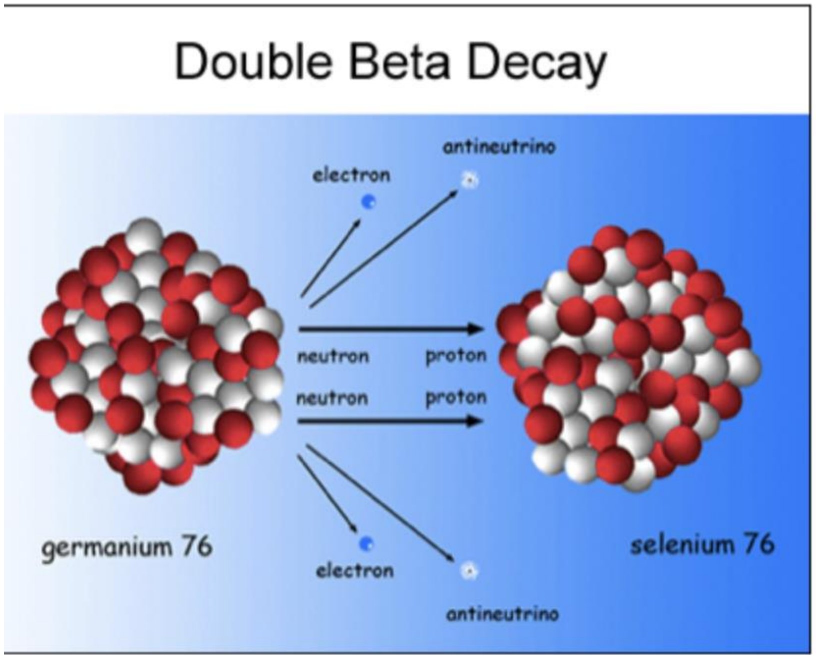
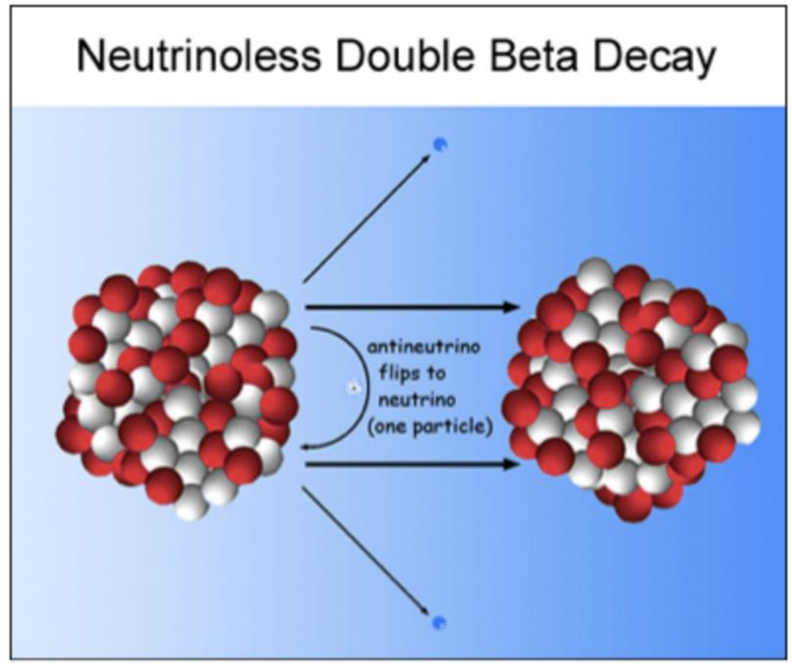
The science of neutrinoless double beta decay – presence and future





