The EXO-200 Detector

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Frontier Detectors for Frontier Physics

11th Pisa meeting on advanced detectors

24-30 May 2009

Double Beta Decay …

- Rare nuclear transition between same mass nuclei
  - Energetically allowed for even-even nuclei

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

$$\left[T_{1/2}^{2\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G^{2\nu}(Q_{\beta\beta}, Z)\left|M^{2\nu}\right|^2$$

Allowed in SM and already observed!

$$\beta\beta 0\nu: \quad (Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^-$$

Neutrinos are Majorana particles!

$$\nu \equiv \bar{\nu} \qquad m_\nu \neq 0$$

$$\Delta L = 2 \quad (Z,A) \rightarrow (Z+2,A) + e_1^- + e_2^- + \chi$$

$$\left[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\left|M^{0\nu}\right|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$$\left\langle m_{\beta\beta} \right\rangle^2 = \left|\sum_k m_k U_{ek}^2\right|$$

... and its Role in Neutrino Physics

Double beta decay experiments are part of a massive effort to determine the nature and properties of neutrinos!

Cosmological Constraints $\Sigma < 2eV$

$\langle m_\beta \rangle < 2eV$ Beta Decay Endpoint

$\Delta m_{23}^2 = \left(2.4_{-0.5}^{+0.6}\right) \times 10^{-3} eV$

$\Sigma = \sum_k m_k = 92.5eV \times \left(\Omega_\nu h^2\right)$

$\langle m_\beta \rangle^2 = \sum_k m_k^2 \left|U_{ek}\right|^2$

$\theta_{23} \approx 45^\circ$ Neutrino Oscillations Atmospheric and Reactor

$\theta_{13} < 7^\circ$ Neutrino Oscillations Reactor and Beam

CP violation

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \ldots$$

Neutrino Oscillations Solar and Reactor

$\theta_{12} \approx 34^\circ$

$\Delta m_{12}^2 = \left(8.0_{-0.3}^{+0.4}\right) \times 10^{-5} eV$

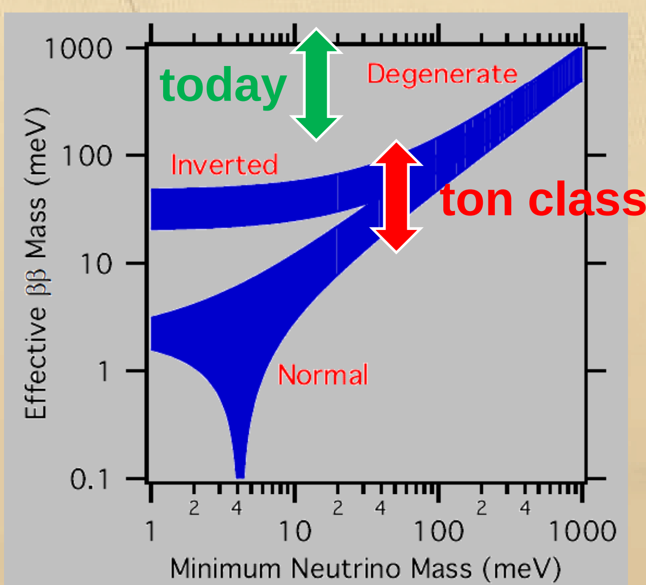
$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha/2} & 0 & 0 \\ 0 & e^{i\beta/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrinoless Double Beta Decay Only!

$\langle m_{\beta\beta} \rangle < 0.7eV$

Experimental Requirements

Effective neutrino mass as a function of the smallest neutrino mass for various scenarios



- **Large Mass:** at least 100 kg of source isotope
  - Scanning the quasi degenerate region
  - Ton scale for the inverted hierarchy region
  - Enrichment helps minimizing volume and improves source purity
- **Very Low Background:** 1 count per ton per year range
  - Survey, selection and purification of materials and components
  - Cleanroom assembly and detector operation
  - Deep underground installation and muon veto required
- **Very Good Energy Resolution:** in the 1% range
  - Limits the allowed double beta decay background
  - Increases signal to radioactive background ratio
- **And …**
  - Large $Q_{\beta\beta}$ to have the signal out of the region densely populated by radioactive background for natural chains
  - Tagging the daughter isotope would eliminate most radioactive background or event topology and advanced kinematics details

