Testing the Standard Model in beta-decay: status and prospects

PSI 2016
October 20th, 2016

Nathal Severijns
KU Leuven University, Belgium
Outline

- Exotic weak currents  
  scalar / tensor contributions  
  $\beta\nu$ correlation / beta asymmetry measurements

- Nuclear / neutron beta decay versus LHC

- Weak magnetism

- Beta spectrum shape measurements
1. Exotic weak currents (scalar, tensor)

a) $\beta$-$\nu$ correlation

$$a \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} \quad \text{exp.} \quad \tilde{a} = \frac{a}{1 + b \frac{\gamma m_e}{E_e}}$$

with $\gamma = \sqrt{1 - (\alpha Z)^2}$

$$a_F \cong 1 - \left| \frac{C_S}{C_V} \right|^2$$

$$a_{GT} \cong -\frac{1}{3} \left[ 1 - \left| \frac{C_T}{C_A} \right|^2 \right]$$

$$b_F \cong \text{Re} \left( \frac{C_S + C'_S}{C_V} \right)$$

$$b_{GT} \cong \text{Re} \left( \frac{C_T + C'_T}{C_A} \right)$$

Fierz term

!!! for pure transitions weak interaction results are independent of nuclear matrix elements !!!

(assuming maximal P-violation and T-invariance for V and A interactions)

recoil corr. (induced form factors) $\approx 10^{-3}$; radiative corrections $\approx 10^{-4}$
Limits on scalar currents

\[ a_F \approx 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2} \]

\[ \mathcal{F}_{t^{0+} \rightarrow 0^+} = \frac{K}{2G_F^2 V_{ud}^2 C_V^2 (1 + \Delta_R^V)} \frac{1}{(1 + b_F')} \]

with

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

(Fierz term)

\[ 32\text{Ar}: \text{ Adelberger et al., PRL 83 (1999) 1299} \]

\[ 38\text{mK}: \text{ Gorelov, Behr et al., PRL 94 (2005) 142501} \]

\[ 
\begin{align*}
C'_S & \quad C_V \\
\frac{C'_S}{C_V} & \quad \frac{C_S}{C_V}
\end{align*}
\]

\[ 
\begin{align*}
38\text{mK} & \\
32\text{Ar} & \\
P_F & \text{ (}^{14}\text{O, }^{10}\text{C)}} \\
P_{GT} & \\
0^+ - 0^+ & \\
\end{align*}
\]

ongoing experiments in search for scalar weak currents:

- TRINAT (MOT): $^{38m}$K repeat (prep.)
- LPCTrap @ GANIL (Paul): $^{19}$Ne, $^{35}$Ar (analysis)
- Jerusalem (MOT): $^{19}$Ne (prep.)
- TamuTrap, Texas A&M (Penning): $^{32}$Ar, … (T = 2, $\beta$) (prep.)
- WISARD @ ISOLDE (foil): $^{32}$Ar, … (T = 2, $\beta$) (prep.)

$\Delta a/a \sim 0.3\%$

Counts / time bin

Time of flight (µs)

$^{35}$Cl charge state distrib. from the $\beta$ decay of $^{35}$Ar (LPCTrap - GANIL)
Tensor currents - $\alpha - \beta - \nu$ correlation with Paul-trapped $^8$Li Ions

$\alpha$-particle breakup of $^8$Be$^*$

$a_{\beta\nu} = -0.3342^{(26)}_{(29)}$\text{stat} \quad (29)_{\text{sys}}

M.G. Sternberg, G. Savard et al., PRL 115 (2015) 182501

Tensor currents - LPCTrap @ GANIL - $^6$He

2006 ($^6$He): $a_{\beta\nu} = -0.3335^{(73)}_{(75)}$\text{stat} \quad (75)_{\text{syst}}


$^6$He

$\Delta a / a \sim 0.5 \% \text{ (stat)}$ (analysis in progress)
Tensor currents - $^6$He MOT Trap setup @ Univ. Washington, Seattle


Tensor currents - $^6$He EIB Trap (Weizmann Inst., Univ. Jerusalem, ...)