Neutrinoless process is violating lepton number by 2 units

Beyond Standard Model

Kai Zuber, Cellar Meeting 28.11.2022

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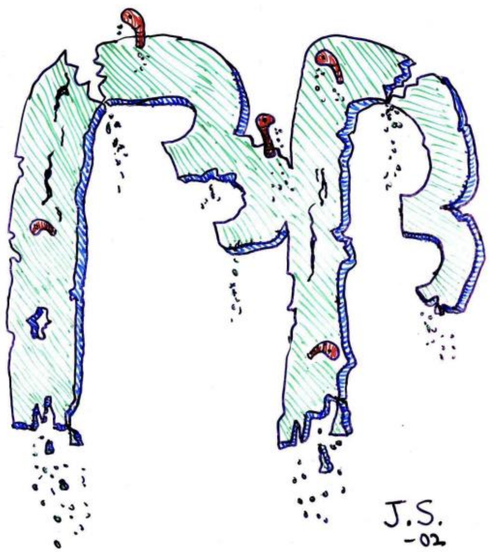
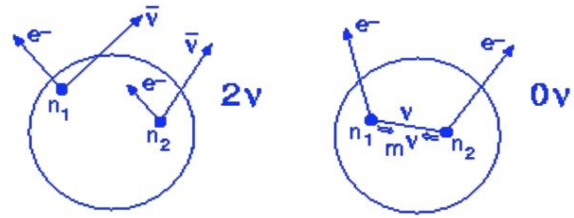
Double beta decay



Produced by J. Suhonen

Double beta decay

- $(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}_e$ $2\nu\beta\beta$
- $(A,Z) \rightarrow (A,Z+2) + 2\,e^-$ $0\nu\beta\beta$



Unique process to measure the character of the neutrino

The smaller the neutrino mass the longer the half-life

Neutrino mass measurement via half-life measurement

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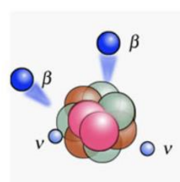
Double beta decay

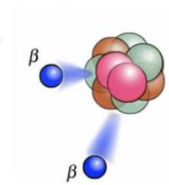
Within a few years...

PHYSICAL REVIEW

Double Beta-Disintegration

M. Goeppert-Mayer, *The Johns Hopkins University*
(Received May 20, 1935)





DECEMBER 15, 1939 PHYSICAL REVIEW

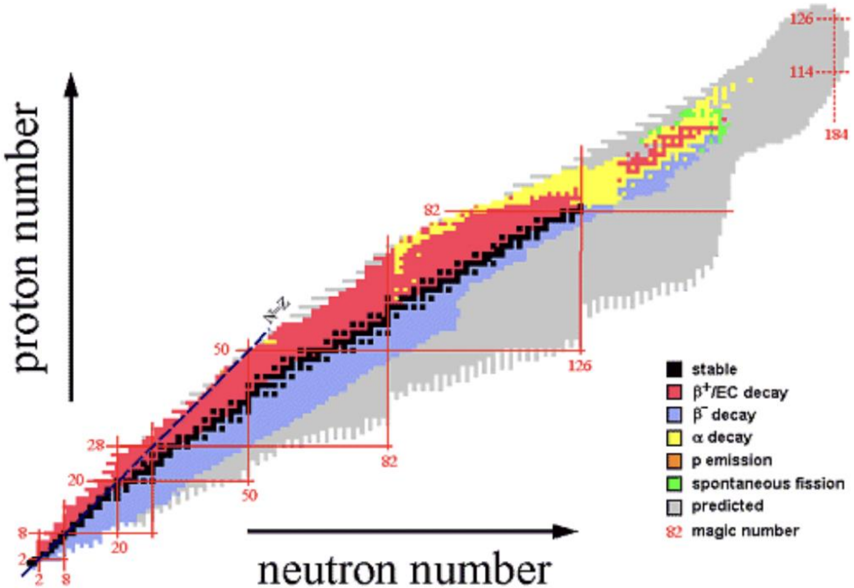
On Transition Probabilities in Double Beta-Disintegration

W. H. Furry
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received October 16, 1939)

+ Racah (1936) and Majorana (1937)

