RECFTA-meeting, Košice, May 27, 2011

Neutrino Physics in Slovakia

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Participants (experiment): P. Povinec, K. Holý, I. Sýkora, J. Staníček, M. Pikna
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R. Hodák (PhD), P. Valko (PhD)

Experiments: $0\nu\beta\beta$ (NEMO3, SuperNEMO – 2004/2010
TGV-2002, COBRA-2005)
$0\nu\varepsilon\varepsilon$ (on ^{74}Se in Bratislava, proposal for LSM Modane) - 2009
charge-changing reaction at RCNP Osaka - 2008
beta beams at ISOLDE -2009

OUTLINE

- ***$0\nu\beta\beta$-decay (theory+experiment)***
- ***$0\nu\varepsilon\varepsilon$-decay (theory+experiment)***
- ***$2\nu\beta\beta$-decay and bosonic neutrinos (theory)***
- ***Measuring of mass of ν with β-decay of ^{3}H, ^{187}Re ... (theory)***
- ***Towards the detection of relic neutrinos (theory)***
- ***Beta beams (experiment)***
- ***Grants and problems***

Neutrinoless Double-Beta Decay
(theory and experiment)

Comenius University group in collaboration with
- NEMO3, SuperNEMO Coll.
- Tuebingen, CALTECH, Ioannina, Valparaiso, Dubna, ...

Study of the 0νββ-decay
is one of the highest priority issues
in particle and nuclear physics

What is the nature of neutrinos?

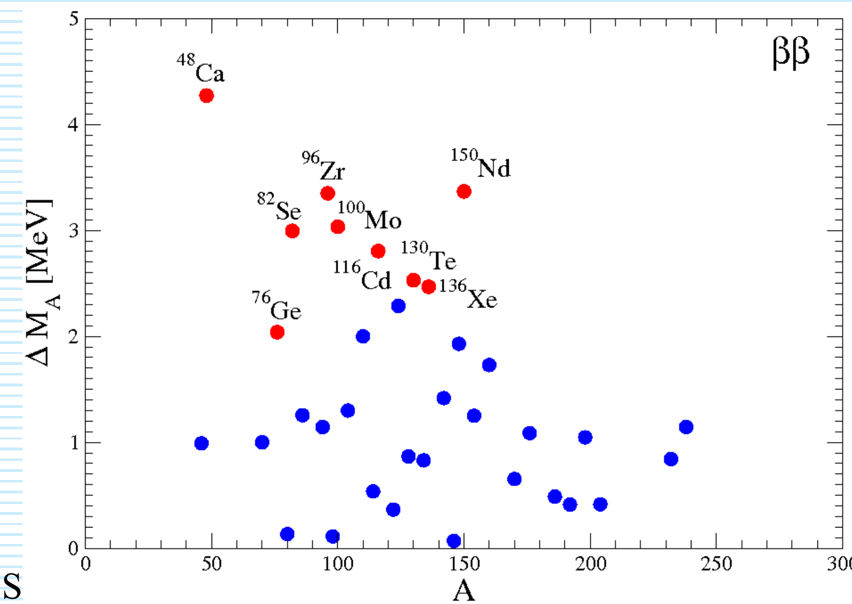
ν $\Rightarrow$

GUT's

Only the 0νββ-decay can answer this fundamental question
(plus absolute mass scale of ν's, hierarchy, CP violation)

The 0νββ-decay is a particle, nuclear and atomic physics problem

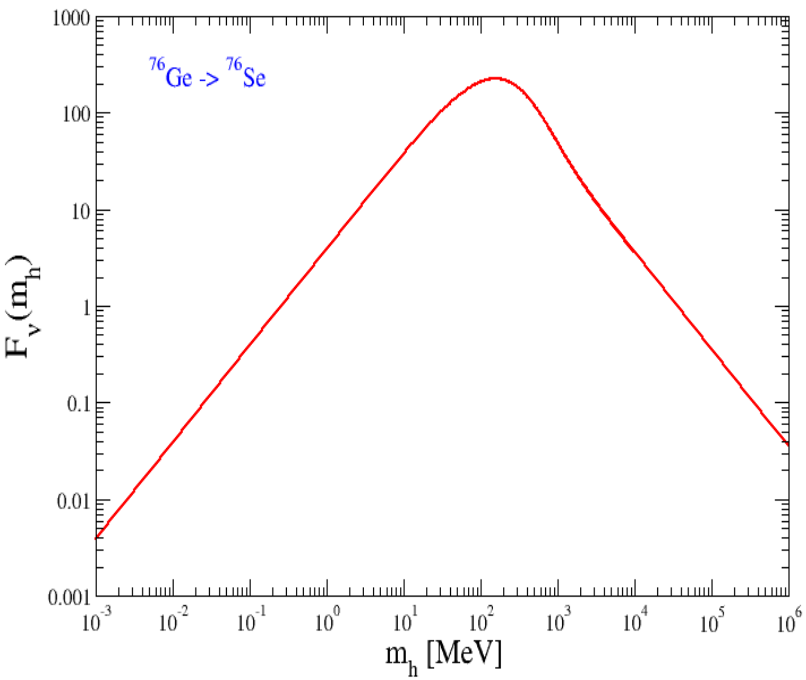
Two basic categories are
long-range
(exchange of light Majorana ν)
and ***short-range***
(exchange of heavy ν, squarks, gluinos …)
contributions to the 0νββ-decay

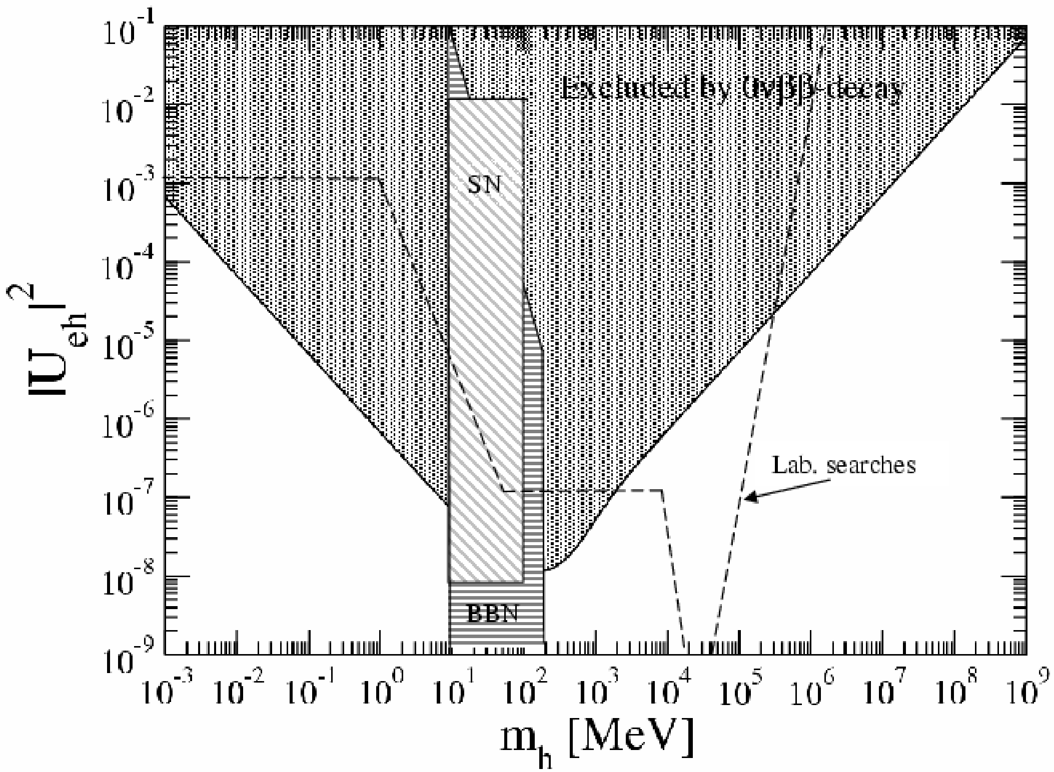


Sterile neutrino in 0νββ-decay

Matrix element depends on ν-mass

$$[T^{0\nu}_{1/2}]^{-1} = G_{01} \left| \frac{\langle m_\nu \rangle_{ee}}{m_e} M^{light}_\nu + U^2_{eh} \frac{m_h}{m_e} M^{0\nu}(m_h) \right|^2 .$$





$$F_\nu(m_h) = \frac{m_h}{m_e} M^{0\nu}(m_h)$$

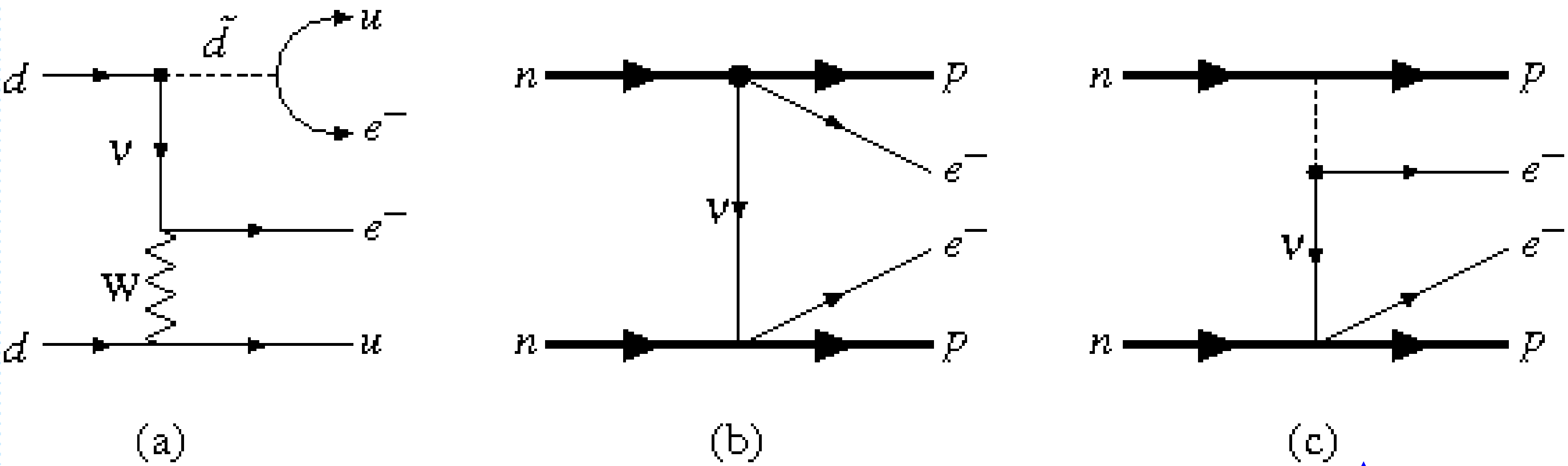
$$|U_{eh}|^2 \leq \frac{1}{|F_\nu(m_h)|} \frac{1}{\sqrt{T^{0\nu-exp}_{1/2} G_{01}}},$$

Beneš, Faesler, F.Š., Kovalenko, PRD 71 (2005) 077901

Squark mixing SUSY mechanism

Mixing between scalar superpartners of the left- and right-handed fermions

$$M^2_{\tilde{d}^k} = \begin{pmatrix} m^2_{\tilde{d}^k_L} + m^2_{d^k} - \frac{1}{6}(2m^2_W + m^2_Z)\cos 2\beta & -m_{d^k}((\mathbf{A}_D)_{kk} + \mu \tan\beta) \\ -m_{d^k}((\mathbf{A}_D)_{kk} + \mu\tan\beta) & m^2_{\tilde{d}^k_R} + m^2_{d^k} + \frac{1}{3}(m^2_W - m^2_Z)\cos 2\beta \end{pmatrix}$$



Hirsch, Klapdor-Kleingrothaus, Kovalenko PLB 372 (1996) 181

A. Faessler, Th. Gutsche, S. Kovalenko, F.Š., PRD 77 (2008) 113012

Co-existence of 2, 3 or more mechanisms of the 0νββ-decay

It is well-known that there exist many mechanisms that may contribute to the 0νββ. Let consider 3 mechanisms: i) light ν-mass mechanism, ii) heavy ν-mass mechanism, iii) R-parity breaking SUSY mechanism with gluino exchange and CP conservation

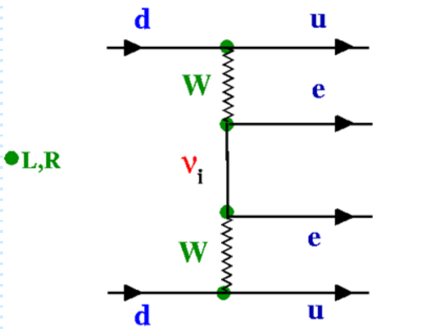
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(E_0, Z)\left|\frac{m_{\beta\beta}}{m_e} M^{0\nu}_{\nu} + \eta^L_N M^{0\nu}_N + \eta_{\lambda'_{111}} M^{0\nu}_{\lambda'_{111}} \dots\right|^2$$

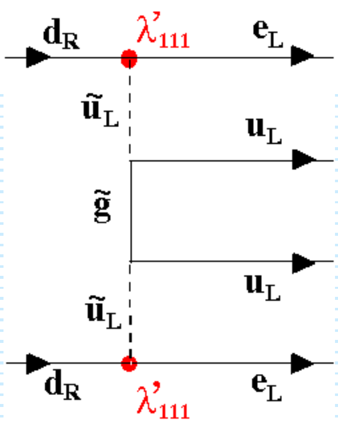
$$m_{\beta\beta} = \sum_k \left(U^L_{ek}\right)^2 \xi_k m_k$$

$$\eta^L_N = \sum_{k=4}^{6} |U^L{}_{ek}|^2 \, \xi'_k \, \frac{m_p}{M_k},$$

$$\eta^R_N = \sum_{k=4}^{6} |U^R{}_{ek}|^2 \, \xi'_k \, \frac{m_p}{M_k}.$$

$$\eta_{\lambda'_{111}} = \frac{\pi\alpha_s}{6} \frac{\lambda'^2_{111}}{G_F^2 m^4_{\tilde{d}_R}} \frac{m_p}{m_{\tilde{g}}} \left[1 + \left(\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}}\right)^2\right]^2 .$$





Claim of evidence: $T^{0\nu}_{1/2}(^{76}Ge) = 2.23^{+0.44}_{-0.31} \times 10^{25}$ y

$T^{0\nu}_{1/2}(^{100}\mathrm{Mo}) \geq 5.8 \times 10^{23}$ y

$T^{0\nu}_{1/2}(^{130}\mathrm{Te}) \geq 3.0 \times 10^{24}$ y

Bilenky, Faessler, Potzel, F.Š, arXiv: 1104.1952[hep-ph]
Faessler, Fogli, Lisi, Rotunno, F.Š., arXiv: 1104.3716[hep-ph]
Faessler, Meroni, Petcov, F.Š., Vergados, arXiv: 1103.2334, accepted in PRD
F.Š., Vergados, Faessler, PRD 82, 113015 (2010)

NEMO 3

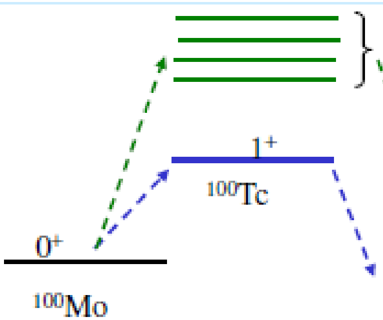
Fréjus Underground Laboratory: 4800 m.w.e.

