
26 SEP > 1 OCT 2021 Autrans-Méaudre en Vercors, FRANCE

XXIInd COLLOQUE GANIL

Correlation measurements in nuclear beta decay

- General context & motivations
- Measurements of the beta neutrino angular correlation parameter
- Ft-values in 0+→0+ transitions
- New prospects: the shape of the beta energy spectrum

cnrs

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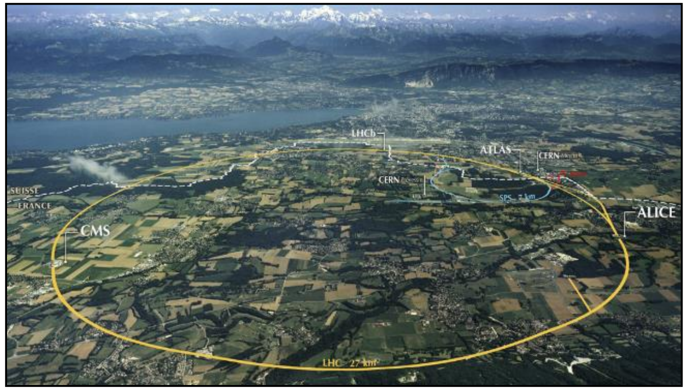
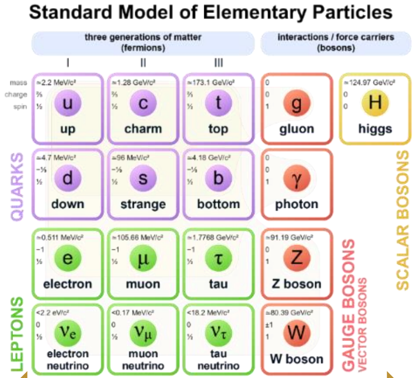
Search for Physics beyond the Standard Model

- **Two complementary approaches:**

High energy frontier

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





Linked through EFT

Precision/intensity frontier

Look for tiny deviations from SM predictions

- Non zero EDMs
- ν oscillations
- Search for WIMPs
- Dark decay of neutron
- …
- **Correlation measurements in nuclear beta decay**
  → exotic couplings of electroweak interaction

The Fermi theory of nuclear beta decay

- **Fermi Basic hypothesis:**

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

$$H = \underbrace{g_F}_{\substack{\text{Fermi Coupling Constant} \\ \text{(weak interaction strength)}}} \sum_i \underbrace{(\bar{\psi}_p \, \mathcal{O}_i \, \psi_n)}_{\text{Hadron current}} (\bar{\psi}_e \underbrace{\mathcal{O}_i \, (C_i + C_i' \gamma_5) \, \psi_\nu)}_{\text{Lepton current}} + h.c.$$

- **Lorentz invariance :**

$\mathcal{O}_i$ → 4 possible effective currents: *Scalar, Vector, Axial-vector, Tensor*
(Dirac γ-matrix operators)

C_i & C_i' → 8 coupling constants giving their relative strength (Wilson coefficients)
$i = S, V, A, T$

C_i → *H* even part

C_i' → *H* odd part

C_S , C_V , C_A , C_T , C_S', C_V', C_A', C_T → 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 → C_i & C'_i *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)*

$C_A = C'_A \simeq -1.25$ *(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: $|C_S/C_V| \sim |C_T/C_A| < 0.1\%$
    $(\boldsymbol{C_i = C'_i})$ →Sensitive to masses of order 10-100 TeV
    (Beyond reach of LHC)

  - Scenario with right-handed neutrinos: $|C_S/C_V| < 5\%$ $|C_T/C_A| < 7\ \%$
    $(\boldsymbol{C_i = -\,C'_i})$ →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:**

$$\omega(\langle\mathbf{J}\rangle|E_e,\Omega_e,\Omega_\nu)\,\mathrm{d}E_e\,\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu = \underbrace{\overset{\text{Fermi function}}{\frac{F(\pm Z,E_e)}{(2\pi)^5}}}\;\underbrace{\overset{\text{Phase space}}{p_eE_e(E_0-E_e)^2\,\mathrm{d}E_e\,\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu}}$$

$$\underbrace{\times\frac{1}{2}\xi}_{\substack{\text{nuclear transition}\\ \text{matrix elements}}}\left\{1+\underbrace{a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+b\frac{m}{E_e}+\frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e}+B\frac{\mathbf{p}_\nu}{E_\nu}+D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]}_{\substack{\text{Correlation parameters } a,\,b,\,A,\,B,\text{ and } D\\ \text{(correlation between spin \& momenta of particles)}}}\right\}$$

Access to exotic couplings

- **The probability rate function of beta decay:**

Fermi function

Phase space

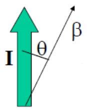
$$\omega(\langle \mathbf{J}\rangle | E_e, \Omega_e, \Omega_\nu)\, \mathrm{d}E_e\, \mathrm{d}\Omega_e\, \mathrm{d}\Omega_\nu = \underline{\frac{F(\pm Z, E_e)}{(2\pi)^5}}\, \underline{p_e E_e (E_0 - E_e)^2\, \mathrm{d}E_e\, \mathrm{d}\Omega_e\, \mathrm{d}\Omega_\nu}$$

$$\underline{\times \frac{1}{2}\xi} \left\{ 1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \frac{\langle \mathbf{J} \rangle}{J} \cdot \left[\underline{A \frac{\mathbf{p}_e}{E_e}} + \underline{B \frac{\mathbf{p}_\nu}{E_\nu}} + \underline{D \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu}} \right] \right\}$$

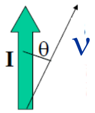
nuclear transition matrix elements

with polarized nuclei

beta asymmetry



neutrino asymmetry



D triple correlation

Sensitive to CP violation

MORA project
Talk by Sacha Daumas
Poster by Nishu Goyal

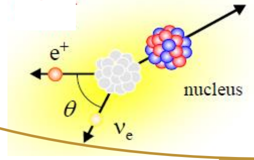
Access to exotic couplings

- **With non polarized nuclei:**

$$\omega(\langle \mathbf{J}\rangle|E_e,\Omega_e,\Omega_\nu)\,\mathrm{d}E_e\,\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu = \overset{\text{Fermi function}}{\underline{\frac{F(\pm Z,E_e)}{(2\pi)^5}}}\,\overset{\text{Phase space}}{\underline{p_eE_e(E_0-E_e)^2\,\mathrm{d}E_e\,\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu}}$$

$$\times\underbrace{\frac{1}{2}\xi}_{\text{nuclear transition matrix elements}}\left\{1+\underbrace{a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}}_{\text{beta-neutrino angular correlation } a}+\underbrace{b\frac{m}{E_e}}_{\text{Fierz term } b}\right\}$$

beta-neutrino
angular correlation *a*



Fierz term *b*

a & b sensitive to exotic couplings → acces to coefficients $C_S, C'_S,\ C_T\ and\ C'_T$

Access to exotic couplings

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

	For beta neutrino angular correlation a	For Fierz term b
Pure F	$\boxed{a_F \cong 1} - \frac{\lvert C_S\rvert^2 + \lvert C'_S\rvert^2}{\lvert C_V\rvert^2}$ (= 1 in SM)	$b_F \cong \left(\frac{C_T + C'_T}{C_A}\right)$ (= 0 in SM) $\gamma = \sqrt{1-(\alpha Z)^2}$
Pure GT	$\boxed{a_{GT} \cong -\frac{1}{3}}(1 - \frac{\lvert C_T\rvert^2 + \lvert C'_T\rvert^2}{\lvert C_A\rvert^2})$ (= -1/3 in SM)	$b_{GT} \cong \gamma \left(\frac{C_T + C'_T}{C_A}\right)$ (= 0 in SM)

- a sensitive to left-& right-handed neutrinos
- Quadratic dependence on couplings

$\Delta a/a$ =0.01 → ΔC_i ~ 0.1

- b sensitive to left-handed neutrinos only $(C_i = C'_i)$
- Linear dependence

Δb=0.01 → ΔC_i ~ 0.01

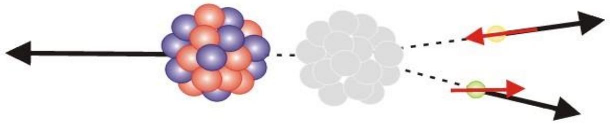
(→ tighter constraints on left-handed contributions)

2) Measurements of the *beta-neutrino* angular correlation parameter $a_{\beta\nu}$

Measurements of $a_{\beta\nu}$

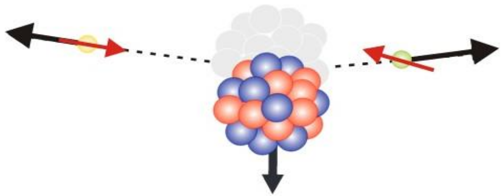
Decay probability rate proportional to: $$P \propto \left[1 + a\frac{p_e p_\nu}{E_e E_\nu}\cos(\theta)\right]$$

- **$a_{\beta\nu}$= 1 (max)**
- **Preferred β–ν angle: θ = 0°**



- **Maximum recoil energy**

- **$a_{\beta\nu}$= -1 (min)**
- **Preferred β–ν angle: θ = 180°**



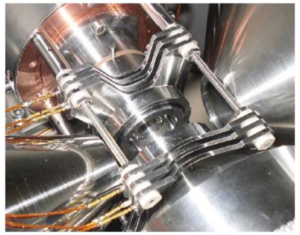
- **Minimum recoil energy**

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

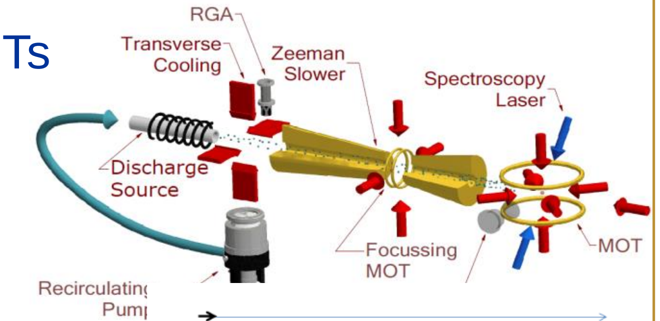
- **Experimental difficulty: recoil ion energy KE_{RI} ~ 100 eV**

- Use of Traps & TOF techniques
- Use of secondary particle emission *p*, α, γ (‘Doppler shift measurement’)

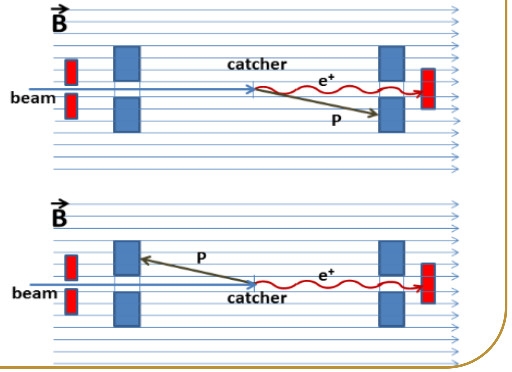
Ion traps



MOTs



Doppler shift



Sensitivity to a, b and to new physics

- **If b ≠ 0 (LH neutrinos scenario)**

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

Also impacts recoil distribution

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

Sensitivity to both a & b

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

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

k gives the sensitivity to b
must be determined by means of simulations
(depends on experimental technique & geometry)

