Searching for chirality flipping interactions in nuclear beta decay

Presentation to

REU Students

July 2015

Weak interactions in nuclei: a probe to search for new physics

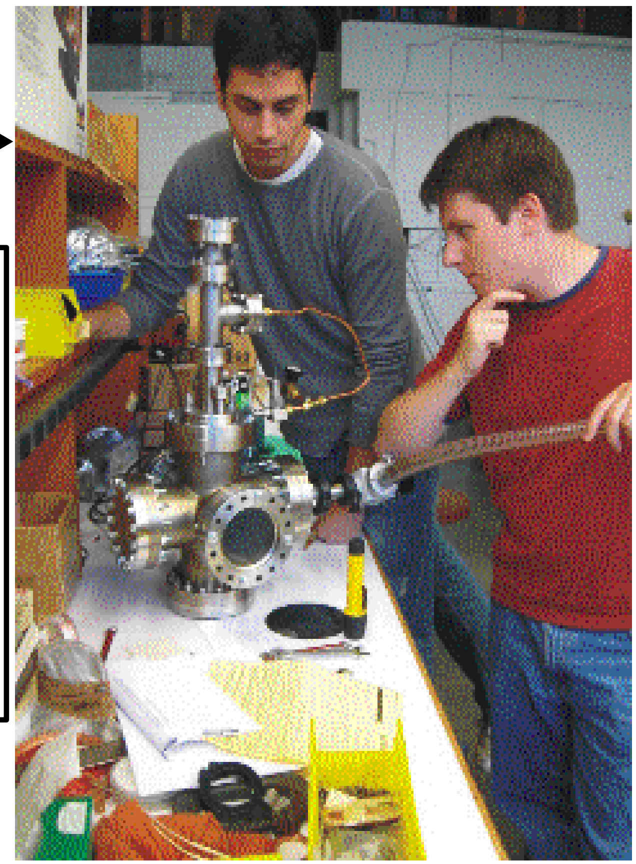
Alejandro Garcia

University of Washington

While the LHC searches at the energy frontier.

Precision experiments in nuclear beta decays can be more sensitive in some specific areas

Students David Zumwalt and Andy Palmer look at the device they built to produce 6He at UW



Helicity

$$\mathcal{H} = \frac{\vec{p} \cdot \vec{J}}{\left|\vec{p}\right| \cdot \left|\vec{J}\right|}$$

For a spin ½ particle helicity can be *Right* or *Left*

Remarkable: neutrinos emitted in beta decay are *Left*-handed

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Problem: helicity is *not* a relativistic invariant. (Think about an observer moving faster than the particle: ***p*** flips direction but ***J*** doesn't)

Solution: chirality. Correct definition deals with relativistic quantum mechanics and I will avoid it today. Two important conclusions to remember:

- *m*=0 particles (e.g. photons) chirality == $\mathcal{H}$.
- *m*≠0 particles with well-defined chirality can be thought off as linear combinations of both helicities with amplitudes $\sqrt{\frac{1+v/c}{2}}$ and $\sqrt{\frac{1-v/c}{2}}$

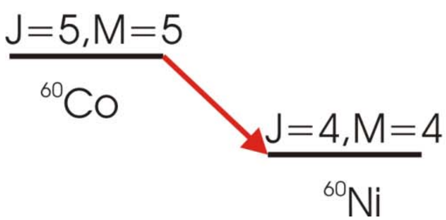
Helicities and nuclear beta decays: Parity Violation (58 years!)

$$P\,\vec{r} = -\vec{r}$$

$$P\,\vec{p} = -\vec{p}$$

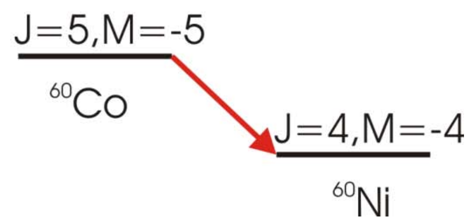
$$P(\vec{r}\times\vec{p}) = (\vec{r}\times\vec{p})$$

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

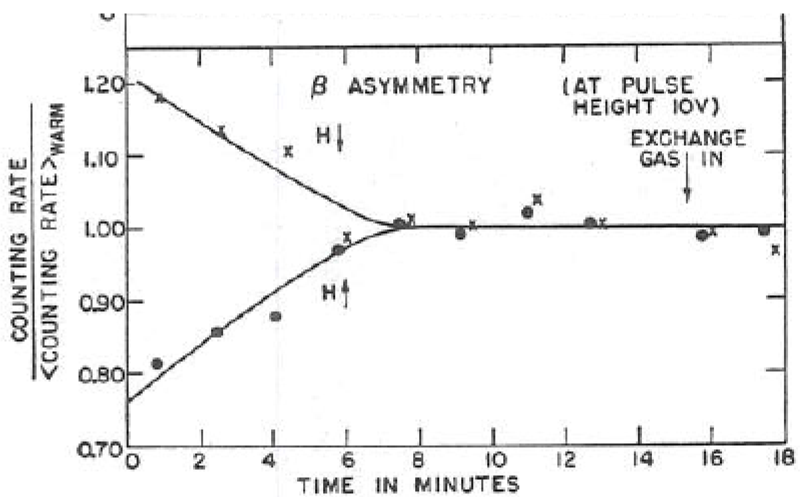


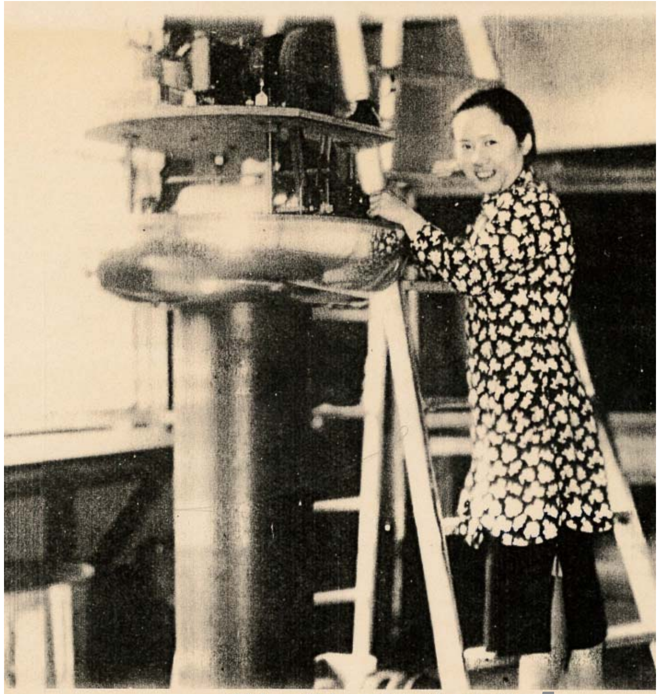
Equivalent
if *P* is conserved

⇄



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

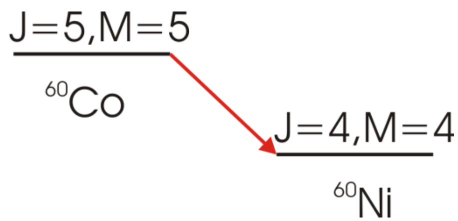


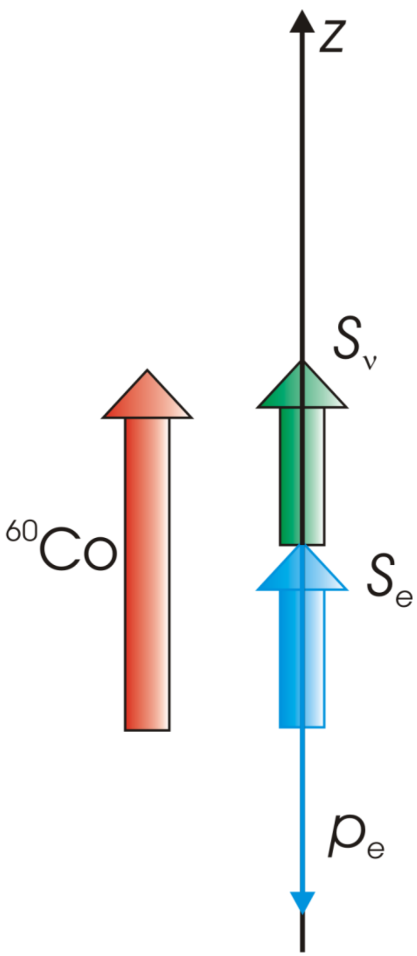


Chien-Shiung Wu (b. 1912)
Nuclear Physicist

Helicities and nuclear beta decays: Parity Violation

What makes electrons come out preferentially opposite the polarization?



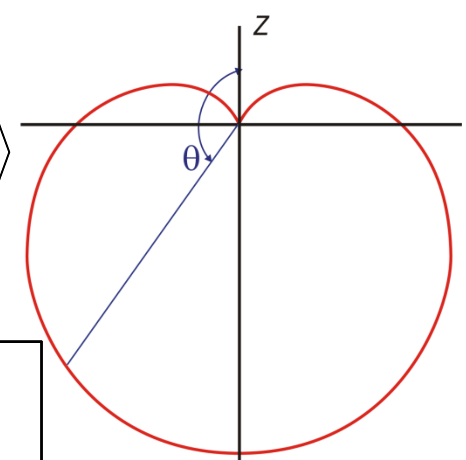


1) Conservation of Ang. Mom.: e and ν spins have to align along the direction of initial polarization.

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

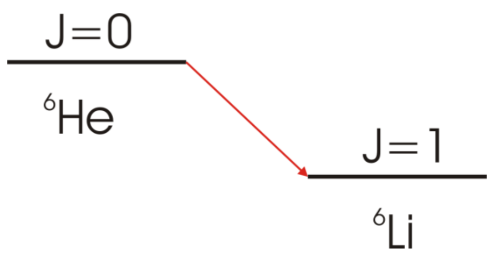
Probabilities work just as for ideal "Stern-Gerlach device"

$$|\theta_+\rangle = \cos(\theta/2)|+\rangle - e^{i\varphi}\sin(\theta/2)|-\rangle$$

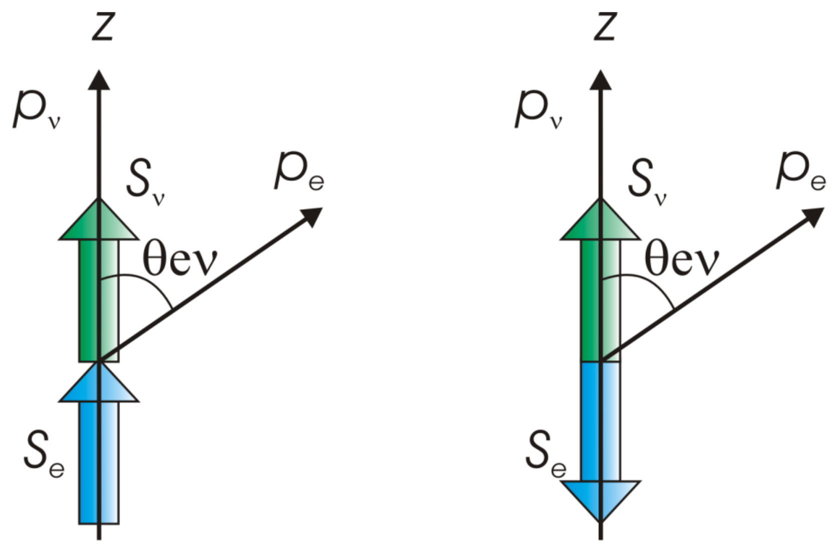


Probabilities of observing e at angle θ $\approx \sin^2(\theta/2)$

6He beta decay: e-ν correlation



Taking the ν direction as axis of quantization:



$M=+1$ $\qquad$ $M=0$

$\langle\rangle^2=1$ $\qquad$ $\langle\rangle^2=\frac{1}{2}$

$\sin^2(\theta/2) \propto 1-\cos(\theta)$ $\qquad$ $\cos^2(\theta/2) \propto 1+\cos(\theta)$

So, for 6He: $\quad d\Gamma/d\Omega \propto 3/2\,[1-(1/3)\cos(\theta)]$

The modern context. The Standard Model and some open questions.

