AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

Measurements of β energy spectra in Gamow-Teller decays

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Context

- Search/Constraint exotic (*Tensor*) couplings in charged weak current processes.
- Focus on semi-leptonic processes (nuclear β decay)
- Select pure Gamow-Teller decays which are sensitive to *Tensor* type interactions.

Phenomenology guidance

- Is there any niche left by the LHC to constraint new physics?

- What is the complementarity between low- and high energy searches and (in any) which is the required precision for low energy experiments?

M. Gonzalez-Alonso, arXiv:1209.0689v1
T. Bhattacharya et al., PRD **85** (2012) 054512
V. Cirigliano, S. Gardner, B.R, Holstein, Prog. Part. Nucl. Phys. **71** (2013) 93

$$\varepsilon_T \approx 10^{-4}$$

(Current limits from beta decay are at the level $2\text{–}4\times10^{-3}$)

- Largest sensitivity obtained by observables which are linear in the couplings.

Observable and kinematic sensitivity

- The Fierz term in the β spectrum

$$N(W) = pW(W_0 - W)^2 Q(W)\left(1 + \frac{m}{W} b_{GT}\right) S_R(W)$$

- The Fierz term is linear in the couplings

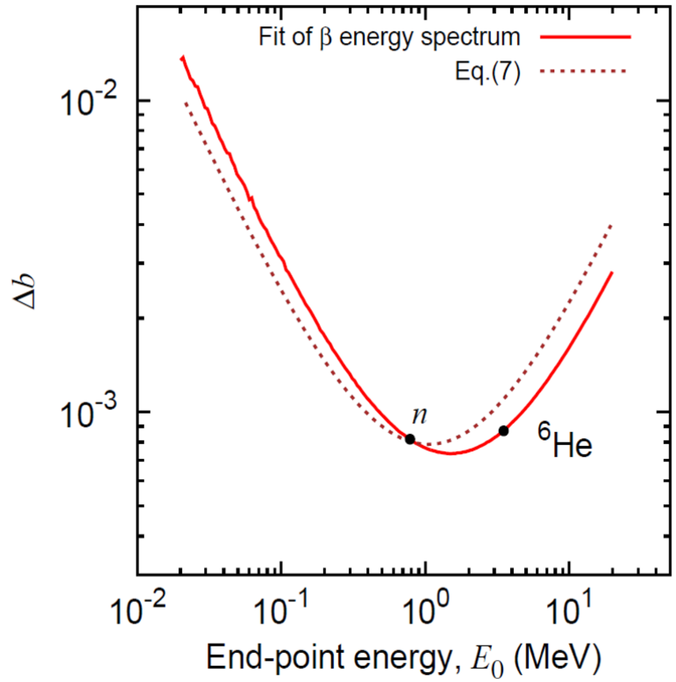
$$b_{GT} \propto (C_T C_A + C_T' C_A')$$

$$b_{GT} \approx 8\varepsilon_T$$

Kinematic sensitivity (^{6}He comparable to neutron decay)

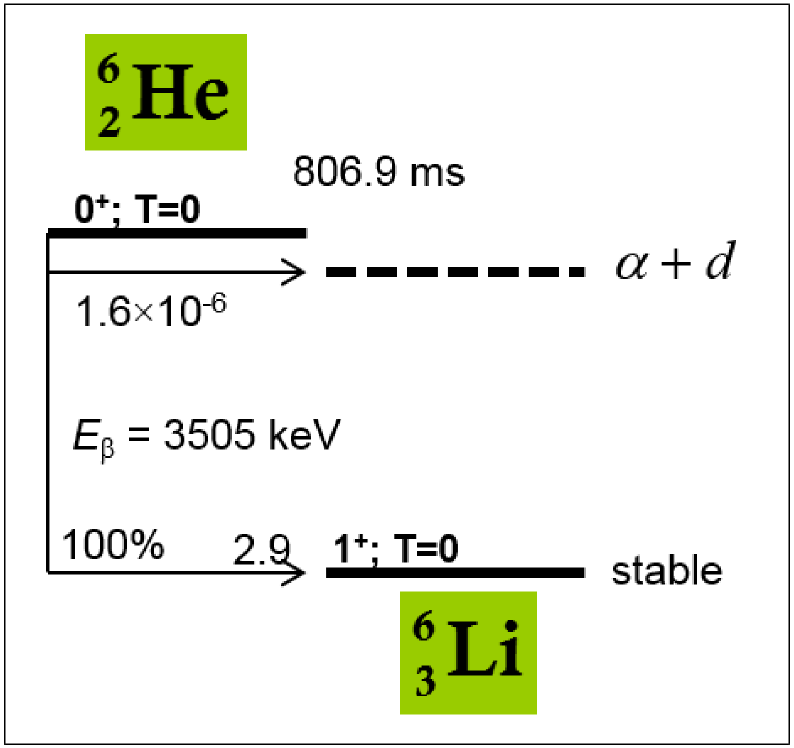
Stat error for 10^8 events

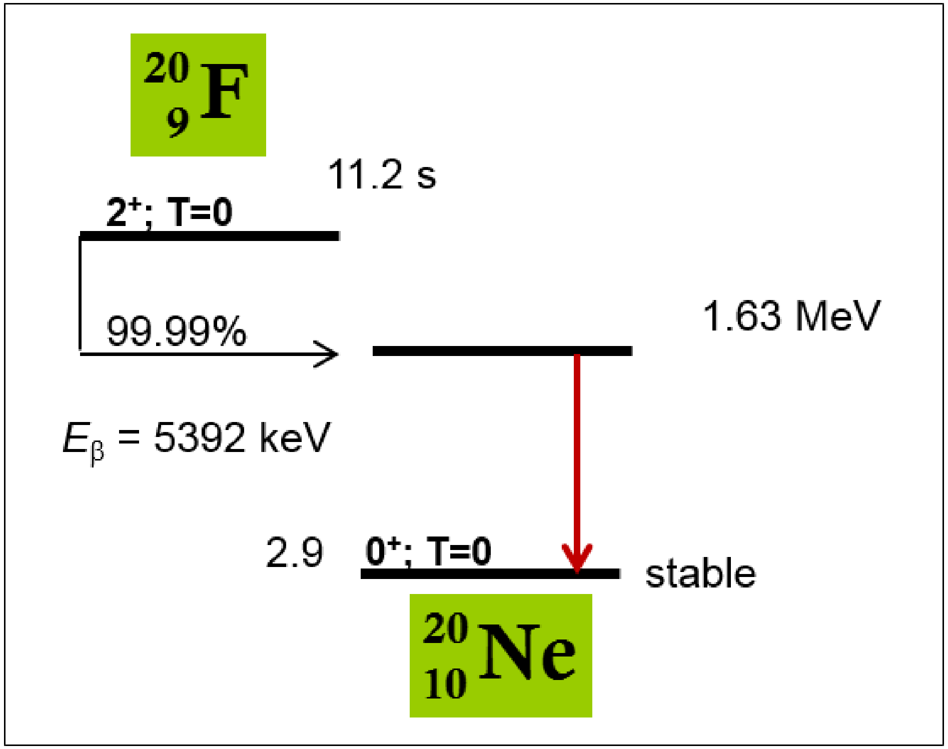
M. Gonzalez-Alonso and O. N.-C
Phys. Rev. C **94** (2016) 035503



Selection of candidates

Gamow-Teller decays in isospin triplets





Hadronic effects (*weak magnetism*) are well under control.
They serve as a sensitivity test of the experimental technique.

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

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

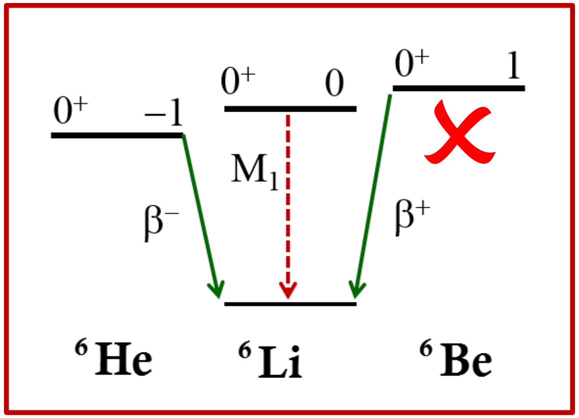
B.R. Holstein and S.B. Treiman, PRC **3** (1971) 1921

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

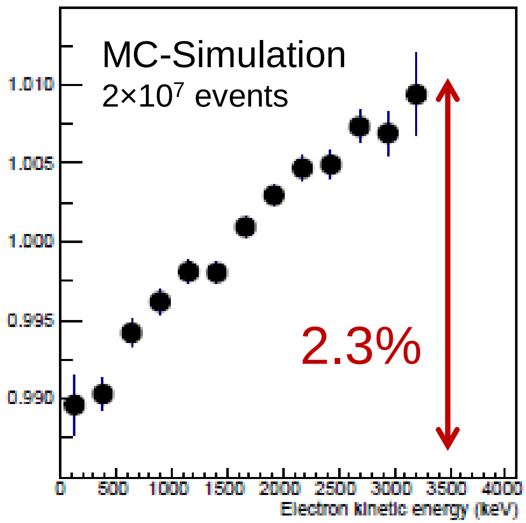
$$C_1 = \frac{2}{3M}\left(5 + 2\frac{b_{WM}}{c}\right) = 0.6502(69)\ \%/\mathrm{MeV}$$

