WEAK INTERACTION STUDIES WITH ^{6}HE

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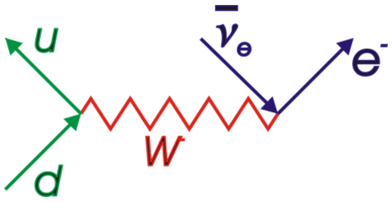
INT WORKSHOP
NOVEMBER 2012

The Weak Interaction for “point-like particle” decays

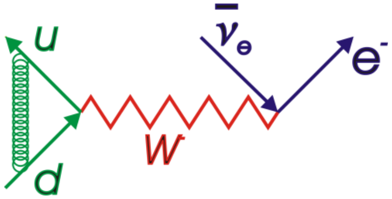
$$H = \boxed{2C_V}\,\overline{\Psi}_f^{\,L}\gamma^{\mu}\Psi_i^{\,L} \qquad \overline{e}^{\,L}\gamma_{\mu}\nu_e^{L}$$

Ignore propagator ($q^2 << M_W{}^2$)



The Weak Interaction for nucleons

$$H = \begin{cases} \overline{\Psi}_f V^{\mu}\Psi_i \quad 2C_V\,\overline{e}^{\,L}\gamma_{\mu}\nu_e^{L} + \\ \overline{\Psi}_f A^{\mu}\Psi_i \quad 2C_A\,\overline{e}^{\,L}\gamma_{\mu}\gamma_5\nu_e^{L} \end{cases}$$



$$\overline{\Psi}_f V^{\mu}\Psi_i = \overline{\Psi}_f\left(f_V\gamma_{\mu} + f_{WM}\sigma_{\mu\nu}q^{\nu}\right)\Psi_i$$

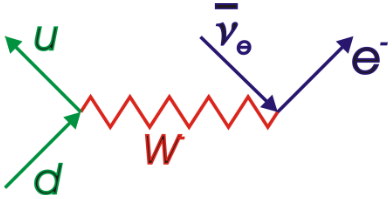
$$\overline{\Psi}_f A^{\mu}\Psi_i = \overline{\Psi}_f\left(f_A\gamma_{\mu}\gamma_5 + f_T\sigma_{\mu\nu}\gamma_5 q^{\nu}\right)\Psi_i$$

`Vector’ Conserved current

`Axial V’ Not conserved

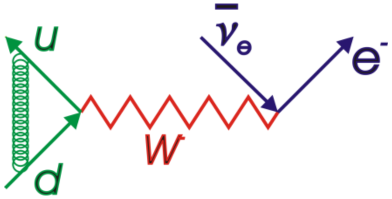
The Weak Interaction for “point-like particle” decays

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



The Weak Interaction for *nucleons*

$$H = \begin{cases} \overline{\Psi}_f V^\mu \Psi_i & 2C_V \, \bar{e}^L \gamma_\mu \nu_e^L \; + \\ \overline{\Psi}_f A^\mu \Psi_i & 2C_A \, \bar{e}^L \gamma_\mu \gamma_5 \nu_e^L \end{cases}$$



Weak Magnetism

$$\overline{\Psi}_f V^\mu \Psi_i = \overline{\Psi}_f \left(f_V \gamma_\mu + \boxed{f_{WM} \sigma_{\mu\nu} q^\nu} \right) \Psi_i$$

$$\overline{\Psi}_f A^\mu \Psi_i = \overline{\Psi}_f \left(f_A \gamma_\mu \gamma_5 + \boxed{f_T \sigma_{\mu\nu} \gamma_5 q^\nu} \right) \Psi_i$$

\`Vector’	Conserved current
\`Axial V’	Not conserved

Pseudo-Induced Tensor

(fashionable in 70’s, not now!)

The Weak Interaction in nuclear “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 !

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

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

$$A_{\mu} \equiv \varphi_f \left(\gamma_{\mu} \gamma_5 I^{\pm} \right) \varphi_i =$$

$$\varphi_f (\frac{\vec{v}}{c} . \vec{\sigma}, \vec{\sigma}) I^{\pm} \varphi_i \approx \varphi_f (0, \vec{\sigma}) I^{\pm} \varphi_i$$

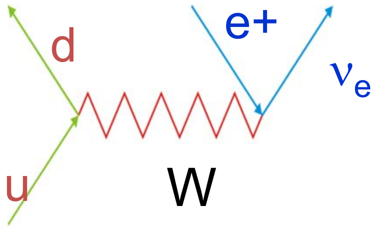
More complicated.

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

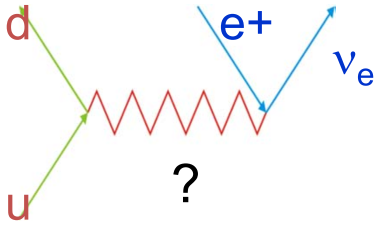
$\Delta J^{\pi} \equiv \vec{1}^{+}$ “Gamow-Teller”

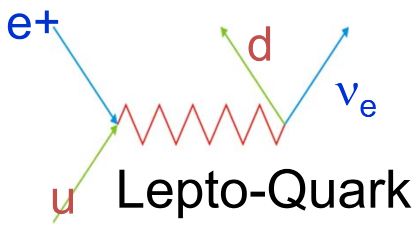
Searches for Scalar and Tensor currents.

Are weak decays
carried only by W's?



Or is there something new?





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

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

Decay rate:

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

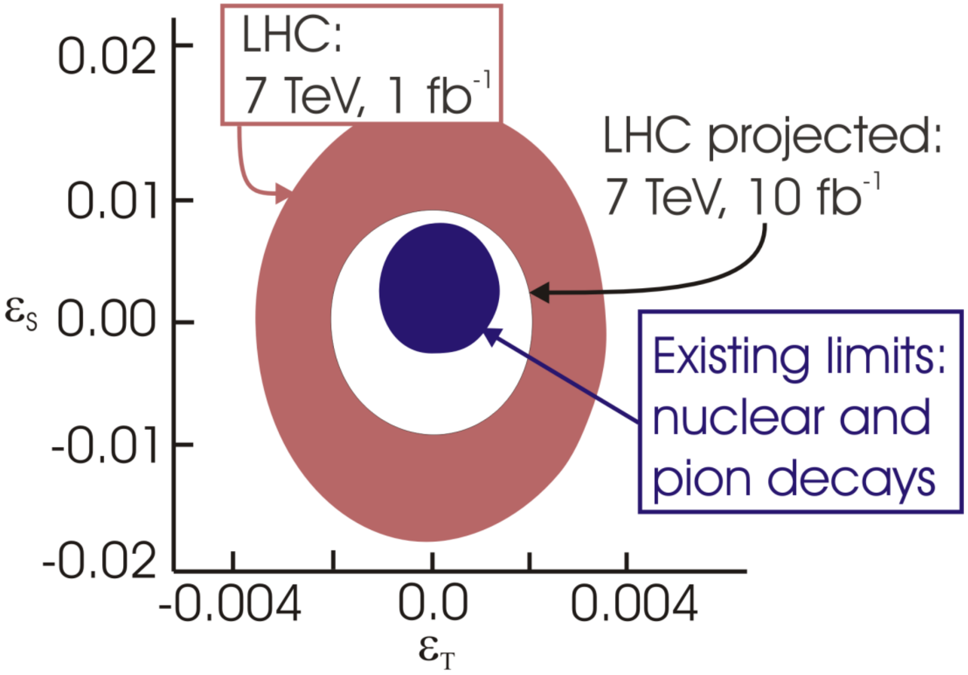
$$b \approx \frac{\mathrm{Re}\left[2C_A \left(C_T + C_T^{'} \right) \right]}{2|C_A|^2 + |C_T|^2 + |C_T^{'}|^2}$$

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

Precision beta decay versus "LHC":

Can "precision" compete with "energy"? Yes.

From Bhattacharya et al.
Phys Rev D **85**, 054512 (2012)



Need more accurate calculations.
Huey-Wen Lin et al.

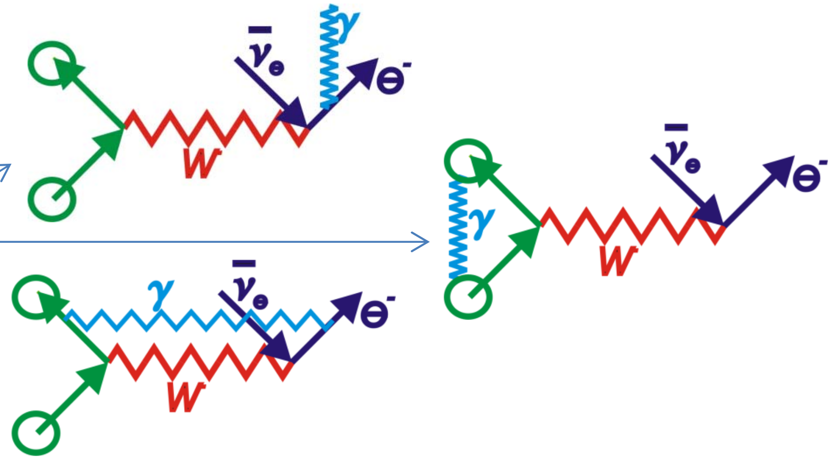
$$\varepsilon_S = \frac{C_S + C_S'}{2\, g_S} \qquad \varepsilon_T = \frac{C_T + C_T'}{8\, g_T}$$

$$g_S = 0.8(4) \longrightarrow g_T = 1.05(35)$$

Ultimate accuracy:
Need to calculate “forbidden” components

… and radiative corrections.

$$\left.\begin{array}{l} C_V \int \vec{\alpha} \times \vec{r} \rightarrow \dfrac{f_V}{M}[\int \vec{\sigma} + \int \vec{r} \times \vec{p}] - 2 f_{WM} \int \vec{\sigma} \\ C_A i \int \gamma_5 \vec{r} \rightarrow g_A i \int \tau^{+} \vec{\sigma} \times \vec{r} \end{array}\right\}$$

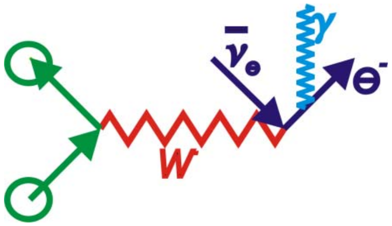


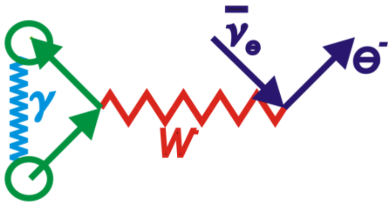
Under control for neutron decay.

