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Prospects for low-energy weak interaction studies in the β decay of fission products

SPES-Nusprasen Workshop

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Outline

- **structure of the weak interaction:**

  - searching for **tensor currents** in pure Gamow-Teller β decays
  - observable: **Fierz term**, from: β-ν correlation,

    β asymmetry parameter,

    β-spectrum shape, …

  - **complementary to** direct searches for new bosons at **LHC**

    for precision on Fierz term **of 10^{-3}** and better (challenge!)

- **towards higher precision →** need to **understand better weak magnetism**

  (small Standard Model term)

  - would also contribute to (or solve) **reactor neutrino problem**
  - best observable is β-spectrum shape

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

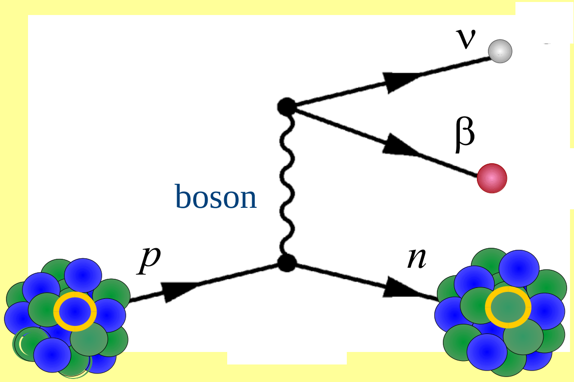
the Standard Model:

- * 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 $\left|C_T^{(')}/C_A\right|$ and $\left|C_S^{(')}/C_V\right|$ at several % level (neutron and nuclear β-decay)



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

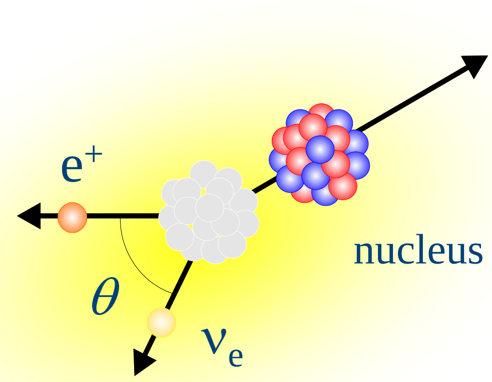
$$C_i \propto \frac{M_W^2}{M_{new}^2}$$

Major observables in β decay

1. β-ν correlation

$$a \, \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu}$$

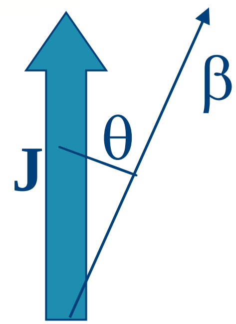
sensitive (quadratically) to scalar and tensor currents



2. β-asymmetry

$$A \, \frac{\vec{J}}{J} \cdot \frac{\vec{p}_e}{E_e}$$

sensitive to right-handed Vector and Axial-vector currents



- $\vec{p}_e$ electron momentum
- $\vec{q}$ neutrino momentum
- E_e, E_ν electron/neutrino energy
- $\frac{\vec{J}}{J}$ nuclear spin polarization
- $\gamma = \sqrt{(1-(\alpha Z)^2}$
- m_e electron rest mass

Note: - correlation coefficients (a, A, …) depend on physics ($C_i^{(')}$: coupling constants)

- 'kinematics' factors ($\frac{\vec{J}}{J} \cdot \frac{\vec{p}_e}{E_e}$, …) tell us how to organize the setup

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Major observables in β decay

3. Fierz term $b\,\frac{\gamma m_e}{E_e}$

- most experiments (because of the normalization) do not measure ***X* = *a*, *A*, …**

  but instead : $\tilde{X} = \dfrac{X}{1 + b\,\dfrac{\gamma m_e}{E_e}}$

- ***b*** **depends linearly on the $C_i^{(\prime)}$ coupling constants** (instead of quadratically, as ***a***)
- **measurements of** $\tilde{a},\ \tilde{A},\ldots$ **are thus essentially measurements of *b* !!**

Major observables in β decay

The Fierz term $b\,\frac{\gamma m_e}{E_e}$ is sensitive to scalar and tensor weak currents via:

$$b_F \cong Re\,\frac{C_S + C_S'}{C_V}$$

$$b_{GT} \cong Re\,\frac{C_T + C_T'}{C_A}$$

at SPES:
search for tensor currents
in pure Gamow-Teller decays
of fission products

Note: - b_F and b_{GT} are zero in the standard model

- for pure Fermi and Gamow-Teller transitions b_F and b_{GT} (and also *a, A, …*) do not depend on the nuclear matrix elements !!

