Correlation measurements in nuclear beta decay

- General context & motivations
- Measurements of the beta neutrino angular correlation parameter
- \( F_t \)-values in \( 0^+ \rightarrow 0^+ \) transitions
- New prospects: the shape of the beta energy spectrum
Two complementary approaches:

**High energy frontier**
« Direct » observation of new particles at high energy colliders (LHC)

**Precision/intensity frontier**
Look for tiny deviations from SM predictions
- Non zero EDMs
- $\nu$ oscillations
- Search for WIMPs
- Dark decay of neutron
- ...
- Correlation measurements in nuclear beta decay
  → exotic couplings of electroweak interaction

Linked through EFT
The Fermi theory of nuclear beta decay

- **Fermi Basic hypothesis:**
  
  Analogy with Electro-magnetism: Hamiltonian product of *hadron and lepton currents*

  \[
  H = g_F \sum_i (\bar{\psi}_p \, \mathcal{O}_i \, \psi_n)(\bar{\psi}_e \, \mathcal{O}_i \, (C_i + C'_i \gamma_5) \, \psi_\nu) + h.c.
  \]

- **Lorentz invariance:**

  4 possible effective currents: *Scalar, Vector, Axial-vector, Tensor* (Dirac $\gamma$-matrix operators)

  8 coupling constants giving their relative strength (Wilson coefficients)

  $C_i$ & $C'_i$ with $i = S, V, A, T$

  $H$ even part & $H$ odd part

  $C_S, C_V, C_A, C_T, C'_S, C'_V, C'_A, C'_T \rightarrow$ have to be determined experimentally
Wilson coefficients in the SM

- **Simplifications from hadronic part of Hamiltonian:**
  - For Fermi transitions: only Vector & Scalar currents (no spin involved)
  - For GT transitions only Axial & Tensor currents (spin change involved)

- **Assumed in the Standard Model** (from previous experiments):
  - No time-reversal symmetry violation \( \Rightarrow C_i & C'_i \text{ are all real} \)
  - Parity violation is maximal with only left handed-neutrinos \( C_i = C'_i \)
  - No observation of exotic Scalar or Tensor currents \( C_S = C'_S = C_T = C'_T = 0 \)

- only 2 parameters (V-A theory):
  - \( C_V = C'_V = 1 \) (For Fermi transitions)
  - \( C_A = C'_A \approx -1.25 \) (For GT transitions)
Wilson coefficients in the SM

- **Present experimental constraints on exotic couplings (not so tight):**
  (A. Falkowsky et. Al. JHEP 04(2021)126, from nuclear & neutron decay)

  - Scenario with only left-handed neutrinos: $|C_S/C_V| \sim |C_T/C_A| < 0.1\%$
    $(C_i = C'_i)$
    $\rightarrow$ Sensitive to masses of order 10-100 TeV
    (Beyond reach of LHC)

  - Scenario with right-handed neutrinos: $|C_S/C_V| < 5\%$ $|C_T/C_A| < 7\%$
    $(C_i = -C'_i)$
    $\rightarrow$ Sensitive to masses of order 100 GeV -1 TeV
    (Within reach of LHC)

  - Complementarity with high energy physics
  - Real potential for new physics discovery
Access to exotic couplings

- The probability rate function of beta decay:

\[
\omega(J|E_e, \Omega_e, \Omega_v) \, dE_e \, d\Omega_e \, d\Omega_v = \frac{F(\pm Z, E_e)}{(2\pi)^5} \frac{p_e E_e (E_0 - E_e)^2}{p_e E_e (E_0 - E_e)^2} \, dE_e \, d\Omega_e \, d\Omega_v \\
\times \frac{1}{2\xi} \left\{ 1 + a \frac{p_e \cdot p_v}{E_e E_v} + b \frac{m}{E_e} + \frac{J}{J} \cdot \left[ A \frac{p_e}{E_e} + B \frac{p_v}{E_v} + D \frac{p_e \times p_v}{E_e E_v} \right] \right\}
\]

Fermi function
Phase space

Fermi function

- Nuclear transition matrix elements
- Correlation parameters \( a, b, A, B, \) and \( D \)

