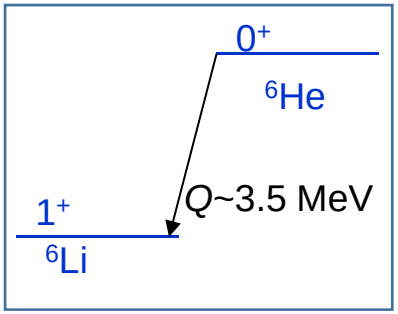
Fundamental symmetries studies with electron spectroscopy at FRIB

- Chirality flipping interactions
  - Axial and tensor
  - Fermi and scalar
  - Tools: *R*×*B* spectrometer
    Cyclotron Radiation Emission Spectroscopy

- Examples of other uses of beta spectroscopy:
  - Nuclear structure for 2β decays
  - Efficiency of some neutrino detectors

Alejandro Garcia
University of Washington

Fundamental symmetries studies with ^{6}He



- Simple decay (~100% to ground state)
- Pure Gamow-Teller decay
- Half-life ~1 sec → appropriate for trapping
- Large *Q*-value → good for seeing effects of n
- Noble gas → no worries about chemistry
- **Light nucleus → ab-initio calculations**

Compare to neutron:
- No backgrounds from neutron captures
- Pure GT transition (simpler decay, no polarization)

6He "little *a*"

P. Muller, A. Leredde *Argonne National Lab*

X. Fléchard, E. Liennard, *LPC, CAEN, France*

O. Naviliat-Cuncic, *NSCL, MSU*

A. Knecht, *PSI, Switzerland*

Y. Bagdasarova, A. Garcia, R. Hong, M. Sternberg, D. Storm, H.E. Swanson, F. Wauters, D. Zumwalt
University of Washington

6He "little *b*"

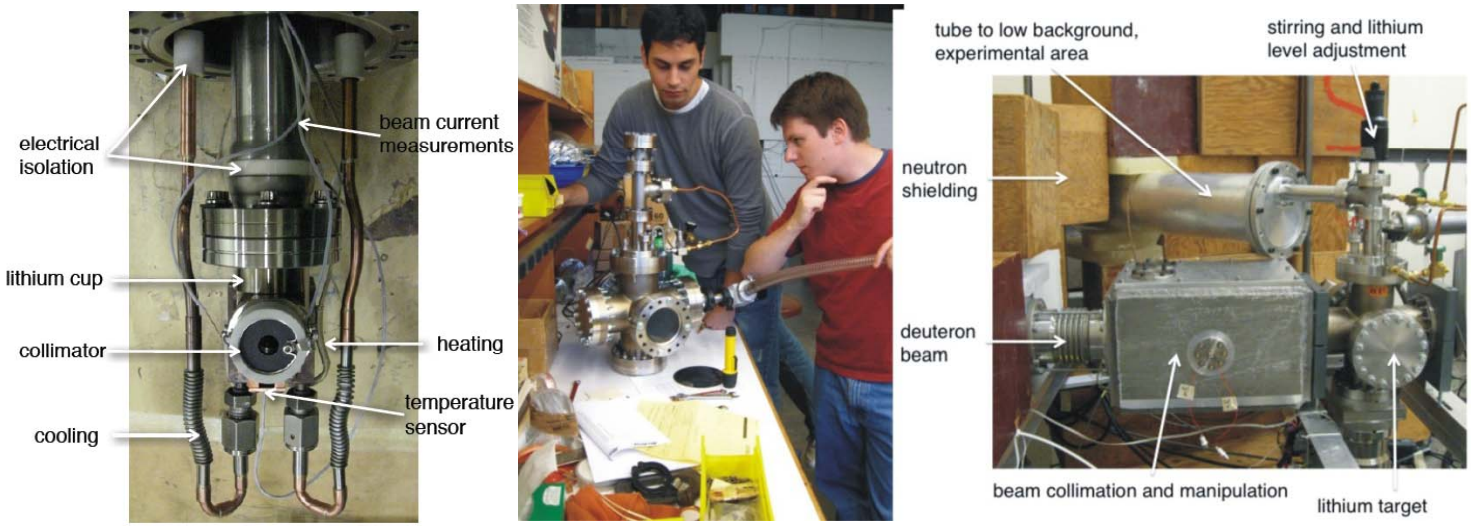
P. Muller, A. Leredde *Argonne National Lab*

A. Knecht, *PSI, Switzerland*

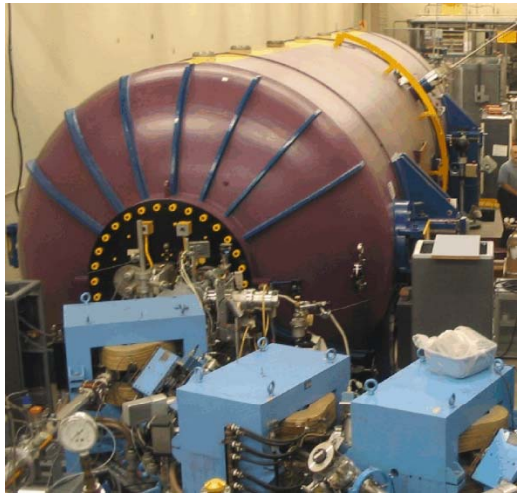
A. Hime, B. Vandebender, *PNNL,*

Y. Bagdasarova, A. Garcia, D. Hertzog, R. Hong, P. Kammel, J. Kofron, G. Rybka, **M. Sternberg,** D. Storm, H.E. Swanson, F. Wauters, D. Zumwalt
University of Washington

Now ~10^{10} atoms of ^{6}He/s at Seattle via ^{7}Li(d,^{3}He)^{6}He



A. Knecht et al. NIM A. **660**, 43 (2011)



Most intense source of 6He in the world here at CENPA.

Typical decay density is about 10^9 decays/s cm^3…

(Good neutron decay density is1 decay/s cm^3)

^{6}He lifetime, ab-initio calculations, g_A(nuclear)

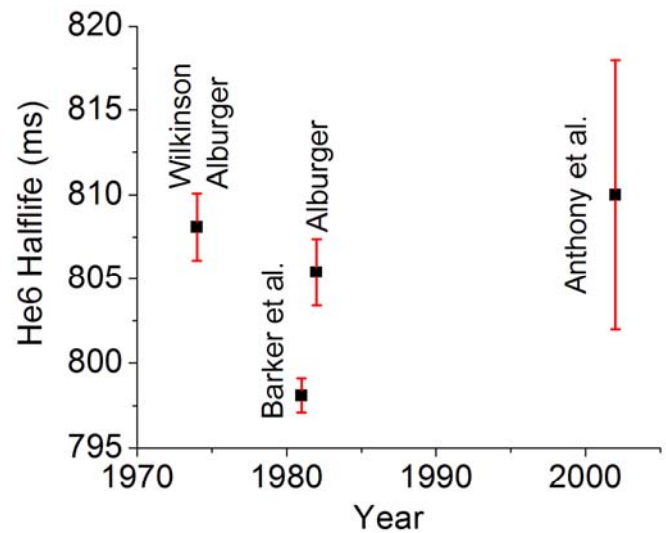
With calculated $\langle f|\hat{O}|i\rangle$ and lifetime can extract g_A

$$\frac{1}{f(E)t} = \frac{(G_F V_{ud})^2}{K} g_A^2 \left|\langle f|\hat{O}|i\rangle\right|^2$$

Several `ab-initio' calculations show agreement on matrix element at the few percent level:

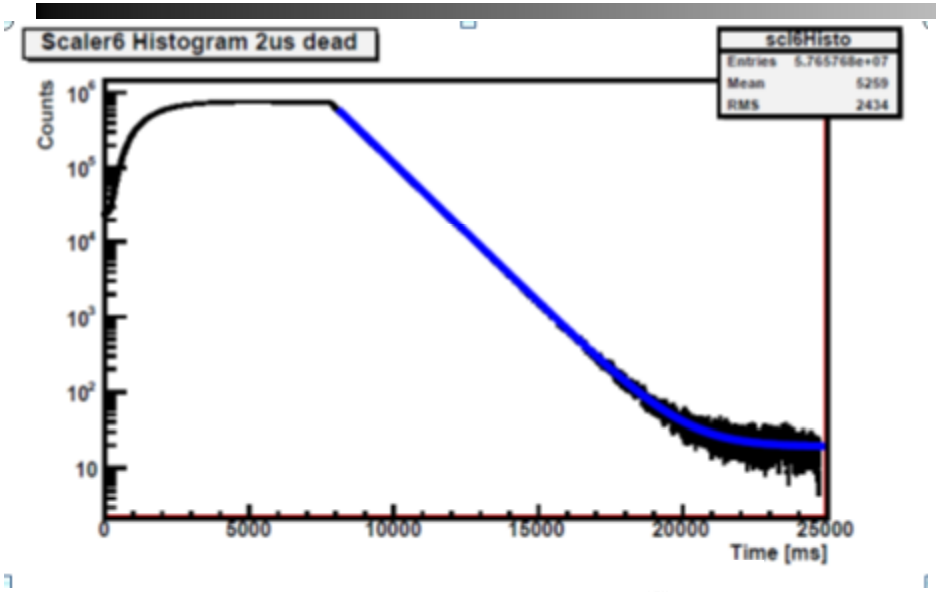
Schiavilla & Wiringa PRC **65**, 054302 (2002)
Navratil & Ormand, PRC **68**, 034305 (2003)
Previn et al., PRC **76**, 064319 (2007)
Vaintraub et al., PRC **79**, 065501 (2009)

But experimental situation was unclear.

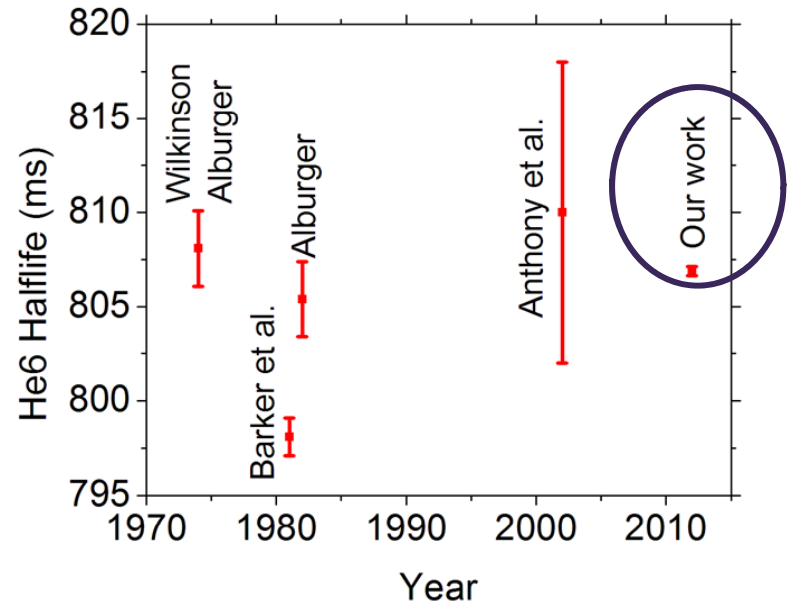


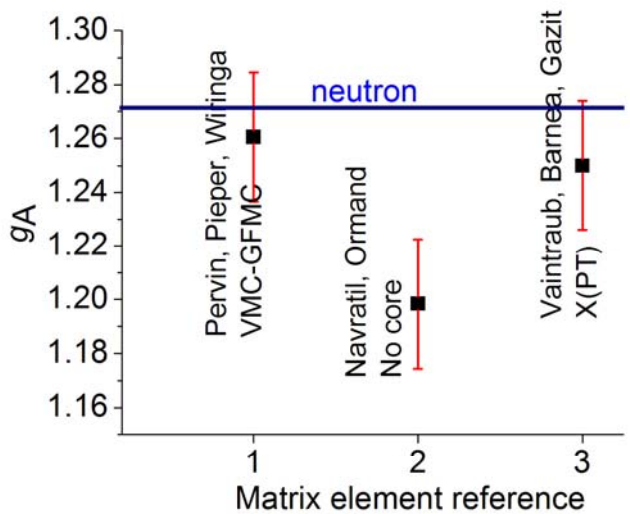
^{6}He lifetime, ab-initio calculations, g_A(nuclear)

Knecht et al. ,
Phys. Rev. Lett. **108**, 122502 (2012);
Phys. Rev. C **86**, 035506 (2012).



- We resolved the discrepancy.



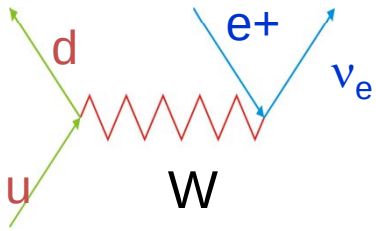


Our result in combination with ab-initio calculations shows that extraneous quenching is at most about 2%.

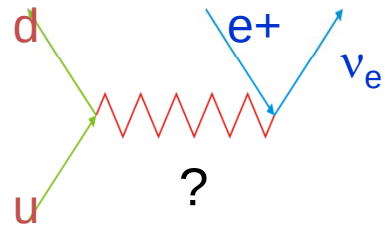
Now limited by theoretical uncertainty.

