FUNDAMENTAL SYMMETRIES WITH ^{6}HE

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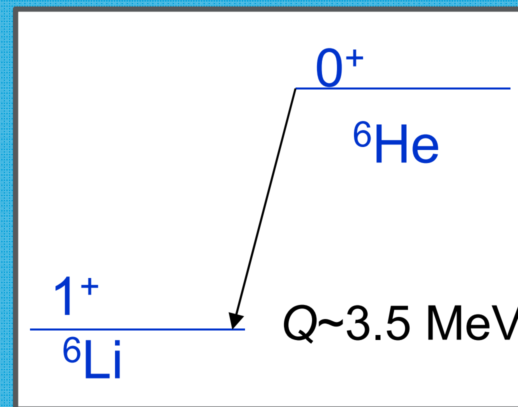
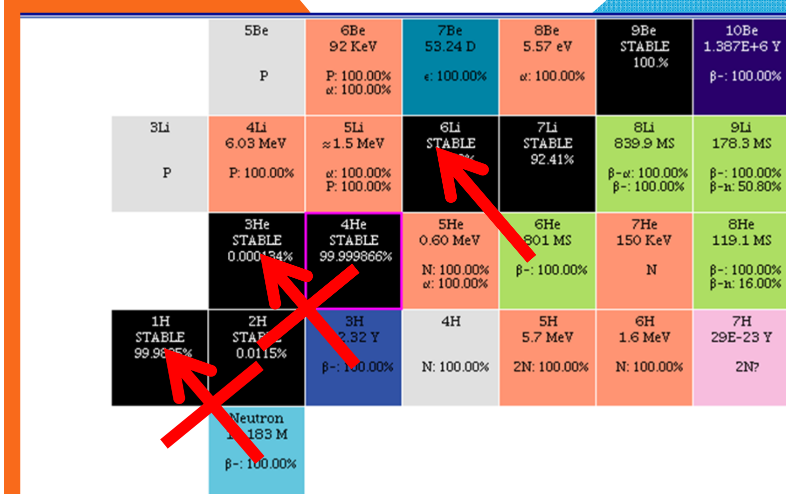
AUGUST 2013

6He good properties for fundamental symmetries studies

- 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 ν
- Noble gas → no worries about chemistry
- Light nucleus → ab-initio calculations



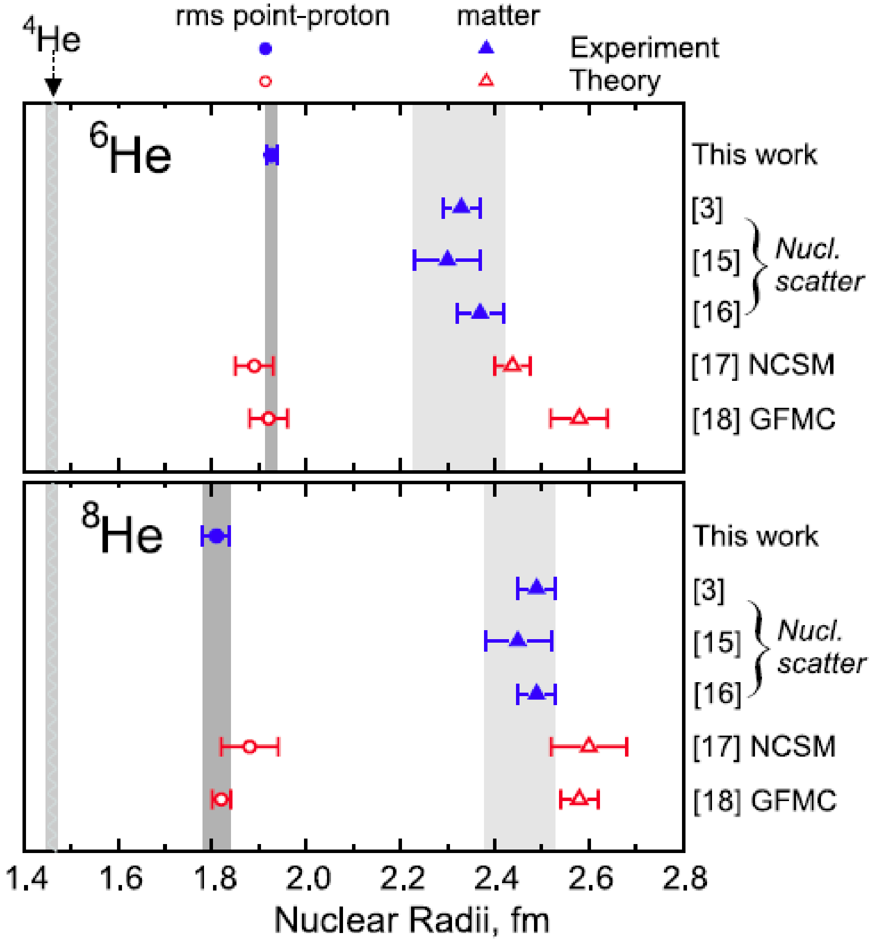


Nuclear Charge Radius of ^8He

P. Mueller, I. A. Sulai, A. C. C. Villari, J. A. Alcántara-Núñez, R. Alves-Condé, K. Bailey, G. W. F. Drake, M. Dubois, C. Eléon, G. Gaubert, R. J. Holt, R. V. F. Janssens, N. Lecesne, Z.-T. Lu, T. P. O'Connor, M.-G. Saint-Laurent, J.-C. Thomas, and L.-B. Wang

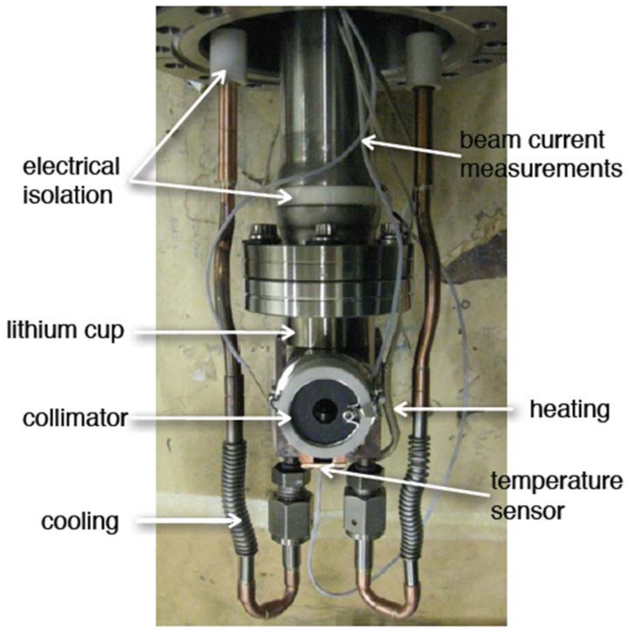
Phys. Rev. Lett. 99, 252501 – Published 21 December 2007

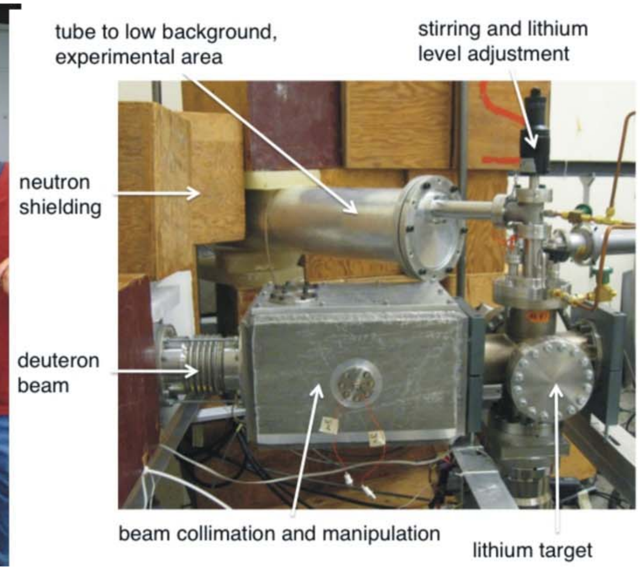
Cited 82 times - Show Abstract - View PDF



Trapping of radioactive He isotopes and charge radius measurement achieved by ANL group (Z.-T. Lu, P. Mueller et al.)

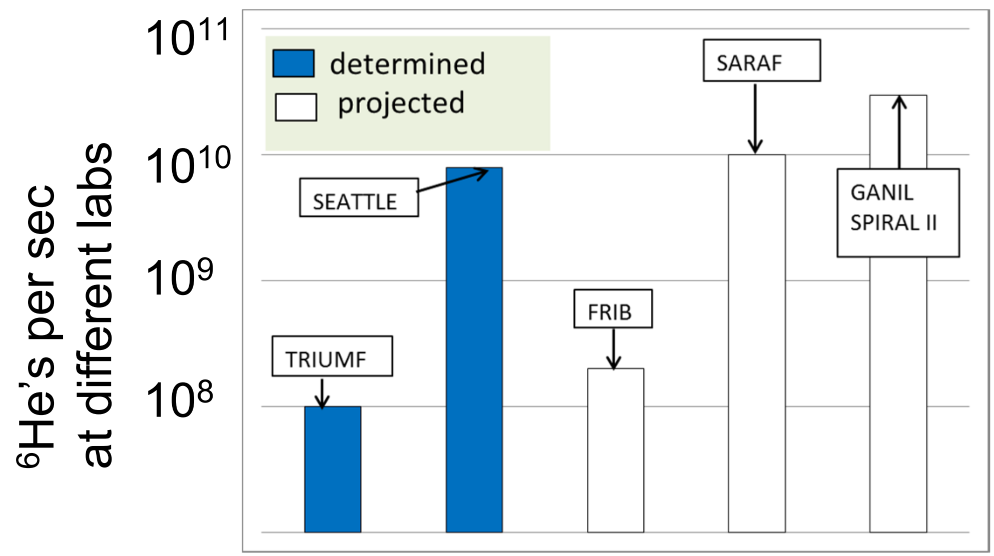
Now have ~10^{10} atoms of ^6He/s at Seattle via $^7Li(d,^3He)^6He$





Now have a reliable source of ^6He yielding ~8 × 10^9 atoms/s in a clean room!

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



"Allowed" decays

$$H = \overline{\Psi}_f \gamma^{\mu} \Psi_i \quad 2C_V \, \overline{e}^L \gamma_{\mu} \nu_e^L + \overline{\Psi}_f \gamma^{\mu} \gamma_5 \Psi_i \quad 2C_A \, \overline{e}^L \gamma_{\mu} \gamma_5 \nu_e^L$$

`Vector'

`Axial Vector'

Nucleons move slowly

$$V_{\mu} \equiv \varphi_f \left(\gamma_{\mu} I^{\pm} \right) \varphi_i = \varphi_f (1, \frac{\vec{v}}{c}) I^{\pm} \varphi_i \approx \varphi_f (1,0) I^{\pm} \varphi_i$$

Simplest operator !

$$A_{\mu} \equiv \varphi_f \left(\gamma_{\mu} \gamma_5 I^{\pm} \right) \varphi_i = \varphi_f (\frac{\vec{v}}{c} . \vec{\sigma}, \vec{\sigma}) I^{\pm} \varphi_i \approx \varphi_f (0, \vec{\sigma}) I^{\pm} \varphi_i$$

Spin-flip

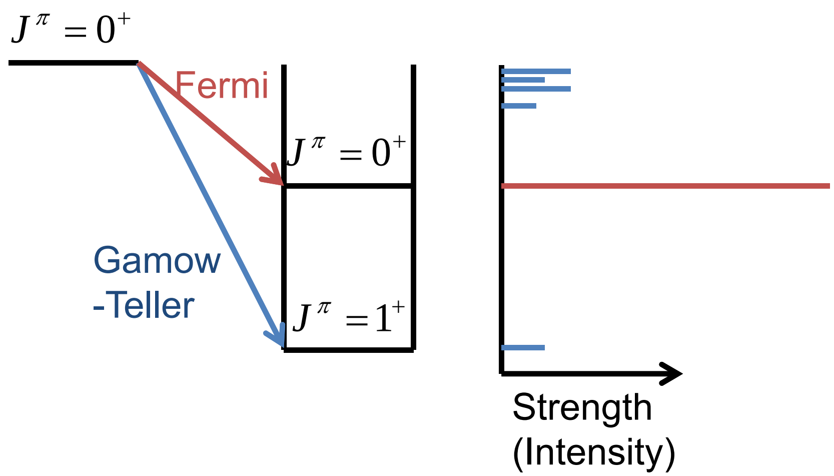
$$\left\langle \varphi_f \left(\gamma_{\mu} \right) \varphi_i \right\rangle \approx \int d^3x \, \varphi_f^* \, I^{\pm} \varphi_i$$

$$\left\langle \varphi_f \left(\gamma_{\mu} \gamma_5 \right) \varphi_i \right\rangle \approx \int d^3x \, \varphi_f^* \vec{\sigma} \, I^{\pm} \varphi_i$$

$\Delta \vec{J}^{\pi} = \vec{0}^{+}$ "Fermi"

$\Delta J^{\pi} \equiv \vec{1}^{+}$ "Gamow-Teller"

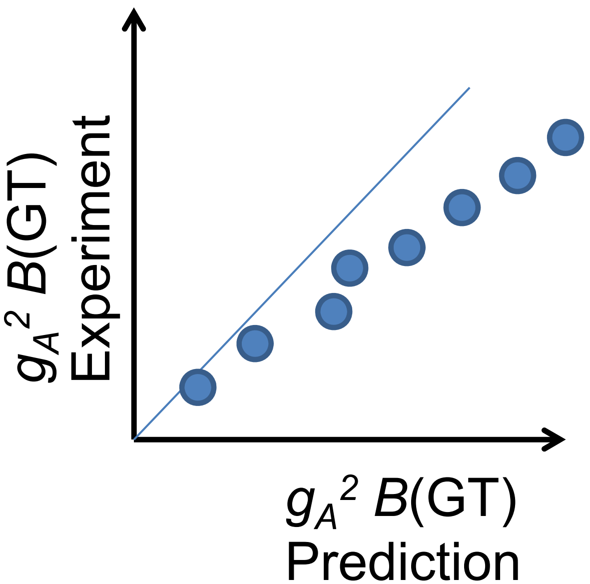
Typical decays



Gamow-Teller operator is good to probe nuclear wave functions calculations because:

1) No radial dependence → selection rule prevents connection to other shells
2) Good spread over daughter excitation energies

Problem: when comparing calculations with experiment found less strength than predicted: `quenching of g_A'.



g_A (neutron) ~ 1.27

g_A (sd-shell OXBASH) ~1.00

One source of the problem:

Calculations are performed in a reduced shell-model space

$$\left\langle \Psi_f P^{-1} \middle| P\sigma\tau P^{-1} \middle| P\Psi_i \right\rangle \neq \left\langle \Psi_f P^{-1} \middle| \sigma\tau \middle| P\Psi_i \right\rangle$$

P : projection operator into the reduced space.
The renormalization of g_A is to account for using a reduced space.

Should be called *The enhancement of the GT strength*. It is a shortcoming in the prediction and the renormalization factor depends on the size of the space used.

VOLUME 74, NUMBER 9 PHYSICAL REVIEW LETTERS 27 FEBRUARY 1995

Missing and Quenched Gamow-Teller Strength

E. Caurier,[1] A. Poves,[2] and A. P. Zuker[1]
[1]*Groupe de Physique Théorique, CRN IN2P3–CNRS/Université Louis Pasteur, B.P. 20, F–67037 Strasbourg Cedex 2, France*
[2]*Departamento de Física Teórica, Universidad Autónoma de Madrid, 28049 Madrid, Spain*
(Received 12 January 1994; revised manuscript received 14 June 1994)

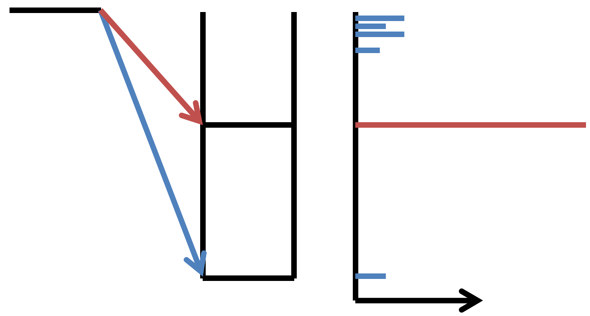
Gamow-Teller strength functions in the resonance region are calculated in the full $(pf)^8$ space. The observed profile is very sensitive to the level density and may become so diluted as to be confused with background. A model independent proof is given that standard quenching originates in nuclear correlations, and that some 30% of the total strength must be due to states outside the $(pf)^8$ space. By combining this argument with the results of shell model calculations, comparison with the $^{48}Ca(p,n)^{48}Sc$ experimental data strongly suggest that most of the strength that is currently thought to be missing is actually observed.

