Helicity, Chirality and Fundamental Interactions

Presentation to
REU Students
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Helicity, Chirality and Fundamental Interactions

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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

Chirality and human conventions

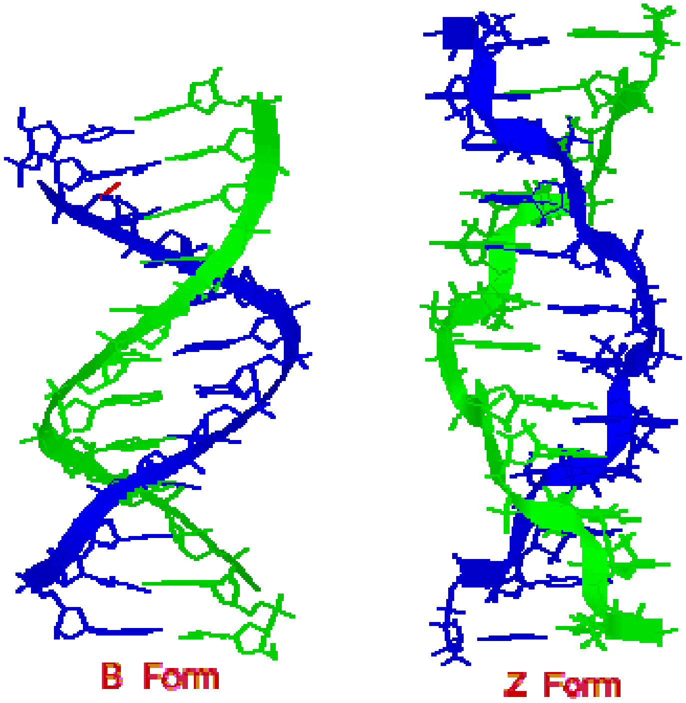
Screws can be *right handed* or *left handed*. For simplicity humans have made ***conventions*** so we know which way to turn the corkscrew to get the cork out of the bottle…

Or to tighten a screw…

Chirality and molecules

Surprising: Nature distinguishes chirality, at the molecular level.

Chirality -- or 'handedness' -- is a striking property of the biological world. Many organic molecules, including glucose and most biological amino acids are chiral and the DNA double helix in its standard form always twists like a right-handed screw.



Chirality and molecules

Surprising: Nature distinguishes chirality, at the molecular level.

Chirality and drug development -- the Thalidomide tragedy

Thalidomide was prescribed widely to pregnant women between 1957 and 1962 for its benefits in reducing morning sickness.

However, when taken during the first trimester of pregnancy, Thalidomide prevented the proper growth of the fetus and the result was that thousands of children around the world were born with severe birth defects.

Thalidomide is a chiral molecule and the drug that was marketed was a 50/50 mixture of left and right-handed molecules. While the left-handed molecule was effective, the right-handed one was highly toxic.

Symmetries in fundamental laws: discrete symmetries → Parity

Parity is the inversion of spatial coordinates:

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

$$\begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} \xrightarrow{P} \begin{pmatrix} ct \\ -x \\ -y \\ -z \end{pmatrix}$$

But, notice angular momentum does *not* flip sign:

$$\vec{L} = \vec{r} \times \vec{p} \xrightarrow{P} (-\vec{r}) \times (-\vec{p}) = \vec{r} \times \vec{p} = \vec{L}.$$

Pseudo-vector
or *Axial* vector.

Scalars, like *E*, don't flip sign under *P*. But some scalars do:

$$\vec{a} \cdot (\vec{b} \times \vec{c}) \xrightarrow{P} (-\vec{a}) \cdot (-\vec{b} \times -\vec{c}) = -\vec{a} \cdot (\vec{b} \times \vec{c}).$$

Pseudo-scalar.

A Brief History of Parity

Parity is symmetry under the inversion of coordinates:

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

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

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

1924: Laporte discovered two classes of atomic states with special *selection rules* for their decays.
1927: Wigner explains atomic selection rules based on Parity symmetry of E&M interaction.
1927-1956 → Parity elevated to dogma: must be a symmetry that all elementary interactions follow.

1956: Yang-Lee suggest Parity may be broken by Weak Interaction.
1957: Parity found to be maximally broken by Weak Interaction in 3 experiments.

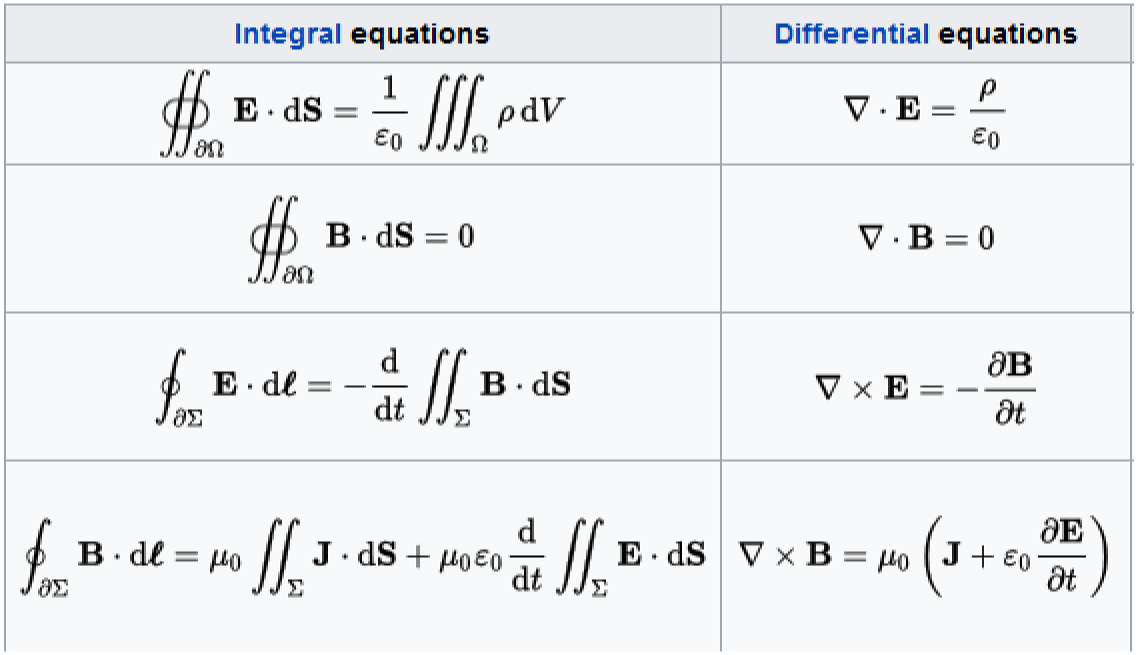
Examples of *P* conservation

- Harmonic oscillator even under *P*:

$$H = \frac{p^2}{2m} + \frac{1}{2} m\omega^2 x^2 \xrightarrow{P} \frac{(-p)^2}{2m} + \frac{1}{2} m\omega^2 (-x)^2 = H$$

- Newton's gravity eqs. remain unchanged: $m\,\frac{d^2\vec{r}}{dt^2} = \vec{F} = \frac{C}{r^2}\,\hat{r}$

- Maxwell's Eqs. under *P*:



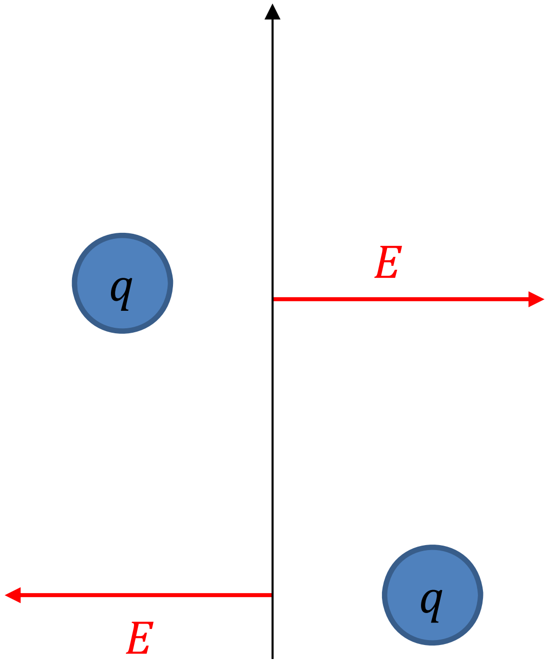
Integral equations	Differential equations
$\oiint_{\partial\Omega} \mathbf{E}\cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0}\iiint_{\Omega} \rho\,\mathrm{d}V$	$\nabla\cdot\mathbf{E} = \frac{\rho}{\varepsilon_0}$
$\oiint_{\partial\Omega} \mathbf{B}\cdot \mathrm{d}\mathbf{S} = 0$	$\nabla\cdot\mathbf{B} = 0$
$\oint_{\partial\Sigma} \mathbf{E}\cdot \mathrm{d}\boldsymbol{\ell} = -\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma} \mathbf{B}\cdot \mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\oint_{\partial\Sigma} \mathbf{B}\cdot \mathrm{d}\boldsymbol{\ell} = \mu_0\iint_{\Sigma} \mathbf{J}\cdot \mathrm{d}\mathbf{S} + \mu_0\varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma} \mathbf{E}\cdot \mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial \mathbf{E}}{\partial t}\right)$

Under *P:*

$\rho \longrightarrow \rho$
$\vec{E} \longrightarrow -\vec{E}$
$\vec{J} \longrightarrow -\vec{J}$
$\vec{B} \longrightarrow \vec{B}$

Eqs. remain unchanged

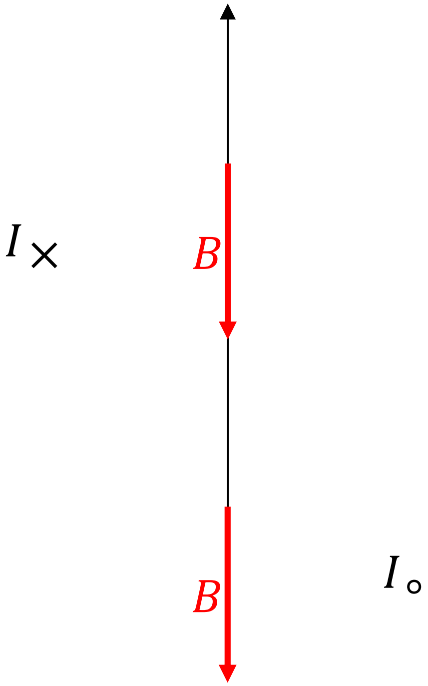
Parity and E field



Under *P:*

$$\rho \longrightarrow \rho$$
$$\vec{E} \longrightarrow -\vec{E}$$

Parity and *B* field



Under *P:*

$$\vec{J} \longrightarrow -\vec{J}$$
$$\vec{B} \longrightarrow \vec{B}$$

Parity and E&M: With the rules we can now check Maxwell's Eqs.

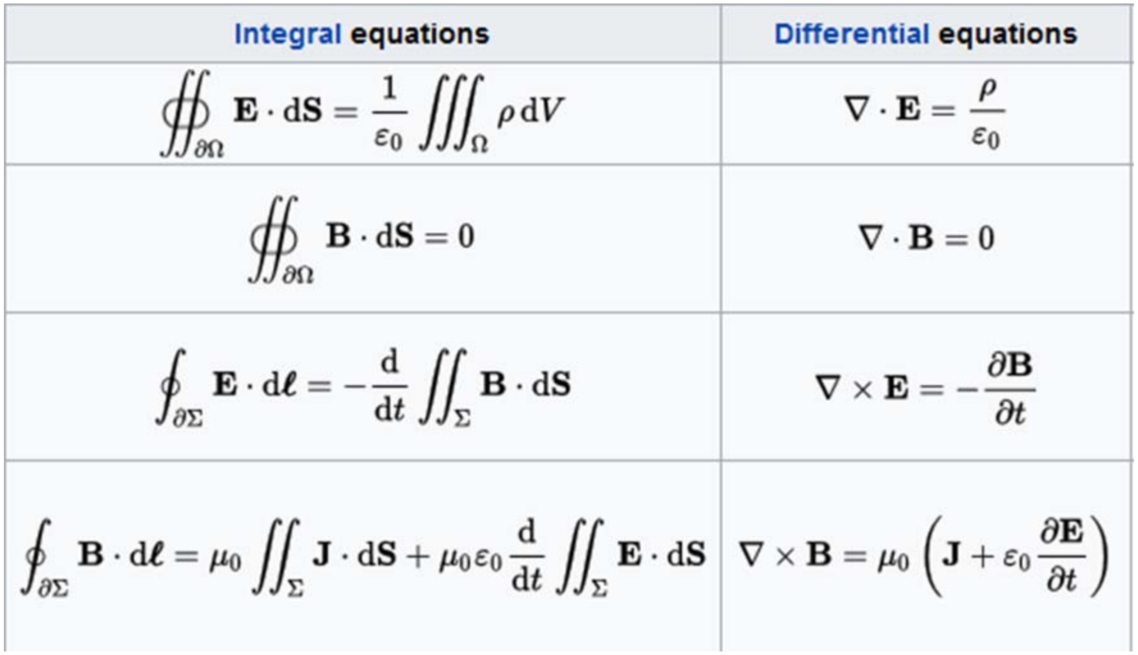
Under *P:*

$\rho \longrightarrow \rho$

$\vec{E} \longrightarrow -\vec{E}$

$\vec{J} \longrightarrow -\vec{J}$

$\vec{B} \longrightarrow \vec{B}$



Integral equations	Differential equations
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$\oint_{\partial\Sigma} \mathbf{B}\cdot \mathrm{d}\boldsymbol{\ell} = \mu_0\iint_{\Sigma} \mathbf{J}\cdot \mathrm{d}\mathbf{S} + \mu_0\varepsilon_0\frac{\mathrm{d}}{\mathrm{d}t}\iint_{\Sigma} \mathbf{E}\cdot \mathrm{d}\mathbf{S}$	$\nabla\times\mathbf{B} = \mu_0\left(\mathbf{J} + \varepsilon_0\frac{\partial \mathbf{E}}{\partial t}\right)$

It is easy to verify that none of the equations gets changed by applying *P*.

