ANDES: in search of new physics

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Plan of the talk

- First part: neutrino physics
  - The neutrino mass problem
  - The two-neutrino double beta decay
  - The neutrinoless double beta decay
  - Constraints on the neutrino mass and W_R mass from LHC-CMS and $0\nu\beta\beta$
- Second part: dark matter
  - Dark matter detection and the sensitivity of the modulations upon the coordinates of the laboratory
- Summary

Neutrino oscillations

- Building neutrino flavor states from mass eigenstates

$$\nu_l = \sum_i U_{li} \nu_i$$

- Energy of the state

$$E_i \approx pc + \frac{m_i^2 c^4}{2E}$$

- Probability of survival/dissapearance

$$P(\nu_l \to \nu_{l'}) = \mid \delta(l, l') + \sum_{i \neq p} U_{l'i} (e^{-i(E_i - E_p)t/\hbar} - 1) U_{li}{}^* \mid^2$$

$$\frac{(m_i{}^2 - m_p{}^2) c^4 L}{2E\hbar c} \geq 1$$

Neutrino oscillations

- The existence of neutrino oscillations was demonstrated by experiments conducted at SNO and Kamioka.
- The Swedish Academy rewarded the findings with two Nobel Prices : Koshiba, Davis and Marconi (2002) and Kajita and Mc Donald (2015)
- Some of the experiments which contributed (and still contribute) to the measurements of neutrino oscillation parameters are K2K, Double CHOOZ, Borexino, MINOS, T2K, Daya Bay.
- Like other underground labs ANDES will certainly be a good option for these large scale experiments.

SNO

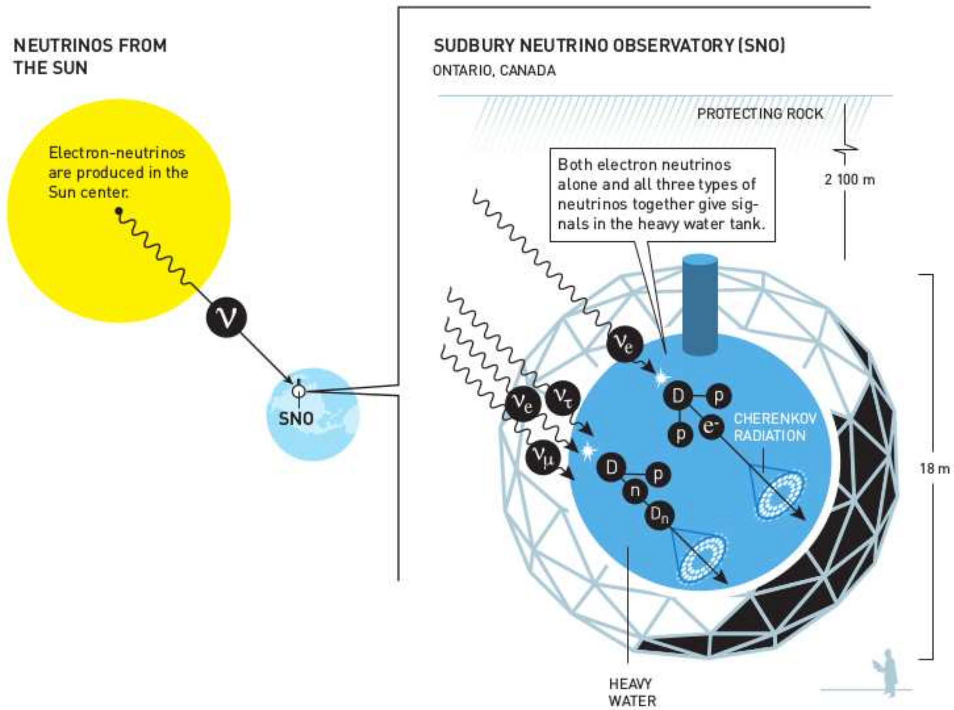


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

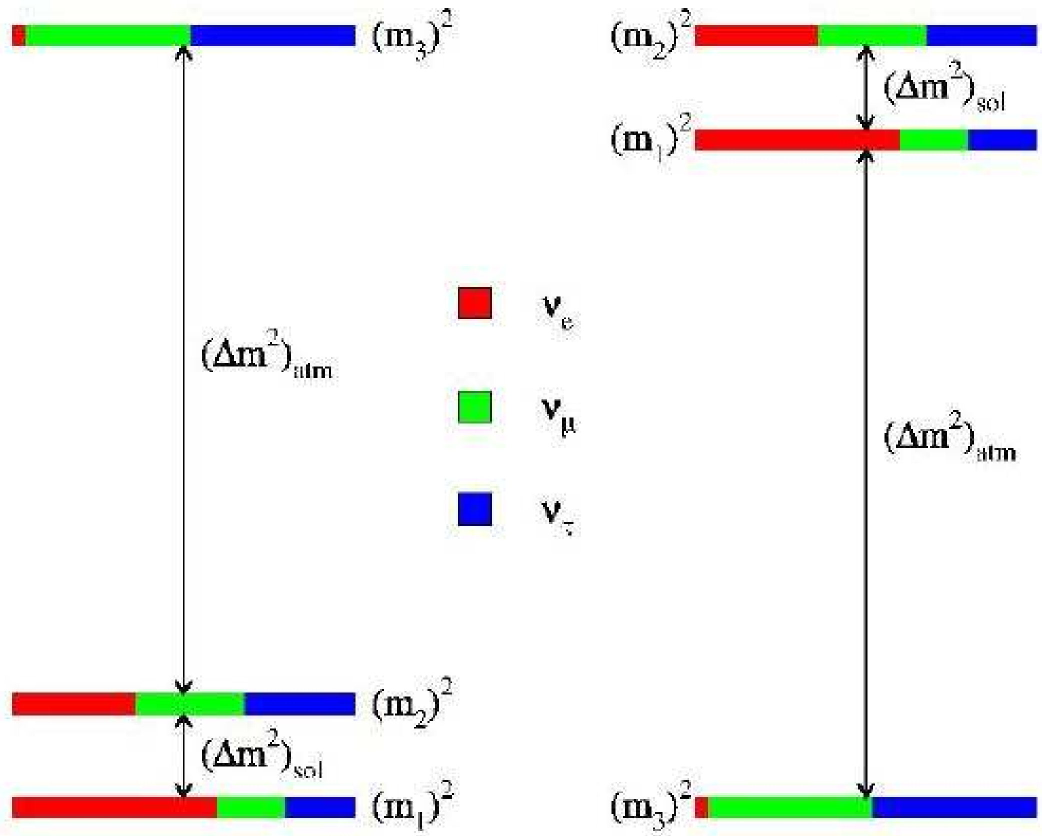
Mixing matrix U

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

$$\begin{aligned} U(Dirac) &= U \\ U(Majorana) &= U diag(e^{i\alpha_1}, e^{i\alpha_2}, 1) \end{aligned}$$

Majorana phases do not enter in the analysis of neutrino oscillations

Neutrino Mass Hierarchy



Best global fit

Parameter	Normal (H)	Inverted (H)
$\sin^2(\theta_{12})$	0.304(+0.013,-0.012)	0.304(+0.013,-0.012)
$\sin^2(\theta_{23})$	0.412(+0.012,-0.028)	0.579(+0.025,-0.032)
$\sin^2(\theta_{13})$	0.0218(+0.001,-0.001)	0.0219(+0.001,-0.001)
$\delta(^\circ)$	306(+39,-70)	254(+63,-62)
$\Delta m^2_S(10^{-5}eV^2)$	7.50(+0.19,-0.17)	7.50(+0.19,-0.17)
$\Delta m^2_{atm}(10^{-3}eV^2)$	2.457(+0.047,-0.047)	2.449(+0.048,-0.047)

Oscillation parameters from A. Marrone et al. Nucl.Phys. B908 (2016) 218-234.

