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Beta decay probing weak interaction properties

Parts 4 - 6

TU Darmstadt, Sept. 3-5, 2018

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Outline- 1

1. Introduction / 2 lectures

- role of beta decay in weak interaction physics
- beta decay Hamiltonian
- beta decay angular distribution

2. ft-values / 3 lectures

- definition
- corrected ft-values
- test of CKM matrix unitarity
- role of mirror beta transitions and neutron decay

3. Correlation measurements / 5 lectures

- correlation formula
- physics content and opportunities
- testing parity violation
- searching for time reversal violation
- probing the structure of the weak interaction (scalar and tensor currents)

Outline - 2

4. Status of new physics searches / 1 lecture

- overview
- prospects and comparison to LHC
- weak magnetism

5. Beta spectrum shape / 1 lecture

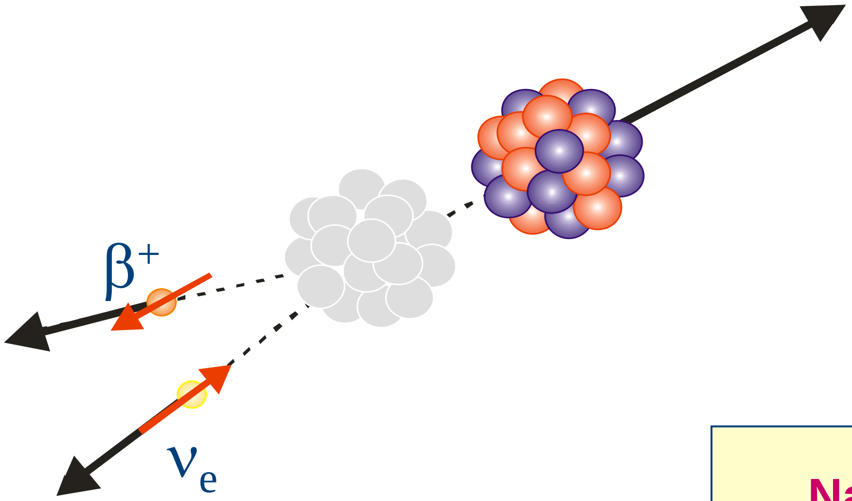
- description
- ongoing and planned experiments

6. Reactor neutrino anomaly / 1 lecture

- the problem (rate and bump)
- critical analysis
- searches for a fourth, sterile neutrino
- role of first-forbidden beta transitions

4. Status of new physics searches

overview
comparison to LHC and prospects
weak magnetism



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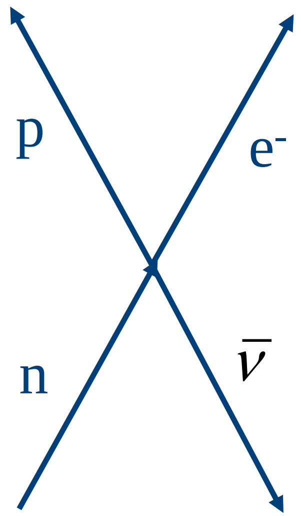
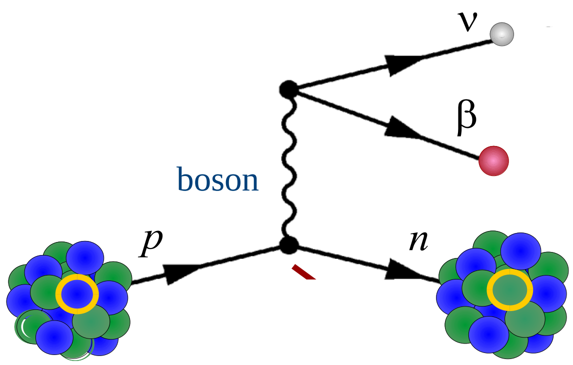
Structure of the weak interaction in β decay

β-decay Hamiltonian (Lee & Yang, 1956) :



$$H_\beta/g \propto (\bar{p}\,1\,n)\,[\bar{e}\,1\,(C_S + C_S'\gamma_5)\,\nu]$$
$$+ (\bar{p}\,\gamma_\mu\,n)\,[\bar{e}\,\gamma_\mu\,(C_V + C_V'\gamma_5)\,\nu]$$
$$+ \frac{1}{2}(\bar{p}\,\sigma_{\mu\nu}\,n)\,[\bar{e}\,\sigma_{\mu\nu}\,(C_T + C_T'\gamma_5)\,\nu]$$
$$- (\bar{p}\,\gamma_\mu\gamma_5\,n)\,[\bar{e}\,\gamma_\mu\gamma_5(C_A + C_A'\gamma_5)\,\nu]$$
$$+ \underbrace{(\bar{p}\,\gamma_5\,n)}_{\approx 0}\,[\bar{e}\,\gamma_5\,(C_P + C_P'\gamma_5)\,\nu]$$



with γ_i (i = 1, 2, 3, 4) Dirac matrices $(\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4)$

and $\sigma_{\mu\nu} = -\frac{i}{2}(\gamma_\mu\gamma_\lambda - \gamma_\lambda\gamma_\mu)$

P-violation if $C_i \neq 0$ and $C_i' \neq 0$

T-violation if $\mathrm{Im}(C_i^{(')}/C_j) \neq 0$

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$C_i^{(')}$: coupling constants for the different types of weak interaction

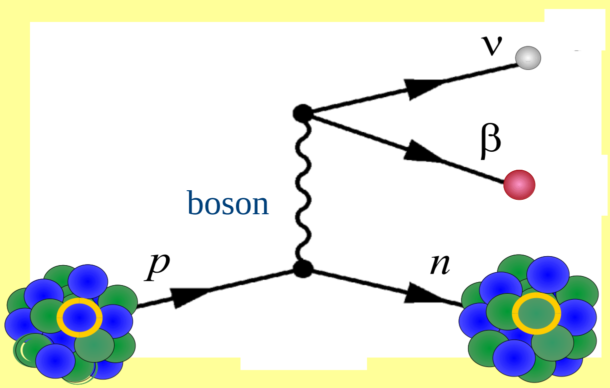
the Standard Model:

- * V-A interaction — $C_V \equiv 1$; $C_A = -1.27$ (C_A/C_V from n-decay)
- * maximal P violation — $C_V' = C_V$ & $C_A' = C_A$
- * no S, T, or P components — $C_S = C_S' = C_T = C_T' = C_P = C_P' \equiv 0$
- * no time reversal violation — all C's are real

(except for the CP-violation included in the CKM matrix)

and Beyond:

experimental upper limits for $|C_T^{(')}/C_A|$ and $|C_S^{(')}/C_V|$ at few % level
(neutron and nuclear β-decay)



5% level → ~ 350 GeV
per mille level → ~ 2.5 TeV

$$C_i \propto \frac{M_W^2}{M_{new}^2}$$

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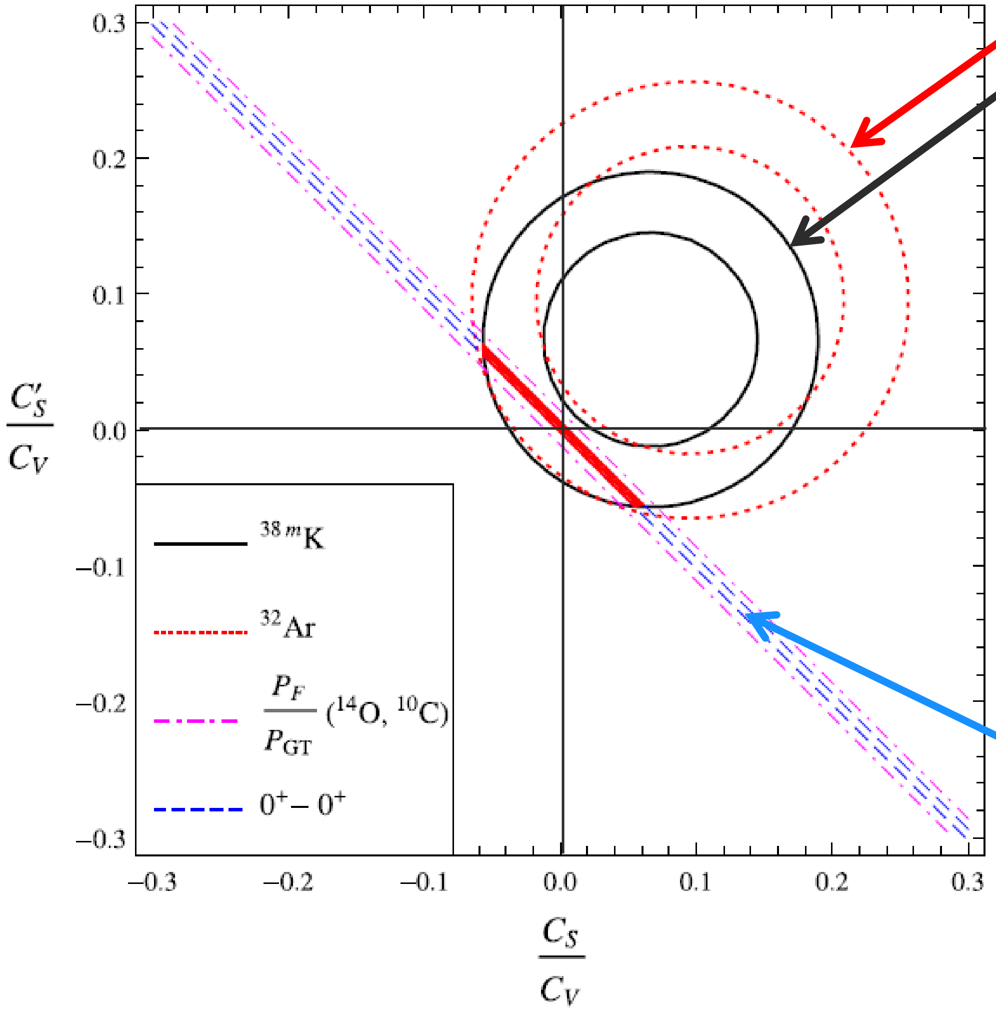
Limits on scalar currents



^{32}Ar: Adelberger et al., PRL 83 (1999) 1299

^{38m}K: Gorelov, Behr et al., PRL 94 (2005) 142501

$$\tilde{a} = \frac{a}{1 + b\,\frac{\gamma m_e}{E_e}}$$

with:

$$a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2}$$

$$b_F = \frac{\gamma m_e}{\langle E_e \rangle}\left(\frac{C_S + C'_S}{C_V}\right)$$

$$\mathcal{F}t^{0^+\to 0^+} = \frac{K}{2G_F^2 V_{ud}^2 C_V^2 \left(1 + \Delta_R^V\right)} \frac{1}{(1 + b_F)}$$

Hardy & Towner , Phys. Rev. C 91 (2015) 025501

B. R. Holstein, J. Phys. G 41 (2014) 114001

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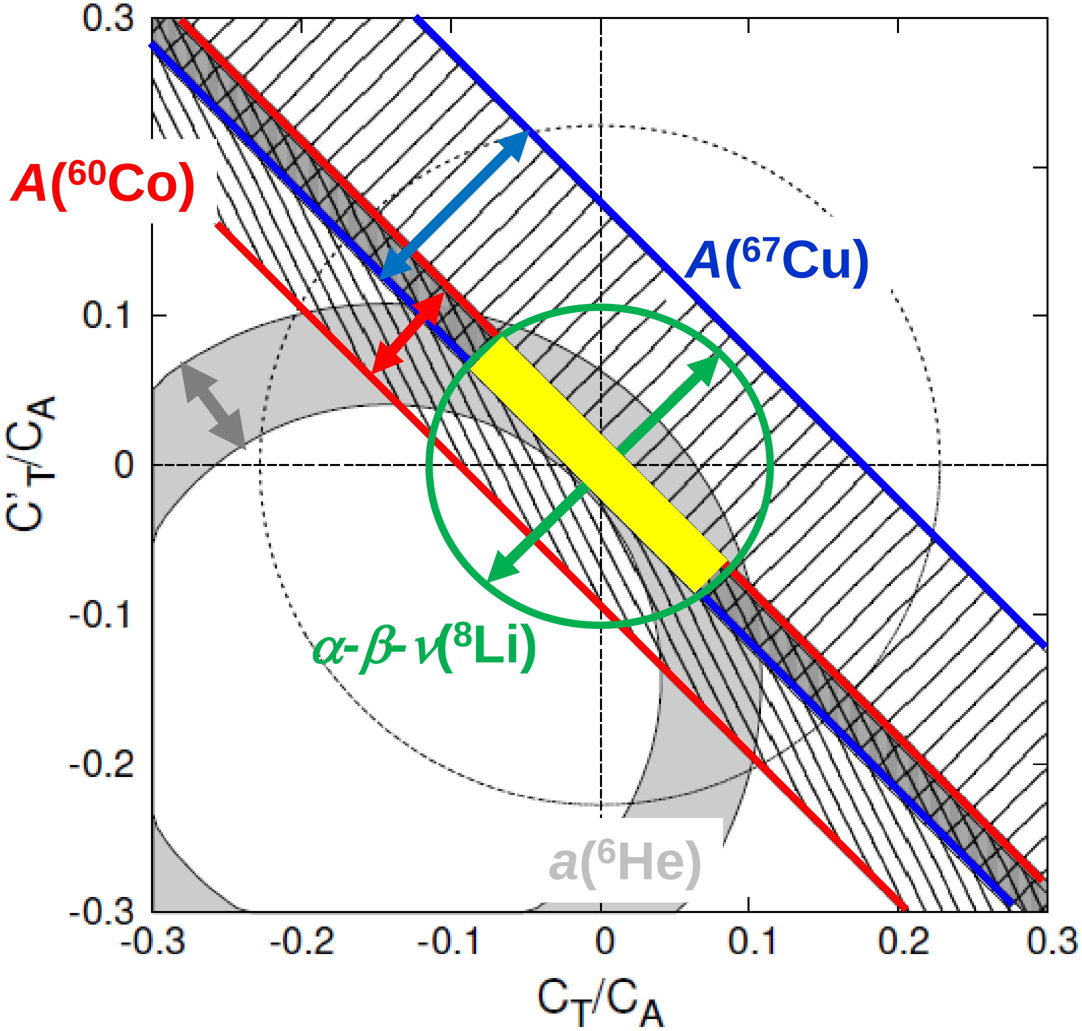
Limits on tensor currents



a(^{6}He)
C. Johnston et al., PR 132 (1963) 1149

α-β-ν(^{8}Li)
M.G. Sternberg, G.Savard et al., PRL 115 (2015) 182501

A(^{60}Co)
F. Wauters, N.S. et al., PR C 82 (2010) 055502

A(^{67}Cu)
G. Soti, N.S. et al., PR C 90 (2014) 035502

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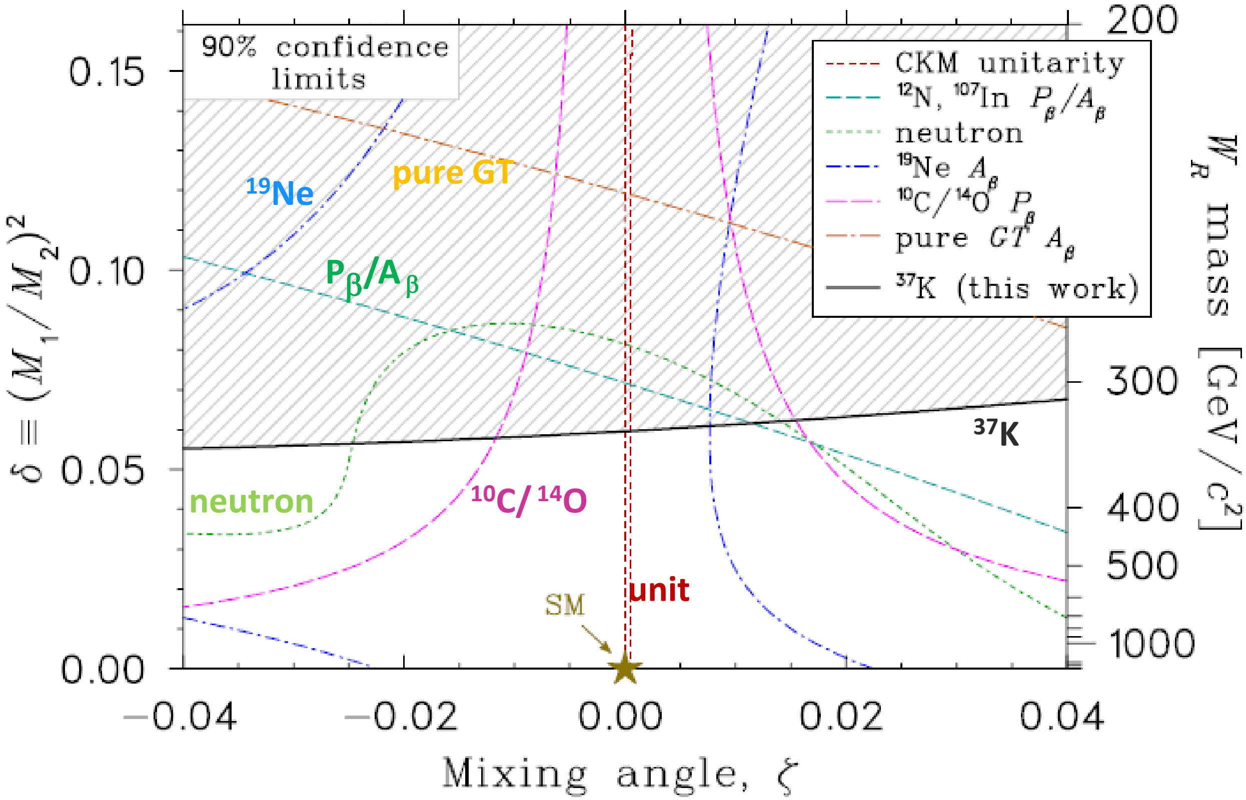

FIG. 5. (Color online) Constraints on manifest L-R symmetric models from nuclear and neutron [34] β decay. We show complementarity of our result with: CKM unitarity [16]; the ratio of β^+ polarization to A_β of ^{12}N and ^{107}In [2, 35]; A_β of mixed GT/F ^{19}Ne [14, 36–38]; the β^+ polarization of ^{10}C compared to ^{14}O [39]; and the weighted average of A_β of three recent GT cases [40–42]. All present results include SM, i.e. $\zeta = 0$ and $\delta = 0$, at 90%.