0.1% measurement - 2015
b) β-asymmetry parameter in nuclear beta decay

\[ W(\theta) = \frac{N(\theta)_{\text{pol}}}{N(\theta)_{\text{unpol}}} = 1 + \tilde{A} \frac{v}{c} Q \cos \theta \]

\( \tilde{A} = \frac{A}{1 + b_{GT}'} \)

\( b_{GT}' = \frac{\gamma m_e}{\langle E_e \rangle} \left( \frac{C_T + C'_T}{C_A} \right) \)

**Analysis:**

\[ \left[ \frac{W(\theta) - 1}_{\text{exp}} \right] \frac{1}{\left[ W(\theta) - 1 \right]_{\text{Geant}}} = \left[ \frac{\tilde{A}}{\tilde{A}_{SM}} \frac{P}{c} \frac{V}{Q \cos \theta} \right]_{\text{exp}} = \frac{\tilde{A}}{\tilde{A}_{SM}} \]
F. Wauters et al.,

(KU Leuven, NICOLE-ISOLDE, NPI Rez-Prague, Uni Bonn)

$^3$He - $^4$He dilution refrigerator set-up

$^60$Co, $B = 13$ T

experiment

region analysed

Geant4
$A_{\text{exp}}^{(60}\text{Co}) = -1.014(12)_{\text{stat}}(16)_{\text{syst}}$


$A_{\text{exp}}^{(114}\text{In}) = -0.990(10)_{\text{stat}}(10)_{\text{syst}}$


$A_{\text{exp}}^{(67}\text{Cu}) = 0.587(8)_{\text{stat}}(12)_{\text{syst}}$


$^{60}\text{CoCu}$, $B_{\text{ext}} = 13$ T

$^{114}\text{InFe}$, $B_{\text{hf}} = 27$ T

$^{67}\text{CuFe}$, $B_{\text{hf}} = 21$ T

no energy dependence left $\rightarrow$ corrections OK

IS431-experiment
Limits on tensor currents

$A^{(60)Co}$

$A^{(67)Cu}$

$\alpha-\beta-\nu^{(8)Li}$

$A^{(60)Co}$

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

$\alpha-(6\text{He})$

C. Johnston et al.,
PR 132 (1963) 1149

$\alpha-\beta-\nu^{(8)Li}$

M.G. Sternberg, G.Savard et al.,
PRL 115 (2015) 182501

Also: Poster F. Lenaers – $^{35}\text{Ar}$
PhD Behling 2015 – $^{37}\text{K}$
2. Measurements in nuclear/neutron $\beta$ decay in the LHC era

nuclear and neutron decay, pion decay

limits on scalar/tensor couplings obtained by CMS collaboration in $pp \rightarrow e + \text{MET} + X$ channel

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

V. Cirigliano, et al.,

S. Chatrchyan et al. (CMS Collab.)
J. High. Energ. Phys. 08 (2012) 023
3. Good knowledge of **induced / recoil terms** required

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

→ **extra terms induced by strong interaction**

**neutron / nuclear beta decay:**

\[
V_\mu(q^2) = \bar{p}[g_V(q^2)\gamma_\mu + g_M(q^2)\sigma_{\mu\nu}\frac{q_\nu}{2M}]n
\]

\[
A_\mu(q^2) = \bar{p}[g_A(q^2)\gamma_\mu\gamma_5 + ig_P(q^2)\frac{q_\mu}{m_e}\gamma_5]n
\]

→ affects values for **correlation coefficients** at level of per mil to 1%
weak magnetism term $b_{WM}$ (CVC) (N.S. et al., in prep.)

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

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

$c = g_A M_{GT}$ from $\Im t$-value

$T = 1/2$ $J^\pi \rightarrow J^\pi$ mirror $\beta$ transitions

F.P. Calaprice and B.R. Holstein, NP A 273 (1976) 301

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

GT $\beta$ decays of isospin triplet states

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

$c = g_A M_{GT}$ from $ft$-value
weak magnetism term $b_{WM}$ - experimental data

mirror $\beta$ transitions: - updated $F_t$-values ($A < 75$; rel. prec. $< 0.2\%$ for $A < 41$)
- extracted weak magnetism form factor

$\frac{b_{WM}}{Ac}$

N. Severijns, I.S. Towner, et al., to be published
weak magnetism term $b_{WM}$ - experimental data

$\frac{b_{WM}}{Ac}$

$\approx \mu_p - \mu_n$

mirror $\beta$ transitions

j = $l + 1/2$

j = $l - 1/2$
weak magnetism $b_{WM}$ - mirror $\beta$ transitions

\[
c \approx g_A M_{GT}
\]

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

avg = 0.96(8)

avg = 1.01(25)

\[\frac{(b/\Lambda c)_{exp}}{(b/\Lambda c)_{theo}}\]

mirror ($A = 3$-$45$) 0.97(11)

triplet ($A = 6$-$30$) 1.01(15)

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

B. R. Holstein, RMP 46 (1974) 789
F.P. Calaprice et al., PR C 15 (1977) 2178
Too crude approximation for $b_{WM}$ in fission fragment beta decays may be (in part) responsible (see also A.C. Hayes et al., PRL 112 (2014) 202501)
Effect on spectral shape:

\[ 1 + \delta_{WM} E \]

\[ \rightarrow \frac{dN}{dE} = \frac{4}{3M_n} \frac{b}{Ac} \]