Systematic measurements are needed to set more stringent constraints on these values

Sterile neutrinos

If we assume other mass eigenstates, the previous expressions will look like

- flavor eigenstates

$$\nu_\alpha = \sum_i^{3+ns} U_{\alpha i}\nu_i \quad \alpha = e, \mu, \tau, s_1, s_2..s_{ns}$$

- Probability of survival/dissapearance with sterile neutrinos

$$P(\nu_\alpha \to \nu_{\alpha'}) = \delta(\alpha,\alpha') - 4\sum_i \mid U_{\alpha i} \mid^2 (\delta(\alpha,\alpha') - \mid U_{\alpha i} \mid^2) \sin^2(\Delta_{pi})$$
$$+8\sum_{i\rangle k} ReU_{\alpha' i}U_{\alpha i}{}^* U_{\alpha' k}{}^* U_{\alpha k} \cos(\Delta_{pi} - \Delta_{pk}) \sin(\Delta_{pi}) \sin(\Delta_{pk})$$
$$+8\sum_{i\rangle k} ImU_{\alpha' i}U_{\alpha i}{}^* U_{\alpha' k}{}^* U_{\alpha k} \sin(\Delta_{pi}) \sin(\Delta_{pk})$$

Sterile neutrinos

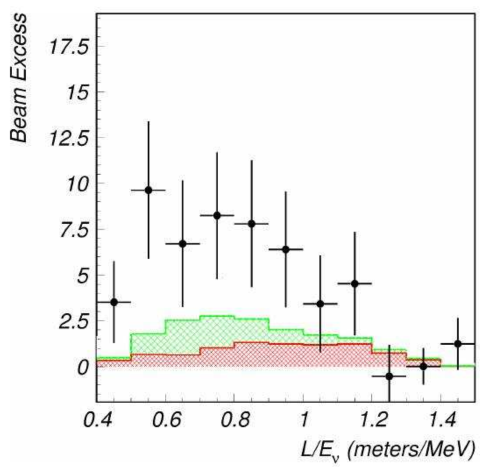
KARMEN, LNSD, MiniBooNe, Gallex, Reactor electron neutrino anomaly

light sterile neutrino: $\Delta m^2_{14} \approx 1.3 \;\; eV^2 \quad \sin^2(2\theta_{14}) \approx 0.04$

LSND

[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e \qquad 20\,\text{MeV} \leq E \leq 52.8\,\text{MeV}$



- Well-known and pure source of $\bar{\nu}_\mu$

$p + \text{target} \to \pi^+ \xrightarrow{\text{at rest}} \mu^+ + \nu_\mu$

$\mu^+ \xrightarrow[\text{at rest}]{} e^+ + \nu_e + \bar{\nu}_\mu$

$L \simeq 30\,\text{m}$

$\bar{\nu}_e + p \to n + e^+$

Well-known detection process of $\bar{\nu}_e$

- $\approx 3.8\sigma$ excess
- But signal not seen by KARMEN at $L \simeq 18\,\text{m}$ with the same method

[PRD 65 (2002) 112001]

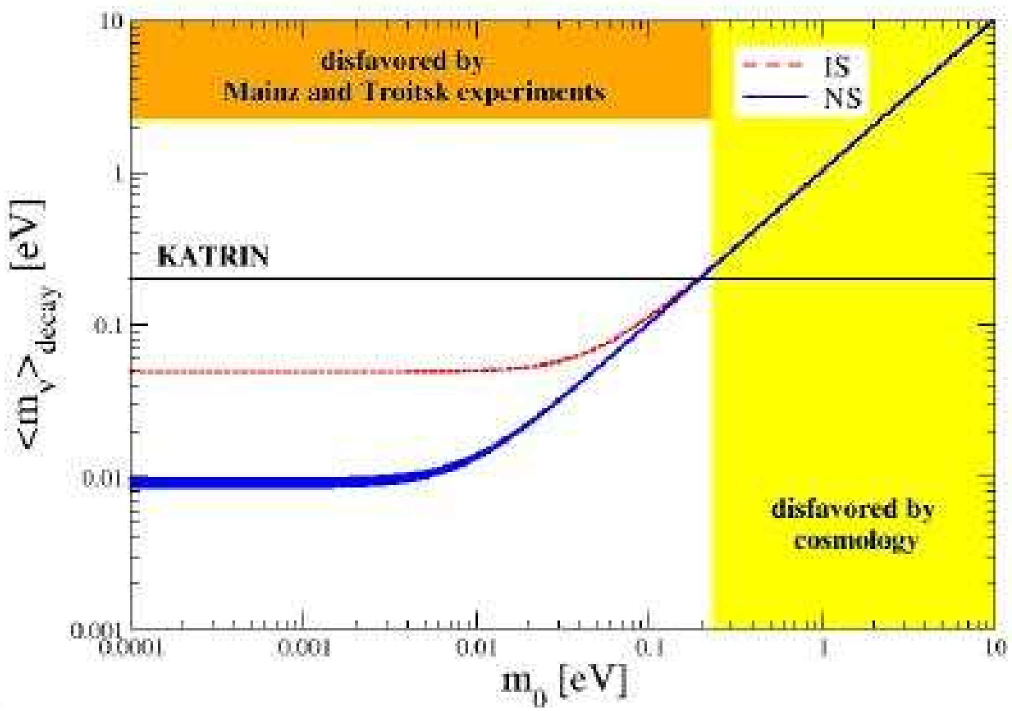
Sterile neutrinos

Effects of light sterile neutrinos should also be seen in:

- β Decay Experiments
  [Hannestad et al, JCAP 1102 (2011) 011, PRC 84 (2011) 045503; Formaggio, Barrett, PLB 706 (2011) 68; Esmaili, Peres, PRD 85 (2012) 117301; Gastaldo et al, JHEP 1606 (2016) 061]
- Neutrinoless Double-β Decay Experiments
  [Rodejohann et al, JHEP 1107 (2011) 091; Li, Liu, PLB 706 (2012) 406; Meroni et al, JHEP 1311 (2013) 146, PRD 90 (2014) 053002; Pascoli et al, PRD 90 (2014) 093005; CG, Zavanin, JHEP 1507 (2015) 171; Guzowski et al, PRD 92 (2015) 012002]
- Long-baseline Neutrino Oscillation Experiments
  [de Gouvea et al, PRD 91 (2015) 053005, PRD 92 (2015) 073012, arXiv:1605.09376; Palazzo et al, PRD 91 (2015) 073017, PLB 757 (2016) 142, JHEP 1602 (2016) 111, JHEP 1609 (2016) 016, arXiv:1605.04299; Gandhi et al, JHEP 1511 (2015) 039; Pant et al, NPB 909 (2016) 1079, Choubey, Pramanik, PLB 764 (2017) 135]
- Solar neutrinos
  [Dooling et al, PRD 61 (2000) 073011, Gonzalez-Garcia et al, PRD 62 (2000) 013005; Palazzo, PRD 83 (2011) 113013, PRD 85 (2012) 077301; Li et al, PRD 80 (2009) 113007, PRD 87, 113004 (2013), JHEP 1308 (2013) 056; Kopp et al, JHEP 1305 (2013) 050]
- Atmospheric neutrinos
  [Goswami, PRD 55 (1997) 2931; Bilenky et al, PRD 60 (1999) 073007; Maltoni et al, NPB 643 (2002) 321, PRD 67 (2003) 013011; Choubey, JHEP 0712 (2007) 014; Razzaque, Smirnov, JHEP 1107 (2011) 084, PRD 85 (2012) 093010; Gandhi, Ghoshal, PRD 86 (2012) 037301; Barger et al, PRD 85 (2012) 011302; Esmaili et al, JCAP 1211 (2012) 041, JCAP 1307 (2013) 048, JHEP 1312 (2013) 014; Rajpoot et al, EPJC 74 (2014) 2936; Lindner et al, JHEP 1601 (2016) 124; Behera et al, arXiv:1605.08607]
- Supernova neutrinos
  [Caldwell, Fuller, Qian, PRD 61 (2000) 123005; Peres, Smirnov, NPB 599 (2001); Sorel, Conrad, PRD 66 (2002) 033009; Tamborra et al, JCAP 1201 (2012) 013; Wu et al, PRD 89 (2014) 061303; Esmaili et al, PRD 90 (2014) 033013]
- Cosmic neutrinos
  [Cirelli et al, NPB 708 (2005) 215; Donini, Yasuda, arXiv:0806.3029; Barry et al, PRD 83 (2011) 113012]
- Indirect dark matter detection [Esmaili, Peres, JCAP 1205 (2012) 002]
- Cosmology [see: Wong, ARNPS 61 (2011) 69; Archidiacono et al, AHEP 2013 (2013) 191047]

List compiled by C. Giunti. See also M. Mosquera et al.IJMP E23 (2014) 1450080

Neutrino mass limits from tritium beta decay and Planck



Tritium beta decay: $m_\beta^2 = \sum_i \mid U_{ei} \mid^2 m_i^2$

Mainz and Troitsk results: $\rightarrow m_\beta$ < 2.3 eV (Mainz) 2.05 eV (Troitsk)

