Precise beta decay calculations for searches for new physics
Trento, April 8-12, 2019

Searches for new physics via β-energy spectra

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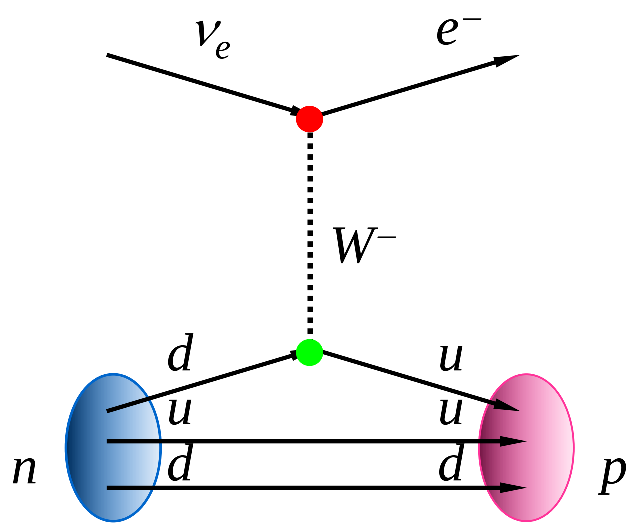
NSCL
NSF
MICHIGAN STATE UNIVERSITY

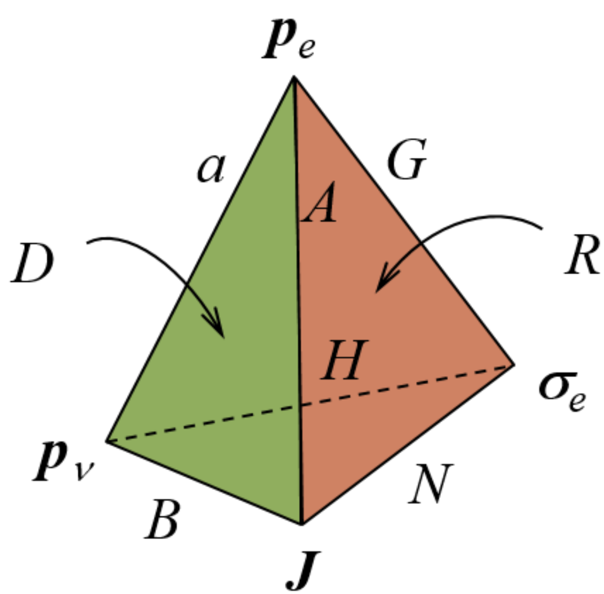
Thanks to:
N. Birge, L. Broussard, N. Fomin, A. García, X. Fléchard, E Liénard, N. Severijns, A. Young

Beta decay couplings



- The general phenomenological β-decay Hamiltonian contains *S*, *V*, *A*, *T* and *P* operators (and couplings)

- Couplings are probed through measurements of correlation coefficients



O. N-C, M. Gonzalez-Alonso, Ann. Phys. (Berlin) **525** (2013) 600

General motivation

- We know the SM is V and A with maximal parity violation.

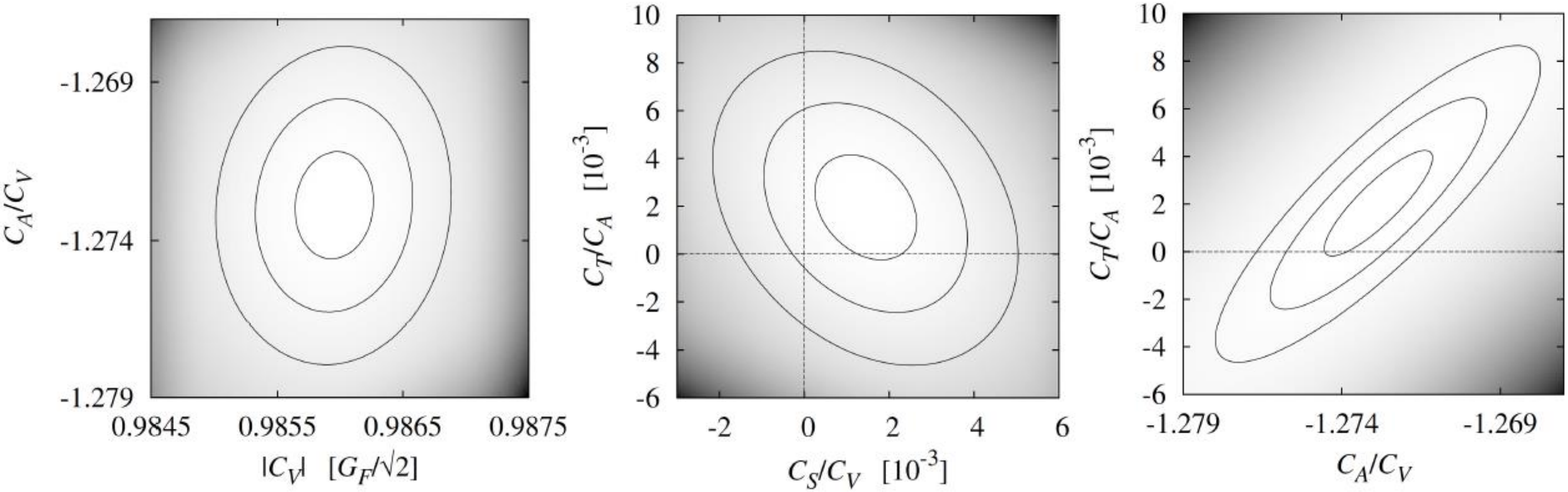
- The search for NP translates into probing the presence of S and T contributions in the correlations.

Status of constraints on S and T couplings

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

- "Minimal fit" (LH-ν)

- From contributions of the Fierz term to $\mathcal{F}t(0^+\rightarrow 0^+)$, t_n and A_n



- Other neutron and nuclear data have very small impact.
- Constraint on Tensor is ~2 weaker than on Scalar.

How precise do we need to measure?…

- …to impact couplings in β decay.

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

Coefficient	Absolute uncertainty	Relative uncertainty	SM value
b_n	3.2×10^{-3}		0
a_n	4.7×10^{-4}	4.4×10^{-3}	$-0.10648(19)$
$\tilde{a}_n$	6.4×10^{-4}	6.1×10^{-3}	$-0.10648(19)$
A_n	5.9×10^{-4}	5.0×10^{-3}	$-0.11935(24)$
$\tilde{A}_n$	7.8×10^{-4}	6.5×10^{-3}	$-0.11935(24)$
$\tilde{B}_n$	1.2×10^{-4}	1.2×10^{-4}	$0.98713(5)$
b_F	2.3×10^{-3}		0
b_{GT}	3.9×10^{-3}		0
a_F	6.4×10^{-6}	6.4×10^{-6}	1
$\tilde{a}_F$	4.7×10^{-4}	4.7×10^{-4}	1
a_{GT}	4.0×10^{-6}	1.2×10^{-5}	$-1/3$
$\tilde{a}_{GT}$	3.7×10^{-4}	1.1×10^{-3}	$-1/3$

- Competition with HE (see Vincenzo's talk)

Pure quadratic observables are very insensitive

(in pure F and GT transitions)

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

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- *a* in mixed transitions (like neutron decay) provide additional info (mixing ratio).

The most sensitive observables

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

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Two main approaches to the Fierz term

- "Indirect" measurements (*Ft*-values, correlation coefficients), integrated or differential:

$$\tilde{X} = \frac{X}{1 + b\langle m_e/E_e \rangle}$$

- "Direct" measurement (β-energy spectrum shape):

$$\left(1 + b\,\frac{m}{W}\right)$$

- The constraint on the *S* couplings (from *Ft*-values) is strong. Most projects focus on pure GT transitions.

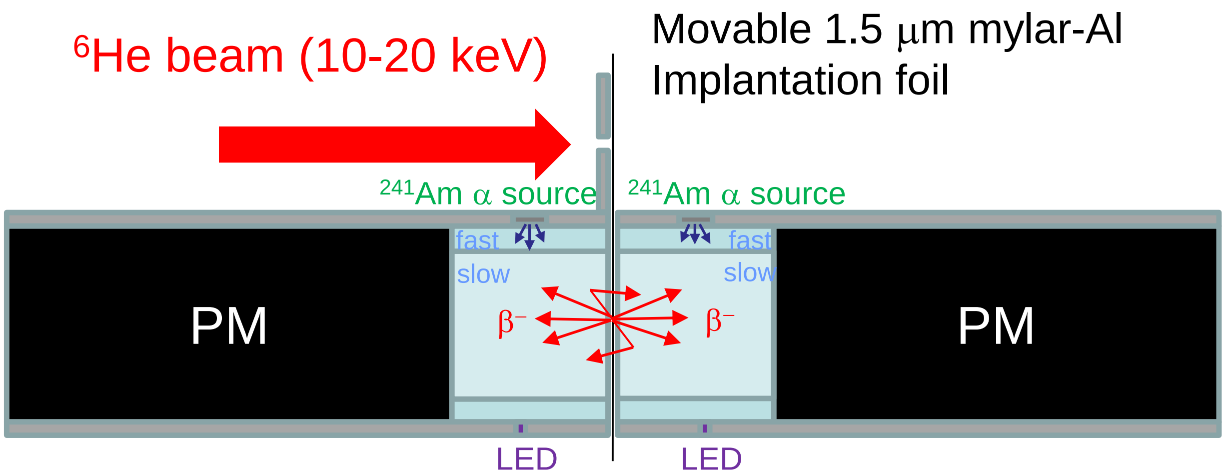
Current direct measurements of *b* and projects