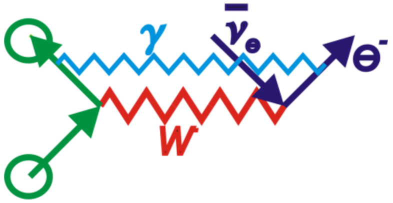
Ultimate accuracy:
Need to calculate “forbidden” components

$$\left.\begin{aligned} C_V\int\vec{\alpha}\times\vec{r} &\rightarrow \frac{f_V}{M}\left[\int\vec{\sigma}+\int\vec{r}\times\vec{p}\right]-2f_{WM}\int\vec{\sigma} \\ C_A i\int\gamma_5\vec{r} &\rightarrow g_A i\int\tau^+\vec{\sigma}\times\vec{r} \end{aligned}\right\}$$

… and radiative corrections.







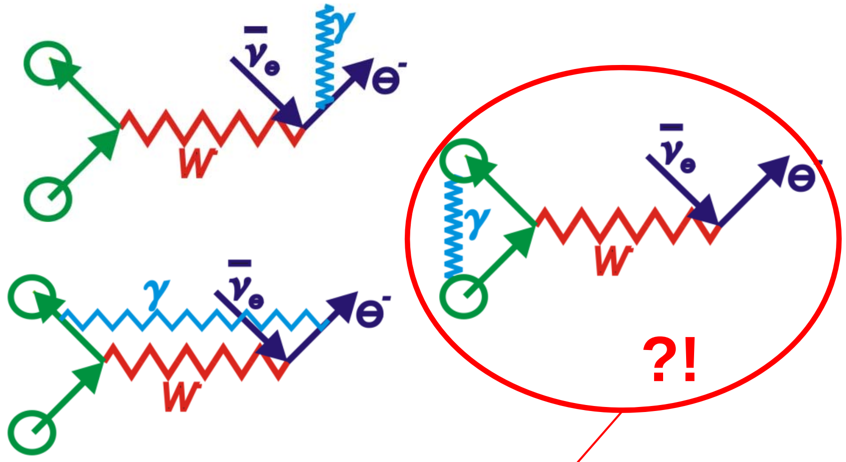
Under control for neutron decay.

However, experiments with neutrons are difficult.

6He:
“forbidden” components

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

… and radiative corrections.



Small and under control for 6He decay.

Can nuclear theorists save us?

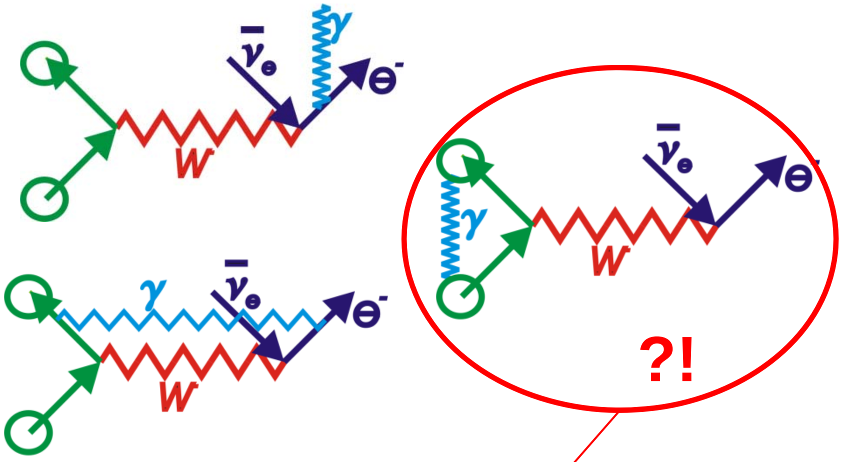
	5Be P	6Be 92 KeV P: 100.00% α: 100.00%	7Be 53.24 D ϵ: 100.00%	8Be 5.57 eV α: 10[illegible]	9Be STABLE 100%	10Be 1.387E+6 Y β-: 100.00%
3Li P	4Li 6.03 MeV P: 100.00%	5Li ≈1.5 MeV α: 100.00% P: 100.00%	6Li STABLE [illegible]	7Li STABLE 92.41%	8Li 839.9 MS β-α: 100.00% β-: 100.00%	9Li 178.3 MS β-: 100.00% β-n: 50.80%
	3He STABLE 0.000134%	4He STABLE 99.999866%	5He 0.60 MeV N: 100.00% α: 100.00%	6He 801 MS β-: 100.00%	7He 150 KeV N	8He 119.1 MS β-: 100.00% β-n: 16.00%
1H STABLE 99.9885%	2H STABLE 0.0115%	3H 12.32 Y β-: 100.00%	4H N: 100.00%	5H 5.7 MeV 2N: 100.00%	6H 1.6 MeV N: 100.00%	7H 29E-23 Y 2N?
	Neutron 10.183 M β-: 100.00%					

ANL group: Talk this afternoon at CENPA

6He:
“forbidden” components

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

… and radiative corrections.



Small and under control for 6He decay.

	5Be P	6Be 92 KeV P: 100.00% α: 100.00%	7Be 53.24 D ϵ: 100.00%	8Be 5.57 eV α: 10	9Be STABLE 100.%	10Be 1.387E+6 Y β-: 100.00%
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1H STABLE 99.98[illegible]5%	2H STABLE 0.0115%	3H 12.32 Y β-: 100.00%	4H N: 100.00%	5H 5.7 MeV 2N: 100.00%	6H 1.6 MeV N: 100.00%	7H 29E-23 Y 2N?
	Neutron 1[illegible].183 M β-: 100.00%					

Can nuclear theorists save us?

6He:
“forbidden” components

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

Small: why?

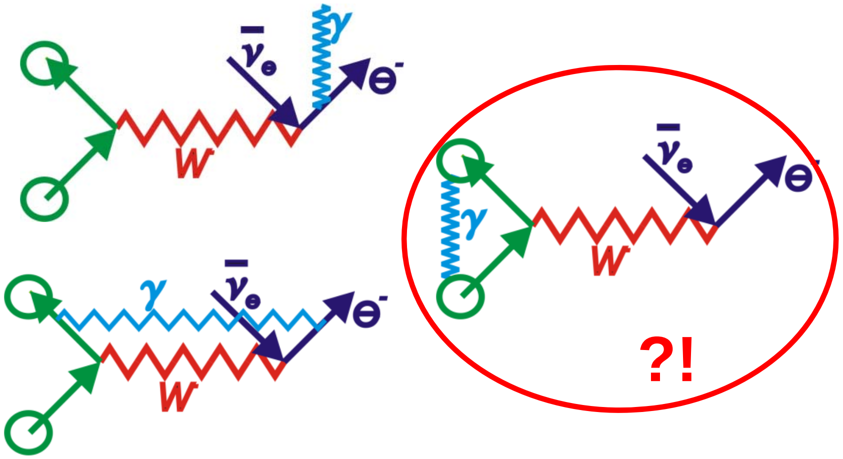
1) First element is multiplied by a kinematic factor that integrates to zero in the limit of zero Coulomb corrections.
2) LS-scheme wave fn for 6He→6Li

$$\left|{}^6\mathrm{He}\right\rangle\cong 0.95\left|{}^1S_0\right\rangle-0.31\left|{}^3P_0\right\rangle$$

$$\left|{}^6\mathrm{Li}\right\rangle\cong 0.99\left|{}^3S_1\right\rangle-0.10\left|{}^1P_1\right\rangle+0.10\left|{}^3D_1\right\rangle$$

Little room for orbital ang. mom. in wave fn.

… and radiative corrections.



Can nuclear theorists save us?

6He collaboration

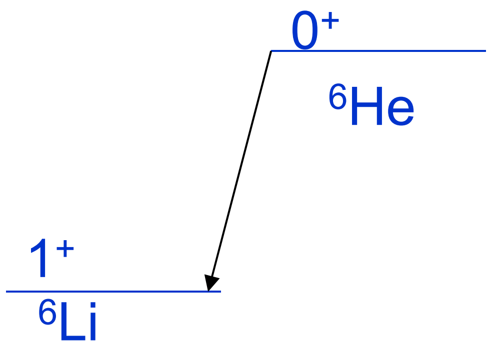
P. Muller, W. Williams
Argonne National Lab

