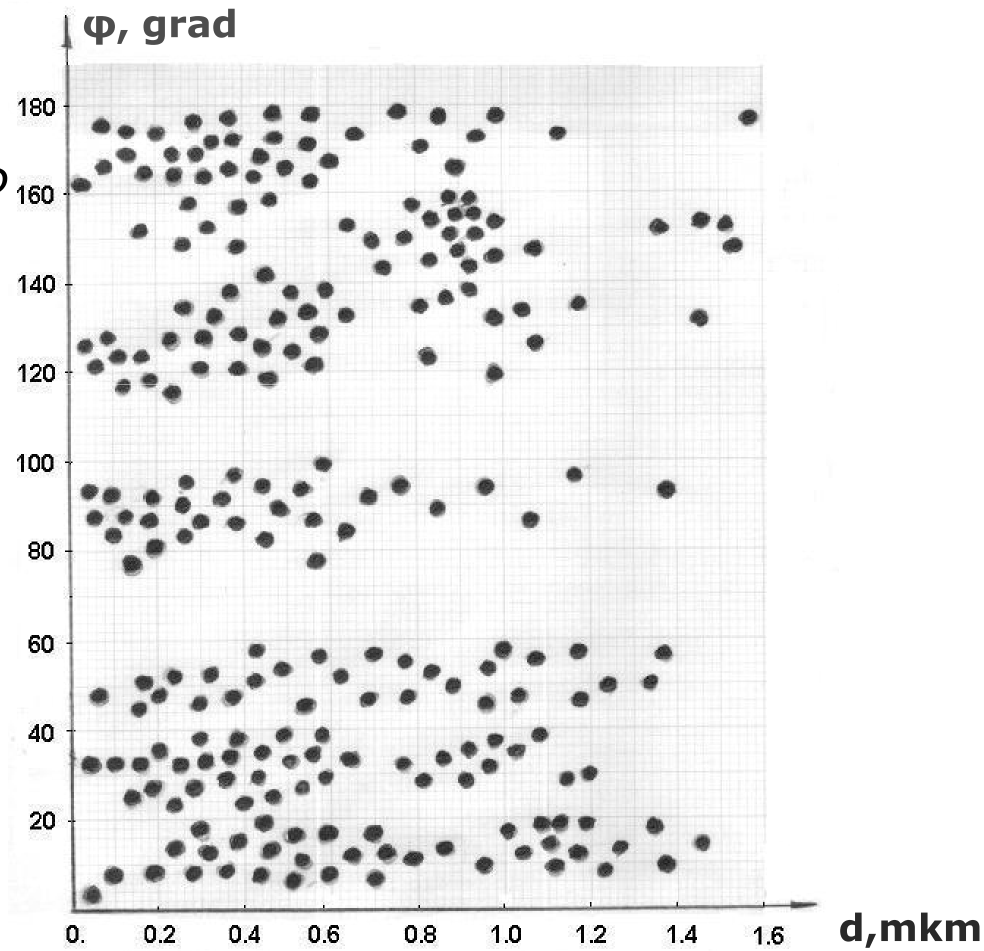
Possibility of exclusion of events imitating 2β- decay

Fig.4. Distribution of value d, minimal distance between two tracks, generated the particles from point of collision positron and emulsion nuclei



Possibility of exclusion of events imitating 2β- decay

Fig.5. Distribution of value d, minimal distance between two tracks, with regard to angle φ between two tracks



Possibility of exclusion of events imitating 2β- decay

WE assume that grain size is **<R_k>=3 micron and its “danger area” is about ~d (0.6 micron).**
In this case, the exposure with 1 кg of ^{100}Mo(5.6 liters of emulsion) the number of background decays will be suppressed by a factor of **~1.5x10^{-2}**

Clean up potassium up to ~**10^{-8} g/g gives the number of decays** ^{40}K in a “dangerous zone” ~**0.7x10^{-5} decay/year*grain and two electron observing ~5x10^{-11}** . This probability should be reduced by the accuracy of determining the escape of two electrons from one point.

Thus, due to ^{40}K we have ββ-decay: ~ 5 events a year in exposure of 1 kg ^{100}Mo and less than one event in the energy range of (3±0.3) MeV.