^{100}Mo (6.914 kg) $T_{1/2}^{0\nu\beta\beta} > 4.6\ 10^{23}$ years

$Q_{\beta\beta} = 3034$ keV $|m_{\beta\beta}| < 2.7$ eV

^{82}Se (0.932 kg) $T_{1/2}^{0\nu\beta\beta} > 1.0\ 10^{23}$ y

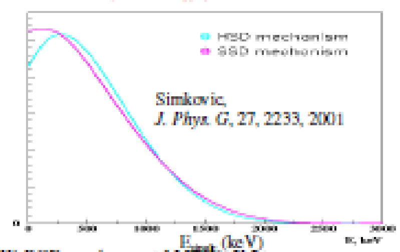
$Q_{\beta\beta} = 2995$ keV $|m_{\beta\beta}| < 4.1$ eV

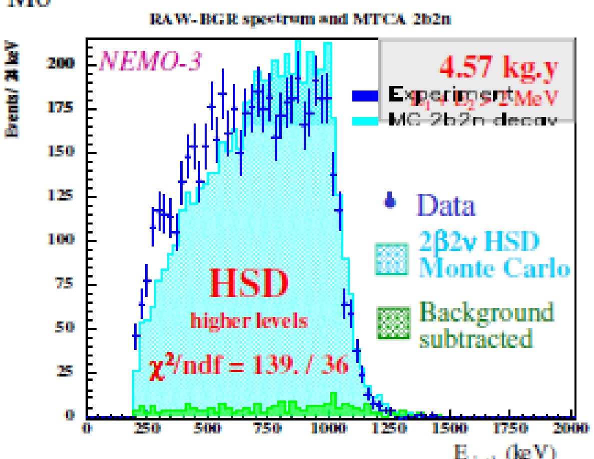


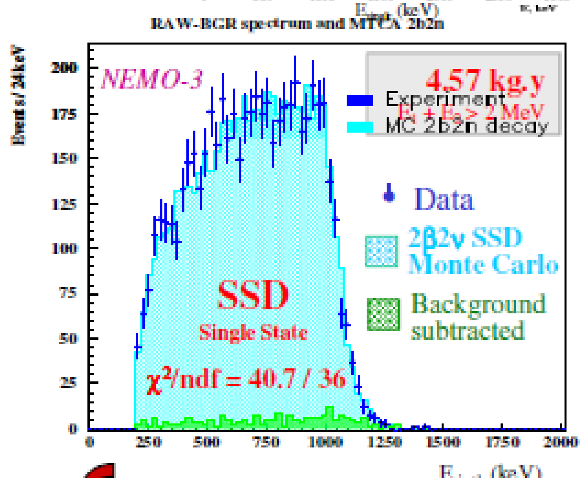
HSD, higher levels contribute to the decay

SSD, 1^+ level dominates in the decay (Abad et al., 1984, *Ann. Fis.* A 80, 9)

Single electron spectrum different between SSD and HSD







NEMO3 experiment

$2\nu\beta\beta$-decay ~10^6 events

HSD: $T_{1/2} = 8.61 \pm 0.02\ (stat) \pm 0.60\ (syst) \times 10^{18}$ y

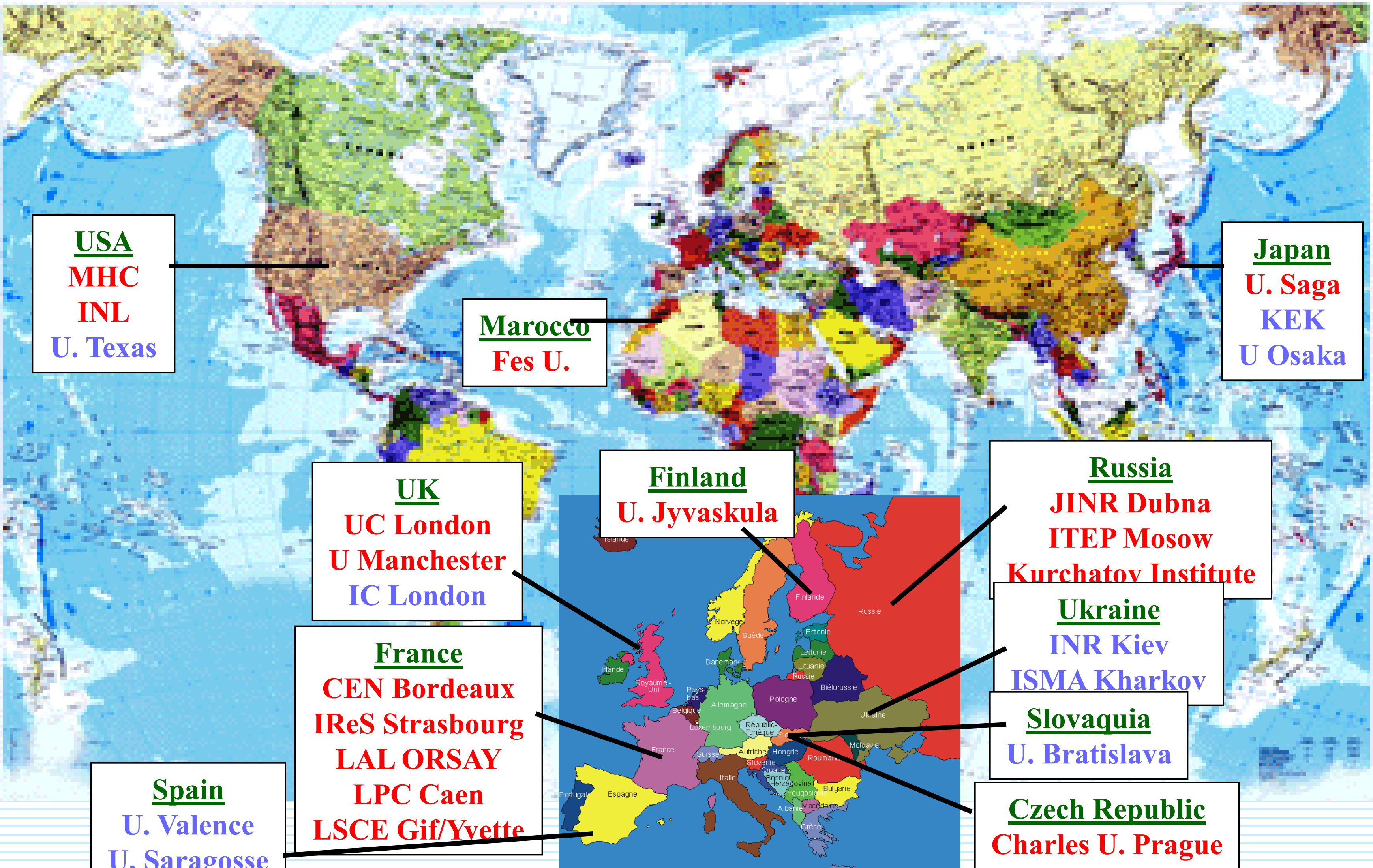
SSD: $T_{1/2} = 7.72 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ y

^{100}Mo $2\beta2\nu$ single energy distribution in favour of Single State Dominant (SSD) decay

SuperNEMO project

Objective: to built a detector sensitive to 2 10^{26} y

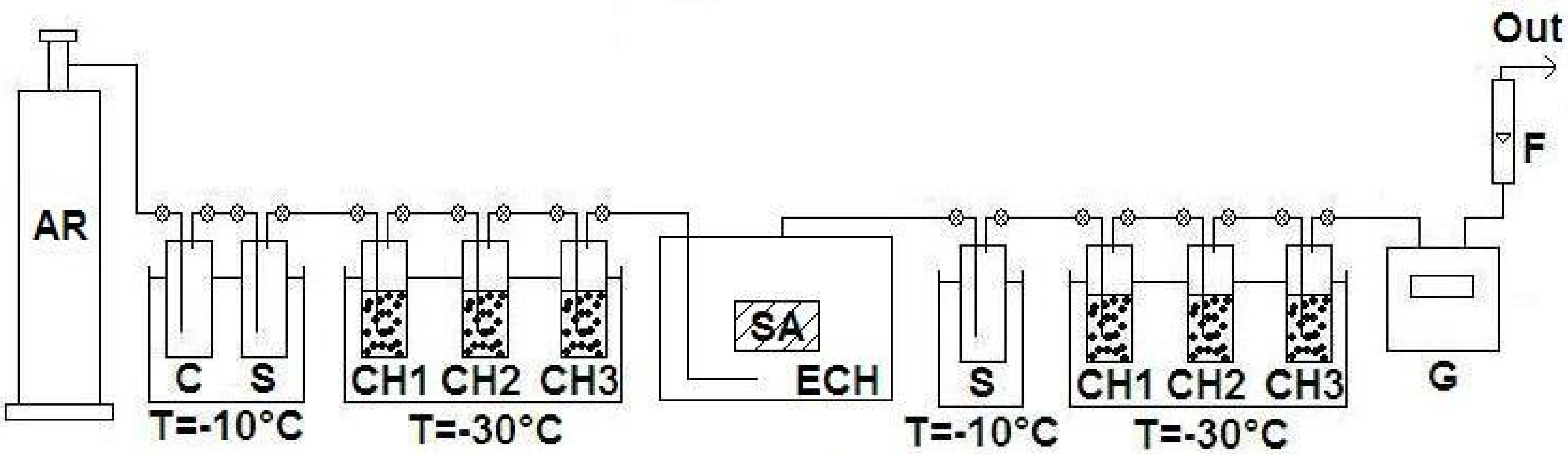
Collaboration NEMO + new labs ~ 70 physicists, 11 countries, 27 laboratories



Emanation of ^{222}Rn from the Hamamatsu photomultiplier R6594

(Karol Holý group)

Scheme of the measurement



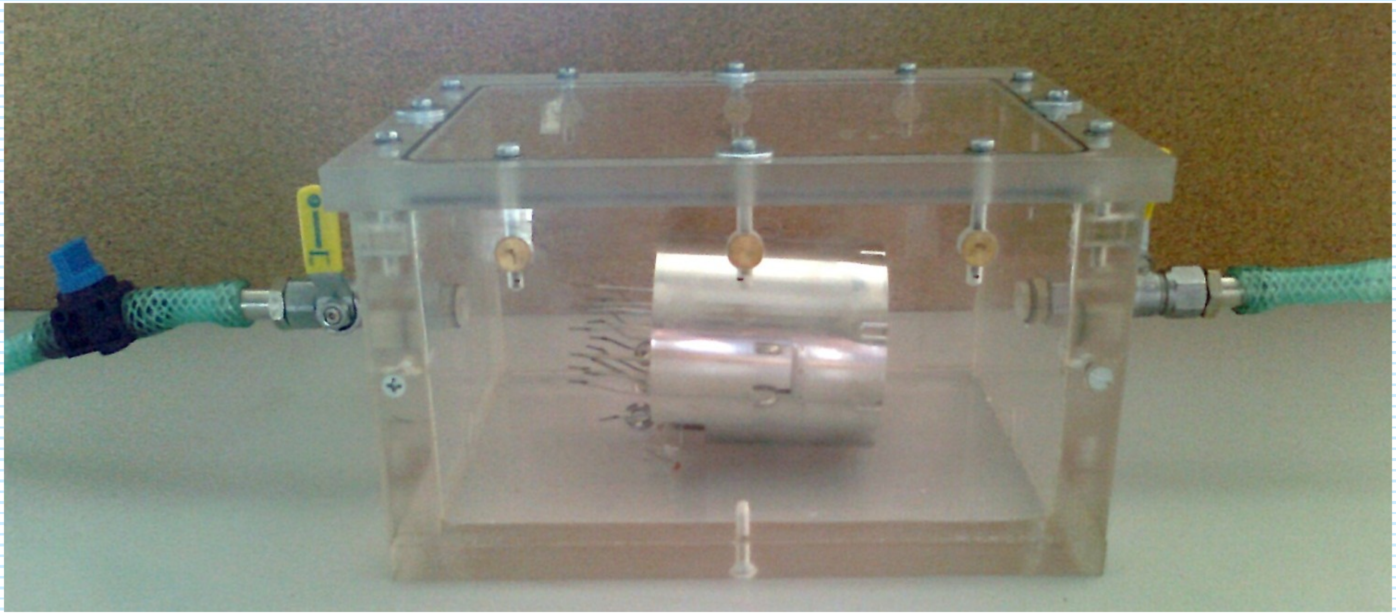
AR – argon reservoir; C – water trap; S – silica gel; CH1 ... CH6 – cooled charcoal columns; SA – sample; ECH – emanation chamber; G – gas meter; F – flow rate meter.