Measurements of $a_{\beta\nu}$

Present limits:

Parent	type	Technique	Team	$\tilde{a}$		Year
^{6}He	GT	Spectro	ORNL	-0.3308(30)	0.9%	1963
^{32}Ar	F	*p* recoil	UW, ISOLDE	0.9989(52)(39)	0.65%	1999
^{38m}K	F	MOT	SFU, TRIUMF	0.9981(30)(34)	0.45%	2004
^{21}Na	M	MOT	Berkeley, BNL	0.5502(38)(46)	1.1%	2008
^{6}He	GT	Paul Trap	LPCC, GANIL	-0.3335(73)(75)	3,1%	2011
^{8}Li	GT	Paul Trap	ANL	-0.3342(26)(29)	1.2%	2015

GT: ~ 1% precision

F: ~ 0.5% precision

Ongoing & future projects:

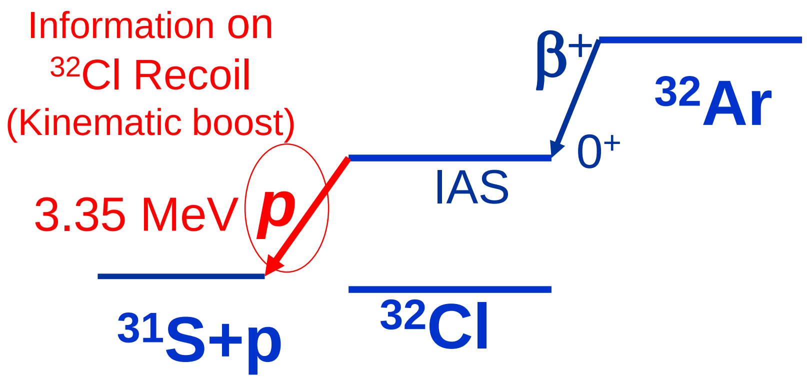
^{8}Li	GT	Paul Trap	ANL	−0.3346(9)(24)	0.7%
^{6}He	GT	MOT	ANL,CENPA, LPCC	−0.3268(46)(41)	1.9%
^{6}He	GT	Paul Trap	LPCC, GANIL	Analysis almost completed (~1%)	
^{32}Ar	F & GT	*p* recoil	WISArD	In preparation (~0.1%, test at 3.6%)	
^{35}Ar	M	Paul Trap	LPCC, GANIL	Analysis under way (~1%)	
^{19}Ne	M	Paul Trap	LPCC, GANIL	Analysis under way (~3%)	
^{6}He	GT	EIBT	Weizman, SOREQ	In preparation (~0.1%)	
Ne	M	MOT	Weizman, SOREQ	In preparation (~0.1%)	
^{32}Ar	F & GT	Penning	Texas A&M	In preparation (~0.1%)	
^{38m}K	F	MOT	SFU, TRIUMF	In preparation (~0.1%)	

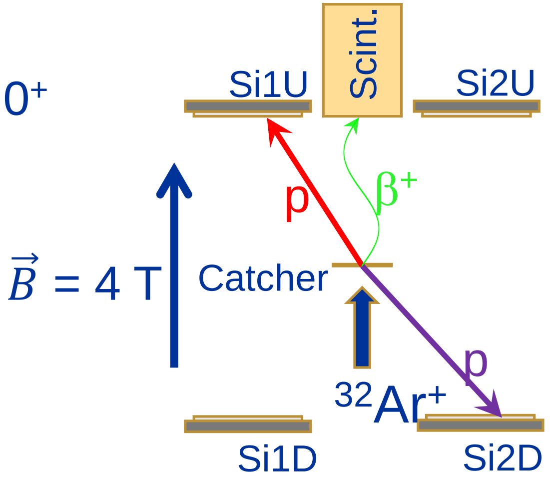
Last results discussed in this talk
(not published yet)

All new projects aim at 0.1% precision level…

Pure Fermi transition: WISArD experiment (ISOLDE)

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





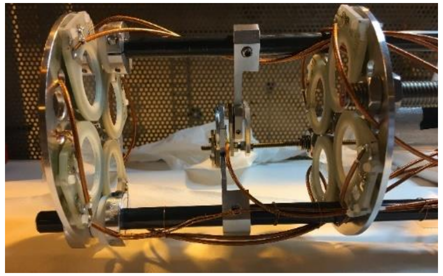
- **Measure the proton energy shift** for same & opposite emission directions
- **ΔE_p is a linear function of $\tilde{a}_{\beta\nu}$**

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

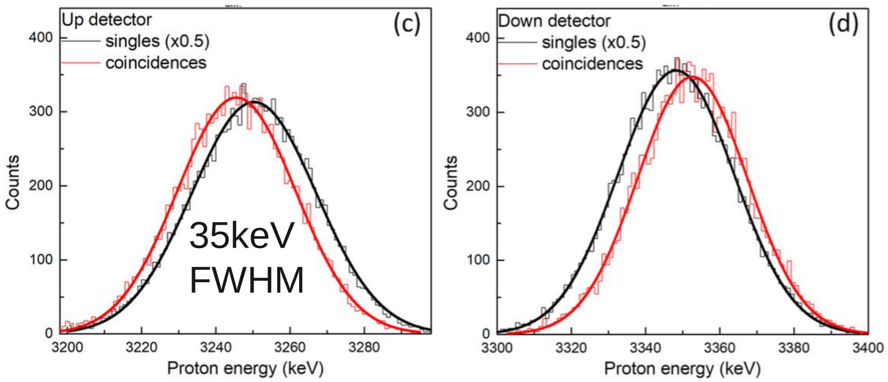
WITCH Magnet

Test experiment @ ISOLDE (1.5 days, 2018)

Test Setup



Average E_p shift: ΔE_p= 4.49(3) keV



$\tilde{a}^F_{\beta\nu}$ **= 1.007(32)$_{(stat)}$(25)$_{(syst)}$ (3.6%)**

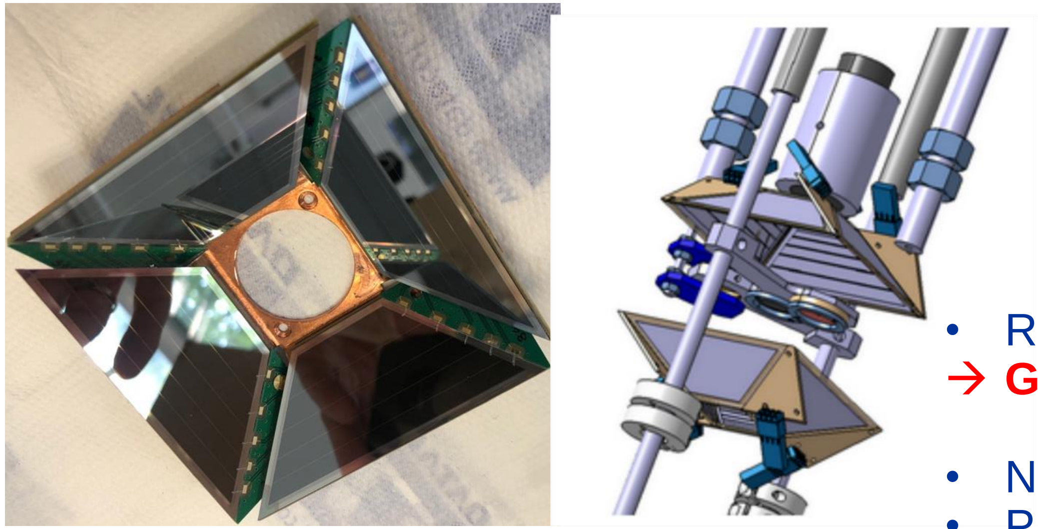
extremely promising!

V. Araujo-Escalona et al., PRC 2020

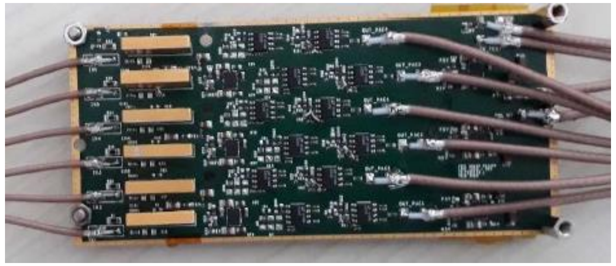
Pure Fermi transition: WISArD experiment (ISOLDE)

- **WISArD status: next experiment accepted (1st run in October 2021 & 2d 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**

+

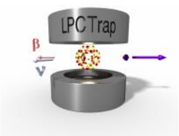
- Negligible dead-layer effect (60±4nm)
- Precise beta detector calibration (10-30keV) range
- Dedicated backscattering measurements
- x 10 thinner catcher

Main sources of systematic error under control

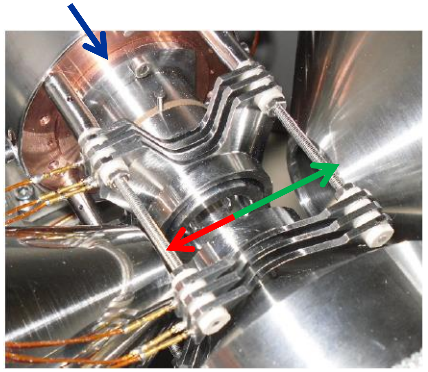
- goal of 0.1-0.2 % uncertainty on $\tilde{a}$ achievable at ISOLDE with new setup
- **Long term:**
  - Other nuclei (test theoretical corrections, higher sensitivity)
  - Other facilities ? → DESIR

Pure GT transition: LPCTrap @ GANIL

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)
- β - recoil ion detection in coincidence
- $a_{\beta\nu}$ deduced from recoil time-of-flight distribution



beam

beta detector (DSSSD + scintillator)

TOF tube Position sensitive MCP detector

Low stat results & shakeoff study published

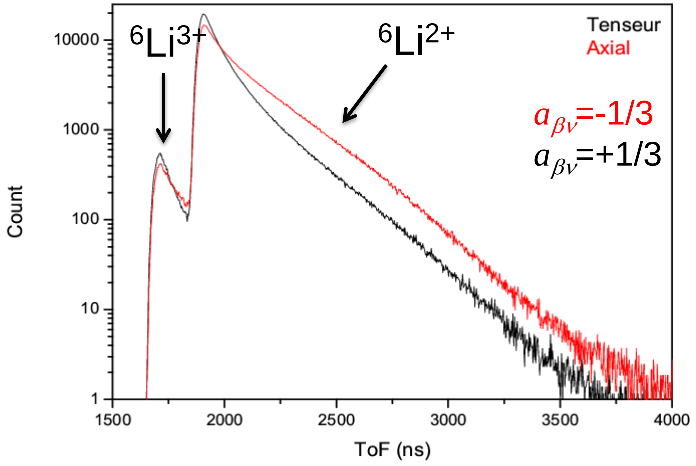
Fléchard et al., J.Phys.G 38 (2011)

Couratin et al., PRL108 (2012)

Analysis for high stat runs still being completed

Difficulty: the measurement rely on TOF shape analysis

Simulation for ^{6}He$^+$ decay



TOF very sensitive to:

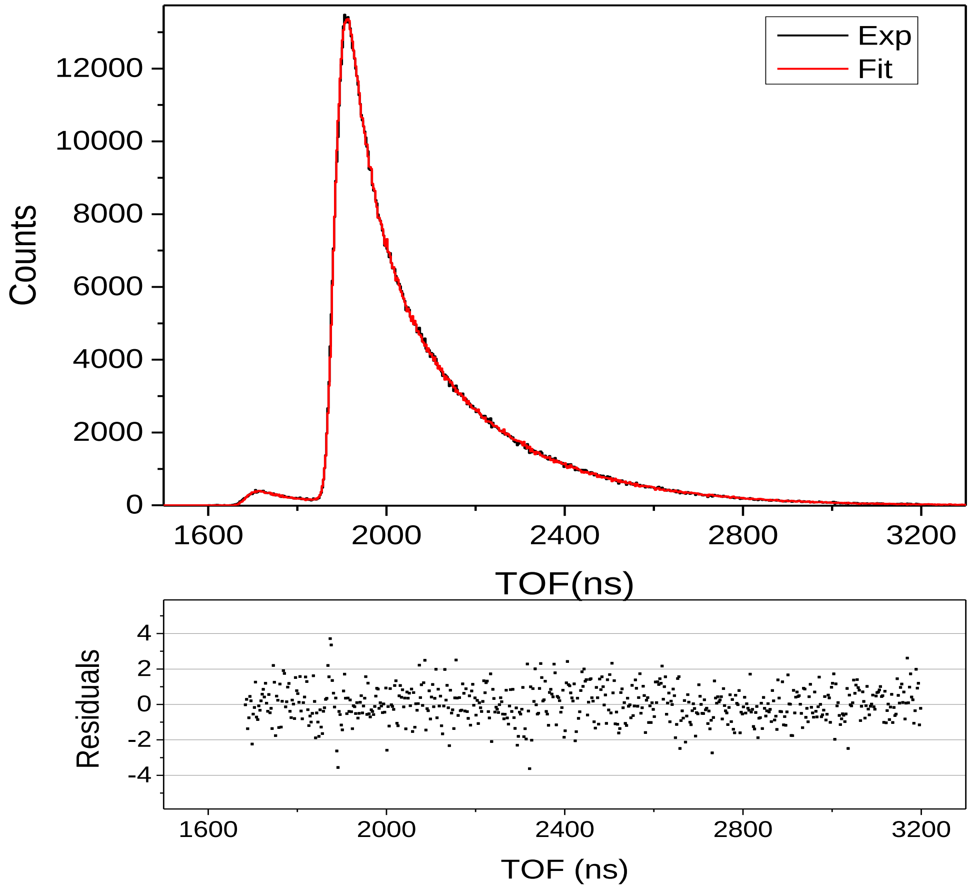
- Trapped ion cloud shape & temperature
- Relative position of cloud & detector
- Scattering of β particles

- Complex simulation & analysis tools
- Perfect agreement for all observables

We are working on that for a long long time…

Pure GT transition: LPCTrap @ GANIL

Fit of the TOF spectrum



Preliminary result:

$$\tilde{a}_{\beta\nu}^{GT} = -0.33??(15)_{(stat)}(30)_{(syst)} \quad (1.0\%)$$

Source of syst.	Uncertainty	$\Delta a/a$ (%)
Cloud temperature	<10K	<0,5
Beta Scattering	10%	0,5
TOF_{T0}	0.35ns	0,4
TDC	1,00E-04	0,25
VRF	1%	0,2
E_β calibration	-	0,15
VIRD	2V	0,03
BKG	-	0,03
total		0,88

To be done:

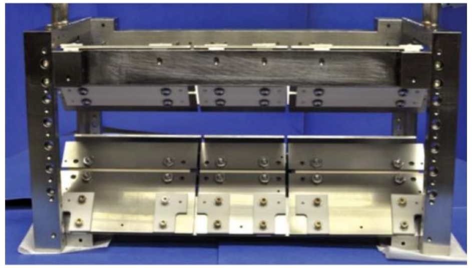
- Include corrections (radiative & recoil)
- Run more stat in simulations

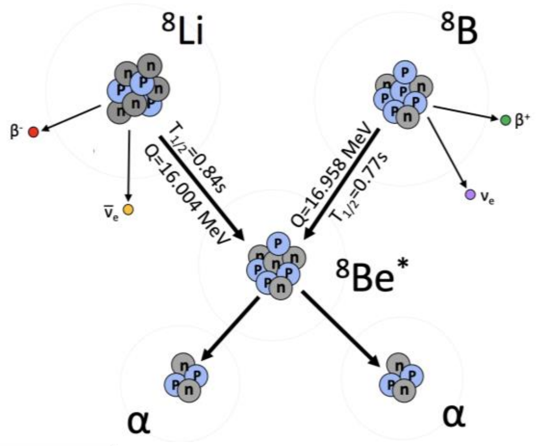
Very satisfactory after many years spent on this analysis…

GT transitions: other recent measurements

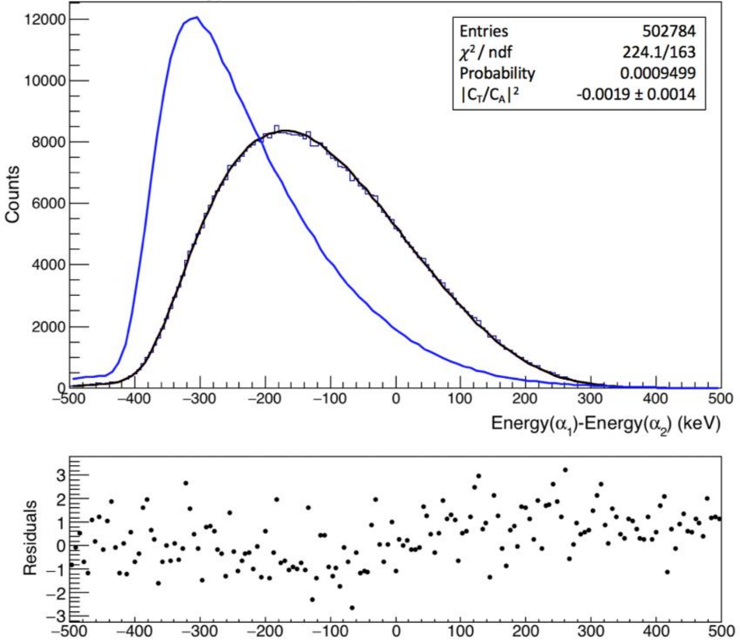
- **Decay of ^{8}Li^{+}**

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



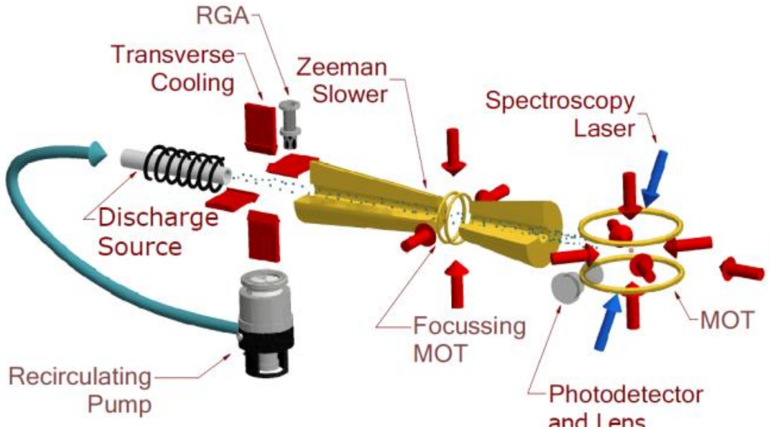


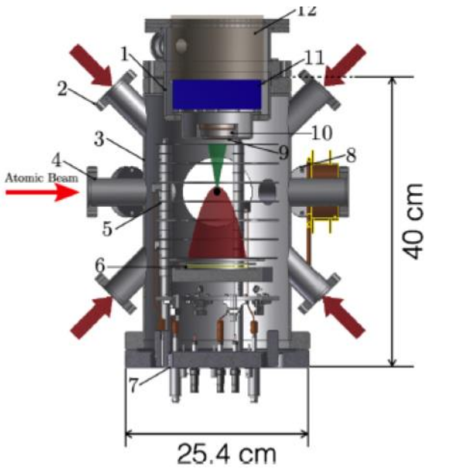
Total α Energy Difference Spectra

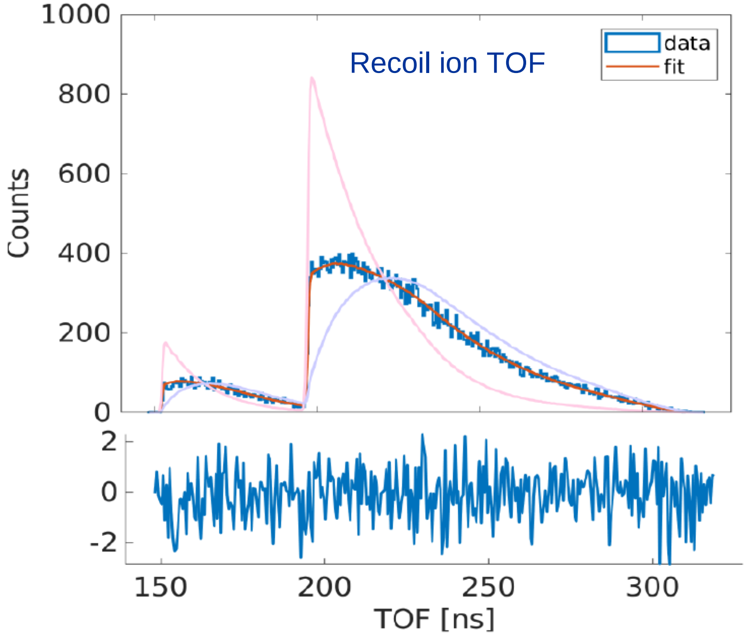


$\tilde{a}_{\beta\nu} = -0.3346(09)_{stat}(24)_{syst}$ (0.7%)

- **Decay of ^{6}He atoms**







$\tilde{a}_{\beta\nu} = -0.3268(46)_{stat}(41)_{syst}$ (1.9%)