Double beta decay

Requirements - I



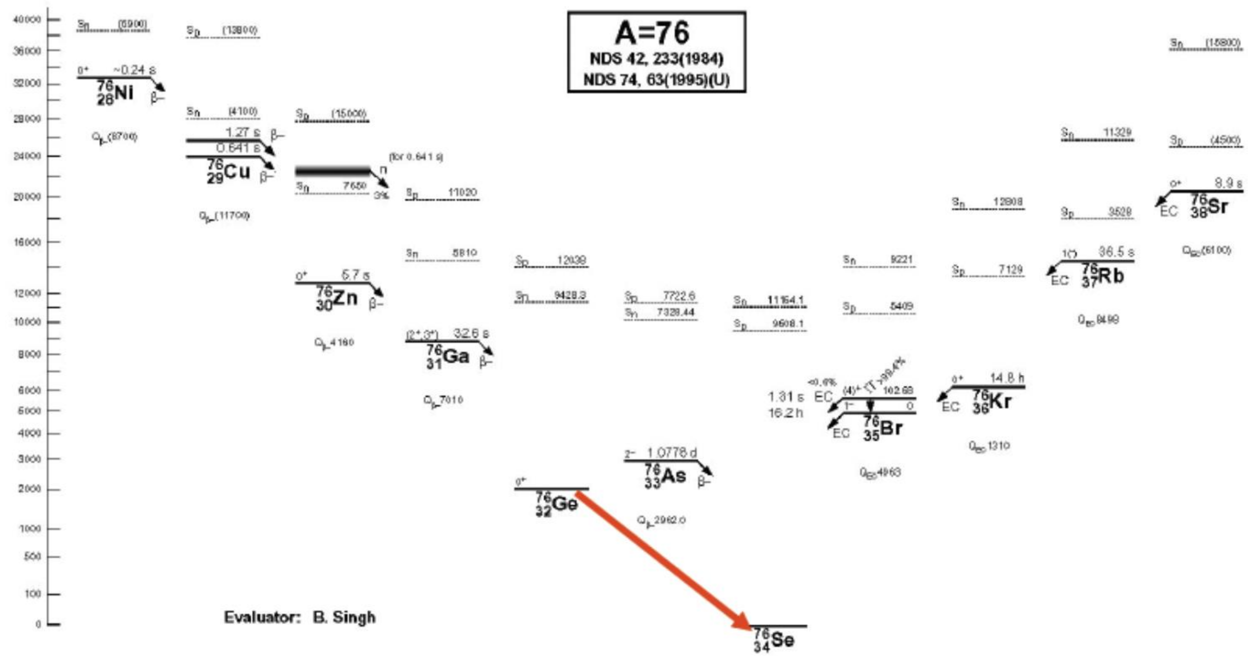
1.) m(A,Z) > m(A,Z+2)

2.) Single beta decay must be forbidden (m (A,Z) < m (A,Z+1))
or at least strongly suppressed (large change in angular momentum)