Major observables in β decay

4. β-spectrum shape

$$d\Gamma \propto G_F \underbrace{F(Z,E)}_{\text{Fermi function}} \left[1 + k \frac{1}{E_\beta} b_{Fierz} + k' E_\beta b_{WM} \right]$$

sensitive to both:

- b_{Fierz} : scalar / tensor weak currents
- b_{WM} : weak magnetism (Standard Model term)
  - induced by strong interaction because the decaying quark is not free but bound in a nucleon;
  - is to be known better when reaching sub-percent precision

Note the different energy dependence of both effects !!

Complementarity of nuclear / neutron β decay with LHC searches

Projected limits on scalar/tensor couplings, ε_S and ε_T

T. Bhattacharya et al.

PHYSICAL REVIEW D 85, 054512 (2012)

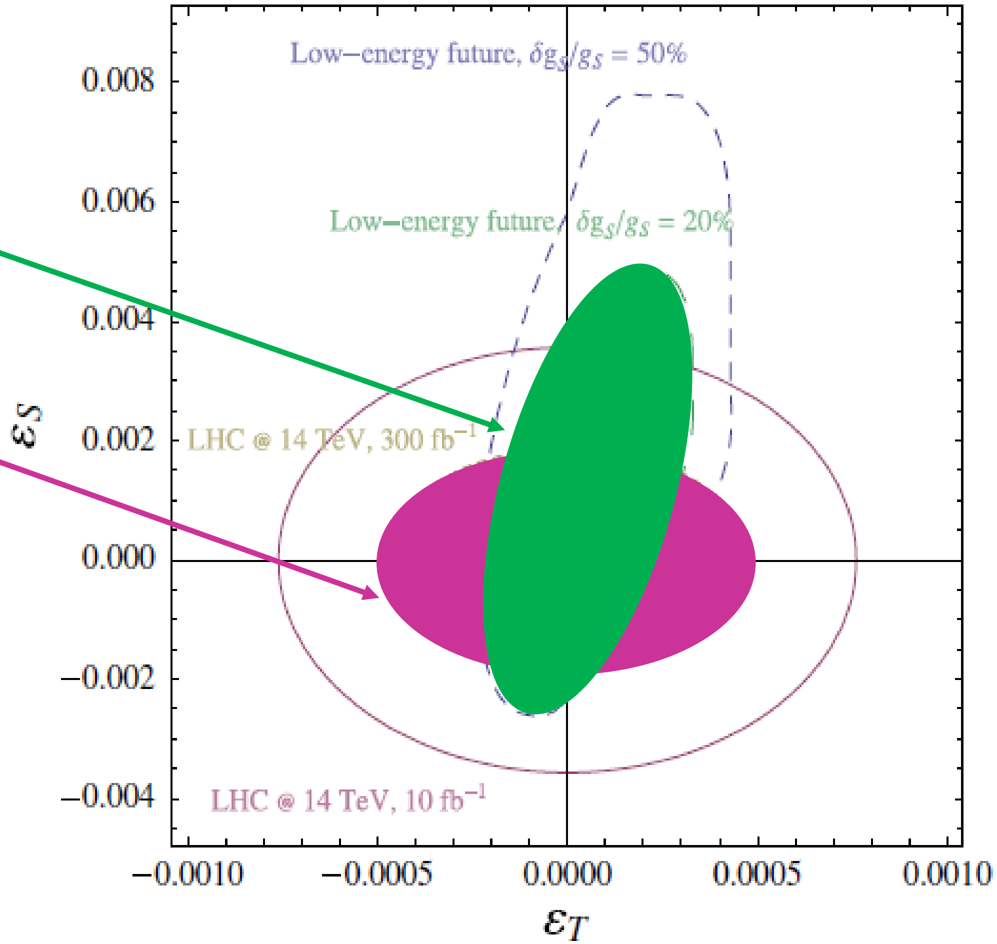
nuclear & neutron decay, pion decay

+ future 10^{-3} precision on b_{Fierz}

projected LHC limits for the channel

pp* → *e* + MET + *X

(for LHC @ 14 TeV and 300 fb^{-1})



see also e.g. :