Can one do better than just looking at individual transitions?

Ikeda sum rule: $<\sigma^2>=3$ implies

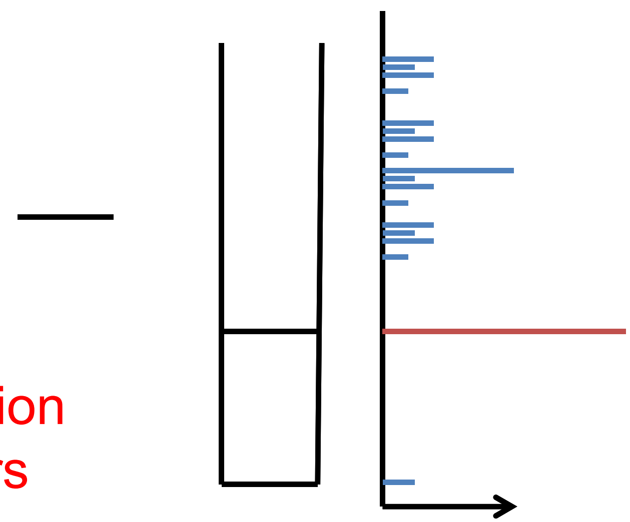
$$\sum_f B_f(GT^+) - \sum_{f'} B_{f'}(GT^-) = 3(Z-N)$$

Problem: Beta decays usually cover only low excitation energies.



Solution: Use instead charge exchange reactions.
Example: (*p*,*n*) has same quantum numbers as beta decay.

Great improvement in recent years: better energy resolution; detailed studies; resolution of many old puzzles (see talks by R. Zegers and D. Frekers).



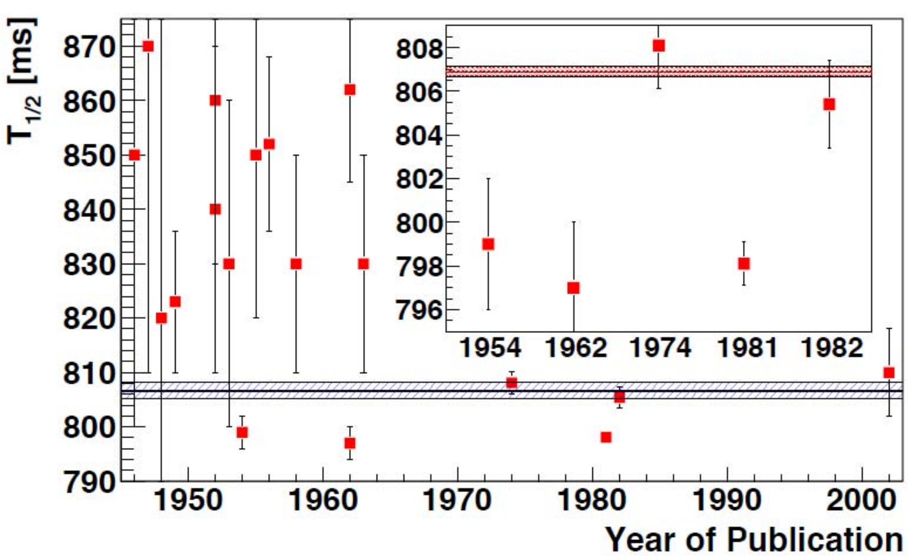
^{6}He and ^{3}H: very simple transitions; light enough for ab-initio calculations.

The decay of ^{3}H is used to determine the Nucleon-Delta excitation effect and it turns out to be small (2% correction). Several `ab-initio' calculations show agreement at the few percent level:

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

However, experimental situation was somewhat unclear.

Veintraub et al.
…our accuracy in estimating the GT matrix element is at the level of per mil… validates the use of the 6He β-decay as a testing ground for an axial MEC model.



Extracting g_A from the lifetime of ^6He

Experimental Setup

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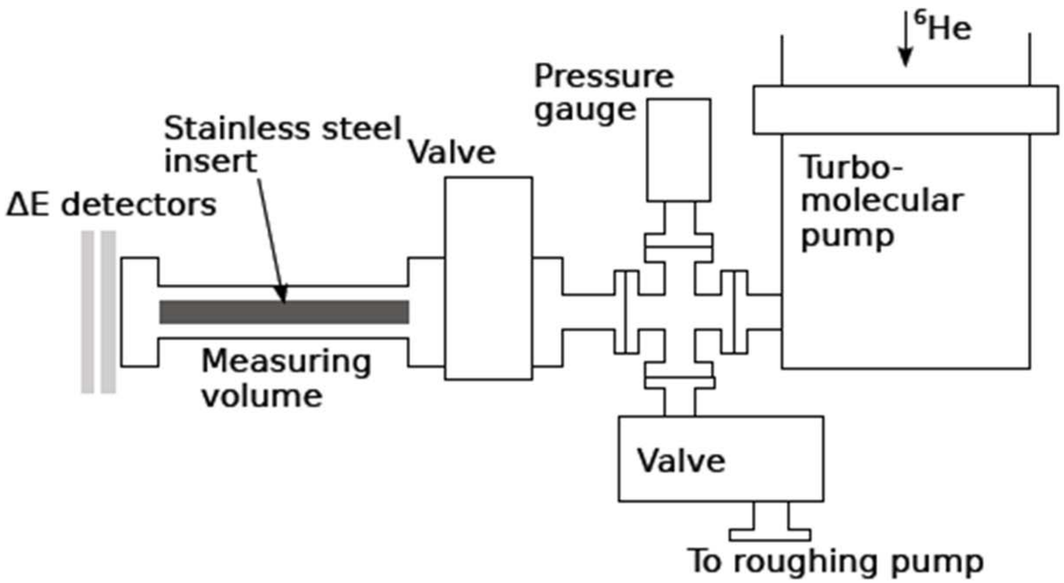
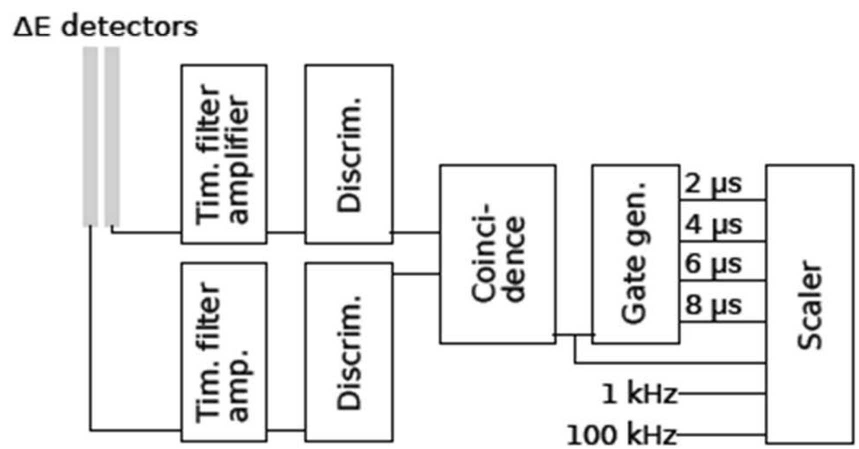


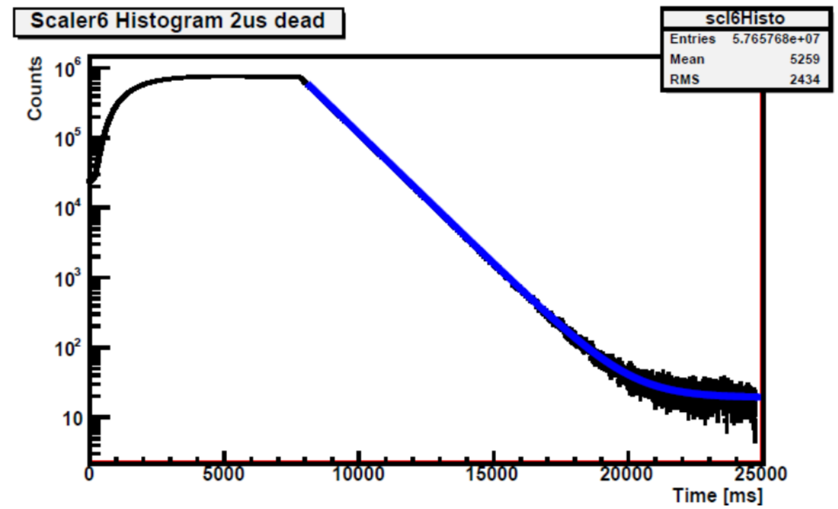
- Stainless steel measuring volume with insert to check for diffusion
- Scaler based DAQ

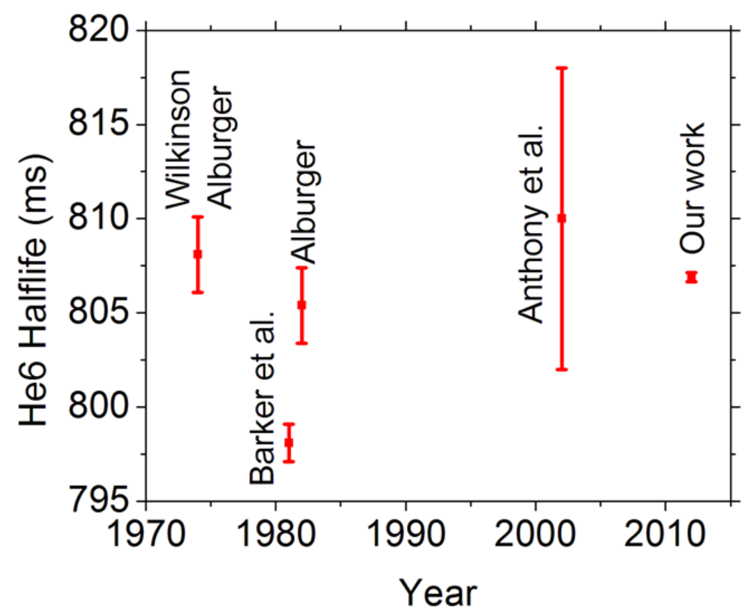


Extracting g_A from the lifetime of ^{6}He

- Two previous experiments disagreed by 9 ms. Resolved the discrepancy.
- Our results in combination with ab-initio calculations shows that quenching is at most about 2%.

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





Overview of Calculations

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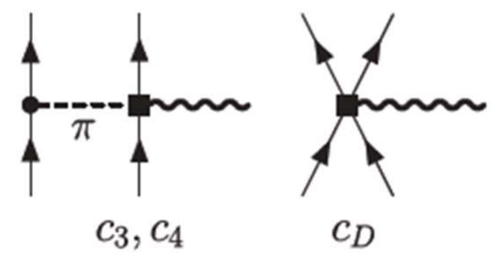
- Schiavilla and Wiringa, Phys. Rev. C **65**, 054302 (2002)
  - Argonne v_{18} two-nucleon and Urbana-IX three nucleon interaction
  - Including meson-exchange current fixed to ^3H
  - Variational Monte Carlo calculation
- Navratil and Ormand, Phys. Rev. C **68**, 034305 (2003)
  - Argonne V8' two-nucleon and Tucson-Melbourne TM'(99) three nucleon interaction
  - Ab-initio shell model calculation
- Pervin, Pieper and Wiringa, Phys. Rev. C **76**, 064319 (2007)
  - Argonne v_{18} two-nucleon and Illinois-2 three nucleon interaction
  - Variational and Green's function Monte Carlo calculation
- Vaintraub, Barnea and Gazit, Phys. Rev. C **79**, 065501 (2009)
  - J-matrix inverse scattering (JISP16) two-nucleon potential for wave functions
  - Including meson-exchange current fixed to ^3H
  - Chiral perturbation theory calculation

The Influence of MEC

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 ^3H 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

Long range Short range



Missing and Quenched Gamow-Teller Strength

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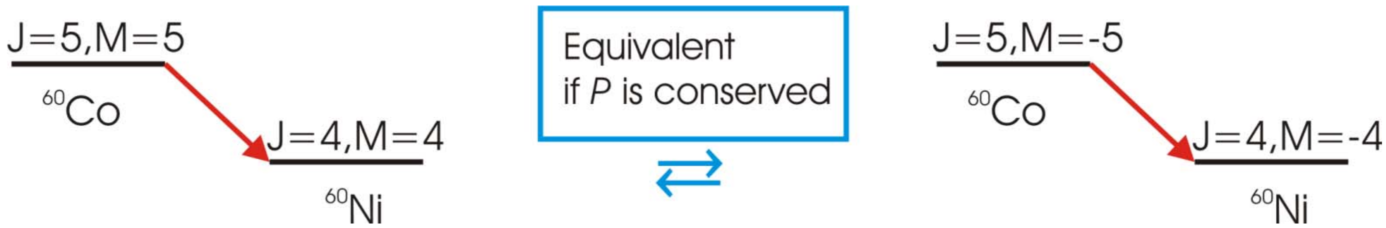
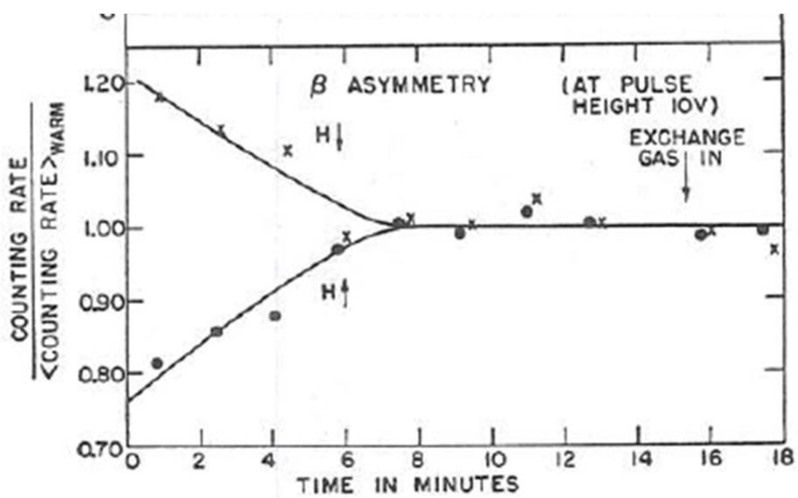
Helicities and nuclear beta decays: Parity Violation (56 years!)

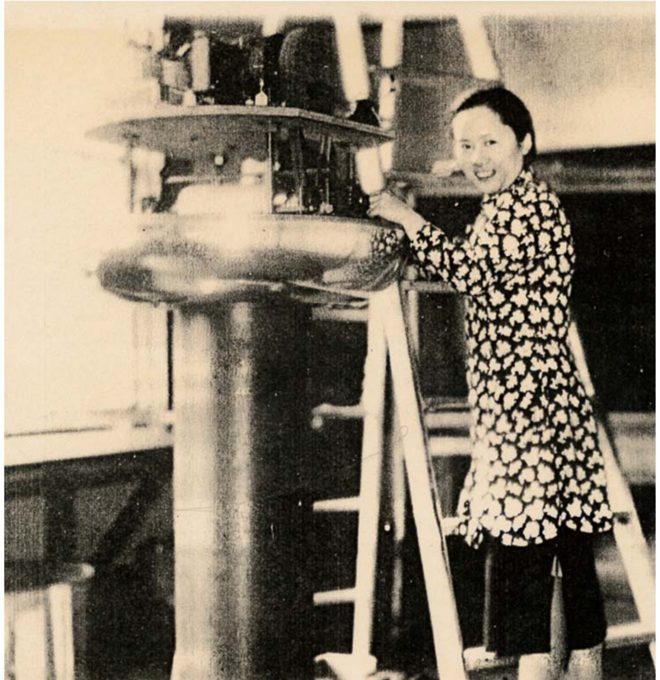
$$P\,\vec{r} = -\vec{r}$$
$$P\,\vec{p} = -\vec{p}$$
$$P(\vec{r}\times\vec{p}) = (\vec{r}\times\vec{p})$$

P inverts coordinates and momenta, but *not* angular momenta → If *P* were conserved electrons should come out isotropically from polarized ^{60}Co.