Sensitivity to a , b and to new physics

- **New constraints from these experiments:**

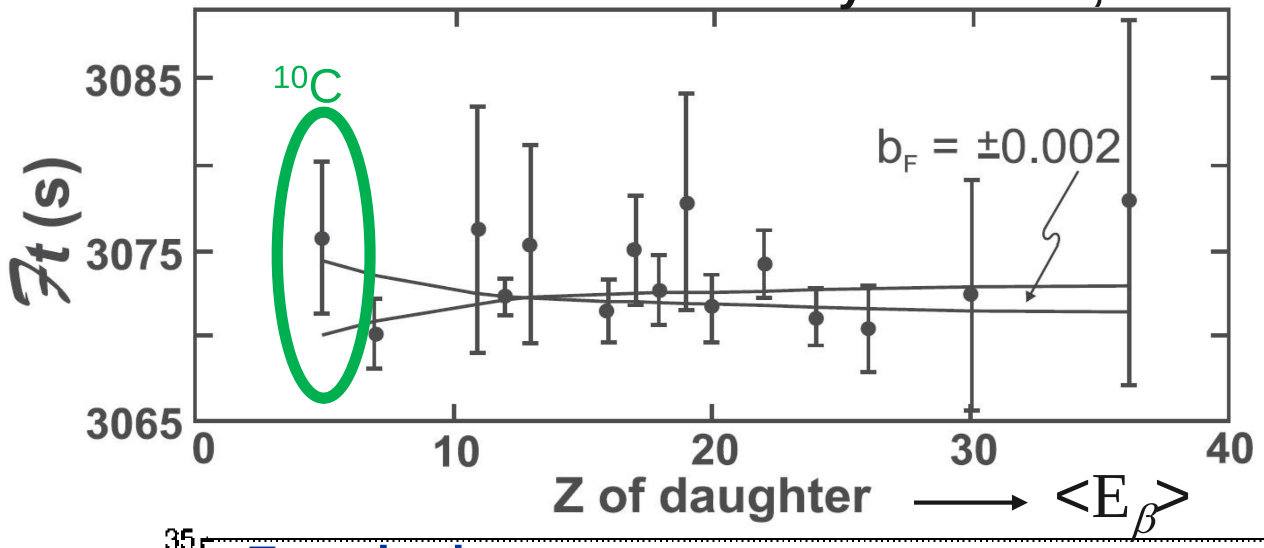
		Pure Fermi		**Pure Gamow-Teller**		
		WISArD	Adelberger	LPCTrap	ANL Trap	Seattle MOT
Right-handed neutrinos $C_i = -C_i'$	$\Delta a/a \approx \Delta\tilde{a}/\tilde{a}$	0.2%	0.65%	1.0%	0.7%	1.9%
	$\lvert C_S/C_V \rvert$ or $\lvert C_T/C_A \rvert$	**3%**	6%	**7%**	**6%**	10%

3) Other way to measure *b*: $\mathcal{F}t$-values in 0+ → 0+ transitions

$\mathcal{F}t$-values in 0+ → 0+ pure Fermi transitions

- **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 $<E_\beta>$**

Hardy & Towner, 2020

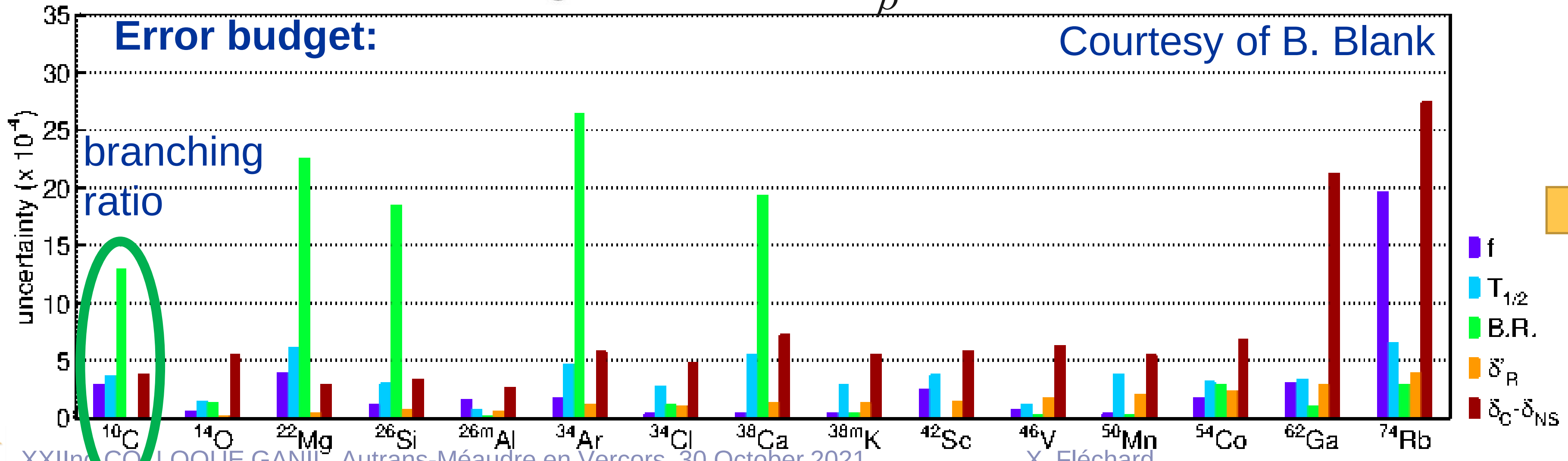


$$\mathcal{F}t_i(b_F) \rightarrow \mathcal{F}t_0\ (1+ b_F\ m_e/<E_\beta>)^{-1}$$

b_F = -1.0 (2.1) 10^{-3} (Seng et.al.)

Best constraints on Scalar couplings!

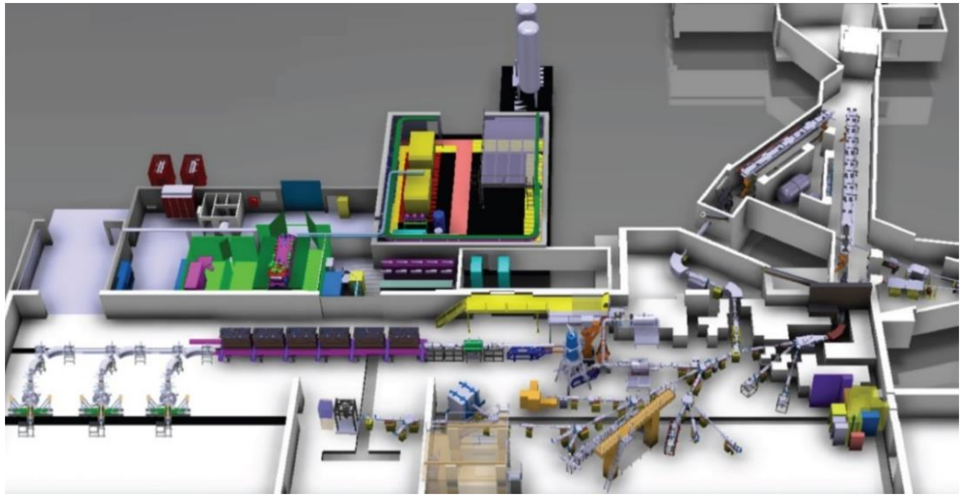
(involving left-handed neutrinos)



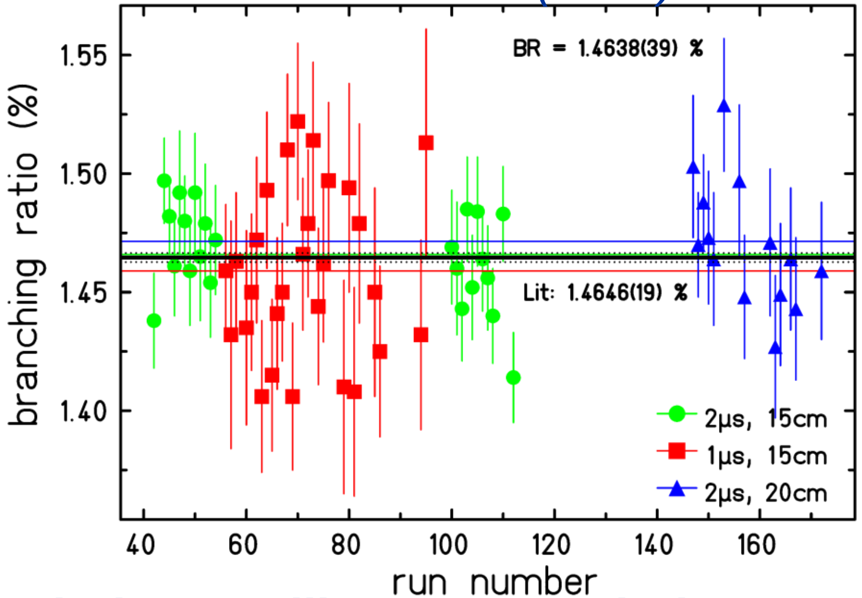
Improve B.R. in ^{10}C

$\mathcal{F}t$-values in 0+ → 0+ pure Fermi transitions

- **Recent measurements at ISOLDE :** CENBG



B.Blank EPJA 56(2020)156



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

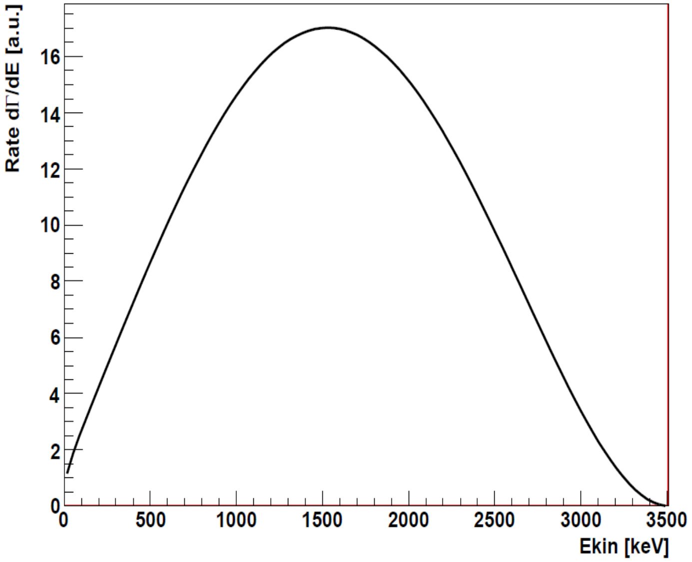
4) New prospects:
measurements of the shape of the beta energy spectrum

Shape of the beta energy spectrum

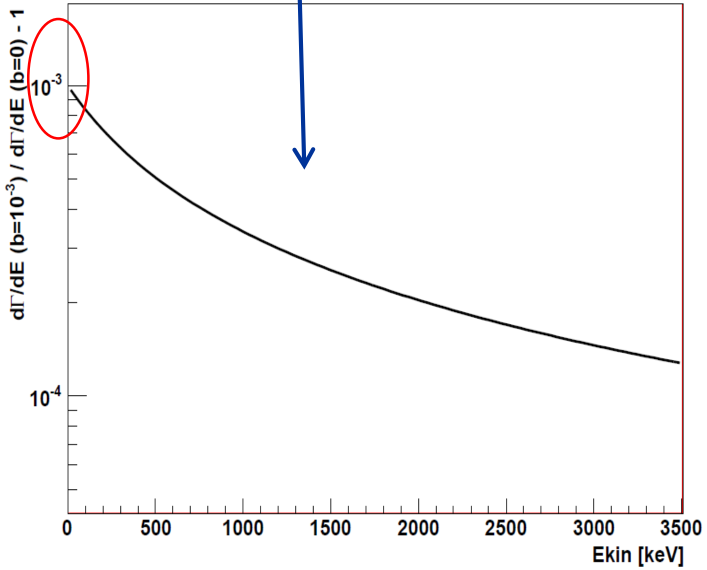
- **With detection of beta particle only:**

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

Phase space and Fermi function (known)



^{6}He β energy spectrum (b=0)