O. Naviliat-Cuncic and M. Gonzalez-Alonso
Annalen der Physik 525 (2013) 600.

V. Cirigliano, et al.,
J. High. Energ. Phys. 1302 (2013) 046

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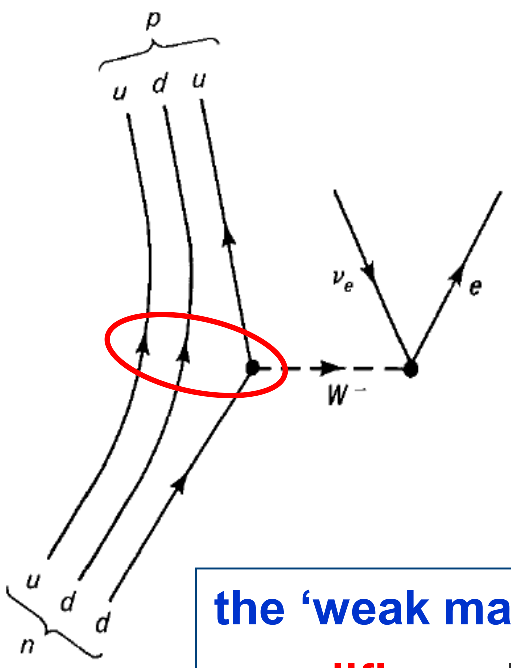
2. Weak magnetism



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;
the largest extra term is the 'weak magnetism'

the 'weak magnetism' term:

- modifies values for correlation coefficients at level of per mil to 1%
  → important for correlation measurements at sub-percent level

- could be (in part) responsible for the reactor neutrino problem

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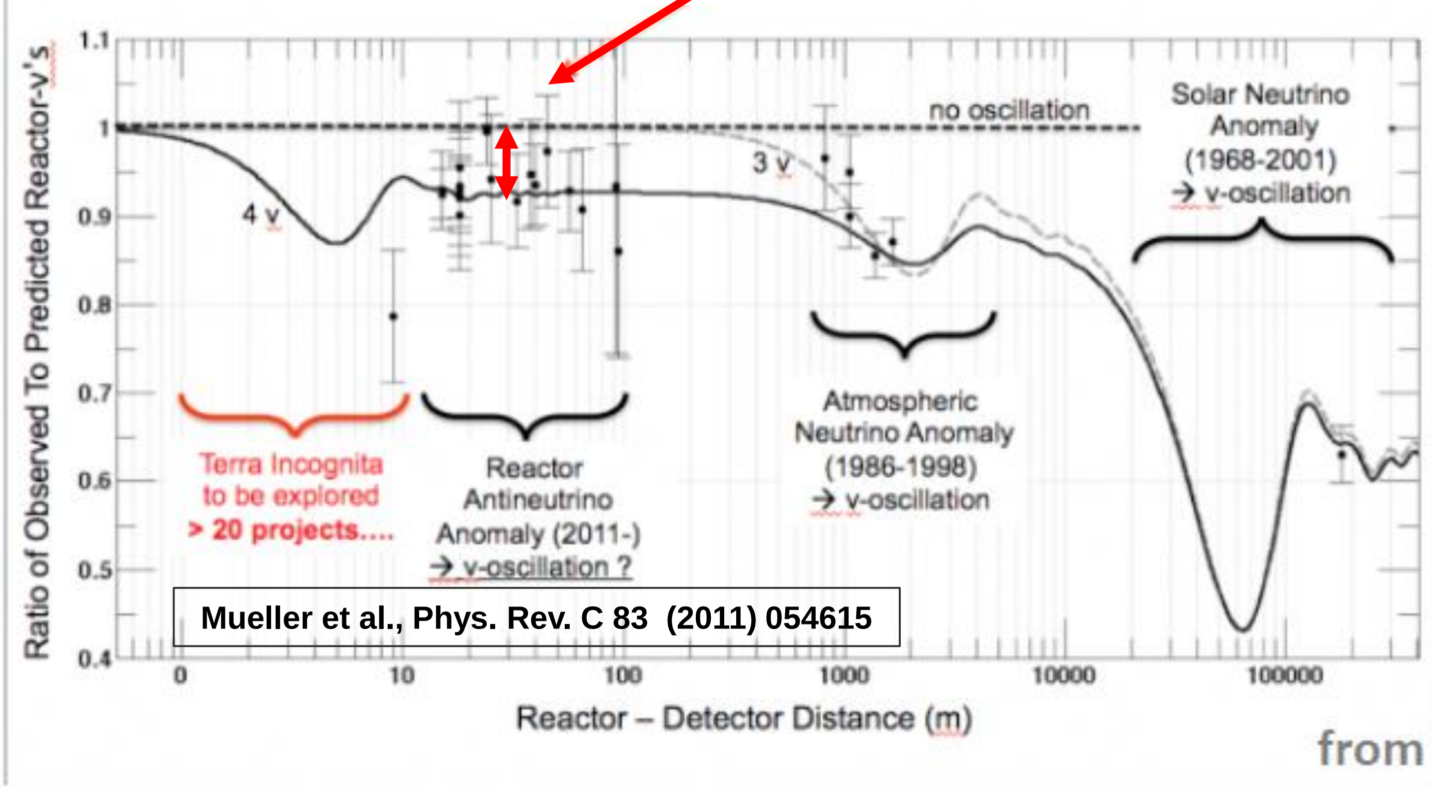
the Reactor Neutrino Problem

