Henry Primakoff Lecture:
Neutrinoless Double-Beta Decay

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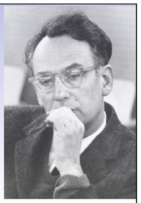
Renewed Impetus for 0νββ

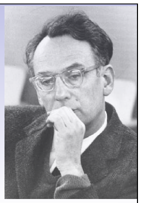


The recent discoveries of atmospheric, solar, and reactor neutrino oscillations and the corresponding realization that neutrinos are not massless particles, provides compelling arguments for performing neutrinoless double-beta decay (0νββ) experiments with increased sensitivity.

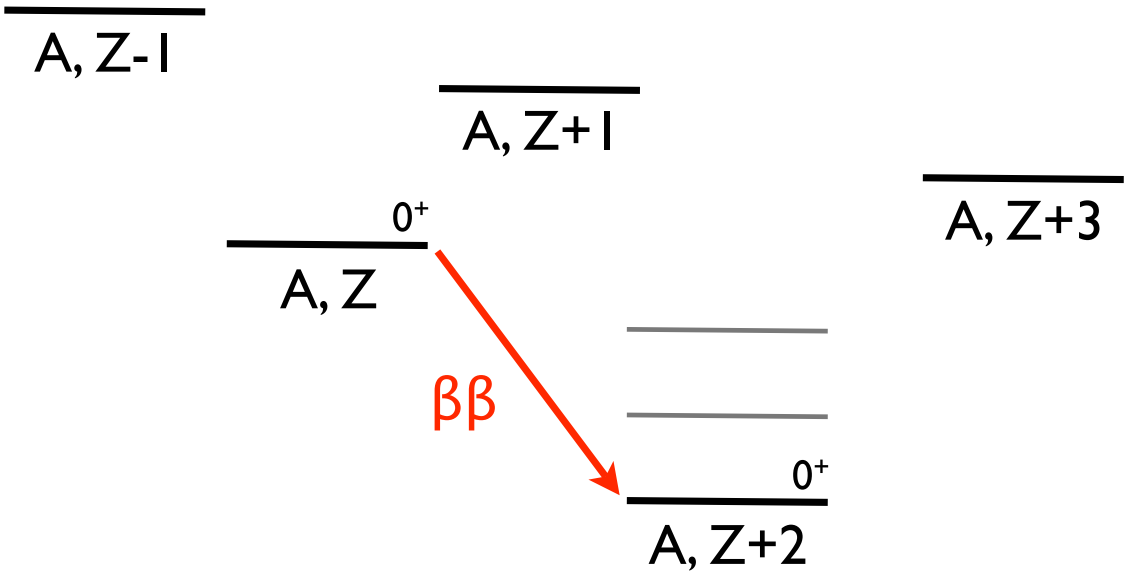
0νββ decay probes fundamental questions:

- Tests one of nature's fundamental symmetries, Lepton number conservation.
- The only practical technique able to determine if neutrinos might be their own anti-particles — Majorana particles.
- If 0νββ is observed:
  - Provides a promising laboratory method for determining the overall absolute neutrino mass scale that is complementary to other measurement techniques.
  - Measurements in a series of different isotopes potentially can reveal the underlying interaction process(es).

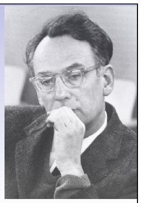
Double-Beta Decay



In a number of even-even nuclei, β-decay is energetically forbidden, while double-beta decay, from a nucleus of (A,Z) to (A,Z+2), is energetically allowed.



Double-Beta Decay



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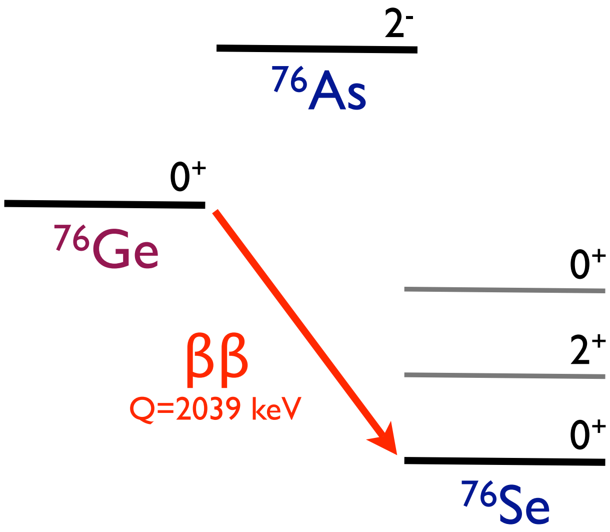
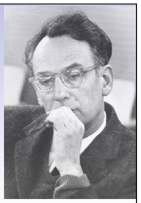


^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

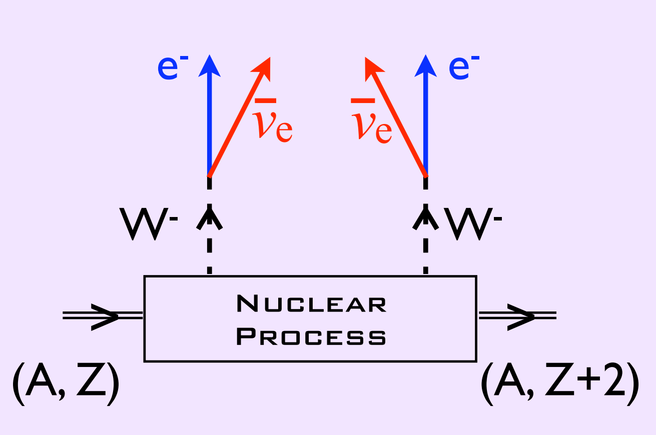
Double-Beta Decay Modes



2ν double-beta decay ($2\nu\beta\beta$): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + $\bar{\nu}_e$ + e^- + $\bar{\nu}_e$

Allowed second-order weak process
Maria Goeppert-Mayer (1935)

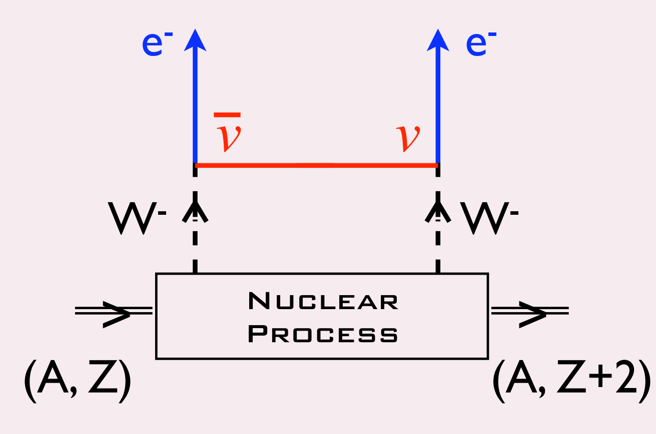
$2\nu\beta\beta$ observed for
^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{150}Nd