(corsrelation between spin & momenta of particles)
Access to exotic couplings

- The probability rate function of beta decay:

\[
\omega(J|E_e, \Omega_e, \Omega_v) \, dE_e \, d\Omega_e \, d\Omega_v \, = \, \frac{F(\pm Z, E_e)}{(2\pi)^5} \, p_e E_e (E_0 - E_e)^2 \, dE_e \, d\Omega_e \, d\Omega_v \times \frac{1}{2^\xi} \left\{ 1 + a \frac{p_e \cdot p_v}{E_e E_v} + b \frac{m}{E_e} + \frac{<J>}{J} \cdot \left[ \frac{A p_e}{E_e} + B \frac{p_v}{E_v} + D \frac{p_e \times p_v}{E_e E_v} \right] \right\}
\]

Fermi function

Phase space

nuclear transition matrix elements

with polarized nuclei

beta asymmetry

neutrino asymmetry

\( D \) triple correlation

Sensitive to CP violation

MORA project

Talk by Sacha Daumas

Poster by Nishu Goyal
Access to exotic couplings

- With non polarized nuclei:

\[
\omega(\langle J \rangle | E_e, \Omega_e, \Omega_v) \, dE_e \, d\Omega_e \, d\Omega_v = \frac{F(\pm Z, E_e)}{(2\pi)^5} \, p_e E_e (E_0 - E_e)^2 \, dE_e \, d\Omega_e \, d\Omega_v \\
\times \frac{1}{2 \xi} \left\{ 1 + a \frac{p_e \cdot p_v}{E_e E_v} + b \frac{m}{E_e} \right\}
\]

Fermi function

Phase space

nuclear transition matrix elements

beta-neutrino angular correlation \( a \)

Fierz term \( b \)

\( a \) & \( b \) sensitive to exotic couplings \( \rightarrow \) access to coefficients \( C_S, C'_S, C_T \) and \( C'_T \)
## Access to exotic couplings

- **In pure Fermi & pure GT transitions** $\rightarrow a$ & $b$ are independent of nuclear matrix elements

<table>
<thead>
<tr>
<th>For beta neutrino angular correlation $a$</th>
<th>For Fierz term $b$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pure F</strong></td>
<td><strong>Pure GT</strong></td>
</tr>
<tr>
<td>$a_F \approx 1$</td>
<td>$b_F \approx 0$</td>
</tr>
<tr>
<td>($= 1$ in SM)</td>
<td>($= 0$ in SM)</td>
</tr>
<tr>
<td>$\left</td>
<td>C_s \right</td>
</tr>
<tr>
<td>$\frac{1}{\left</td>
<td>C_v \right</td>
</tr>
<tr>
<td>$\gamma = \sqrt{1 - (\alpha Z)^2}$</td>
<td></td>
</tr>
</tbody>
</table>

- **Pure GT**
- $a \approx -\frac{1}{3}$
- ($= -1/3$ in SM)
- $b \approx \gamma \left( \frac{C_T + C'_T}{C_A} \right)$
- ($= 0$ in SM)

- **For beta neutrino angular correlation**
  - $a$ sensitive to **left- & right-handed neutrinos**
  - Quadratic dependence on couplings
  - $\Delta a/a = 0.01 \rightarrow \Delta C_i \approx 0.1$

- **For Fierz term**
  - $b$ sensitive to **left-handed neutrinos only** ($C_i = C'_i$)
  - Linear dependence
  - $\Delta b = 0.01 \rightarrow \Delta C_i \approx 0.01$
  - ($\rightarrow$ tighter constraints on left-handed contributions)
2) Measurements of the *beta-neutrino* angular correlation parameter $a_{\beta\nu}$
Measurements of $a_{\beta\nu}$

Decay probability rate proportional to: \[ P \propto \left[ 1 + a \frac{p_e p_\nu}{E_e E_\nu} \cos(\theta) \right] \]

- $a_{\beta\nu} = 1$ (max)
- Preferred $\beta - \nu$ angle: $\theta = 0^\circ$

- Maximum recoil energy $a_{\beta\nu}$ extracted from recoil energy distribution

- $a_{\beta\nu} = -1$ (min)
- Preferred $\beta - \nu$ angle: $\theta = 180^\circ$

- Minimum recoil energy

- Experimental difficulty: recoil ion energy $KE_{RI} \sim 100$ eV

- Use of Traps & TOF techniques
- Use of secondary particle emission $p, \alpha, \gamma$ ('Doppler shift measurement')
Sensitivity to $a, b$ and to new physics

- If $b \neq 0$ (LH neutrinos scenario)

$$ P \propto \left[ 1 + a \frac{p_e p_\nu}{E_e E_\nu} \cos(\theta) + b \frac{m_e}{E_e} \right] $$

