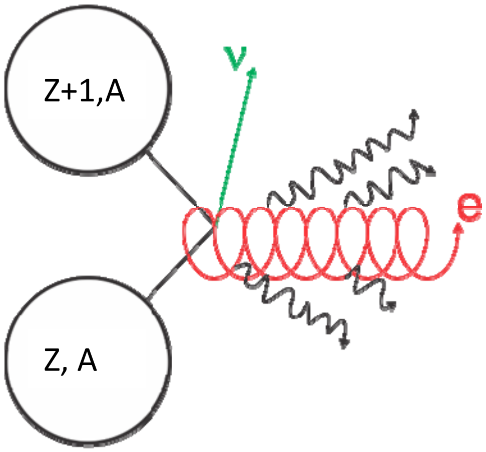
Weak Interactions and Fundamental Symmetries
Exotic Beam Summer School



Alejandro Garcia
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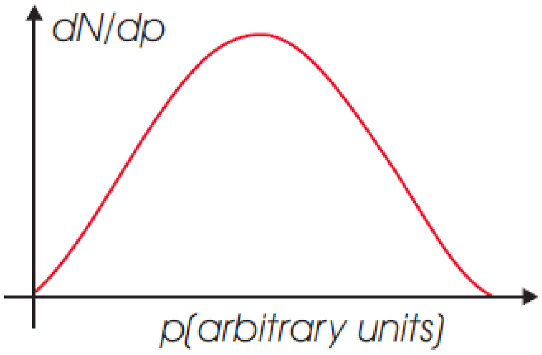
Outline

LECTURE I
Fermi's Golden rule, phase space
Determination of the neutrino mass: Katrin, P8
Structure of the weak interaction, history, P violation
The quark mixing and Vud
Neutron beta decay life-time and beta asymmetry

LECTURE II
Right-handed currents
Chirality flipping currents
Time Reversal symmetry breaking and Electric Dipole Moments

Fermi's Golden rule (for nuclear beta decay)

$$dN \propto \left|\langle\psi_f|\hat{O}|\psi_i\rangle\right|^2 d^3p_e\, d^3p_\nu\, \delta(E_e + E_\nu - E_0)$$



Beta spectrum:

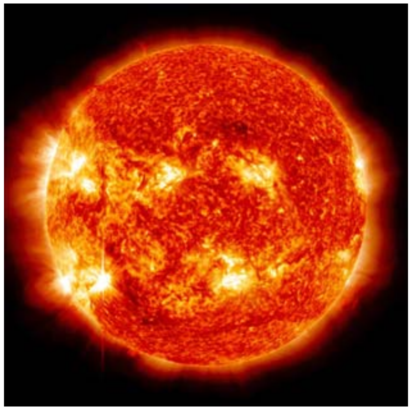
$$dN \propto \left|\langle\psi_f|\hat{O}|\psi_i\rangle\right|^2 p_e{}^2 dp_e\;\; p_\nu{}^2 dp_\nu\, \delta(E_e + E_\nu - E_0)$$ (neglect small recoil contribution)

$$dN \propto \left|\langle\psi_f|\hat{O}|\psi_i\rangle\right|^2 p_e E_e dE_e\;\; p_\nu E_\nu dE_\nu\;\; \delta(E_e + E_\nu - E_0)$$ (use $p_e dp_e = E_e dE_e; p_\nu dp_\nu = E_\nu dE_\nu$)

$$dN \propto \left|\langle\psi_f|\hat{O}|\psi_i\rangle\right|^2 p_e E_e dE_e \sqrt{(E_0 - E_e)^2 - m_\nu{}^2}(E_0 - E_e)$$ (integrating over the unobserved neutrino)

Fermi's Golden rule (for nuclear beta decay)

$$dN \propto \left|\langle\psi_f|\hat{O}|\psi_i\rangle\right|^2 p_e E_e dE_e \sqrt{(E_0-E_e)^2 - m_\nu{}^2}(E_0-E_e)$$



From careful analysis of solar and atmospheric neutrinos we now know

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ \dots & \dots & \dots\\ \dots & \dots & \dots\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mass eigenstates

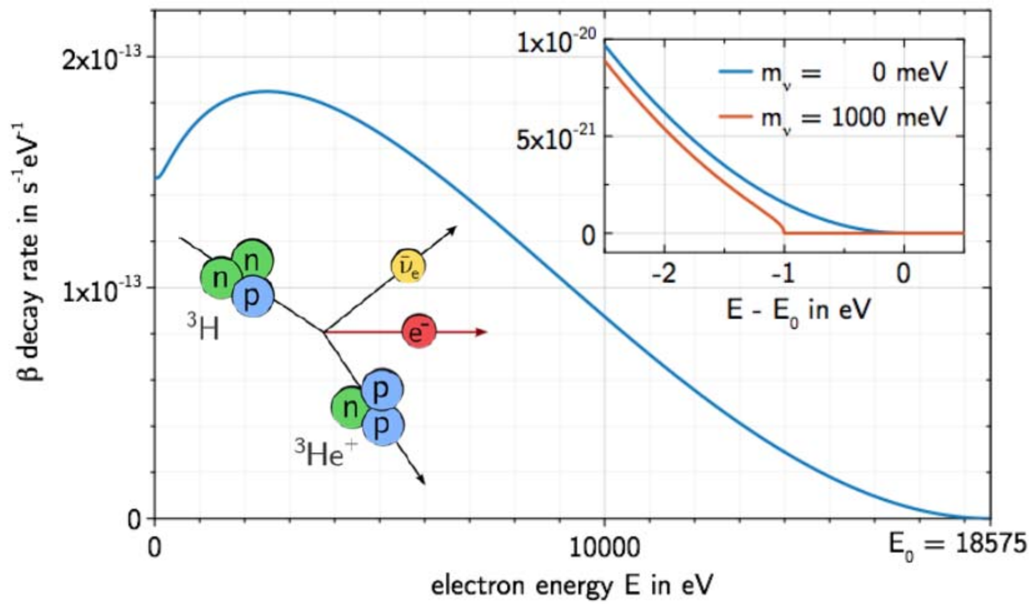
Weak eigenstates

$$dN/dE_e \propto p_e E_e \sum_i |U_{ei}|^2 \sqrt{(E_0-E_e)^2 - m_{\nu i}{}^2}(E_0-E_e)$$

Kinematic determination of neutrino mass from tritium beta decay:

$$\frac{dN}{dE_e} \propto F(E_e)\; p_e E_e \;\sum_i |U_{ei}|^2 \sqrt{(E_0 - E_e)^2 - m_{\nu i}{}^2}\,(E_0 - E_e)$$

"Coulomb" correction



Key requirements:

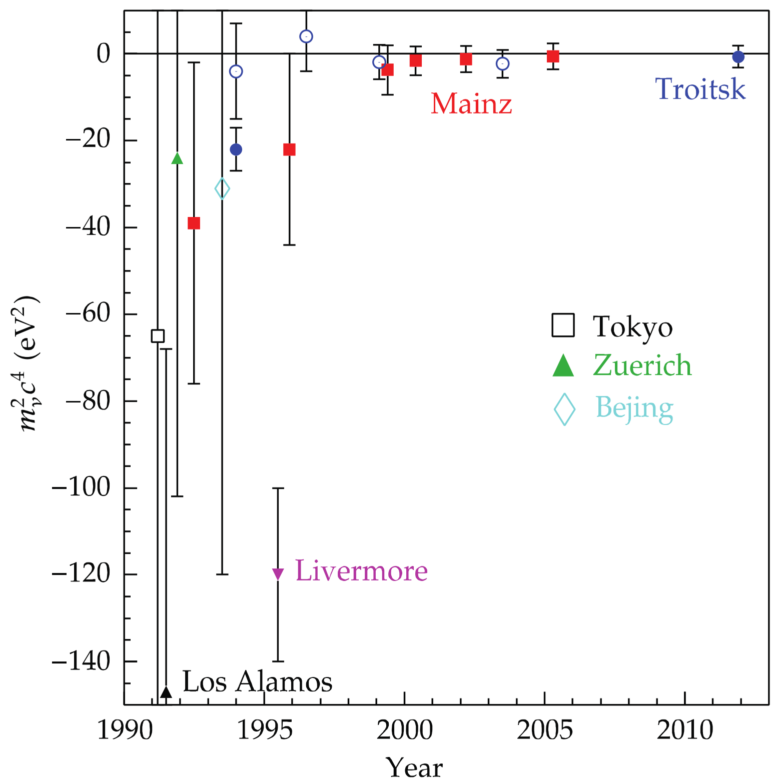
- High activity source
- Low-endpoint β emmitter
- Excellent energy resolution (MAC-E filter)

Spectral distortion measures **"effective" mass squared**
$m^2(\nu_e) := \sum_i |U_{ei}|^2\, m_i^2$

Neutrino mass… Via Tritium Beta Decay

T_2 beta decay has long, rich history: 1949 - present

Chalk River 1949 (M_ν< 500 eV), ITEP' 80's, Los Alamos '91, Tokyo '91, Zurich 91, Bejing '93, Livermore '95, Mainz and Troitsk experiments, 2000 – 2012 (Current limit M_ν< 2 eV), KATRIN 2018 - 2023



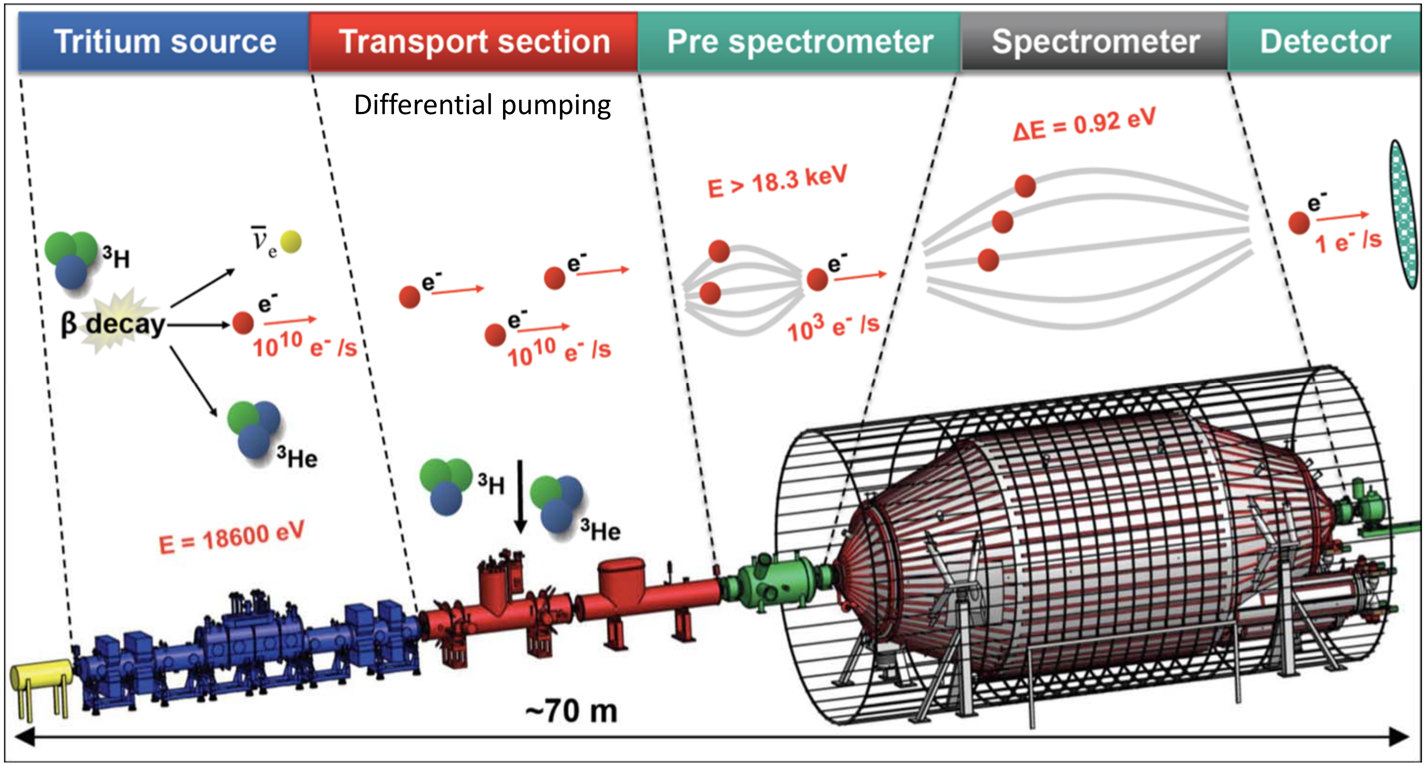
Goals of KATRIN

- A model independent (mostly) probe of the ν mass:
  After 5 calendar years of running:
  Sensitivity: $M_\nu \leq$ 200meV (90% C.L.)
  Discovery potential : M_ν= 360meV (5 sigma)

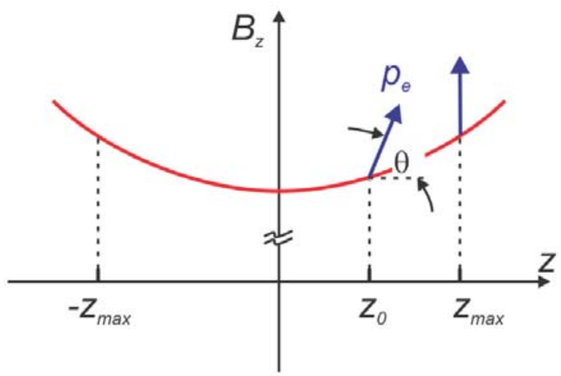
- Search for evidence of sterile neutrino, eV and keV region

KATRIN design:

- Drawing on the experience of past experiments…
- Intense (10^{11} Bq) window-less gaseous T2 source.
- Hi resolution (0.93 eV) retarding potential spectrometer.
- Control of systematic errors.



Adiabatic invariance and pitch angle
(theme will come back later)



If cyclotron period much shorter than characteristic time for changes in *B*-field intensity:

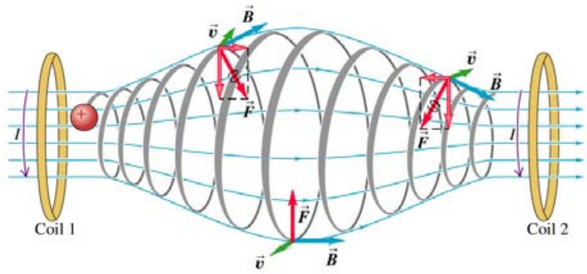
$$\frac{2\pi}{\omega} \gg \frac{B}{\nabla B}\frac{1}{v_\parallel}$$

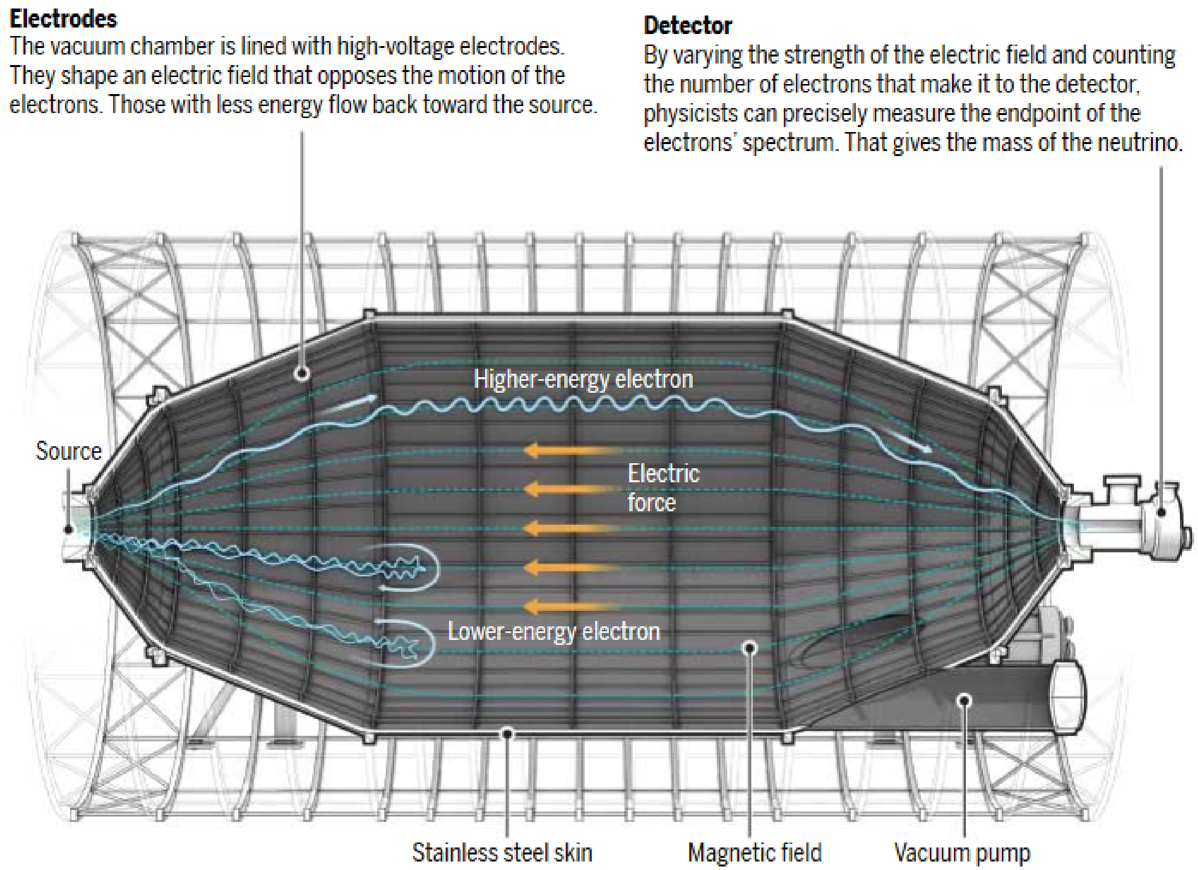
then flux of *B* through the cyclotron orbits is constant of motion.