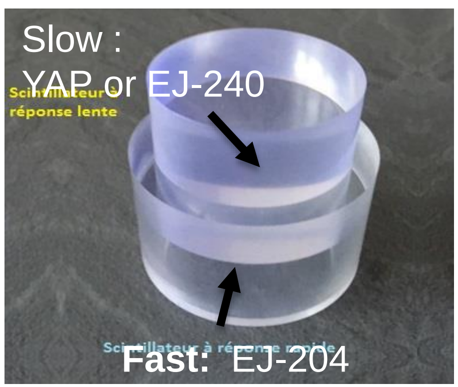
…explicitly considering the determination of b_{GT}

Isotope	Method	Lab/Institution
^{6}He	thin foil; 4π detector	GANIL/LPC-Caen
^{114}In	MWDC+scintillators	Krakow, Leuven
^{45}Ca	source in UCNA spectr.	UT, ORNL, NCSU, KUL++
^{6}He	CRES	UW, ANL++
^{6}He, ^{20}F	Calorimetry	NSCL/MSU, Wittenberg

^{6}He at GANIL

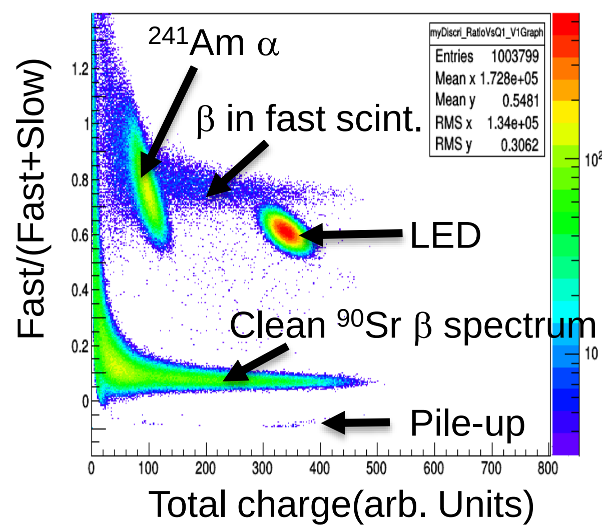
Courtesy: X. Flechard





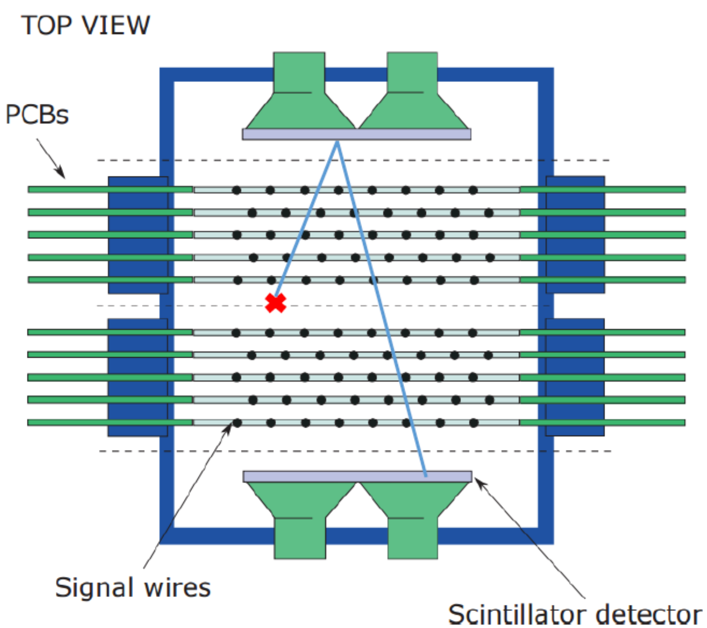
Calibration with ATRON electron accelerator

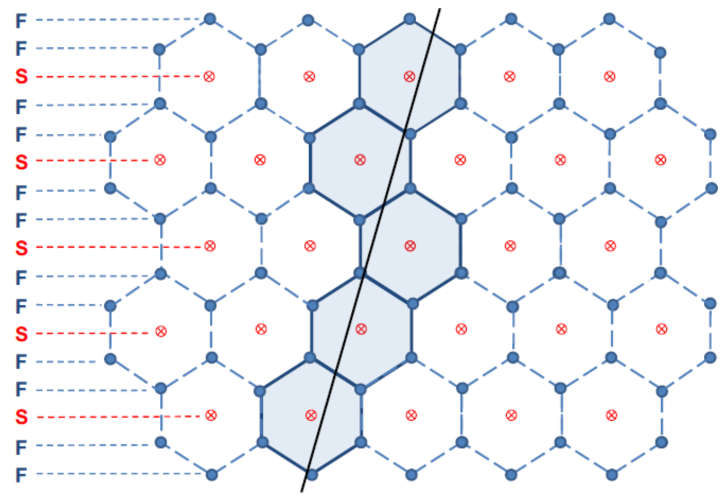
Tests with ^{90}Sr β source
EJ-240 & EJ-204 scintillators

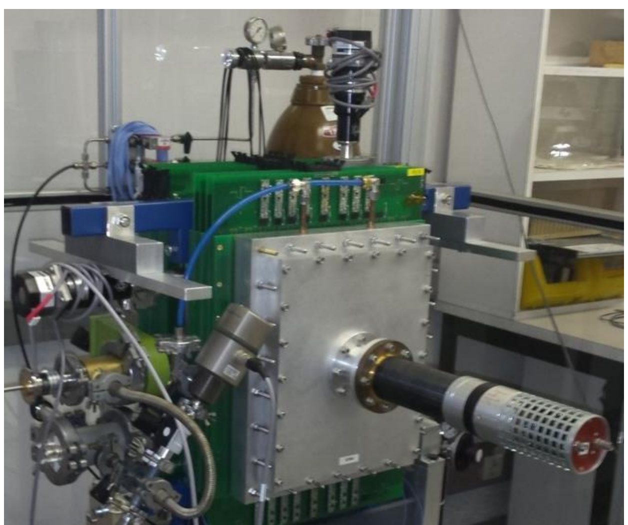


miniBETA (Leuven, Krakow)

Courtesy: N. Severijns
(M. Perkowski, Mazurian Lakes Conf. 2017)







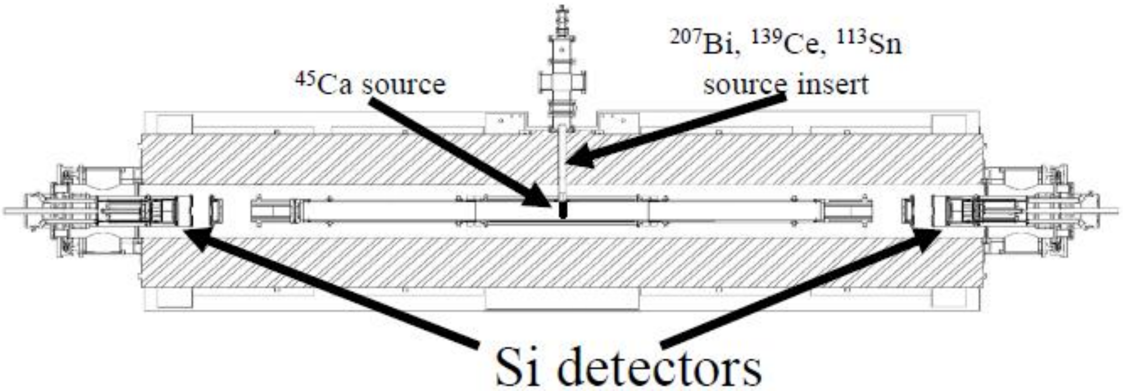
- Beta source inside detector
- Trigger with plastic scintillators
- Track with MWDC

- Tested with cosmics:
- average efficiency ~90%
- position resolution ~0.5mm

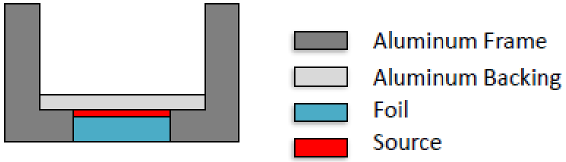
- First measurement with ^{114}In for b_{WM}

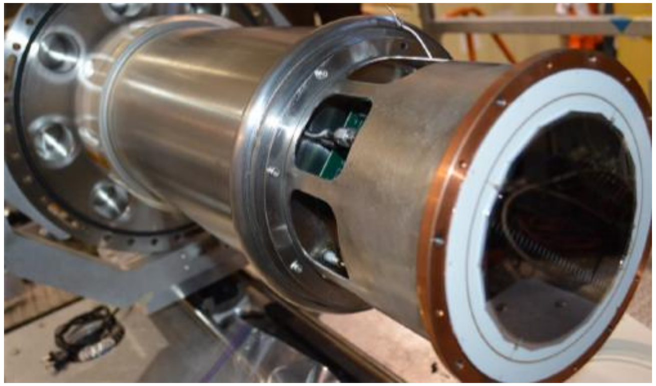
^{45}Ca at LANL

Courtesy: N. Birge, N. Fomin



Source geometry





- Recorded waveforms for each pixel
- 10^8 events collected

- Single crystal Si
- 100 nm dead layer
- 1.5 mm thick

- MC simulations under way
- Analysis in progress including corrections for cross-talk, backscattering, etc.