Possibility of exclusion of events imitating 2β- decay

In the strontium disintegration both electrons are emitted from a single point and can be perceived as ββ-decay particles.

When the strontium activity is **~1 mBq/kg and the amount of emulsion is 21.3 kg** (1 kg of ^{100}Mo), about 1 event a year can be detected in the "danger area" with the energy of electrons (~0.5 and ~2.3 MeV),
> 2.8 MeV (with energy resolution 10%).

This background can be reduced due to the "symmetrical" ββ-decay.

Background from natural radioactive elements: Thorium, Uranium, Radium and Actinium series

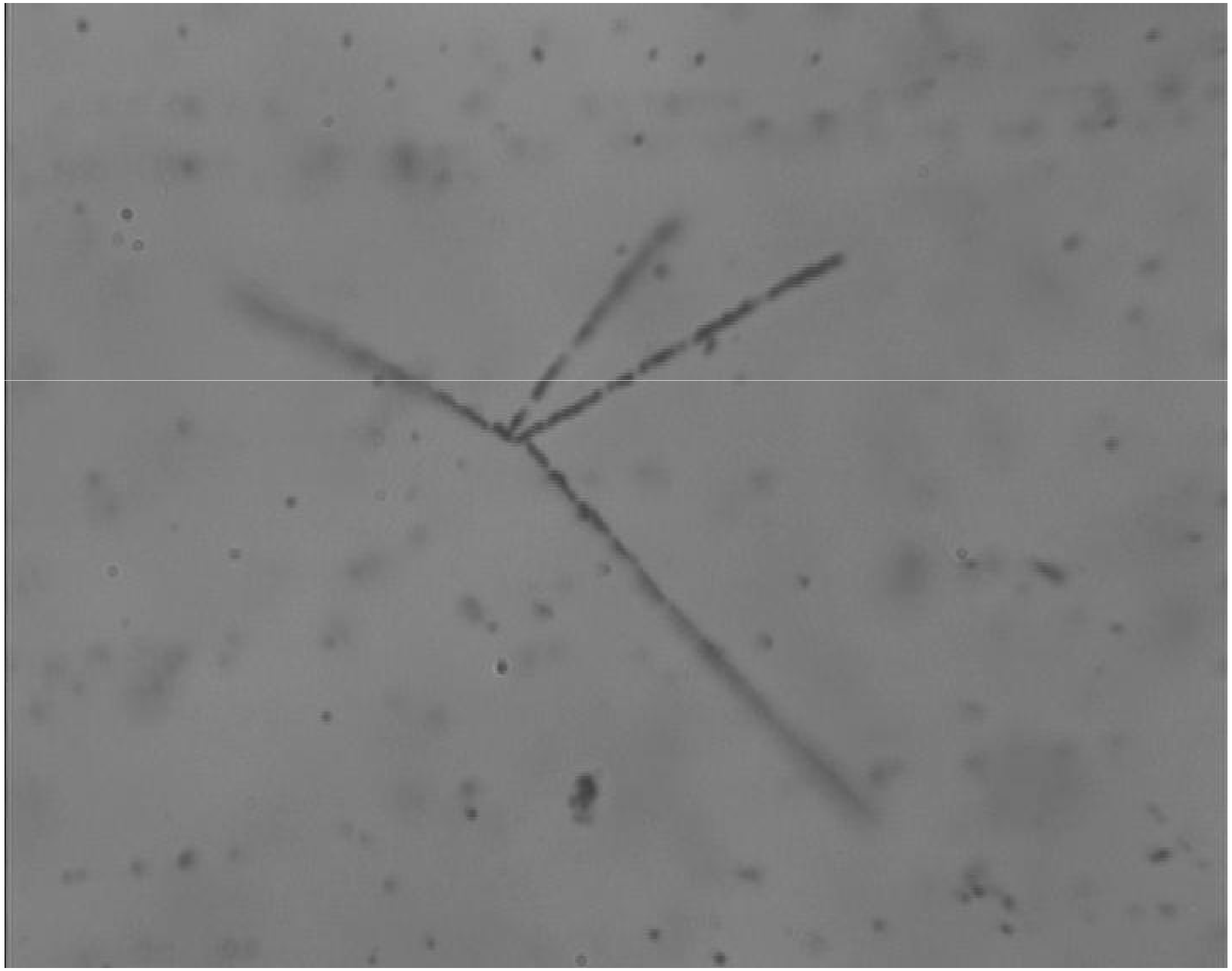
In a typical, not extreme, case **1 cm^3** of emulsion contains about 20 decays, forming **3-5 ray stars of** α-particles.

