Fundamental Symmetries Experiments: Neutron and Nuclear Beta Decay

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Neutrinos and Fundamental Symmetries LRP Town Meeting

Outline

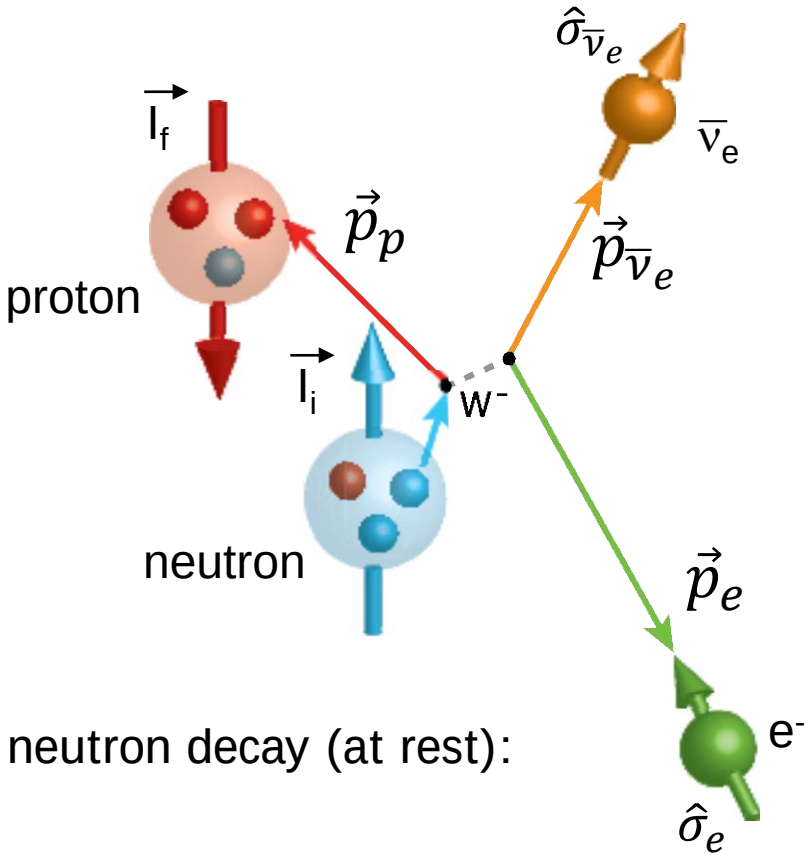
- Review motivation and observables
- Superallowed decays
- Angular correlations measurements and beta spectroscopy on Nuclei
- Neutron decay measurements

Theory Synopsis (from Cirigliano's talk)

Motivation Strong

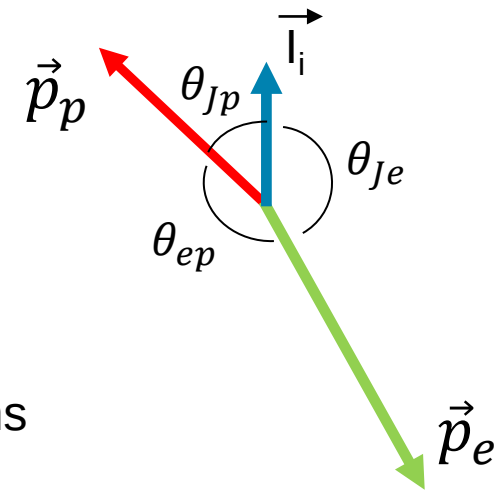
- CKM unitarity test is an unmatched constraint on (V,A) BSM physics
- Extracting V_{ud} from neutrons or mirror nuclei can check nuclear structure corrections for $0^+ \rightarrow 0^+$ decays (this comparison is also sensitive to exotic couplings)
- Fierz terms b (and b_ν) offer a window on LHC and post-LHC sensitivity, need $\sim 10^{-3}$ level and below to improve (current best constraints on S from $0^+ \rightarrow 0^+$, T from combined nuclear beta-decay data set)
- A high precision value for the neutron lifetime is a critical input for BBN predictions for ^{4}He
- Interest in recoil order terms and symmetries of charged current

Beta Decay Observables



neutron decay (at rest):

Don't observe final state spins or neutrino



Many accessible observables

$\{\vec{I}_i, \vec{I}_f, \vec{p}_p, E_p, \hat{\sigma}_e, \vec{p}_e, E_e\}$

- **Decay rate**
- **Energy spectrum**: p, e
- Directional distribution (**angular correlations**)

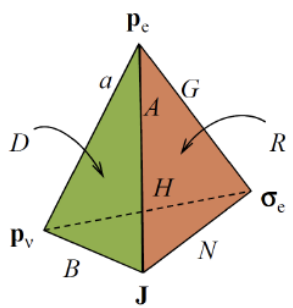
Use momentum consv: $\vec{p}_{\bar{\nu}_e} = -\vec{p}_p - \vec{p}_e$

Beta Decay Parameters

Jackson, Treiman and Wyld (Phys. Rev. **106** and Nucl. Phys. **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu\text{ correlation}} + \overbrace{b\frac{\Gamma m_e}{E_e}}^{\text{Fierz term}}\right.$$

$$\left. + \frac{\langle\vec{I}\rangle}{I}\cdot\left[\underbrace{A_\beta\frac{\vec{p}_e}{E_e}}_{\beta\text{ asym}} + \underbrace{B_\nu\frac{\vec{p}_\nu}{E_\nu}}_{\nu\text{ asym}} + \underbrace{D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}}_{T\text{-violating}}\right]\right) + \ldots$$



US program has on-going or planned efforts to measure:

(1) **Decay rates and β-spectra** ($G_F V_{ud}, \xi, b$)

(2) **Unpolarized angular correlations** ($a_{\beta\nu}, b$)

(3) **Polarized angular correlations** (A_β, B_ν, b, b_ν)

(4) New program to measure **circular polarization asymmetry**

Useful Decay Systems

Requirements for fundamental symmetries:

Small nuclear structure corrections (*e.g.* isobaric analog states)
Calculable recoil order effects (low A, **theory input important**)
Experimentally tractable

Nuclei:

- many decay systems to **check systematics** of experimental technique and structure corrections
- systems available to **optimize sensitivity** for particular physics (selection rules, endpoint energy, transition moments, A value)

$0^+ \rightarrow 0^+$ superallowed decays, mirror decays, & pure GT decays

Neutron:

- **no multi-nucleon, nuclear structure effects**
- very clean decay, many observables
- Direct relevance for astrophysics (BBN, solar fusion, etc…)

At least 10 US Laboratories involved, 34 US groups

Berkeley UNIVERSITY OF CALIFORNIA
NIST
TUNL
The University of Chicago
NORTHWESTERN UNIVERSITY 1851
CYCLOTRON INSTITUTE TEXAS A&M UNIVERSITY
NSCL
Argonne NATIONAL LABORATORY
OAK RIDGE National Laboratory
Lawrence Livermore National Laboratory
UNIVERSITY OF VIRGINIA
ASU
CALIFORNIA INSTITUTE OF TECHNOLOGY
UNIVERSITY OF WASHINGTON 1861
IDAHO STATE UNIVERSITY
LSU LOUISIANA STATE UNIVERSITY
VT
UK
Los Alamos NATIONAL LABORATORY EST. 1943
BERKELEY LAB
UNM
UNIVERSITY OF MICHIGAN

Superallowed Decays: Overview

- Current limits already **exceed** scales accessible by high luminousity LHC
- Work ongoing with incremental progress on inputs to data-set, led by Hardy and Towner and TAMU group
- Central focus of current work is tests of the **structure dependent corrections**
- Effort in Europe concentrating on mirror decays and the neutron (Ganil group: ion trapped ^{35}Ar, other species targeting ~0.05% in V_{ud}, HUJI: optically trapped ^{19}Ne)

Superallowed Decays

Figures and plots courtesy of John Hardy

Decay between 0^+ isobaric analog states: only vector coupling contributes and SM matrix elements known very precisely known, so measurement of absolute decay rate provides the vector coupling

Inputs:

Decay rates, Branching Ratios, Q Values

G_F from μ decay & Theoretical Corrections

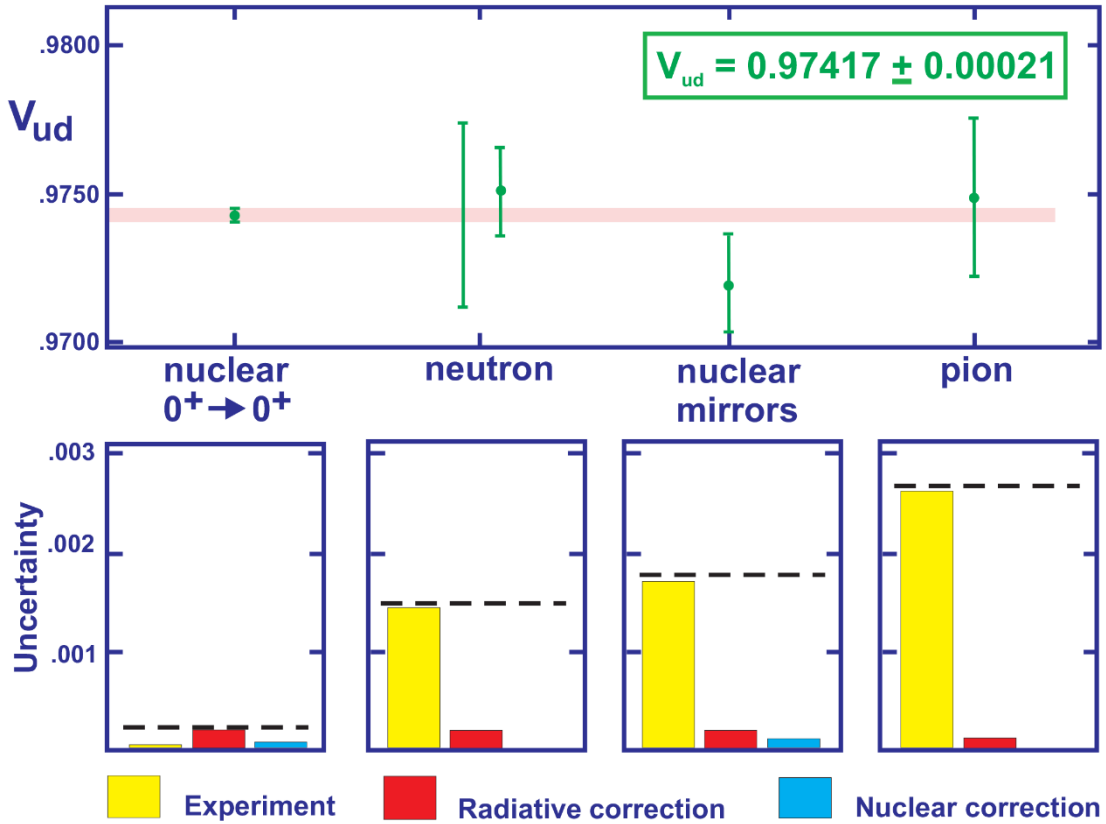
Q Values – trapping groups in US

LEBIT (NSCL), CPT (Argonne) and (Brodeur at ND)

Most precise value for V_{ud}: $V_{ud}^2 = G_V^2/G_\mu^2 = 0.94900 \pm 0.00042$

Test of CKM unitarity: $V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99992 \pm 0.00048$

V_{ud} Status



T=1 systems: ongoing incremental improvements…
(Hardy and Towner)

Intensive ongoing investigations for isospin symmetry-breaking corrections

e.g. T=1 mirror cases

Structure Dependent Corrections: T=1, $0^+ \rightarrow 0^+$ Decays

INCLUDING RADIATIVE AND ISOSPIN-SYMMETRY-BREAKING CORRECTIONS

$$\mathcal{F}t = ft\,(1 + \delta_R')[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

$f(Z, Q_{EC})$ ~1.5%

f(nuclear structure) 0.3-1.5%

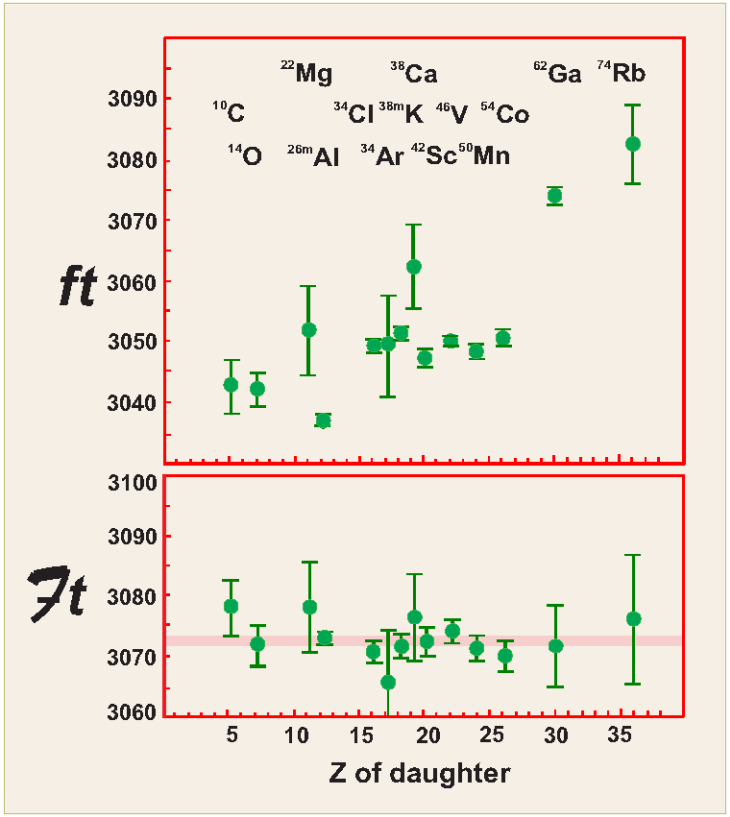
f(interaction) ~2.4%

After all corrections, should be the same number!