Double beta nculides

A=76

Example: Ge-76



There are only 35 isotopes in nature for double electron emission

Potential isotopes-1

Book: F. Böhm, P. Vogel
Physics of massive neutrinos

$\beta^-\beta^-$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
$^{46}Ca \rightarrow ^{46}Ti$	987 ±4	0.0035	8.71E21	7.16E26
$^{48}Ca \rightarrow ^{48}Ti^{a}$	4271 ±4	0.187	2.52E16	4.10E24
$^{70}Zn \rightarrow ^{70}Ge$	1001 ±3	0.62	3.17E21	4.27E26
$^{76}Ge \rightarrow ^{76}Se$	2039.6±0.9	7.8	7.66E18	4.09E25
$^{80}Se \rightarrow ^{80}Kr$	130 ±9	49.8	8.20E27	2.34E28
$^{82}Se \rightarrow ^{82}Kr$	2995 ±6	9.2	2.30E17	9.27E24
$^{86}Kr \rightarrow ^{86}Sr$	1256 ±5	17.3	3.00E20	1.57E26
$^{94}Zr \rightarrow ^{94}Mo$	1145.3±2.5	17.4	4.34E20	1.57E26
$^{96}Zr \rightarrow ^{96}Mo^{a}$	3350 ±3	2.8	5.19E16	4.46E24
$^{98}Mo \rightarrow ^{98}Ru$	112 ±7	24.1	1.03E28	1.49E28
$^{100}Mo \rightarrow ^{100}Ru$	3034 ±6	9.6	1.06E17	5.70E24
$^{104}Ru \rightarrow ^{104}Pd$	1299 ±2	18.7	1.09E20	8.32E25
$^{110}Pd \rightarrow ^{110}Cd$	2013 ±19	11.8	2.51E18	1.86E25
$^{114}Cd \rightarrow ^{114}Sn$	534 ±4	28.7	6.93E22	6.10E26
$^{116}Cd \rightarrow ^{116}Sn$	2802 ±4	7.5	1.25E17	5.28E24
$^{122}Sn \rightarrow ^{122}Te$	364 ±4	4.56	9.55E23	1.16E27
$^{124}Sn \rightarrow ^{124}Te$	2288.1±1.6	5.64	5.93E17	9.48E24
$^{128}Te \rightarrow ^{128}Xe$	868 ±4	31.7	1.18E21	1.43E26
$^{130}Te \rightarrow ^{130}Xe$	2533 ±4	34.5	2.08E17	5.89E24
$^{134}Xe \rightarrow ^{134}Ba$	847 ±10	10.4	1.16E21	1.30E26
$^{136}Xe \rightarrow ^{136}Ba$	2479 ±8	8.9	2.07E17	5.52E24
$^{142}Ce \rightarrow ^{142}Nd$	1417.6±2.5	11.1	1.38E19	2.31E25
$^{146}Nd \rightarrow ^{146}Sm^{b}$	56 ±5	17.2	2.06E29	7.05E27
$^{148}Nd \rightarrow ^{148}Sm^{b}$	1928.3±1.9	5.7	9.35E17	7.84E24
$^{150}Nd \rightarrow ^{150}Sm$	3367.1±2.2	5.6	8.41E15	1.25E24
$^{154}Sm \rightarrow ^{154}Gd$	1251.9±1.5	22.6	2.44E19	2.38E25
$^{160}Gd \rightarrow ^{160}Dy$	1729.5±1.4	21.8	1.51E18	7.99E24
$^{170}Er \rightarrow ^{170}Yb$	653.9±1.6	14.9	1.82E21	6.92E25

Potential isotopes –2

$\beta^-\beta^-$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
$^{176}Yb \rightarrow {}^{176}Hf$	1078.8±2.7	12.6	3.26E19	1.75E25
$^{186}W \rightarrow {}^{186}Os^b$	490.3±2.2	28.6	7.68E21	6.95E25
$^{192}Os \rightarrow {}^{192}Pt$	417 ±4	41.0	1.98E22	7.70E25
$^{198}Pt \rightarrow {}^{198}Hg$	1048 ±4	7.2	1.63E19	8.74E24
$^{204}Hg \rightarrow {}^{204}Pb$	416.5±1.1	6.9	1.23E22	5.06E25
$^{232}Th \rightarrow {}^{232}U^b$	858.2±6	100	1.68E19	3.97E24
$^{238}U \rightarrow {}^{238}Pu^b$	1145.8±1.7	99.27	1.47E18	1.68E24
$\beta^+\beta^+$ candidates	T_0 (keV)	Abundance (%)	$(G^{2\nu})^{-1}$ (y)	$(G^{0\nu})^{-1}$ (y)
$^{78}Kr \rightarrow {}^{78}Se$	838	0.35	2.56E24	1.8E29
$^{96}Ru \rightarrow {}^{96}Mo$	676	5.5	3.34E25	8.8E29
$^{106}Cd \rightarrow {}^{106}Pd$	738	1.25	1.69E25	7.4E29
$^{124}Xe \rightarrow {}^{124}Te$	822	0.10	7.57E24	5.9E29
$^{130}Ba \rightarrow {}^{130}Xe$	534	0.11	6.92E26	6.4E30
$^{136}Ce \rightarrow {}^{136}Ba$	362	0.19	5.15E28	6.1E31