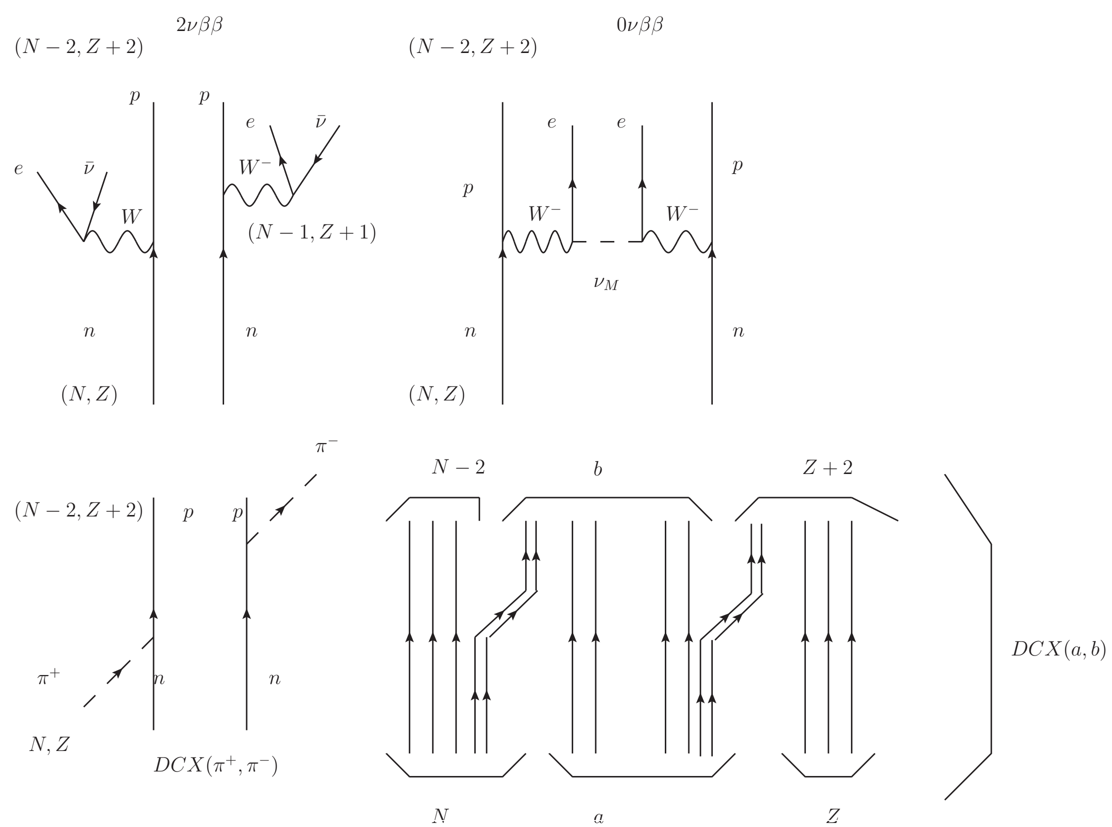
From Cosmology: $< m_\nu >= \sum_i m_i$ Planck result: $< m_\nu > < 0.23$ eV

Open questions

- Lepton number non-conservation
- Nature of the neutrino: Majorana or Dirac
- Light/heavy mass ratio in the seesaw mechanism
- Absolute mass scale
- Mass hierarchy
- CP violation in the lepton sector
- Minimal extension of the Standard Model ($SU(2)_R U(1)_{(B-L)}$)
- Limits on the couplings to the singlet-scalar Majoron

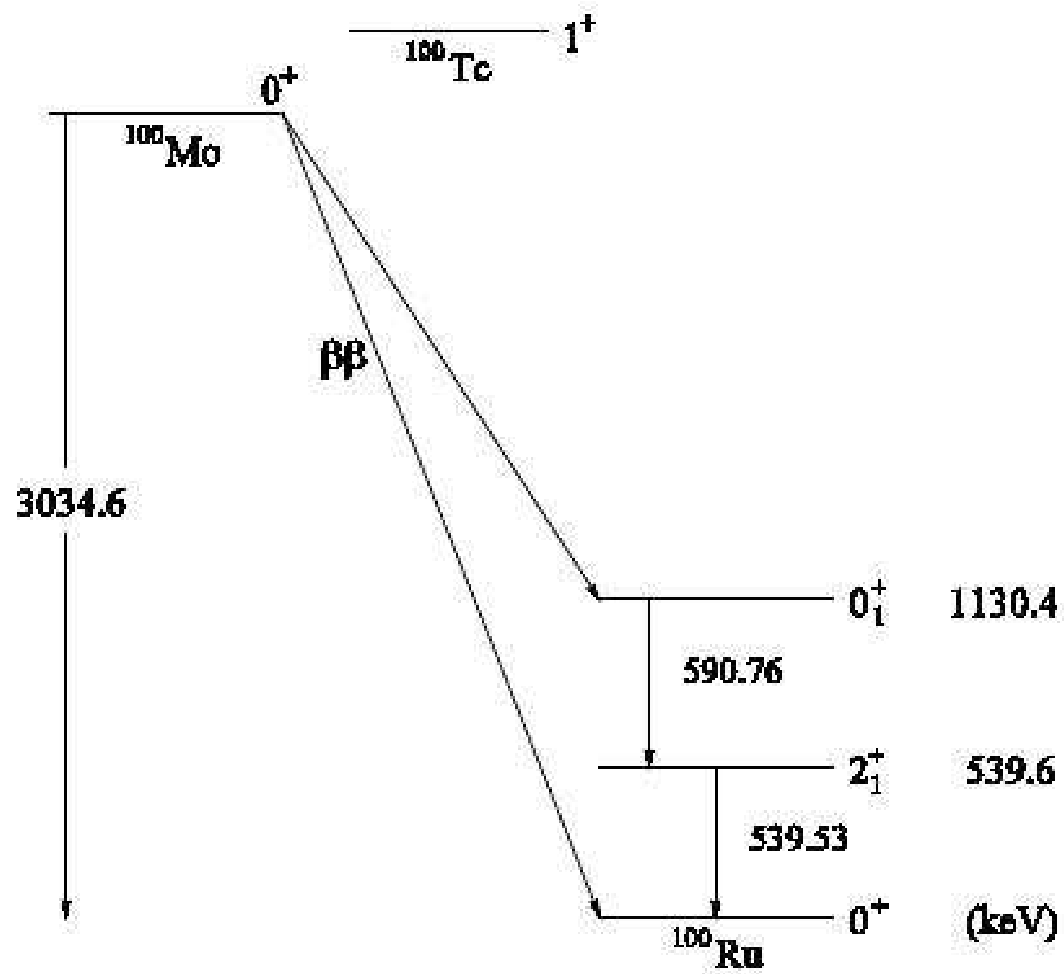
This questions may be answered in the near future by the measurements of the Nuclear Double Beta Decay

Nuclear Double beta decay



The NUMEN project (F. Cappuzzello et al.EPJ A 51 (2015) 145) LNS (Catania) offers a nice new possibility of testing both DBD and DCX observables)

Nuclear Double beta decay



About the $2\nu\beta\beta - decay$

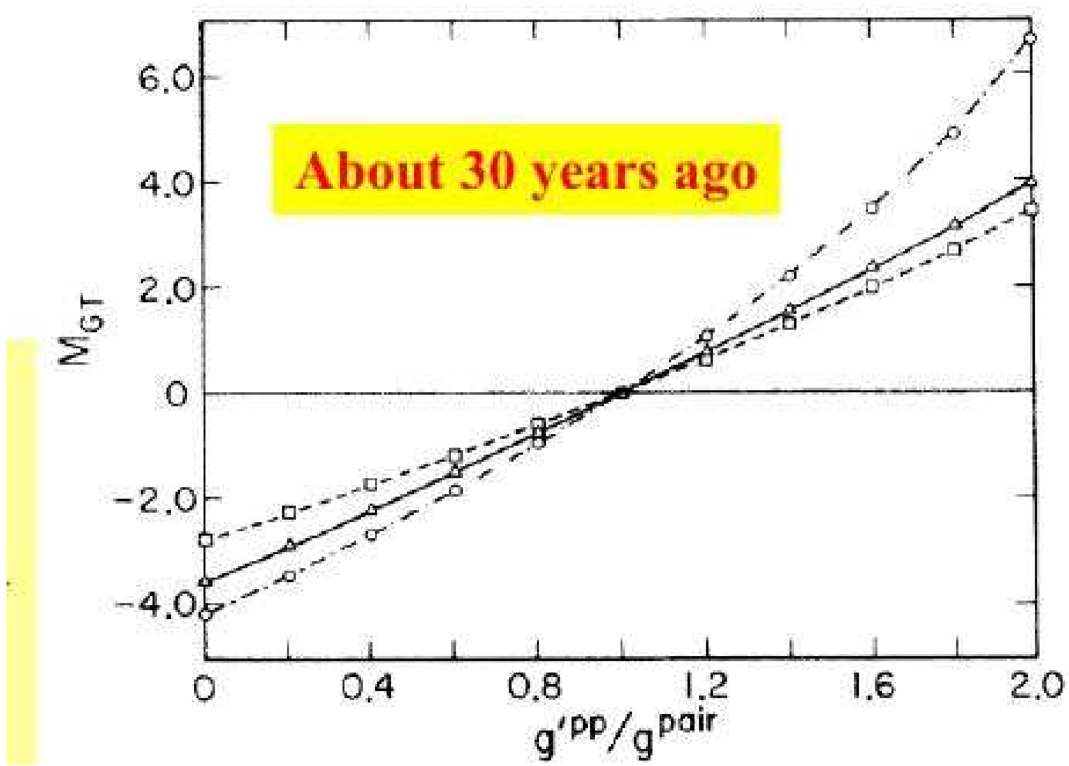
- It is a rare decay (N,Z) $\rightarrow$ (N-2,Z+2)+2 electrons
- It is allowed in the Standard Model since it conserves lepton number
- Does not tell us if the neutrinos are Dirac or Majorana particles
- It has been measured in various nuclei
- Its long half-life tell us that the nuclear physics component of it is strongly suppressed.
- The suppression is related to isospin and Pauli bloocking effects in nuclei.