Cyclotron radius: $R = \frac{\gamma m v_\perp}{qB}$

Flux $\propto B\left(\frac{v_\perp}{B}\right)^2 = \frac{{v_\perp}^2}{B} = \frac{(\sin\theta)^2}{B}$ (as B increases, θ increases)

Typical example of consequence of adiabatic invariance





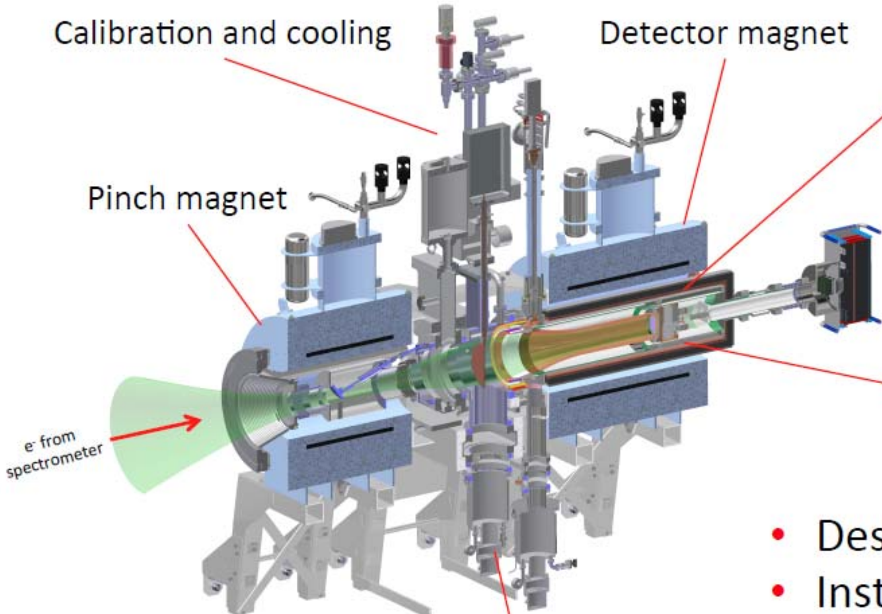
GRAPHIC: C. BICKEL/*SCIENCE*

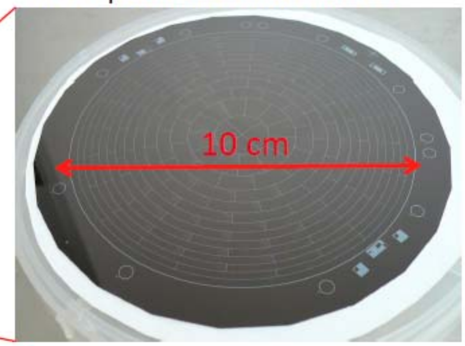
MAC-E filter

Retarding spectrometer: integrate number of e's that make it through an electrostatic barrier.

Transverse (cyclotron) motion not affected by *E* field.

Improve sensitivity minimizing transverse motion → let trajectories expand in low *B* field so longitudinal comp. of $\vec{p}_e$ highest.





- Design, fabrication 2007-2010
- Installation at KIT 2010-2011

2013 – Present... Primary KATRIN commissioning tool

KATRIN present status:

All detection systems ready;
The recent very successful operation using Kr sources is a major step towards ensuring that KATRIN will begin Tritium operation as planed in June 2018

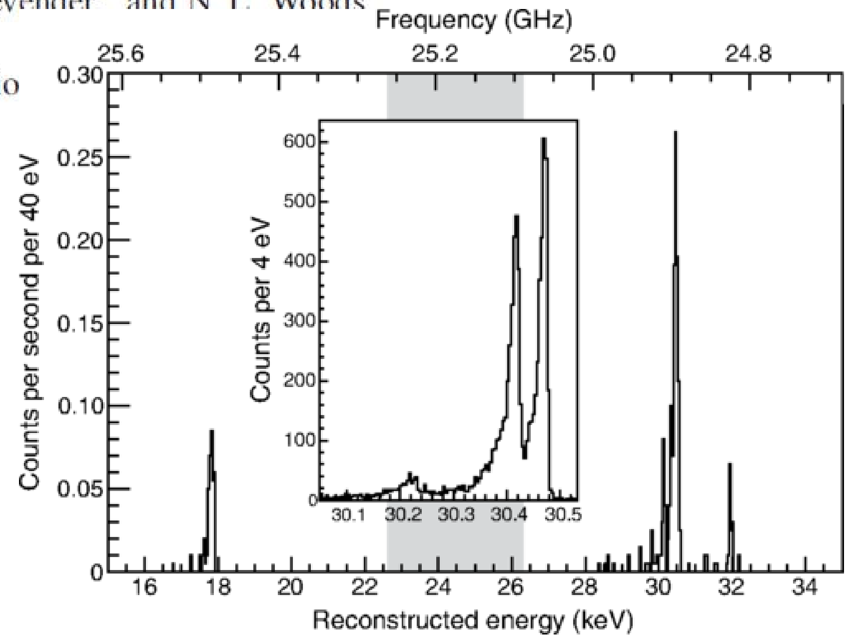
Data collection expected: 2018+ 5 years

Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015) 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 Collaboratio

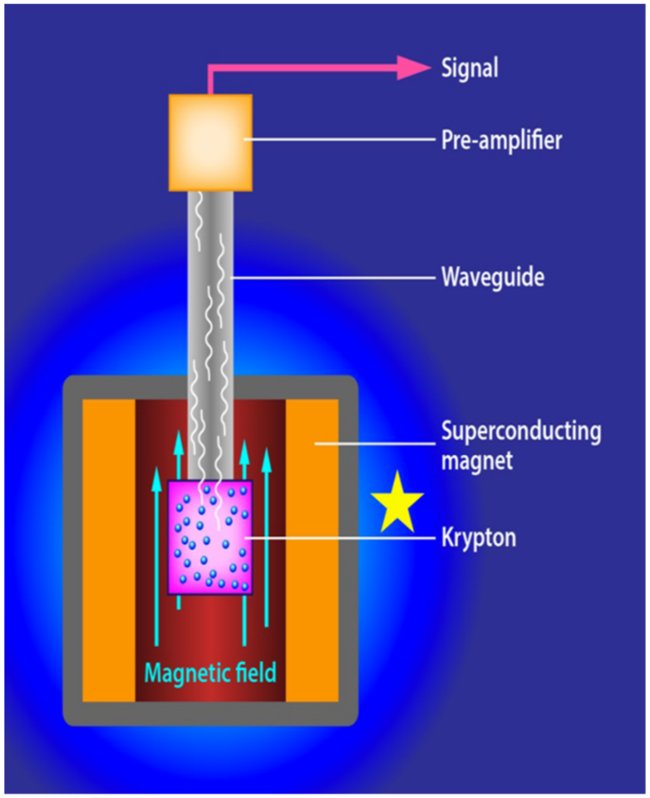


Project 8 collaboration gets FWHM/E ~ < 10^{-3} resolution for conversion electrons of 18-32 keV.

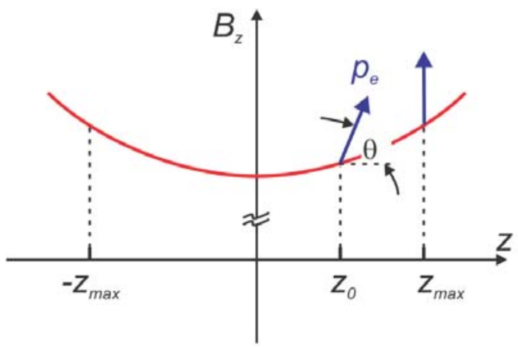
Project 8 in a nutshell

Looking at Tritium decay to get ν mass.
Electrons emitted in an RF guide within an axial *B* field. At end, cyclotron radiation is amplified.

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

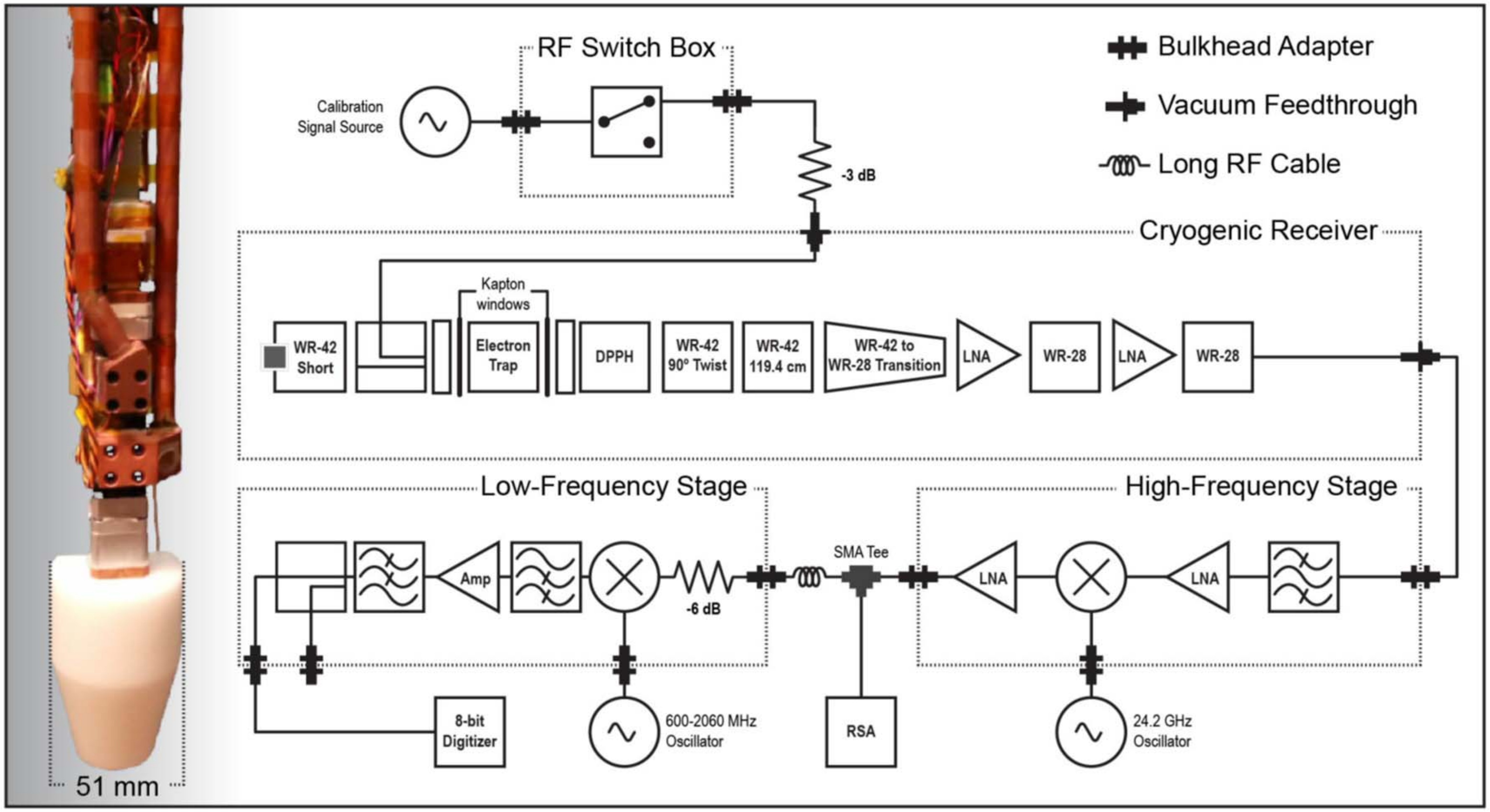


Electrons of ~ 30 keV from a gaseous source were let to decay within a 1 tesla field with an additional pair of coils to set up a *magnetic trap*:



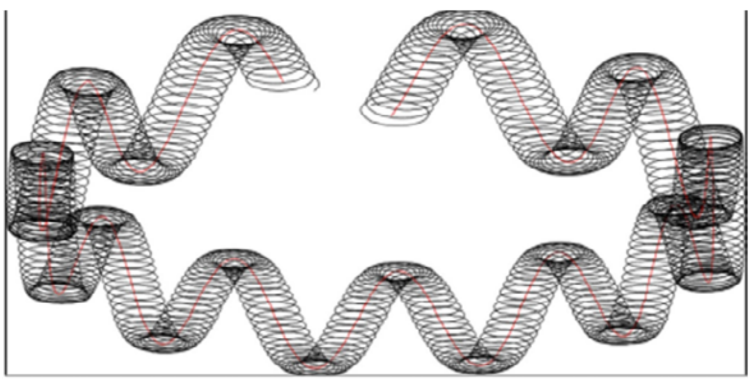
Longitudinal comp. of momentum decreases as *B* increases up to return point, z_{max}. Axial oscillations with ω_z.

Project 8 electronics (guide needs cooling to 15K)



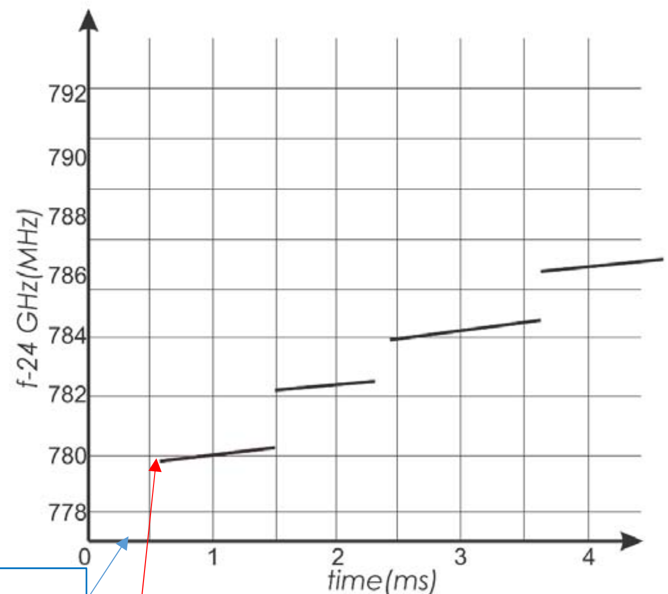
Some details

Motion can be thought off as cyclotron orbits, axial oscillations and magnetron motion.



$$\omega_c : \omega_z : \omega_{mag} = \sim 1 : 4 \times 10^{-3} : 2 \times 10^{-5}$$

Peak frequency of power spectrum versus time.



As electrons loose energy the cyclotron freq. goes up. Jumps due to collisions with hydrogen in imperfect vacuum

Time bins ~ 30 μs.

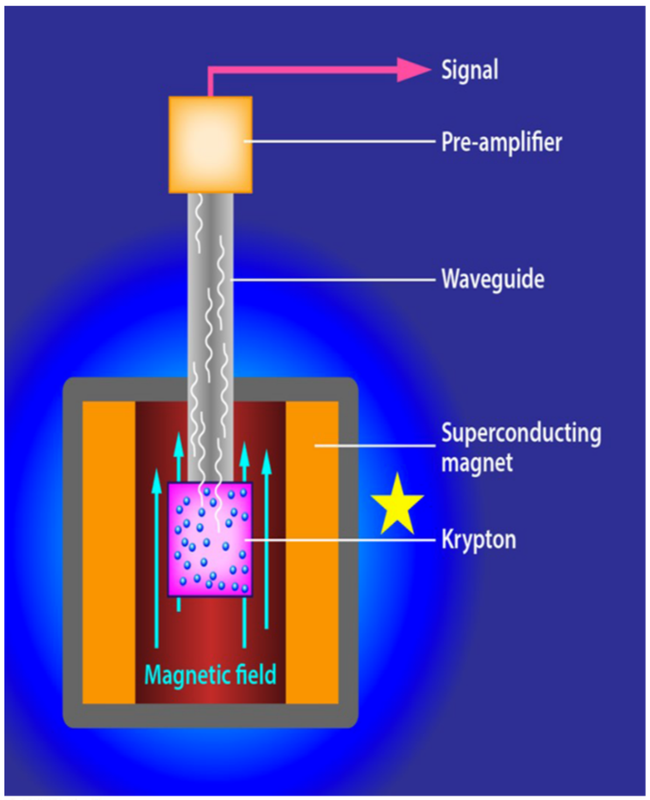
Initial frequency gives *E*

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

Project 8 in a nutshell

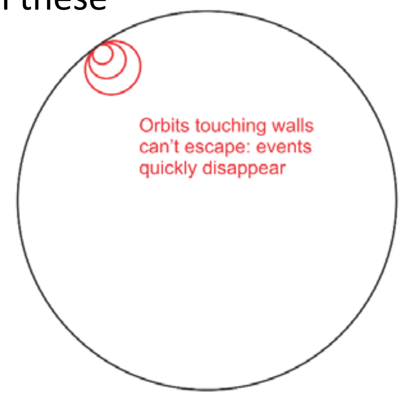
Looking at Tritium decay to get ν mass.
Electrons emitted in an RF guide within an axial *B* field. At end, cyclotron radiation is amplified.

