ACFI Workshop
“Beta decay as a probe of new physics”

My hope for the workshop:

Convey to theorists that there is discovery potential, but we can’t do it without their help.

Outlook for precision beta-decay measurements

Talk at ACFI Workshop
"Beta decay as a probe of new physics"

Beta decay

Amazing history: first steps beyond E&M

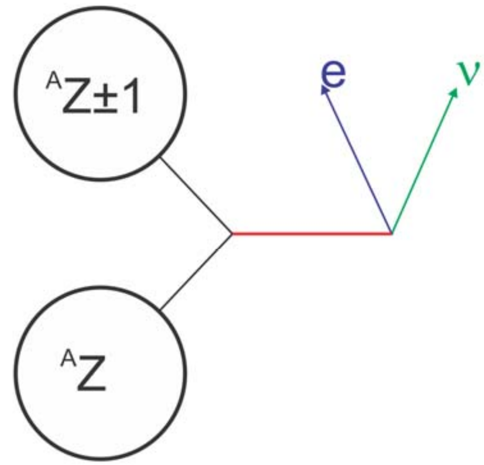
Transmutations in decays

Parity violation

Gauge theories

Unification

…

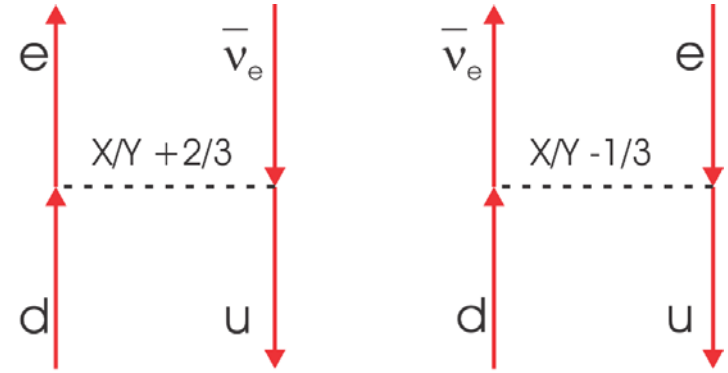


Is there a future for exploring?

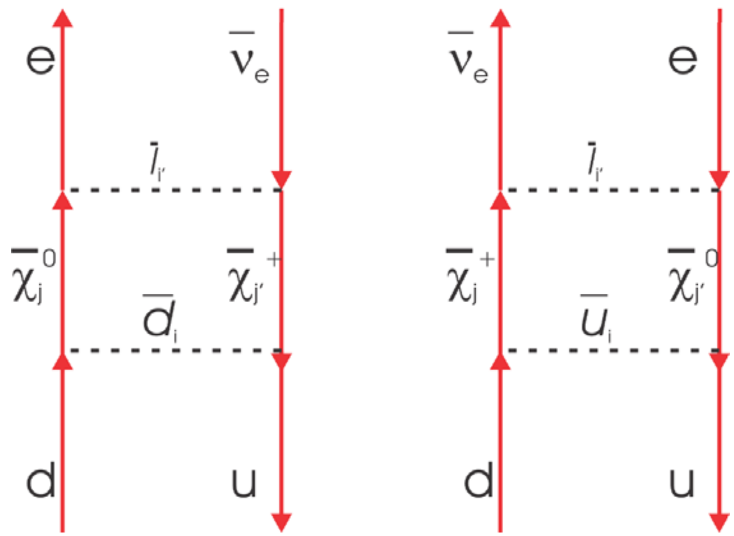
Precision frontier may hold surprises

Chirality-flipping as means of detection of new physics.

Small contribution that could be detected with precision experiments



Leptoquarks:
X: scalar; Y: Vector
Predicted by
Grand Unified Theories



Predicted by Supersymmetric Theories

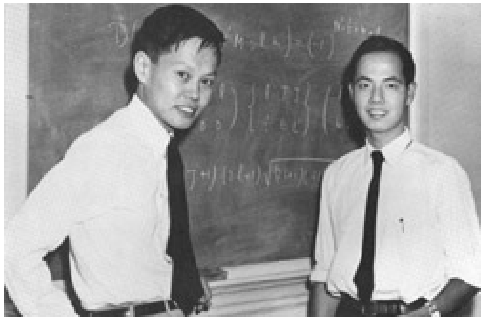
Or maybe something not considered so far…

Profumo, Ramsey-Musolf, Tulin
Phys. Rev. D **75**, 075017 (2007)

Bhattacharya et al.
Phys. Rev. D **94**, 054508 (2016)

Nuclear beta decay phenomenology: beyond *V-A*?

Yang and Lee



Standard Model + non-SM-LL

Leptonic Right-handed

$$H_{V,A} = \sum_{i=V,A} \bar{\Psi}_f\, O_i^{\mu} \Psi_0 \left[(C_i + C_i{}')\, \bar{e}^L\, O_{i,\mu} \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^R O_{i,\mu} \nu_e{}^R \right]$$

$$O_i^{\mu} = \begin{cases} \gamma^{\mu} & i = V \\ \gamma^{\mu}\gamma_5 & i = A \end{cases}$$

chirality flipping

$$H_{S,T} = \sum_{i=S,T} \bar{\Psi}_f\, O_i\;\; \Psi_0 \left[(C_i + C_i{}')\, \bar{e}^R\, O_i \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^L O_i \nu_e{}^R \right]$$

Scalar, Tensor

$$O_i = \begin{cases} 1 & i = S \\ \sigma^{\mu\nu} & i = T \end{cases}$$

Example:

Decay rate for non polarized axial (GT) decay

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

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

β-ν correlation

$$b \approx \pm(C_T + C_T{}')/C_A$$

Fierz interference

"$\beta - \nu$ correlation experiments"

measure ratio: $\dfrac{a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu}}{1 + b \frac{m_e}{E_e}}$

All correlation experiments show some sensitivity to the interference

Polarized parent: more observables.

β-ν — Fierz — β-asymmetry — ν-asymmetry

$$dw \approx dw_0 \left[1 + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \vec{J} \rangle}{J} \cdot \left[A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} \right] \right]$$

… and the "letter soup" extends with observation of the electron polarization…

Nuclear beta decay phenomenology: beyond *V-A*?

Standard Model + non-SM-LL

Leptonic Right-handed

$$H_{V,A} = \sum_{i=V,A} \bar{\Psi}_f\, O_i^{\mu} \Psi_0 \left[(C_i + C_i{}')\, \bar{e}^L\, O_{i,\mu} \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^R O_{i,\mu} \nu_e{}^R \right]$$

$$O_i^{\mu} = \begin{cases} \gamma^{\mu} & i = V \\ \gamma^{\mu}\gamma_5 & i = A \end{cases}$$

chirality flipping

$$H_{S,T} = \sum_{i=S,T} \bar{\Psi}_f\, O_i\; \Psi_0 \left[(C_i + C_i{}')\, \bar{e}^R\, O_i \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^L O_i \nu_e{}^R \right]$$

Scalar, Tensor

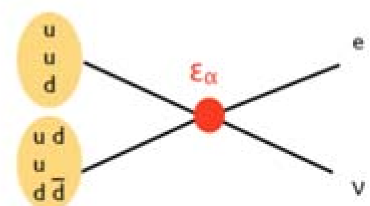
$$O_i = \begin{cases} 1 & i = S \\ \sigma^{\mu\nu} & i = T \end{cases}$$

Helicity overlap interference: $\frac{m_e}{E_e}$

Comparison with the LHC: the EFT "blow"

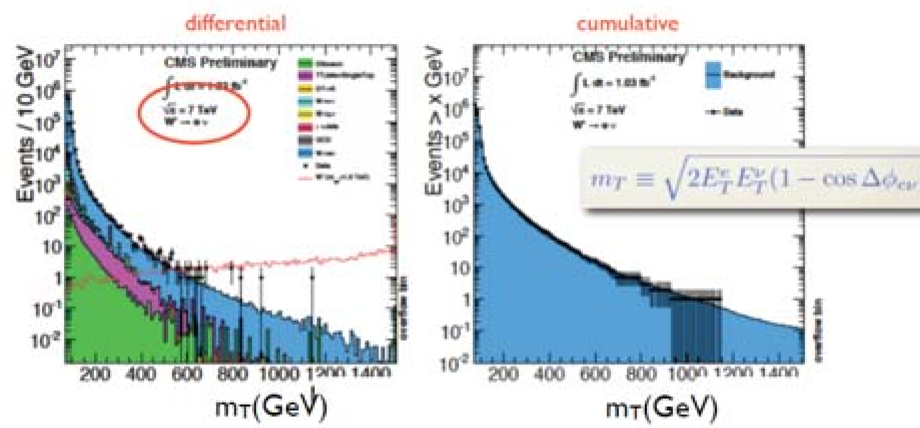
Vincenzo et al. brought us in comparison with the LHC.
Before: hard to compare, we thought model dependency implied nuclear sensitivity could be higher than hep experiments.

- The effective couplings ε_α contribute to the process $p\, p \to e\, \nu + X$



Cirigliano et al.
PPNP **71**, 93 (2013)

- No excess events in transverse mass distribution: bounds on ε_α



Comparison with the LHC: the EFT "blow"

V. Cirigliano et al. have established a connection between hep and beta-decay observables via EFT.

Assuming only left-handed ν's:

From Bhattacharya et al. Phys. Rev. D **94**, 054508 (2016)

$$\mathcal{L}_{\text{CC}} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}}(1 + \epsilon_L + \epsilon_R)$$
$$\times[\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}[\gamma^\mu - (1-2\epsilon_R)\gamma^\mu\gamma_5]d$$
$$+ \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}[\epsilon_S - \epsilon_P\gamma_5]d$$
$$+ \epsilon_T \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d] + \text{H.c.},$$

$$C_i = \frac{G_F}{\sqrt{2}} V_{ud} \bar{C}_i \quad (6a)$$
$$\bar{C}_V = g_V(1 + \epsilon_L + \epsilon_R) \quad (6b)$$
$$\bar{C}_A = -g_A(1 + \epsilon_L - \epsilon_R) \quad (6c)$$
$$\bar{C}_S = g_S \epsilon_S \quad (6d)$$
$$\bar{C}_T = 4 g_T \epsilon_T, \quad (6e)$$

Rough result of analysis of LHC limits:

$$\epsilon' s \leq \vartheta(10^{-3})$$

Beta decay sensitivity could reach beyond LHC.