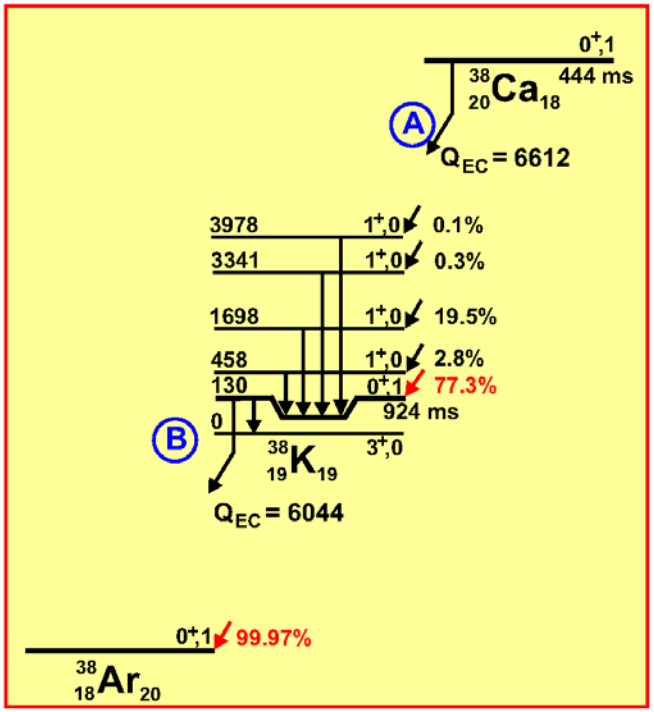
THEORETICAL UNCERTAINTIES 0.05 – 0.10%

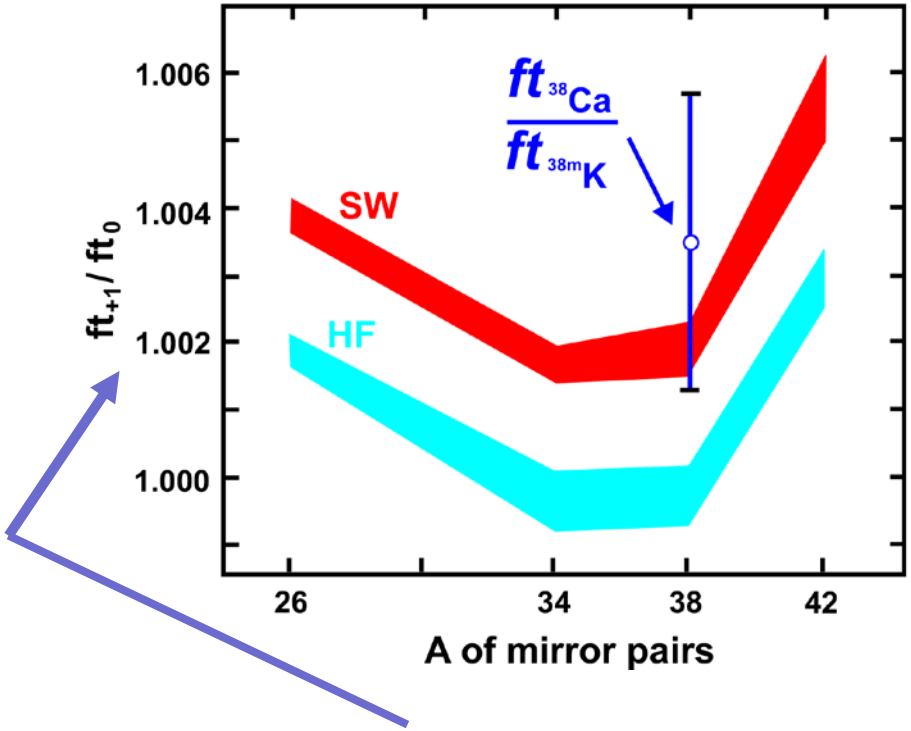
Test for accuracy of structure corrections: measured Ft values independent of Z (CVC)

Systematic shifts? Consistent definition of isospin? Questions raised but no serious challenges…



Some Tests of Structure-Dependent Corrections





Test of accuracy: expected ft values almost identical for mirror decays, compare measure ft values for ^{38}Ca to ^{38}K to those predicted by candidate theory

Very large corrections expected 4.6(5)% and measured 5.3(9)% in ^{35}Cl

Phys. Rev Lett. **107**, 182301 (2011)

Angular Correlations in Nuclear Systems

- Ion trap measurements of the beta-neutrino correlations, $a_{\beta\nu}$
- Laser trap measurements of A_β, $a_{\beta\nu}$
- Spin-asymmetry

Ion recoil spectrum measurements of $a_{\beta\nu}$ before 1999:

Highest precision:
1% ^{6}He, 5% n

Decay	Ji	Jf	a_{expt}	Reference	Year
$n \rightarrow pe^-\bar{\nu}_e$	$\frac{1}{2}$	$\frac{1}{2}$	-0.1017 ± 0.0051	Stratowa *et al.*	1978
$^{19}Ne \rightarrow {}^{19}Fe^+\nu_e$	$\frac{1}{2}$	$\frac{1}{2}$	0.00 ± 0.08	Allen *et al.*	1959
$^{35}Ar \rightarrow {}^{19}Cle^+\nu_e$	$\frac{3}{2}$	$\frac{3}{2}$	0.97 ± 0.14	Allen *et al.*	1959
$^6He \rightarrow {}^6Lie^-\bar{\nu}_e$	0	1	-0.3343 ± 0.0030	Johnson *et al.*	1963
$^{23}Ne \rightarrow {}^{23}Nae^-\bar{\nu}_e$	$\frac{3}{2}$	$\frac{3}{2}$	-0.33 ± 0.03	Johnson *et al.*	1963

Overview (post-2000) of β-ν correlation projects

(nuclei)

Parent	Technique	Team, laboratory	Remarks
^{6}He	Spectrometer	ORNL	$a = -0.3308(30)$
^{32}Ar	Foil; p recoil	UW-Seattle, ISOLDE	$\tilde{a} = 0.9989(52)(39)$
^{38m}K	MOT	SFU, TRIUMF	$\tilde{a} = 0.9981(30)(34)$
^{21}Na	MOT	Berkeley, BNL	$a = 0.5502(38)(46)$
^{6}He	Paul trap	LPC-Caen, GANIL	$\tilde{a} = -0.3335(73)(75)$
^{6}He	Paul trap	LPC-Caen, GANIL	Analysis under way
^{8}Li	Paul trap; $\beta\alpha$	ANL	$a = -0.3307(60)(67)$
^{35}Ar	Paul trap	LPC-Caen, GANIL	First data June 2011
^{35}Ar	Penning trap	Leuven, ISOLDE	First data June 2011
^{19}Ne	Paul trap	LPC-Caen, GANIL	Ready to take data
^{6}He	EIBT	Weizmann, SOREQ	In progress
^{6}He	MOT	ANL, CENPA	In progress
Ne	MOT	Weizmann, SOREQ	In progress
^{32}Ar	Penning trap	Texas A&M	In preparation

at and below 1% level

N.S. & O. Naviliat-Cuncic, Physica Scripta T152 (2013) 014018

Angular Correlations in Nuclear Systems

- Ion trap measurements of the beta-neutrino correlations, $a_{\beta\nu}$
- Laser trap measurements of A_β, $a_{\beta\nu}$

All experiments target 0.1% precision and sensitivity to LHC scale effects or recoil order terms

How to improve precision:

- Produce highly localized, "massless" source

  Ion and optical traps ideal

- Reduce/eliminate scattering effects from grids, apertures, detectors

  Use position sensitive reconstruction, low mass, low Z components

- Eliminate backgrounds

  Two-stage trapping, pure samples, coincidence signals, event reconstruction

Common elements of current expts

Note: actually measure

$$\tilde{a}_{\beta\nu} = \frac{a_{\beta\nu}}{1 + \frac{m_e \Gamma}{E} b}$$

Iteration and R&D essential: Evaluate performance→eliminate sources of systematic error→ rachet up source strength→improve limit

Angular Correlations: Summary

Species	Decay	Method	Corr.	Corr. unc	Fierz unc	Group
^{8}Li	GT	Ion trap	$\tilde{a}_{\beta\nu}$	0.1%	1%	ANL-LLNL
^{32}Ar	F	Ion trap	$\tilde{a}_{\beta\nu}$	0.1%	0.1%	TAMU
^{37}K	F/GT	MOT	$\tilde{A}_{\beta}$	0.1%		TRINAT-TAMU
^{6}He	GT	MOT	$\tilde{a}_{\beta\nu}$	0.1%	0.01%	UW/CENPA-ANL
^{6}He	GT	spectr			<0.1%	UW/CENPA-ANL
^{6}He	GT	spectr			0.1%	NSCL

^{8}Li (ANL-LLNL): Current $\tilde{a}_{\beta\nu}$ precision ~ 1%, ^{8}B neutrino spectrum and recoil terms with (^{8}B & ^{8}Li) also planned

^{32}Ar (TAMU): Under construction, in operation early in LRP period
Ideal configuration for beta energy measurements ($a_{\beta\nu}$ and spect)

^{37}K (TRINAT-TAMU): *In situ* polarimetry precision at 0.5%, target for A_{β} 0.1%

^{6}He (UW): most intense 6He source developed, δb < 0.1%
--β spectroscopy R&D**: RXB** and project 8

^{6}He (NSCL): spectroscopy by implantation

Spin-asymmetry (NSCL): under construction, very strong constraints on RHC

Angular Correlations in Ion Traps

Impact and competing measurements

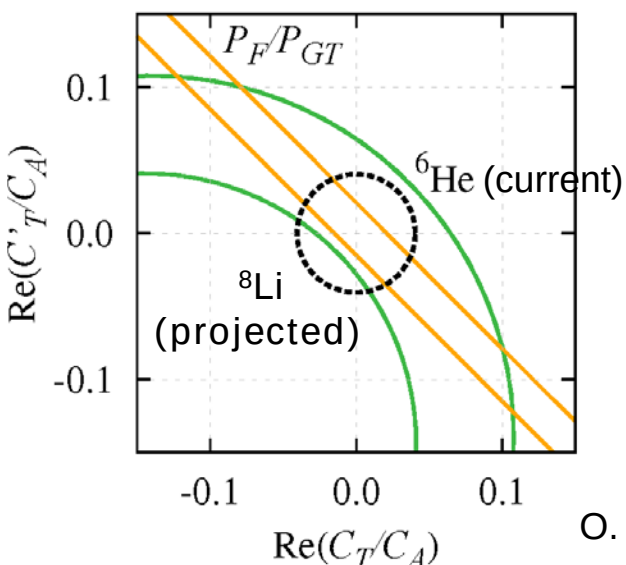
- ^{8}Li decays (GT) in an rf-trap (ANL-LLNL)

Integrated $\tilde{a}_{\beta\nu}$ constrains T→ ^{6}He similar (cross-check vital), ^{8}B neutrino spectrum and ^{8}Li/^{8}B recoil order study unique

- ^{32}Ar (F) decay in an open Penning trap (TAMU)

Integrated $\tilde{a}_{\beta\nu}$ constrains S→ ^{38m}K (TRINAT) provides similar S constraints, high B field, open trap for b from spectroscopy unique

Integral $\tilde{a}_{\beta\nu}$ sensitivity ∝ $\left|\frac{C_T}{C_A}\right|^2$

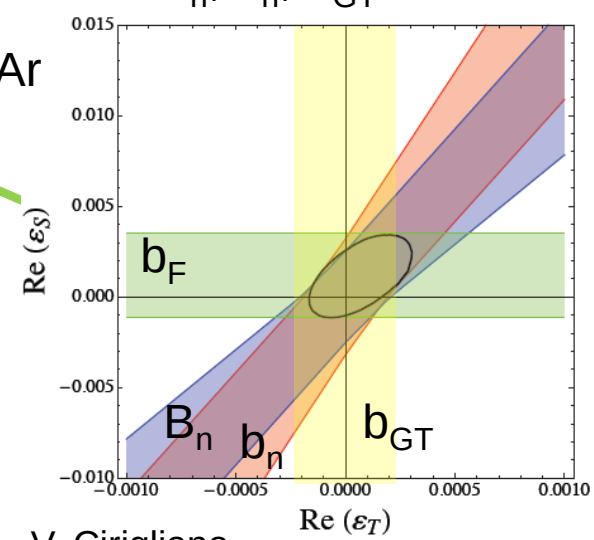


O. Naviliat-Cuncic

b_F at 0.1% from ^{32}Ar would cut allowed range by ~2!

Analysis of recoil terms.req'd..

B_n, b_n, b_{GT} ~0.1%



V. Cirigliano

$\beta^- - \bar{\nu}_e$ Correlation in Ion-trapped ^{8}Li (LLNL-ANL)

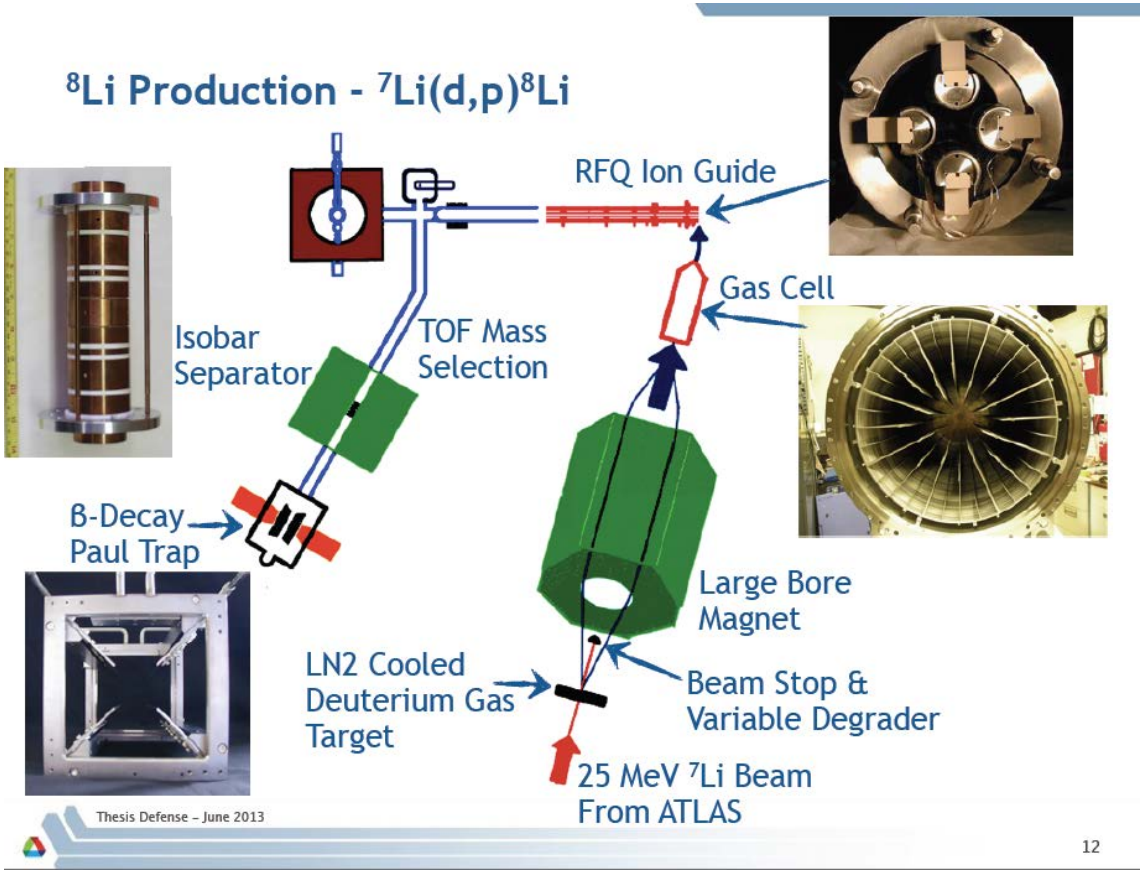
Figures from N. Scielzo

$^8\mathrm{Li} \rightarrow {}^8\mathrm{Be}^* + \beta^- + \nu$

$\hookrightarrow \alpha + \alpha$

***Q* ≈ 13 MeV** (broad ^{8}Be* state at 3 MeV)

***t*$_{1/2}$ = 0.840 sec**



Production: ATLAS facility at Argonne National Laboratory, utilizing **FRIB** technology

$2^+ \rightarrow 2^+$, ΔT=1 decay essentially pure Gamow-Teller

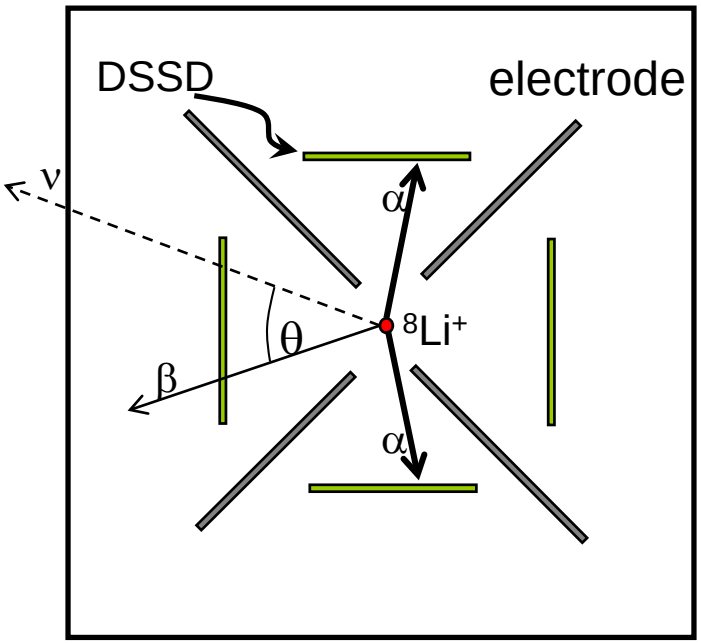
- only axial vector and tensor contribute
- Fermi admixture is only $(5.0\pm1.5)\times10^{-4}$ (R.B. Wiringa *et al.*, PRC **88**, 044333 (2013)).