EXO Project & EXO-200 Phase

- EXO project searches for double beta decay using ^{136}Xe
  - Ton scale implementation either as liquid or gas phase TPC
  - Relatively large Q value and straight forward enrichment technique
  - ^{136}Ba daughter tagging either in-situ or in external RF cage

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{1}{Nt} \right)^{1/4}$$

No Background! $\langle m_{\beta\beta} \rangle \propto \sqrt{\frac{1}{Nt}}$

- EXO-200 is the first phase using 200 kg of 80% enriched Xe
  - Major R&D effort precursory to the ton-scale experiment
  - Exploration of the quasi-degenerate region with ^{136}Xe
  - Allowed double beta decay never observed in xenon!
  - No tagging but massive progress for radioactive background reduction and energy resolution improvement (easily scalable to future detectors)

EXO Collaboration

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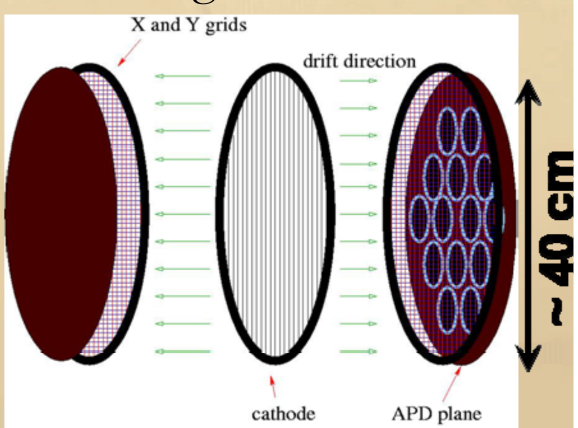
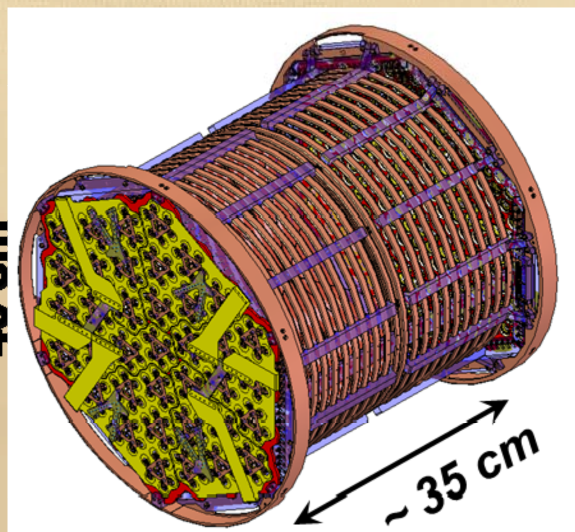
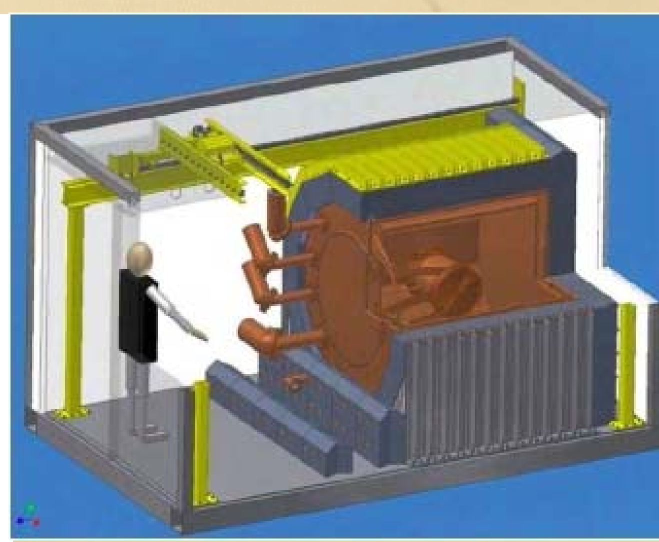
EXO-200 Detector

