High Sensitivity Experiments Beyond the Standard Model

Quy Nhon, Vietnam, July 31 – August 7, 2016

Measurements of β energy spectra in nuclear β decay

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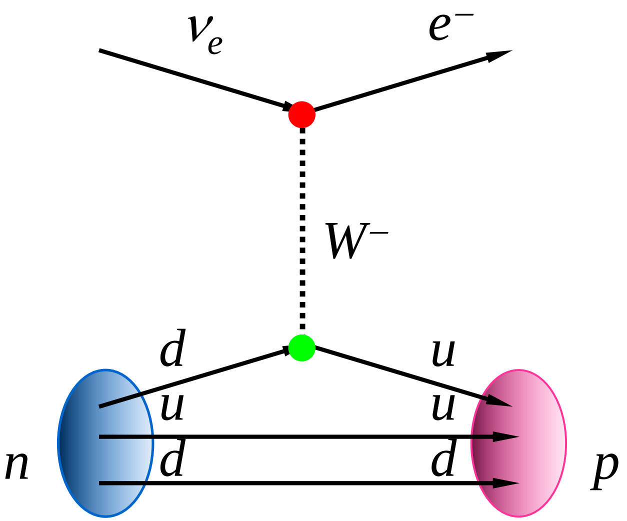
Outline

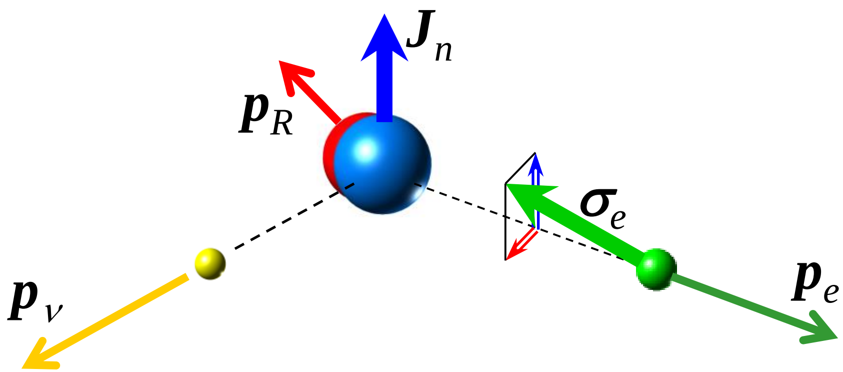
1. Motivation and goals
2. Selection of sensitive candidates
3. Previous experiments and new technique
4. Measurement of ^{6}He decay
5. Data analysis and systematic effects
6. Measurement of ^{20}F decay
7. Summary

Nuclear beta decay



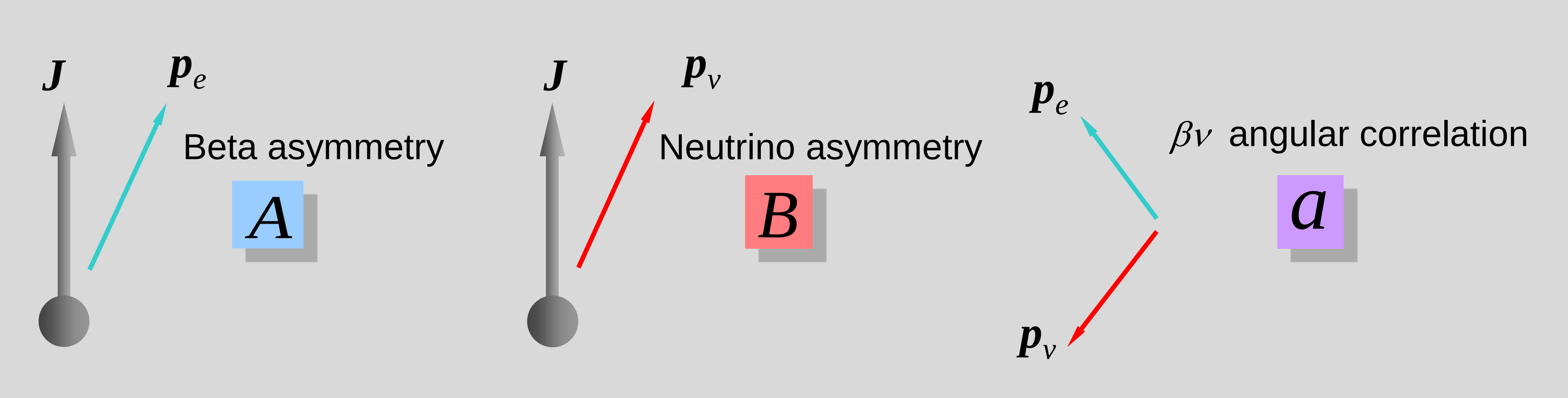
- What we think to occur at the quark-lepton level: *Vector boson exchange with maximal parity violation*.

- Is this all? Are there other bosons? (masses, couplings)

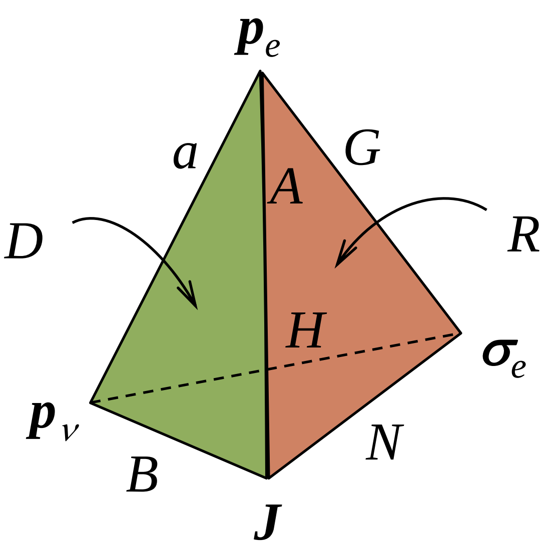


- What we have access to experimentally

Correlations in beta decay



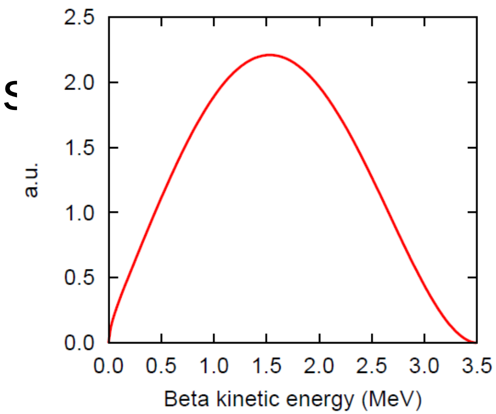
ONC, M. Gonzalez-Alonso,
Ann. Phys. (Berlin) **525** (2013) 600



- Observables *A, B, a, b*…are so-called correlation coefficients (Jackson-Treiman-Wyld " notation).
- They contain the dynamics of the process.

- *A, B,* neutron decay: talk by Takeyasu Ito
- *a, A,* (North America): talk by Dan Melconian
- *a, A,* in ^{35}Ar: talk by Philippe Velten
- *a, D* at GANIL: talk by Pierre Delahaye

The Fierz term, b



• Integrate decay rate over all spins variables and directions

$$N(W) \approx pW(W_0 - W)^2\left(1 + \frac{m}{W}b\right)$$

Expected to affect the spectrum shape

• The Fierz term was first addressed in the 1940-60's to determine the nature of the weak interaction. But it failed: an example of conspiracy in Nature:

$$b_F \propto (C_S C_V + C_S' C_V') \qquad b_{GT} \propto (C_T C_A + C_T' C_A')$$

• *b* is one of the few parameters in beta decay which is linear in the couplings. It provides the tightest constraints on "exotic" couplings involving left-handed neutrinos.

Phenomenology of semi-leptonic processes

Effective Field Theory approach

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

Low energy/high energy connection

Assuming that the energy scale of new physics (NP) appears at significantly larger energies than those accessible at the LHC, the EFT approach enables to compare constraints from low energy and high energy experiments

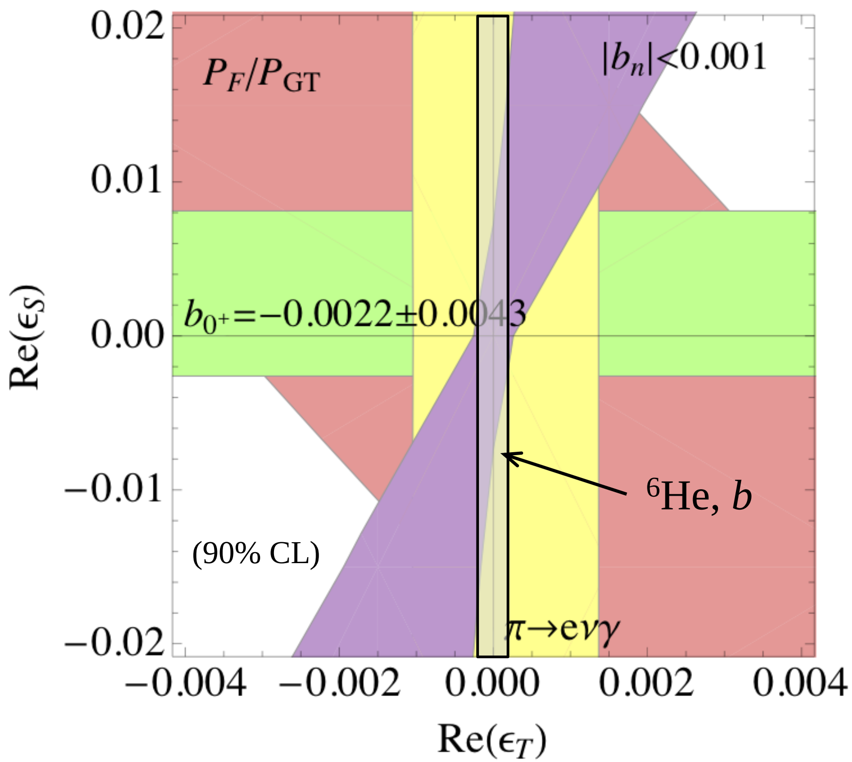
$$C_S = g_S \varepsilon_S$$
$$C_T = g_T \varepsilon_T$$

The g's are calculated within QCD and are known to ~10% accuracy

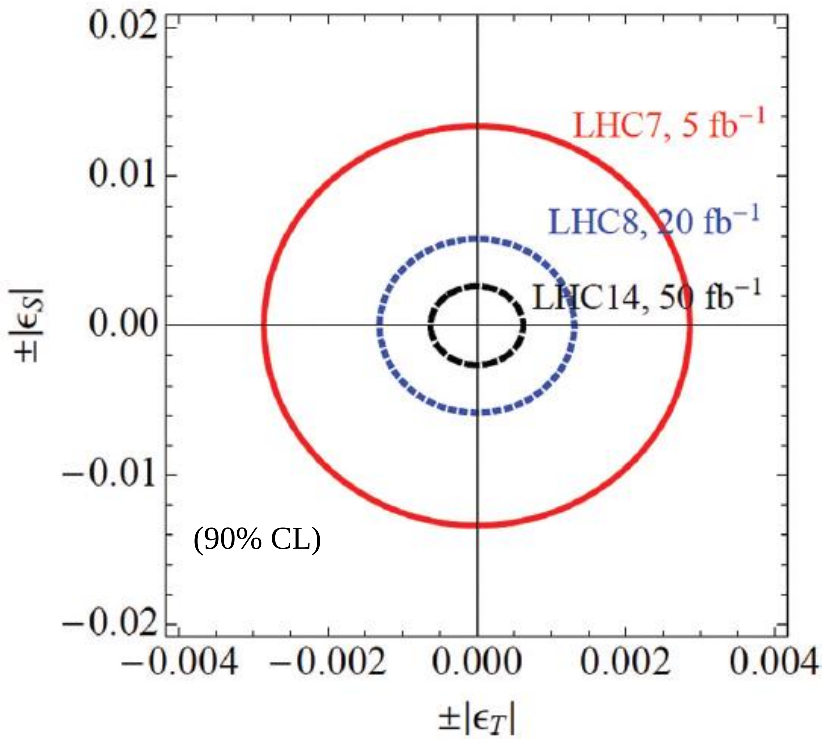
$$\frac{1}{M_{NP}^2 + q^2} \rightarrow \frac{1}{M_{NP}^2}$$

Connection with high energy

ONC and M. Gonzalez-Alonso,
Ann. Phys. (Berlin) **525** (2013) 600



channel: $pp \to e\,\nu + X$



- Further progress requires precisions $\Delta b < 10^{-3}$
- We focus here on Gamow-Teller transitions.