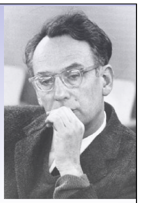
0ν double-beta decay ($0\nu\beta\beta$): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + e^-

Ettore Majorana (1937) realized symmetry properties of Dirac's theory allowed the possibility for electrically neutral spin-1/2 fermions to be their own anti-particle

Racah (1937),	$n \rightarrow p + e^- + \bar{\nu}$
Furry (1938)	$\nu + n \rightarrow p + e^-$



Est. ββ Decay Rates (prior to 1957)



2ν double-beta decay ($2\nu\beta\beta$)

Maria Goeppert-Mayer (1935)
using Fermi Theory

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \propto \text{Phase Space (4-body)} \propto Q^{10-12}$$

$$T_{1/2}^{2\nu\beta\beta} \approx 10^{25} \text{ years}$$

0ν double-beta decay ($0\nu\beta\beta$)

Furry (1939), assuming Parity
conserved, so no preferential handedness

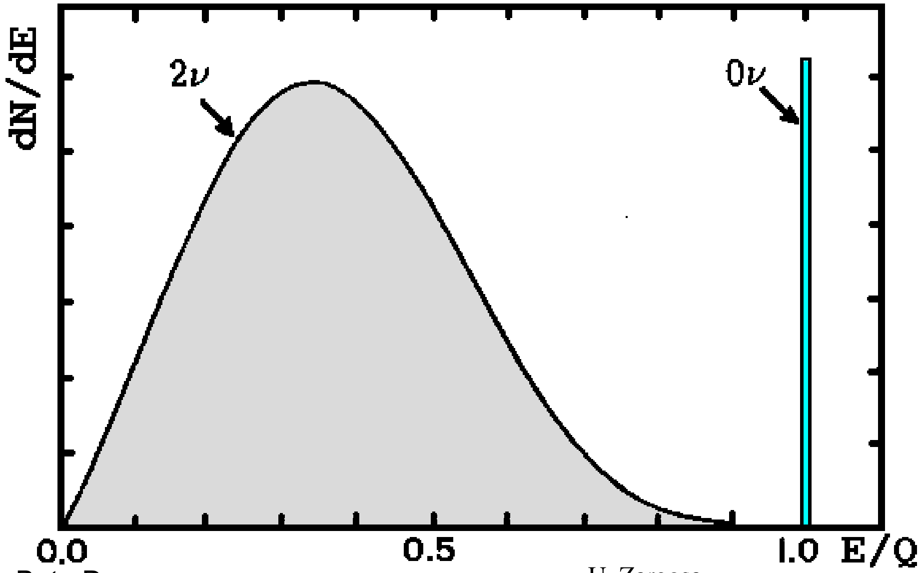
$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} \propto \text{Phase Space (2-body)} \propto Q^{5}$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{19} \text{ years}$$

$0\nu\beta\beta$ mode highly favored over $2\nu\beta\beta$

If observe
$2\nu\beta\beta \Rightarrow$

neutrinos are
Dirac

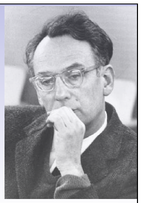


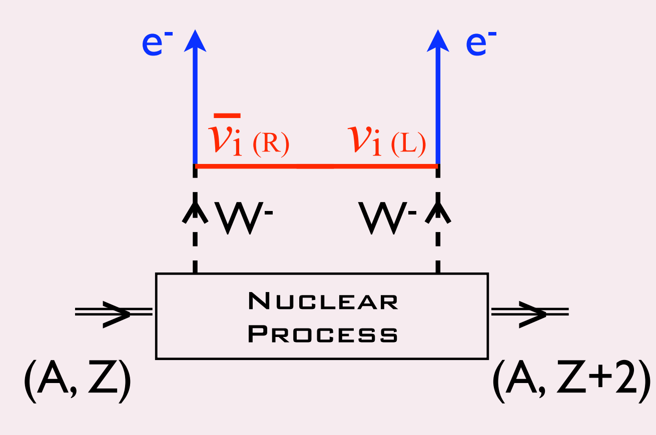
U. Zargosa

If observe
$0\nu\beta\beta \Rightarrow$

neutrinos are
Majorana

1957 Maximal Parity Violation





0νββ strongly suppressed compared to 2νββ!

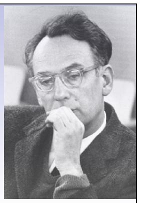
"wrong-handed" helicity admixture ~ m_i/E_{ν_i}

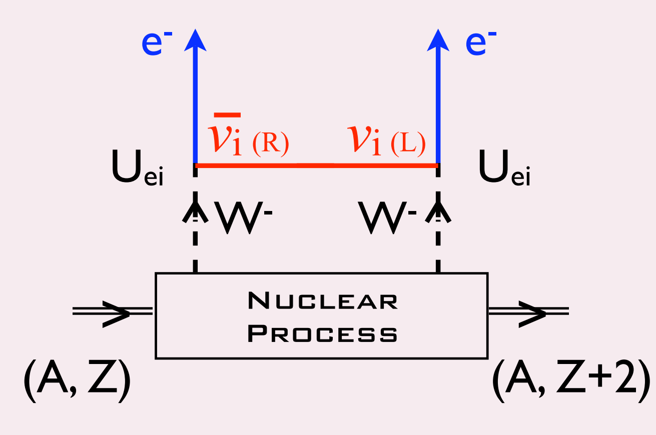
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \eta^2$$

Primakoff and Rosen Rep. Prog. Phys. **22** 121 (1959)

1. Recognized that the relative rates were "swapped" (absolute change of 10^6)
   Observation of 2νββ tells one nothing about Dirac/Majorana nature.
2. Formalism included the possibility of both L-conserving (SM) and L-violating interactions, along with potential contributions from S and T interactions.
3. Included a serious approach to account for the Nuclear Process in calculating rates - nuclear structure, average separation between neutrons, ...
   Intersection of Nuclear and Particle Physics.