Double beta decay

Signal information

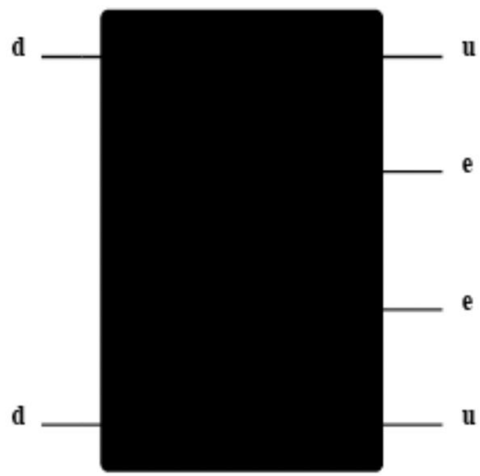
Signal: One new isotope (ionised), two electrons (fixed total energy)

- Single electron energies
- Angle between electrons
- Sum energy of both electrons
- Daughter ion (A,Z+2)
- Gamma rays (eg. four 511 keV photons in or excited state transitions)

Double beta decay

$0\nu\beta\beta$ -Total lepton number violation

Any $\Delta L=2$ process can contribute to $0\nu\beta\beta$



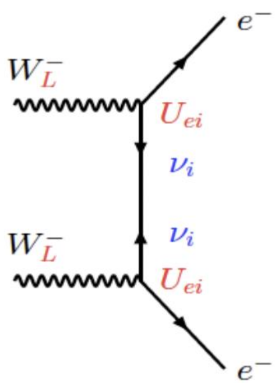
R_p violating SUSY
V+A interactions
Extra dimensions (KK- states)
Leptoquarks
Double charged Higgs bosons
Compositeness
Heavy Majorana neutrino exchange
Light Majorana neutrino exchange
...

Nice interplay with LHC

$$1 / T_{1/2} = PS * NME^2 * \varepsilon^2$$

Double beta decay

Light Majorana neutrinos



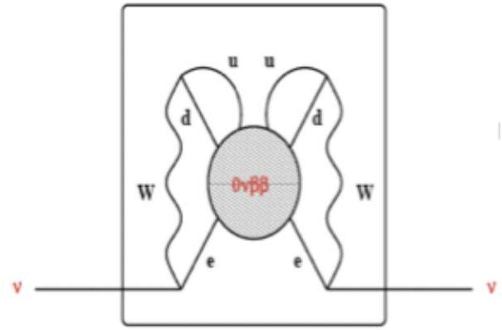
$$\longrightarrow \quad \varepsilon \equiv \langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right|$$

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3 \right|$$

$\longrightarrow$ $1 / T_{1/2} = PS * NME^2 * (<m_\nu> / m_e)^2$

Schechter and Valle 1982:

Independent of mechanism for neutrinoless DBD
Majorana neutrino mass will appear in higher order!



Observe $0\nu\beta\beta$ decay

$\equiv$

Neutrinos are Majorana particles

Actual calculation: M. Duerr, M. Lindner, A. Merle, JHEP 1106,091 (2011) -> very small

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Double beta decay

$0\nu\beta\beta$ -Total lepton number violation

Two more phases (Majorana phases) only appear in double beta decay

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i2\alpha_1} m_2 + s_{13}^2 e^{i2(\alpha_2-\delta)} m_3 \right|$$

Compare to beta decay

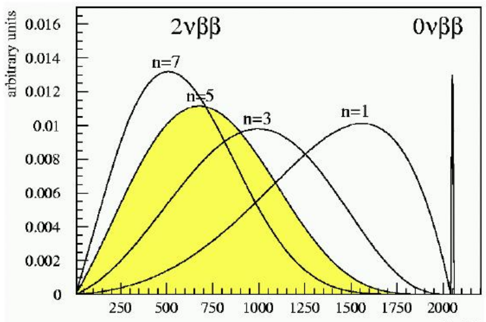
$$m^2(\nu_e) = \sum_i |U_{ei}|^2 m^2(\nu_i)$$