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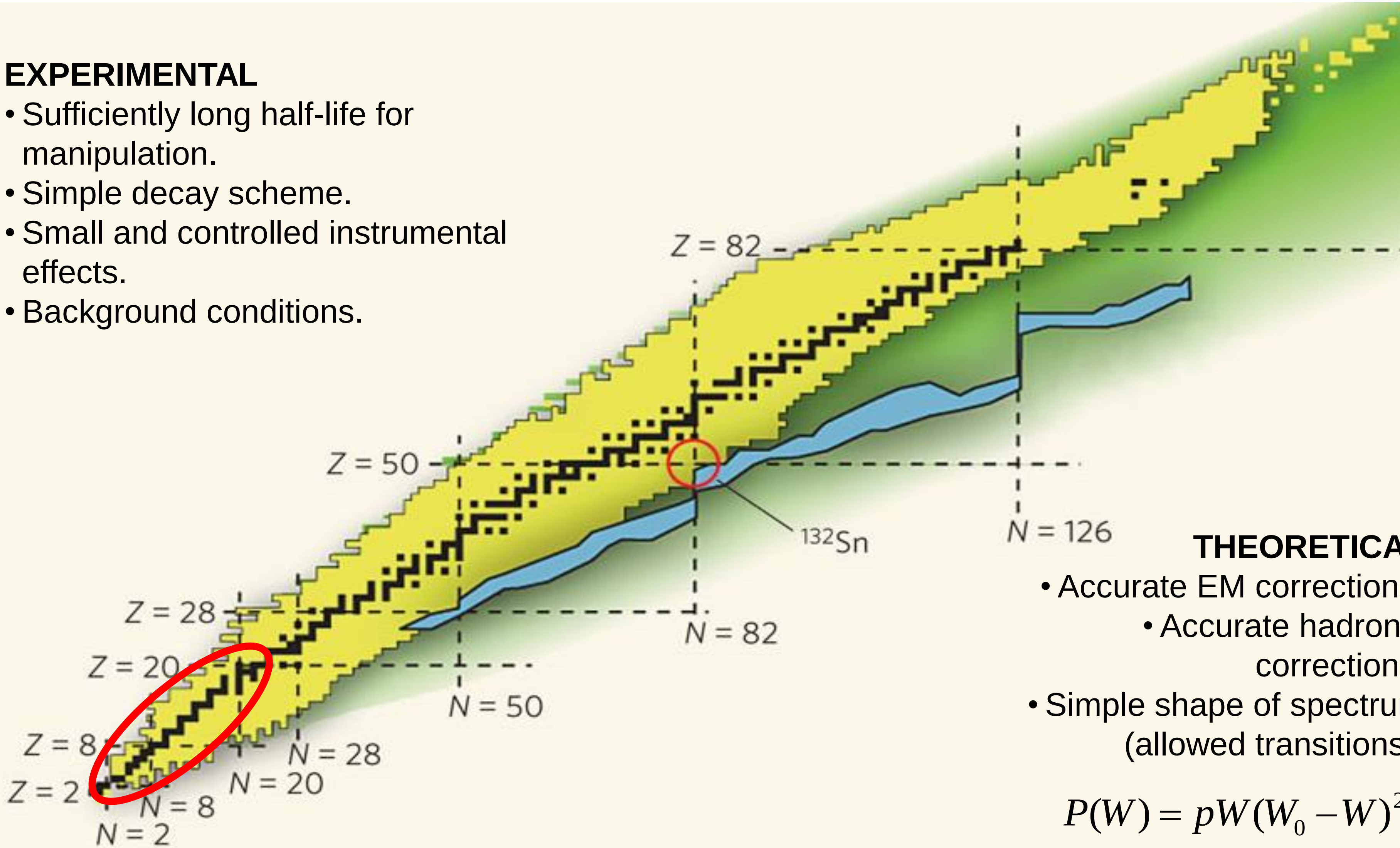
Which nucleus is convenient?

EXPERIMENTAL

- Sufficiently long half-life for manipulation.
- Simple decay scheme.
- Small and controlled instrumental effects.
- Background conditions.



THEORETICAL

- Accurate EM corrections.
- Accurate hadronic corrections.
- Simple shape of spectrum (allowed transitions).

$$P(W) = pW(W_0 - W)^2$$

Selection criteria ("theoretical")

- The Fierz term, ***b***, affects the shape of the β energy spectrum.
- Look at corrections to the spectrum.

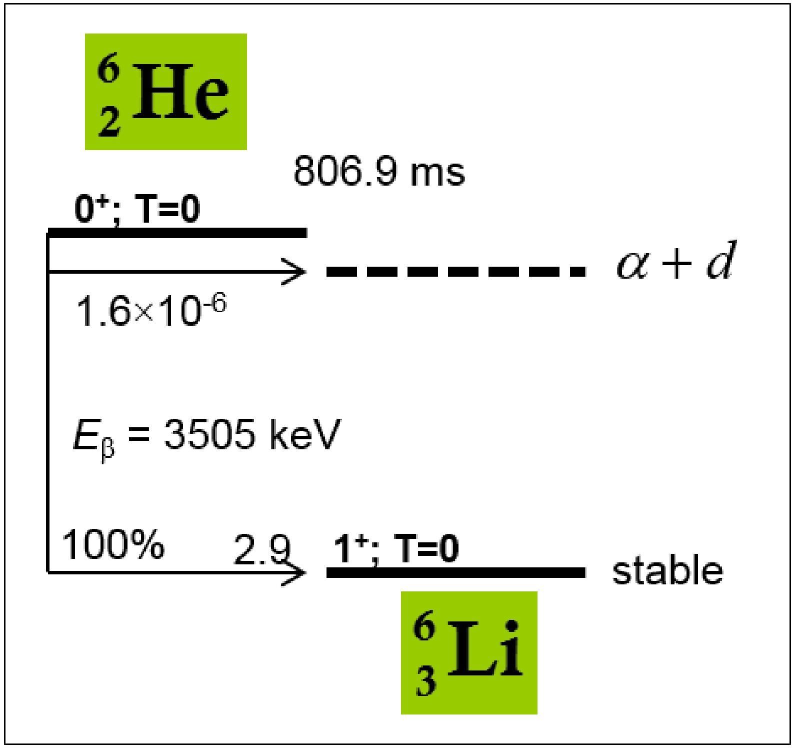
$$N(W) = P(W)Q(W)\left(1 + b\frac{m}{W}\right)S(W)$$

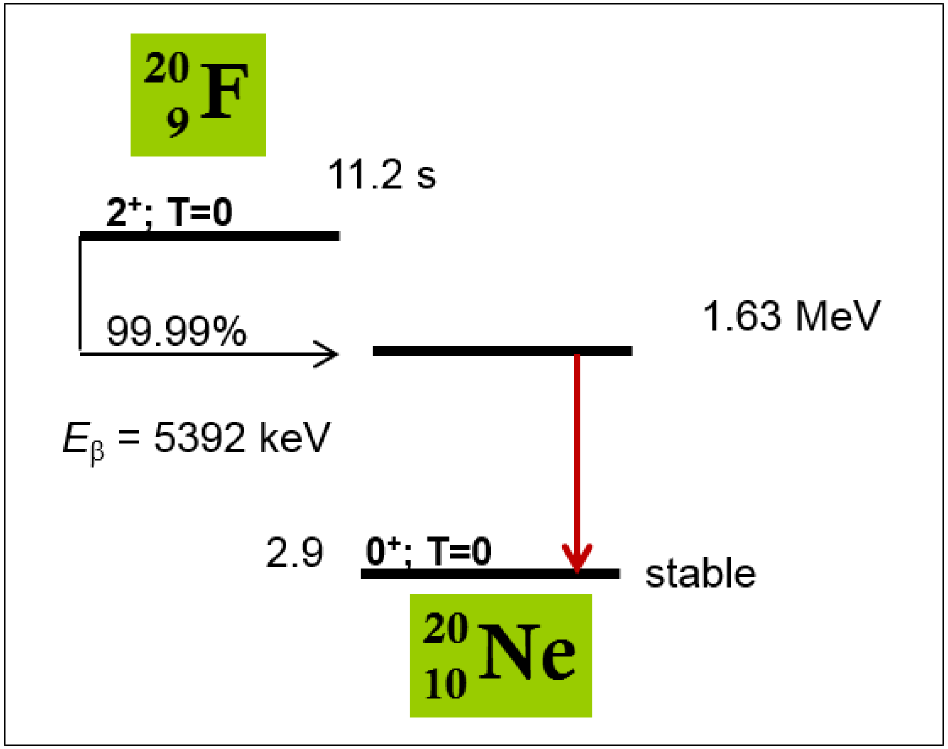
1. What is the optimal kinematic sensitivity (m/W)? 1-3 MeV endpoint energy.

2. Accurately known Coulomb and radiative corrections (EM): low Z and large kinetic energy.

3. Accurately known shape factor; contains hadronic contributions (SM background): application of CVC.

and the winners are…





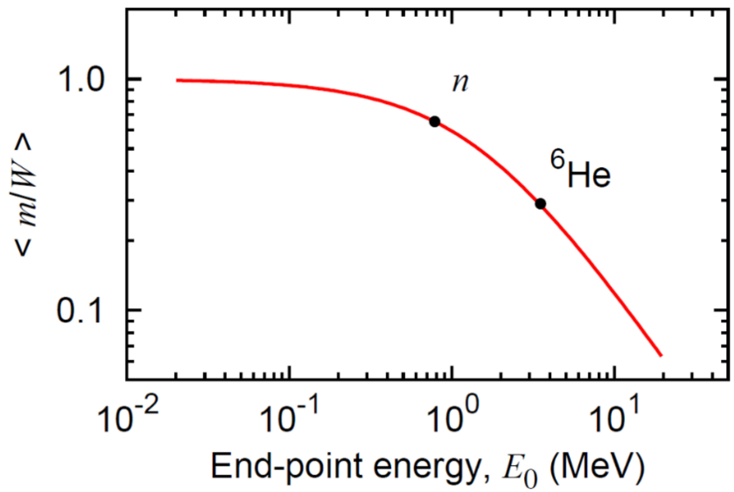
…for allowed Gamow-Teller transitions

(1) Kinematic sensitivity (1/2)

$$N(W) = P(W)Q(W)\left(1 + b\frac{m}{W}\right)S(W)$$

The integration of the differential decay rate, normalized by the integral of the corrected phase space, gives

$$N_0 = 1 + b\langle\frac{m}{W}\rangle$$



It is sometimes naively believed that: *"the lower the energy, the larger the sensitivity to b",* for all observables in beta decay.

This is simply wrong!

This property has been used to constraint scalar couplings from *Ft* values in superallowed Fermi transitions.