0νββ Decay - Current Understanding





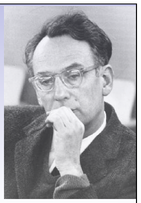
$$Amp[0\nu\beta\beta] \propto \left| \sum_i m_i U_{ei}^2 \right| \equiv \langle m_{\beta\beta} \rangle$$

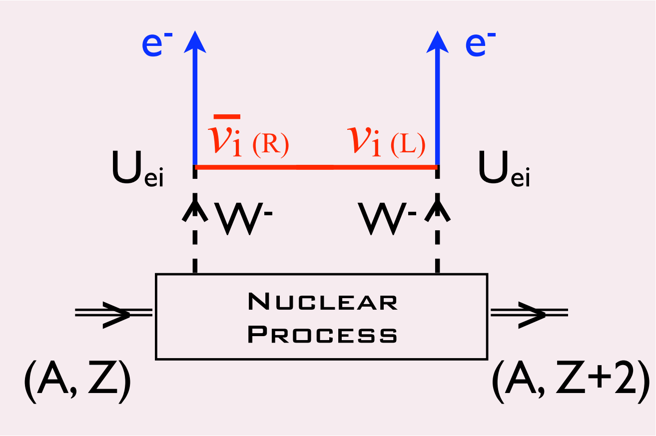
For 0νββ to occur requires:

- neutrinos have mass
  - “wrong-handed” helicity admixture ~ m_i/E_{ν_i}
- Lepton number violation
  - No experimental evidence that Lepton number is conserved

Given that neutrinos have non-zero mass - if 0νββ decay is observed ⇒ neutrinos are Majorana particles

Relationship of η vs. $\langle m_{\beta\beta}\rangle$





$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \eta^2$$

$$\Downarrow$$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \left\langle m_{\beta\beta}\right\rangle^2$$

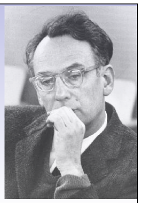
Any process that allows 0νββ to occur requires Majorana neutrinos with non-zero mass.

Schechter and Valle (1982)

"... we parameterized a possible lepton nonconservation by inclusion in the lepton weak current of an "opposite-helicity" term (η) ... however we kept our "Majorana" neutrino massless; even though a nonvanishing η in general implies a nonvanishing m_ν *proportional to η"*

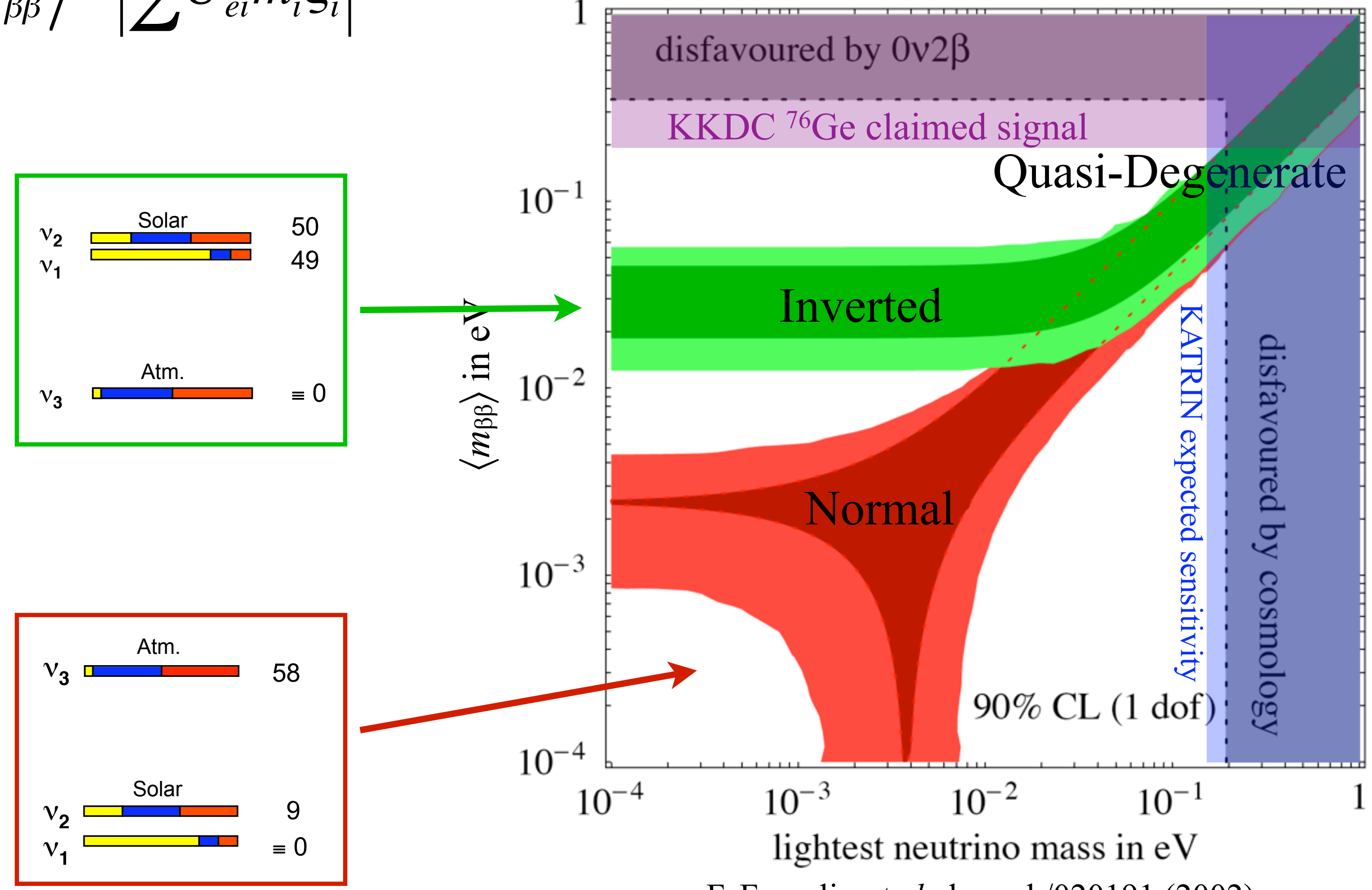
Primakoff and Rosen Phys. Rev. **184** 1925 (1969)