Also impacts recoil distribution

- Recoil ion energy measurement gives access to: $\tilde{a} \approx a - kb$

Sensitivity to both $a \& b$

RH neutrinos scenario $\rightarrow \tilde{a} = a$

LH neutrinos scenario $\rightarrow \tilde{a} \approx a_{SM} - kb$

$k$ gives the sensitivity to $b$

must be determined by means of simulations

(depends on experimental technique & geometry)
Measurements of $a_{\beta V}$

### Present limits:

<table>
<thead>
<tr>
<th>Parent</th>
<th>Type</th>
<th>Technique</th>
<th>Team</th>
<th>$\bar{a}$</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^9$He</td>
<td>GT</td>
<td>Spectro</td>
<td>ORNL</td>
<td>-0.3308(30)</td>
<td>1963</td>
</tr>
<tr>
<td>$^{32}$Ar</td>
<td>F</td>
<td>$p$ recoil</td>
<td>UW, ISOLDE</td>
<td>0.9989(52)(39)</td>
<td>1999</td>
</tr>
<tr>
<td>$^{38m}$K</td>
<td>F</td>
<td>MOT</td>
<td>SFU, TRIUMF</td>
<td>0.9981(30)(34)</td>
<td>2004</td>
</tr>
<tr>
<td>$^{21}$Na</td>
<td>M</td>
<td>MOT</td>
<td>Berkeley, BNL</td>
<td>0.5502(38)(46)</td>
<td>2008</td>
</tr>
<tr>
<td>$^{6}$He</td>
<td>GT</td>
<td>Paul Trap</td>
<td>LPCC, GANIL</td>
<td>-0.3335(73)(75)</td>
<td>2011</td>
</tr>
<tr>
<td>$^8$Li</td>
<td>GT</td>
<td>Paul Trap</td>
<td>ANL</td>
<td>-0.3342(26)(29)</td>
<td>2015</td>
</tr>
</tbody>
</table>

GT: ~ 1% precision  
F: ~ 0.5% precision

### Ongoing & future projects:

<table>
<thead>
<tr>
<th>Parent</th>
<th>Type</th>
<th>Technique</th>
<th>Team</th>
<th>$\bar{a}$</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^8$Li</td>
<td>GT</td>
<td>Paul Trap</td>
<td>ANL</td>
<td>-0.3346(9)(24)</td>
<td>2015</td>
</tr>
<tr>
<td>$^6$He</td>
<td>GT</td>
<td>MOT</td>
<td>ANL, CENPA, LPCC</td>
<td>-0.3268(46)(41)</td>
<td>2015</td>
</tr>
<tr>
<td>$^6$He</td>
<td>GT</td>
<td>Paul Trap</td>
<td>LPCC, GANIL</td>
<td>Analysis almost completed (~1%)</td>
<td></td>
</tr>
<tr>
<td>$^{32}$Ar</td>
<td>F &amp; GT</td>
<td>$p$ recoil</td>
<td>WISArD</td>
<td>In preparation (~0.1%, test at 3.6%)</td>
<td></td>
</tr>
<tr>
<td>$^{35}$Ar</td>
<td>M</td>
<td>Paul Trap</td>
<td>LPCC, GANIL</td>
<td>Analysis under way (~1%)</td>
<td></td>
</tr>
<tr>
<td>$^{19}$Ne</td>
<td>M</td>
<td>Paul Trap</td>
<td>LPCC, GANIL</td>
<td>Analysis under way (~3%)</td>
<td></td>
</tr>
<tr>
<td>$^6$He</td>
<td>GT</td>
<td>EIBT</td>
<td>Weizman, SOREQ</td>
<td>In preparation (~0.1%)</td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>M</td>
<td>MOT</td>
<td>Weizman, SOREQ</td>
<td>In preparation (~0.1%)</td>
<td></td>
</tr>
<tr>
<td>$^{32}$Ar</td>
<td>F &amp; GT</td>
<td>Penning</td>
<td>Texas A&amp;M</td>
<td>In preparation (~0.1%)</td>
<td></td>
</tr>
<tr>
<td>$^{38m}$K</td>
<td>F</td>
<td>MOT</td>
<td>SFU, TRIUMF</td>
<td>In preparation (~0.1%)</td>
<td></td>
</tr>
</tbody>
</table>

Last results discussed in this talk (not published yet)

All new projects aim at 0.1% precision level…
Pure Fermi transition: WISArD experiment (ISOLDE)