The decay chain always begin with a successive emission of α-particles, and only at the end of the chain the elements emitting β and gamma particles arise.

Path of α-particles in emulsion is **10 – 50 micron** (E_α = 3 ÷ 9 MeV). The α-stars are detected in the emulsion with about ~100% efficiency.

"Double events": grain of ^{100}Mo and α-star allow to exclude the background of electrons from natural radioactive elements.

Emulsion “star” from consecutive α-decay of Thorium radioactive elements



SUMMARY

Result

10 – 12 emulsion chambers, filled with 1 kg ^{100}Mo, are processed on three scanning microscopes for 1 year. The expected result of the decay period measurement is ~1.5x10^{24} years.

Background (ββ)

Background from ^{40}**K** is ~5events/year and **<1** event in the region **(3±0.3) MeV**.

Background from ^{90}**Sr** is about **~1** event/year with the electron energy **>2.8 MeV**. Background from natural radioactivity is almost completely excluded.

Accuracy of energy measurement of charged particles by their range in nuclear emulsion.

The energy of muons from $\pi \rightarrow \mu\nu$ decay is monochromatic one.

According to our measurements

$$E_{\mu} = (4.12 \pm 0.1) \text{ MeV}$$

Thank you for attention

Background slides

Background slides

Next generation experiments

- Main goal:

  Reaching sensitivity

  ~0.01 – 0.1 eV
- Strategy:

  investigation more than one isotopes **> 2-3**;

  use different strategy

Experiments are going to be realized in the nearest ~ 3÷10 years

- CUORE (^{130}Te)
- GERDA (^{76}Ge)
- MAJORANA (^{76}Ge)
- EXO (^{136}Xe)
- SuperNEMO (^{82}Se)
- KamLAND (^{136}Xe)
- SNO+ (^{150}Nd)

CUORE

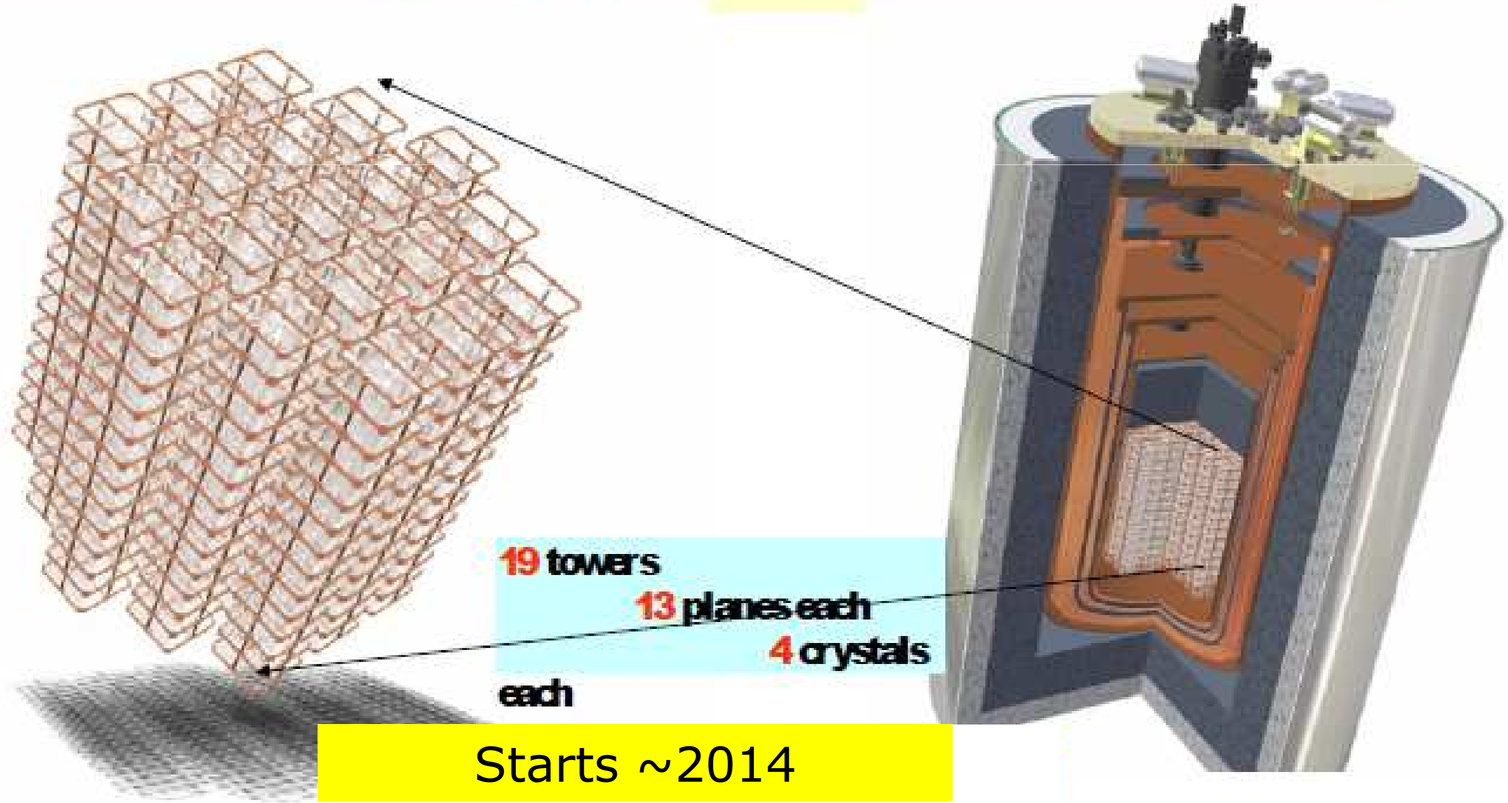
Cryogenic Underground Observatory for Rare Events