Fenker, Behr, Melconian et al., PRL 120 (2018) 062502

Status of new physics searches in beta decay

New full analysis of all experimental data available in neutron and nuclear β decay

M. Gonzalez-Alonso, O. Naviliat-Cuncic, NS, in Prog. Part. Nucl. Phys. (2018)
https://doi.org/10.1016/j.ppnp.2018.08.002 and arXiv:1803.08732

Data that were used in the fits (see arXiv:1803.08732 for details):

$\mathcal{F}t$ values from superallowed Fermi decays

Parent	$\mathcal{F}t$ (s)	$\langle m_e/E_e \rangle$
^{10}C	3078.0 ± 4.5	0.619
^{14}O	3071.4 ± 3.2	0.438
^{22}Mg	3077.9 ± 7.3	0.310
^{26m}Al	3072.9 ± 1.0	0.300
^{34}Cl	3070.7 ± 1.8	0.234
^{34}Ar	3065.6 ± 8.4	0.212
^{38m}K	3071.6 ± 2.0	0.213
^{38}Ca	3076.4 ± 7.2	0.195
^{42}Sc	3072.4 ± 2.3	0.201
^{46}V	3074.1 ± 2.0	0.183
^{50}Mn	3071.2 ± 2.1	0.169
^{54}Co	3069.8 ± 2.6	0.157
^{62}Ga	3071.5 ± 6.7	0.141
^{74}Rb	3076.0 ± 11.0	0.125

Experimental data from neutron decay

Parameter	Value	Rel. error
τ_n (s)	879.75(76)	0.09 %
a_n	−0.1034(37)	3.6 %
$\tilde{a}_n$	−0.1090(41)	3.8 %
$\tilde{A}_n$	−0.11869(99)	0.83 %
$\tilde{B}_n$	0.9805(30)	0.31 %
λ_{AB}	−1.2686(47)	0.37 %
D_n	−0.00012(20)	
R_n	0.004(13)	

Note: these are often weighted average values, including results from several experiments (see the reference above for more details).

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Data that were used in the fits (see arXiv:1803.08732 for details):

Data from measurements in nuclear decays

Parent	J_i	J_f	Type	Parameter	Value	Rel. error
^{6}He	0	1	GT/β^-	a	$-0.3308(30)^{a)}$	0.91 %
^{32}Ar	0	0	F/β^+	$\tilde{a}$	0.9989(65)	0.65 %
^{38m}K	0	0	F/β^+	$\tilde{a}$	0.9981(48)	0.48 %
^{60}Co	5	4	GT/β^-	$\tilde{A}$	−1.014(20)	2.0 %
^{67}Cu	3/2	5/2	GT/β^-	$\tilde{A}$	0.587(14)	2.4 %
^{114}In	1	0	GT/β^-	$\tilde{A}$	−0.994(14)	1.4 %
^{14}O/^{10}C			F-GT/β^+	P_F/P_{GT}	0.9996(37)	0.37 %
^{26}Al/^{30}P			F-GT/β^+	P_F/P_{GT}	1.0030 (40)	0.4 %
^{8}Li	2	2	GT/β^-	R	0.0009(22)	

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Major results from the fits (see arXiv:1803.08732 for details)

type of fit	SM	general
χ^2/ν		
$\lvert C_V \rvert$		
C_A/C_V		
C_S/C_V		
C_T/C_V		

with $|C_V| = |V_{ud}|\,(1+\Delta_R)^{1/2}\,G_F/\sqrt{2}$ and Δ_R = **0.02361(38)**

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Major results from the fits (see arXiv:1803.08732 for details)

	only Ft^{0+0+}	
type of fit	SM	general
χ^2/ν	0.51	0.44
$\lvert C_V \rvert$	0.98558(11)	0.98595(34)
C_A/C_V		
C_S/C_V		0.0014(12)
C_T/C_V		

with $\lvert C_V \rvert = \lvert V_{ud} \rvert \, (1+\Delta_R)^{1/2} \, G_F/\sqrt{2}$ and Δ_R = **0.02361(38)**

Major results from the fits (see arXiv:1803.08732 for details)

type of fit	only Ft^{0+0+} SM	only Ft^{0+0+} general	Ft^{0+0+} and neutron τ and *A* SM	Ft^{0+0+} and neutron τ and *A* general
χ^2/ν	0.51	0.44	0.61	0.46
$\lvert C_V \rvert$	0.98558(11)	0.98595(34)	0.98559(11)	0.98595(34)
C_A/C_V			-1.27510(66)	-1.2728(17)
C_S/C_V		0.0014(12)		0.0014(12)
C_T/C_V				0.0020(22)

with $\lvert C_V \rvert = \lvert V_{ud} \rvert\,(1+\Delta_R)^{1/2}\,G_F/\sqrt{2}$ and Δ_R = **0.02361(38)**

Major results from the fits (see arXiv:1803.08732 for details)

type of fit	only Ft^{0+0+} SM	only Ft^{0+0+} general	Ft^{0+0+} and neutron τ and A SM	Ft^{0+0+} and neutron τ and A general	Ft^{0+0+} and all neutron and nuclear β decay general
χ^2/ν	0.51	0.44	0.61	0.46	0.65
$\|C_V\|$	0.98558(11)	0.98595(34)	0.98559(11)	0.98595(34)	reduction of statistical uncertainty by up to 10%
C_A/C_V			-1.27510(66)	-1.2728(17)	
C_S/C_V		0.0014(12)		0.0014(12)	
C_T/C_V				0.0020(22)	

M. Gonzalez-Alonso, O. Naviliat-Cuncic, N.S., in Prog. Part. Nucl. Phys. (2018)
https://doi.org/10.1016/j.ppnp.2018.08.002 and arXiv:1803.08732

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Major results from the fits (see arXiv:1803.08732 for details)

type of fit	Ft^{0+0+} and neutron τ and A general	present uncertainty x 10^{-4}	projected uncertainty x 10^{-4}
χ^2/ν	0.44		
$\lvert C_V \rvert$	0.98595(34)	3.4	2
C_A/C_V	-1.2728(17)	17	2
C_S/C_V	0.0014(12)	12	7
C_T/C_V	0.0020(22)	22	4

type of error and observable	present uncertainty	projected uncertainty
$\Delta\tau$	0.8 s	0.1 s
δa_n	3.6%	0.1%
$\delta \tilde{A}_n$	0.8%	0.1%
$\delta \tilde{a}_F$	0.5%	0.1%
δa_{GT}	0.9%	0.1%
Δb_{GT}	0.01	0.001

M. Gonzalez-Alonso, O. Naviliat-Cuncic, N.S., in Prog. Part. Nucl. Phys. (2018)
https://doi.org/10.1016/j.ppnp.2018.08.002 and arXiv:1803.08732

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Major results from the fits (see arXiv:1803.08732 for details)

type of fit	Ft^{0+0+} and neutron τ and *A* general	present uncertainty x 10^{-4}	projected uncertainty x 10^{-4}
χ^2/ν	0.44		
$\lvert C_V \rvert$	0.98595(34)	3.4	2
C_A/C_V	-1.2728(17)	17	2
C_S/C_V	0.0014(12)	12	7
C_T/C_V	0.0020(22)	22	4

using $C_i \approx \frac{M_W^2}{M_{new}^2}$

Note: values below are very approximative !!

C_S/C_V (present): $M_S > 2.15^{+3.50}_{-0.60}$ TeV

C_S/C_V (projected): $M_S > 3.0$ TeV

C_T/C_V (present): $M_T > 1.80^{+\infty}_{-0.55}$ TeV

C_T/C_V (projected): $M_S > 4.0$ TeV

Precision meas[ts] in nuclear/neutron β decay in the LHC era

if particles that mediate new interactions are above threshold for LHC
→ Effective Field Theory allowing
direct comparison of low-energy and collider constraints

low-scale O(1 GeV) effective Lagrangian for semi-leptonic transitions
(contributions from W-exchange diagrams and four-fermion operators)

link betw. EFT couplings ε_i and Lee-Yang nucleon-level effect. couplings C_i:

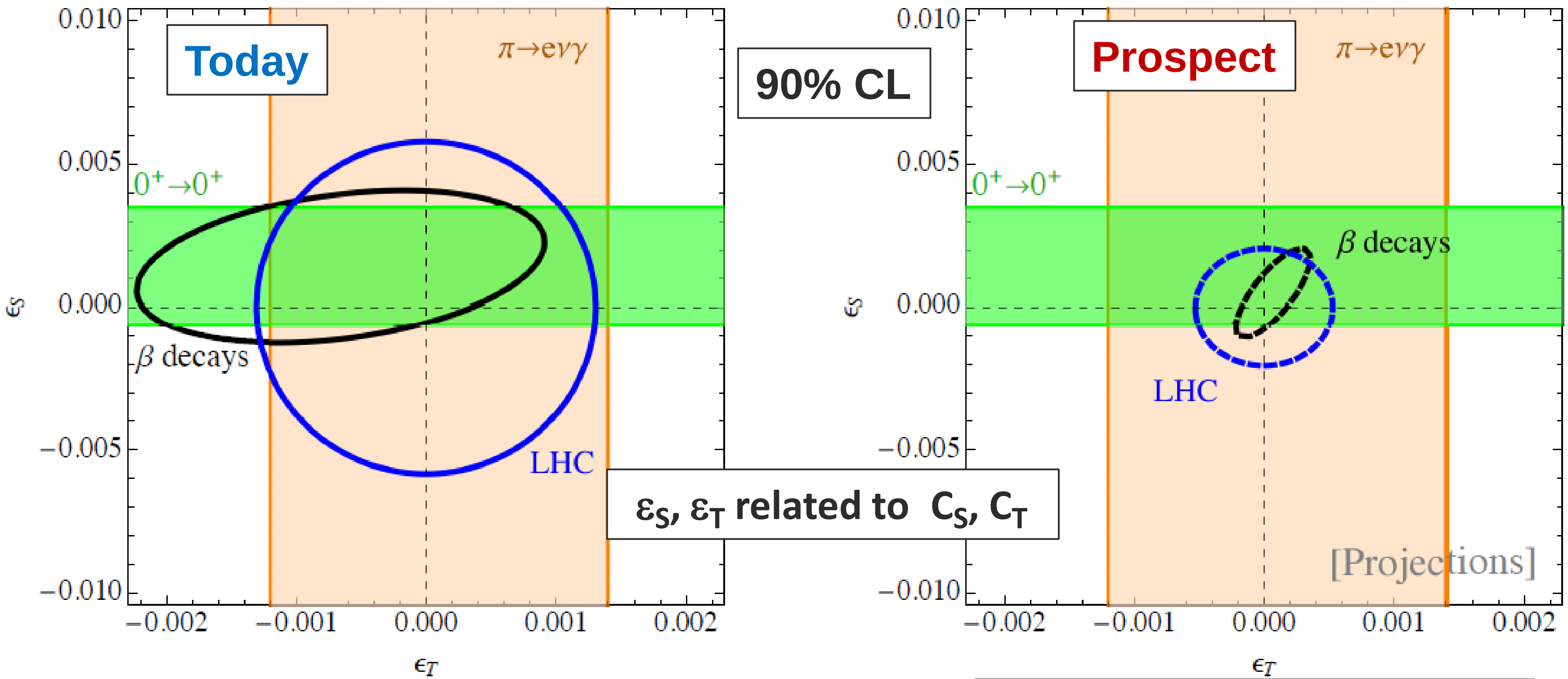
$$C_i = \frac{G_F(0)}{\sqrt{2}} V_{ud} \bar{C}_i \quad \text{with} \quad \bar{C}_S = g_S(\varepsilon_S + \tilde{\varepsilon}_S), \; \bar{C}_T = 4 g_T(\varepsilon_T + \tilde{\varepsilon}_T), \; \ldots$$

$$\varepsilon_i, \; \tilde{\varepsilon}_i \approx \; v^2 / \Lambda^2_{BSM} \quad \text{with} \quad v = (2\sqrt{2}\; G_F^{(0)})^{-1/2} \approx 170 \text{ GeV}$$

$$\text{if} \;\; \Lambda_{BSM} \sim 5 \text{ TeV} \;\; \rightarrow \;\; \varepsilon_i \sim 10^{-3}$$

T. Bhattacharya et al., Phys. Rev. D 85 (2012) 054512
V. Cirigliano, et al., J. High. Energ. Phys. 1302 (2013) 046
O. Naviliat-Cuncic and M. Gonzalez-Alonso, Annalen der Physik 525 (2013) 600
V. Cirigliano, et al., Progr. Part. Nucl. Phys. 71 (2013) 93

Measurements in nuclear/neutron β decay in the LHC era



- current status of beta decays;
- LHC $pp \to e + \mathrm{MET} + X$ at 8 TeV, 20 fb^{-1}.

Prospects for:

- 0.1 s on neutron lifetime
- 0.1 % for A_n, a_n, a_F and a_{GT}
- abs.unc. of 0.001 on b_{GT}
- LHC: 14 TeV, 300 fb^{-1}.

see also:

V. Cirigliano et al., J. High. Energ. Phys. 1302 (2013) 046
O. Naviliat-Cuncic and M. Gonzalez-Alonso, Annalen der Physik 525 (2013) 600

Table 3: Selected ongoing and planned experiments discussed in Section 3. See main text for details. The approximate relative precision goals are given together with their reference. If the SM value is zero, the absolute precision goal is then given. When precision goals are given as a percentage, relative uncertainties are meant. The symbol $\mathcal{O}$ refers to the estimated order of magnitude for a precision goal. The precisions given for a are obtained setting the Fierz term b to zero (see Section 4.2 and Ref. [95]).