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

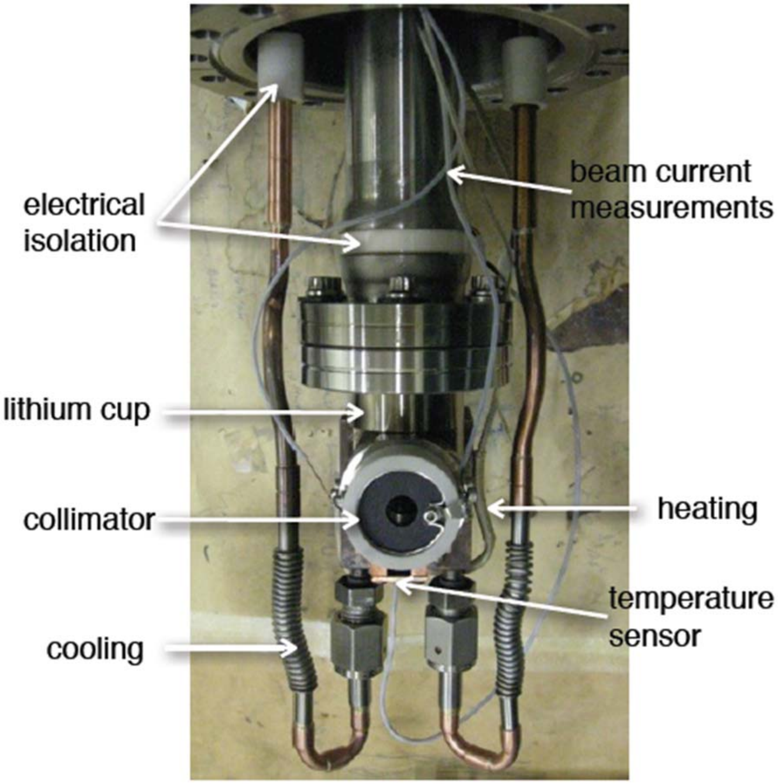
O. Naviliat-Cuncic
NSCL, Michigan State University

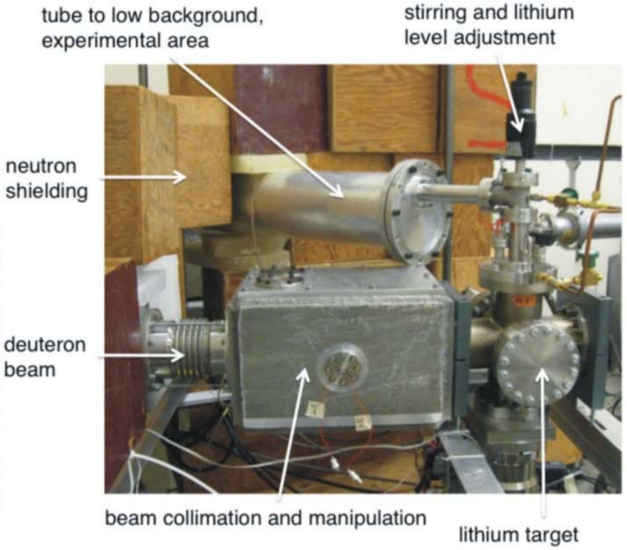
Z. Alexander, Y. Bagdasarova, T. Cope, A. Garcia, G. Harper, D. Hertzog, R. Hong, P. Kammel, Y. Kim, A. Knecht, H.E. Swanson, F. Wauters, D. Zumwalt
University of Washington ,

- 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



Production of ^{6}He at Seattle via ^{7}Li(d,^{3}He)^{6}He



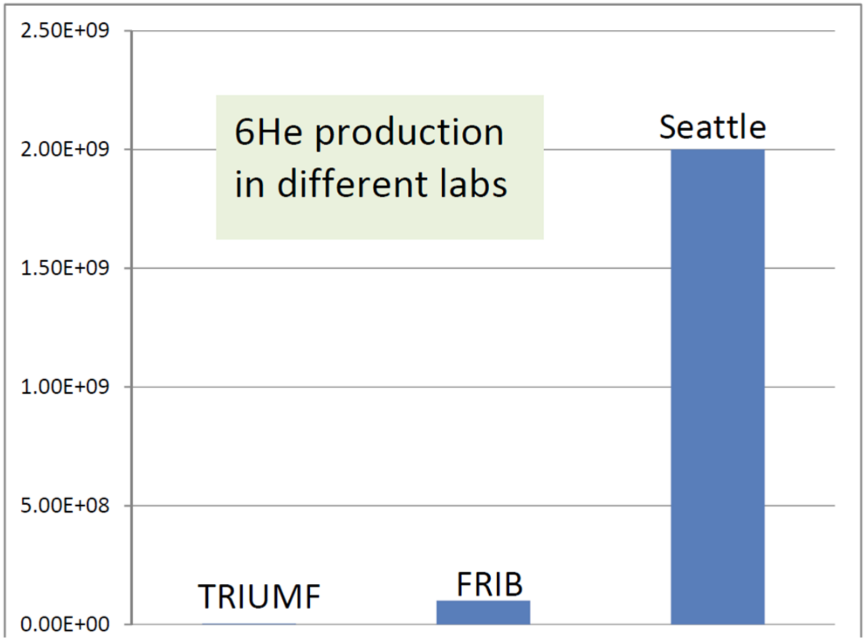


Now have a reliable source of ^{6}He yielding ~4 ×10^9 atoms/s in a clean room!

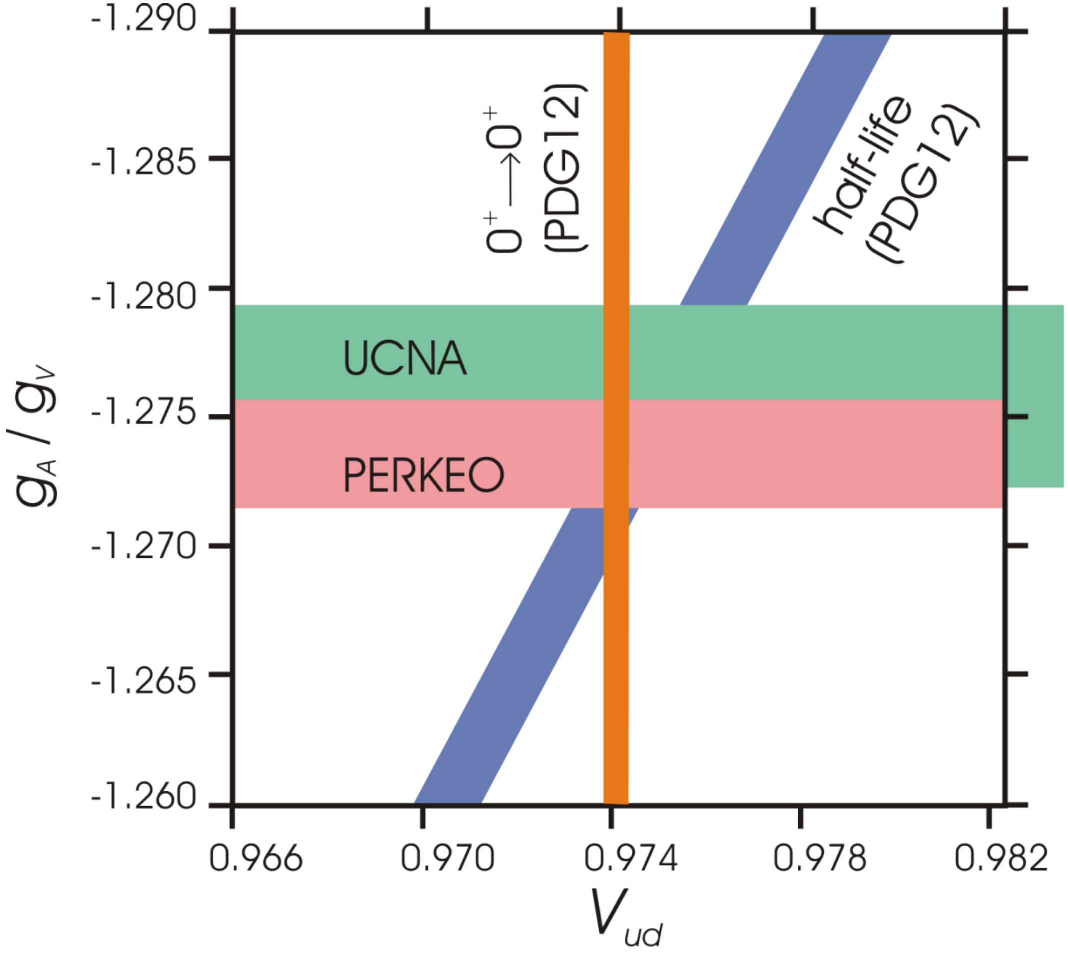
[A High-Intensity Source of 6He Atoms for Fundamental Research]

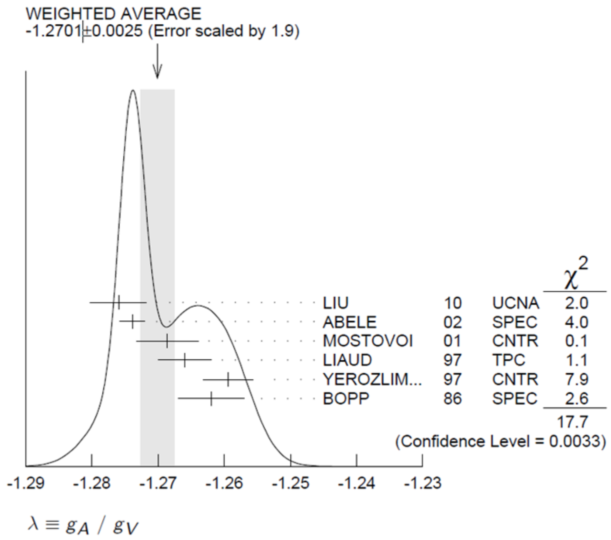
A. Knecht et al.

