

# Double beta decay review

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**Abstract.** The neutrinoless double beta decay is the most sensitive process to search the leptonic number violation in the neutrino sector. Its discovery will prove the Majorana nature of neutrino (neutrino and anti-neutrino are the same state). This paper will present the status of the running experiments ( 10 kg of  $\beta\beta$  emitter sources) as well as the projects of detectors for 100 kg of isotopes.

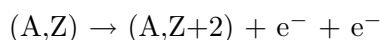
## 1. Introduction

The recent discovery of the neutrino oscillations coming from various neutrino sources (atmosphere, reactors, sun) have shown that the neutrino is a massive particle. It is the first manifestation of physics beyond the Standard Model of the electroweak interaction. Nevertheless, various properties of the neutrino are still unknown: absolute mass, hierarchy scheme mass, nature (Dirac or Majorana), CP violation, magnetic moment,..... Establishing whether neutrinos are Dirac fermions (different from their antiparticle) or Majorana fermions (spin 1/2 particles identical to their antiparticles) is of fundamental importance for understanding the underlying symmetries of particle interactions and the origin of  $\nu$  masses. The observation of neutrinoless double beta decay  $\beta\beta(0\nu)$  could answer to some of these questions. Independantly of the process leading to the  $\beta\beta(0\nu)$  decay, its discovery would imply the non-conservation of the leptonic number and will show that the neutrinos are Majorana fermions.

There is an intensive experimental search for neutrinoless double beta decay with various techniques. Today, the detectors are able to accommodate 10 kg of enriched isotopes. The next step is to built detectors with at least 100 kg of  $\beta\beta$  emitters . This article will present the experimental status as well as the main experiments and projects. More complete reviews can be find in [1],[2], [3],

## 2. Double beta decay

The neutrinoless double beta decay consists to the decay of two neutrons in two protons with emission of two electrons:



This process is forbidden in the Standard Model of the electroweak interaction because of the non-conservation of the leptonic number. The electron sum energy of the  $\beta\beta(0\nu)$  decay would be simply a peak at the value of the transition energy. Due to the energy resolution the ultimate

background is the allowed double beta decay ( $\beta\beta(2\nu)$ ):

$$(A,Z) \rightarrow (A,Z+2) + e_1^- + e_2^- + \bar{\nu}_1 + \bar{\nu}_2$$

There are several possible processes leading to the  $\beta\beta(0\nu)$  process: exchange of light neutrino, exchange of Majoron, right-handed interaction, exchange of supersymmetric particles, ... In the case of light neutrino exchange, the expression of the half-live depends on the effective neutrino mass:

$$[T_{\frac{1}{2}}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_\nu \rangle^2$$

Where  $G^{0\nu}$  is the calculable phase space factor,  $M^{0\nu}$  is the nuclear matrix element (NME) of the process. The calculation of the NME is a difficult subject, several models (QRPA methods, Shell Model) are used. There are recent progress on these calculations and the discrepancies between models tend to be reduced.

$\langle m_\nu \rangle = ||U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 \exp i\phi_1 ||U_{e3}|^2 m_3 \exp i\phi_2$  is the effective Majorana neutrino mass  $m_1, m_2, m_3$  are the neutrino mass eigenstates,  $U_{e1}, U_{e2}, U_{e3}$  are the coefficients of the neutrino mixing matrix and  $\phi_1, \phi_2$  are the Majorana CP phases ( $\pm 1$  if CP is conserved).

In this paper, the range for the limit on the effective neutrino mass is calculated taking into account NME calculations from [5], [6], [7]

The effective neutrino mass can be rewritten as a function of the oscillation parameters and the CP phase violation. Three regions corresponding to the three hierarchy mass schemes are observed:

- The quasi-degenerate (QD) scheme where  $m_1 \simeq m_2 \simeq m_3$  in this case  $m_{\nu_{min}} > \sqrt{|\delta m_{32}^2|}$ . In this case the predicted range for the effective neutrino mass is  $\langle m_\nu \rangle > 0.05$  eV
- The inverted hierarchy (IH) where  $m_3 \ll m_1 < m_2$  ( $m_3 = m_{\nu_{min}}$ ) corresponding to  $0.01 < \langle m_{nu} \rangle < 0.05$  eV
- the normal hierarchy (NH) where  $m_1 < m_2 \ll m_3$  ( $m_1 = m_{\nu_{min}}$ ) would imply  $\langle m_\nu \rangle < 0.005$  eV

Detailed discussion can be found in [4].