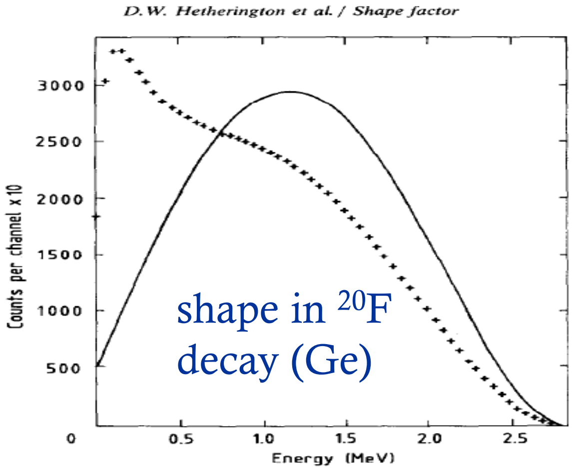


Distortion for $b = 10^{-3}$

Precise measurement of β energy shape
→ direct access to *b*

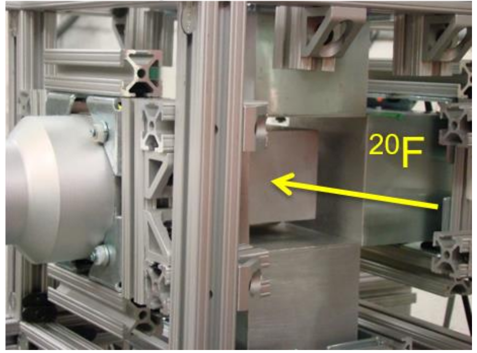
Difficulty:

- β backscattering on detector surface

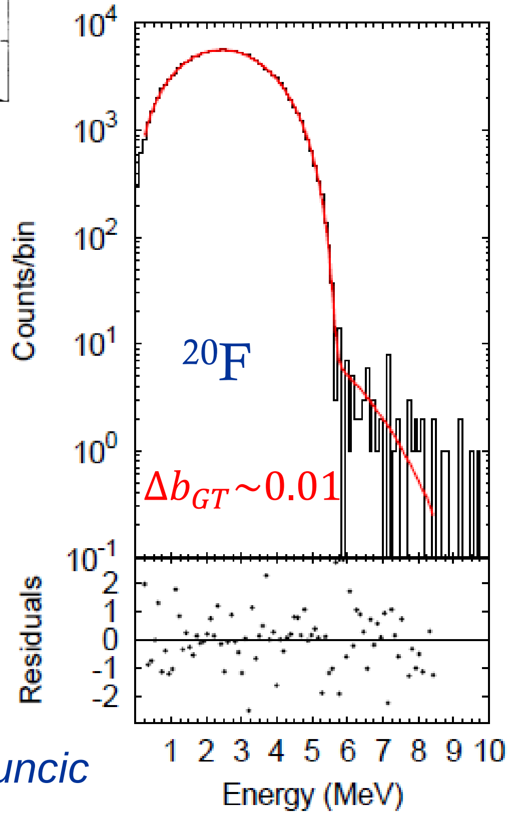


shape in ^{20}F decay (Ge)

Deep implantation
132 MeV/nucleon



M. Hughes, PhD, MSU 2019



Courtesy of O. Naviliat-Cuncic

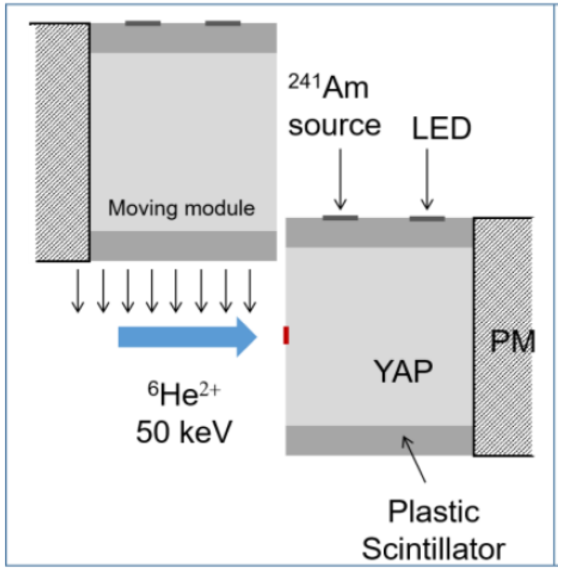
Shape of the beta energy spectrum

- **b-STILED project @ GANIL**

  (**b**: **S**earch for **T**ensor **I**nteractions in nuc**L**ear b**E**ta **D**ecay)

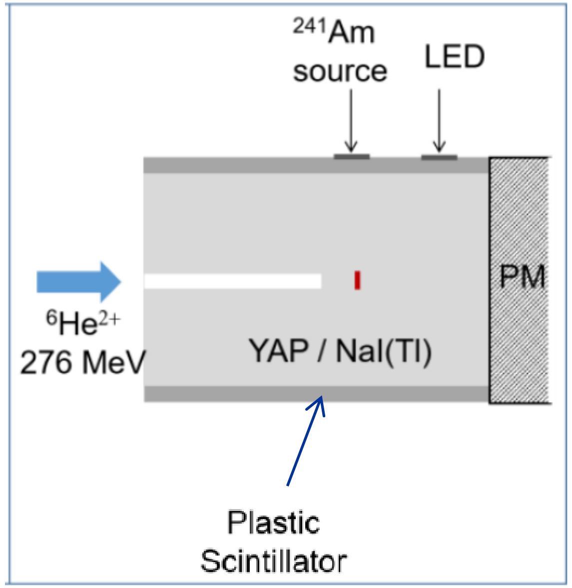
- **Goal:** measure b_{GT} in ^{6}He beta decay with a precision better than 4 10^{-3} (phase 1)
  (direct improvement on present constraints from nuclear beta decay) *M. Gonzalez-Alonso, O.N.C., N. Severijns, Prog. Part. Nucl. Phys.* ***104*** *(2019) 165*
- **Technique proposed:** use the 4Pi calorimetry technique at both low and high energy

Low energy setup (LIRAT)



- No beam induced background
- Movable detector → 4Pi

High energy setup (LISE)



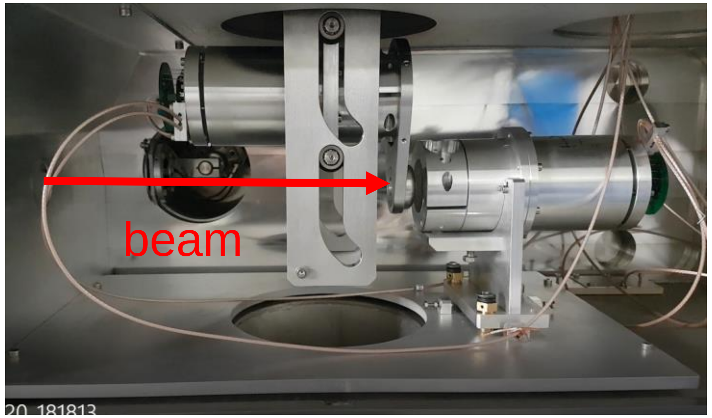
- Similar to NSCL ^{20}F experiment
- Hole to reduce escape of Bremsstrahlung radiation

- YAP (27ns)→ very linear response
  → good sensitivity to γ
- Plastic (2ns) as veto
- ^{241}Am for gain monitoring

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

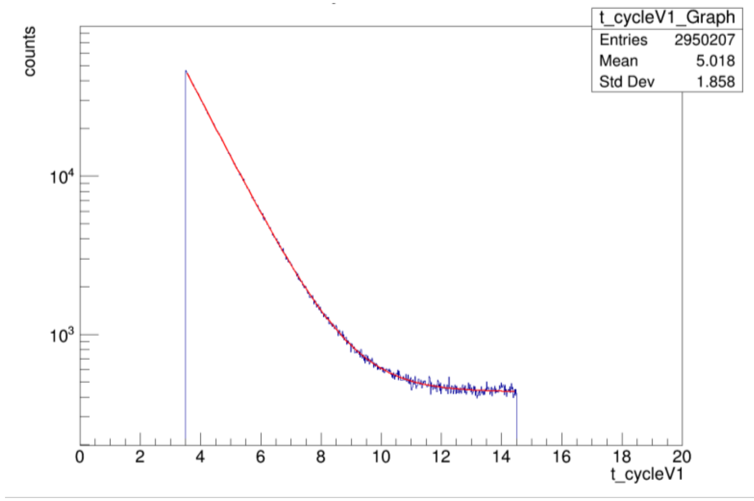
Shape of the beta energy spectrum

- **1st run at low energy on GANIL LIRAT beam line (June 2021)**



2s implantation

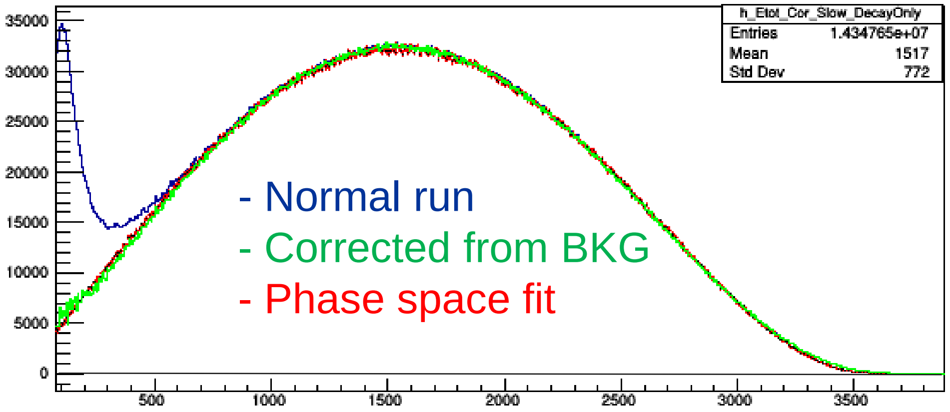
10s measurement



Stat: ~4.5 10^7 events
(different intensities & PM gain)

- $T_{1/2}$ with ~2 10^{-4} relative precision
  analysis ongoing (M. Kanafani Thesis)
- $\Delta b_{GT(stat)}$ ~ 2 10^{-3}
  fine analysis to come (M. Kanafani Thesis)