Beta decay with nuclei:

Confining radioactivity helps measuring kinematics

Trapping can also allow polarization

Amazing atom and ion traps have come a long way!

Initial developments:

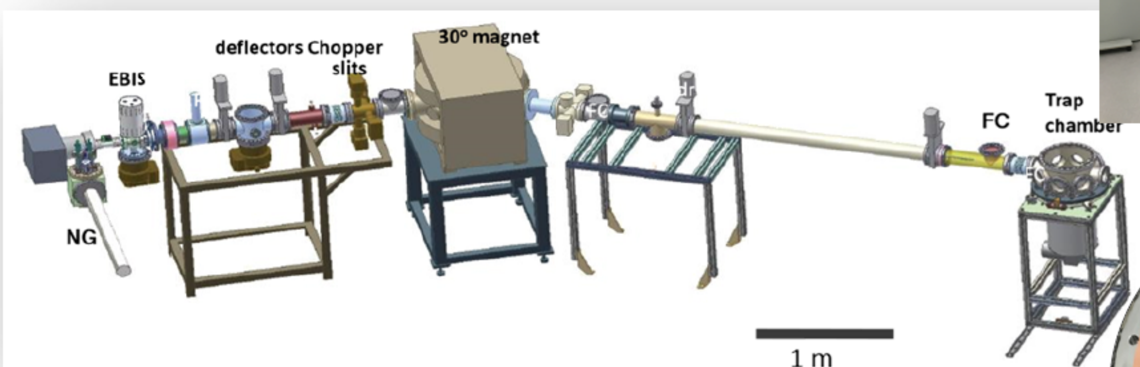
Berkeley, Stony Brook, TRIUMF (atoms)

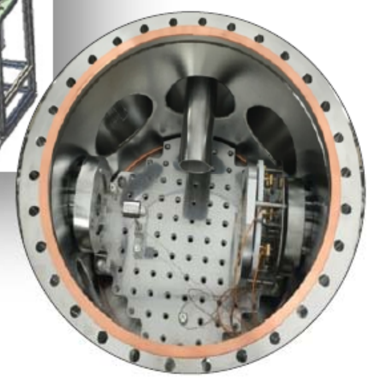
CERN, Argonne, CAEN, TRIUMF (ions)

What follows are vignettes showing aim of some groups (not complete…)

Ion trap at Hebrew University of Jerusalem and Racah Institute

Electrostatic ion beam trap

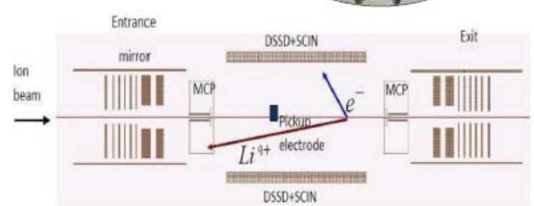




EBIT ion source

Position/ Energy sensitive beta detector

Position sensitive MCP for recoil ions

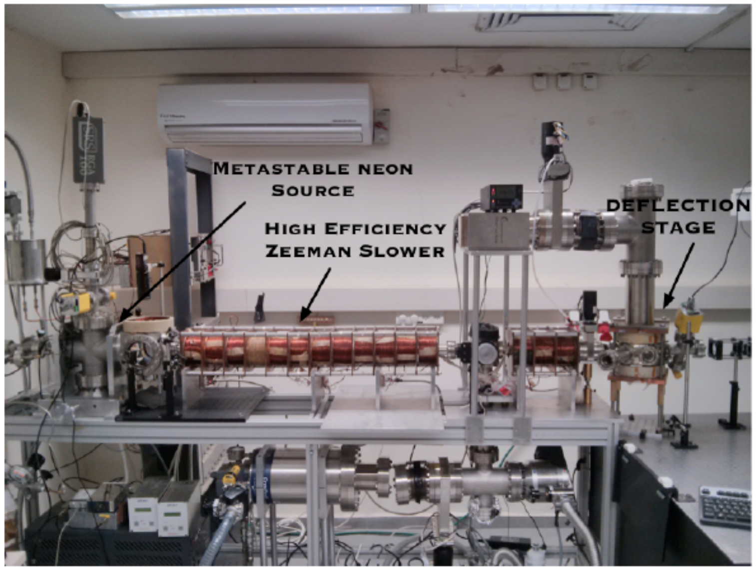


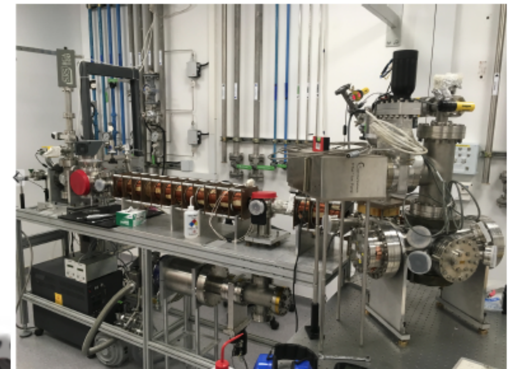
Experimental Scheme

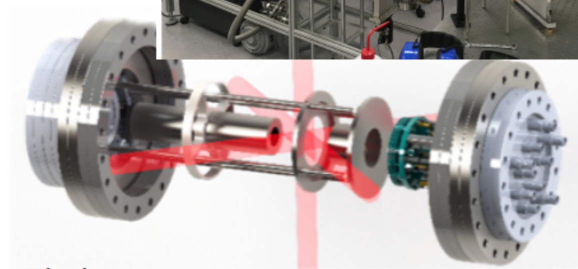
Thanks: Guy Ron

Ion trap at Hebrew University of Jerusalem and Racah Institute

Neon MOT

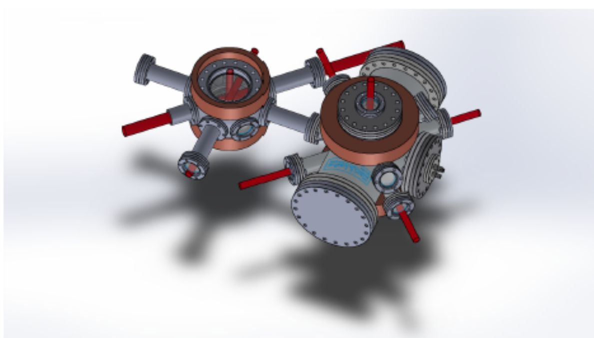


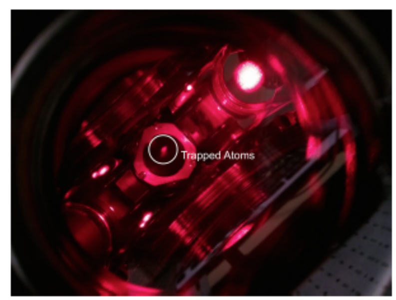




Timing detector for shake off electrons

Position sensitive detector for recoil ions





Thanks: Guy Ron

Ion trap at Hebrew University of Jerusalem and Racah Institute

Current status

- Both EIBT and MOT systems up and running and installed at SARAF, including trapping, detectors, and DAQ.
- High power Liquid-Li target (for n-production) produced and being installed (beam on target - Nov 2018).
- ^{6}He and ^{23}Ne production (using solid LiF target - lower flux) demonstrated at SARAF and will scale up with the new neutron targets.
- He experiment to start by Jan 2019.
- Ne experiments to start by Mar 2019.

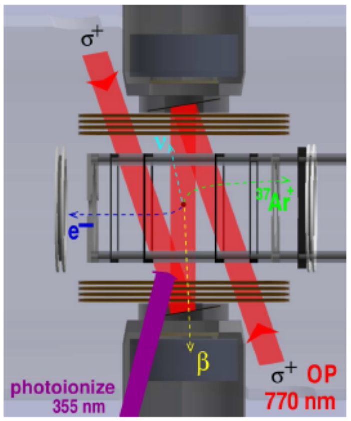
Thanks: Guy Ron

TRIUMF atomic trap

j.a. behr,

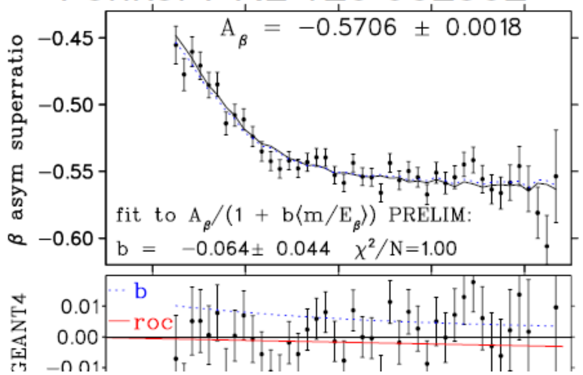
TRIumf Neutral Atom Trap for β decay

TEXAS A&M UNIVERSITY

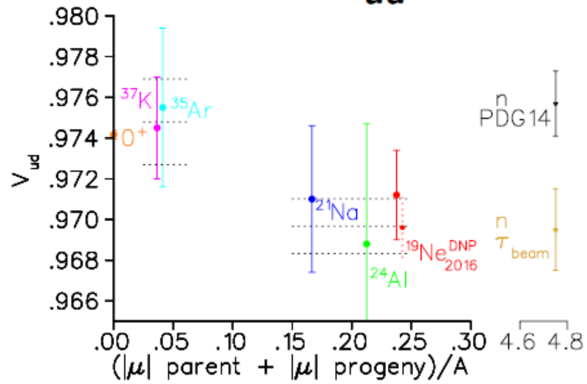


Most accurate β asymmetry:

Fenker PRL 120 062502



Constraints on V_{ud}



Best β-decay limit

$M_W^R \geq 352$ GeV 90%

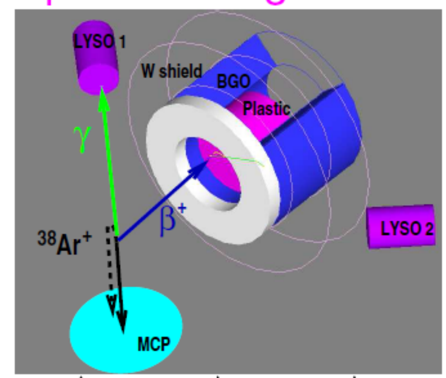
Future: asymmetry of nuclear recoils

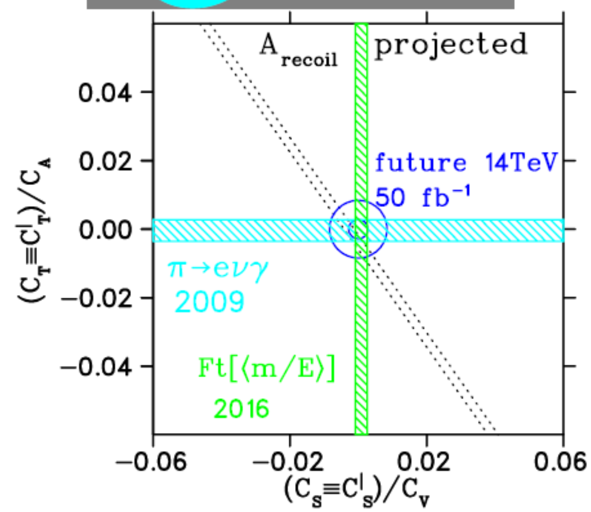
Similar sensitivity to 4-fermion contact interactions as

$p+p \to e^- + E_\perp^{miss} \to$

$\mathcal{T}$ in $^{38m}K \to {}^{38}Ar + \beta\nu\gamma$

Unique for 1st generation





Thanks: John Behr, Dan Melconian

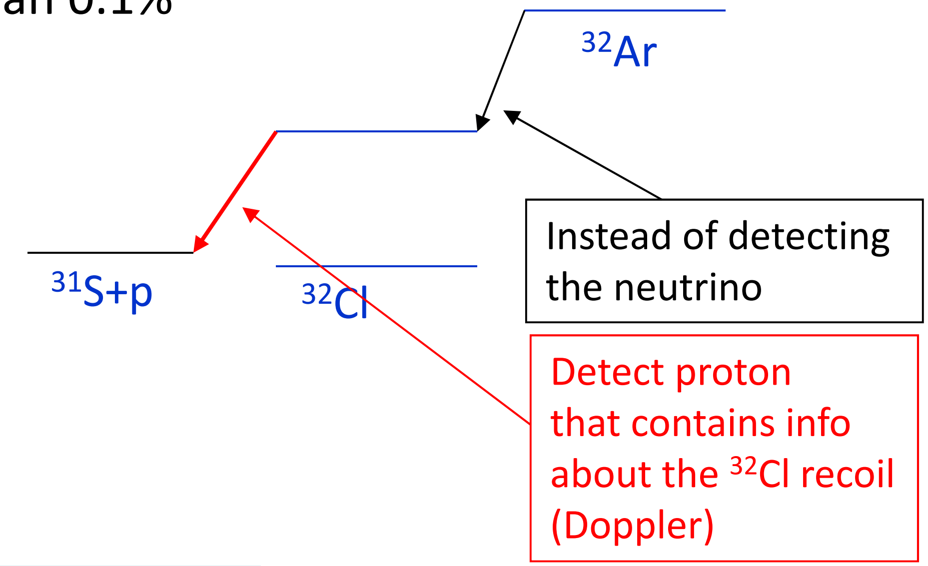
CENPA Center for Experimental Nuclear Physics and Astrophysics

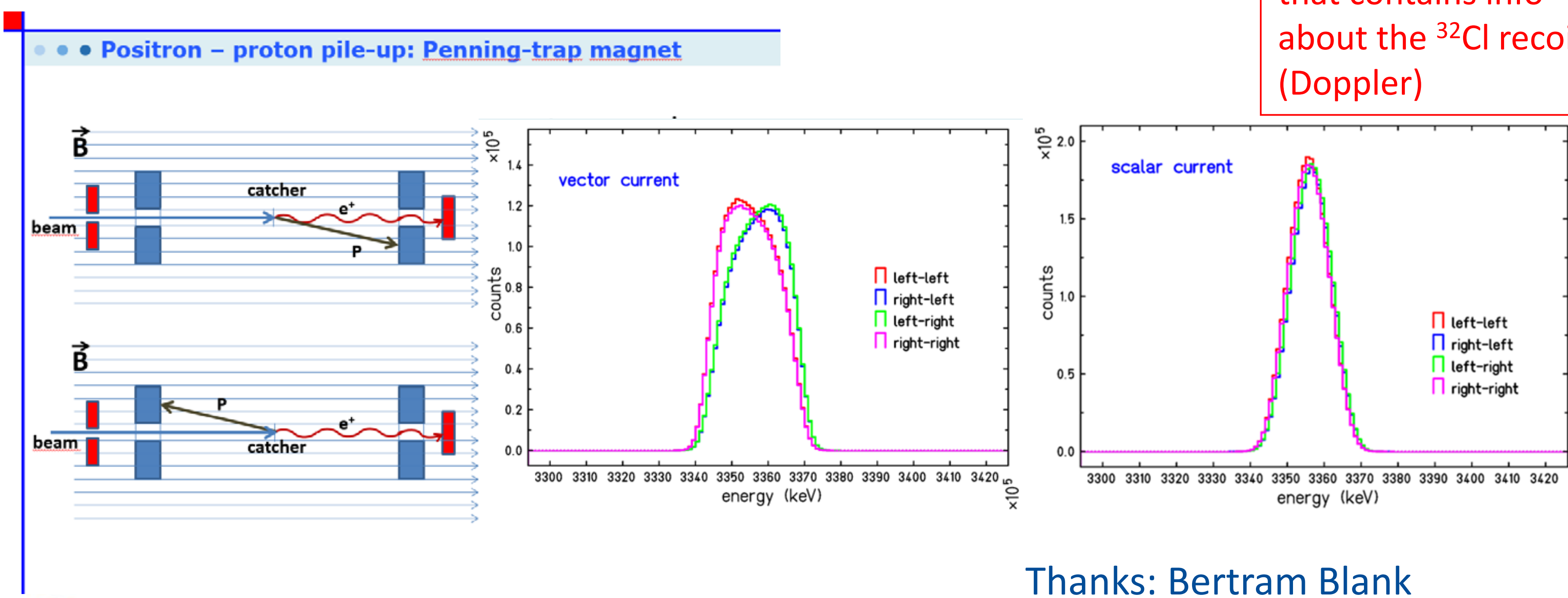
CERN ion trap

^{32}Ar Decay at WISArD

Aim: little-a to better than 0.1%

Bertram Blank et al. – CEN Bordeaux-Gardignan
N. Severijns et al. – KU Leuven
D. Zakoucky et al. – NPI Rez
E. Lienard et al. – LPC CAEN

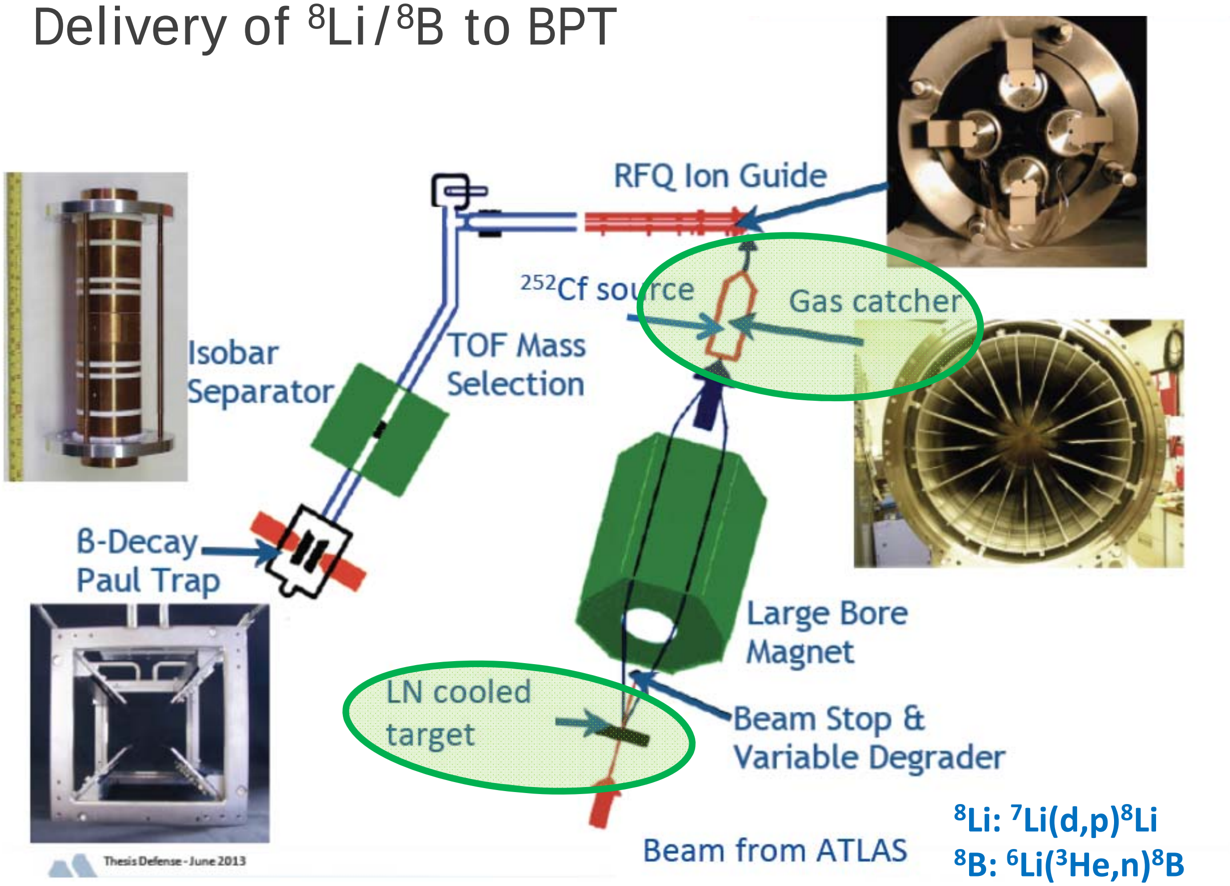




Thanks: Bertram Blank

ANL trap: *A=8* experiments

Delivery of ^{8}Li/^{8}B to BPT



- **Gas target geometry better matched to reactions**
- **New gas catcher optimized to handle lighter masses and space-charge issues**