- Liquid xenon TPC with two cylindrical drift volumes
  - Charge collection using 114 by 114 wire planes (at 60º pitch)
  - Scintillation light readout using 37 groups of 7 bare LAAPD (Large Area Avalanche Photodiodes) at both end caps
- High purity copper cryostat with external refrigeration-based cooling

~ 115 kg fiducial mass

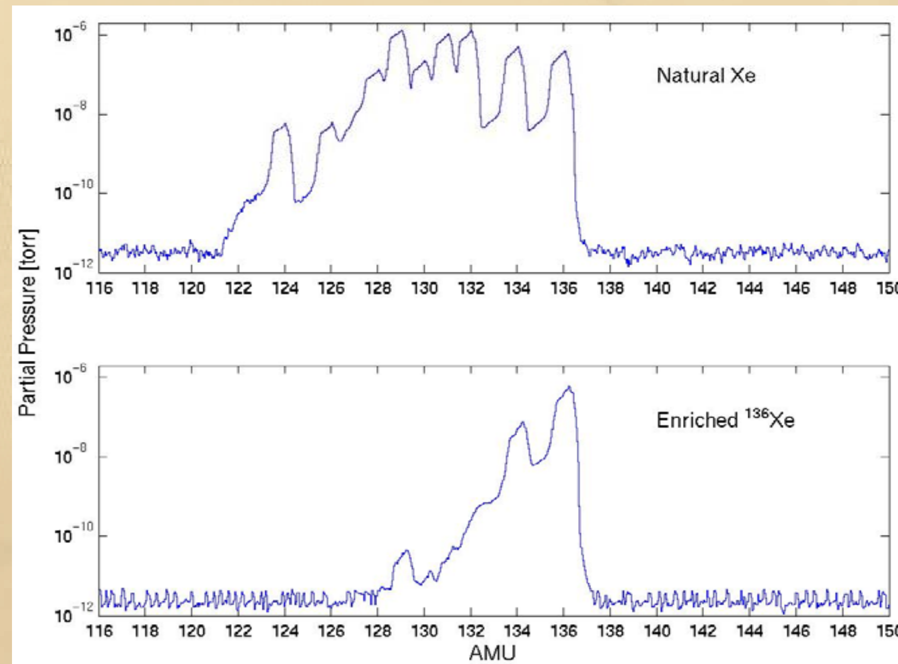






Successful Enrichment Program

200 kg of 80% enriched Xe delivered in 2003!
Used mass-separating centrifuges in Russia
The other isotopes can be returned to provider!