Electrons come mostly opposite the polarization of ^{60}Co.

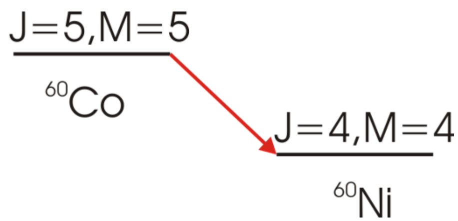


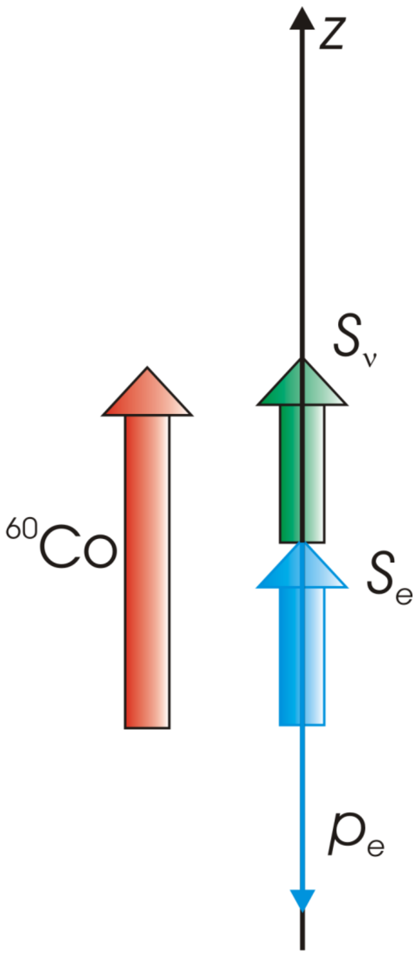


Chien-Shiung Wu (b. 1912)
Nuclear Physicist

Helicities and nuclear beta decays: Parity Violation

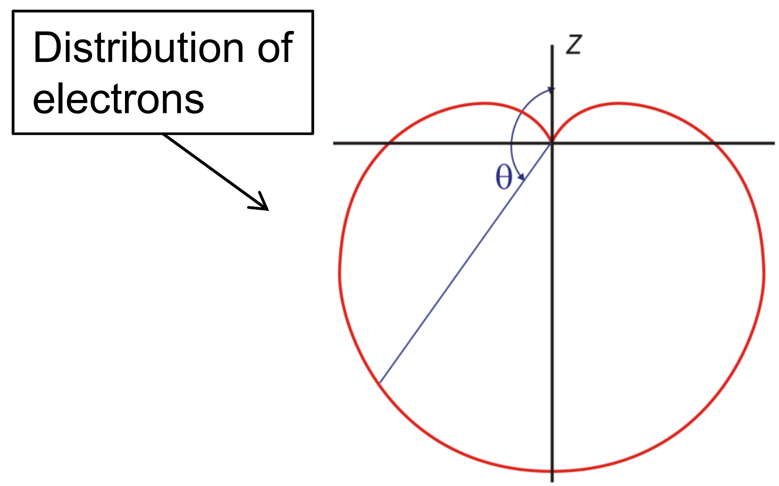
What makes electrons come out preferentially opposite the polarization?





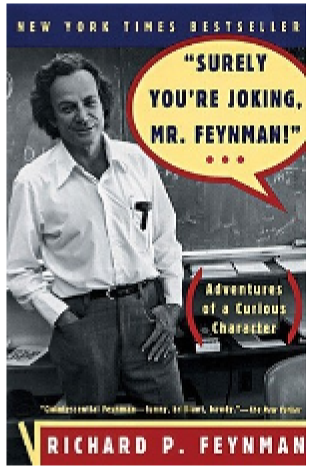
1) Conservation of Ang. Mom.: e and ν spins have to align along the direction of initial polarization.

2) e's are left handed (momentum preferentially opposite spin).



“*The 7 percent solution*” in

The thrill of knowing an important law that nobody understood and the ability to ignore an incorrect experiment (6He)



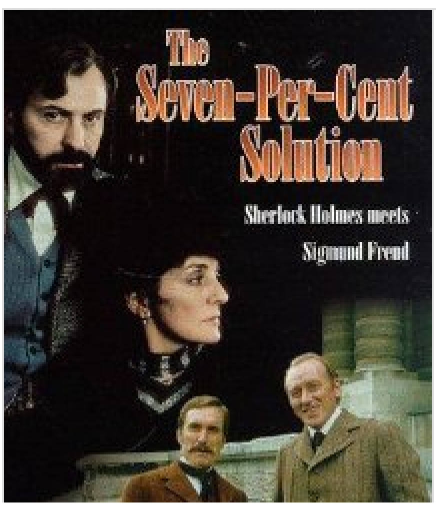
Surely You're Joking, Mr. Feynman!

by Richard P. Feynman

4.32 · rating details · 38,201 ratings · 1,535 reviews

Richard Feynman (1918-1988), winner of the Nobel Prize in physics, thrived on outrageous adventures. Here he recounts in his inimitable voice his experience trading ideas on atomic physics with Einstein and Bohr and ideas on gambling with Nick the Greek; cracking the uncrackable safes guarding the most deeply held nuclear secrets; painting a naked female toreador - and muc...more

Paperback, 352 pages



The Seven-Per-Cent Solution (1976)

SEE RAN

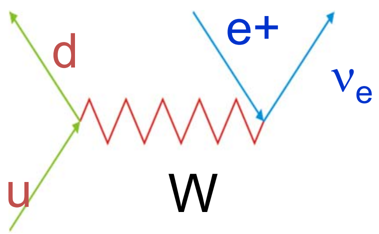
PG 113 min - Adventure | Comedy | Crime - 2 June 1977 (Netherlands)

The Seven-Per-Cent Solution was ranked ninth in the *Publishers Weekly* list of bestselling novels from 1974 and made the *The New York Times* Best Seller list for forty weeks between September 15, 1974 and June 22, 1975.[1]

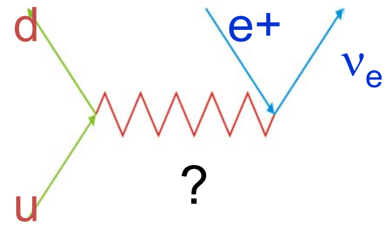
To treat his friend's cocaine induced delusions, Watson lures Sherlock Holmes to Sigmund Freud.

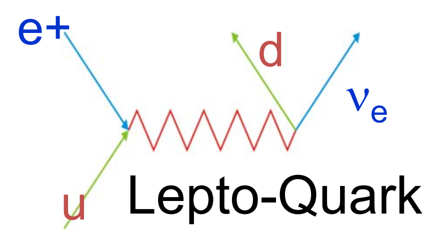
Searches for Scalar and Tensor currents.

Are weak decays carried only by W's?



Or is there something new?





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

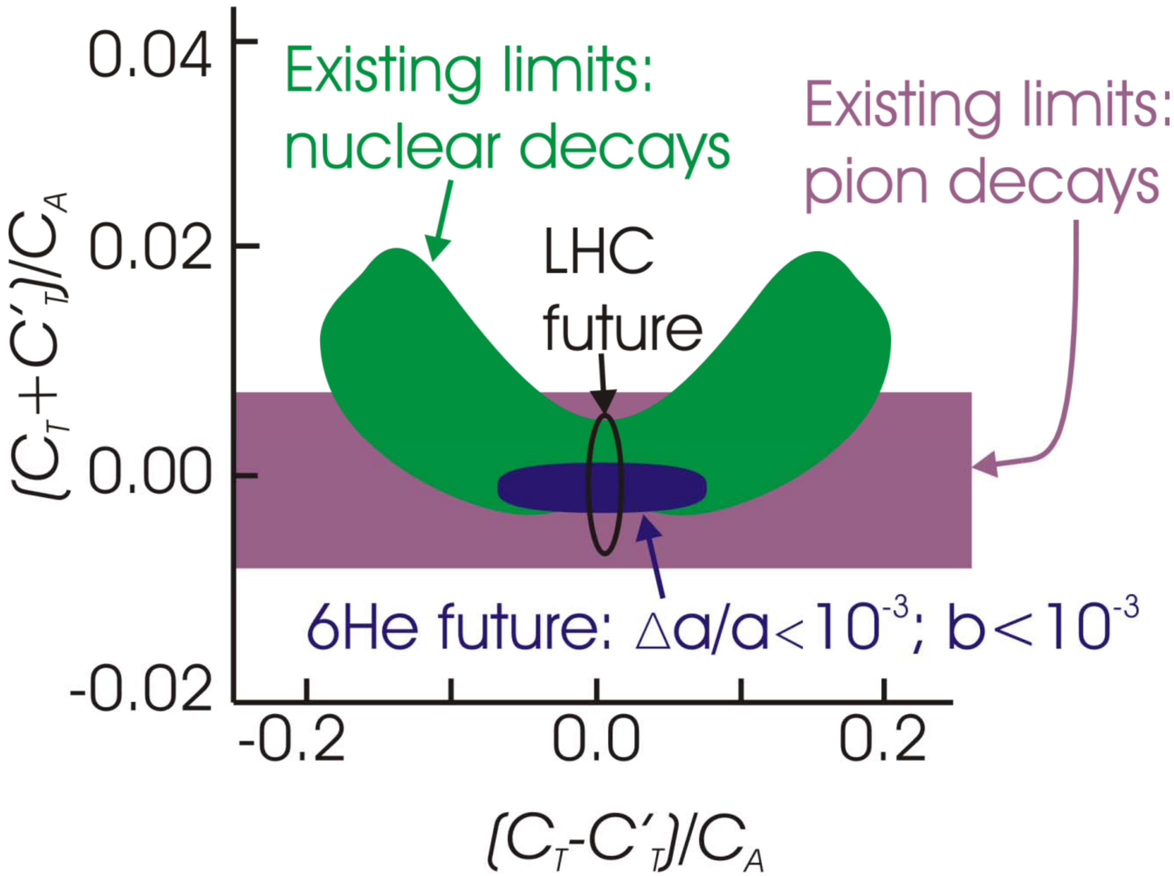
Decay rate:

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

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

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

Precision beta decay versus pion and “LHC”:
(Wauters et al. ArXiv)
Can “precision” compete with “energy”? Yes.

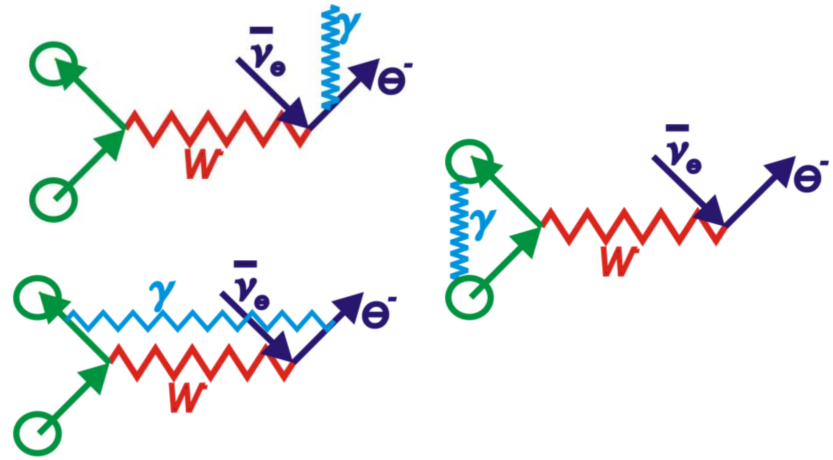


6He:
"recoil order"

$$C_V\int\vec{\alpha}\times\vec{r} \rightarrow \frac{f_V}{M}\left[\int\tau^+\vec{\sigma}+\int\tau^+\vec{r}\times\vec{p}\right]-2f_{WM}\int\tau^+\vec{\sigma}$$

$$C_A i\int\gamma_5\vec{r} \rightarrow g_A i\int\tau^+\vec{\sigma}\times\vec{l}$$

… and radiative corrections.



Small and under control for 6He decay.

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

6He collaboration

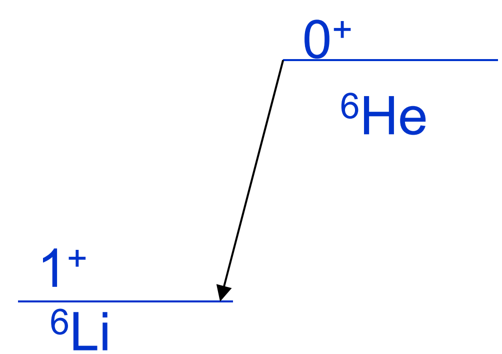
P. Muller, A. Leredde
Argonne National Lab

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

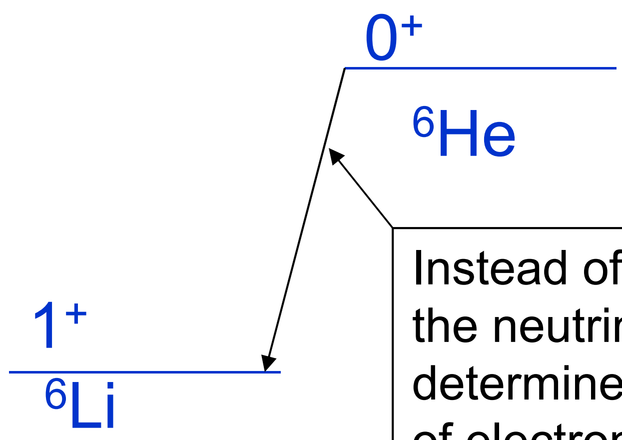
O. Naviliat-Cuncic
NSCL, Michigan State University

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

- Simple decay (~100% to ground state)
- Pure Gamow-Teller decay
- Half-life appropriate for trapping (~1 sec)
- Large Q-value, good for seeing effects of ν
- Noble gas $\rightarrow$ no worries about chemistry
- Simple nuclear structure



Searching for tensor currents in 6He



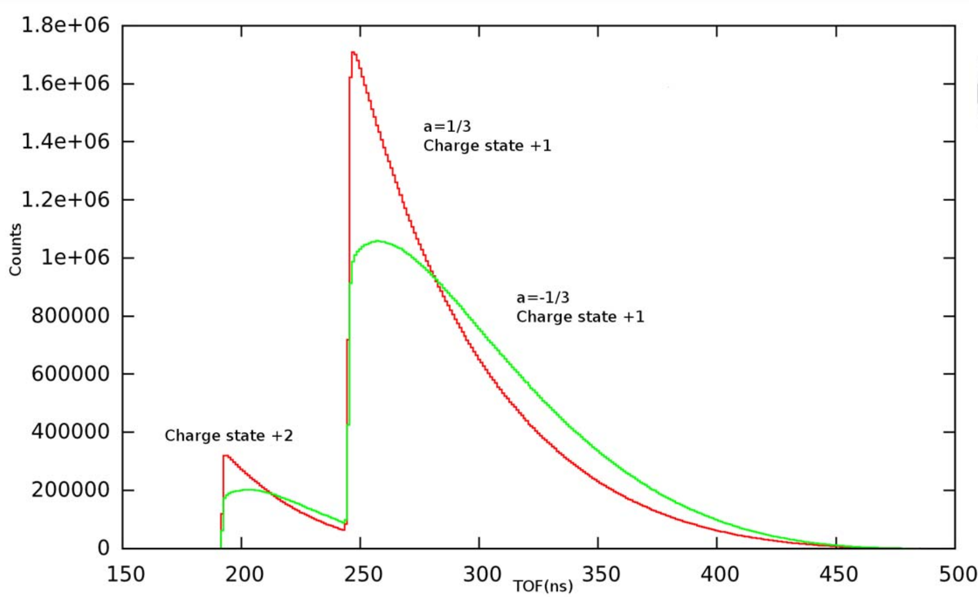
Instead of detecting the neutrino, determine momentum of electron and 6Li.