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

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



Effect on the ^{6}He spectrum shape



First goal

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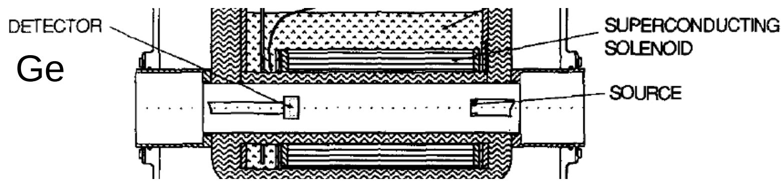
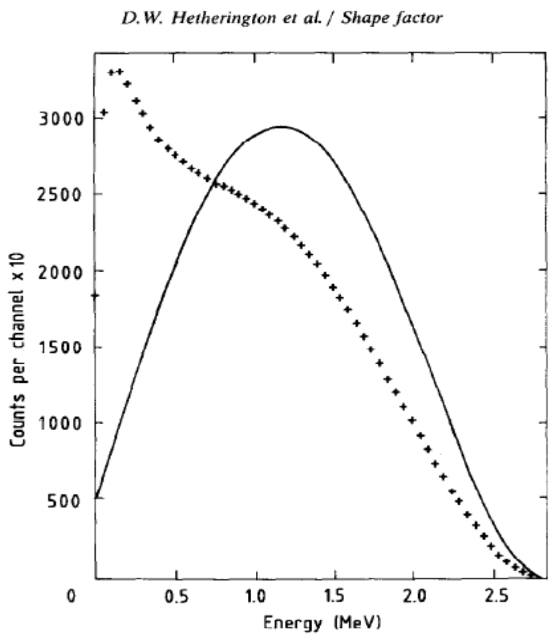
Instrumental effects in β spectra measurements

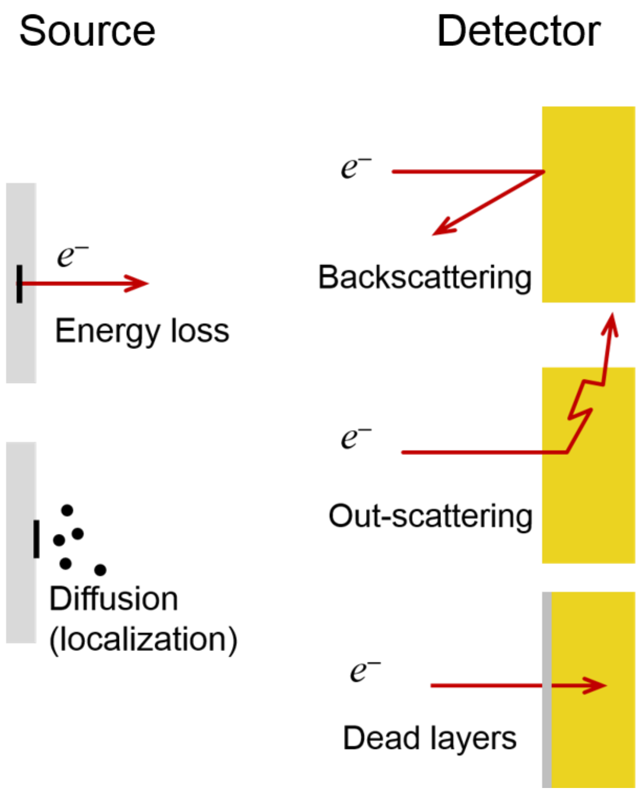
- Why such a simple experiment has not been performed so far?



D.W. Hetherington, A. Alousi and R.M. Moore, NPA **494** (1989) 1

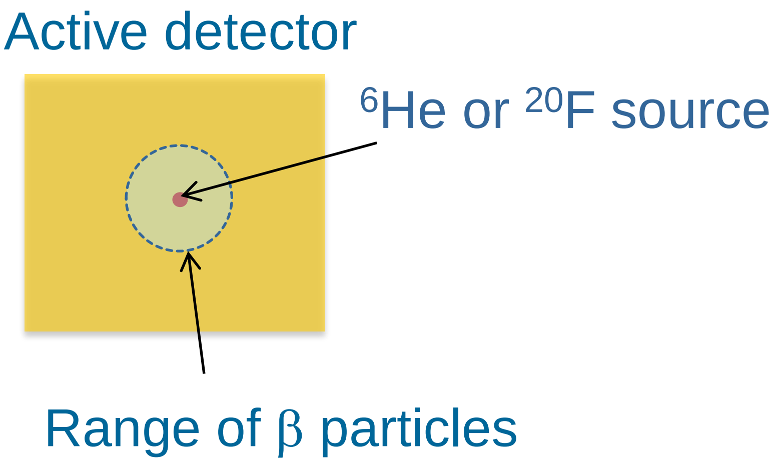


Detector response function for a measurement of the shape in ^{20}F decay



Calorimetric technique

- We have eliminated all those effects using a calorimetric technique

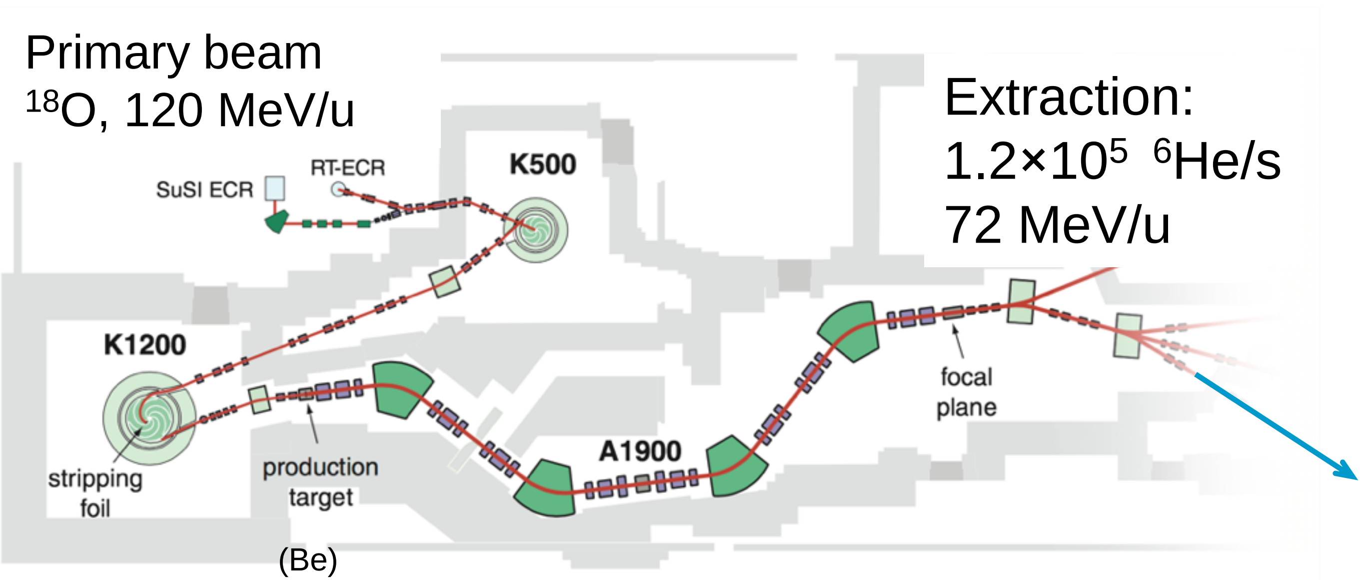


- Requires the appropriate beam energy to implant ions inside a detector.