Beta energy spectrum



- Normal run
- Corrected from BKG
- Phase space fit

"Zero order" analysis shows no obvious problem

Shape of the beta energy spectrum

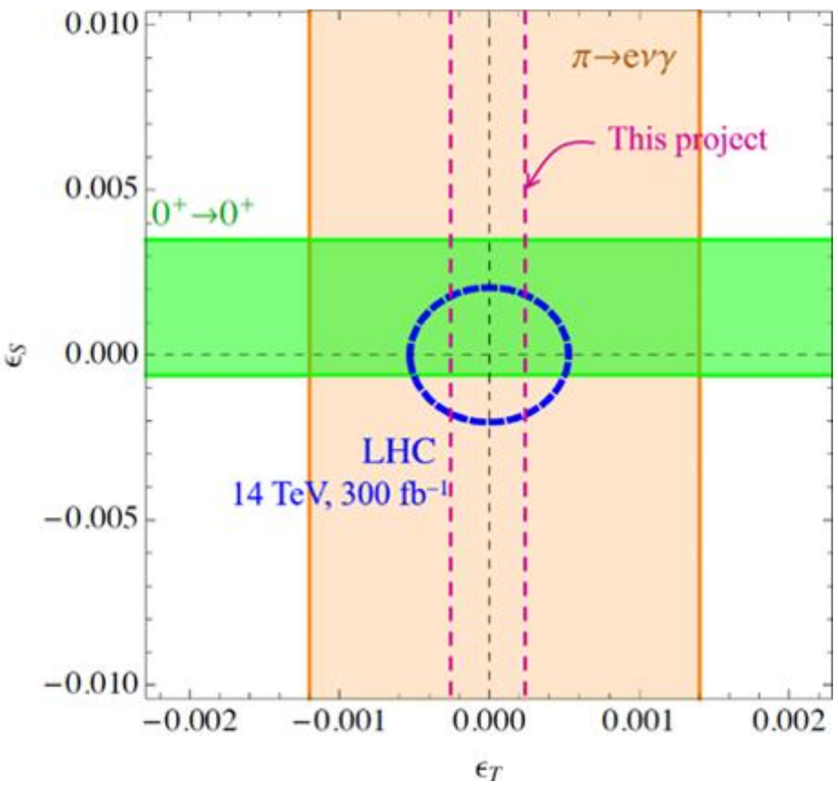
- **Next step: 2d run at high energy on LISE in 2022**

  → 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}



Summary

- For exotic couplings involving RH neutrinos :

Measurements of $\tilde{a}$ remain unique (strong potential for the WISArD experiment). But real breakthroughs (x10 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:

$\mathcal{O}$ → Quantum mechanical operators (Dirac γ-matrix)

"Diracology"

OperatorO_i	Number of independent matrices	Relativistic transformation properties of $\bar{\psi}_a\,\mathcal{O}_i\,\psi_b$
1	1	**S**calar
γ_μ	4	**V**ector
$\gamma_\mu\gamma_\lambda$	6	antisymmetric **T**ensor of rank 2
$\gamma_\mu\gamma_5\ (=\gamma_\nu\gamma_\lambda\gamma_\sigma)$	4	**A**xial vector
$\gamma_5\ (=\gamma_1\gamma_2\gamma_3\gamma_4)$	1	**P**seudoscalar

5 different possible forms of currents: **S, V, T, A & P**

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

→ ~ same operators in Hadron and Lepton current

$$H_i^{even} = g_i(\bar{\psi}_p\,\mathcal{O}_i\,\psi_n)(\bar{\psi}_e\,\mathcal{O}_i\,\psi_\nu) + h.c.$$ (scalar)

$$H_i^{odd} = g_i'(\bar{\psi}_p\,\mathcal{O}_i\,\psi_n)(\bar{\psi}_e\,\mathcal{O}_i\gamma_5\,\psi_\nu) + h.c.$$ (pseudoscalar)

With: $g_i = g_F C_i$ $\qquad g_i' = g_F C_i'$ $\qquad i = S, V, T, A, P$

The Fermi theory

- **To respect Lorentz invariance**

H must be a Scalar or a Pseudoscalar:

⇒ same operators in Hadron and Lepton current

$$H_i^{even} = g_i(\bar{\psi}_p\, \mathcal{O}_i\, \psi_n)(\bar{\psi}_e\, \mathcal{O}_i\, \psi_\nu) + h.c.$$ (scalar)

$$H_i^{odd} = g_i'(\bar{\psi}_p\, \mathcal{O}_i\, \psi_n)(\bar{\psi}_e\, \mathcal{O}_i\gamma_5\, \psi_\nu) + h.c.$$ (pseudoscalar) ⇒ For parity violation

With: $g_i = g_F C_i$ $g_i' = g_F C_i'$ $i = S, V, T, A, P$

- **The generalized form is then:**

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

In the NRA approximation, the Dirac γ-matrix for nucleons can be simplified for $(\bar{\psi}_p\, \mathcal{O}_i\, \psi_n)$
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 γ-matrix for nucleons can be simplified for $(\bar{\psi}_p \mathcal{O}_i \psi_n)$

It can be shown that:

For $i=P$: $\mathcal{O}_i = 0$ → *no pseudoscalar term*

For $i=S$: $\mathcal{O}_i = 1$ → *no spin involved*

For $i=V$: $\mathcal{O}_i = \gamma^0$ → *no spin involved*

V & *S* currents
For Fermi transitions
With $\Delta I = 0$

For $i=A$ & T: $\mathcal{O}_i = f(\sigma)$ → *spin involved*

(Pauli Matrix)

A & *T* currents
For Gamow-Teller (GT)
With $\Delta I = 1$

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: $\vec{I}\,,\vec{\sigma}\,,\overrightarrow{p_e}\,,\overrightarrow{p_\upsilon}$

Nuclear polarization

Spin vector of β particle

Leptons *momentum*

If one integrate the Hamiltonian with the γ-matrix we get:

$$
\begin{aligned}
&\omega(\langle\vec{I}\rangle,\vec{\sigma}|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu \propto\\
&F(\pm Z,E_e)p_e E_e(E_0-E_e)^2 dE_e d\Omega_e d\Omega_\nu \times\\
&\xi\left\{1+\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu}a+\frac{m}{E_e}b+\right.\\
&\frac{\vec{I}}{I}\cdot\left[\frac{\vec{p_e}}{E_e}A+\frac{\vec{p_\nu}}{E_\nu}B+\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu}D\right]+\\
&\left.\vec{\sigma}\cdot\left[\frac{\vec{p_e}}{E_e}G+\frac{\langle\vec{I}\rangle}{I}N+\frac{\vec{p_e}}{E_e+m}\left(\frac{\langle\vec{I}\rangle}{I}\cdot\frac{\vec{p_e}}{E_e}\right)Q+\frac{\langle\vec{I}\rangle}{I}\times\frac{\vec{p_e}}{E_e}R\right]\right\}
\end{aligned}
$$

Phase space (density of states)

Correlation coefficients

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*:

$$a\xi = |M_F|^2 \left[-|C_S|^2+|C_V|^2-|C'_S|^2+|C'_V|^2 \mp 2\frac{\alpha Z m}{p_e} Im\left(C_S C_V^* + C'_S C'^*_V\right)\right]$$
$$+\frac{|M_{GT}|^2}{3}\left[|C_T|^2-|C_A|^2+|C'_T|^2-|C'_A|^2 \pm 2\frac{\alpha Z m}{p_e} Im\left(C_T C_A^* + C'_T C'^*_A\right)\right]$$

$$b\xi = \pm 2\gamma Re\left[|M_F|^2\left(C_S C_V^* + C'_S C'^*_V\right)\right.$$
$$\left.+|M_{GT}|^2\left(C_T C_A^* + C'_T C'^*_A\right)\right]$$

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)

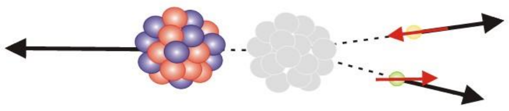
Measurements of $a_{\beta\nu}$

- **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 ΔJ=0

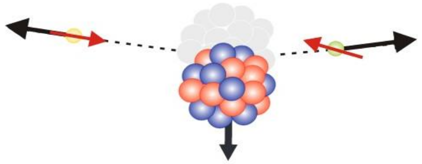
➪ S=0 : spin of leptons anti-parallel

Only V couplings
Opposite helicity



- **Preferred β–ν angle:** **θ = 0°**
- $a_{\beta\nu}^{F} = 1$
- **Maximum recoil energy**

Only S couplings
Same helicity



- **Preferred β–ν angle:** **θ = 180°**
- $a_{\beta\nu}^{F} = -1$
- **Minimum recoil energy**

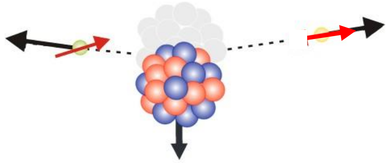
Measure recoil energy spectrum to extract $a_{\beta\nu}$

(neutrinos cannot be detected)

pure Gamow-Teller transitions

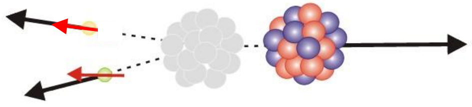
➪ S=1 : spin of leptons can be parallel (CG →x 1/3)

Only A couplings
Opposite helicity



- **Preferred β–ν angle:** **θ = 180°**
- $a_{\beta\nu}^{GT} = -\frac{1}{3}$
- **Minimum recoil energy**

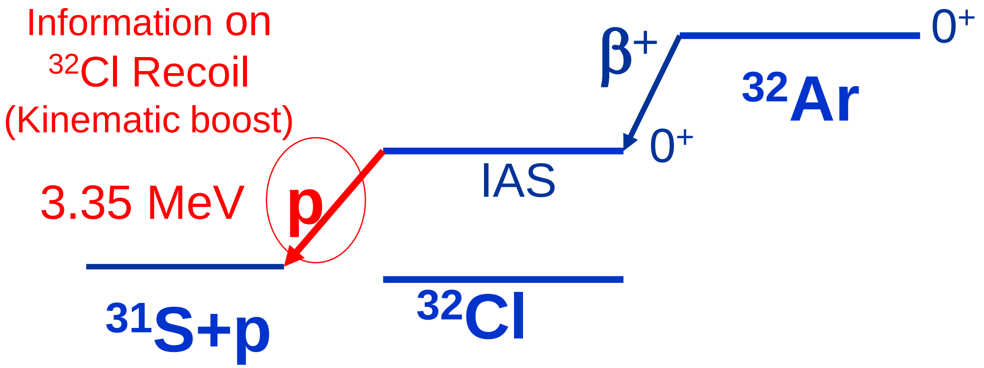
Only T couplings
Same helicity

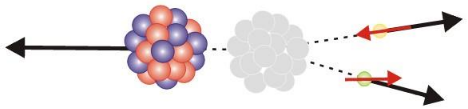


- **Preferred β–ν angle:** **θ = 0°**
- $a_{\beta\nu}^{GT} = +\frac{1}{3}$
- **Maximum recoil energy**

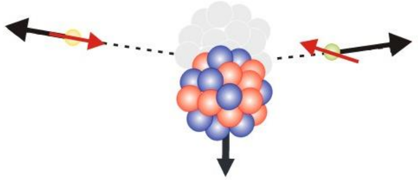
Pure Fermi transition: WISArD experiment (ISOLDE)