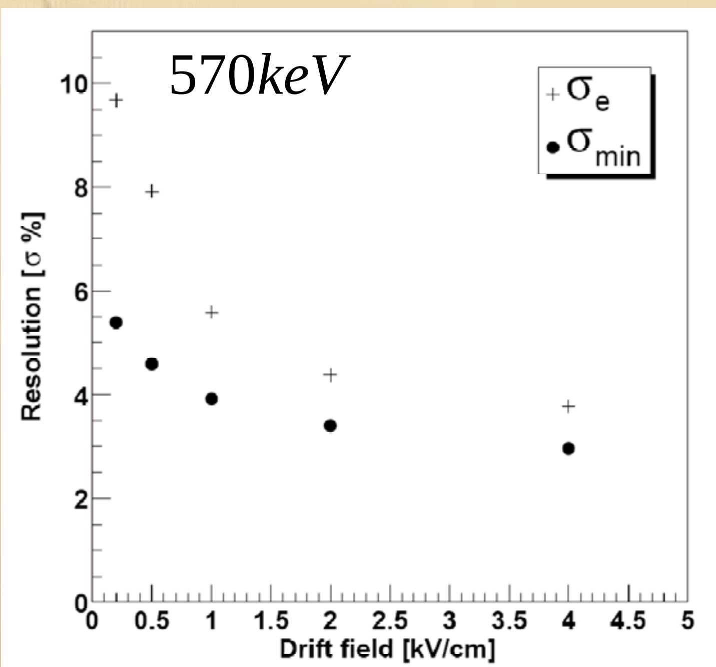
Radio-Purity Survey

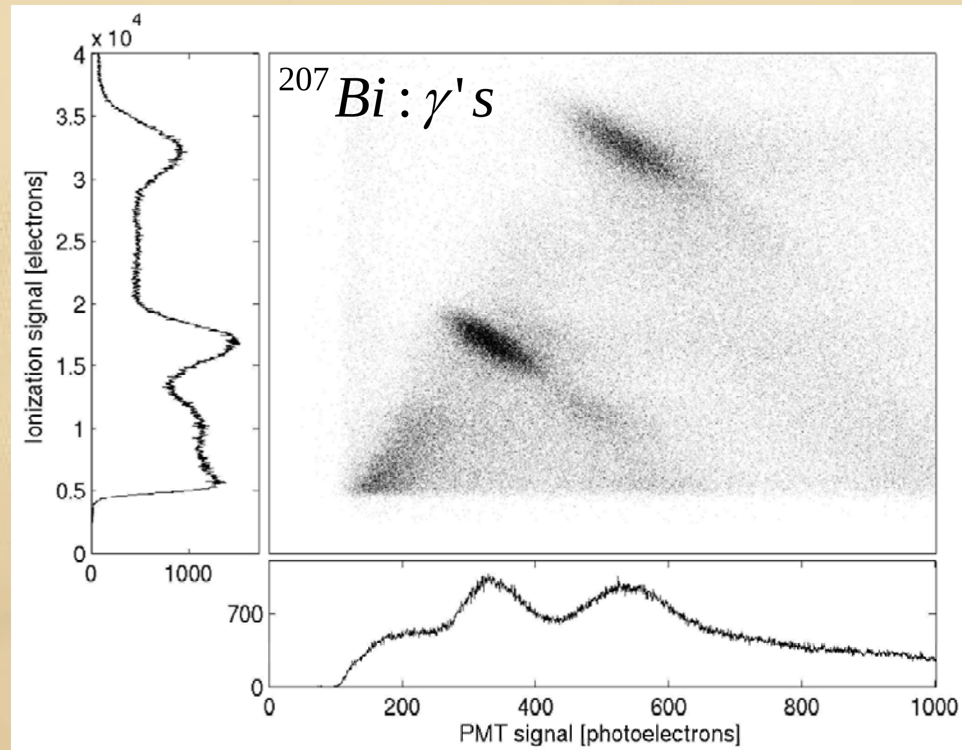
- Large effort to determine the residual radioactive contamination of the materials employed for the construction of EXO-200 detector
  - **Mass spectrometry (MS)**
  - **Neutron activation analysis (NAA)**
    - Very sensitive but expensive, potential background from main elements
  - **Alpha counting** (evaluation of the ^{210}Pb concentration in the shield lead)
  - **Glow discharge MS (GD-MS), inductively coupled plasma MS (ICP-MS)**
    - ICP-MS has better sensitivity when pre-concentration procedures are employed but the samples have to be soluble in acids (preferably HNO_3)
  - **Direct gamma counting**
    - Large mass samples and long duration exposures are necessary
- Published database of characterized materials
  - ***Nucl. Instr. Meth. A 591, 490-509, 2008***
- Detailed Monte Carlo simulation of expected background

Improving the Energy Resolution

Strong anti-correlation between ionization and scintillation signals in liquid xenon has been observed!