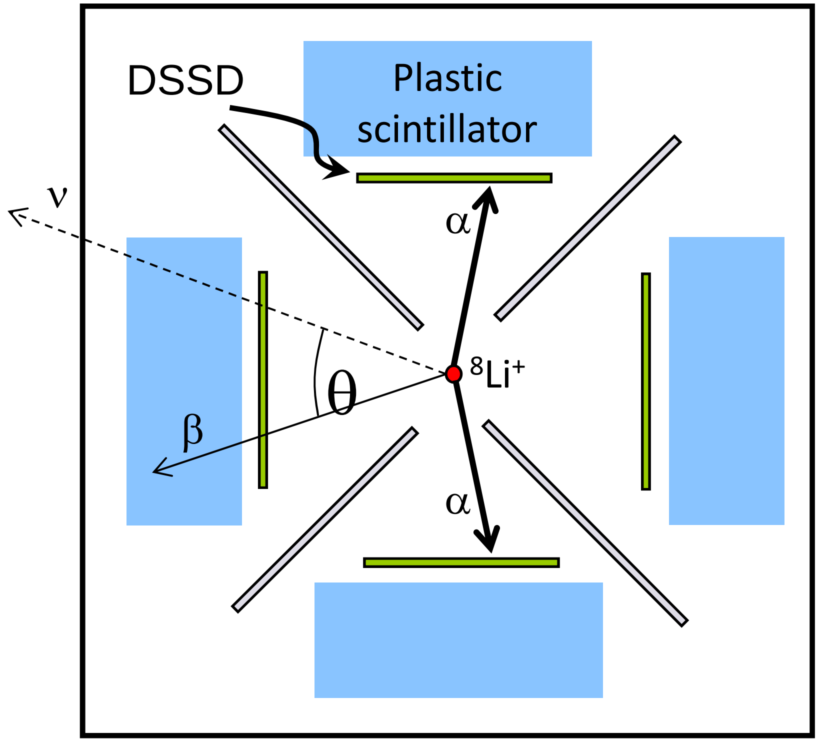
Upgrades resulted in 10× increase in ion delivery to BPT

→ measure ^{8}B to study decay correlations + recoil-order terms

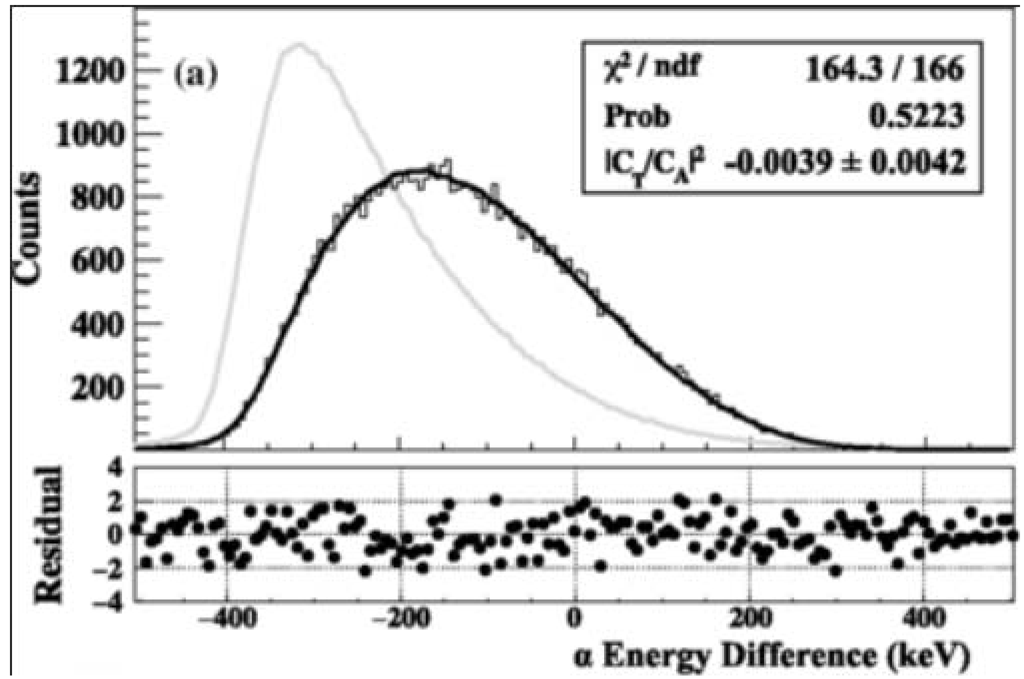
→ revisit ^{8}Li with 10× higher statistics

Thanks: Guy Savard

ANL trap: *A=8* experiments



Ion trap to hold the A=8 nuclei. α's and β's are measured with streep Si detectors.
Hit locations allow tracking back to the emission point.



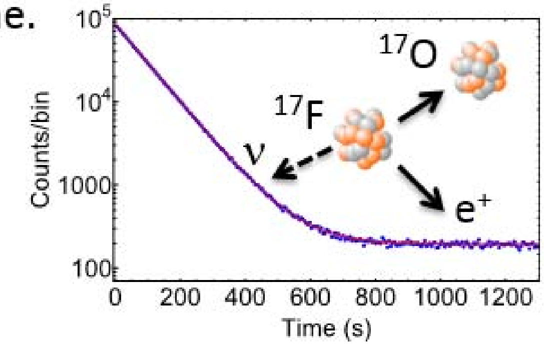
Spectrum from events with β and α particles detected on the top and bottom detector.
(a) Energy difference along with the fit to the simulated spectrum and the normalized residual. The gray curve shows the expected spectra for a pure T interaction.

Thanks: Guy Savard

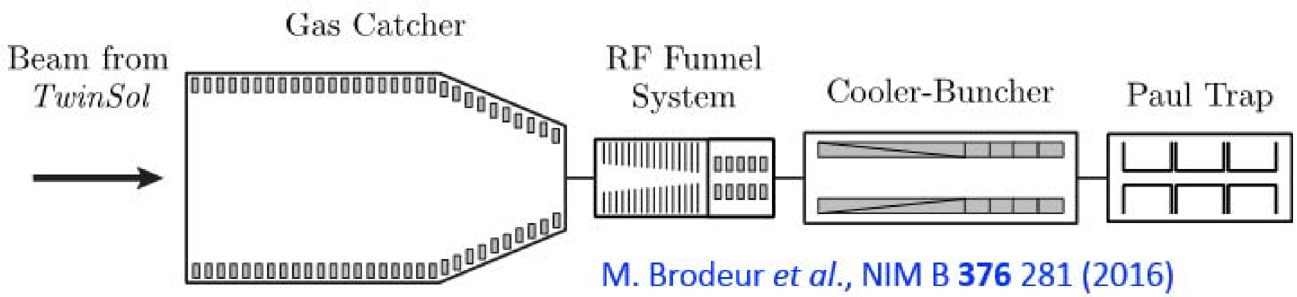
Precision β-decay at Notre Dame

- Precision measurements on superallowed mixed β-decay transition between mirror nuclides using the TwinSol RIBs at Notre Dame.
- Precision half-life measurements: measured $t_{1/2}$ of ^{17}F, ^{11}C, ^{25}Al, more under analysis and planned.

^{17}F: M. Brodeur *et al.*, PRC **93** 025503 (2016)
^{25}Al: J. Long *et al.*, PRC **96** 015502 (2017)
^{11}C: A. Valverde *et al.*, PRC **97** 035503 (2018)



- Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict) ion trapping system to measure the β-ν angular correlation parameter.
- Gas catcher has been donated by ANL, RF funnel under design, cooler-buncher has been assembled, and Paul trap being simulated.



M. Brodeur *et al.*, NIM B **376** 281 (2016)

PHYS-1713757 (Nuclear Science Laboratory)
PHYS-1725711 (MRI for St. Benedict)

UNIVERSITY OF NOTRE DAME

Thanks: Maxime Brodeur

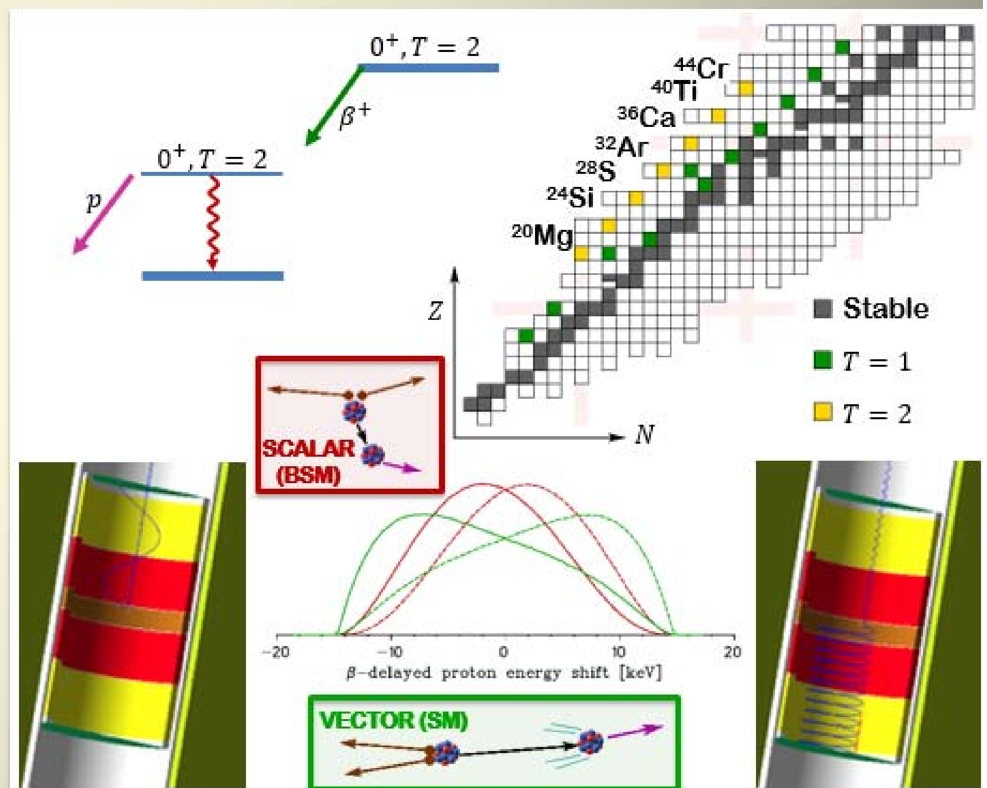
Texas A&M ion trap: TAMU

Superallowed $T = 2$ β-delayed proton transitions: Theory needs

Goal is $\lesssim 0.1\%$ precision in correlation parameters to search for BSM physics, both in experiment *and* theory predictions