NIM A. **660**, 43 (2011)



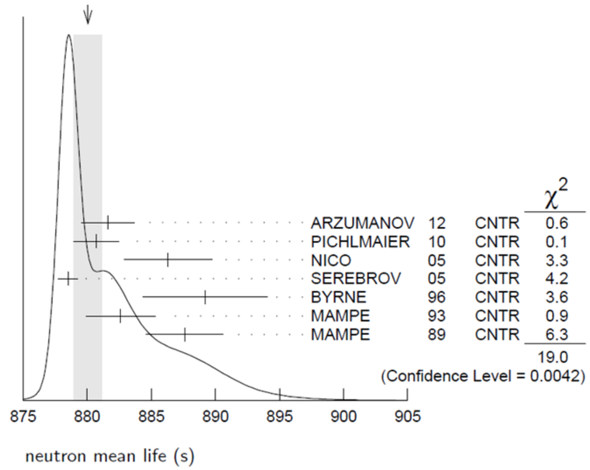
g_A/g_V for free neutrons is determined by measurements of the Beta Asymmetry (PERKEO, UCNA)





			χ^2
LIU	10	UCNA	2.0
ABELE	02	SPEC	4.0
MOSTOVOI	01	CNTR	0.1
LIAUD	97	TPC	1.1
YEROZLIM...	97	CNTR	7.9
BOPP	86	SPEC	2.6
			17.7

(Confidence Level = 0.0033)



			χ^2
ARZUMANOV	12	CNTR	0.6
PICHLMAIER	10	CNTR	0.1
NICO	05	CNTR	3.3
SEREBROV	05	CNTR	4.2
BYRNE	96	CNTR	3.6
MAMPE	93	CNTR	0.9
MAMPE	89	CNTR	6.3
			19.0

(Confidence Level = 0.0042)

Fermi’s Golden rule

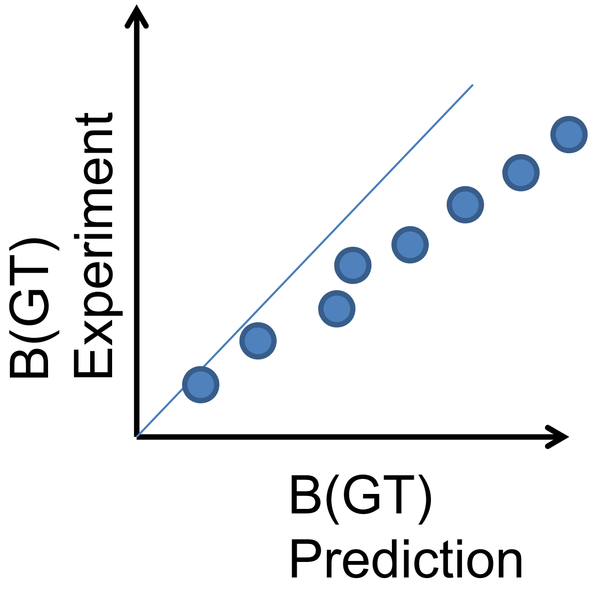
$$\frac{K}{f\,t} = B(GT) = g_A{}^2 \left| \langle \Psi_f | \sigma\tau | \Psi_i \rangle \right|^2$$

with $K \approx 6340\,\mathrm{s}$

$$f \approx \int F(Z, E_e)\, d^3 p_e\, d^3 p_\nu$$

`Phase space’

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



g_A from neutron ~ 1.27

g_A for (sd-shell) nuclei ~ 1.00

`quenching of g_A'.

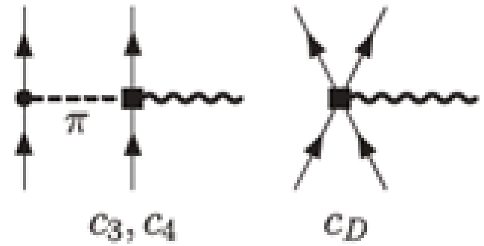
Two alternative explanations

Calculations are performed in a reduced shell-model space

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

P ==projection operator into the reduced space.
Need to *renormalize* to account for the reduced config. space.

Vector current protected by CVC, but Axial current is not.
Meson Exchange Currents yield a mechanism for a different effective g_A.

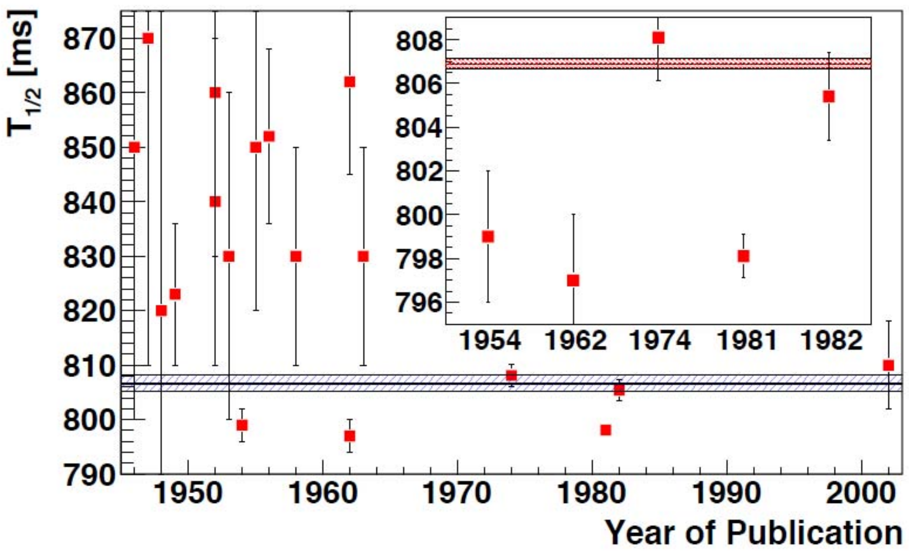


^{6}He and ^{3}H: very simple transitions; light enough for ab-initio calculations.

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)

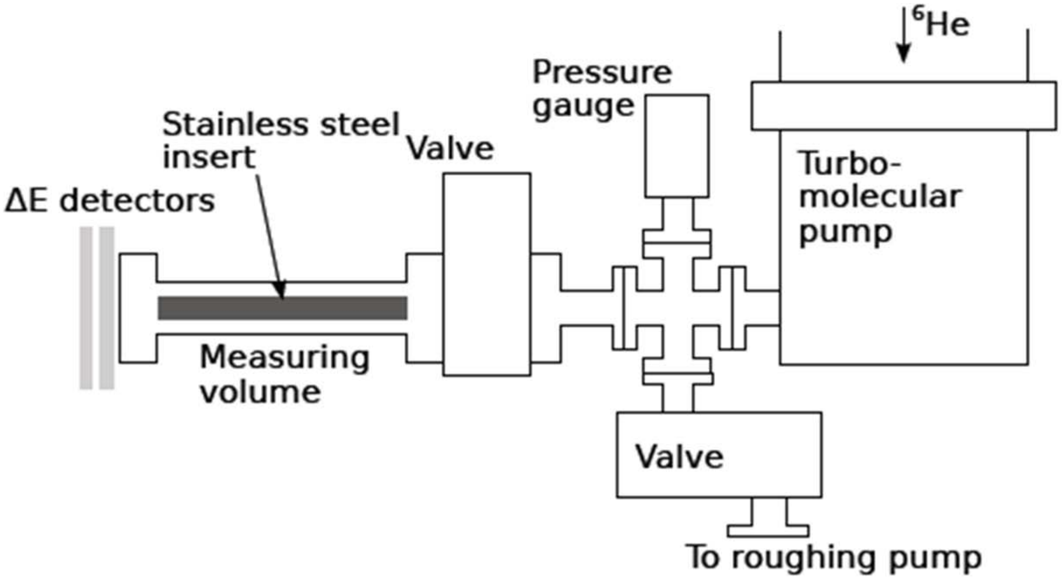
However, experimental situation was somewhat unclear.



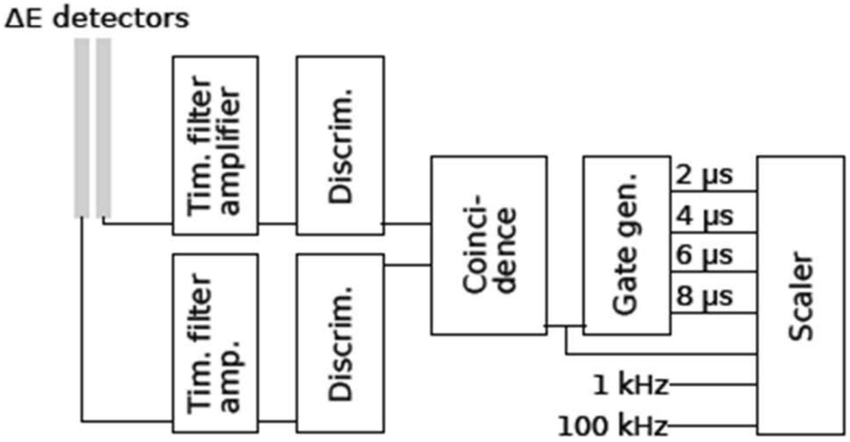
Veintraub et al.
…our accuracy in estimating the GT matrix element is at the level of per mil… validates the use of the 6He β-decay as a testing ground for an axial MEC model.