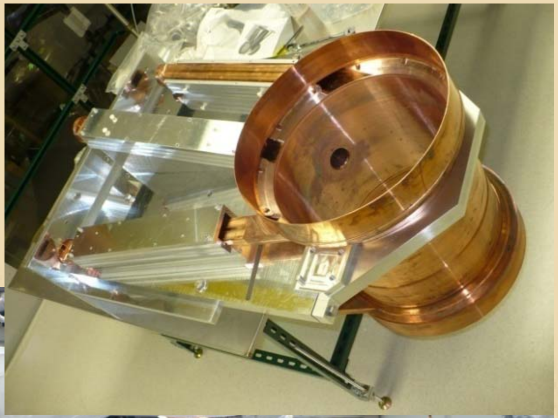
$$\frac{\Delta E}{E} = 1.4\% @ Q_{\beta\beta} = 2479 keV$$



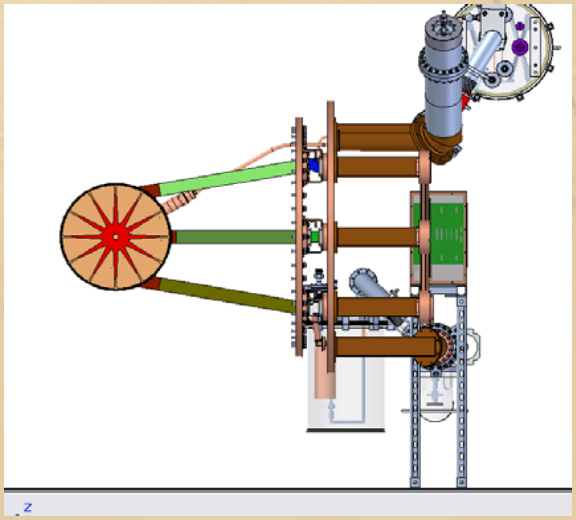


EXO-200 Detector

EXO-200 Chamber



Ultra low radioactivity copper!
Shielded surface transport and storage
Only 1.5 mm thickness to reduce mass
PLC-based real-time pressure control
e-beam welded components
TIG welding for the final assembly



Charge and Light Readout

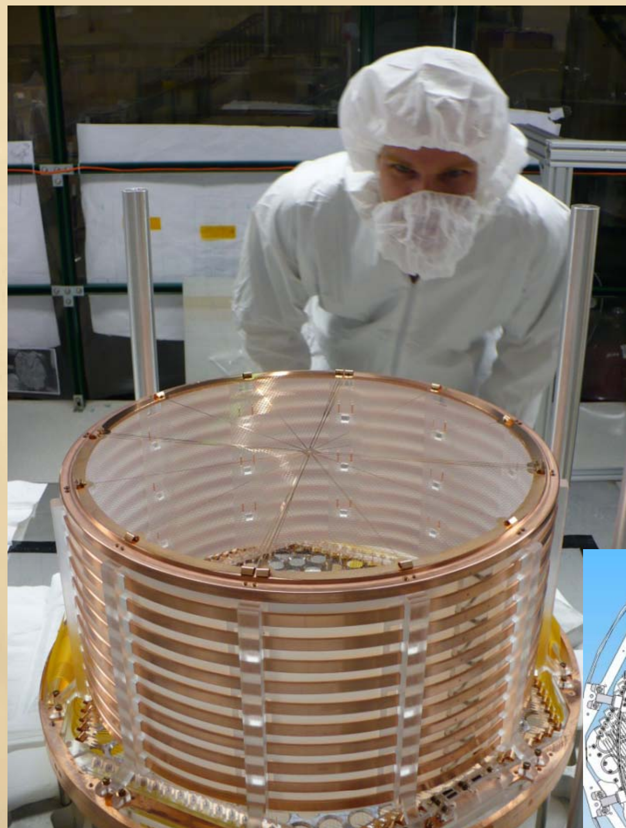
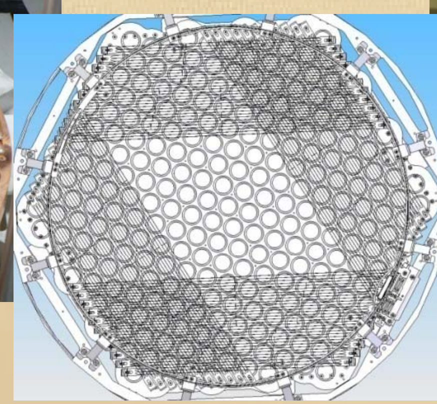


Photo-etched phosphor-bronze cathode
Induction & charge collection wire grids
259 LAAPD (37 groups of 7) per plane
- 1.6 cm active diameter
- very clean and low mass
- QE > 1 @ 174 nm
- gain 100× to 150× @ ~ 1500V