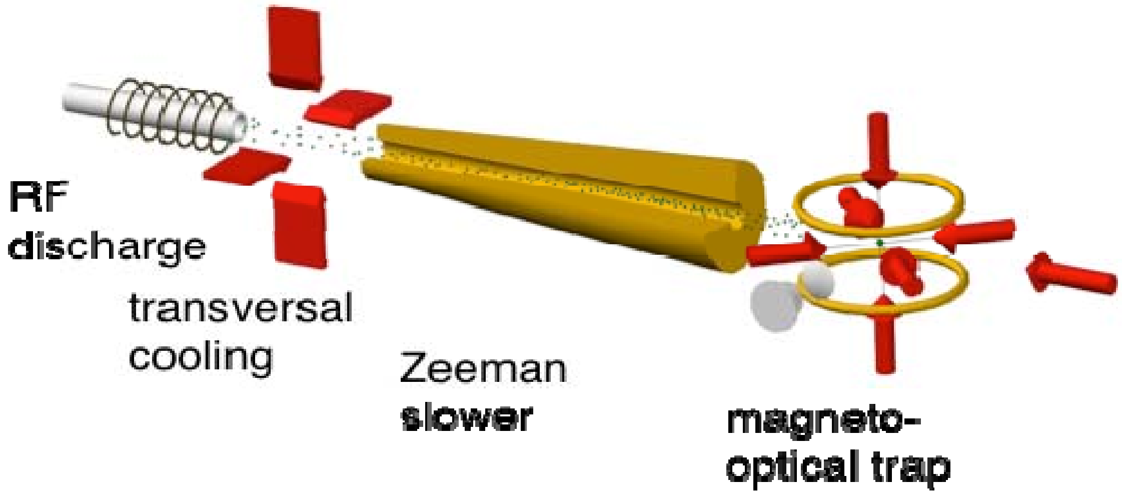
- Corrections for the $\mathcal{F}t$ value (δ_C, δ_{NS}, δ_R'; Δ_R^V); T-dependence to discern?
- Matrix elements for recoil-order corrections
  - $M_{r^2}, M_{\sigma r^2}, M_Q, M_{\{r,p\}}, M_{r \cdot p}, M_L, M_{\sigma L}, \ldots$
- More complete and detailed radiative corrections; 4-body decay (e.g. Gluck Comp Phys Comm **101** (1997))
- Suggest ancillary measurements to help benchmark shell models?

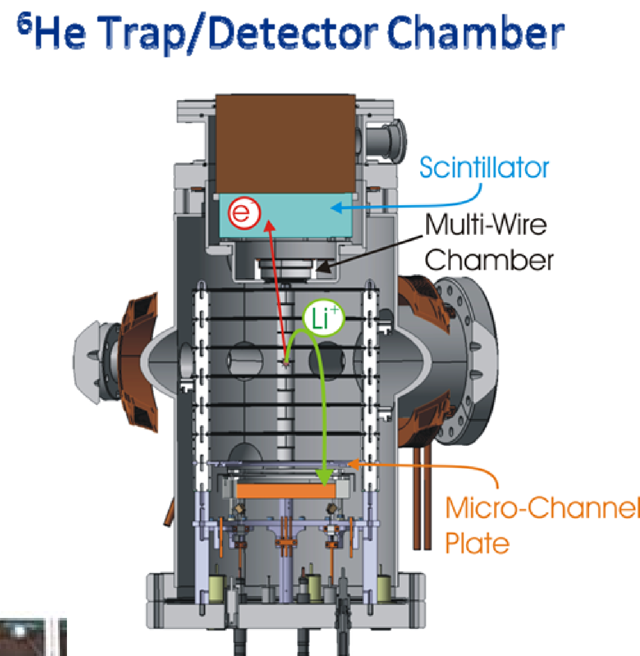
TAMUTRAP is especially suited for β-delayed proton decays



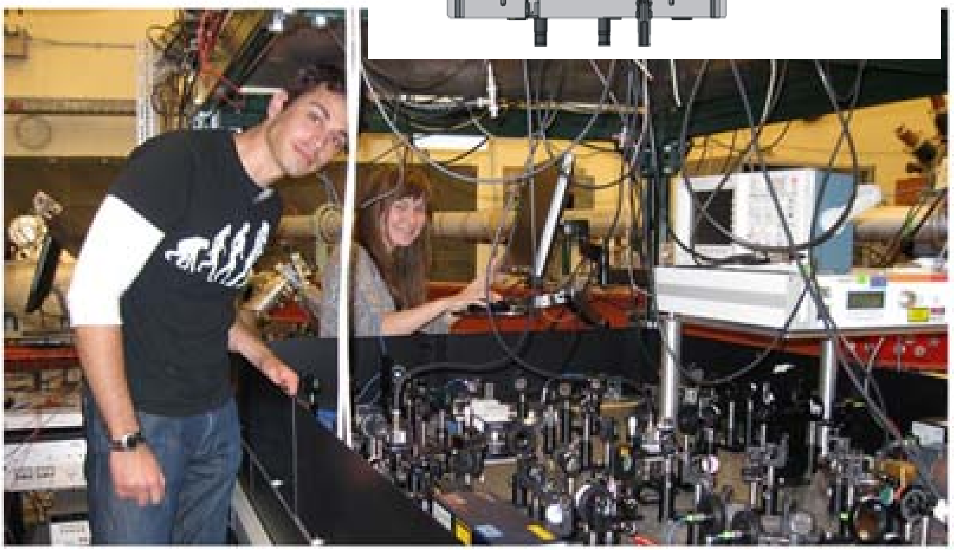
Thanks: Dan Melconian

Seattle-ANL atomic trap





- Goal: measure “little *a*” to 0.1% in ^{6}He
- Laser cooling and trapping of ^{6}He
- Detect electron and ^{6}Li in coincidence
- ΔE-E scintillator system for e.
- Micro-channel plate detector for ^{6}Li.

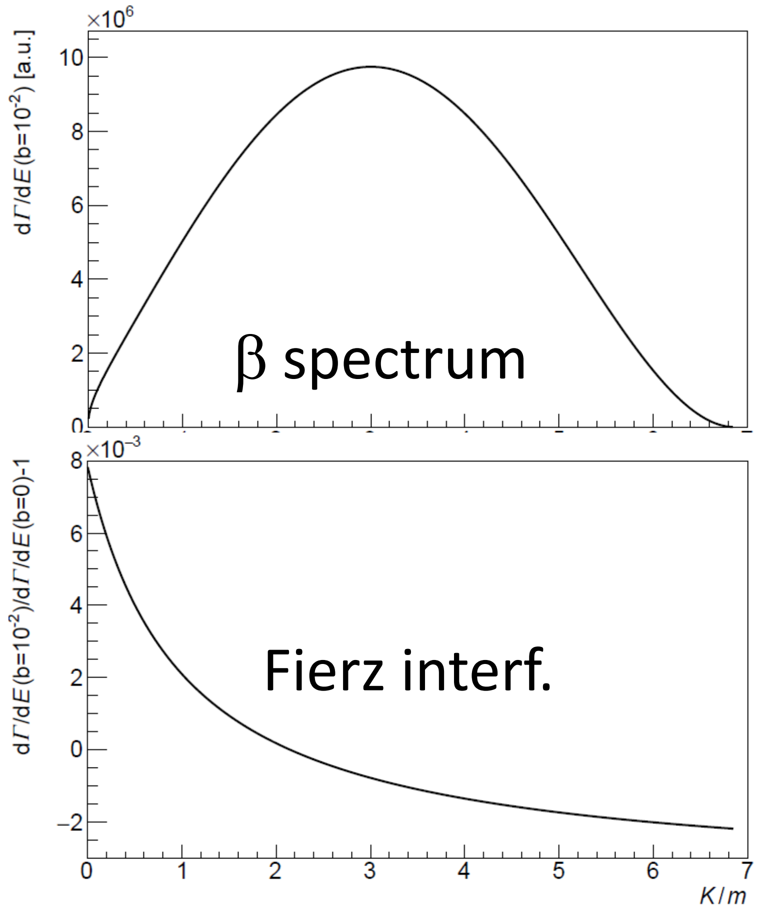


19σ discrepancy with atomic theory on charge distribution:

Phys. Rev. A **96**, 053411 (2017)

Beta spectra

From above: most sensitive measurement could be β spectra.
(Look for Fierz interference distortion $\frac{m_e}{E_e}$)



Warning: β spectra are known to be difficult to measure.

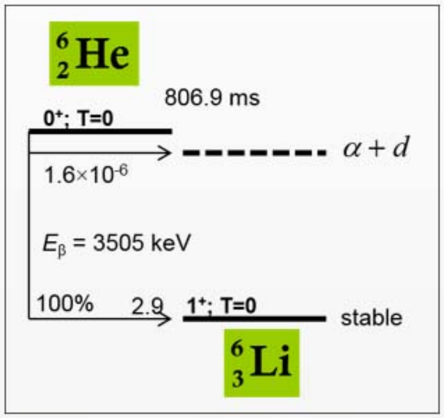
Typical setup: magnetic spectrometer…
Difficult to overcome systematic uncertainties.