Coefficient	Precision goal	Experiment (Laboratory)	Comments
τ_n	1.0 s; 0.1 s [210]	BL2, BL3 (NIST) [210]	In preparation; two phases
	1.0 s; 0.3 s [214]	LiNA (J-PARC) [211, 214]	In preparation; two phases
	0.2 s [215]	Gravitrap (ILL) [203, 215]	Apparatus being upgraded
	0.3 s [201]	Ezhov (ILL) [201]	Under construction
	0.1 s [222]	PENeLOPE (Munich) [222]	Being developed
	$\lesssim$ 0.1 s [223]	UCNτ (LANL) [188, 189, 223, 224]	Ongoing
	0.5 s [225]	HOPE (ILL) [188, 225, 226]	Proof of principle Ref. [226]
	1.0 s; 0.2 s [188]	τSPECT (Mainz) [188, 227]	Taking data; two phases
β-spectrum	$\mathcal{O}(0.01)$ [256]	Supercond. spectr. (Madison) [256]	Shape factor Eq. (51). Ongoing
β-spectrum	$\mathcal{O}(0.01)$ [253]	Si-det. spectr. (Saclay) [253, 254]	Shape factor Eq. (51). Ongoing
b_{GT}	0.001	Calorimetry (NSCL) [115, 260]	Analysis ongoing (^{6}He, ^{20}F)
	$\mathcal{O}(0.001)$ [270]	miniBETA (Krakow-Leuven) [263–265, 270]	Being commissioned
	$\mathcal{O}(0.001)$ [276]	UCNA-Nab-Leuven (LANL) [271, 272, 276]	Analysis ongoing (^{45}Ca)
b_n	< 0.05 [293, 294]	UCNA (LANL) [390]	Ongoing with A_n data
	0.03 [295]	PERKEO III (ILL) [295]	Possible with A_n data
	0.003 [289]	Nab (LANL) [188, 289, 357, 358]	In preparation
	0.001 [291]	PERC (Munich) [291, 292]	Planned

M. Gonzalez-Alonso, O. Naviliat-Cuncic, N.S., in Prog. Part. Nucl. Phys. (2018)
https://doi.org/10.1016/j.ppnp.2018.08.002 and arXiv:1803.08732

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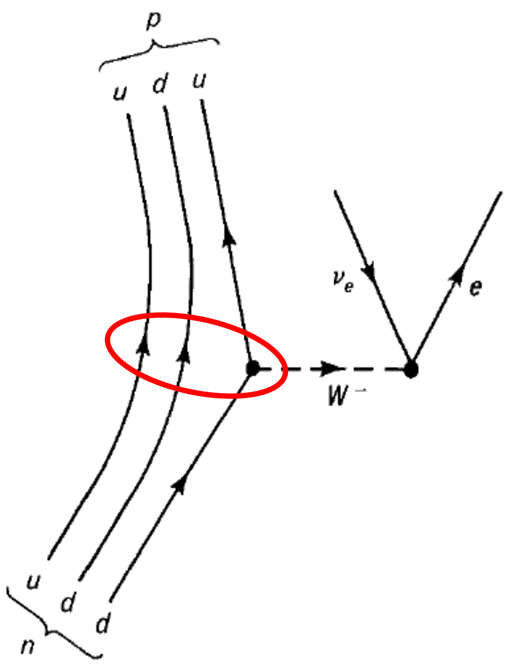
Table 3, continued

a_F	0.1% [306]	TRINAT (TRIUMF) [306, 310]	Planned (^{38}K)
	0.1% [343]	TAMUTRAP (TA&M) [343]	Superallowed βp emitters
	0.1% [79]	WISArD (ISOLDE) [79, 177]	In preparation (^{32}Ar βp decay)
a	not stated	Ne-MOT (SARAF) [311, 312]	In preparation (^{18}Ne, ^{19}Ne, ^{23}Ne)
a_{GT}	$\mathcal{O}(0.1)$% [315]	^{6}He-MOT (Seattle) [313, 315]	Ongoing (^{6}He)
	not stated	EIBT (Weizmann Inst.) [316–318]	In preparation (^{6}He)
	0.5% [182]	LPCTrap (GANIL) [182, 321, 323, 324]	Analysis ongoing (^{6}He, ^{35}Ar)
a_{mirror}	0.5% [273]	NSL-Trap (Notre Dame) [273, 344, 345]	Planned (^{11}C, ^{13}N, ^{15}O, ^{17}F)
$\tilde{a}_n$	1.0% [350]	*a*CORN (NIST) [350, 352–354]	Data taking ongoing
a_n	1.0 – 1.5% [351]	*a*SPECT (ILL) [228, 229, 351]	Analysis being finalized
	0.15% [188, 358]	Nab (LANL) [188, 289, 357, 358]	In preparation
$\tilde{A}_n$	0.14% [391]	UCNA (LANL) [390]	Data taking planned
	0.18% [295]	PERKEO III (ILL) [295]	Analysis ongoing
$\tilde{A}_{mirror}$	$\mathcal{O}(0.1)$% [78]	TRINAT (TRIUMF) [78]	Planned
$\tilde{B}_n$	0.01% [397]	UCNB (LANL) [397]	Planned
$\tilde{A}_n$ $(a_n, \tilde{B}_n, \ldots)$	0.05% [291]	PERC (Munich) [291, 292]	In preparation
$\tilde{A}_n$ $(a_n, \tilde{B}_n, \ldots)$	$< \mathcal{O}(0.1)$% [399]	BRAND (ILL/ESS) [399, 400]	Proposed
D	$\mathcal{O}(10^{-4})$ [418]	MORA (GANIL / JYFL) [418]	In preparation (^{23}Mg)
R	$\mathcal{O}(10^{-3})$ [427]	MTV (TRIUMF) [427–429]	Data taking ongoing (^{8}Li)
D, R	$\mathcal{O}(0.1)$% [399]	BRAND (ILL) [399, 400]	Proposal

M. Gonzalez-Alonso, O. Naviliat-Cuncic, N.S., in Prog. Part. Nucl. Phys. (2018)
https://doi.org/10.1016/j.ppnp.2018.08.002 and arXiv:1803.08732

Taking into account effects of strong interaction



quark involved in β decay is not free
but **bound in a nucleon**

→ extra **terms induced** by the **strong interaction,**
in addition to those related to F and GT matrix elements;
largest is 'weak magnetism' term

$$J_\mu^{\mathrm{HS}} = i\langle \bar{u}_p \left[g_V \gamma_\mu - \frac{g_M - g_V}{2M} \sigma_{\mu\nu} q^\nu + i \frac{g_S}{2M} q_\mu + g_A \gamma_5 \gamma_\mu - \frac{g_{II}}{2M} \sigma_{\mu\nu} \gamma_5 q^\nu + i \frac{g_P}{2M} \gamma_5 q_\mu \right] u_n \rangle, \quad (83)$$

where[12] $\sigma_{\mu\nu} = -(i/2)[\gamma_\mu, \gamma_\nu]$ and all C and g are functions of q^2.

'weak magnetism' term:

- modifies values for correlation coefficients at level of per mille to 1%

→ **important for correlation measurements at sub-percent level**

weak magnetism term b_{WM} (Impulse Approximation)

$$b_{WM} \cong A\,(g_M M_{GT} + g_V M_L)$$

Matrix element	Operator form
M_{GT}	$\langle\beta\|\Sigma\tau_i^{\pm}\vec{\sigma}_i\|\alpha\rangle$
M_L	$\langle\beta\|\Sigma\tau_i^{\pm}\vec{l}_i\|\alpha\rangle$

$$\frac{b_{WM}}{Ac} \cong \left[\frac{g_M}{g_A} + \frac{g_V}{g_A}\frac{M_L}{M_{GT}}\right]$$

$$c \cong g_A M_{GT}$$

A: mass of nucleus

g_M: weak magn. coupl. const. = 4.706 (= μ_p - μ_n)

g_V: vector coupl. const. = 1

g_A: axial-vector coupl. const. = 1.00 (quenched)

(Impulse approximation neglects interactions with neighboring nucleons)

B. R. Holstein, RMP 46 (1974) 789 - F.P. Calaprice et al., PR C 15 (1977) 2178

weak magnetism for T = 1/2 $J^\pi \rightarrow J^\pi$ mirror β transitions

e.g. ${}^{19}_{10}Ne_9 \rightarrow {}^{19}_{9}F_{10}\ e^+\ \bar{\nu}_e$

$$b_{WM}(\beta^\mp) = A\sqrt{\frac{J}{J+1}}\,M_F^0\ \mu^\mp$$

$$\mu^\mp = \mp(\mu_M - \mu_D)$$

(based on CVC)

e.g. F.P. Calaprice and B.R. Holstein
Nucl. Phys. A 273 (1976) 301

observables usually expressed in terms of $\dfrac{b}{Ac}$

$c = g_A M_{GT}$ from Ft-value :

$$\mathcal{F}t^{mirror} \equiv f_V t(1+\delta_R')(1+\delta_{NS}^V - \delta_C^V) = \frac{2\mathcal{F}t^{0^+\to 0^+}}{\left(1+\frac{f_A}{f_V}\rho^2\right)}$$

$$\rho \cong g_A M_{GT}^0 = c$$

N. Severijns, I.S. Towner et al.,
Phys. Rev. C 78 (2008) 055501

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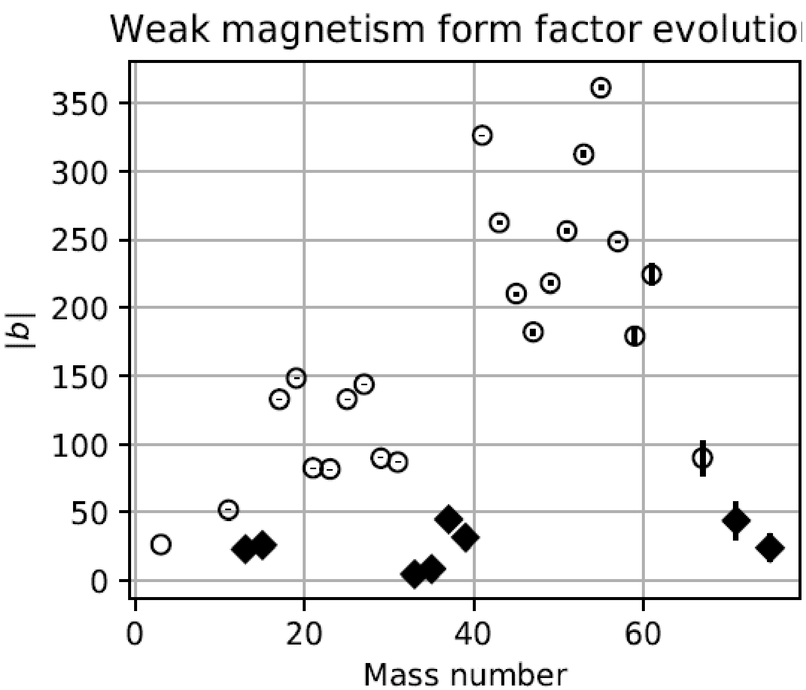
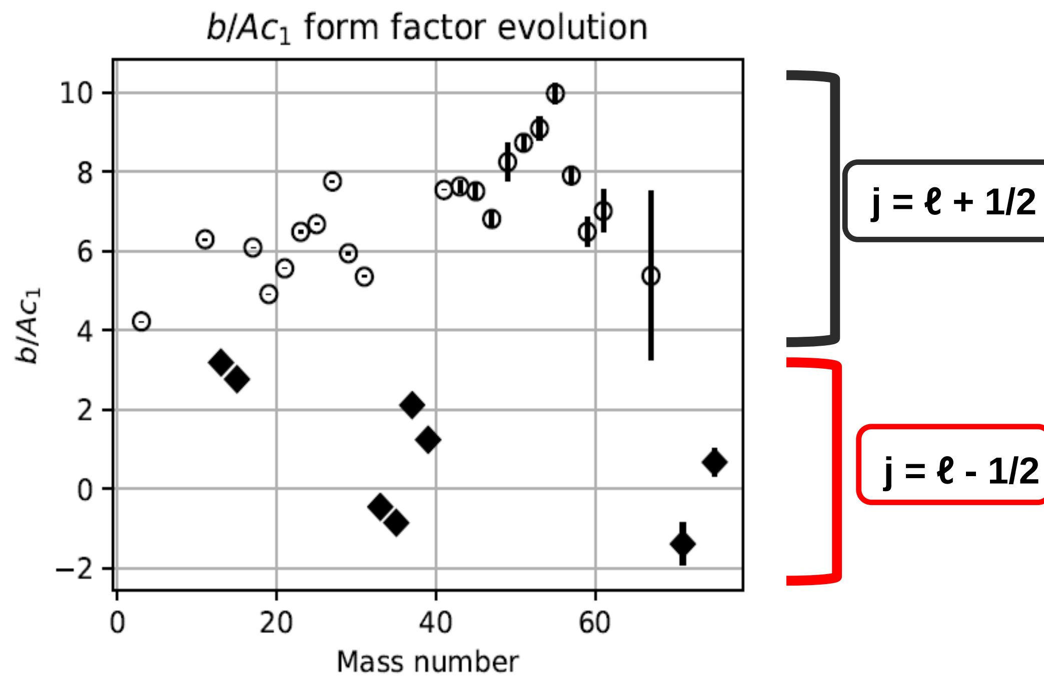
weak magnetism term b_{WM} - T=1/2 mirror transitions

mirror β transitions - results

- updated Ft-values (A < 75; rel. prec. < 0.2% up to A < 41)
- extracted weak magnetism form factor





N. Severijns, L. Hayen, I.S. Towner, et al., to be published

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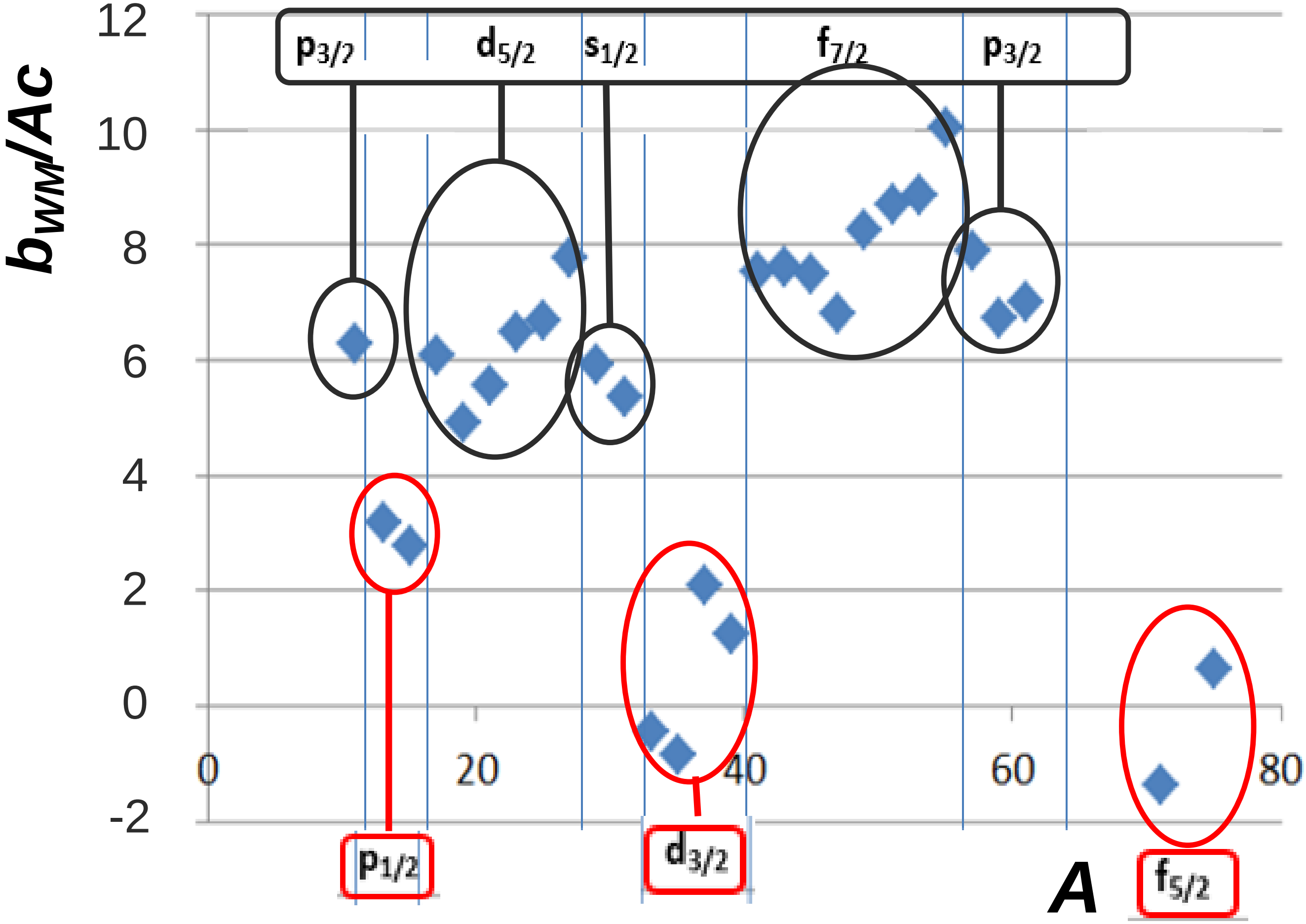
mirror β transitions - results

$$b_{WM} \approx \mu_{mother} - \mu_{daughter}$$



the value of b_{WM}/Ac depends on the shell-model orbital of the odd-particle,

and is large for shells with j = ℓ + 1/2:

j = ℓ + 1/2

and small for shells with j = ℓ + 1/2:

j = ℓ - 1/2

(this is related to the Schmidt values)