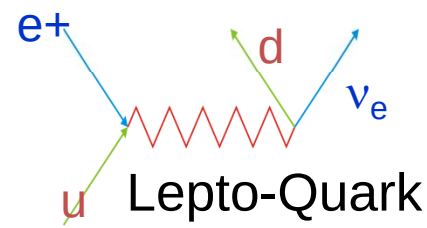
Searches for Tensor currents.

Are nuclear weak decays carried only by W's?



Or chirality-flipping interactions?





$$H = \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \quad 2C_A \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L +$$
$$\overline{\Psi}_f \sigma^{\mu\nu} \Psi_i \quad \left[(C_T - C_T^{'}) \overline{e}^L \sigma_{\mu\nu} \nu_e^R + (C_T + C_T^{'}) \overline{e}^R \sigma_{\mu\nu} \nu_e^L \right]$$

Finding these would be a big deal

Decay rate:

$$dw = dw_0 \left[1 + a \frac{\overrightarrow{p_e}}{E_e} \cdot \frac{\overrightarrow{p_\nu}}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

$$b \approx \frac{\mathrm{Re}\left[2C_A\left(C_T + C_T^{'}\right)\right]}{2\left|C_A\right|^2 + \left|C_T\right|^2 + \left|C_T^{'}\right|^2}$$

$$a \approx -\frac{1}{3} \frac{2\left|C_A\right|^2 - \left|C_T\right|^2 + \left|C_T^{'}\right|^2}{2\left|C_A\right|^2 + \left|C_T\right|^2 + \left|C_T^{'}\right|^2}$$

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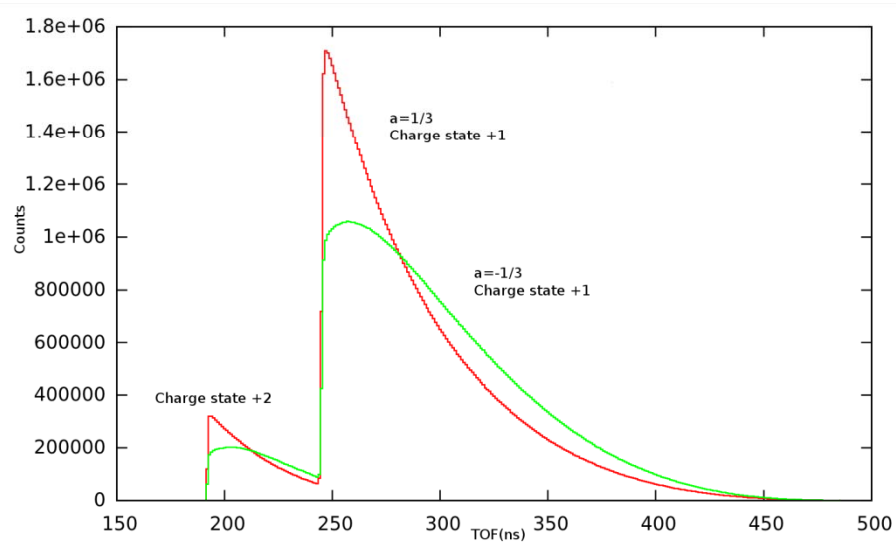
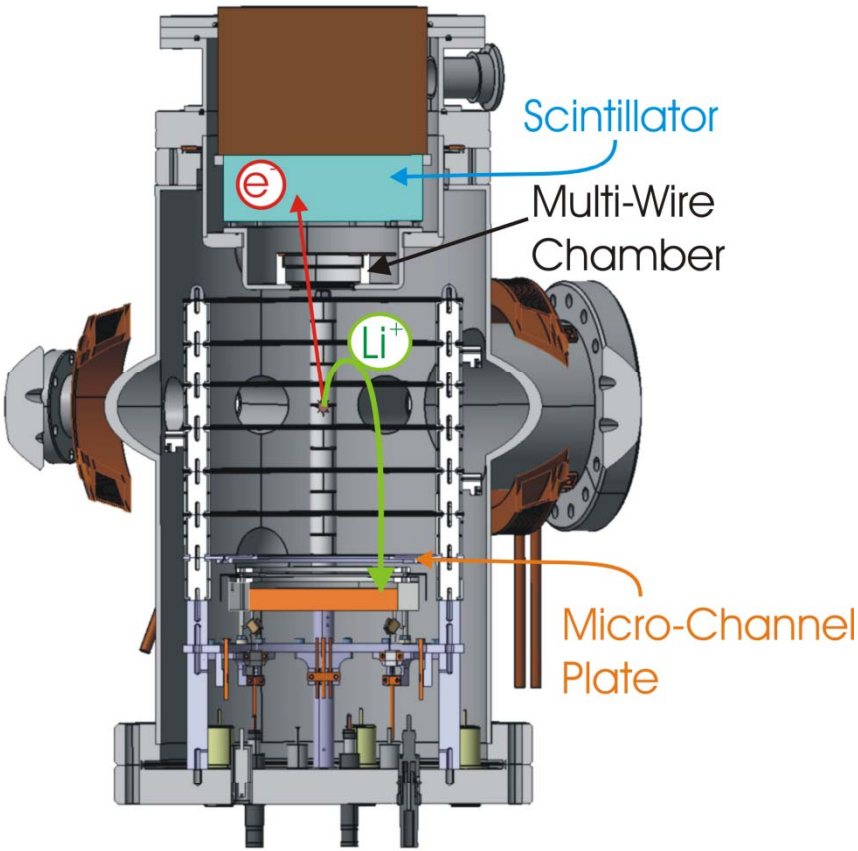
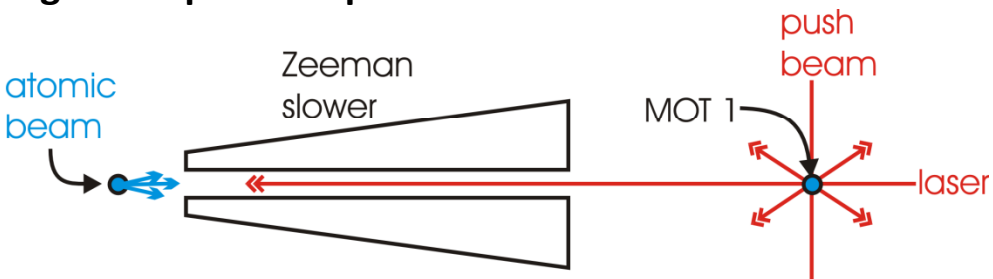
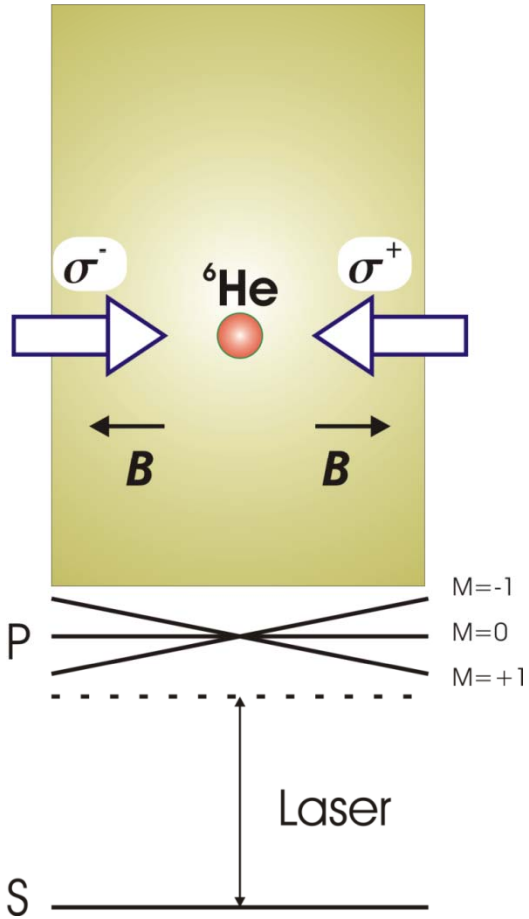
- Electron and ^{6}Li detected in coincidence
- ΔE-E scintillator system for electron (energy, start of time-of-flight)
- Micro-channel plate for ^{6}Li (position, TOF)

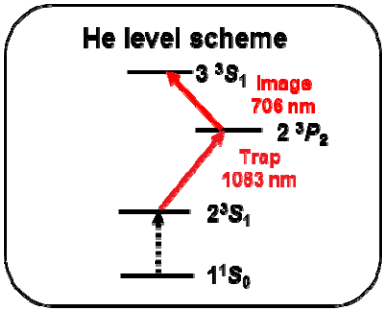


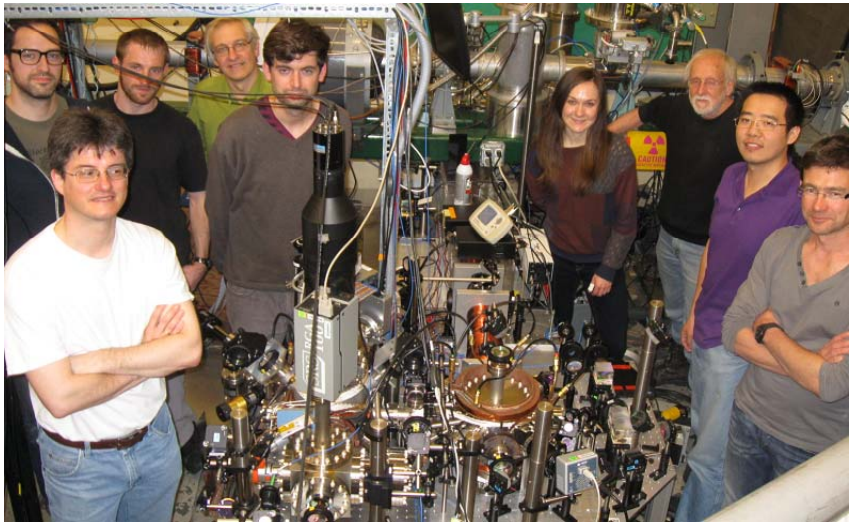


Magneto-Optical Trap





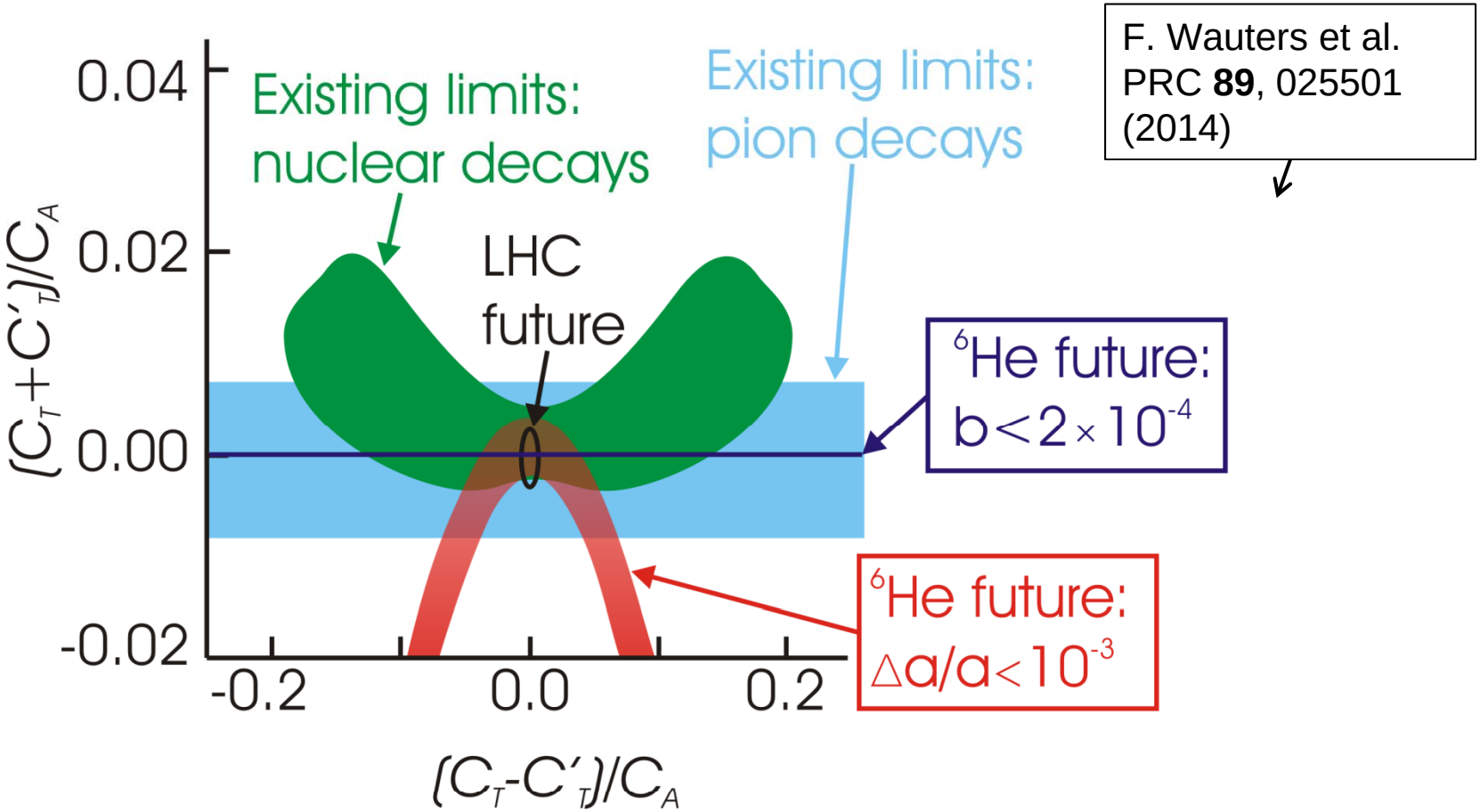




- RF discharge in xenon/krypton to excite into metastable state
- Cycling on 1083 nm transition to slow down and magneto-optically trap
- Based on experience from ^{6}He, ^{8}He charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL **93**, 142501 (2004)
  P. Mueller et al., PRL **99**, 252501 (2007)