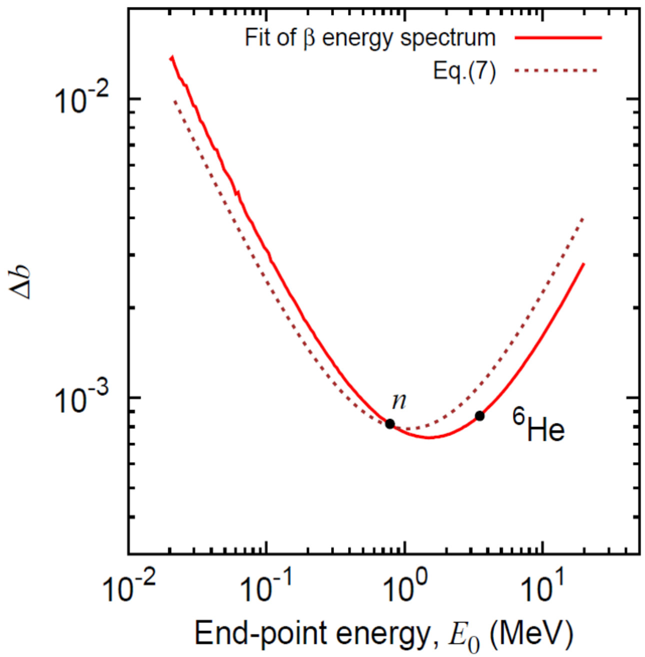
(1) Kinematic sensitivity (2/2)

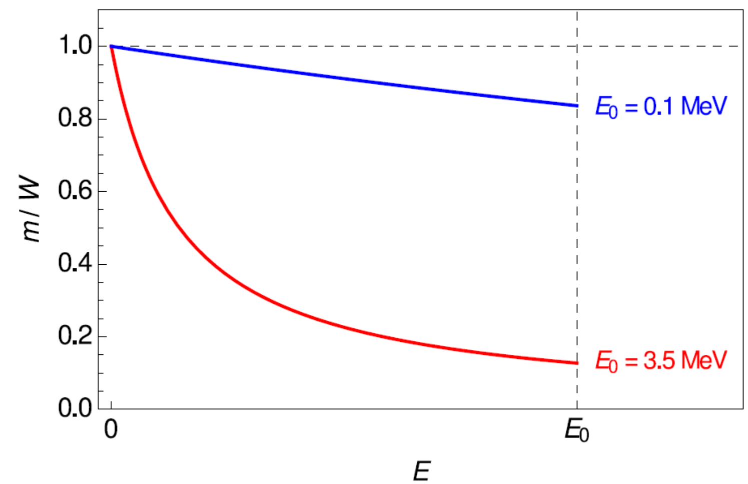
$$N(W) = P(W)Q(W)\left(1 + b\frac{m}{W}\right)S(W)$$

For differential observables (shapes of spectra), the monotonic increase of sensitivity towards lower energy **does not hold!!!**

M. Gonzalez-Alonso and ONC
Submitted to PRC
arXiv-1607.08347

$$N(W) = P(W)\left(1 + \frac{m}{W}b\right)$$





It doesn't help to go to lower energies!

Optimal sensitivity: 1-3 MeV endpoint.

MC simulations of allowed spectra with 10^8 events.
Fit from 5 to 95% of energy range to extract *b* and overall normalization.

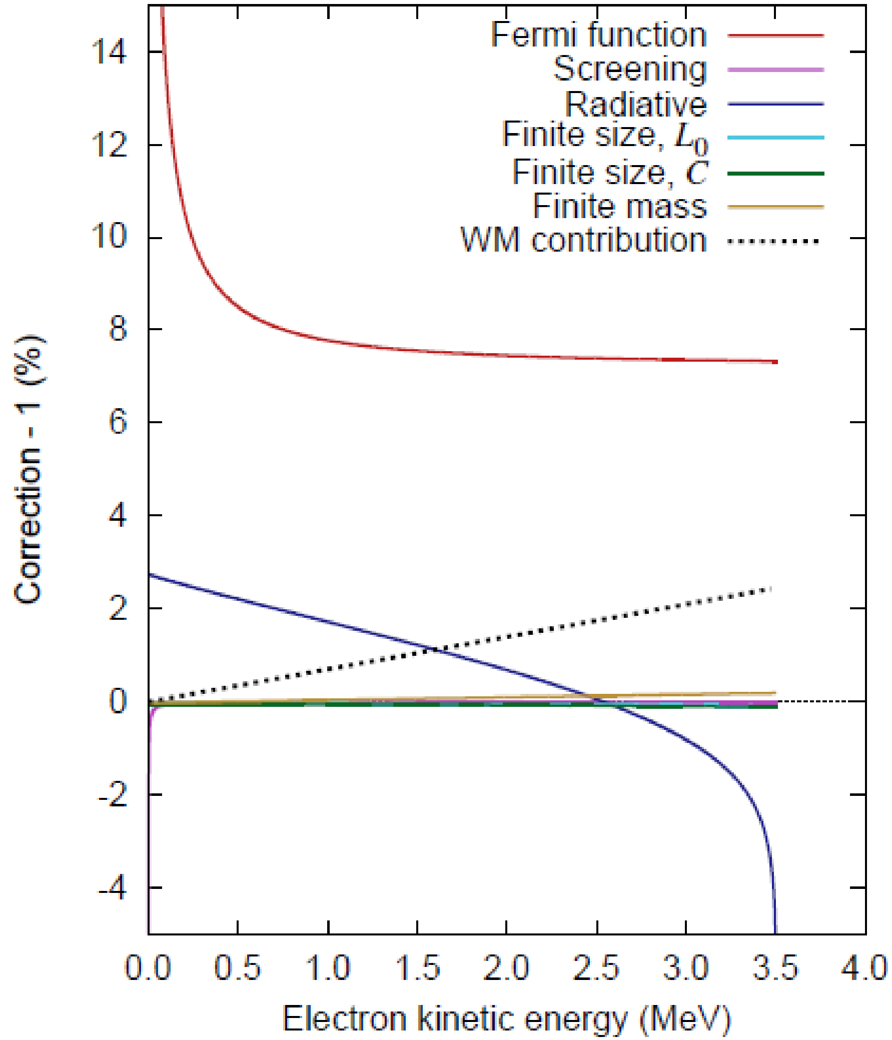
(2) Coulomb and radiative corrections: ^{6}He

Talk by Leendert Hayen

$$N(W) = P(W)Q(W)\left(1+b\frac{m}{W}\right)S(W) \qquad Q(W) \propto F(Z,W)\cdot L_0 \cdot C \cdot S \cdot R \cdot M$$

- D.H. Wilkinson, NIMA, 335 (1993) 182
- D.H. Wilkinson, NIMA 335 (1993) 201

- In ^{6}He decay the EM corrections are dominated by the Fermi function and by radiative corrections (accurately known).
- Screening and other EM corrections are small for nuclei with low Z and transition with moderately high β energy.



X. Huyan et al.,
In preparation

(3) Hadronic corrections

$$N(W)=P(W)Q(W)\left(1+b\frac{m}{W}\right)S(W)$$

$$S(W)=\left(1+C_0+C_1W+C_{-1}/W\right)$$

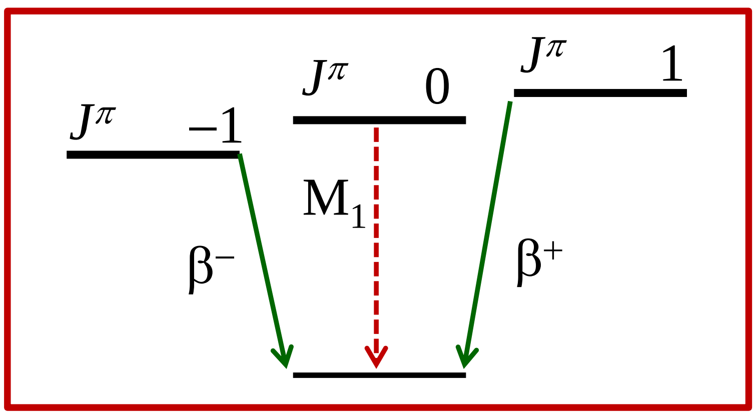
Shape factor: accounts for *"recoil order effects"* in the hadronic weak currents

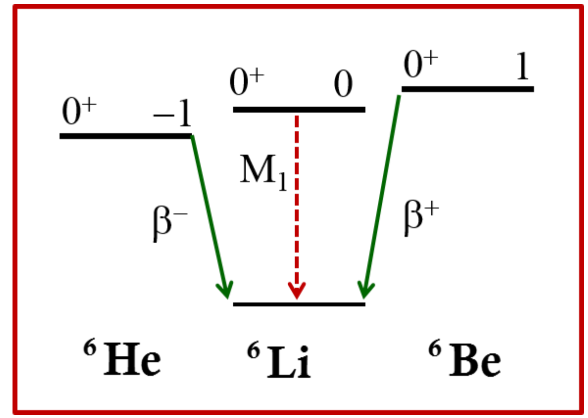
- In GT transitions, the dominant recoil effect is due to the *weak magnetism form factor*.

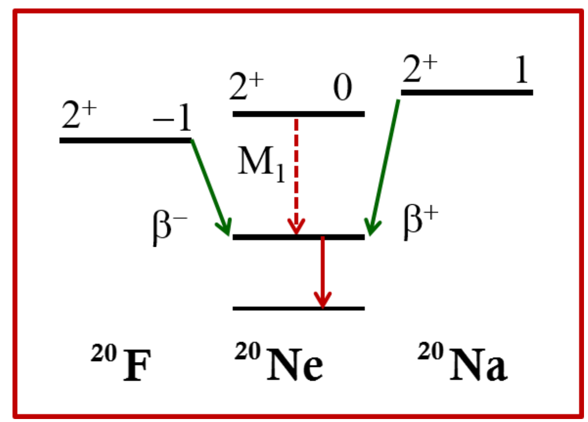
- CVC relates transitions within an isospin multiplet
- The weak magnetism form factor is

$$b_{WM}=\left(\frac{6\Gamma_{M1}M^2}{\alpha E_\gamma^3}\right)^{1/2}$$

M mass of recoil







Weak magnetism contribution in ^{6}He decay

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

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

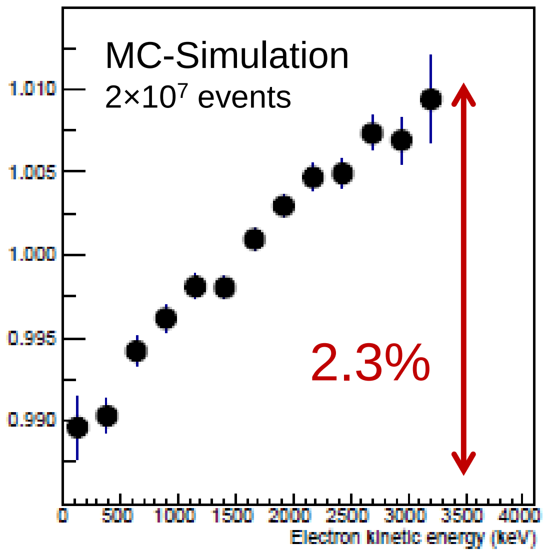
$$c = g_A \left|M_{GT}\right|$$ GT matrix element

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

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

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

Effect on the ^{6}He spectrum shape



- Any sensitive search for NP through a measurement of the spectrum shape should first see the effect of weak magnetism.
- The WM form factor has never been measured in ^{6}He decay.
- ***This is our first goal.***

For the remaining of the presentation, keep in mind that the dominant term is C_1 and a typical value is 1 %/MeV.

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Previous work: spectrum shape measurements

The only dedicated publication

The Beta-Spectrum of He^6†

C. S. Wu, B. M. Rustad, V. Perez-Mendez, and L. Lidofsky
Columbia University, New York, New York
(Received August 5, 1952)

Magnetic spectrometer; Extract end-point energy.

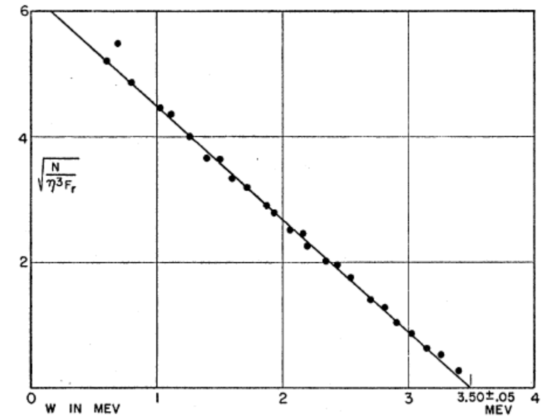
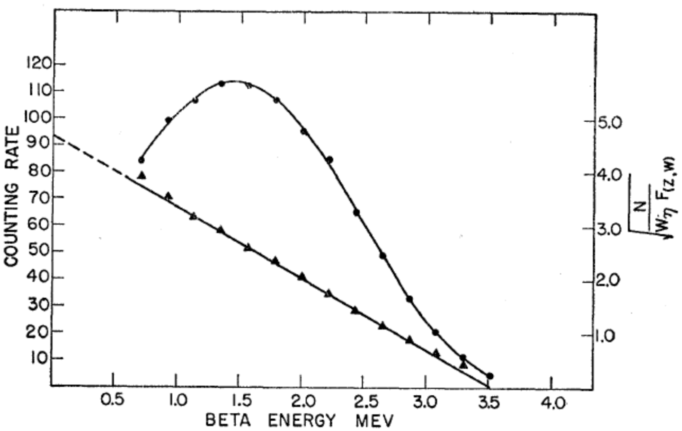


FIG. 2. Kurie plot of He^6 beta-spectrum.