^{6}He *b* measurement at UW

Courtesy: A. Garcia

W. Byron[1], M. Fertl[1], A. Garcia[1], G. Garvey[1], B. Graner[1], M. Guigue[2], A. Leredde[3], P. Mueller[3], N. Oblath[2], R.G.H. Robertson[1], G. Rybka[1], G. Savard[3], D. Stancil[4], H.E. Swanson[1], B.A. Vandeevender[2], F. Wietfeldt[5], A. Young[4]

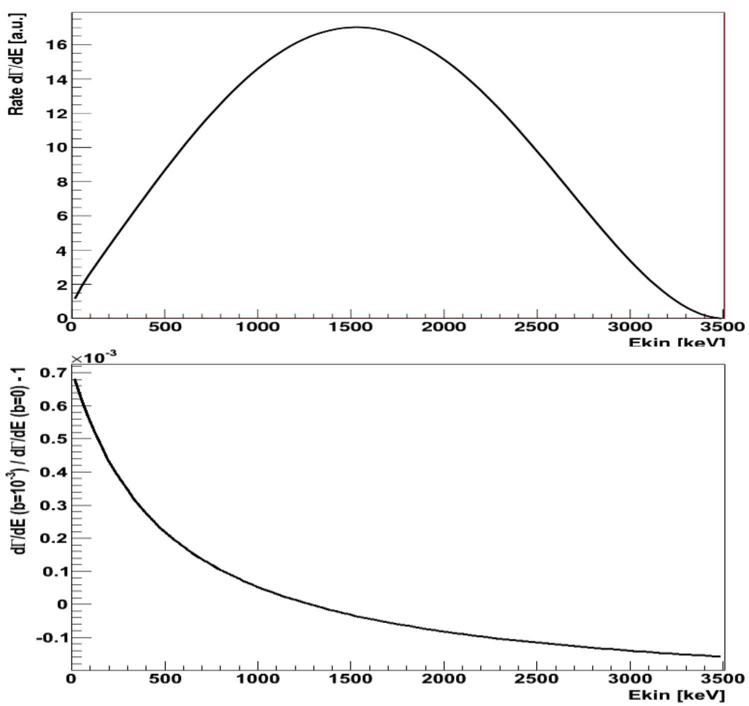
[1]*University of Washington*, [2]*Pacific Northwest National Laboratory*, [3]*Argonne National Lab*, [4]*North Carolina State University*, [5]*Tulane*

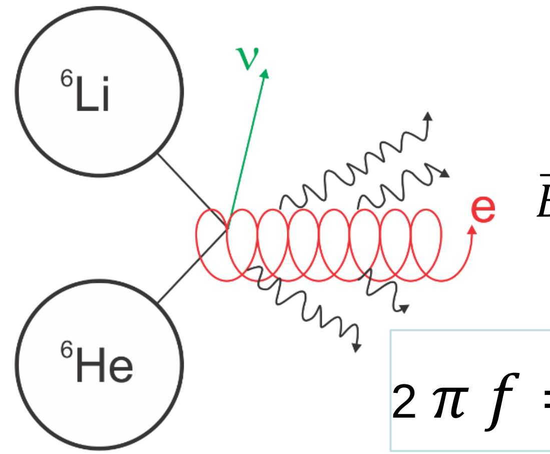
Use cyclotron radiation spectroscopy.
Similar to Project 8 setup for tritium decay.

PRL **114**, 162501 (2015)

Goal: measure "little *b*" to 10^{-3} or better in ^{6}He

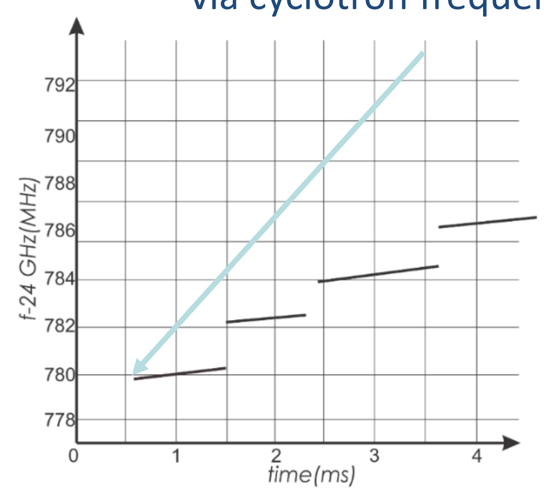
St





$$2\pi f = \frac{q B c^2}{E}$$

Determine e's energy at birth via cyclotron frequency



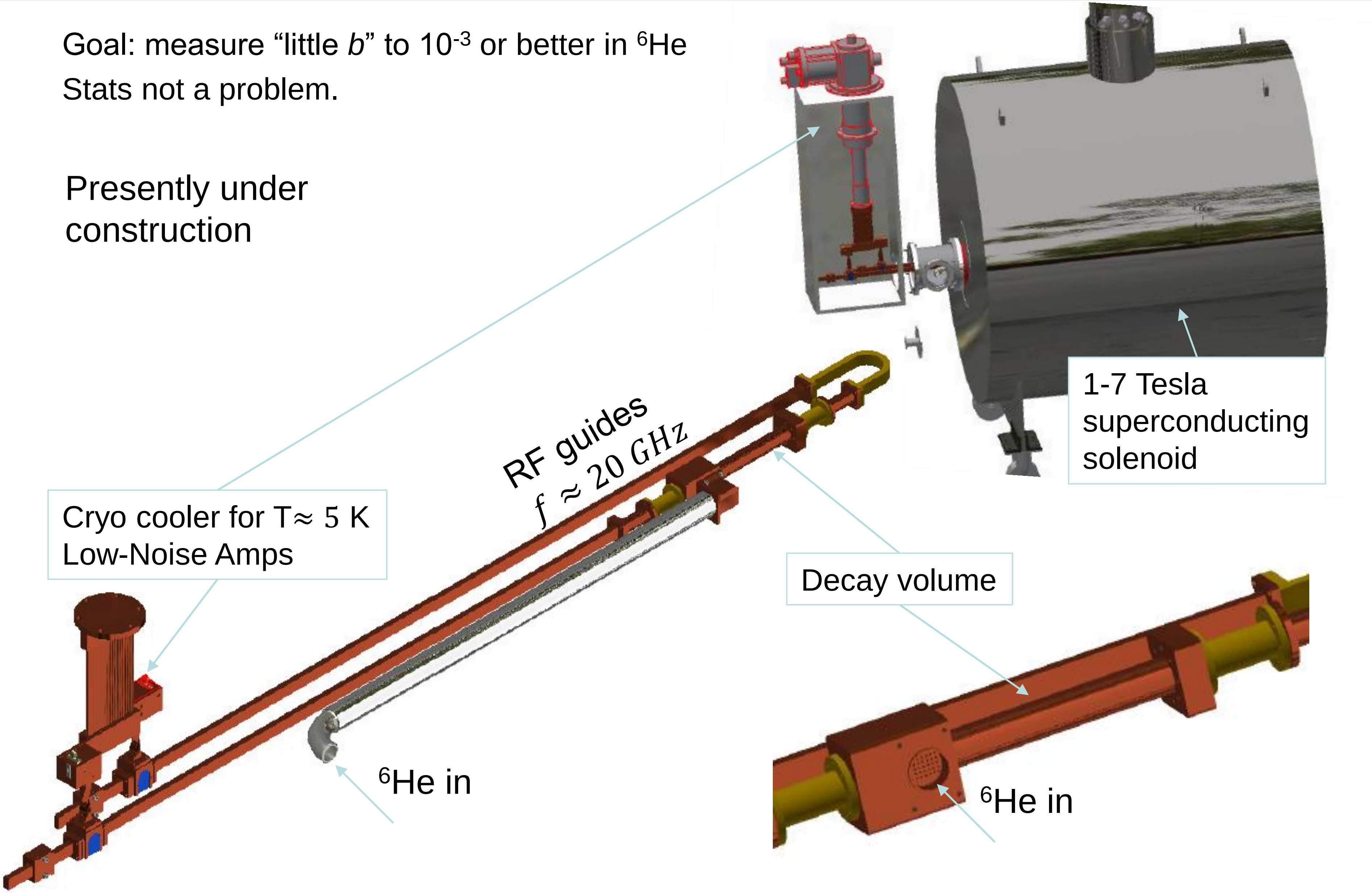
^{6}He *b* measurement at UW

Courtesy: A. Garcia

Goal: measure "little *b*" to 10^{-3} or better in ^{6}He

Stats not a problem.