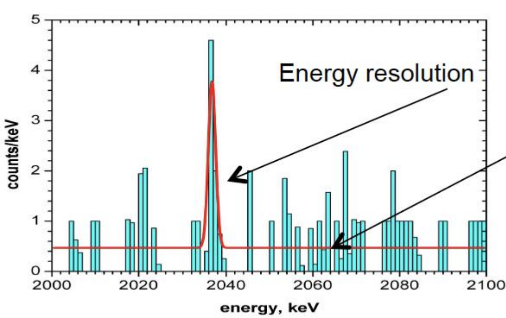
Double beta decay

Spectral shapes

$0\nu\beta\beta$: Peak at Q-value of nuclear transition

Sum energy spectrum of both electrons





Measured quantity: Half-life

$1 / T_{1/2} = PS * NME^2 * (\langle m_\nu \rangle / m_e)^2$

Experimental sensitivity depends on

(BG limited)

$$T_{1/2}^{-1} \propto a\varepsilon\sqrt{\frac{Mt}{\Delta EB}}$$

(BG free)

$$T_{1/2}^{-1} \propto a\varepsilon Mt$$

If background limited $\quad m_\nu \propto \sqrt[4]{\frac{\Delta EB}{Mt}}$

Double beta decay

Back of an envelope

This is the 50 meV option, just add 0's to moles and kgs if you want smaller neutrino masses

$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t / N_{\beta\beta}$ $(\tau >> T)$ (Background free)

For half-life measurements of 10^{26-27} yrs

1 event/yr you need 10^{26-27} source atoms

This is about 1000 moles of isotope, implying about 100 kg

Now you only can loose: nat. abundance, efficiency, background, ...

Double beta decay

Experimental approaches

$0\nu\beta\beta$ decay rate scales with Q^5 $\rightarrow$ only those with Q>2000 keV

11 isotopes of interest

Isotope	Nat. abund. (%)	Q-values 2016
Ca-48	0.187	4262.96 ± 0.84
Ge-76	7.44	2039.006 ± 0.050
Se-82	8.73	2997.9 ± 0.3
Zr-96	2.80	3356.097 ± 0.086
Mo-100	9.63	3034.40 ± 0.17
Pd-110	11.72	2017.85 ± 0.64
Cd-116	7.49	2813.50 ± 0.13
Sn-124	5.79	2292.64 ± 0.39
Te-130	33.80	2527.518 ± 0.013
Xe-136	8.9	2457.83 ± 0.37
Nd-150	5.64	3371.38 ± 0.20

Candles
GERDA, Majorana
SuperNEMO, LUCIFER

MOON, AMore

COBRA
Tin.Tin
CUORE, SNO+
EXO, KamLAND-Zen, NEXT, XMASS
MCT

There is no super-isotope!