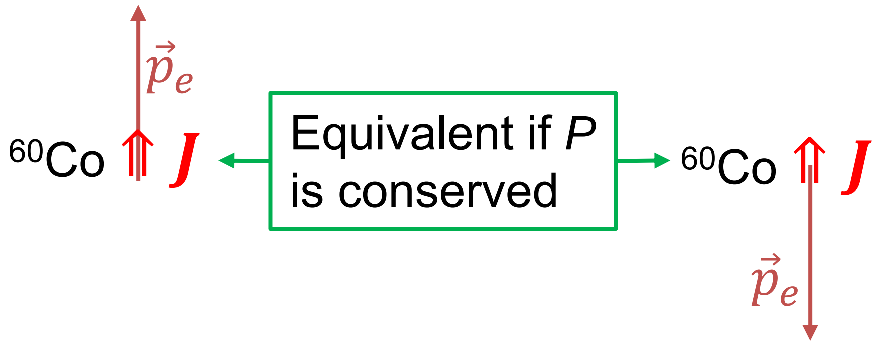
Experimental Observation of Parity Violation (1957)

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

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

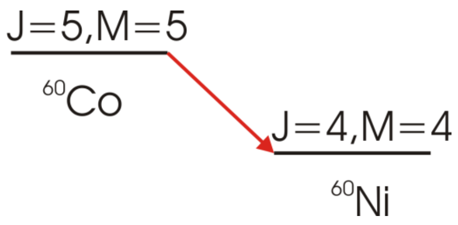
$$P(\vec{r}\times\vec{p}) = (\vec{r}\times\vec{p})$$

P inverts coordinates and momenta, but *not* angular momenta

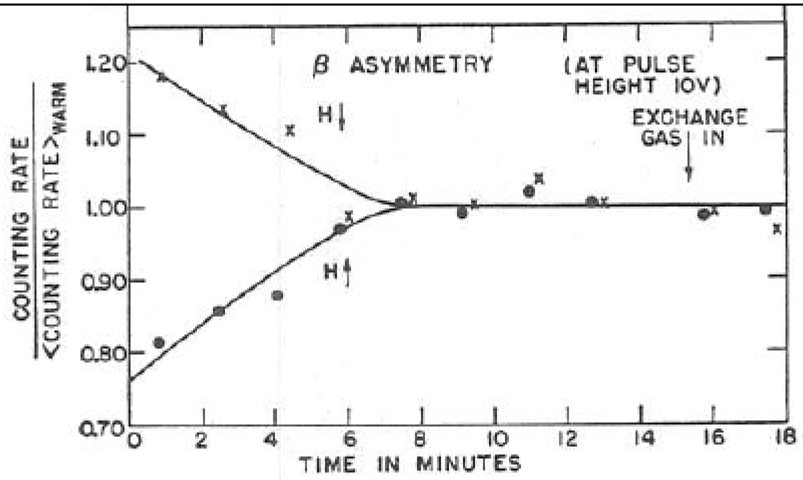


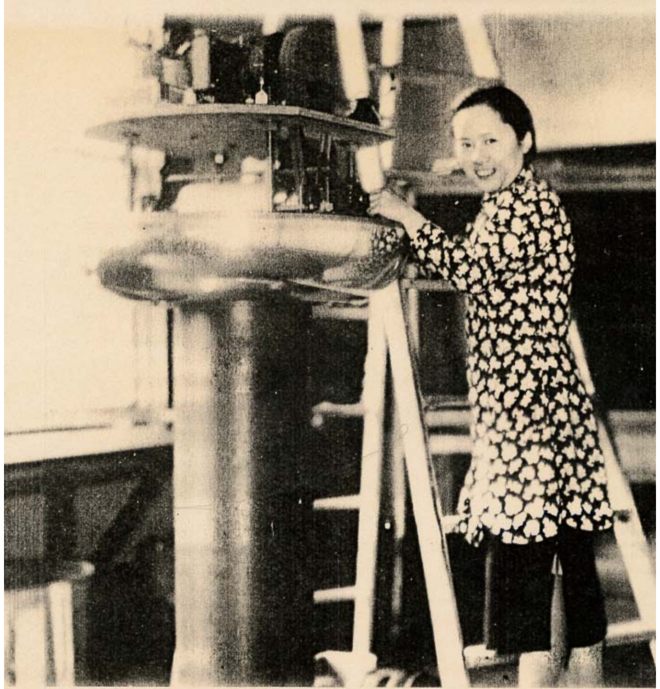
Equivalent if *P* is conserved

Experiment with polarized ^{60}Co



Chien-Shiung Wu showed that electrons come mostly opposite the polarization of ^{60}Co.

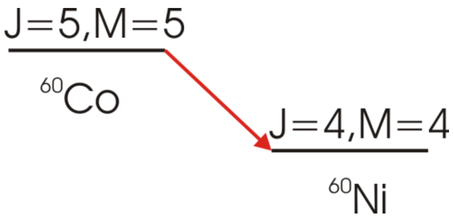


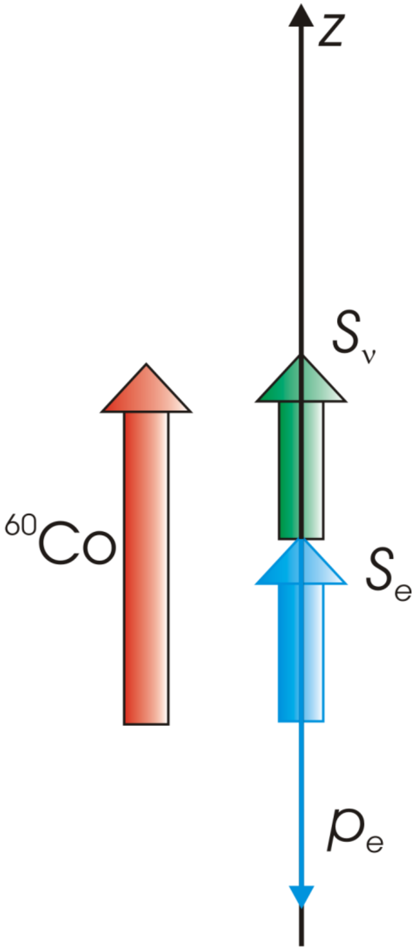


Chien-Shiung Wu (b. 1912)
Nuclear Physicist

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 Weak interaction couples to *left-handed fermions* and *right-handed anti-fermions*.

Helicity

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

For a spin ½ particle $\mathcal{H}$ can be *Right* (+) or *Left* (-).

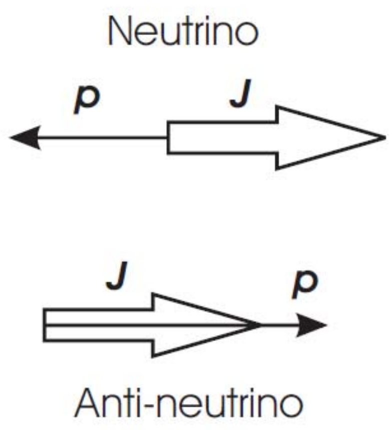


Figure 7.2: Neutrino and antineutrino are always *polarized* if we neglect their very small masses. The neutrino has its spin always opposite to its momentum; the antineutrino has parallel spin and momentum.

Remarkable:

Neutrinos and e's emitted in beta decay are *Left*-handed

Anti-neutrinos and positrons emitted in beta decay are *Right*-handed

Quiz:

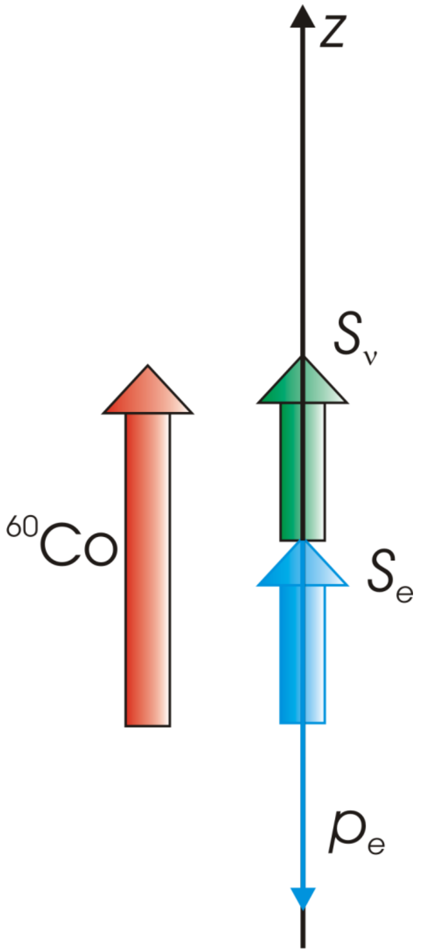
In the decay of polarized $^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^{-} + \bar{\nu}_e$ the electrons come mainly opposite the $^{60}\mathrm{Co}$ polarization.

The anti-neutrinos come mainly:

1. In the same direction as the $^{60}\mathrm{Co}$ polarization.
2. Opposite the $^{60}\mathrm{Co}$ polarization.
3. Neither along or opposite the $^{60}\mathrm{Co}$ polarization.

Quiz:

In the decay of polarized $^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^{-} + \bar{\nu}_e$ the electrons come mainly opposite the $^{60}\mathrm{Co}$ polarization. The anti-neutrinos come mainly:



The Weak interaction couples to *left-handed fermions* and *right-handed anti-fermions*.

1. In the same direction as the $^{60}\mathrm{Co}$ polarization.
2. Opposite the $^{60}\mathrm{Co}$ polarization.
3. Neither along or opposite the $^{60}\mathrm{Co}$ polarization.

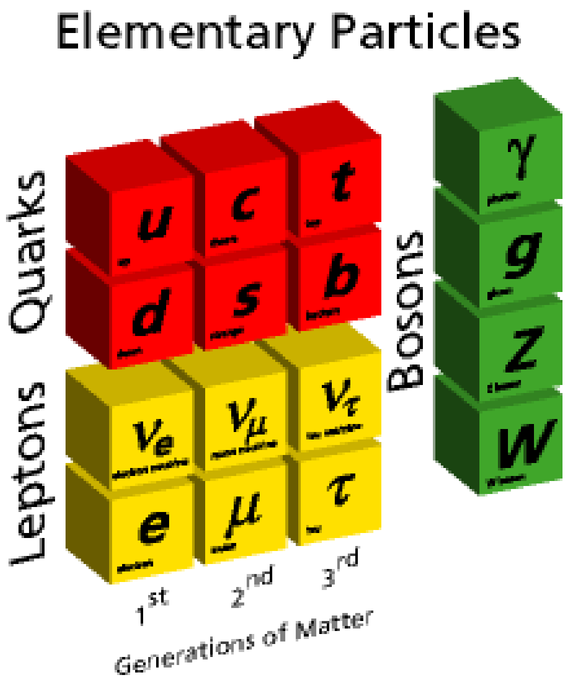
The modern context. The Standard Model and some open questions.

What is the mechanism for the mass of neutrinos? (hints that it doesn’t work like for the other particles)…

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

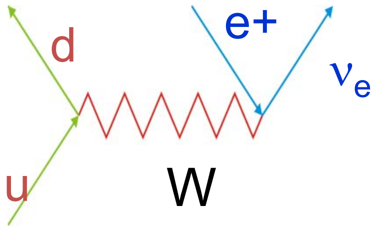
Why are the number of generations for quarks identical to those of leptons?

Answers should also illuminate “new physics”

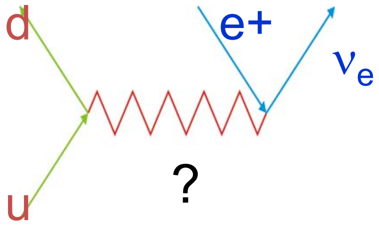


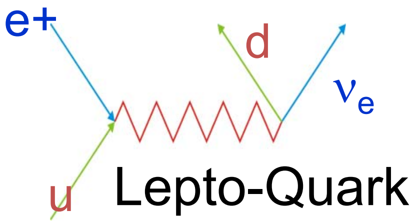
Searches for Scalar and Tensor currents.

Are weak decays carried only by W's?



Or is there something new?