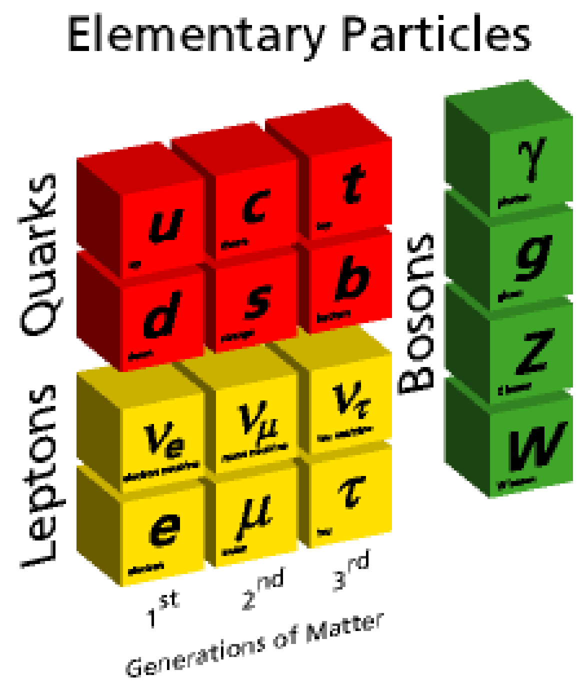
What is the mechanism for the mass of neutrinos? (hints that it doesn't work like the others)…

Can there be right-handed neutrinos from nuclear beta decays?

Why are the number of generations for quarks identical to those of leptons?

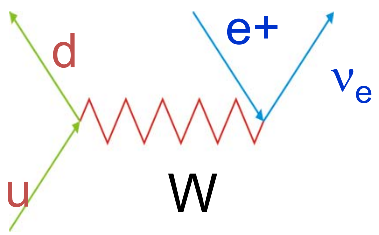
↓

Answers should illuminate "new physics"

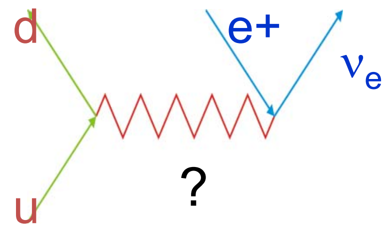


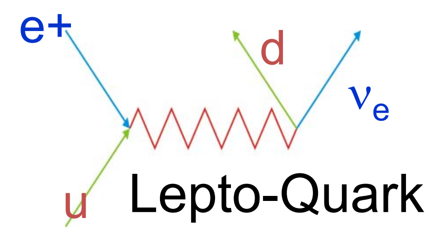
Searches for Scalar and Tensor currents.

Are weak decays carried only by W's?



Or is there something new?





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

Decay rate:

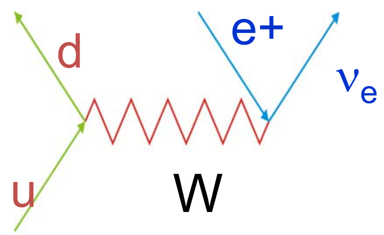
$$dw = dw_0 \left[1 + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

$$b \approx \left(\frac{C_T + C_T^{'}}{C_A} \right)$$

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

Searches for Scalar and Tensor currents.

Are weak decays carried only by W's?



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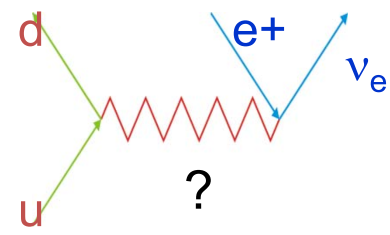

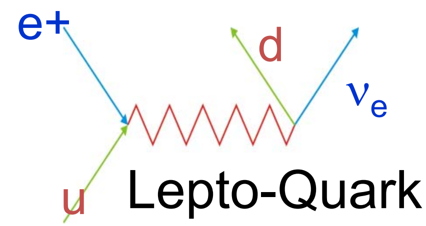

$$H = \overline{\Psi}_f \gamma^{\mu}\gamma_5 \Psi_i \quad 2C_A \overline{e}^L \gamma_{\mu}\gamma_5 \nu_e^L +$$

Standard model

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

Tensor currents

Decay rate:

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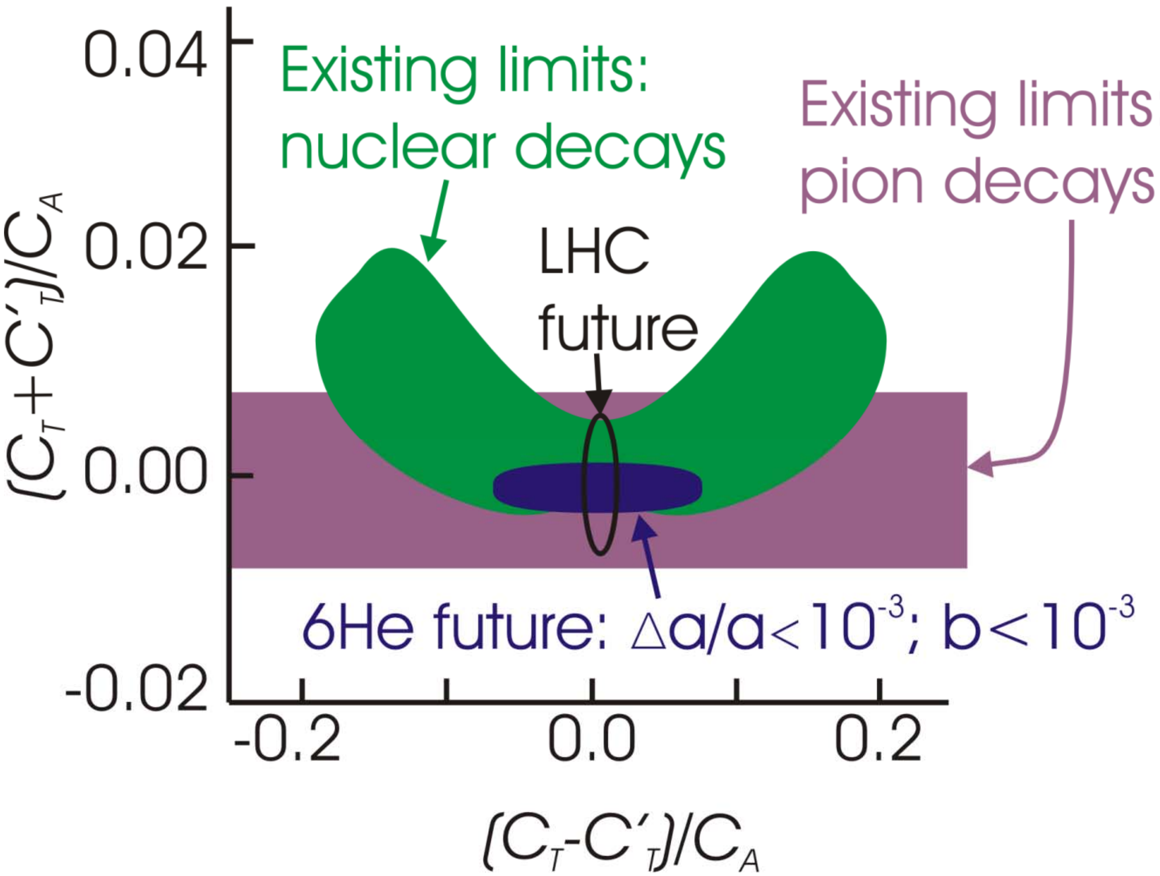
Precision beta decay versus pion decays and “LHC”:

F. Wauters, A. García, and R. Hong
Phys. Rev. C 89, 025501 (2014).
Can “precision” compete with “energy”? Yes.



6He little-a collaboration

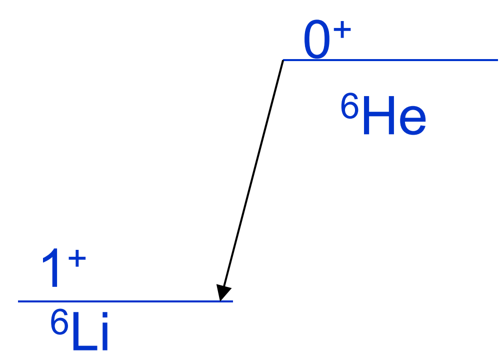
P. Muller, A. Leredde
Argonne National Lab

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

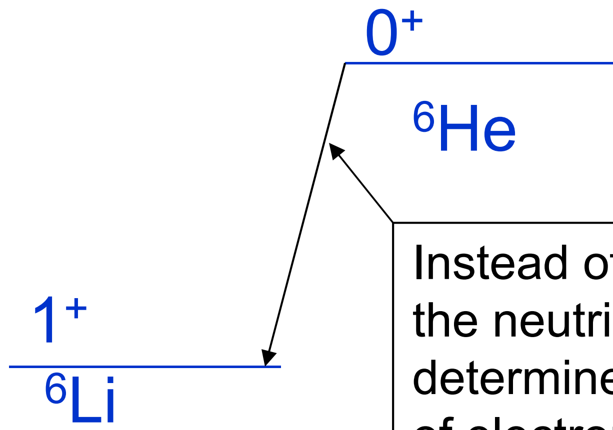
O. Naviliat-Cuncic
NSCL, Michigan State University

Y. Bagdasarova, A. Garcia, R. Hong, 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 → no worries about chemistry
- Simple nuclear structure



Searching for tensor currents in 6He



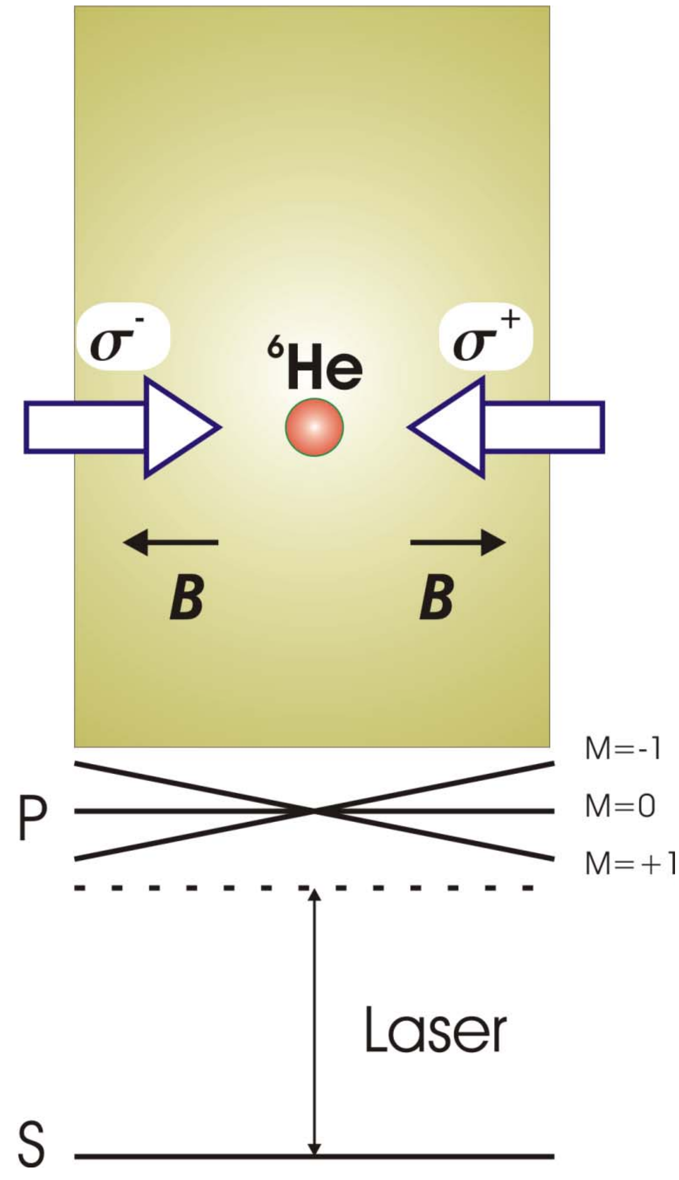
Instead of detecting the neutrino, determine momentum of electron and 6Li.