B.M. Rustad and S.L. Ruby, PR **97** (1955) 991

Plastic scintillator; Control spectrum for β-recoil coincidence measurement; Concluded that weak interaction is dominated by Tensor!

A. Schwarzschild, PhD thesis, Univ. Columbia, New York, 1957; Unpublished; Cited in several articles and books; Impossible to find today at UC, BNL and in theses data bases.

Magnetic spectrometer

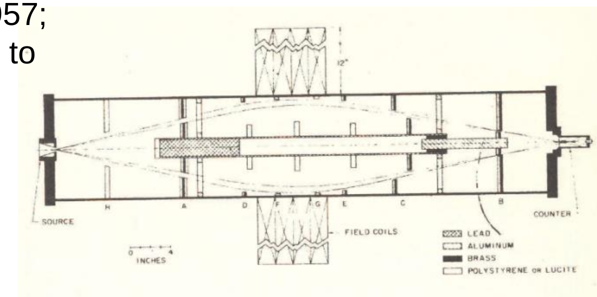
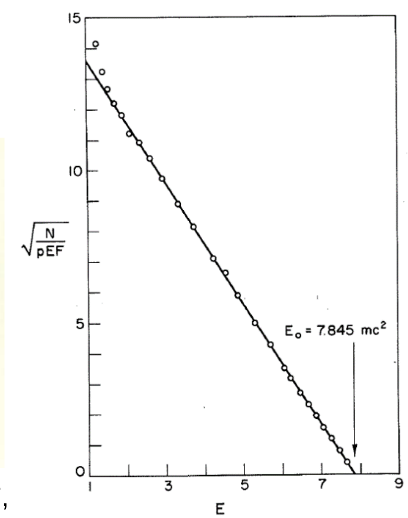


Fig. 6. Thin lens spectrometer



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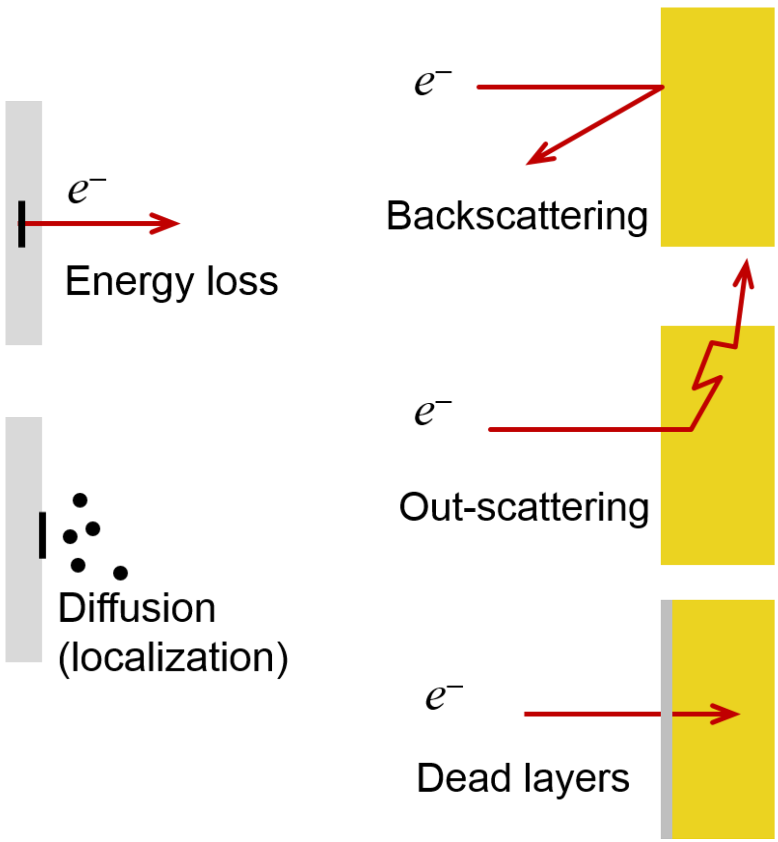
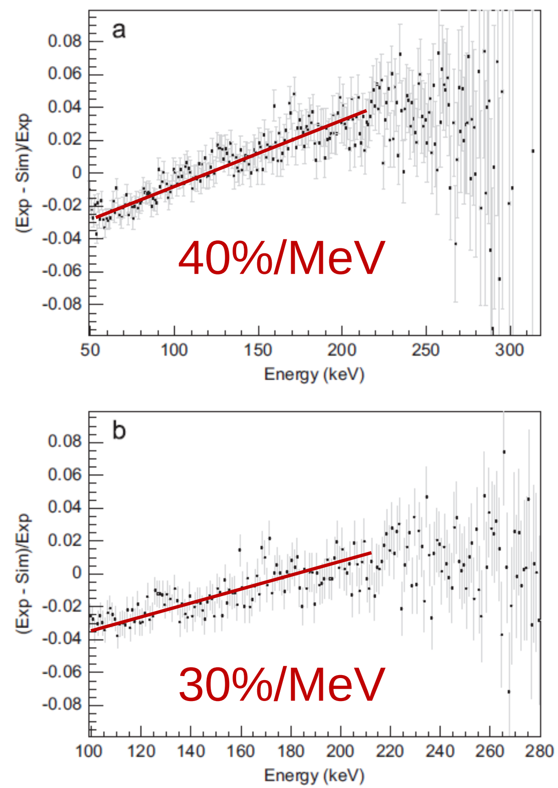
Instrumental effects in β energy measurements

Source | Detector



G. Soti et al., NIMA **728** (2013) 11 (K.U. Leuven)

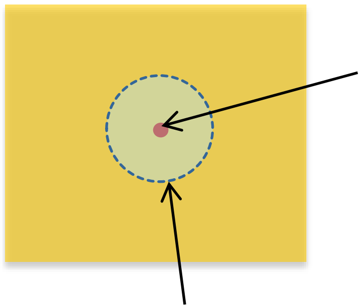
Comparison between G4 and dedicated measurements using ^{60}Co source



Current tools do not appear to be sufficiently accurate for precision measurements using sources located outside standard detectors. New techniques need to be explored.

Considering a new technique

1. Choose your favorite isotope (see the selected "winners")



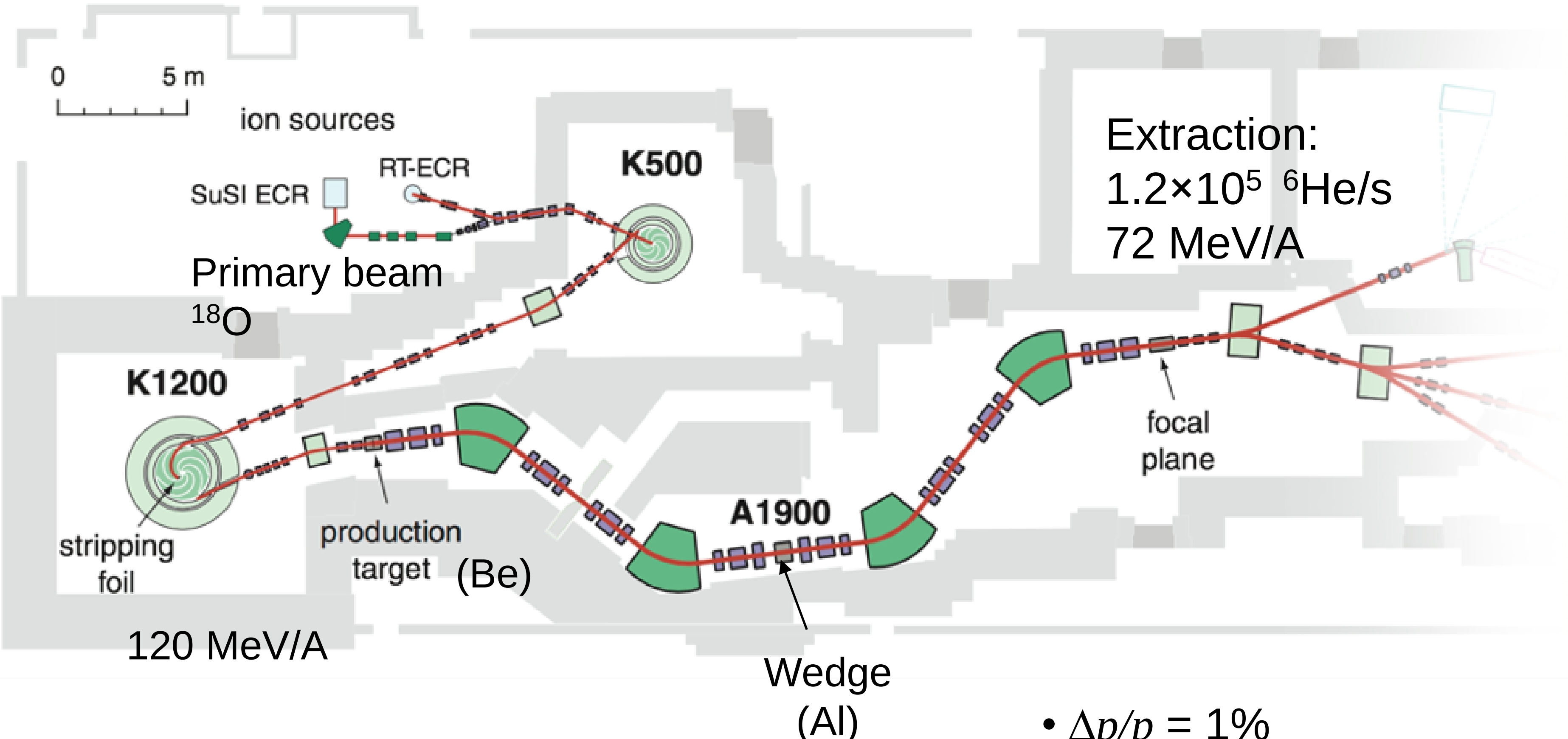
2. Put them deep enough in a single active detector

3. Measure the energy of beta particles and make sure they don't escape

- Well localized source.
- 4π solid angle and 100% detection efficiency.
- No backscattering, no out-scattering, no dead-layers.

Outline

NSCL Coupled Cyclotron Facility



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

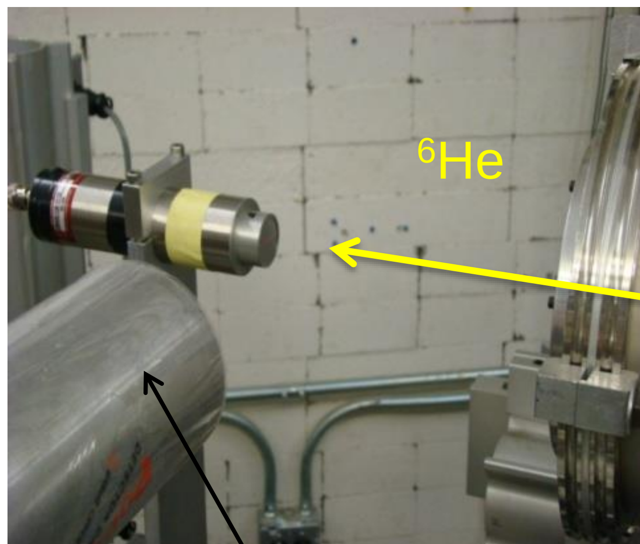
Experimental setup: "apparatus"

Al degrader

CsI(Na) or
NaI(Tl)

- Implant ^{6}He ions in detectors deep enough (12 mm) so that β particles do not escape
- Range of 3.5 MeV e^- in CsI is 6 mm.
- Requires 40-50 MeV/A ions