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



Advantage

Electrons hitting walls quickly (<1 ns) loose energy and disappear.
No signal from these



For the same reason: background radiation hitting walls does not generate signals.

Project 8 timeline

From Esfahani et al. arXiv:1703.02037

- Have performed proof-of-principle of detection of cyclotron radiation.
- Next phase: show detection of molecular tritium.
- Eventually: trap atomic tritium

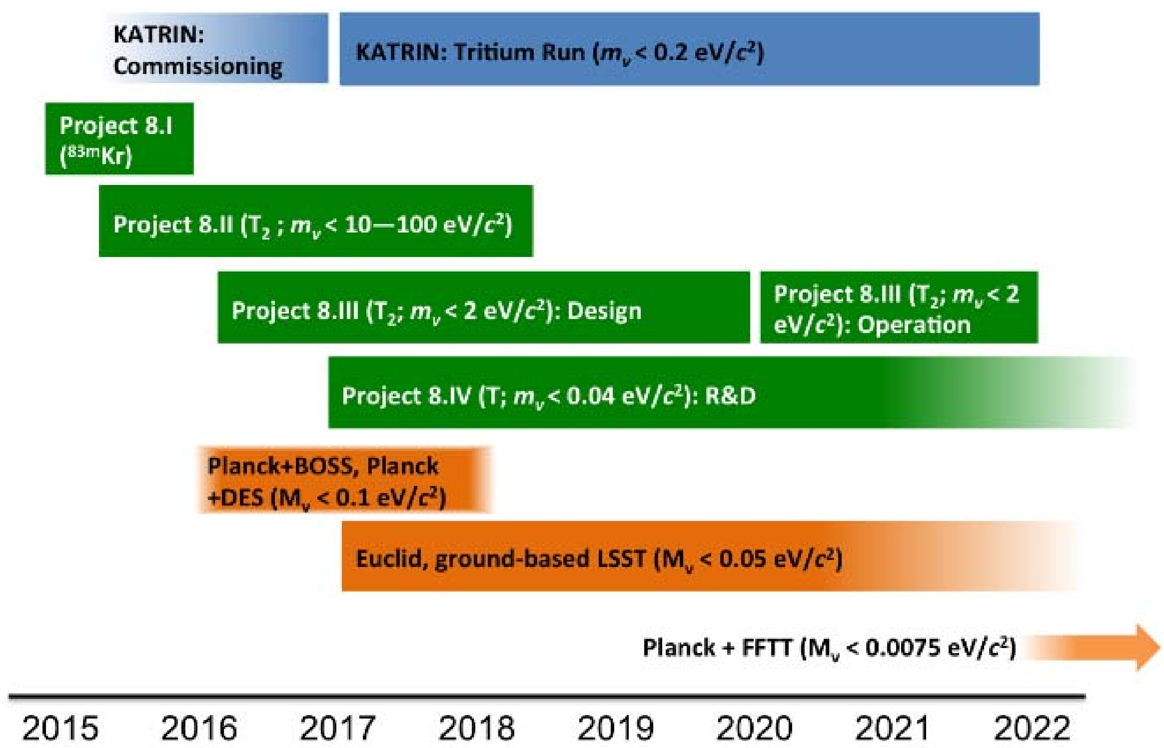


Figure 8. Timeline for Project 8 phases, with reference to expectations from KATRIN and cosmological observations. Cosmological expectations are from Lesgourgues and Pastor [4]

Structure of the weak interaction

A bit of history: the Dirac Eq.
To reconcile QM with Relativity, Dirac used

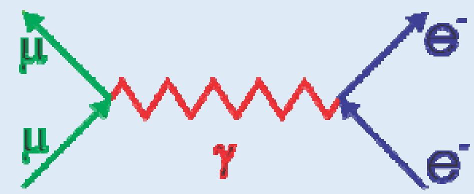
$$H = -\alpha \cdot \nabla + \beta\, m$$

with $\alpha_i = \gamma^0 \gamma^i$ and $\beta = \gamma^0$ and

$$\gamma^0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}, \qquad \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}$$

$$\gamma^\mu \ (\mu = 0, 1, 2, 3)$$

E&M interaction by Dirac



$$H_{EM} = \bar{\psi}_\mu \gamma^\mu \psi_\mu \frac{-e^2}{-q^2} \bar{\psi}_e \gamma_\mu \psi_e$$

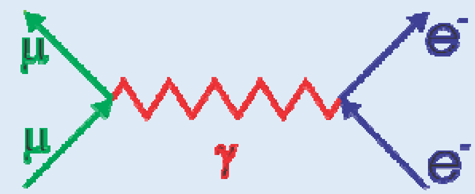
Structure of the weak interaction

Fermi proposed assuming the Weak current had similar structure

$$H_W = \bar{\psi}_\nu \ \gamma^\mu \psi_\mu \ \frac{-g^2}{M^2 - q^2} \ \bar{\psi}_e \ \gamma^\mu \psi_\nu$$

To account for the short range

E&M interaction by Dirac



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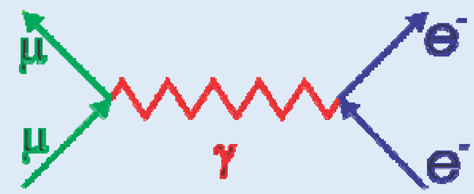
$$H_W = \overline{\psi}_\nu \ \gamma^\mu \psi_\mu \frac{-g^2}{M^2 - q^2} \overline{\psi}_e \ \gamma^\mu \psi_\nu$$

Nuclear beta decay
$q \ll M \Rightarrow$

$$H_W \approx \overline{\psi}_\nu \ \gamma^\mu \psi_\mu \frac{-g^2}{M^2} \overline{\psi}_e \ \gamma^\mu \psi_\nu$$

"Weak" interaction looks weak at nuclear beta decay momenta. But g of same order as e.

E&M interaction by Dirac

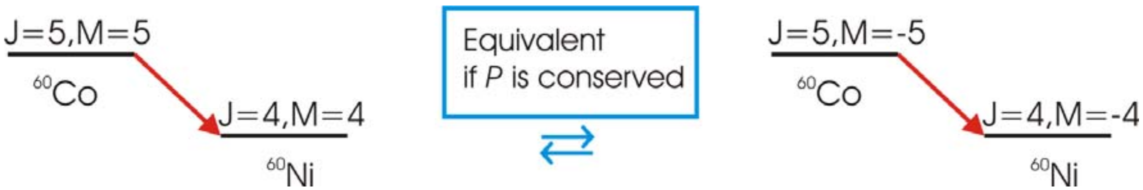


$$H_{EM} = \overline{\psi}_\mu \gamma^\mu \psi_\mu \frac{-e^2}{-q^2} \overline{\psi}_e \gamma_\mu \psi_e$$

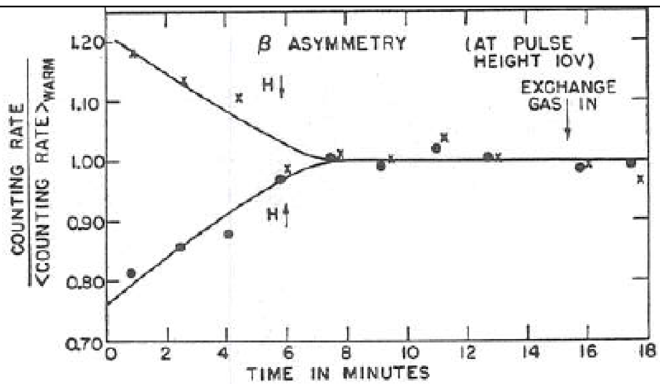
Experimental Observation of Parity Violation (1957)

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

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



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



Chien-Shiung Wu (b. 1912)
Nuclear Physicist

Helicity

Projection of spin onto momentum

$$\mathcal{H} = \frac{\sigma . p}{|\sigma|\ |p|}$$

$$\mathcal{H} = +1 \qquad \mathcal{H} = -1$$

Helicity *is not* a Lorentz *invariant*:
moving faster than an *R*-handed particle makes it look *L*-handed

Chirality

A Lorentz invariant property related to helicity

The instantaneous velocity of a particle:

$$v = \lim_{\Delta t \to 0} \frac{\Delta x}{\Delta t}$$

But in QM: $\Delta t\, \Delta E \sim \hbar$ so instantaneous velocity

$$v = \pm c$$

A state with finite E,p and spin in a particular direction can be expressed as linear comb. of the *R* and *L chirality* states.

$$u_\uparrow(E,p) = \sqrt{\frac{1+\frac{p}{E}}{2}}\,\phi_\uparrow(+c) + \sqrt{\frac{1-\frac{p}{E}}{2}}\,\phi_\uparrow(-c)$$

State with well-defined spin and *E*,*p*.

Right-chiral

Left-chiral

For $v \approx c$ chirality ≡ helicity

Chirality: γ^5

Reminder: we showed above how Dirac used matrices to combine QM and Relativity.

$$\gamma^0 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}, \qquad \gamma^i = \begin{pmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{pmatrix}$$

It turns out that the operator: $\gamma^5 = \mathrm{i}\,\gamma^1\gamma^2\gamma^3\gamma^0 = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$ is a relativistic invariant related to the helicity.

For relativistic particles $-\gamma^5 \equiv \mathcal{H}$.

Projectors on *chirality* states:

$$P_L = \frac{1}{2}(1 + \gamma^5) \quad \Rightarrow \psi_e^L = P_L \psi_e$$

$$P_R = \frac{1}{2}(1 - \gamma^5) \quad \Rightarrow \psi_e^R = P_R \psi_e$$

E&M current is not biased to a particular *chirality.*

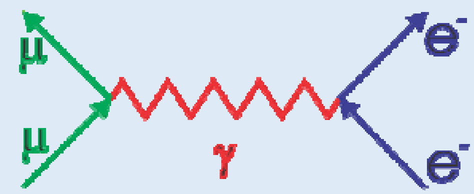
$$\bar{\psi}_\mu \gamma^\nu \psi_\mu = \bar{\psi}_\mu^R \gamma^\nu \psi_\mu^R + \bar{\psi}_\mu^L \gamma^\nu \psi_\mu^L$$

Projectors on *chirality* states:

$$P_L = \frac{1}{2}(1+\gamma^5) \Rightarrow \psi_e^L = P_L \psi_e$$

$$P_R = \frac{1}{2}(1-\gamma^5) \Rightarrow \psi_e^R = P_R \psi_e$$

E&M interaction by Dirac



$$H_{EM} = \bar{\psi}_\mu \gamma^\mu \psi_\mu \frac{-e^2}{-q^2} \bar{\psi}_e \gamma_\mu \psi_e$$

Charged weak current in SM only sensitive to *L*:

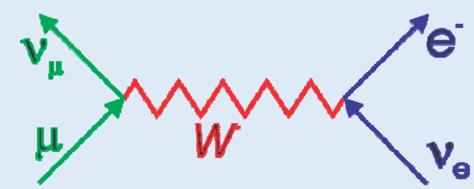
$$\bar{\psi}_e O^\mu \psi_\nu = \bar{\psi}_e^L \gamma^\mu \psi_\nu^L$$

Projectors on *chirality* states:

$$P_L = \frac{1}{2}(1+\gamma^5) \quad \Rightarrow \psi_e^L = P_L \psi_e$$

$$P_R = \frac{1}{2}(1-\gamma^5) \quad \Rightarrow \psi_e^R = P_R \psi_e$$

Weak charged current in SM



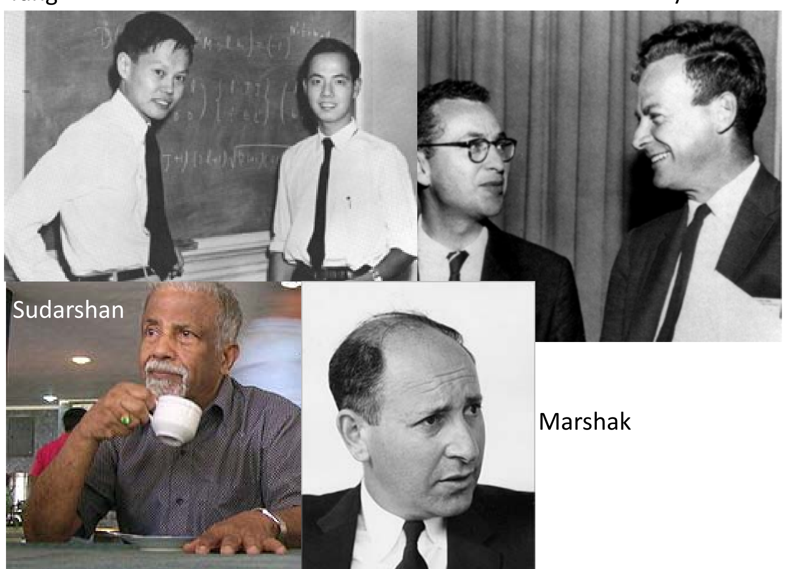
$$H_W = \bar{\psi}_\nu^L \gamma^\mu \psi_\mu^L \frac{-g^2}{M^2 - q^2} \bar{\psi}_e^L \gamma^\mu \psi_\nu^L$$

Charged weak current in SM only sensitive to *L*:

$$\bar{\psi}_e O^{\mu} \psi_{\nu} = \bar{\psi}_e^{L} \gamma^{\mu} \psi_{\nu}^{L}$$

Sorting this out took much experimental effort and ingenuity to come out of confusing times

Yang Lee Gell-Mann Feynman



Marshak

From "The 7% solution" article in
Surely you are joking, Mr. Feynman!

(Circa 1957)

When I came back to the United States, I wanted to know what the situation was with beta decay. I went to Professor Wu's laboratory at Columbia, and she wasn't there, spinning to the left in the beta decay, came out on the right in some cases. Nothing fit anything. When I got back to Caltech, I asked some of the experimenters what the situation was with beta decay. I remember three guys, Hans Jensen, Aaldert Wapstra, and Felix Boehm, sitting me down on a little stool, and starting to tell me all these facts: experimental results from other parts of the country, and their own experimental results. Since I knew those guys, and how careful they were, I paid more attention to their results than to the others. Their results, alone, were not so inconsistent; it was all the others plus theirs.

Finally they get all this stuff into me, and they say, "The situation is so mixed up that even some of the things they've established for years are being questioned - such as the beta decay of the neutron is S and T. It's so messed up, Murray says it might even be *V* and *A*."

I jump up from the stool and say, "Then I understand EVVVVVERYTHING!"

Charged weak current in SM only sensitive to *L*:

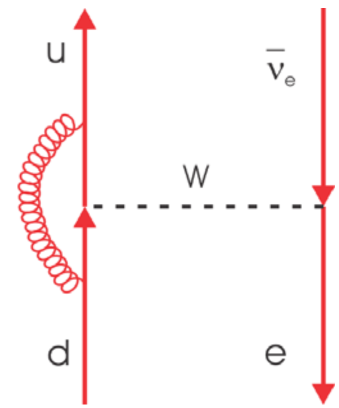
$$\bar{\psi}_e O^\mu \psi_\nu = \bar{\psi}_e^L \gamma^\mu \psi_\nu^L$$

Although the currents look very simple for leptons, for quarks within the nucleon/nuclear medium, we have to separate them according to their properties under *P* and rotations:

$$H_{int} = \bar{\psi}_p (C_V \gamma^\mu - C_A \gamma^\mu \gamma^5) \psi_n \;\; \bar{\psi}_e^L \gamma^\mu \psi_\nu^L$$

Vector

Axial Vector



C_V and C_A don't need to be identical: due to the strong interaction within the nucleon/nuclear medium $C_A/C_V \approx -1.27$.

Isospin

Notice *n+n, n+p, p+p* hadronic interactions are very similar.