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

Solution: hold 6He with light.

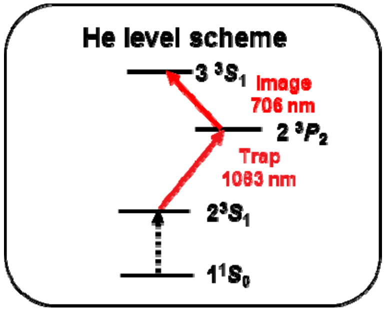
Magneto-Optical Trap

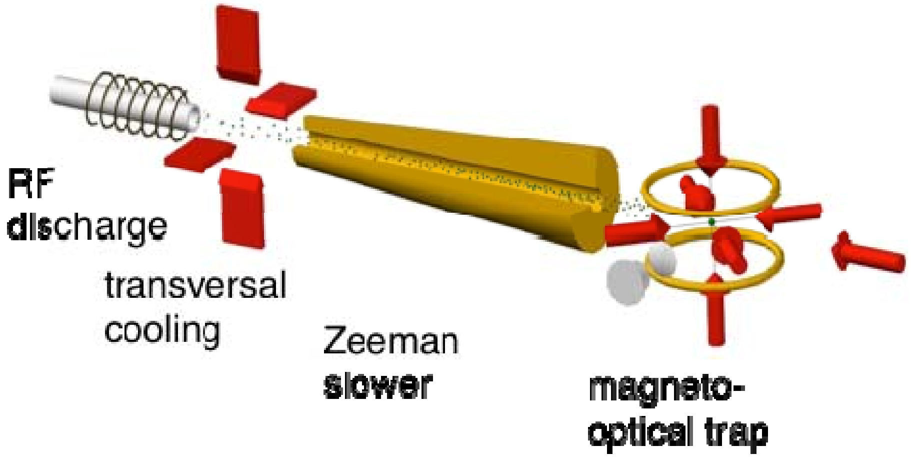
- Six orthogonal, counter-propagating beams of opposite circular polarization are red-detuned as in the Doppler cooling configuration
- Anti-Helmholtz coils introduce a quadrupole field with zero magnetic field at the center and linearly increasing field in the directions of the lasers

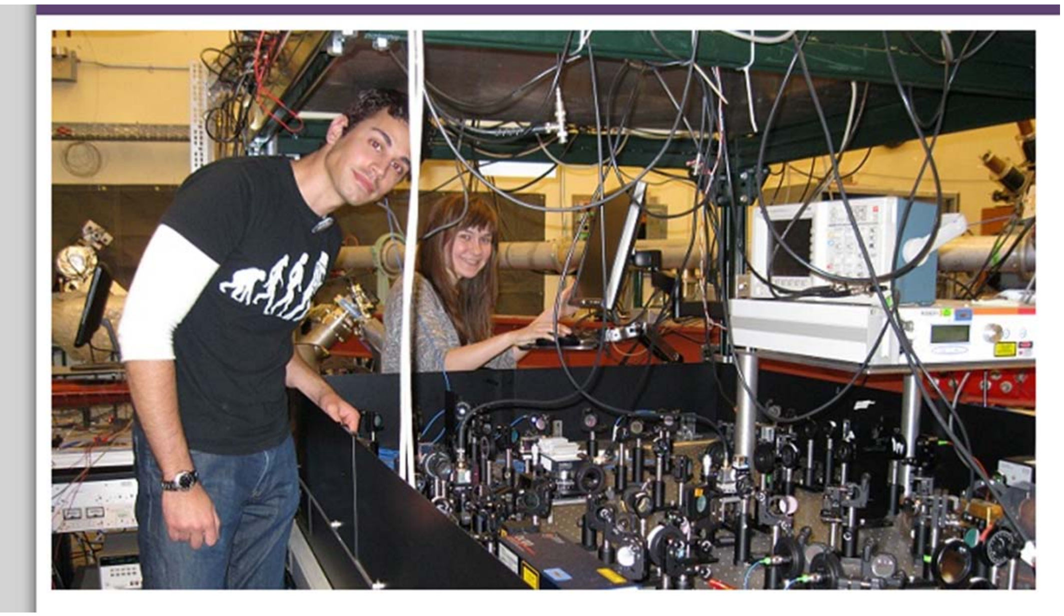


Trapping of ^{6}He

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

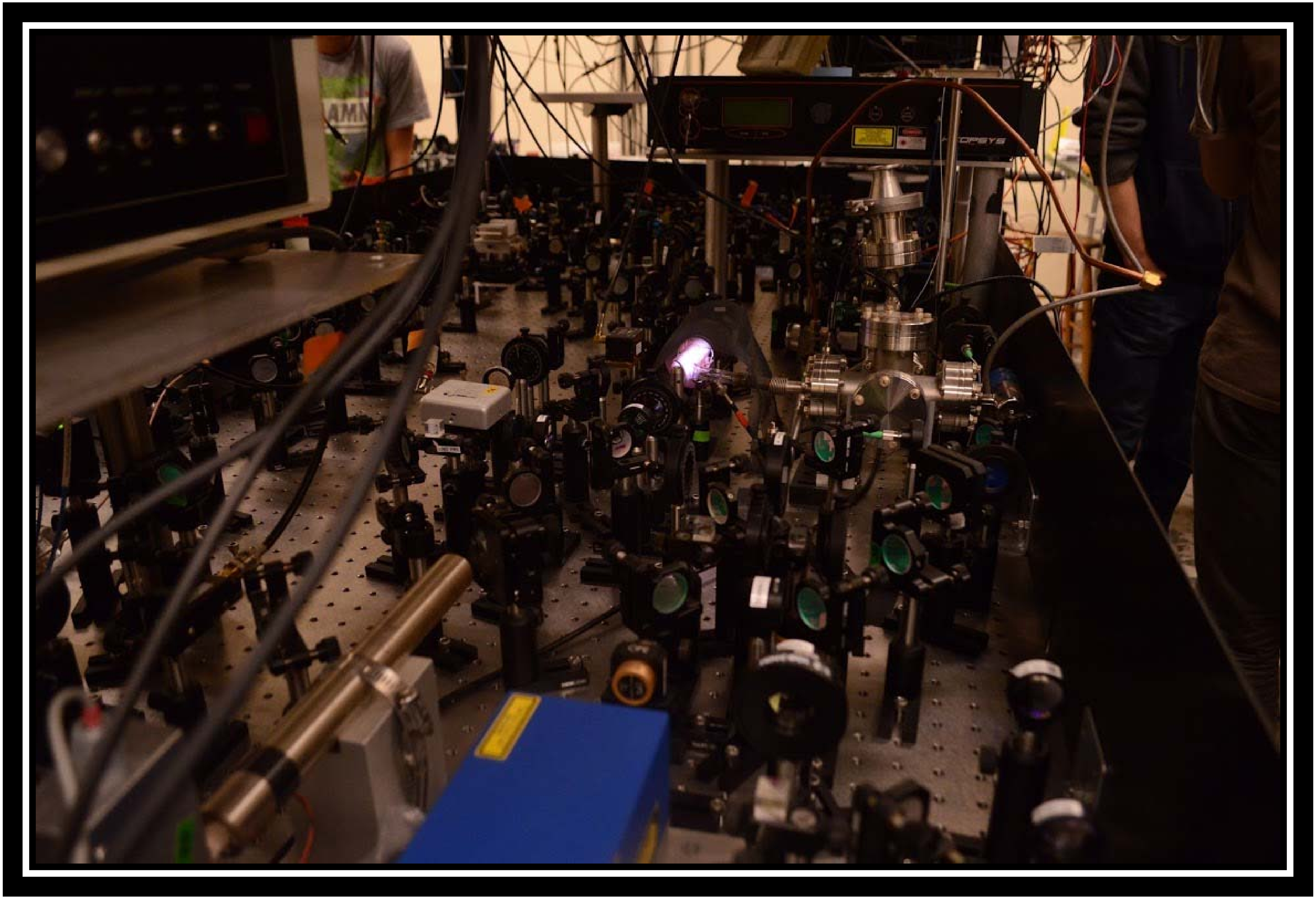






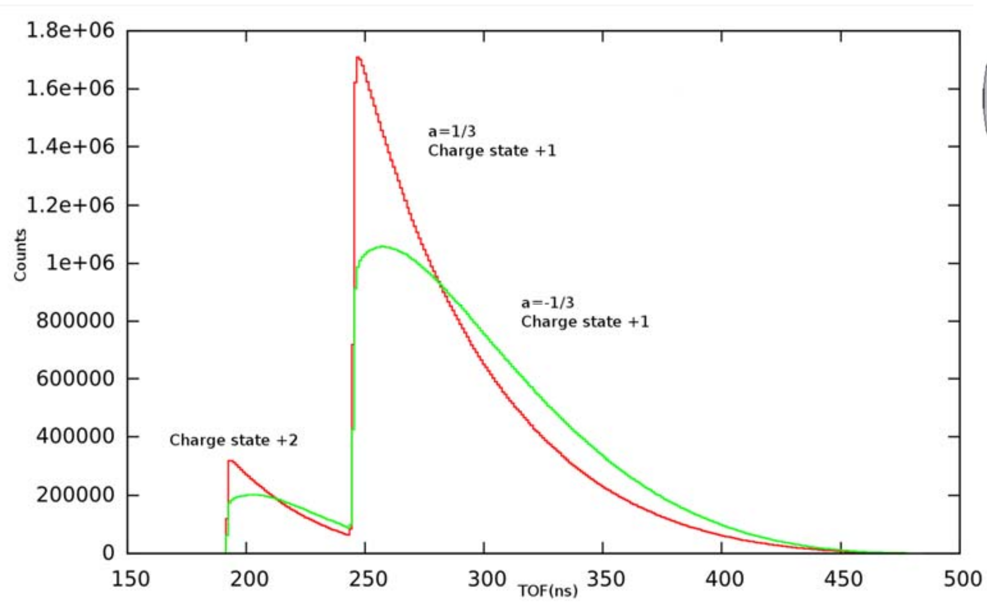
- Trapped atoms transferred to detection chamber with 2nd MOT
- Based on experience from ^{6}He, ^{8}He charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL **93**, 142501 (2004)
  P. Mueller et al., PRL **99**, 252501 (2007)