Charcoal columns:

$V = 10m\ell$; $m_{CH} = 2g$; type = DB1; $A_{Ra,CH} = (7.50 \pm 0.02)Bq/kg$

Modulation of the radon emanation measurement

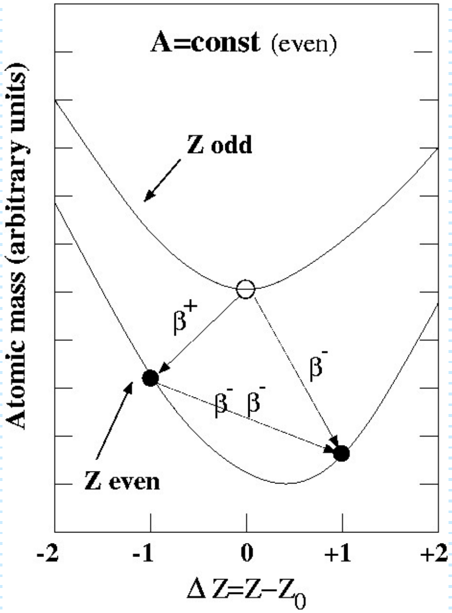
We used small emanation chamber in Bratislava
V = 2.5 ℓ, Material of walls: plexiglas,
Thickness of walls: 10 cm



Plexiglass decrease background emanation of radon approximately 10 times. Our detection limit for radon exhalation is now:

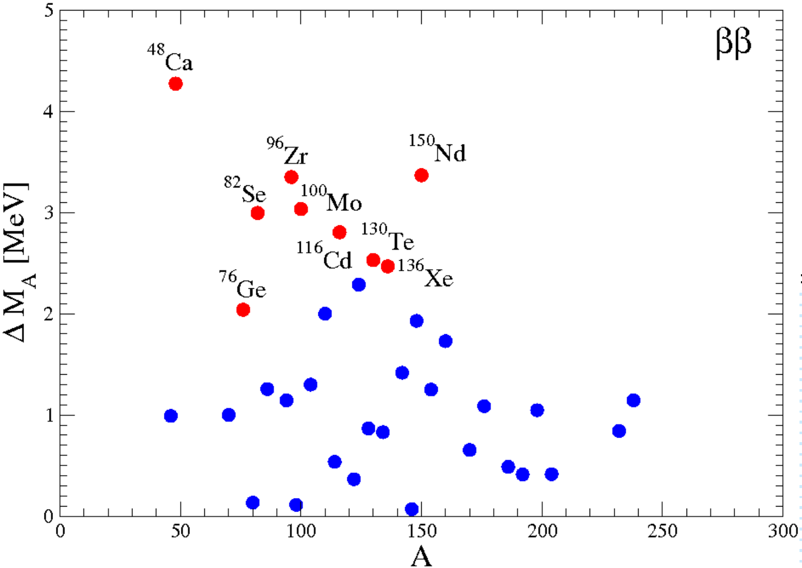
$\sim 3 \cdot 10^{-9}$ Bq·s^{-1}

The double beta decay process can be observed due to nuclear pairing interaction that favors energetically the even-even nuclei over the odd-odd nuclei



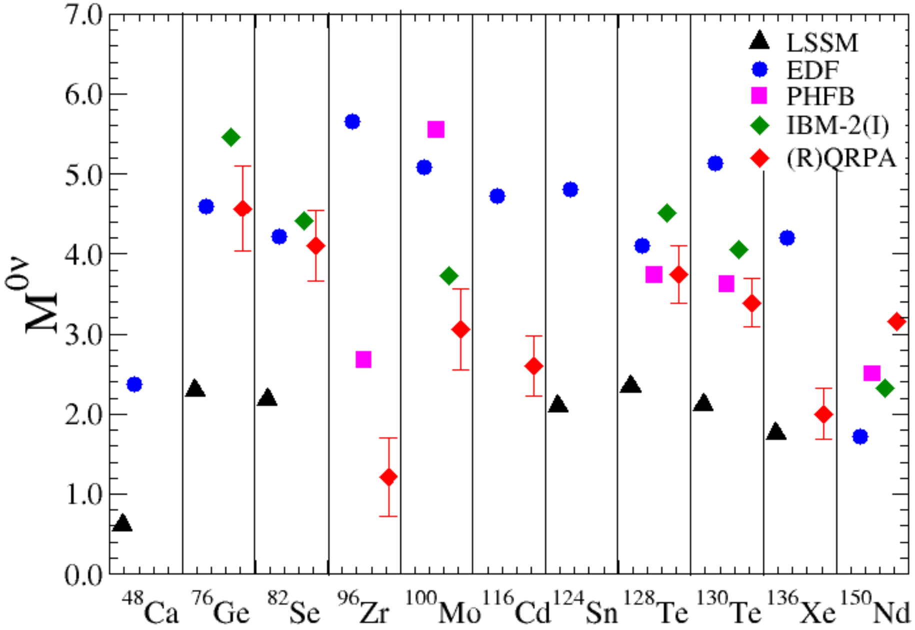
$$\frac{1}{T^{0\nu}_{1/2}} = \left|\frac{m_{\beta\beta}}{m_e}\right|^2 G^{01}(E_0, Z) \left|M^{0\nu}\right|^2$$

transition	$G^{01}(E_0, Z)$ $\times 10^{14} y$	$Q_{\beta\beta}$ [MeV]	Abund. (%)	$\lvert M^{0\nu}\rvert^2$
$^{150}Nd \rightarrow {}^{150}Sm$	26.9	3.667	6	?
$^{48}Ca \rightarrow {}^{48}Ti$	8.04	4.271	0.2	?
$^{96}Zr \rightarrow {}^{96}Mo$	7.37	3.350	3	?
$^{116}Cd \rightarrow {}^{116}Sn$	6.24	2.802	7	?
$^{136}Xe \rightarrow {}^{136}Ba$	5.92	2.479	9	?
$^{100}Mo \rightarrow {}^{100}Ru$	5.74	3.034	10	?
$^{130}Te \rightarrow {}^{130}Xe$	5.55	2.533	34	?
$^{82}Se \rightarrow {}^{82}Kr$	3.53	2.995	9	?
$^{76}Ge \rightarrow {}^{76}Se$	0.79	2.040	8	?



The NMEs for 0νββ-decay must be evaluated using tools of nuclear theory

The 0νββ-decay NMEs (Status:2010)



Nuclear structure approaches

Large Scale Shell Model: Caurier, Menendez, Nowacki, Poves, PRL 100, 052503 (2008).

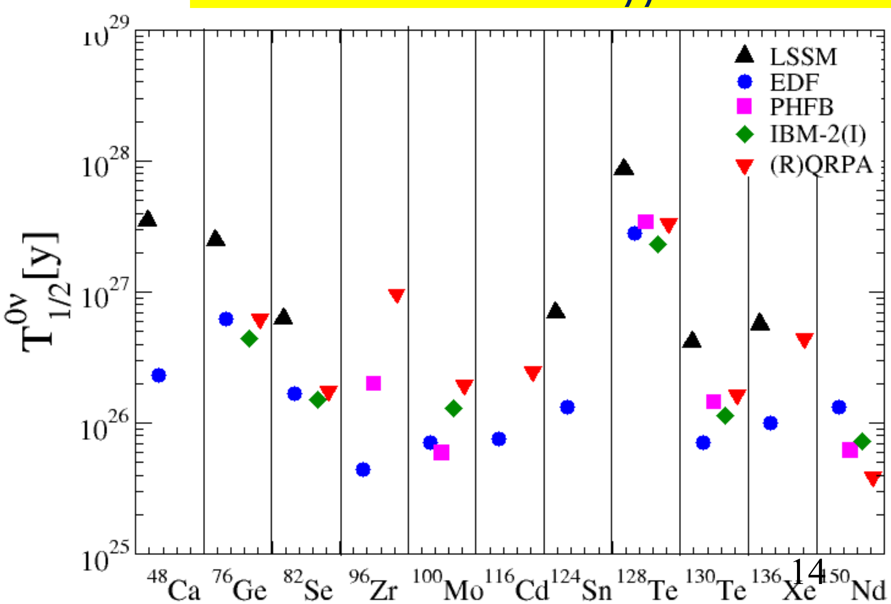
(Renormalized) QRPA: Šimkovic, Faessler, Müther, Rodin, Stauf, PRC 79, 055501 (2009).

Interacting Boson Model: Barea, Iachello, PRC 79, 044301 (2009).

Projected Hartree-Fock-Bogoliubov: Rath, Chandra, et al. PRC 82, 064310 (2010).

Energy Dendity Functional appr.: Rodrígez, Martínez-Pinedo, arXiv:1008.5260 [nucl-th].

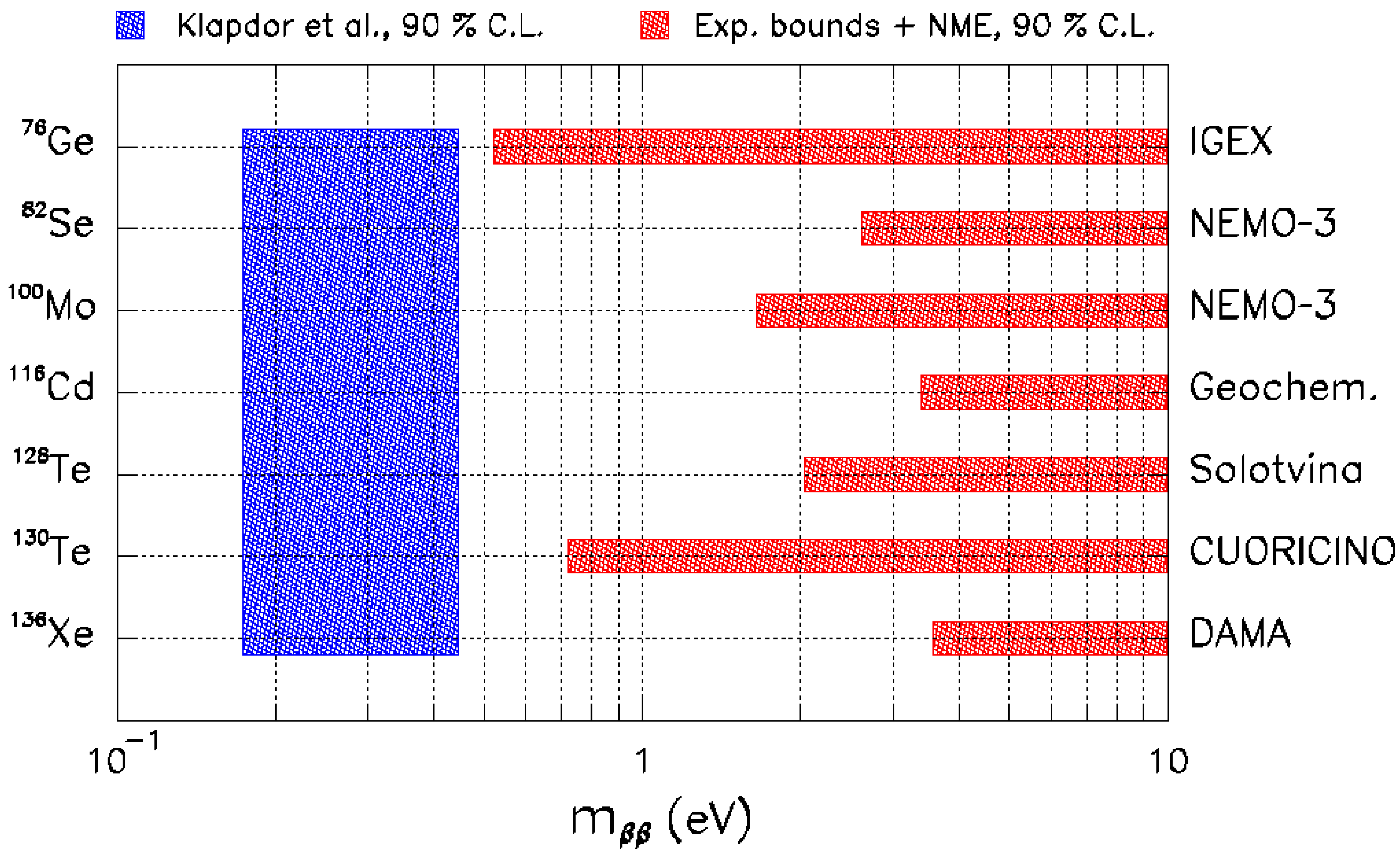
Half-life $T_{1/2}$ for $m_{\beta\beta}$ = 50 meV



Bratislava contributions

- **Role of occupancies of individual orbits**
- **Brueckner short-range correlations**
- **Effect of nuclear deformation**
- **The case of competing of 0νββ-decay mechanisms**

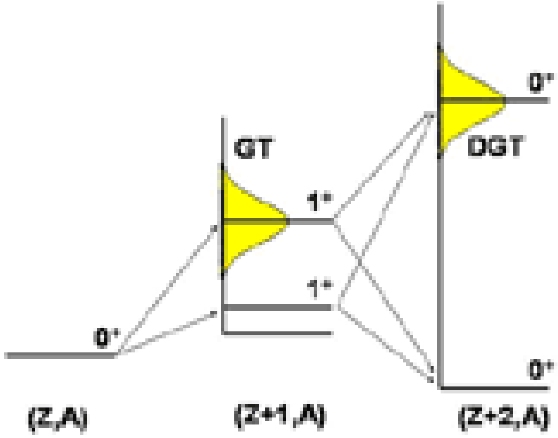
A claim of evidence and other experiments (current status)

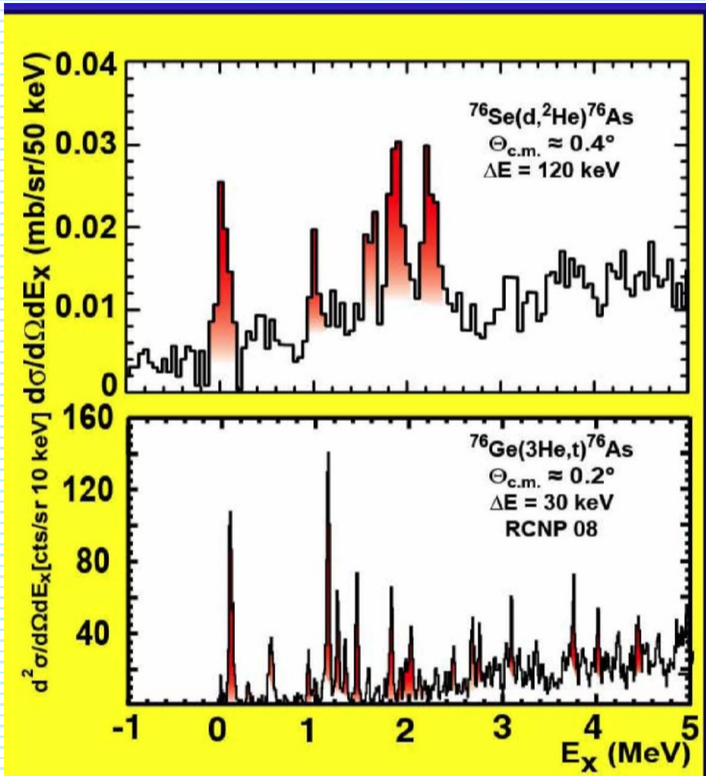


Faessler, Fogli, Lisi, Rodin, Rotunno, F.Š., PRD 79, 053001 (2009)