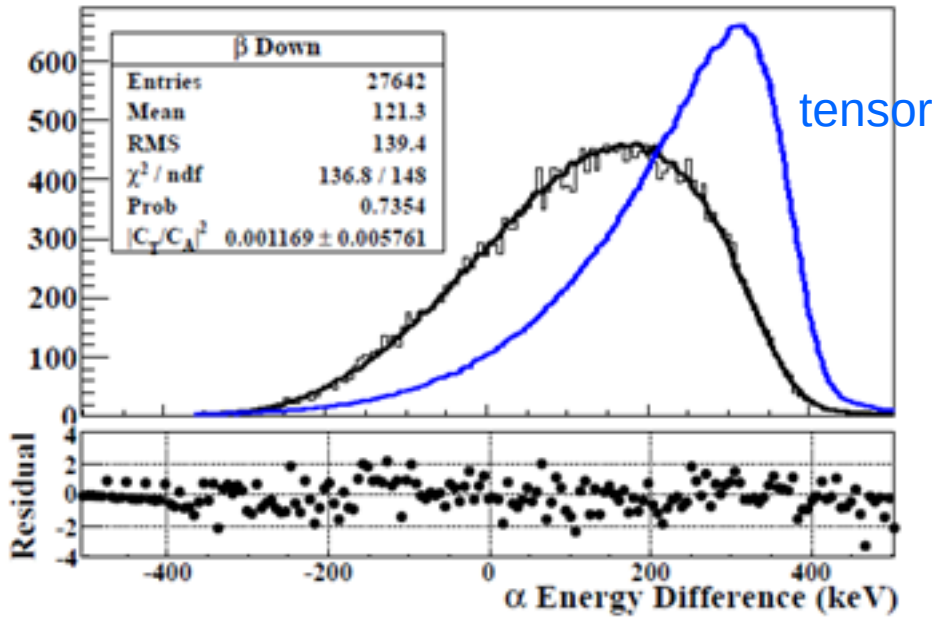
^{8}Li Decay

"Pure" Gamow-Teller decay

a_{SM} = -1/3

Reconstruct $\vec{p}_{recoil}$ from $\vec{p_\alpha} + \vec{p_\alpha}$





$$|C_T/C_A|^2 = 0.0018 \pm 0.0036_{stat} \pm 0.0041_{syst}$$

$$a_{\beta\nu} = -0.3321 \pm 0.0036$$

He buffer gas cools to 0.1 eV, trap ~ 1mm

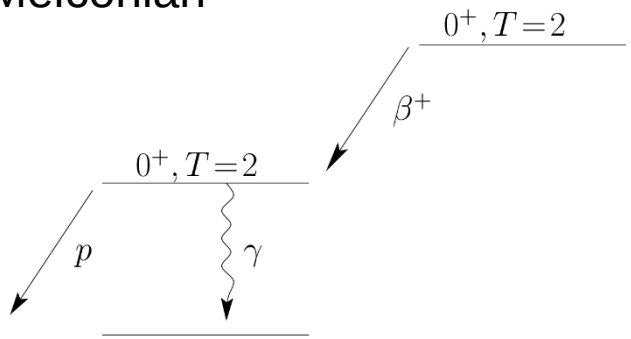
M.G. Sternberg, PhD Thesis, UChicago (2013)
M.G. Sternberg *et al.*, to be submitted to Phys. Rev. Lett. (2014)

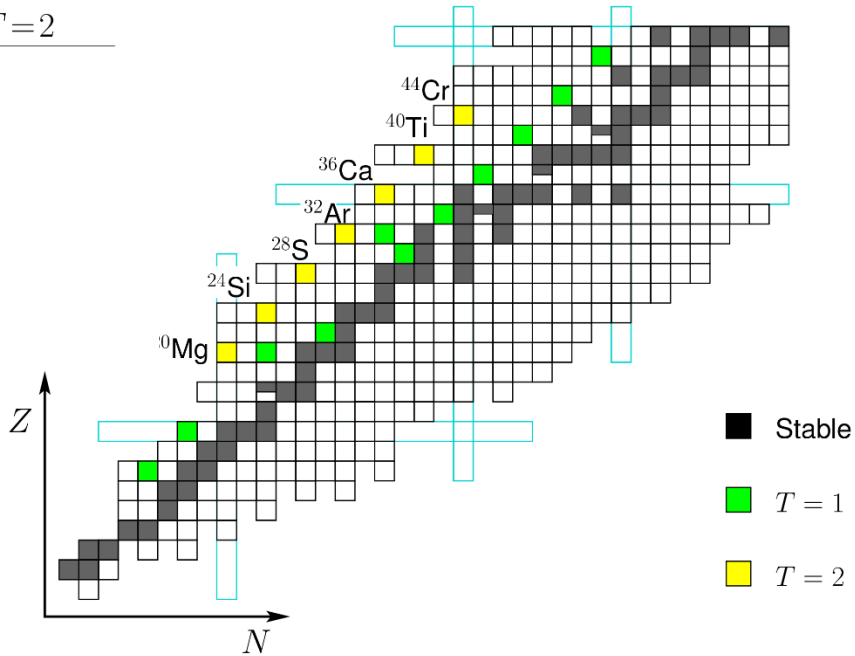
Immediate goal: $\left|\frac{C_T}{C_A}\right|^2$<0.001, improved beta detection for measurement of b ~0.01

Longer term: **^{8}B neutrino spectrum**, CVC and recoil order terms (^{8}Li/^{8}B)

$\beta^+ - \upsilon_e$ Correlation in ^{32}Ar Decay in an Open Penning Trap

Figures from D. Melconian



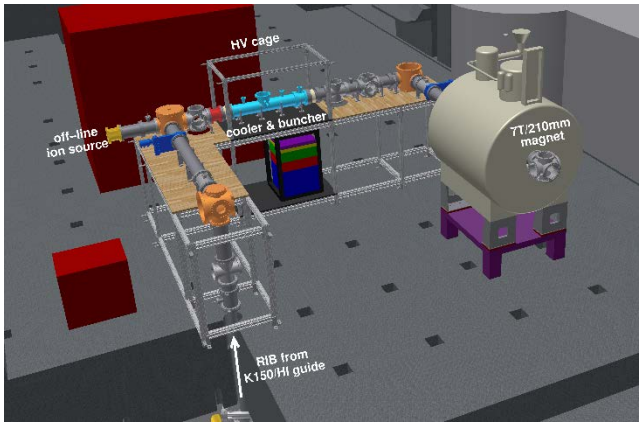


Generic decay scheme:
decay to particle-unstable level

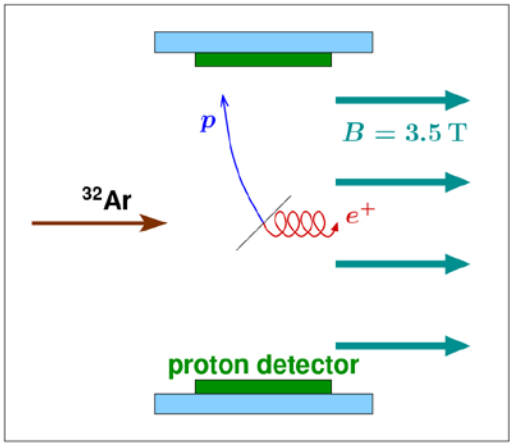
Delayed proton inherits kinematic information of beta-decay leptons -- Doppler shift of proton energy sensitive to $\tilde{a}_{\beta\nu}$

^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar, ^{36}Ca, ^{40}Ti

Reasonable production rates at TAMU facility!



^{32}Ar Decay



VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Positron-Neutrino Correlation in the $0^+ \rightarrow 0^+$ Decay of ^{32}Ar

E. G. Adelberger,[1] C. Ortiz,[2] A. García,[2] H. E. Swanson,[1] M. Beck,[1] O. Tengblad,[3] M. J. G. Borge,[3] I. Martel,[4] H. Bichsel,[1] and the ISOLDE Collaboration[4]
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(Received 24 February 1999)

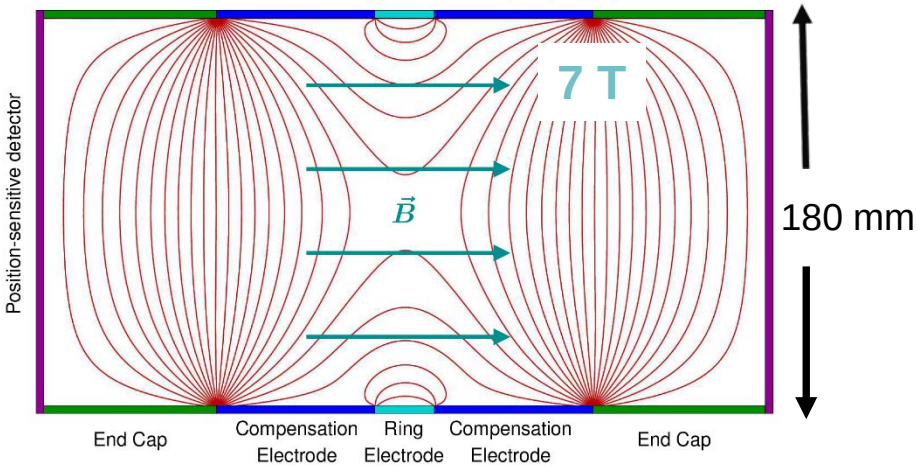
The positron-neutrino correlation in the $0^+ \rightarrow 0^+$ β decay of ^{32}Ar was measured at ISOLDE by analyzing the effect of lepton recoil on the shape of the narrow proton group following the superallowed decay. Our result is consistent with the standard model prediction. For vanishing Fierz interference we find $a = 0.9989 \pm 0.0052 \pm 0.0039$, which yields improved constraints on scalar weak interactions.

Statistics limited…

World's "Most Open" Penning Trap Geometry

Source dim ~mm

Mehlman *et al.*, NIM **A712**, 9 (2013)



Improving on Adelberger *et al*…

- "Big Sol" – high purity production
- Full event containment: large guiding fields inside and outside trap
- Coincidence tag
- High statistics (~1 mo. Counting, 0.1%)
- Tag branch with protons for b -- good geometry for beta-spectroscopy

Initial goal: 0.1% in $\tilde{a}_{\beta\nu}$

Longer term: 0.1% in b

Angular Correlations in Optical Traps

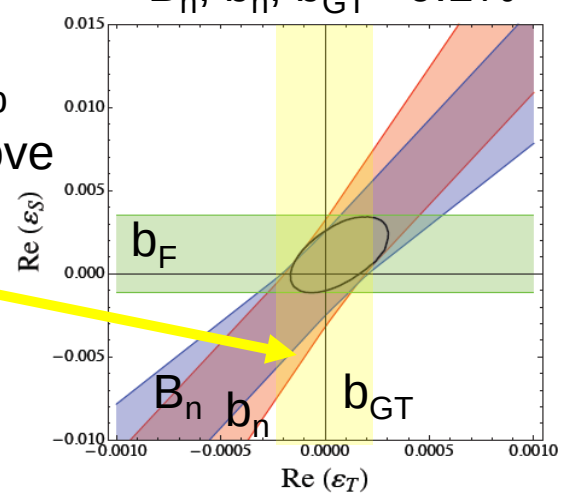
Measurements of A_β, $a_{\beta\nu}$: impact and and competing measurements

- ^{37}K (mixed F/GT) Mirror decays in a MOT (TRIUMF-TAMU) Complementary work on ion-trapped ^{35}Ar at Ganil (current data ~0.25%), ^{19}Ne possible at HUJI starting at end of 2015, similar constraints from neutron
- ^{6}He (GT) decay in a MOT (UW/CENPA-ANL)

^{6}He is of strong interest for at least 4 groups, including WI, Ganil (0.6% measurement under analysis), NSCL, UW-ANL. Optical trap development and aspects of their beta spectroscopy R&D unique

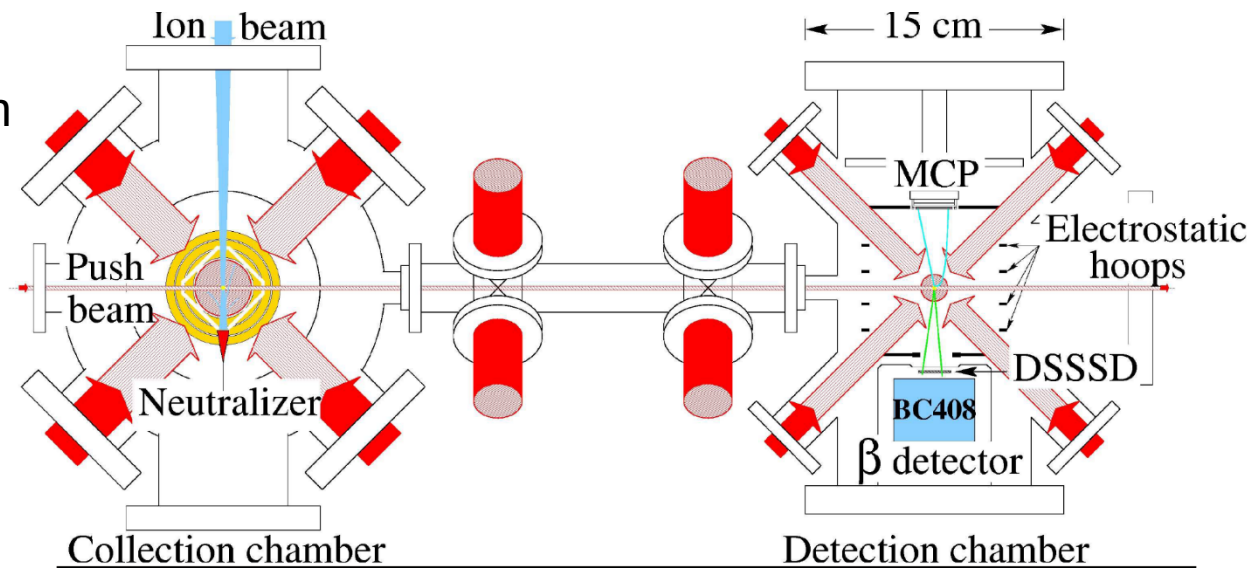
^{6}He limits for b_{GT}~0.1% put T coupling well above LHC scale