deficit of about 6% in observed vs. predicted neutrino rate in 'near' detectors (at d = 10 – 100 m from core) - requires 4th, sterile ν !!



from Th. Lasserre

A too crude approximation for *weak magnetism* in the fission fragment β spectra, which are converted to neutrino spectra, could be (in part) responsible for this

(see also A.C. Hayes et al., PRL 112 (2014) 202501)

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weak magnetism term b_{WM} (CVC)

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

$$\frac{b_{WM}}{Ac} = \sqrt{\frac{J}{J+1}}\, M_F \,\frac{\mu_{mother} - \mu_{daughter}}{c}$$

- A = mass number
- M_F = 1 Fermi matrix element
- μ = magnetic moment
- c = $g_A M_{GT}$

this equation is from 'Conserved Vector Current' hypothesis
e.g. F.P. Calaprice and B.R. Holstein, Nucl. Phys. A 273 (1976) 301

with $c = g_A M_{GT} \cong \rho$ from $Ft^{mirror} = \dfrac{2Ft^{0^+\rightarrow 0^+}}{1+\dfrac{f_A}{f_V}\rho^2}$

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

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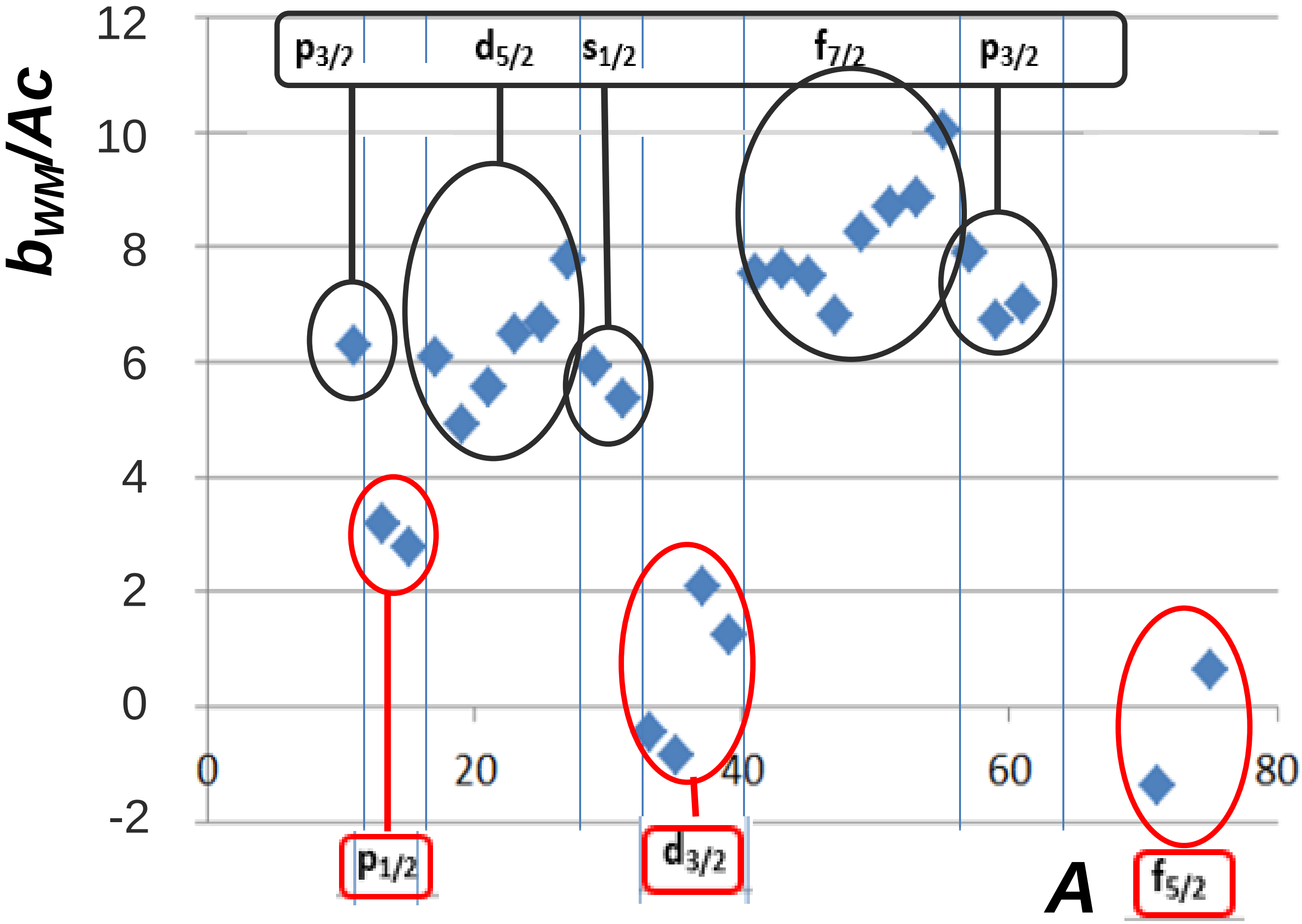
weak magnetism term b_{WM}/Ac - experimental data