- **Principle:** study proton-energy shift in $0^+ \rightarrow 0^+$ transition of $^{32}\text{Ar}$ (inspired from Adelberger 1999)

  - Measure the proton energy shift for same & opposite emission directions
  - $\Delta E_p$ is a linear function of $\tilde{a}_{\beta\gamma}$

  - High sensitivity to $\tilde{a}_{\beta\gamma}$ ($\times 2.5$ vs Adelberger99)
  - Independent of $p$ detector response function
  - Independent of $p$ peak intrinsic shape

Information on $^{32}\text{Cl}$ Recoil (Kinematic boost)

- Test experiment @ ISOLDE (1.5 days, 2018)

  - Average $E_p$ shift: $\Delta E_p = 4.49(3) \text{ keV}$

  $\tilde{a}_{\beta\gamma}^F = 1.007(32)_{\text{(stat)}}(25)_{\text{(syst)}} (3.6\%)$

  Extremely promising!

  V. Araujo-Escalona et al., PRC 2020
Pure Fermi transition: WISArD experiment (ISOLDE)

- **WISArD status: next experiment accepted (1\textsuperscript{st} run in October 2021 & 2\textsuperscript{nd} run in 2022)**

  New Silicon detectors (8 x 6 channels) with cooling system

  High resolution preamps (3.5 keV FWHM)

  - Resolution <10 keV FWHM (alpha) ⇒ Gain of factor ~ 8 in sensitivity
  
    - Negligible dead-layer effect (60±4nm)
    - Precise beta detector calibration (10-30keV) range
    - Dedicated backscattering measurements
    - x 10 thinner catcher

  Main sources of systematic error under control

  - goal of 0.1-0.2 % uncertainty on $\tilde{\alpha}$ achievable at ISOLDE with new setup

  - **Long term:**
    - Other nuclei (test theoretical corrections, higher sensitivity)
    - Other facilities? ⇒ DESIR
TOF measurement of $^6$Li recoil in $^6$He$^+$ beta decay (2005-2014)

- Decay source confined in a transparent Paul trap (beam preparation on LIRAT-SPIRAL1)
- $\beta$ - recoil ion detection in coincidence
- $a_{\beta V}$ deduced from recoil time-of-flight distribution

Difficulties:
- TOF shape analysis
  - TOF very sensitive to:
    - Trapped ion cloud shape & temperature
    - Relative position of cloud & detector
    - Scattering of $\beta$ particles
  - Complex simulation & analysis tools
  - Perfect agreement for all observables

Low stat results & shakeoff study published

- Couratin et al., PRL108 (2012)

Analysis for high stat runs still being completed
Pure GT transition: LPCTrap @ GANIL

- **Fit of the TOF spectrum**

\[ \tilde{\alpha}_{\beta\nu}^{GT} = -0.33\text{??(15)(stat)(30)(syst)} \quad (1.0\%) \]

<table>
<thead>
<tr>
<th>Source of syst.</th>
<th>Uncertainty</th>
<th>( \Delta \alpha/\alpha ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud temperature</td>
<td>&lt;10K</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Beta Scattering</td>
<td>10%</td>
<td>0.5</td>
</tr>
<tr>
<td>( TOF_{T0} )</td>
<td>0.35ns</td>
<td>0.4</td>
</tr>
<tr>
<td>TDC</td>
<td>1.00E-04</td>
<td>0.25</td>
</tr>
<tr>
<td>VRF</td>
<td>1%</td>
<td>0.2</td>
</tr>
<tr>
<td>( E_p ) calibration</td>
<td>-</td>
<td>0.15</td>
</tr>
<tr>
<td>VIRD</td>
<td>2V</td>
<td>0.03</td>
</tr>
<tr>
<td>BKG</td>
<td>-</td>
<td>0.03</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>0.88</td>
</tr>
</tbody>
</table>

To be done:
- Include corrections (radiative & recoil)
- Run more stat in simulations

Very satisfactory after many years spent on this analysis…
Decay of $^8$Li$^+$

Images and results taken from M. T. Burkey Thesis and 2020 DNP Presentation (LLNL-PRES-815970)

$\bar{\alpha}_{\beta\nu} = -0.3346(09)_{\text{stat}}(24)_{\text{syst}}$ (0.7%)

Decay of $^6$He atoms

XXIInd COLLOQUE GANIL, Autrans-Méaudre en Vercors, 30 October 2021

X. Fléchard

$\bar{\alpha}_{\beta\nu} = -0.3268(46)_{\text{stat}}(41)_{\text{syst}}$ (1.9%)
### Sensitivity to $a$, $b$ and to new physics