B_n, b_n, b_{GT} ~0.1%



A_β in ^{37}K decay in an optical MOT (TRINAT)

Figures from
D. Melconian



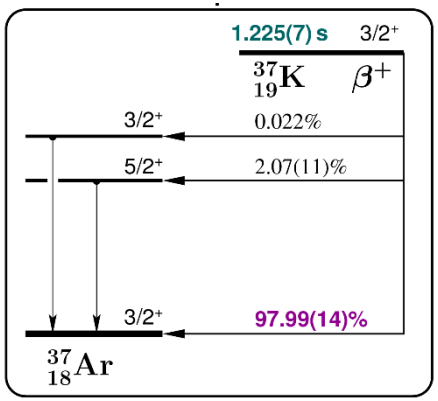
TRINAT experiment measures $a_{\beta\nu}$ in ^{38m}K decay, and A_β in ^{37}K decay

Melconian group working with TRINAT to measure the beta-asymmetry, A_β, in ^{37}K

Mirror decays are mixed F/GT:: lifetime + angular correlation provide vector coupling strength and V_{ud}

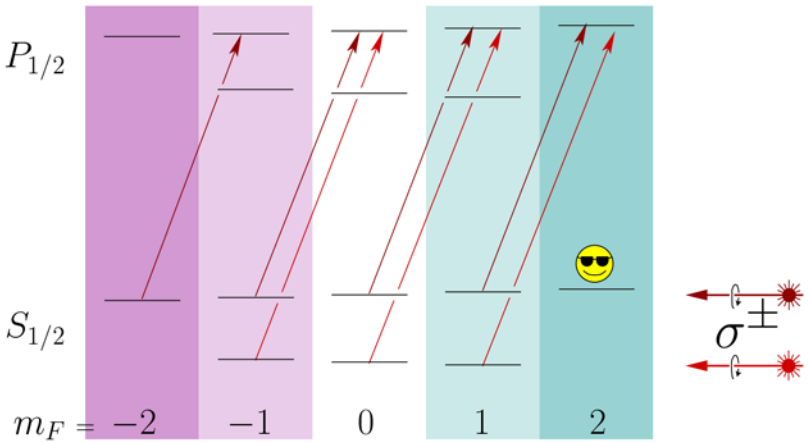
Need the sample nuclear polarization!

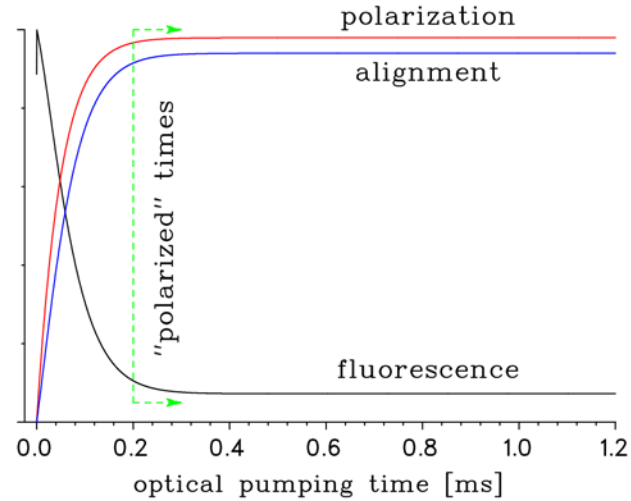
$$dW \propto 1 + \langle P \rangle \beta \tilde{A}_\beta$$



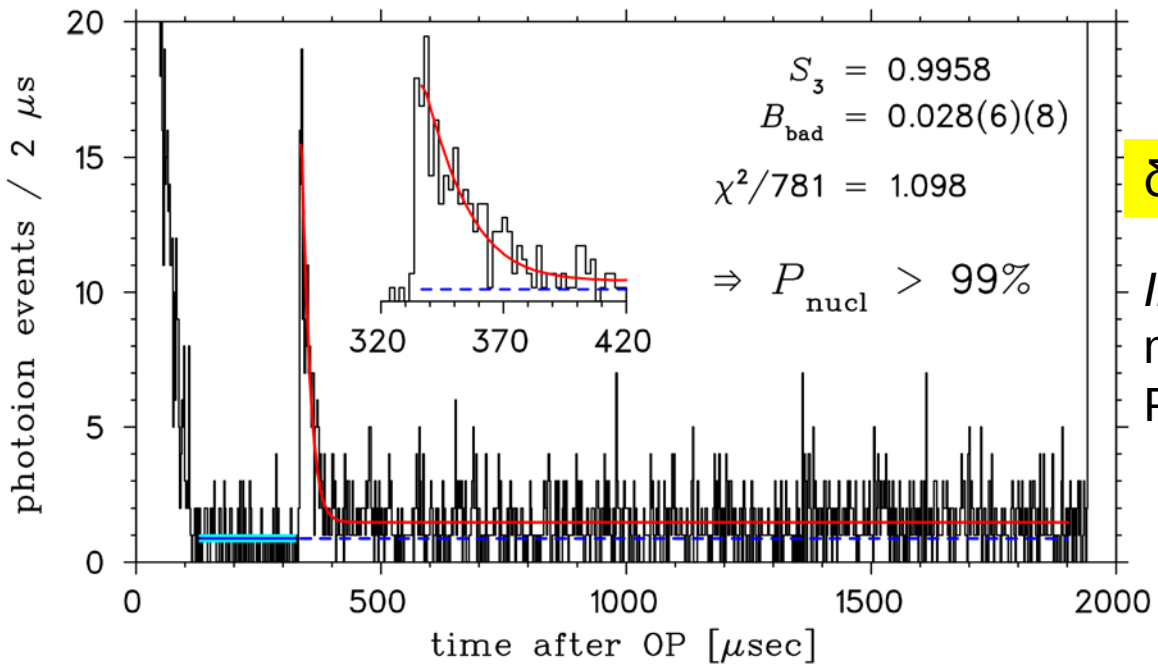
Lifetime precision improved to 0.08%

Deduce P based on model of excited state populations:





Probe states by photoionizing $P_{1/2}$ level



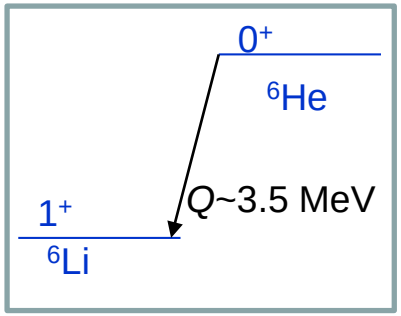
δP/P ~0.5%

In situ, optically monitored Polarization!

Fundamental symmetries studies with ^{6}He

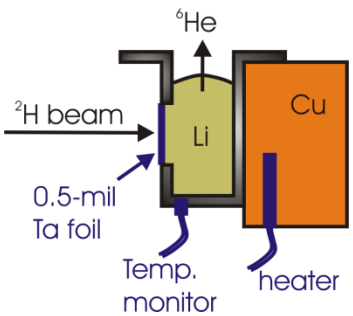
Slides courtesy of A. Garcia

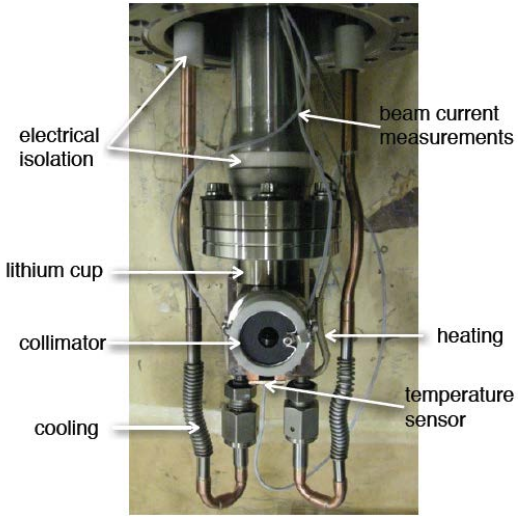
- Simple decay (~100% to ground state)
- Pure Gamow-Teller decay
- Half-life ~1 sec → appropriate for trapping
- Large *Q*-value → good for seeing effects of n
- Noble gas → no worries about chemistry
- **Light nucleus → ab-initio calculations**

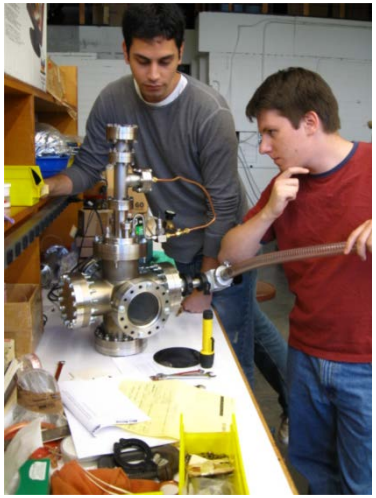


Compare to neutron:
- No backgrounds from neutron captures
- Pure GT transition (simpler decay, no polarization)

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





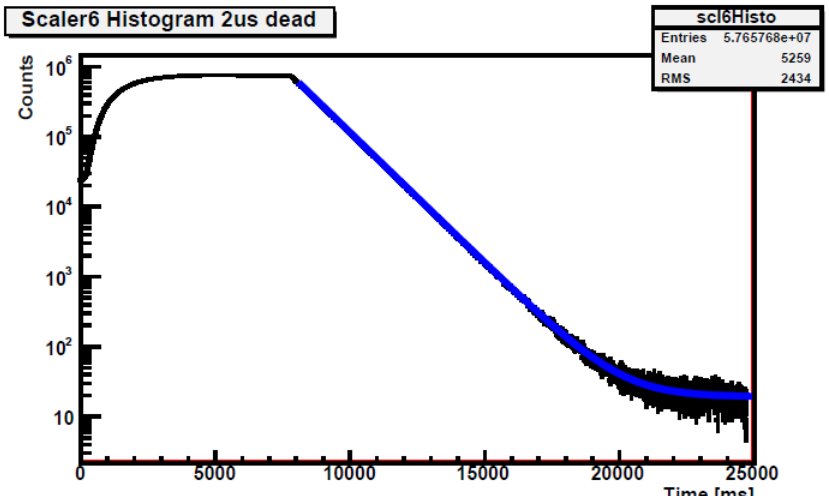


Most intense source of 6He in the world at CENPA.

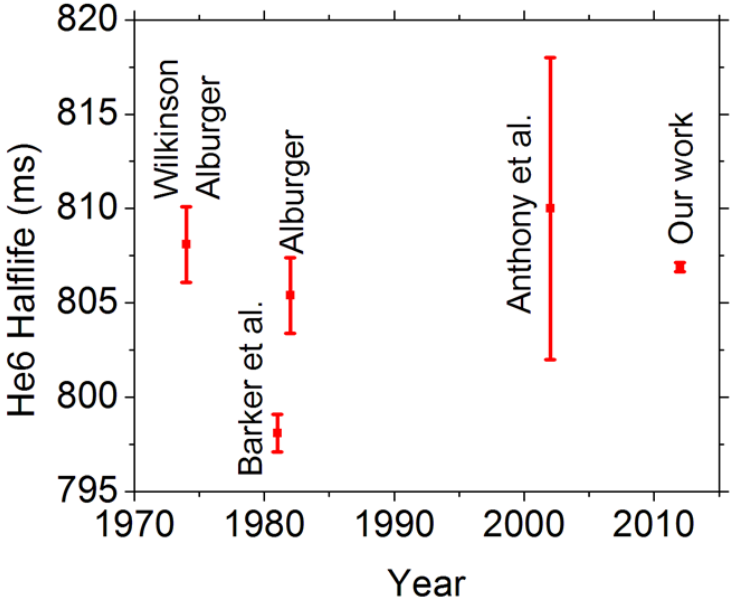
^{6}He and ab-initio calculations

Gamow Teller operator is simplest and good to test calculations. 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)



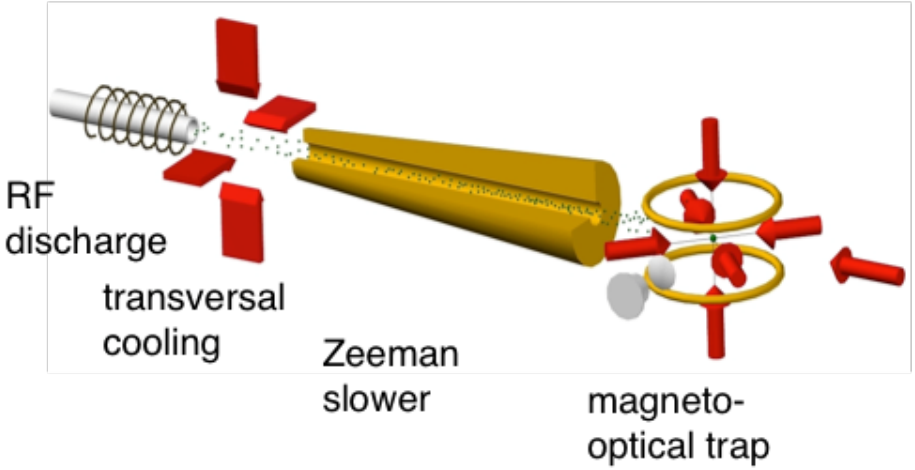
- Two previous experiments disagreed by 9 ms. Resolved the discrepancy.
- Result in combination with ab-initio calculations shows that extraneous quenching of g_A is at most about 2%.



Knecht et al. ,

Phys. Rev. Lett. 108, 122502 (2012)
Phys. Rev. C 86, 035506 (2012).

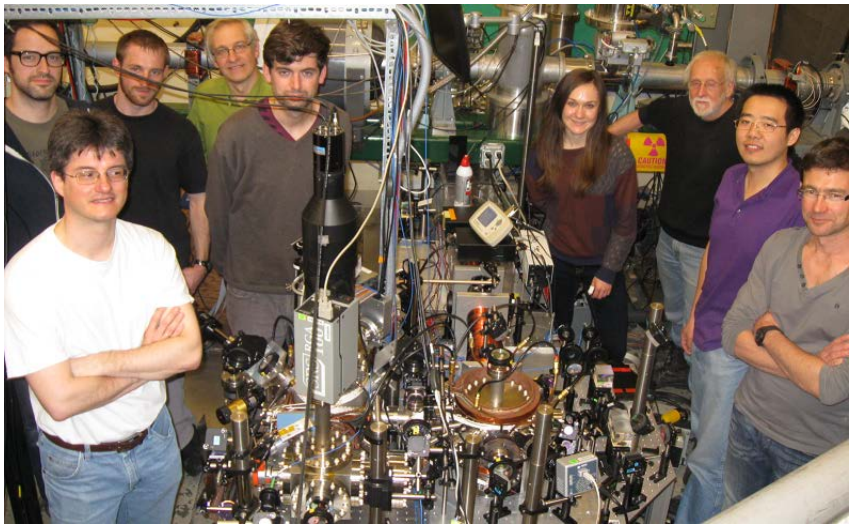
^{6}He trapping and "little *a*"



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

6He "little *a*" collaboration

P. Muller, A. Leredde *Argonne National Lab*
X. Fléchard, E. Liennard, *LPC, CAEN, France*
O. Naviliat-Cuncic, *NSCL, MSU*
A. Knecht, *PSI, Switzerland*
Y. Bagdasarova, A. Garcia, R. Hong, M. Sternberg, D. Storm, H.E. Swanson, F. Wauters, D. Zumwalt
University of Washington



Present work (little a):

- Several ongoing upgrades. Expect trapping about 1000 atoms with small bkgd.
- Expect first results ($\tilde{a}$ to ~1%) by end of 2014.
- Calibration of apparatus parameters: E field, geometry, efficiencies, instabilities.