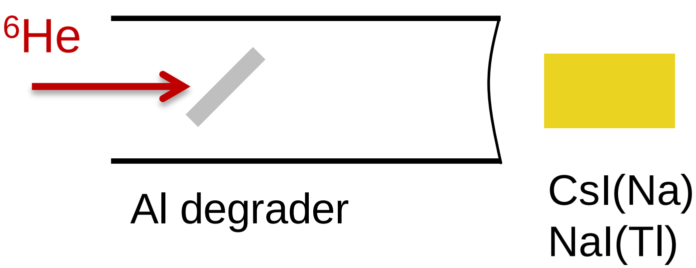
Experiment with implanted ^{6}He at the NSCL

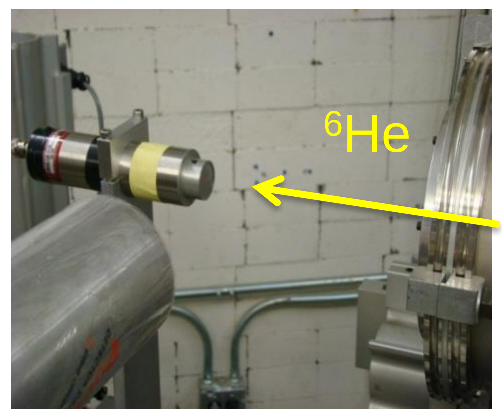
Primary beam
^{18}O, 120 MeV/u

Extraction:
1.2×10^{5} ^{6}He/s
72 MeV/u



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

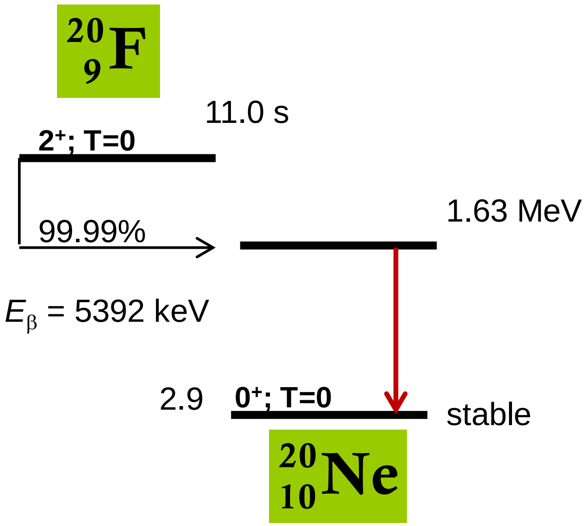


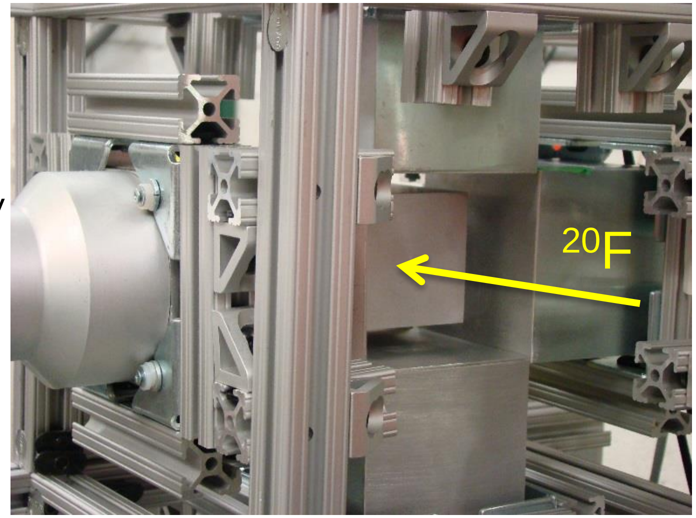


- CsI(Na) (2"×2"×5")
- NaI(Tl) (Ø3"×3")
- (Ø1"×1") CsI(Na)
- (Ø1"×1") NaI(Tl)

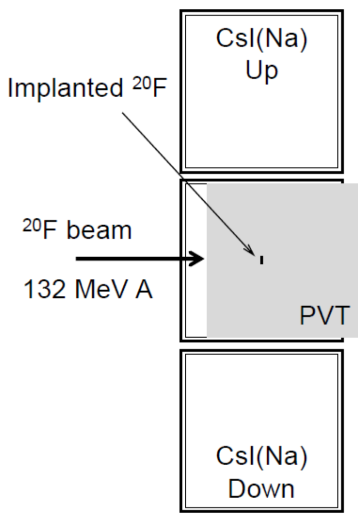
46 MeV/nucleon after degrader

Experiment with implanted ^{20}F

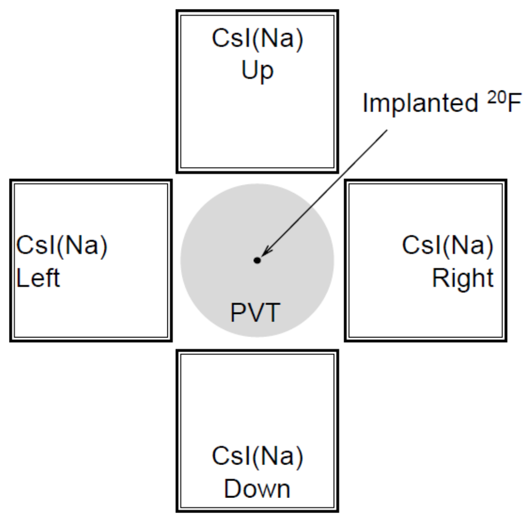




- ^{22}Ne primary beam
- ^{20}F implanted at132 MeV/nucleon
- 4 (3"×3"×3") CsI(Na) for γ
- PVT (Ø3"×3") and (2"×2"×4") CsI(Na) implantation detectors for β



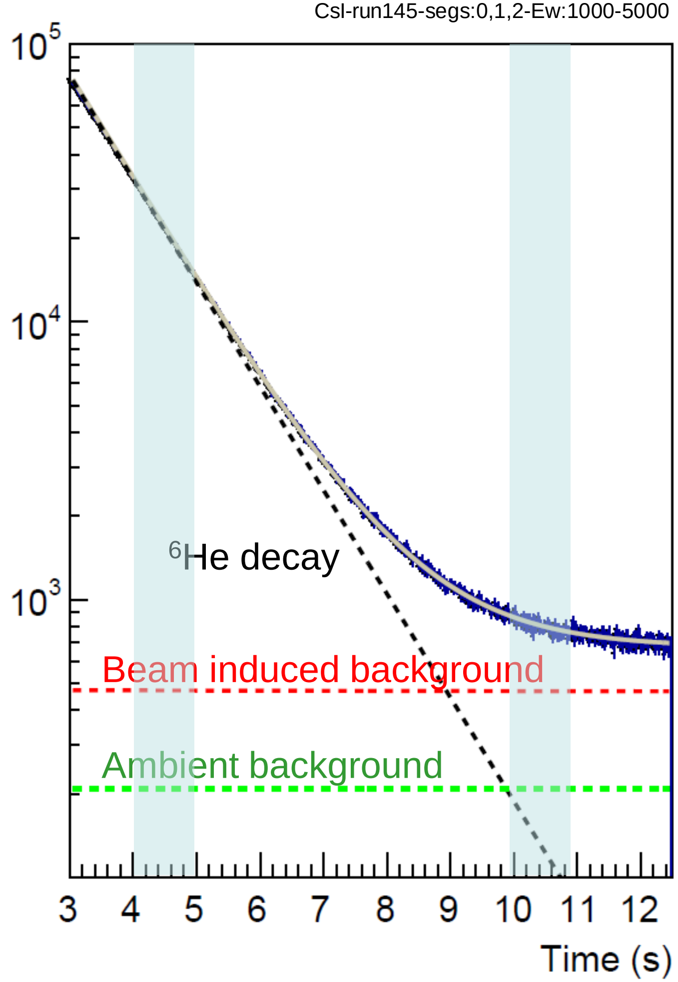
Side view

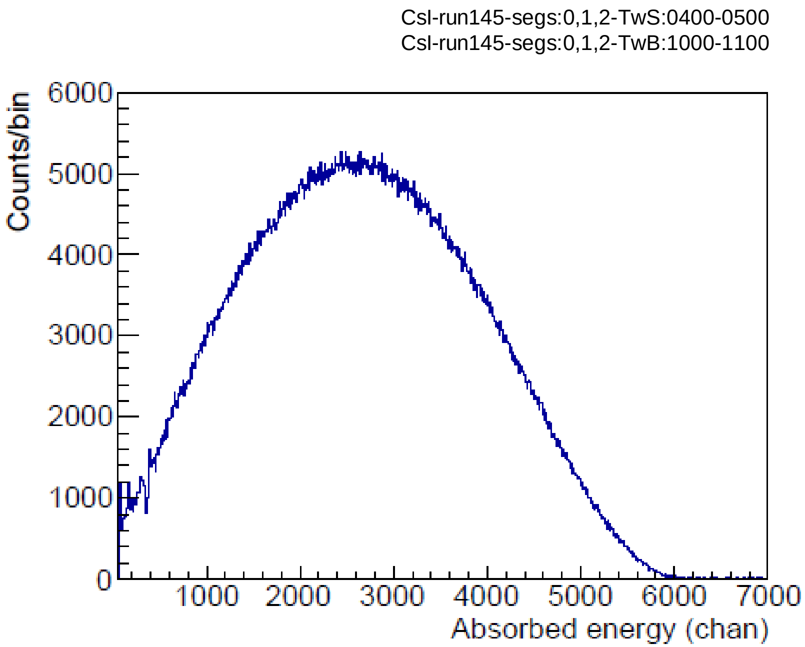


Front view

Sample spectra (^{6}He)