- Closely packed array of 988 TeO_2 crystals 5×5×5 cm^3 (750 g)

741 kg TeO_2 granular calorimeter

600 kg Te = 203 kg ^{130}Te

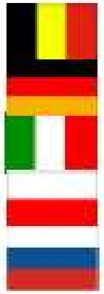
- Single high granularity detector

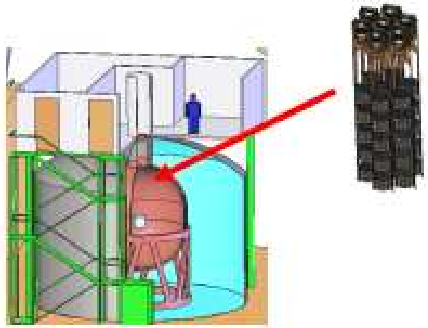


Starts ~2014

GERDA - Majorana

GERDA

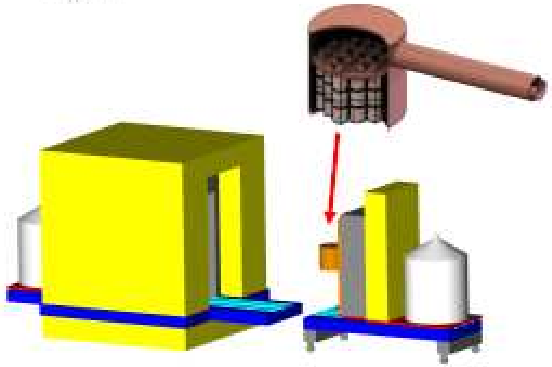




- 'Bare' ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I (~ 2011): ~ 18 kg (HdM/IGEX diodes)
- Phase II (~ 2013): add ~ 20 kg new detectors

Total ~ 40 kg

Majorana



- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D prototype module (~ 2013)

Total ~ 40 kg

Joint Cooperative Agreement:

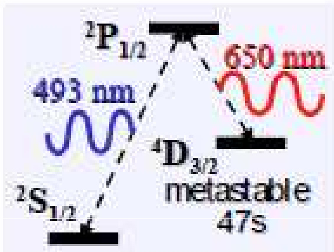
- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention to merge for 1 ton exp. Select best techniques developed and tested in GERDA and Majorana