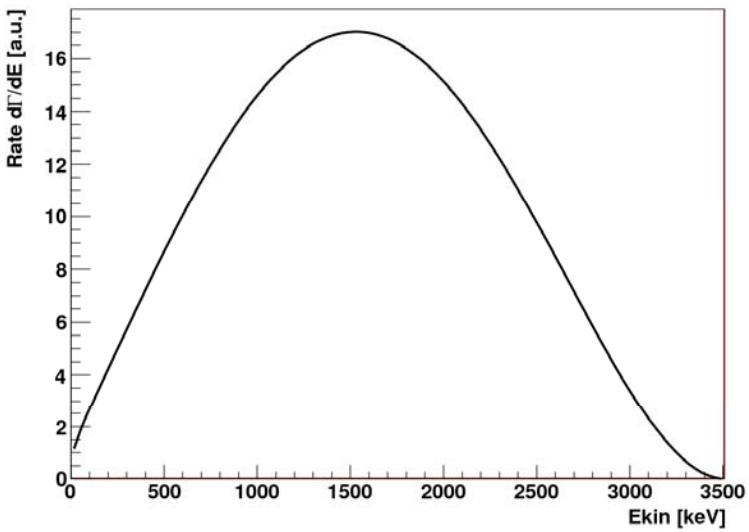
Precision beta decay versus others:

Can “precision” compete with “energy”? Yes.



Detect little *b*

Is it possible to break the "*b* ~ 10^{-3} barrier" and reach into *really interesting* terrain?



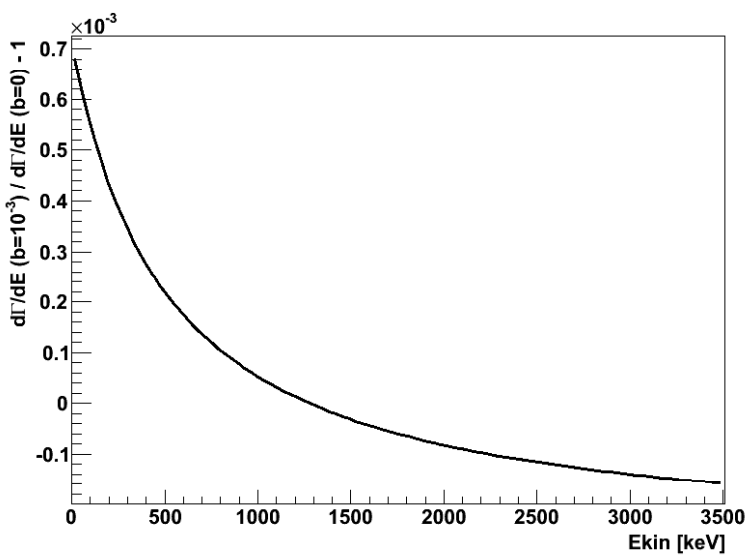
$$dw = dw_0 \left[1 + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

quadratic

$$a \approx -\frac{1}{3} \frac{2|C_A|^2 - |C_T|^2 + |C_T'|^2}{2|C_A|^2 + |C_T|^2 + |C_T'|^2}$$

linear

$$b \approx \frac{\mathrm{Re}\left[2C_A\left(C_T + C_T'\right)\right]}{2|C_A|^2 + |C_T|^2 + |C_T'|^2}$$



$$E_{thres} = 200 \text{ keV}$$

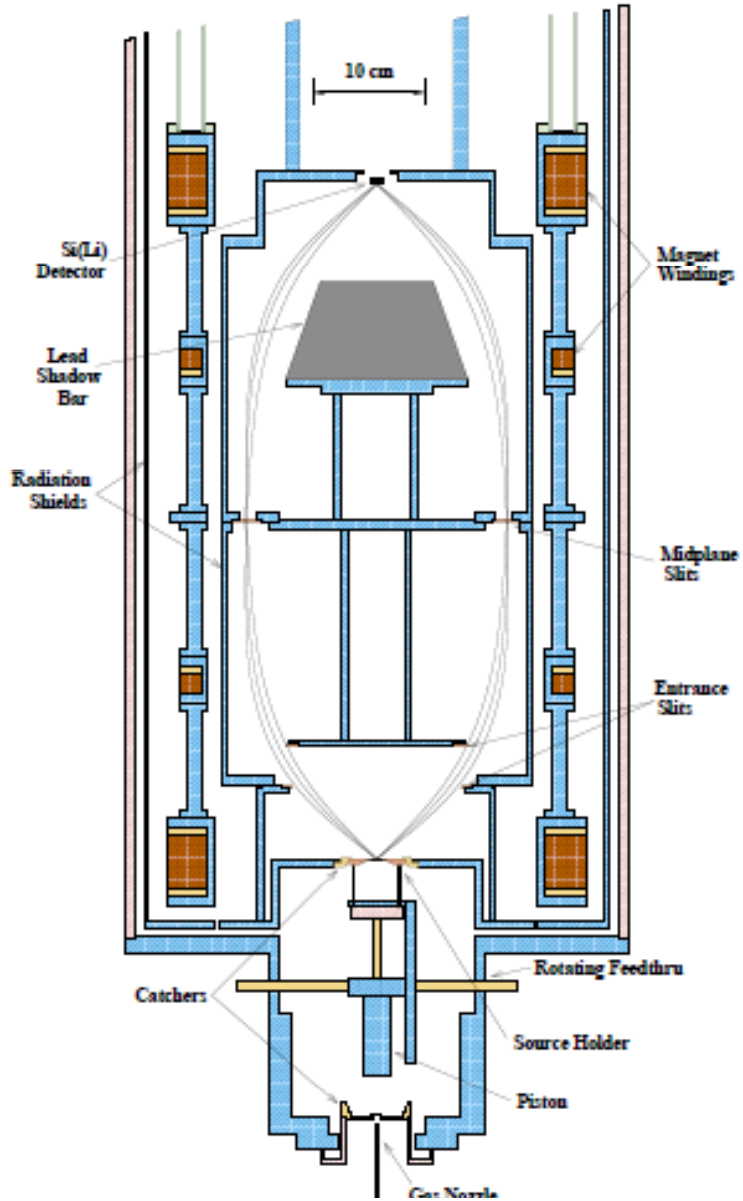
$$\Rightarrow \Delta b \approx 10/\sqrt{N}$$

Can get stats with rates of about 10^4 Hz.

Detect little *b*

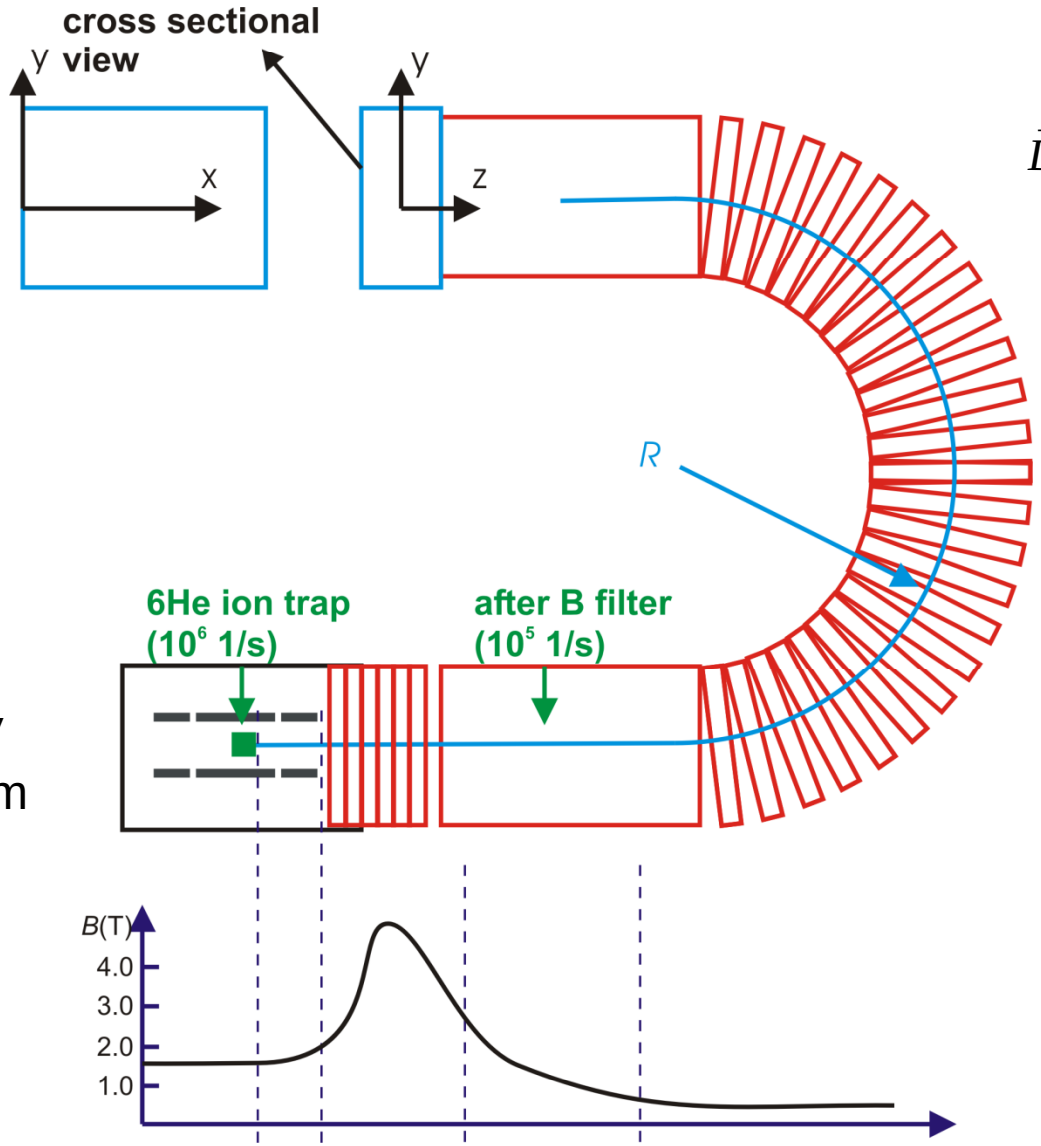
Typical beta spectrometers work best with a `point' source

From Knutson et al. submitted to PRC (Recent work on the shape of the beta spectrum of 14O.)



Hard to apply this technique for 6He: presently we can load only ~1000 atoms in laser trap

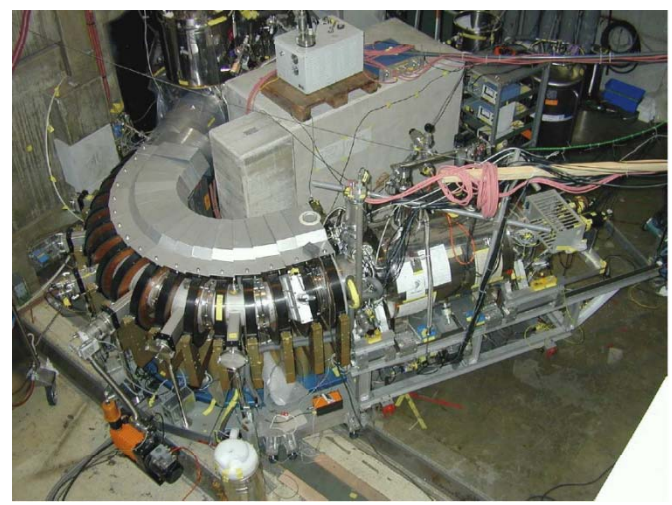
R*×*B spectrometer for 6He (similar to idea being pursued by PERC):



100 kV platform

$$\vec{D} = \pi \underbrace{R_{\max}(p)}_{\frac{(pc/MeV)}{3(B/Tesla)}} \underbrace{\frac{\cos^2\theta + \frac{\sin^2\theta}{2}}{\cos\theta}}_{\approx 1} \frac{\vec{R}\times\vec{B}}{RB}$$

Existing device at PSI



Comparison of neutron to 6He shape measurement with *R*×*B* spectrometer

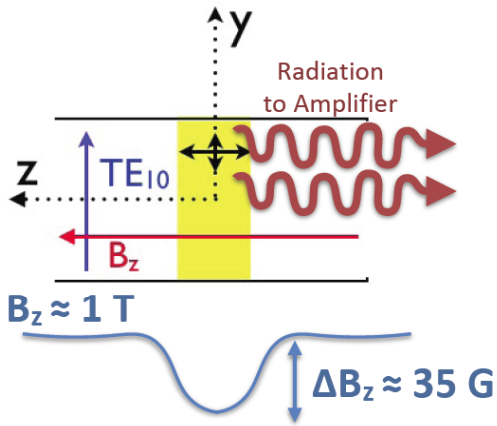
Parameter		Neutron (PERC)	6He (CENPA)
K_{eMax}(MeV)		0.97	3.5
B3 (Tesla)		0.15	0.15
Effective decay rate (1/s)		10^6	10^5
Trappable		No	Yes
Image size at p≈0		1×1 cm2	0.3×0.3 cm2

Systematic uncertainties:

- Singles measurement: backgrounds? Looks ok.
- Effects from unobserved backscattering? Looks ok.
- Non-trapped 6He? Looks manageable.
- Trajectories in realistic configuration: any surprises? Needs more study

^{6}He "little *b*": Project 8 collaboration is aiming at detecting electrons from 3H decay.