Basic definitions ($2\nu\beta\beta - decays$)

$$\left[t_{1/2}^{(2\nu)}(0_i^+ \to J_f^+)\right]^{-1} = G^{(2\nu)}(J)\left|M^{(2\nu)}(J)\right|^2$$

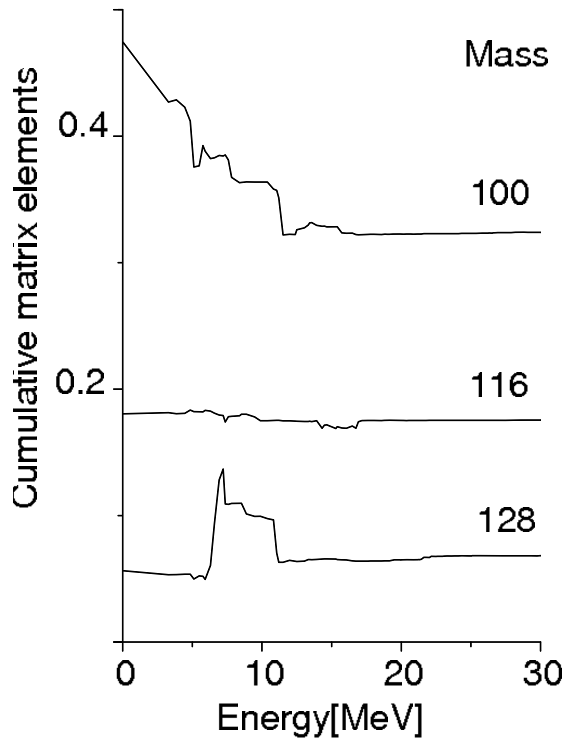
$$M^{(2\nu)}(J) = \sum_{k_1 k_2} \frac{M_{\mathrm{F}}^J(1_{k_1}^+)\langle 1_{k_1}^+|1_{k_2}^+\rangle M_{\mathrm{I}}(1_{k_2}^+)}{\left(\frac{1}{2}\Delta + \frac{1}{2}[E(1_{k_1}^+) + \tilde{E}(1_{k_1}^+)] - M_i c^2\right)/m_{\mathrm{e}}c^2} \, .$$

The peculiar behavior of $M^{(2\nu)}$



The matrix element is strongly suppressed due to particle-particle interactions in the nucleus.O.Civitarese, A.Faessler, T.Tomoda.PLB 194 (1987) 11.

The peculiar behavior of $M^{(2\nu)}$



It can be tested experimentally, by measuring the energy dependence of the strength distribution in (p,n) reactions

Experimental results

Recommended values for half-lives:

[A.S.B. Nucl. Phys. A 935 (2015) 52]

- ^{48}Ca - $(4.4^{+0.6}_{-0.5})\cdot 10^{19}$ y
- ^{76}Ge – $(1.65^{+0.14}_{-0.12})\cdot 10^{21}$ y
- ^{82}Se – $(0.92 \pm 0.07)\cdot 10^{20}$ y
- ^{96}Zr – $(2.3 \pm 0.2)\cdot 10^{19}$ y
- ^{100}Mo – $(7.1 \pm 0.4)\cdot 10^{18}$ y
- ^{100}Mo – ^{100}Ru (0^+_1) – $(6.7^{+0.5}_{-0.4})\cdot 10^{20}$ y
- ^{116}Cd – $(2.87 \pm 0.13)\cdot 10^{19}$ y
- ^{128}Te(geo) – $(2.0 \pm 0.3)\cdot 10^{24}$ y
- ^{130}Te – $(6.9 \pm 1.3)\cdot 10^{20}$ y
- ^{136}Xe – $(2.19 \pm 0.06)\cdot 10^{21}$ y
- ^{150}Nd - $(8.2 \pm 0.9)\cdot 10^{18}$ y
- ^{150}Nd – ^{150}Sm (0^+_1) – $(1.2^{+0.3}_{-0.2})\cdot 10^{20}$ y
- ^{238}U(rad) - $(2.0 \pm 0.6)\cdot 10^{21}$ y
- ECEC(2ν): ^{130}Ba(geo) - $\sim 10^{21}$ y

$0\nu\beta\beta$

$$
\begin{aligned}
t^{(0\nu)}_{1/2} &= g^{(0\nu)} \left| M^{(0\nu)\prime} \right|^{-2} \left(|\langle m_\nu \rangle| [\mathrm{eV}] \right)^{-2} \\
\langle m_\nu \rangle &= \sum_j \lambda_j^{\mathrm{CP}} m_j |U_{\mathrm{e}j}|^2 \, . \\
M^{(0\nu)\prime} &= \left(\frac{g_\mathrm{A}}{g_\mathrm{A}^\mathrm{b}} \right)^2 \left[M^{(0\nu)}_{\mathrm{GT}} - \left(\frac{g_\mathrm{V}}{g_\mathrm{A}} \right)^2 M^{(0\nu)}_{\mathrm{F}} + M^{(0\nu)}_{\mathrm{T}} \right] \\
M^{(0\nu)}_{\mathrm{F}} &= \sum_k (0^+_f || \sum_{mn} h_\mathrm{F}(r_{mn}, E_k) || 0^+_i) \, , \quad r_{mn} = |\mathbf{r}_m - \mathbf{r}_n| \, , \\
M^{(0\nu)}_{\mathrm{GT}} &= \sum_k (0^+_f || \sum_{mn} h_\mathrm{GT}(r_{mn}, E_k) (\boldsymbol{\sigma}_m \cdot \boldsymbol{\sigma}_n) || 0^+_i) \, ,
\end{aligned}
$$

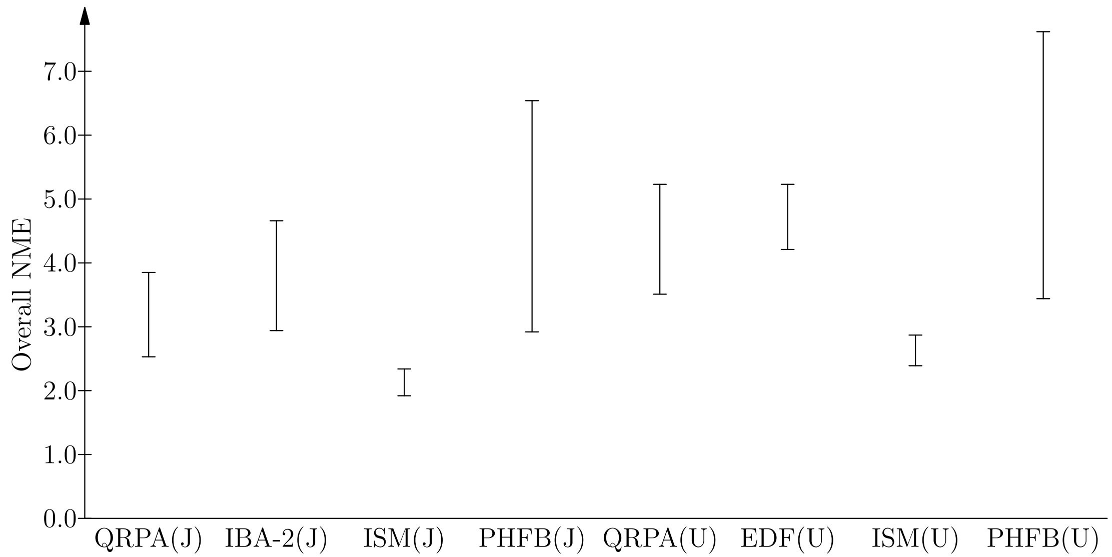
Calculated ground-state-to-ground-state NMEs for $g_{\mathrm{A}} = 1.25$. The last line summarizes the overall magnitude and the associated dispersion of the NMEs of the cited nuclear model (without ^{48}Ca included).

Transition	pnQRPA(U)	EDF(U)	ISM(U)	PHFB(U)
$^{48}\text{Ca} \to {}^{48}\text{Ti}$	-	2.37	0.85	-
$^{76}\text{Ge} \to {}^{76}\text{Se}$	5.18 ± 0.54	4.60	2.81	-
$^{82}\text{Se} \to {}^{82}\text{Kr}$	4.20 ± 0.35	4.22	2.64	-
$^{96}\text{Zr} \to {}^{96}\text{Mo}$	3.12	5.65	-	3.32 ± 0.12
$^{100}\text{Mo} \to {}^{100}\text{Ru}$	3.93	5.08	-	7.22 ± 0.50
$^{110}\text{Pd} \to {}^{110}\text{Cd}$	5.63 ± 0.49	-	-	8.23 ± 0.62
$^{116}\text{Cd} \to {}^{116}\text{Sn}$	3.93	4.72	-	-
$^{124}\text{Sn} \to {}^{124}\text{Te}$	4.57 ± 1.33	4.81	2.62	-
$^{128}\text{Te} \to {}^{128}\text{Xe}$	5.26 ± 0.40	4.11	2.88	4.22 ± 0.31
$^{130}\text{Te} \to {}^{130}\text{Xe}$	4.76 ± 0.41	5.13	2.65	4.66 ± 0.43
$^{136}\text{Xe} \to {}^{136}\text{Ba}$	3.16 ± 0.25	4.20	2.19	-
Overall NME	4.37 ± 0.86	4.72 ± 0.51	2.63 ± 0.24	5.53 ± 2.09