0νββ Decay Sensitivity to <m$_{\beta\beta}$>



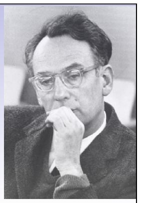
0$\nu\beta\beta$ limits for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd
^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

$$\langle m_{\beta\beta}\rangle = \left|\sum U_{ei}^2 m_i \xi_i\right|$$



F. Feruglio *et al.*, hep-ph/020191 (2002).

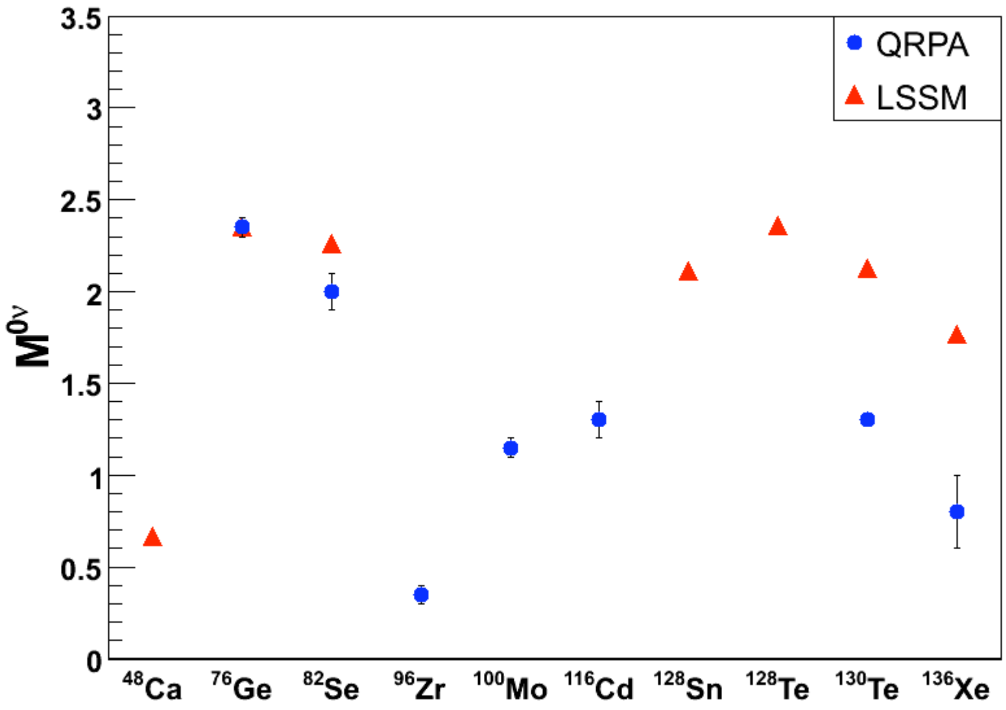
Nuclear Matrix Elements



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^{2}\left\langle m_{\beta\beta}\right\rangle^{2}$$

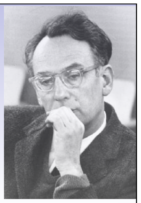
NME are calculated using two different techniques, the Shell Model and Quasi-random phase approximation (QRPA)

Extracting an effective neutrino mass requires an understanding of the nuclear matrix elements (NME) at about the 20% theoretical uncertainty level.



QRPA: Nucl. Phys. A, **766** 107 (2006)
LSSM: From Poves NDM06 talk (Caurier, Nowacki, Poves)

Underlying $0\nu\beta\beta$ Decay Mechanisms



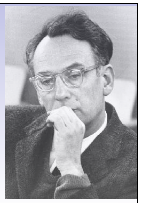
There are many possible underlying mechanisms for $0\nu\beta\beta$ Decay

- light Majorana neutrino exchange
- heavy Majorana neutrino exchange
- right-handed currents (RHC)
- exchange mechanisms arising from R-Parity violating supersymmetry models.

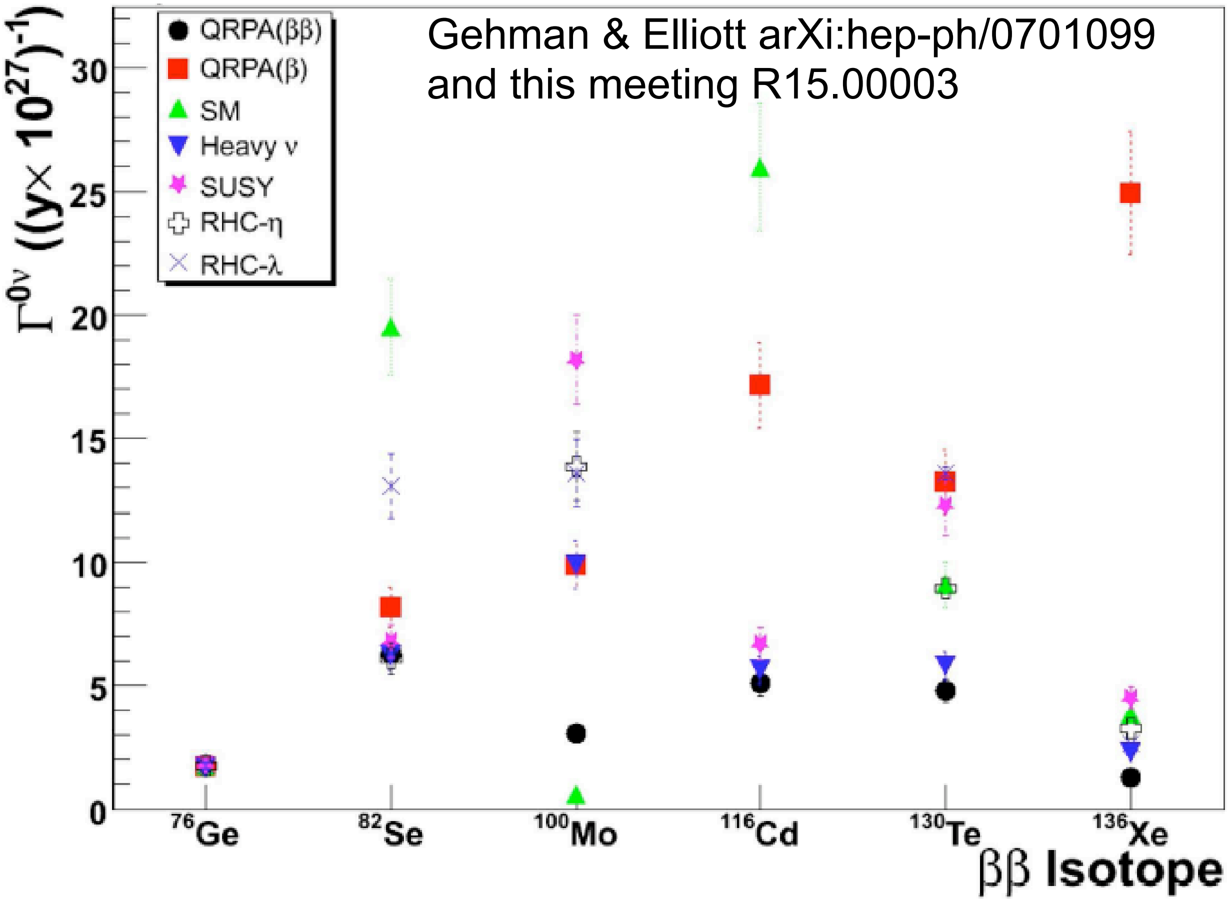
Primakoff and collaborators published a number of papers exploring $0\nu\beta\beta$ and potential Lepton violating interactions. Their 1976 paper considered a coupling to massive Majorana neutrinos (Halprin, Minkowski, Primakoff, and Rosen). Using calculated rates based on experimental $0\nu\beta\beta$ limits, they concluded that any such neutrino has to be at least 10^4 GeV or greater.