Use spin formalism to take into account Pauli exclusion principle etc.

The charge is given by: $\hat{q} = e\left(\frac{1}{2} + \hat{I}_z\right)$

$$|p\rangle = \begin{bmatrix}1\\0\end{bmatrix}; \qquad |n\rangle = \begin{bmatrix}0\\1\end{bmatrix}$$

$$\hat{I}_z|p\rangle = \frac{1}{2}|p\rangle$$
$$\hat{I}_z|n\rangle = -\frac{1}{2}|n\rangle$$

Think of spin for the electron. The fact that e's come in two varieties, spin-up and -down, allows to circumvent the Pauli principle.

Likewise here: the nucleons (p and n) can be thought off as being identical *except* for their elec. charge.
(Only an approximation, but a useful one).

Isospin

$$p = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad n = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Nucleons form an isospin doublet.

$$\pi^+ = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix},$$

$$\pi^0 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix},$$

$$\pi^- = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}.$$

Pions form an isospin triplet.

Isospin

$$p = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad n = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

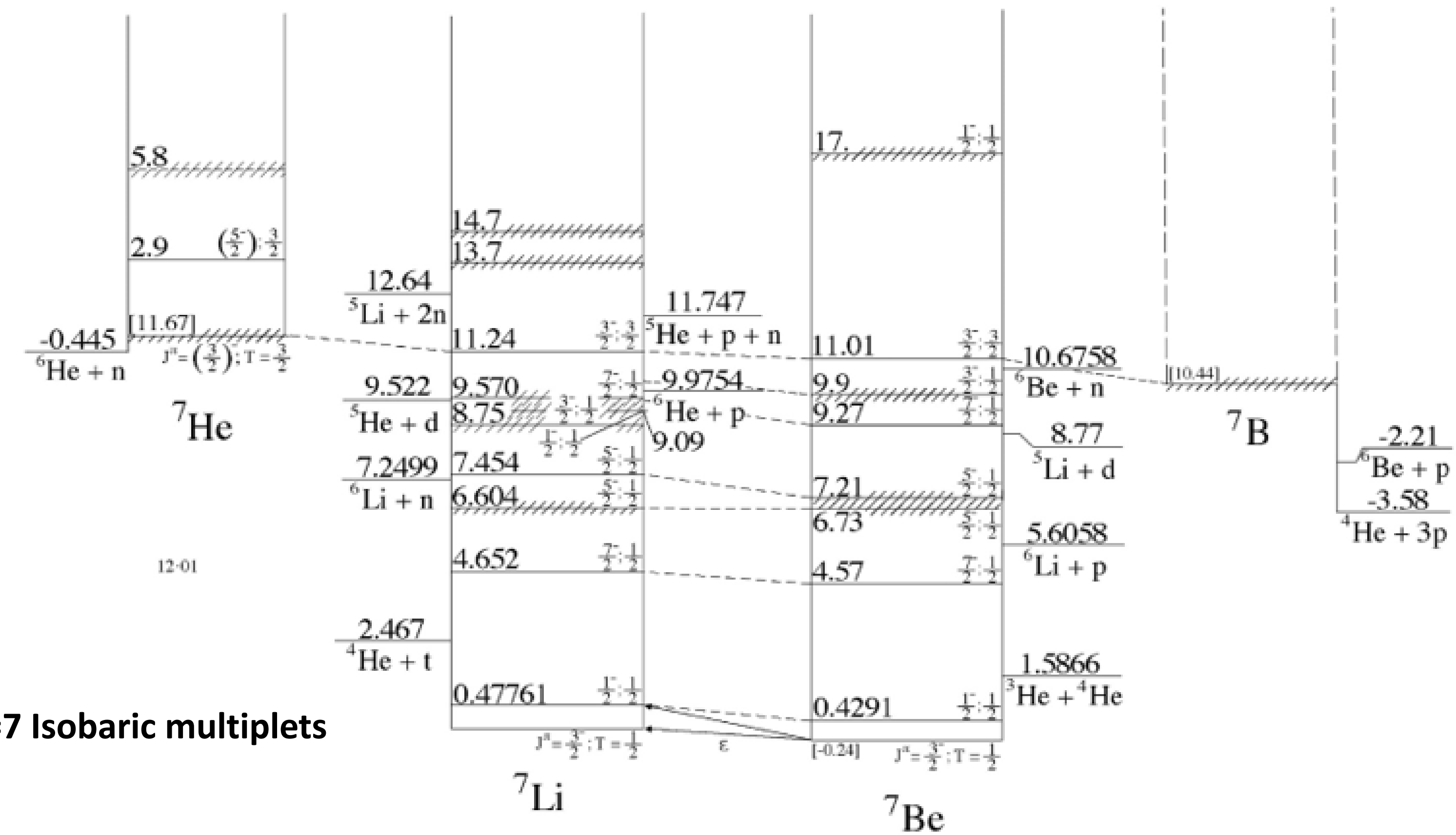
$$\pi^+ = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix},$$

$$\pi^0 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix},$$

$$\pi^- = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}.$$

Hadron	*Mass* (MeV/c^2)	I	I_3
p	938.3	1/2	1/2
n	939.6	1/2	−1/2
π^+	139.6	1	1
π^0	135.0	1	0
π^-	139.6	1	−1
K^+	494.6	1/2	1/2
K^0	497.7	1/2	−1/2
$\overline{K}^0$	497.7	1/2	1/2
K^-	494.6	1/2	−1/2
η^0	548.8	0	0
Λ^0	1115.6	0	0
Σ^+	1189.4	1	1
Σ^0	1192.6	1	0
Σ^-	1197.4	1	−1
Ω^-	1672.4	0	0

^{4}He+3n $I_z = -3/2$ | ^{4}He+p+2n $I_z = -1/2$ | ^{4}He+2p+n $I_z = 1/2$ | ^{4}He+3p $I_z = 3/2$

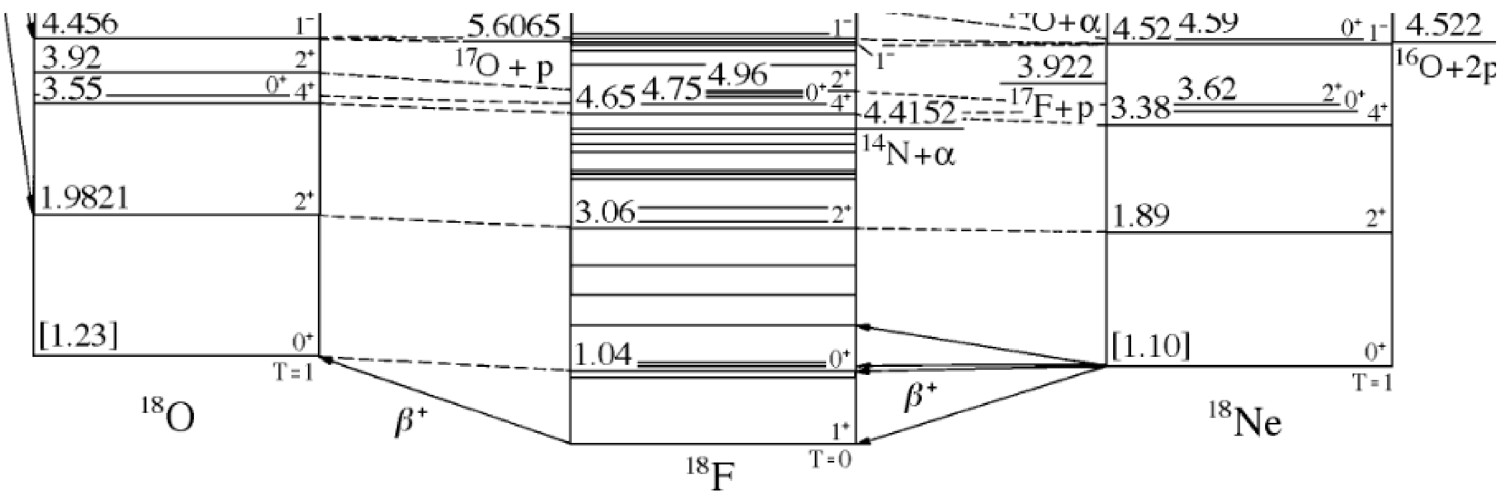


A=7 Isobaric multiplets

Notice the higher level density in ^{7}Li, ^{7}Be, which can have both *I* = 1/2 and *I* = 3/2.

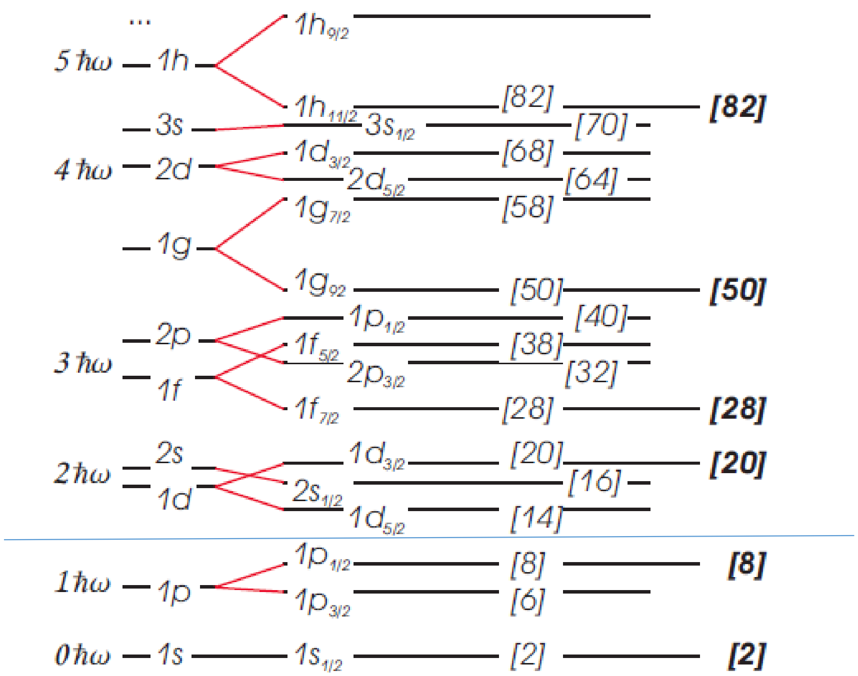
Isospin symmetry in *A* = 18 nuclei. Model as ^{16}O+2 nucleons
Each nucleon (n or p) has *I* = ½. So one can get *I* = 0 or *I* = 1.
Near stability: lower I → lower E

^{16}O+2n	^{16}O+1n+1p	^{16}O+2p
$I_z = -1$	$I_z = 0$	$I_z = +1$



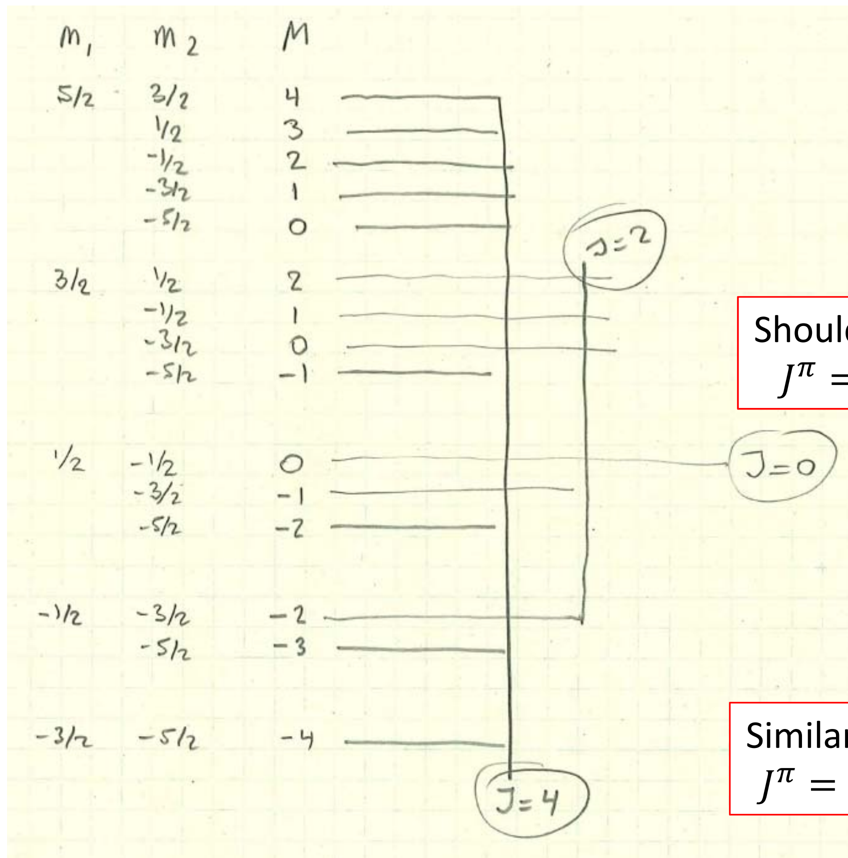
Notice the higher level density in ^{18}F, which can have both *I* = 0 and *I* = 1.

Useful trick to get the expected J^{π}, I
(and understand the gross features)



Basic shell model scheme from spherical harm. oscillator with spin-orbit interaction.

For A=18 lowest orbits from $1d_{5/2}$ orbits with identical particles (I = 1) :



Should see ($I = 1$) $J^{\pi} = 0^{+}, 2^{+}, 4^{+}$

Similarly ($I = 0$) $J^{\pi} = 1^{+}, 3^{+}, 5^{+}$

$$H_{int} = \bar{\psi}_p (C_V\, \gamma^\mu - C_A\, \gamma^\mu \gamma^5)\psi_n \;\; \bar{\psi}_e^L\, \gamma^\mu \psi_\nu^L$$

Vector — Axial Vector

C_V and C_A don't need to be identical: due to the strong interaction within the nucleon/nuclear medium $C_A/C_V \approx -1.27$.

The non-relativistic limits of these are:

			Operator	Selection rules
(Vector)	$I^{\pm}\gamma_\mu \to \tau^{\pm}(1, \vec{v}/c)$	Fermi:	$\hat{O}_F = I^{\pm}$	$\Rightarrow \Delta J = 0, \Delta I = 0$
(Axial Vector)	$I^{\pm}\gamma_\mu\gamma_5 \to \tau^{\pm}(\lvert\vec{v}/c\rvert, \vec{\sigma})$	Gamow-Teller:	$\hat{O}_{GT} = \sum_i I_i^{\pm}\sigma_i$	$\Rightarrow \Delta\vec{J} = 1, \Delta\vec{I} = 1$

$$\hat{O} = \begin{cases} (Vector) & I^{\pm}\gamma_\mu \to \tau^{\pm}(1, \vec{v}/c) \\ (Axial\ Vector) & I^{\pm}\gamma_\mu\gamma_5 \to \tau^{\pm}(|\vec{v}/c|, \vec{\sigma}) \end{cases}$$

Charged Weak current involves quark transformations

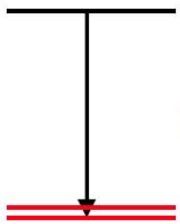
$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

From top to bottom
Or bottom to top.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

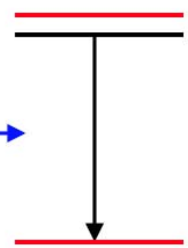
Non-diagonal elements of the matrix are small. So largest transitions are *u-d*, *c-s*, *t-b*.

Manifestations of the mixing



One manifestation of the mixing is flavor oscillations: e.g. ν's, K_0's

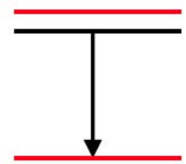
Another is the alteration of the decay strength.

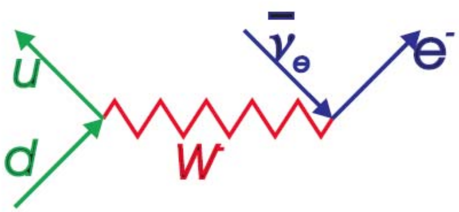


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

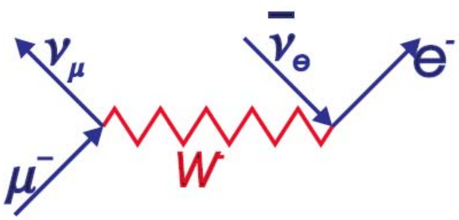
In nuclear beta decay there is not enough energy to produce s quarks.

Alteration of the decay strength.



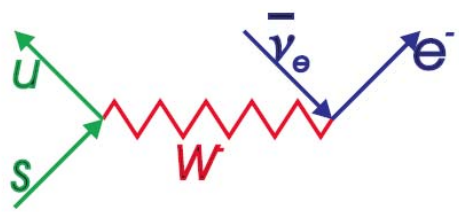


$$decay\ rate \propto (GVud)^2$$
$$e.g.\quad n \rightarrow pe^- \nu_e$$



$$decay\ rate \propto G^2$$

Ratio of nuclear /muon yields V_{ud}.



$$decay\ rate \propto (GVus)^2$$
$$e.g.\quad K^+ \rightarrow \pi^0 e^+ \nu_e$$

Is the CKM matrix really unitary?