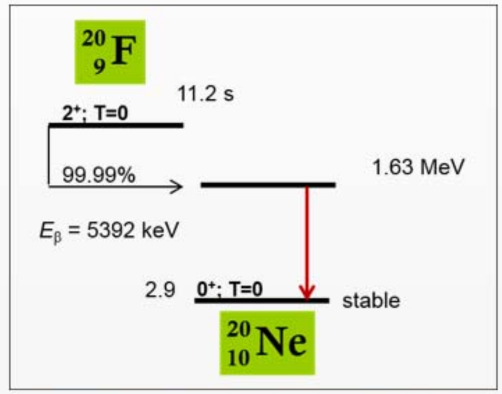
Beta spectra → implantations into scintillators

Measurements of energy spectra at NSCL

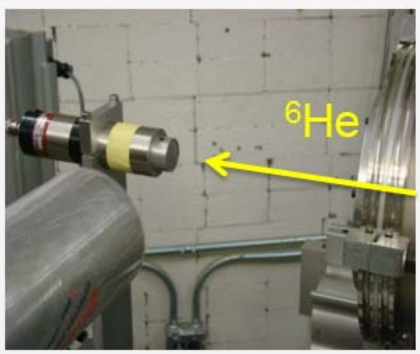
Uses a calorimetric technique which eliminates electron backscattering from detectors.

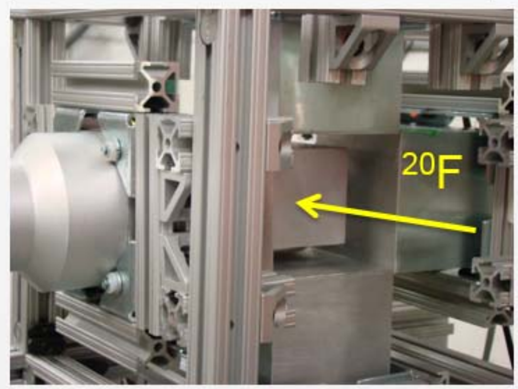
Applied to β^- GT transitions in isospin triplets





CsI(Na)
NaI(Tl)





CsI(Na)
PVT

46 MeV/nucleon

132 MeV/nucleon

Thanks: Oscar Naviliat-Cuncic

Beta spectra → implantations into scintillators

Status and Plans

- Current level of statistical sensitivity for Fierz term:
  - 3×10^{-3} for ^{20}F
  - 1.5×10^{-3} for ^{6}He (with CsI and NaI detectors)

- New beam time requests in preparation to push systematic errors below the level of current statistical sensitivity.

Thanks: Oscar Naviliat-Cuncic

Beta spectra → CRES technique

Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

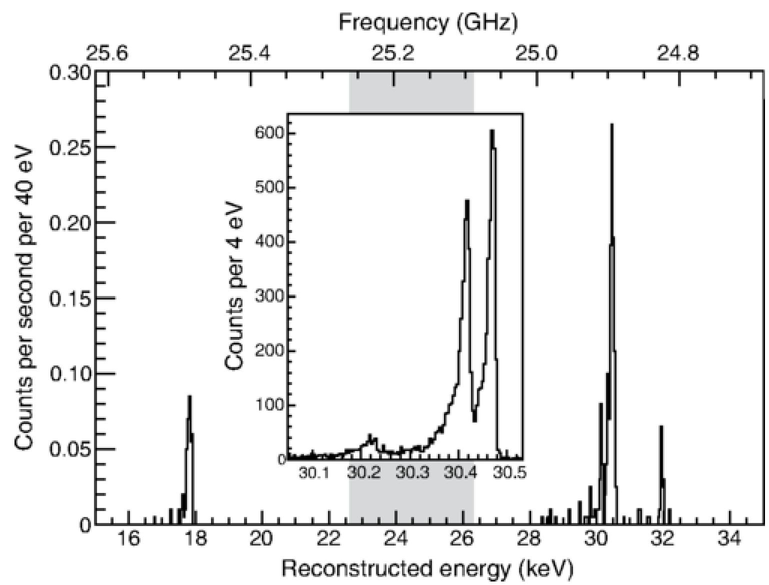
Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

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 Collaboration)

In principle: allows determination of the beta energy at creation.

Seattle-ANL-PNNL-NCSU-Tulane
→ He6-CRES collaboration.
Measure ^{6}He, ^{19}Ne, ^{14}O.

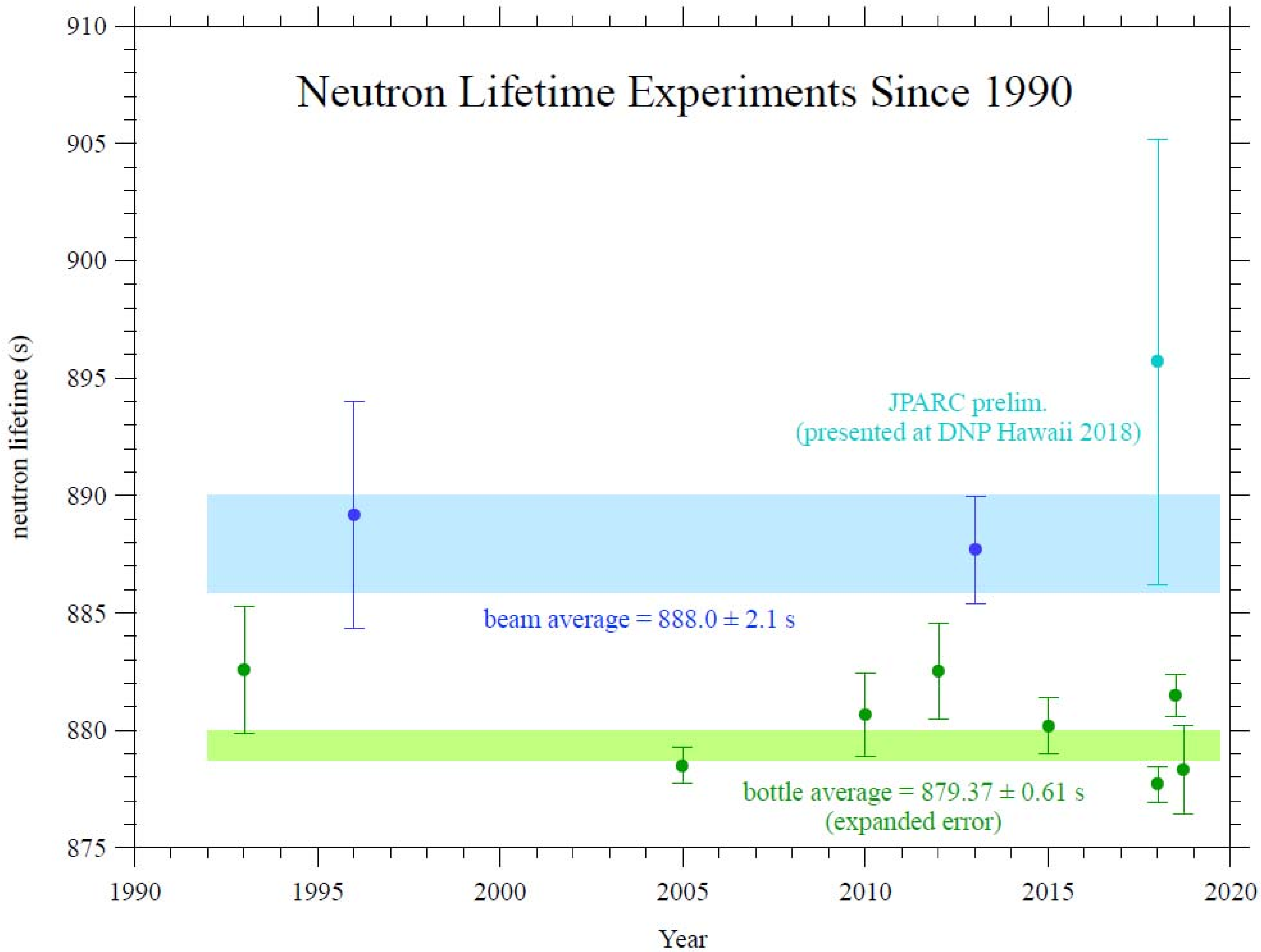


Neutron beta decay.

After many years of developments,
many recent important results…

Vignettes follow.

Neutron lifetime

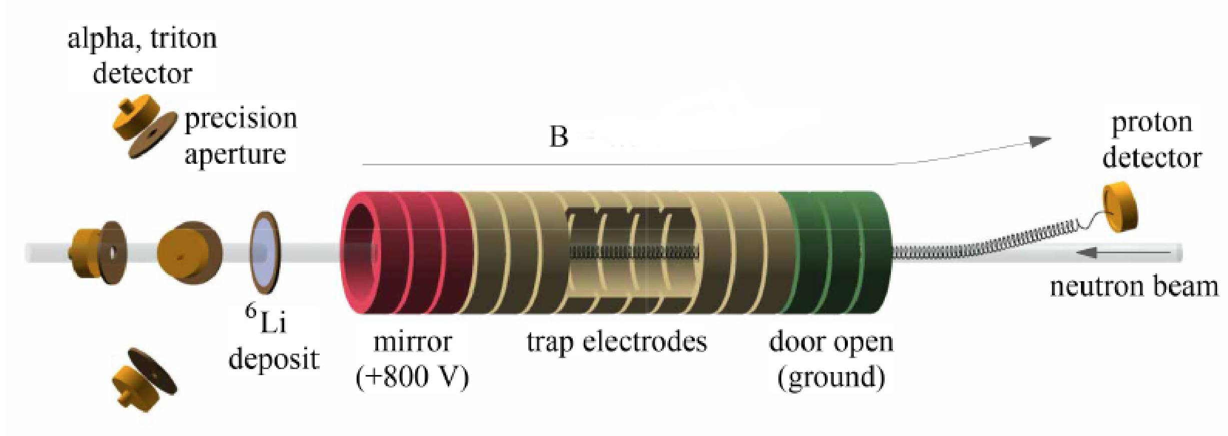


Thanks: Fred Wietfledt

BL3

Beam Lifetime 3

A next generation beam neutron lifetime experiment



Goals:

1) Cross check, explore, verify all systematic effects in the beam method to the 0.1 s level
2) Reduce the beam neutron lifetime uncertainty to < 0.3 s.