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

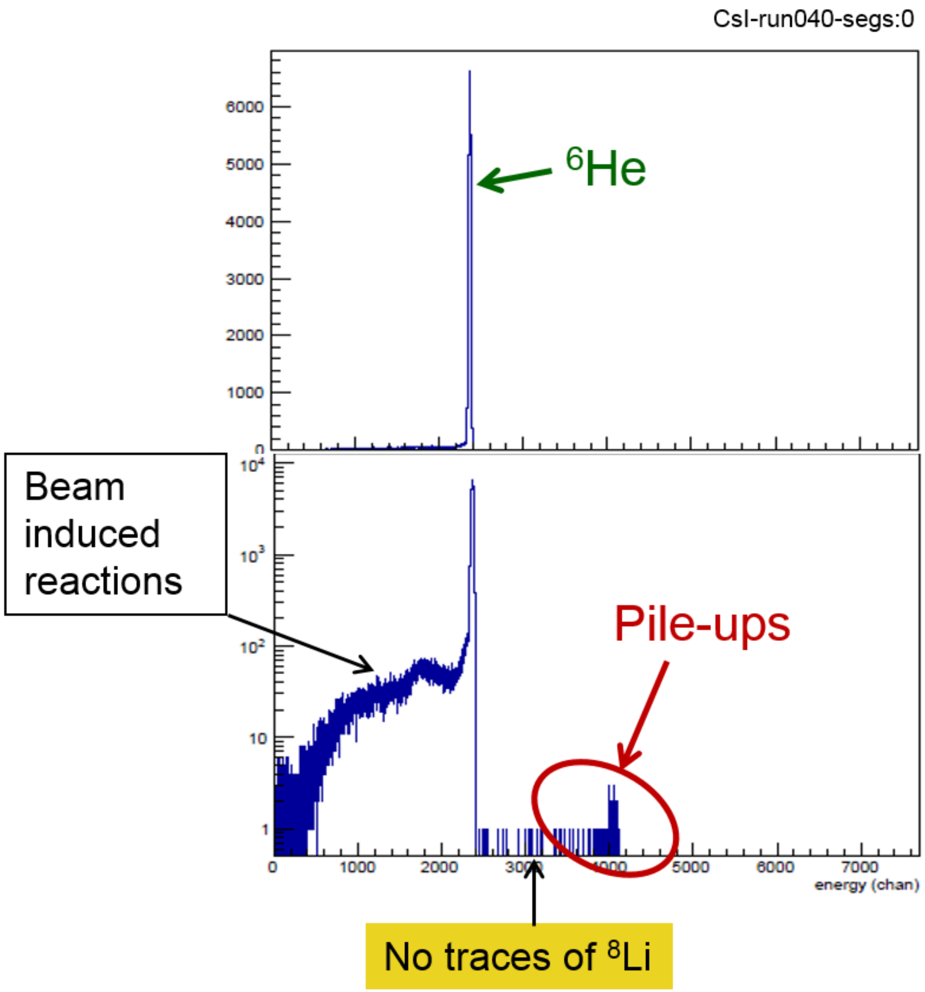


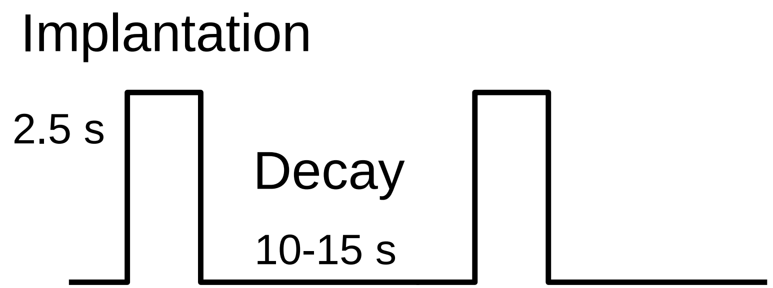
- 46 MeV/nucleon after degrader

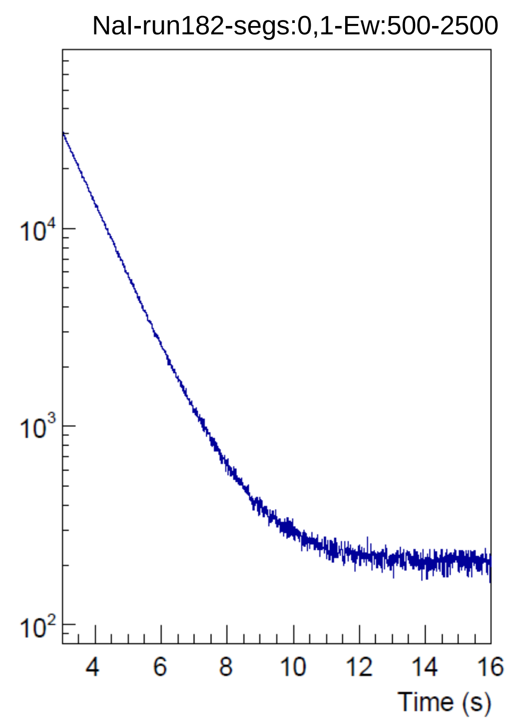
γ detectors for background identification

Beam purity and measuring sequence

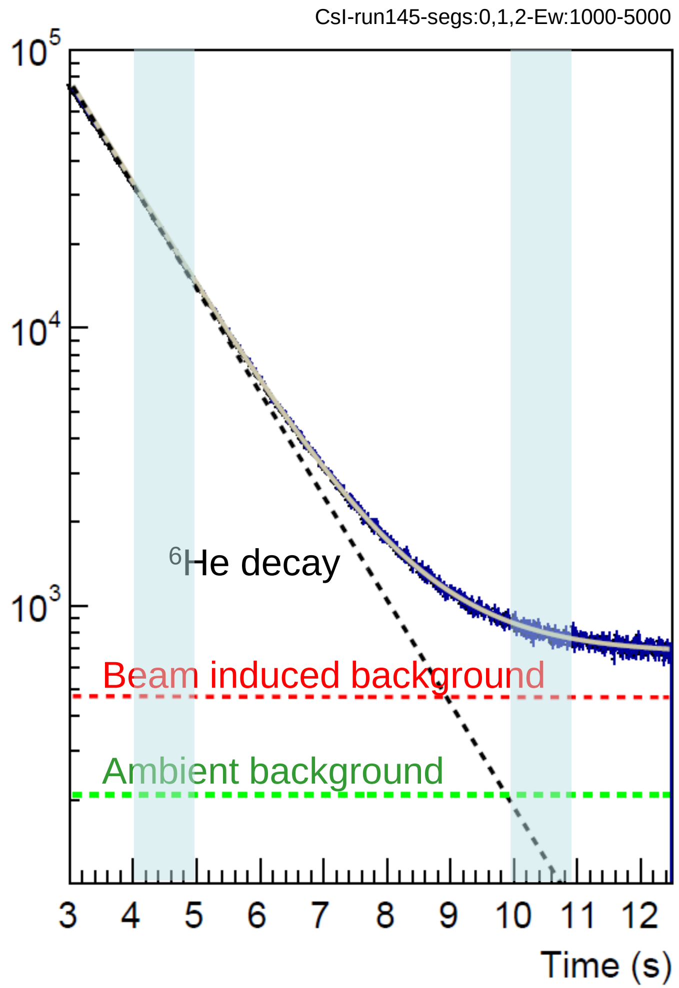
Beam energy measured with implantation detector
(operating detector at low gain)



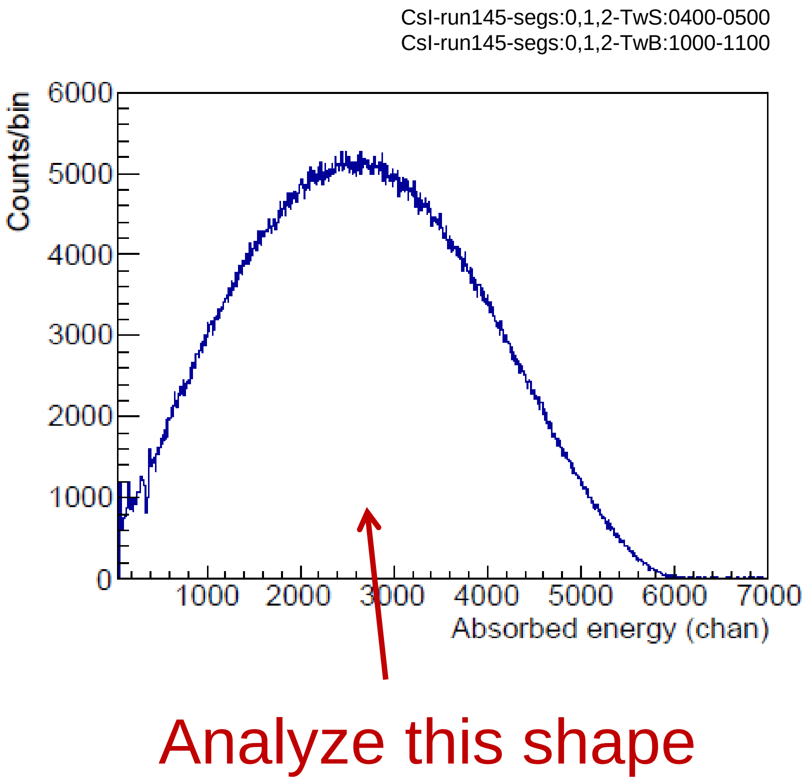




Background



No traces of “short lived” beam induced background



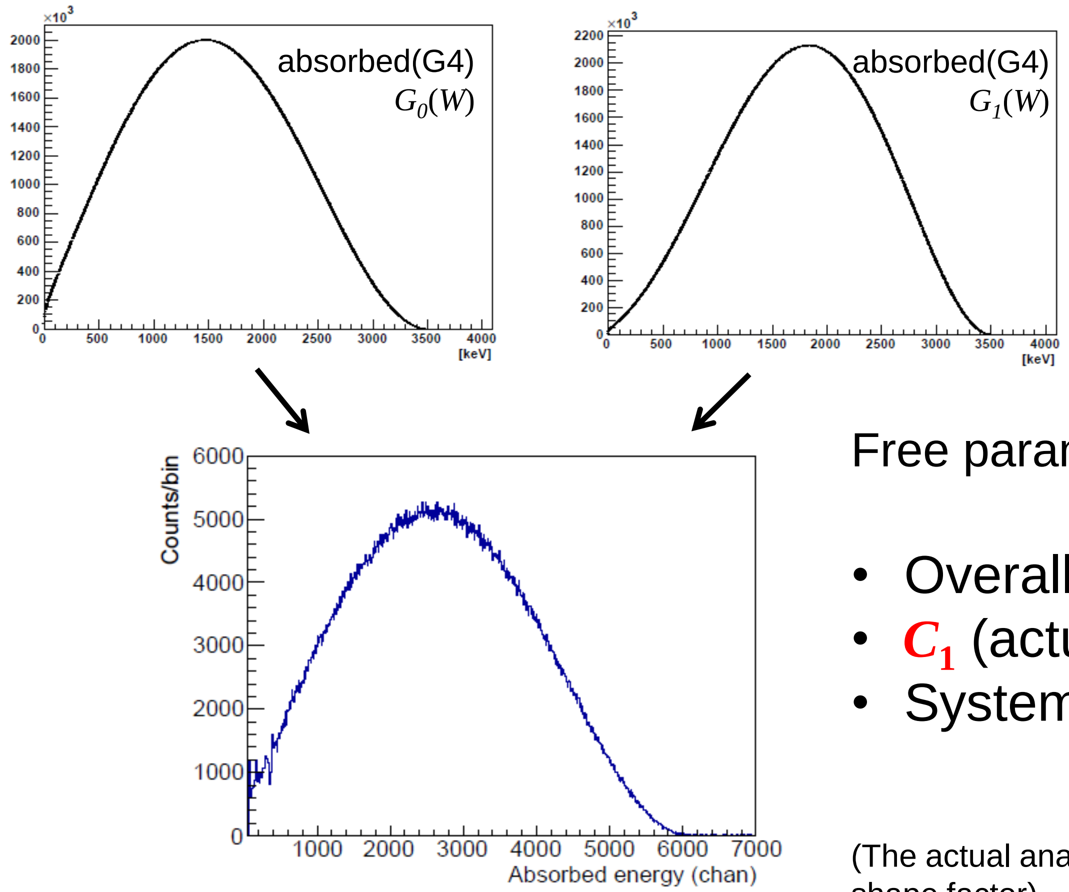
- Define 6-7 slices between 3 and 5 s, with about 10^6 events in each spectrum.
- We collected typically 10^7 events in 1 h run.