Extracting g_A from the lifetime of ^{6}He

Experimental Setup



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

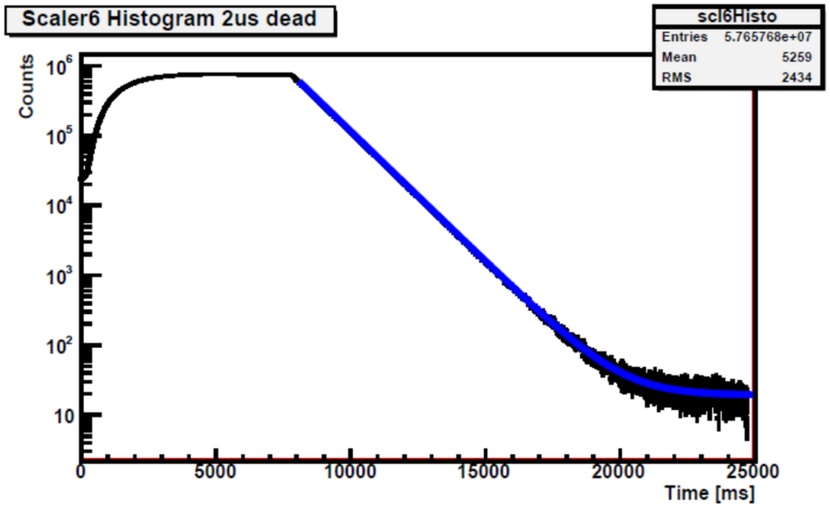


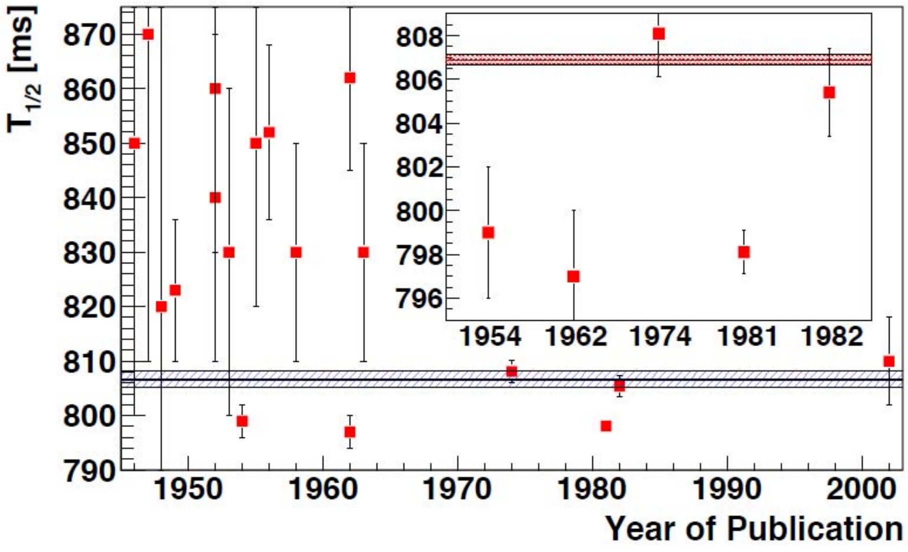
Extracting g_A from the lifetime of ^{6}He

- 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).





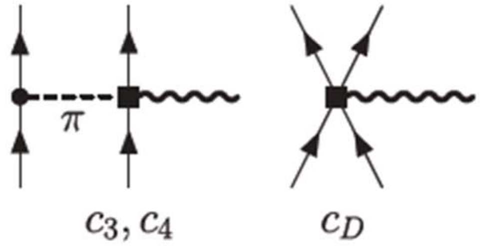
Overview of Calculations

- 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

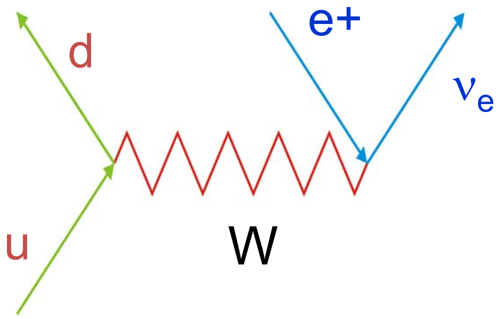
Calculation	**M_{GT} (no MEC)**	**Change from g_A(n)**	**M_{GT} (incl. MEC)**	**Change from g_A(n)**
Schiavilla/ Wiringa	2.254(5) (Ψ_T I) 2.246(10) (Ψ_T II)	-3.9% -3.6%	2.284(5) (Ψ_T I) 2.278(10) (Ψ_T II)	-5.2% -5.0%
Vaintraub/ Barnea/Gazit	2.225(2)	-2.7 %	2.198(7)	-1.5 %

- Free low-energy constant in calculation of meson-exchange currents:
  → fixed by ^{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

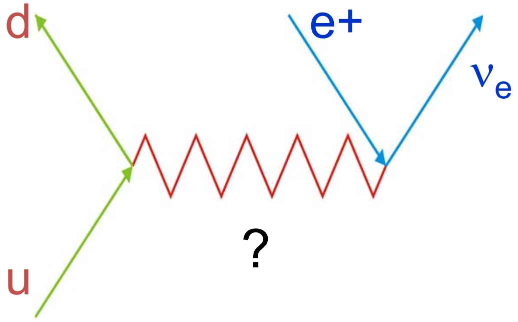


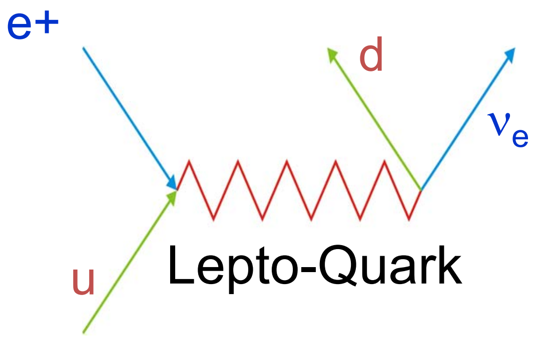
Searches for Scalar and Tensor currents.

Are weak decays carried only by W's?

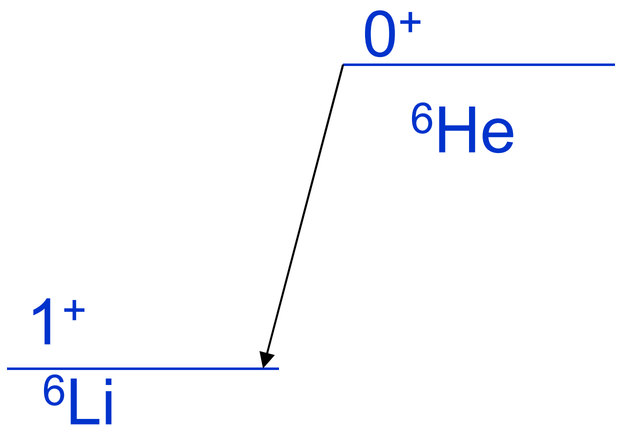


Or is there something new?





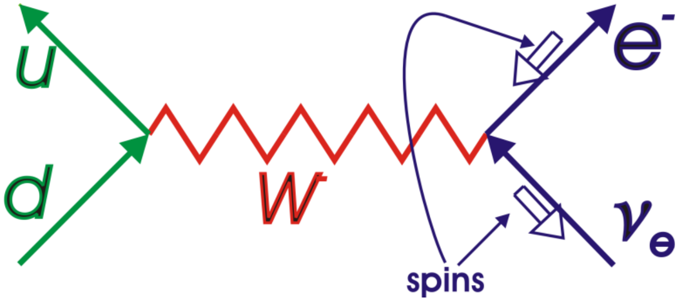
Searches for *Tensor* Currents in spin flip decays



Searches for Tensor currents: Helicities in the Standard Model

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

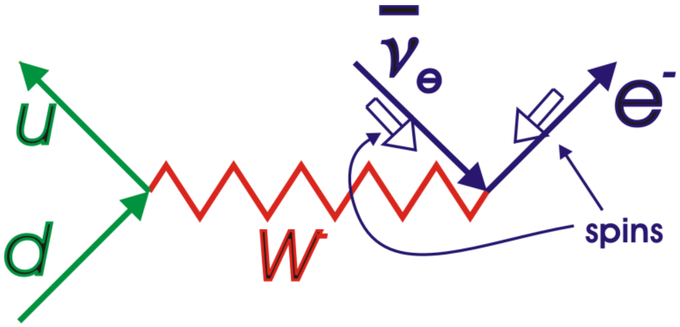
Example: photons have $\mathcal{H}$=±1.



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

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

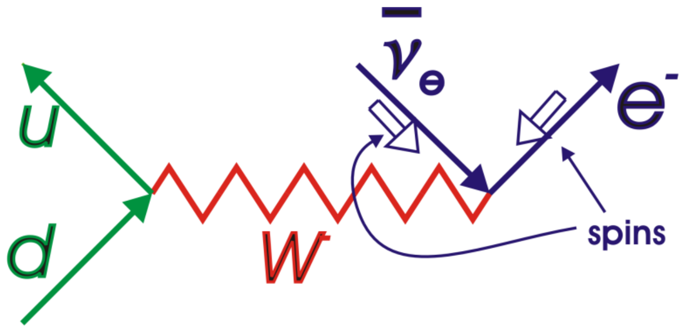
Or equivalently (notice anti nu):



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

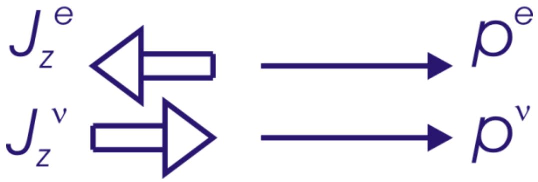
Particles → Left handed
Anti particles → Right handed

Helicities in the Standard Model



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

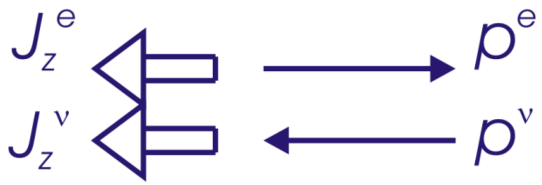
Consequence: e-antinu correlation



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

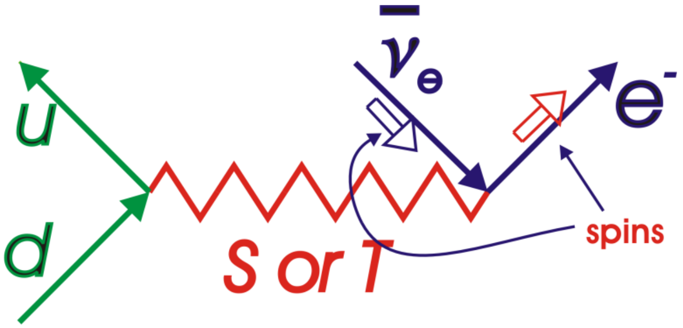
If the nuclear spins flip then the leptons have total *Jz=1*