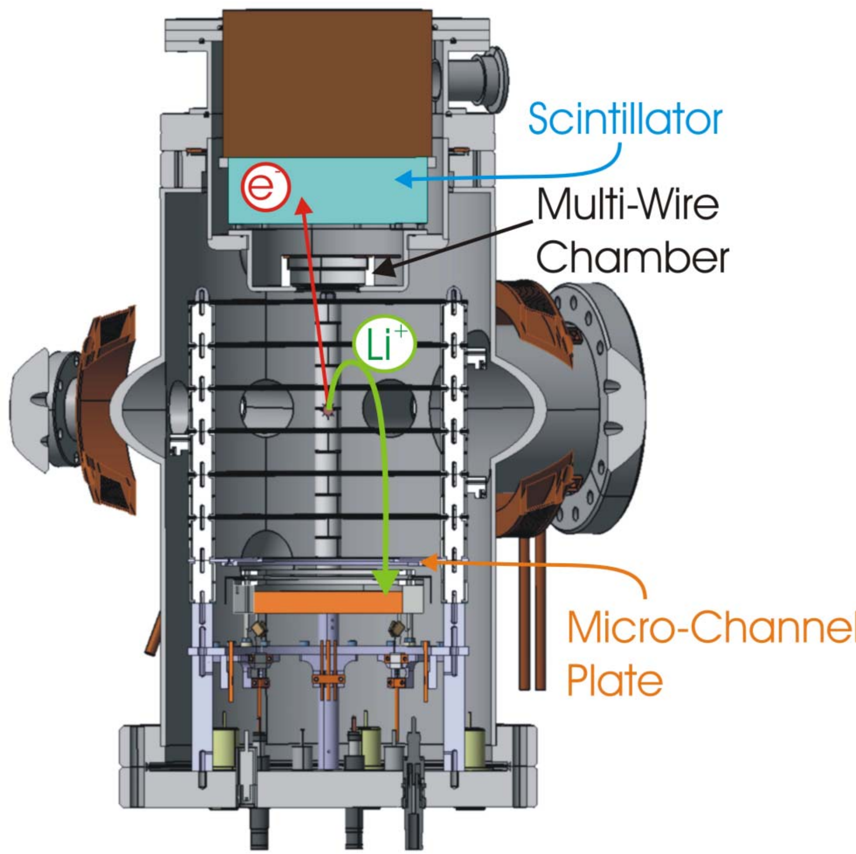
Problem: slow 6Li, will loose momentum in ANY supporting layer.

Solution: hold 6He with light.

^{6}He Little a, detection

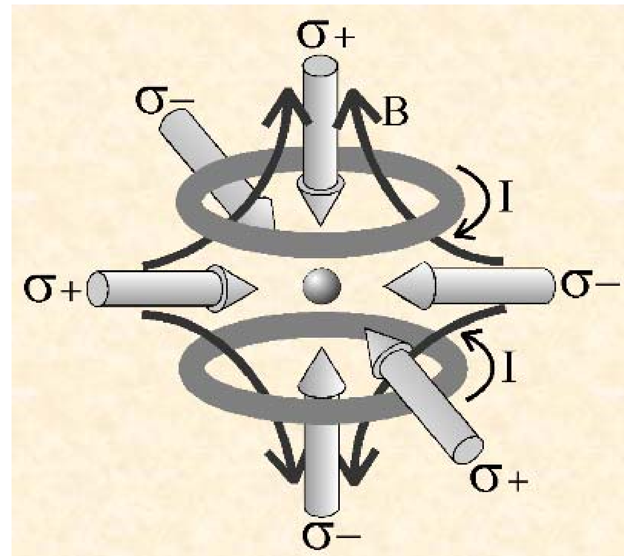
- Electron and ^{6}Li recoil nucleus detected in coincidence
- ΔE-E scintillator system for electron detection (energy, start of time-of-flight)
- Micro-channel plate detector for detection of recoil nucleus (position,





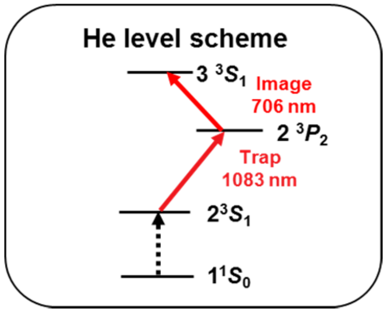
Magneto-Optical Trap

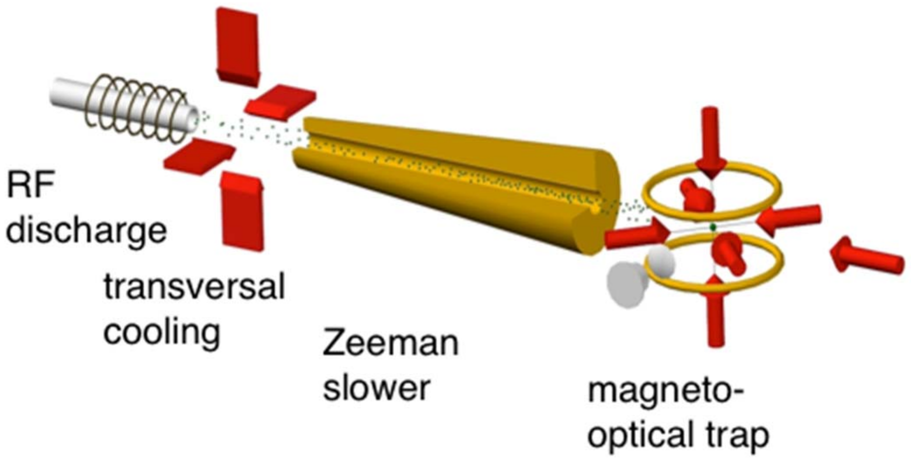
- Six orthogonal, counter-propagating beams of opposite circular polarization are red-detuned as in the Doppler cooling configuration
- Anti-Helmholtz coils introduce a quadrupole field with zero magnetic field at the center and linearly increasing field in the directions of the lasers

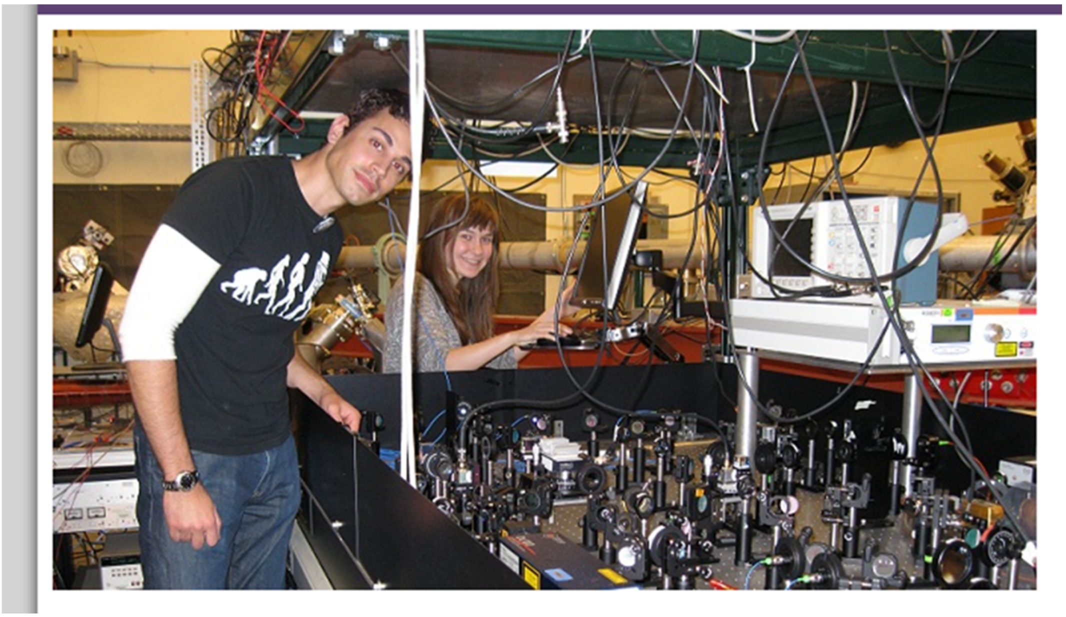


Trapping of ^{6}He

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

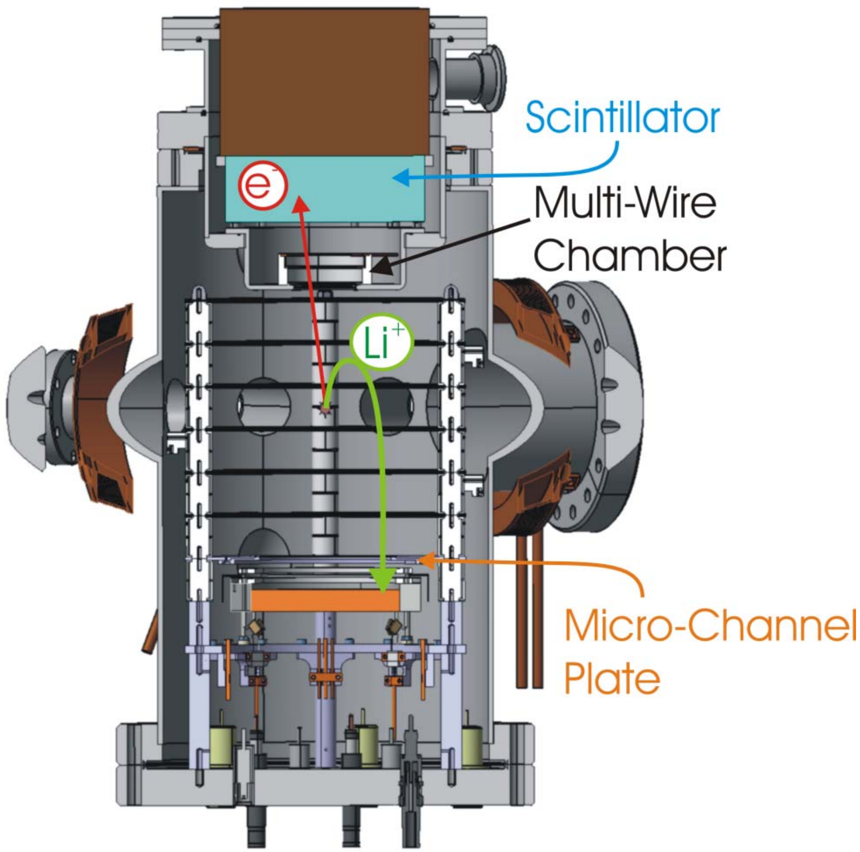


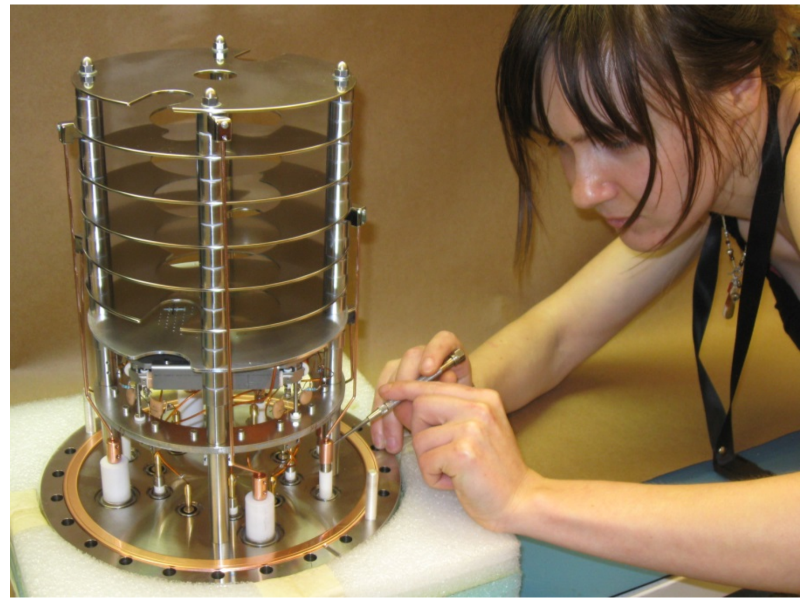


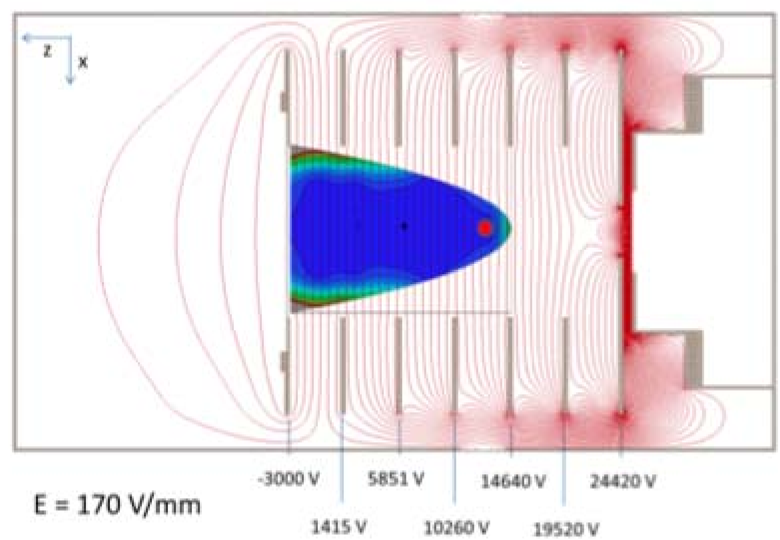


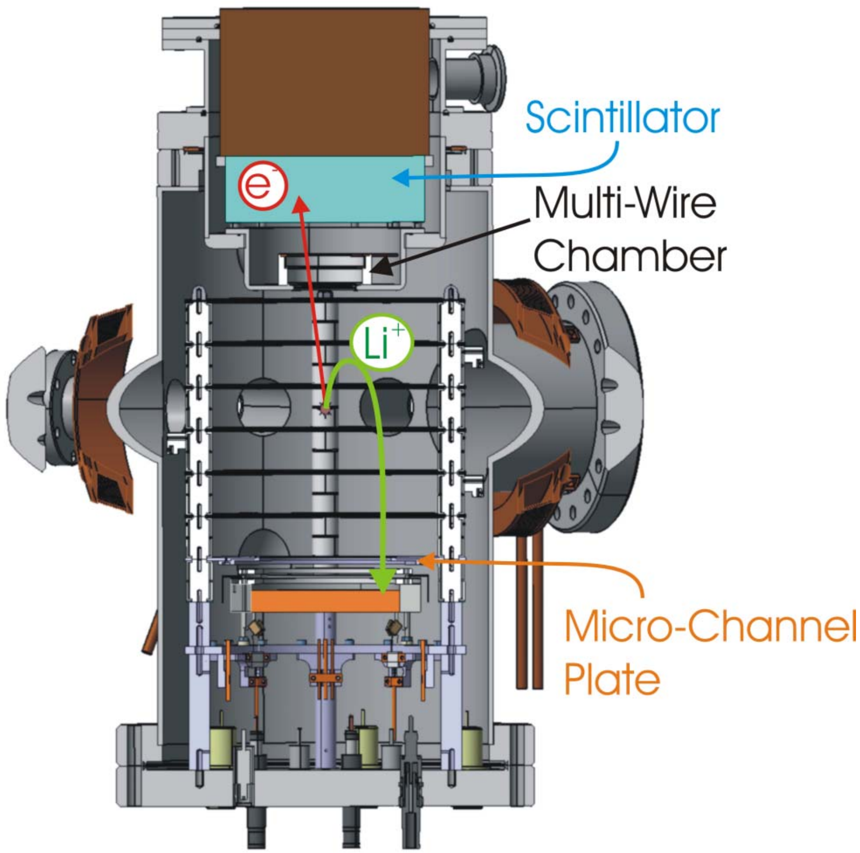
- Trapped atoms transferred to detection chamber with 2nd MOT
- Based on experience from ^{6}He, ^{8}He charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL **93**, 142501 (2004)
  P. Mueller et al., PRL **99**, 252501 (2007)

Electric field (1.7 kV/cm) guides ^{6}Li ions.