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

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

Standard model

Tensor currents

Decay rate:

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

Measure E_e spectrum

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

$$a \approx -\frac{1}{3}\left(1 - (C_T/C_A)^2 - (C'_T/C_A)^2\right)$$

$\rightarrow$ Measure $e - \nu$ correlation

6He little-a collaboration

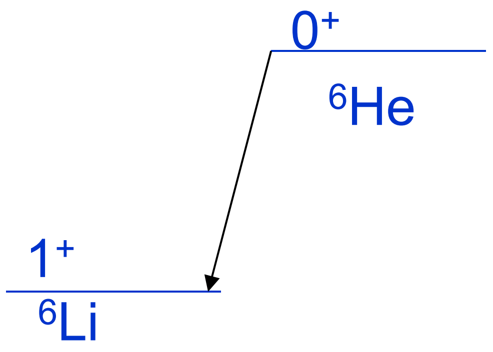
P. Muller, A. Leredde
Argonne National Lab

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

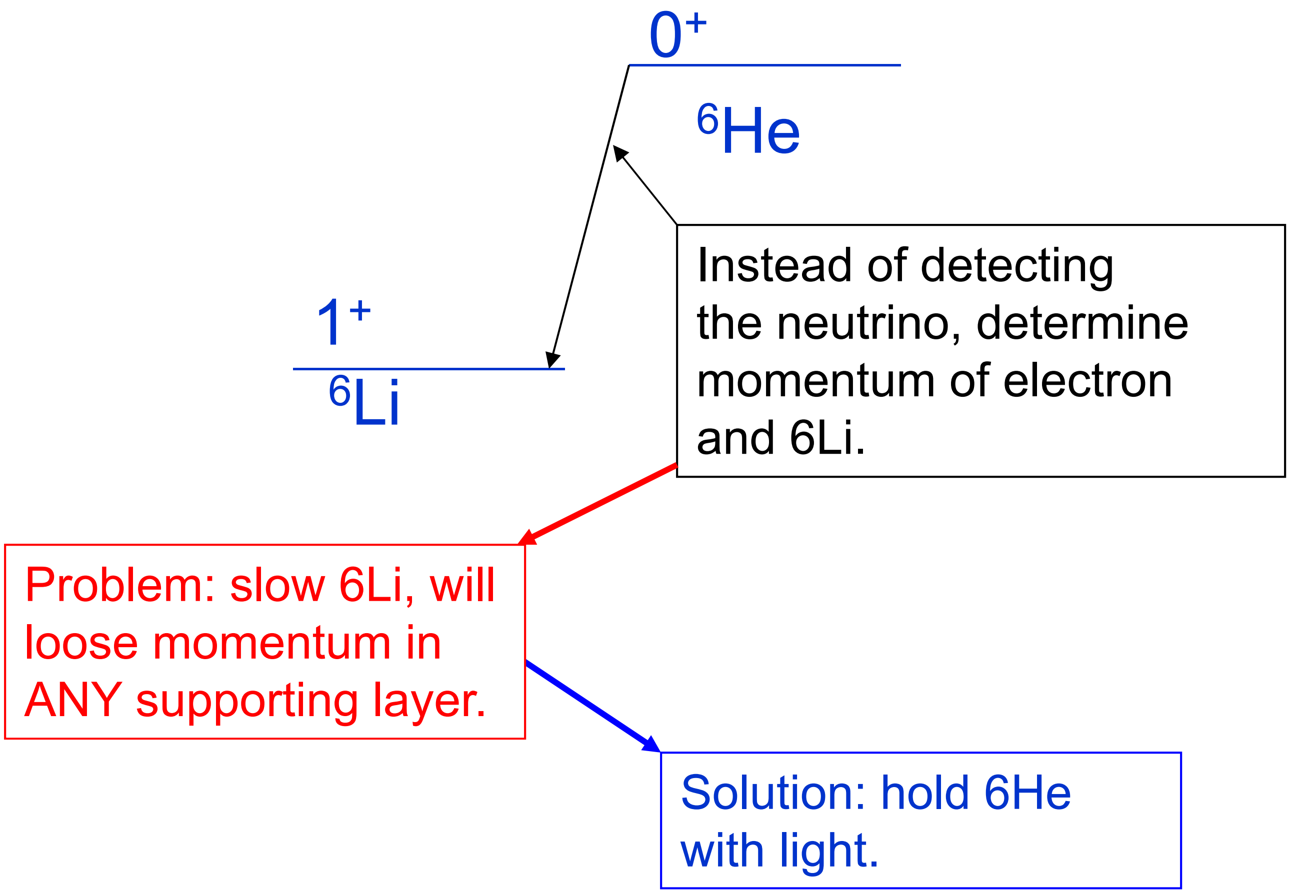
O. Naviliat-Cuncic
NSCL, Michigan State University

Y. Bagdasarova, A. Garcia, B. Graner, R. Hong, D. Storm, H.E. Swanson
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



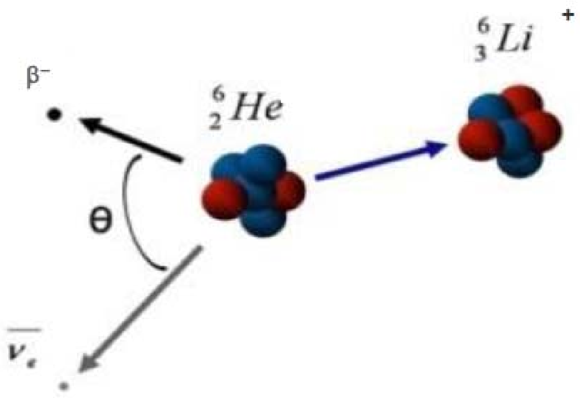
Instead of detecting the neutrino, determine momentum of electron and 6Li.

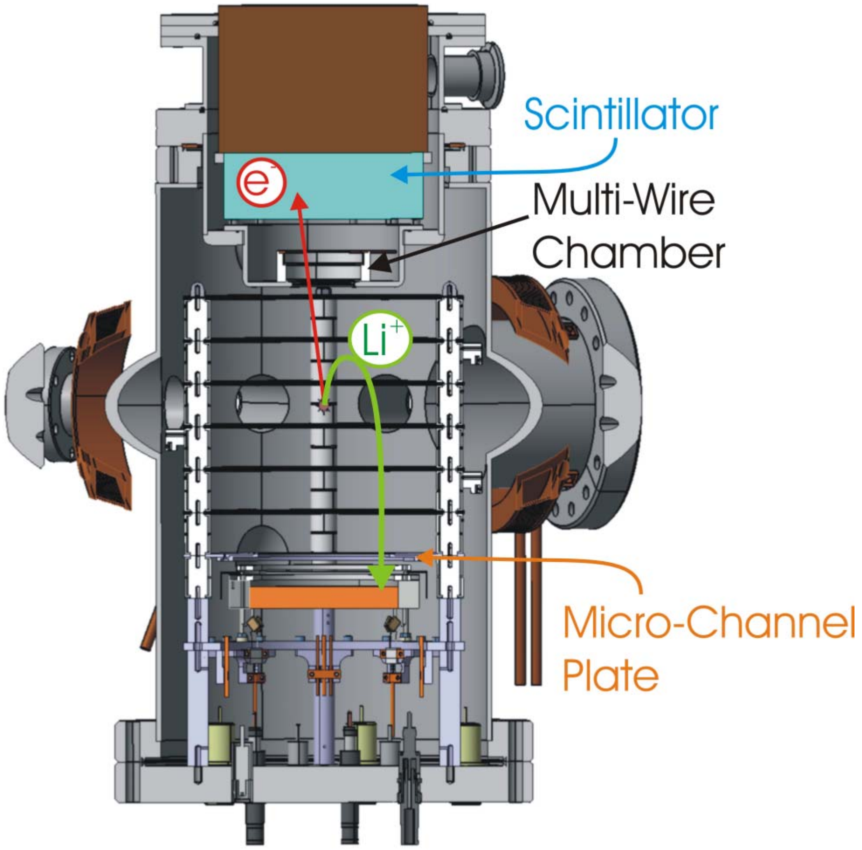
Problem: slow 6Li, will loose momentum in ANY supporting layer.

Solution: hold 6He with light.

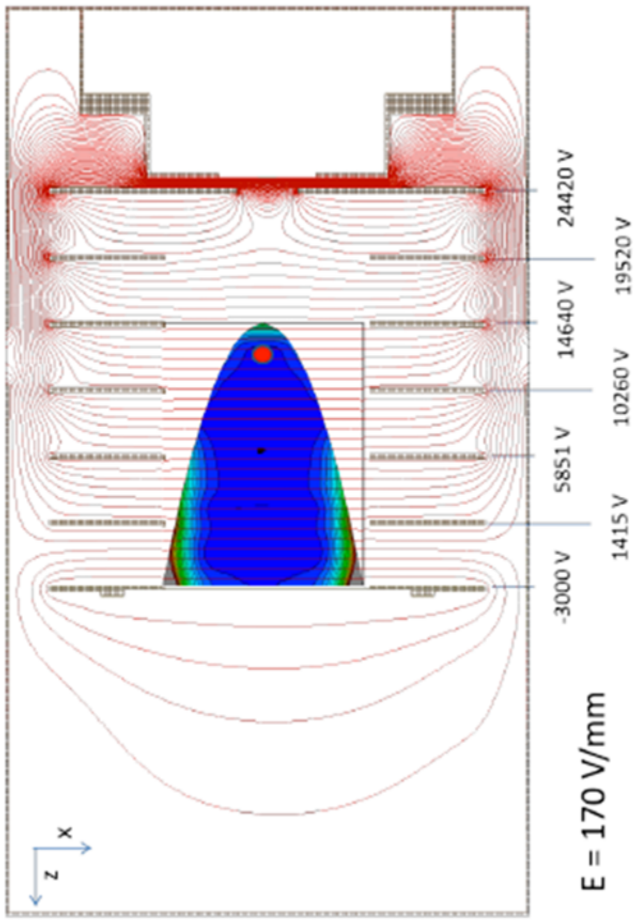
^{6}He little a, measurement

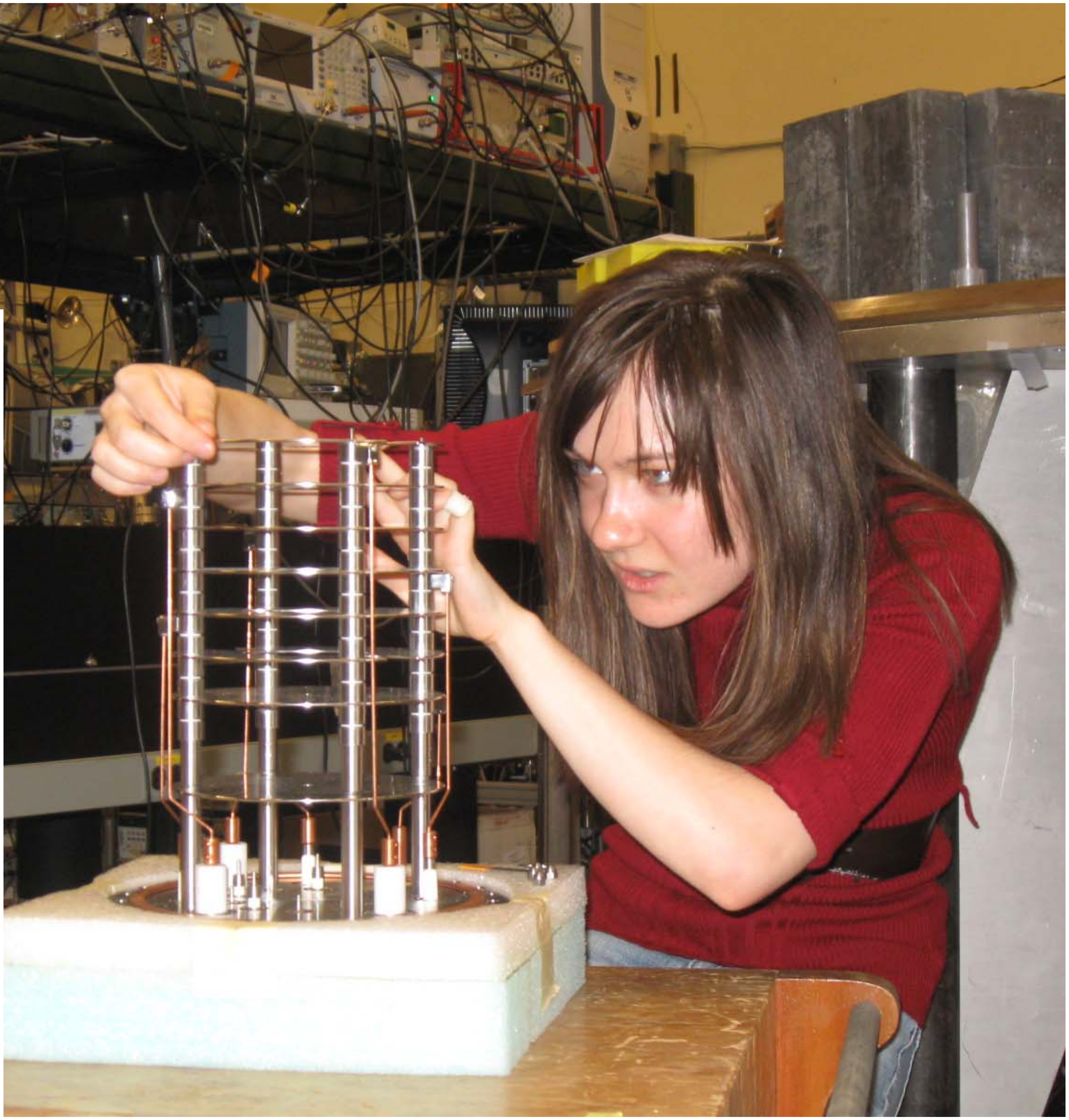
- Electron and ^{6}Li recoil nucleus detected in coincidence
- ΔE-E scintillator system for electron detection (energy, start of time-of-flight)
- Micro-channel plate detector for detection of recoil nucleus (position, time-of-flight)