"The existence of such heavy neutrinos has been discussed in the context of vectorlike gauge theories of elementary particle interactions"

0νββ as a Probe of New Physics



If 0νββ is observed, then measurements on 3-4 multiple isotopes might be able to distinguish potential physics mechanisms



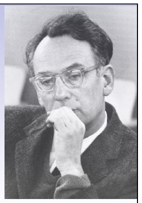
Gehman & Elliott arXi:hep-ph/0701099
and this meeting R15.00003

Comparison assumes a single dominant mechanism.

Requires results from 3-4 isotopes & calculation of NME to ~20%

Also see
Deppisc & Päs
arXi:hep-ph/0612165

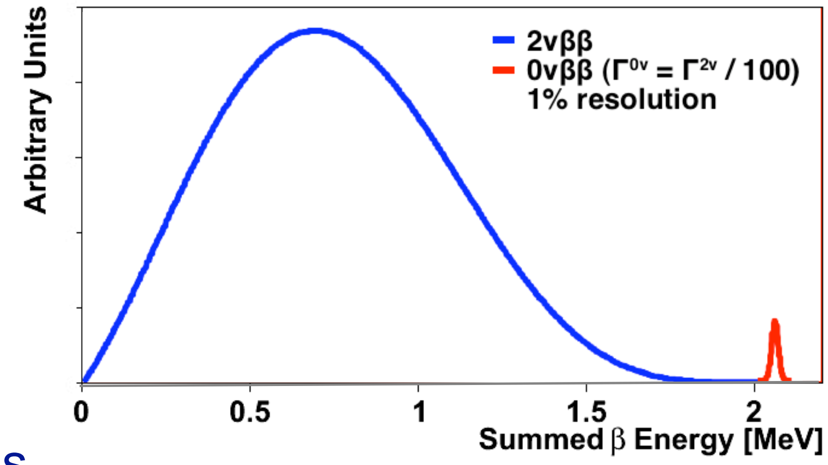
Experimental Considerations



Extremely slow decay rates

($0\nu\beta\beta$ $T_{1/2} \sim 10^{26}$ - 10^{27} years)

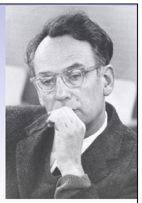
Best case, 0 background !	$\propto$ Source Mass • time_{exp}

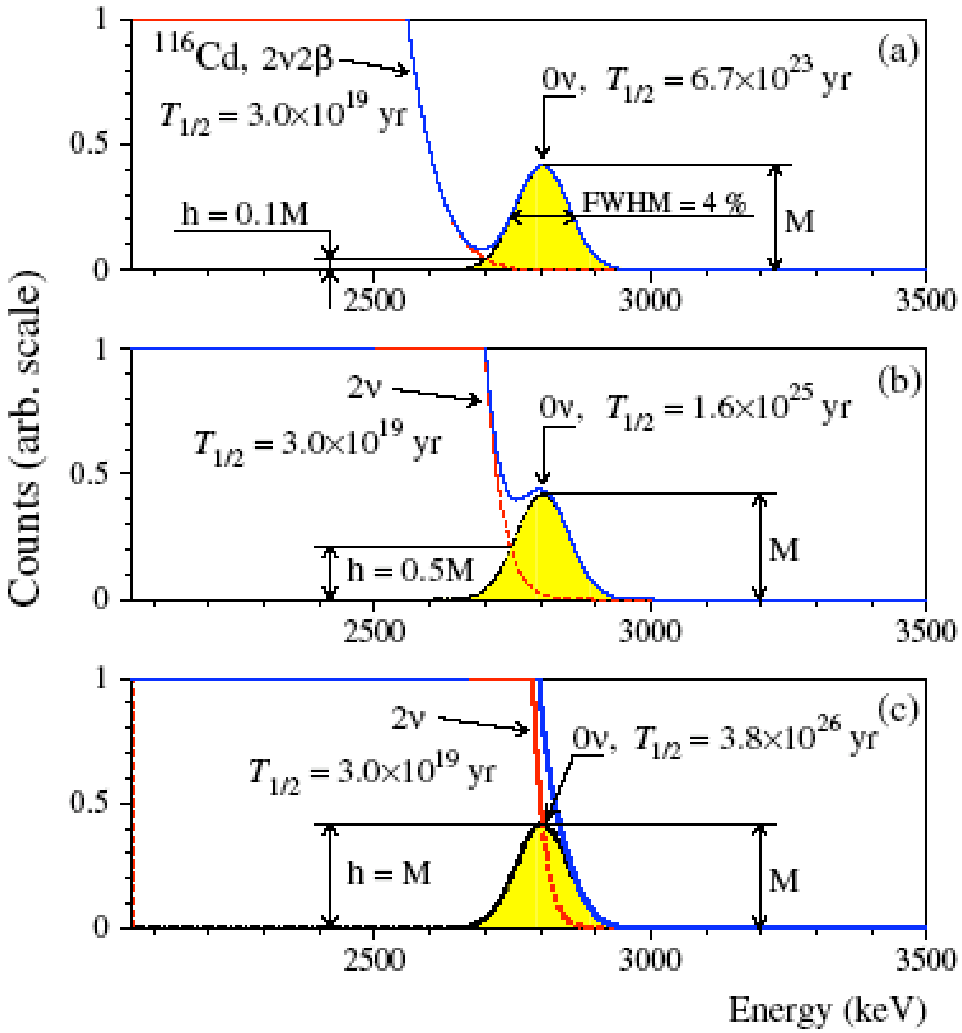


Requires

- Large, highly efficient source mass
  - detector as source
- Best possible energy resolution
  - minimize $0\nu\beta\beta$ peak ROI to maximize S/B
  - separate from $0\nu\beta\beta$ from irreducible $2\nu\beta\beta$ ($\sim T_{1/2} \sim 10^{19}$ - 10^{21} years)
- Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region
  - requires ultra-clean radiopure materials
  - the ability to discriminate signal from background

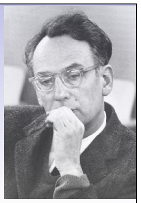
Resolution & Sensitivity to 0νββ





From Zdesenko, Danevich, Tretyak, J. Phys. G 30 (2004) 971

Backgrounds & Sensitivity to 0νββ



Backgrounds - Next generation experiments are striving for backgrounds in the 0νββ region of **cnts/t-y**.