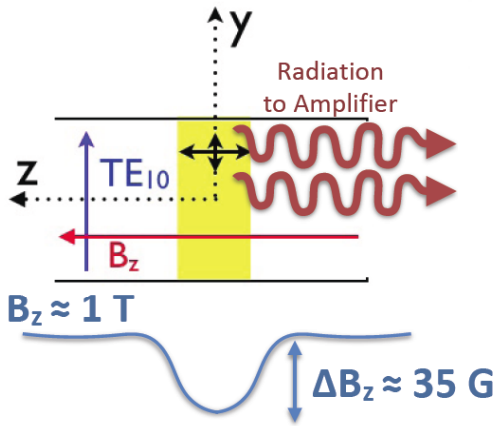
P8 idea: Pick up cyclotron radiation



- None of the usual problems of calorimetry: scattering, dead layers, low resolution, etc…
- Good linearity between cyclotron frequency and energy.
- Excellent resolution

^{6}He "little *b*": Project 8 collaboration is aiming at detecting electrons from 3H decay.

P8 idea: Pick up cyclotron radiation



Project 8 recently showed impressive results from a conversion electron source (Asner et al. arXiv:1408.5362)

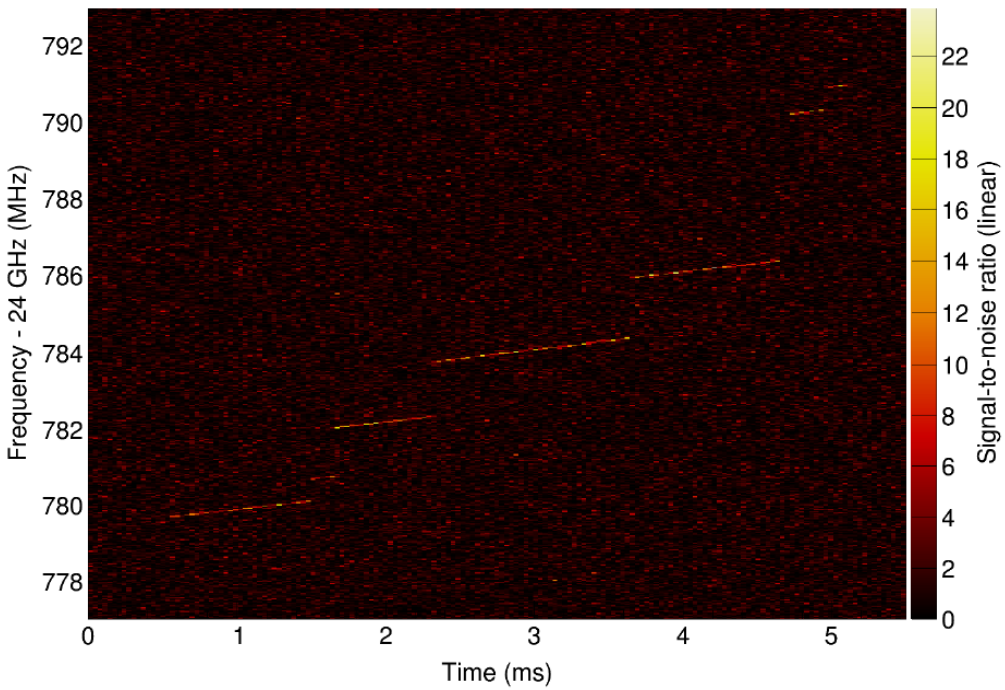


FIG. 2. A typical signal from the decay of ^{83m}Kr characterized by an abrupt onset of narrowband power over the thermal noise of the system. The measured frequency reflects the kinetic energy of the electron, in this case 30 keV. The frequency

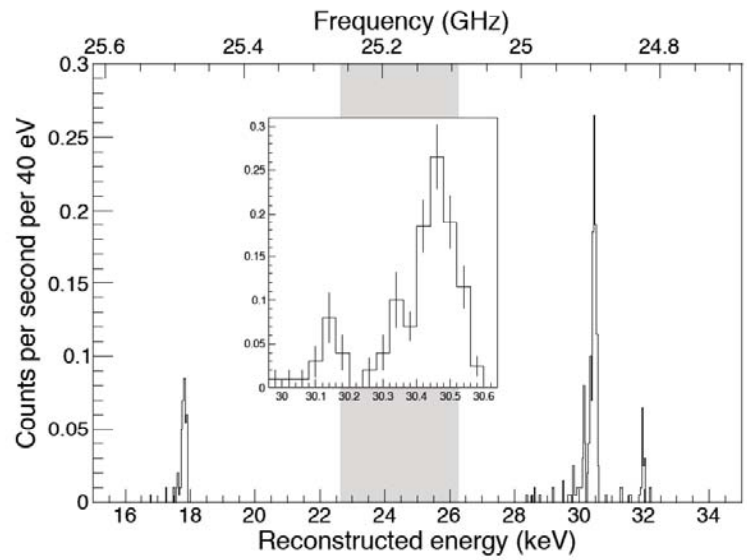
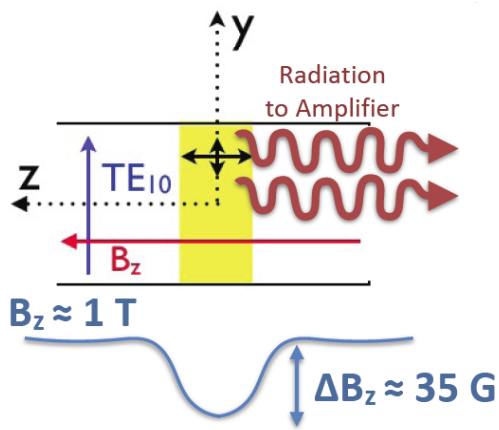


FIG. 3. The kinetic energy distribution of conversion electrons from ^{83m}Kr as determined by CRES. The spectrum shows both the 17 keV, 32 keV and 30 keV-complex conversion electron lines. The shaded region indicates the bandwidth where no data

^{6}He "little *b*": aiming for 10^{-4} with Project-8 like system

Pick up cyclotron radiation



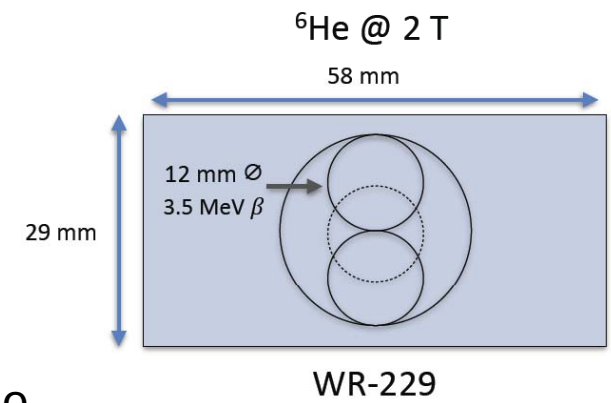
Intense production at CENPA (decay density up to about 10^9 decays/s cm^3!) and ^{6}He as gas make it well suited for P8-like approach.

Need larger guide (58x29 mm^2 vs. 11x4 mm^2)

--loose power prop to area $P \propto 1/A \approx 1/40$

--but compensate due to higher energies $P \propto (\gamma^2 - 1)B^2$

--many alternative schemes to be considered



Next: test with conversion lines at energies closer to 6He

Isotope	Decay	$t_{1/2}$ (days)	*Ee*(keV)
131mXe	IT	12	129,158,163
133mXe	IT	2.2	233
133Xe	β-	5.3	346

^{6}He "little *b*": aiming for 10^{-4} with Project-8 like system

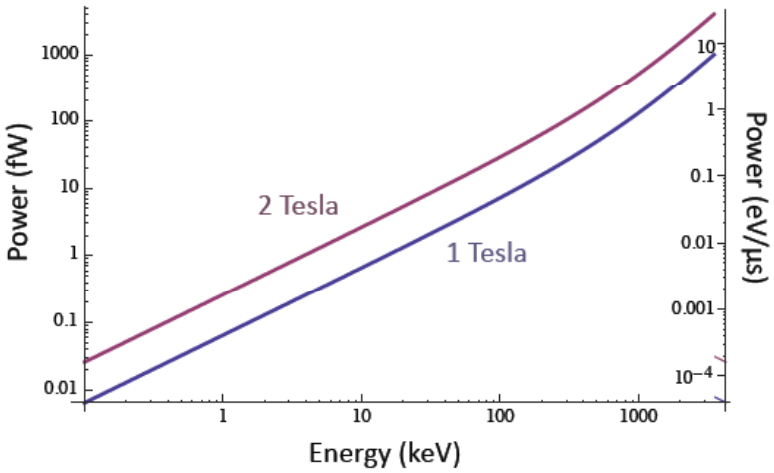
What's different about measuring ^{6}He spectrum?

Cyclotron Radius

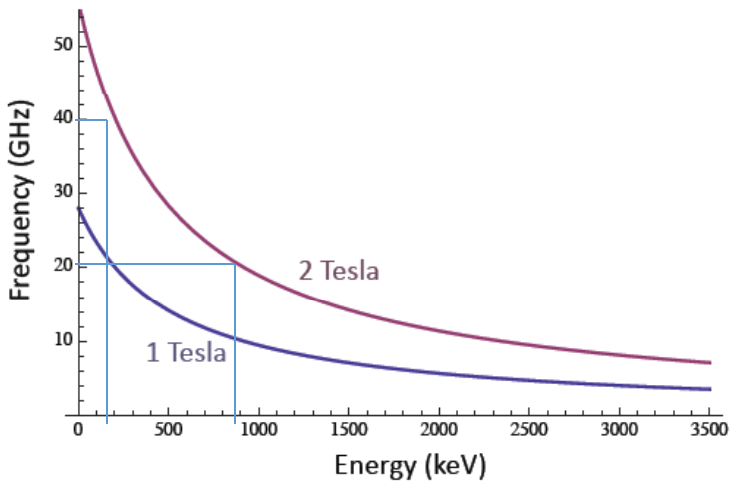
$$R_c = \frac{\gamma \beta m_e c}{qB}$$

→ R = 1.2 cm @ 1 T
R = 0.6 cm @ 2T
(For 3.5 MeV β)

Radiated Power



Frequency Range



^{6}He at CENPA summary:

Present and near future work (little a):

- Several ongoing upgrades. Expect trapping about 1000 atoms with little bkgd.
- Determination of apparatus parameters: E field, geometry, efficiencies, instabilities.

Present and near future work (little b):

- Test "Project8-like" setup with higher energy conversion sources.
- Put together similar system to detect betas in 200-900 keV range.
- We would consider again the "*R*×*B* Spectrometer" idea if the above fails.

Goals 3 years:
Determination of a to ~0.1%; R&D to determination of b.
Determine b to ~10^{-3}.

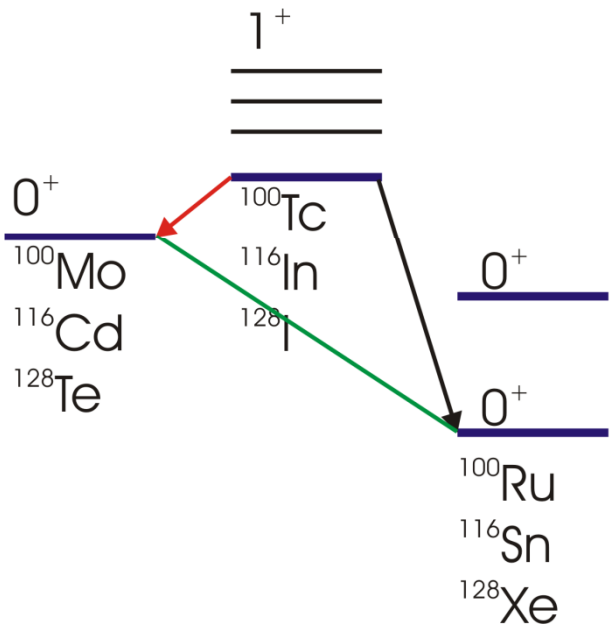
Goals 6 years:
Determine b to ~10^{-4}.