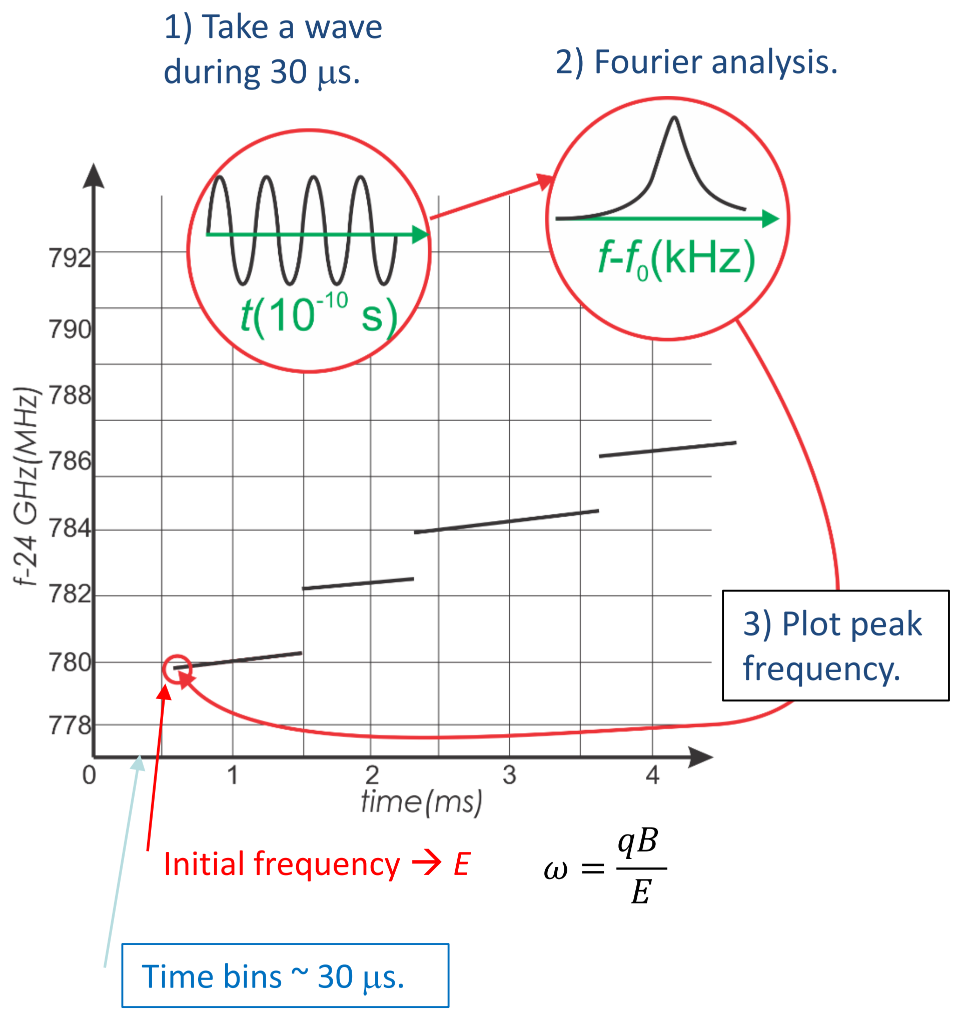
Presently under construction



Why do they like the CRES technique for ^{6}He?

Courtesy: A. Garcia

- Measures beta energy at creation, before complicated energy-loss mechanisms.
- High resolution allows debugging of systematic uncertainties.
- Room photon or e scattering does not yield background.
- 6He in gaseous form works well with the technique.
- 6He ion-trap (shown by others to work) allows sensitivity higher than any other proposed.
- Counts needed not a big demand on running time.



$$\omega = \frac{qB}{E}$$

Timeline for CRES with ^{6}He

Courtesy: A. Garcia

We have put together a collaboration, written and submitted a proposal.
Now kick-started by DOE and UW funds.

Phase I: proof of principle
2 GHz bandwidth.
Show detection of cycl. radiation from 6He.
Study power distribution.

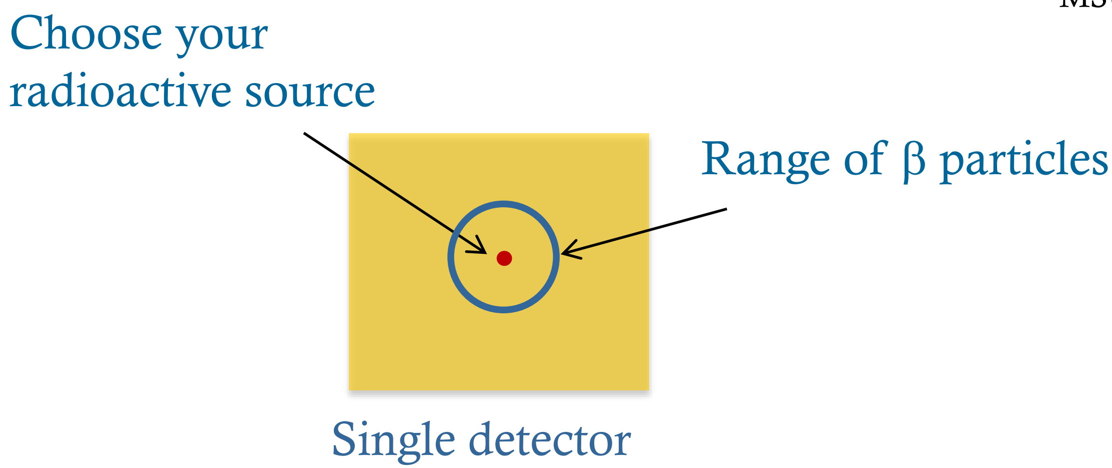
Mission until Aug. 2020

Phase II: first measurement ($b < 10^{-3}$)
6 GHz bandwidth.
6He and 19Ne measurements.

Phase III: ultimate measurement ($b < 10^{-4}$)
ion-trap for no limitation from geometric effect.

Calorimetry technique at MSU (general principle)

MSU: M. Hughes, X. Huyan, ONC
U.Witt: E. George, P. Voytas



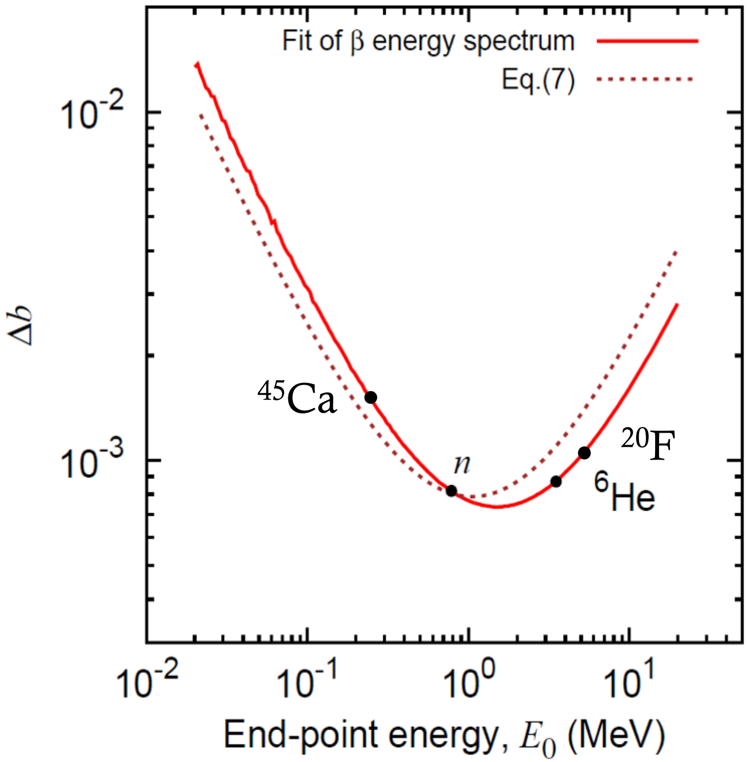
- Well localized and clean source
- 4π solid angle and 100% detection efficiency
- Detection of β particles without backscattering, out-scattering, or energy loss in dead-layers.

The "source" can be chosen from available radioactive beams produces by fragmentation.

Selection of candidates

Kinematic sensitivity

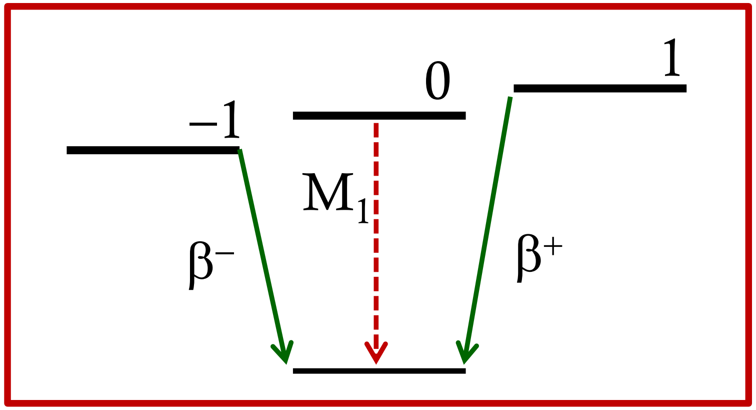
Uncertainty for 10^8 events
(assuming fit from 5% to 95% of end-point)