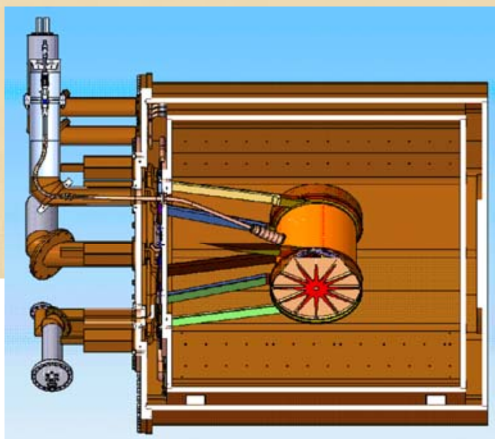
Radial Teflon UV light reflectors

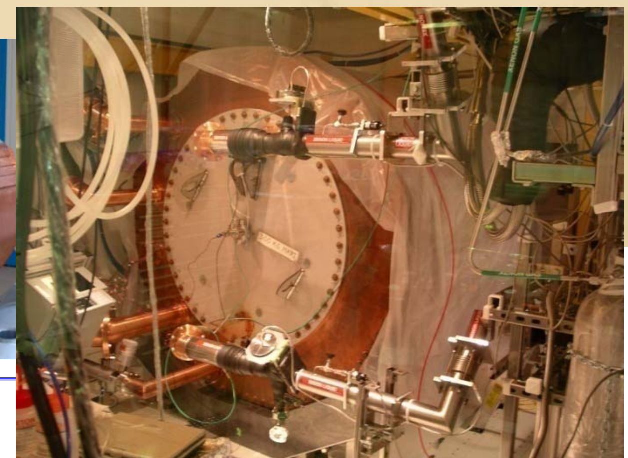
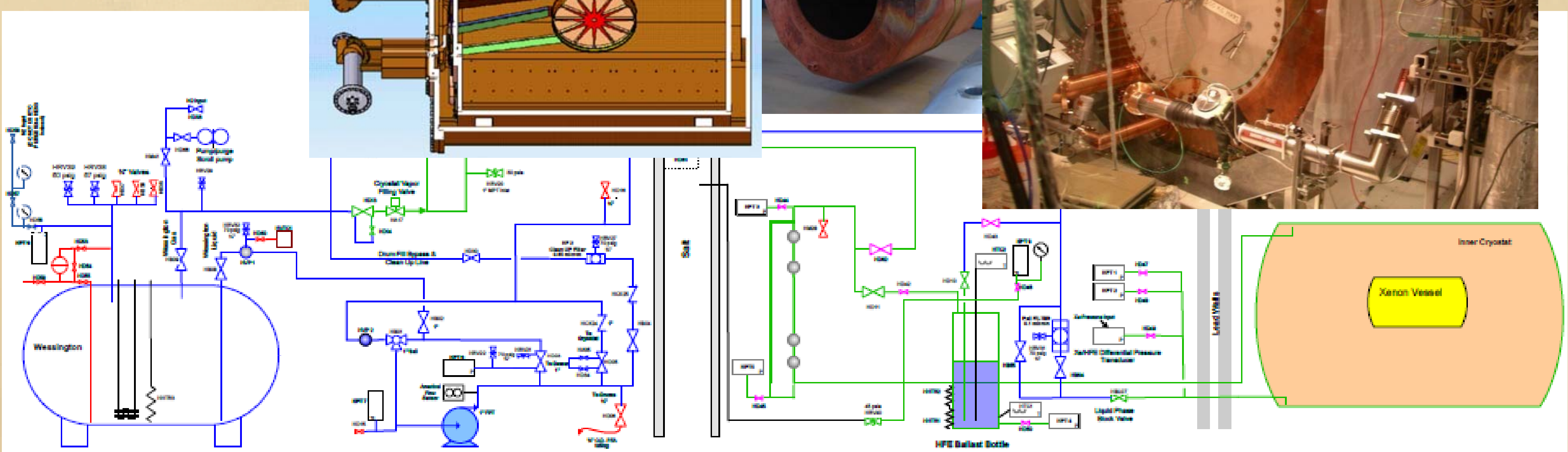


Chamber Assembly

Cryostat and Cooling System

Refrigeration based cooling (3 × 1500 W PolyCold units)
4.2 tons of high purity heat transfer fluid (3M HFE-7000)
Serves also as inner shield!