From nuclear 0.974 (V_{ud})

Ke3 0.225 (V_{us})

$b \to u l \nu$ 0.035 (V_{ub})

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} Vud & Vus & Vub \\ Vcd & Vcs & Vcb \\ Vtd & Vts & Vtb \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|Vud|^2 + |Vus|^2 + |Vub|^2 = 1?$$

If not, who is the culprit?

- Contributions that affect μ and quark decays in different ways? Right-handed currents,

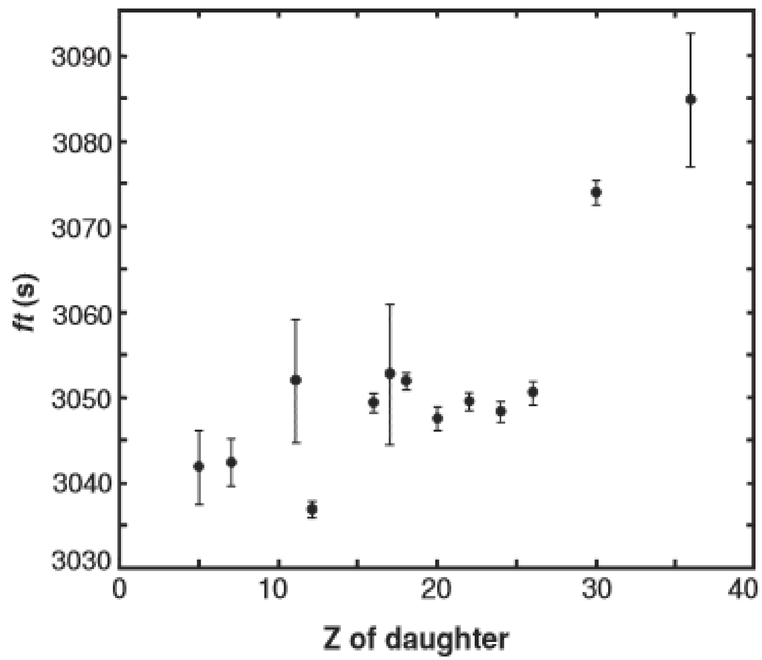
  Super-symmetry,...

- ...

Determine V_{ud} ; Fermi's golden rule:

From Hardy, Towner
PRC **79**, 055502 (2009)

$$\frac{1}{f(E)\,t} = \frac{2\pi}{\hbar}\left|\langle f\; e\; \nu|\hat{H}|i\rangle\right|^2 = \frac{(G_F\,V_{ud})^2}{K}\frac{2\pi}{\hbar}\left|\langle f|\hat{O}|i\rangle\right|^2$$



Naïve approach: *approximate*

$$\left|\langle f|\hat{O}|i\rangle\right|^2 \approx I(I+1) - I_z(I_z-1)$$

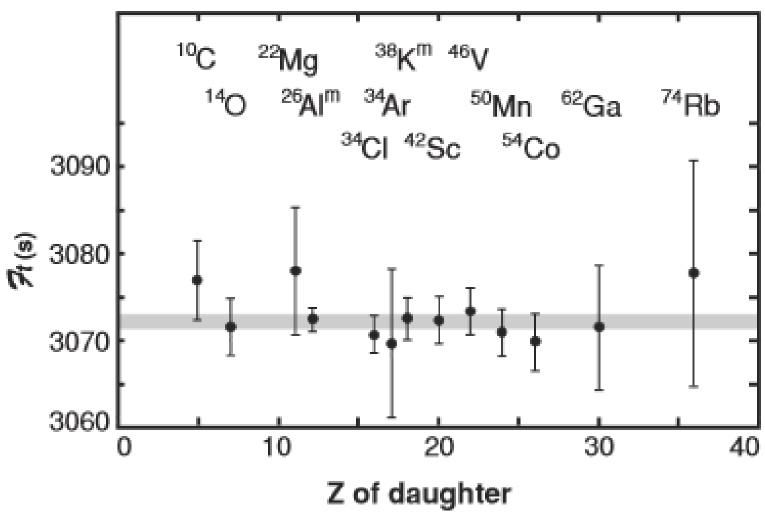
→ *extract $G_F\,V_{ud}$*. Works to few %.

Problem: *ft*-value depends on Z.

Determine V_{ud} ; Fermi's golden rule:

From Hardy, Towner
PRC **79**, 055502 (2009)

$$\frac{1}{f(E)\,t} = \frac{2\pi}{\hbar}\left|\langle f\, e\, \nu|\hat{H}|i\rangle\right|^2 = \frac{(G_F\, V_{ud})^2}{K}\frac{2\pi}{\hbar}\left|\langle f|\hat{O}|i\rangle\right|^2$$



Naïve approach: *approximate*

$$\left|\langle f|\hat{O}|i\rangle\right|^2 \approx I(I+1) - I_z(I_z-1)$$

→ *extract $G_F\, V_{ud}$.* Works to few %.

Problem: *ft*-value depends on Z.

Solution: isospin-breaking and radiative corrections:

$$Ft = ft(1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

$$\frac{1}{F\,t} = \frac{(G_F\, V_{ud})^2}{K}(1+\Delta_R^V)$$

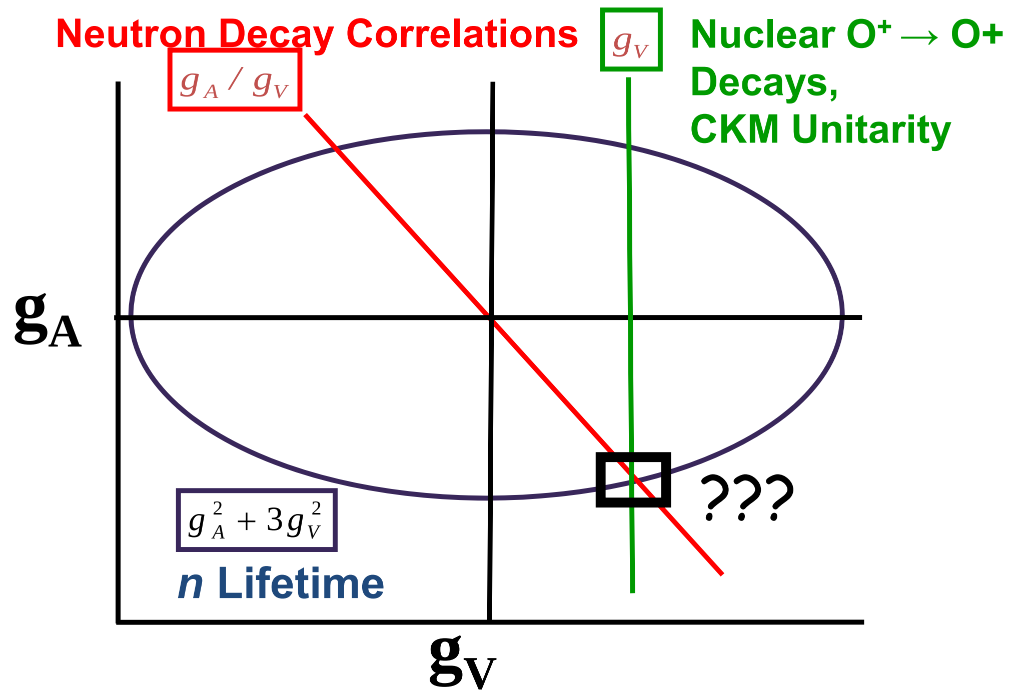
Determine V_{ud} from neutron decay.

Advantage: avoid nuclear structure details (isospin breaking etc.)

$$\frac{1}{f(E)\,t} = \frac{(G_F\,V_{ud})^2}{K}\frac{2\pi}{\hbar}(1+3\lambda^2)$$

$$\lambda = \frac{g_A}{g_V}$$

Now in addition to half-life need *another* observable to determine λ



Neutron lifetime: recent results from UCNτ collaboration

UCNτ: a measurement of the neutron lifetime using ultra-cold neutrons stored in an asymmetric magnetic trap*

Authors:

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Student
Postdoc
Spokesperson
Spokesperson emeritus

*R. W. Pattie, submitted to Science; submitted to Arxiv

Fundamental symmetries

Thanks: Dan Salvat, C. Morris

UCN for beta decay measurements

$$V_{^{58}Ni} = \frac{2\pi\hbar^2 \rho_n a}{m} = 335\, nV \rightarrow v = 8\, m/\sec$$

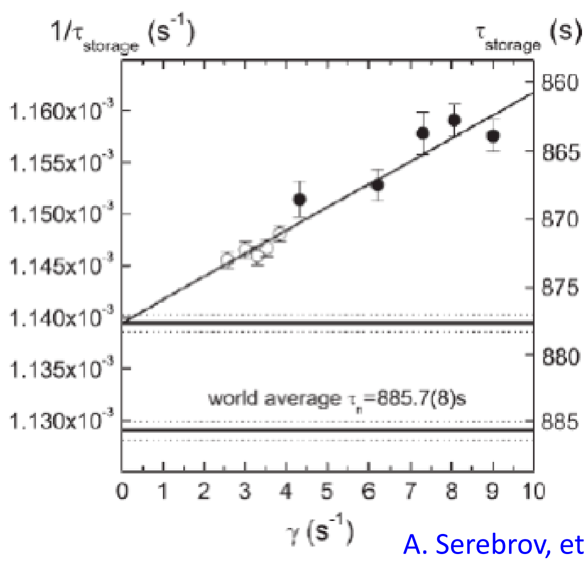
$$V = mgh = 102\, nV/m$$

$$V = \vec{\mu} \bullet \vec{B} = 60\ nV/T$$

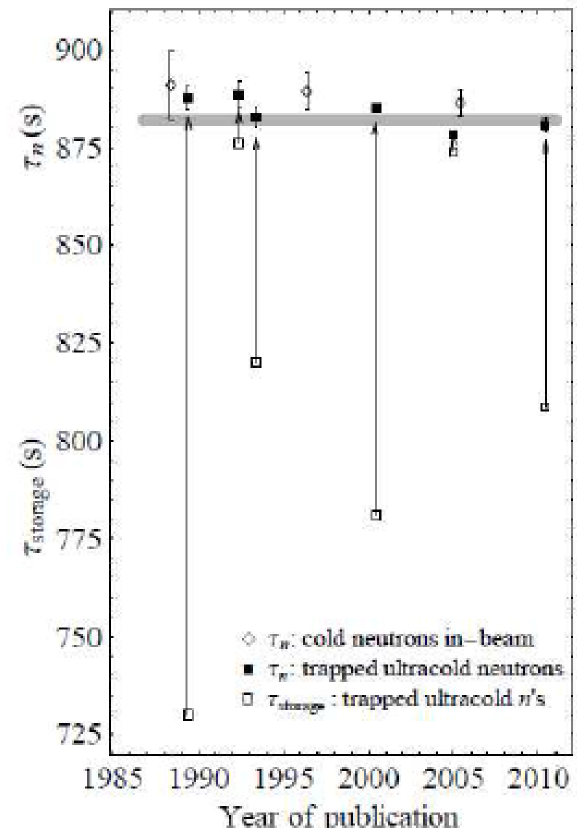
- UCN can be stored using materials, gravity, and magnetic fields
- Decays/beam large
- Backgrounds low

Measuring the lifetime with bottled UCN is challenging

- Beam measurements require precise determination of the neutron beam fluence, decay volume, and absolute proton detector efficiency
  - Have involved multiple systematic corrections of order 5 sec
- Bottle measurements must correct for UCN losses other than neutron beta decay
  - These corrections are often of the same order as the quoted uncertainty
- We have designed a bottle that has negligible intrinsic losses



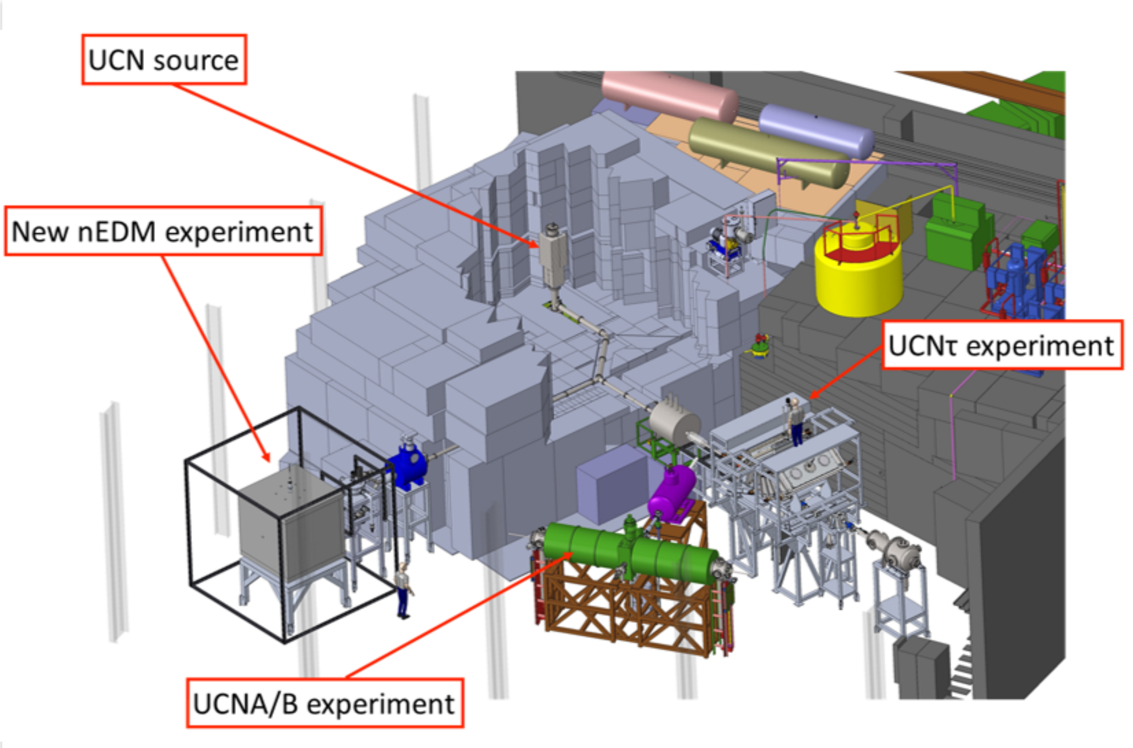
A. Serebrov, et al. (2008)



Dubbers & Schmidt, *Reviews of Modern Physics* **83** (1111) 2011

Thanks: Dan Salvat, C. Morris

UCN "*Pokotilovsky*"source operating at the Los Alamos Neutron Science Center (LANSCE)



Source upgrade:

- Better moderator cooling
- NiP guides
- Optimized geometry

UCN density measured by Vanadium activation: 184 UCN/cc.