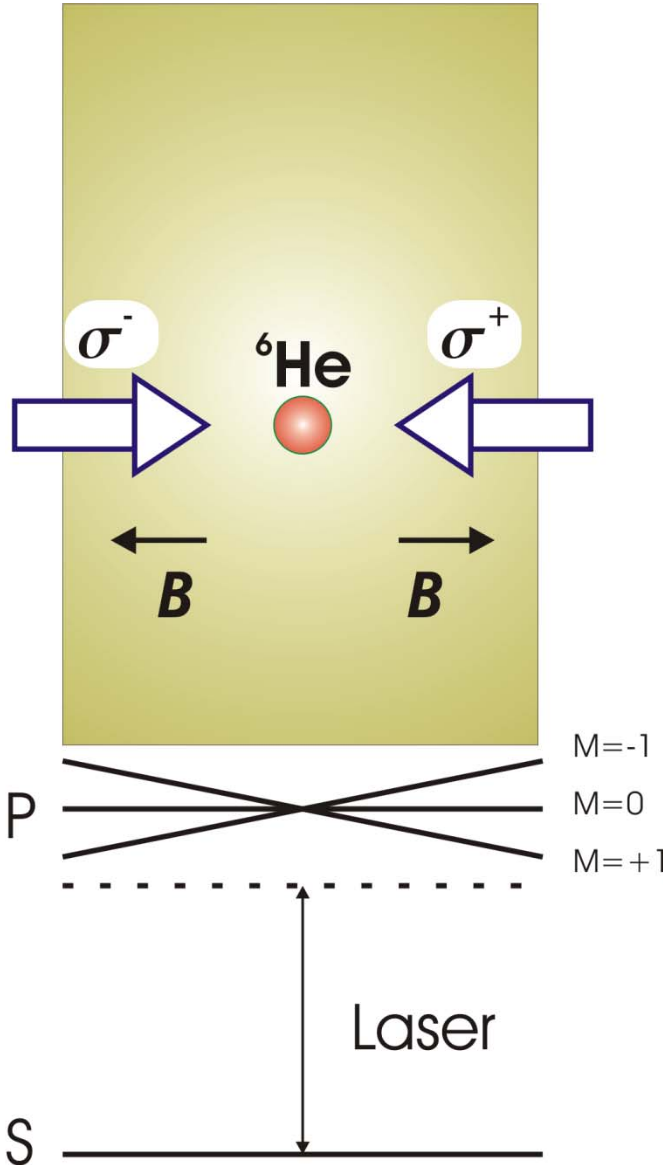
Electric field of apprx 2 kV/cm to guide 6Li ions.





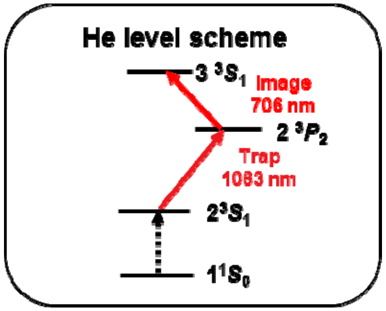
Magneto-Optical Trap

- 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

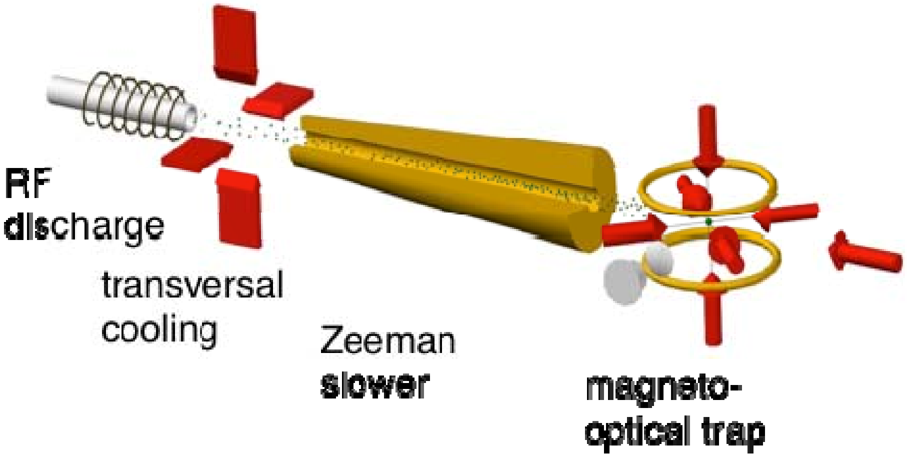


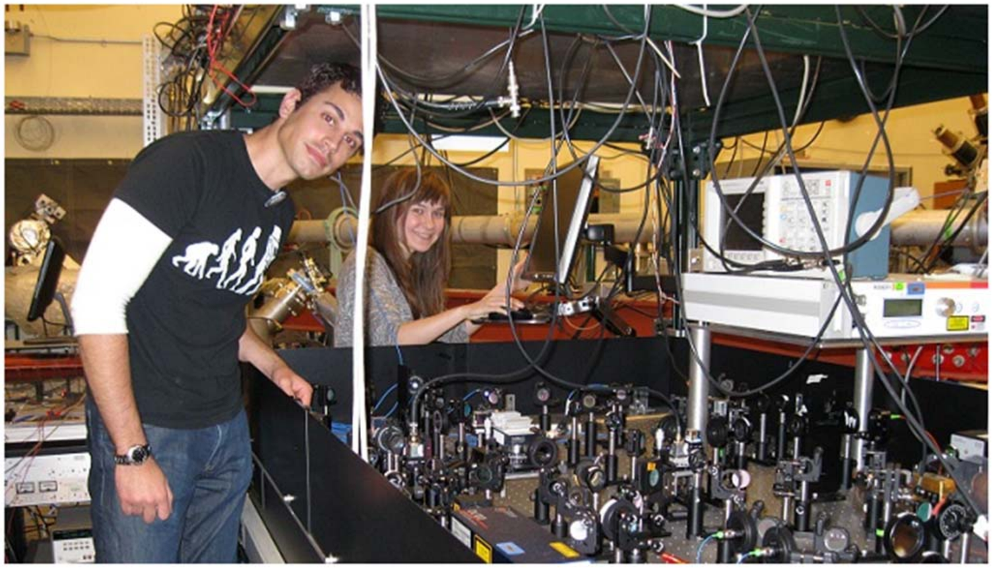
Trapping of ^{6}He

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

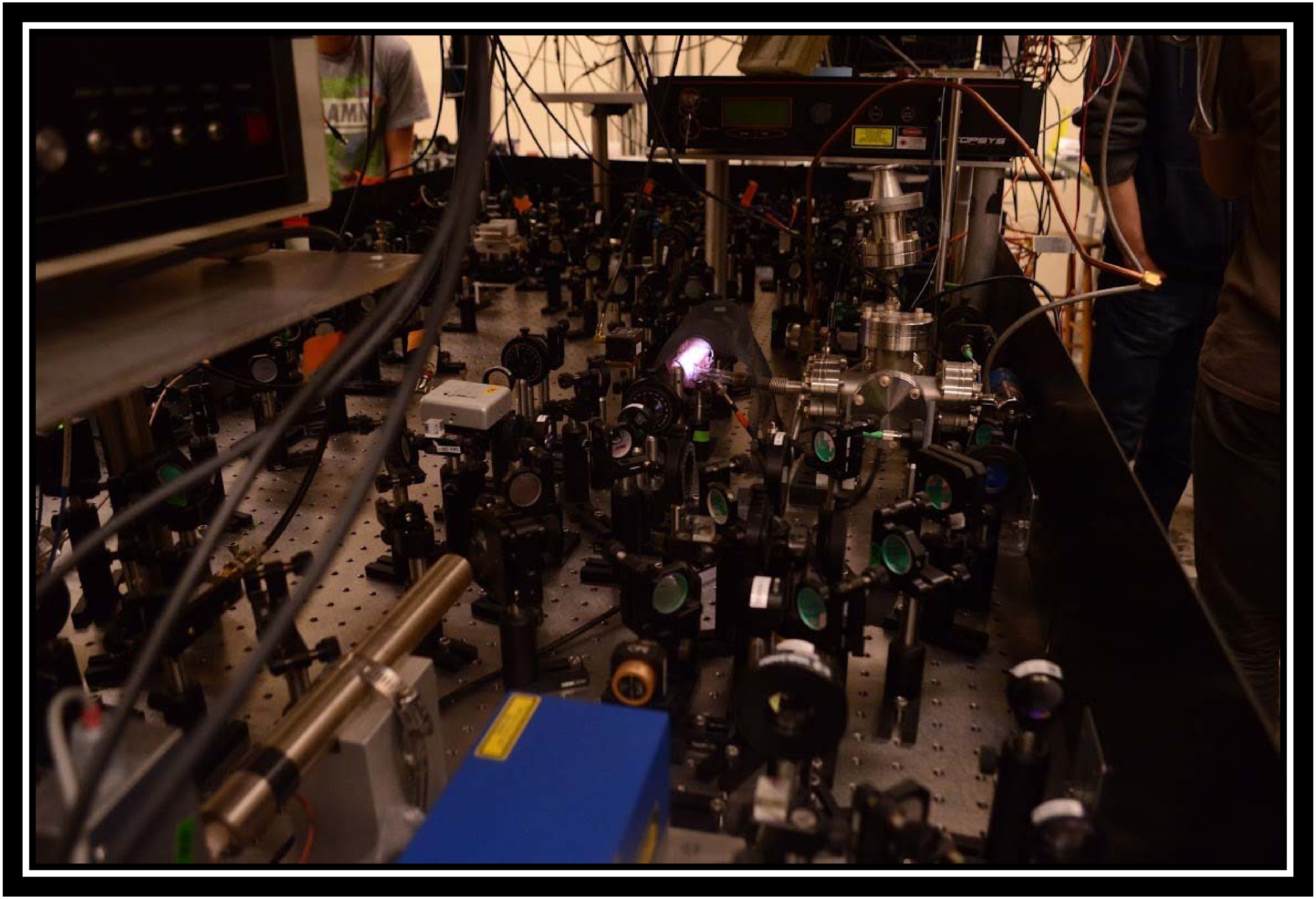


- Trapped atoms transferred to detection chamber with 2nd MOT
- Based on experience from ^{6}He, ^{8}He charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL **93**, 142501 (2004)
  P. Mueller et al., PRL **99**, 252501 (2007)

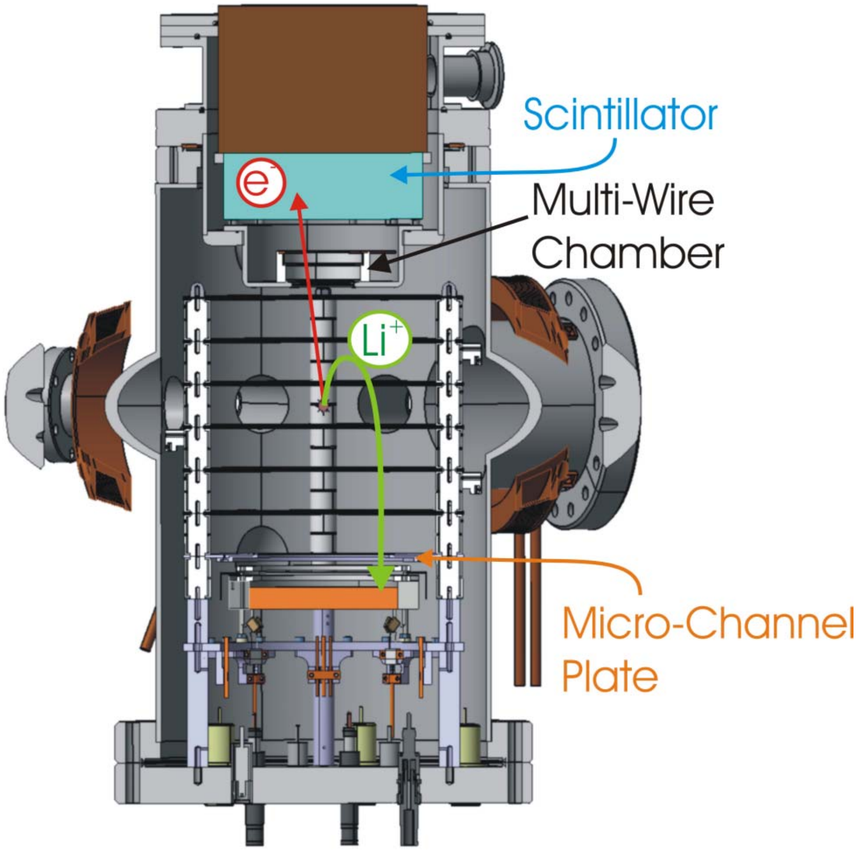




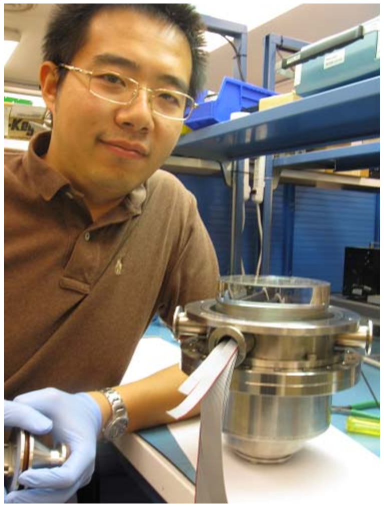
One of the laser tables:

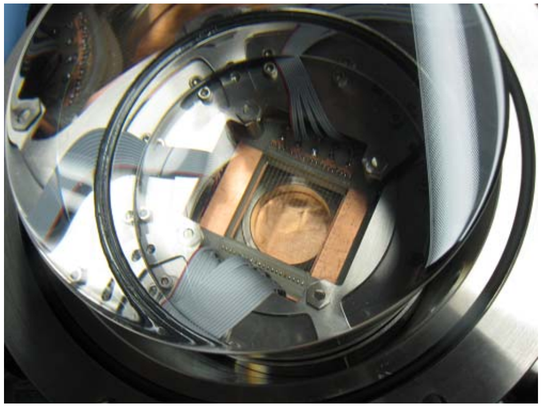


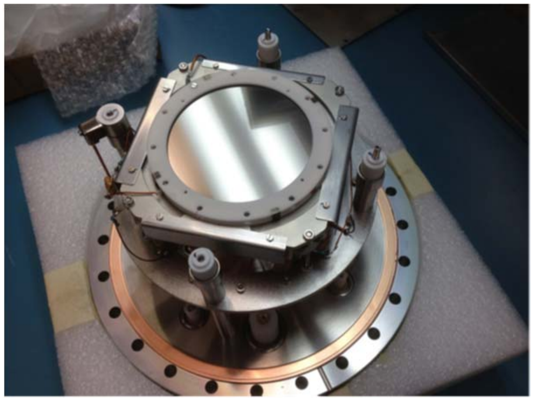
Some of the detectors



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

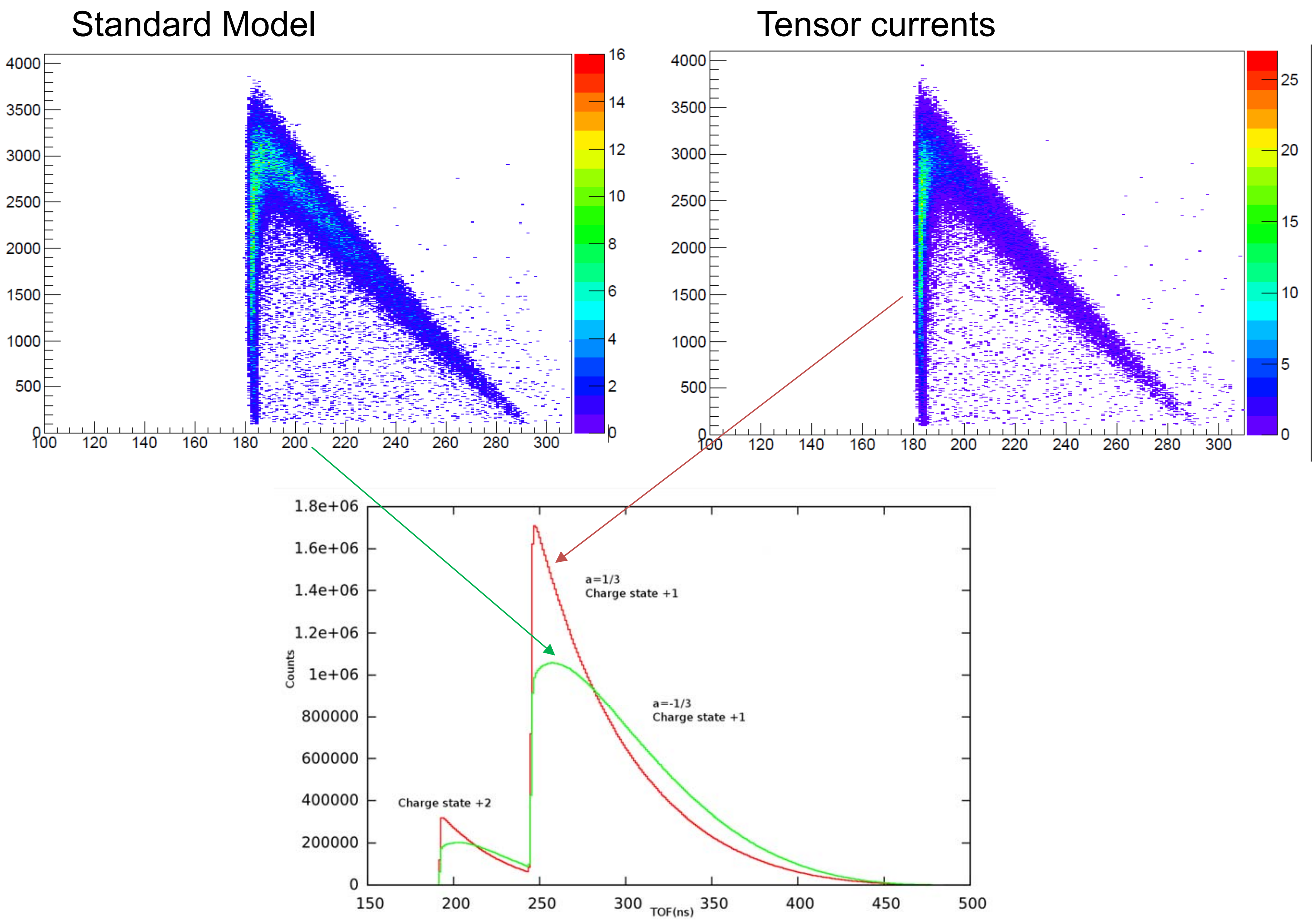






Micro-channel plate detector for detection of ^{6}Li recoil nucleus (position, time-of-flight)

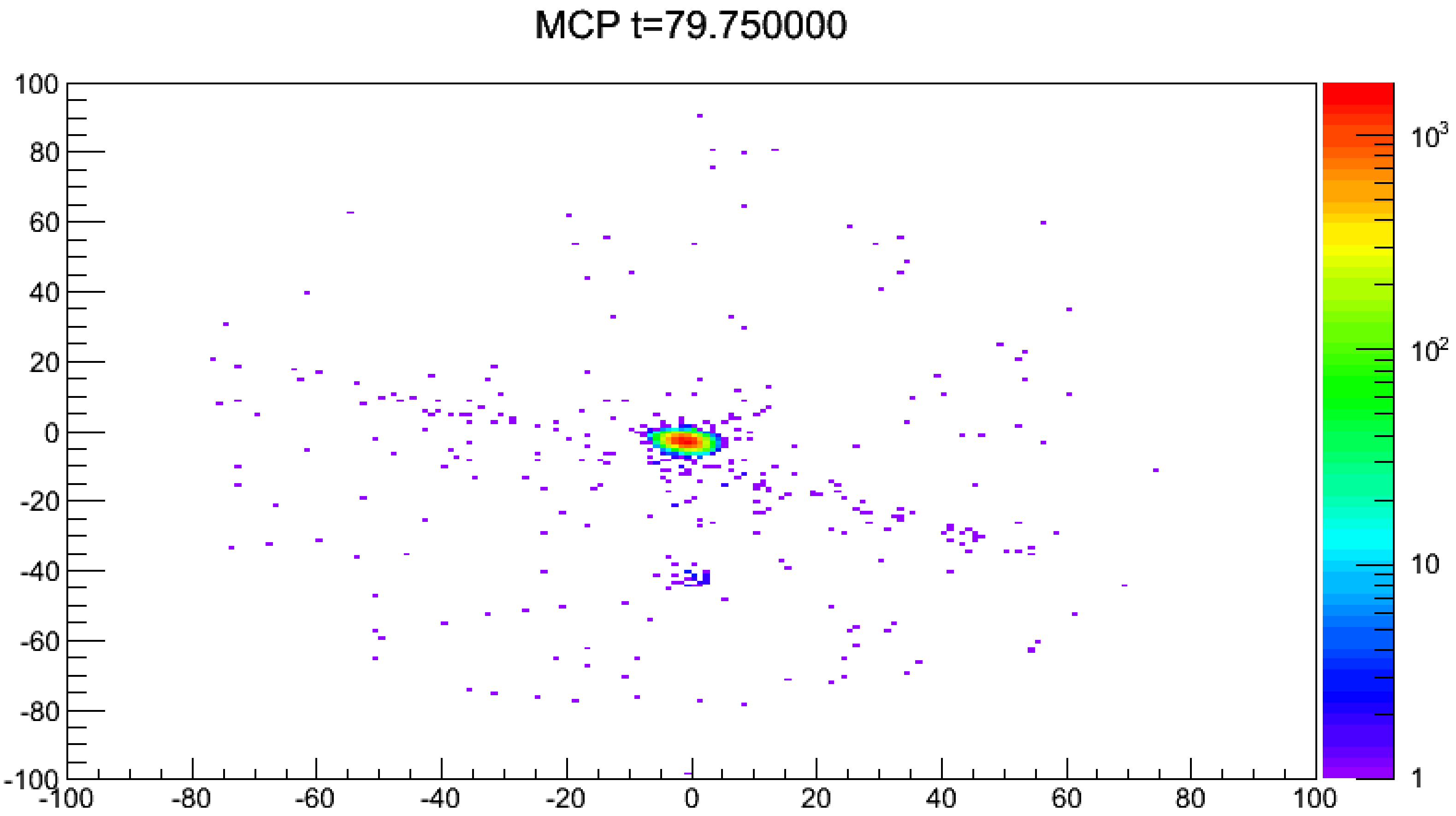
Ebeta versus TOF simulations



Standard Model

Tensor currents

Show Penning ionization animation



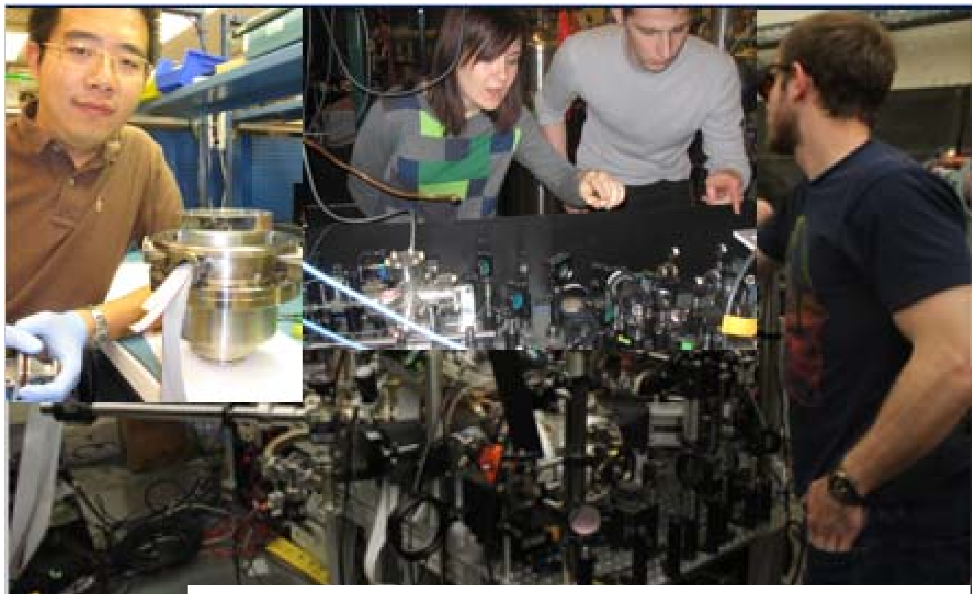
^{6}He β-ν correlation at U. of Washington

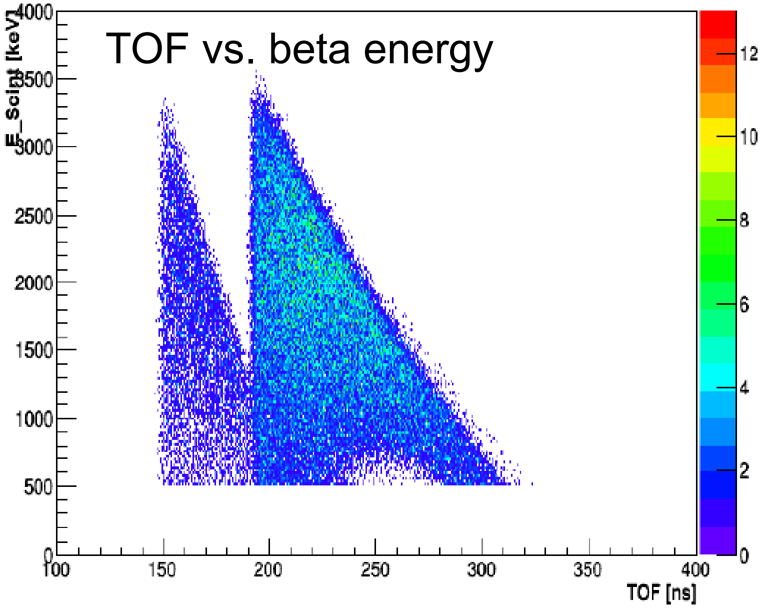
6He Source:
Reliable source of ~10^{10} ^{6}He's/s in low-background environment
NIM A **660**, 43 (2011).
Laser trapping and detection systems:
All systems working after much development.

First physics results:
Measurement of Li-ions charge distribution and comparison with atomic theory. Interesting discrepancies.
PRA **96**, 053411 (2017).