Goals 3 years:

Determination of $\tilde{a}$ to ~0.1%

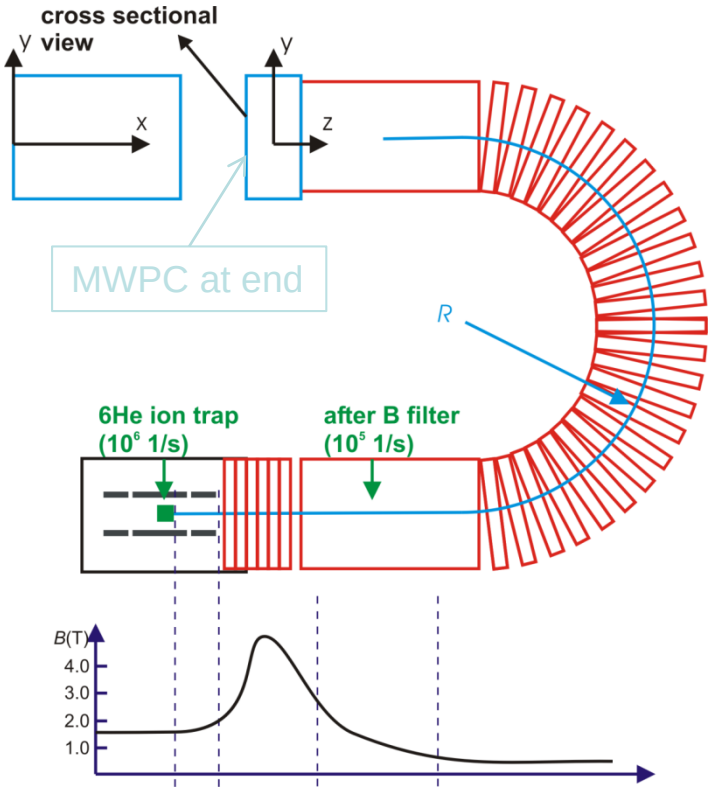
^{6}He "little *b*": aiming for 10^{-4}

Two ideas look plausible

^{6}He "little *b*" discussion group

P. Muller, A. Leredde *Argonne National Lab*
A. Knecht, *PSI, Switzerland*
A. Hime, B. Vandevender, *PNNL*
Y. Bagdasarova, A. Garcia, R. Hong, P. Kammel, J. Kofron, G. Rybka, M. Sternberg, D. Storm, H.E. Swanson, F. Wauters, D. Zumwalt *University of Washington*

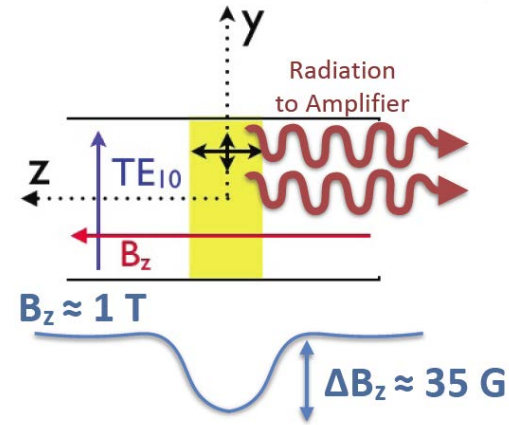
R*x*B *spectrometer:*



Displacement in ***RxB*** direction proportional to *p*.

Project-8 like system :

Pick up cyclotron radiation



In shallow trap *e*'s gyrate almost perp. to B field.

Intense production at CENPA (decay density up to about 10^9 decays/s cm^3!) and ^{6}He as gas make it well suited for P8-like approach.

Asner *et al.*, ArXiv1408.5362v1, Aug. (2014)

Towards a measurement of b in ^{6}He decay

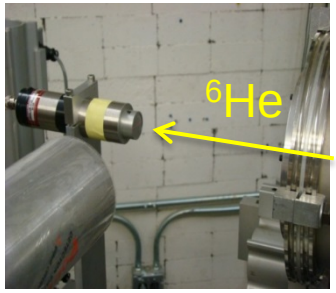
Slides courtesy of O. Naviliat-Cuncic

M. Hughes, X. Huyan, K. Minamisono, W. Mittig, O. Naviliat-Cuncic. S. Paulauskas (NSCL-MSU); P. Voytas (Uni. Wittenberg); T. Ahn, M. Brodeur, J. Kolata (Notre Dame); G. Ban, X. Flechard, E. Lienard (LPC-Caen, France)

- Short term: Observe the contribution of the WM form factor in the beta energy spectrum. Linear contribution estimated to be 0.6%/MeV.

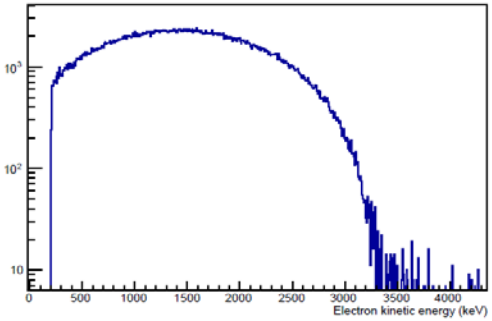
- Exploratory measurement at NSCL with ions implanted in NaI and CsI scintillators (completely contained events, suppress backscattering).
- ~10^8 events collected; analysis underway to investigate beam-induced background and electron bremsstrahlung; (first pass: separated beam is absolutely pure and beam induced activation ~3x smaller than ambient background).

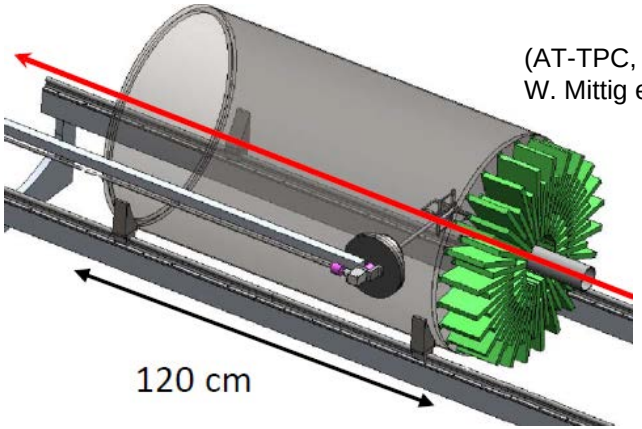
- Next step: use a TPC with ^{6}He ions stopped inside the TPC and track electrons in a magnetic field. Planned tests with AT-TPC (NSCL) to compare MC simulations. Goal δb ~ 0.1%.



46 MeV/nucleon
after degrader

CsI-run145-segs:0,1,2



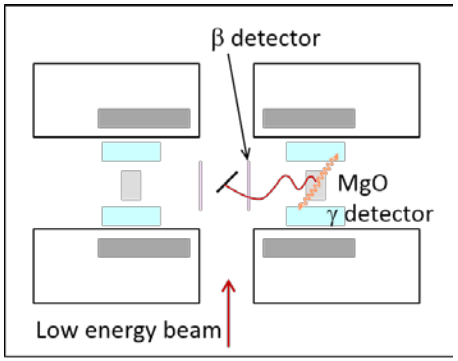


(AT-TPC, NSCL,
W. Mittig et al.)

Asymmetry-polarization correlation

M. Hughes, X. Huyan, K. Minamisono, O. Naviliat-Cuncic. S. Paulauskas (NSCL-MSU)

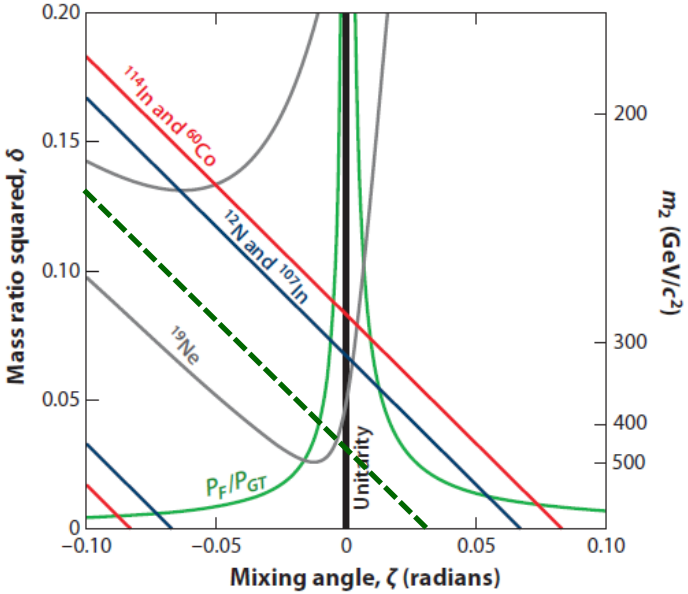
- NSCL is constructing a positron polarimeter to be installed at the BECOLA low energy beam line



- Will measure the relative longitudinal polarization of positrons emitted from spin polarized nuclei (candidates ^{21}Na and ^{37}K, optically pumped).

- Phase I: energy integrated measurement.
- Pase II: differential measurement vs positron energy (never performed in beta decay)

N. Severijns and O.Naviliat-Cuncic, Annu.Rev.Nucl.Part.Sci. **61** (2011) 23



- Will provide the most stringent constraints on RHC mass from beta decay

Neutron and Nuclear Mirror Decays

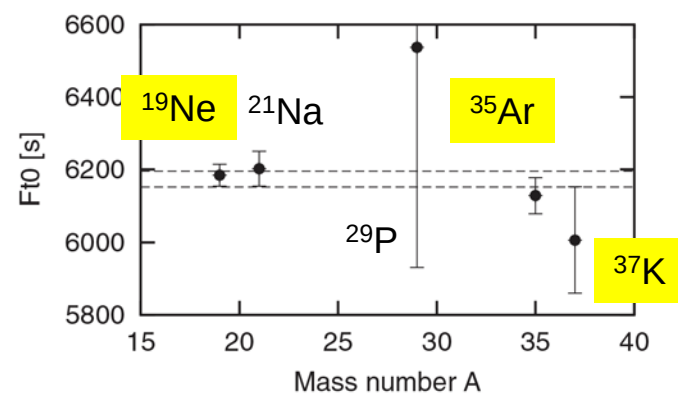
Motivation (1): an independent cross-check of vector coupling strength

For mixed F/GT decays need **2** quantities to specify decay parameters

e.g. Mirror decays: $\xi = 1 + 3\left(\frac{G_A}{G_V}\right)^2$ Need the axial coupling constant ($g_A M_{GT}$)!

Obtain these from measurements of **the lifetime** and an **angular correlation:** $a_{\beta\nu}$, A_β

Vincenzo's talk: need $a_{\beta\nu}$, A_β at 0.1% level, lifetime at 0.03% level to for neutron to compete with $0^+ \rightarrow 0^+$



2009: Phys. Rev. Lett. **102**, 142302

PDG2014

$$\frac{\delta a_{\beta\nu}}{a_{\beta\nu}} = 3.9\%, \frac{\delta A_\beta}{A_\beta} = 0.8\%, \frac{\delta\tau}{\tau} = 0.12\%$$

Significant progress being made on ^{19}Ne, ^{35}Ar, ^{37}K

$$|V_{ud}|_{0+} = 0.97425(22), \quad |V_{ud}|_n = 0.97520(140), \quad |V_{ud}|_m = 0.97190(170)$$

More Motivation: Neutron Decay

- Motivation (2): (S,T) BSM physics at comparable sensitivity to LHC (Vincenzo's talk) requires E dependence of correlations and/or spectrum measurement

Neutron decays are a clean system one can push into the post-LHC sensitivity regime (Unitarity and (S,T) constraints) with precision below 0.1% level: important long term goal!

- Motivation (3): Lifetime critical input for BBN predictions of ^{4}He (dominant source of uncertainty) – ~1s level required for envisioned BBN needs

More…

Challenge: field a diverse and sensitive enough set of experiments to provide a robust assessment of systematic uncertainties…

Neutrons: Summary

- Angular correlations
  - aCORN ($a_{\beta\nu}$): ongoing at NIST CN beam, $\delta\tilde{a}_{\beta\nu}/\delta\tilde{a}_{\beta\nu}$~1%, current data at ~3%
  - UCNA (A_β): ongoing at LANL UCN src, $\delta\tilde{A}_\beta/\tilde{A}_\beta$<0.3%, current data at 0.5-0.6%
  - Nab ($a_{\beta\nu}, b$): in preparation at SNS CN beam, $\delta\tilde{a}_{\beta\nu}/\delta\tilde{a}_{\beta\nu}$ ~0.1%, δb ~ 0.3%

    Nab detector R&D at LANL UCN src: UCNB (A_β, B_ν, b, b_ν) ~few 10^{-3} possible

International competition: aSPECT ($\delta a_{\beta\nu}/a_{\beta\nu}$~1%) at ILL, PERKEO III ($\delta A_\beta/A_\beta$ ~0.2%) at ILL, Perc in preparation ($\delta A_\beta/A_\beta$ ~0.05% and other correlations) at Munich

US approach distinct, targets relevant precision, and provides robust counterpoint to European program

- Lifetime
  - NIST UCN lifetime: analyzing systematic issues
  - Radiative Decay: ongoing at NIST CN
  - BL2/BL3: ongoing at NIST CN, staged w/ $\delta\tilde{\tau}$ ~1s in next 3y, $\delta\tilde{\tau}$ ~0.2s
  - UCNτ: in prep at LANL UCN, staged w/ $\delta\tilde{\tau}$ ~1s in next 3y, $\delta\tilde{\tau}$ ~0.2s

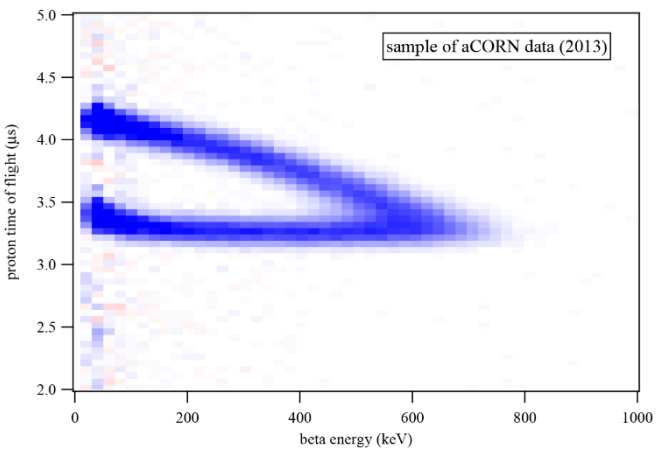
International competition: CN beam – J-PARC TPC (δτ ~1s); UCN – PENeLOPE (δτ~0.1s) at Munich, Ezhov, HOPE and Gravitrap at ILL (δτ~0.3s), Mainz (δτ~0.3s),