The cross sections of **(t,^{3}He)** *and* **(d,^{2}He)** *reactions give* **B(GT$^\pm$)** *for* β^+ *and* β^-*, product of the amplitudes* **(B(GT)$^{1/2}$)** *entering the numerator of* $M^{2\nu}_{GT}$

$$M^{2\nu}_{GT} = \sum_m \frac{M^{(+)}_{GT}(m)\ M^{(-)}_{GT}(m)}{Q_{\beta\beta}/2 + m_e + E_x(1^+_m) - E_0}$$





2νββ-matrix element

0.16 ± 0.04 MeV^{-1}

with

G$^{(2\nu)}$ = 3.4x 10^{-20} MeV^2 a^{-1}

2νββ - half-life

(1.1 ± 0.2) x 10^{21} a

recommended. exp. value:

(1.5 ± 0.1) x 10^{21} a

Closure 2νββ-decay NME

$$M^{2\nu}_{GT-cl} = \sum_m M^{(+)}_{GT}(m)\ M^{(-)}_{GT}(m)$$

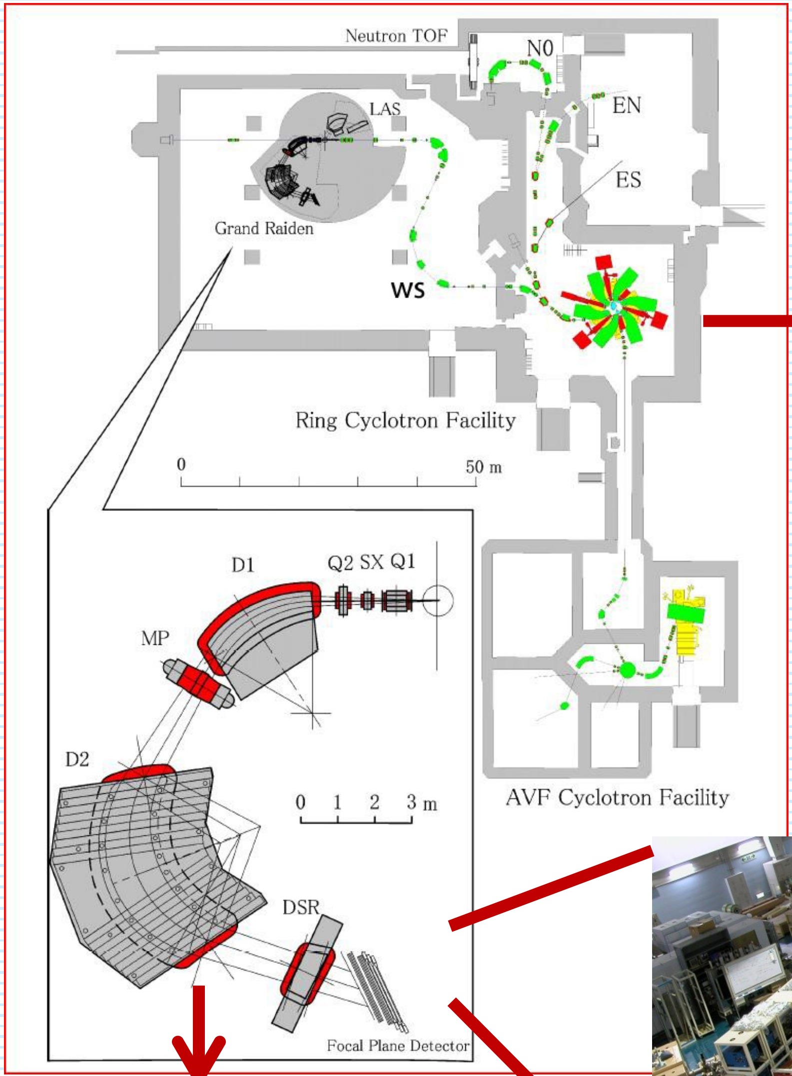
SSD hypothesis

$$g_A^2\ M^{2\nu}_{GT-cl} = \frac{3\ D}{\sqrt{ft_{EC}ft_{\beta^-}}}$$

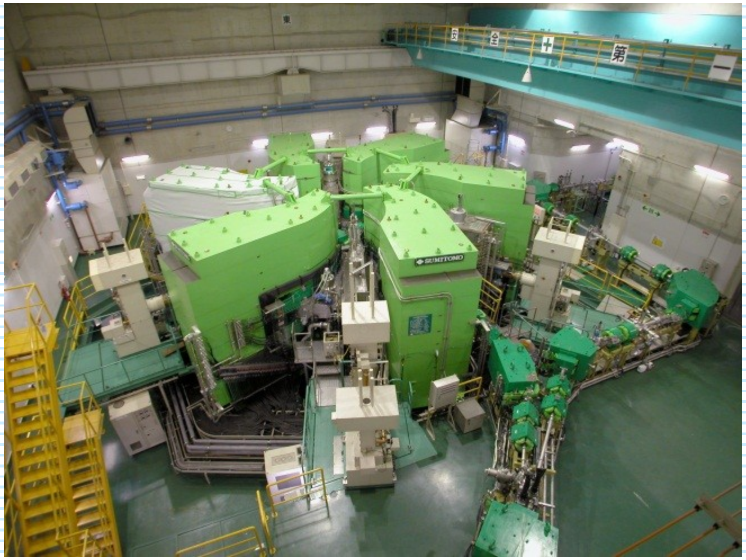
Grewe, …Frekers at al, PRC 78, 044301 (2008)

RCNP of Osaka University

Ejiri group (Osaka), Frekers group (Muenster), Hodák, Povinec, Šimkovic (Bratislava)

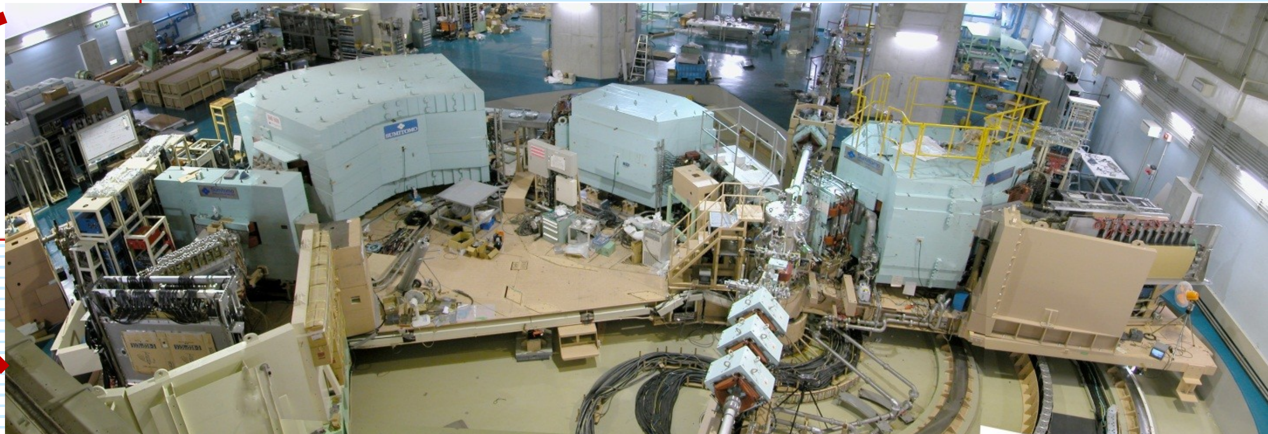


Facility founded in 1971



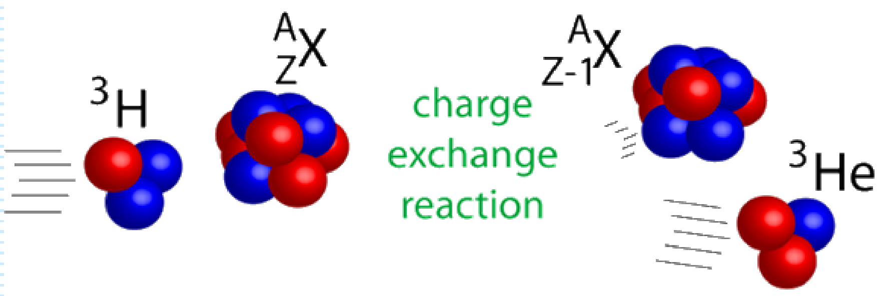
- ❑ Dispersion matching technique
- ❑ High resolution - 30 keV
- ❑ High intensities ~ 10 pnA

High resolution spectrometer Grand Raiden



Research programs: Nuclear physics, fundamental physics, nuclear chemistry and biology

Charge exchange reactions for studies of double β-decay NME



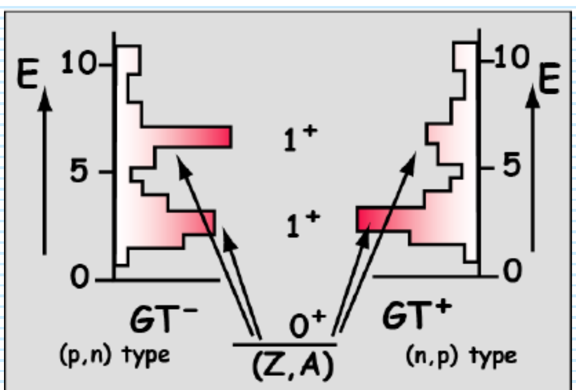
Beam requirements:

- ❑ Type of particle: ^{3}He
- ❑ Beam energy: 420 MeV
- ❑ Beam intensity: 20 nA
- ❑ Energy resolution: $\Delta E \leq 100$ keV

Targets:

- ❑ ^{128,130,nat}Te ($\approx$ 1 mg/cm^2)
- ❑ ^{69,71,nat}Ga

- ❑ Measure B(GT$^+$) through (n,p)-type reaction
- ❑ Measure B(GT$^-$) through (p,n)-type reaction



$$B(GT^{\pm}) = \frac{1}{2J_i + 1}\left|M(GT^{\pm})\right|^2$$

$$B(GT) \approx \hat{\sigma}(GT)\frac{d\sigma(q=0)}{d\Omega}$$

- Phase can not be measured
- Simple relation σ ↔ B(GT)

Neutrinoless Double-Electron Capture (theory and experiment)

Povinec,´Holý, Sýkora, Staníček, Šimkovic ... (Comenius University)

TGV collaboration, Štekl group (Prague), Brudanin (Dubna)
Frekers group (U. Muenster)
Blaum (MPI Heidelberg)
Krivoruchenko (ITEP Moscow)

Oscillations of atoms

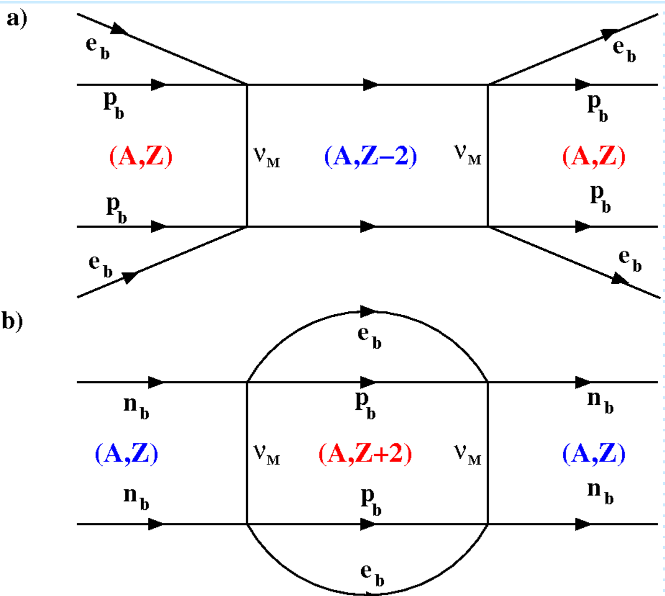
$$H^{atom}_{eff} = \begin{pmatrix} M_i & V^{LNV} \\ V^{LNV} & M_f - \frac{i}{2}\Gamma \end{pmatrix}$$

Oscillation of atoms (lepton number violation)

F.Š., M. Krivoruchenko, Phys.Part.Nucl.Lett. 6 (2009) 485.