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



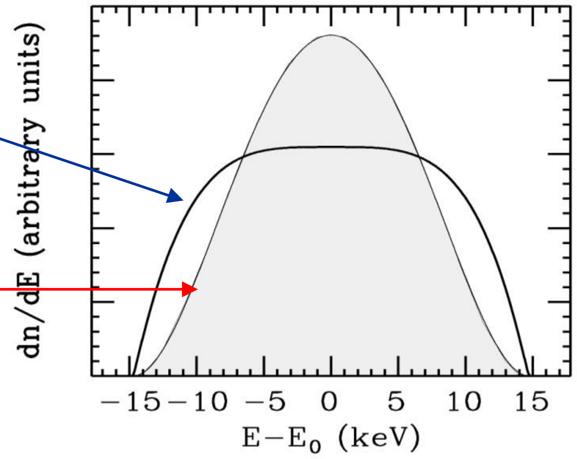


Vector, *a*=1
high recoil energy
large broadening



Scalar, *a*=-1
low recoil energy
small broadening

Proton peak shape



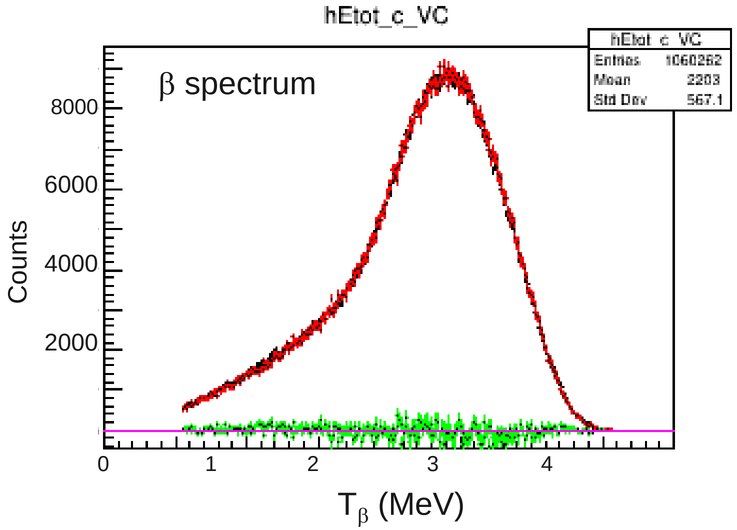
Pure GT transition: LPCTrap @ GANIL

- **Present status: finally getting there!**

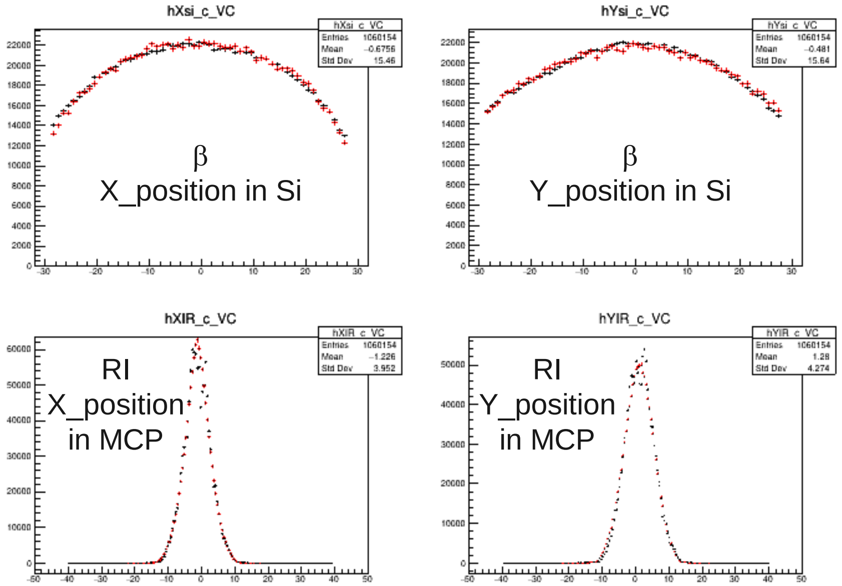
(Mostly thanks to the simulation tool **CLOUDA** and refined analysis)

Comparison experiment vs simulation (residuals)

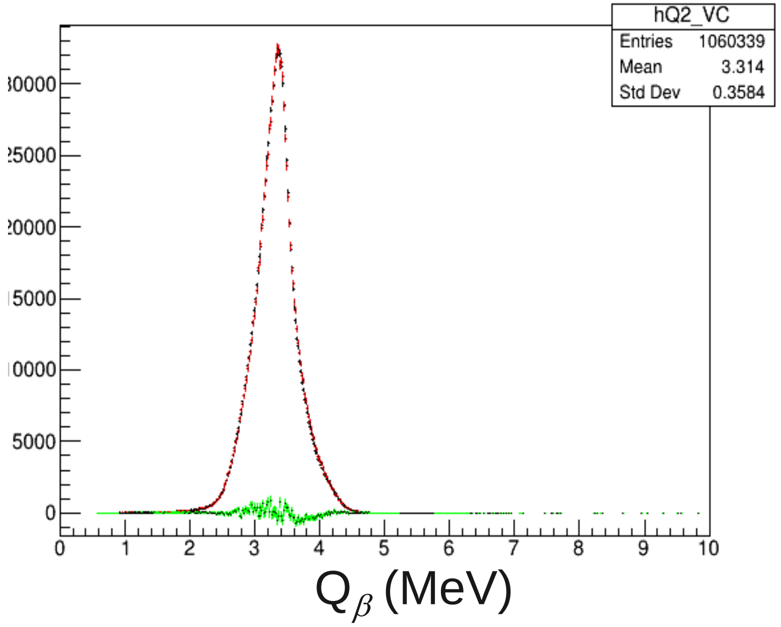
Beta deposited energy spectrum



Particle position on detectors



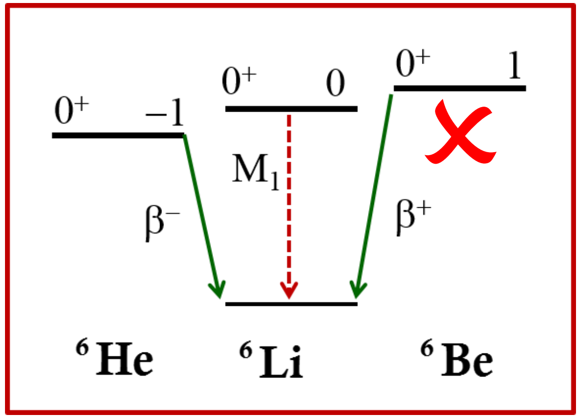
Reconstructed Q-value
(all observables including TOF)



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

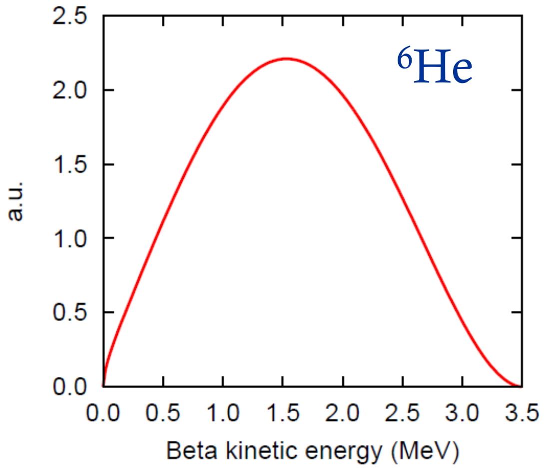
$$C_0 = \frac{2}{3}\frac{W_0}{M}\left(1+\frac{b_{WM}}{c}\right) = -1.234(14)\ \%$$

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

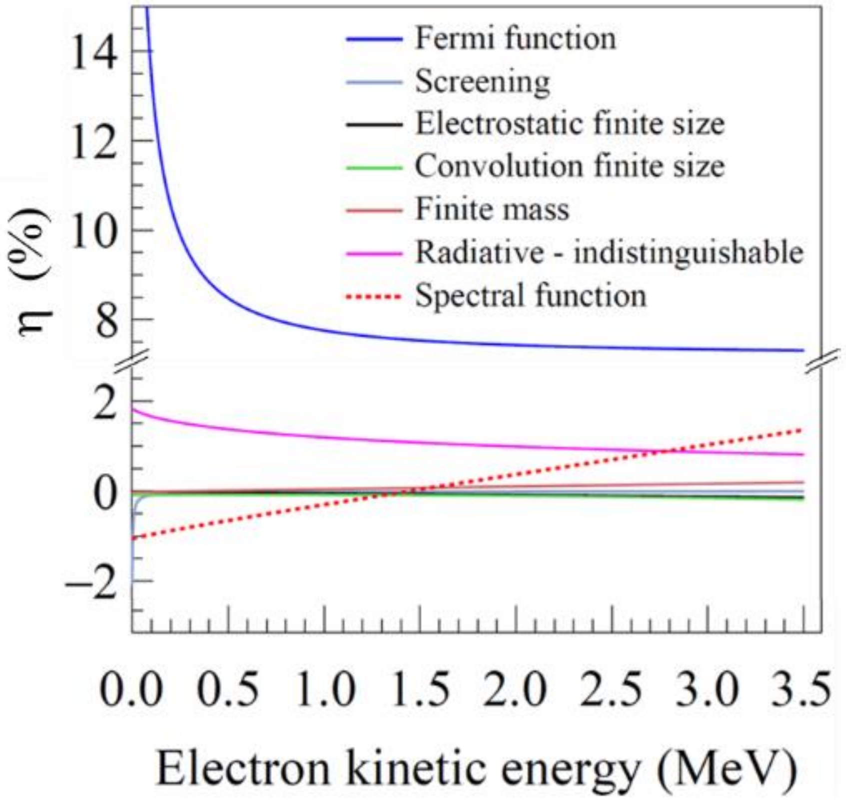
$$C_{-1} = -\frac{2m^2}{3M}\left(1+\frac{b_{WM}}{c}\right) = -0.0802(9)\ \%\times\mathrm{MeV}$$

$$\boxed{b_{WM}^{CVC} = 68.22 \pm 0.79} \qquad c = g_A|M_{GT}|$$

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}He decay, theoretical corrections for the description of the beta spectrum are known with sufficient accuracy.

Source	Δb_{GT}
Nuclear charge radius of ^{6}Li	4.6×10^{-5}
End-point energy of the transition	1.8×10^{-4}
Weak magnetism form factor	5.7×10^{-4}
Induced tensor form factor	1.9×10^{-5}
Total theoretical uncertainty	$\mathbf{6.0\times10^{-4}}$

Shape of the beta energy spectrum

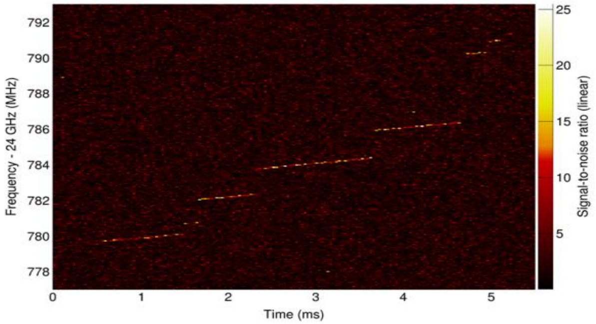
- **Many projects / techniques under development worldwide**

• Project 8 @ Uni. Washington

Based on cyclotron radiation measurement of single beta (tritium for ν mass, and ^{6}He for *b*)

Phys. Rev. Lett. 114, 162501 (2015)

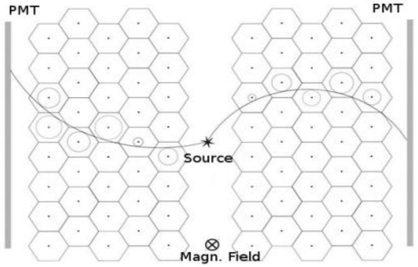
Under development



• miniBETA @ KU Leuven

multi-wire drift chamber + scint (later DSSSD)