Refs. E, Caurier et al PRL 100(2008) 052503, M. Vaquero et al.PRL 111(2013) 142501, J. Barea et al.PRC 87 (2013) 014315, J. Suhonen and O. Civitarese NPA 924 (2014) 1, T. Rodriguez et al.PLB 719 (2013) 174, F. Simkovic et al PRC 77 (2008) 045503. J. Menendez et al. arXiv 1605:05059

$0\nu\beta\beta$ NME gs-gs transitions

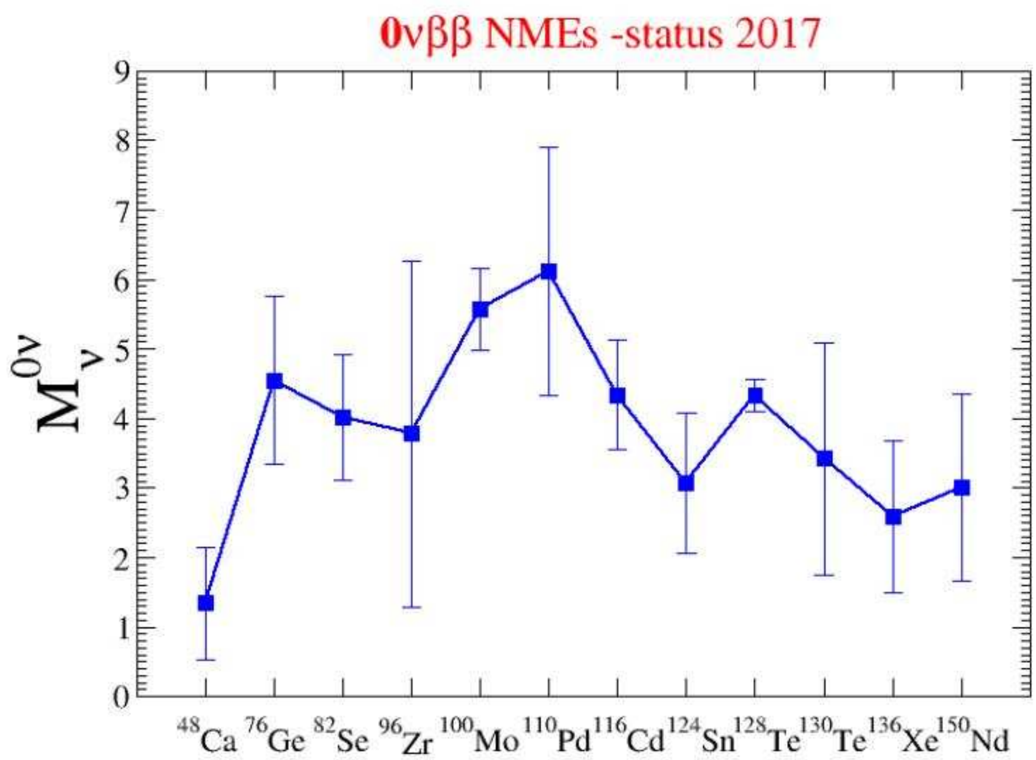
NME for different models



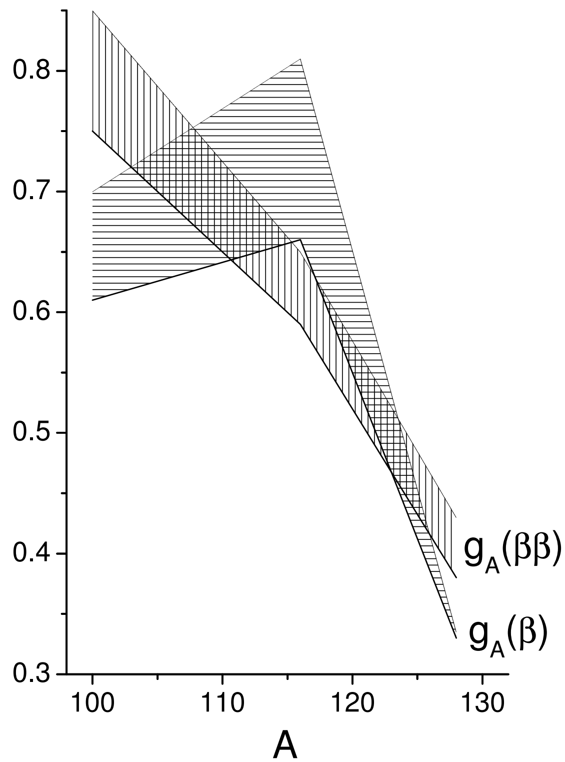
Ref.J. Suhonen and O. Civitarese Journal of Physics G 39 (2012)124005

Overall $0\nu\beta\beta$ NME gs-gs transitions

Ranges of values of the overall nuclear matrix elements for $0\nu\beta\beta$ ground state to ground state transitions

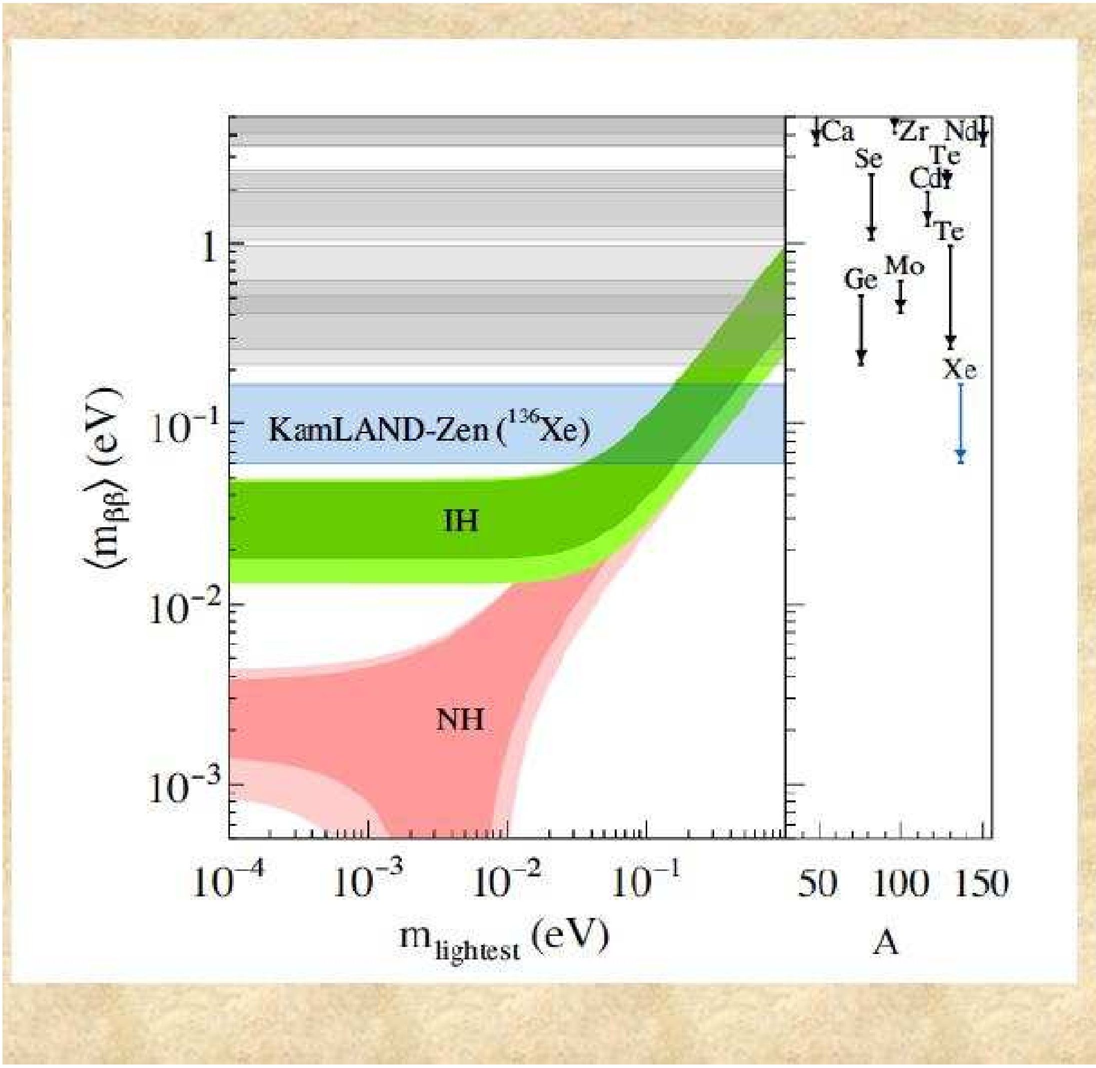


Effective values of g$_A$



The situation is unclear and it calls for a systematic study of media-effects upon single-beta decays, particularly for highly forbidden decays (F. Deppisch et al, PRC 94 (2016)055501, J. Suhonen, O.Civitarese NPA 924 (2014)1 and Phys. Lett. B 725, (2013) 153)