Status

- Data collected for ~0.7% statistical uncertainty in ***a***
- Study of systematic effects from recoil spectrometer and beta detector on-going
- Pending results, runs with higher statistics & improved detector system are anticipated for FY2019





Helicity

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

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

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

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 $\sqrt{\frac{1+pc/E}{2}}$ and $\sqrt{\frac{1-pc/E}{2}}$

^{6}He little-*b* measurement

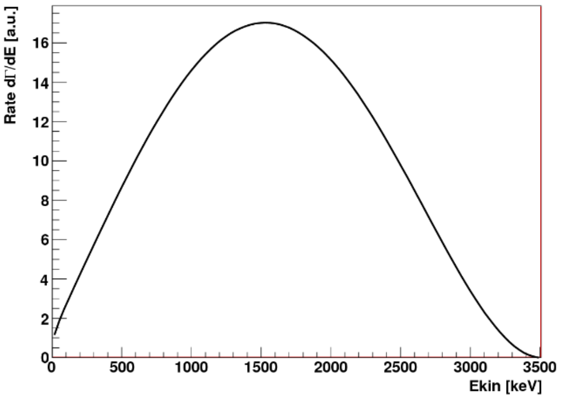
W. Byron[1], M. Fertl[1], A. Garcia[1], G. Garvey[1], B. Graner[1], M. Guigue[4], D. Hertzog[1], K.S. Khaw[1], P. Kammel[1], A. Leredde[2], P. Mueller[2], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[3], H.E. Swanson[1], B.A. Vandeevender[4], F. Wietfeldt[5], A. Young[3]

[1]*University of Washington,*
[2]*Argonne National Lab,*
[3]*North Carolina State University,*
[4]*Pacific Northwest National Laboratory*
[5]Tulane University

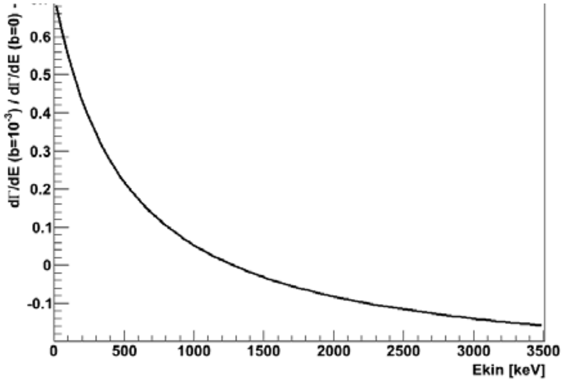
- **Electron spectrum is much more sensitive (than e-ν correlation) to new physics.**
- Goal: measure beta spectrum with high precision to search for "little b" better than 10^{-3} in ^{6}He.
- Most sensitive experiment proposed to search for chirality-flipping interactions. Sensitivity more than 1 order of magnitude higher than LHC.

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

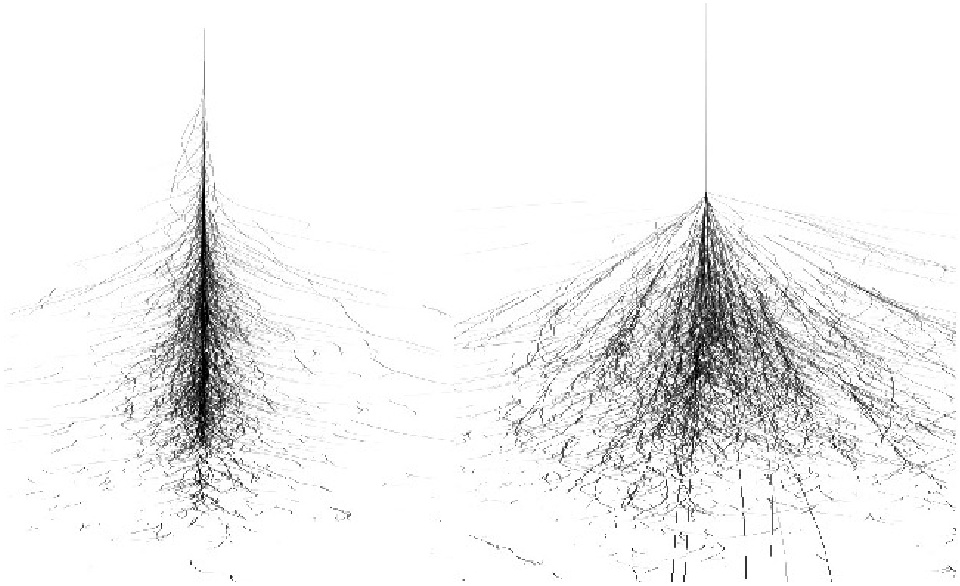
E_e spectrum



Distortion due to little-*b*



Typically electron energies are determined after MANY interactions take place.



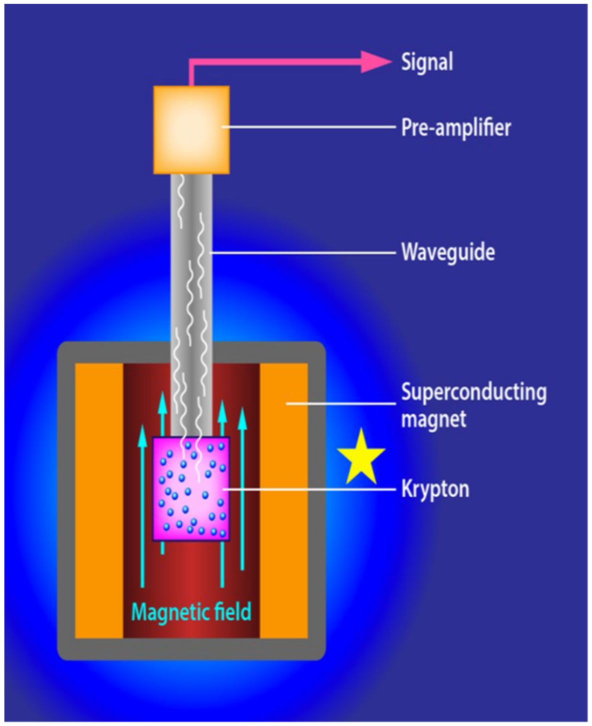
Remarkably, the statistical averages work out to yield fairly good energy resolution, as, for example, in a Si detector.

This does not mean that all the energy is converted with efficiency *strictly independent* on the incoming electron energy.

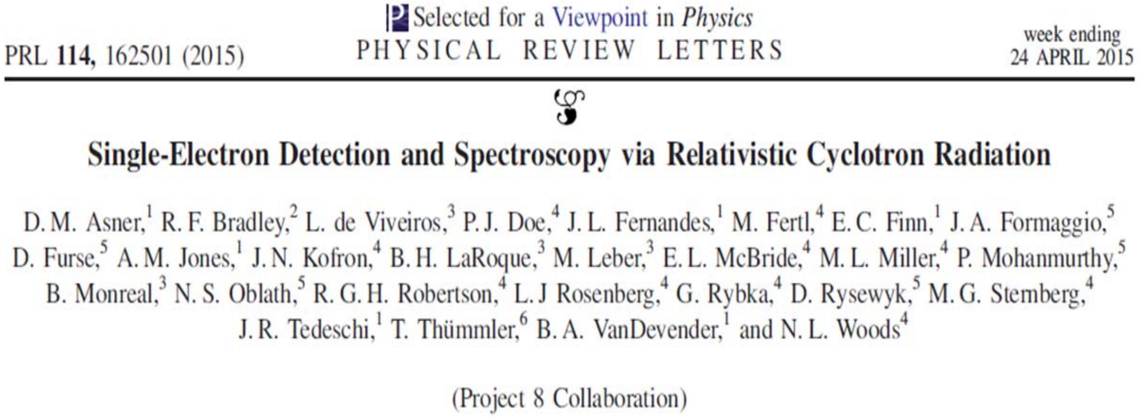
New idea: use *Cyclotron Radiation Emission Spectroscopy* technique

CRES in a nutshell

Electrons emitted in an RF guide within an axial *B* field. Antenna detects cyclotron radiation.
Get energy from frequency: $\omega = \frac{qB\,c^2}{E}$



Technique for measuring electron energies demonstrated recently by Project 8 collaboration


PRL **114,** 162501 (2015)

Selected for a Viewpoint in *Physics*

PHYSICAL REVIEW LETTERS

week ending
24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Sternberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender,[1] and N. L. Woods[4]

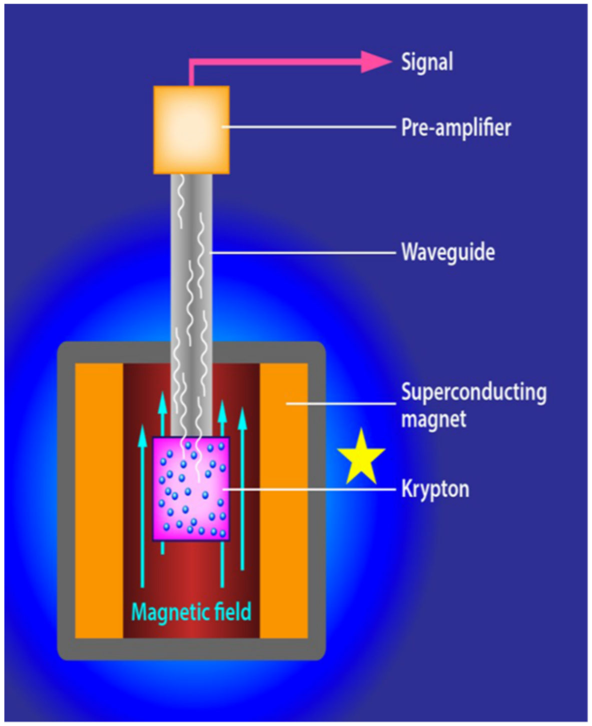
(Project 8 Collaboration)

New idea: use *Cyclotron Radiation Emission Spectroscopy* technique

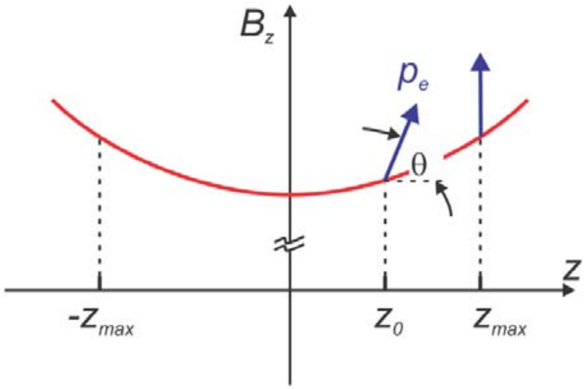
CRES in a nutshell

Electrons emitted in an RF guide within an axial *B* field. Antenna detects cyclotron radiation.

Get energy from frequency: $\boldsymbol{\omega = \frac{qB\ c^2}{E}}$

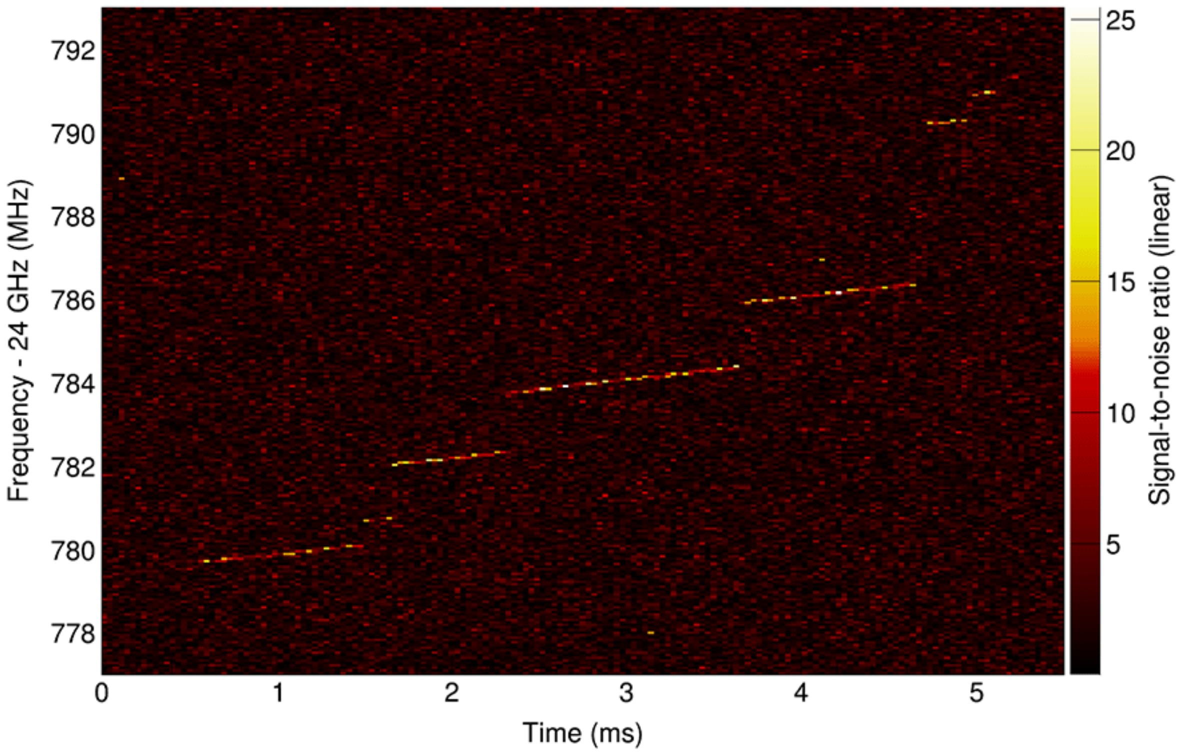


To keep electrons for milli-seconds use a *magnetic trap*:



Longitudinal comp. of momentum decreases as *B* increases up to return point, z_{max}.