In analogy with oscillations of n-anti{n} (baryon number violation)

$$H^{n\bar{n}}_{eff} = \begin{pmatrix} M & V^{BNV} \\ V^{BNV} & M - \frac{i}{2}\Gamma \end{pmatrix}$$



Oscillations of stable atoms (Γ=0)

$$|<f|e^{-iH_{eff}t}|i>|^2 = \frac{4V^2}{(M_i - M_f)^2}\sin^2[t\ (M_i - M_f)/2]$$

$$^{164}_{68}Er \rightarrow\ ^{164}_{66}Dy$$

$$(M_i - M_f) = 24.1\ keV$$

$$|<f|e^{-iH_{eff}t}|i>|^2 \leq 3\ 10^{-55}$$

Oscillations of unstable atoms (Γ≠0)

Double electron capture (resonant enhancement)

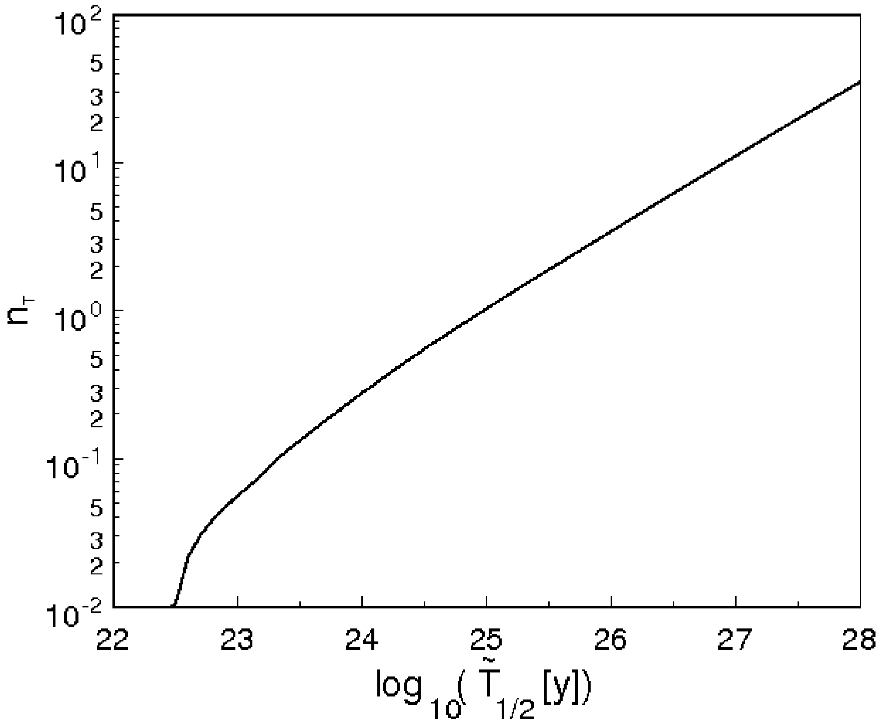
Data analysis of most likely resonant transitions

Half-life of a particular isotope

1 chance of 100 for $T_{1/2} < 10^{25}$ y
10 100 $< 10^{27}$ y

$$\tilde{T}_{1/2} = \tilde{T}^{\min}_{1/2} \frac{\Delta M^2 + \Gamma_\gamma^2/4}{\Gamma_\gamma^2/4}$$

$$\Delta M(\tilde{T}_{1/2}) = \frac{\Gamma_\gamma}{2}\left(\frac{\tilde{T}_{1/2}}{\tilde{T}^{\min}_{1/2}} - 1\right)^{1/2}.$$



Number of transitions n with half –life $T^a_{1/2} < T_{1/2}$

$$n = \sum_{T^a_{1/2} < T_{1/2}} \frac{\Delta M(\tilde{T}^a_{1/2})}{\Delta M_{\rm expt}}$$

M. Krivoruchenko, F.Š., D. Frekers, A. Faessler, arXiv: 1012.1204[hep-ph] accepted in Nucl. Phys. A

Improved Q-value measurements
Klaus Blaum (MPI Heidelberg)

nucl. tr.	Q_{old}	$E = B + E_\gamma$	Orbit.	$\Delta = Q(old) - E$	Q_{new}	$\Delta = Q(new) - E$
$^{112}Sn \rightarrow ^{112}Cd$	1919.5(4.8)	1901.7	KL_1	17.8(4.8)	1919.82(16)	18.12(16)
		1924.4	KK	-4.9(4.8)		-4.56(16)
$^{152}Gd \rightarrow ^{152}Sm$	54.6(3.5)	54.79+0	KL_1	-0.19(3.50)	55.70(18)	0.91(18)
$^{164}Er \rightarrow ^{164}Dy$	23.3(3.9)	18.09	l_1L_1	5.21(3.90)		

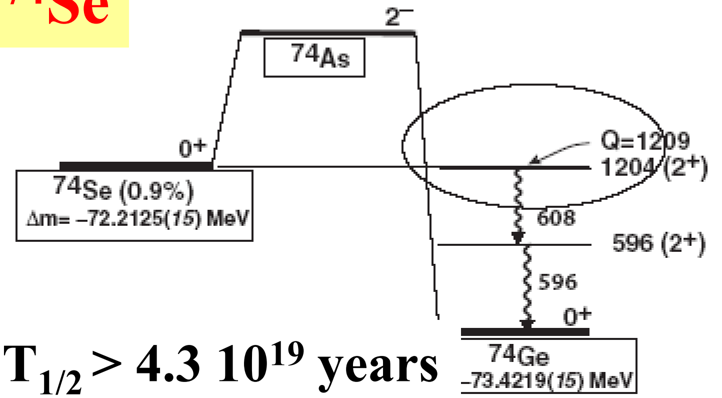
^{152}Gd→^{152}Sm (Eliseev, et al., F.Š, M. Krivoruchenko, PRL 106, 052504 (2011))
(F.Š., Krivoruchenko, Faessler, PPNP 66, 446 (2011))

$$\Gamma_{\varepsilon\varepsilon} = |V_{\varepsilon\varepsilon}|^2 \frac{\Gamma}{\Delta^2 + \Gamma^2/4} = |V_{\varepsilon\varepsilon}|^2 R$$

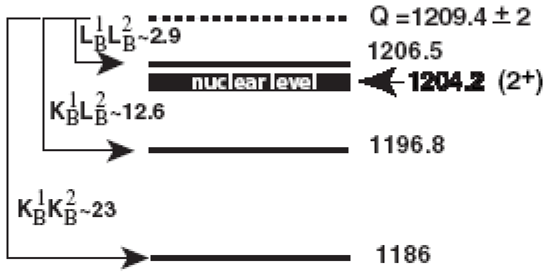
$$V_{\varepsilon\varepsilon} = m_{\beta\beta} \frac{\sqrt{2} g_A^2 G_\beta^2}{(4\pi)^2 R_{nucl}} \overline{f}_a \overline{f}_b M^{0\nu}$$

$$T_{1/2}^{0\nu} = 4 \times 10^{26} \left(\frac{1\ \text{eV}}{m_{\beta\beta}}\right)^2 \ \text{years.}$$

^{74}Se

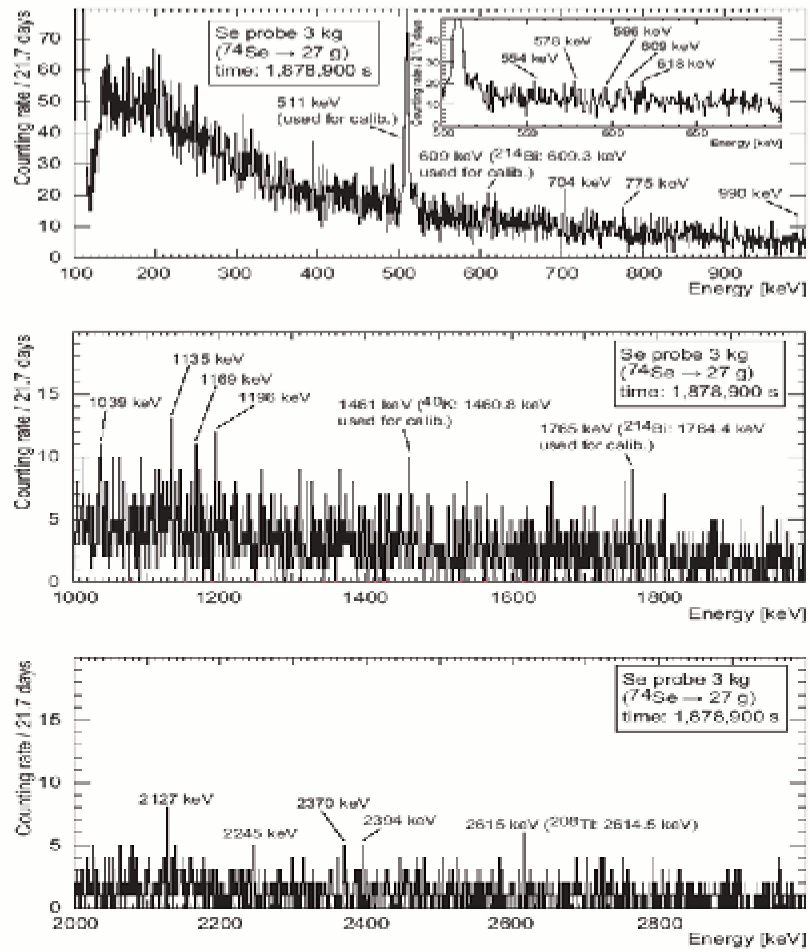


$T_{1/2} > 4.3\ 10^{19}$ years

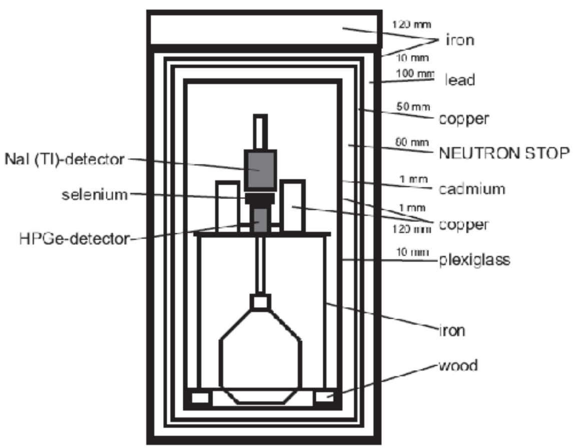


Experiment in Bratislava!

Muenster and Bratislava groups

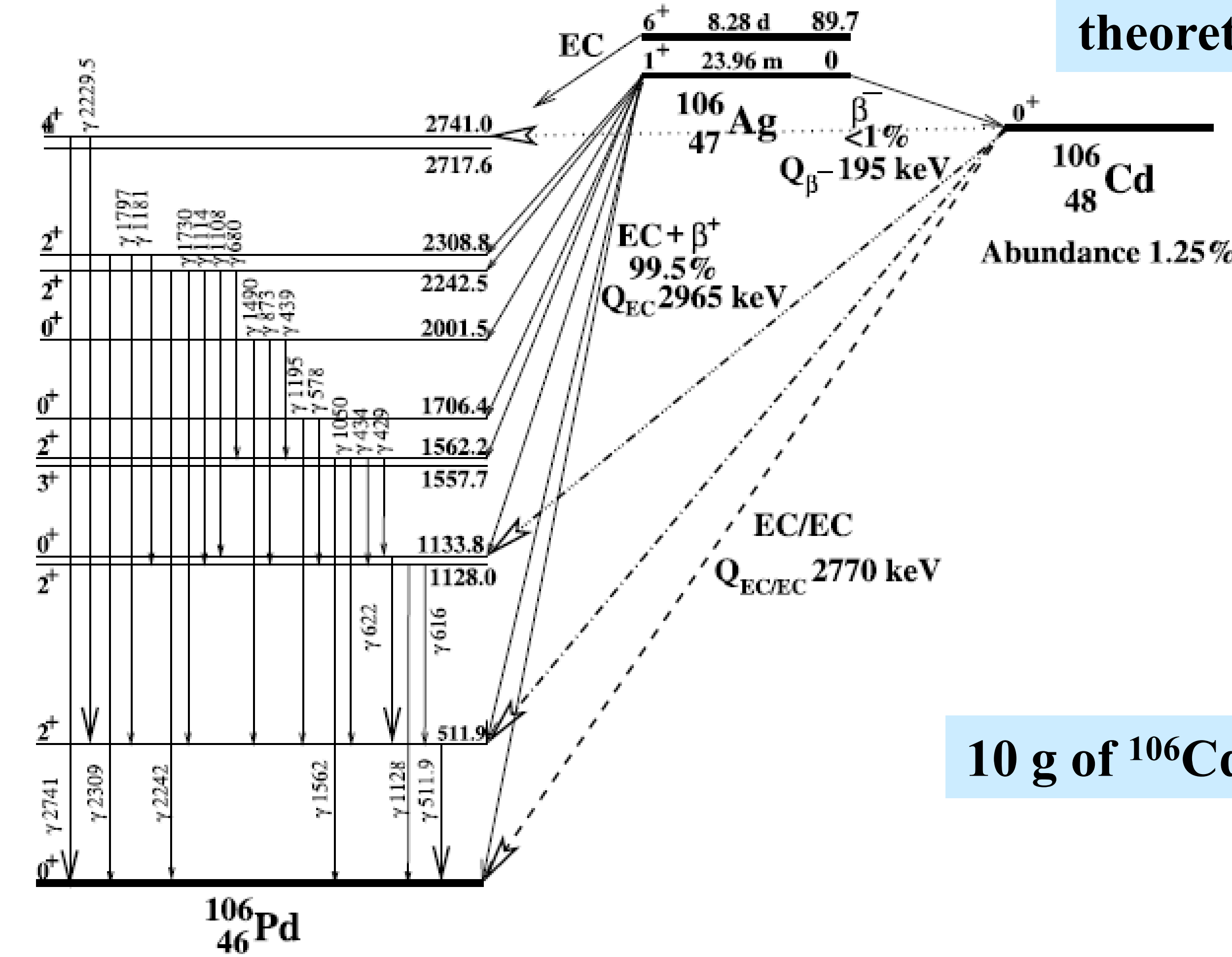


Frekers, Puppe, Thies, Povinec, Šimkovic, Staníček, Sýkora, accepted in NPA



TGV experiment in Modane underground laboratory

theoretical support



10 g of ^{106}Cd

$T_{1/2}^{2\nu\varepsilon\varepsilon}$ (^{106}Cd) > 3.6 10^{20} y

TGV Coll, Rukhadze et al., NPA 852, 197 (2011)

$T_{1/2}^{0\nu\varepsilon\varepsilon}$ (^{106}Cd) > 1.1 10^{20} y

Two-neutrino Double-Beta Decay and statistical properties of ν (theory)

Šimkovic, Dvornický (Comenius University)

Barabash (ITEP Moscow)
Smirnov (ICTP Trieste)
Dolgov (U. Ferrara)

Mixed statistics for neutrinos

Definnition of mixed state

$$
\begin{aligned}
|\nu> &= \hat{a}^\dagger |0> \\
&\equiv \cos\delta \;\; \hat{f}^\dagger |0> \;+\; \sin\delta \;\; \hat{b}^\dagger |0> \\
&= \cos\delta \;\; |f> \;+\; \sin\delta \;\; |b>
\end{aligned}
$$

with commutation Relations

$$
\begin{aligned}
\hat{f}\hat{b} &= e^{i\phi}\hat{b}\hat{f} \qquad \hat{f}^\dagger\hat{b}^\dagger = e^{i\phi}\hat{b}^\dagger\hat{f}^\dagger \\
\hat{f}\hat{b}^\dagger &= e^{-i\phi}\hat{b}^\dagger\hat{f} \qquad \hat{f}^\dagger\hat{b} = e^{-i\phi}\hat{b}\hat{f}^\dagger
\end{aligned}
$$