- Requires materials with sub μBq/kg level radioimpurities.
  - Very difficult to achieve this sensitivity with direct radioassays
- "New background regimes" -- background sources that could previously be ignored

Scalability - Need to move from few kg to 100's of kg and perhaps 1000s of kgs of material.

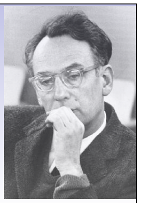
- Requires large scale cleanliness.

Signal and Background Characterizations

- Reliably simulate the entire observed spectrum.
- Demonstrate capability to measure the 2νββ spectrum
- Search for excited state decays for 0νββ and 2νββ

The KKDC Result

Klapdor-Kleingrothaus, Krivosheina, Dietz and Chkvorets, *Phys. Lett.* B **586** 198 (2004).



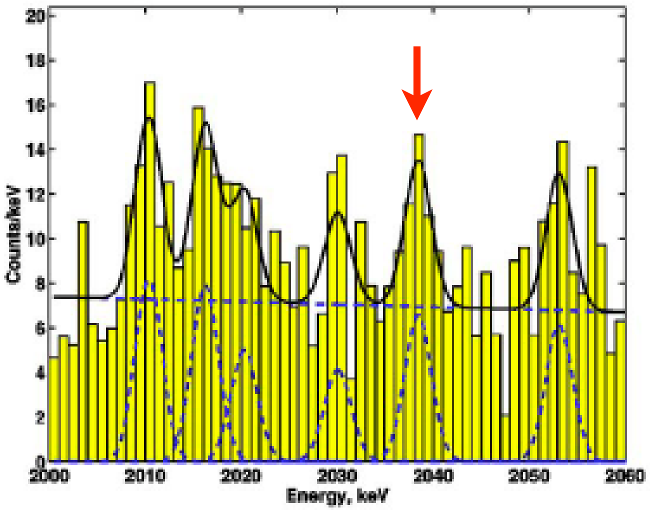
Result: Five ^{76}Ge crystals, 10.96 kg of total mass, 71 kg-years of data.

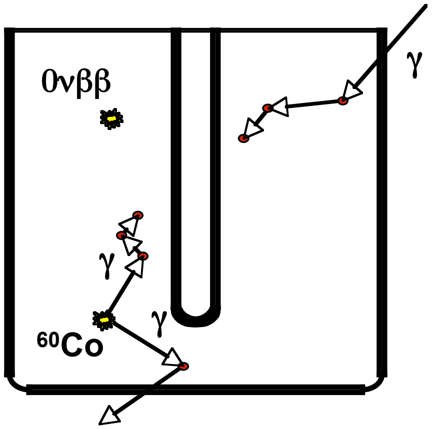
$$T_{1/2} = (1.19 +2.99/-0.5\ ) \times 10^{25}\ y$$

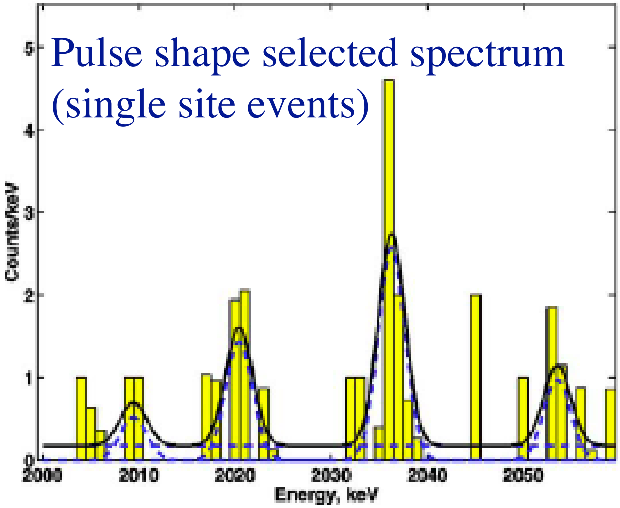
$$0.24 < m_\nu < 0.58\ \text{eV}\ \ (3\sigma)$$

Plotted a subset of the data for four of five crystals, 51.4 kg-years of data.