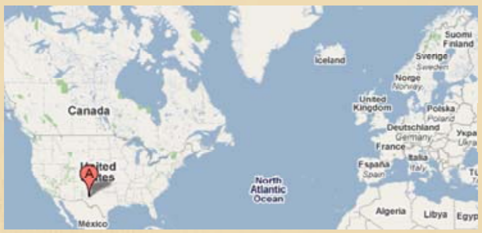
WIPP Installation

Experimental Area

Waste Isolation Pilot Plant, Carlsbad, New Mexico

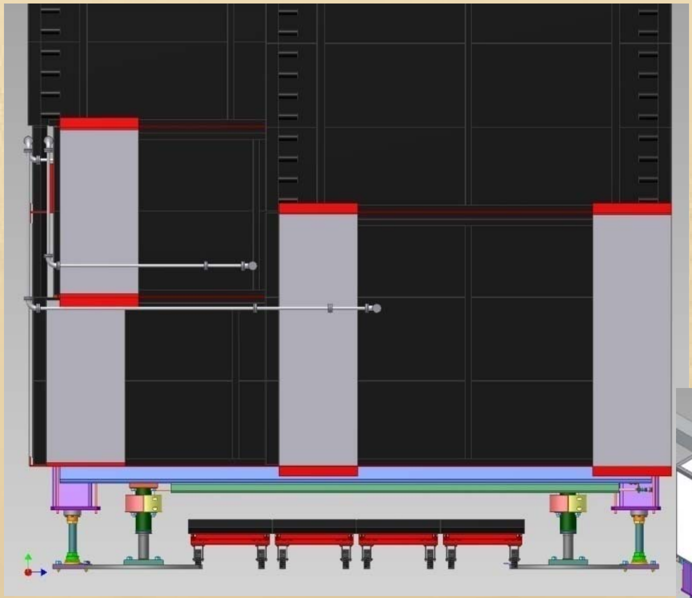
~ 1600 m.w.e. (muon flux reduction by ~ 10×)

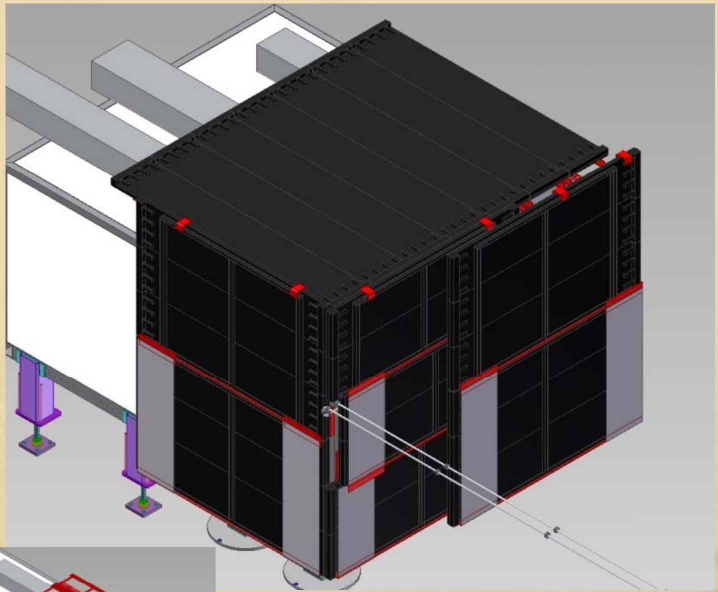
Large and wide remote experimental area available!