M. Gonzalez-Alonso and O. N.-C
PRC **94** (2016) 035503

Hadronic corrections

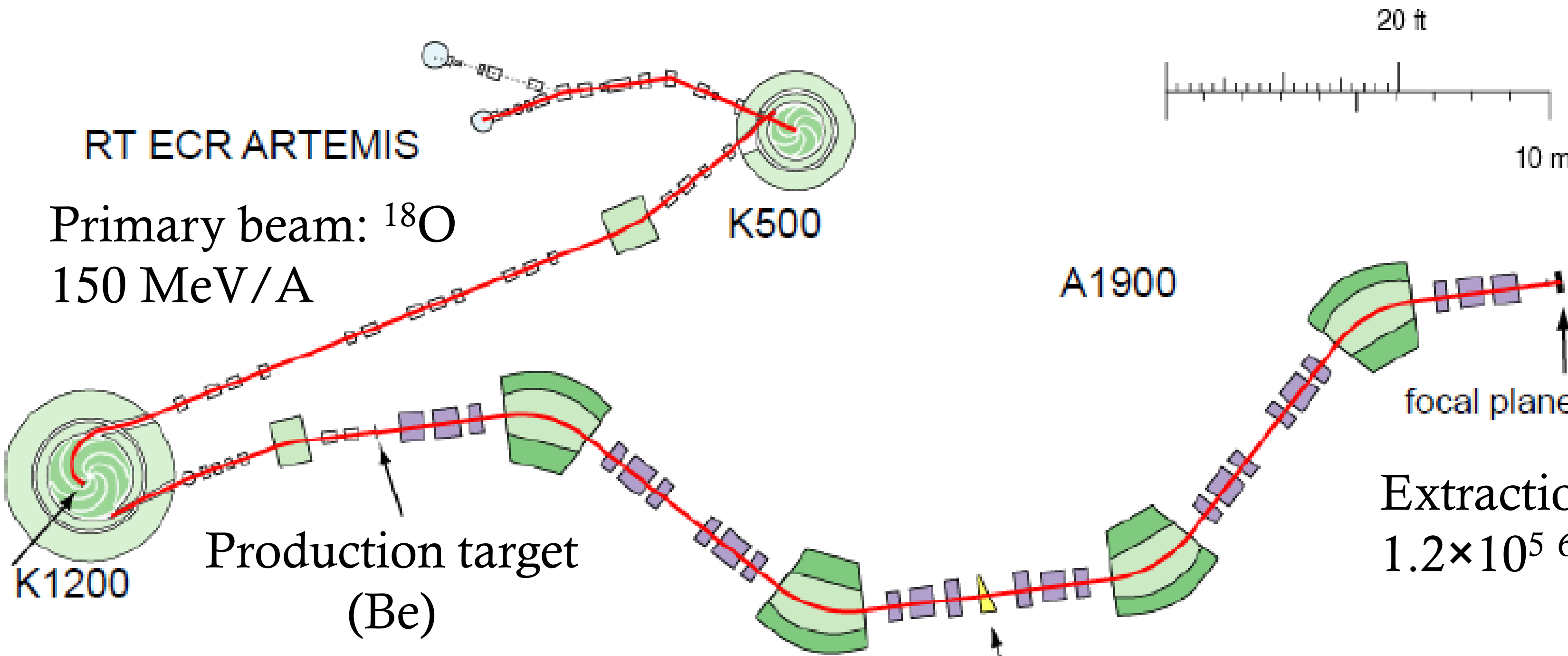
In an isospin triplet, the weak magnetism form factor can be determined from CVC



Candidates

^{6}He ^{20}F

NSCL Coupled Cyclotron Facility (^{6}He beam)



Primary beam: ^{18}O
150 MeV/A

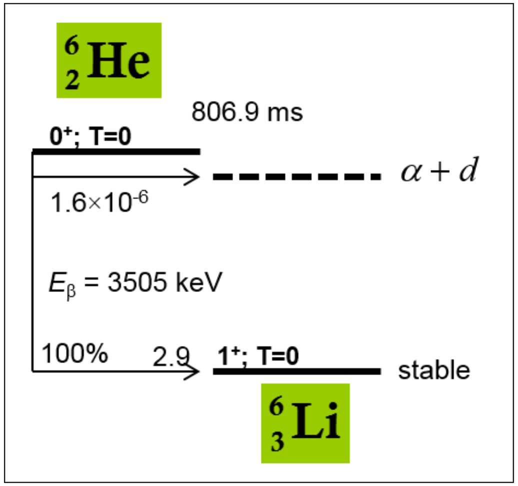
Production target
(Be)

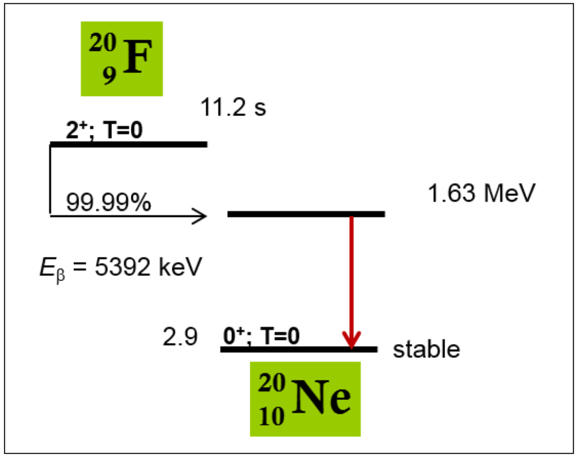
Wedge
(Al)

Extraction:
1.2×10^5 ^{6}He/s

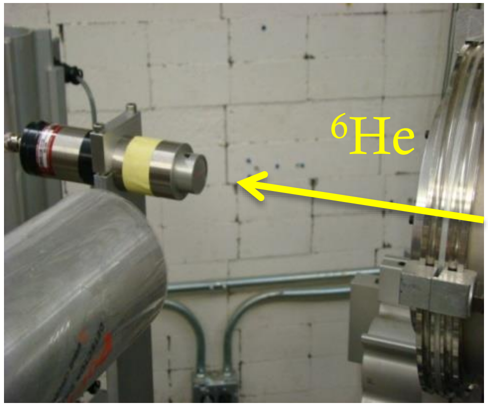
- $\Delta p/p = 1\%$
- $\Delta x \times \Delta y = 1.5 \times 2$ mm^2

Setups, detectors

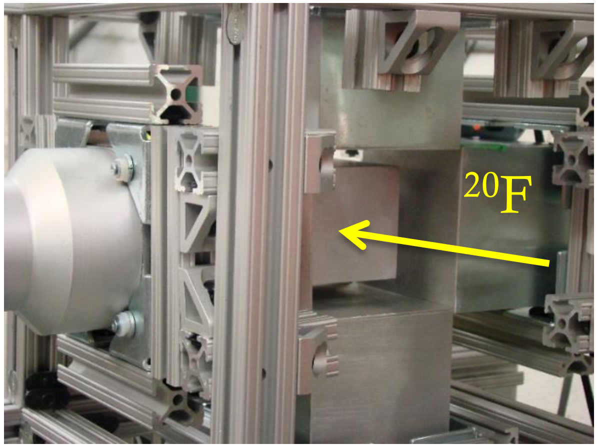




- CsI(Na) (2"×2"×5")
- CsI(Na) (Ø1"×1")
- NaI(Tl) (Ø3"×3")
- NaI(Tl) (Ø1"×1")



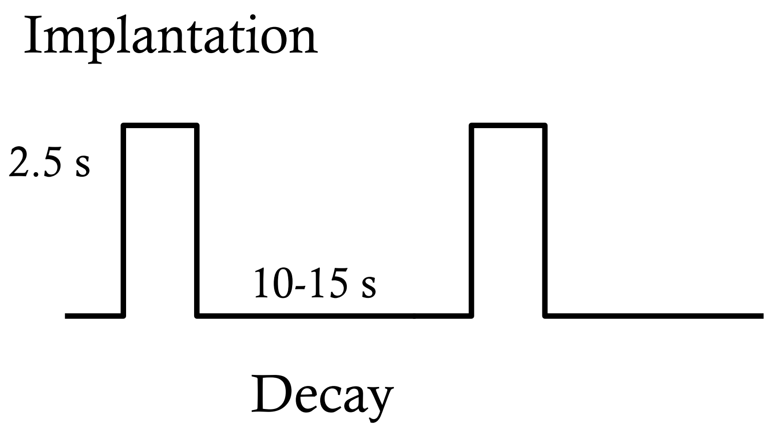
46 MeV/nucleon



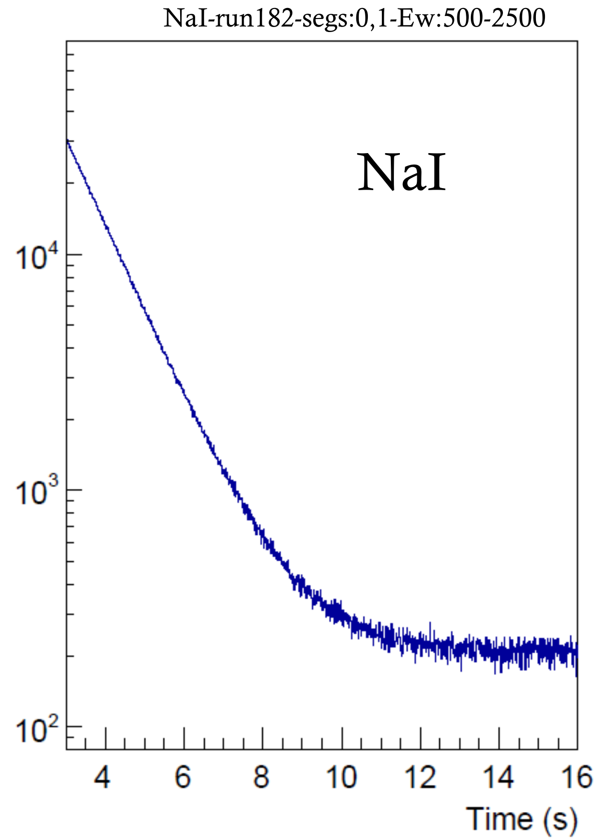
132 MeV/nucleon

CsI(Na)
PVT

Measuring sequence (^{6}He)