Exploring the mass hierarchy



RL currents from LHC and $0\nu\beta\beta$ decay

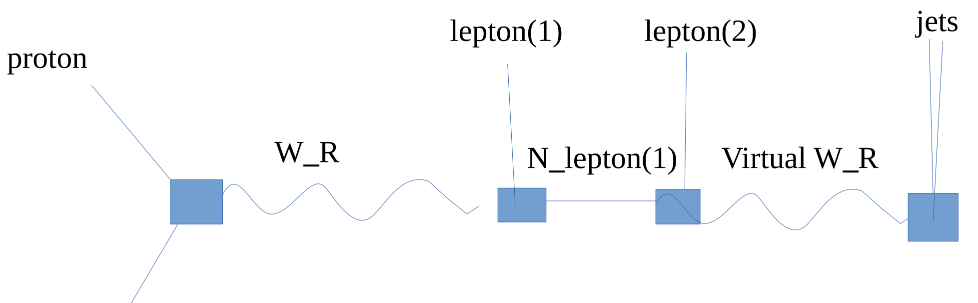
The left-right and right-right electroweak interactions (Hamiltonian density)

$$h_{\mathrm{W}} = \frac{G}{\sqrt{2}} \cos\theta_{\mathrm{CKM}} \left(j_{\mathrm{L}} J_{\mathrm{L}}^{\dagger} + \eta j_{\mathrm{R}} J_{\mathrm{L}}^{\dagger} + \lambda j_{\mathrm{R}} J_{\mathrm{R}}^{\dagger} \right) + \mathrm{h.c.}\ ,$$

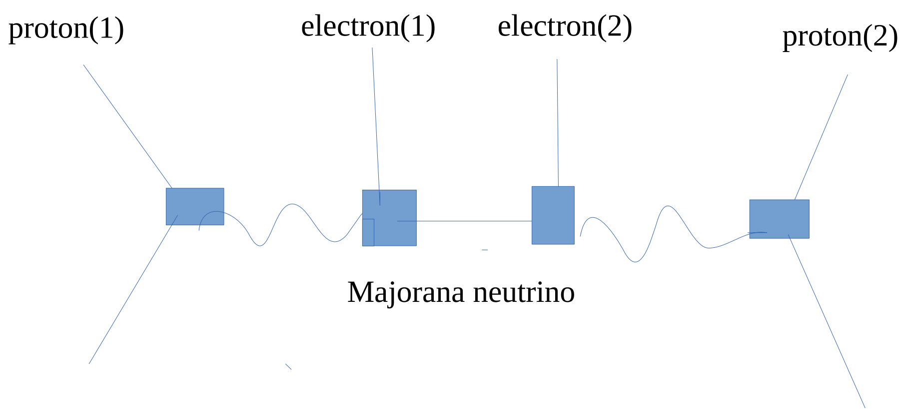
$$\begin{aligned} \mathrm{W}_{\mathrm{L}} &= \mathrm{W}_1 \cos\zeta - \mathrm{W}_2 \sin\zeta \\ \mathrm{W}_{\mathrm{R}} &= \mathrm{W}_1 \sin\zeta + \mathrm{W}_2 \cos\zeta \end{aligned}$$

$$\begin{aligned} \left[T_{1/2}^{(0\nu)} \right]^{-1} &= C_{mm}^{(0\nu)} \left(\frac{\langle m_\nu \rangle}{m_{\mathrm{e}}} \right)^2 + C_{m\lambda}^{(0\nu)} \langle \lambda \rangle \left(\frac{\langle m_\nu \rangle}{m_{\mathrm{e}}} \right) \\ &+ C_{m\eta}^{(0\nu)} \langle \eta \rangle \left(\frac{\langle m_\nu \rangle}{m_{\mathrm{e}}} \right) + C_{\lambda\lambda}^{(0\nu)} \langle \lambda \rangle^2 \\ &+ C_{\eta\eta}^{(0\nu)} \langle \eta \rangle^2 + C_{\lambda\eta}^{(0\nu)} \langle \eta \rangle \langle \lambda \rangle \end{aligned}$$

Same Physics



proton-proton to W_R to lepton+neutrino to two leptons+virtual W_R to two-leptons and quark-antiquark pairs.



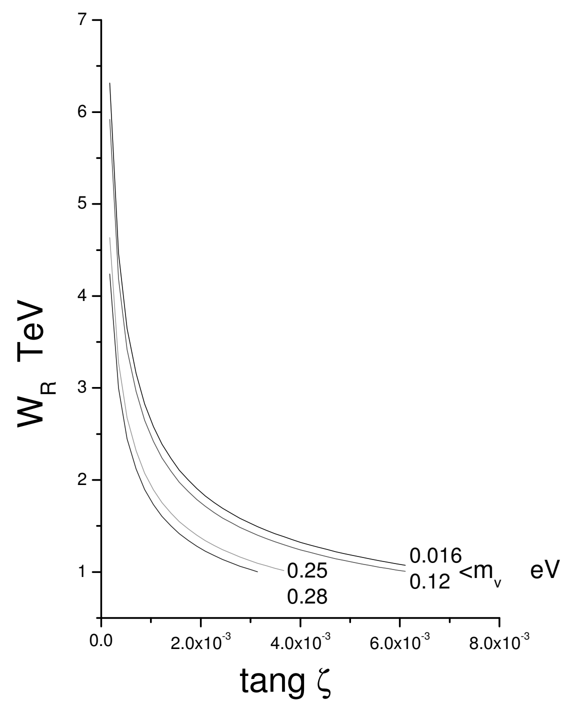
$$\frac{\mathrm{M_L}}{\mathrm{M_R}} = \sqrt{\frac{(\alpha - \tan\zeta)\tan\zeta}{(1+\alpha\tan\zeta)}}$$

$$\alpha = \langle\lambda\rangle/\langle\eta\rangle$$

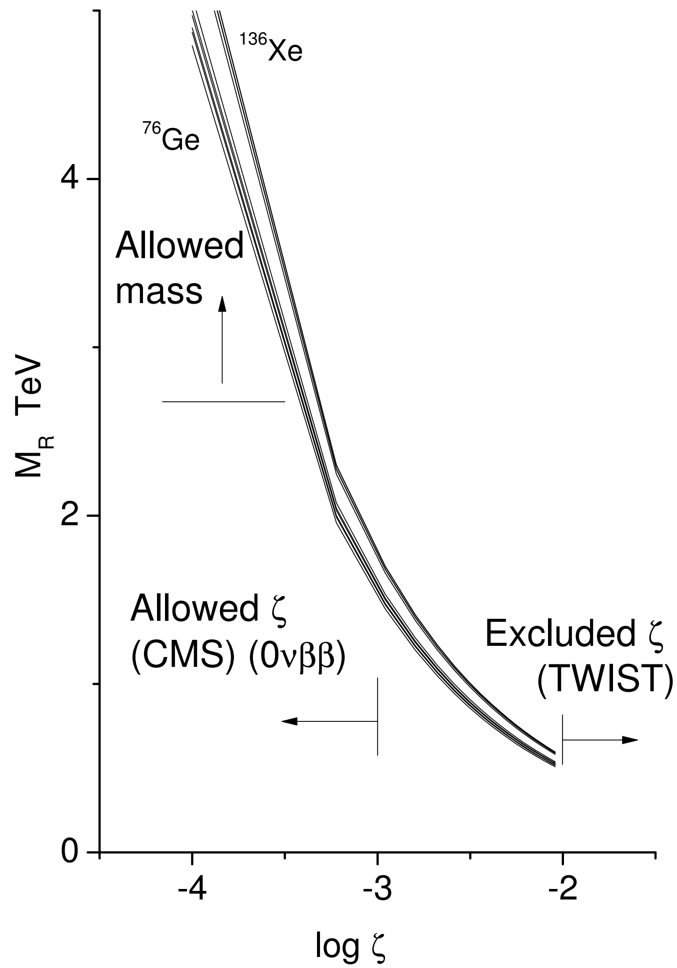
Case	$C_{mm}^{(0\nu)}$	$C_{m\lambda}^{(0\nu)}$	$C_{m\eta}^{(0\nu)}$	$C_{\lambda\lambda}^{(0\nu)}$	$C_{\eta\eta}^{(0\nu)}$	$C_{\lambda\eta}^{(0\nu)}$
^{76}Ge	$1.33(-13)$	$-6.77(-14)$	$2.58(-11)$	$1.76(-13)$	$4.88(-9)$	$-9.54(-14)$
^{136}Xe	$9.40(-13)$	$-6.02(-13)$	$1.49(-10)$	$2.18(-12)$	$2.92(-8)$	$-1.25(-12)$

Case	Half-life limit (10^{25}yr)	$\langle m_\nu\rangle_{\max}$ (eV)	$\langle\lambda\rangle_{\max}$	$\langle\eta\rangle_{\max}$	$\frac{\langle\lambda\rangle_{\max}}{\langle\eta\rangle_{\max}}$
^{76}Ge	2.5	0.325	$0.431(-6)$	$0.286(-8)$	$1.507(2)$
^{136}Xe	1.1	0.182	$0.197(-6)$	$0.176(-8)$	$1.119(2)$
	1.9	0.138	$0.150(-6)$	$0.134(-8)$	$1.119(2)$

Dependence on the neutrino mass



Mass of the right-handed boson



Compatibility of the results for W_R and the neutrino mass

- The results show that a mass $\mathrm{M_R}$ of the order of 3 TeV, for the right handed boson, and a mixing angle ζ of the order of 10^{-3}, are compatible with the measured $0\nu\beta\beta$ half-life limits and with the extracted upper limit of the average neutrino mass.
- These values may be ultimately explored at large by the $0\nu\beta\beta$ experiments, in conjunction with the ATLAS and CMS measurements.
- In the event of possitive evidences about the existence of neutrinoless double beta decay, the understanding of the mechanism (nucleonic or non-nucleonic) will depend upon the advances in the calculation of the nuclear matrix elements and of the related particle physics theory.