Outline

Analysis procedure: Monte-Carlo fit

Fit a MC generated spectrum obtained with G4 and convoluted

$$N(W) \approx G(W)(1+C_1W) \otimes D(E) \;\rightarrow\; f_0(E) + C_1 f_1(E)$$



Free parameters

- Overall normalization
- C_1 (actually b_{WM})
- System gain ($Ch = AE+B$)

(The actual analysis includes all terms in the shape factor)

Instrumental and analysis effects

1. Detection system gain (“calibration”)
2. Detector response, convolution (γ sources)
3. “Fast” pile-up (digital DAQ)
4. Bremsstrahlung escape (Geant4)
5. Fitting range, histogram binning
6. Theoretical corrections to spectrum
7. After-glow pile-up (system gain)
8. Detection system linearity (fit model)

System gain – (calibration) (1/3)

- The energy/channel relationship is determined by the "gain" of the full detection chain (scintillator light emission, HV stability, electronics, etc…).
- We want to determine C_1 with a relative precision of 3-5%. What accuracy do we need in the calibration?

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

- We need an integrated calibration accurate at the ~10^{-4} level, due to phase space.

- We used γ sources, ^{22}Na, ^{60}Co, ^{137}Cs, and background lines to get a "zero-order" calibration. We observed no deviations from linearity within $\pm 3\times10^{-3}$.
- We scanned the detector volumes and see no deviations from homogeneity within ~1×10^{-3}

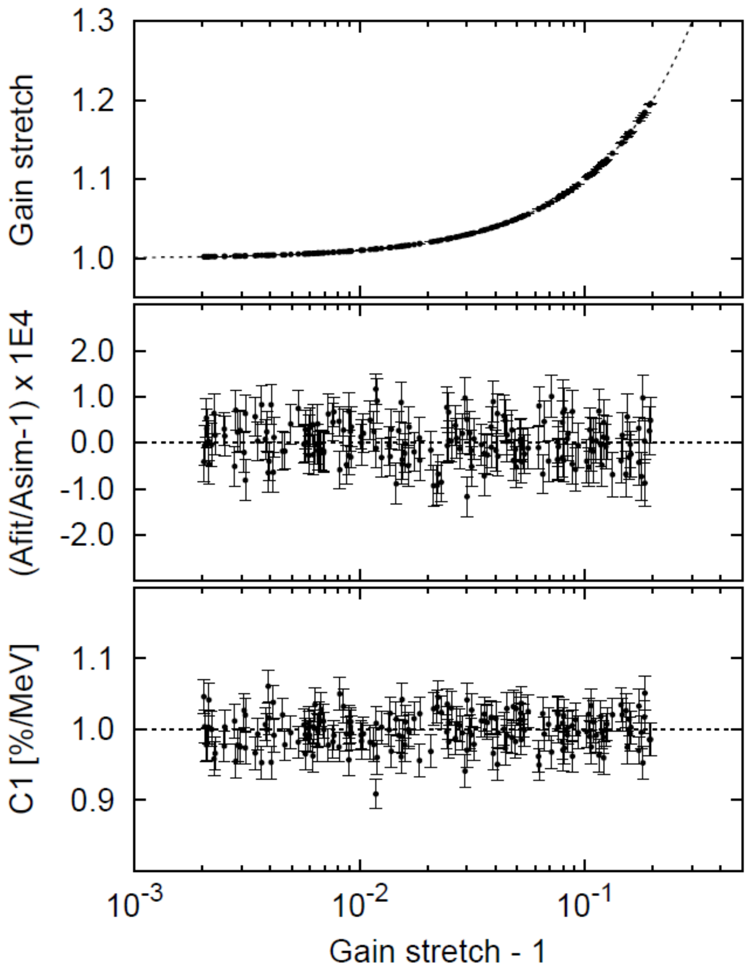
- Even if one could reach the required accuracy, such a procedure (external off-line calibration sources) is not appropriate because:

- "external" γ sources do not probe the crystal at the same location where the β particles are detected
- there are differences between e/γ responses
- drifts between calibrations
- possible beam induced changes in the detector
- after-glow pile-up (history of detector)

System gain – (calibration) (2/3)

- We want a calibration running simultaneously than the main run and with a e "source" probing the same volume where the β particles are detected.
- This is rather impossible without strongly disturbing the main measurement, so… we don't calibrate!
- The technique relies on the extraction of the system gain from the same measured spectra.
- What about the correlations with the physics?

MC simulations, 10^8 events per run
Assume C_1 = 1%/MeV and vary gain with offset fixed

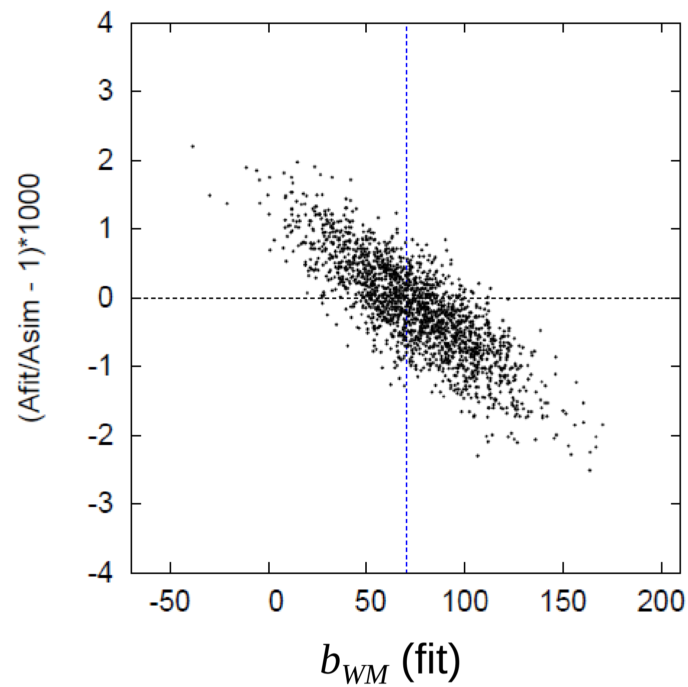


You get out from the fits what you put into the MC

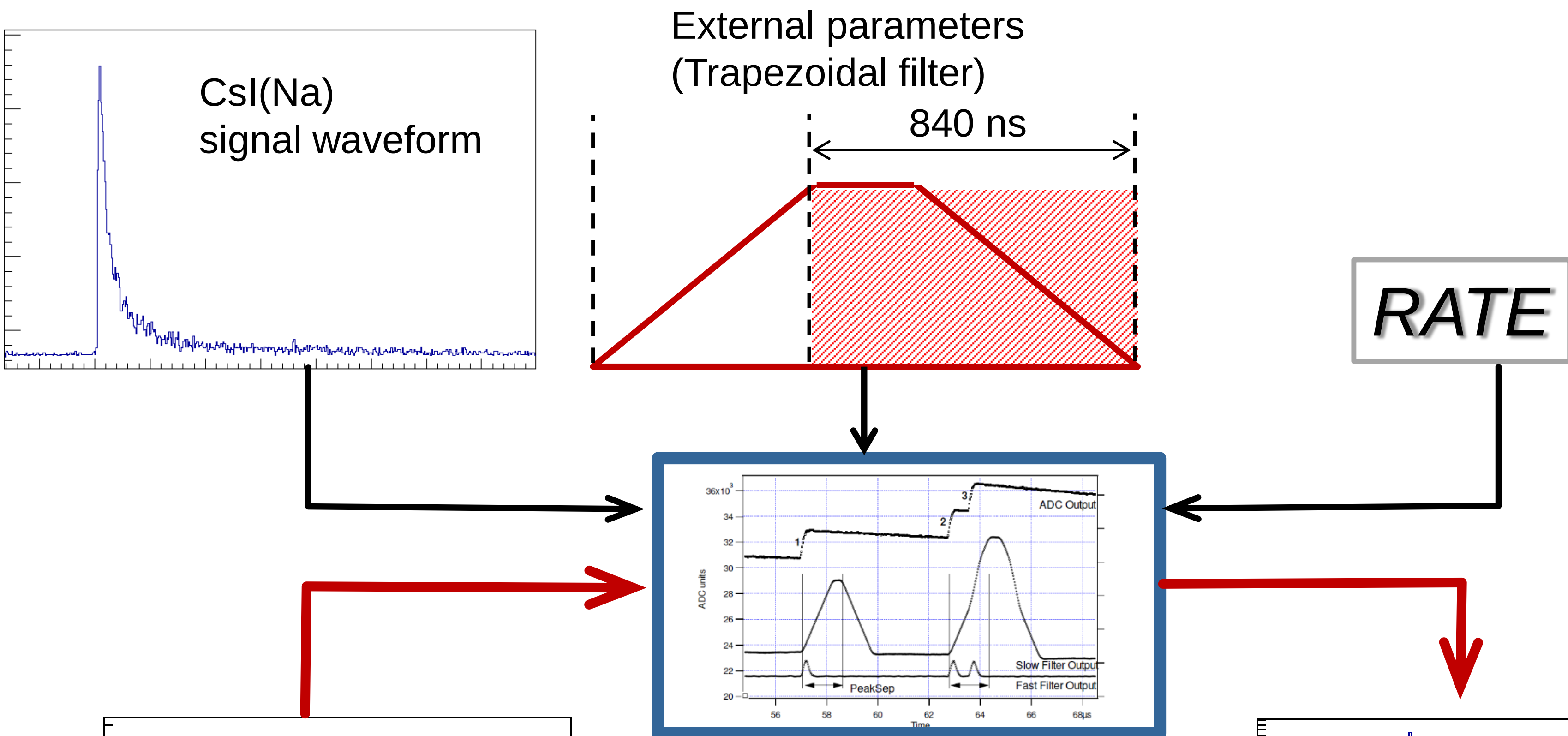
System gain – calibration (3/3)

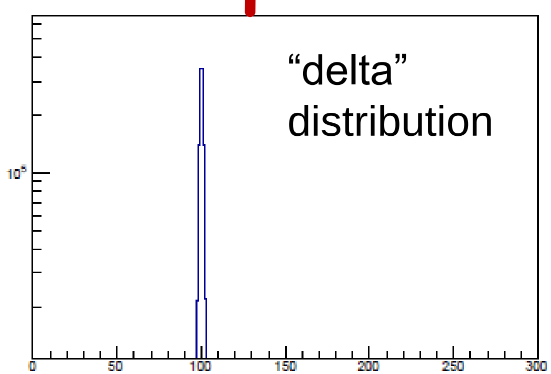
- There is NO correlation between the **actual value** of the system gain and the form factor.
- There is a correlation between the **systematic error** made in the determination of (whatever the value of) the system gain and the form factor.
- The relative statistical uncertainty on the gain obtained from the fit of a single spectrum with 10^6 events (just one time slice of a 1h run) is smaller than 10^{-3}. This is the size of the systematic error made on the gain when fitting data for one time slice.