Examples of other applications of electron spectroscopy

Benchmarks for $2\nu-2\beta$ decays nuclear structure:

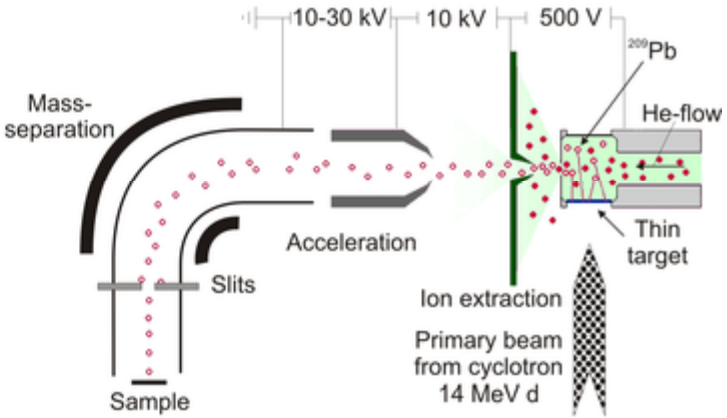
- $2\nu-2\beta$ decays
- single beta decays
- single electron capture decays

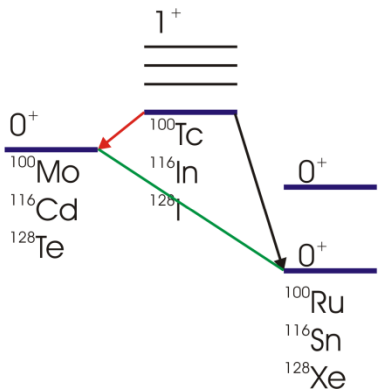
In 3 cases one can check all of the above for the same nucleus: *good for understanding overarching issues (role of p-p, p-h correlations, deformation, etc...)*



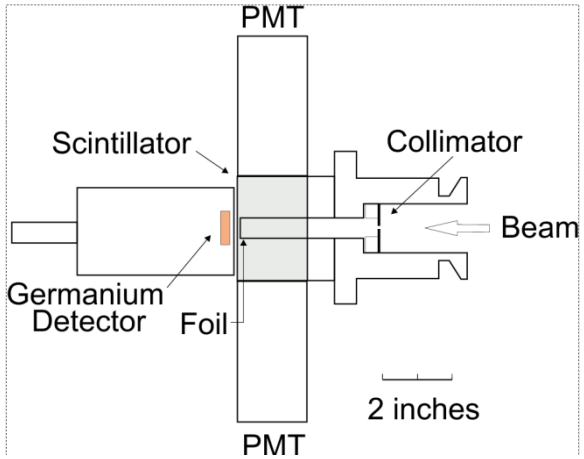
We developed a device to determine the tiny EC branches.

We developed a device to determine the tiny EC branches using the radioactive beams available at IGISOL (JYFLTRAP).



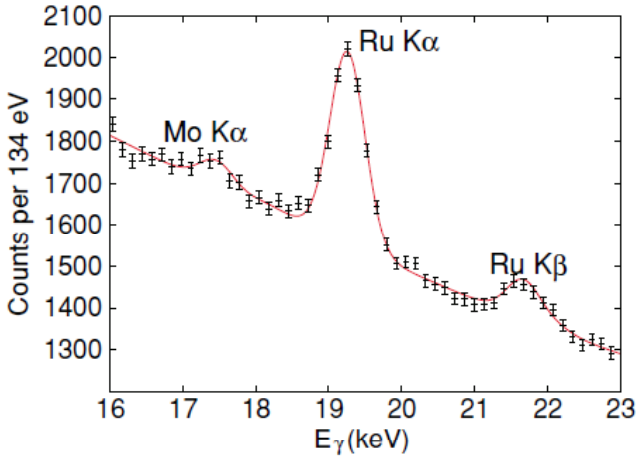


Use ion trap for clean activity
High-resolution Ge for x rays
Scintillator for vetoing beta-decays



CENPA
Center for Experimental Nuclear Physics and Astrophysics

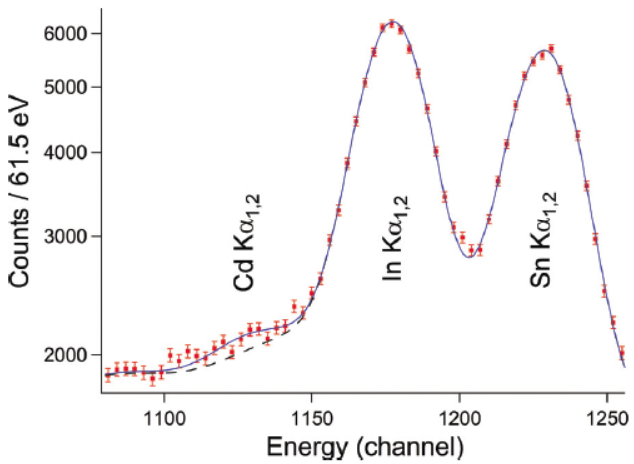
^{100}Tc EC decay:
BR(EC) = (2.6±0.4)×10^{-5}



S. Sjue, Thesis 2008;
Sjue et al.,
PRC **87**, 032501 (2013).

^{116}In EC decay:
BR(EC) = (2.3±0.6)×10^{-4}

PHYSICAL REVIEW C **87**, 031303(R) (2013)



Wrede et al.,
PRC **87**, 032501 (2013).

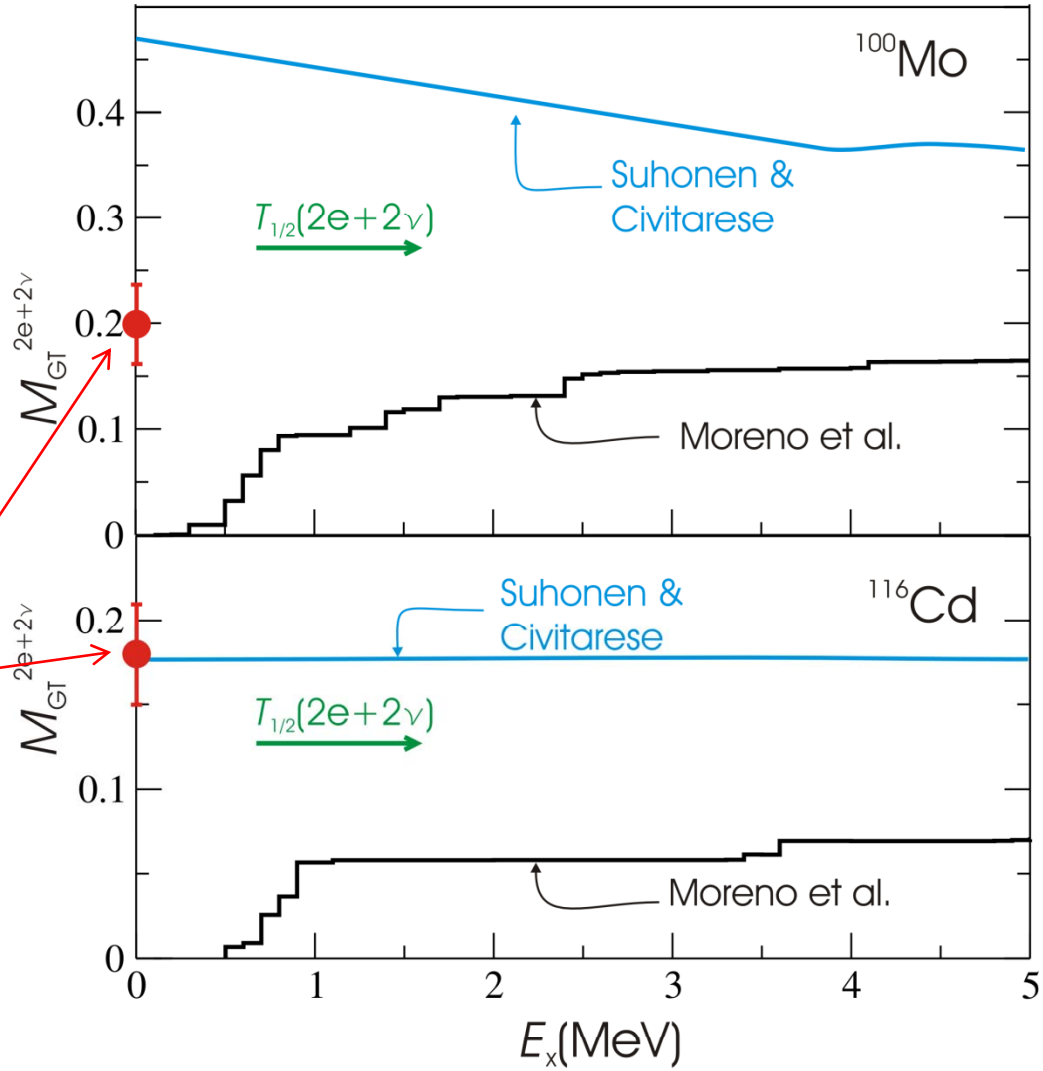
Both of our results are consistent with complete *ground state dominance*: just using the ground state accounts for the measured 2ν-2β decay rate.

Comparison with 2 different QRPA calculations

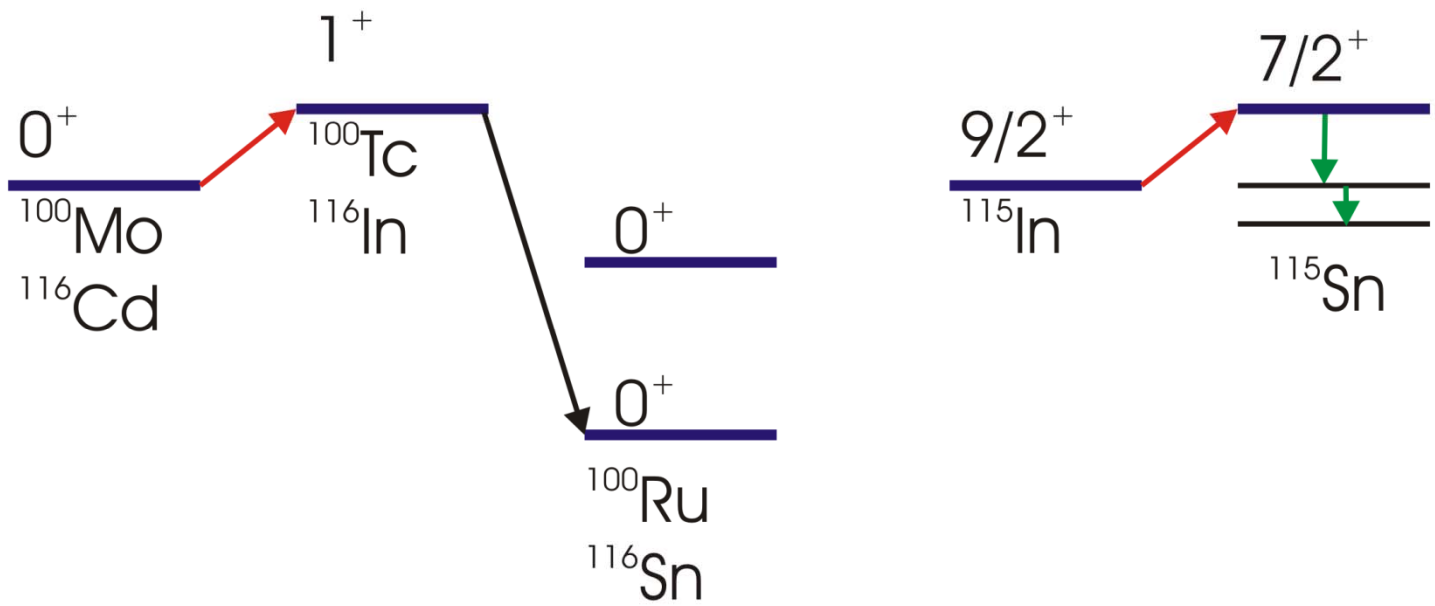
O. Moreno, R. Alvarez-Rodriguez, P. Sarriguren, E. Moya de Guerra, F. Simkovic, A. Faessler
J. Phys. G **36**, 015106 (2009)

Suhonen & Civitarese
Phys. Lett. **B725**, 753 (2013)

Our measurements



High resolution Auger spectroscopy would determine the efficiencies of solar pp neutrino detectors



High-resolution beta spectroscopy

Perhaps FRIB would be the place for the most intense production of some gaseous molecular species or trapped ions that could be used for cyclotron-radiation detection in pure axial and pure Fermi decays to search for tensor and scalar currents.

High-resolution Auger spectroscopy with ions of choice could help with spectroscopy relevant for neutrino physics (double beta decay, solar neutrinos).