Shift of \( \frac{dN}{dE} \) by 0.5% MeV\(^{-1}\)

\[ \rightarrow \text{shift in } \nu\text{-rate of } \approx -1\% \]
New vistas and prospects in the LHC era

- new generation of (trap-based) correlation experiments
  \[ \rightarrow \text{towards 0.1\% precision level} \]

- precise $\beta$-spectrum shape measurements:

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

- $b_{\text{Fierz}}$: scalar / tensor weak currents
- $b_{\text{WM}}$: 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!!
4. $\beta$ spectrum shape measurements

Table VI Overview of the features present in the $\beta$ 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.

<table>
<thead>
<tr>
<th>Item</th>
<th>Effect</th>
<th>Formula</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Phase space factor</td>
<td>$pW(W_0 - W)^2$</td>
<td>Unity or larger</td>
</tr>
<tr>
<td>2</td>
<td>Traditional Fermi function</td>
<td>$F_0$ (Eq. (5))</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Finite size of the nucleus</td>
<td>$L_0$ (Eq. (17))</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Radiative corrections</td>
<td>$R$ (Eq. (27))</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Shape factor</td>
<td>$C$ (Eq. (125))</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Atomic exchange</td>
<td>$X$ (Eq. (63))</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Atomic mismatch</td>
<td>$r$ (Eq. (76))</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Atomic screening</td>
<td>$S$ (Eq. (54))</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Shake-up</td>
<td>See item 7 &amp; Eq. (66) b</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Shake-off</td>
<td>See item 7 &amp; Eq. (69) &amp; $\chi_{ex}$</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Distorted Coulomb potential due to recoil</td>
<td>$Q$ (Eq. (26))</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Diffuse nuclear surface</td>
<td>$U$ (Eq. (20))</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Recoiling nucleus</td>
<td>$R_N$ (Eq. (22))</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Molecular screening</td>
<td>$\Delta S_{Mol}$ (Eq. (81))</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Molecular exchange</td>
<td>Case by case</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Bound state $\beta$ decay</td>
<td>$\Gamma_b/\Gamma_c$ (Eq. (77))</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Neutrino mass</td>
<td>Negligible</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Forbidden decays</td>
<td>Not incorporated</td>
<td></td>
</tr>
</tbody>
</table>

---

Analytical description + code, accurate to few $10^{-4}$ level
L. Hayen, N. Severijns et al., in prep.

Poster by L. Hayen
miniBETA spectrometer (Leuven / Krakow)

- multi-wire drift chamber
- scintillator (later DSSDD)
double-Si spectrometer (Leuven / LANL, A. Young)

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

- data in May 2016
- analysis ongoing

Talk of J. Wexler
**Beta energy spectrum shape in $^6$He decay - NSCL/MSU**

(O. Naviliat-Cuncic et al.)

- **Long term goal**: Measure the **Fierz interference term ($b$)** in $^6$He decay to search for weak tensor currents.

- **Current goal**: measure the **weak magnetism (WM)** form factor in $^6$He 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.

---

**Poster of Xuejing Huyan**

- Collected statistics enables extracting the WM form factor at $\sim 5\%$ relative error

---

**Experiment at NSCL**

- $^6$He
- 46 MeV/A

---

[Run182-segs:0,1-Ew:500-2500]  
[Run145-segs:0,1,2-Tw:550-850]  
[Run145-segs:0,1,2-Tw:550-850]  

- Single detector
- Radioactive $^6$He source
- Range of $\beta$ particles

---

- $^6$He decay
- Pile-up fraction $<1.8x10^{-3}$

---

Electron kinetic energy (chan)
microcalorimeter measurements (CEA-Saclay)

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

1. $\beta$-$\nu$ correlation and $\beta$ asymmetry measurements + Ft-values
   \[\rightarrow\] improved limits on scalar and 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 $b$ and beyond
   many experiments ongoing or in preparation / planned