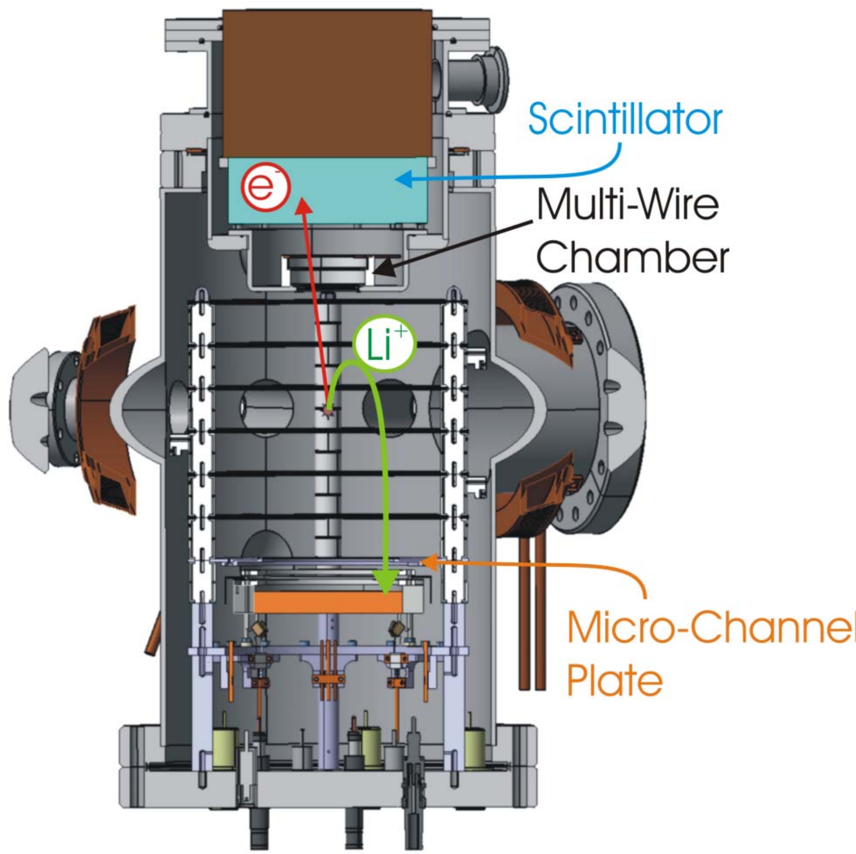
One of the laser tables:



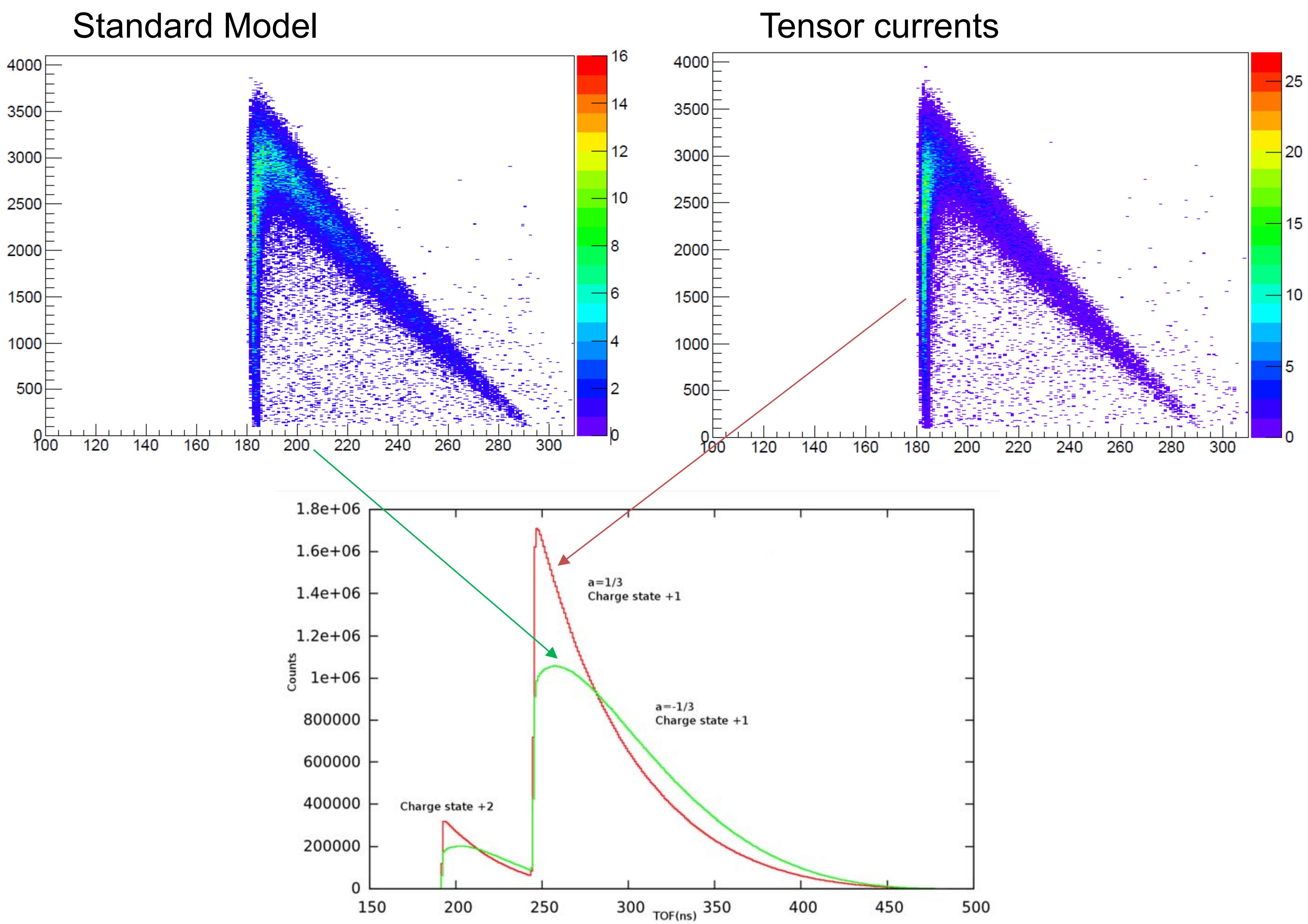
^{6}He Little a, detection

- 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,

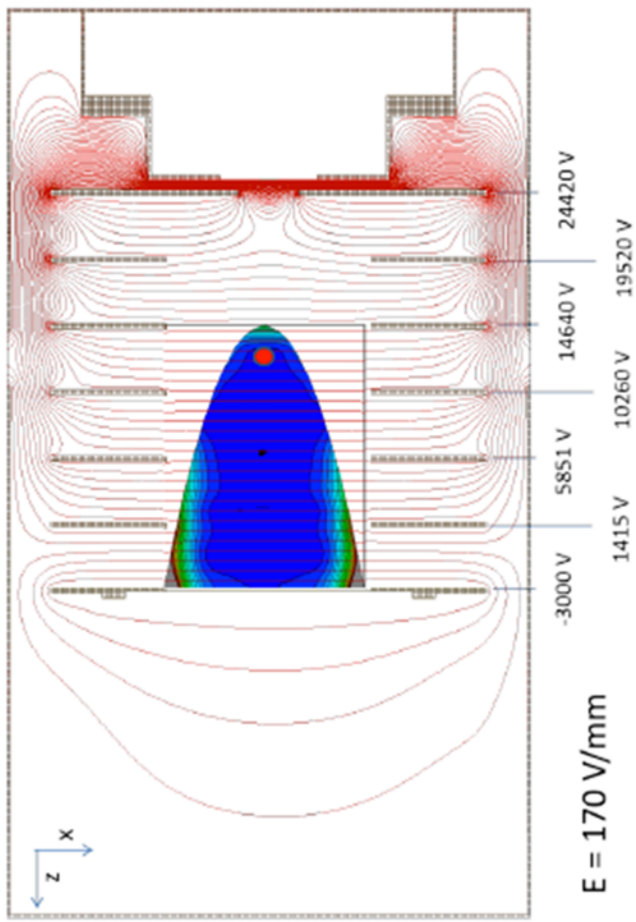


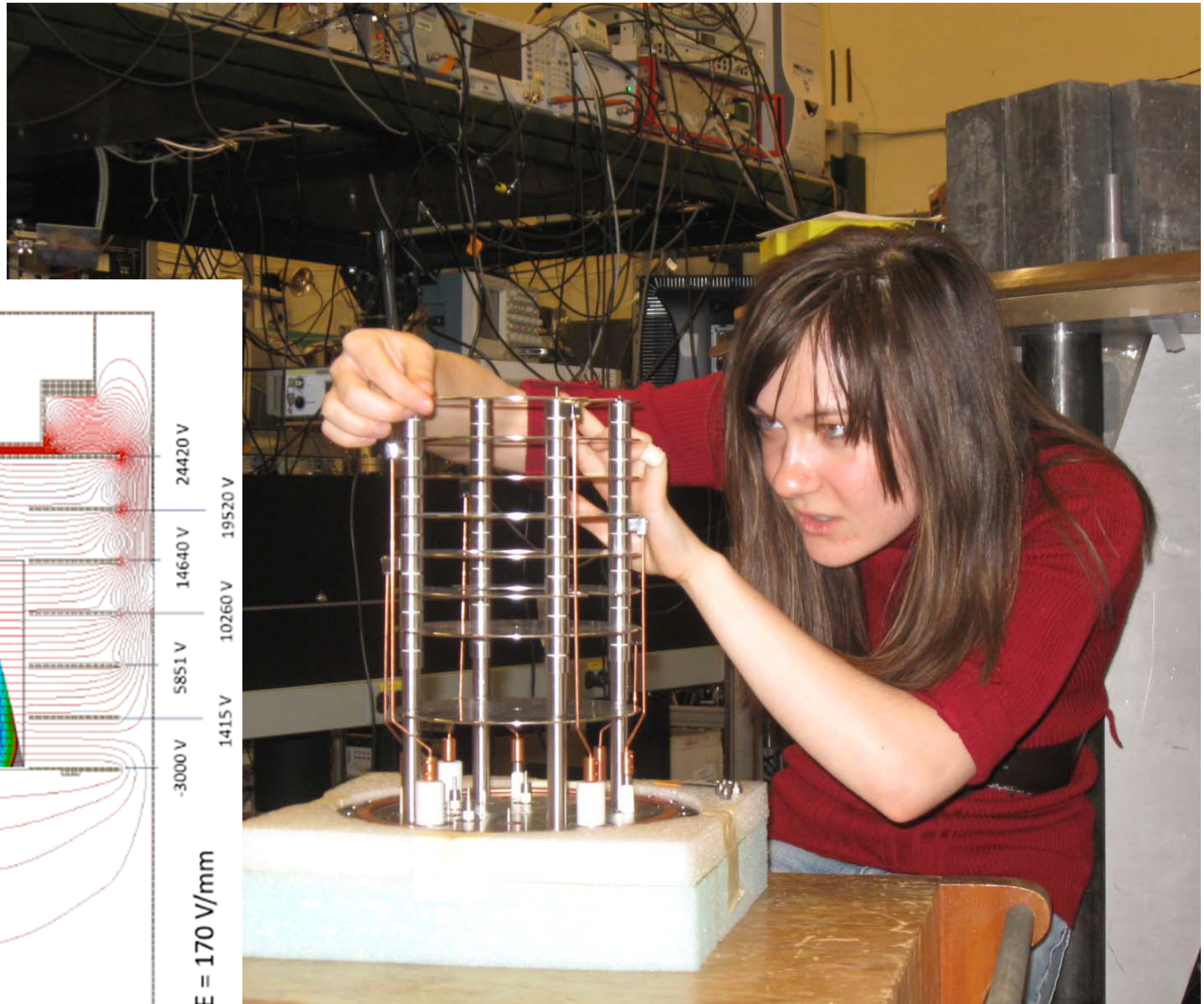


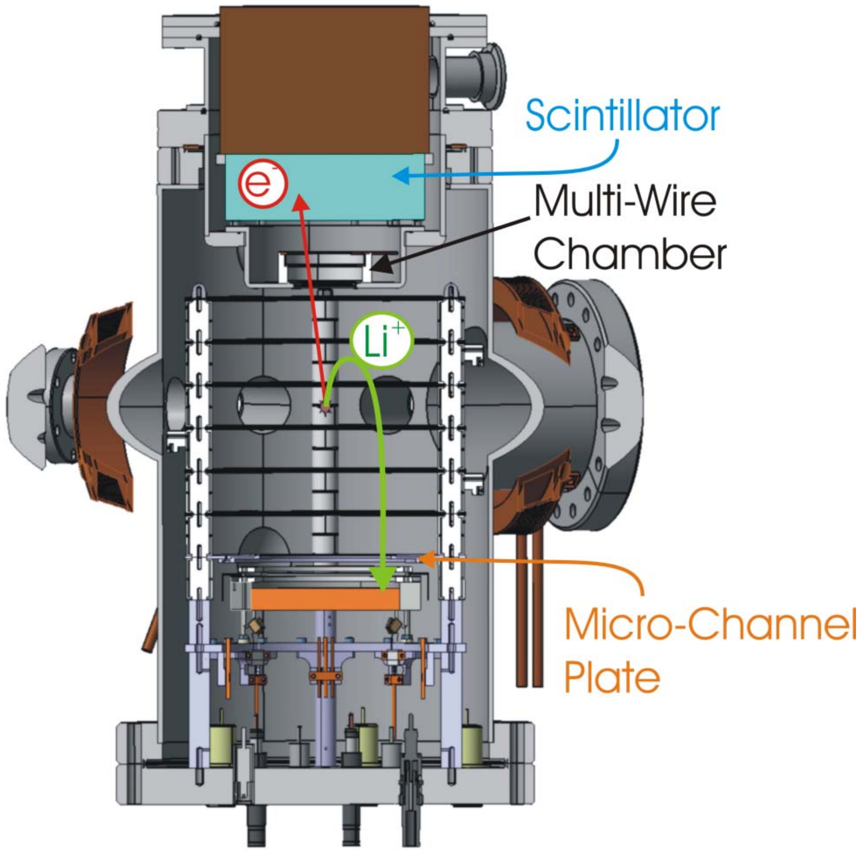
Ebeta versus TOF simulations



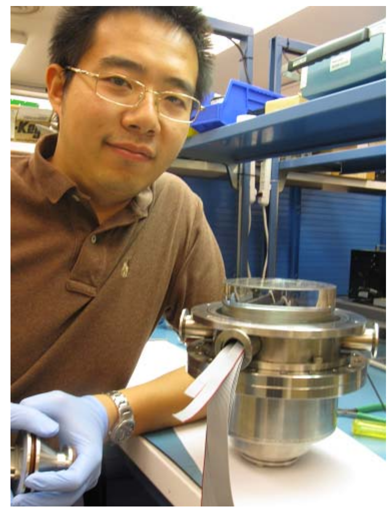
Electric field of apprx 2 kV/cm to guide 6Li ions.

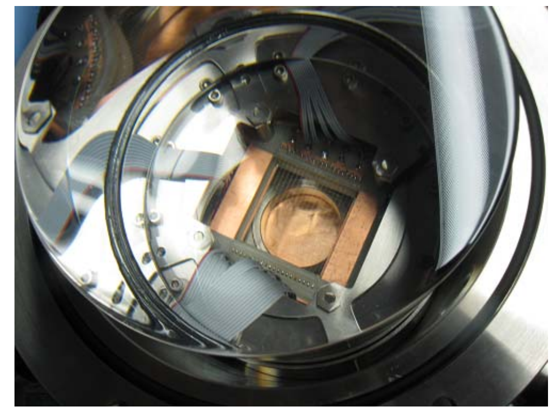


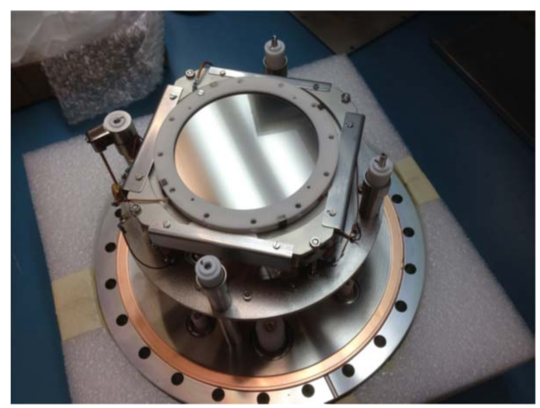




ΔE-E scintillator system for electron detection (energy, start of time-of-flight)



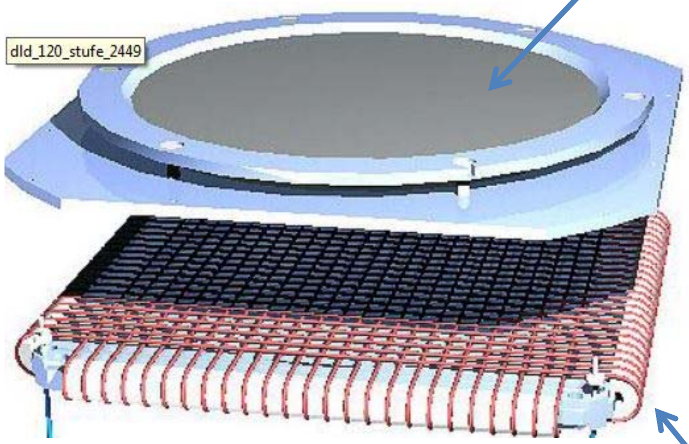


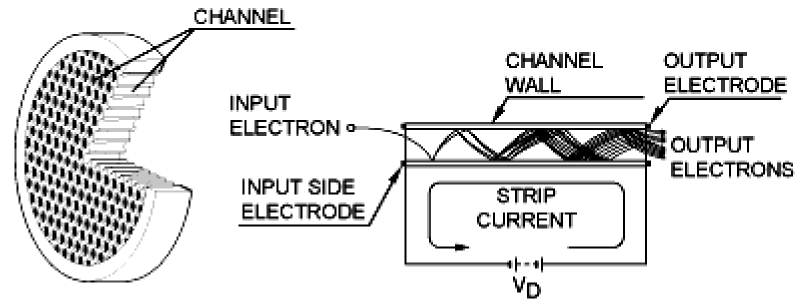


Micro-channel plate detector for detection of ^{6}Li recoil nucleus (position, time-of-flight)

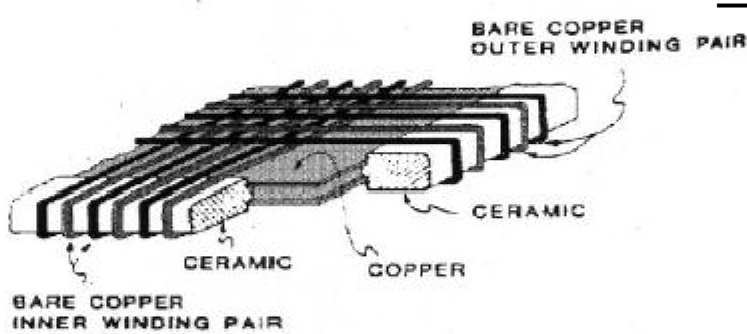
MCP (micro chanel plates with delay line anodes)

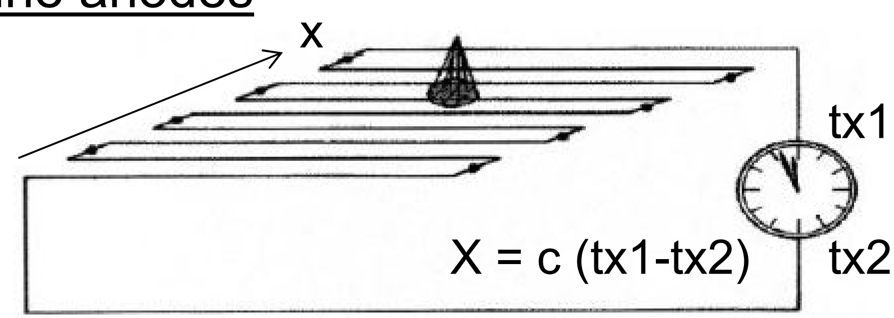
MCPs (micro channel plates)