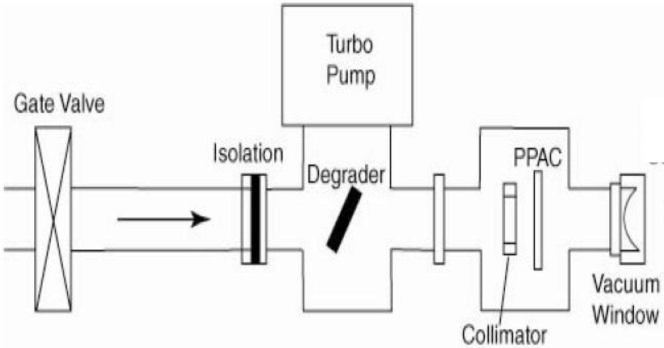
Decay spectrum



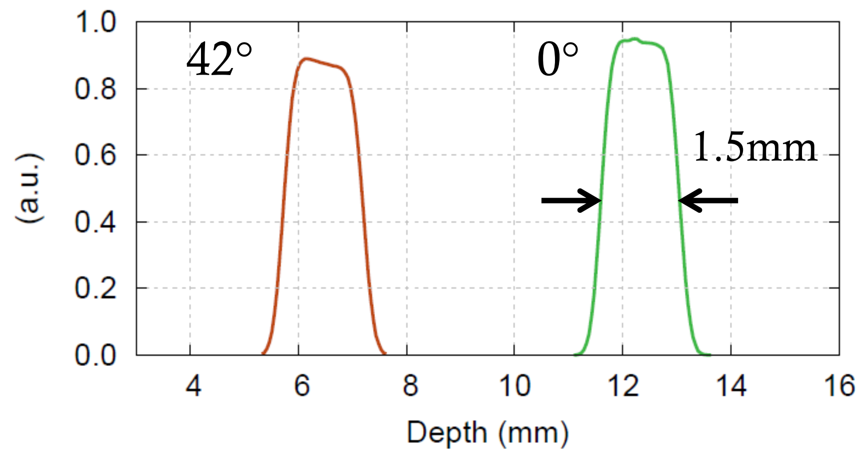
(Consistent with ^{6}He half-life and a single decay component)

Control of implantation depth and straggling

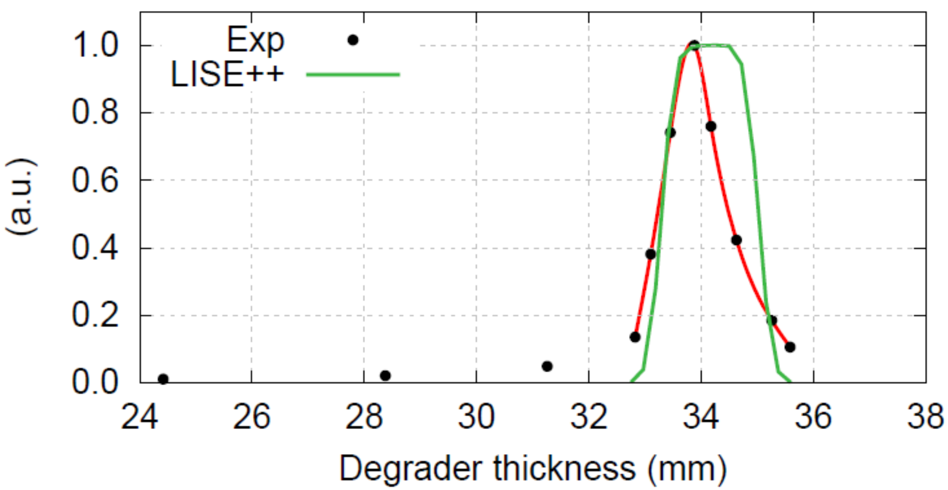
Vary degrader thickness by rotation



Deduce implantation depth profile in CsI (LISE++/SRIM) vs degrader angle.

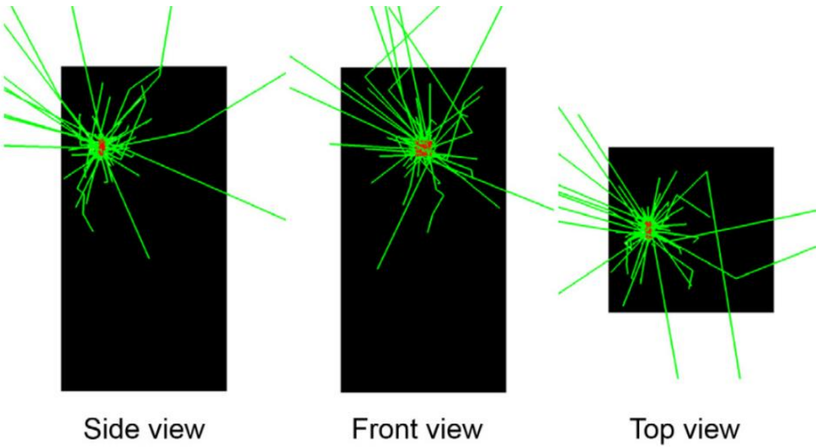


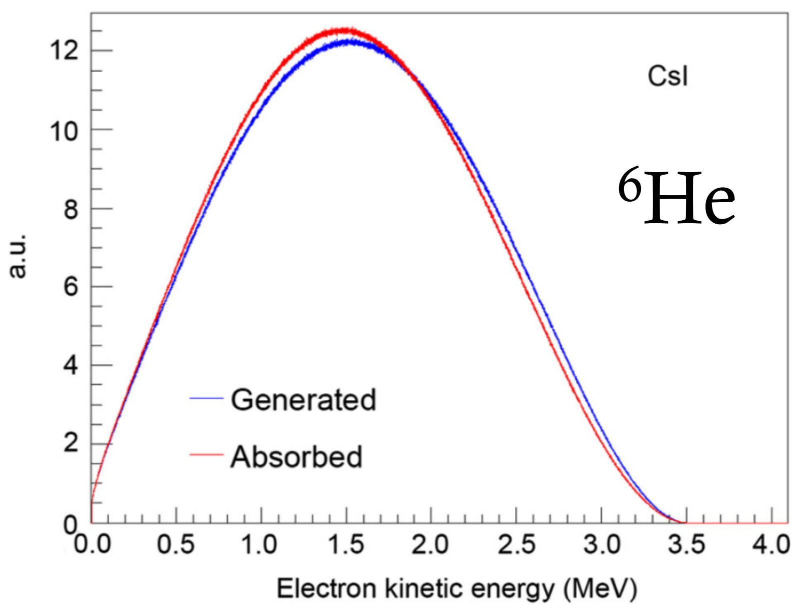
Deduce range distribution in Al degrader from transmitted counts recorded in implantation detector



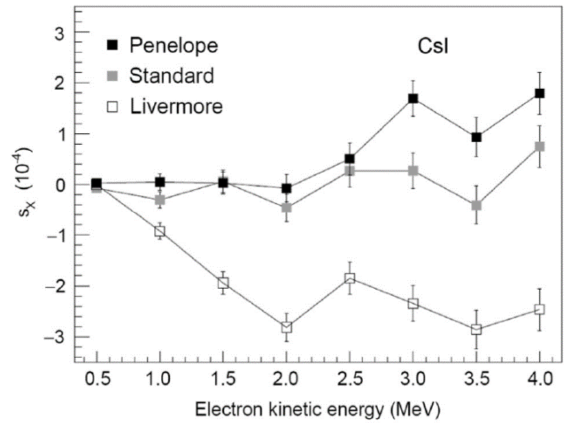
Escape of Bremsstrahlung radiation (Geant4)

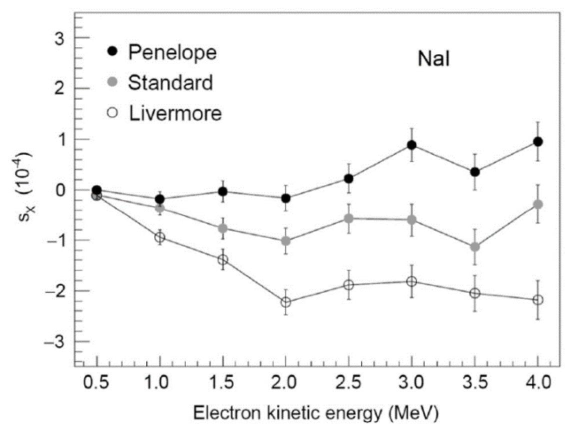
X. Huyan et al. NIMA **97** (2018) 054328