MC simulations, 10^6 events per run
Assume b_{WM} = 71 and vary gain

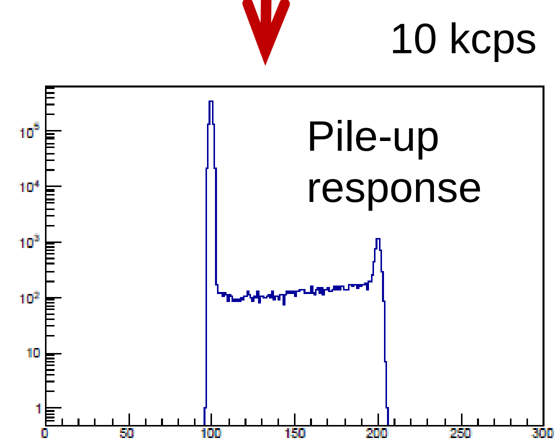


Pile-up (1/3): Determine response of digitizer



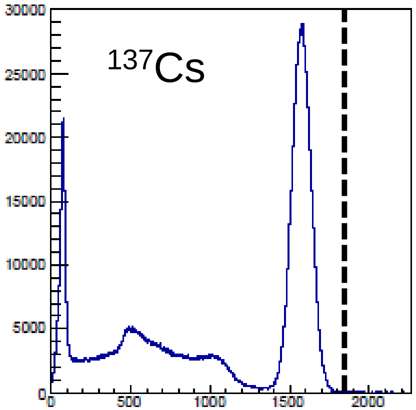


Digitizer



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

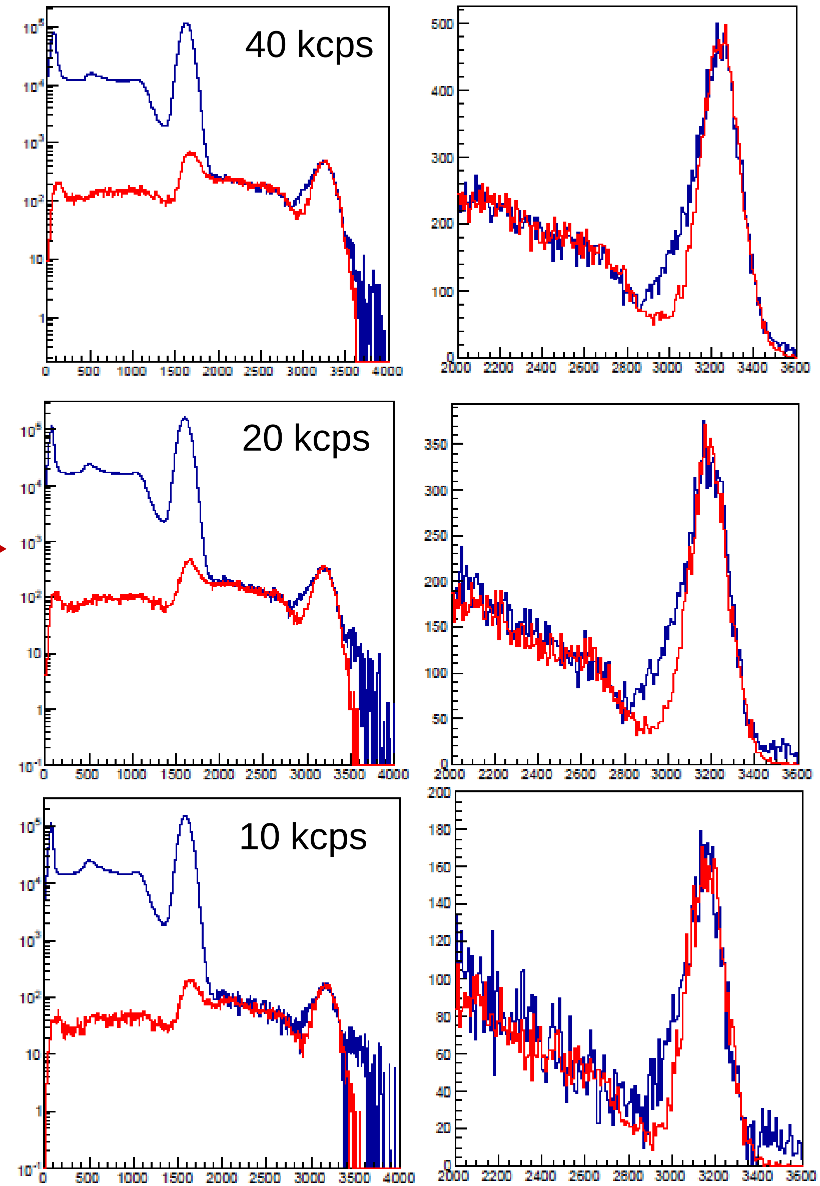
Pile-up (2/3): Benchmark response of digitizer



Measured distribution

Digitizer simulation

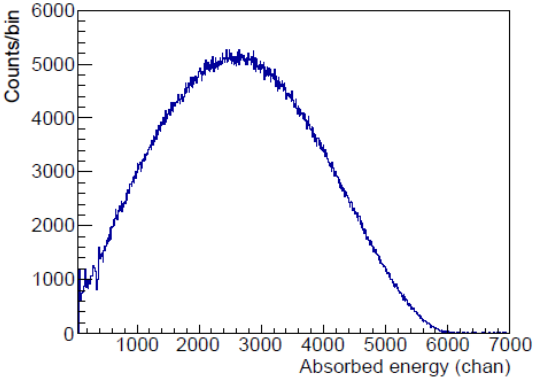
- Experiment
- Pile-up calculation



NO FIT !

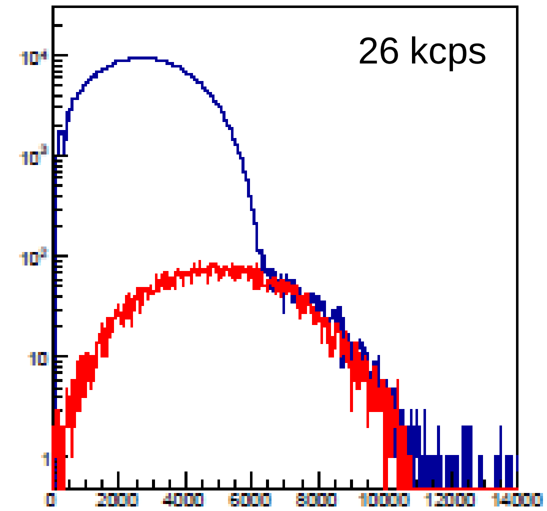
(Does not include pile-ups beyond the trapezoidal time window)

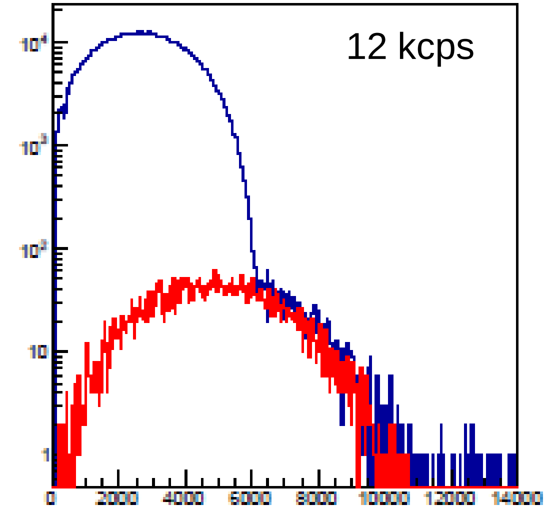
Pile-up (3/3): Apply to beta energy spectrum



Measured distribution

- Experiment
- Pile-up calculation

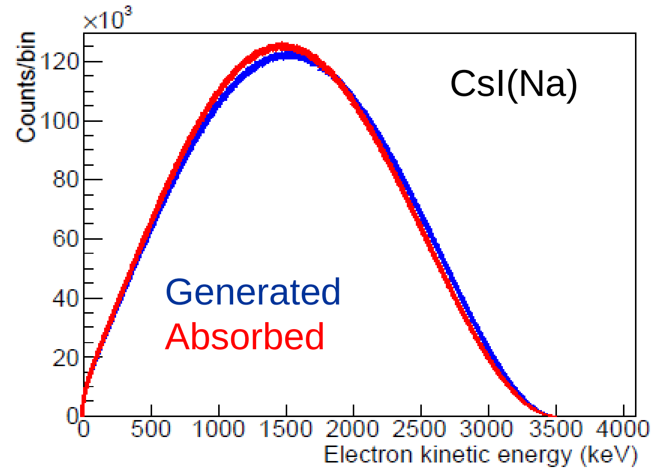


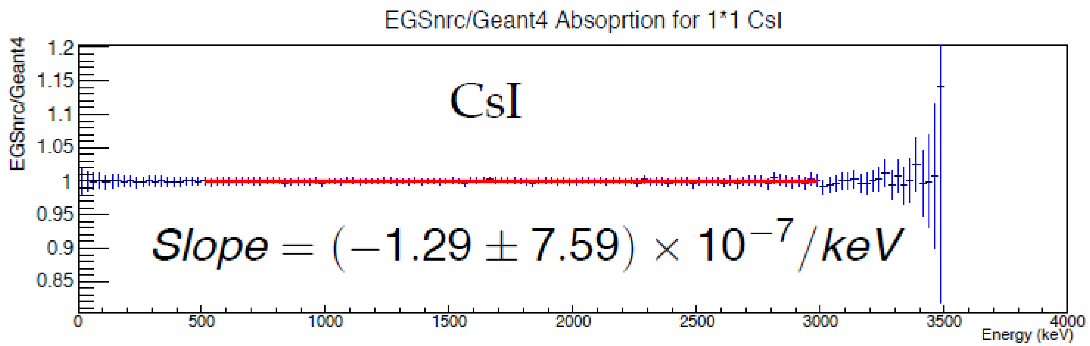


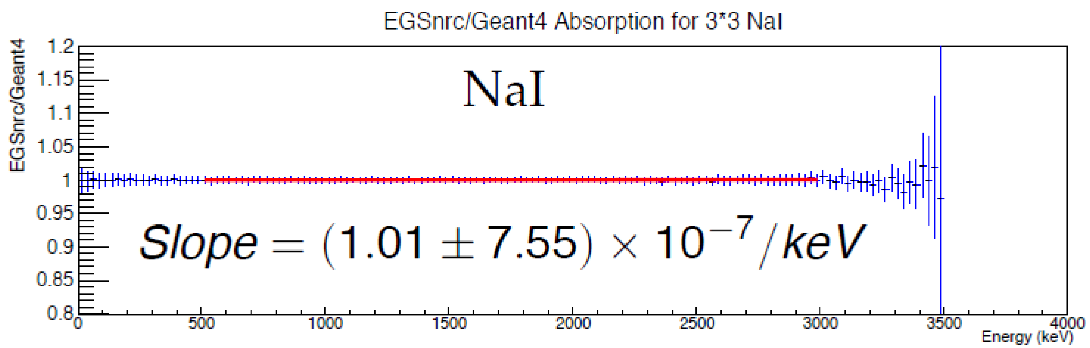
NO FIT !

Bremsstrahlung escape simulations (1/2)

- Part of the β energy loss occurs through Bremsstrahlung.
- Some Bremsstrahlung radiation escapes the detector and produces a distortion in the spectrum shape.
- Use MC simulations to account for this effect.





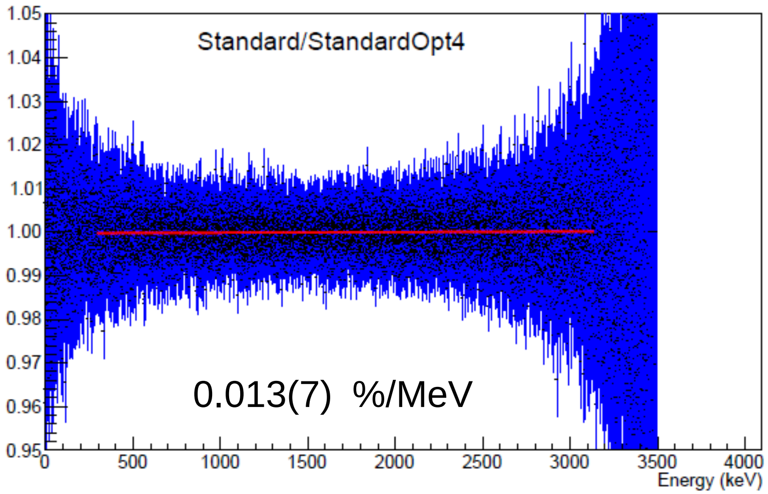


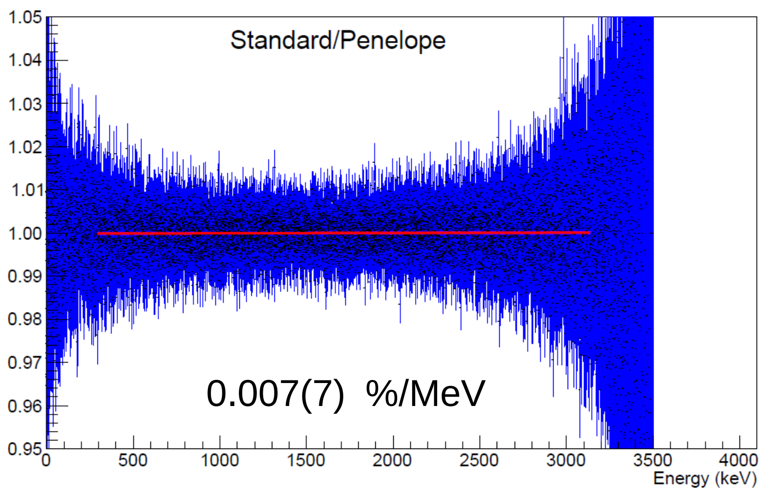
P. Voytas (Wittemberg U): EGSnrc
X. Huyan (MSU): Geant4

The uncertainty is due to the statistics in MC

Bremsstrahlung escape simulations (2/2)