Amplitude for 2νββ

$$
\begin{aligned}
A^{2\nu} &= [\cos\delta^4 + \cos\delta^2 \sin\delta^2 (1-\cos\phi)] A^f \;+\; [\cos\delta^4 + \cos\delta^2 \sin\delta^2 (1+\cos\phi)] A^b \\
&= \cos\chi^2 A^f \;+\; \sin\chi^2 A^b
\end{aligned}
$$

Decay rate

$$
\begin{aligned}
W^{2\nu} &= \cos\chi^4 \; W^f \;+\; \sin\chi^4 \; W^b \\
&= (1-b^2) \; W^f \;+\; b^2 \; W^b
\end{aligned}
$$

Partly bosonic neutrino requires knowing NME or log ft values for HSD or SSD

(calculations coming up soon)

Looking for a signature of bosonic ν

2νββ–decay half-lives $(0^+ \to 0^+_{g.s.},\ 0^+ \to 0^+_1,\ 0^+ \to 2^+_1)$

- **HSD – NME needed**
- **SSD – log ft_{EC}, log ft_{β} needed**

$$\frac{T_{1/2}^{2\nu-SSD}(2^+_f)}{T_{1/2}^{2\nu-SSD}(0^+_f)} = 2.41 \times 10^4 \quad \text{fermionic } \nu \qquad T_{1/2}^{2\nu}(2^+) = 1.73 \times 10^{23} years$$

$$= 403 \quad \text{bosonic } \nu \qquad = 2.74 \times 10^{21} years$$

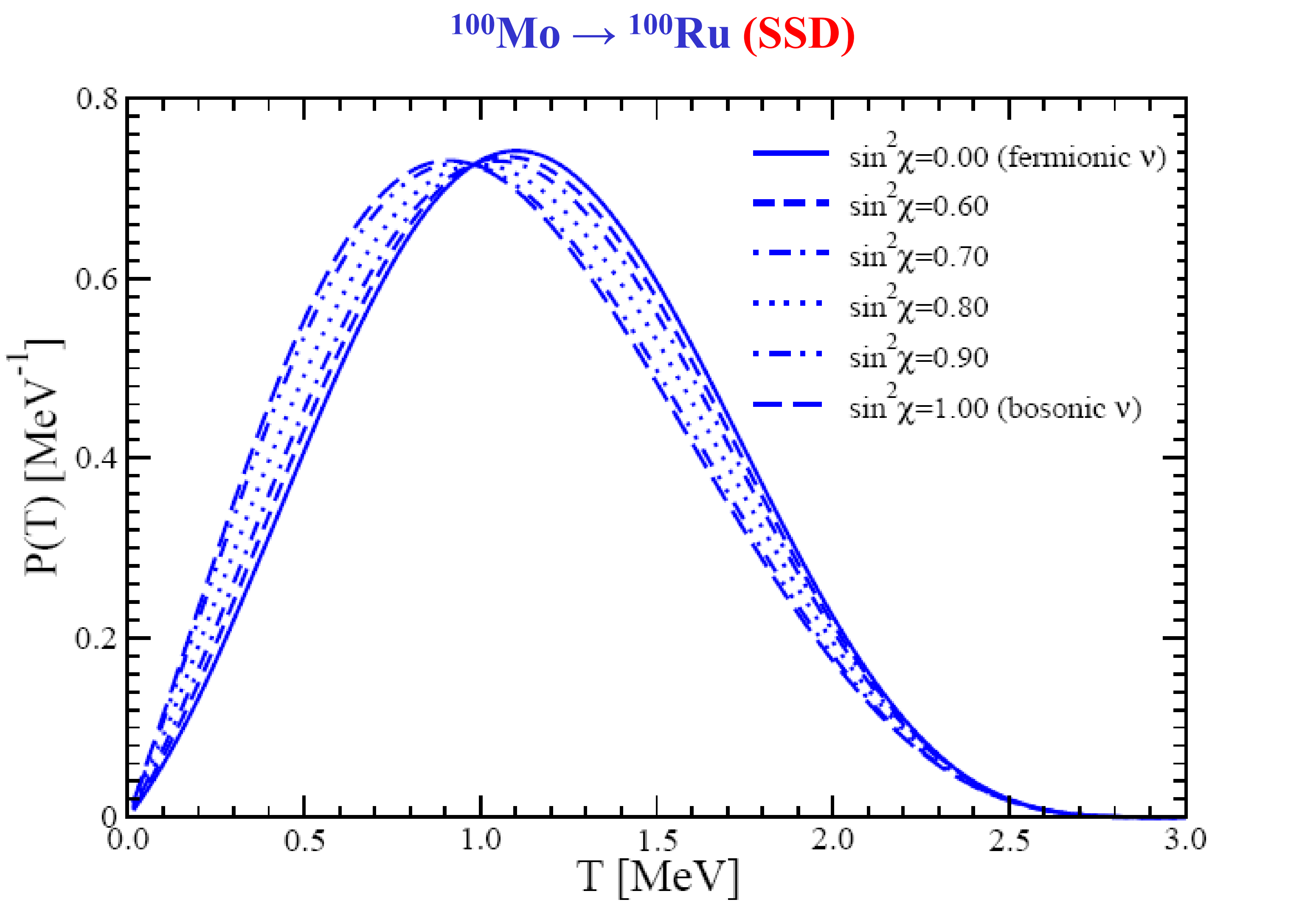
$$T_{1/2}^{2\nu-exp}(2^+) > 1.6 \times 10^{21} years$$

Normalized differential characteristics

- **The single electron energy distribution**
- **The distribution of the total energy of two electrons**
- **Angular correlations of two electrons**

(free of NME and log ft)

Mixed ν excluded for $\sin^2\chi < 0.6$ (NEMO3 data)



Barabash, Dolgov, Dvornický, F. Š., Smirnov, NPB 783, 90 (2007)

Measuring mass of neutrinos with β-decays of ^{3}H, ^{187}Re, ^{115}In and electron capture of ^{163}Ho (theory)

Šimkovic, Dvornický (Comenius University)

Muto (Tokyo Technical U.)
Faessler (Tuebingen)

Relativistic approach to ^3H decay nuclear recoil (3.4 eV) taken into account

Standard approach

- **non-relativistic nuclear w.f.**
- **nuclear recoil neglected**
- **phase space analysis**

$$E_e^{max} = M_i - M_f - m_\nu$$

$$\frac{d\Gamma}{dT} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E) pE (Q-T) \sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

Relativistic EPT approach (Primakoff)

- **Analogy with n-decay**

  (^{3}H,^{3}He) $\leftrightarrow$ (n,p)
- **nuclear recoil of 3.4 eV by E_e^{max}**
- **relevant only phase space**

$$E_e^{max} = \frac{1}{2M_f}\left[M_i^2 + m_e^2 - \left(M_f^2 - m_\nu^2\right)\right]$$

$$\begin{aligned}
\frac{d\Gamma}{dE_e} = & \frac{1}{(\pi)^3}(G_F \cos\theta_c)^2 F(Z,E_e) p_e \\
& \times \frac{M_i^2}{(m_{12})^2}\sqrt{y\left(y + 2m_\nu \frac{M_f}{M_i}\right)} \\
& \times \left[(g_V+g_A)^2 y\left(y + m_\nu\frac{M_f}{M_i}\right)\frac{M_i^2(E_e^2 - m_e^2)}{3(m_{12})^4}\right. \\
& (g_V+g_A)^2 (y + m_\nu \frac{M_f + m_\nu}{M_i})\frac{(M_iE_e - m_e^2)}{m_{12}^2} \\
& \times (y + M_f\frac{M_f + m_\nu}{M_i})\frac{(M_i^2 - M_iE_e)}{m_{12}^2} \\
& - (g_V^2 - g_A^2) M_f\left(y + m_\nu \frac{(M_f + M_\nu)}{M_i}\right) \\
& \times \frac{(M_iE_e - m_e^2)}{(m_{12})^2} \\
& \left. + (g_V - g_A)^2 E_e\left(y + m_\nu\frac{M_f}{M_i}\right)\right]
\end{aligned}$$

$$y = E_e^{max} - E_e$$
$$(m_{12})^2 = M_i^2 - 2M_iE_e + m_e^2$$

Numerics:

Practically the same dependence of Kurie function on m_ν for $E_e \approx E_e^{max}$

F.Š., R. Dvornický, A. Faessler, PRC 77 (2008) 055502

Spectrum of emitted electrons in rhenium β-decay

Dvornický, F. Š., Muto, Faessler, PPNP (2009)

$$\frac{d\Gamma}{dE} = \frac{G_F^2 V_{ud}^2}{2\pi^3} \left|M\right|^2 pE(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}\ \frac{1}{3} R^2 \left(p^2 F_1(Z,E) + k^2 F_0(Z,E)\right)$$

$$k = \sqrt{(E_0 - E)^2 - m_\nu^2}$$

Electron $p_{3/2}$ decay channel clearly dominates

$$\Gamma_S / \Gamma_P = 1.011 \times 10^{-4}$$

In agreement with

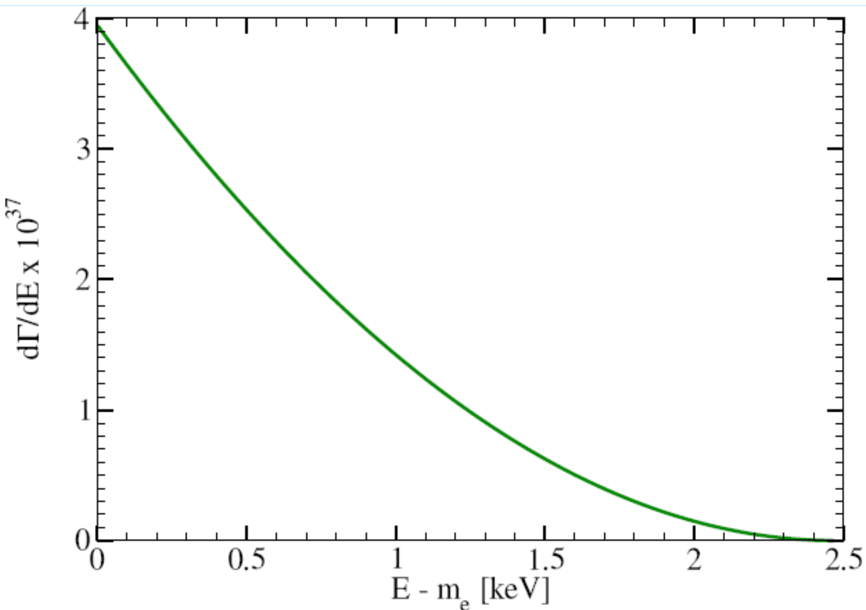
Arnaboldi et al.: PRL 96, 042503 (2006)

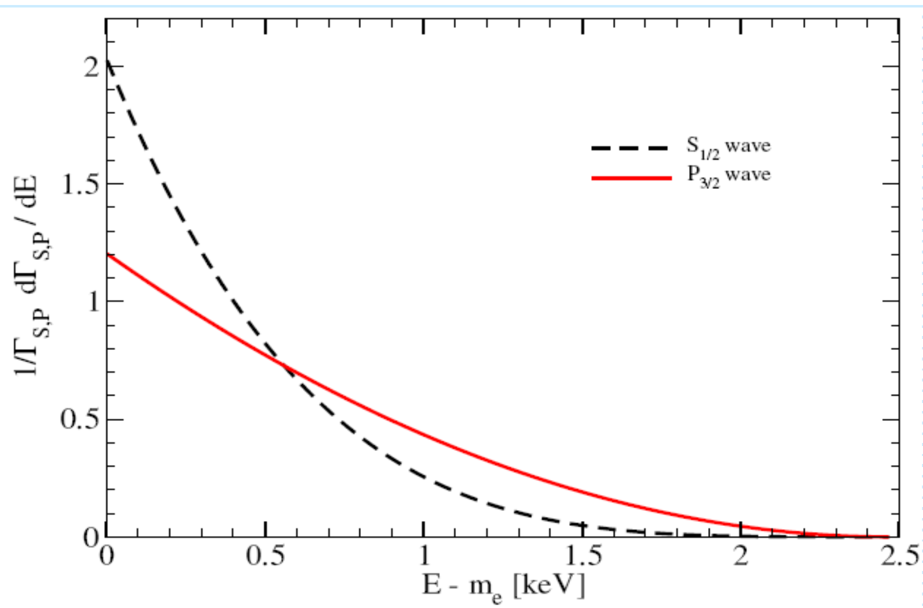
Electron in the $p_{3/2}$ state

$$p^{\max} \cong 50\, keV$$

Electron in the $s_{1/2}$ state

$$k^{\max} = 2.47\, keV$$





Kurie plots for rhenium (MARE) and tritium (KATRIN) β-decay

Rhenium

$$B_{Re} = \frac{G_F V_{ud}}{\sqrt{2\pi^3}} \frac{g_A}{\sqrt{2J_i+1}} \left| \langle {}^{187}Os \| \sqrt{\frac{4\pi}{3}} \sum_n \tau_n^+ \frac{r_n}{R} \{\sigma_1 \otimes Y_1\}_2 \| {}^{187}Re \rangle \right|$$

$$\times \sqrt{\frac{1}{3} R^2 p^2 \frac{F_1(Z,E)}{F_0(Z,E)}}$$

$$K(E_e)/B_{Re} \cong (E_0 - E_e) \sqrt[4]{1 - \frac{m_\nu^2}{(E_0 - E_e)^2}}$$

Tritium

$$B_T = \frac{G_F V_{ud}}{\sqrt{2\pi^3}} \sqrt{g_V^2 + 3 g_A^2}$$

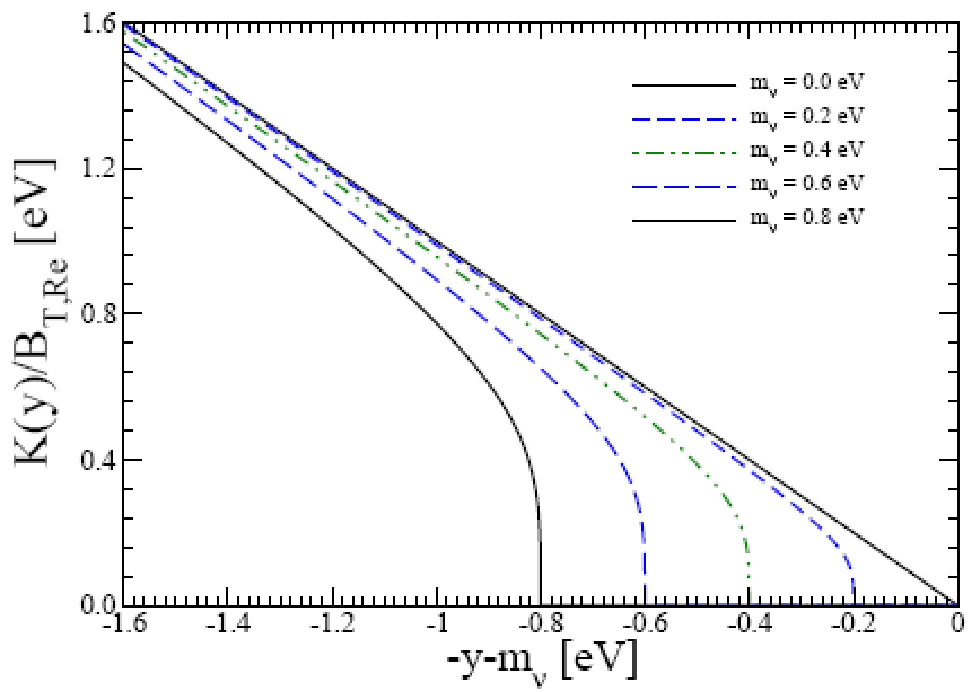
$$K(y)/B_T = \left(\sqrt{y(y + 2m_\nu)} (y + m_\nu) \right)^{1/2}$$