Delay line anodes



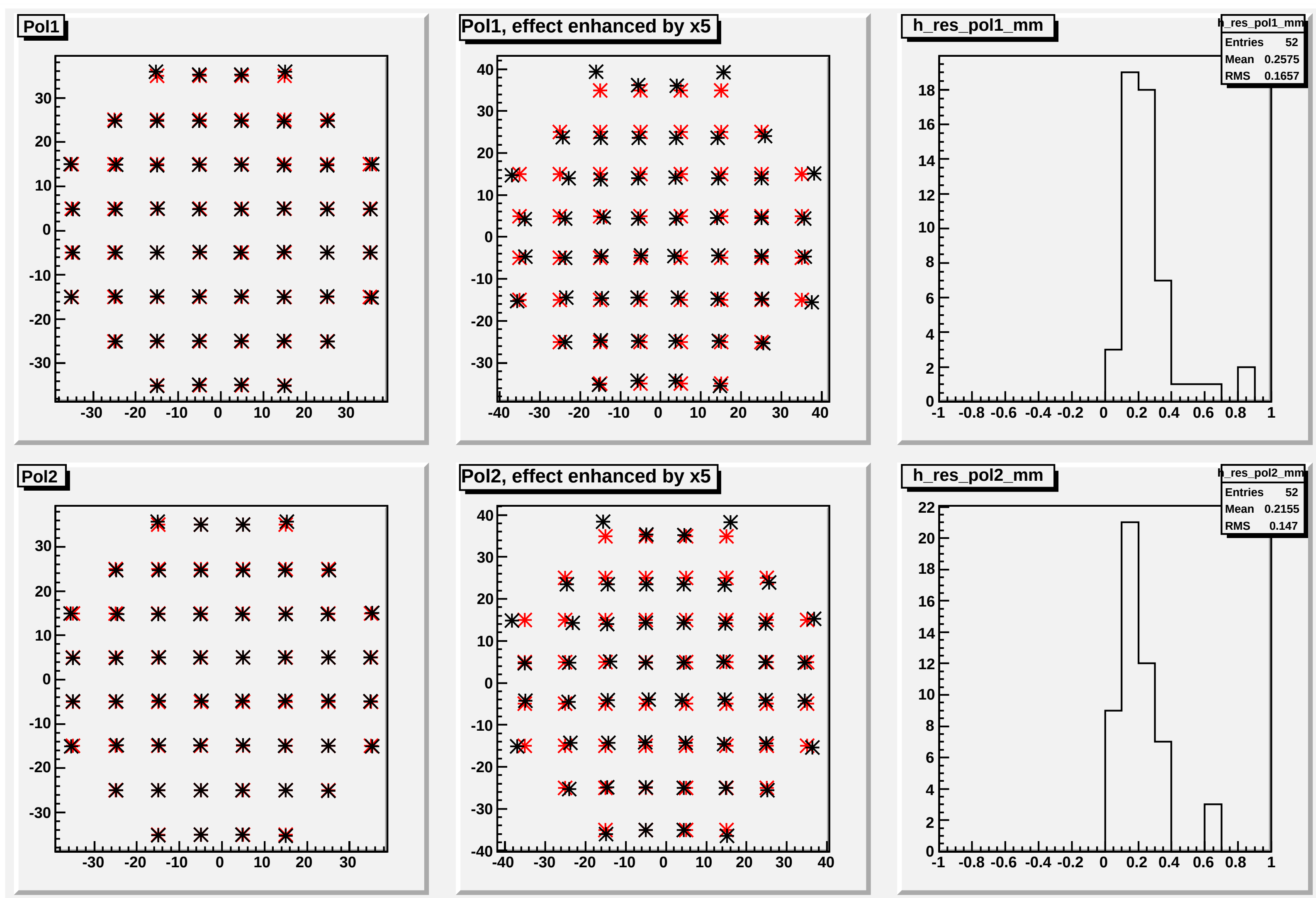


- 5 polarization voltages: front MCP, back MCP, det. frame, anode_ref, anode_sig
- 5 signals: charge emitted by MCPs, charge collected on anodes (x1,x2,y1,y2)

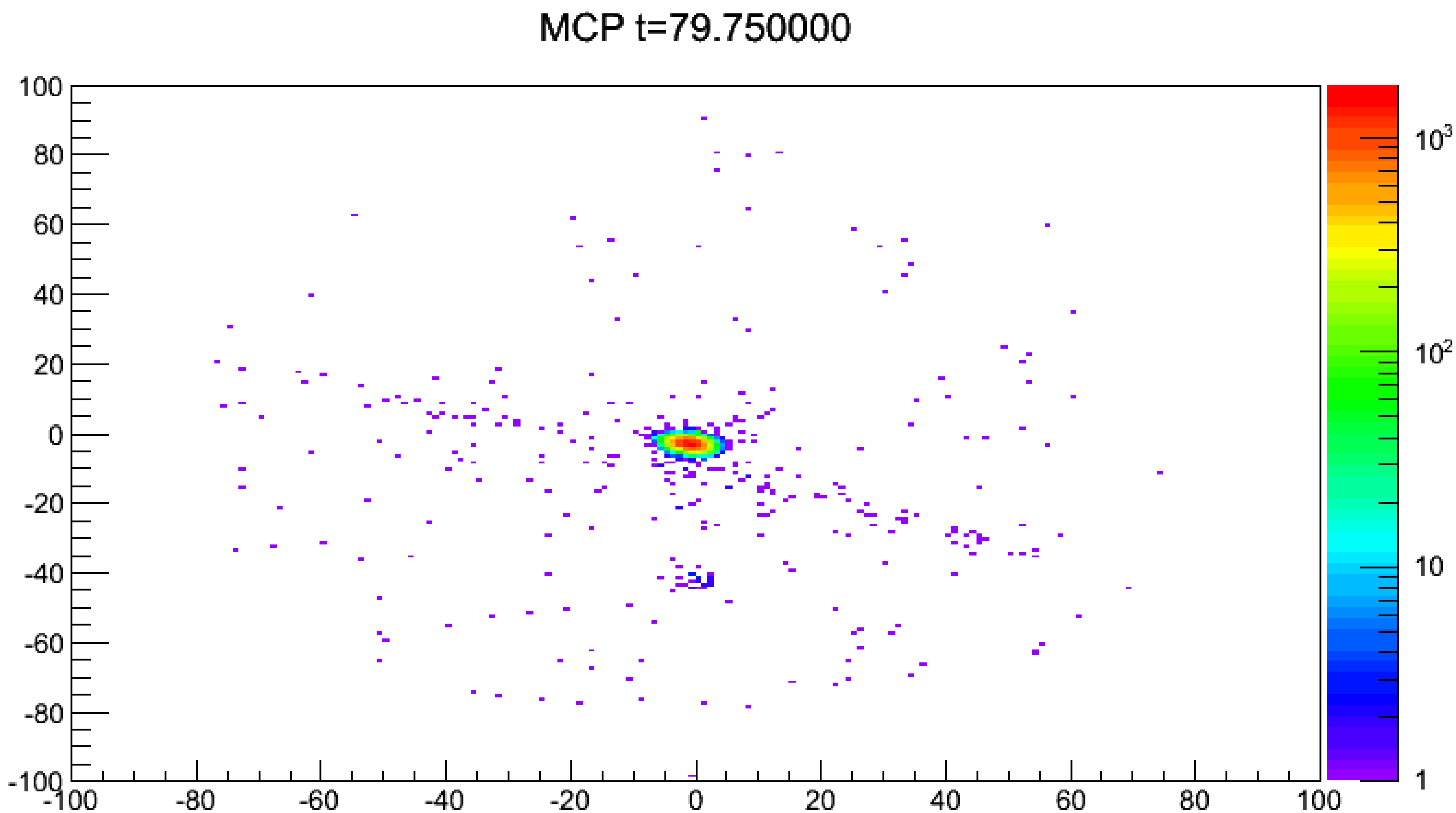
X&Y calibration:

- Reconstruction with 1st and 2d order polynomial functions

  → up to 0.6 mm deviation on the edges of MCPs

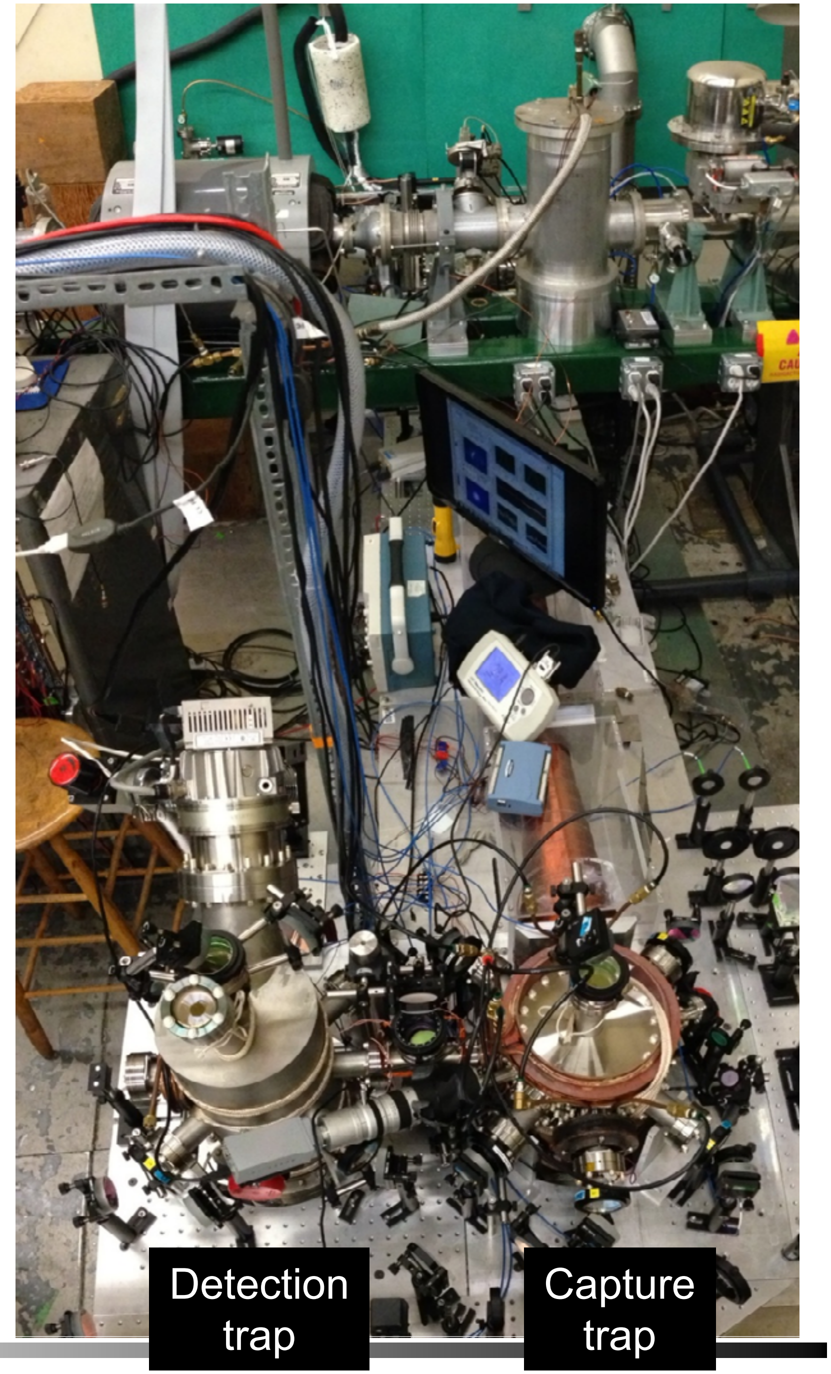


Show Penning ionization animation



^{6}He little-a outlook

- Routinely trap 100 6He atoms. Presently working towards longer stability for a 1-week long experiment.
- Detection systems working.
- First data run planned for later in 2015.
- Aiming for a 1% determination of "little a" by end of 2015.
- R&D for spectrum shape determination (Savanna's talk).

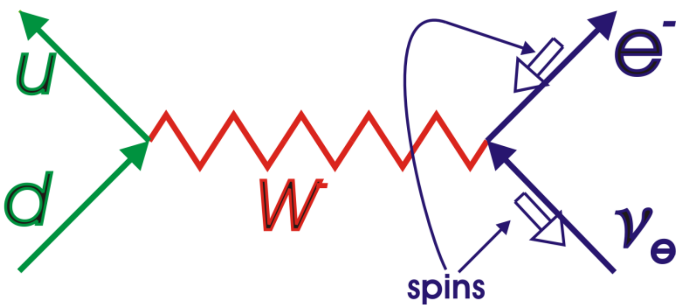


Backup slides

Helicities in the Standard Model

$$\mathcal{H} = \frac{\vec{p}.\vec{J}}{|\vec{p}||J_{\max}|}$$

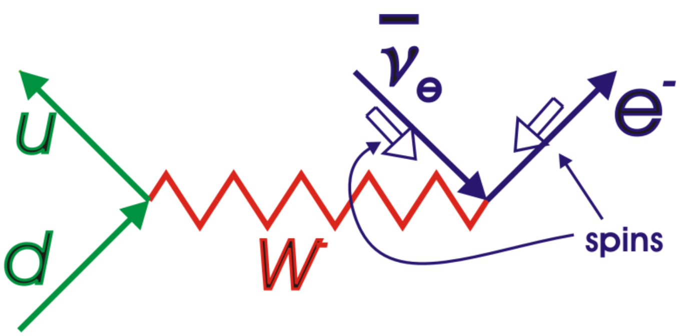
Example: photons have $\mathcal{H}$=±1.