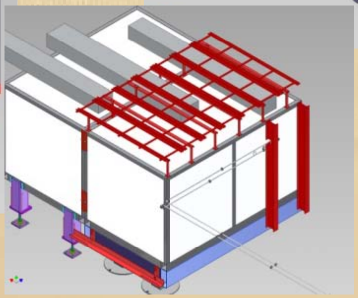


Muon Veto

20× muon induced background reduction (99,7% detection efficiency)







Extensive Monte Carlo simulations to optimize the veto configuration!

Expected Performance

- Very low radioactive background
  - Careful selection of materials, optimized custom design
  - Manufacturing, handling and installation in cleanrooms
- Very good energy resolution

$$\frac{S}{B} = \frac{m_e}{7Q_{\beta\beta}} \left(\frac{E}{\Delta E} \right)^6 \frac{T_{1/2}^{2\nu}}{T_{1/2}^{0\nu}}$$

Chamber underground installation in august 2009

Physics runs starting in 2010, 2 years run time!

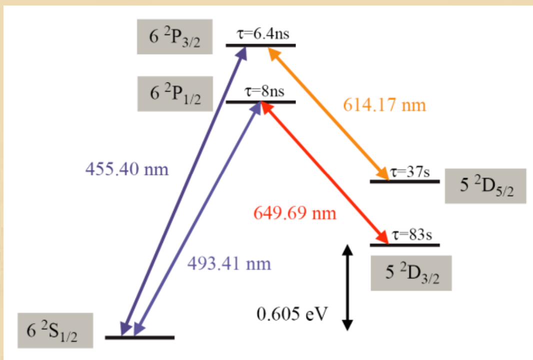
$$T_{1/2}^{2\nu} > 1.2 \times 10^{24}\, y\, @\, 90\%C.L.$$

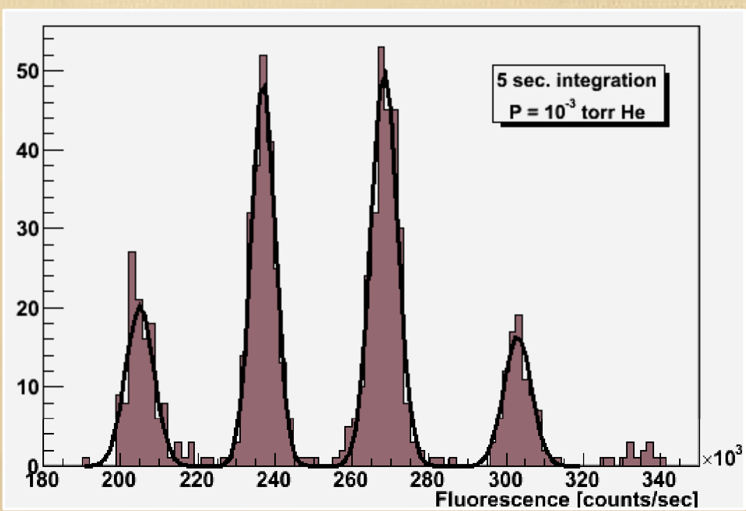
Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5 MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA[1]	Majorana mass (meV) NSM[2]
EXO-200	0.2	70	2	1.6	40	6.4×10^{25}	133	186

1) Rodin et. al., Nucl. Phys. A 793 (2007) 213

2) Caurier et. al., arXiv:0709.2137v1

Ba^+ Tagging





RF cage with low pressure buffer gas

- $Ba^{++} \rightarrow Ba^+$ conversion expected
  - Ionization potentials:
    - Xe^+ = 12.13 eV vs. Ba^+ = 5.21 eV
    - Xe^{++} = 21.21 eV vs. Ba^{++} = 10.00 eV
  - Solid Xe band gap ***(Phys. Rev. B10 4464 1974)***
    - E_G = 9.22 +/- 0.01 eV
  - "Liquid Xe ionization potential" close to E_G ***(J. Phys. C: Solid State Phys. Vol. 7 1974)***
    - 9.28 to 9.49 eV range
  - Use of additives for gas based detectors

Conclusion

- EXO-200 detector soon operational!
- The largest neutrino-less double beta decay detector!
- Successful large scale xenon enrichment proven!