- **New constraints from these experiments:**

<table>
<thead>
<tr>
<th>Pure Fermi</th>
<th>Pure Gamow-Teller</th>
</tr>
</thead>
<tbody>
<tr>
<td>WISArD</td>
<td>LPCTrap</td>
</tr>
<tr>
<td>Adelberger</td>
<td>ANL Trap</td>
</tr>
<tr>
<td></td>
<td>Seattle MOT</td>
</tr>
</tbody>
</table>

|                         | $\Delta a/a \approx \Delta \bar{a}/\bar{a}$ | $|C_S/C_V|$ or $|C_T/C_A|$ | LPCTrap | ANL Trap | Seattle MOT |
|-------------------------|-------------------------------------------|--------------------------|---------|-----------|-------------|
| Right-handed neutrinos  | 0.2%                                      | 0.65%                    | 1.0%    | 0.7%      | 1.9%        |
| $C_i = -C_i'$           | $\approx 0.2\%$                          | $\approx 0.65\%$         | $\approx 1.0\%$ | $\approx 0.7\%$ | $\approx 1.9\%$ |
| $|C_S/C_V|$ or $|C_T/C_A|$ | $\approx 3\%$                           | $\approx 6\%$            | $\approx 7\%$ | $\approx 6\%$ | $\approx 10\%$ |
3) Other way to measure $b$:
$Ft$-values in $0^+ \to 0^+$ transitions
\( \mathcal{F}_{t}(b_{F}) \rightarrow \mathcal{F}_{0} \ (1 + b_{F} \ m_{e}/<E_{\beta}>)^{-1} \)

- Used to test CVC hypothesis & extract Vud (talk by Nadezda Smirnova on Wednesday)
- If one accounts for a non-zero Fierz term \( b_{F} \) the \( \mathcal{F}_{t} \)-value depends on \( <E_{\beta}> \)

**Best constraints on Scalar couplings!**

(involving left-handed neutrinos)

> \( b_{F} = -1.0 \ (2.1) \times 10^{-3} \) (Seng et.al.)

**Error budget:**

**Improve B.R. in \(^{10}\text{C}\)**

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Recent measurements at ISOLDE:

- $\mathcal{F}_t$-values in $0^+ \rightarrow 0^+$ pure Fermi transitions

Final result: 1.4638(50) %; Savard: 1.4625(25)%; Fujikawa: 1.4665(38)%

Another experiment was performed at ALTO with nu-ball (analysis ongoing)

Any improvement for $^{10}$C branching ratio will result in better constraints on $b_F$

Very interesting case for DESIR
4) New prospects: measurements of the shape of the beta energy spectrum
Shape of the beta energy spectrum

- With detection of beta particle only:

\[ W(E_e) \propto N(E_e) \left[ 1 + \frac{b m_e}{E_e} \right] \]

Decay rate: 

Phase space and Fermi function (known)

6He β energy spectrum (b=0) Distortion for \( b = 10^{-3} \)

Precise measurement of β energy shape \( \rightarrow \) direct access to \( b \)

Difficulty:

- β backscattering on detector surface

shape in \(^{20}\text{F}\) decay (Ge)

Deep implantation 132 MeV/nucleon

M. Hughes, PhD, MSU 2019

Courtesy of O. Naviliat-Cuncic

\[ \Delta b_{GT} \approx 0.01 \]
**b-STILED project @ GANIL**

(b: Search for Tensor Interactions in nuclear beta Decay)

- **Goal:** measure $b_{GT}$ in $^6$He beta decay with a precision better than $4 \times 10^{-3}$ (phase 1)
  (direct improvement on present constraints from nuclear beta decay)

  M. Gonzalez-Alonso, O.N.C., N. Severijns,
  Prog. Part. Nucl. Phys. 104 (2019) 165

- **Technique proposed:** use the 4Pi calorimetry technique at both low and high energy

**Low energy setup (LIRAT)**
- No beam induced background
- Movable detector $\rightarrow$ 4Pi

**High energy setup (LISE)**
- YAP (27ns) $\rightarrow$ very linear response
  $\rightarrow$ good sensitivity to $\gamma$
- Plastic (2ns) as veto
- $^{241}$Am for gain monitoring

Proposal was accepted in 2020 by the GANIL PAC (E815S_20)