University of Tennessee

Tulane University

Indiana University

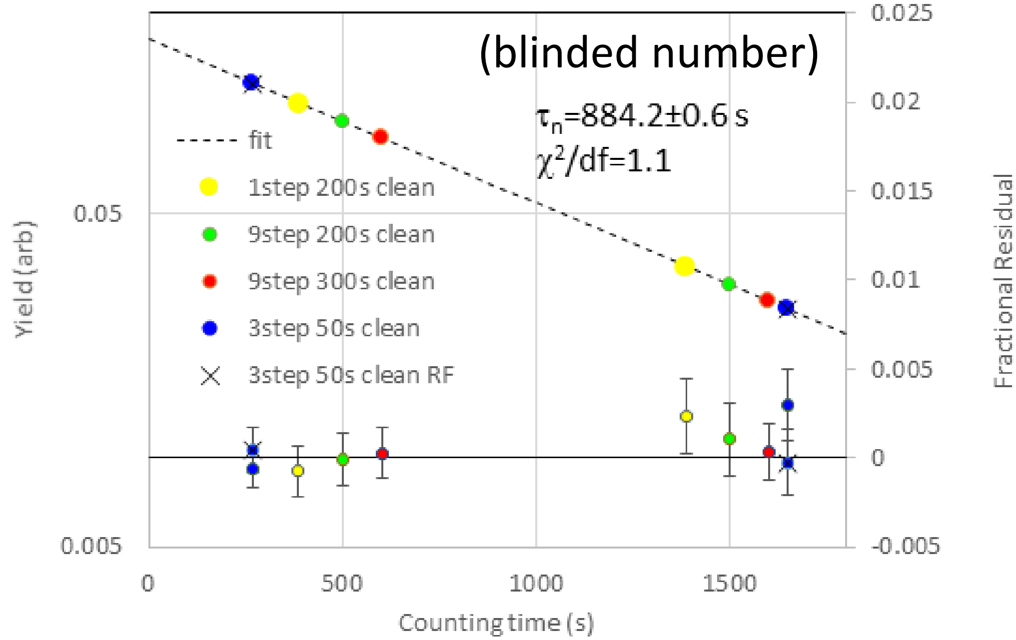
Hamilton

NIST National Institute of Standards and Technology

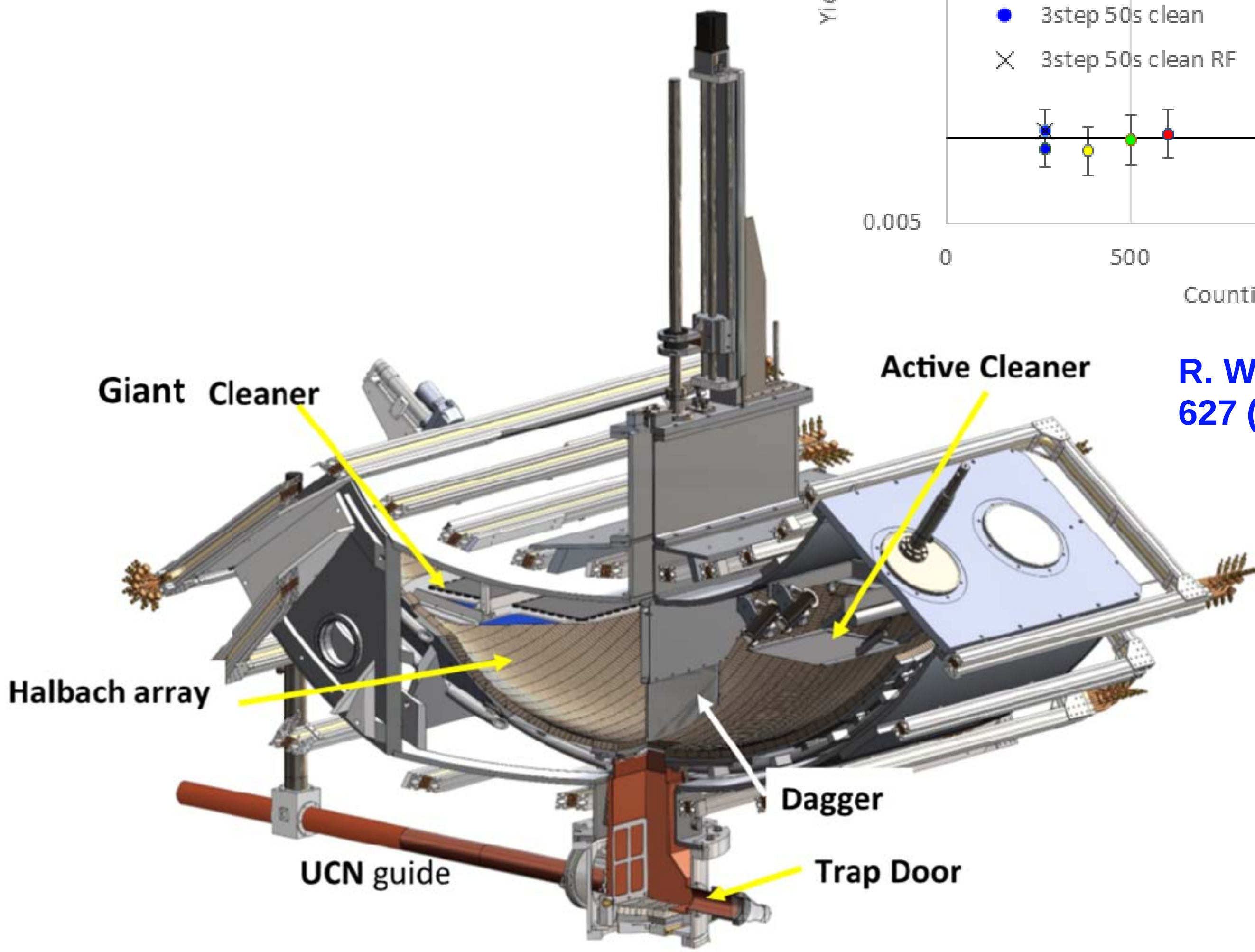
Thanks: Fred Wietfledt

The UCNτ neutron lifetime experiment

Global fit into a single exponential function



R. W. Pattie Jr. *et al.*, Science 360, 627 (2018).

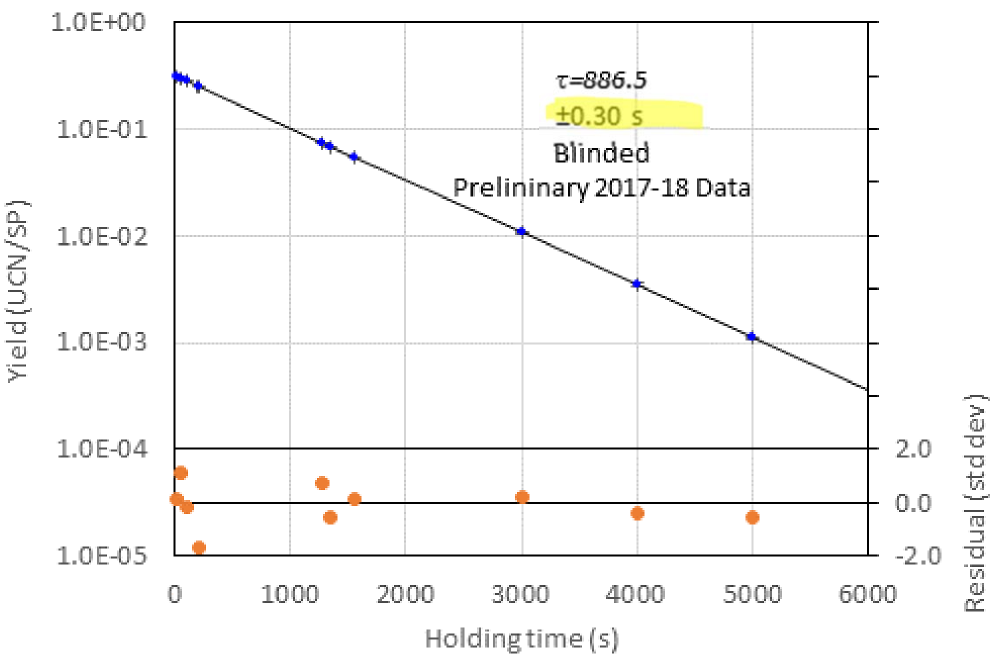


Thanks: Chen-Yu Liu

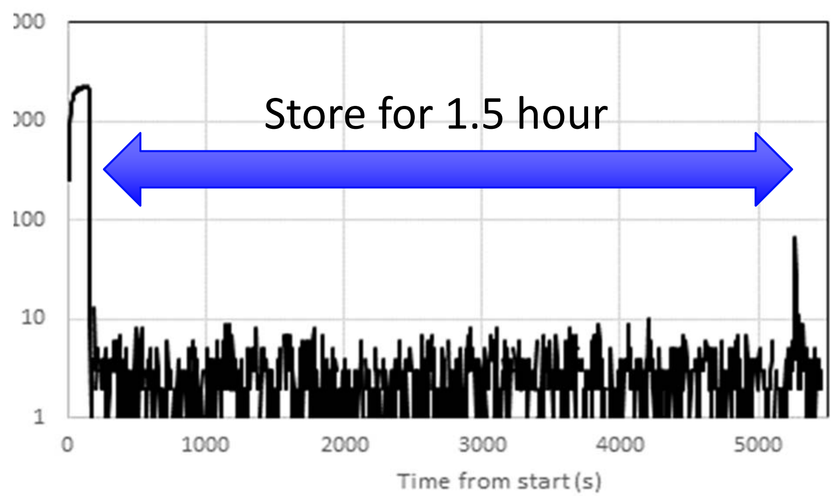
Moving forward

Effect	Upper bound (s)	Direction	Method of evaluation
Depolarization	0.07	+	Varied external holding field
Microphonic heating	~~0.24~~ 0.05	+	Detector for heated neutrons
Insufficient cleaning	~~0.07~~ 0.02	+	Detector for uncleaned neutrons
Dead time/pileup	0.04	±	Known hardware dead time
Phase space evolution	~~0.10~~ 0.02	±	Measured neutron arrival time
Residual gas interactions	~~0.03~~ 0.01	±	Measured gas cross sections and pressure
Background shifts	<0.01	±	Measured background as function of detector position
Total	~~0.28~~ 0.10		(uncorrelated sum)