Double beta decay

Going underground

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Various detectors

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

SNO+

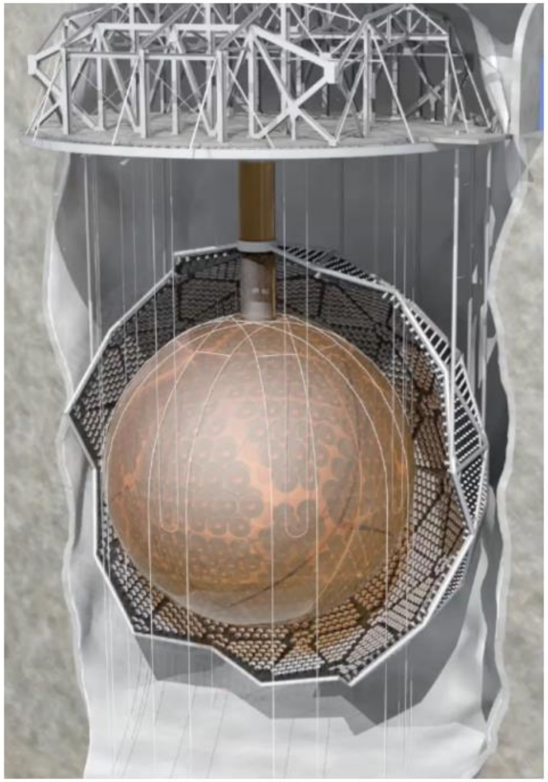
SNO+

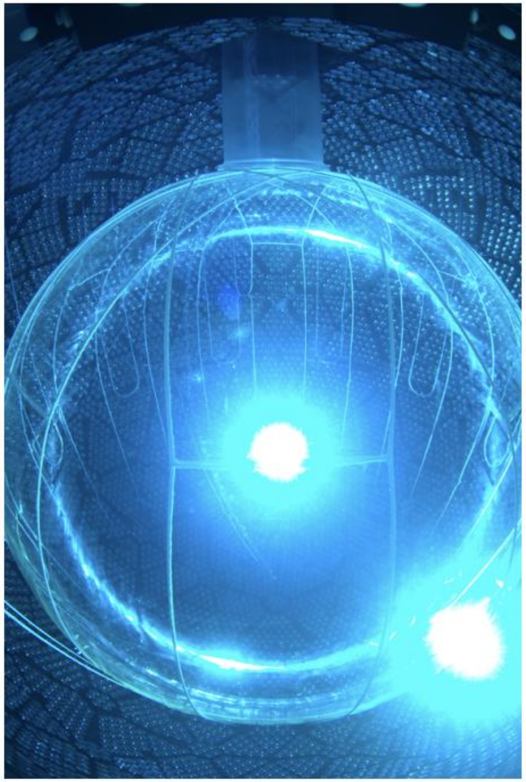
SNO (heavy water) and (SNO+) (liquid Scintillator) located at Sudbury, Canada

Flat rock overburden of 2070 m, equivqlent 6010 m.w.e

Acrylic spherical vessel (AV) with shell thickness of 5.5 cm and about 9500 PMTs.

Left: artistic impression of the cavity containing the detector





Aim:

Double beta decay loaded withTellurium.
Loading up to 1.3 tons of Te.
Q-value about 3 MeV
NB: Quite some physics will be lost because
of below Q-value of Te-130 is at 2.2 MeV
i.e. no light below 2.2 MeV

Nevertheless: Largest amount of all double beta experiments
Other experiments copy this technology now

Array of solid state detectors

Dresden 2022 CELLAR

What is long living ? (personal guess)

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Array of 1 tonne of enriched Ge-76 HPGe detectors

Benefit: Fantastic energy resolution

Requires (nitrogen) cooling

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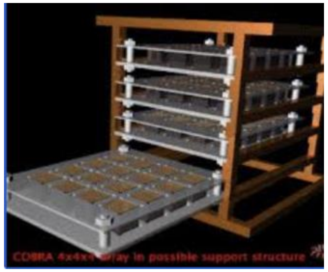
Array of solid state detectors