**Shape of the beta energy spectrum**
1st run at low energy on GANIL LIRAT beam line (June 2021)

- Normal run
- Corrected from BKG
- Phase space fit

“Zero order” analysis shows no obvious problem

Beam off

Stat: \( \sim 4.5 \times 10^7 \) events
(different intensities & PM gain)

- \( T_{1/2} \) with \( \sim 2 \times 10^{-4} \) relative precision
  analysis ongoing (M. Kanafani Thesis)

- \( \Delta b_{GT(stat)} \) \( \sim 2 \times 10^{-3} \)
  fine analysis to come (M. Kanafani Thesis)

2s implantation

10s measurement

Beta energy spectrum
Next step: 2d run at high energy on LISE in 2022

→ Offer for 2-year postdoc position (CNRS portal)

Depending on results for both experiments:
- choose one technique
- push it with precision goal of $10^{-3}$ on $b_{GT}$

Shape of the beta energy spectrum
Summary

- **For exotic couplings involving RH neutrinos:**
  Measurements of $\tilde{a}$ remain unique (strong potential for the WISArD experiment). But real breakthroughs ($\times10$ on constraints) seem out of reach when considering the quadratic dependence of experimental observables on such couplings.

- **For exotic couplings involving LH neutrinos:**
  Measurements of $\tilde{a}$ with high sensitivity to $b$ can still play an important role (again, strong potential for the WISArD experiment).

  *$Ft$-values* for light nuclei ($^{10}$C) should also be improved, to provide direct impact for constraints on Scalar currents.

  For Tensor currents, 4pi beta calorimetry (*b-STILED*) seems to be a very promising technique. It will be very interesting, in the coming few years, to see how far we can go with this technique at GANIL, with both low and high energy beams.
Backup slides
Leads to different forms of currents:

5 different possible forms of currents: \( S, V, T, A \& P \)

To respect Lorentz invariance:
\( H \) must be a Scalar or a Pseudoscalar

\[
H_i^{even} = g_i (\bar{\psi}_p \, O_i \, \psi_n) (\bar{\psi}_e \, O_i \, \psi_v) + h.c. \quad \text{(scalar)}
\]

\[
H_i^{odd} = g'_i (\bar{\psi}_p \, O_i \, \psi_n) (\bar{\psi}_e \, O_i \gamma_5 \, \psi_v) + h.c. \quad \text{(pseudoscalar)}
\]

With:
\[
g_i = g_F C_i \\
g'_i = g_F C'_i \quad i = S, V, T, A, P
\]
The Fermi theory

- To respect Lorentz invariance
  
  \( H \) must be a Scalar or a Pseudoscalar:

  \[
  H_{i\text{even}}^{\text{even}} = g_i (\bar{\psi}_p O_i \psi_n) (\bar{\psi}_e O_i \psi_{\nu}) + h.c. \\
  \quad \text{(scalar)}
  \]

  \[
  H_{i\text{odd}}^{\text{odd}} = g'_i (\bar{\psi}_p O_i \psi_n) (\bar{\psi}_e O_i \gamma_5 \psi_{\nu}) + h.c. \\
  \quad \text{(pseudoscalar)}
  \]

  For parity violation

  With:

  \[
  g_i = g_F C_i \quad \quad g'_i = g_F C'_i \quad \quad i = S, V, T, A, P
  \]

- The generalized form is then:

  \[
  H = g_F \sum_i (\bar{\psi}_p O_i \psi_n) (\bar{\psi}_e O_i (C_i + C'_i \gamma_5) \psi_{\nu}) + h.c.
  \]

  In the NRA approximation, the Dirac \( \gamma \)-matrix for nucleons can be simplified for

  We end up with:

  - 4 coupling constants (Wilson coefficients) for Fermi transitions: \( C_V, C'_V, C_S, C'_S \)
  - 4 coupling constants for GT transitions: \( C_A, C'_A, C_T, C'_T \)

  whose strengths have to be determined experimentally…
Approximation for the hadronic terms:

The nucleons are considered as non relativistic (NRA, for non relativistic approximation)

In the NRA approximation, the Dirac $\gamma$-matrix for nucleons can be simplified for

\[ \left( \gamma^\mu O_i \psi_n \right) \]

It can be shown that:

- For $i=\text{P}$:
  \[ O_i = 0 \] \rightarrow \text{no pseudoscalar term}

- For $i=\text{S}$:
  \[ O_i = 1 \] \rightarrow \text{no spin involved}

- For $i=\text{V}$:
  \[ O_i = \gamma^0 \] \rightarrow \text{no spin involved}

- For $i=\text{A} & \text{T}$:
  \[ O_i = f(\sigma) \] \rightarrow \text{spin involved} (Pauli Matrix)

4 possible coupling constants for Fermi transitions: $C_V, C'_V, C_S, C'_S$

4 possible coupling constants for GT transitions: $C_A, C'_A, C_T, C'_T$
What link with experimental measurements?