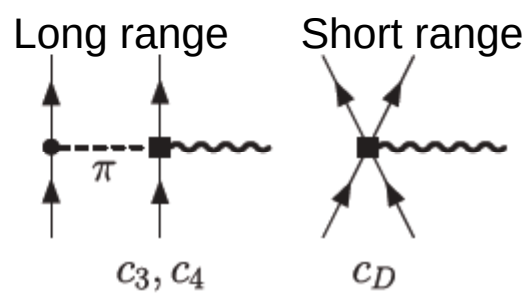
Backup slides

The Influence of MEC

UNIVERSITY of WASHINGTON

Calculation	M_{GT} (no MEC)	Change from $g_A(n)$	M_{GT} (incl. MEC)	Change from $g_A(n)$
Schiavilla/ Wiringa	2.254(5) (Ψ_T I) 2.246(10) (Ψ_T II)	-3.9% -3.6%	2.284(5) (Ψ_T I) 2.278(10) (Ψ_T II)	-5.2% -5.0%
Vaintraub/ Barnea/Gazit	2.225(2)	-2.7 %	2.198(7)	-1.5 %

- Free low-energy constant in calculation of meson-exchange currents:
  → fixed by ^{3}H half-life
- Influence of MEC different in the two calculations
- Vaintraub et al. argue that this is an effect of the correct modeling of the underlying currents in χPT

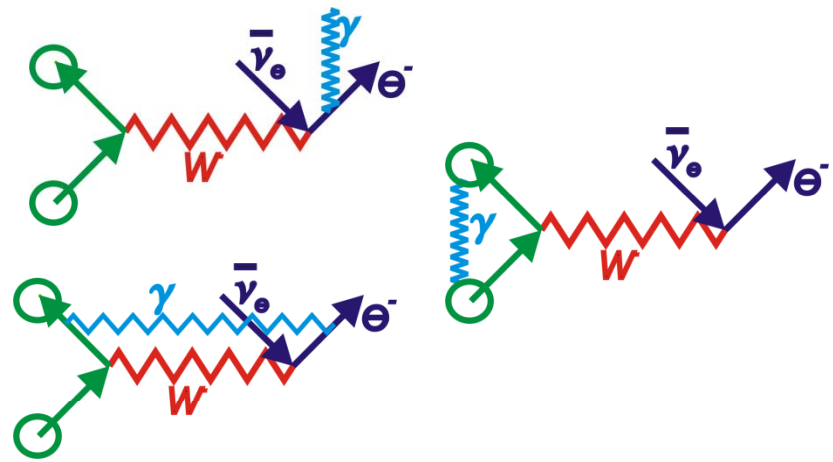


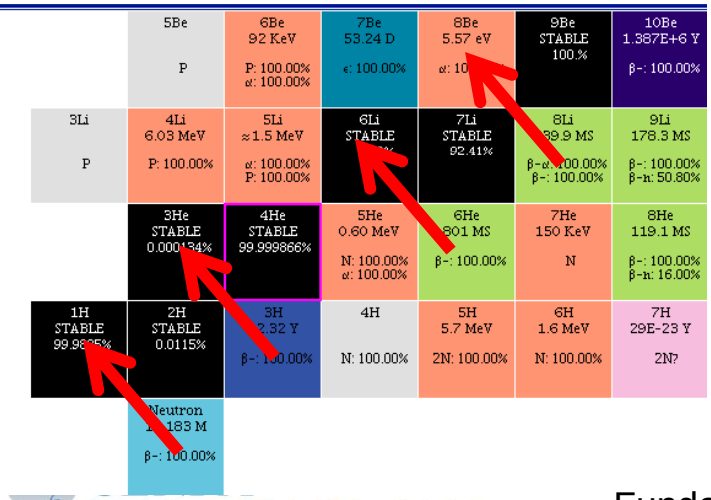
6He:
"recoil order"

$$C_V \int \vec{\alpha} \times \vec{r} \rightarrow \frac{f_V}{M}[\int \tau^+ \vec{\sigma} + \int \tau^+ \vec{r} \times \vec{p}] - 2 f_{WM} \int \tau^+ \vec{\sigma}$$
$$C_A i \int \gamma_5 \vec{r} \rightarrow g_A i \int \tau^+ \vec{\sigma} \times \vec{l}$$

Small and under control for 6He decay.

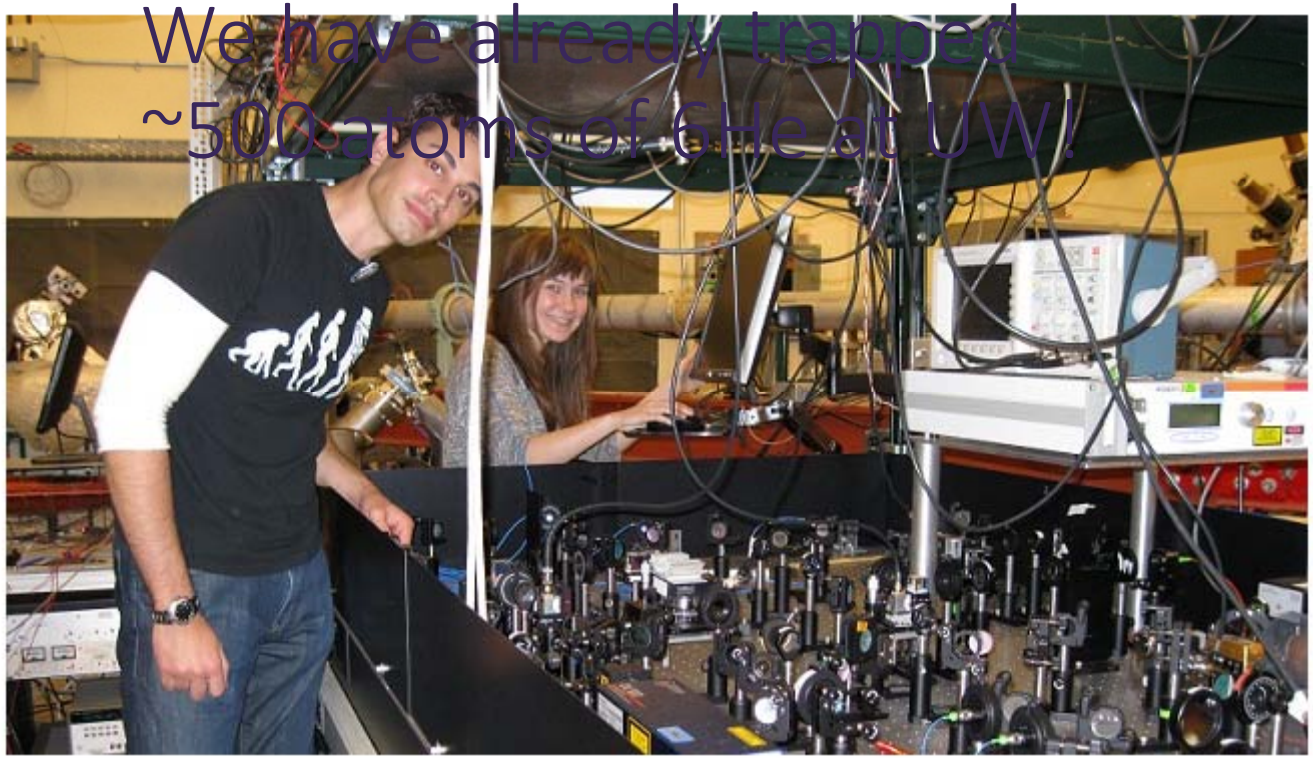
… and radiative corrections.

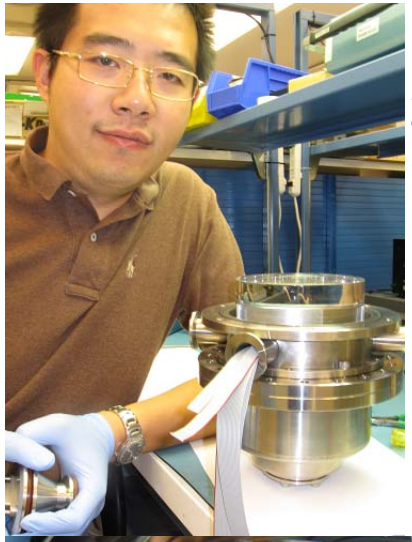


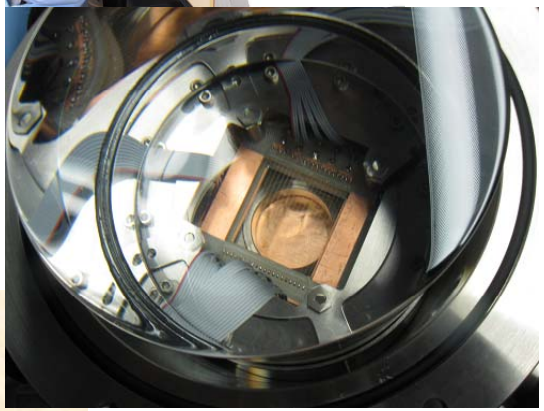


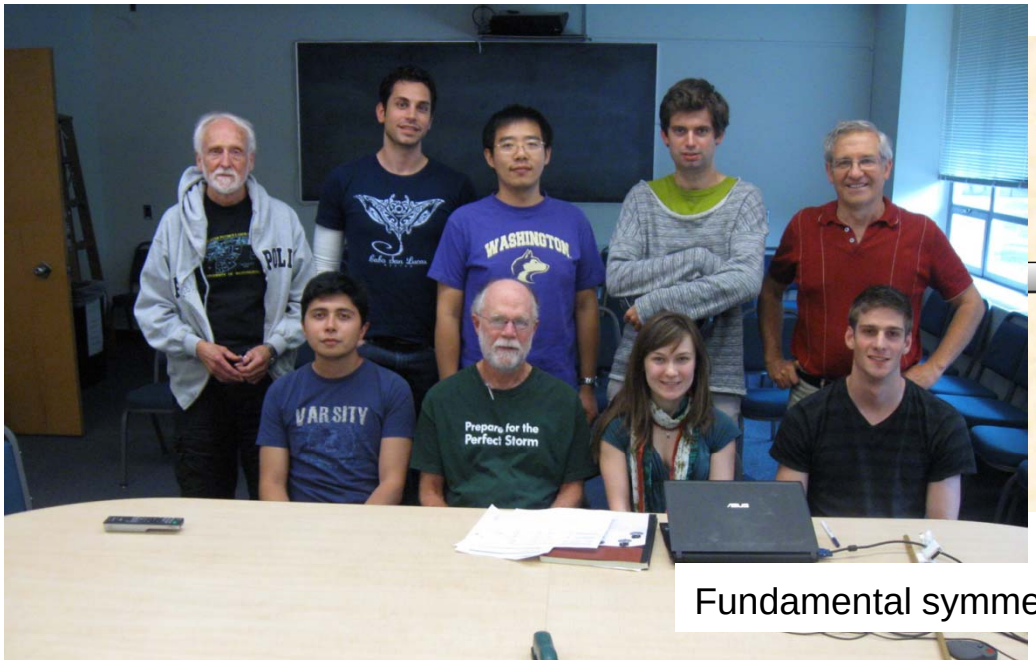
From theorists (Barry Holstein et al.): "no show stoppers"

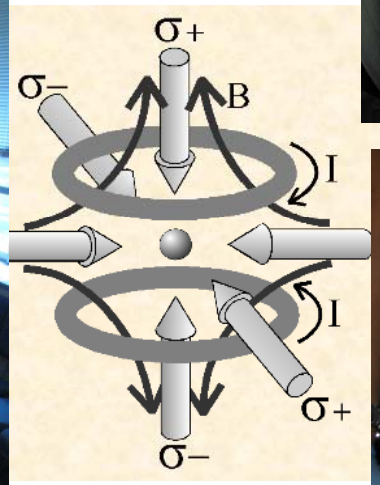
We have already trapped ~500 atoms of 6He at UW!

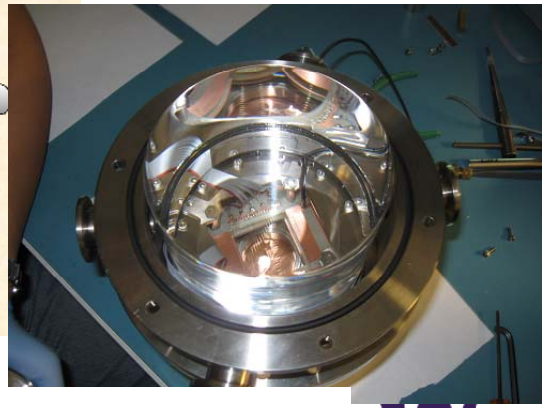












Precision beta decay versus pion and “LHC”: (Wauters et al.)