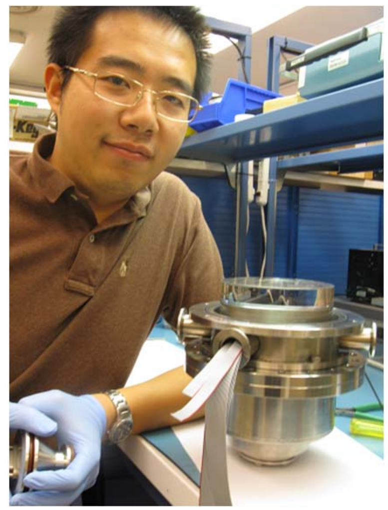


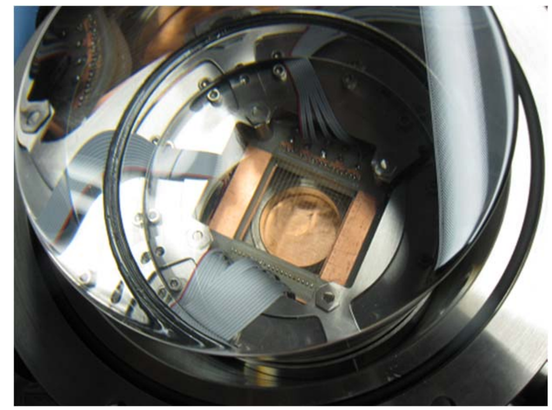


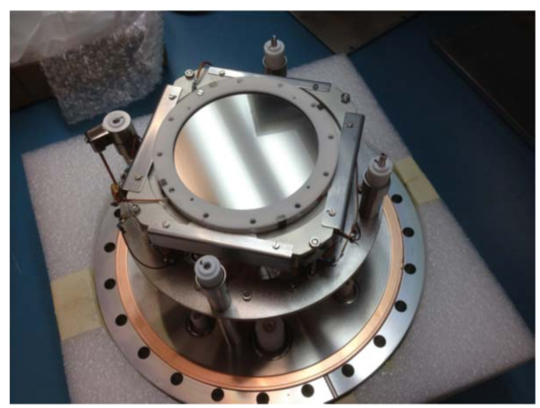




ΔE-E scintillator system for electron detection (energy, start of time-of-flight)

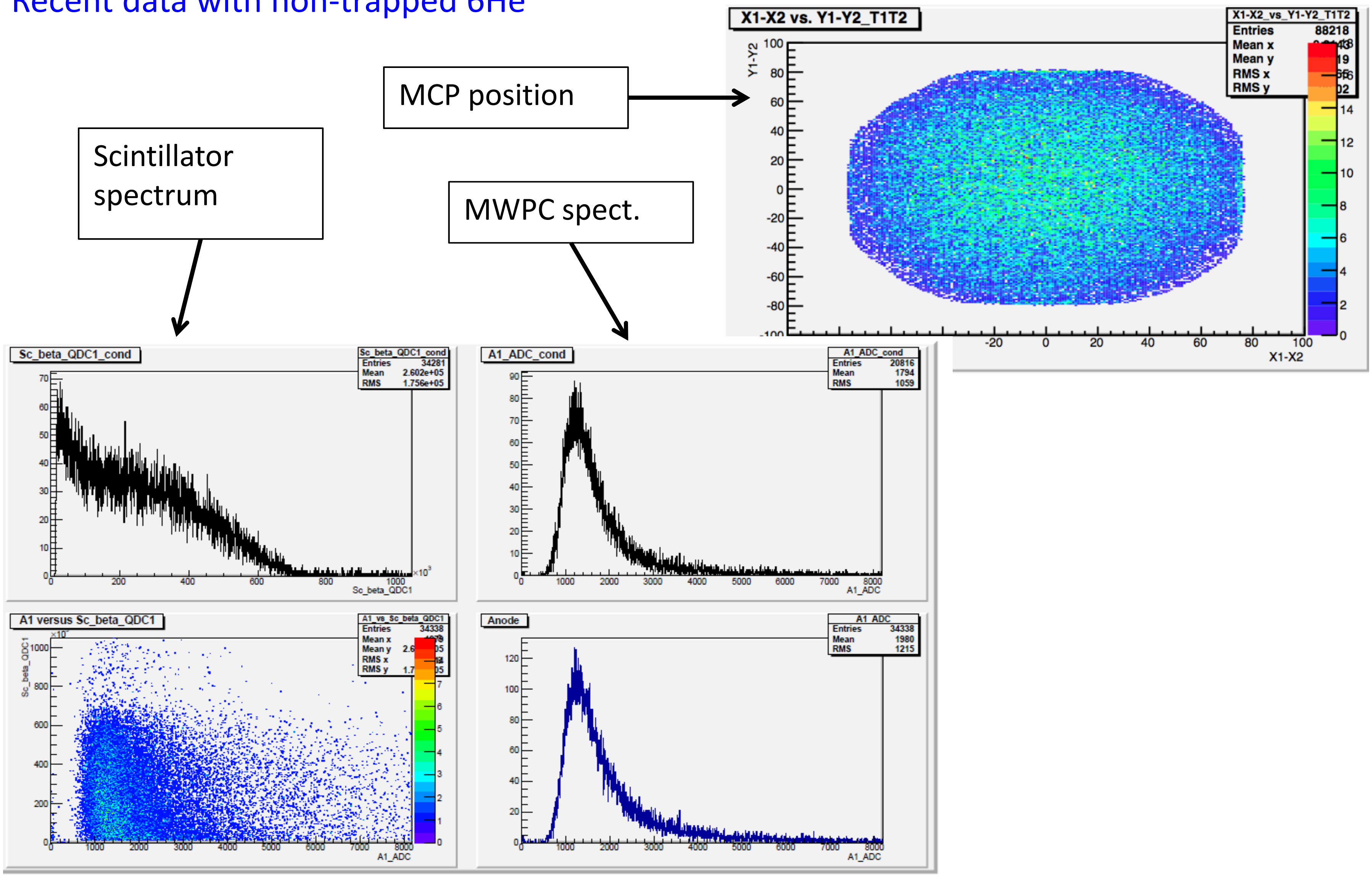






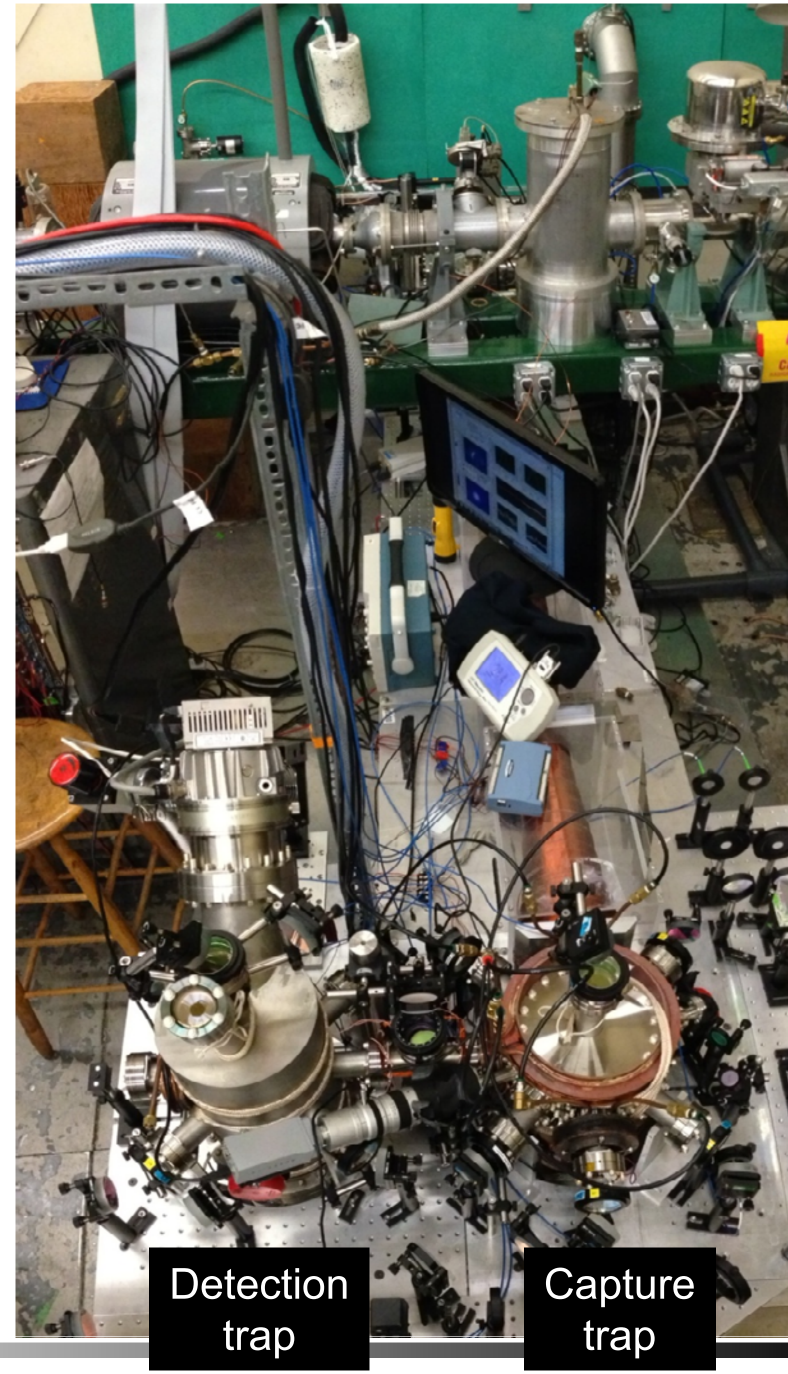
Micro-channel plate detector for detection of ^{6}Li recoil nucleus (position, time-of-flight)

Recent data with non-trapped 6He



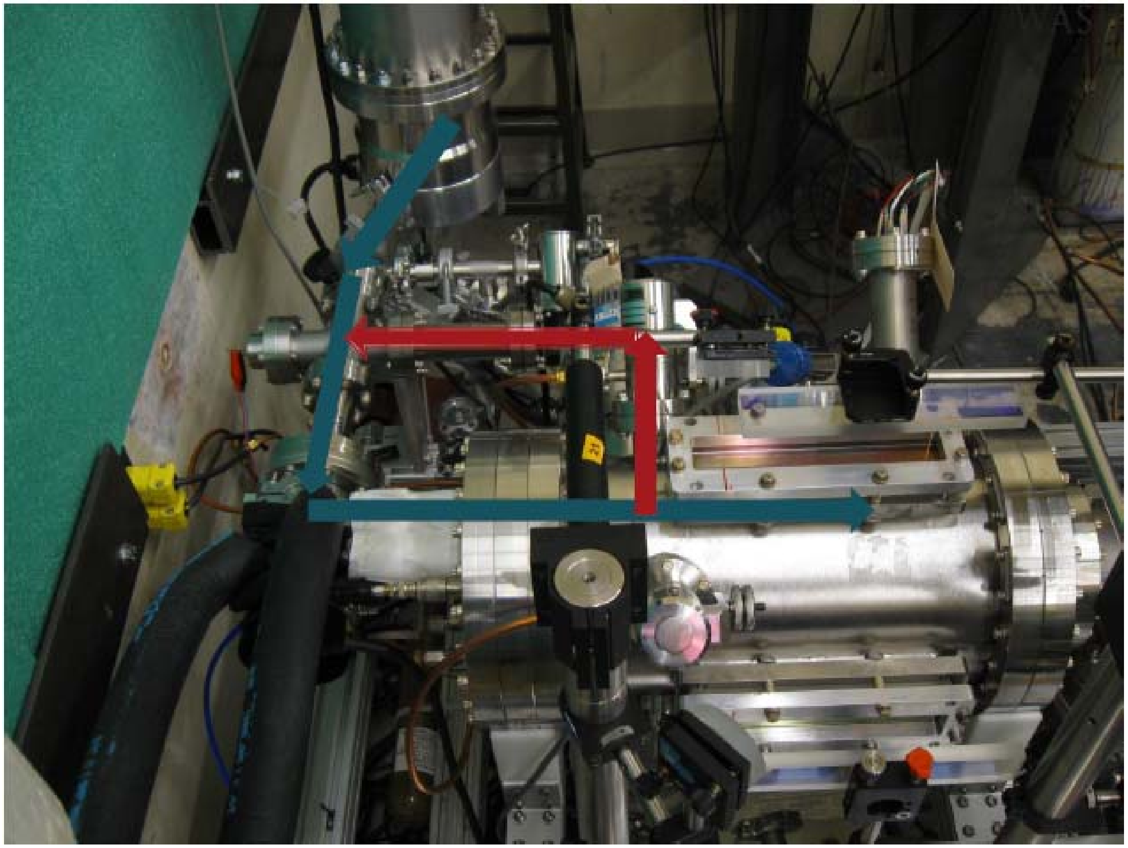
^{6}He little-a outlook

- Have trapped 500-1000 6He atoms. Presently working towards longer stability for a 1-week long experiment.
- Detection systems working.
- First data run planned for later in 2013.
- Aiming for a 0.1% determination of little a by 2015.
- R&D for spectrum shape determination.