Present and future experiments: a short list

- Several double beta decay experiments have been taking data with quantities of enriched isotopes around or above 100 kg and plans are under way for tonne-scale experiments. These efforts revolve around several isotopes and use a broad array of detection techniques (KamLAND-ZEN, SNO+, EXO-200/nEXO, GERDA, CUORE, SuperNEMO, COBRA, Majorana) .
- Experiments of such scale make enormous demands on the progress and reliability of the nuclear matrix elements calculations.
- The research in the field of special modes of $\beta^-\beta^-$, such as $\beta^+\beta^+$ or 2νECEC starts to be more and more interesting from experimental and theoretical points of view (e.g. COBRA, TGV)
- Further development of the theory of such processes is crucial for continuation of the experimental activities in this field.

Current and planned $0\nu\beta\beta$ –experiments

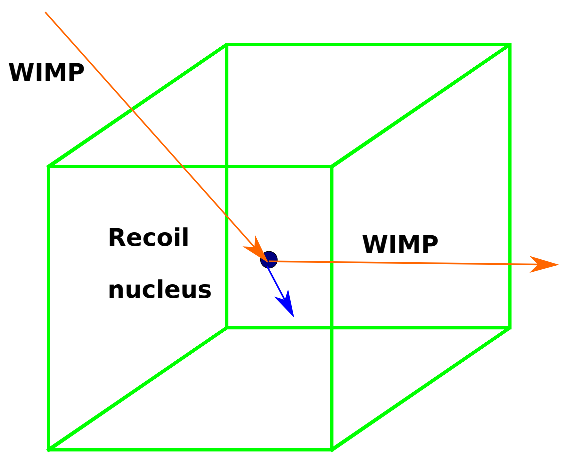
Experiment	Isotope	Lab
GERDA	^{76}Ge	LNGS [Italy]
CUORE	^{130}Te	LNGS [Italy]
Majorana	^{76}Ge	SURF [USA]
KamLAND-Zen	^{136}Xe	Kamioka [Japan]
EXO/nEXO	^{136}Xe	WIPP [USA]
CUPID - Lucifer	^{82}Se, ^{100}Mo	LNGS [Italy]
SNO+	^{130}Te	Sudbury [Canada]
SuperNEMO	^{82}Se (or others)	LSM [France]
CANDLES	^{48}Ca	Kamioka [Japan]
COBRA	^{116}Cd	LNGS [Italy]
DCBA	many	[Japan]
AMoRe	^{100}Mo	[Korea]
MOON	^{100}Mo	[Japan]
PandaX-III	^{136}Xe	[China]

About Dark Matter detection in ANDES

- The observations of Zwicky and Rubin and Ford (Helv. Phys. Acta 6, 110 (1933)) and V. C. Rubin and W. K. Ford, Jr., (Astrophys. J. 159, 379 (1970)) demonstrate the existence of dark matter.
- An electrically neutral WIMP is the most probable candidate for cold DM. The estimates of the mass of the WIMP vary from 1 GeV to 10 TeV.
- Interacts weakly and gravitationally with the ordinary matter but does not interact electromagnetically and/or strongly with other particles.
- It is assumed that the DM in the Galactic Halo is composed mostly by WIMP with velocities which obey Maxwell-Boltzmann distribution function.

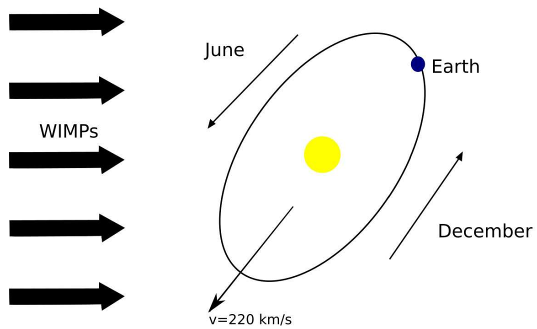
Detection methods

- Direct detection: Search the energy deposited in a detector of low threshold, when the WIMP is scattered by a nucleus. (DAMA, CRESST, CoGeNT, CDMS, XENON,SABRE, DM-ICE.)



- Indirect detection: Energetic neutrinos, from the nucleus of the Sun and Earth, produced by the annihilation of WIMPs. They may be detected with neutrino telescopes. (IceCube, ANTARES, HESS.

Modulation effect



- The flux of the dark matter should vary annually.
- The diurnal modulation of the amplitude depends on the location.
- Measurement of northern and southern laboratories will help to refine parameters of DM
- Extremely low signal-to-noise rates: direct-detection experiments need to be performed in low-background conditions.
- To confirm a positive signal data with the same type of detectors should be collected in different laboratories

Recoil rate

$$\frac{dR}{dE_{\mathrm{nr}}} = \frac{\sigma(q)}{2m_\chi \mu^2} \rho_\chi \eta(E_{\mathrm{nr}}, t)$$

This equation has three factors:

- $2m_\chi \mu^2 \rightarrow$ Dependence on the WIMP and nuclear masses.
- $\rho_\chi \eta(E_{\mathrm{nr}}, t) \rightarrow$ Dependence with the energy and time $\rightarrow$ Astrophysics.
- $\sigma(q) \rightarrow$ Dependence with the energy $\rightarrow$ Particle physics.

Astrophysics

$$\rho_\chi \eta(E_{\rm nr}, t) \quad \rightarrow \quad \rho_\chi \int d^3v \, v \frac{f(\vec{v}, t)}{v}$$

Standard Halo Model $\rightarrow$ Maxwell-Boltzmann

$$\begin{aligned} f(\vec{v}) &= \frac{1}{N(\pi v_0^2)^{\frac{3}{2}}} e^{-(\vec{v})^2/v_0^2}, \quad \text{para } |\vec{v}| < v_{\rm esc} \;, \\ N &= \mathrm{erf}[\frac{v_{\rm esc}}{v_0}] - \frac{2}{\sqrt{\pi}} \frac{v_{\rm esc}}{v_0} e^{-(\frac{v_{\rm esc}}{v_0})^2} \end{aligned}$$

- $v_{\rm esc}$ escape velocity of the galaxy (544 km/s)
- $v_0 = 234$ km/s

Laboratory velocity

$$\begin{aligned}
\vec{v}_{\rm lab} &= \vec{v}_{\odot}^{G} + \vec{v}_{\oplus}(t,t') \\
\vec{v}_{\odot}^{G} &= \vec{v}_{\odot} + \vec{v}_{\textsf{LSR}} \\
\vec{v}_{\oplus}(t,t') &= \vec{v}_{\rm rev}(t) + \vec{v}_{\rm rot}(t')
\end{aligned}$$

- $\vec{v}_{\odot}^{G} = (9, 12, 7)\ \mathrm{km/s}$ is the Sun's velocity with respect to the Galactic System
- $\vec{v}_{\rm LSR} = (0, 220 \pm 50, 0)\ \mathrm{km/s}$ is the velocity of the Local Standard of Rest, with vector-components relative to the Galactic System of coordinates.
- $\vec{v}_{\oplus}(t,t')$ is the sum of the Earth's orbital and rotational velocities, t is expressed in sidereal days, t' in sidereal hours.
- $v_{\rm rev}^{\oplus} = 29.8\,\mathrm{km/s}$
- The orbital (annual)-velocity is

$$\vec{v}_{\rm rev}(t) = v_{\rm rev}^{\oplus}\left[\varepsilon_1^{\rm eclip}\sin(w_{\rm rev}(t-t_{\rm eq})) - \varepsilon_2^{\rm eclip}\cos(w_{\rm rev}(t-t_{\rm eq}))\right]$$

- $w_{\rm rev}$ is the orbital frequency, $t_{\rm eq}$ is the sidereal time of March-equinox.

Coordinates of the Underground Labs.