mirror β transitions

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



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, I.S. Towner, et al., to be published

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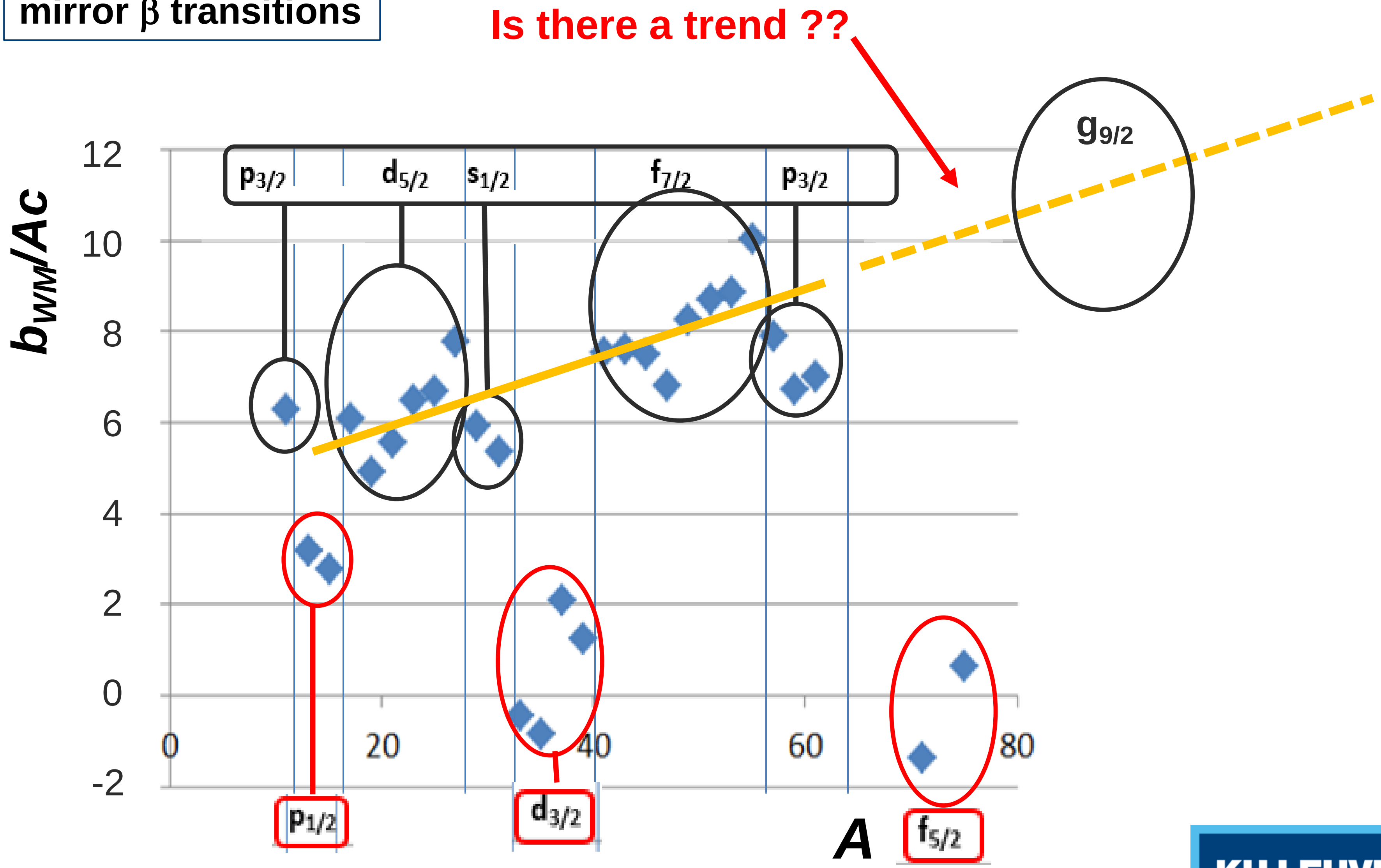
error bars are smaller than the size of the dots