Today, the experiments using 10 kg of enriched isotopes have a sensitivity to explore the QD region. The next generation of double beta decay experiments will have 100 kg of enriched isotopes and will start to explore the IH region. To fully explore the IH scheme, it will be necessary to be able to built detector with a mass of 1 ton of isotope.

### 3. experimental techniques

In case of background the experimental half-life can be written has:

$$T_{1/2}^{0\nu}(y) > \frac{\log 2 \cdot N}{k_{C.L.}} \cdot \frac{\epsilon}{A} \cdot \sqrt{\frac{M \cdot t}{N_{bckg} \cdot \Delta E}}$$

Where: M: mass (g),  $\epsilon$ : efficiency,  $k_{C.L.}$ : Confidence Level, N: Avogadro number, t: time (y),  $N_{bckg}$ : background events ( $\text{keV}^{-1} \cdot \text{g}^{-1} \cdot \text{y}^{-1}$ ),  $\Delta E$ : energy resolution (keV)

Today, there is no experimental technique able to optimize all the parameters. One can distinguish four main techniques for the  $\beta\beta(0\nu)$  decay search:

- Pure calorimeter like semi-conductor detectors or bolometers where the efficiency, mass and good energy resolution are optimized
- Tracko-calor detectors to suppress the background by identification of the electrons and to allow choice of the isotope.
- TPC (Xe) for optimization of the efficiency and mass and also background if the daughter

nucleus can be identified.

- Inorganic scintillators or loaded organic scintillator to optimize efficiency and mass

The main backgrounds come from the natural radioactivity (in particular  $^{208}\text{Tl}$  and  $^{214}\text{Bi}$ ), the neutrons (mainly through  $(n,\gamma)$  reactions), the radon and the cosmic rays (through cosmogenic production and neutron spallation production)

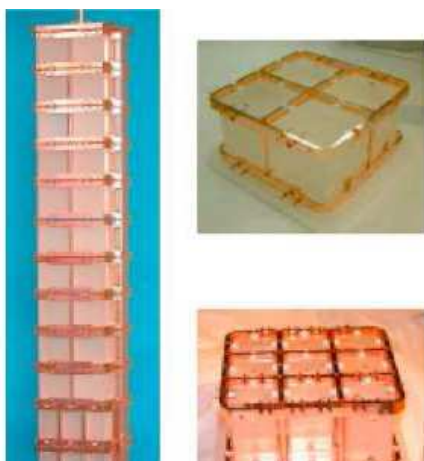
### 3.1. The present experiments

The best results for the limit on the effective neutrino has been obtained with Ge diodes enriched at 86 % in  $^{76}\text{Ge}$  by the Heidelberg-Moscow (11 kg) and IGEX experiments (8.4 kg). There is a very controversial  $4\sigma$  claim about observation of signal from the Heidelberg-Moscow experiment.

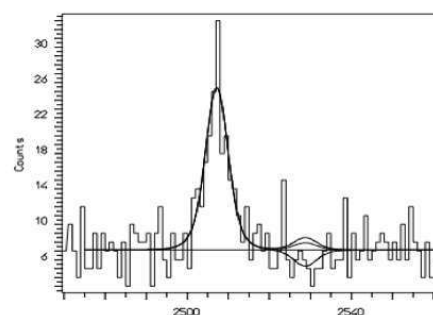
Today, two experiments are running Cuoricino (bolometric experiment) and NEMO3 (track-calo experiment).