Starts with 1000 kg ~ 2016÷2017

Tracking

EXO

- **concept**: scale Gotthard experiment adding **Ba tagging** to suppress background ($^{136}Xe \rightarrow ^{136}Ba^{++} + 2e$)
- single Ba^{+} detected by optical spectroscopy
- two options with 63% enriched Xe
  - ▶ High pressure Xe TPC
  - ▶ LXe TPC + scintillation
- **calorimetry + tracking**
- expected bkg only by $\beta\beta$-2ν
  - ▶ energy resolution σ_E = 2%

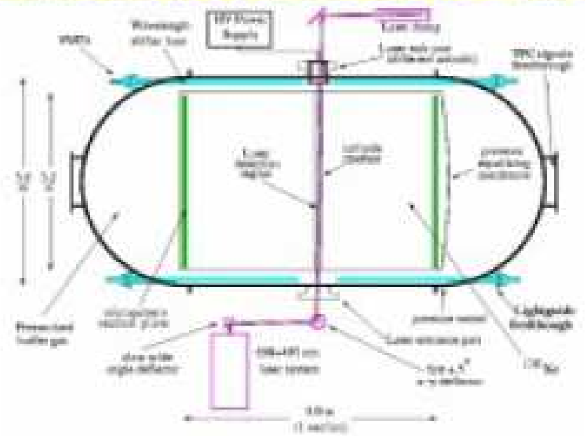


Present R&D

- Ba^{+} spectroscopy in HP Xe / Ba^{+} extr.
- energy resolution in LXe (ion.+scint.)
- Prototype scale:
  - ▶ 200 kg enriched L ^{136}Xe without taggin
  - ▶ all EXO functionality except Ba id
  - ▶ operate in WIPP for ~two years
- Protorype goals:
  - ▶ Test all technical aspects of EXO (except Ba id)
  - ▶ Measure 2ν mode
  - ▶ Set decent limit for 0ν mode (probe Heidelberg- Moscow)