N. Severijns, L. Hayen, I.S. Towner, et al., to be published

error bars are smaller than size of dots

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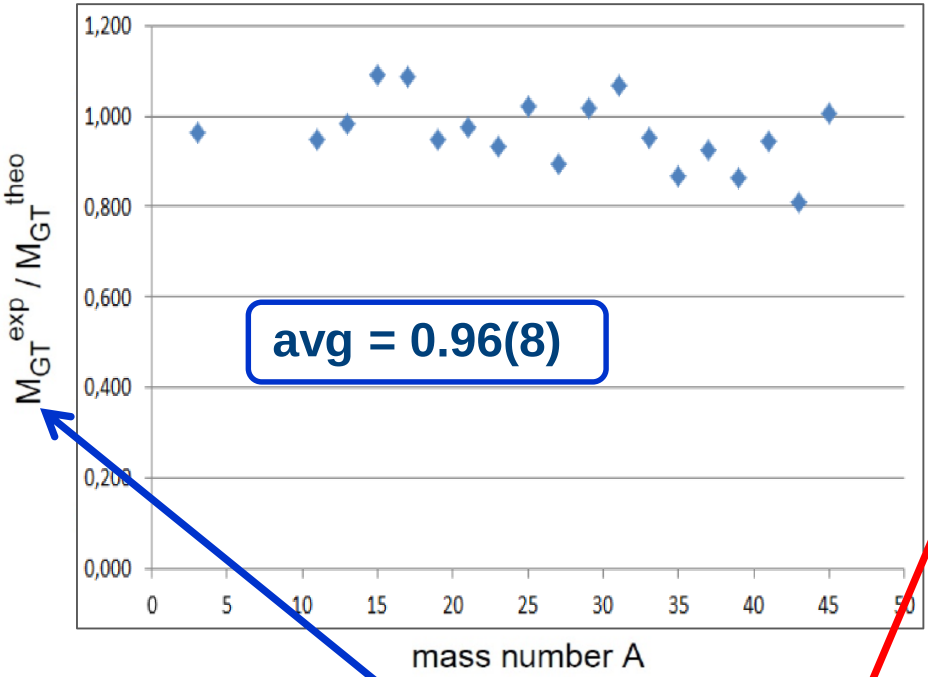
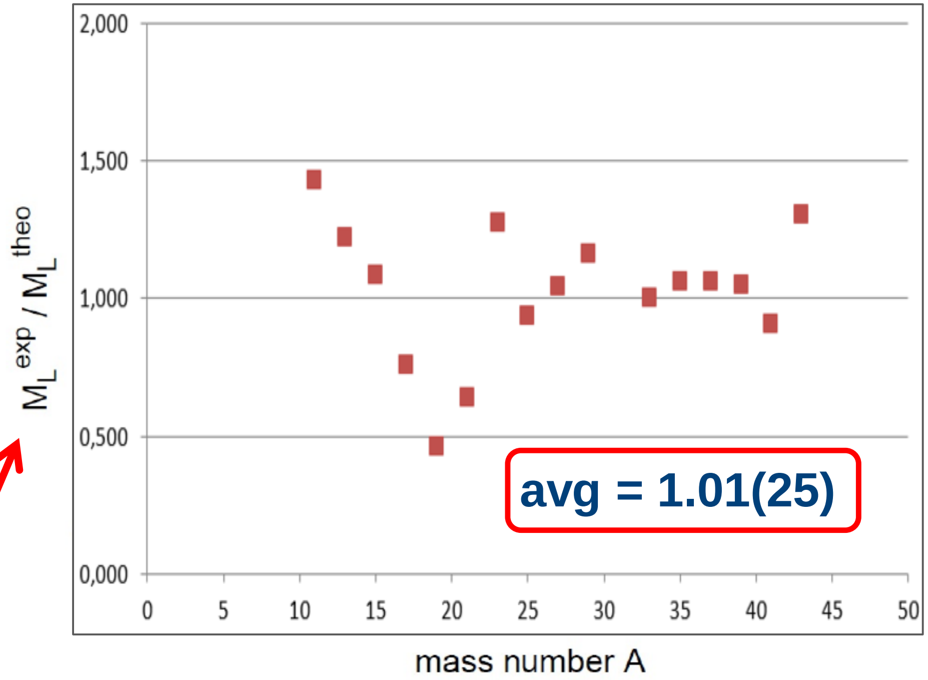
mirror β transitions – comparison with theory





$$c \cong g_A M_{GT}$$

(impulse approx.)

$$\frac{b_{WM}}{Ac} \cong \left[\frac{g_M}{g_A} + \frac{g_V}{g_A} \frac{M_L}{M_{GT}} \right]$$

B. R. Holstein, RMP 46 (1974) 789
F.P. Calaprice et al., PR C 15 (1977) 2178

	$(b/Ac)^{exp} / (b/Ac)^{theo}$
mirror (A = 3-45)	**0.97(11)**
triplet (A = 6-30)	**1.01(15)**

N. S., I.S. Towner, L. Hayen et al., to be published

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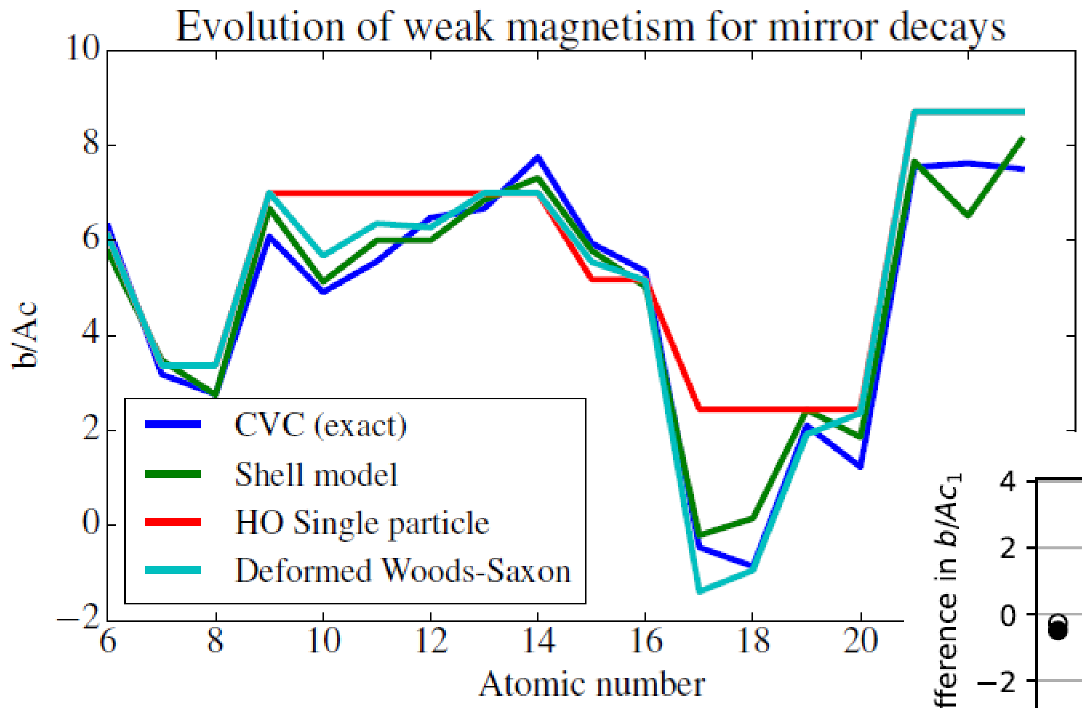
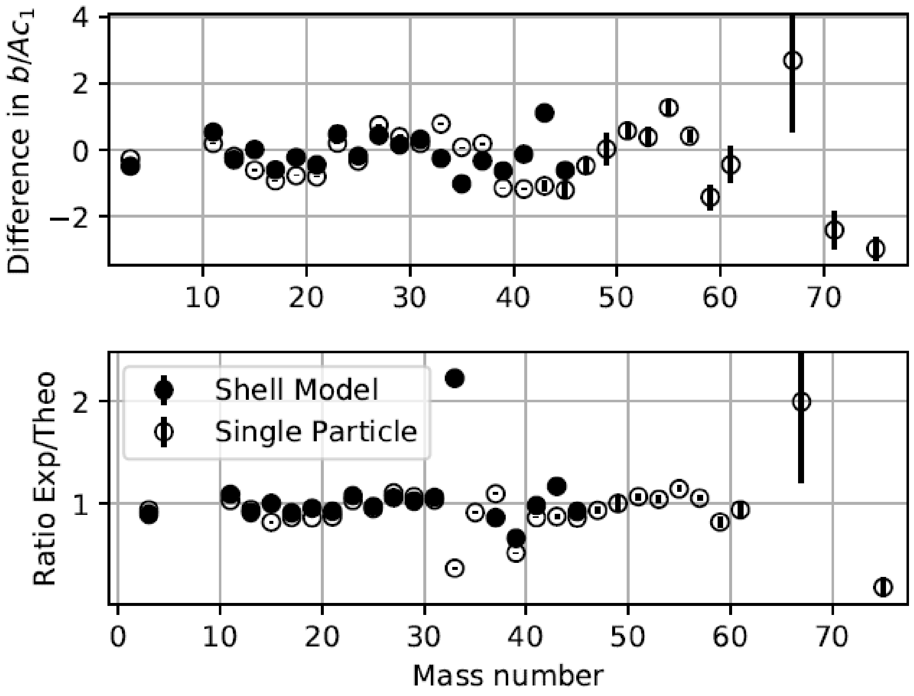
mirror β transitions – comparison with theory



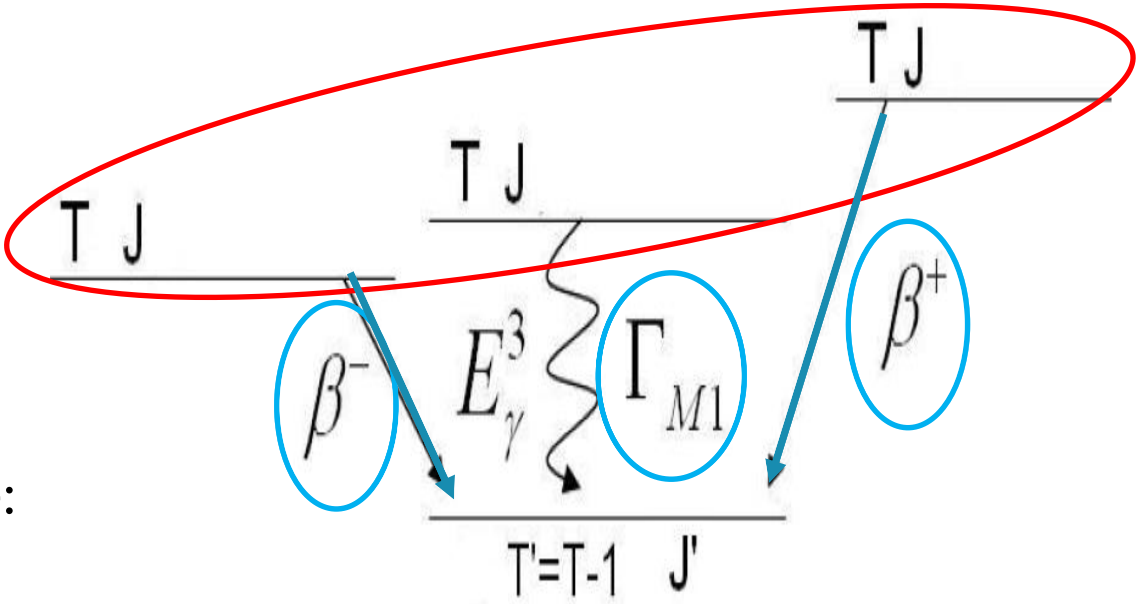
for mirror decays up to mass 45



N. S., L. Hayen, I.S. Towner et al., to be published

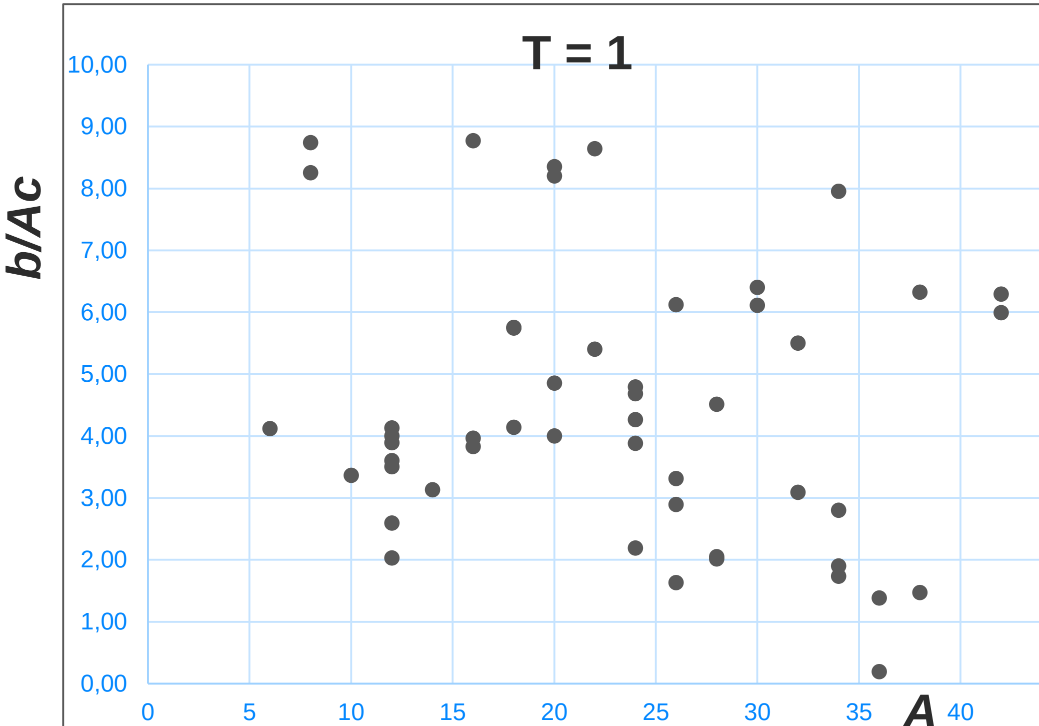
weak magnetism b_{WM} - triplet states

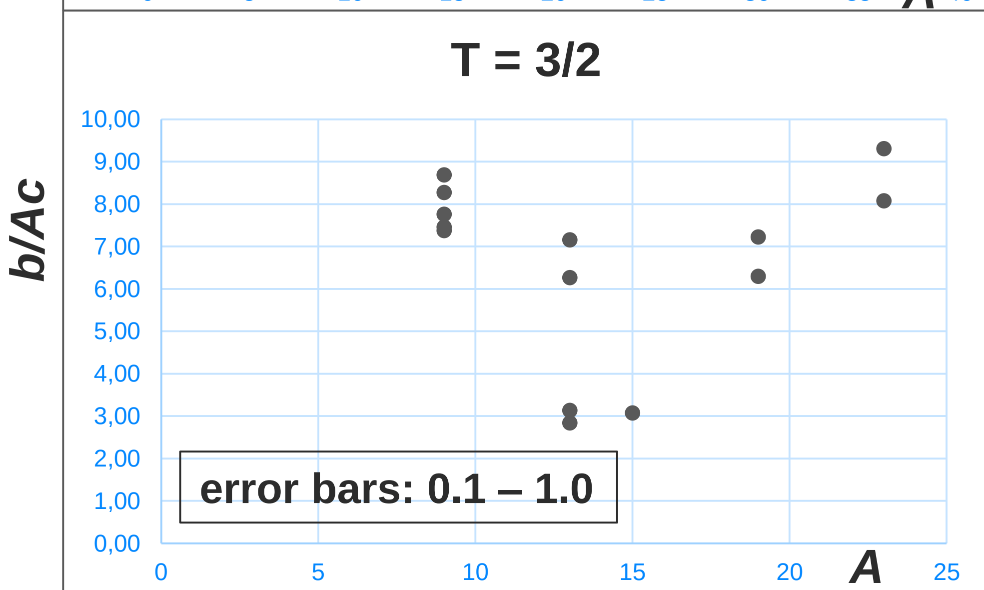
$$b_{WM}^2 = 6\frac{\Gamma_{M1} M^2}{E_\gamma^3 \alpha}$$