Backup slides

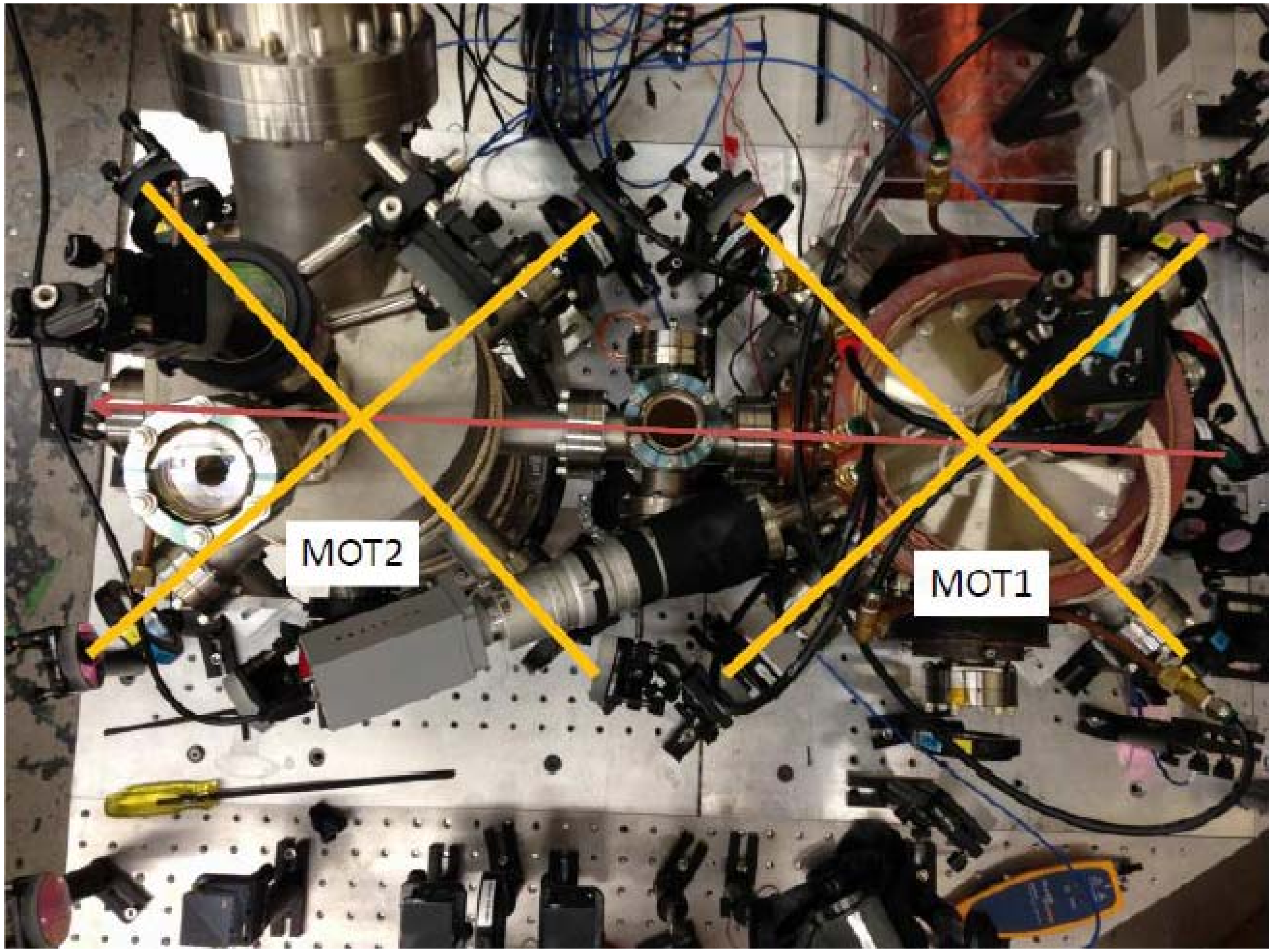
Recirculation of 6He to improve yield



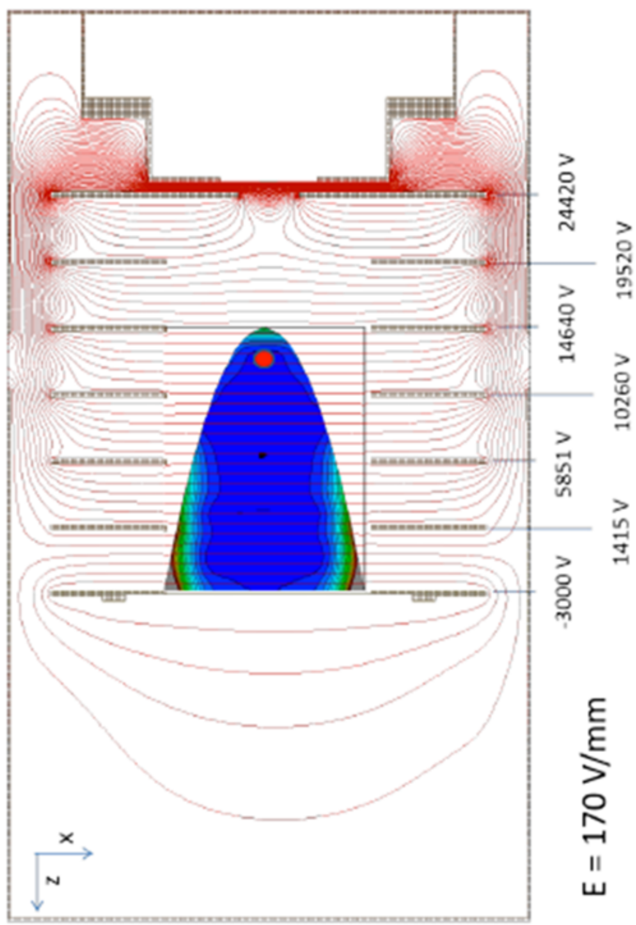
Expected a factor of 5 improvement but so far only 3.

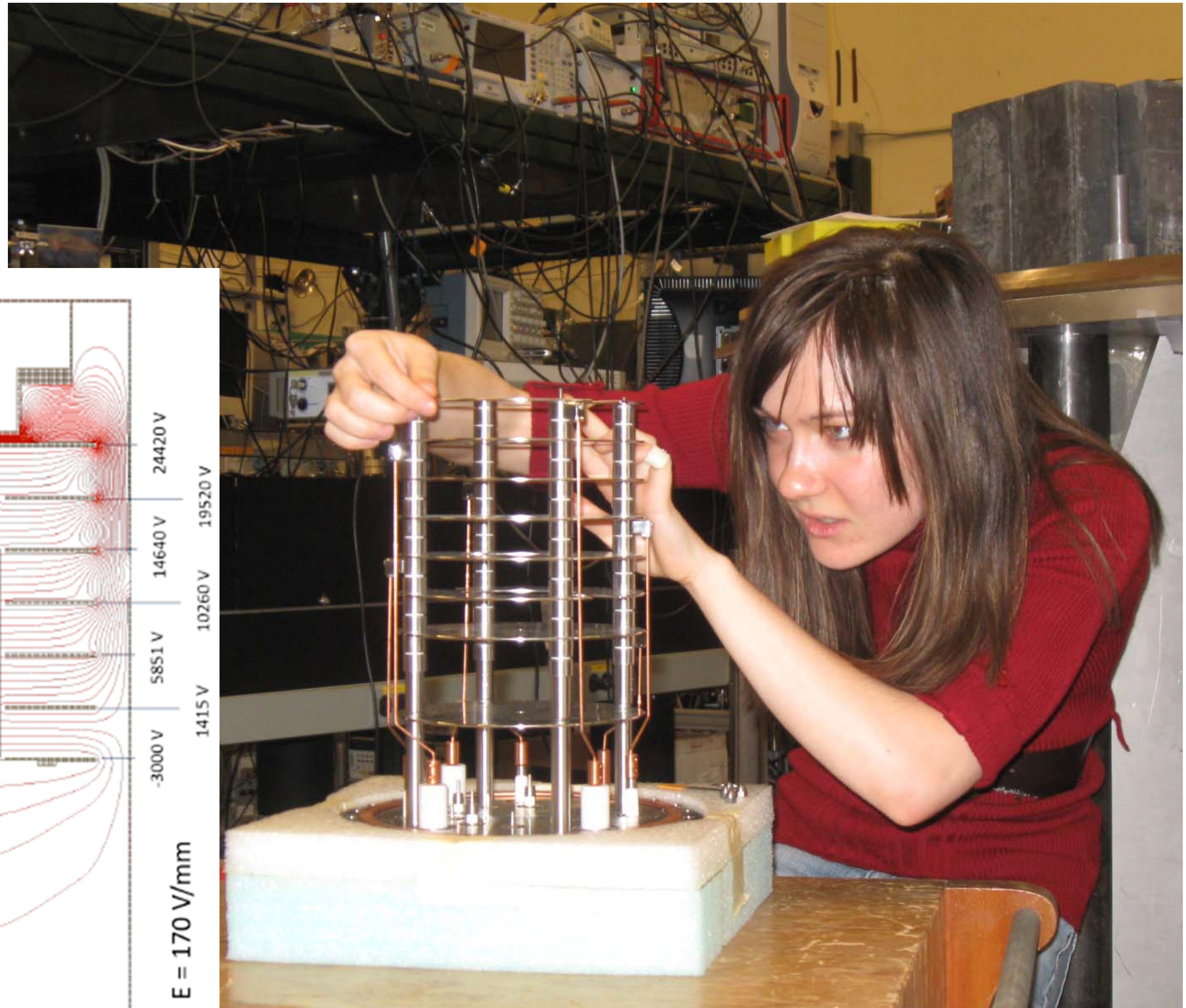
Discharge plasma conditions changed with recirculation.

MOT-to-MOT transfer to decrease 6He's in ground state



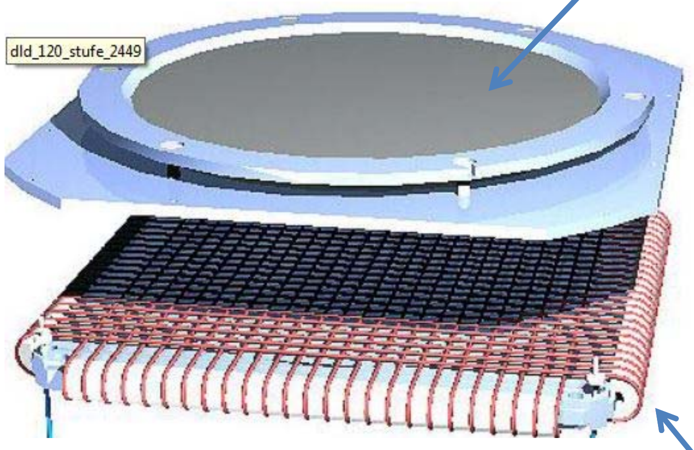
Electric field of apprx 2 kV/cm to guide 6Li ions.

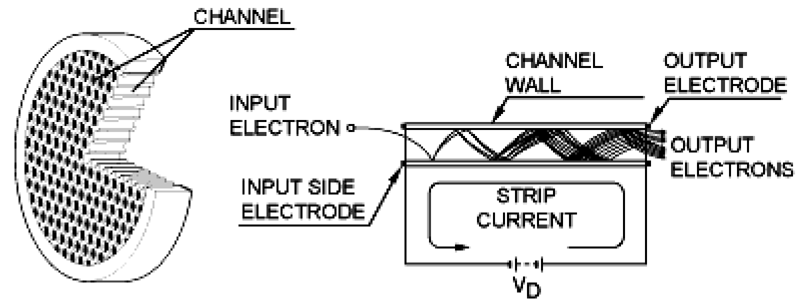




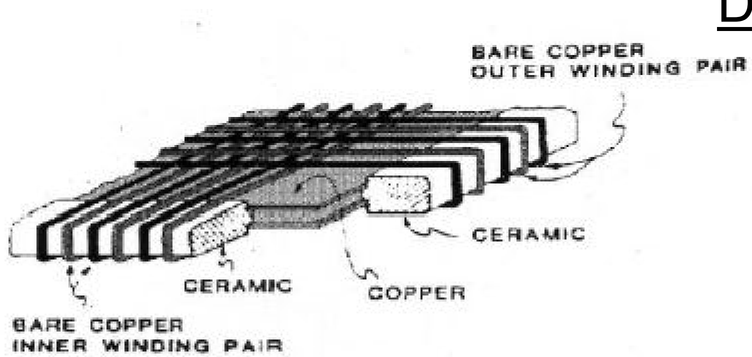
MCPPSD (micro chanel plates with delay line anodes)

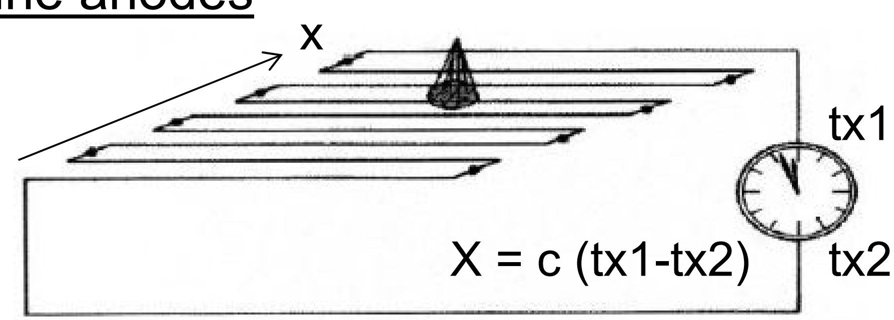
MCPs (micro channel plates)





Delay line anodes

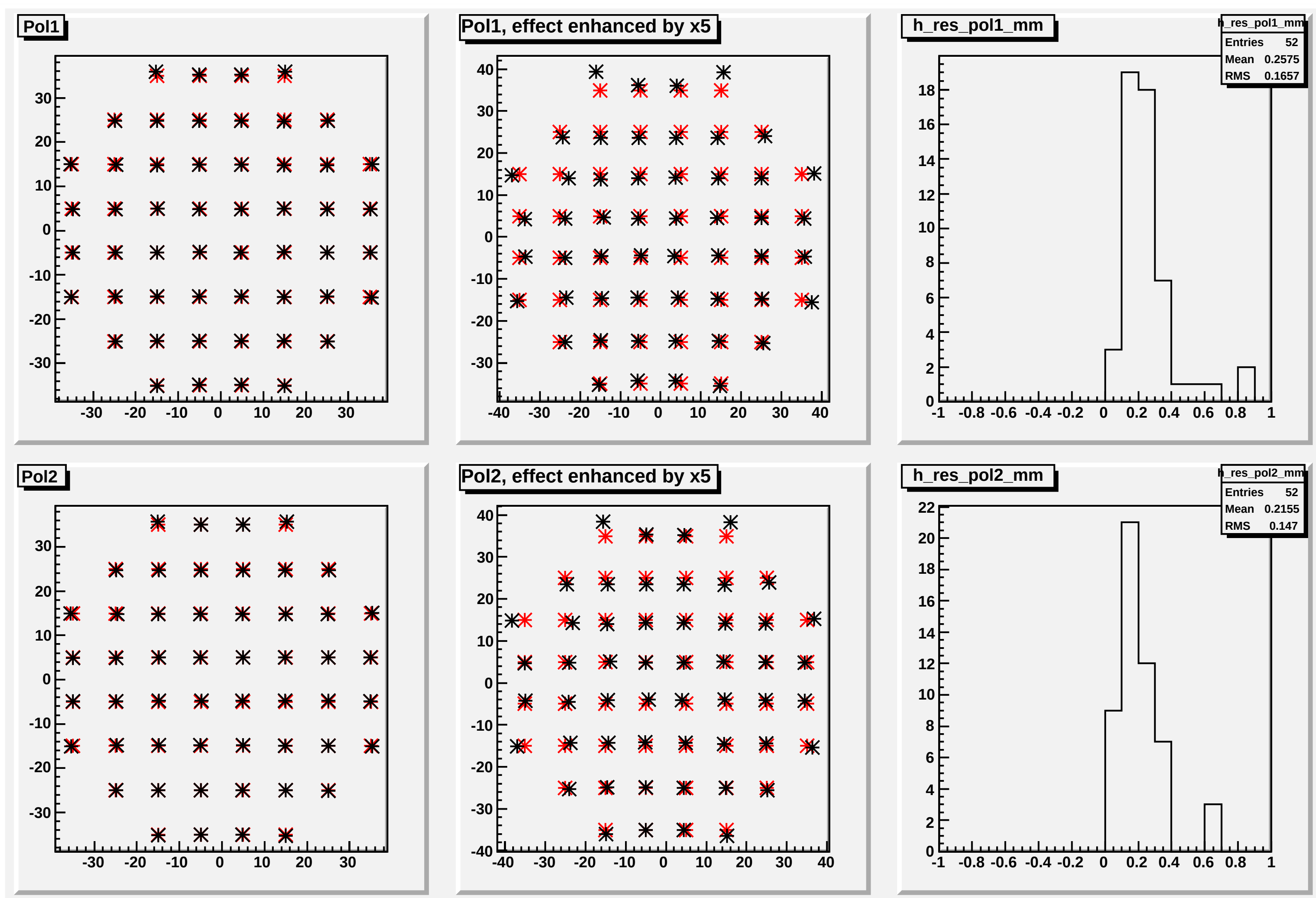




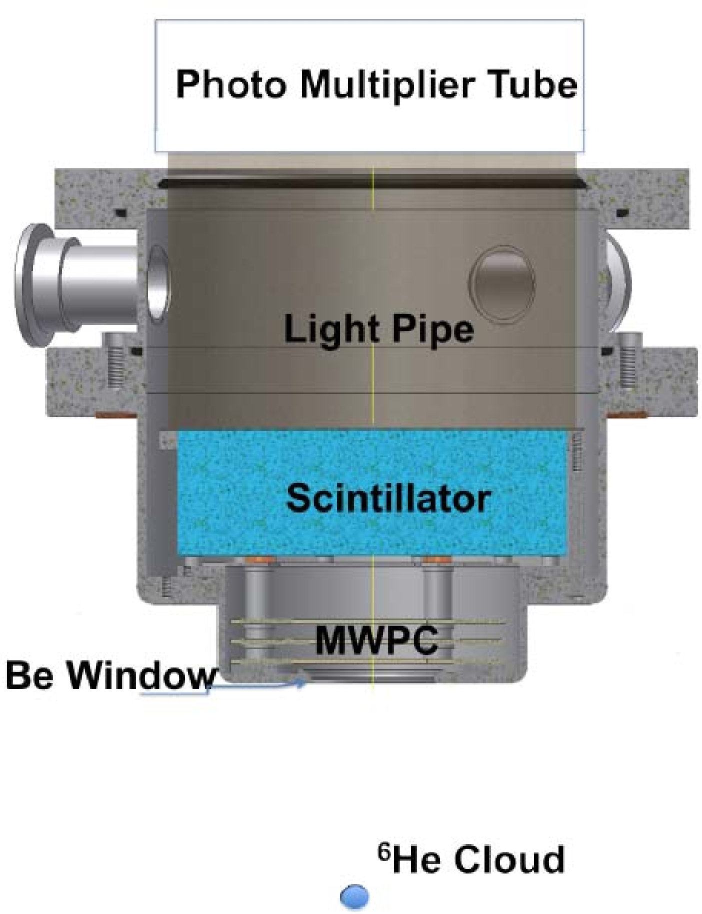
- 5 polarization voltages: front MCP, back MCP, det. frame, anode_ref, anode_sig
- 5 signals: charge emitted by MCPs, charge collected on anodes (x1,x2,y1,y2)