3. at sub-0.5% level of precision have to include effects induced by strong interaction
   \[\rightarrow\] largest is weak magnetism
   \[\rightarrow\] best observable: beta-spectrum shape

   scalar / tensor currents & weak magnetism
distribution in
- electron and neutrino directions and in
- electron energy
from polarized nuclei:

\[ d\Gamma \propto \begin{aligned}
&F(\pm Z, E_e) \frac{p_e E_e (E_0 - E_e)^2}{E_e E_\nu} d\Omega_e d\Omega_\nu \\
&\text{Fermi function}
\end{aligned} \]
\[ \text{phase space} \]

\[ x \left\{ \begin{array}{l}
1 + a \frac{\vec{p}_e \cdot \vec{q}}{E_e E_\nu} + b \frac{\gamma m_e}{E_e} + A \frac{\vec{J} \cdot \vec{p}_e}{J E_e} + \ldots \end{array} \right\} \]
\[ \beta-v \text{ correlation} \]
\[ \text{Fierz interference term} \quad (b = 0 \text{ in standard model}) \]
\[ \beta-\text{asymmetry} \]

\[ \tilde{X} = \frac{X}{1 + b \frac{\gamma m_e}{E_e}} \quad \text{with} \quad \gamma = \sqrt{1 - (\alpha Z)^2} \]

the Standard Model and beyond:

* \( C_A = -1.27 \) (\( g_A/g_V = -1.2699(7) \) from n-decay)

* \( C_V' = C_V \) \& \( C_A' = C_A \) (maximal P-violation)

* \( C_S = C_S' = C_T = C_T' = C_P = C_P' \equiv 0 \) (only V- and A-currents)

experimental upper limits: \( \left| \frac{C_T'}{C_A} \right| \) and \( \left| \frac{C_S'}{C_V} \right| \) at few \% level
(neutron and nuclear \( \beta \)-decay)

N.S., O. Naviliat-Cuncic and M. Beck, Rev. Mod. Phys. 78 (2006) 991,
D. Dubbers and M.G. Schmidt, Rev. Mod. Phys. 83 (2011) 1111,
V. Cirigliano et al., Prog. Part. Nucl. Phys. 71 (2013) 93,
F. Wauters et al., Phys. Rev. C 89 (2014) 025501,

* no time reversal violation
(except for the CP-violation described by the phase in the CKM matrix)
Precision measures in nuclear/neutron $\beta$ 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 $O(1 \text{ GeV})$ effective Lagrangian for semi-leptonic transitions
(contributions from W-exchange diagrams and four-fermion operators)

link between EFT couplings $\varepsilon_i$ and Lee-Yang nucleon-level effect. couplings $C_i$:

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

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

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

\[ \mathcal{F}_{t^0 \to 0^+} = f_V t_{1/2}^0 \left( 1 + \delta_N^V - \delta_C^V \right) \left( 1 + \delta_R^V \right) = \frac{K}{2G_F^2 \left( V_{ud}^2 C_{ud}^2 \right) \left( 1 + \Delta_V^V \right)} \]

- From experiment
- \( |V_{ud}| = 0.97417(21) \)
- |\( V_{us} \)|\(^2 + |\( V_{us} \)|\(^2 + |\( V_{ub} \)|\(^2 = 0.99978(55)\)
- \( |V_{us}| = 0.2253(8) \) (PDG14)
- Hardy & Towner, PR C 91 (2015) 025501

\[ \mathcal{F}_{t^0 \to 0^+} = 3072.27(72) \text{ s} \]
prospects - 1

1. pure Fermi transitions: - new data to improve $F_t$ values
   - testing isospin corrections $\delta_C$
   - nucleus-independent radiative correction $\Delta_R$

2. neutron decay: - lifetime (tSPECT, ...)
   - beta-asymmetry parameter $A$ (PERKEO, UCNA)
   - $\beta\nu$-correlation $a$ (aSPECT, Nab, AbBa, aCORN, ...)

3. $T = 1/2$ mirror $\beta$ transitions:

\[
F_t^{\text{mirror}} \left(1 + \frac{f_A}{f_V} \rho^2 \right) = 2F_t^{0^+ \rightarrow 0^+} = \frac{K}{G_F^2 V_{ud}^2 (1 + \Delta_R^V)}
\]

\[
\rho = \frac{C_A M_{GT}}{C_V M_F}
\]

\[
|V_{ud}| = 0.9719(17)
\]


O. Naviliat-Cuncic & N.S., PRL 102 (2009) 142302
6. $\beta$ spectrum shape measurements

$$N(p)dp = K p^2 (W - W_0)^2 \cdot F(Z, p) \cdot L_0 \cdot C \cdot R_n \cdot R_C \cdot S(E) dp$$

- phase space factor x constants
- $F(Z,p)$: Fermi function
- $L_0$ & $C$: finite size of nucleus
- $R_n$: finite mass of nucleus
- $R_C$: radiative corrections
- $S(E)$: spectrum shape factor

$$\frac{dN}{dE} \approx 1 + \frac{4}{3 M_n} \frac{b_{WM}}{Ac} E_e \Rightarrow \approx 0.8 \% \text{ MeV}^{-1}$$

(for a pure GT transition and neglecting terms $\propto 1/M^2$ and $\propto m_e^2/E$)

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

KU LEUVEN