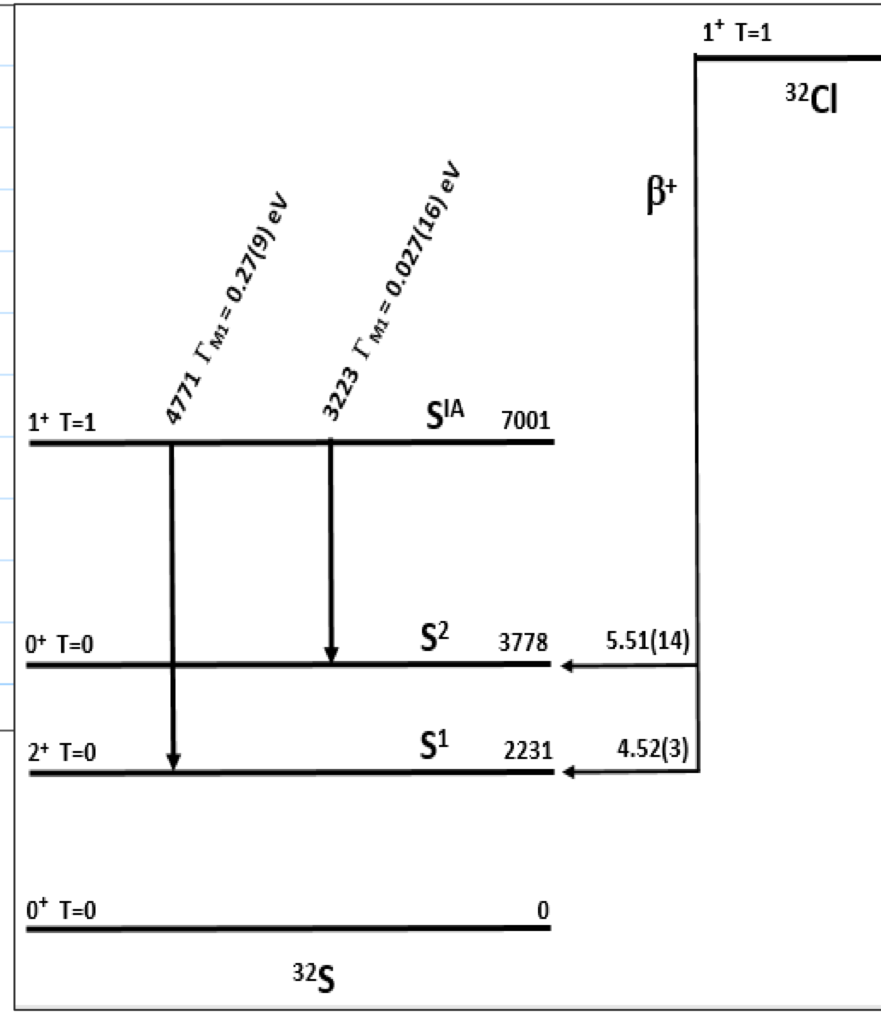


$c = g_A M_{GT}$ from *ft*-value:

$$ft = \frac{K}{G_F^2\ V_{ud}^2} \frac{1}{[M_F^2 C_V^2 + M_{GT}^2 C_A^2]}$$







N. Severijns et al., in preparation

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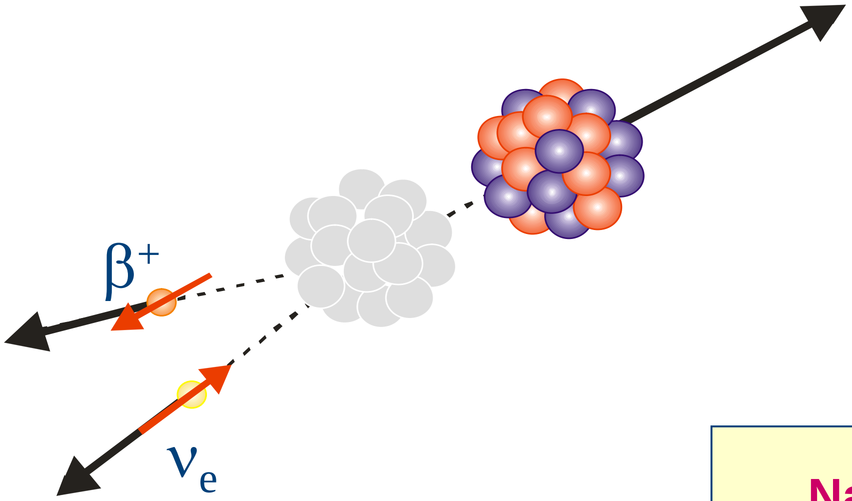
5. Beta spectrum shape



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β spectrum shape measurements

precise β-spectrum shape measurements:

$$d\Gamma \propto G_F \; F(Z,E) \left[1 + \mathrm{k} \frac{1}{E_\beta} b_{Fierz} + k^{'} \, E_\beta \, b_{WM} \right]$$

b_{Fierz} : scalar / tensor weak currents

b_{WM} : weak magnetism (Standard Model term)

- induced by strong interaction because decaying quark is not free but bound in a nucleon;
- is to be known better when reaching sub-percent precisions

Note the different energy dependence of both effects !!

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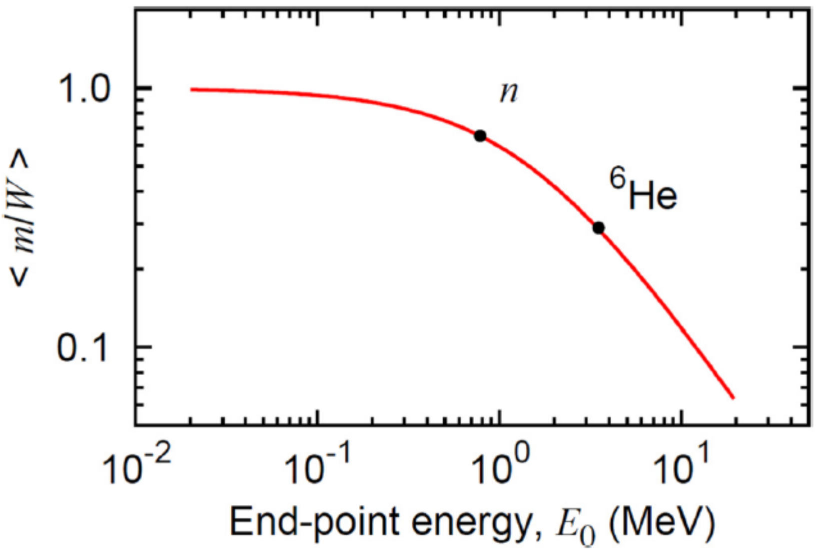
Kinematic sensitivity to the Fierz term of beta decay differential spectra

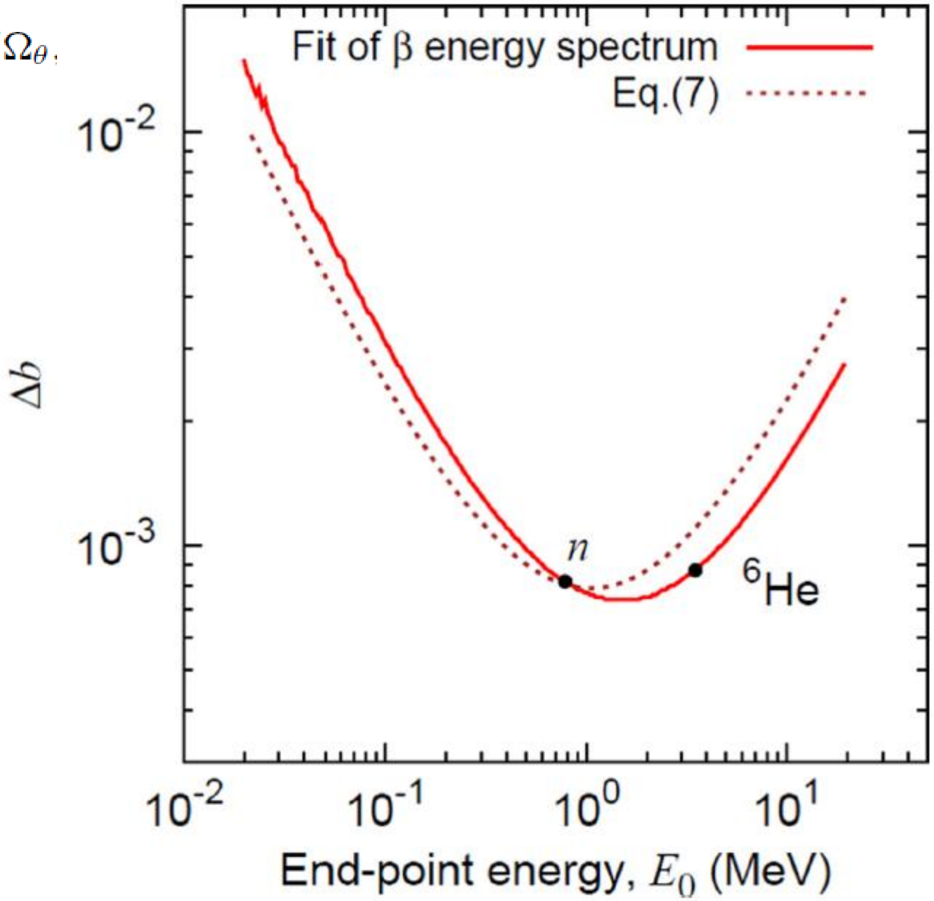
M. Gonzalez-Alonso, O. Naviliat-Cuncic
Phys. Rev. C 94 (2016) 035506

$$N(W,\theta)dW d\Omega_\theta = P(W)\left[1 + b\frac{m}{W} + a\frac{p}{W}\cos\theta\right]dW d\Omega_\theta,$$

with $$P(W)dW = pWq^2 dW.$$

$$\rightarrow \quad N_0 = 1 + b\left\langle \frac{m}{W} \right\rangle$$





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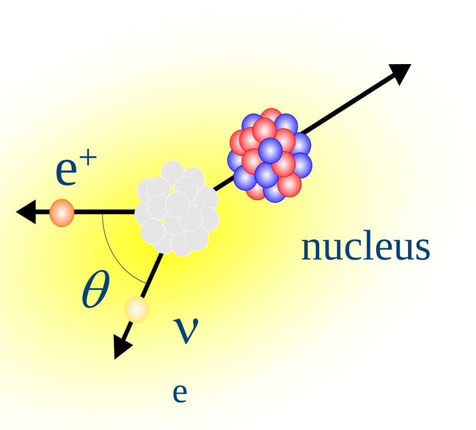
description of β spectrum shape

Analytical description + code, accurate to few 10^{-4} level
L. Hayen, N.S. et al., Rev. Mod. Phys. 90 (2018) 015008

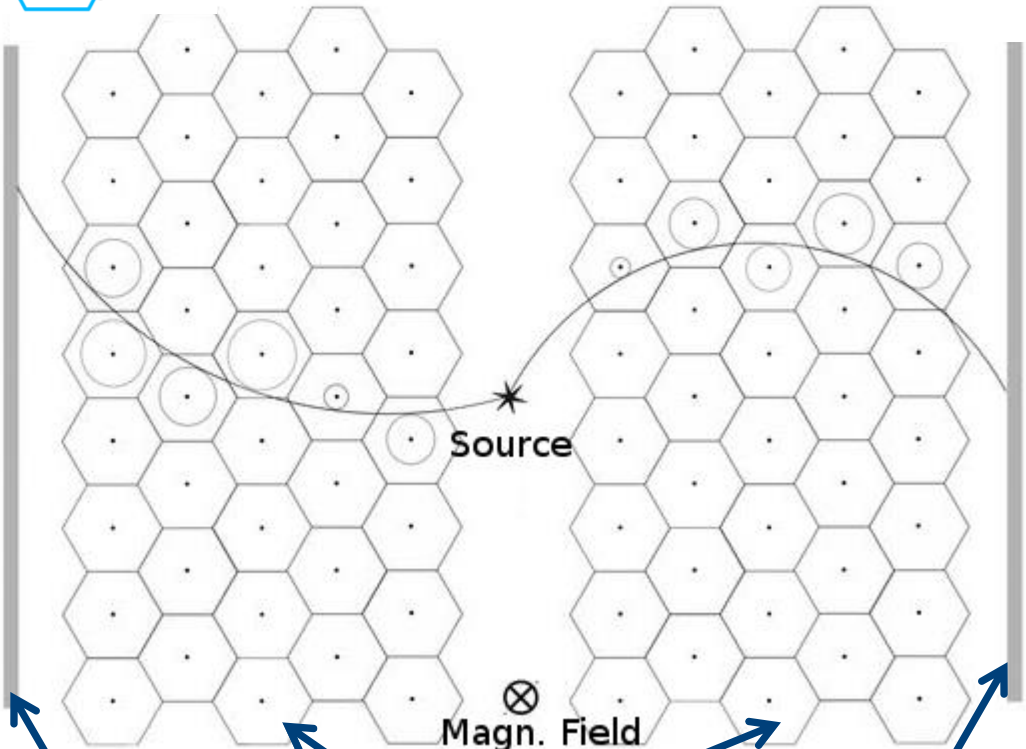
Table VI Overview of the features present in the β spectrum shape (Eq. (4)), and the effects incorporated into the Beta Spectrum Generator Code. Here the magnitudes are listed as the maximal typical deviation for medium Z nuclei with a few MeV endpoint energy. Some of these corrections fall off very quickly (e.g. the exchange correction, X) but can be sizeable in a small energy region. Varying Z or W_0 can obviously allow for some migration within categories for several correction terms.

Item	Effect	Formula	Magnitude
1	Phase space factor	$pW(W_0 - W)^2$	Unity or larger
2	Traditional Fermi function	F_0 (Eq. (5))	
3	Finite size of the nucleus	L_0 (Eq. (17))	10^{-1}-10^{-2}
4	Radiative corrections	R (Eq. (27))	
5	Shape factor	C (Eq. (125))	
6	Atomic exchange	X (Eq. (63))	
7	Atomic mismatch	r (Eq. (76))	
8	Atomic screening	S (Eq. (54)) [a]	10^{-3}-10^{-4}
9	Shake-up	See item 7 &	
10	Shake-off	See item 7 &	
11	Distorted Coulomb potential due to recoil	Q (Eq. (26))	
12	Diffuse nuclear surface	U (Eq. (20))	
13	Recoiling nucleus	R_N (Eq. (22))	
14	Molecular screening	ΔS_{Mol} (Eq. (81))	
15	Molecular exchange	Case by case	
16	Bound state β decay	Γ_b/Γ_c (Eq. (77))	Smaller than $1 \cdot 10^{-4}$
17	Neutrino mass	Negligible	
18	Forbidden decays	Not incorporated	



[a] Here the Salvat potential of Eq. (57) is used with X (Eq. (55)) set to unity.
[b] The effect of shake-up on screening was discussed in Sec. VI.C.1 with Eq. (66).
[c] Shake-off influences on screening and exchange corrections were discussed separately in Sec. VI.C.2. This has to be evaluated in a case by case scenario.