A. Saunders, et al. REVIEW OF SCIENTIFIC INSTRUMENTS 84, 013304 (2013)

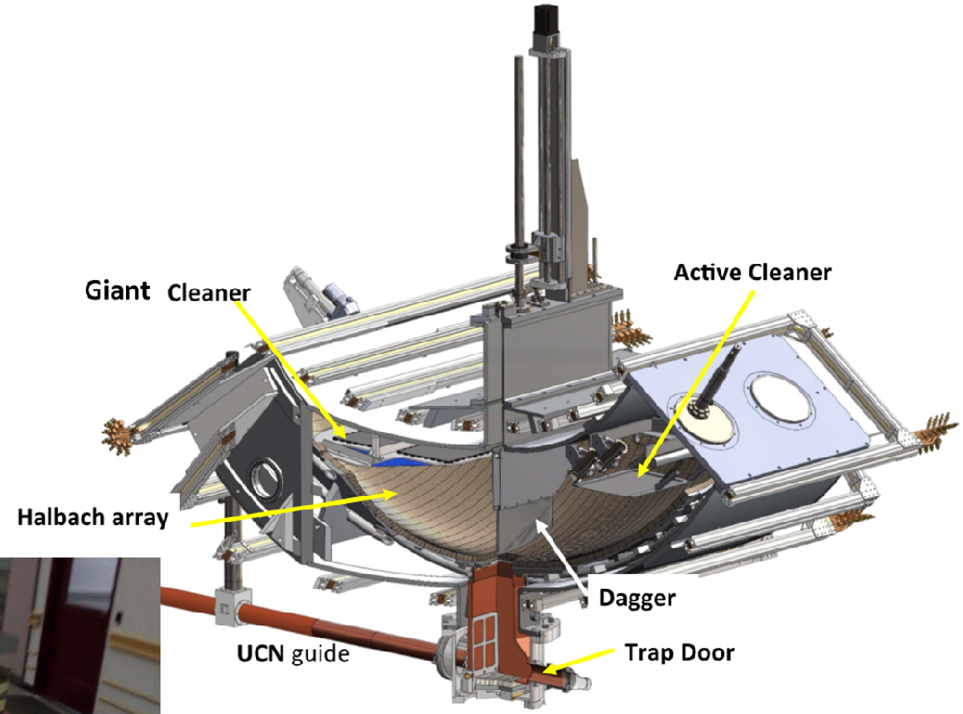
Los Alamos NATIONAL LABORATORY EST. 1943

UCNτ

5

UCNτ Magneto-gravitational trap

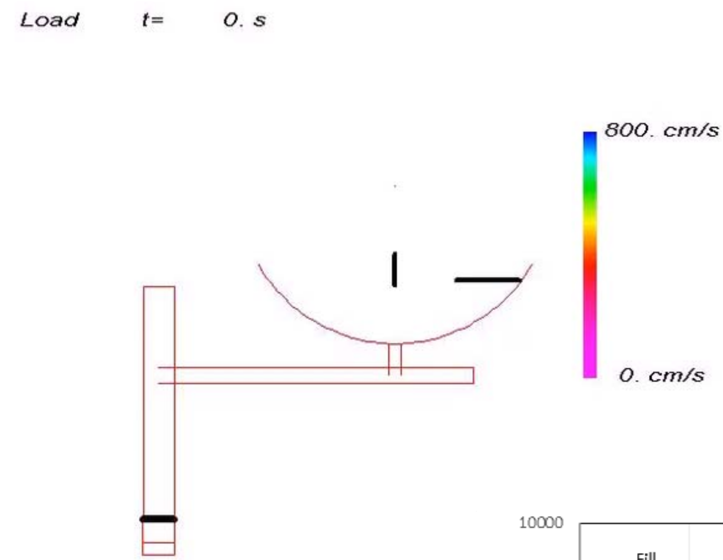
- Large Halbach array of permanent magnets – large neutron statistics
- Intrinsically long lifetime - no material interactions during storage period
- Asymmetric trap for rapid evolution and mixing of the phase space – fast removal of quasi-bound neutrons
- *In situ* active detector – neutron unloading observed in real time

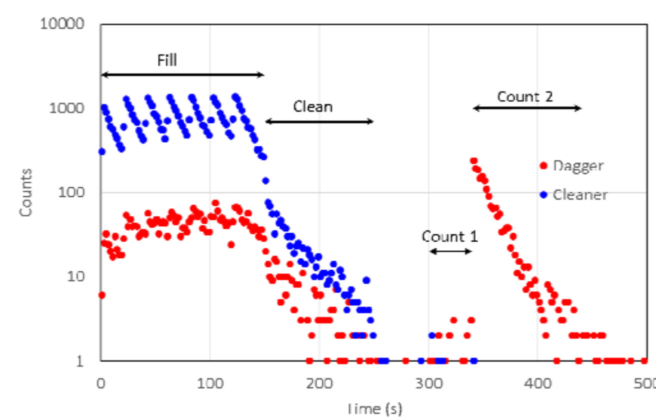


Thanks: Dan Salvat, C. Morris

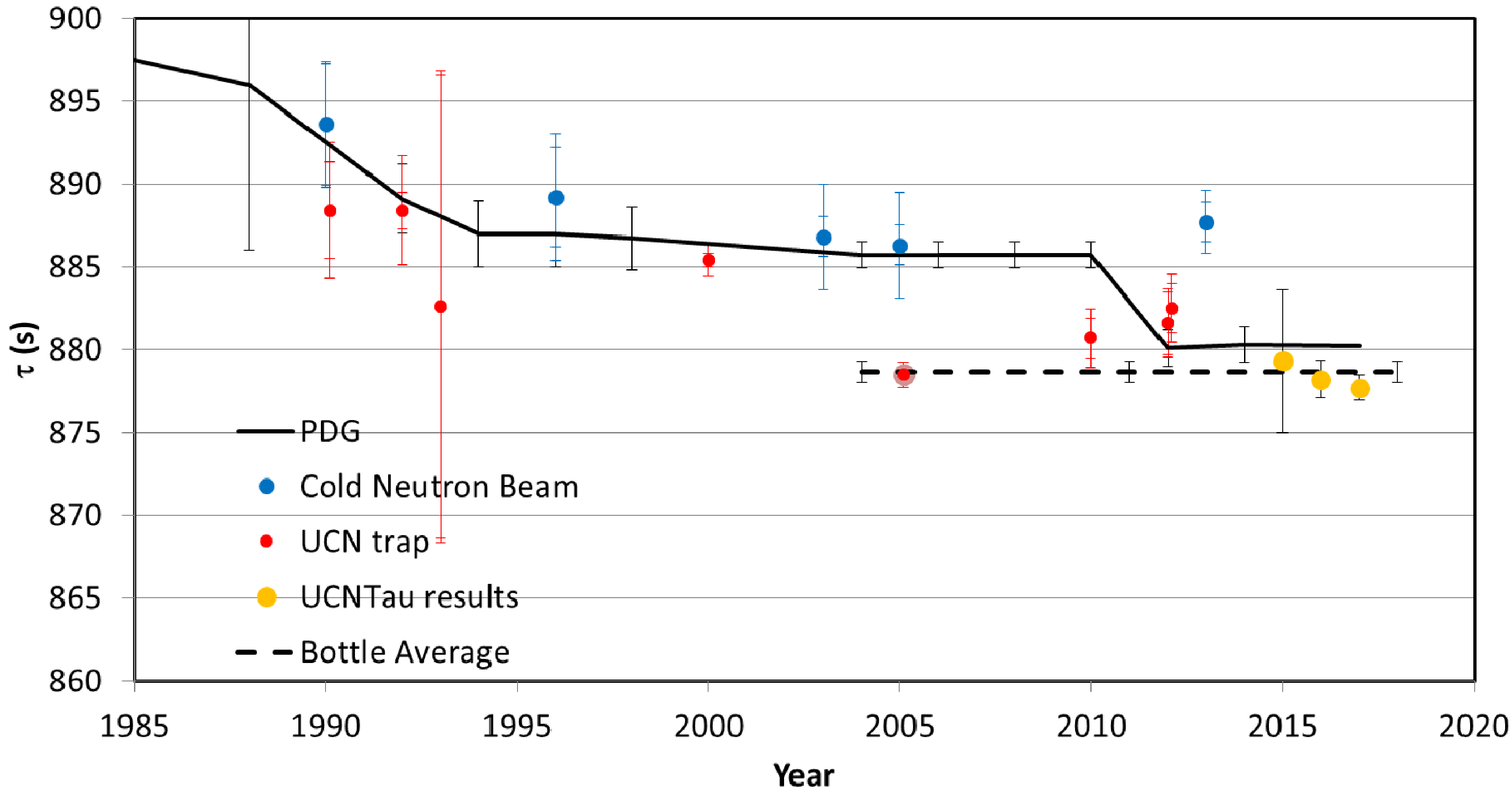
Illustration of cleaning and unloading

- Load trap for 150 sec
- Clean for a variable time (100-400 sec)
- Cleaners in trap for loading and cleaning
- Dagger can also be lowered during loading and cleaning – “dagger cleaning”
- Cleaners and dagger raised during storage time (10 – 1510 sec)
- Dagger lowered to count remaining UCN – either in 1 single step, or multiple steps





UCNτ: New results

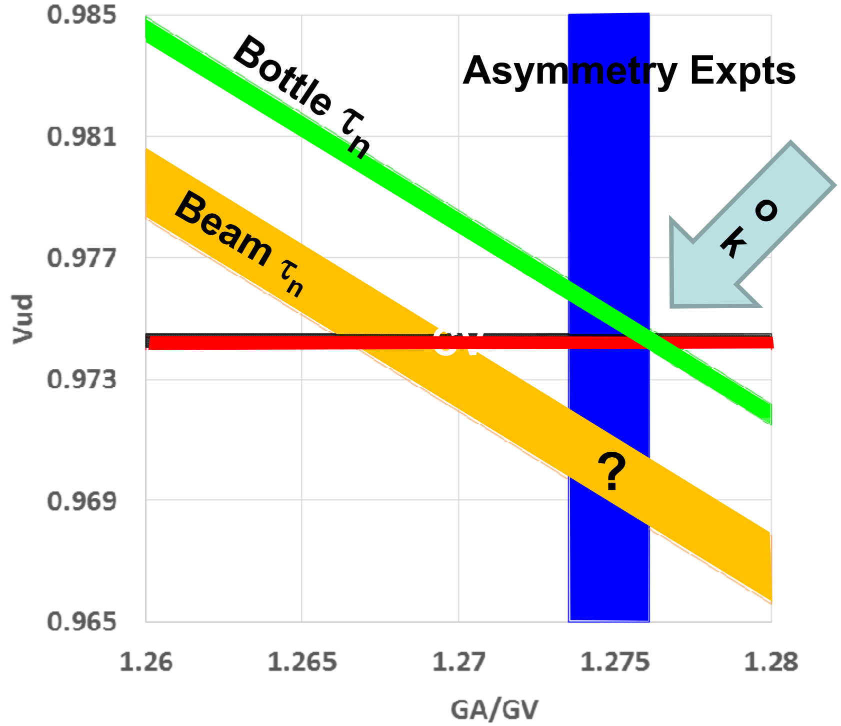


Thanks: Dan Salvat, C. Morris

2017 Picture: Lifetime, Correlations, V_{ud} all painting a very consistent picture now IF we use the "precision" results only

$$A = -\frac{2\lambda(\lambda+1)}{1+3\lambda^2}$$

$$|V_{ud}|^2 = \frac{4908.7\,\mathrm{sec}}{\tau_n\left(1+3\lambda^2\right)}$$



bottle τ_n

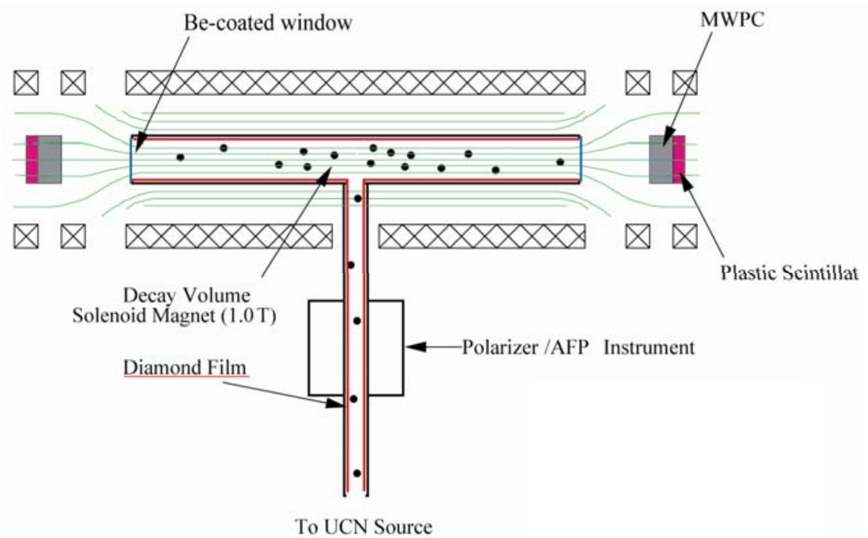
beam τ_n

UCN+beam λ

$0^+ \rightarrow 0^+$ decays

Backup slides

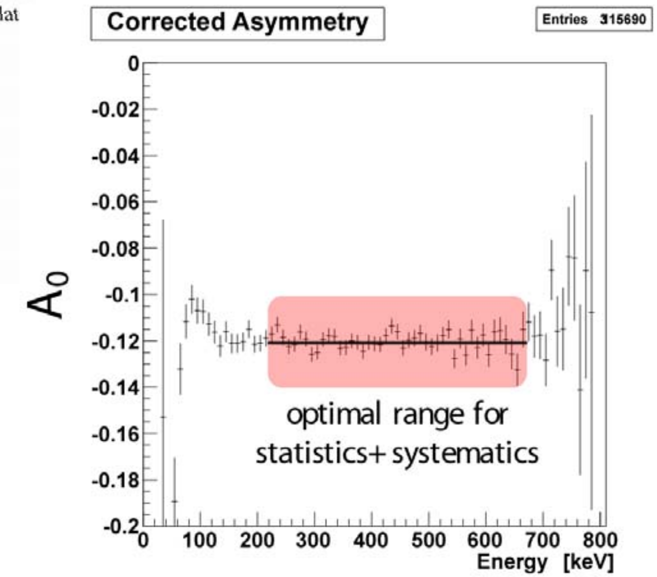
UCNA



- First measurement of angular correlations using UCN (measures correlation between neutron spin and p_β)
- Utilizes first spallation-driven solid deuterium source of UCN

2013 Publication

A_0 = -0.11954(55)$_{stat}$(98)$_{syst}$



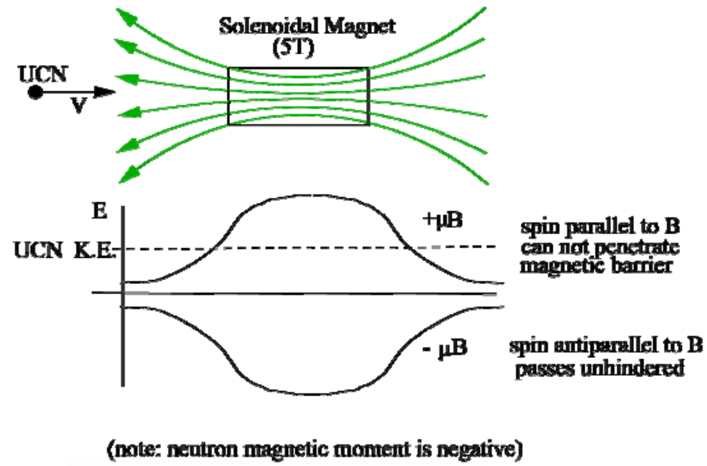
M. P. Mendenhall *et al.*,
Phys. Rev. C 87, 032501(R) (2013)

CENPA
Center for Experimental Nuclear Physics and Astrophysics

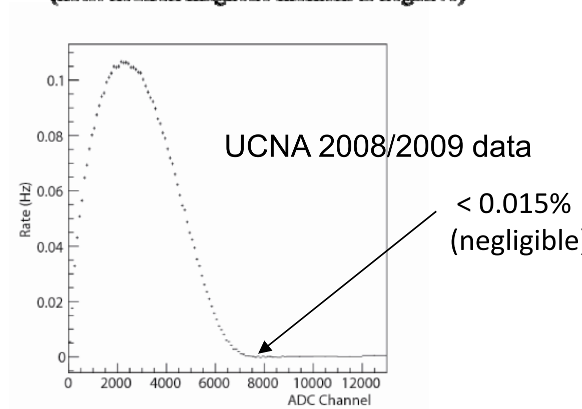
Why UCN?

UCN provide a unique handle on key neutron-related systematic errors.