Beam ON/OFF sequence





No traces of “short lived” beam induced background

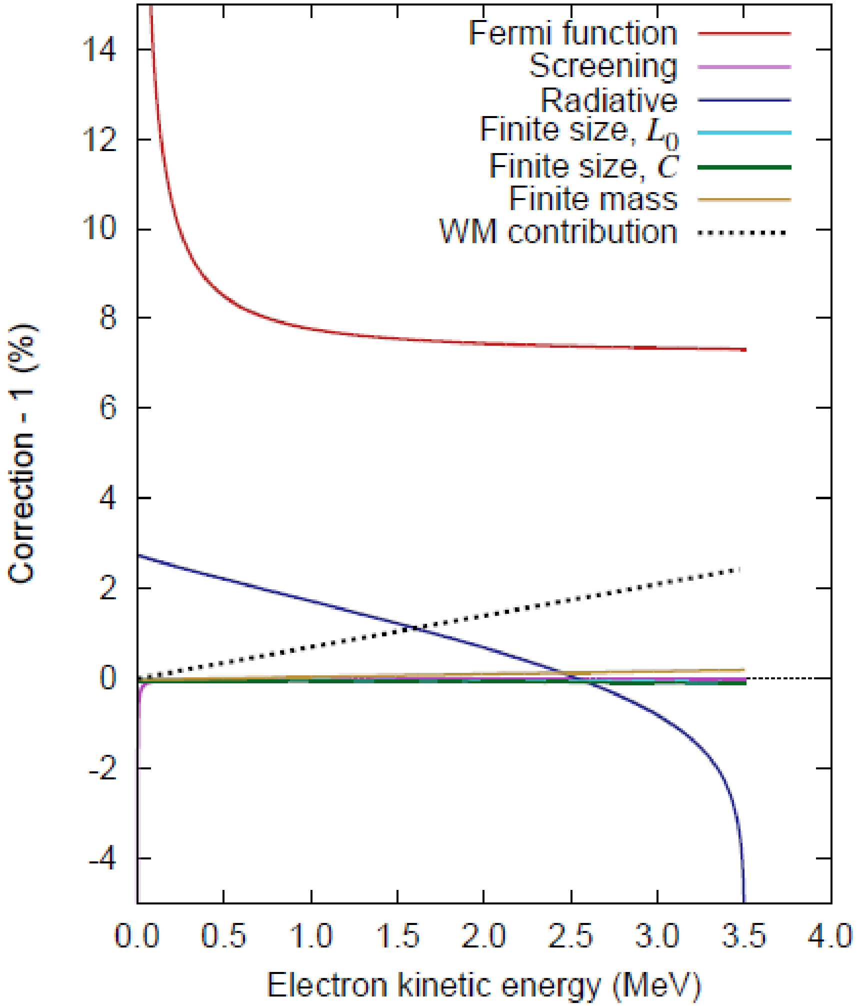
- Collected typically 10^7 events in 1 h run
- Define slices between 3.5 and 5.0 s, with:
  - 10^6 events in each spectrum
  - Rate < 20 kcps
  - S/B > 20

- ~50 spectra with CsI(Na)
- ~50 spectra with NaI(Tl)

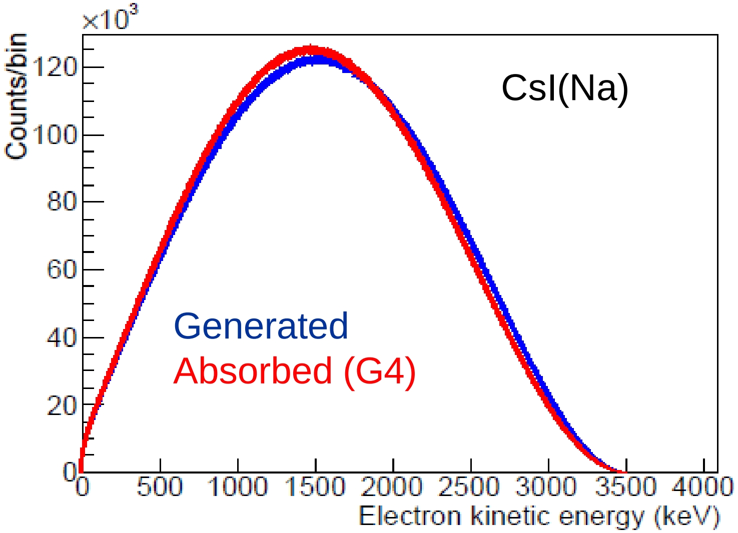
Theoretical spectrum and Geant4 simulation

- EM and radiative corrections

$$Q(W) \propto F(Z,W) \cdot L_0 \cdot C \cdot S \cdot R \cdot M$$



- The measured spectrum is distorted due to the escape of Bremsstrahlung radiation.
- The absorbed energy spectrum was determined using G4 simulations.



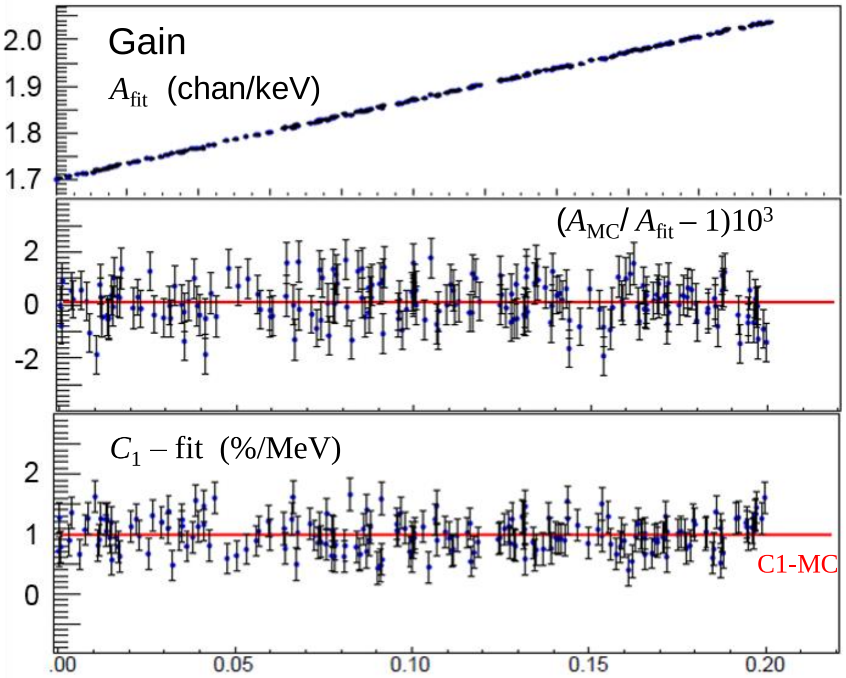
G4 simulations:
X. Huyan et al. submitted to NIM-A

Systematics: gain of detection system

- The technique relies on the extraction of the system gain for each measured spectrum ("auto-calibration").

$$N(W) \approx P(W)(1 + C_1 W)$$

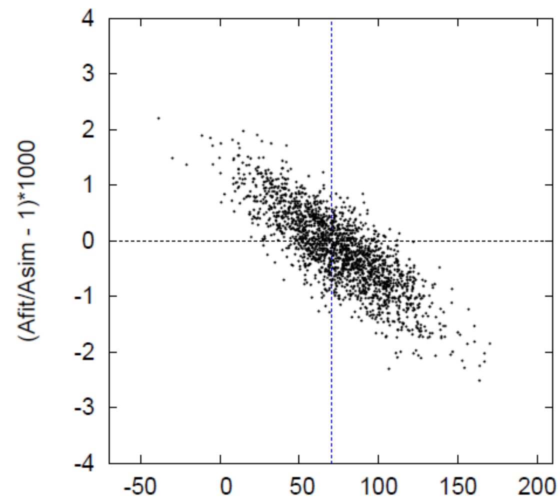
MC simulation: 10^6 events/run



Gain stretch - 1

- There is a correlation between individual <u>systematic errors</u> made in the determination of the system gain and the form factor.

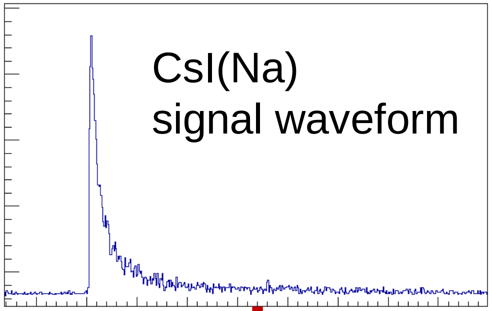
1000 MC runs

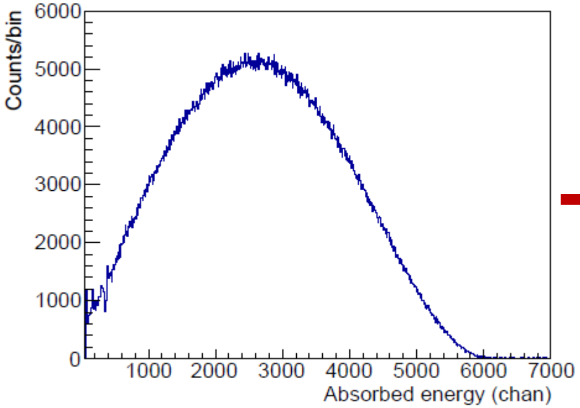


b_{WM} (fit)

- There is no correlation between the <u>actual value</u> of the system gain and the form factor.