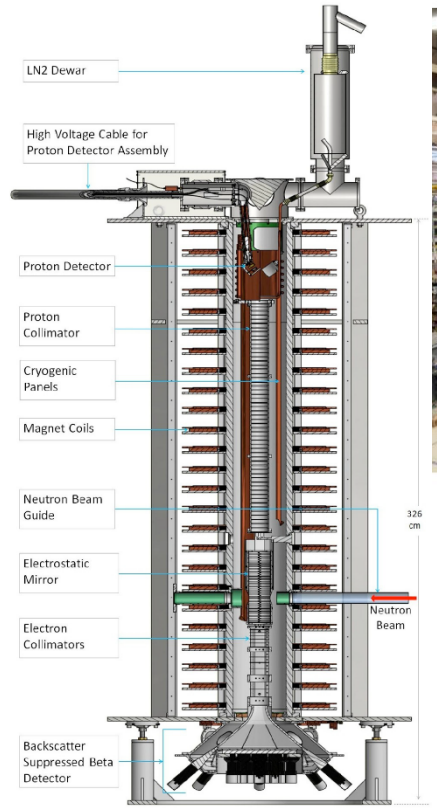
US research in very strong position

aCORN

Figures from F. Wietfeldt

Unique collimator geometry permits kinematic cuts to resolve electron-proton relative motion (for fixed electro energy)



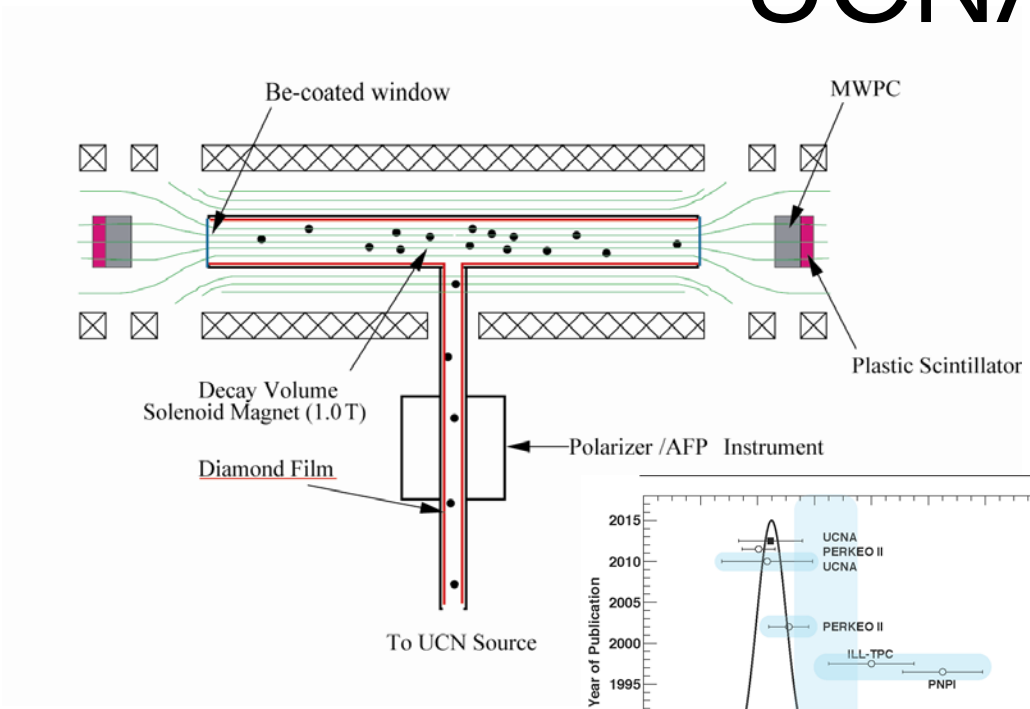


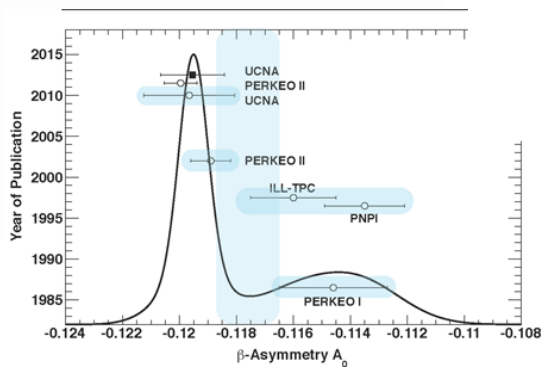
NIST upgrade: x5 at NG-C
Another x(1.5-2) with cold source upgrade in 2016

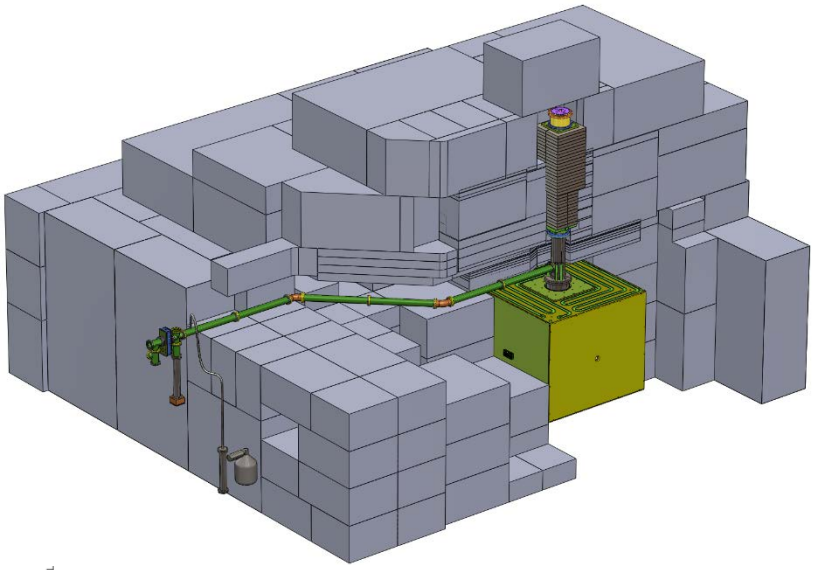
Current analysis (from NG-6 run): $\delta\tilde{a}_{\beta\nu}/\delta\tilde{a}_{\beta\nu}$ ~3%

Move to NG-C in 2015 after current analysis compete: $\delta\tilde{a}_{\beta\nu}/\delta\tilde{a}_{\beta\nu}$~1%

UCNA







2010: 52±6 UCN/cm^3

One of the strongest UCN sources in the world

Use UCN to address systematic issues of polarization and backgrounds in previous CN beam expts

LANL source upgrade: projected gain from 2013: x10 (LDRD, T. Ito PI)

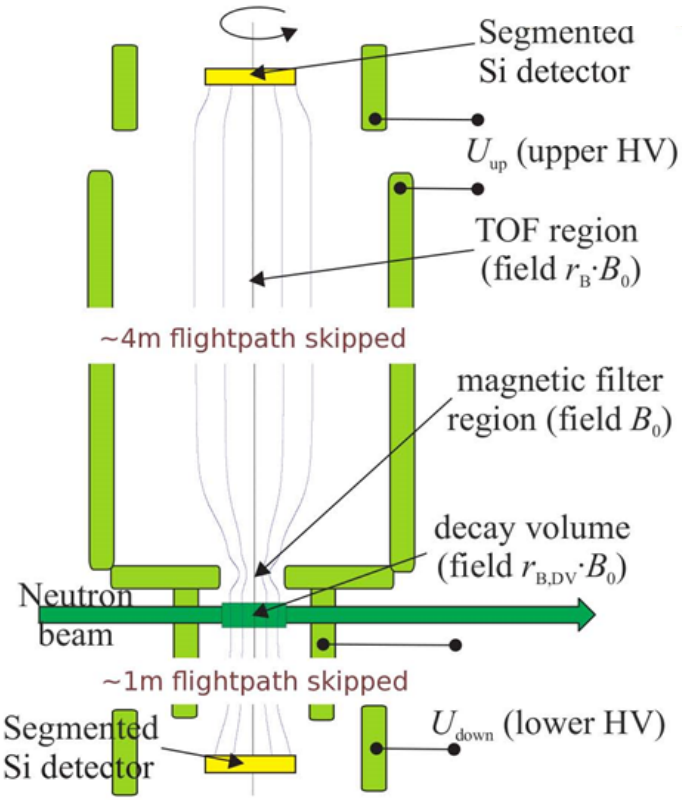
Phys. Rev. C **87**, 032501(R) 2013

A_o =-0.11972(55), $\lambda=g_A/g_V$=-1.23756(30)

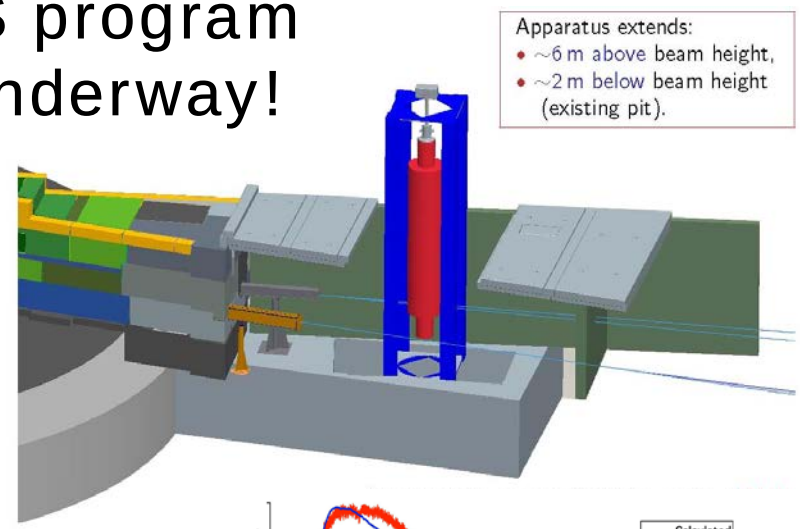
$\delta\widetilde{A}_\beta/\widetilde{A}_\beta$<0.3%, current data at 0.5-0.6%

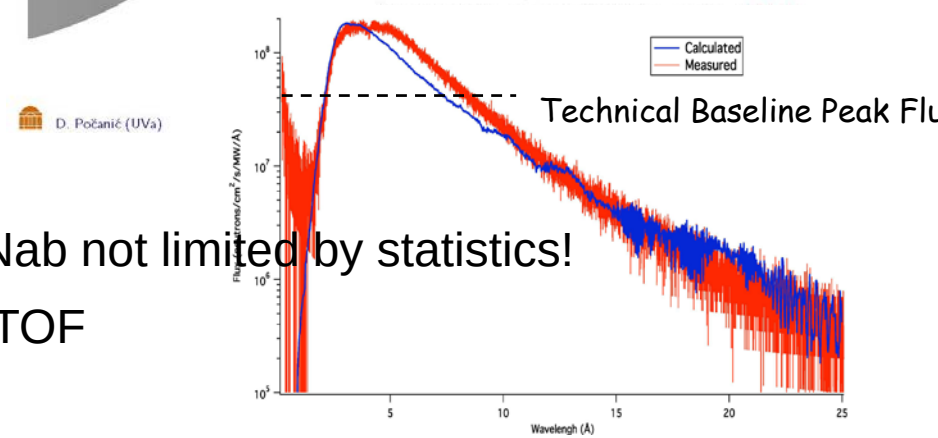
16 publications, 6 theses since 2009

Nab



SNS program is underway!





Nab not limited by statistics!

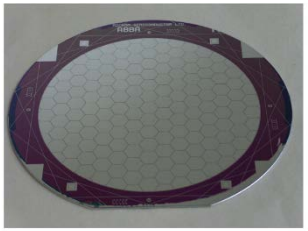
Utilizes optimized spectrometer for proton TOF
No aperture and grid
Custom Si detectors
Pulsed beam at the SNS

$\delta\tilde{a}_{\beta\nu}/\delta\tilde{a}_{\beta\nu}$ ~0.1%, δb ~ 0.3%

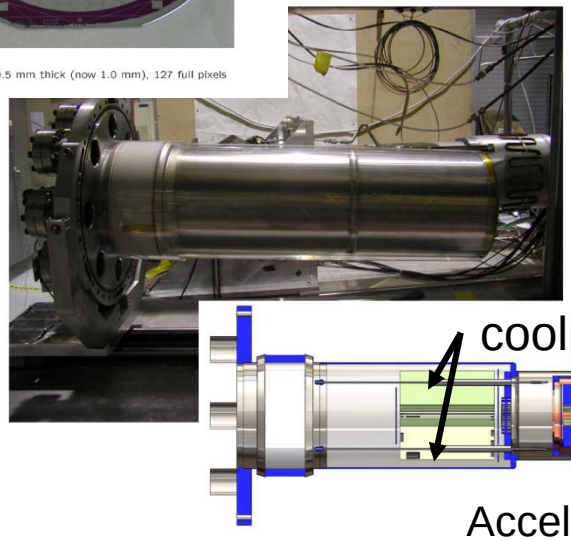
Setup in 2016, run through end of 2017
0.1% statistics in less than 1 mo

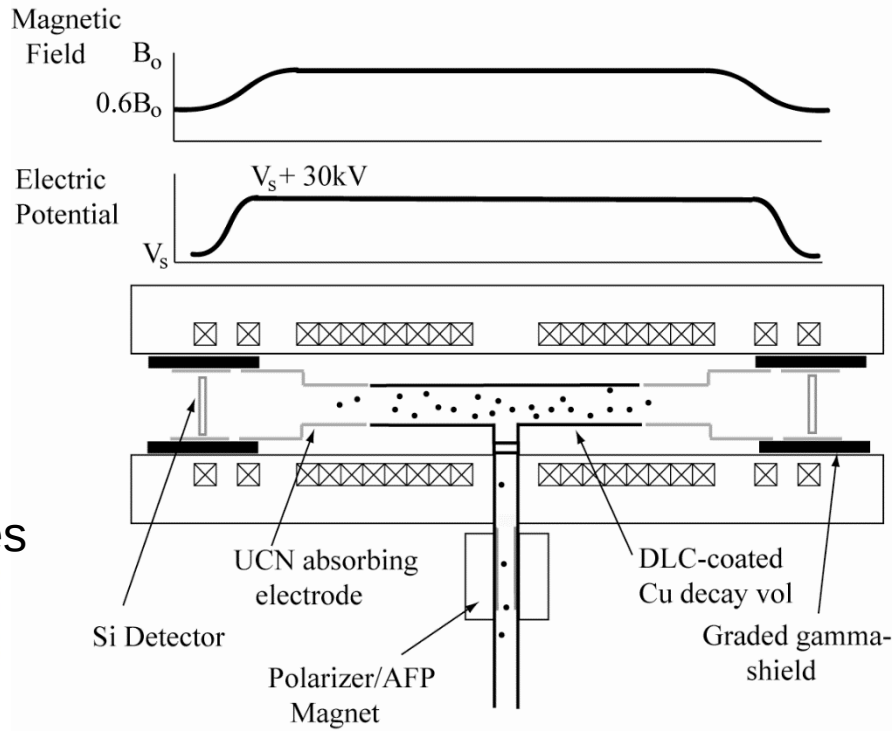
Nab/UCNB Detector R&D: Si detector development and the UCN spectrometer at LANSCE

Prototype Si detector



6″ wafer, 0.5 mm thick (now 1.0 mm), 127 full pixels





- Large area Si detectors the key to high precision β-spectroscopy and proton detection: 2mm thick, 127 pixels, ~15 cm diam, 2.5 keV res
- Development program underway at LANL using UCN spectrometer (ideal for Nab R&D, physics measurements possible)

Radiative Neutron Decay - RDK II

$$n \rightarrow p + e^- + \bar{\nu}_e + \gamma$$

Slide courtesy of J. Nico

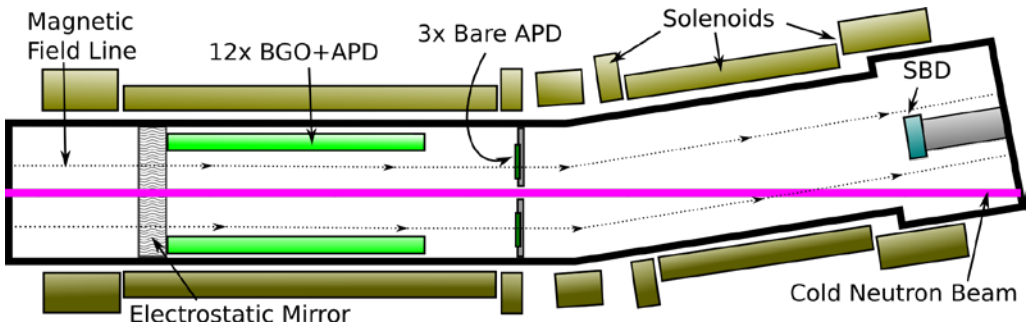
➢ Perform precision measurement of the radiative photon branching ratio and energy spectrum.