Laboratory	ϕ_0	λ_0
LNGS	$42°27'$ N	$13°34'$ E
SUL	$47°48'$ N	$92°14'$ W
ANDES	$30°15'$ S	$69°53'$ W
SUPL	$37°3'$ S	$142°46'$ E
South Pole	$89°59'$ S	$139°16'$ E

Annual and diurnal modulation rates

We can write the recoil rate in terms of the annual and diurnal modulation rates as

$$\frac{dR}{dE_{\rm nr}} \simeq S_0 + S_{\rm m}(E_{\rm nr})\cos(w(t-\tilde{t_0})) + S_{\rm d}(E_{\rm nr})\cos(w_{\rm rot}(t'-t_{\rm d})).$$

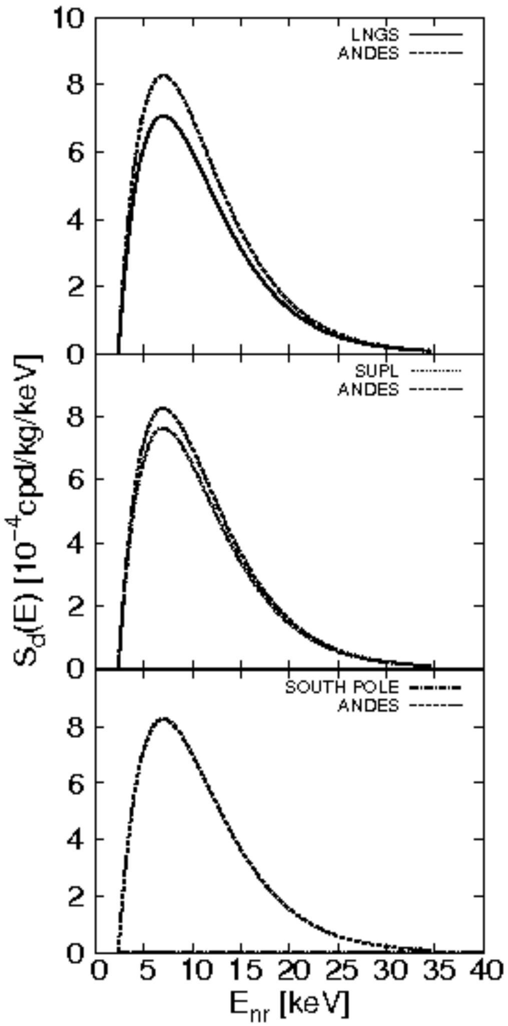
<u>Annual modulation</u>:

$$S_{\rm m}(E_{\rm nr}) = \frac{\rho_\chi}{m_\chi}\frac{\sigma_0}{2\mu^2}F^2(q)v_{\rm rev}^{\oplus}A_{\rm m}\left.\frac{\partial\eta}{\partial v_{\rm lab}}\right|_{\tilde{t_0};t_{\rm d}}$$

<u>Diurnal modulation</u>:

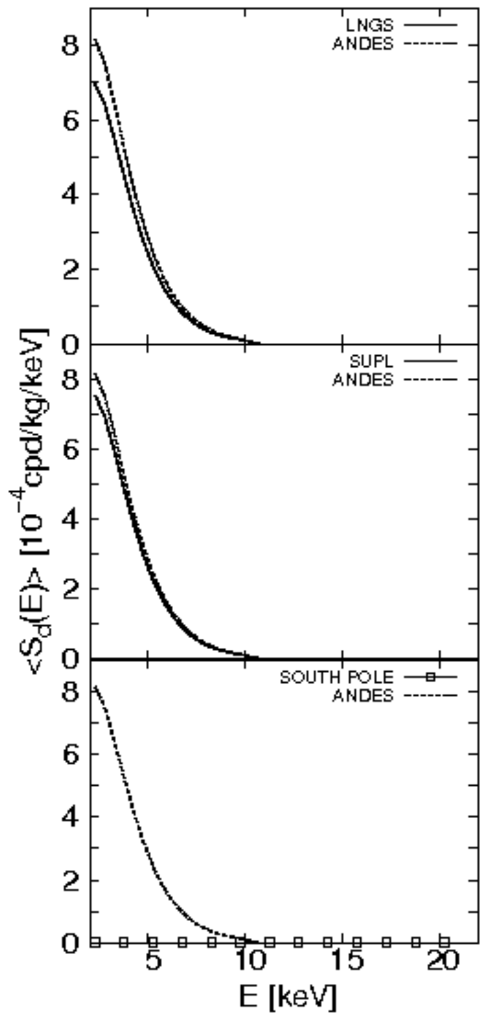
$$S_{\rm d}(E_{\rm nr}) = \frac{\rho_\chi}{m_\chi}\frac{\sigma_0}{2\mu^2}F^2(q)v_{\rm rot}^{\oplus}A_{\rm d}\left.\frac{\partial\eta}{\partial v_{\rm lab}}\right|_{\tilde{t_0};t_{\rm d}}$$

Results: Na Detector's



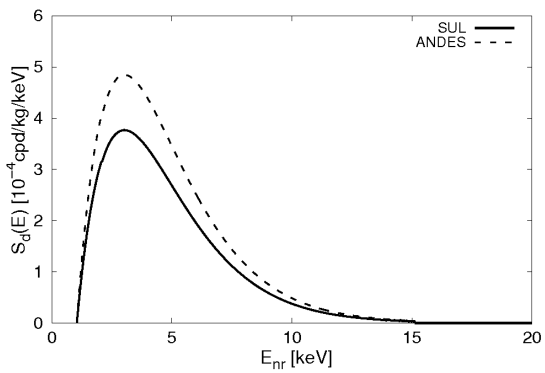
Diurnal modulation amplitude as a function of the recoil energy, in units of cpd Kg^{-1}

Results: Na Detector’s



Average modulation amplitude as a function of the energy

Results: Ge Detector's



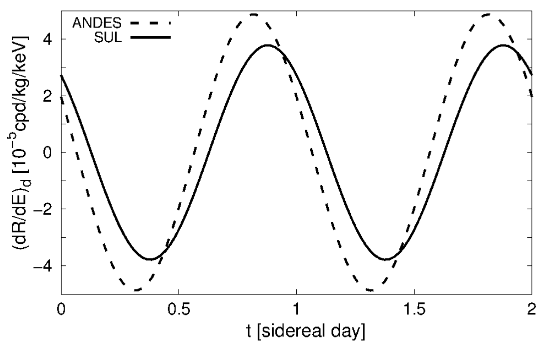
Diurnal modulation amplitude as a function of the recoil energy, in units of cpd Kg^{-1} keV^{-1}.

Parameters:

- $\sigma_s^{\mathrm{SI}} = 2.0 \;\; 10^{-15}\mathrm{fm}^2$
- m_χ=10 GeV

C. E. Aalseth et al., ArXiv e-prints 1401.6234 (2014). The results for ANDES are taken from O. Civitarese, K. J. Fushimi, and M. E. Mosquera Jour.Phys. G (2016) 43 125201

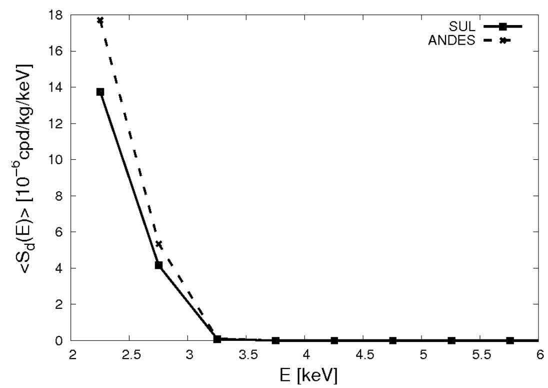
Results: Ge Detector's



Diurnal modulation as a function of the sidereal time (in days) for an energy E = 2 keV .

- Shift between the calculated signals.
- The amplitude of the modulation is larger for the case of the ANDES laboratory.

Results: Ge Detector's



At the maximum, the results for ANDES are larger by a factor of the order of 1.29, respect to the results of SUL.

$$< S_{\rm d} >= \frac{1}{E_2 - E_1} \int_{E_1}^{E_2} S_{\rm d}(E_{\rm nr}) dE_{\rm nr}$$

Summary

- The amplitudes for modulations and recoil-rates, for two different detectors, NaI and Ge, and for the best-fit values of the WIMP mass and cross section, depend on the location of the detector on the Earth.
- The value of the average diurnal modulation, for NaI and Ge detectors placed in ANDES, is larger than the values of detectors placed in other labs.
- The enhancement of the signals correlates with the ratio of the latitude’s cosine of the sites.

The research in ANDES: a view

- The neutrino puzzle is not yet solved and future experiments in ANDES may play an important role in the quest for the solutions.
- ANDES may host modulus of extended detectors, like Majorana and Super-Nemo, and in due time build its own Double Beta Decay Experiment. A good candidate will be the decay of ^{128,130}Te
- More refined measurements of the neutrino oscillation parameters in ANDES may be planned in view of the space available for large detectors.
- DAMA like experiments in ANDES may confirm the findings of experiments performed in the northern hemisphere. The location of ANDES is very convenient for it.
- The activities around ANDES, both in theory and experiments, will certainly give a great impulse to physics, astrophysics and detector-technology.
- ANDES should not be a repository but a generator of new and challenging experiments.

Acknowledgements

- The results presented in the talk have been obtained in collaboration with J.Suhonen (Jyvaskyla) (DBD) , Kai Zuber (Dressden) (CMS-LHC), D. Bes (CNEA, Bs.As) (Te decay), K. Fushimi, M. Saez and M. Mosquera (UNLP) (Sterile neutrinos).
- To Alejandro Ceccatto (President of the CONICET) for his continuous interest in the ANDES project.

Thanks for your attention