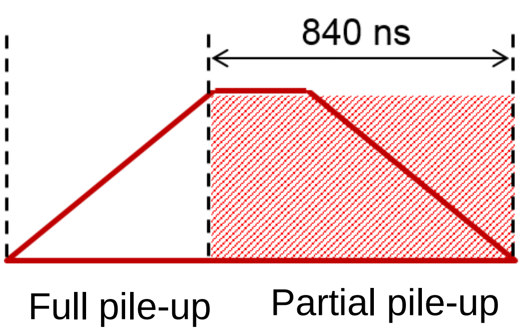
Systematics: “fast” pile-up

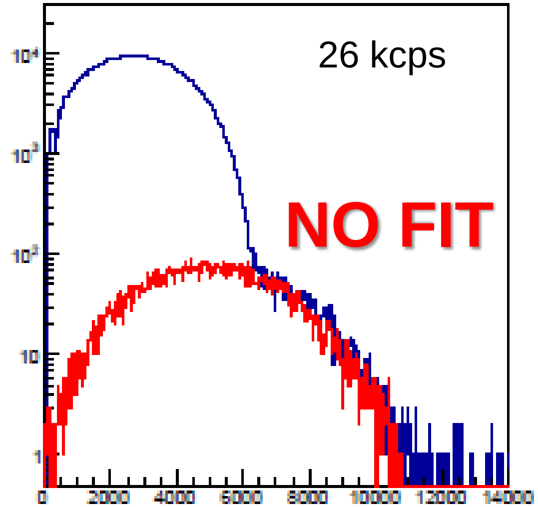




Measured spectrum

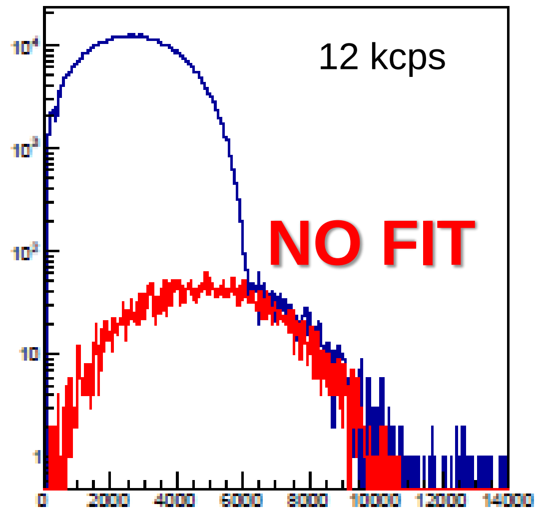
Digitizer simulation





Experiment

Pile-up calculation



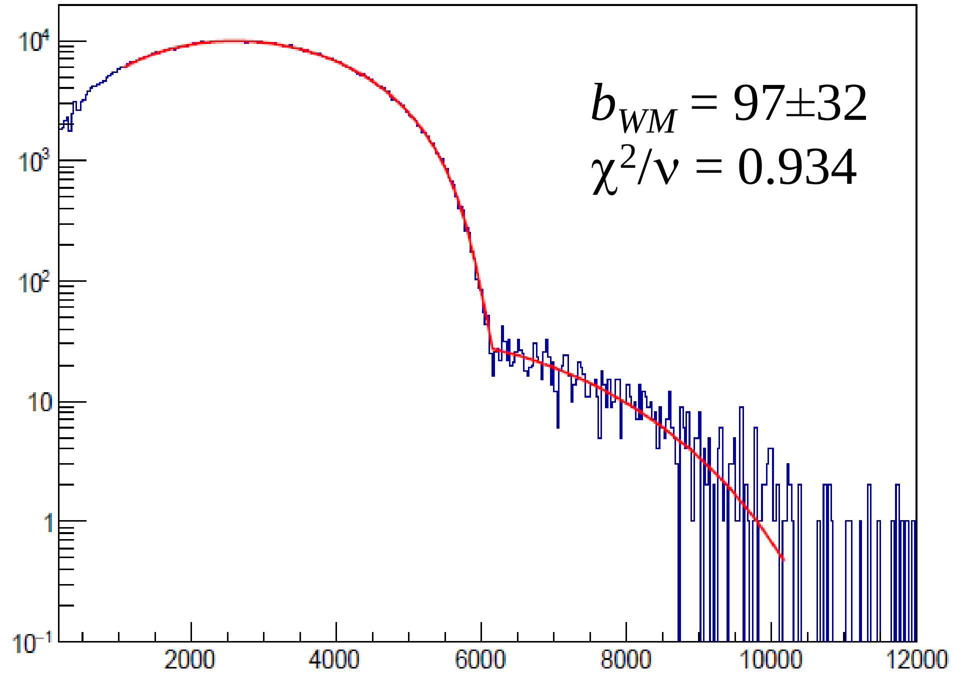
Data analysis: example of Monte-Carlo fit

Fit data with G4 simulated spectra convoluted with the detector response, including pile-up contribution

$$N(W) \approx G(W)(1 + C_0 + C_1 W + C_{-1}/W)$$

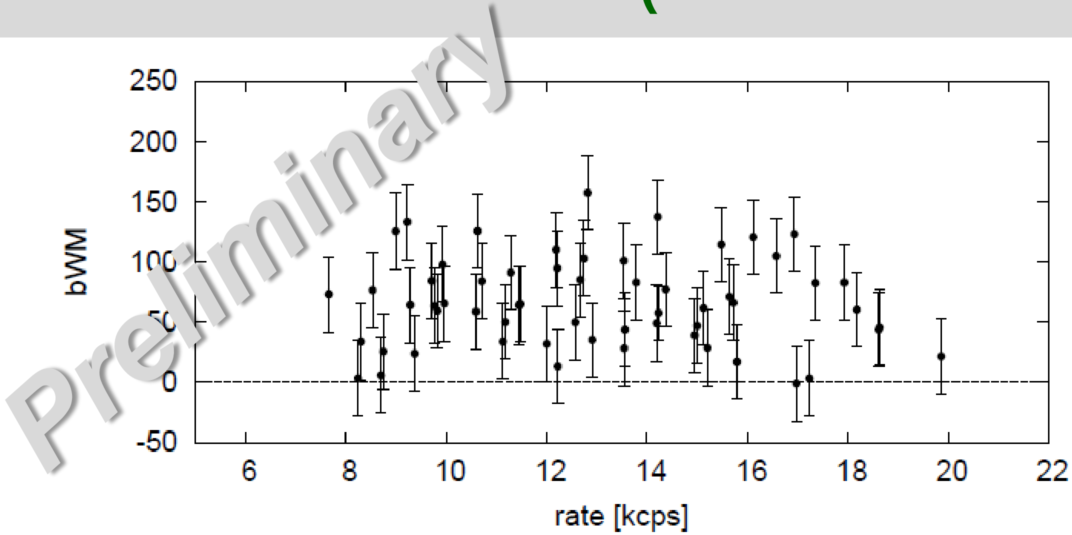
Free parameters

- Overall normalization $\boldsymbol{N_0}$
- $\boldsymbol{b_{WM}}$
- System gain ($Ch = \boldsymbol{A}E+B$)



Electron energy (ADC units)

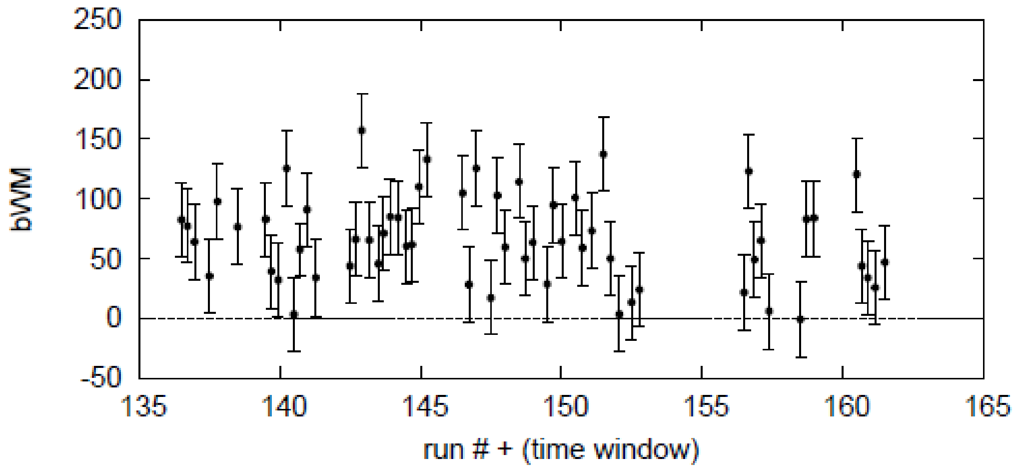
Current results (CsI detector)



No indication of a rate dependent effect over this range

E = 650-8000 keV
S/B > 22
T_{min} = 3.5 s
B = 32
csi_ET_00muS

- The rate correlated change of gain is about 2-3% over this range.
- This would potentially induce a systematic effect by a factor 6 to 9!!!