weak magnetism term b_{WM}/Ac - experimental data

mirror β transitions



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

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- Whether there is a trend towards larger values for b_{WM}/Ac

can be studied at SPES via β-spectrum shape measurements

to extract b_{WM}/Ac for the $1g_{9/2}$ shell (mass A = 80 – 100).

- Measurements on isotopes in the $1h_{11/2}$ shell (below A = 132) are also possible.

Note that:

- **there are currently no experimental values for b_{WM}/Ac available for A > 80**
- **experimental values for b_{WM}/Ac for the mirror β transitions up to A = 45 are rather well reproduced within the shell model within 10% - 25%**
  (N.Severijns, I.S. Towner et al., to be published)
- **shell-model calculations for A > 45 suffer from too large truncation**
- **mean-field calculations of b_{WM} for higher A are ongoing (coll. with M. Martini)**
- **experimental data for pure GT transitions of fission fragments with 80 < A < 132 would be very useful to check the reliability of these calculations**

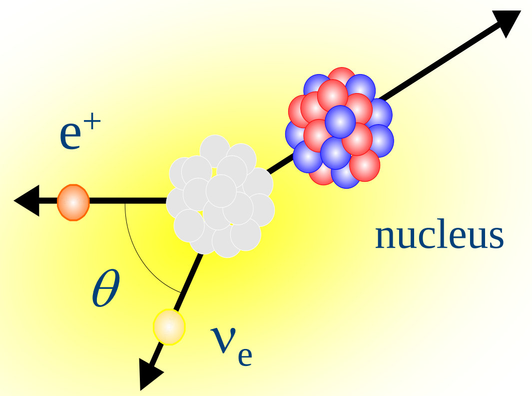
The effect of weak magnetism on the spectral shape is $\propto \ (1 + b_{WM} E_e)$

$$\rightarrow \quad \frac{dN}{dE_e} = \frac{4}{3M_n}\frac{b_{WM}}{Ac} \approx 0.7\%\ \mathrm{MeV}^{-1} \quad \text{for} \quad \frac{b_{WM}}{Ac} = 6 \qquad (M_n = \text{nucleon mass} \approx 930\ \mathrm{MeV})$$

A value of $\frac{dN}{dE}$ of $0.5\%\ \mathrm{MeV}^{-1}$ corresponds to a shift in the ν-rate of $\approx$ -1%

$\rightarrow$ the -6% discrepancy in the neutrino rate in the near detectors could thus be fully accounted for if ALL fission products have a $\frac{b_{WM}}{Ac} \simeq 25$ (but not realistic)

$\rightarrow$ the reactor neutrino problem can be in part accounted for by a more correct treatment of b_{WM} (now only a fixed linear electron-energy dependence is considered for b_{WM})



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Selected sotopes of interest at SPES (at 40 keV) to:

- **measure the Fierz term (proportional to $1/E_e$),**
  via correlations or β-spectrum shape measurements
- **measure the weak magnetism term (proportional to E_e),**
  via correlation or beta-spectrum shape measurements

Isotope	$t_{1/2}$	log ft	Jp ® Jp	branching ratio (%)	Beta endpoint energy (MeV)	useful part of transtion (MeV)		
77As	39 h	5.71	3/2- --> 1/2-	97	0.68	0.68	golden case	
79As	9.0 m	5.27	3/2- --> 1/2-	94	2.20	0.27		
80As	15 s	5.7	1+ --> 0+	56	5.70	0.67		
82As	19 s	6.19	(1+) --> 0+	81	7.27	0.65		
83Br	2.4 h	5.0	3/2- --> 1/2-	99	0.93	0.52	golden case	
84Br	6.0 m	5.1	(6)- --> 5-	100	1.86	1.86	(golden case)	
121In	23 s	4.33	9/2+ --> 7/2+	100	2.43	2.43	(golden case)	contamination from 121mIn ?
122In	1.5 s	5.11	1+ --> 0+	69	6.37	1.14		
125mSn	9.5 m	5.45	3/2+ --> 5/2+	98	2.00	0.31		contamination from 125Sn ?
127mSn	4.1 m	5.62	(3/2)+ --> (5/2)+	91	2.70	0.76	(golden case)	contamination from 127Sn ?