LXe TPC

Conceptual schema of a high pressure Xe gas TPC with laser tagging

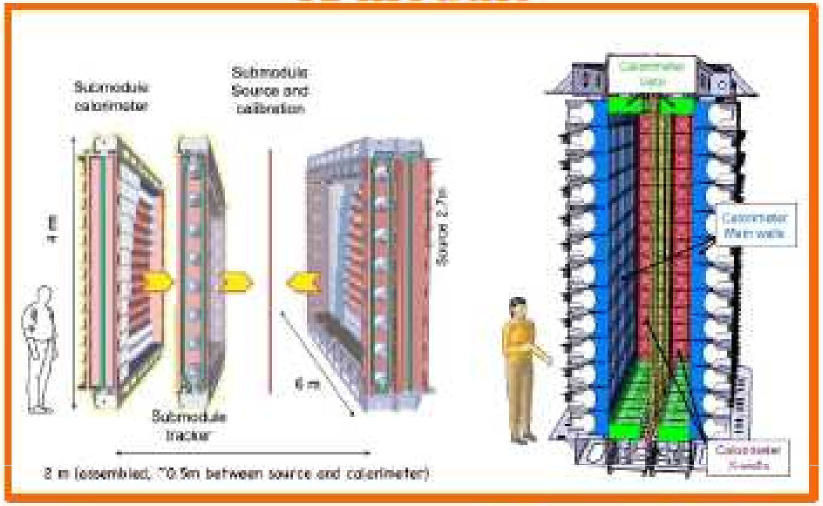


Full scale experiment at WIPP or SNOLAB

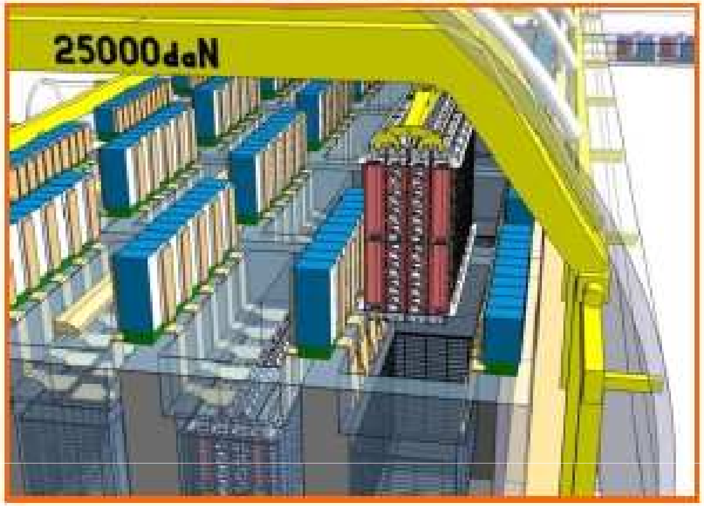
- **10 t** (for LXe ⇒ 3 m^3)
  - $b = 4 \times 10^{-3}$ c/keV/ton/y
  - $T_{1/2} > 1.3 \times 10^{28}$ y in 5 years
  - $\langle m_\nu \rangle < 0.013 \div 0.037$ eV

SuperNEMO

A module



20 modules

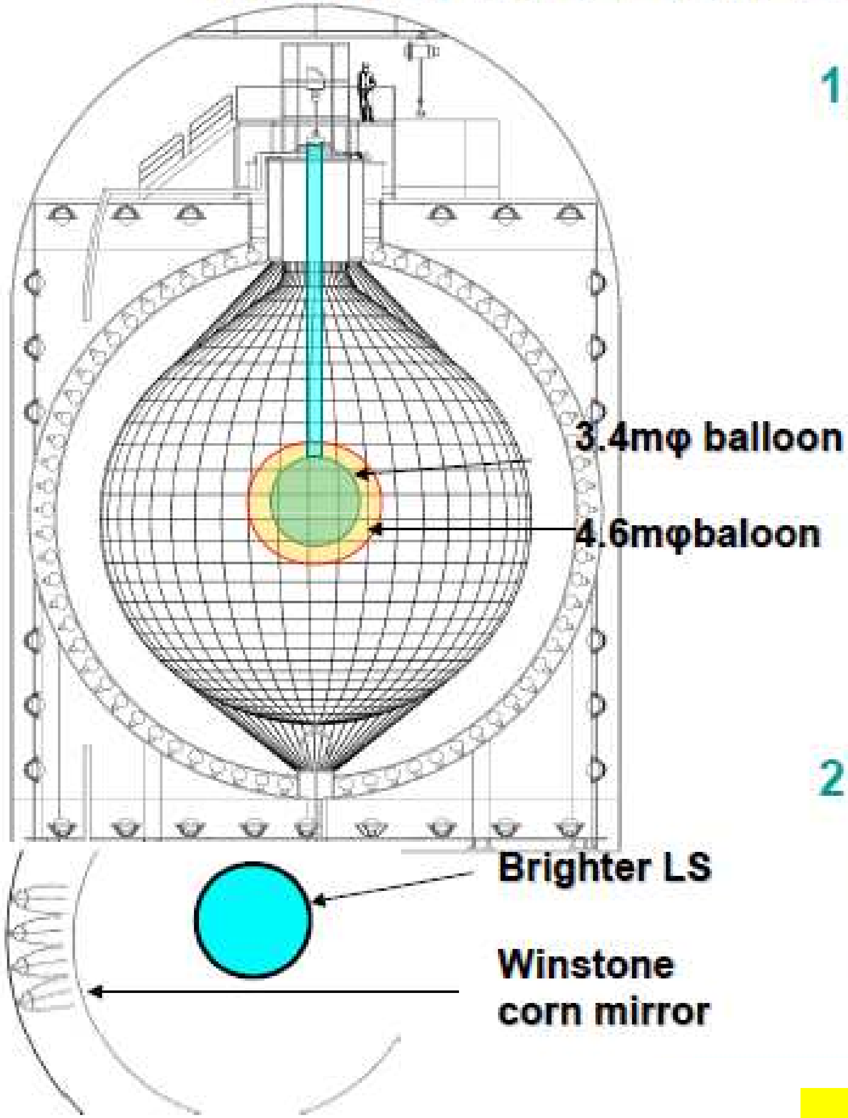


	Demonstrator module	20 Modules
Source : ^{82}Se	7 kg	140 kg
Drift chambers for tracking	2 000	40 000
Electron calorimeter	500	10 000
γ veto (up and down)	100	2 000
$T_{1/2}$ sensitivity	6.6 10^{24} y (No background)	1. 10^{26} y
$<m_\nu>$ sensitivity	200 – 400 meV	40 – 100 meV