1. miniBETA spectrometer
Leuven / Krakow



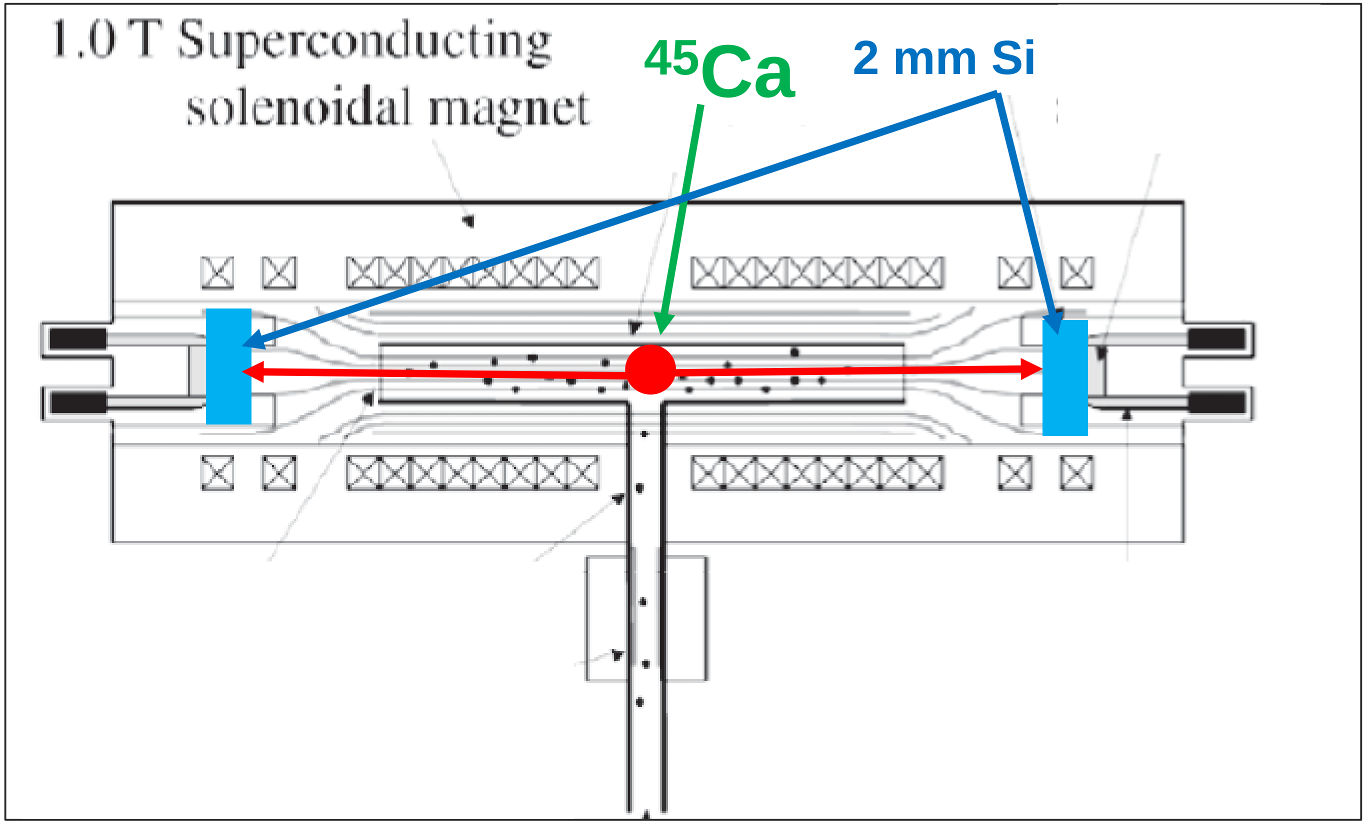
multi-wire drift chamber

scintillator (later DSSDD)

2. double-Si spectrometer
Leuven / LANL, A. Young

two 2 mm segmented **Si** detectors in B- field, replacing UCNA MWPCs

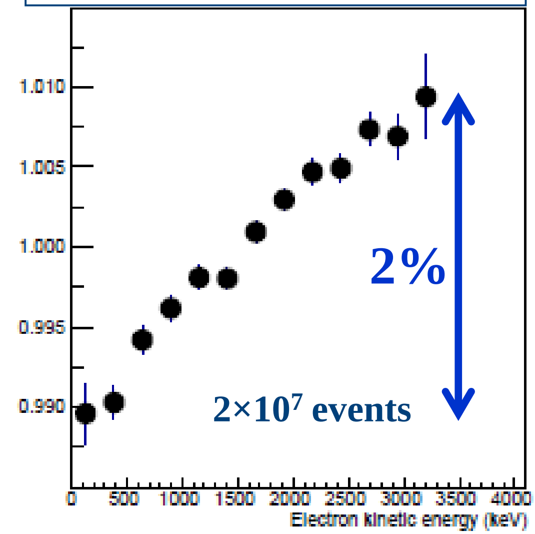
- data in May 2017
- analysis ongoing

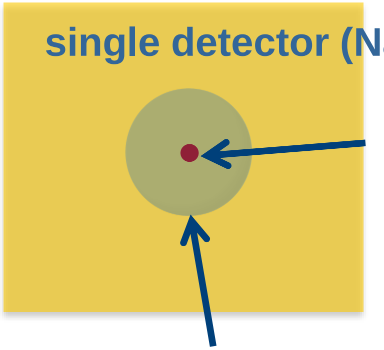


3. Beta energy spectrum shape in ^{6}He decay NSCL/MSU

- **Long term goal**: Measure the **Fierz interference term** (*b*) in ^{6}He, ^{20}F decay to search for weak tensor currents.
- **Current goal**: measure the **weak magnetism** (WM) form factor in ^{6}He, ^{20}F decay for a tests of the strong form of CVC. The WM is the largest "hadronic SM background" in a measurement of *b*.

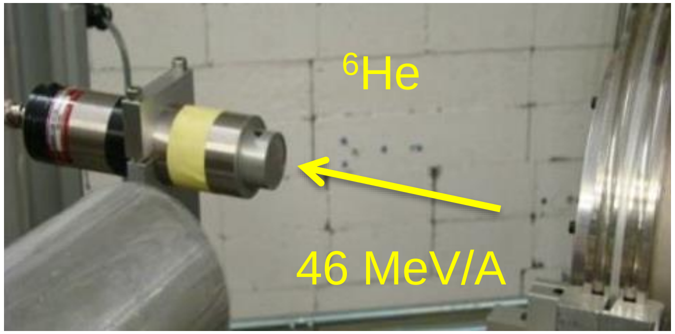
Effect of weak magnetism
(Monte-Carlo simulation)

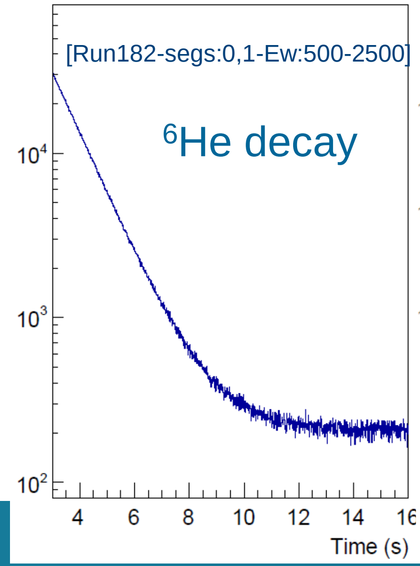


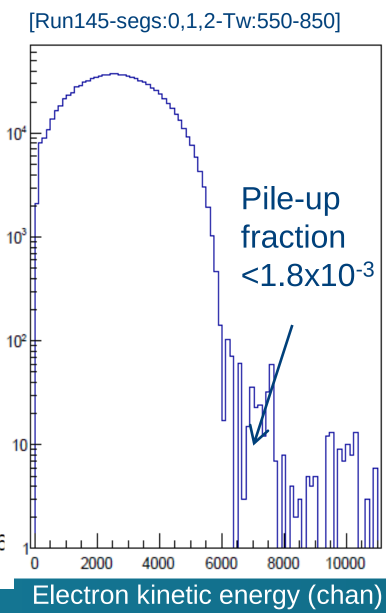


- **Principle**: use a **fragmented separated beam** to eliminate distortions in beta spectrum due to **back-scattering, out-scattering or dead-layers**.

Experiment at NSCL

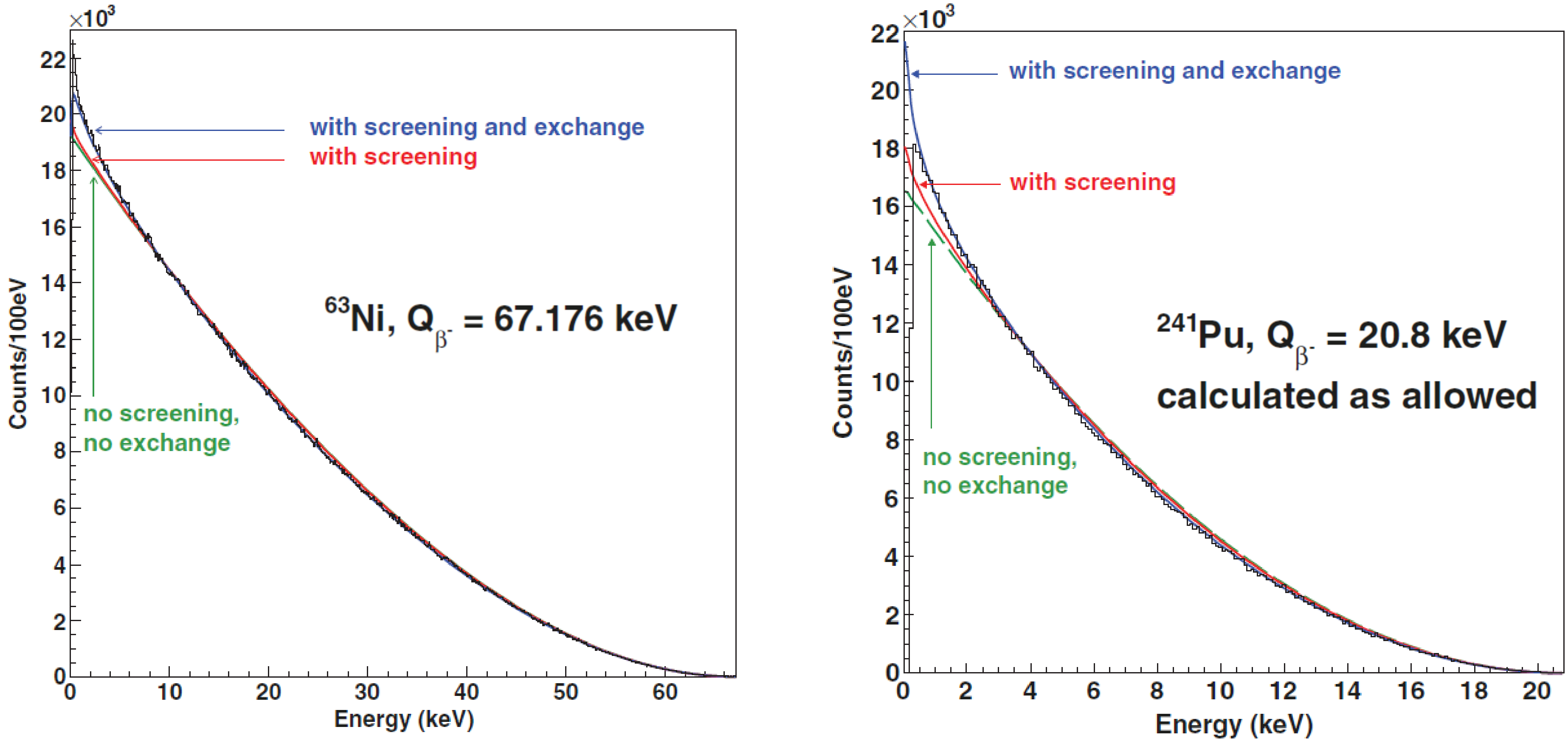






X. Huyan, O. Naviliat-Cuncic et al., Hyp. Interact 237 (2016) 93

4. microcalorimeter measurements
(CEA-Saclay)



X. Mougeot et al., PR A 86 (2012) 042506 and PR A 90 (2014) 012501

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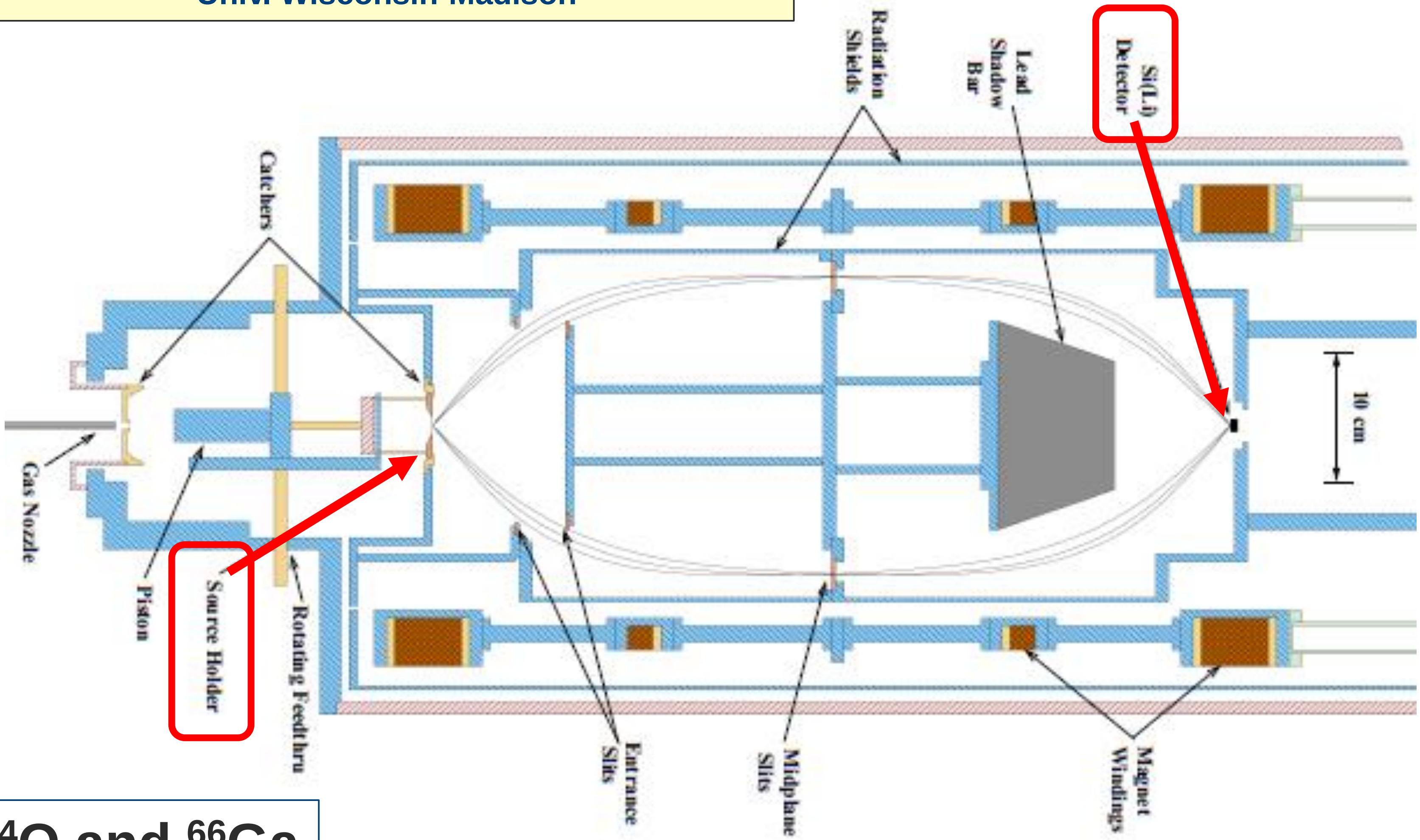
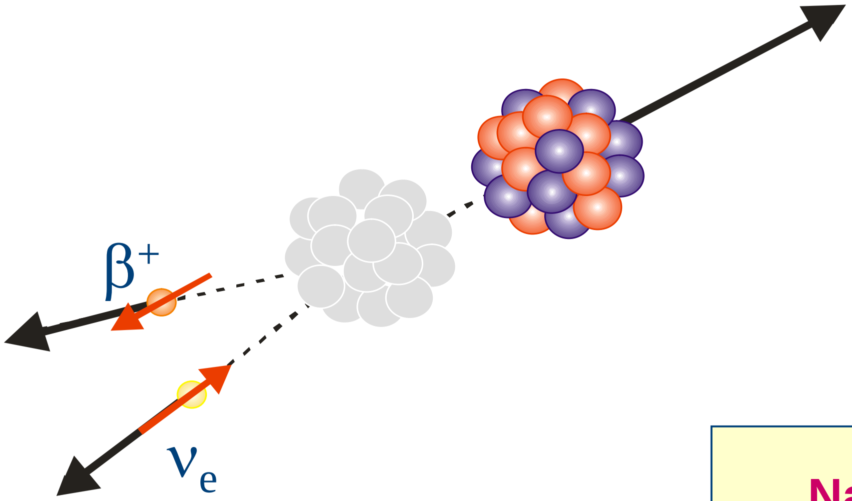
5. superconduct. β spectrometer
Univ. Wisconsin-Madison