A new, improved description of β spectrum shape is available

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	
3	Finite size of the nucleus	L_0	10^{-1}-10^{-2}
4	Radiative corrections	R	
5	Shape factor	C	
6	Atomic exchange	X	
7	Atomic mismatch	r (	
8	Atomic screening	S (Eq. (54)) [a]	10^{-3}-10^{-4}
9	Shake-up	See item 7	
10	Shake-off	See	
11	Distorted Coulomb potential due to recoil		
12	Diffuse nuclear surface		
13	Recoiling nucleus		
14	Molecular screening		
15	Molecular exchange		
16	Bound state β decay		Smaller than $1 \cdot 10^{-4}$
17	Neutrino mass		
18	Forbidden decays		

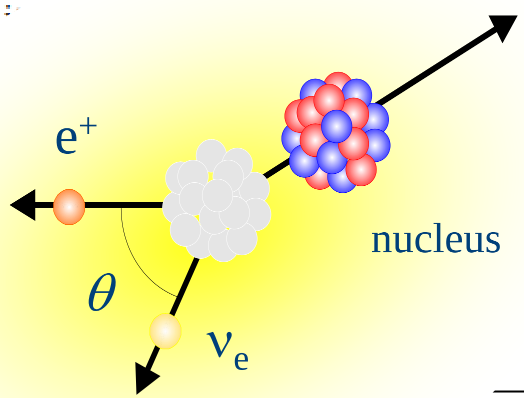
[a] Here the Salvat potential of Eq. (57) is used with

[b] The effect of shake-up on screening was discussed in

[c] Shake-off influences on screening and exchange corrections … in Sec. VI.C.2. This has to be evaluated in a case by case scenario.

Analytical description & code, accurate to few 10^{-4} level

L. Hayen, N. Severijns et al., Rev. Mod. Phys., in print



several new β spectrometers are in business now - 1

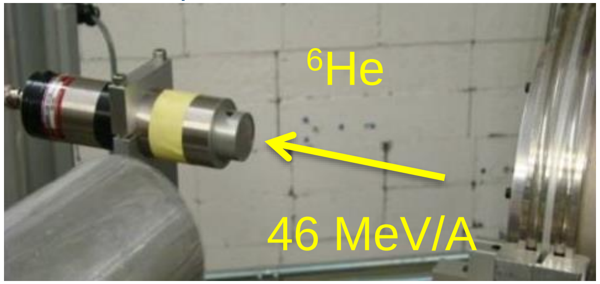
1. **miniBETA** (Leuven-Krakow; Severijns, Bodek) →
   (multi-wire drift chamber + sciltillators; ^{114}In)

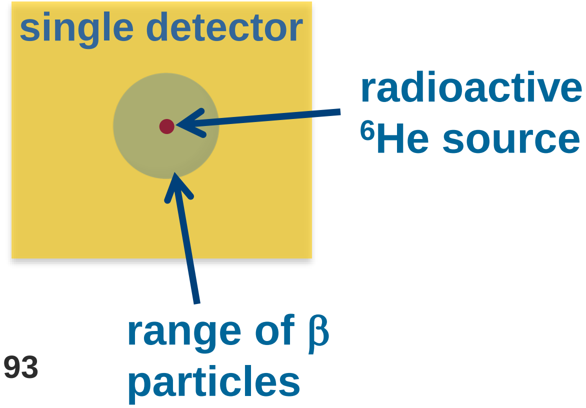
   K. Lojek et al., NIM A 802 (2015) 38

2. **source between two Si detectors in 1T field**
   (Leuven-Los Alamos- … ; Severijns, Young)
   (uses UCNA apparatus; ^{45}Ca)

3. **implantation of fragmented, separated beam into large scintillator crystals** (NSCL-MSU; Naviliat-Cuncic)