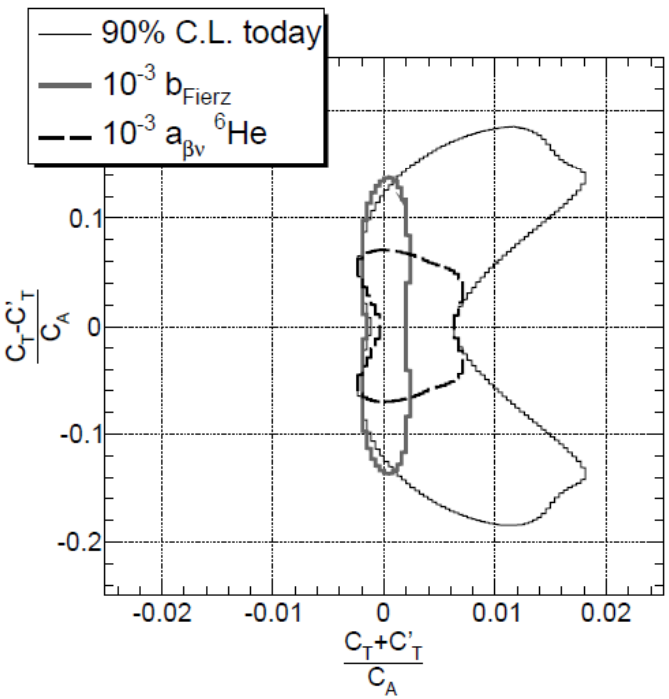


FIG. 5. Limits on tensor currents from envisaged measurements of the correlation coefficient for ^{6}He at 0.1% [53] or of the Fierz interference term b_{Fierz} to 10^{-3} in ^{6}He or neutron decays [54]. In the formalism of Eq. 3, the current LHC limits from Ref. [9] are $|(C_T + C_T')/C_A| < 6 \times 10^{-3}$ and $|(C_T - C_T')/C_A| < 2 \times 10^{-2}$.

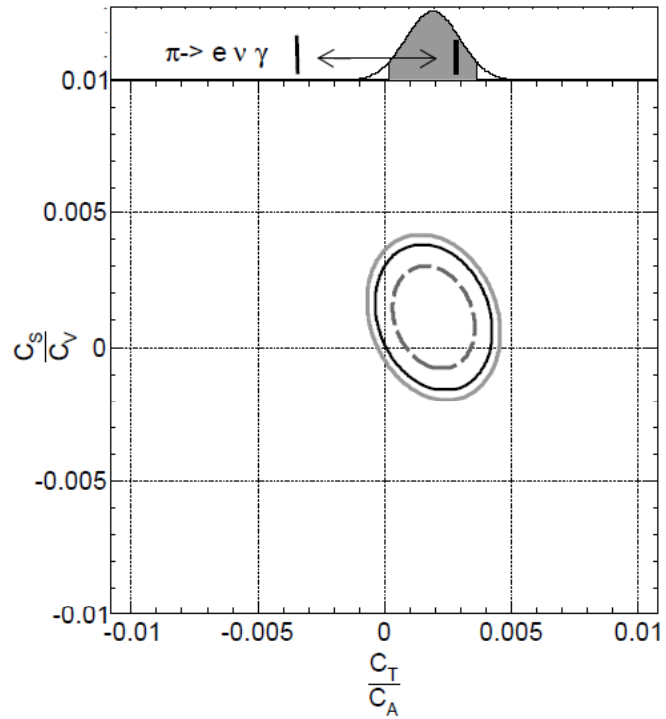
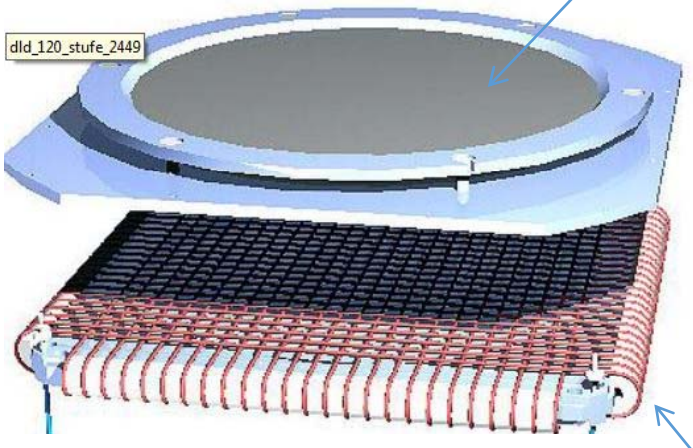
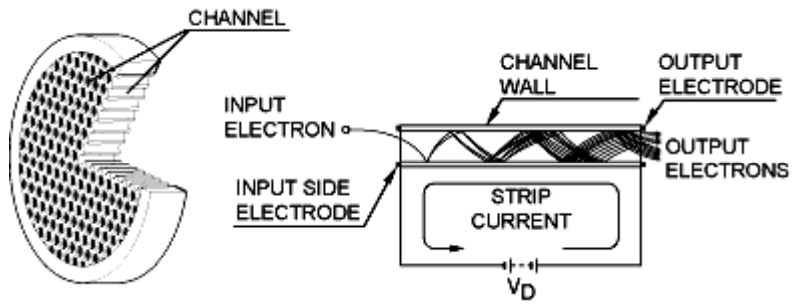


FIG. 3. Limits C_T and C_S combining neutron and nuclear β decay data for the 3-parameter fit. On top we show the probability distribution of the limits on C_T obtained by projecting the 2D distribution and compare to the limits from pion decay data.

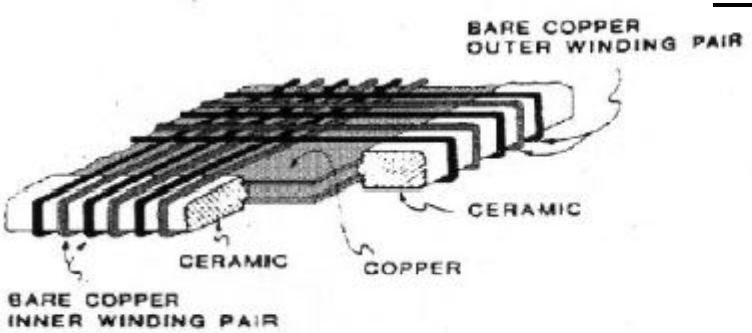
MCPPSD (micro chanel plates with delay line anodes)

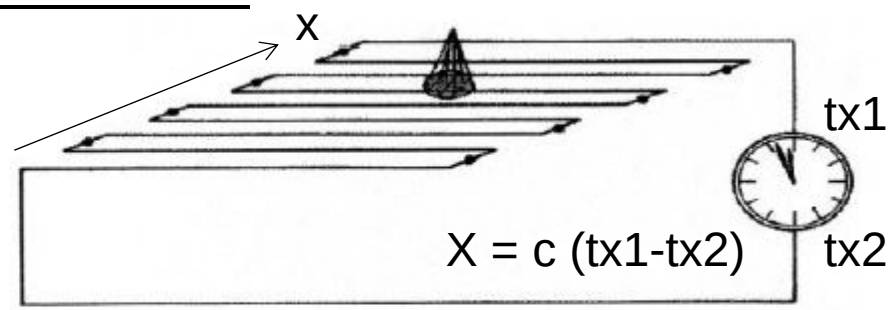
MCPs (micro channel plates)





Delay line anodes

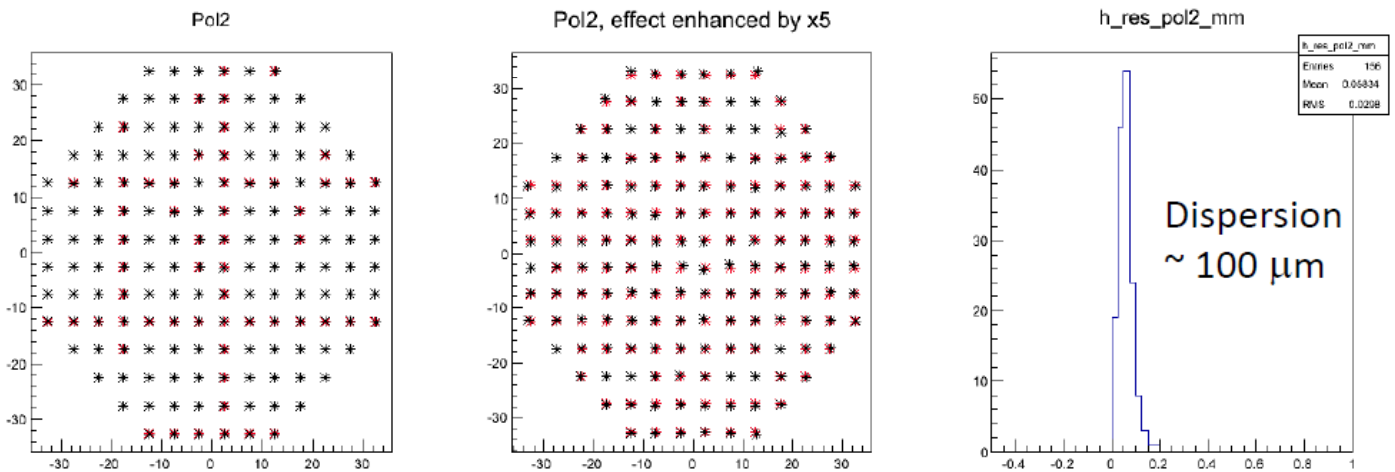




- 5 polarization voltages: front MCP, back MCP, det. frame, anode_ref, anode_sig
- 5 signals: charge emitted by MCPs, charge collected on anodes (x1,x2,y1,y2)

X&Y calibration:

- Reconstruction with 2^{d} order polynomial functions



Detect little *b*. *Betas in adiabatic motion in B:* basic ideas

1) $Flux = B\, r_0^{\,2} \sin^2\theta = \text{constant}$

$$r_0 = \frac{p}{qB}$$

$$\left.\right\} \frac{\sin^2\theta}{B} = \text{constant}$$

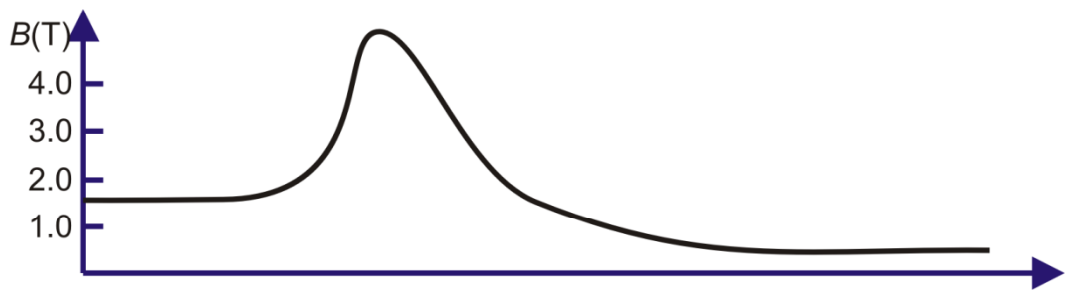
2) Orbital magnetic moment conserved:

$$\mu = \pi \left(r_0 \sin\theta\right)^2 e \frac{\omega}{2\pi} = \text{constant}$$

*3) A force **F** applied perpendicular to **B** generates a "drift velocity":*

$$u = \frac{(\vec{F}/e)\times\vec{B}}{B^2}$$

4) A solenoidal field with intensity varying as in the figure yields smaller pitch-angle betas, good for minimizing backscatter