^{14}O and ^{66}Ga

E.A. George et al., PR C 90 (2014) 065501 and G.W. Severin PR C 89 (2014) 057302

6. Solving the Reactor Antineutrino Problem(s)?



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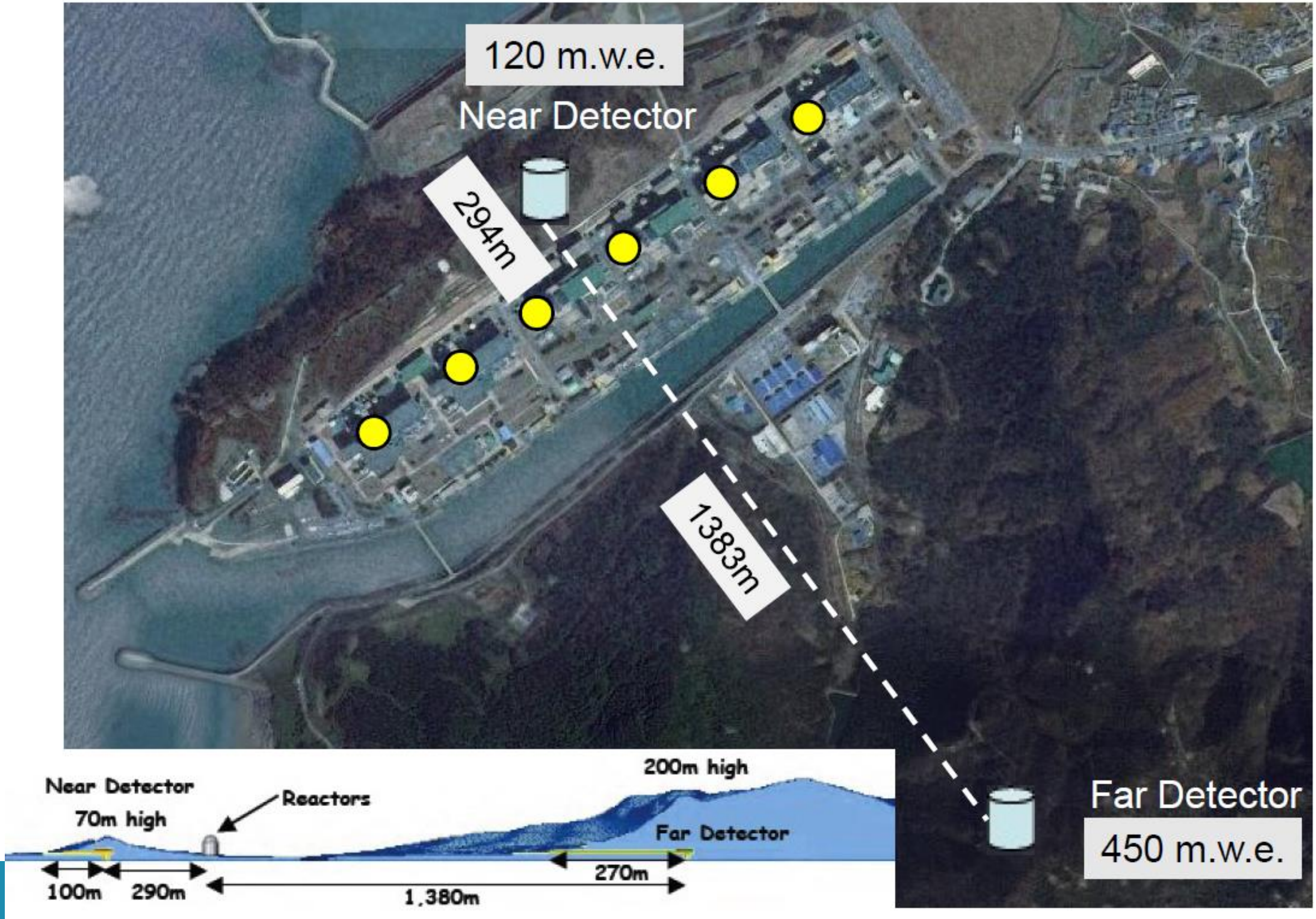
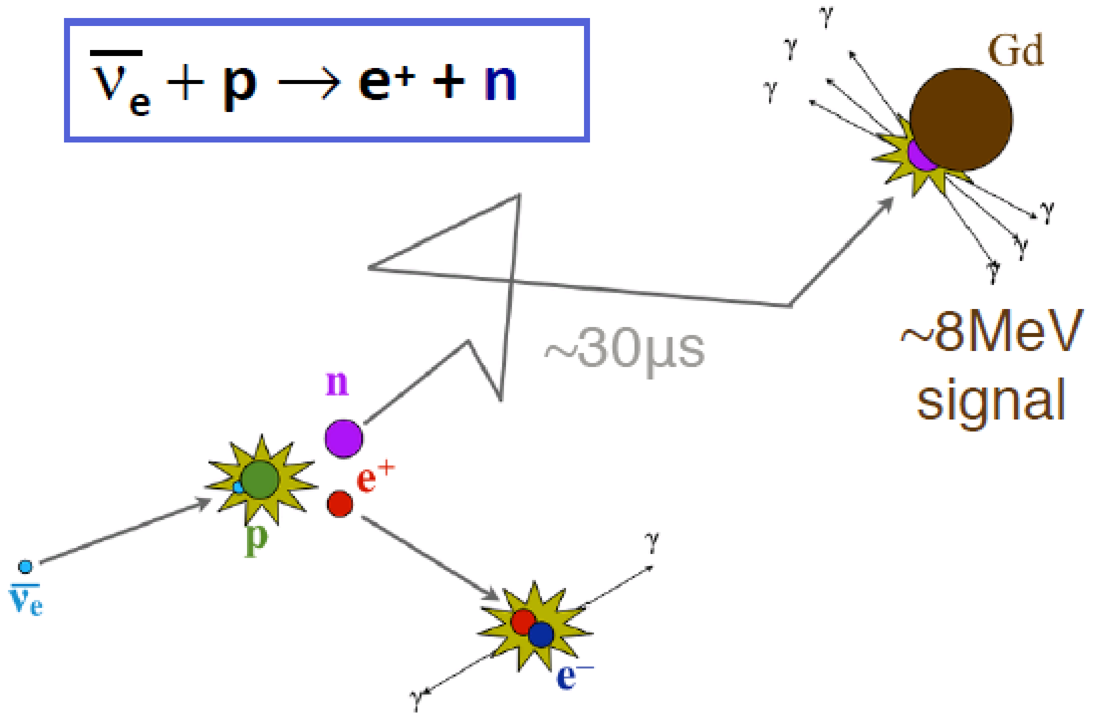
RENO Experimental Set-up



use inverse beta decay in water doped with Gd

$$\overline{\nu}_e + p \rightarrow e^+ + n$$



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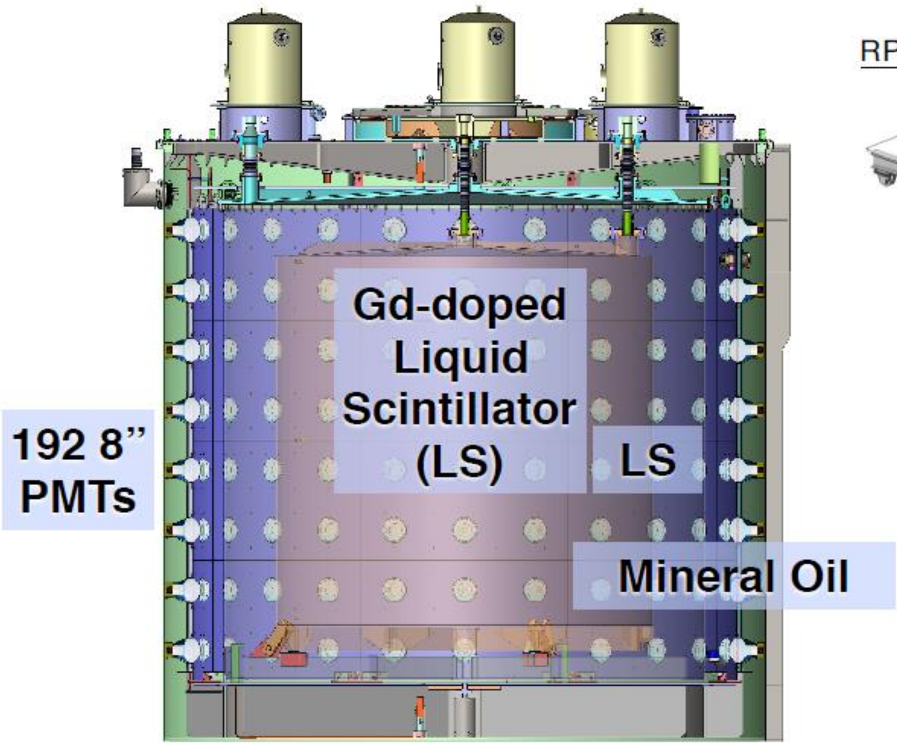
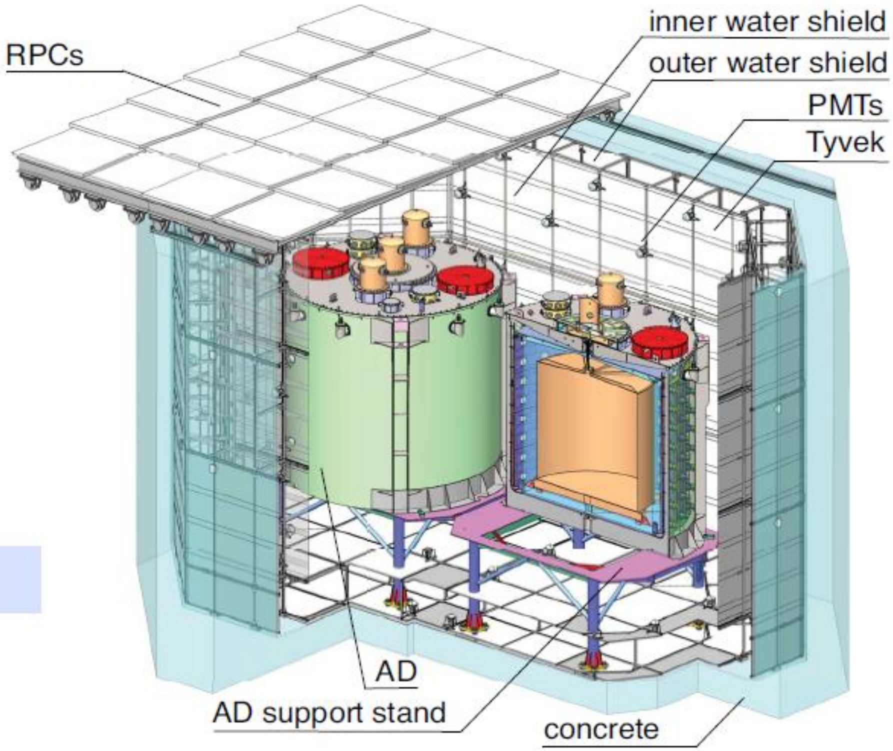
Daya Bay Detectors

- The antineutrino detectors (ADs) are "three-zone" cylindrical modules immersed in water pools:



Energy resolution:
$\sigma_E/E \cong 8.5\%/\sqrt{E[\text{MeV}]}$

NIM A 811, 133 (2016)



Double purpose: shield the ADs and veto cosmic ray muons

NIM A 773, 8 (2015)

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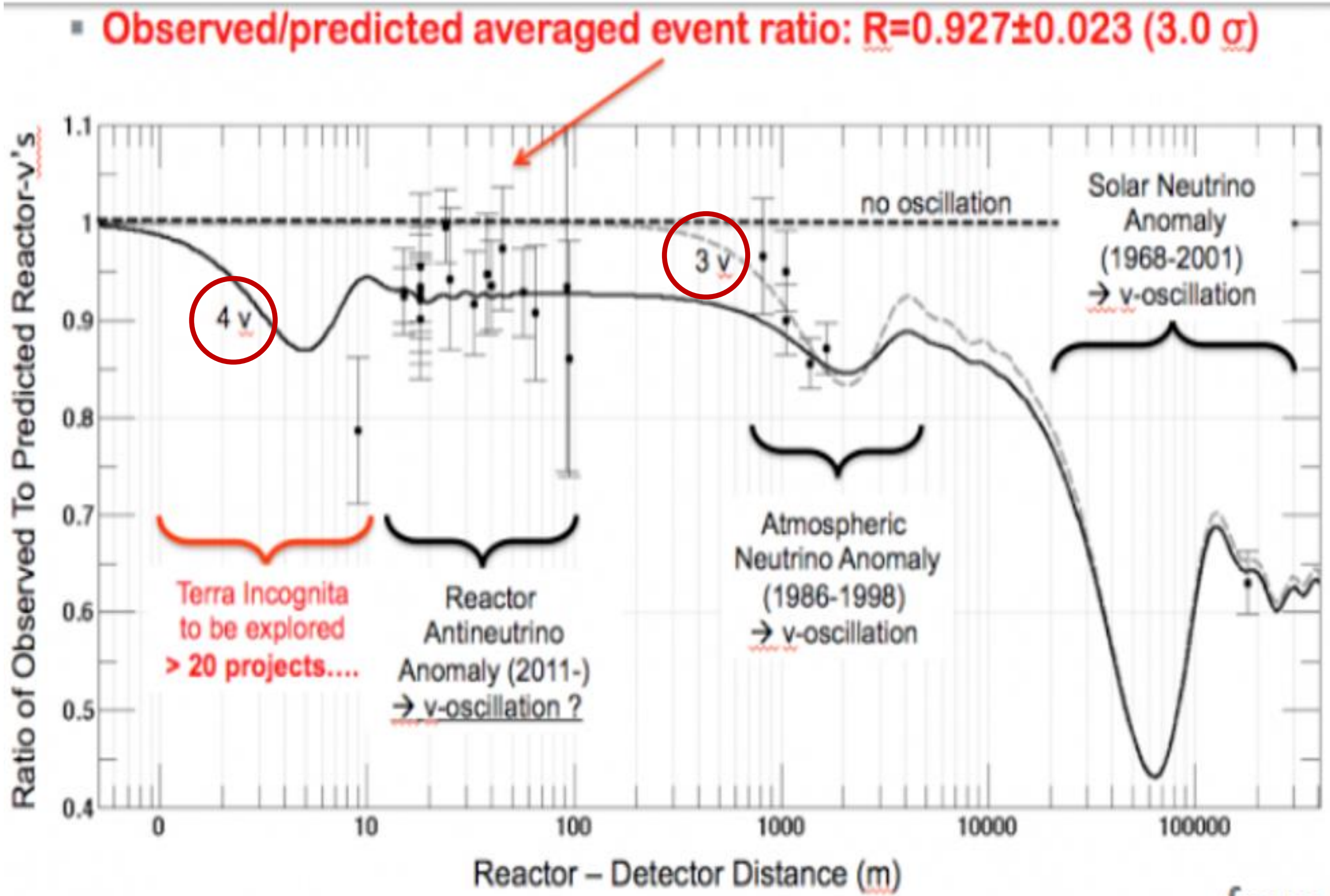
courtesy Daya Bay Collaboration (NEUTRINO2018, Heidelberg)

Problem 1:
Abolute antineutrino flux: exp. 7% lower than theory

(observed with ALL neutrino detectors at 10 - 100 m from a reactor core)



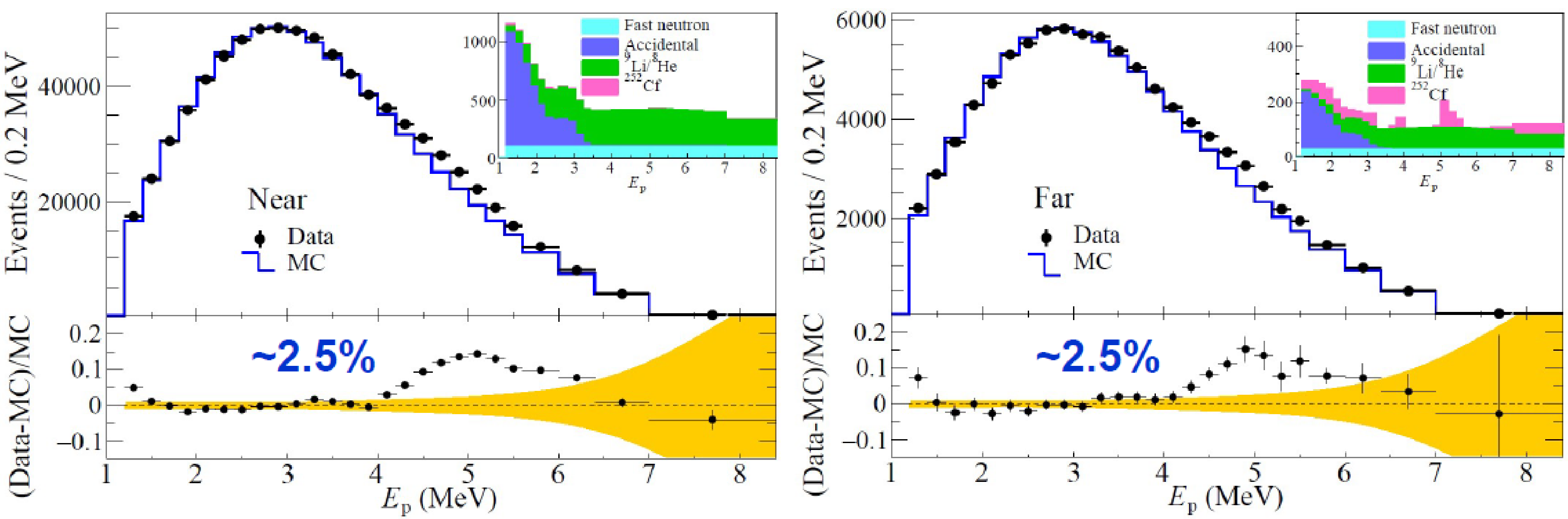
Mueller et al., Phys. Rev. C 83 (2011) 054615

can be explained by assuming a 4th, sterile neutrino with mass ≅ 1 eV

from Th. Lasserre

Problem 2:
Clear excess in counts at ~5 MeV compared to theory

(observed at Daya Bay (China), RENO (Sth.Korea), Double Chooz (France))