$$T_{1/2} = (1.25 +6.05/-0.57) \times 10^{25}\ y$$

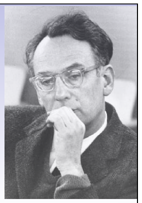






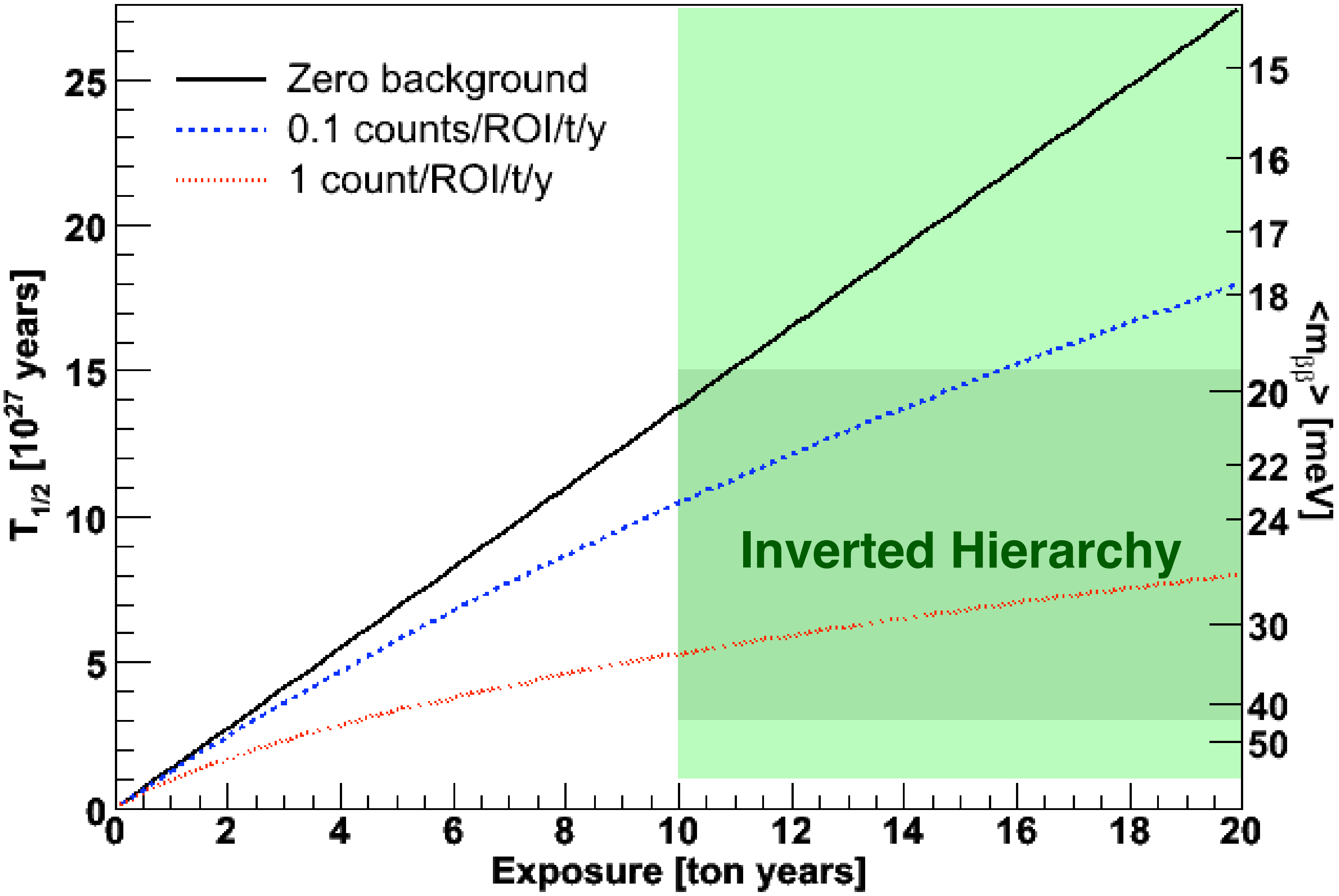
Pulse shape selected spectrum (single site events)

Scaling up and backgrounds

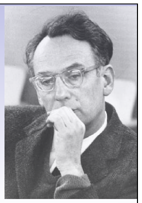


^{76}Ge Example

$T_{1/2}^{0\nu}$ = ln(2)$N\epsilon t$/UL(B)