$y = E_e max-$

Properly normalized Kurie functions are practically the same by the endpoint !

$$K(E)/B_{Re} \cong K(y)/B_T$$

Dvornický, Muto, F.Š, Faessler, PRC 83, 045502 (2011)



Towards laboratory detection of relic neutrinos (theory)

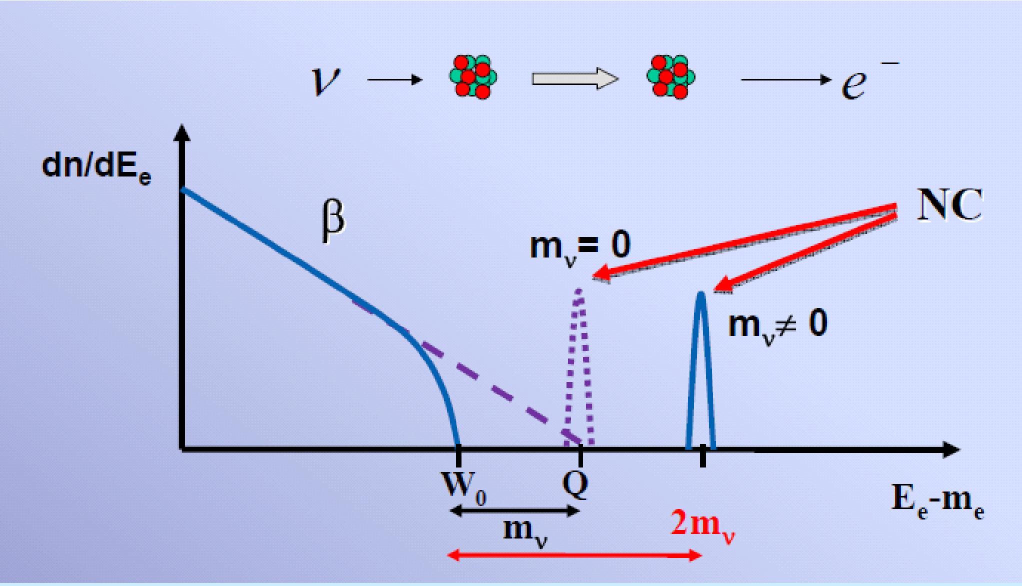
Šimkovic, Hodák (Comenius University)

Kovalenko (University Valparaiso)
Krivoruchenko (ITEP Moscow)
Faessler (U. Tuebingen)

Detection of relic neutrinos by KATRIN experiment

$$\nu + {}^3H((1/2)^+) \to {}^3He((1/2)^+) + e^-$$

$$\Gamma^\nu({}^3H) = \frac{1}{\pi} G_\beta^2 \, F_0(2,p) \, p \, p_0 \, \left(|M_F|^2 + g_A^2 |M_{GT}|^2\right) \frac{\eta_\nu}{<\eta_\nu>} <\eta_\nu>$$



Assuming $M_F=1$, $M_{GT}=\sqrt{3}$ and $\eta_\nu=<\eta_\nu>$ the capture rate

$$\Gamma^\nu({}^3H) = 4.2 \;\; 10^{-25} \;\; y^{-1}$$

KATRIN will use ~50 μg of ^3H

Faessler, Hodák, Kovaenko, F.Š., arXiv: 1102.1799[hep-ph] accepted in J. Phys. G

$$N^\nu_{capt}(KATRIN) \approx 4.2 \; 10^{-6} \; \frac{\eta_\nu}{<\eta_\nu>} \; y^{-1}$$

Even considering effect of clustering of ν, $\eta_\nu/<\eta_\nu> \sim 10^3\text{-}10^4$:

$N^\nu_{capt}(KATRIN) < 1 \; y^{-1}$

Sterile relic neutrino detection using ν_h capture on ^3He

$$\nu_h + {}^3He \rightarrow {}^3H^- + e^+$$

Mixing of neutrinos

$$\nu_e = \sum_{i=1}^{3} U_{ei}\nu_i + U_{eh}\nu_h$$

Capture rate per atom

$$\Gamma^{\nu_h}({}^3He) = |U_{eh}|^2 \frac{1}{\pi} G_\beta^2 . F_0(1,p) . p_{e^+} . p_0 \left(|M_F|^2 + g_A^2 |M_{GT}|^2 \right) \frac{\eta_\nu}{\langle \eta_\nu \rangle} \langle \eta_\nu \rangle$$

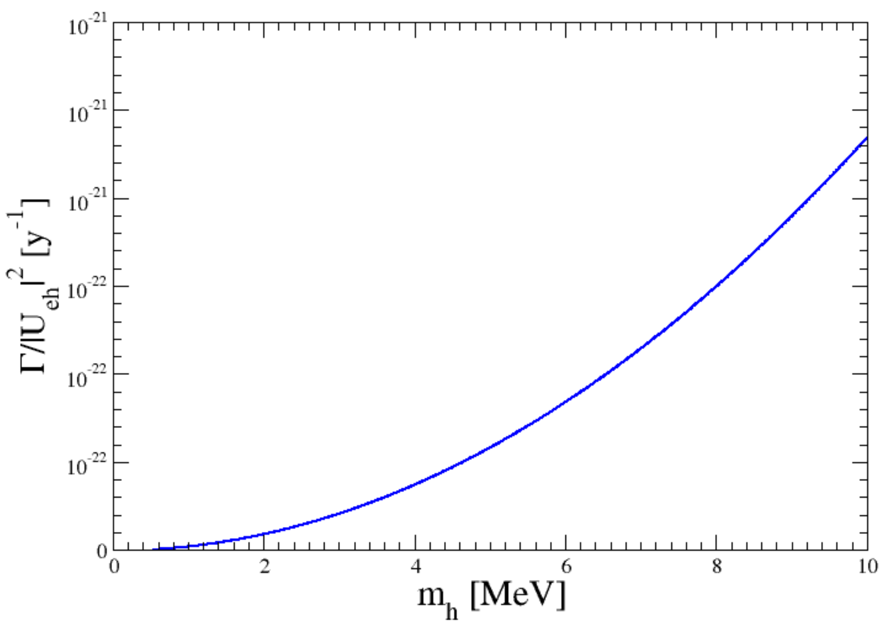
$$p_{e^+} = \sqrt{E_e^2 - m_e^2} = \sqrt{(m_{\nu_h} - 18.6\,keV)^2 - m_e^2}$$

Hodák, F.Š., Kovaenko, Faessler, PPNP 66, 452 (2011)

$$m_{\nu_h} > 18.6\,keV + m_{e^+}$$

Production rate for 1kg of ^3He

m_{ν_h} [MeV]	$N_{\nu_h} / (\lvert U_{eh}\rvert^2 . \frac{\eta_\nu}{\langle \eta_\nu \rangle})$ [y^{-1}]
1.0	$7.9\ 10^2$
5	$2.3\ 10^4$
10	$9.4\ 10^4$



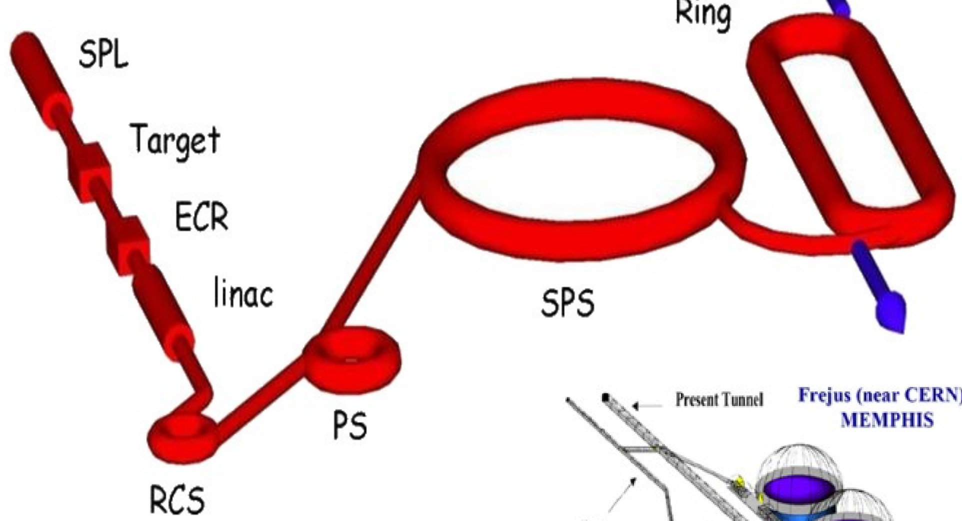
Beta Beams at CERN
(experiment)

Thierry Stora group (CERN)

Rastislav Hodák, Peter Valko (Comenius University)

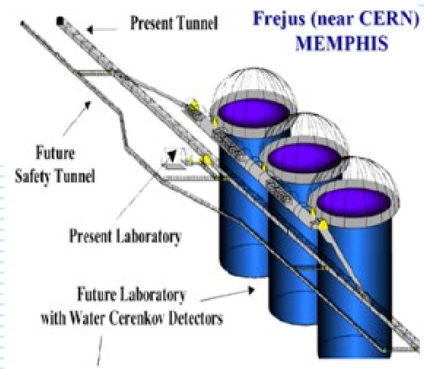
Beta beams concept

Phys. Lett. B 532, (2002), 166-172

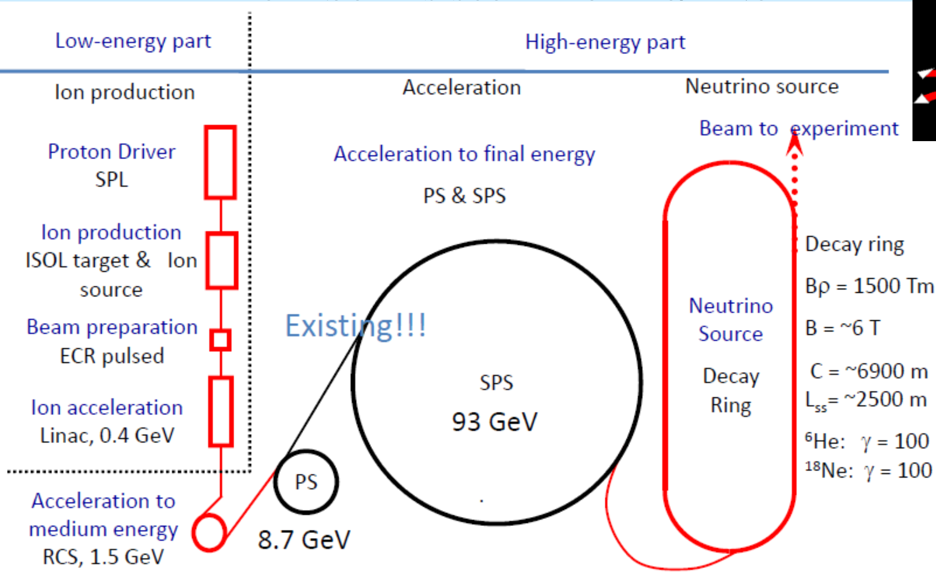


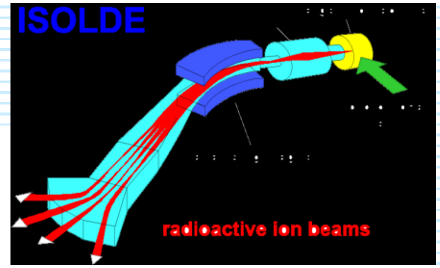
- Idea by **Piero Zucchelli** (2002)
- **Aim:** Production of pure and collimated ultra-relativistic (anti)neutrino beams from the beta decay of radioactive ions circulating in a storage ring.
- **Physical applications:**

  - **High energy → Neutrino oscillation physics (mixing angle θ_{13} and CP violation phase)**
  - **Low energy → Cross-sections of neutrino-nucleus interaction**



Beta beams scenario $^{6}He/^{18}Ne$



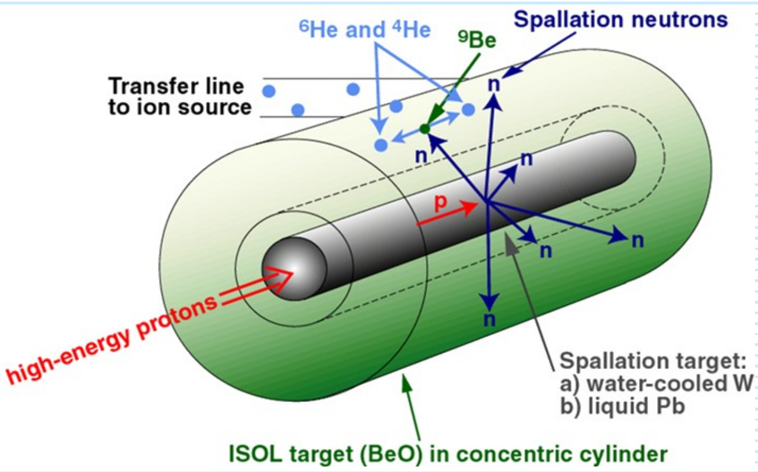


Orme Ch., arXiv:1004.0939v1 (2010)