Relative escape yield



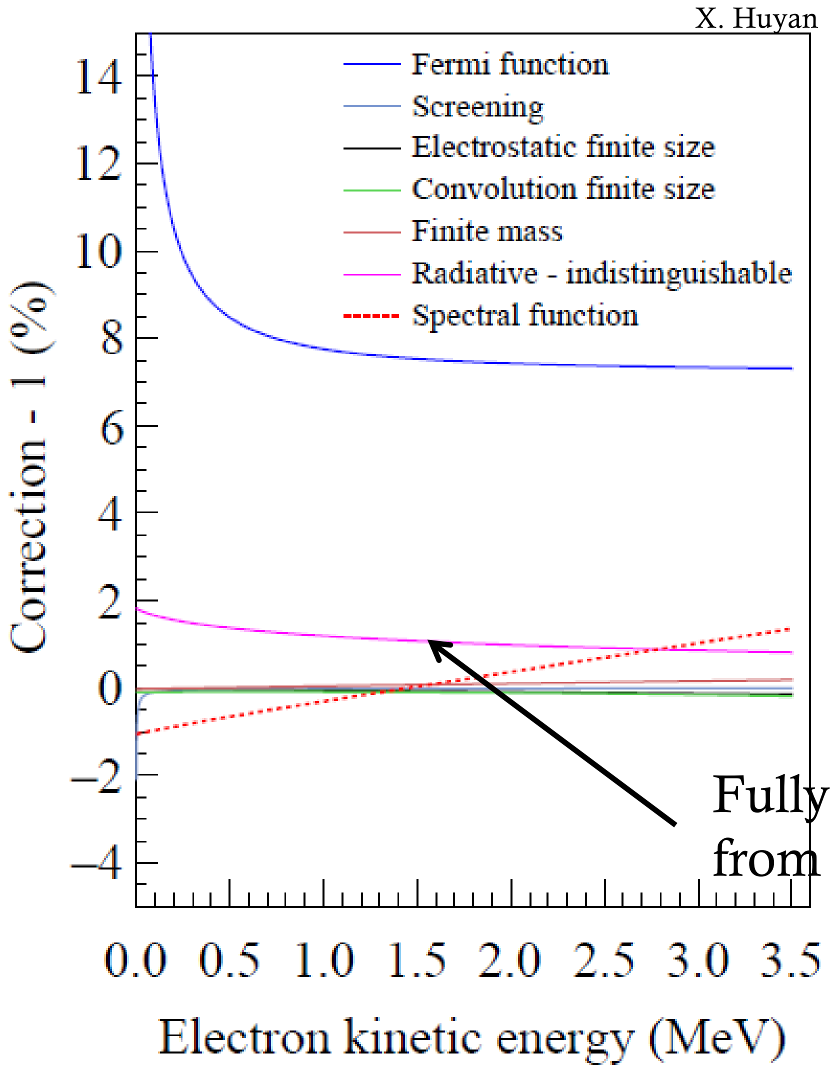


(relative to Option4)

For ^{6}He, the differences correspond to about 5% of the linear term due to WM.

Corrections to phase space (^6He)

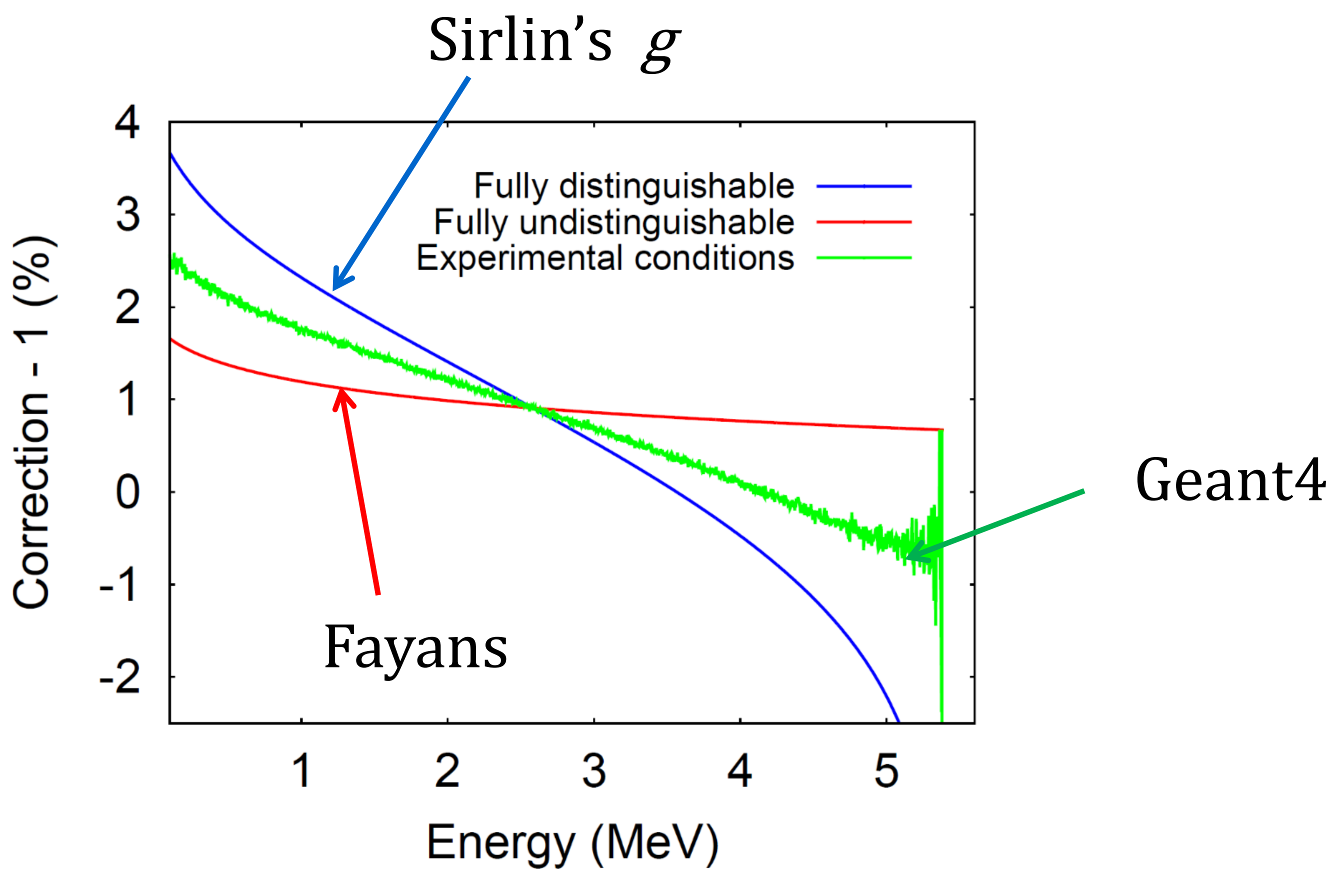
$$W(E) \propto F(Z,E) \cdot L_0 \cdot C \cdot S \cdot R \cdot M \cdot pE(E_0 - E)^2$$



- Generally small corrections (small *Z*)
- Dominated by radiative and shape factor ("spectral function")

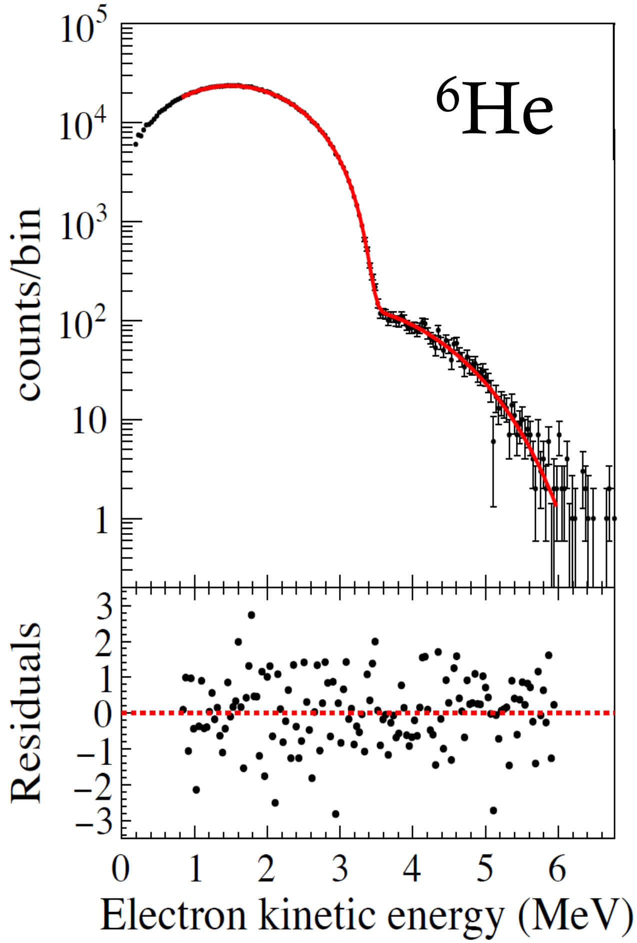
Fully distinguishable β and real photons from inner Bremsstrahlung

Effect of inner Bremsstrahlung absorption (^{20}F)