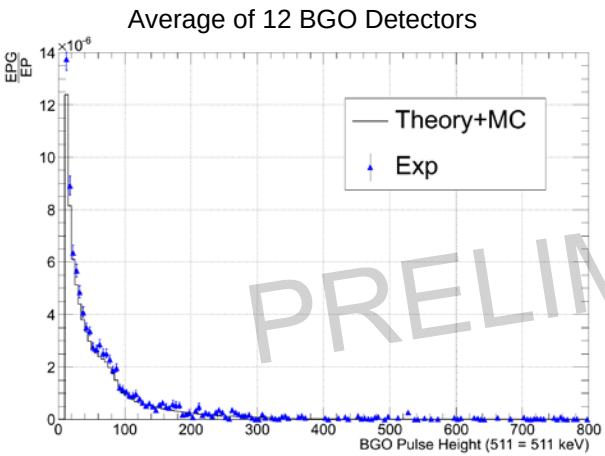
➢ Test of V-A physics and QED calculations; measure other correlations with tagged photon (e.g., Fierz term); progress toward sub-1% measurement.

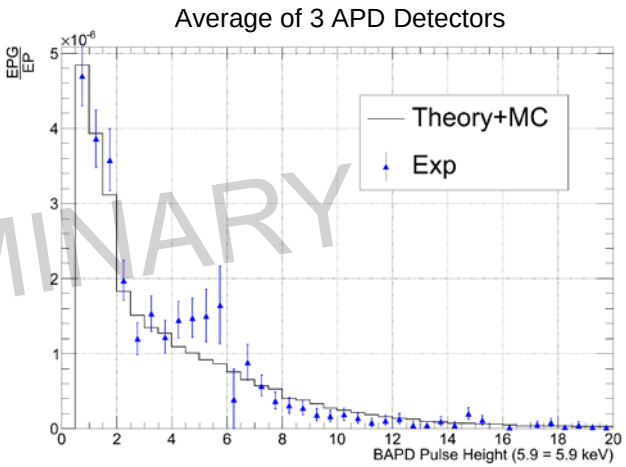
➢ Detect photon and electron in coincidence followed by delayed proton.

➢ Photon detection performed by 12 BGO crystals (10-780 keV) and bare APD detectors (0.25 - 25 keV).

➢ Data run performed on NG-6 beam at NIST Center for Neutron Research







➢ RDK II run and offline detector characterization and response studies completed.

➢ Extensive MC simulations of apparatus and decays complete.

➢ Nearing completion of statistical analysis and systematic effects.

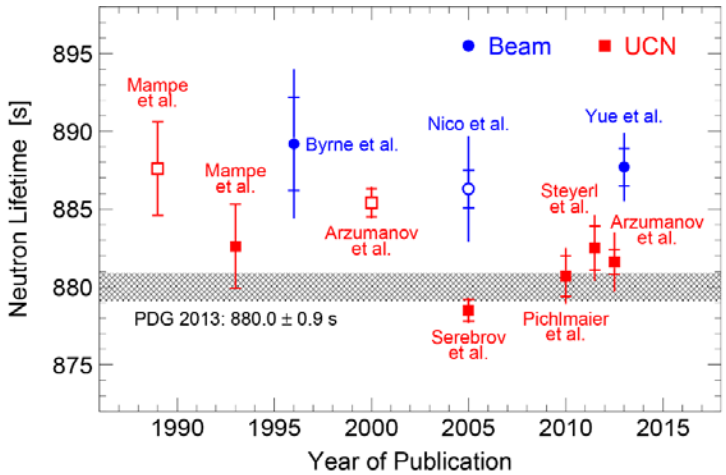
➢ Expect final result in early 2015. Precision on BGO of a few percent and bare APD of about 10%

Collaboration: Arizona State, Indiana, Kentucky, Maryland, Michigan, NIST, Sussex, and Tulane

Support: NIST, DoE, NSF

Sept. 2014: “Measuring the Neutron Lifetime” Workshop

Hosted by: Umass Amherst and the Amherst Center for Fundamental Interactions



$\tau_n^{beam} = 886.3(3.4) \rightarrow 888.0(2.1)$

$\tau_n^{beam} = 888.0(2.1)$

$\tau_n^{UCN} = 879.6.0(0.8)$

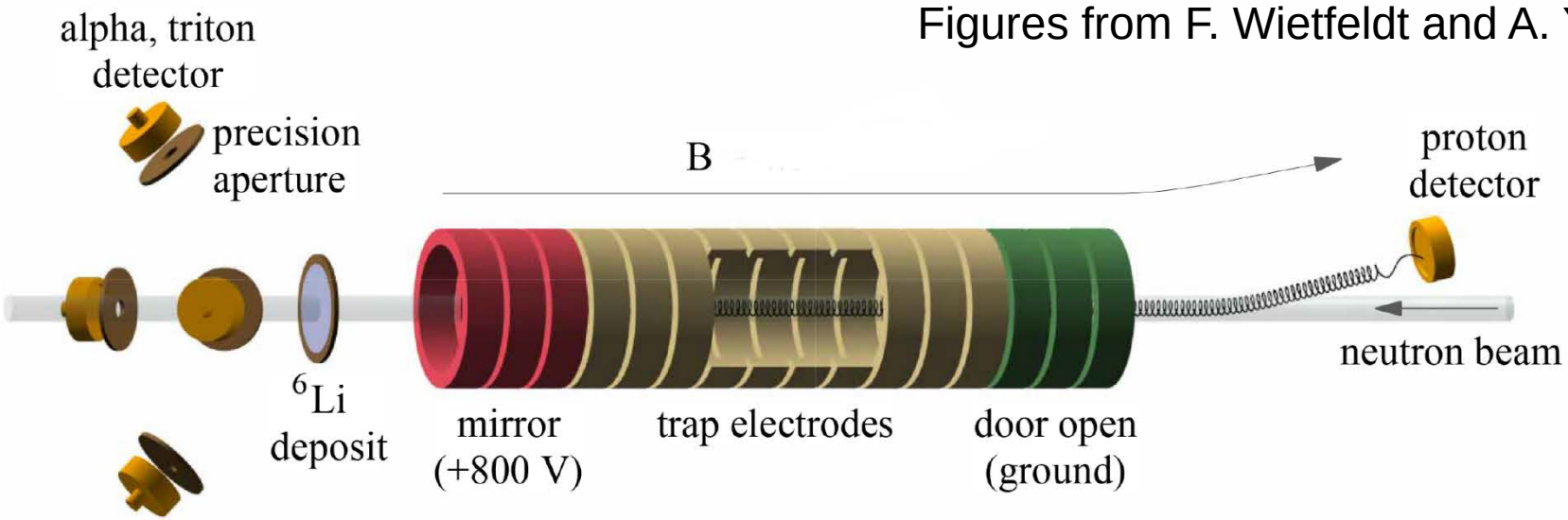
~4σ discrepancy

Phys. Rev. Lett.**111** 222501 (2013)

- There are two ways to measure the neutron lifetime: beams and bottles
- Recent beam results reinforced existing 4σ discrepancy between beam and bottle
- Conclusion of Workshop: only way to resolve this is to pursue experiments with both methods and improved precision

NIST Lifetime (BL1)

Figures from F. Wietfeldt and A. Yue



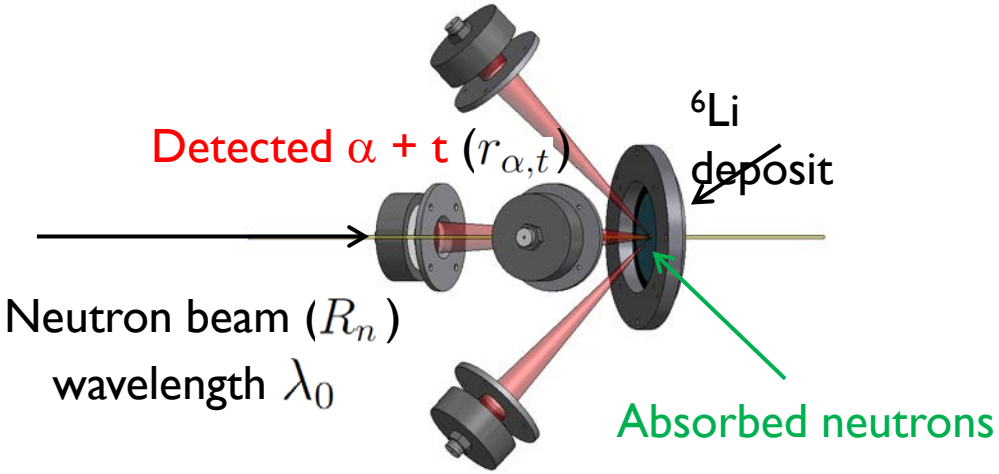
Nico *et al*., Phys. Rev. C **71**, 055502 (2005)

- 30 years of experience developing CN beam lifetime method
- Measurement first published in 2003

$\tau_n = 886.3(1.2)_{stat}(3.2)_{sys}$ updated to $\tau_n = 887.7(1.2)_{stat}(1.9)_{sys}$

- Method involves counting the decay protons from a well-defined region inside a the Penning trap, and requires a determination of the absolute neutron fluence (number of neutrons in trap volume)
- Dominant error: absolute neutron beam fluence

Determining absolute fluence



$$\epsilon_0 = \left[\frac{N_A}{A}\rho\left(0,0\right)\sigma_0\right] \times \left[2 \cdot \Omega_{\mathrm{FM}}\left(0,0\right)\right]$$

α, t detection probability

Neutron absorption probability

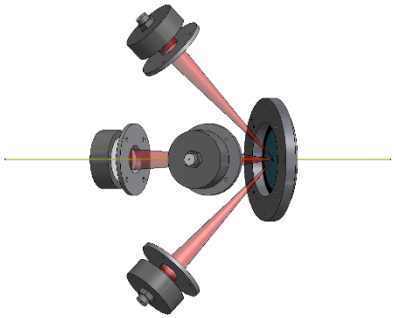
Old way: measure area density , solid angle, and use evaluated cross-section

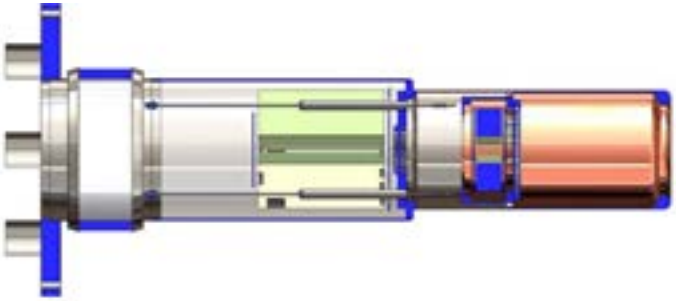
New way: monoenergetic beam, measure fluence monitor rate $r_{\alpha,t}$ and simultaneously the calibrated rate in 100% absorbing, gamma emitter, R_n

$$\epsilon_0 = \frac{r_{\alpha,t}}{R_n}\frac{\lambda_0}{\lambda_{\mathrm{mono}}}$$

NIST lifetime: BL2 and BL3

- Improved lifetime measurement in a staged program, based on enabling technologies



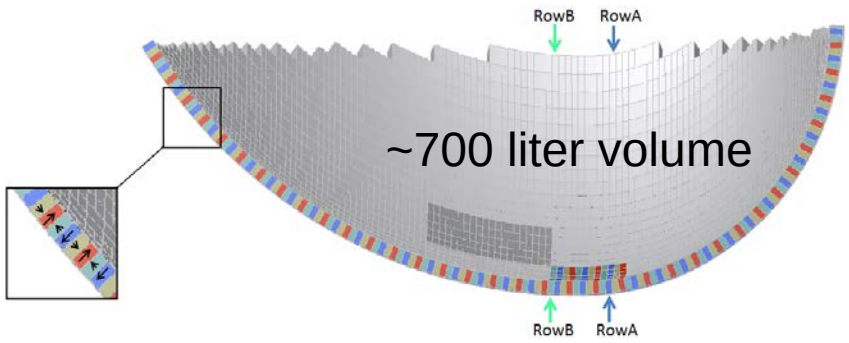


- BL2 will use existing apparatus, with new calibration procedure and additional statistics to push to $\delta\tau \sim 1$s over next 3 years

- BL3: scale up existing experiment, explore additional absolute counting schemes and use large segmented Si detectors to improve proton counting systematic issues, goal $\delta\tau$ well below 1 s

UCNτ: an Asymmetric Gravito-Magnetic Trap

- UCN trap with walls paved with ~5000 permanent magnets in a Halbach array, forming a gravito-magnetic trap for one spin state, and avoiding losses on the material walls

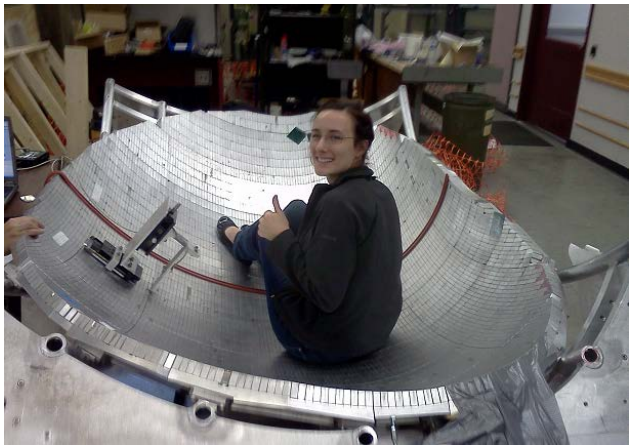


Asymmetric structure: two torus patches of different curvatures join along middle row

- Neutrons populations are cleaned to remove "quasi-bound" UCN

- Neutrons stored for at least two different storage times, t_1 and t_2 with the measured normalized survivors, N_1 and N_2

$$\tau_n = \frac{t_2 - t_1}{ln\left(\frac{N_1}{N_2}\right)}$$



UCNτ unique features

UCNτ has unique features, and is the only UCN experiment to combine

- Multiple sampling methods include a detector which can be inserted fully into the trap
  - Drain to UCN detector
  - **In situ V activation**