Under development



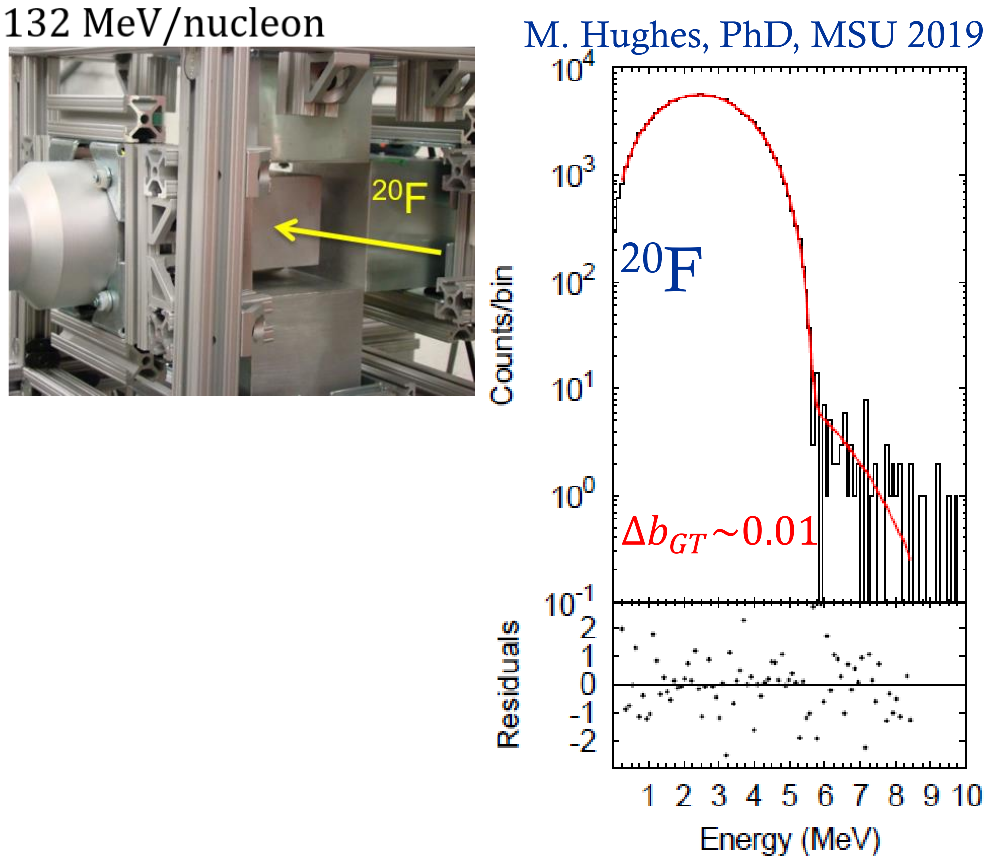
• 114In @ WISArD

Beta particle confinement in strong B-field

Under development

• ^{6}He & ^{20}F @ NSCL

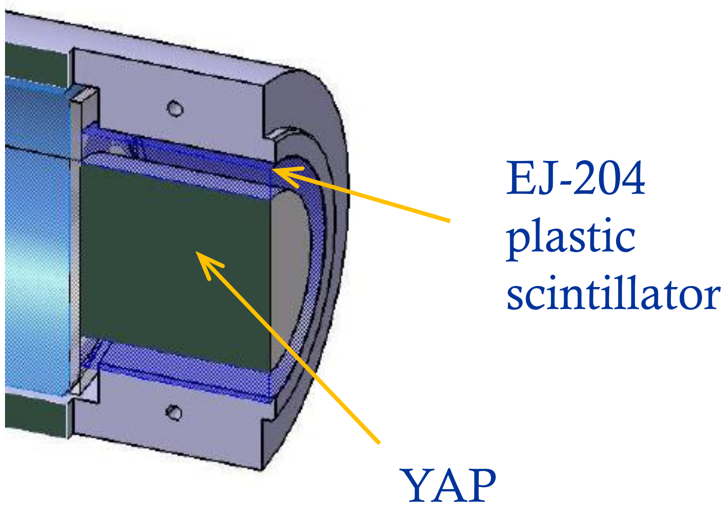
Fragment implantation in the core of The detection volume (no backscattering)



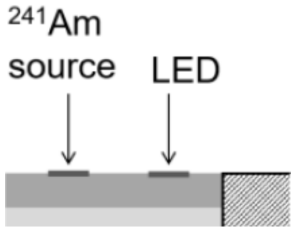
Courtesy of O. Naviliat-Cuncic

Detector developments

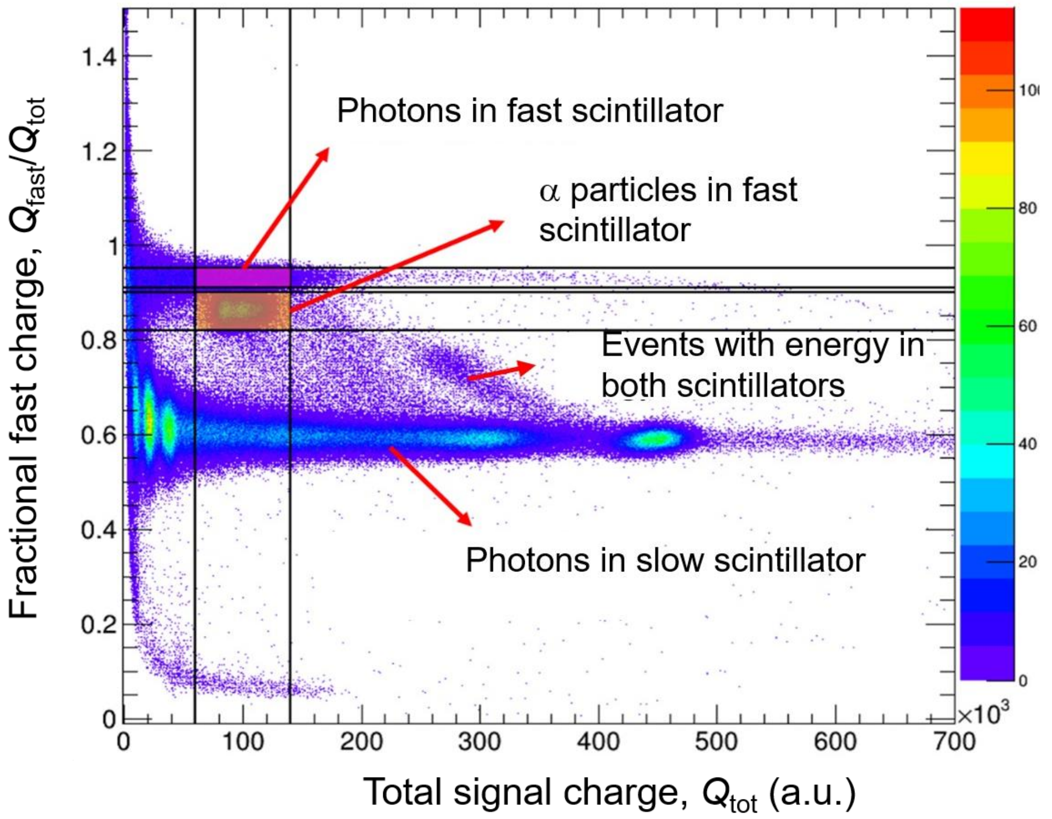
Phoswich configuration



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

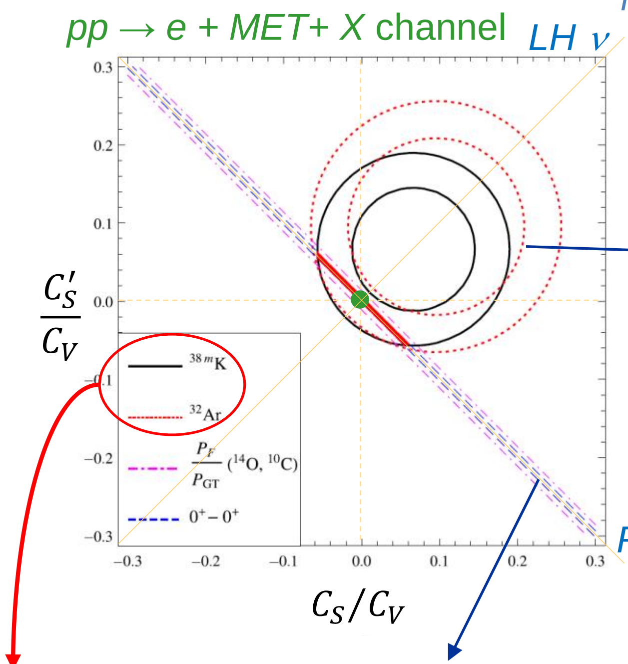


Use pulse shape discrimination on signals sampled by the digital DAQ.



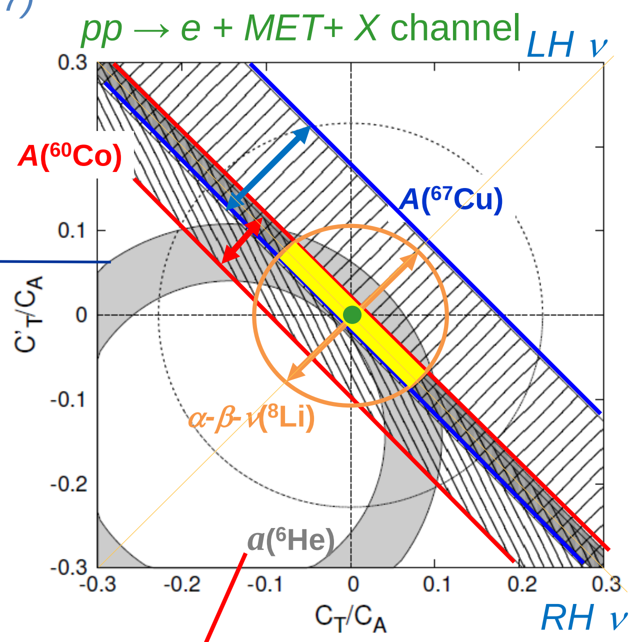
Exotic currents beyond *V-A* theory: status

SCALAR



B.R. Holstein JPG41(2014)
N. Severijns & B. Blank, JPG44(2017)

TENSOR



$$\tilde{a} \approx a(1+\kappa b)$$

Circles because

$$a\,(C_{S,T}^2, C_{V,A}^2)$$

$$b\,(C_{S,T}, C_{V,A})$$

	LH	RH
$\lvert C_S/C_V\rvert <$	0.0038	0.068
$\lvert C_T/C_A\rvert <$	0.0064	0.078

González-Alonso et al PPNP104 (2019)

a @ ~ 0.5%

$$Ft \propto \left(1+\langle m/E\rangle b_F\right)^{-1}$$

Hardy et al PRC79(2015)

a @ ~ 1%

- Best constraints from "*b*", but "*a*" adds limits... ("*b*" unsensitive to right-handed ν !)
- In green: constraints from LHC (CMS data) *Cirigliano et al PPNP71 (2013)* *González-Alonso et al PPNP104 (2019)* *Thanks to EFT!*

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