Experiment at NSCL





X. Huyan et al., Hyp. Interact 237 (2016) 93

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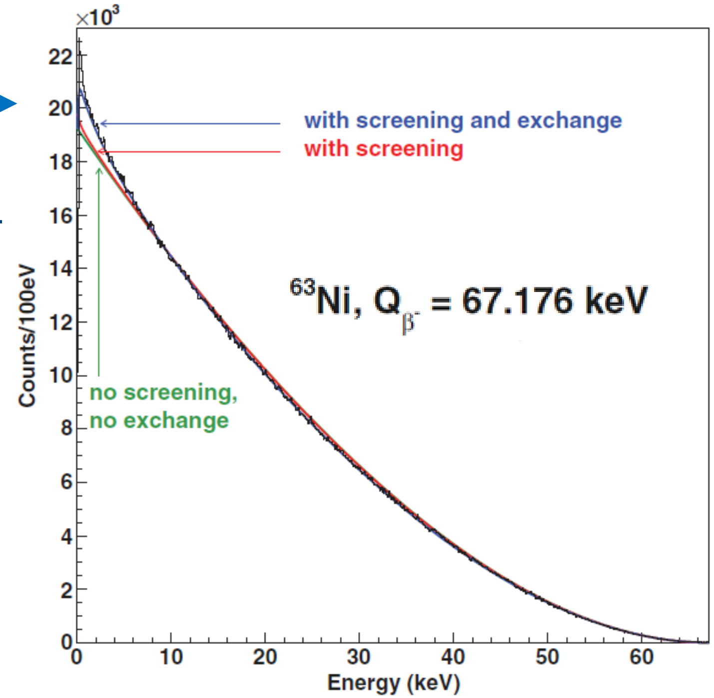
several new β spectrometers are in business now - 2

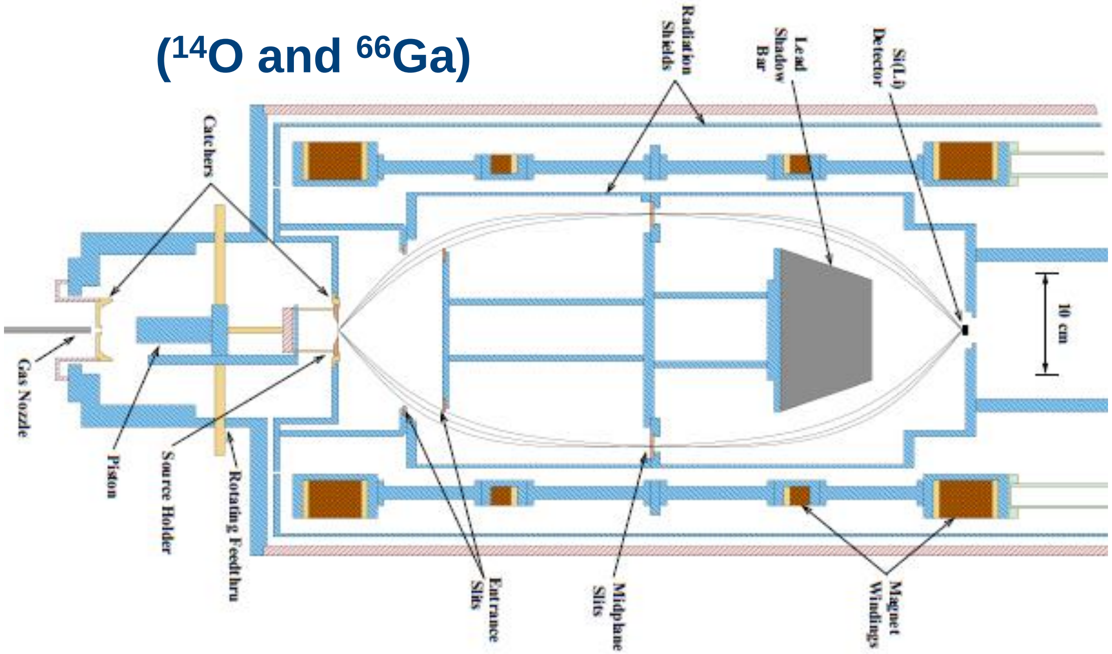
4. microcalorimeter measurements
   (CEA-Saclay; Mougeot-Loidl)

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



5. superconducting spectrometer
   (Univ. of Wisconsin-Madison; Knutson)

(^{14}O and ^{66}Ga)



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

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Conclusions and Outlook

Studies of pure Gamow-Teller transitions of fission fragments at SPES at 40 keV :

1. **β-ν correlation, β asymmetry and β spectrum shape** measurements
   → improved limits on **tensor** type weak currents;

2. searches for new physics (bosons) at **low energies are competitive** with direct searches at **LHC** for 10^{-3} precisions of Fierz term ***b*** and beyond

3. at sub-0.5% level of precision have to include effects induced by strong interaction
   → largest is **weak magnetism**
   → best observable: **β -spectrum shape** **(would also contribute to reactor ν problem)**

4. **several good isotopes are available at SPES !!**

5. **β-spectrum shape measurements would be the first choice !**
   (require no nuclear polarization and no detection of the nuclear recoil)

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