Near Live time = 1807.88 days	Far Live time = 2193.04 days
# of IBD candidate = 850,666	# of IBD candidate = 103,212
# of background = 17,233 (2.0 %)	# of background = 4,879 (4.8 %)

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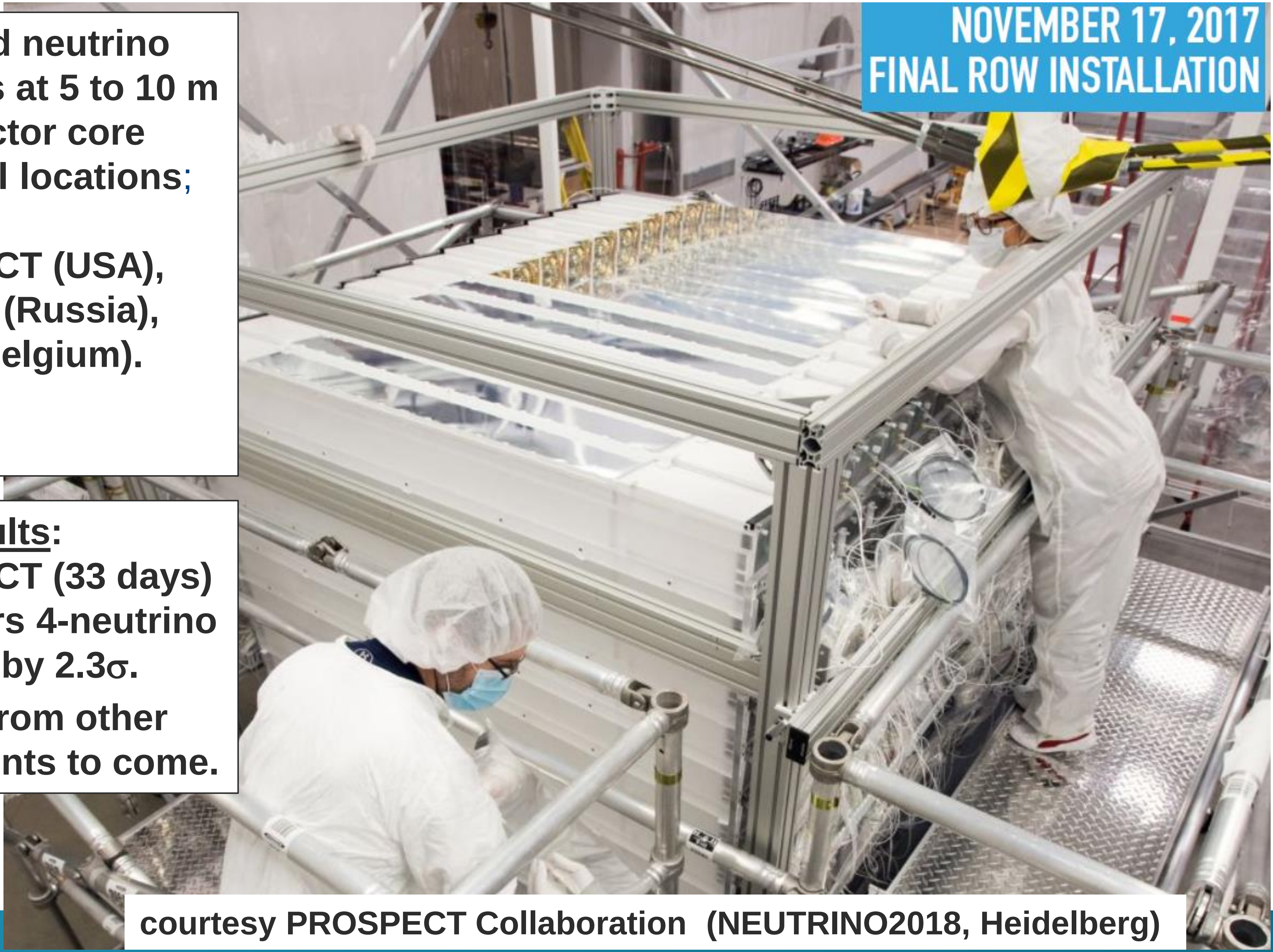
courtesy RENO Collaboration (NEUTRINO2018, Heidelberg)

To the ‘rate’ problem

dedicated neutrino detectors at 5 to 10 m from reactor core at several locations; e.g.
PROSPECT (USA),
DANSSE (Russia),
SOLID (Belgium).
…

First results:
PROSPECT (33 days) disfavours 4-neutrino scenario by 2.3σ.

Results from other experiments to come.



courtesy PROSPECT Collaboration (NEUTRINO2018, Heidelberg)

The Reactor Antineutrino Problems

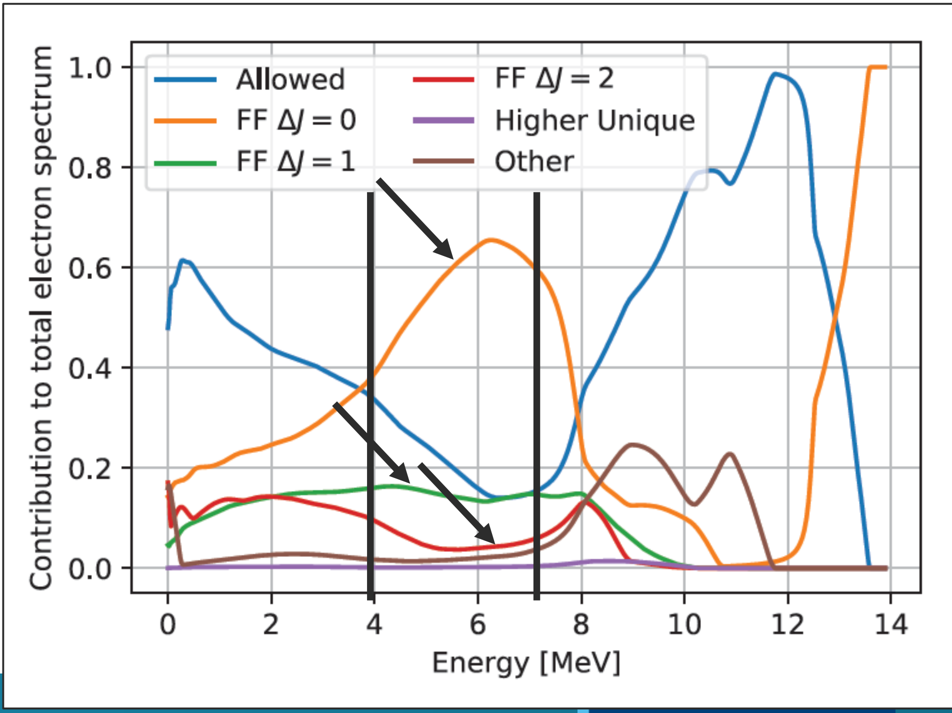
Problems:

1. **rate deficit of about 7%** in observed vs. predicted antineutrino rate in 'near' detectors (at d = 10 – 100 m from core) - **requires 4th, sterile ν !!**
2. energy spectrum exp/theo has a **bump in 4 to 7 MeV region**

Difficulty: theory depends on knowledge of ~8000 (**forbidden**) β decays: **HARD!**

BUT: **forbidden decays dominate** in most of experimental range (account for ~80% in bump region!)

Action: used **Shell Model** to calculate 29 dominant forbidden transitions (not approximating them as allowed anymore)



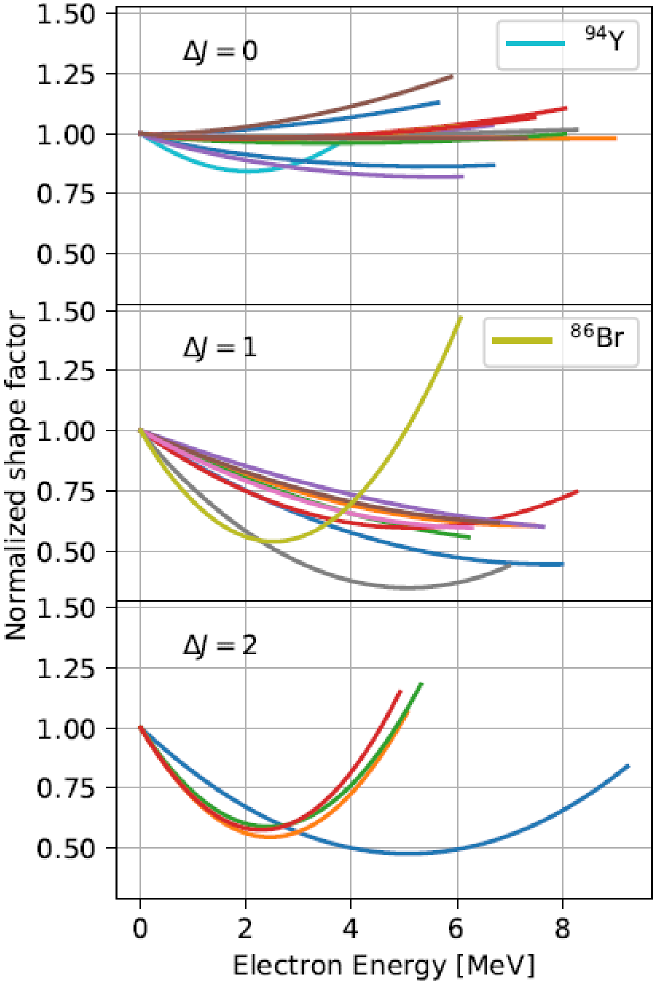
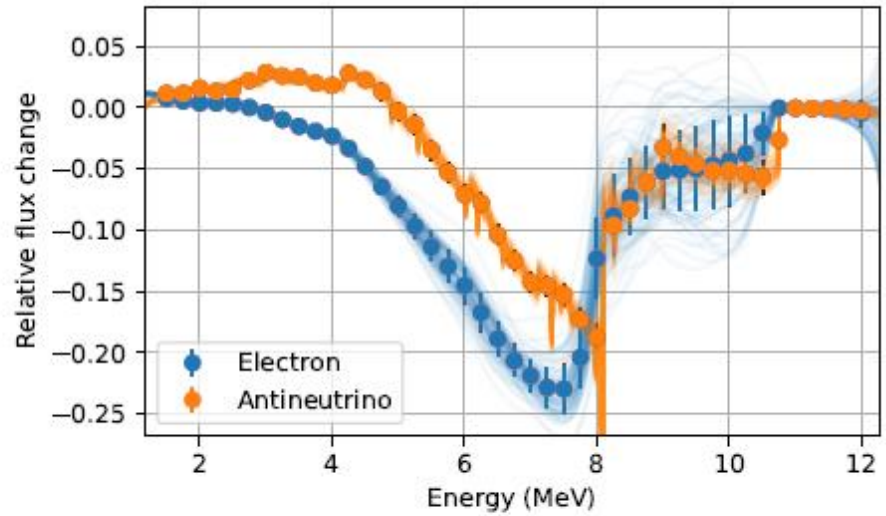


Figure 1. Overview of the calculated shape factors C, categorized according the spin-parity change of the transition. For allowed transitions $C = 1$. Each shape factor was normalized to its value at $E = 0$. Two cases stand out: ^{94}Y ($2^- \to 2^+$) and ^{86}Br ($1^- \to 2^+$). Both contain strong admixtures of $\Delta J = 2$ operators, since both 2^+ final states identify as vibrational excitations of the 0^+ ground state.



Change of electron and antineutrino spectra for forbidden transitions in comparison to the Huber-Mueller model.

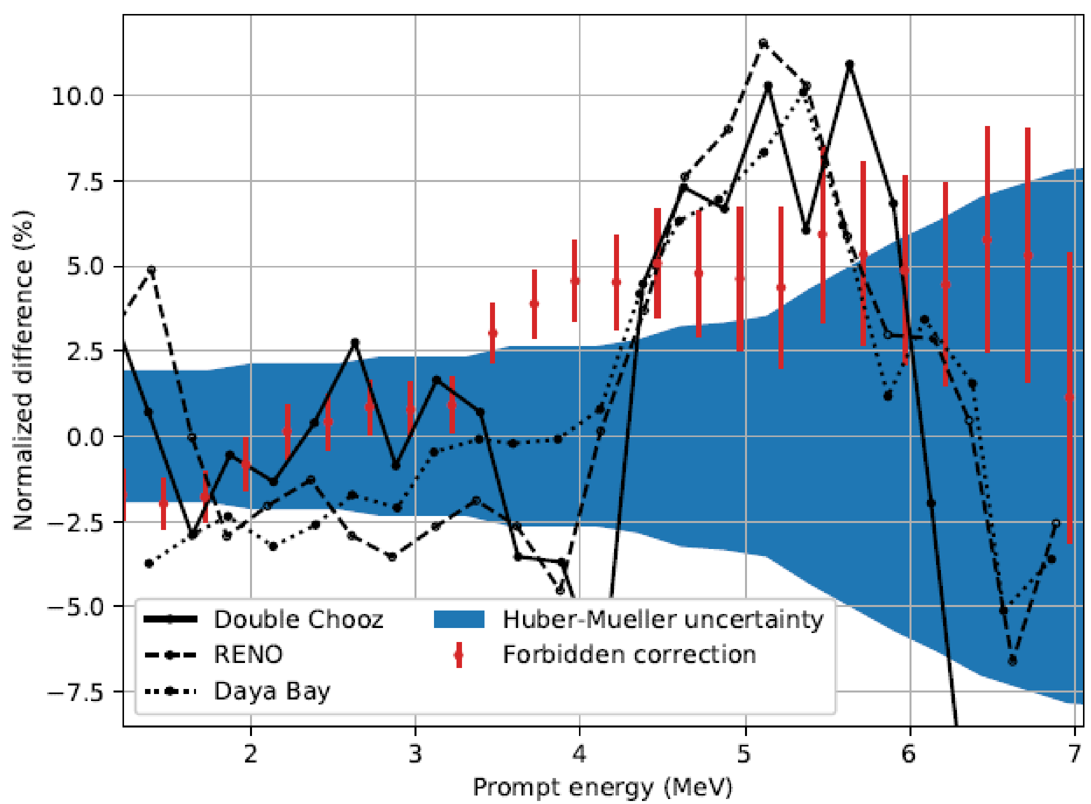
L. Hayen, J. Kostensalo, N. Severijns, J. Suhonen, arXiv:1805.12259

Taking into account the (first-forbidden) decays of

$^{86}Br(0+)$, $^{86}Br(2+)$, ^{87}Se, ^{88}Rb, $^{89}Br(3/2+)$, $^{89}Br(5/2+)$, ^{90}Rb, $^{91}Kr(5/2-)$, $^{91}Kr(3/2-)$, ^{92}Rb, ^{92}Y, ^{93}Rb, $^{94}Y(0+)$, $^{94}Y(0+)$, $^{95}Rb(7/2+)$, $^{95}Rb(3/2+)$, ^{95}Sr, ^{96}Y, ^{97}Y, ^{98}Y, ^{133}Sn, $^{134m}Sb(6+)$, $^{134m}Sb(6+?)$, ^{135}Te, ^{136m}I, ^{137}I, ^{138}I, ^{139}Xe, ^{140}Cs, ^{142}Cs

(account for about 60 % of rate in bump region !)

decreases the $\bar{\nu}$ flux by 5% !



The spectral sholder appears due to forbidden spectral corrections !

L. Hayen, J. Kostensalo, N. Severijns, J. Suhonen, arXiv:1805.12259