Consequence: e-antinu correlation

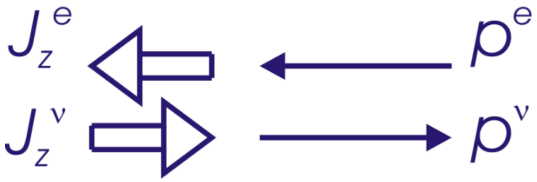


$$\frac{d\Gamma}{d\Omega_{e\nu}} = 1 - \frac{\vec{p}^{\,e}}{E_e} \bullet \frac{\vec{p}^{\,\nu}}{E_\nu}$$

Helicities
with Scalar or Tensor Currents



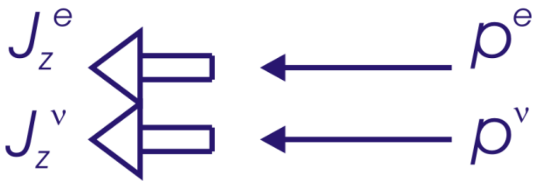
If the nuclear spins don't flip then the leptons have total *Jz=0*



Consequence: e-antinu correlation

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

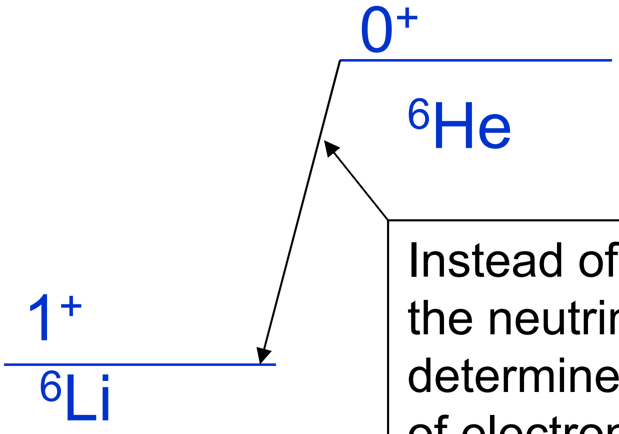
If the nuclear spins flip then the leptons have total *Jz=1*



Consequence: e-antinu correlation

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

Searching for tensor currents in 6He



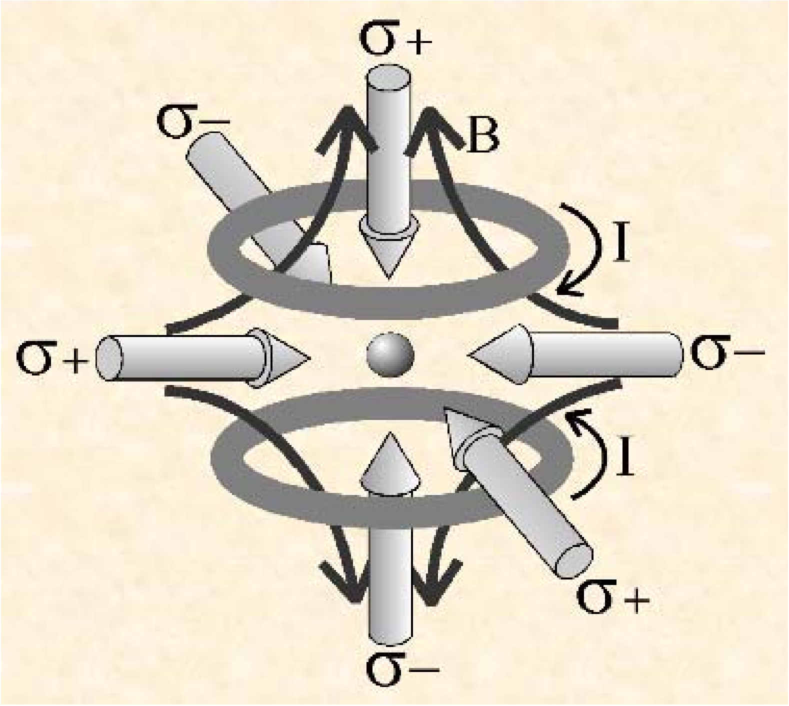
Instead of detecting the neutrino, determine momentum of electron and 6Li

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

Solution: hold 6He with light!

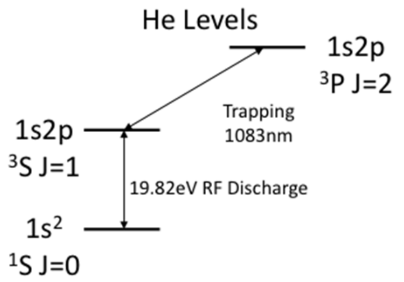
Magneto-Optical Trap

- 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


He Levels

1s2p ^{3}P J=2

Trapping 1083nm

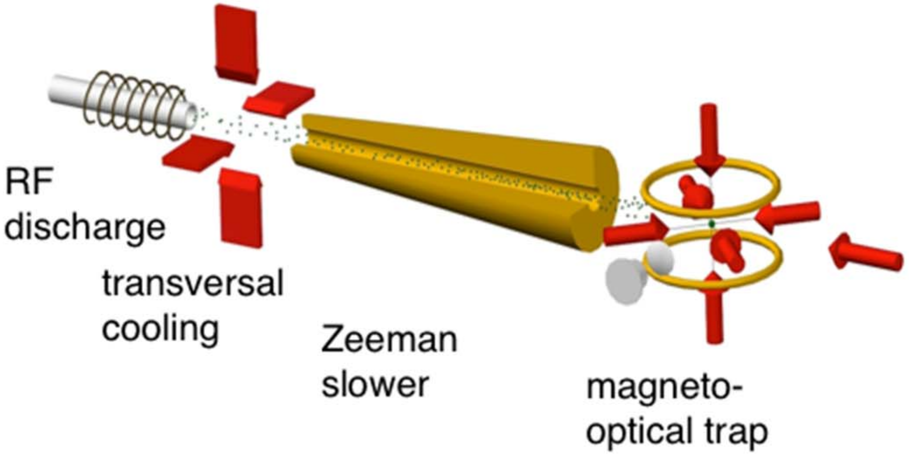
1s2p ^{3}S J=1

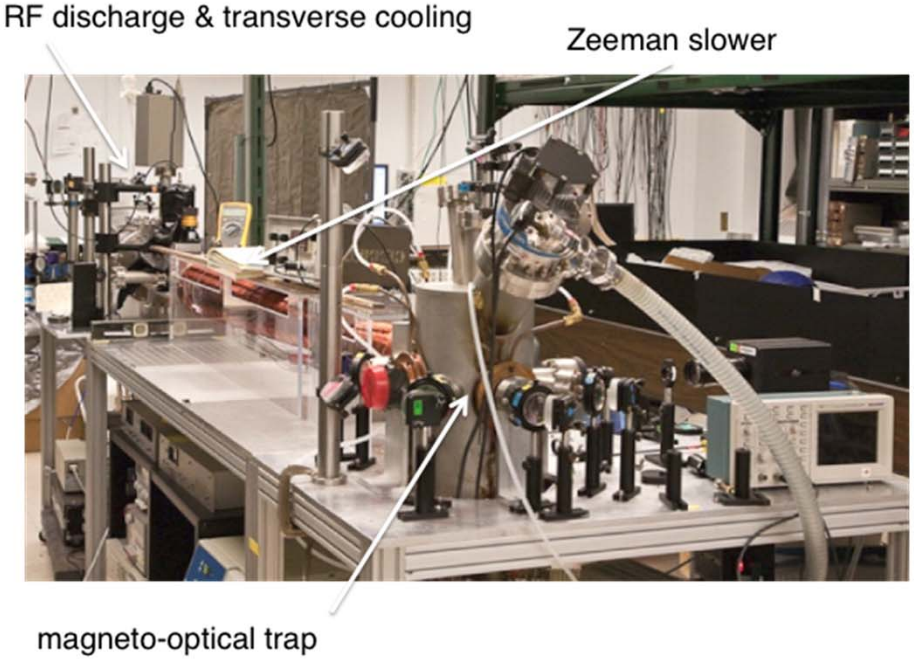
19.82eV RF Discharge

1s^2 ^{1}S J=0

- Trapped atoms transferred to detection chamber with dipole trap

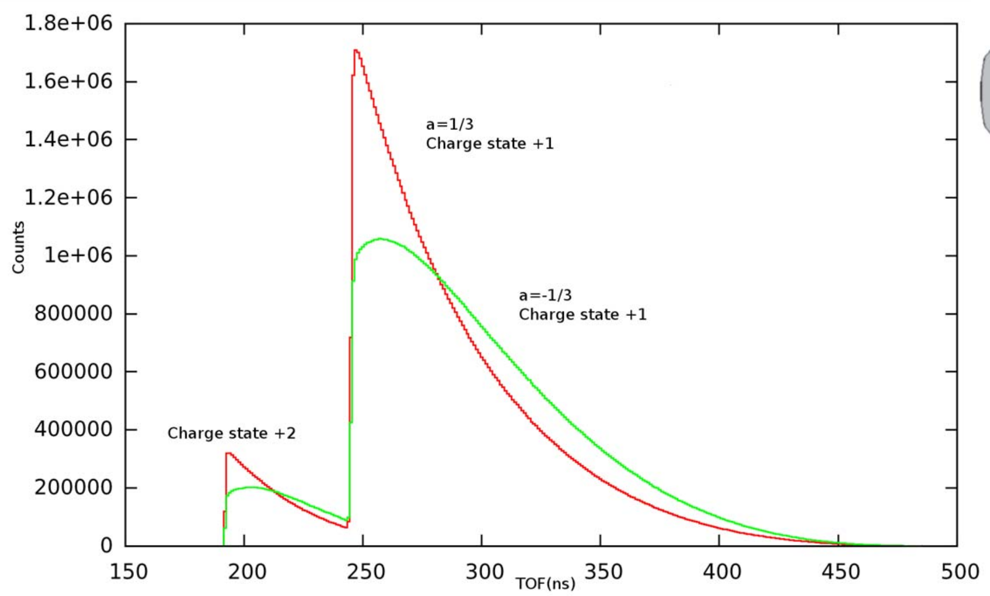
- Based on experience from ^{6}He, ^{8}He charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL **93**, 142501 (2004)
  P. Mueller et al., PRL **99**, 252501 (2007)