Demonstrator ~2013
SuperNEMO ~2015

Demonstrator module(7 kg) under construction

KamLAND-Zen-2 project



1st phase enriched Xe 400kg (2011)

R=1.7m balloon

V=20.5m³,S=36.3m²

LS : C10H22(81.8%)+PC(18%)

+PPO+Xe(~2.5wt%)

ρLS : 0.78kg ⁄ ℓ

high sensitivity with low cost

tank opening (2013 or 2015)

2nd phase enriched Xe 1000kg

R=2.3m balloon

V=51.3m³,S=66.7m²

improvement of energy resolution

(brighter LS, higher light concentrator)

Starts with 1000 kg ~ 2015

SNO+ (2)

- Using existing SNO infrastructure
- Well understood detector

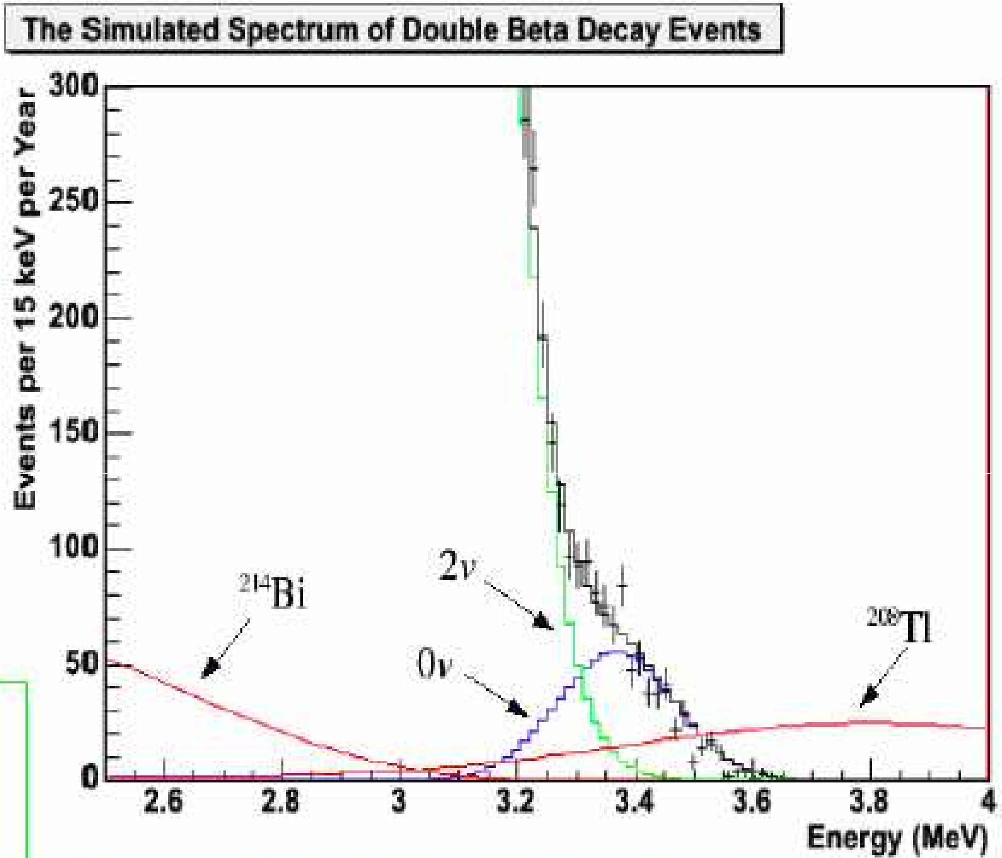
1057 events per year with 500 kg ^{150}Nd-loaded liquid scintillator in SNO+.

Simulation assuming light output and background similar to Kamland.

Sensitivity Limits (3 yrs):

- **Natural Nd (56 kg isotope):**
  m_ν ~ 0.1-**0.3 eV**
- **500 kg enriched ^{150}Nd**
  m_ν ~ 0.04-**0.12 eV**

Starts ~ 2014



Funded by NSERC for final design/engineering and initial construction 2008-2012
Beginning of 2013 → ready for scintillator filling