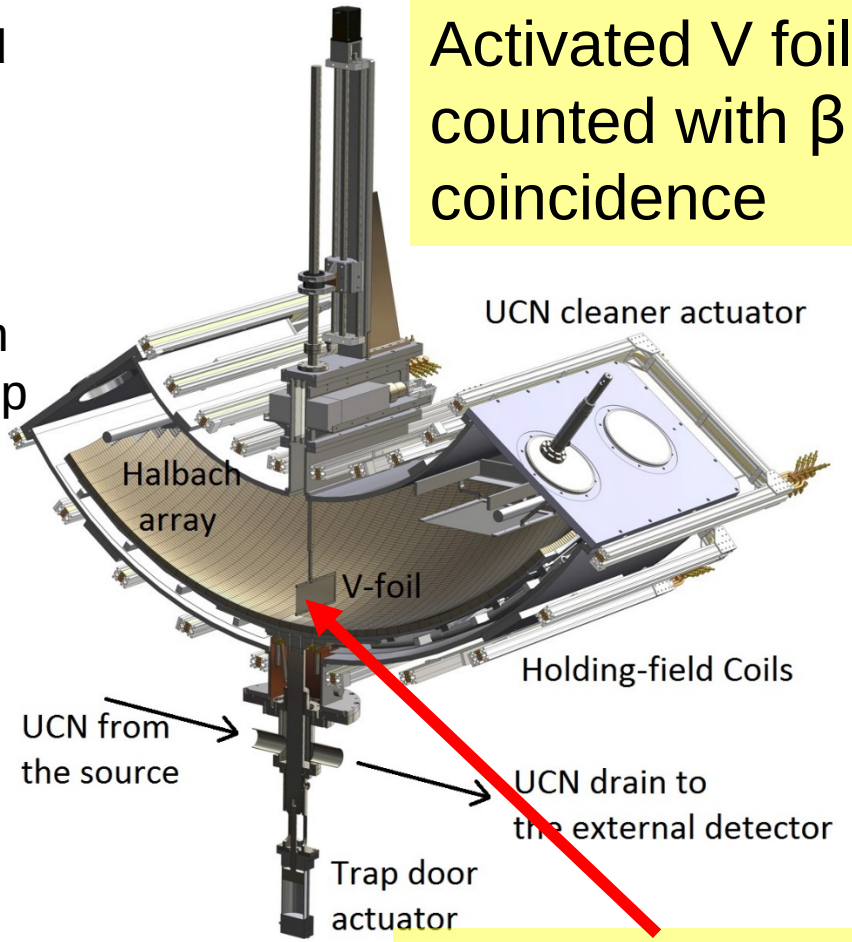
Control for UCN which empty slowly from trap through guide

- **Asymmetric structure**

Promotes orbit mixing for rapid removal of quasi-bound neutrons

- together with large volume (700 liters)

High statistics

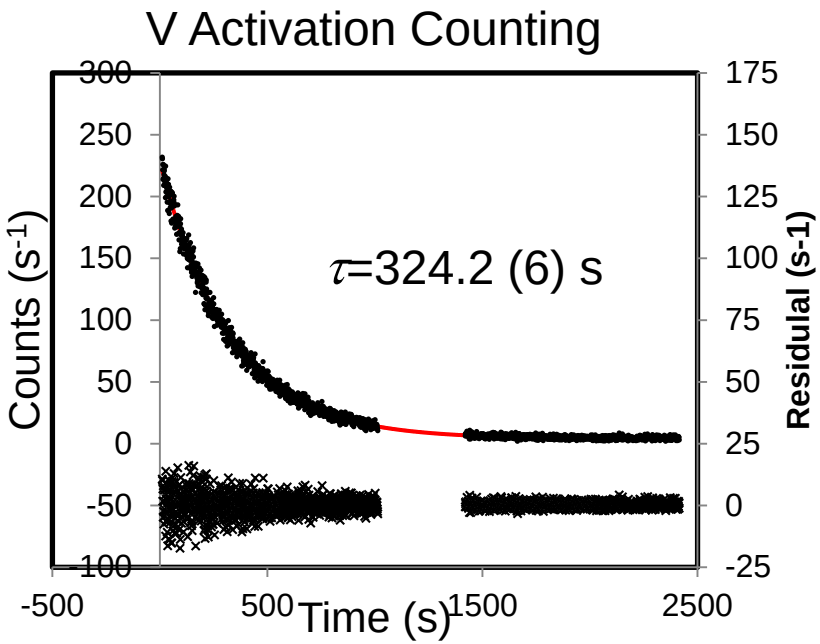


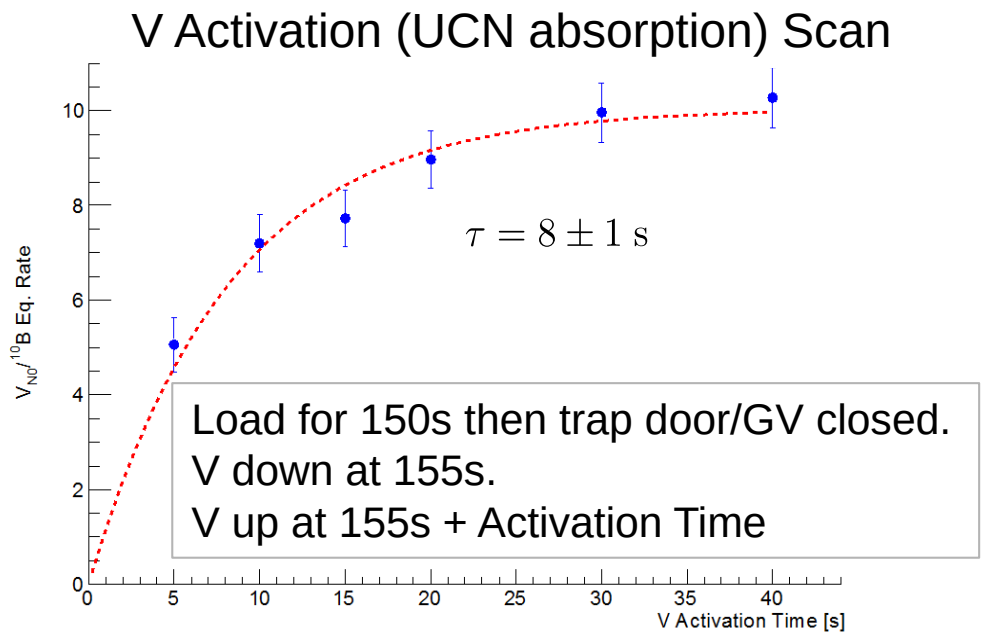
Activated V foil counted with β-γ coincidence

V foil lowered into trap

Control for trajectories with long emptying time and possibly monitor spectral variations

UCNτ R&D progress





- First measurement of storage time 860±19s (Phys. Rev. C **89**, 052501 (2013))
- Order of magnitude improvement (>10^5 UCN per fill) with prototype new loading arrangement over the geometry used to produce published storage curve

Also anticipate staged approach: over next 3 years, target δτ~1s, then focus on improvement to well below 1s precision

Summary

- Essentially all groups in a cycle of construction, data-taking or analysis, with only modest R&D investment hoped for over the LRP period
- Motivation remains excellent, highlighting essential role of theory
    - Rigorous form factors for kaons and nucleons from lattice
    - MI particle physics phenomenology
    - Recoil matrix elements and nuclear structure corrections
- Assessment of alternatives for beta-spectroscopy an emerging priority for field – Project 8 technology may have impact
- Neutrons: the SNS is now online and there are source upgrades underway at LANL and NIST. Community sharpening focus on lifetime, with both beam and bottle experiments envisioned
- Beginning to assess opportunities at FRIB in longer term

Testing CVC and CKM unitarity via superallowed nuclear β decay

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Open trap

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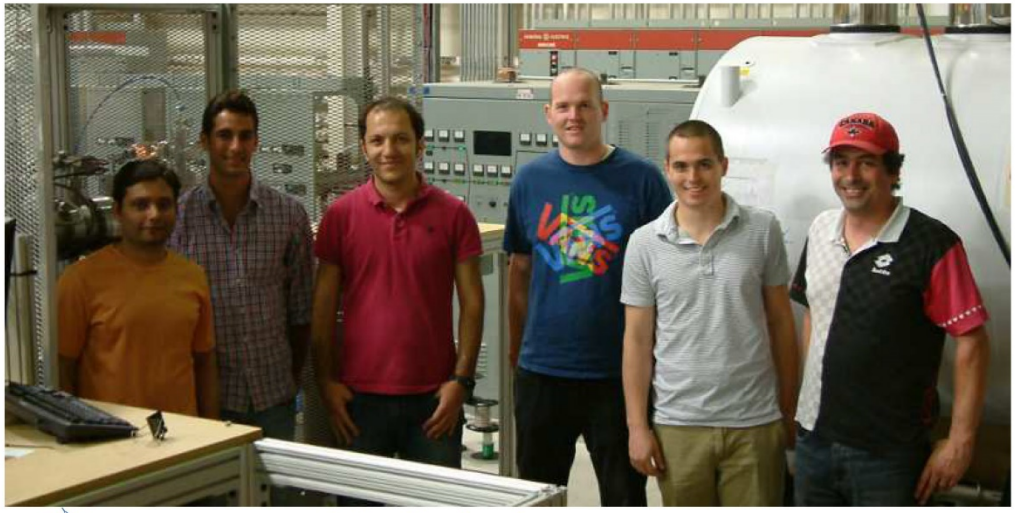
R. Segel

K.S. Sharma, G. Morgan, T. Hirsch

A. Aprahamian, S. Marley, N. Paul, S. Strauss, K. Siegl

The Mad Trappers/Thanks

TAMU: Spencer Behling, Mike Mehlman, Ben Fenker, Praveen Shidling
+ TAMU/REU undergrads



TRINAT: TRIUMF M. Anholm, J.A. Behr, A. Gorelov,
L. Kurchananov, K. Olchanski, K.P. Jackson

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Funding/Support:

DOE DE-FG02-93ER40773, Early Career ER41747

TAMU/Cyclotron Institute

also NSERC, NRC through TRIUMF, WestGrid, Israel Science Foundation

NSCL Projects:

^{6}He spectroscopy

M. Hughes, X. Huyan, K. Minamisono, W. Mittig, O. Naviliat-Cuncic. S. Paulauskas (NSCL-MSU); P. Voytas (Uni. Wittenberg); T. Ahn, M. Brodeur, J. Kolata (Notre Dame); G. Ban, X. Flechard, E. Lienard (LPC-Caen, France)

spin-asymmetry

M. Hughes, X. Huyan, K. Minamisono, O. Naviliat-Cuncic. S. Paulauskas (NSCL-MSU)

UW-ANL Projects

^{6}He electron-neutrino corr.

6He "little *a*" collaboration

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A. Knecht, *PSI, Switzerland*
Y. Bagdasarova, A. Garcia, R. Hong, M. Sternberg, D. Storm, H.E. Swanson, F. Wauters, D. Zumwalt
University of Washington

^{6}He spectroscopy

^{6}He "little *b*" discussion group

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Y. Bagdasarova, A. Garcia, R. Hong, P. Kammel, J. Kofron, G. Rybka, M. Sternberg, D. Storm, H.E. Swanson, F. Wauters, D. Zumwalt *University of Washington*

aCORN Collaboration

current 19 Sept 2014

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Indiana University: Ed Stephenson*

Hamilton College: Brian Collett, Gordon Jones*

DePauw University: Alex Komives*

University of Tennessee: Jonathan Mulholland

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University of Kentucky
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University of Winnipeg
J. W. Martin
Virginia Polytechnic Institute and State University
X. Ding, M. L. Pitt, R. B. Vogelaar

Funding proposal for the neutron decay spectrometer Nab at SNS

Precise Measurement of $\lambda = G_A/G_V$ and Search for Non-(V−A) Weak Interaction Terms in Neutron Decay

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[l] *Department of Physics, University of Winnipeg, Winnipeg, Manitoba R3B2E9, Canada*
[m] *Department of Physics, North Carolina State University, Raleigh, NC 27695-8202*

NIST Beam Neutron Lifetime (BL2, BL3)

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University of Tennessee, Knoxville
N. Fomin, K. B. Grammer, G. L. Greene, J. Mulholland

Tulane University
C. DeAngelis, F. E. Wietfeldt

Indiana University
E. Anderson, W. M. Snow

Hamilton College
B. Collett, G. L. Jones

The Neutron Lifetime Experiment at LANL

Steven Clayton for the UCNτ collaboration

S. Clayton, M. Makela, C. Morris, J. Ramsey, A. Saunders, S. Seestrom, P. Walstrom, Z. Wang (LANL)

D. Bowman, S. Penttila (ORNL)

E. Adamek, W. Fox, A. Holley, M. Hozo, C.-Y. Liu, N. Callahan, D. Salvat, J. Vanderwerp, B. Slaughter, K. Solberg, M. Snow (Indiana U.)

B. Vogelaar (V. Tech)

K. Hickerson (UCLA)

A. R. Young, B. VornDick, E. B. Dees, C. Cude (NCSU)

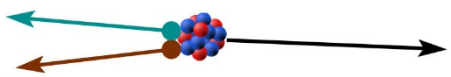
PSI2013

A little more specifically…

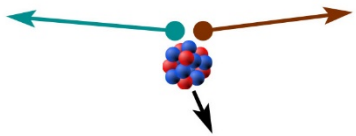
Test SM via the **angular distribution** of β decay: the often-quoted Jackson, Treiman and Wyld (Phys Rev **106** and Nucl Phys **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu\text{ correlation}} + \overbrace{b \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}}\right)$$

vector



scalar



$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2}{|C_V|^2 + |C'_V|^2}$$

$$a_{\beta\nu} = \frac{-|C_S|^2 - |C'_S|^2}{|C_S|^2 + |C'_S|^2}$$

$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2}$$

A little more specifically…

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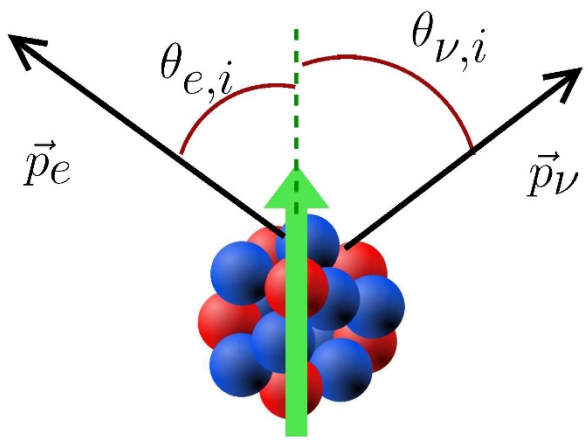
$$\left. + \frac{\langle\vec{I}\rangle}{I}\cdot\left[\underbrace{A_\beta\frac{\vec{p}_e}{E_e}}_{\beta\text{ asym}} + \underbrace{B_\nu\frac{\vec{p}_\nu}{E_\nu}}_{\nu\text{ asym}} + \underbrace{D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}}_{T\text{–violating}}\right]\right) + \ldots$$



$$A_\beta = \frac{-2\rho}{1+\rho^2}\left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)}\right]$$

where $x \approx (M_L/M_R)^2 - \zeta$

and $y \approx (M_L/M_R)^2 + \zeta$

are right-handed current parameters that are zero in the SM