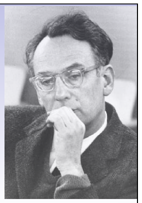
“Ideal” Experiment

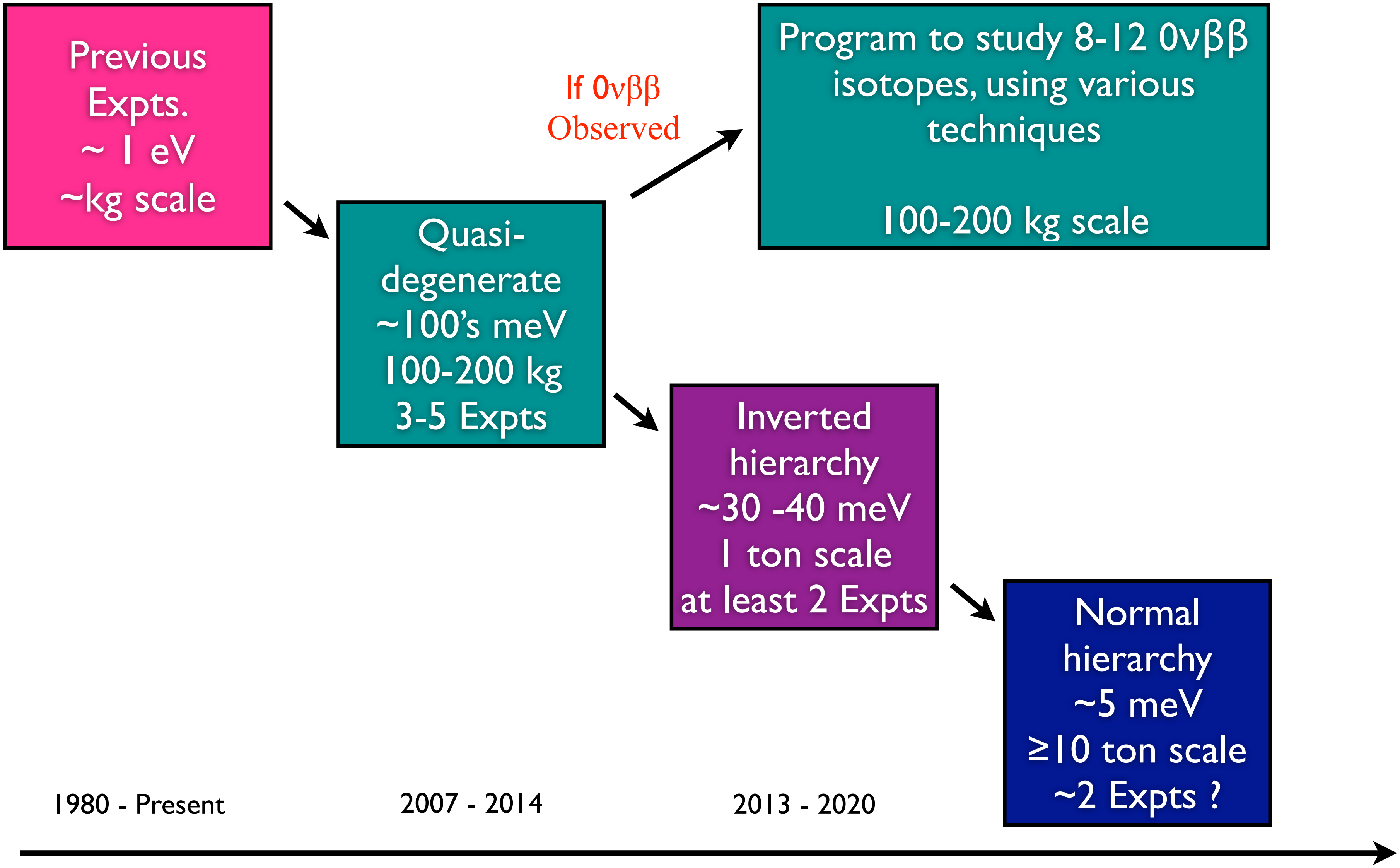


- Source serves as the detector
- Elemental (enriched) source to minimize active material.
- Large Q value - faster 0 rate and also places the region of interest above many potential backgrounds.
- Relatively slow 2νββ rate helps control this irreducible background.
- Direct identification of the decay progeny in coincidence with the 0νββ decay eliminates all potential backgrounds except 2νββ.
- Full Event reconstruction, providing kinematic data such as opening angle and individual electron energy aids in the elimination of backgrounds and demonstration of signal (can possibly use 2νββ)
- Spatial resolution and timing information to reject background processes.
- Demonstrated technology at the appropriate scale.
- The nuclear theory is better understood in some isotopes than others. The interpretation of limits or signals might be easier to interpret for some isotopes.

No one ideal isotope, experimental technique

Experimental Program in 0νββ





Previous Expts.
~ 1 eV
~kg scale

Quasi-degenerate
~100's meV
100-200 kg
3-5 Expts

If 0νββ Observed

Program to study 8-12 0νββ isotopes, using various techniques

100-200 kg scale

Inverted hierarchy
~30 -40 meV
1 ton scale
at least 2 Expts

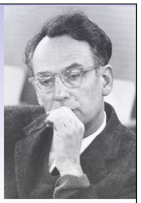
Normal hierarchy
~5 meV
≥10 ton scale
~2 Expts ?

1980 - Present

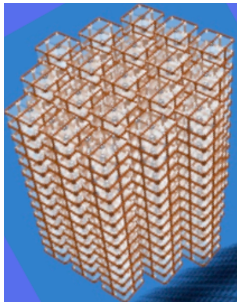
2007 - 2014

2013 - 2020

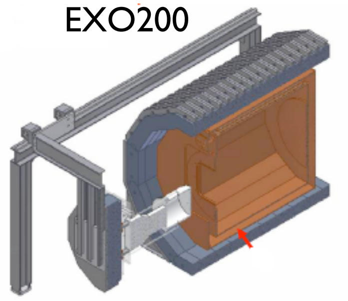
0νββ decay Experiments - Efforts Underway



CUORE



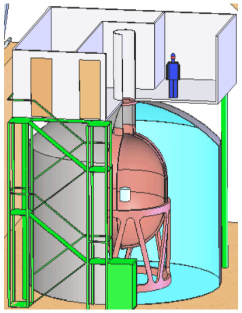
EXO200



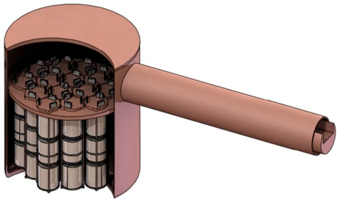
NEMO

Collaboration	Isotope	Technique	Mass	Status
CAMEO	Cd-116	$CdWO_4$ crystals	1 t	
CANDLES	Ca-48	60 CaF_2 crystals in liq. scint	6 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	100 kg	
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUROICINO	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D
EXO200	Xe-136	Xe TPC	200 kg	Construction
EXO	Xe-136	Xe TPC	1-10t	R&D
GEM	Ge-76	Ge diodes in LN	1 t	
GERDA	Ge-76	Seg. and UnSeg. Ge in LAr	35-40 kg 1 t	Construction Future
GSO	Gd-160	Gd_2SiO_5:Ce crystal scint. in liquid scint	2t	
HPXeTPC	Xe-136	High Pressure TPC	1t	R&D
Majorana	Ge-76	Segmented Ge	60 kg 1 t	Proposed Future
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Operating
SuperNEMO	Se-82	Foils with tracking	100 kg	Proposed
MOON	Mo-100	Mo sheets	200 kg 1 t	R&D
SNO+ ββ	Nd-150	0.1% suspended in Scint.	56 kg	R&D
Xe	Xe-136	Xe in liq. Scint.	1.56 t	
XMASS ββ	Xe-136	Liquid Xe	10 kg	Feasibility

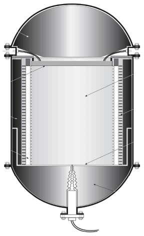
GERDA



Majorana (R15.00002)

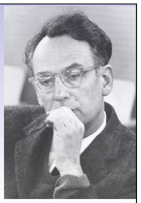


HPXeTPC



Operating Construction Proposed/R&D

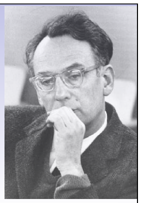
The U.S. Process



Substantial community involvement and guidance on the program and priorities.

- 2002 National Research Council's (NRC) Quarks to Cosmos study
- 2003 NRC Neutrino Facilities Assessment Committee's report
- Nov 2004 APS Multidivisional Neutrino Study: 0νββ program one of three top recommendations
- Sep 2005 NuSAG Review of US 0νββ program: "CUORE, EXO, and Majorana have the highest funding priority"
- Nov 2005 DOE Mission Need for "Generic" ββ decay
- Nov 2006 Particle Physics Project Prioritization Panel Physics Roadmap: "CUORE, EXO, and Majorana should be investigated vigorously"

Summary



- The observation of 0νββ would demonstrate Lepton number violation and indicate that neutrinos are Majorana particles - constituting a major discovery.
  - Need to be confirmed from independent experiments and in different isotopes.

- If 0νββ decay is observed then it opens an exquisitely sensitive window to search for physics beyond the Standard model.
  - Measurement of $\langle m_{\beta\beta} \rangle$ is complementary to direct and cosmological measurements of neutrino mass.
  - Measurements in different isotopes should provide insights into the underlying physics process(es).

Primakoff and Rosen

Over the past 50 years there have been dramatic changes in our understanding of the framework of nuclear and particle physics. And yet 0νββ remains extremely relevant as we endeavor to elucidate the underlying framework of our universe.

It was also fifty years ago that Henry Primakoff and Peter Rosen started their long and productive collaboration and friendship. Along the way they provided significant insights into our understanding of 0νββ.

When Peter passed away in September, we lost an eloquent spokesman and tireless advocate for 0νββ who is greatly missed by his friends and colleagues.

Special thanks to Jason Detwiler, Steve Elliott, Stuart Freedman, Boris Kayser, Hamish Roberston, and Lincoln Wolfenstein.