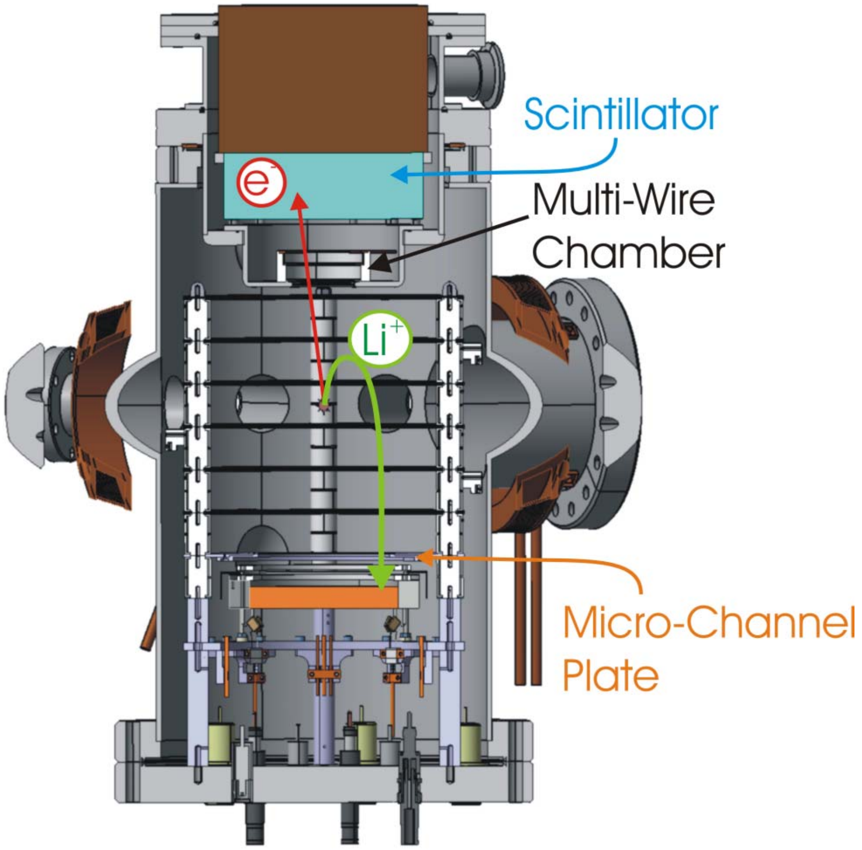




^{6}He Little a, detection

- 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,



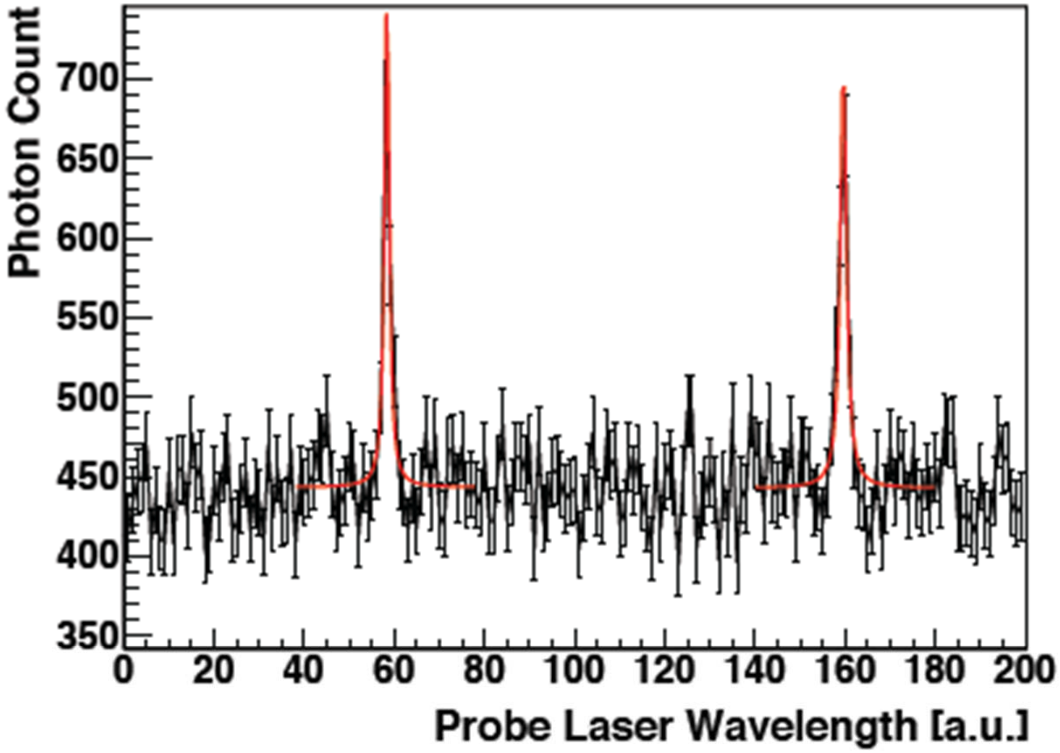


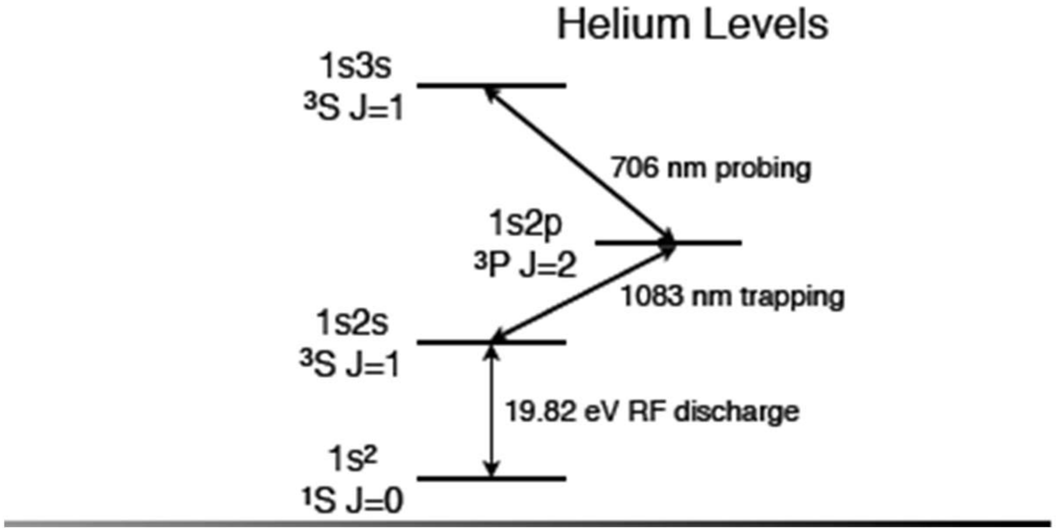
So far we have managed to trap 500-1000 6He atoms.

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

Presently working on many developments.

First physics run likely early 2013.





Interaction for GT transitions

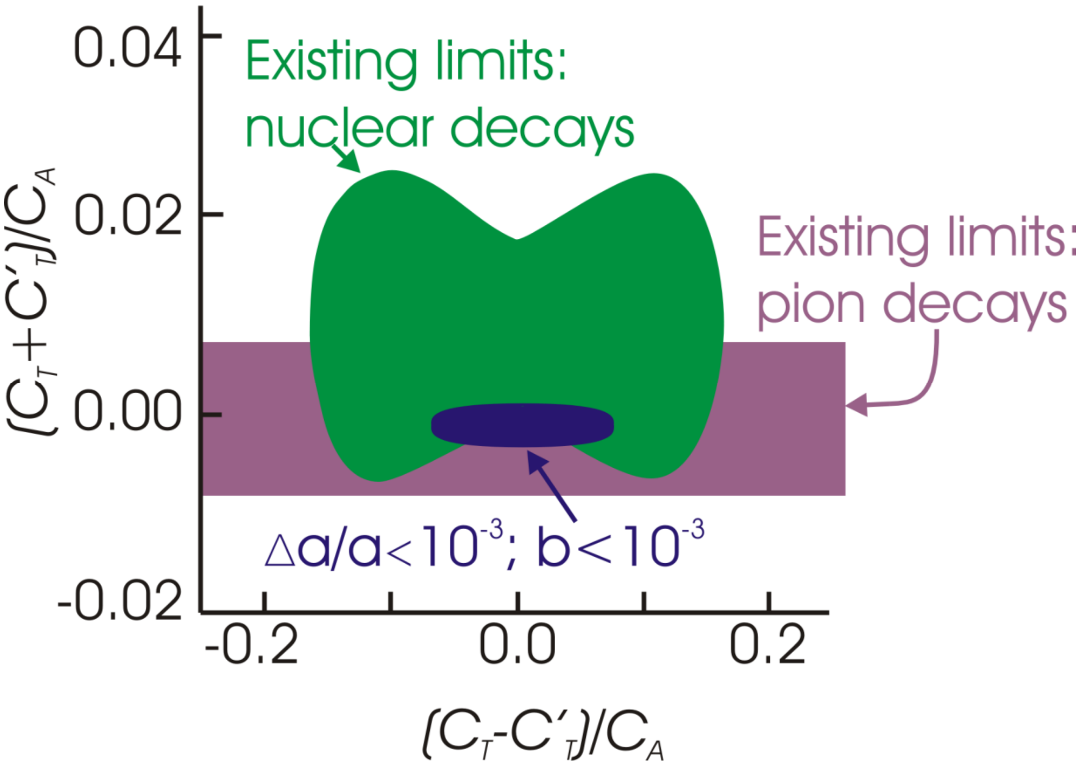
$$H = \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \quad 2C_A \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L + \\ \overline{\Psi}_f \gamma^\mu \gamma^\nu \Psi_i \quad \left[(C_T - C_T^{'}) \overline{e}^L \gamma_\mu \gamma_\nu \nu_e^R + (C_T + C_T^{'}) \overline{e}^R \gamma_\mu \gamma_\nu \nu_e^L \right]$$