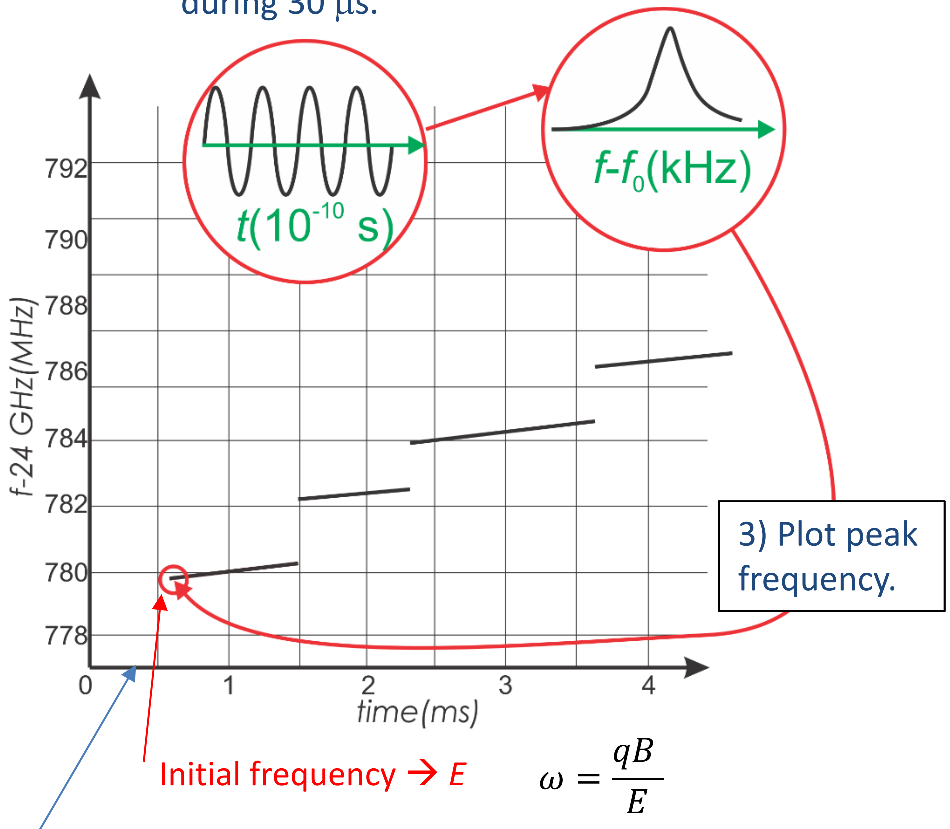
Project-8 technique



Power from a single electron orbiting in a magnetic field versus time and the frequency of the electron's orbit. The straight streaks correspond to the electron losing energy (and orbiting faster) as it radiates. The jumps are due to collisions with atoms in the imperfect vacuum.

Advantages of the CRES technique

- **Measures beta energy at creation, before complicated energy-loss mechanisms.**
- High resolution allows debugging of systematic uncertainties.
- Room photon or e scattering does not yield background.
- 6He in gaseous form works well with the technique.
- 6He ion-trap (shown by others to work) allows sensitivity higher than any other proposed.
- Counts needed not a big demand on running time.



1) Take a wave during 30 µs.

2) Fourier analysis.

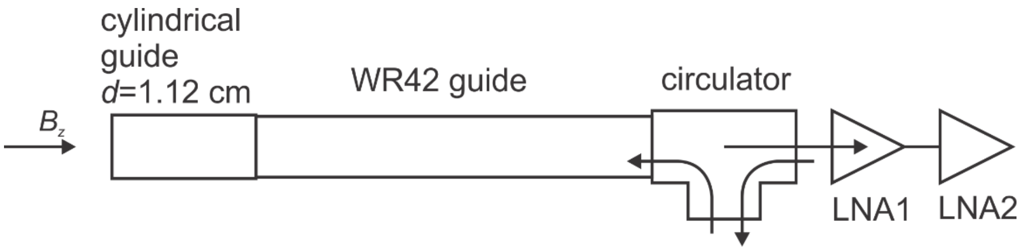
3) Plot peak frequency.

Initial frequency → *E*

$$\omega = \frac{qB}{E}$$

Time bins ~ 30 µs.

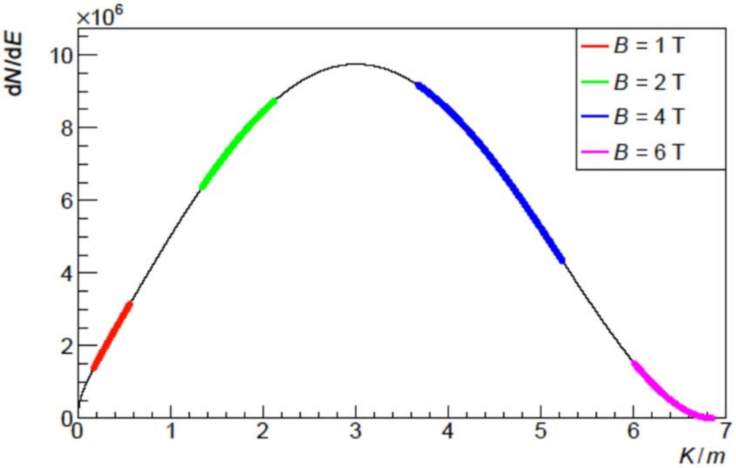
^{6}He little-*b* measurement at Seattle



Stage	Rate (1/s)
Incoming atoms	2×10^9
Decays within trap	1×10^6
Trapped betas	3×10^4
Trapped betas (not hitting walls)	1×10^4
Events observed within frequency window	1×10^3

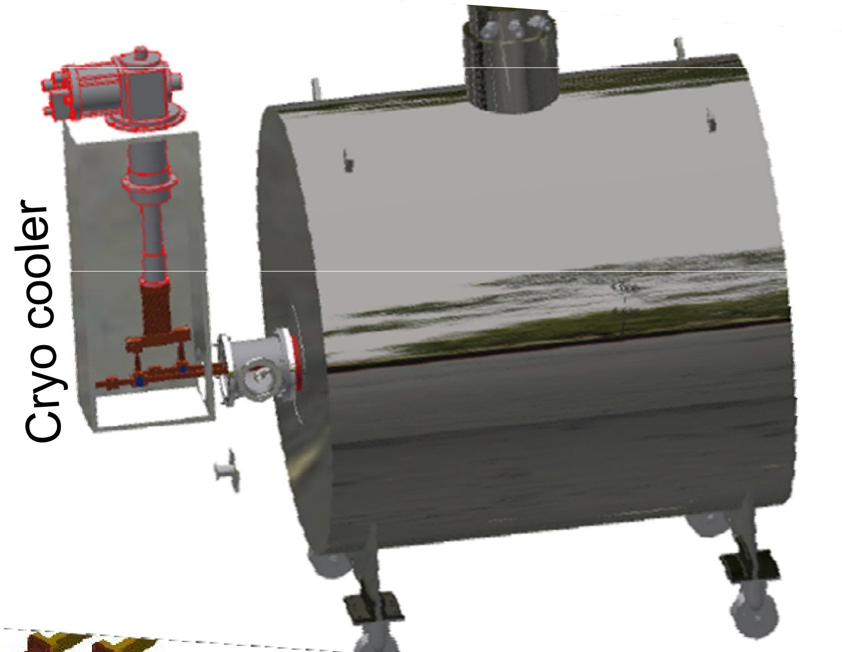
Frequency band: *f*=18-24 GHz.

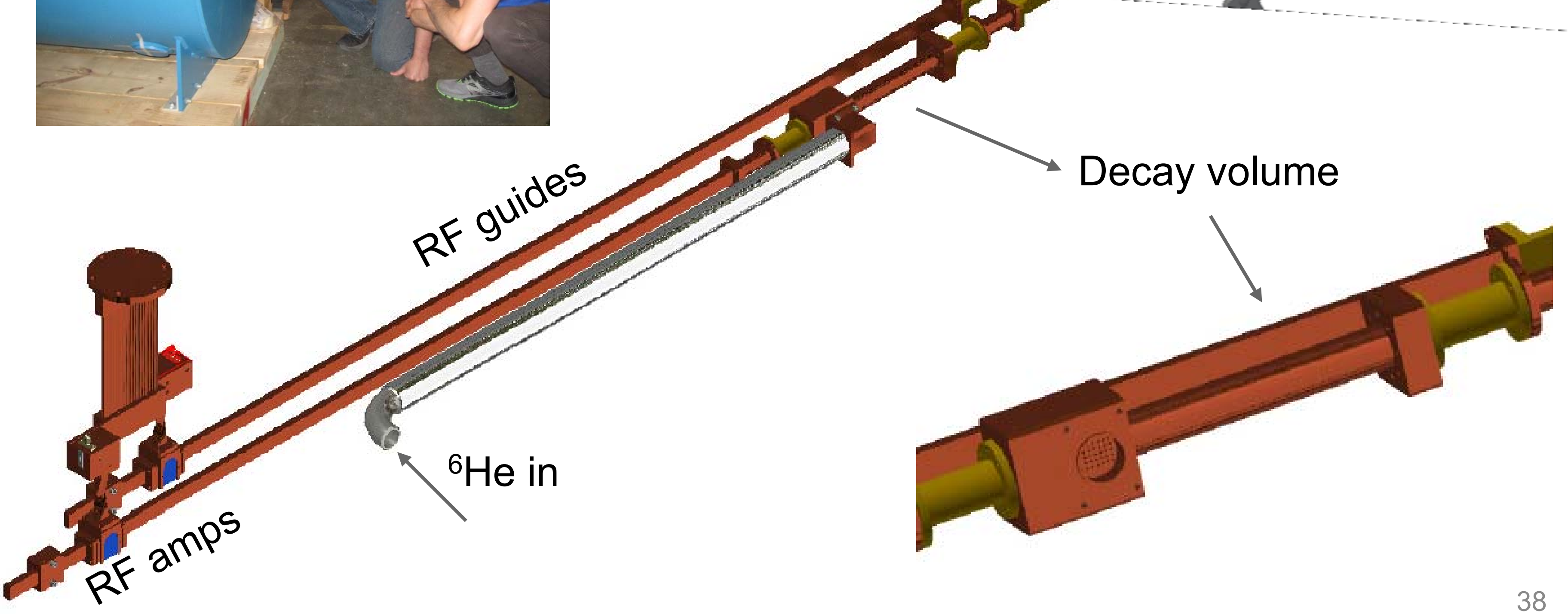
Monte Carlo simulation of observation in
Few days of running



^{6}He little-*b* measurement at Seattle

Apparatus presently being built.
Need to map B field. Jessie Thwaites
starting this part.

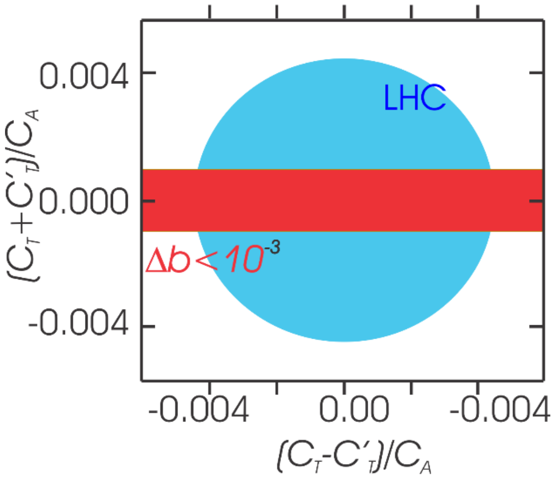




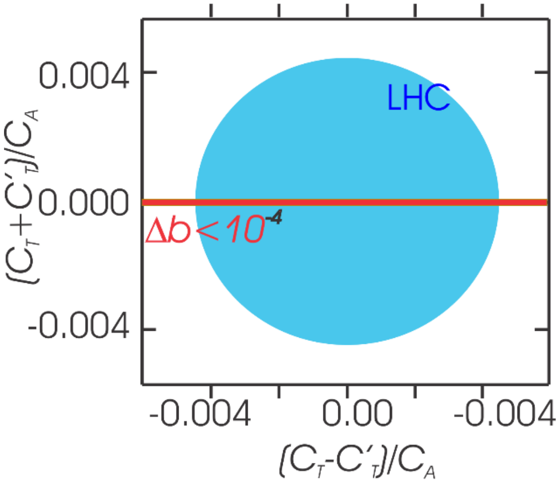
Potential reach (Monte Carlo simulations)