One can “solve” the Hamiltonian to express the decay rate as a function of all relevant observables of the system: \( \hat{I}, \ \vec{\sigma}, \ \vec{p}_e, \ \vec{p}_\nu \)

Nuclear polarization \( \rightarrow \) Spin vector of \( \beta \) particle \( \rightarrow \) Leptons momentum

**If one integrate the Hamiltonian with the \( \gamma \)-matrix we get:**

\[
\omega(\langle \hat{I} \rangle, \vec{\sigma}|E_e, \Omega_e, \Omega_\nu) dE_e d\Omega_e d\Omega_\nu \propto
F(\pm Z, E_e) p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \times
\]

\[
\xi \left\{ 1 + \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} a + \frac{m}{E_e} b + \right.
\]

\[
\frac{\hat{I}}{I} \left[ \frac{\vec{p}_e}{E_e} A + \frac{\vec{p}_\nu}{E_\nu} B + \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} D \right] +
\]

\[
\vec{\sigma} \cdot \left[ \frac{\vec{p}_e}{E_e} G + \frac{\langle \hat{I} \rangle}{I} \vec{N} + \frac{p_e}{E_e + m} \left( \frac{\langle \hat{I} \rangle}{I} \cdot \frac{\vec{p}_e}{E_e} \right) Q + \frac{\langle \hat{I} \rangle}{I} \times \frac{\vec{p}_e}{E_e} R \right] \}
\]
What link with experimental measurements?

All the correlation coefficients can be expressed as a function of the couplings $C_V, C'_V, C_S, C'_S, C_A, C'_A, C_T, C'_T$

For example, for $a \& b$:

$$a \xi = |M_F|^2 \left[ -|C_S|^2 + |C_V|^2 - |C'_S|^2 + |C'_V|^2 \mp 2 \frac{\alpha Z m}{p_e} \text{Im} (C_S C_V^* + C'_S C'_V^*) \right]$$

$$+ \frac{|M_{GT}|^2}{3} \left[ |C_T|^2 - |C_A|^2 + |C'_T|^2 - |C'_A|^2 \pm 2 \frac{\alpha Z m}{p_e} \text{Im} (C_T C_A^* + C'_T C'_A^*) \right]$$

$$b \xi = \pm 2 \gamma \text{Re} \left[ |M_F|^2 (C_S C_V^* + C'_S C'_V^*) \right.$$

$$\left. + |M_{GT}|^2 (C_T C_A^* + C'_T C'_A^*) \right]$$

With

$$\xi = |M_F|^2 \left( |C_S|^2 + |C_V|^2 + |C'_S|^2 + |C'_V|^2 \right)$$

$$+ |M_{GT}|^2 \left( |C_T|^2 + |C_A|^2 + |C'_T|^2 + |C'_A|^2 \right)$$

(Where $M_F$ & $M_{GT}$ are the Fermi & Gamow-Teller nuclear Matrix elements)
Measurements of $a_{\beta\nu}$

- Beta neutrino angular correlation is linked to the leptons helicity:
  - SM currents (V & A) → lead to opposite helicity of the two leptons
  - NP currents (S & T) → lead to same helicity of the two leptons

**pure Fermi transitions $\Delta J=0$**

- $S=0$: spin of leptons anti-parallel
  - Only $V$ couplings
  - Opposite helicity

- $\theta = 0^\circ$
- $a_{\beta\nu}^F = 1$
- Maximum recoil energy

- Preferred $\beta-\nu$ angle:

**pure Gamow-Teller transitions**

- $S=1$: spin of leptons can be parallel (CG $\rightarrow x$ $1/3$)
  - Only $S$ couplings
  - Same helicity

- $a_{\beta\nu}^{GT} = -\frac{1}{3}$
- Minimum recoil energy

**Measure recoil energy spectrum to extract $a_{\beta\nu}$**

(neutrinos cannot be detected)
Pure Fermi transition: WISArD experiment (ISOLDE)

- Inspired from the proton-pic broadening experiment in 32Ar decay (Adelberger 1999):

Information on 
32Cl Recoil
(Kinematic boost)

3.35 MeV

\[ ^{31}\text{S} + p \rightarrow ^{32}\text{Cl} \]

\[ ^{32}\text{Ar} \rightarrow ^{0+}\beta^+ \]

\[ IAS \]

Proton peak shape

Vector, \( a=1 \)
high recoil energy
large broadening

Scalar, \( a=-1 \)
low recoil energy
small broadening

\( ^{31}\text{S} + p \rightarrow ^{32}\text{Cl} \)
Present status: finally getting there!