### 3.2. Cuoricino experiment

Cuoricino is based on the technique of cryogenic detectors. Such detectors are operating at very temperature ( $\bar{8}$  mK). They have a very low heat capacity allowing to measure the small energy released by a radioactive decay event in the crystal. The Cuoricino detector (Figure 1 is tower made of modules of crystals of  $\text{TeO}_2$  corresponding to a total mass of 40 kg. There are two sizes of crystals:  $5\times 5\times 5\text{ cm}^3$  (44 detectors) and  $3\times 3\times 6\text{ cm}^3$  (18 detectors). The energy resolution at 2530 keV (energy of the  $\beta\beta(0\nu)$  decay for  $^{130}\text{Te}$ ) is between 7 and 9 keV (FWHM) depending of the crystal size. The detector is shielded by 20 cm of lead (10 cm internal layer of roman archaeological lead) and 10 cm polyethylen for neutrons. It is running since 2003 in the Laboratori Nazionali del Gran Sasso (LGNS, Italy). Due to the high natural enrichment of Te in  $^{130}\text{Te}$  (34%), there is no need to have isotopic enrichment. Nevertheless 2 crystals ( $3\times 3\times 6\text{ cm}^3$ ) are enriched in  $^{130}\text{Te}$  (75%) and two in  $^{128}\text{Te}$  (82.3 %) for the  $\beta\beta(2\nu)$  search. The Figure 2 shows the results for 11.83 kg.y of  $^{130}\text{Te}$ . A limit for the  $\beta\beta(0\nu)$  decay is set to  $T_{1/2} > 3.010^{24}\text{y}$  (90% C.L.) corresponding to a range for the effective neutrino mass limit :  $\langle m_\nu \rangle < 0.19 - 0.68\text{ eV}$  depending of the nuclear matrix element calculations [10].



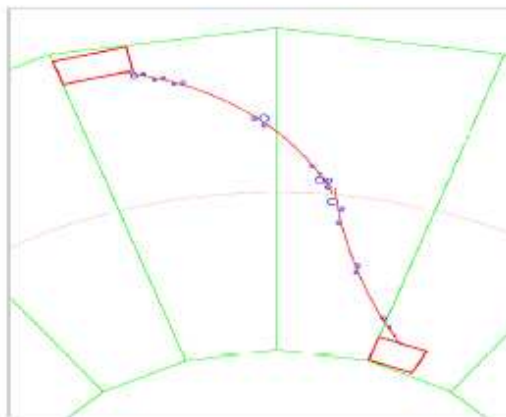
**Figure 1.** Cuoricino tower and individual 4 and 9 modules.



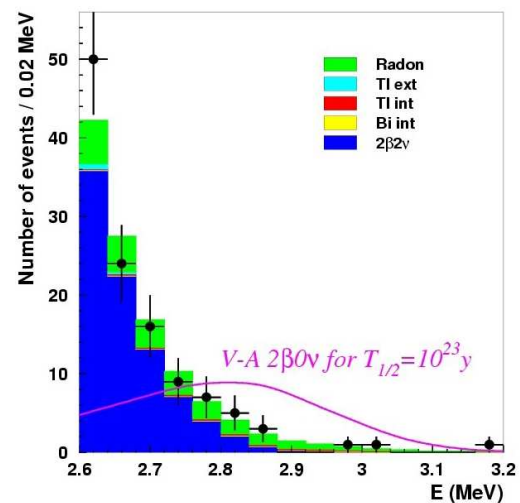
**Figure 2.** Cuoricino spectrum for 11.83 kg.y. The solid lines are the best fit to the region, and the bounds (68% and 90%) CL on the number of candidate  $\beta\beta(0\nu)$ -decay events .

### 3.3. NEMO3 experiment

The NEMO3 detector is looking for  $\beta\beta(0\nu)$  decay by the direct detection of the two emitted electrons by the mean of a tracking device associated to a calorimeter. The detection of the electron as well as the measurement of the angular distribution and the individual energy of the electron allow to reduce drastically the background and in case of signal to distinguish the process leading to the  $\beta\beta(0\nu)$  decay. The detector is running since 2003 in the Laboratoire Souterrain de Modane (France). It consists in a thin central source foil (40-60 mg/cm<sup>2</sup>) sandwiched by 6180 open drift cells operating in Geiger mode to reconstruct three-dimensionnal tracks and surrounded by a calorimeter made of 1940 plastic scintillator coupled to low radioactive photomultipliers developed by Hamamatsu company. The energy resolution (FWHM) at 1 MeV ranges from (14% to 16%) depending of scintillator size. A solenoid intalled around the detector produce a 25 gauss in order to distinguish electrons and positrons. The detector is shield by 20 cm of iron, water and wood to reduced background from external  $\gamma$ -rays and neutrons. A typical event is shown in Figure 3. The detector contains <sup>100</sup>Mo (6914 g) and <sup>82</sup>Se (932 g) for  $\beta\beta(0\nu)$  searches but also <sup>130</sup>Te (454 g), <sup>116</sup>Cd (405 g), <sup>150</sup>Nd (37 g), <sup>96</sup>Zr (9.4 g) and <sup>48</sup>Ca (6.99 g) for the  $\beta\beta(2\nu)$  half-live measurements . The Mo source has been purified to reduce content of <sup>214</sup>Bi and <sup>208</sup>Tl. The Figure 4 shows the results for <sup>100</sup>Mo for 693 days of data taking. The limits obtained for <sup>100</sup>Mo are  $T_{1/2} > 5.8 \cdot 10^{23} y$  (90% C.L.) and  $\langle m_\nu \rangle < 0.8 - 1.3 eV$ . For <sup>82</sup>Se, the present results are  $T_{1/2} > 2.1 \cdot 10^{23} y$  (90% C.L.) and  $\langle m_\nu \rangle < 1.4 - 2.2 eV$  [11].