Polarization: "Potential barrier" polarization demonstrated effective alternative to supermirror/^{3}He cell technology currently with P ≥ 99.5% and uncertainties at or below ~0.35% level, limited by statistics of polarimetry measurements



Neutron generated backgrounds: small number of neutrons and high probability of decay in the cell create negligible beam-generated backgrounds

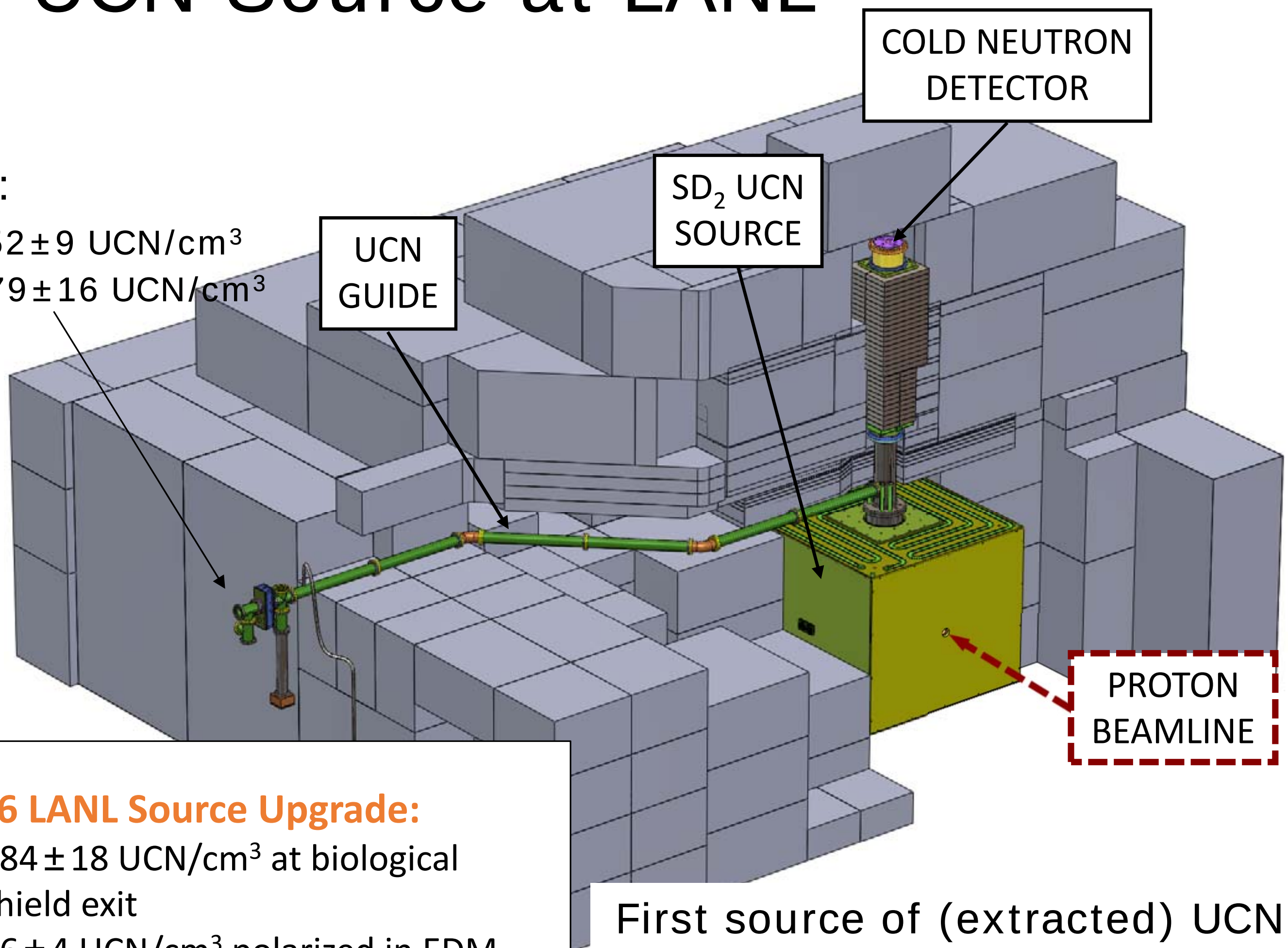


The UCN Source at LANL

2010:

V: 52±9 UCN/cm^3

Mon: 79±16 UCN/cm^3



2016 LANL Source Upgrade:

- 184±18 UCN/cm^3 at biological shield exit
- 36±4 UCN/cm^3 polarized in EDM cell

First source of (extracted) UCN for experiments in US constructed for UCNA at LANL!

Pushing Down the Limits: 2011/2012 and beyond…

Systematic	corr. (%)	unc. (%)
Polarization	+0.67	±0.56
$\Delta_{backscattering}$	+1.36	±0.34
Δ_{angle}	−1.21	±0.30
Energy reconstruction		±0.31
Gain fluctuation		±0.18
Field non-uniformity	+0.06	±0.10
ϵ_{MWPC}	+0.12	±0.08
Muon veto efficiency		±0.03
UCN-induced background	+0.01	±0.02
$\sigma_{statistics}$		±0.46
Theory contributions		
Recoil order [19–21]	−1.71	
Radiative [22]	−0.10	

Polarimetry

2010 method calibrated, but required MC corrections:
add shutter, remove MC corrections

Scattering corrections

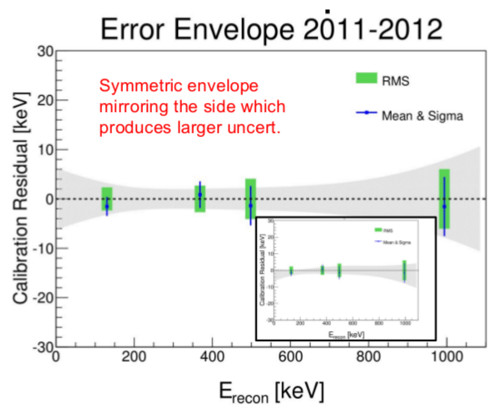
Backscattering limited by foils:
reduce areal density

Energy Reconstruction

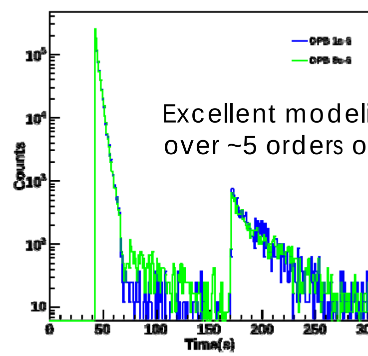
Add more conversion sources, Xe position-dependent gain maps, LED pulser

Analysis of 2011/2012 Data-Set: Current Status

- Present (still blinded uncertainties) which depend on energy cut – total between 0.6 and 0.7% at present
  - Statistical ~0.46%
  - Polarization <~ 0.33% (2010: 0.56)
  - Energy reconstruction ~0.14% (2010: 0.31)
- Significant progress made in calibration (esp. interpreting MWPC signals, and modeling response)
- Polarimetry also improved w/ shutter (raw unc. currently < ~0.05%)
- Unblinding this summer



Preliminary



Sim. vs. data – switcher signals

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Future Prospects

- With LANL UCN source upgrade, can achieve < 0.15% statistics within one run cycle (depends on useful energy window)
- Learned how to use LED pulser signals – should permit further reduction in energy reconstruction errors currently at 0.14% (implementing now for 2011-2013 Fierz analysis)
- Polarimetry now effectively limited by statistics, with 2012 data uncertainties < 0.2% -- source upgrade should permit < 0.1% even without new diagnostic runs and recognized improvements to shutter
- Scattering corrections still under assessment, nominally place at 0.1% level or below – there is enthusiasm within our collaboration to investigate detector and apparatus repairs/upgrades which reduce these corrections further – UCNA+

Conclusion: very promising, R&D needed to settle strategy and projected error budget

Isospin symmetry breaking
(Towner, Hardy, PRC **82**, 065501 (2010))

$$M_F = \sum_{\alpha,\pi} \langle f | \alpha_\alpha^+ | \pi \rangle \langle \pi | \beta_\alpha | i \rangle \qquad \begin{cases} |f\rangle, |i\rangle & \text{A body exact solutions} \\ |\pi\rangle & \end{cases}$$

In the absence of symmetry breaking:

$$M_0 = \sum_{\alpha,\pi} \left| \langle f | \alpha_\alpha^+ | \pi \rangle \right|^2$$

Heaven

Earth

$$\sum_{\alpha,\pi} \langle \bar{f} | \alpha_\alpha^+ | \pi \rangle \langle \pi | \beta_\alpha | \bar{i} \rangle = M_0 \sqrt{1 - \delta_{C1}}$$

$$\sum_{\alpha,\pi} \left| \langle \bar{f} | \alpha_\alpha^+ | \pi \rangle \right|^2 r_\alpha^\pi = M_0 \sqrt{1 - \delta_{C2}}$$

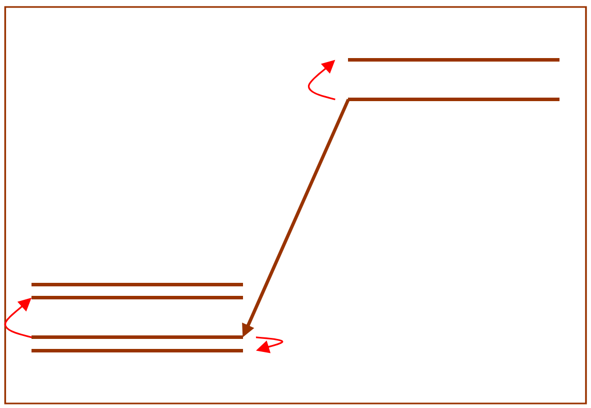
$$\begin{cases} |\bar{f}\rangle, |\bar{i}\rangle & \text{A body approx.} \\ |\pi\rangle & \text{A-1 body approx.} \end{cases}$$

Isospin symmetry breaking: pictorial representation

δ_{C1}

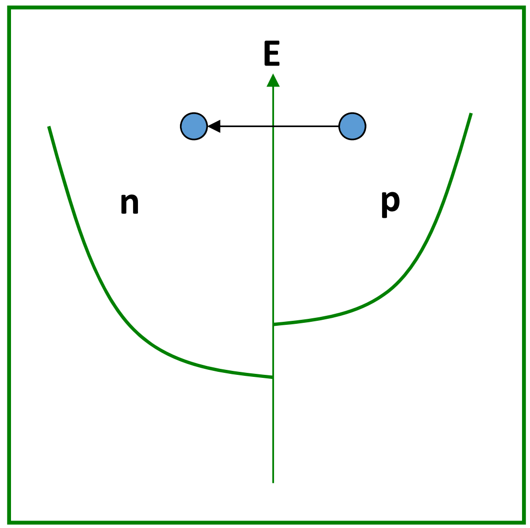
1) `shell-model' configurations get mixed due to ISB interaction

$$|\psi\rangle = |I, I_z\rangle + \varepsilon |I \pm 1, I_z\rangle$$



δ_{C2}

2) decaying proton and daughter neutron sample different mean fields.



The Damgaard (NPA **130**, 233 (1969)) model is illuminating:

- Ignore δ_{C1}
- Use harmonic oscillator wave functions
- Assume all difference between parent neutron and daughter proton is due to proton moving in the (uniform charge) Coulomb field.

Yields a simple expression: $\delta_C \approx 0.26 Z^2 A^{-2/3}(n+1)(n+l+3/2)$

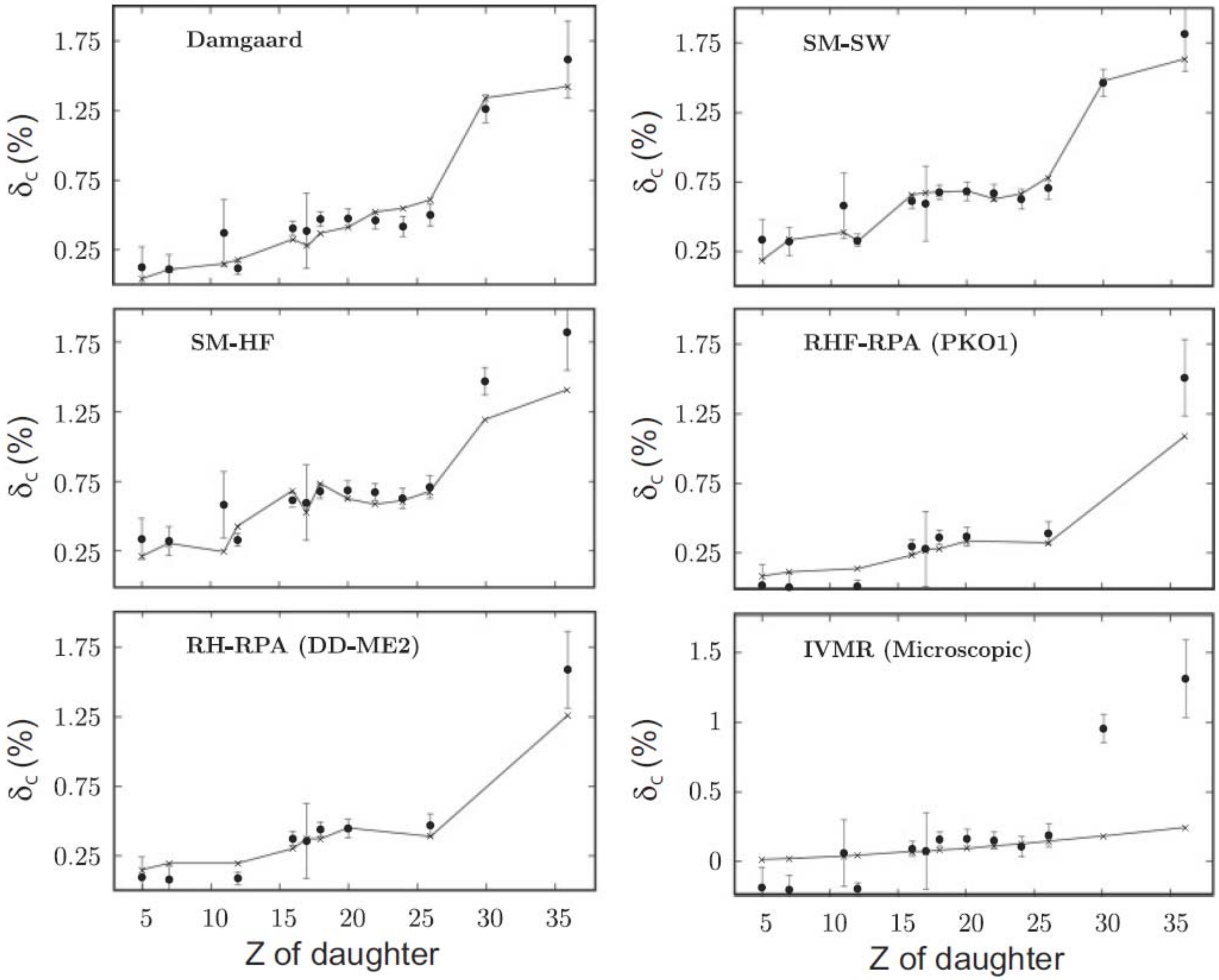
This model, while primitive, does remarkably well. Shows what is the most important effect.

Hardy, Towner propose inverting the relation

$$Ft = ft\left(1+\delta_R^{'}\right)\left(1+\delta_{NS}-\delta_C\right) \quad \Rightarrow \quad \delta_C = 1+\delta_{NS} - \frac{\langle Ft \rangle}{ft\left(1+\delta_R^{'}\right)}$$

to test models

Hardy, Towner, PRC **82**, 065501 (2010)

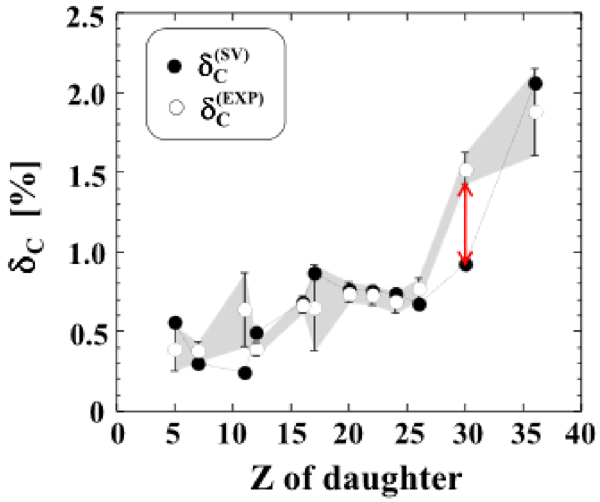


Parent nucleus	Experimental			δ_C (%)					
	ft value (s)	δ'_R (%)	δ_{NS} (%)	Damgaard	SM-SW	SM-HF	RHF-RPA	RH-RPA	IVMR
$T_z = -1$									
^{10}C	3041.7(43)	1.679(4)	−0.345(35)	0.046	0.175	0.225	0.082	0.150	0.008
^{14}O	3042.3(11)	1.543(8)	−0.245(50)	0.111	0.330	0.310	0.114	0.197	0.015
^{22}Mg	3052.0(70)	1.466(17)	−0.225(20)	0.153	0.380	0.260			0.031
^{34}Ar	3052.7(82)	1.412(35)	−0.180(15)	0.285	0.665	0.540	0.268	0.376	0.064
$T_z = 0$									
^{26}Al	3036.9(9)	1.478(20)	0.005(20)	0.182	0.310	0.440	0.139	0.198	0.041
^{34}Cl	3049.4(11)	1.443(32)	−0.085(15)	0.326	0.650	0.695	0.234	0.307	0.064
^{38}K	3051.9(5)	1.440(39)	−0.100(15)	0.370	0.655	0.745	0.278	0.371	0.077
^{42}Sc	3047.6(12)	1.453(47)	0.035(20)	0.414	0.665	0.640	0.333	0.448	0.091
^{46}V	3049.5(8)	1.445(54)	−0.035(10)	0.524	0.620	0.600			0.106
^{50}Mn	3048.4(7)	1.444(62)	−0.040(10)	0.550	0.655	0.620			0.122
^{54}Co	3050.8(10)	1.443(71)	−0.035(10)	0.613	0.770	0.685	0.319	0.393	0.139
^{62}Ga	3074.1(11)	1.459(87)	−0.045(20)	1.339	1.48	1.21			0.175
^{74}Rb	3084.9(77)	1.50(12)	−0.075(30)	1.422	1.63	1.42	1.088	1.258	0.235
χ^2/n_d (statistical experimental uncertainties only)				8.3	1.2	8.3	7.2	6.0	48
Confidence level (%)				0	26	0	0	0	0
χ^2/n_d (uncertainties on experiment, δ'_R and δ_{NS})				1.7	0.4	2.2	2.7	2.1	11
χ^2/n_d (uncertainties on experiment, δ'_R, δ_{NS}, and δ_C)				0.9	0.3	1.1	1.6	1.3	4.5

From Hardy, Towner, PRC **82**, 065501 (2010)

Notice only model that fits well all data is SM-SW.