Comparison of neutron to 6He shape measurement with *R*×*B* spectrometer

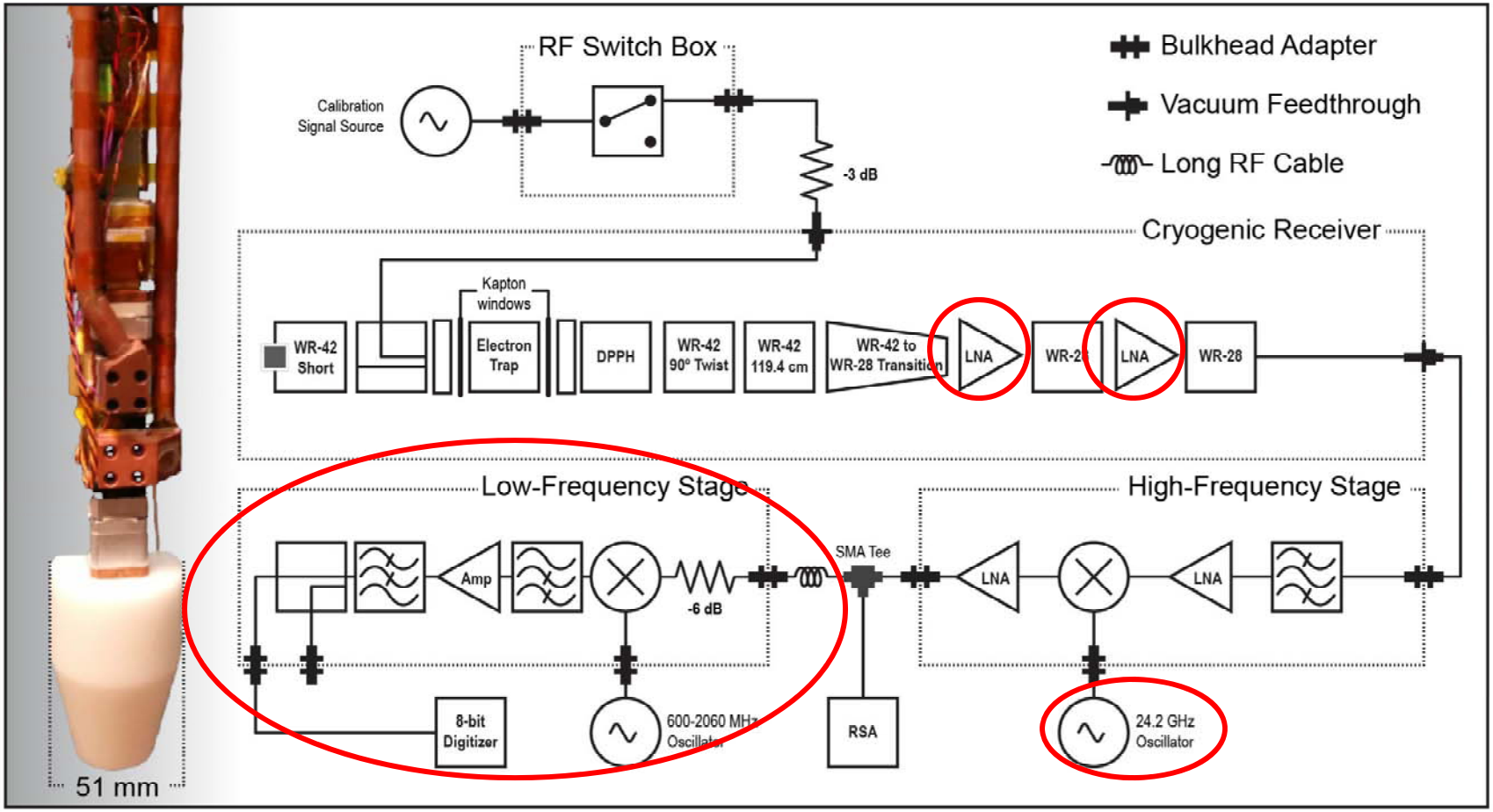
Parameter		Neutron	6He
K_{eMax}(MeV)		0.97	3.5
B3 (Tesla)		0.15	0.15
Effective decay rate (1/s)		10^6	10^5
Trappable		No	Yes
Image size at p≈0		1×1 cm2	0.3×0.3 cm2

Backscattering front foil of a gas counter

Parameter	Backscattered fraction (%)
K_e(MeV)	
0.1	0.3
0.2	0.07
0.3	0.03
0.5	0.01
1.0	0.002

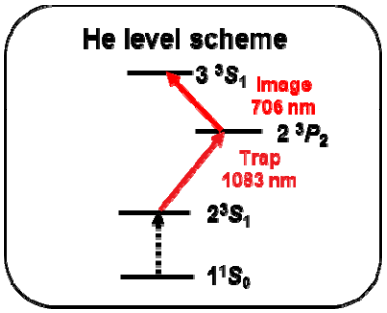
Systematic uncertainties:

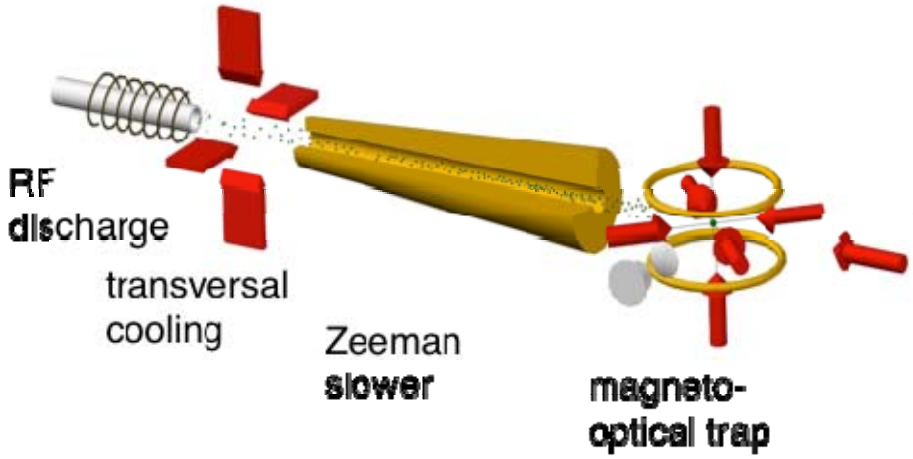
- Singles measurement: backgrounds?
- Effects from unobserved backscattering?
- Non-trapped 6He?
- Trajectories in realistic configuration: any surprises?


RF Switch Box
Bulkhead Adapter
Vacuum Feedthrough
Long RF Cable
Calibration Signal Source
-3 dB
Cryogenic Receiver
Kapton windows
WR-42 Short
Electron Trap
DPPH
WR-42 90° Twist
WR-42 119.4 cm
WR-42 to WR-28 Transition
LNA
WR-28
Low-Frequency Stage
High-Frequency Stage
Amp
-6 dB
SMA Tee
8-bit Digitizer
600-2060 MHz Oscillator
RSA
24.2 GHz Oscillator
51 mm

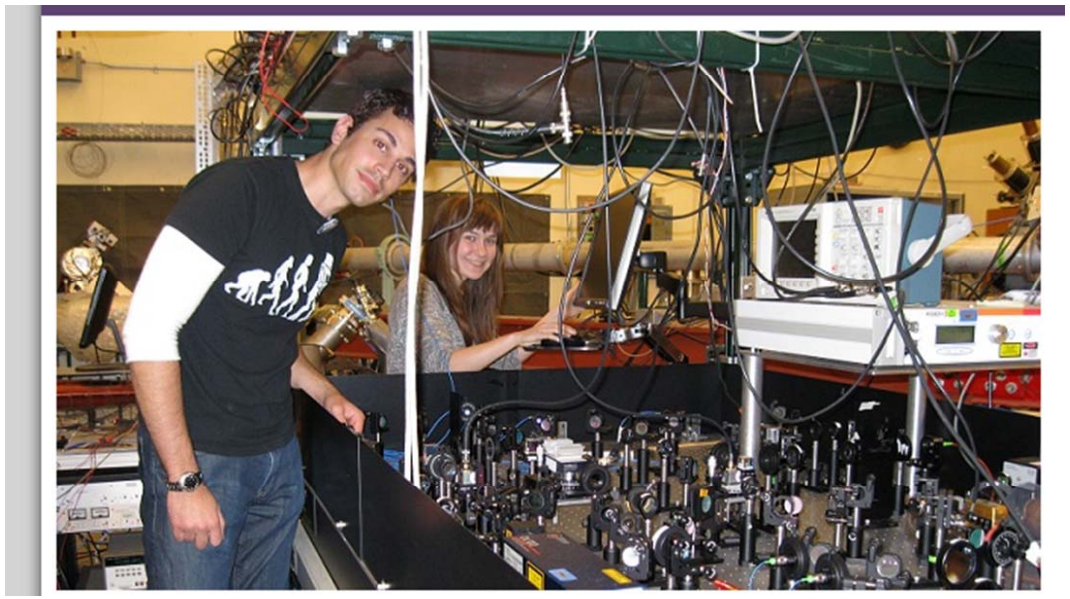
Trapping of 6He

- RF discharge in xenon/krypton to excite into metastable state
- Cycling on 1083 nm transition to transversely cool, slow down and trap magneto-optically





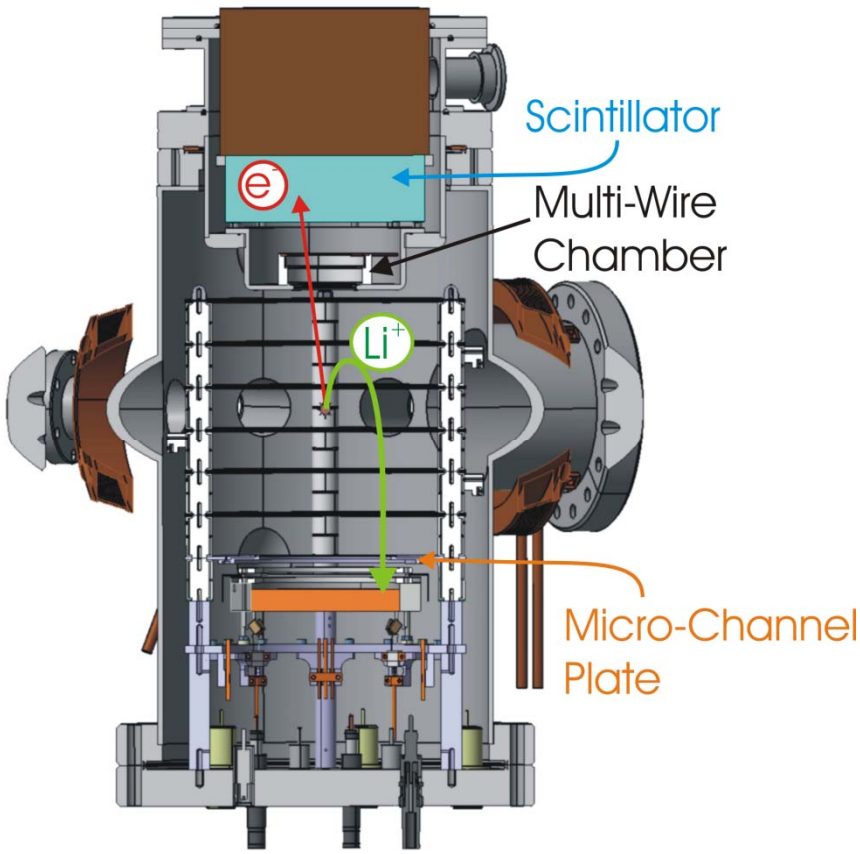
- Trapped atoms transferred to detection chamber with 2nd MOT

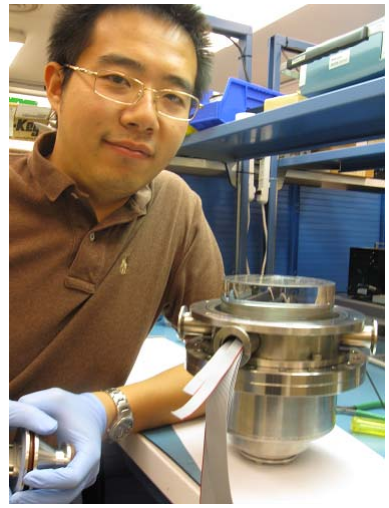


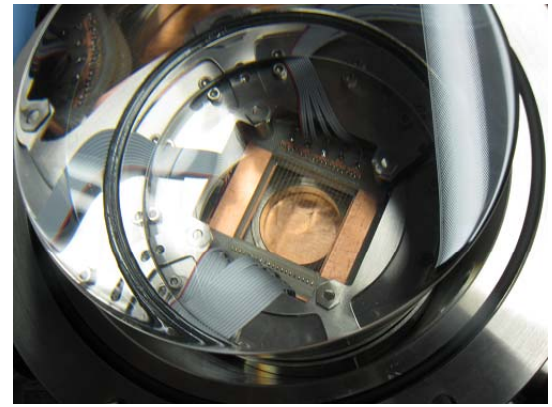
- Based on experience from ^{6}He, ^{8}He charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL **93**, 142501 (2004)
  P. Mueller et al., PRL **99**, 252501 (2007)

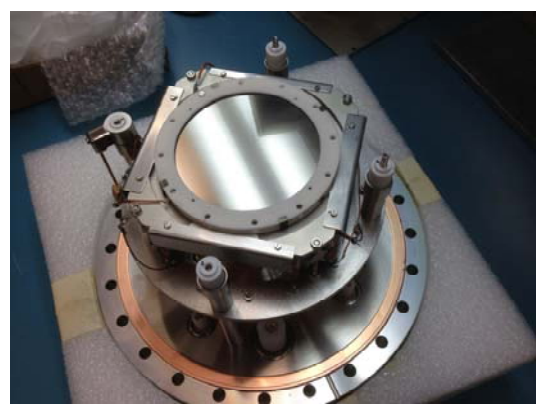
Detection systems

ΔE-E scintillator system for electron detection (energy, start of time-of-flight)









Micro-channel plate detector for detection of ^{6}Li recoil nucleus (position, time-of-flight)

Systematic uncertainties on little a (from MC simulations).

	$\partial a/\partial x$	$(\partial a/\partial x)/a$	δx	$\Delta a/a$
Z-Position	<-3e-4 /0.1mm	<0.1%/0.1mm	δz = 0.1 mm	0.1%
Timing (res)	-7e-4/1ns	0.2%/1ns	$\delta\sigma$ = 1.0 ns	0.2%
MCP: mask for radius cut	-0.02 /mm	6.5%/mm	δr = 15 μm	0.1%
MCP: position	1.5e-3 / mm	0.3%/mm	δpos = 0.3 mm	0.1%
Beta threshold	2e-4/ 10 keV	0.065%/ 10 keV	δTh = 15 keV	0.1%
E-Field Stability	1e-4/V	0.03%/V	δV = 1 V	0.03%
Total				0.3%