**Figure 3.** Transversal view of  $\beta\beta e$  selected in NEMO3 data: two tracks (s circles represent the hit drift cells) coming from the same vertex on the source foil and associated each one to a hit scintillator (rectangular boxes) with an internal time of flight..



**Figure 4.** NEMO3 spectrum of the energy of the two electrons above 2.6 MeV of <sup>100</sup>Mo. The shape of expected  $\beta\beta(0\nu)$  signal corresponds to the pink curve.

### 3.4. GERDA

The basic concept of GERDA experiment is to operate Ge diodes in liquid nitrogen or argon in order to remove materials to reduce the background. Moreover, an active anticoincidence with the scintillation light from the liquid argon can be used. The GERDA collaboration has scheduled three phases. The first one, starting in 2009 in the Laboratori Nazionali del Gran Sasso, will consist in 17.9 kg of enriched Ge (86% in <sup>76</sup>Ge) coming from Heidelberg-Moscow and

IGEX experiments. The aim is decrease the background by a factor 10 ( $10^{-2}$  counts/keV/kg/y) compared to HM and IGEX experiment to reach a sensitivity of  $T_{1/2} > 3.10^{25}y$  and  $\langle m_\nu \rangle < 0.25$  eV to check the claim of ref. The second phase will correspond to 40 kg of enriched  $^{76}\text{Ge}$  diodes with a part of Ge segmented diodes (20 kg). The combination of pulse shape analysis and coincidence method with segmented detectors is a powerwul way to reject the background coming from  $\gamma$ -rays. The expectation for the sensitivity with a background of  $10^{-3}$  counts/keV/kg/y and 3 years of data taking is  $T_{1/2} > 2.10^{26}y$   $\langle m_\nu \rangle < 0.11$  eV. This phase in planned for 2010. If Phase I and II are successful, the collaboration has a project of 1 ton detector to be sensitive to  $T_{1/2} > 5.10^{27}y$   $\langle m_\nu \rangle < 0.02$  eV [8].

### 3.5. Majorana

The Majorana collaboration proposes to operate 500 kg of 86% enriched Ge detectors divided in modules of 60 kg. The objectives are to use very pure materials, to improve the pulse shape discrimination and to use segmented cristals to reject multi-site events corresponding to background events. The  $\beta\beta$  events are single site events. It is plane to use electroformed Copper, free from radioactive contaminants and to form it underground to avoid cosmogenic contaminant production. Presently, segmented Ge crystals are under study to check the impact of the segmentation on signal and background. The R&D phase will start with 30-60 kg of enriched Ge crystals (with some of them segmented). The goal is to reach a background of less than 1 counts/t/y in the region of interest around 2033 keV. The second phase planned for 2011 is to run 30 kg of enriched Ge during three years to reach the following sensitivity sensitivity  $T_{1/2} > 1.10^{26}y$  and  $\langle m_\nu \rangle < 0.14$  eV to check the claim ref. The ultimate goal is to reach  $T_{1/2} > 4.10^{27}y$  with a background less than 1 count/ton/keV/y. To minimize the background from cosmogenic production inside the crystals, the detector will be located in the Sudbury Underground Laboratory (6000 m.w.e.) [9].