- **Ion choice: ^{6}He and ^{18}Ne**
- **Based on existing technology and machines**
- **Production of ν_e and anti-ν_e over 10 years:**

  - 2.9 x10^{19} anti-ν from ^{6}He (3.3 x10^{13} ^{6}He/s)

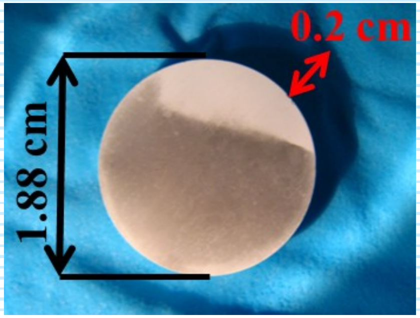
^{6}He production



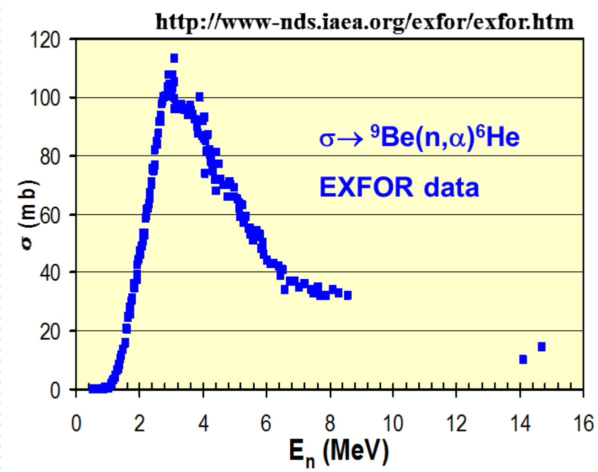
N. Thiolliere et al., EURISOL-DS

$$^{6}_{2}He^{2+}(T_{1/2} = 0.8s) \rightarrow {}^{6}_{3}Li + e^{-} + \overline{\nu}$$

$$Q_{\beta^-} = 3.51 \text{ MeV}$$



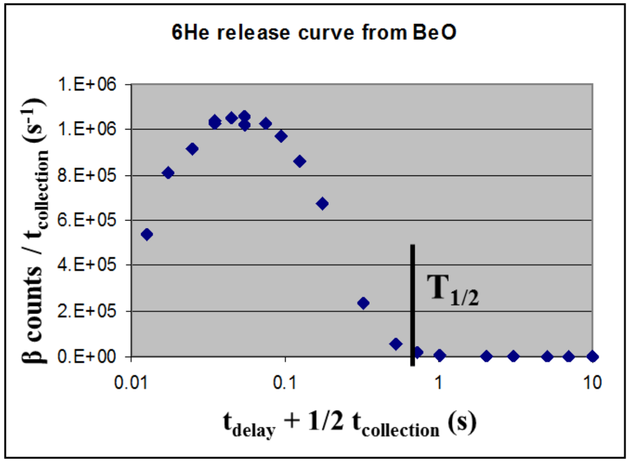
- ❖ **Threshold: 0.6 MeV**
- ❖ **Peak cross-section: 105 mb @ 3MeV**



❖ ^{6}He can be achieved:

– 2 x10^{13} ^{6}He/s 100kW, 1 GeV proton beam

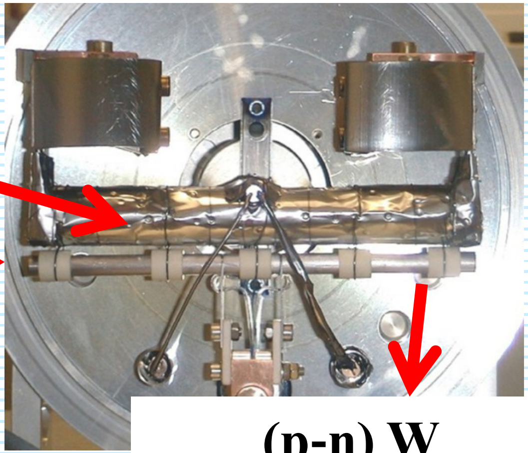
– 1 x10^{14} ^{6}He/s 200kW, 2 GeV p beam in-target production



ISOLDE experiment - CERN, GANIL and Weizmann

BeO Target

p (1.4 GeV)

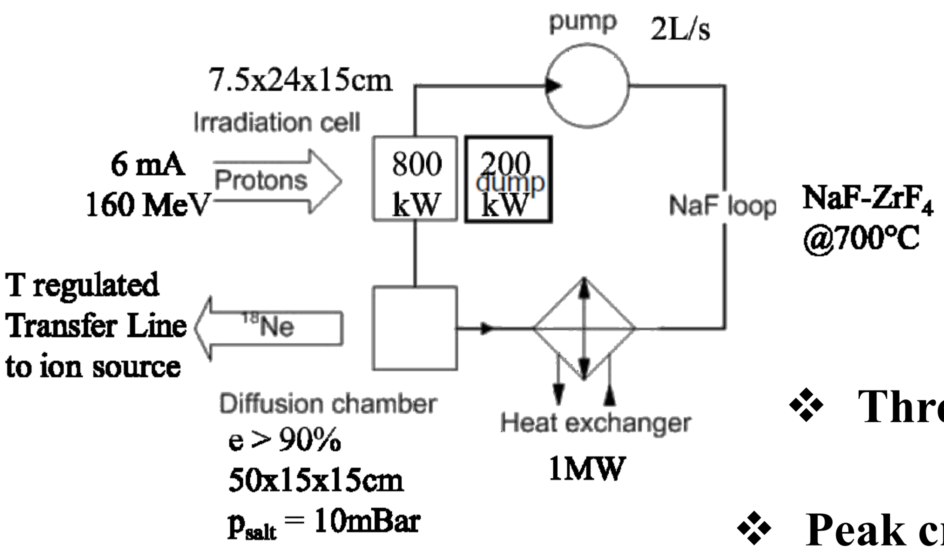


(p-n) W Converter

^{18}Ne production

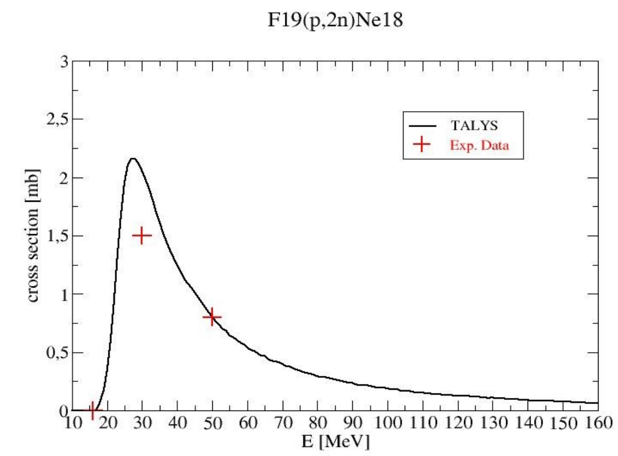
$$^{18}_{10}Ne^{10+}(T_{1/2} = 1.7\,s) \rightarrow {}^{18}_{9}F + e^{+} + \nu$$

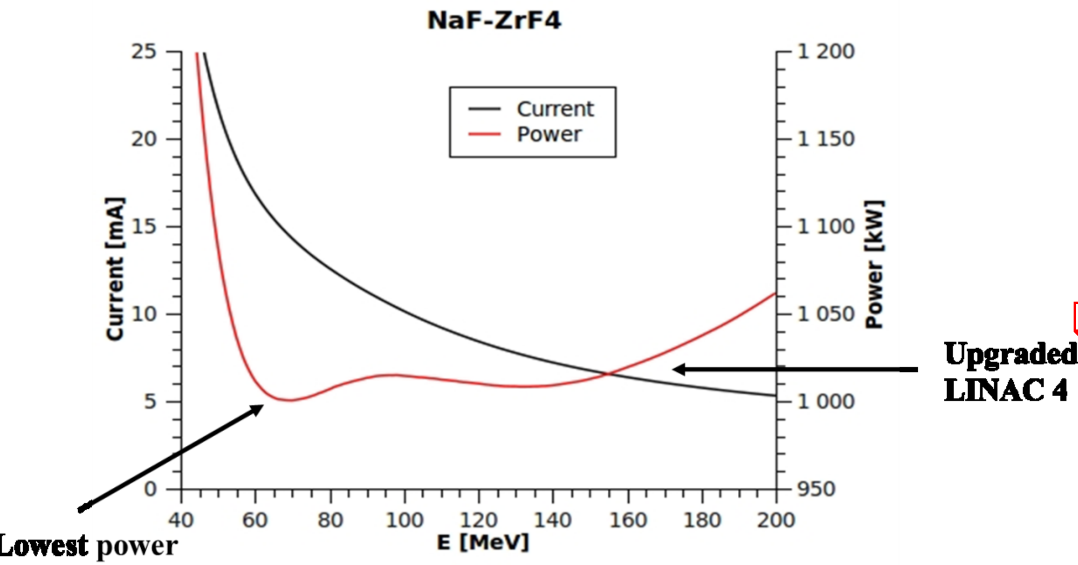
$$Q_{EC} = 4.45 \text{ MeV}$$



Conceptual target loop (^{19}F(p, 2n)^{18}Ne)

- Threshold: 16 MeV
- Peak cross-section: 1.6 mb @ 30 MeV

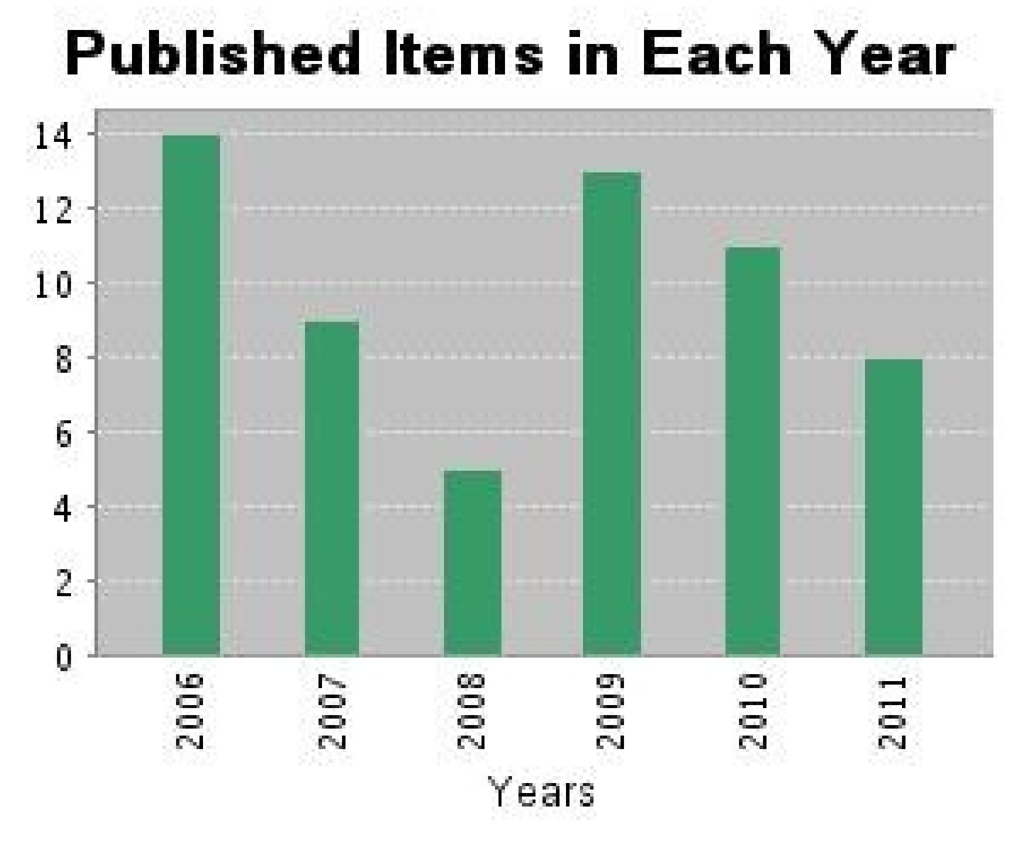




- Melting point of NaF-ZrF$_4$ ≈ 500°C
- Hastelloy N alloy (Ni based) – excellent salt corrosion resistance
- Cooling – by circulating molten salt

EURISOL Design Study

Publications - Citations (2006-2011)



About 60 publications in refereed journals with about 700 citations

Grants -Finances

EU project: **(2004-09) Integrated Large Infrastructures for Astroparticle Science, RII3-CT-2004-506222 (theory)**

DFG project: **(2005-11) Nuclei as laboratory to test lepton number/flavor violation (theory)**

JINR project: **(2005-11) Grand unification, fundamental rare processes and nuclear structure (theory)**

Slovak projects: **VEGA(2006-09) Massive neutrinos and double beta decay**
VEGA(2009-11) Massive neutrinos in astro-, particle and nuclear physics (theory)

Can we get some money for *experimental activities?*

EU project ILIAS-next (theory and experiment), submitted in 2009 and 2010, not approved (twice 13.5 points from 15)

EU structural funds for Slovakia (theory and experiment), Project for construction of small underground laboratory, positive referee's reports, not approved - not enough money allocated for call (2010)?! But, we need such facility (Fukushima)!

APVV project *SuperNEMO experiment* (theory and experiment), 2011, not approved positive referee's reports, Slovak referees gave not enough points 89/100 and 91/100

Slovak particip. in ASPERA? ASPERA meeting in Bratislava in 2008. Suggestion for the APVV to enter ASPERA within ERANET (34 000 EUR). Answer: NO

CERN

Institute for particle and astroparticle physics!

Can we get support for our astroparticle activities from Slovak-CERN commision?

We have no end of fun with neutrino physics.

Mathematics is Egyptian

Neutrino physics is Babylonian

We have to communicate more with neutrinos.