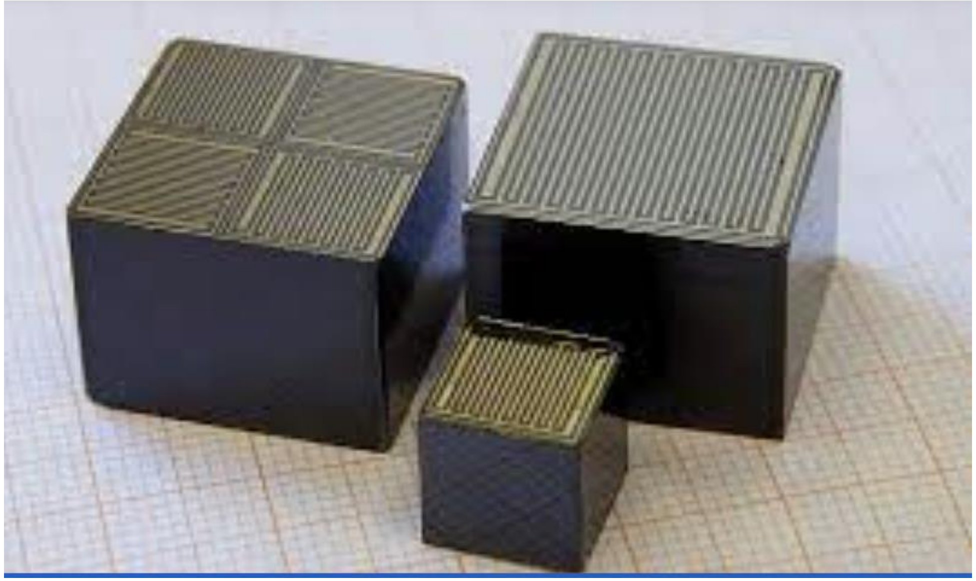
Dresden 2022
CELLAR

COBRA experiment



Array of a large amount of CdZnTe detectors

Benefit: Room temperature, various double beta isotopes in one



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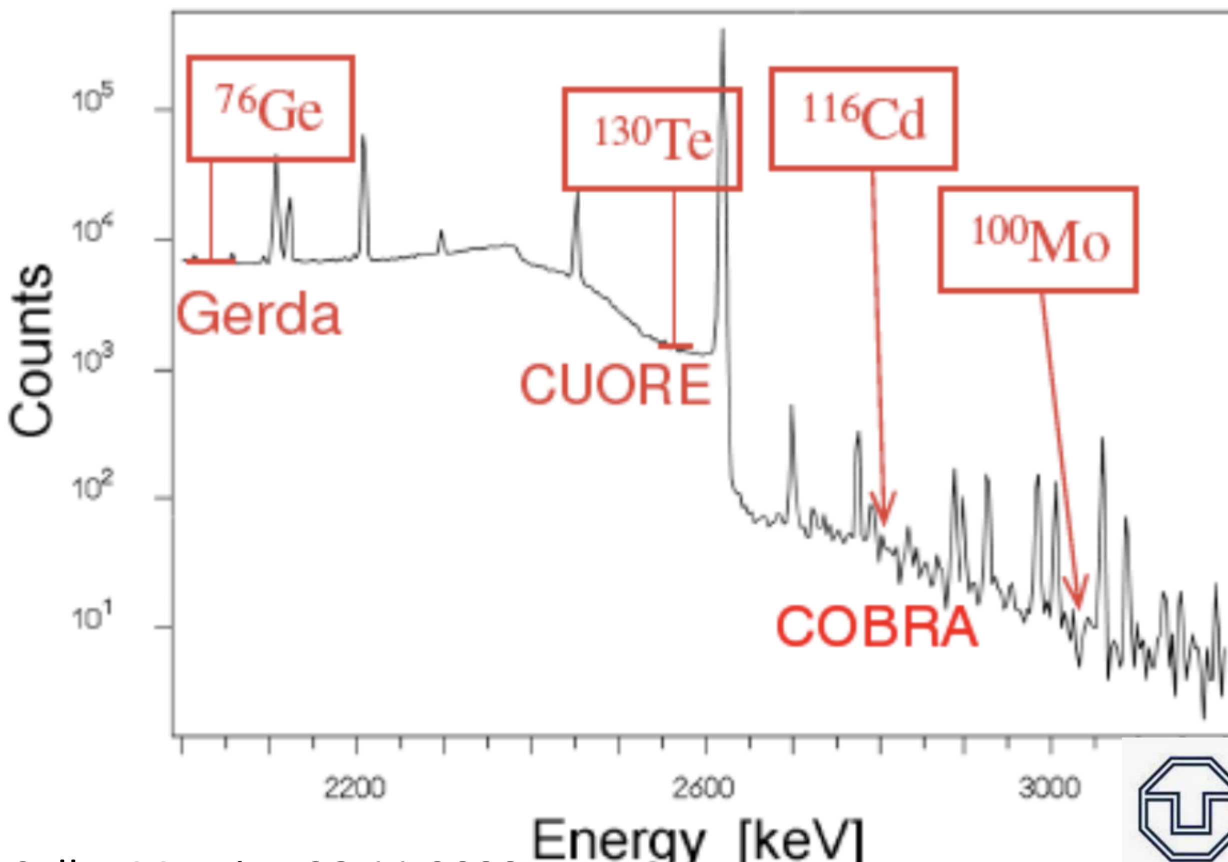
Comparison of some isotopes

Double beta peaks in the region of the 2614 keV line
Background significant lower, i.e. best is peak beyond 2.6 MeV



Dresden 2022
CELLAR

Summary

- Neutrino-less double beta decay is a very hot topic in science
- There is no super-isotope, so different groups focus on this topic
- The observation would prove that lepton number would be violated by 2 units and thus Physics beyond the Standard Modelof Particle Physics

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