No indication of a slow drift variation during the duration of the run

Status and Outlook

- We have performed high statistics measurements of the β spectrum shape in ^{6}He and ^{20}F decays.

- We have analyzed half of the collected data in ^{6}He. This will enable the determination of the weak magnetism form factor with a relative statistical uncertainty of about 6%.

- Assuming CVC the measurement will allow the determination of the Fierz term at the 0.2% statistical level.

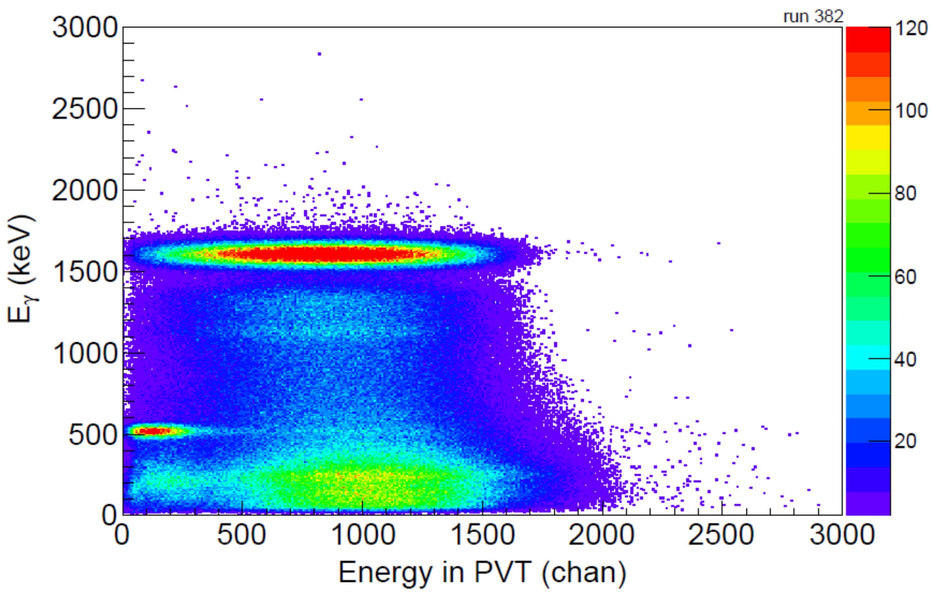
- The full collected statistics in ^{6}He and ^{20}F will allow us to reach a statistical precision of 0.1% on b_{GT}

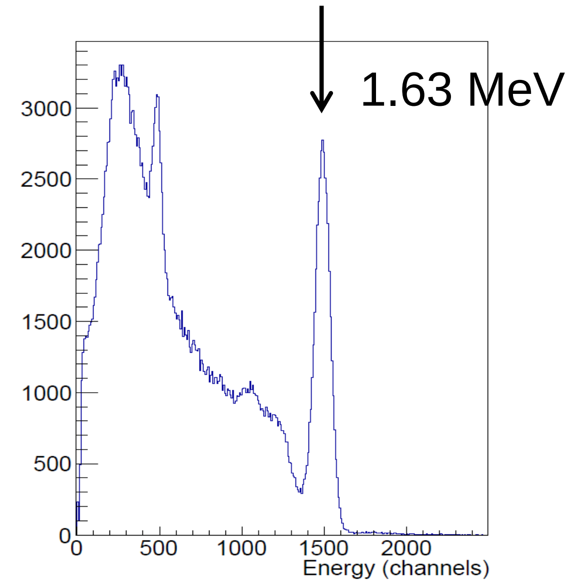
Systematic effects

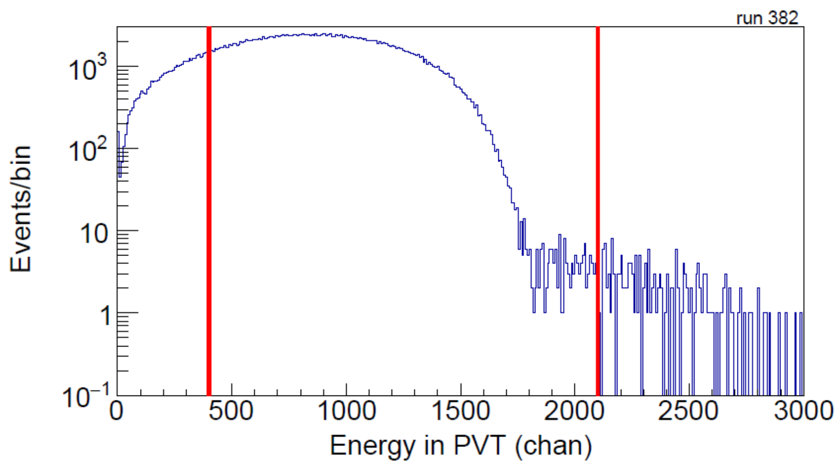
1. Theoretical corrections to beta spectrum	✓
2. Bremsstrahlung escape (Geant4)	✓
3. Detector response function (convolution)	✓
4. “Fast” pile-up (digital DAQ)	✓
5. After-glow pile-up (system gain)	✓
6. Detection system gain (calibration)	✓
7. Calibration offset (base line)	
8. Background subtraction with gain correction	
9. Detection system linearity	