Phase III:
Future development,
couple to an ion trap

Effect	Δb	
	No trap	Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}



Phase II



Backup slides

Helicity

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

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

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

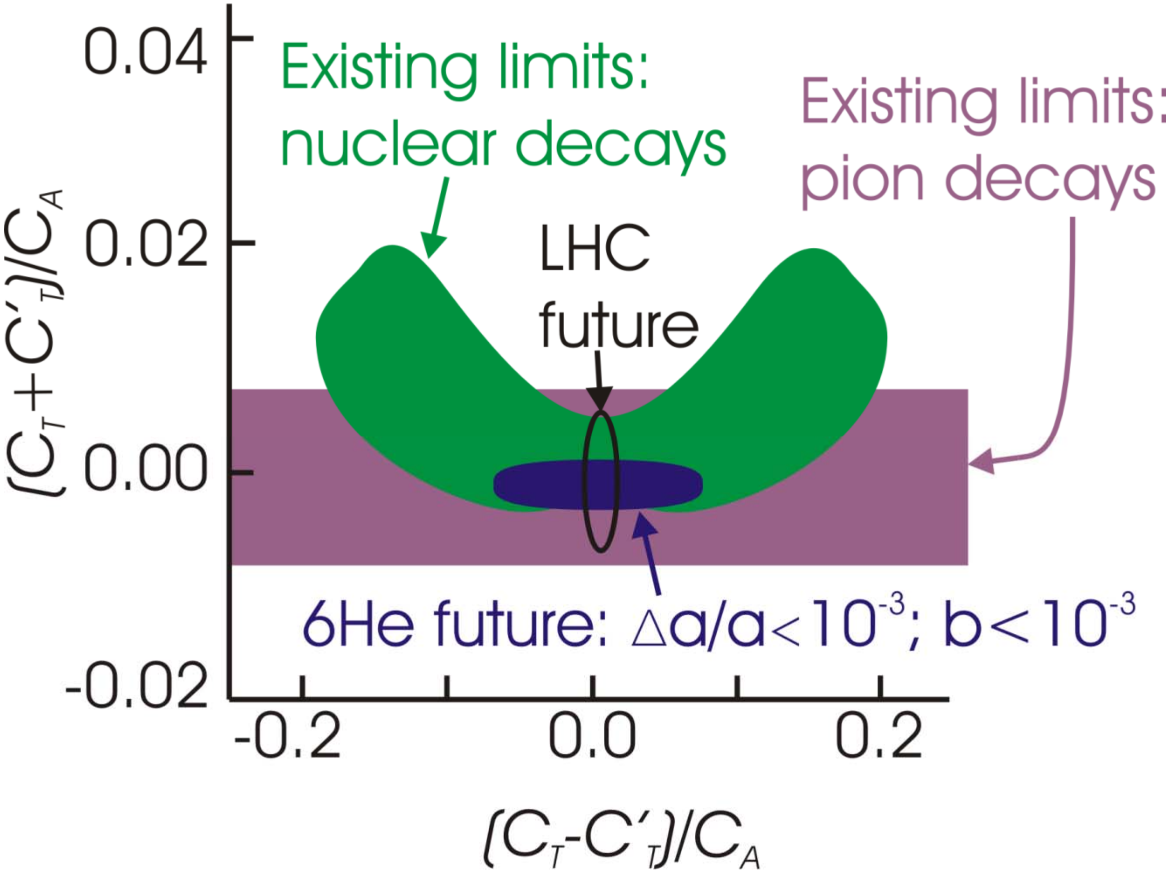
Problem: helicity is *not* a relativistic invariant. (Think about an observer moving faster than the particle: ***p*** flips direction but ***J*** doesn't)

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 $\sqrt{\frac{1-v/c}{2}}$

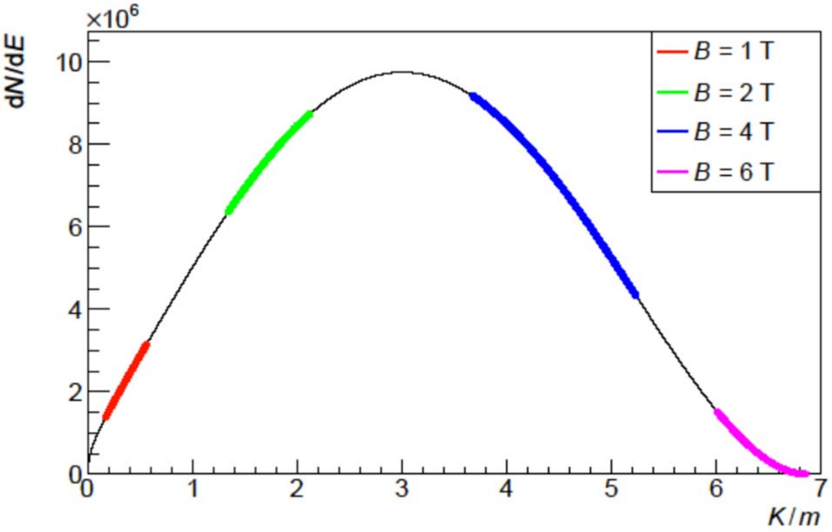
Precision beta decay versus pion decays and “LHC”:

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

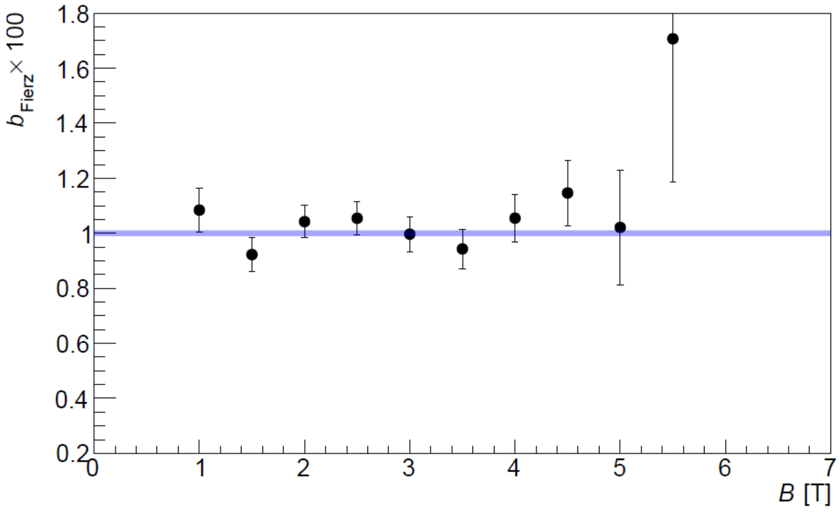


^{6}He little-*b* measurement at Seattle

Monte Carlo simulation of observation in
Few days of running

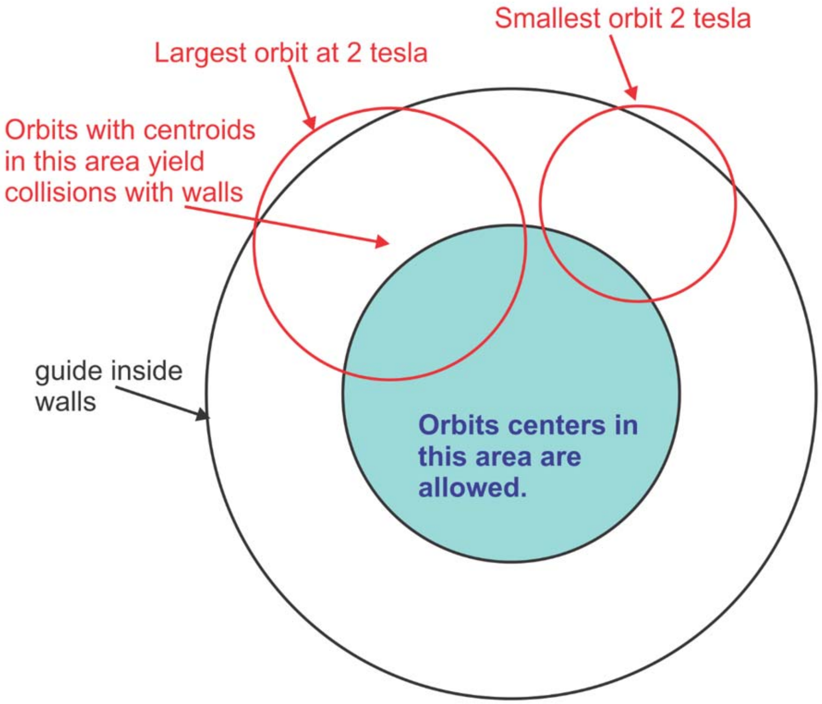


Extracting little *b* vs. *B* field
Few days of running each point
(assumed $b_{MC} = 0.01$)



^{6}He little-b measurement at Seattle

Obvious worry: efficiency depends on energy.



Cross sectional view of guide with electron orbit. For this radius there is a dead region shown by the white frame on the blue area.

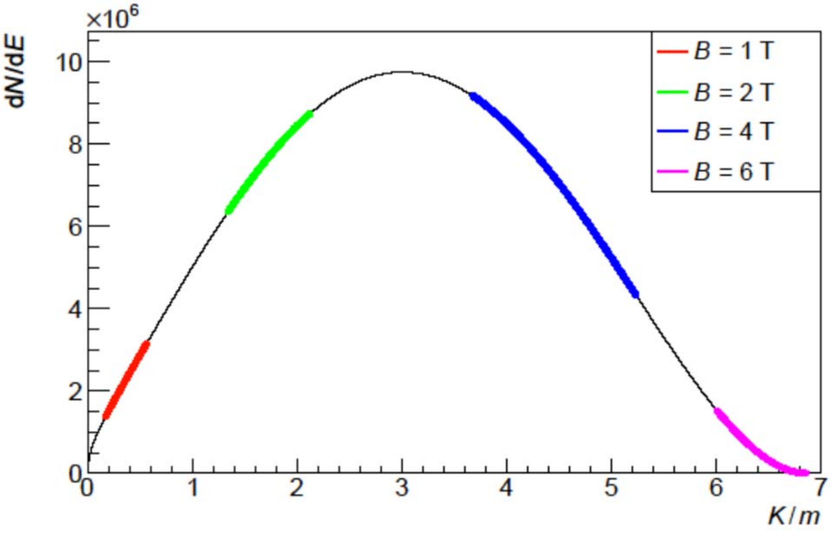
Since blue area depends on energy there is a systematic distortion of the spectrum

Can be studied by varying the *B* field.

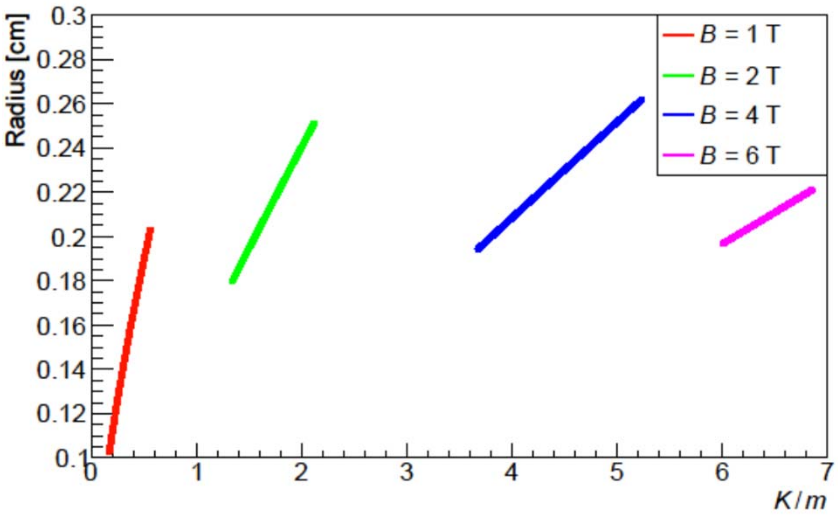
^{6}He little-*b* measurement at Seattle

Obvious worry: efficiency depends on energy.
Can study by varying *B* field.

Monte Carlo simulation of observation in
Few days of running

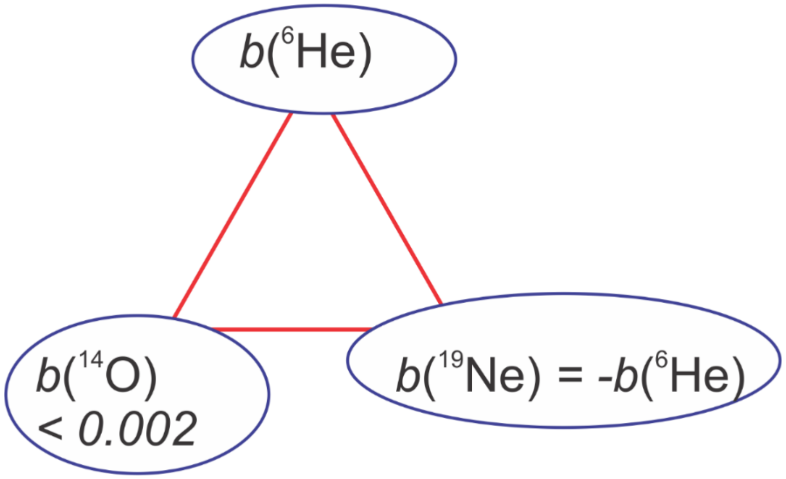


Radii vs. *B* field
Can use this to check geometric effect



^{6}He little-*b* measurement at Seattle

Check on signature by measuring ^{14}O and ^{19}Ne:


b(^{6}He)

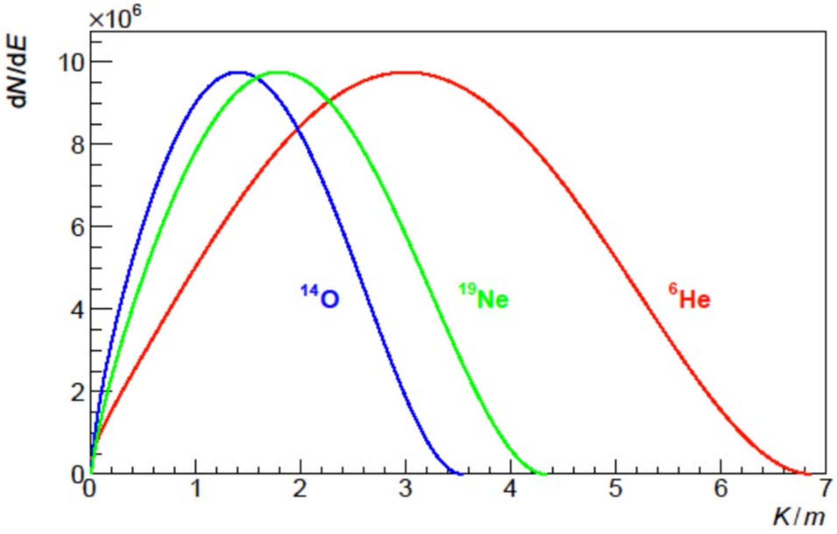
b(^{14}O)
< *0.002*

b(^{19}Ne) = -*b*(^{6}He)

Both ^{14}O and ^{19}Ne can be produced in similar quantities as ^{6}He at CENPA.

^{14}O as CO (T_{freeze} = 68 K)
Previous work at Louvain and TRIUMF.

^{19}Ne source developed at Princeton appropriate.



The End