Density-functional theory calculations:
Satuła, Dobaczewski, Nazarewicz, Rafalski,
PRL **106**, 132502 (2011)



A variation on the potential:
Satuła, Dobaczewski, Nazarewicz, Werner,
PRC **86**, 054316 (2012)

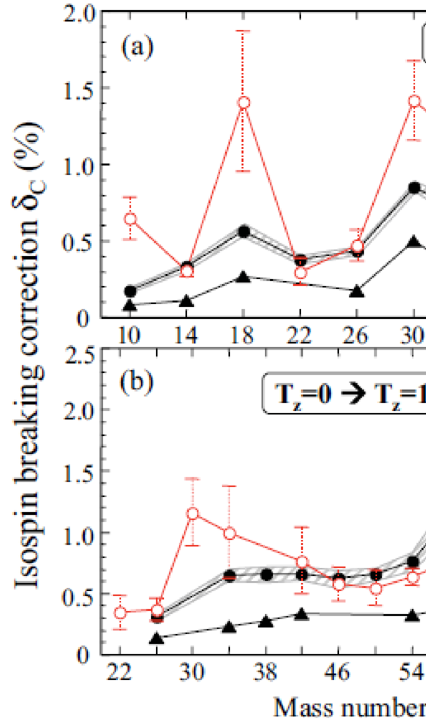


FIG. 6. (Color online) ISB corrections $0^+\beta$ decays calculated for (a) $T_z = -1 \rightarrow T$ $T_z = 1$ transitions. Our adopted values fron with error bars) are compared with ISB corrections from Refs. [2] (filled circles; shaded band marks errors) and [12] (filled triangles).

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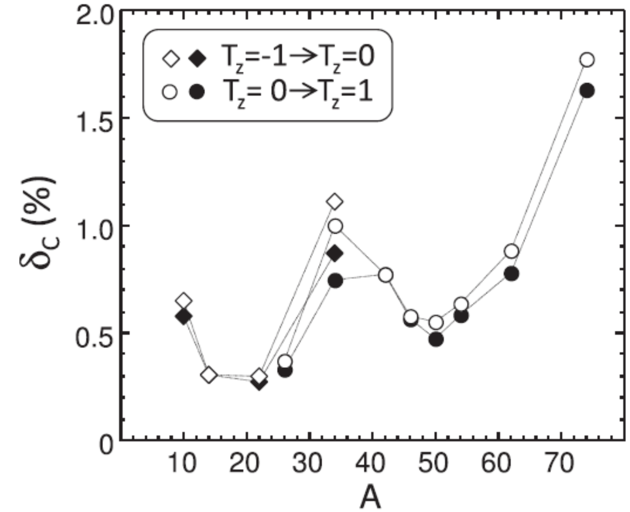
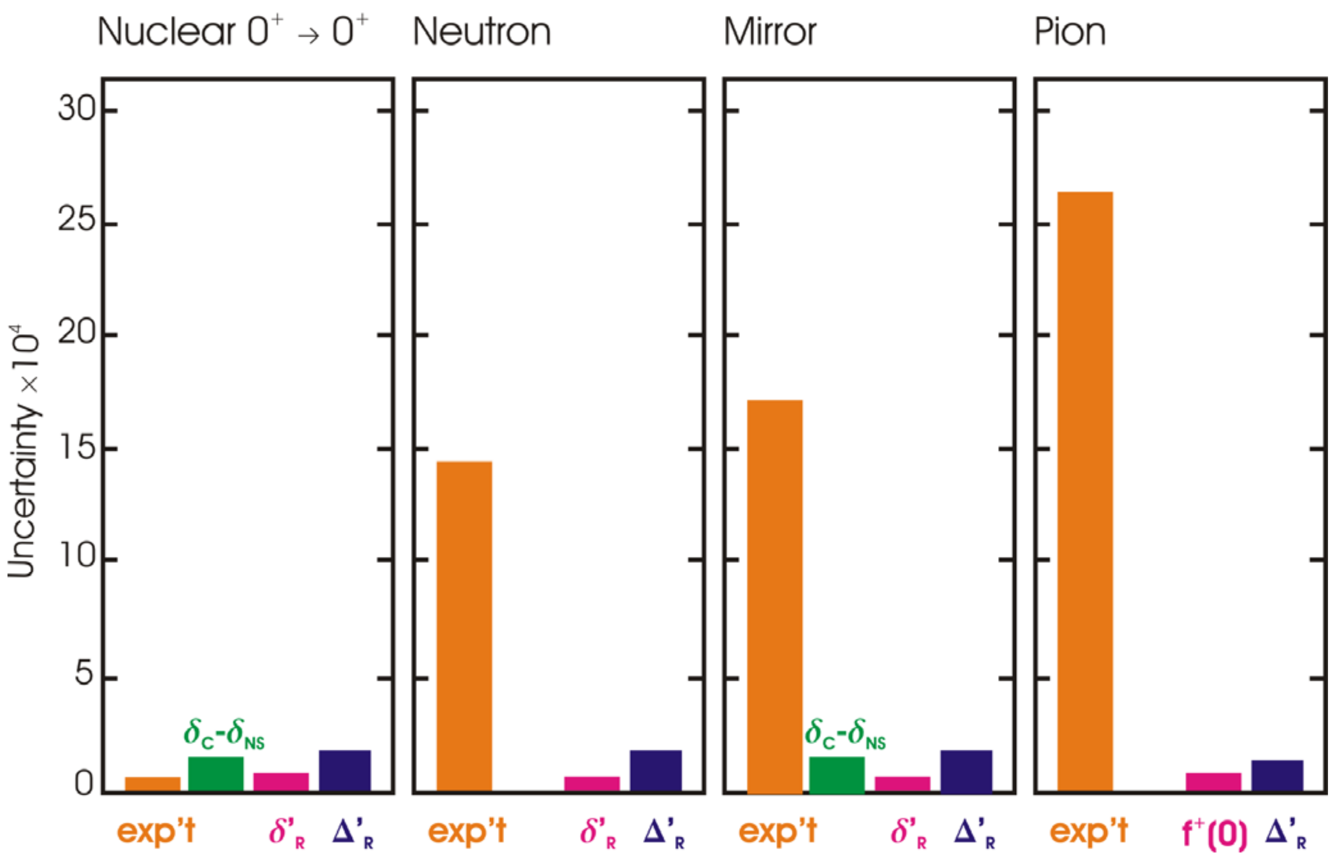


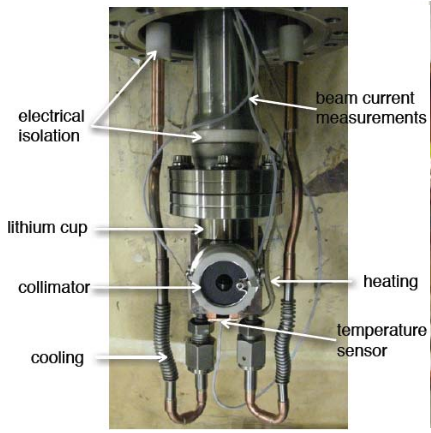
Figure 10. Comparison of the ISB corrections to the 12 canonical superallowed $0^+ \rightarrow 0^+$ transitions calculated in [30] (open symbols) and in [60] (filled symbols). In the latter calculations, the 0^+ states projected from $|\varphi_X\rangle$, $|\varphi_Y\rangle$, and $|\varphi_Z\rangle$ configurations were mixed dynamically by solving the HWG equation. In the former, matrix elements were calculated independently for each orientation and averaged afterwards.

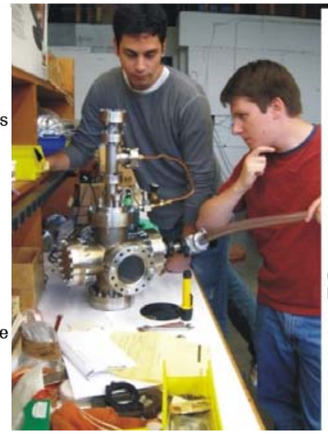
V_{ud} from nuclear, neutron, pion

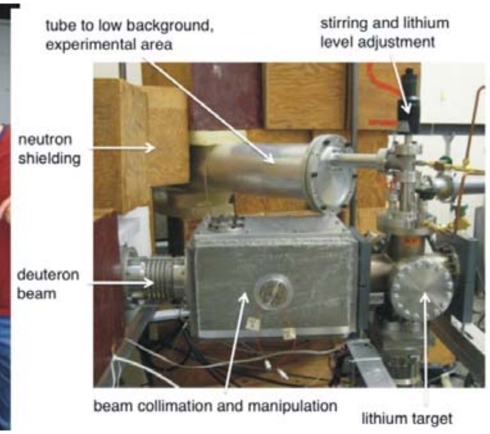
From Hardy, Towner
Ann. Phys. **525**, 443 (2013)



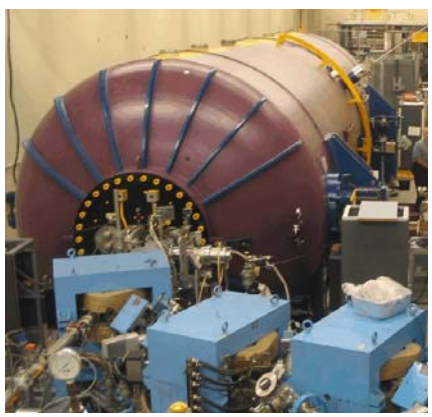
Now ~10^{10} atoms of ^{6}He/s at Seattle via ^{7}Li(d,^{3}He)^{6}He







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



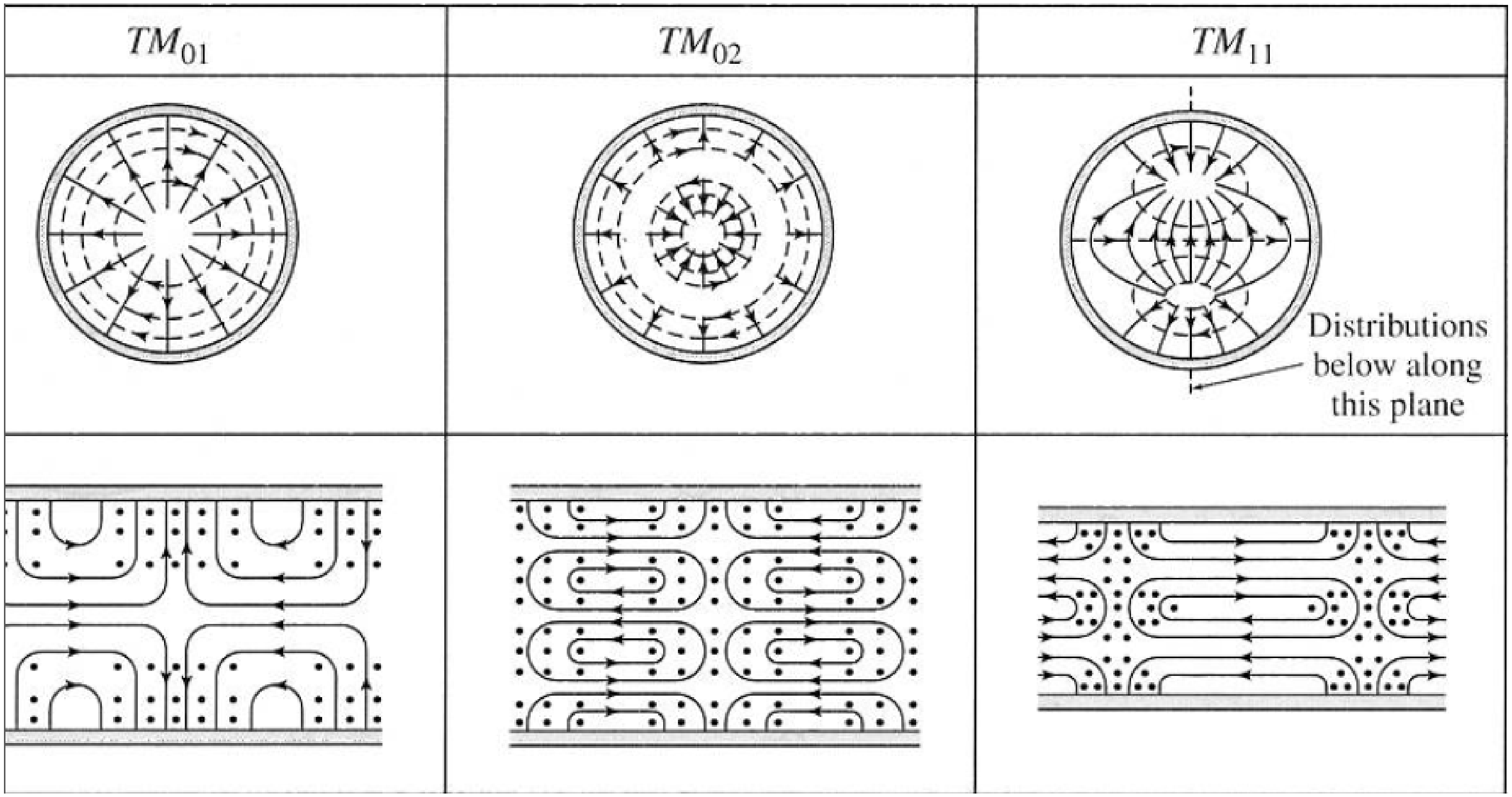
Intense source of 6He at CENPA.

Statistics not a problem.

$$E_{thres} = 1\,\text{keV} \quad \Rightarrow \Delta b \approx 8/\sqrt{N}$$

$$E_{thres} = 1150\,\text{keV} \Rightarrow \Delta b \approx 29/\sqrt{N}$$

TM modes
for cylindrical guides



Waveguides: each mode propagates above a certain *cut-off freq*.

$$\left(\nabla^2 + \frac{\omega^2}{c^2}\right)\begin{Bmatrix}\boldsymbol{E}\\ \boldsymbol{B}\end{Bmatrix} = 0$$

$$\left.\begin{matrix}\boldsymbol{E}\\ \boldsymbol{B}\end{matrix}\right\} = \begin{cases}\boldsymbol{E}(x,y)e^{\pm ikz - i\omega t}\\ \boldsymbol{B}(x,y)e^{\pm ikz - i\omega t}\end{cases}$$

$$\left[\nabla_t^2 + \left(\frac{\omega^2}{c^2} - k^2\right)\right]\begin{Bmatrix}\boldsymbol{E}(x,y)\\ \boldsymbol{B}(x,y)\end{Bmatrix} = 0$$

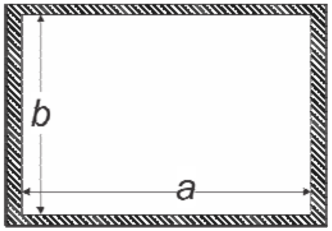
$$\frac{\omega^2}{c^2} - k^2 \equiv \gamma^2$$

$$\boldsymbol{E} = \boldsymbol{E}_z + \boldsymbol{E}_t$$

TM waves: $\boldsymbol{E}_t = \pm \frac{ik}{\gamma^2}\boldsymbol{\nabla}_t\psi$

TE waves: $\boldsymbol{H}_t = \pm \frac{ik}{\gamma^2}\boldsymbol{\nabla}_t\psi$

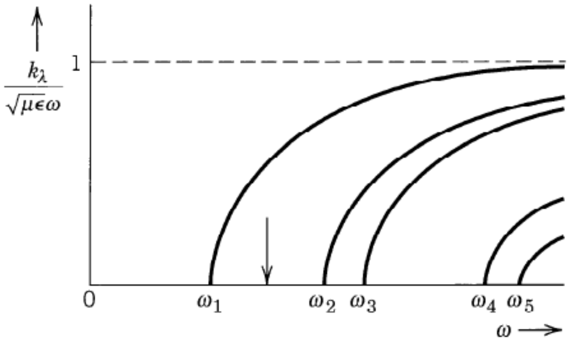
$$(\nabla_t^2 + \gamma^2)\psi = 0$$



$$\psi_{m,n}(x,y) = H_0 \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right)$$

$$k = \frac{\sqrt{\omega^2 - \omega_c^2}}{c}$$

There are *cutoff frequencies* for each mode



Cutoff frequencies for d=1cm guide. For 0.455" divide by 1.1557.

Active in 18-24 GHz: $TE_{1,1}$, $TM_{0,1}$ (but $TM_{0,1}$ doesn't couple to WR42)

n	$f^{TE}_{n,1}$	$f^{TE}_{n,2}$	$f^{TE}_{n,3}$	$f^{TM}_{n,1}$	$f^{TM}_{n,2}$	$f^{TM}_{n,3}$
0	36.57	67.00	97.15	22.97	52.71	82.64
1	17.58	50.90	81.51	36.59	67.00	97.15
2	29.16	64.03	95.21	49.03	80.38	110.96

Only the TE11 mode transmits