### 3.6. CUORE

CORE is an extrapolation of Cuoricino experiment currently running in the Laboratori Nazionali del Gran Sasso. It consists of an array of 19 towers of 13 modules of 4  $\text{TeO}_2$  crystals each  $5\times 5\times 5$   $\text{cm}^3$ . The total mass is 741 kg of  $\text{TeO}_2$  and consequently 203 kg of  $^{130}\text{Te}$ . The present background of Cuoricino in the energy region of the  $\beta\beta(0\nu)$  decay is  $0.18 \pm 0.02$  count/keV/kg/y. This background is mostly coming from the surface contamination of the crystals and the copper frame. A strategy to reduce these surface events is under study. The expected background with suppression of surface event is 0.01 count/keV/kg/y corresponding to a sensitivity of  $T_{1/2} > 2.110^{26}y$  and  $\langle m_\nu \rangle < 0.03 - 0.07$  eV for 5 years of data. The data taking is forseen in 2011. With an improvement of background reduction at the level of 0.001 count/keV/kg/y, the sensitivity would be  $T_{1/2} > 6.610^{26}y$  and  $\langle m_\nu \rangle < 0.02 - 0.04$  eV. [10]

### 3.7. EXO

The EXO experiment is looking for  $\beta\beta(0\nu)$  decay of  $^{136}\text{Xe}$  to  $^{136}\text{Ba}$  with a Time projection chamber (TPC). The main advantages of  $^{136}$  are the ease to enrich it compare to the other  $\beta\beta$  candidates and also the long period of the  $\beta\beta(2\nu)$  process. The challenge is to attempt to tag the  $^{136}\text{Ba}^{++}$  ion after its partial neutralization to  $\text{Ba}^+$ . The identification of the final state of the decay will drastically reduce the background and could be potentially a zero backgorund experiment. The final state ion tagging is possible by the observation of fluorescence light under laser light excitation, a R&D program to extract Ba is in progress. EXO will start by using 200 kg of enriched  $^{136}\text{Xe}$  in liquid phase by detecting the scintillation light without Ba ion tagging. The prototype EXO-200 is under construction in the WIPP laboratory. The expected sensitivity

after 2 years of data taking is  $T_{1/2} > 6.410^{25}y$  and  $\langle m_\nu \rangle < 0.27 - 0.38$  eV. The final goal with Ba tagging is to reach with 1 ton  $T_{1/2} > 8.310^{26}y$  and  $\langle m_\nu \rangle < 0.05 - 0.14$  eV [12]

### 3.8. SuperNEMO

The SuperNEMO experiment is an extrapolation by a factor ten of the NEMO3 experiment. The detector will be modular and consists in 20 modules with 5 kg each of enriched source based on the NEMO 3 principle: a thin central source foil between two tracking volume surrounded by a calorimeter. The total mass of isotope will be 100 kg. The collaboration is in a phase of R&D to improve the energy resolution of the calorimeter. The objective is to reach 4% (FWHM) at 3 MeV instead of 8% for NEMO3. In NEMO 3 the background rate is 0.4 count/kg/y in the region of interest (2.8 -3.2 MeV because of the energy resolution) corresponding to 0.001 count/kg/keV/y for a calorimeter. The origins of the background are to the  $\beta\beta(2\nu)$  decay because of the energy resolution and residual pollution of the source foil in  $^{214}\text{Bi}$  and  $^{208}\text{Tl}$ . A challenge is to reduced by a factor 10 these backgrounds to have activities less than 20  $\mu\text{Bq/kg}$  in  $^{214}\text{Bi}$  and 2  $\mu\text{Bq/kg}$   $^{208}\text{Tl}$ . The gas of the tracking detector must be radon free at the level of 100  $\mu\text{Bq/m}^3$  which impose severe constraint on the activities of the materials use to built the detector. With this technique several isotopes can be studied like  $^{82}\text{Se}$ ,  $^{150}\text{Nd}$ ,  $^{116}\text{Cd}$ ,  $^{100}\text{Mo}$  and  $^{48}\text{Ca}$ . The baseline is to use 100 kg of  $^{82}\text{Se}$ , the expected sensitivity for 5 years of data taking is  $T_{1/2} > 1.10^{26}y$  and  $\langle m_\nu \rangle < 0.07 - 0.12$  eV. The schedule is to start to run the first module in 2011 [11].