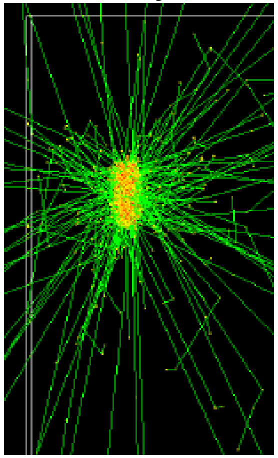
- Comparison of G4 EM-Phys packages





Standard
Standard-Opt4
Penelope

X. Huyan



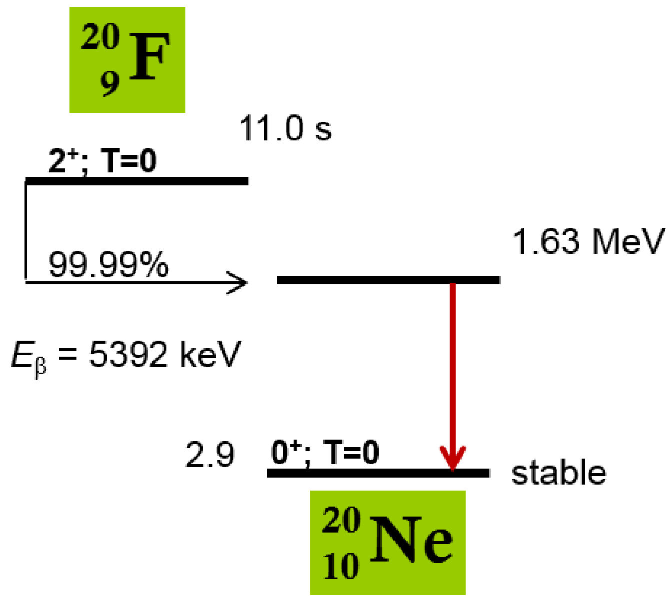
10^9 events

- We do observe differences in the emission BS spectra produced by the tested G4 packages.
- The differences are very strongly reduced in the absorbed energy spectra (geometry).
- Inaccuracies in MC simulations enter “2nd order” for this technique.

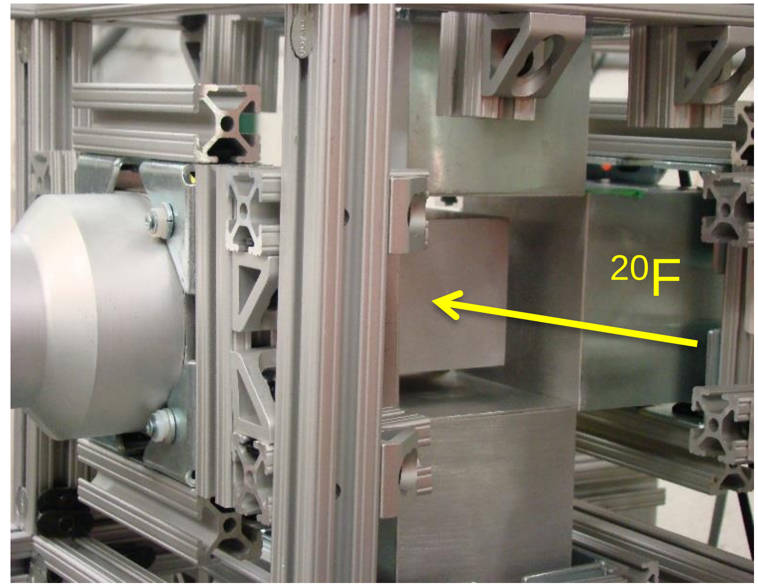
Outline

Decay and setup

^{20}F has a somewhat larger end-point than ^{6}He, but the decay scheme enables to measure coincidences (reduce background contribution)

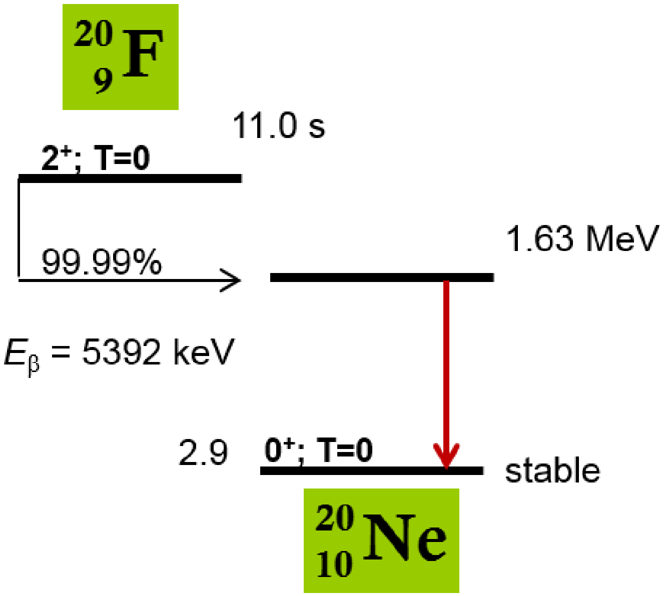


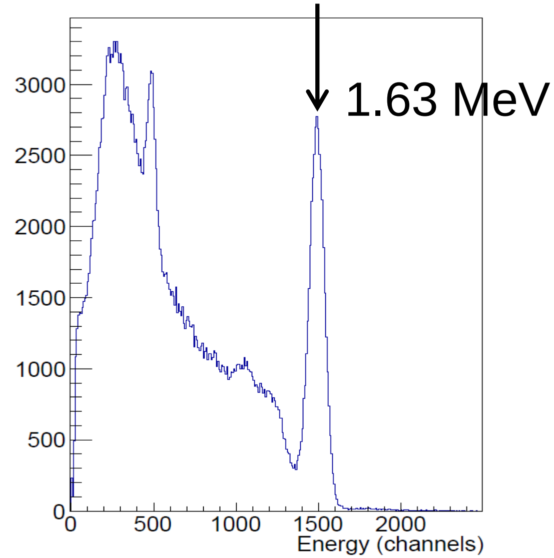
September 2015

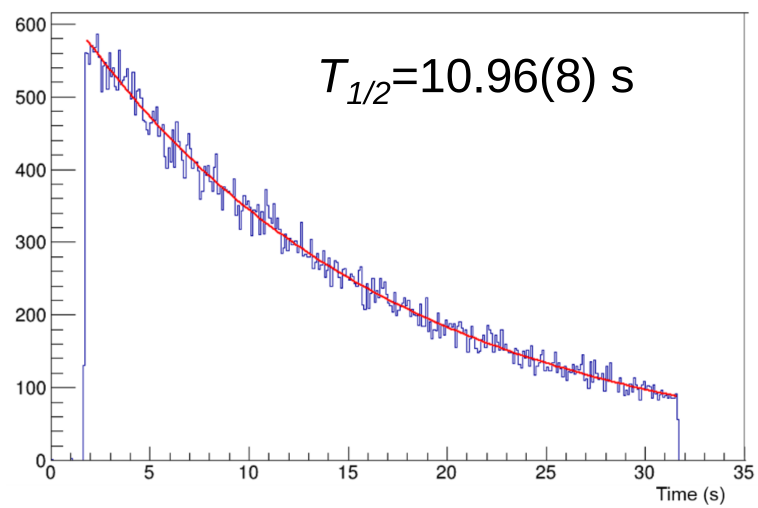


- Separaed fragments: 130 AMeV
- 4 (3"×3"×3") CsI(Na) for γ
- PVT (Ø3"×3") and (2"×2"×4") CsI(Na) implantation detectors for β

Identification spectra



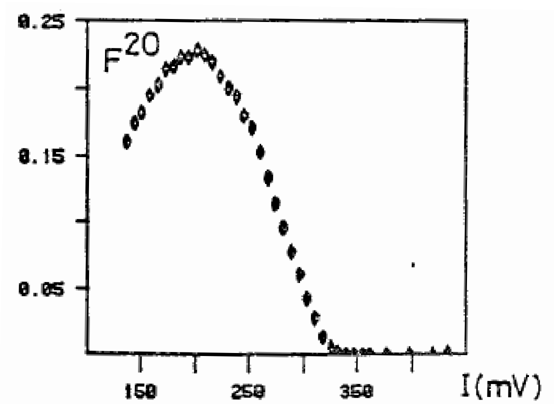




Comparison of measuring techniques

L. van Elmbt, J. Deustch, R. Prieels, NPA **469** (1987) 531

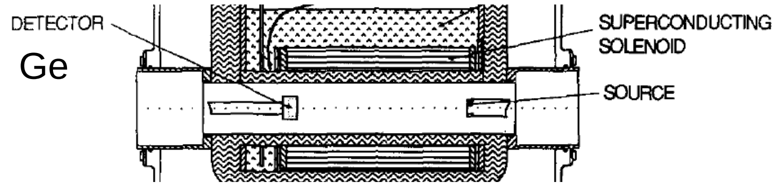
Magnetic Spectrometer

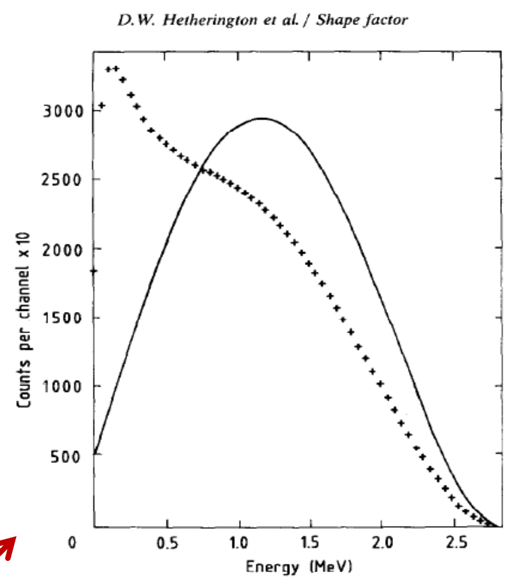


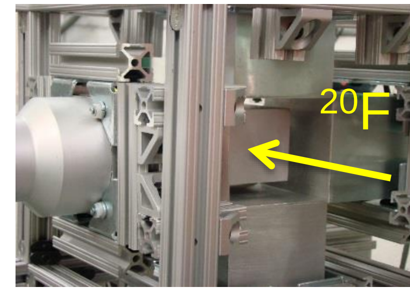
L. van Elmbt, PhD Thesis, 1981

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

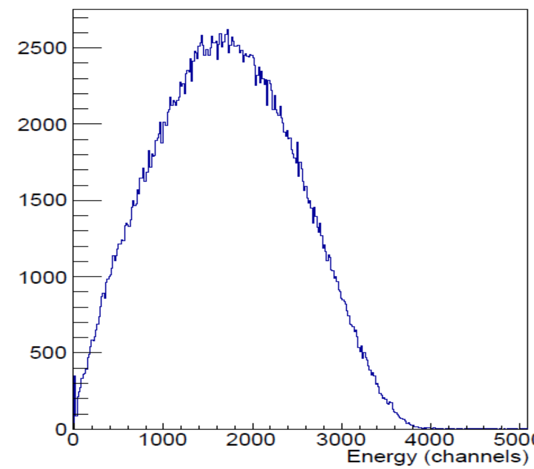
Ge







NSCL, Implanted beam produced by fragmentation



On-line spectrum, 1h run

The two most precise determinations of the weak magnetism form factor in ^{20}F

Summary

• Searches for tensor type contributions to the weak interaction have motivated new precision measurements of β spectrum shapes.

• We have explored the use of implanted ions produced by fragmentation reactions at NSCL and have performed high statistics measurement of β spectra in ^{6}He and ^{20}F (analysis are under way).

• Hadronic contributions (WM) should manifest on the way down to a precision measurement of the Fierz term. This provides a benchmark test to any experimental technique aiming to reach new levels of sensitivity.

People, Institutions

[6]He experiment

D.Bazin[1], A.Gade[1], M.Hughes[1], X.Huyan[1], S.Liddik[1], K.Minamisono[1], O.Naviliat-Cuncic[1], S.Noji[1], S.Paulauskas[1], A.Simon[1], P.Voytas[2], D.Weisshaar[1]

[20]F experiment

G.Ban[3], X.Flechard[3], A.Gade[1], E.George[2], M.Hughes[1], X.Huyan[1], S.Liddik[1], E.Lienard[3], K.Minamisono[1], O.Naviliat-Cuncic[1], S.Paulauskas[1], P.Voytas[2], D.Weisshaar[1]

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[2] *Wittenmebrg University, OH, USA*
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