✓ = systematic error smaller than or comparable to stat. uncertainty

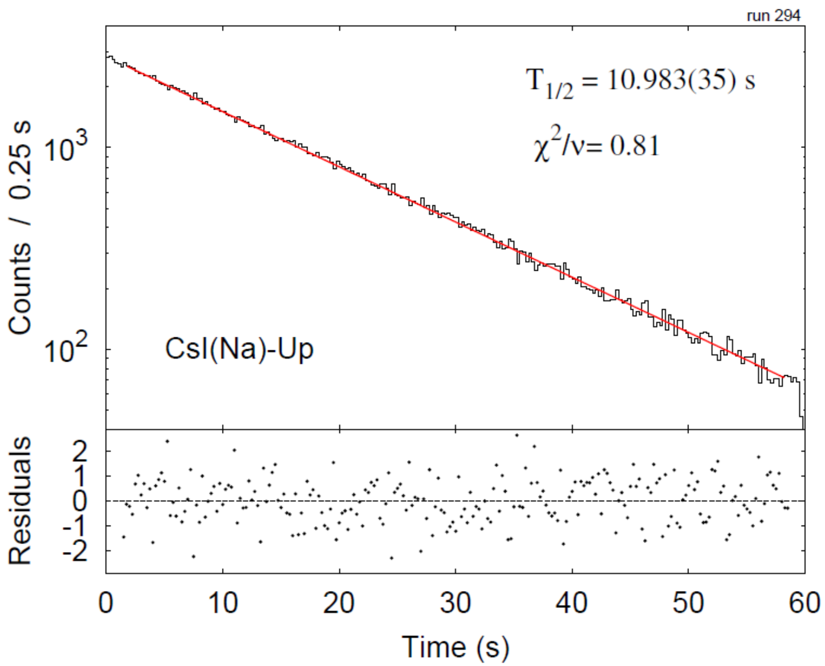
Sample spectra ^{20}F experiment

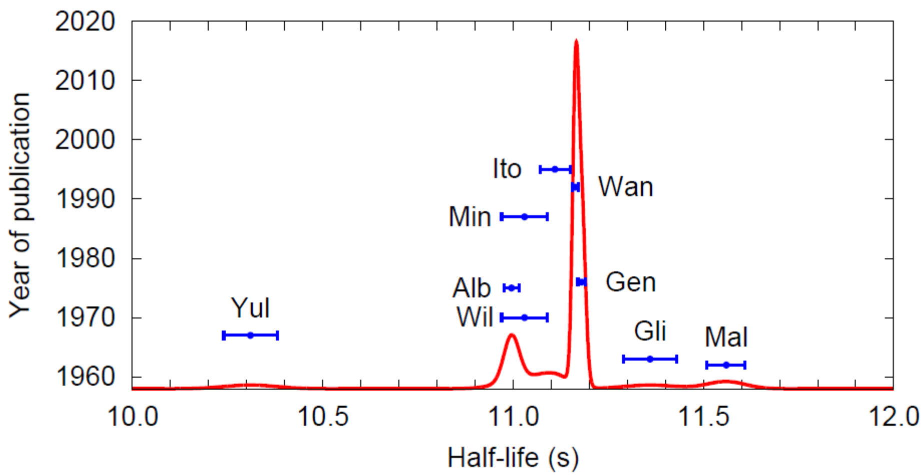


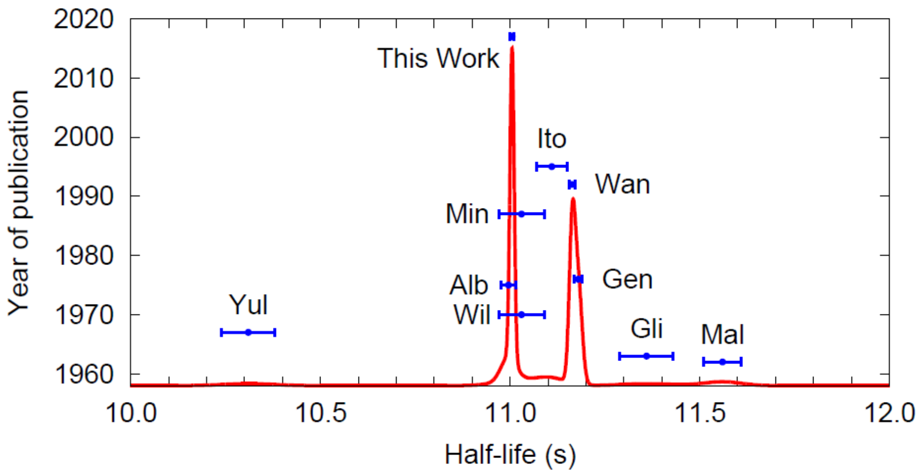




^{20}F half-life analysis







Geant4 simulations: photon yields

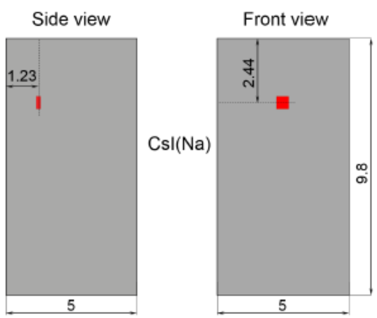


Figure 1: Geometry of the CsI(Na) detector (gray) and position of the electron source (red) used in the simulations. Dimensions are in cm.

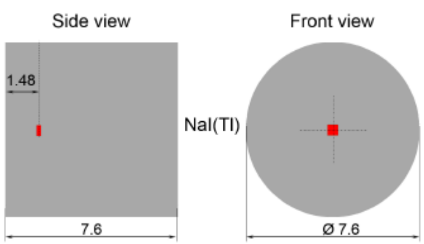


Figure 2: Geometry of the NaI(Tl) detector (gray) and position of the electron source (red) used in the simulations. Dimensions are in cm.

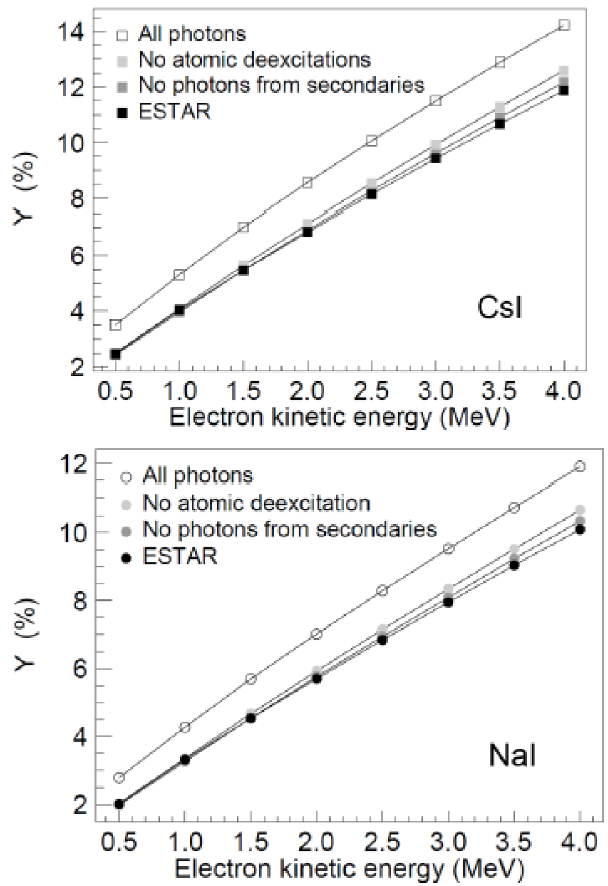


Figure 5: Photon yields produced in CsI (upper pannel) and in NaI (lower pannel) as a function of the initial electron energy obtained with the Standard constructor. The open, light gray and dark gray markers correspond to Geant4 simulations. The black filled markers are values from the ESTAR tables. See text for details.

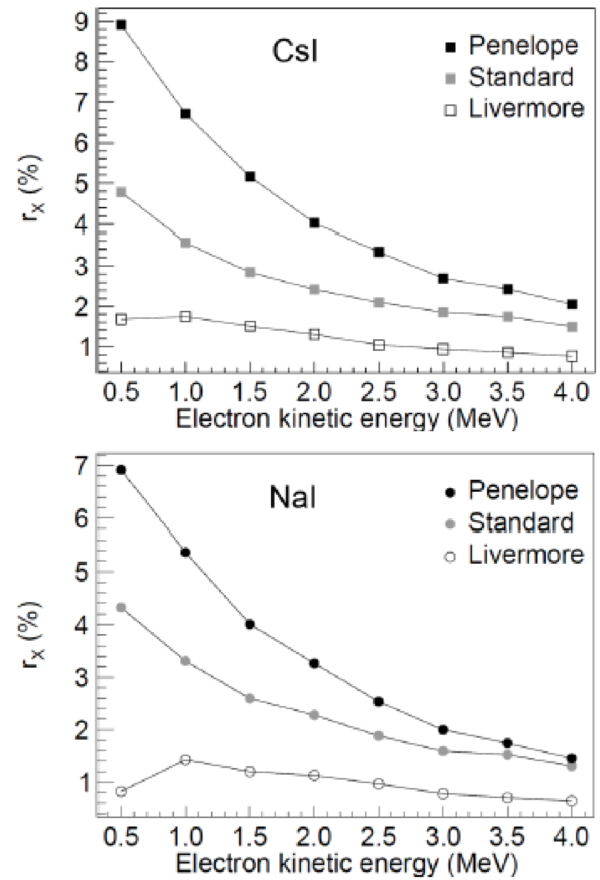


Figure 6: Relative photon yields produced in CsI (upper pannel) and NaI (lower pannel) as a function of the initial electron energy obtained with the Penelope (black markers), Standard (gray markers) and Livermore (open markers) constructors. The yields were normalized relative to those calculated with Option4.

Geant4 simulations: absorption fractions

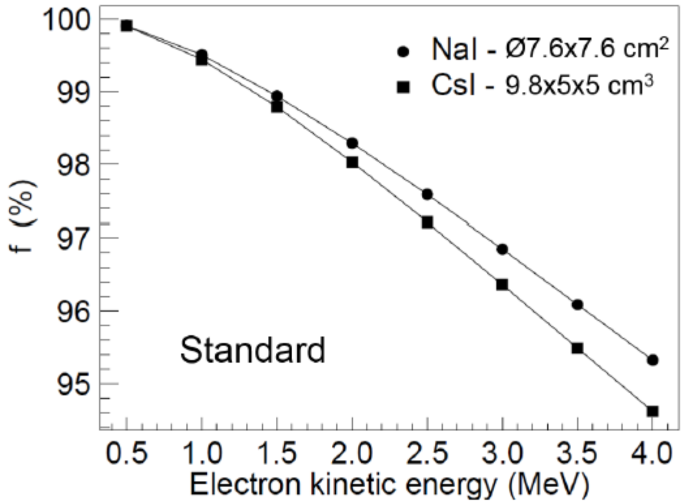


Figure 7: Absorption fraction as a function of the primary electron energy in NaI (circles) and CsI (squares), calculated with the Standard constructor.