The electro-weak interactions are mediated by VECTOR (Spin=1) particles (Photon, Z0, Ws)

A consequence is that the **interactions don't flip helicities.**

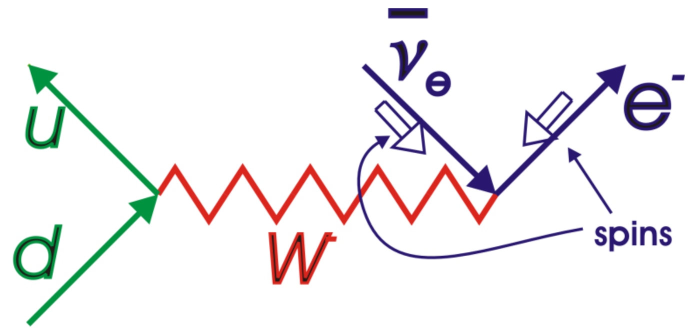
Or equivalently (notice anti nu):



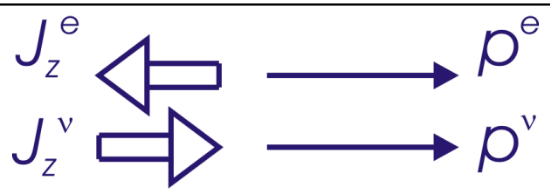
All the particles that couple to the Weak interactions are left handed;

Particles → Left handed
Anti particles → Right handed

Helicities in the Standard Model



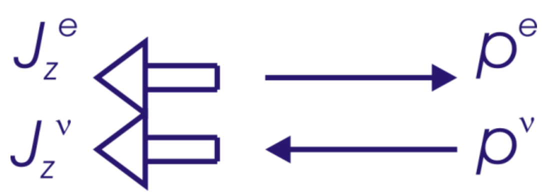
If the nuclear spins don't flip then the leptons have total *Jz=0*



Consequence: e-antinu correlation

$$\frac{d\Gamma}{d\Omega_{e\nu}} = 1 + \frac{\vec{p}^{\,e}}{E_e} \bullet \frac{\vec{p}^{\,\nu}}{E_\nu}$$

If the nuclear spins flip then the leptons have total *Jz=1*



Consequence: e-antinu correlation

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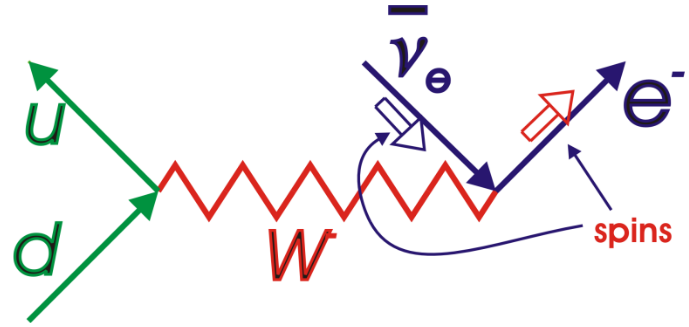
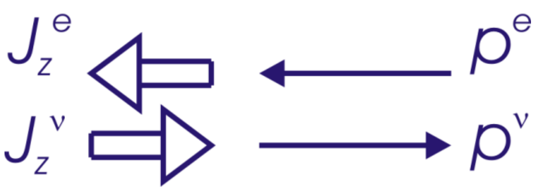
Helicities in with **Scalar or Tensor Currents**



If the nuclear spins don't flip then the leptons have total *Jz=0*



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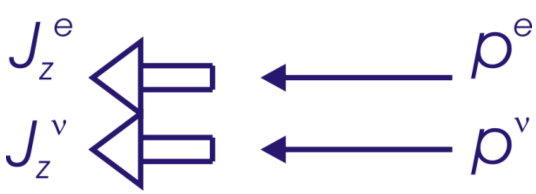
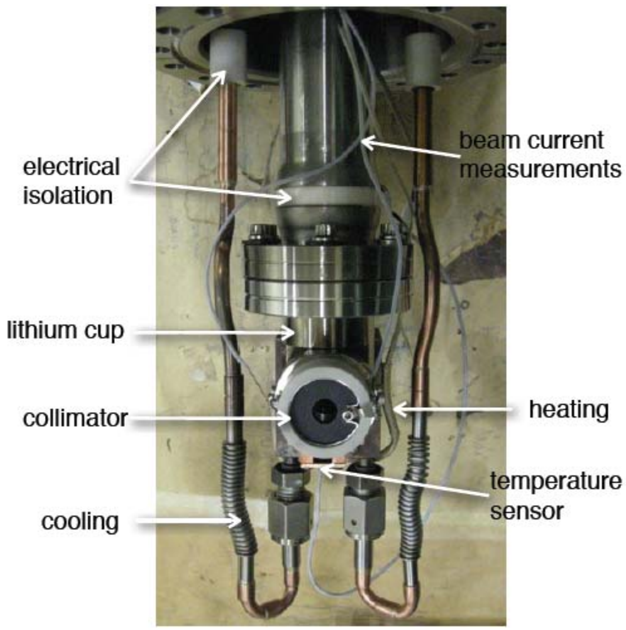
If the nuclear spins flip then the leptons have total *Jz=1*

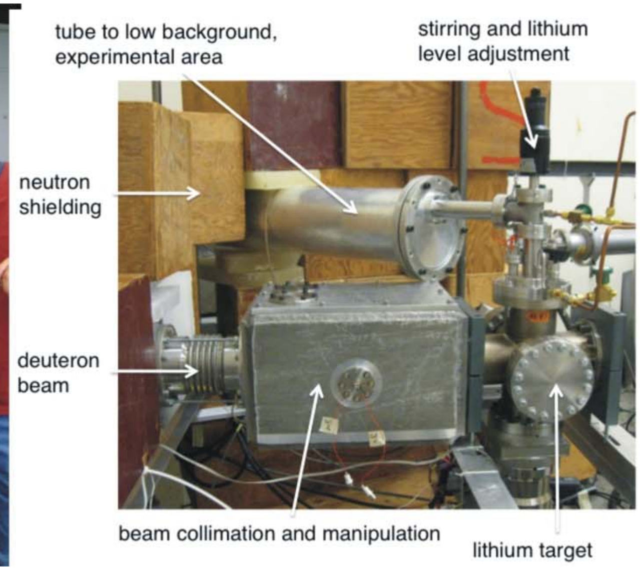


Consequence: e-antinu correlation

$$\frac{d\Gamma}{d\Omega_{e\nu}} = 1 + \frac{\vec{p}^{\,e}}{E_e} \bullet \frac{\vec{p}^{\,\nu}}{E_\nu}$$

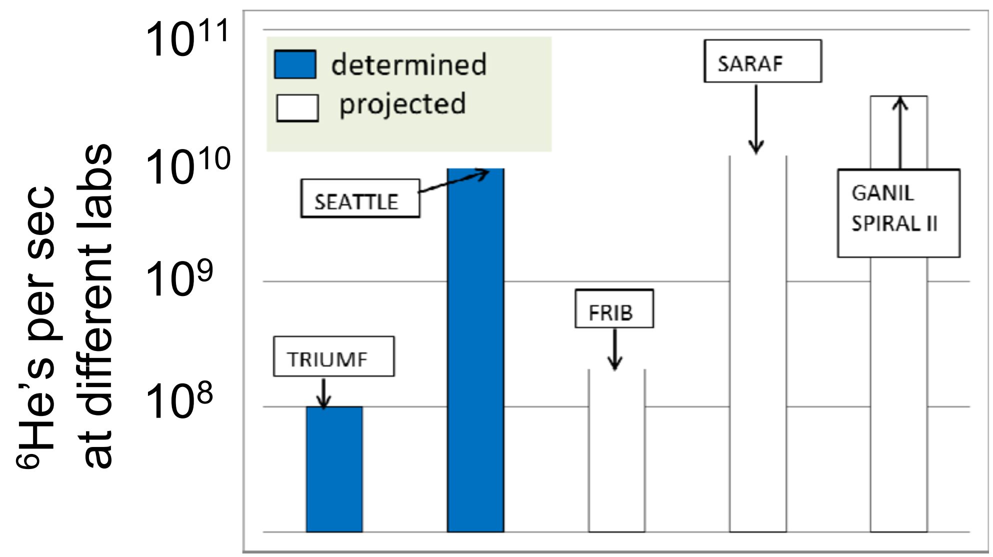
Now have ~10^{10} atoms of ^{6}He/s at Seattle via ^{7}Li(d,^{3}He)^{6}He





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

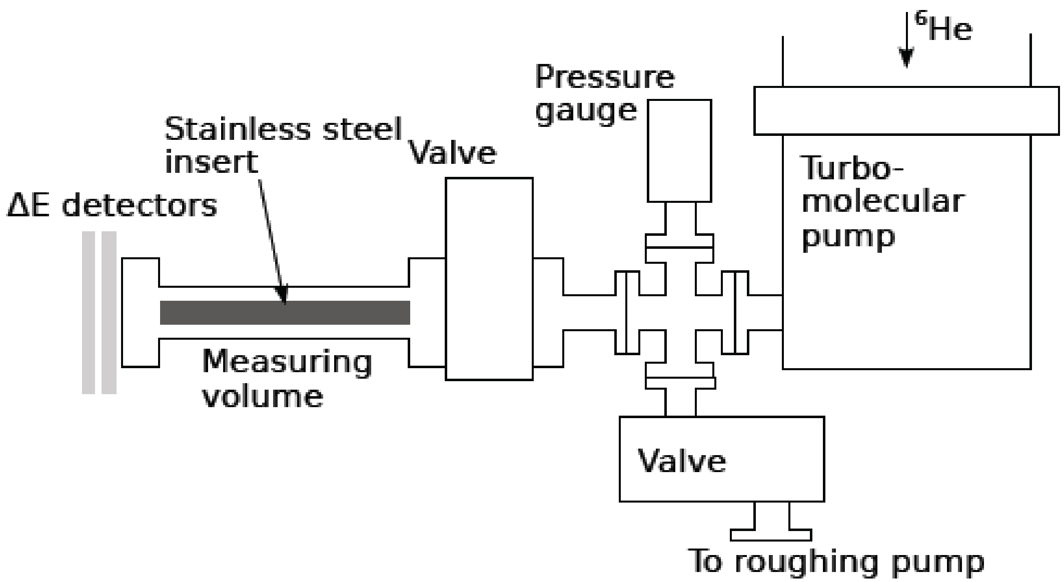
A. Knecht et al.
NIM A. **660**, 43 (2011)



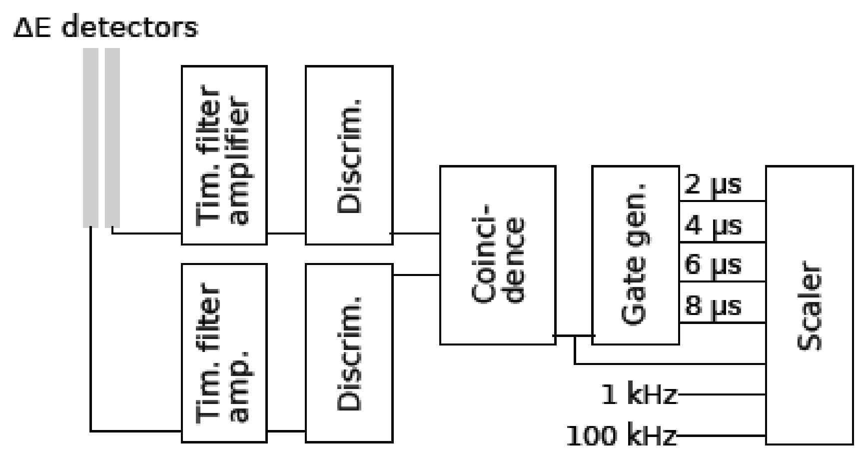
Coupling constant for Weak Decays from the lifetime of ^6He