(Mostly thanks to the simulation tool CLOUDA and refined analysis)

Comparison experiment vs simulation (residuals)

Beta deposited energy spectrum
Particle position on detectors

Reconstructed Q-value (all observables including TOF)

No more mismatch Exp vs Sim…
Example: weak magnetism in $^6$He decay

- The WM form factor, $b_{WM}$, can be calculated with sufficient accuracy using the *strong form of CVC* applied to an isospin triplet.

- The WM contributes to all terms of the spectrum shape factor

\[
S(W) = (1 + C_0 + C_1 W + C_{-1}/W)
\]

B.R. Holstein and S.B. Treiman, PRC 3 (1971) 1921

\[
C_0 = \frac{2}{3M} \left( \frac{W_0}{c} + \frac{b_{WM}}{c} \right) = -1.234(14) \%
\]

\[
C_1 = \frac{2}{3M} \left( 5 + 2 \frac{b_{WM}}{c} \right) = 0.6502(69) \% / \text{MeV}
\]

\[
C_{-1} = -\frac{2m^2}{3M} \left( 1 + \frac{b_{WM}}{c} \right) = -0.0802 (9) \% \times \text{MeV}
\]

\[
b_{WM}^{\text{CVC}} = 68.22 \pm 0.79 \quad c = g_A |M_{GT}|
\]
Theoretical description of the spectrum

\[ N(E) \propto (1 + \eta) pE (E - E_0)^2 \left( 1 + \frac{m}{E} b_{GT} \right) \]

For \(^6\text{He}\) decay, theoretical corrections for the description of the beta spectrum are known with sufficient accuracy.

<table>
<thead>
<tr>
<th>Source</th>
<th>( \Delta b_{GT} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear charge radius of (^6\text{Li})</td>
<td>4.6 \times 10^{-5}</td>
</tr>
<tr>
<td>End-point energy of the transition</td>
<td>1.8 \times 10^{-4}</td>
</tr>
<tr>
<td>Weak magnetism form factor</td>
<td>5.7 \times 10^{-4}</td>
</tr>
<tr>
<td>Induced tensor form factor</td>
<td>1.9 \times 10^{-5}</td>
</tr>
<tr>
<td>Total theoretical uncertainty</td>
<td>6.0 \times 10^{-4}</td>
</tr>
</tbody>
</table>
Many projects / techniques under development worldwide

- **Project 8 @ Uni. Washington**
  Based on cyclotron radiation measurement of single beta (tritium for $\nu$ mass, and $^6$He for $b$)
  Under development

- **miniBETA @ KU Leuven**
  multi-wire drift chamber + scint (later DSSSD)
  Under development

- **114In @ WISArD**
  Beta particle confinement in strong B-field
  Under development

- **$^6$He & $^{20}$F @ NSCL**
  Fragment implantation in the core of
  The detection volume (no backscattering)

  132 MeV/nucleon

  Courtesy of O. Naviliat-Cuncic

Shape of the beta energy spectrum
Detector developments

Phoswich configuration

For gain drift monitoring, use $^{241}$Am source and LED coupled to the plastic scintillator surrounding the beta detector.

Use pulse shape discrimination on signals sampled by the digital DAQ.
Exotic currents beyond $V$-$A$ theory: status

\[ \bar{a} \approx a(1 + \kappa b) \]

\[
\begin{array}{c|c|c}
\hline
& \text{LH} & \text{RH} \\
\hline
|C_S/C_V| & 0.0038 & 0.068 \\
|C_T/C_A| & 0.0064 & 0.078 \\
\hline
\end{array}
\]

Hardy et al PRC79(2015)

- Best constraints from "b", but "a" adds limits... ("b" unsensitive to right-handed \( \nu \))
- In green: constraints from LHC (CMS data) Cirigliano et al PPNP71 (2013)

**Thanks to EFT!**

**Precision level at 10^{-3} needed to compete with LHC**