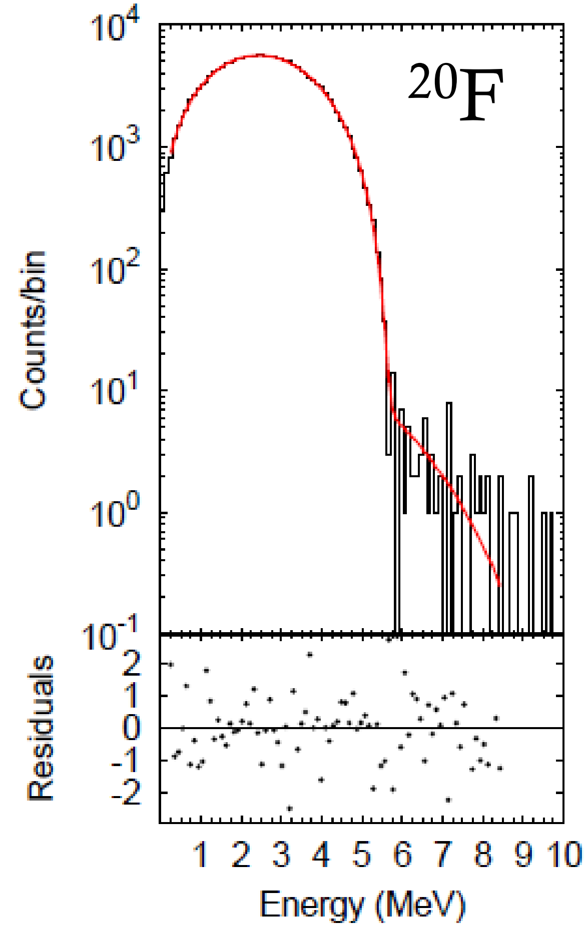
Examples of fits

Xueying Huyan (PhD)



~100 spectra collected with CsI(Na) and NaI(Tl)

Max Hughes (PhD)

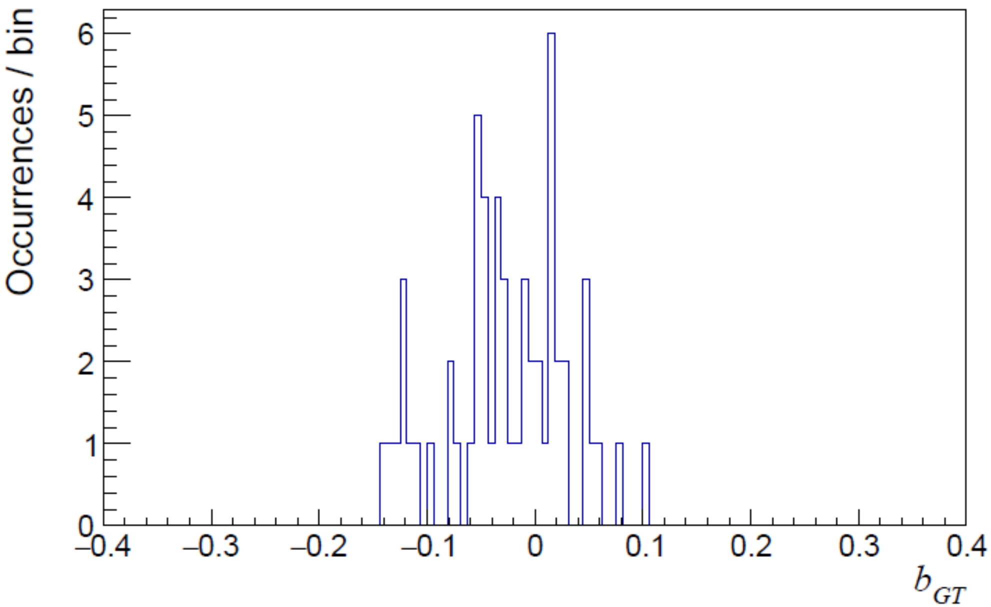


~55 spectra collected with CsI(Na)

Fierz term from ^{20}F

Using form factors from
K. Minamisono et al.,. PRC **84** (2011) 055501

- Statistical uncertainty for each measurement: $\Delta b_{GT} \sim 0.03$



- Statistical uncertainty for current ^{20}F data $\Delta b_{GT} \sim 5\times10^{-3}$

Shape factor in *GT* transitions

F. Calaprice, PRC **12** (1975) 2016

$$S(W) = \left(1 + C_0 + C_1 W + C_{-1}/W\right)$$

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

$$C_1 = \frac{2}{3M}\left(5 + 2\frac{b_{WM}}{c}\right)$$

$$C_{-1} = -\frac{m^2}{3M}\left(2 + \frac{d}{c} + 2\frac{b_{WM}}{c}\right)$$

$c = g_A \left|M_{GT}\right|$ Dominant GT matrix element

b_{WM} Weak magnetism (from CVC)

d Induced tensor

- From the contribution of induced form factors to *a*, Calaprice deduced for ^{6}He

$$d_{\exp} = 33 \pm 25 \qquad \left(\frac{d}{Ac}\right)_{\exp} = 2.0 \pm 1.6$$

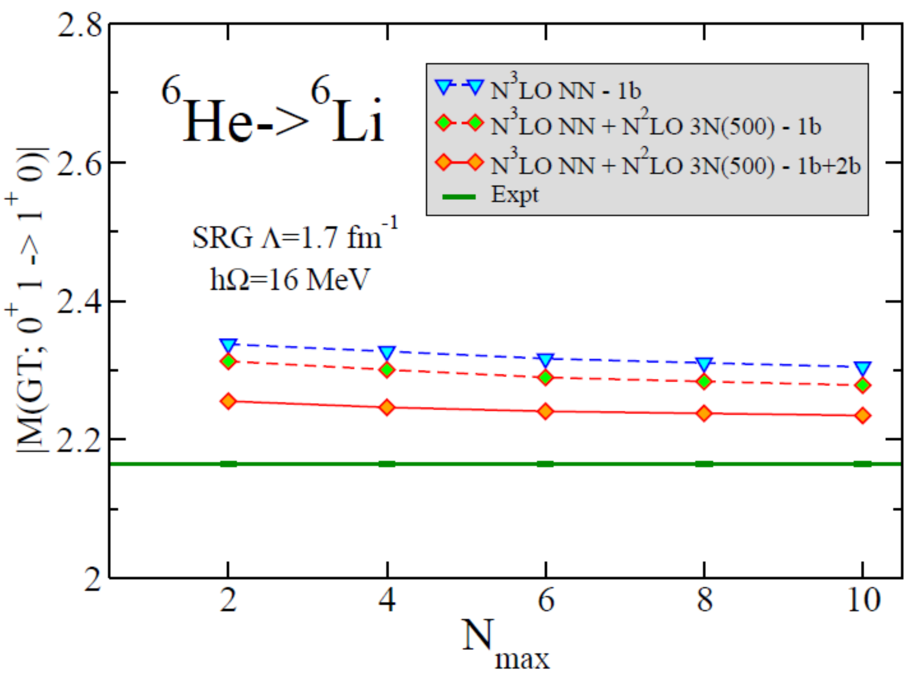
Sensitivity to form factors in ^{6}He decay

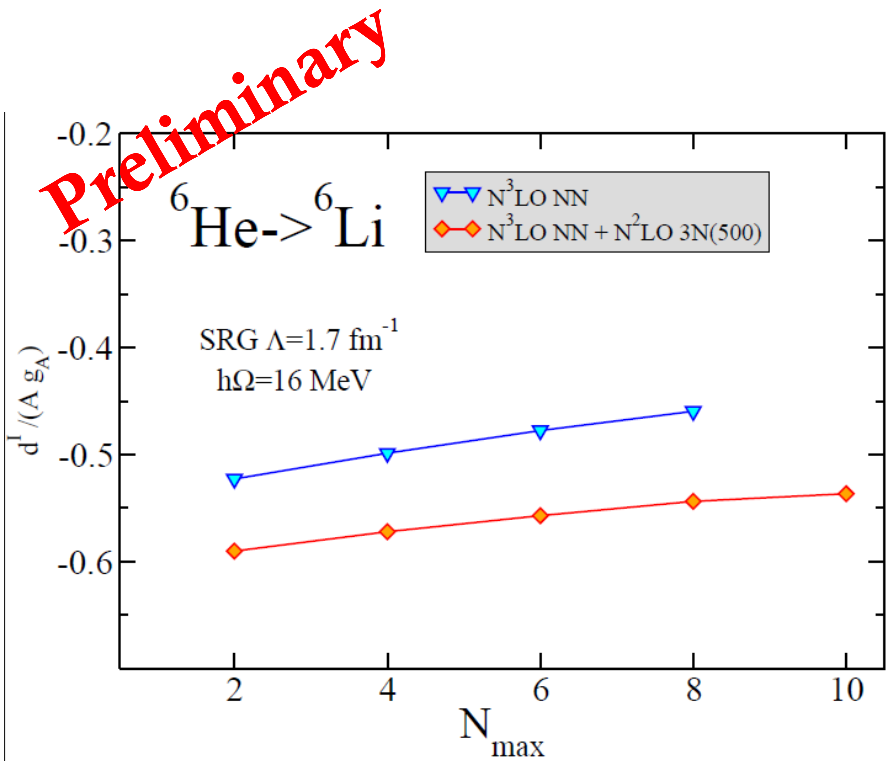
- Sensitivity to induced tensor: $\frac{\Delta b_{GT}}{\Delta d} = 1.8 \times 10^{-5}$
- Sensitivity to weak magnetism: $\frac{\Delta b_{GT}}{\Delta b_{WM}} = 4.2 \times 10^{-4}$

$$b_{WM} = \sqrt{\frac{6\Gamma_{M1} M^2}{\alpha E_\gamma^3}} = 68.22(79) \quad \Rightarrow \quad \Delta b_{GT} = 3.4 \times 10^{-4}$$

Calculations with chiral interactions in ^{6}He

P. Navratil @ TRIUMF
Private communication 2016





Summary

- Several experimental approaches are being considered to reach new levels of sensitivity in measurements of the Fierz term.

- The extraction of constraints on NP require an accurate inclusion of induced form factors and the support from theory.