Experimental Setup

UNIVERSITY of WASHINGTON



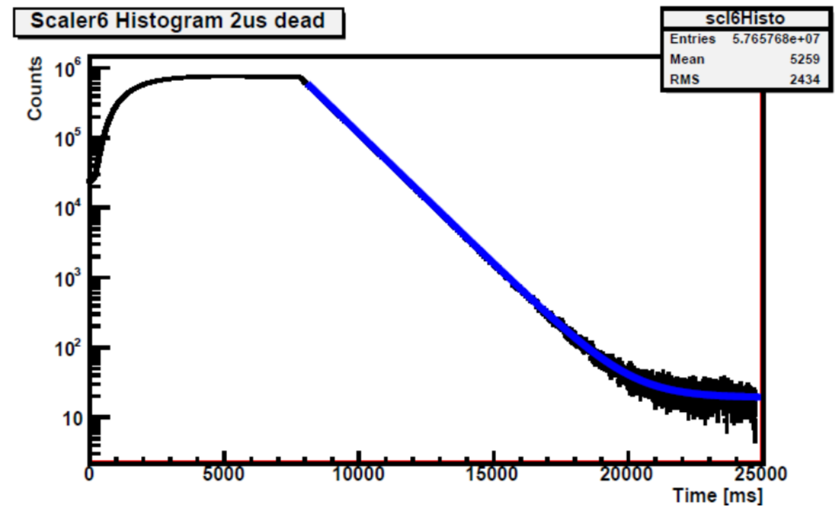
- Stainless steel measuring volume with insert to check for diffusion
- Scaler based DAQ

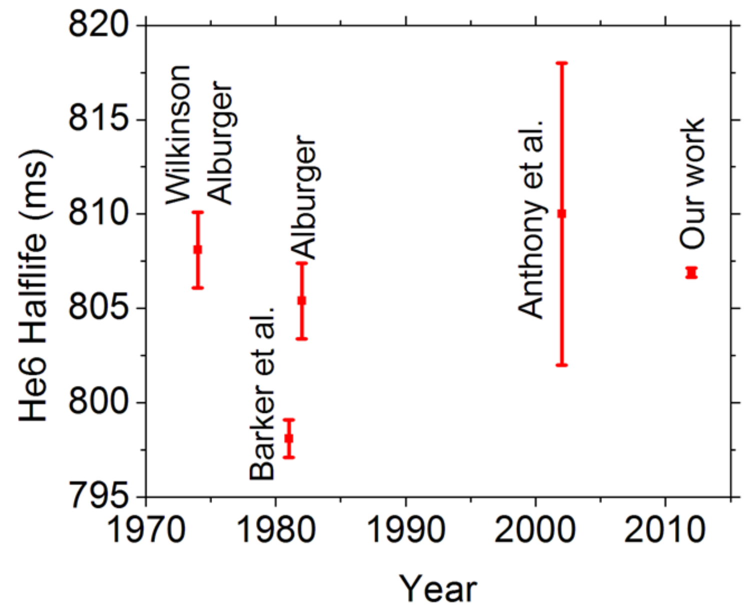


Extracting g_A from the lifetime of ^{6}He

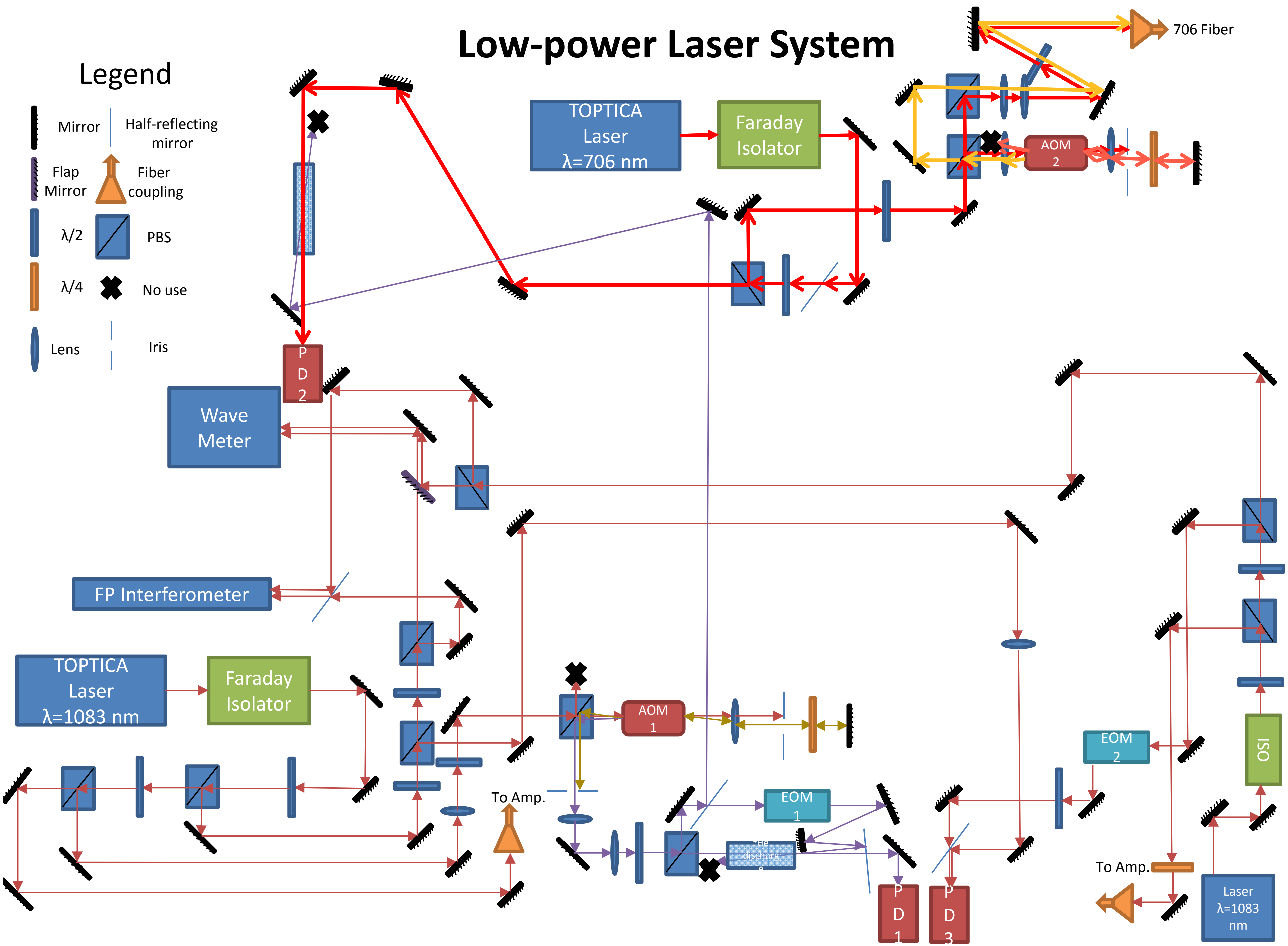
- Two previous experiments disagreed by 9 ms. Resolved the discrepancy.
- Our results in combination with ab-initio calculations shows that quenching is at most about 2%.

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

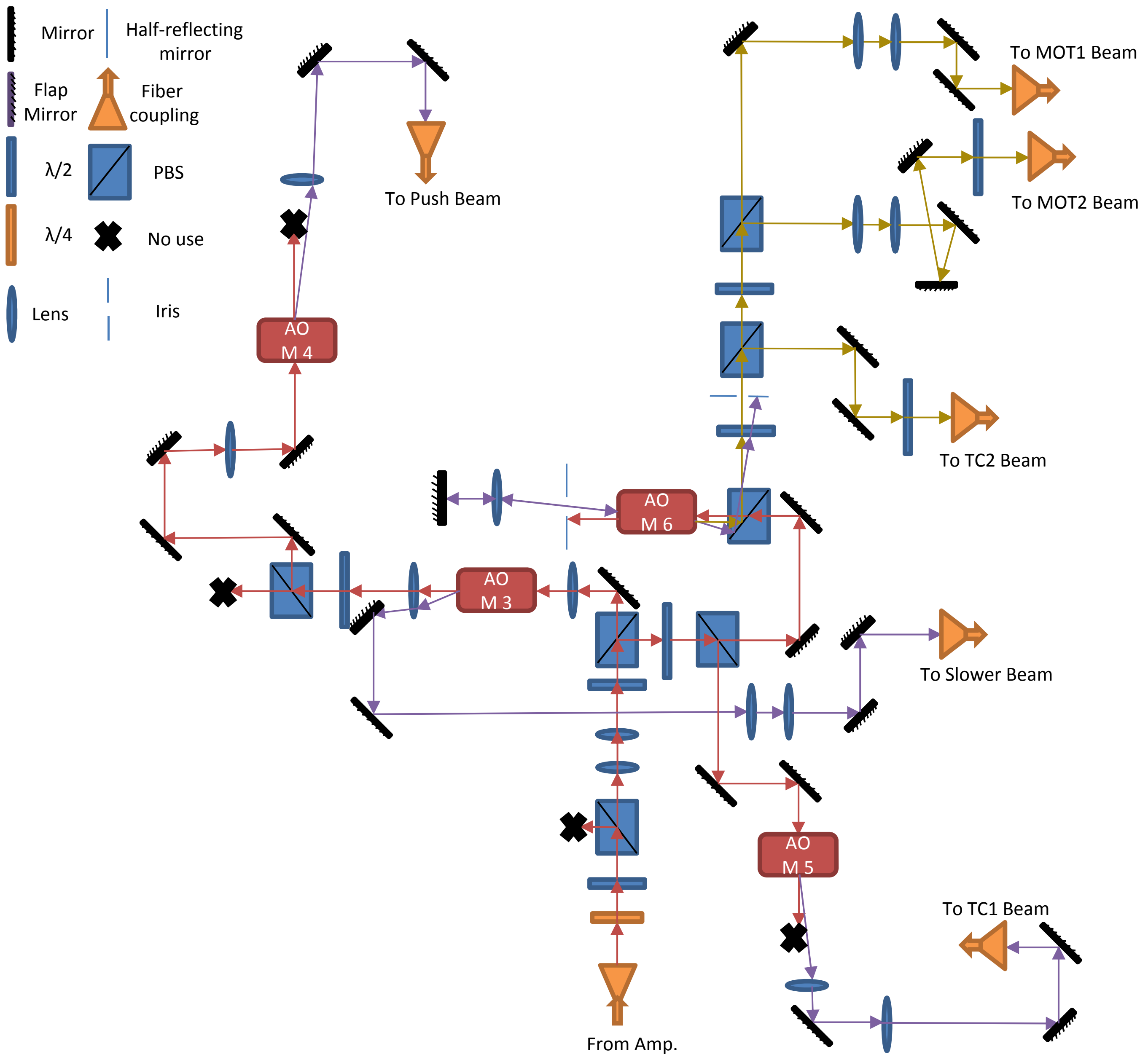




Low-power Laser System



High-power Laser System



The End