### 3.9. Other projects

There are various other projects for double beta decay searches. A non-exhaustive list is:

- CANDLES experiment will use  $\text{CaF}_2$  scintillating crystals to look for  $\beta\beta(0\nu)$  decay of  $^{48}\text{Ca}$ . The very low natural isotopic abundance of  $^{48}\text{Ca}$  will be partly compensate by the number of crystals [13].
- SNO+ experiment proposes to dissolve Nd inside the liquid scintillator. Due to the large volume of liquid scintillator, it is possible to dissolve a large mass of natural Nd or enriched  $^{150}\text{Nd}$ . Such detector allow high mass and have high efficiency [14].
- DCBA is a project of gaseous TPC to study  $\beta\beta(0\nu)$  decay of  $^{150}\text{Nd}$ . The energy will be measure by the curvature of the tracks. This detector could be used with different isotopes [15].
- MOON is a project to study large mass of  $^{100}\text{Mo}$  by inserting thin source foil between plates of plastic scintillators [16].
- COBRA would use semi-conductor crystal of  $\text{ZnCdTe}$  allowing to study several double beta decay isotope at the same time ( $^{150}\text{Cd}$ ,  $^{130}\text{Te}$ ,  $^{128}\text{Te}$ ,...) with a possible tracking capability [17].

A summary of some projects for double beta decay searches is given in Table 1.

## 4. Conclusion

The double beta decay search is a very active field. Several experiments are running or will start very soon using different experimental techniques and studying various isotopes. Because of the uncertainties on the nuclear matrix element calculations, it is not possible today to determine the best candidate for  $\beta\beta(0\nu)$  search. Since few years, progress have been performed in the NME calculation and the discrepancies between the model are decreasing. In the next years, the effective neutrino mass region corresponding to the claim of  $\beta\beta(0\nu)$  signal from HM experiment should be explored. Around 2015, the experiments with isotope mass on the order of 100 kg will provide results starting to test the inverted hierachy for the neutrino mass scheme . This is an essential step before to go to 1 ton detector in order to study and to understand backgrounds.

**Table 1.** Running experiment and some projects for neutrinoless double beta decay searches.

| Experiment     | Isotope           | Mass (kg) | FWHM<br>at $Q_{\beta\beta}$ (KeV) | Background<br>cts/FWHM.kg.y | $T_{1/2}^{0\nu}$ (y) | $\langle m_{\nu} \rangle$ (eV) | Status  |
|----------------|-------------------|-----------|-----------------------------------|-----------------------------|----------------------|--------------------------------|---------|
| Cuoricino      | $^{130}\text{Te}$ | 10.4      | 7 - 9                             | 0.18                        | $6.10^{24}$          | 0.1 - 0.7                      | Running |
| NEMO3          | $^{100}\text{Mo}$ | 6.9       | 240                               | 0.1                         | $2.10^{24}$          | 0.3 - 0.7                      | Running |
| CUORE          | $^{130}\text{Te}$ | 203       | 5                                 | 0.05                        | $2.110^{26}$         | 0.03 - 0.07                    | Funded  |
| GERDA Phase I  | $^{96}\text{Ge}$  | 17.9      | 4                                 | 0.01                        | $3.10^{25}$          | 0.2 - 0.5                      | Funded  |
| GERDA Phase II | $^{96}\text{Ge}$  | 40        | 4                                 | 0.001                       | $2.10^{26}$          | 0.07 - 0.2                     | Funded  |
| MAJORANA       | $^{96}\text{Ge}$  | 30 - 60   | 4                                 | 0.003                       | $1.10^{26}$          | 0.1 - 0.3                      | Funded  |
| EXO-200        | $^{136}\text{Xe}$ | 200       | 50                                | 0.95                        | $6.410^{25}$         | 0.2 - 0.7                      | Funded  |
| SuperNEMO      | $^{82}\text{Se}$  | 100       | 100                               | 0.01                        | $1.10^{26}$          | 0.07 - 0.12                    | R&D     |
|                | $^{150}\text{Nd}$ | 100       | $1.10^{26}$                       | 0.07                        | R&D                  |                                |         |
| CANDLES        | $^{48}\text{Ca}$  | 0.5       |                                   |                             | $1.10^{26}$          | 0.5                            | Funded  |
| SNO++          | $^{150}\text{Nd}$ | 500       | ?                                 | ?                           | $6.10^{26}$          | 0.03                           | R&D     |
| DCBA           | $^{150}\text{Nd}$ | 500       | 100                               | ?                           | $1.10^{26}$          | 0.07                           | R&D     |

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