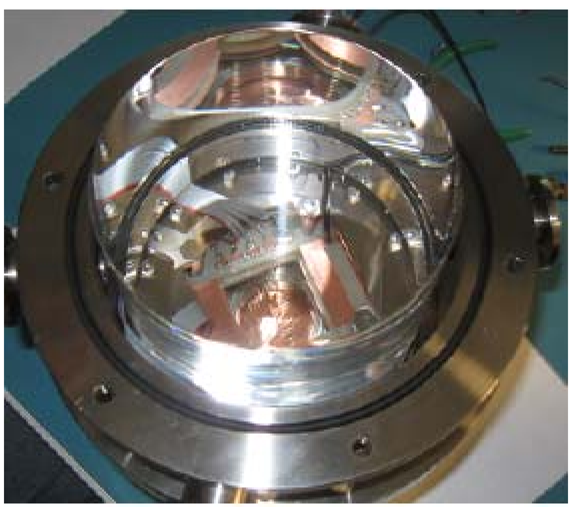
X&Y calibration:

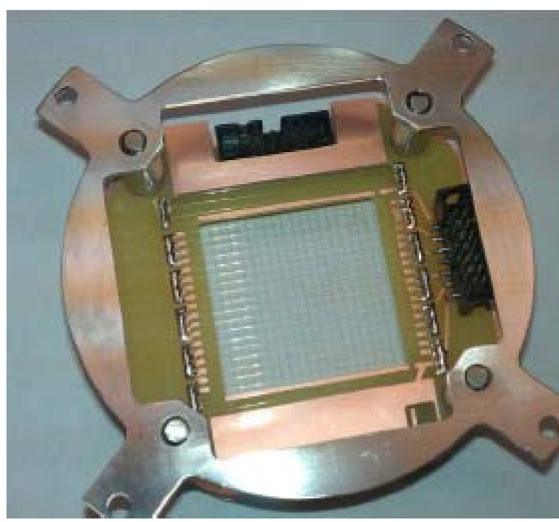
- Reconstruction with 1st and 2d order polynomial functions
  → up to 0.6 mm deviation on the edges of MCPs

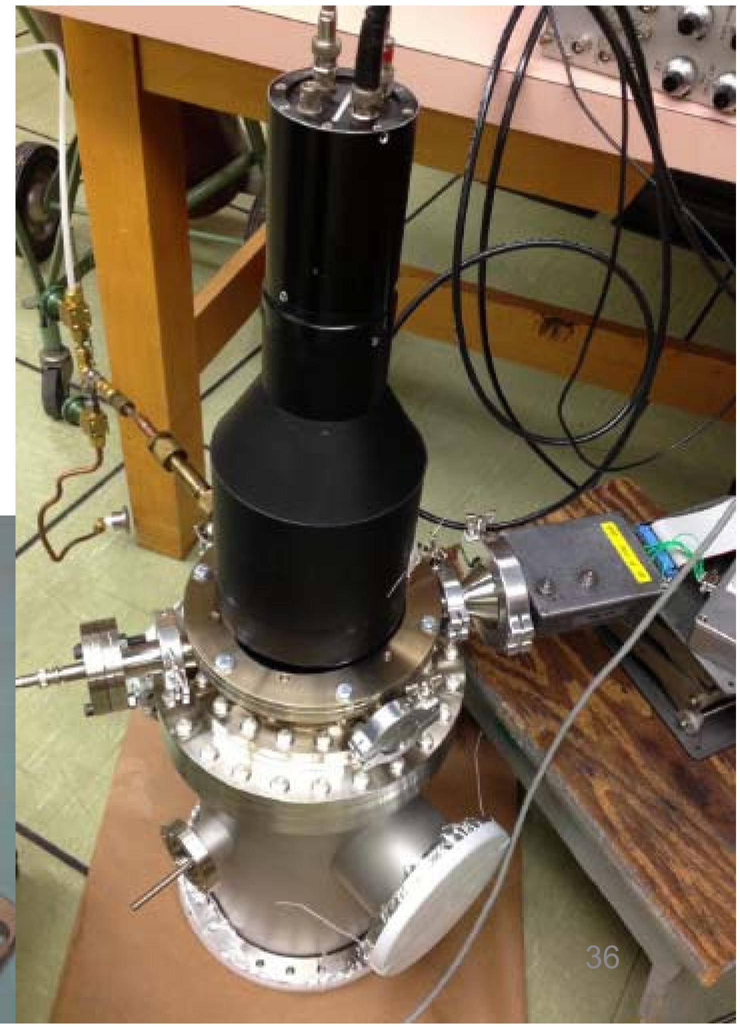


Beta detector:
A multi-wire prop chamber (ΔE)
and a scintillator (E)

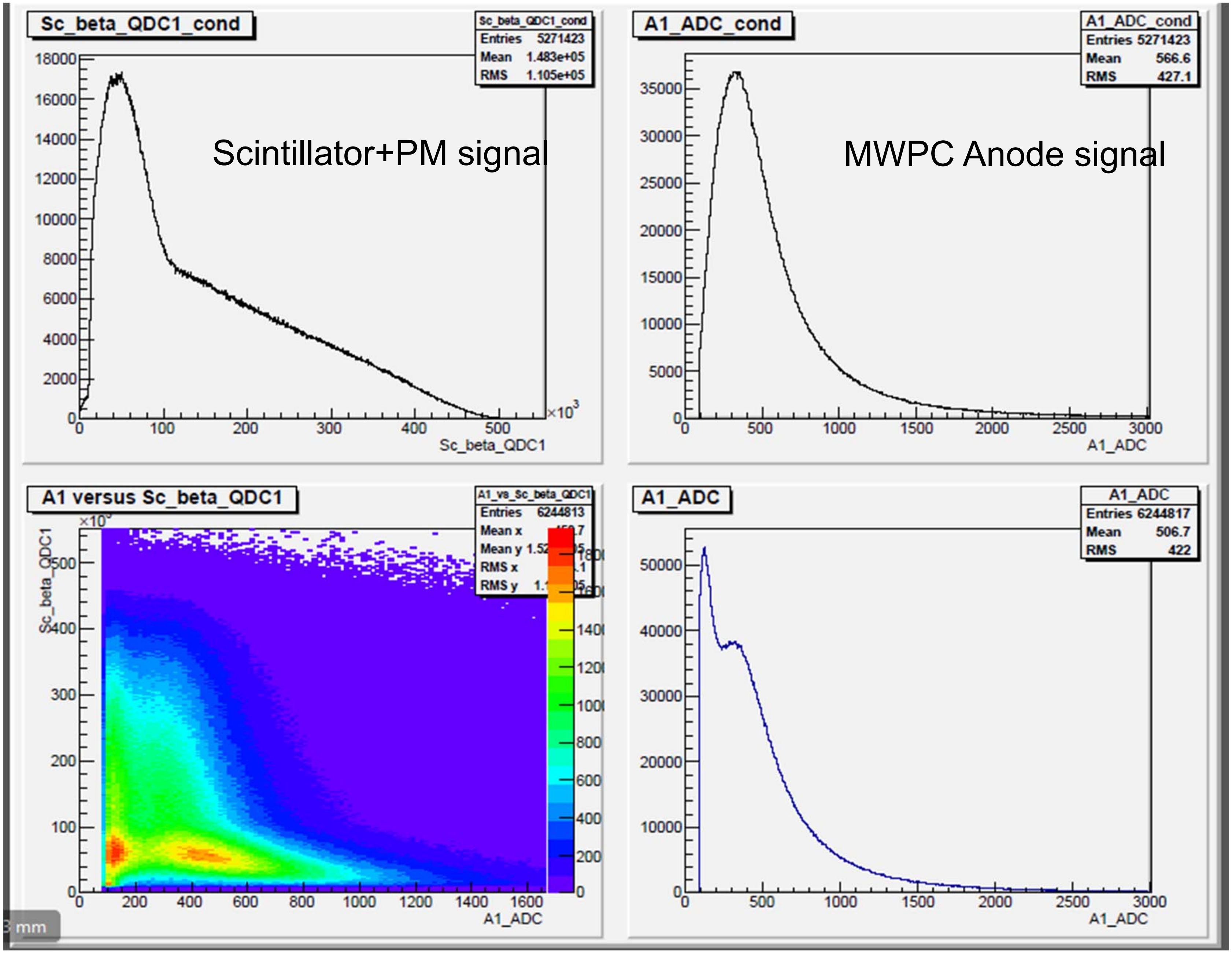




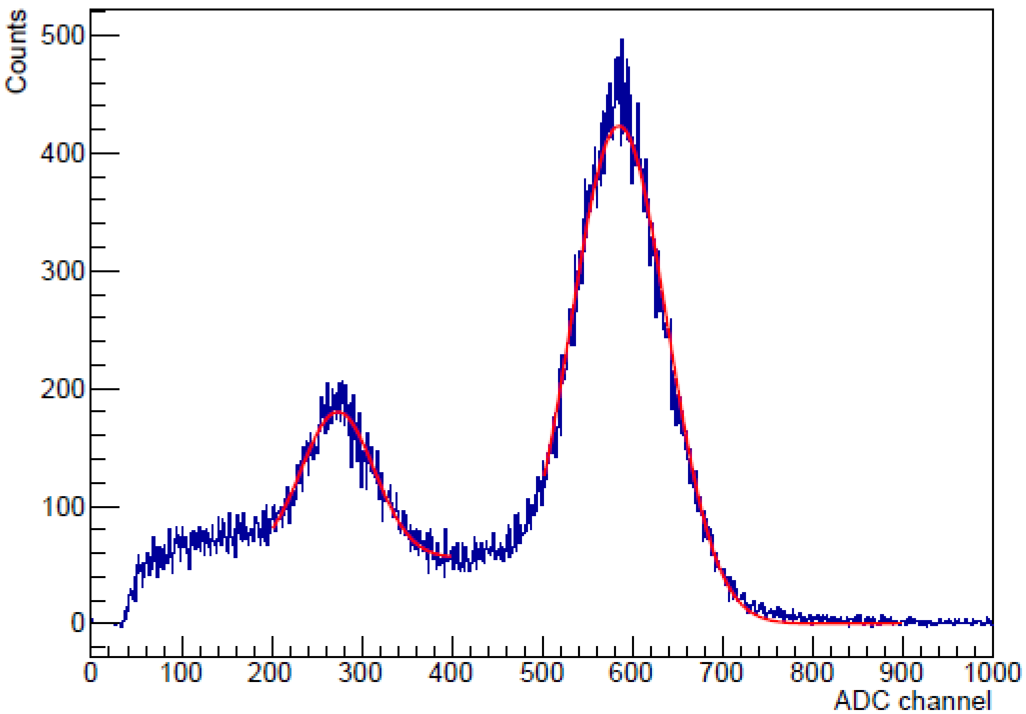




beta detector with ^{90}Sr source



beta detector with 207Bi source



570 keV

1064 keV

9% resolution

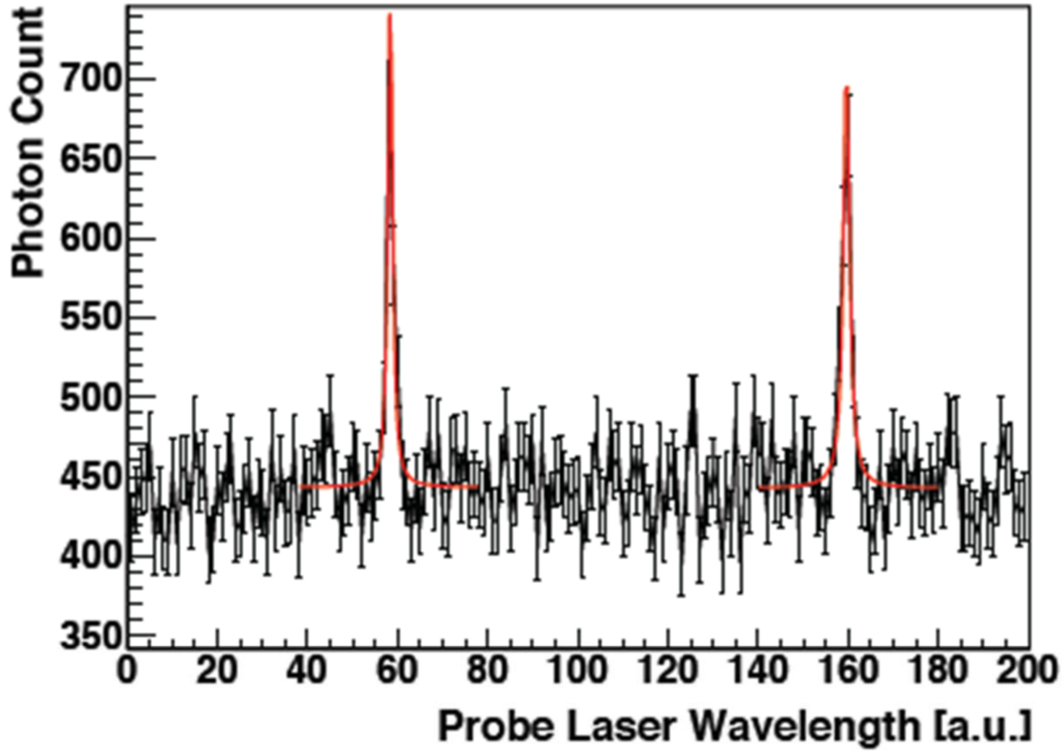
Laser trap outlook

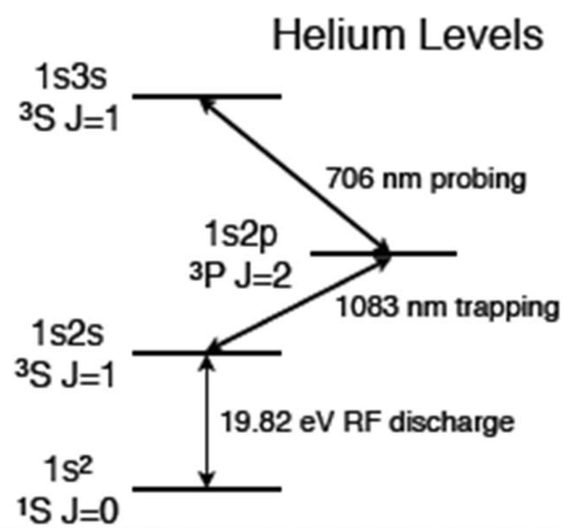
So far we have managed to trap 500-1000 6He atoms.

But only for periods of ½ hour. Need more stability.

Presently working on many developments.

First physics run likely summer of 2013.