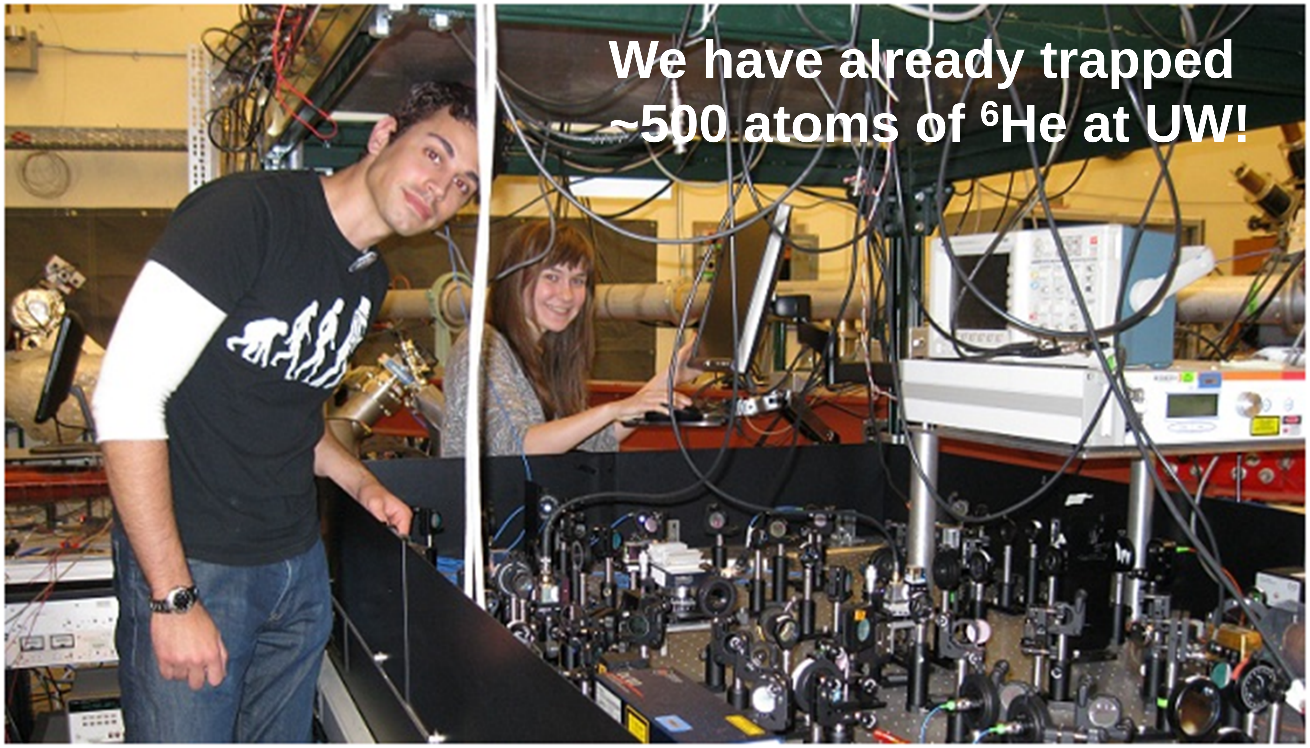
Decay rate:

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

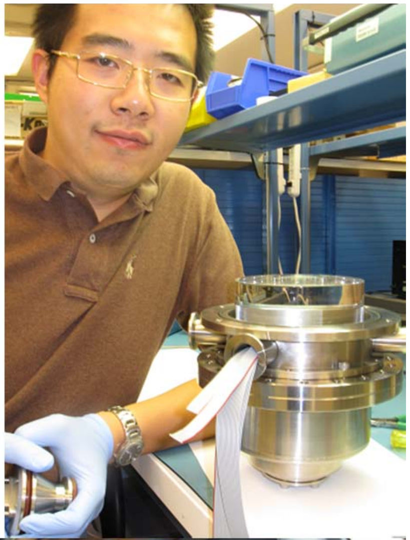
$$b \approx \frac{\mathrm{Re}\left[2C_A\left(C_T + C_T^{'}\right)\right]}{2\left|C_A\right|^2 + \left|C_T\right|^2 + \left|C_T^{'}\right|^2}$$

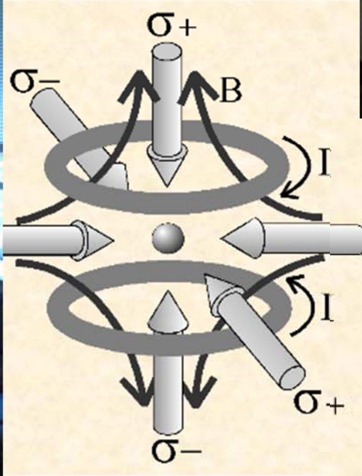
$$a \approx -\frac{1}{3} \frac{2\left|C_A\right|^2 - \left|C_T\right|^2 + \left|C_T^{'}\right|^2}{2\left|C_A\right|^2 + \left|C_T\right|^2 + \left|C_T^{'}\right|^2}$$

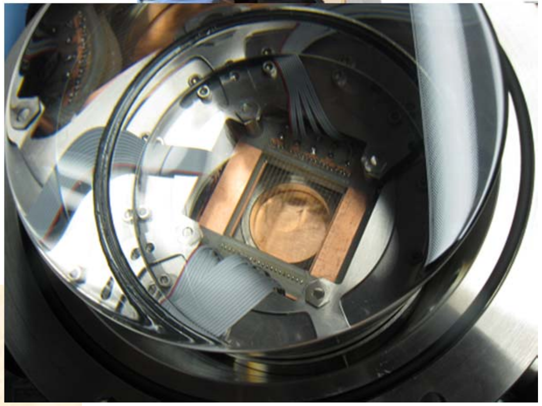


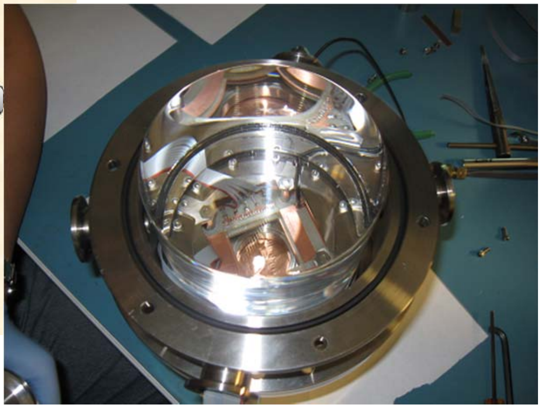


We have already trapped ~500 atoms of ^{6}He at UW!





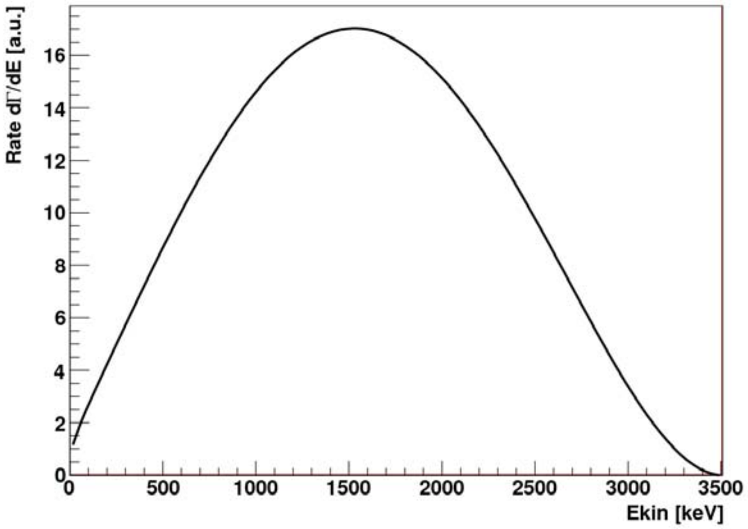


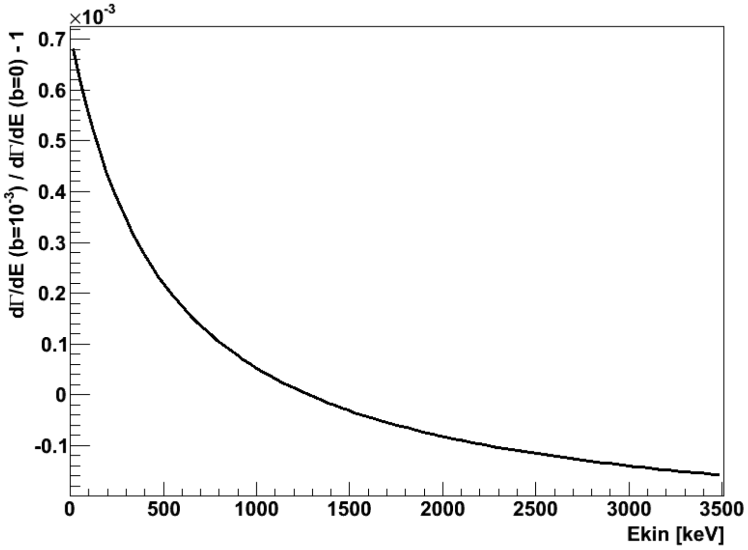


6He: measuring the spectrum in search of the `Fierz interference'

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