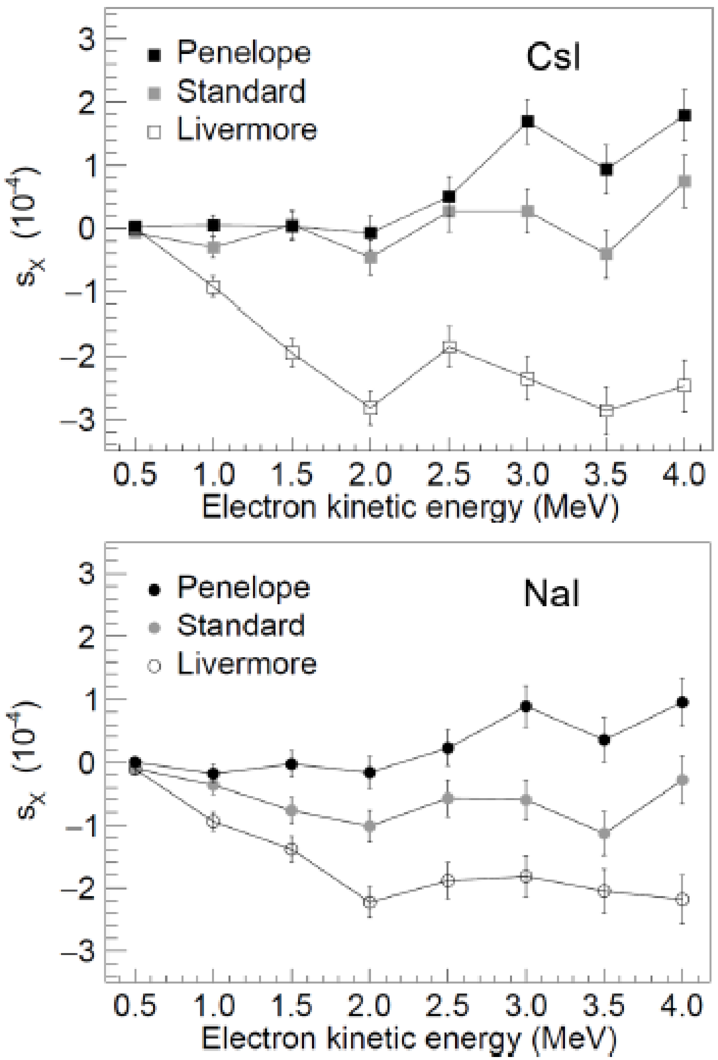


Figure 8: Relative absorption fraction in CsI (upper pannel) and NaI (lower pannel) as a function of the initial electron energy obtained with the Penelope (black markers), Standard (gray markers) and Livermore (open markers). The fractions were normalized relative to those obtained with Option4.

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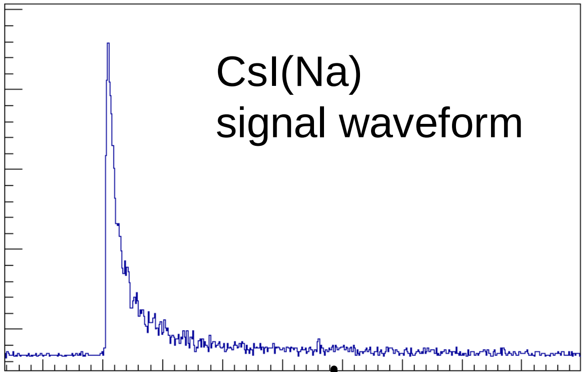
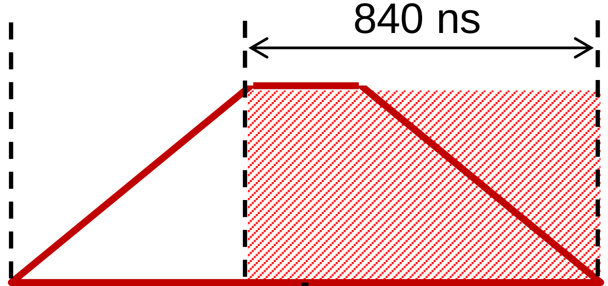
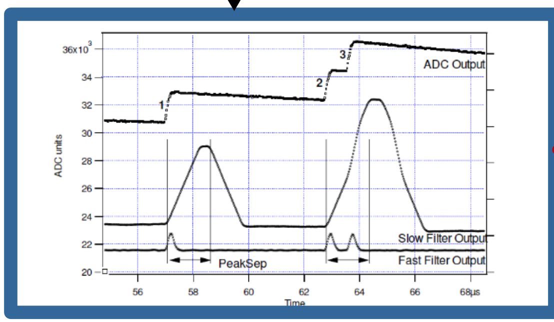
Pile-up: response of digitizer



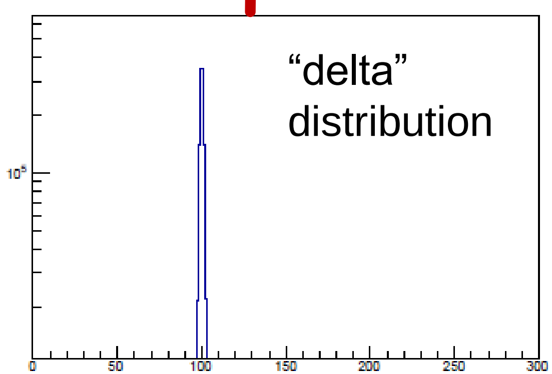
External parameters
(Trapezoidal filter)



RATE

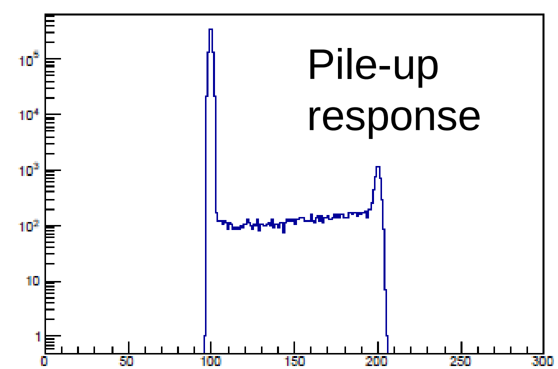


Digitizer

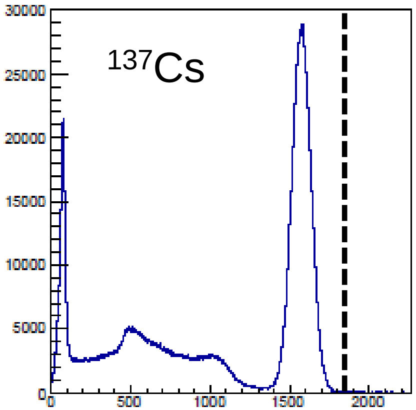


For the ^{6}He run, we didn’t record traces. Need to determine pile-up response from measured distributions.

10 kcps



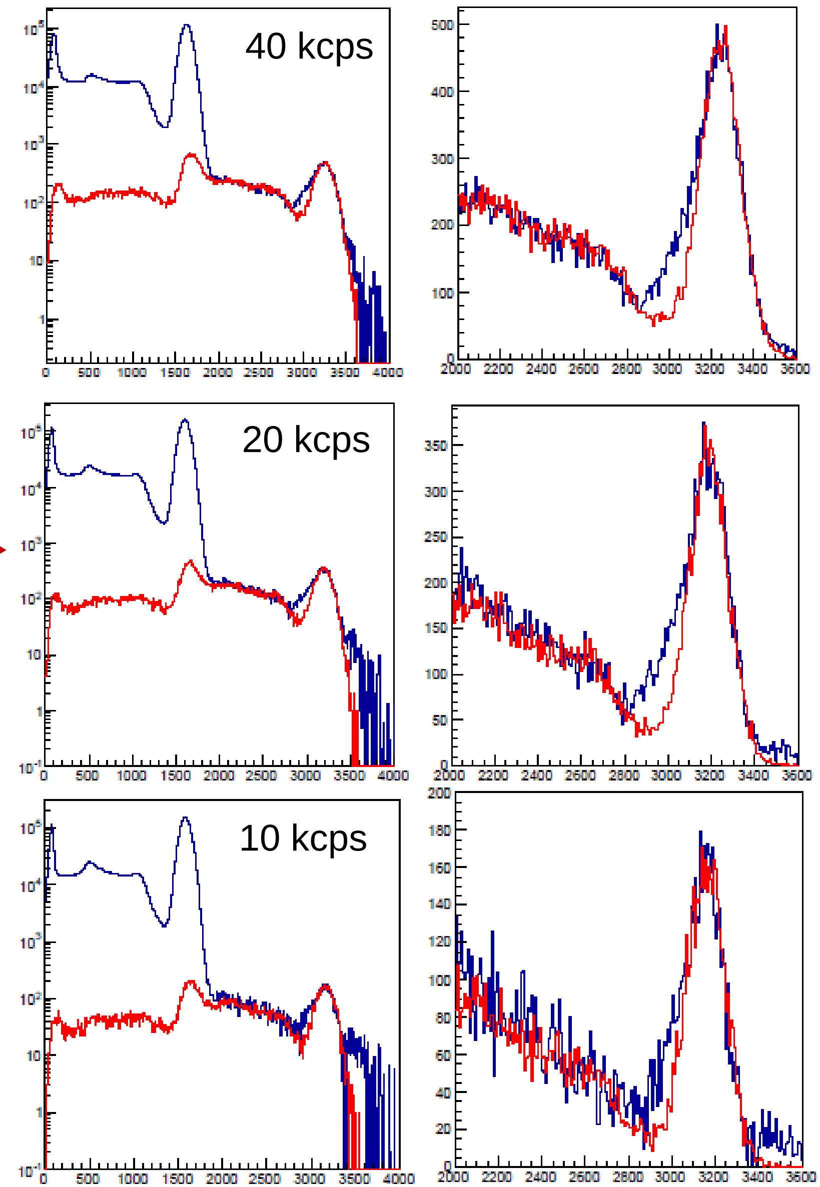
Pile-up: benchmark response of digitizer



Measured distribution

Digitizer simulation

- Experiment
- Pile-up calculation



NO FIT !

(Does not include pile-ups beyond the trapezoidal time window)

Beam purity and measuring sequence

Beam energy measured with implantation detector
(operating detector at low gain)