Interaction for GT transitions

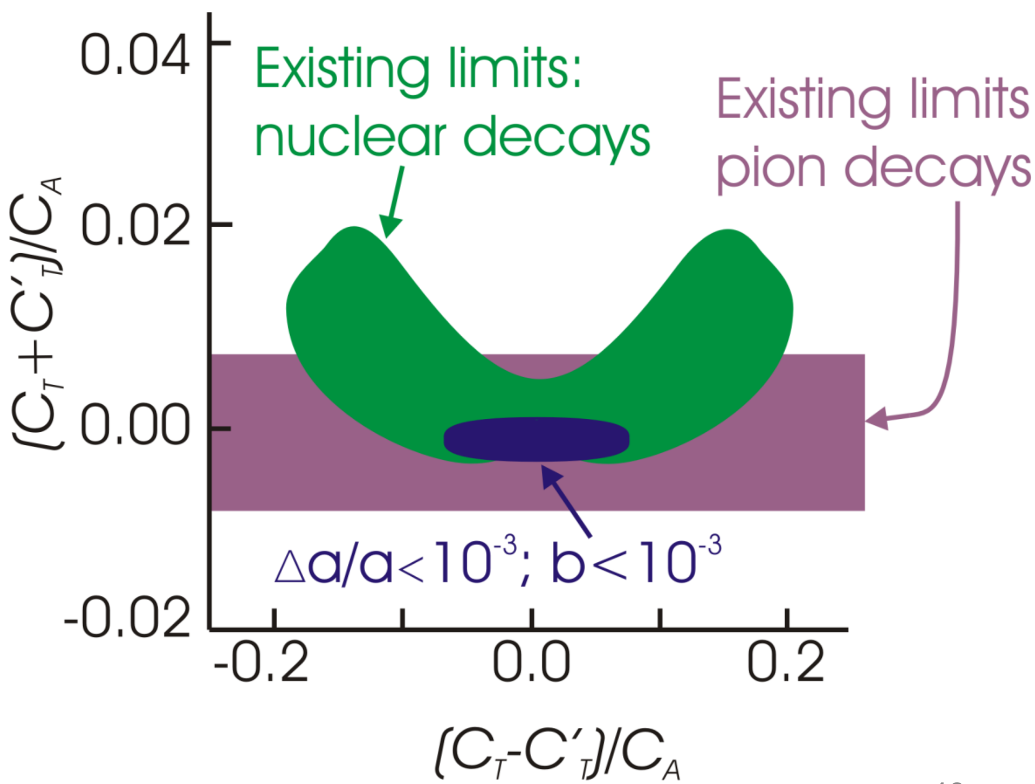
$$H = \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \quad 2C_A \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L +$$
$$\overline{\Psi}_f \gamma^\mu \gamma^\nu \Psi_i \quad \left[(C_T - C_T^{'}) \overline{e}^L \gamma_\mu \gamma_\nu \nu_e^R + (C_T + C_T^{'}) \overline{e}^R \gamma_\mu \gamma_\nu \nu_e^L \right]$$

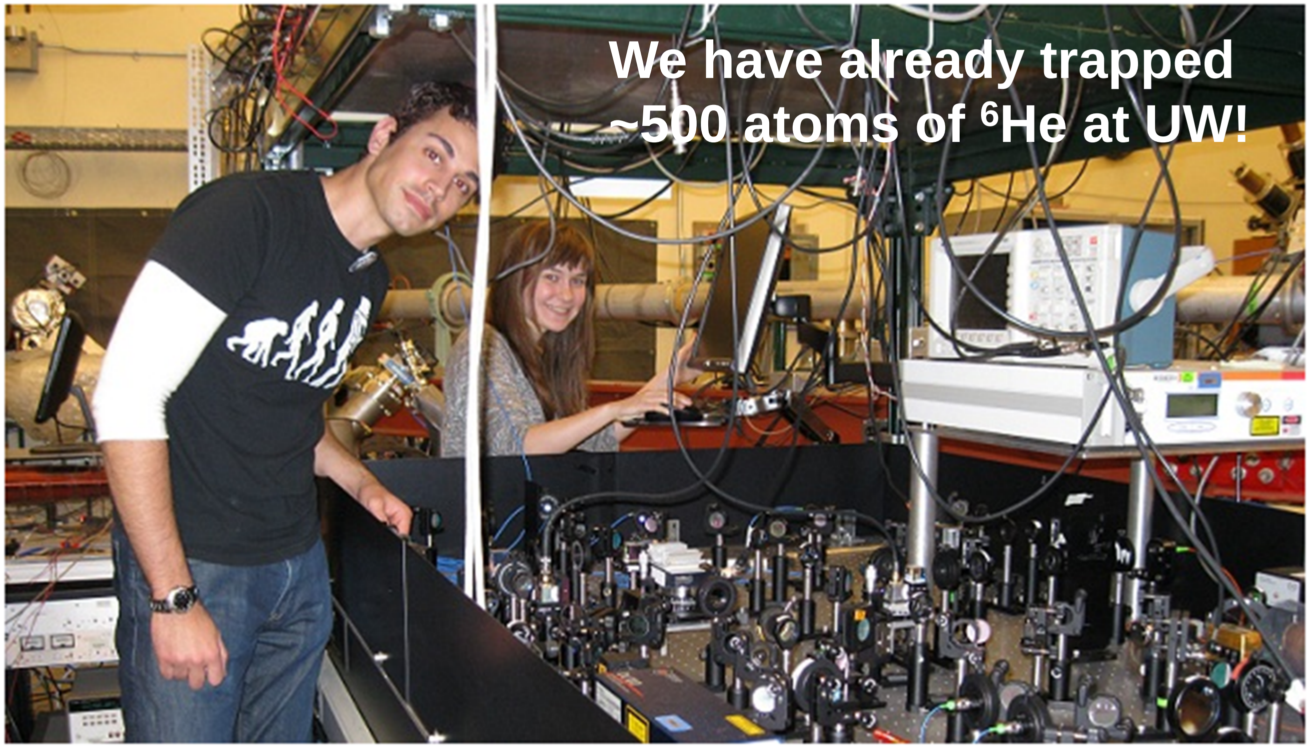
Decay rate:

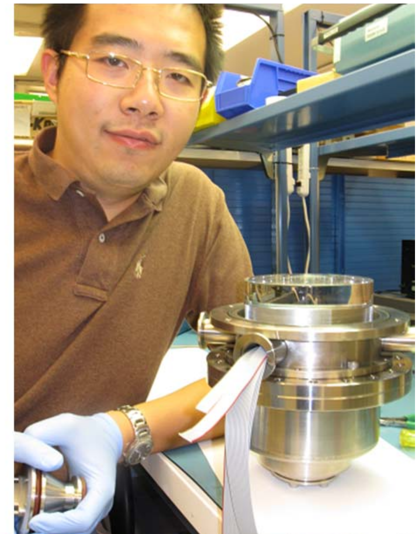
$$dw = dw_0 \left[1 + a \frac{\vec{p_e}}{E_e} \cdot \frac{\vec{p_\nu}}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

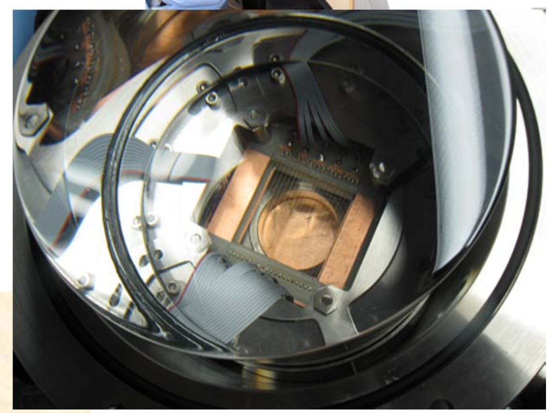
$$b \approx \frac{\mathrm{Re}\left[2C_A\left(C_T + C_T^{'}\right)\right]}{2|C_A|^2 + |C_T|^2 + |C_T^{'}|^2}$$

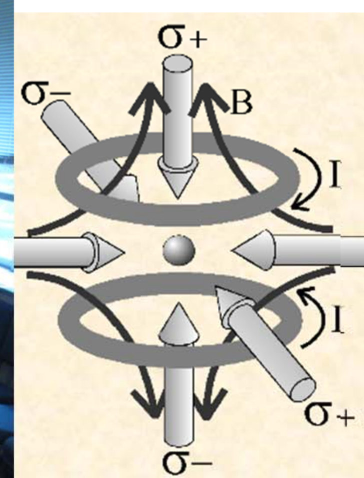
$$a \approx -\frac{1}{3} \frac{2|C_A|^2 - |C_T|^2 + |C_T^{'}|^2}{2|C_A|^2 + |C_T|^2 + |C_T^{'}|^2}$$




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






σ_+
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B
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σ_+
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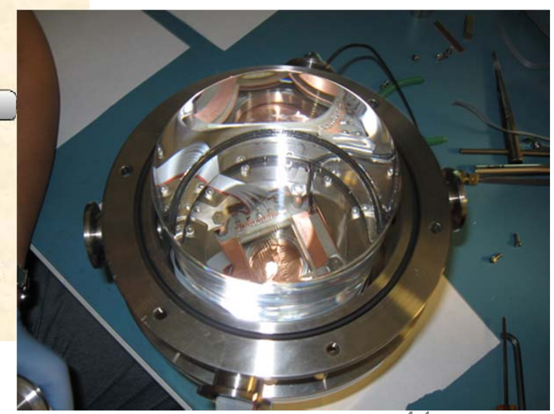
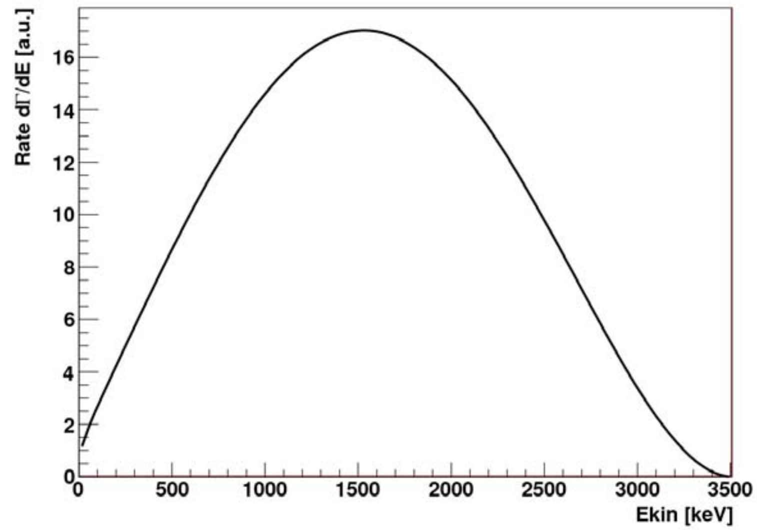
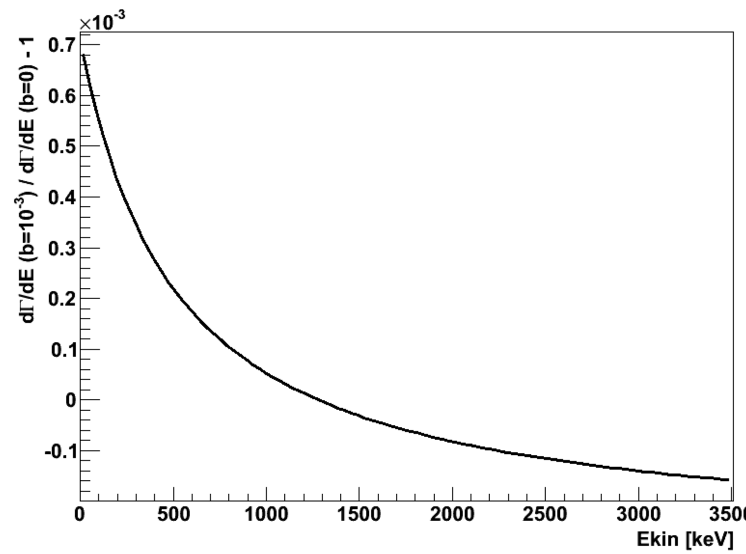


6He: measuring the spectrum in search of the `Fierz interference’

Use MWPC

- Identify backscattering
- Veto non-contained events, backgrounds,





Calibration of line shapes very important.

Follow Tseung, Kaspar, Tolich, arXiv:1105.2100v1:

Use $^{12}C(p,p')$ to generate 4.4 MeV photons an then scatter in TPC to generate Compton electrons.

Ongoing simulations to understand the limits of our methods

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

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

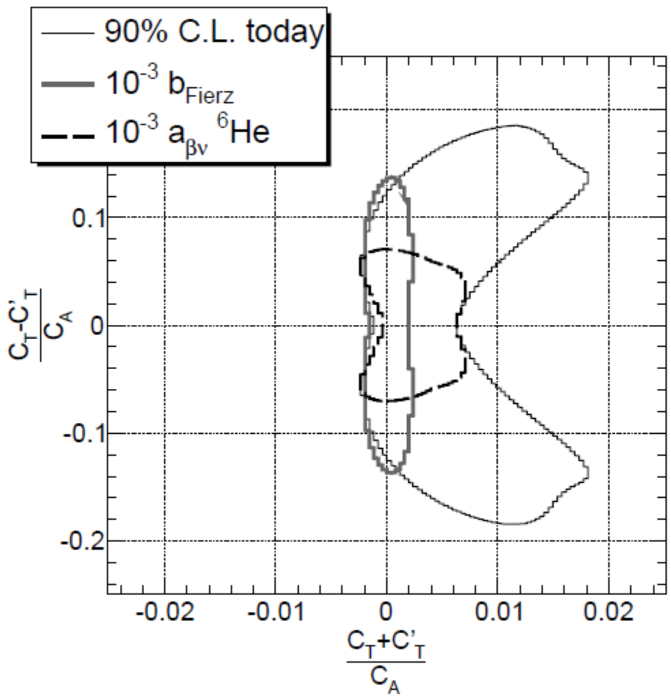


FIG. 5. Limits on tensor currents from envisaged measurements of the correlation coefficient for ^{6}He at 0.1% [53] or of the Fierz interference term b_{Fierz} to 10^{-3} in ^{6}He or neutron decays [54]. In the formalism of Eq. 3, the current LHC limits from Ref. [9] are $|(C_T + C_T')/C_A| < 6 \times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

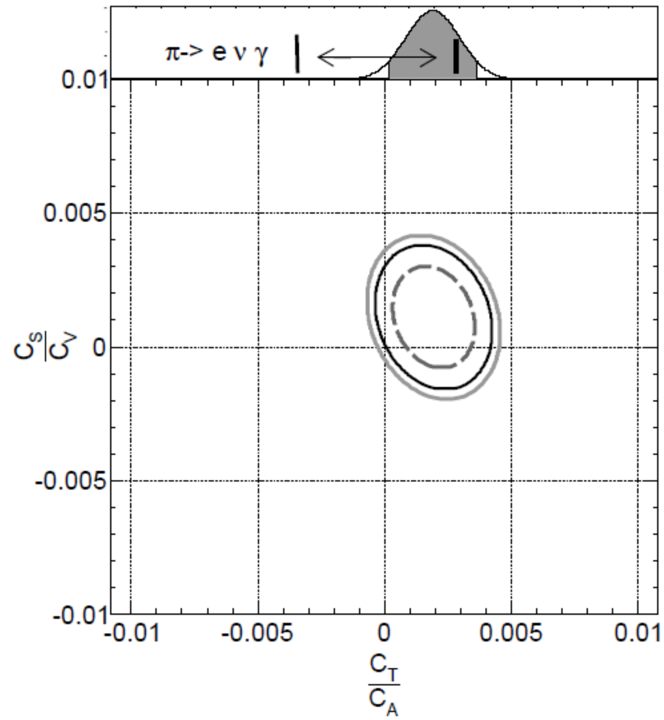


FIG. 3. Limits C_T and C_S combining neutron and nuclear β decay data for the 3-parameter fit. On top we show the probability distribution of the limits on C_T obtained by projecting the 2D distribution and compare to the limits from pion decay data.