Last beam cycle (2017-2018):

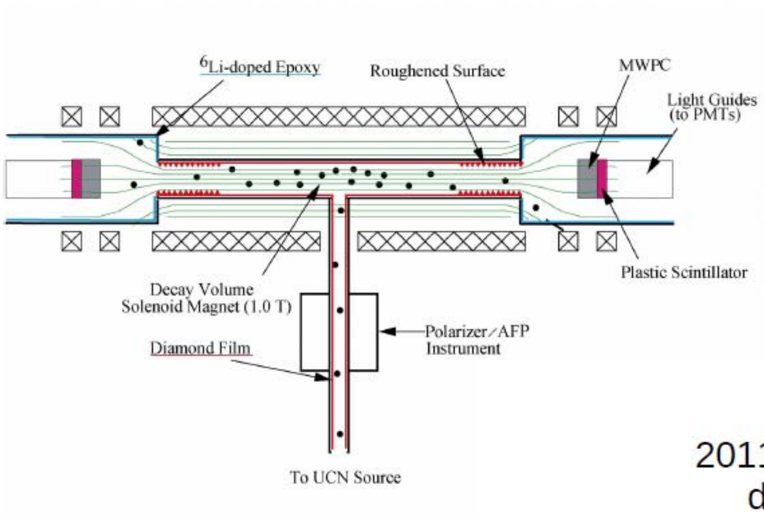


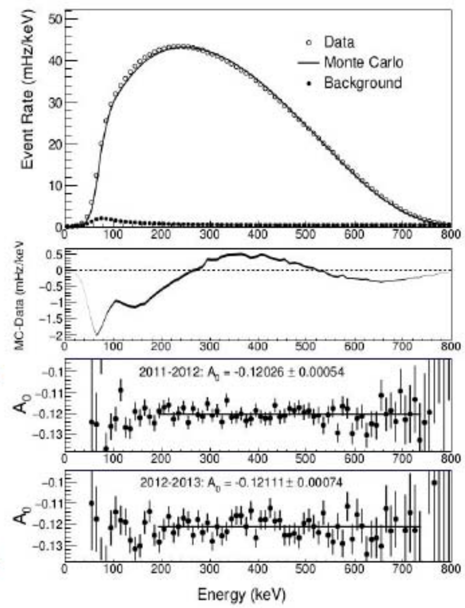
Projected statistical uncertainty: 0.15 s
systematic uncertainty: 0.10 s
→ total uncertainty: 0.18 s
Achievable over the next 2-3 years.



Neutron beta decay

UCNA and UCNA+





2011-2013 data

- 2017: final UCNA resullts
- 2017: limits on Fierz terms (extracted from 2010 data)
- 2018: limits on pair production in DM decay
- Ongoing: Fierz limits from 2011 - 2013 data

$$A_0 = -0.12054(44)_{\text{stat}}(68)_{\text{syst}}$$ **0.67%**

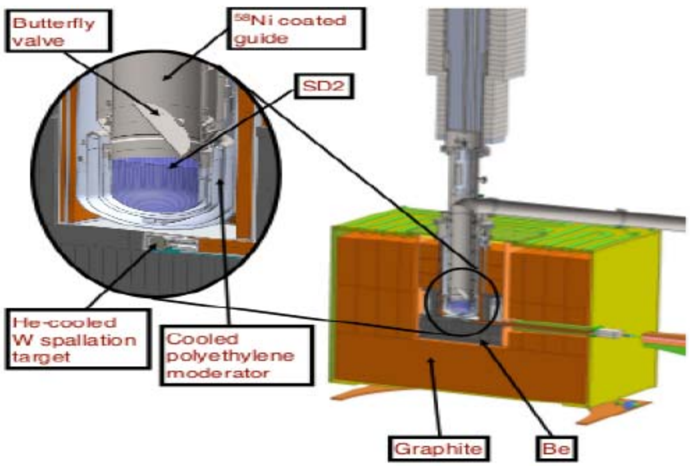
$$\lambda \equiv \frac{g_A}{g_V} = -1.2783(22)$$ **0.17%**

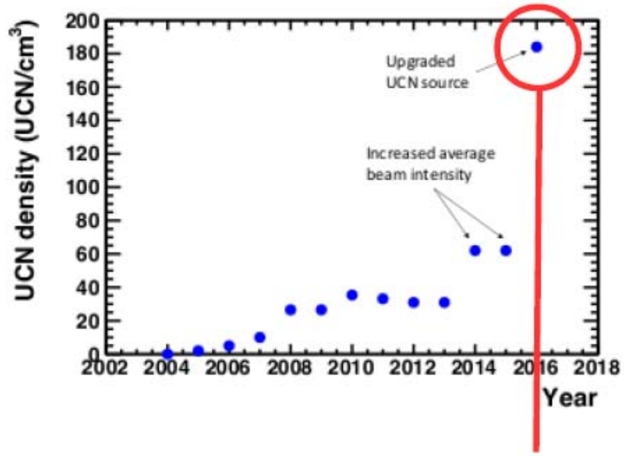
Final PERKEO II run had precision 0.54%

Thanks: Albert Young

Opportunities for Progress: UCNA+

LANSCE Area B Source Upgrade!





2016: **5x** 2010 decay rate!

R&D program underway:

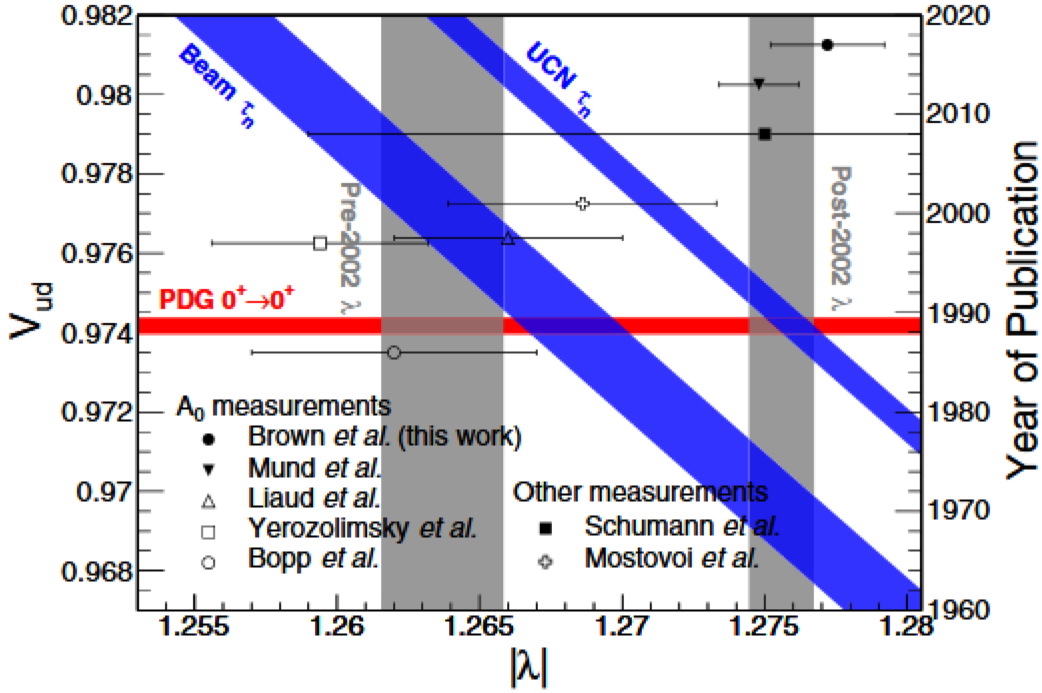
Statistical Precision of 0.12%/year !

- Redesign experiment reduce scattering corrections by eliminating foils
- Improve scinitillator design (synergistic with UCNProbe) to reduce size and dependence on environmental vairables, and produce real-time background monitoring
- Implement 2D scanning with conversion sources

Total Systematic Uncertainty < 0.1%

Thanks: Albert Young

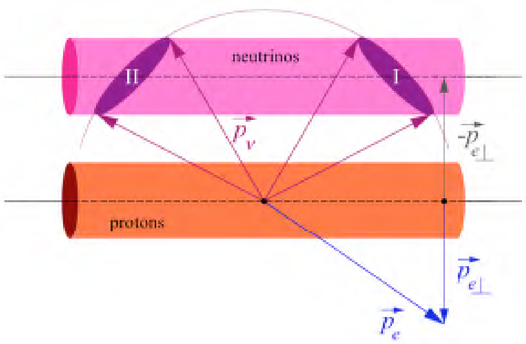
Neutron lifetime, beta asymmetry and $0^+ \rightarrow 0^+$ nuclear



From UCNA
Phys. Rev. C **97**, 035505 (2018)

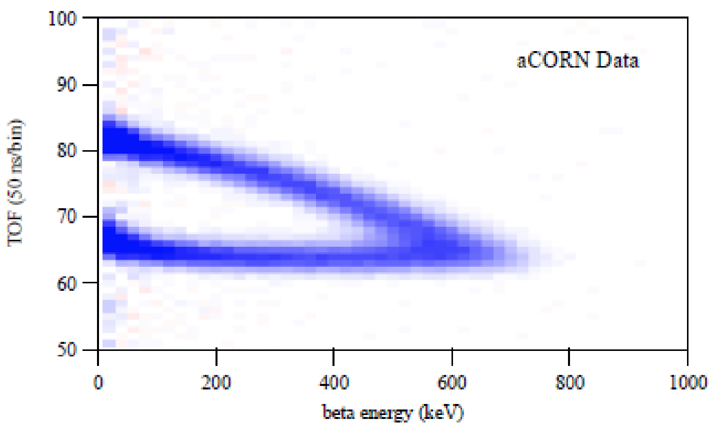
Neutron beta decay: β-ν

aCORN: Measuring the electron-antineutrino correlation (little *a*) in free neutron beta decay



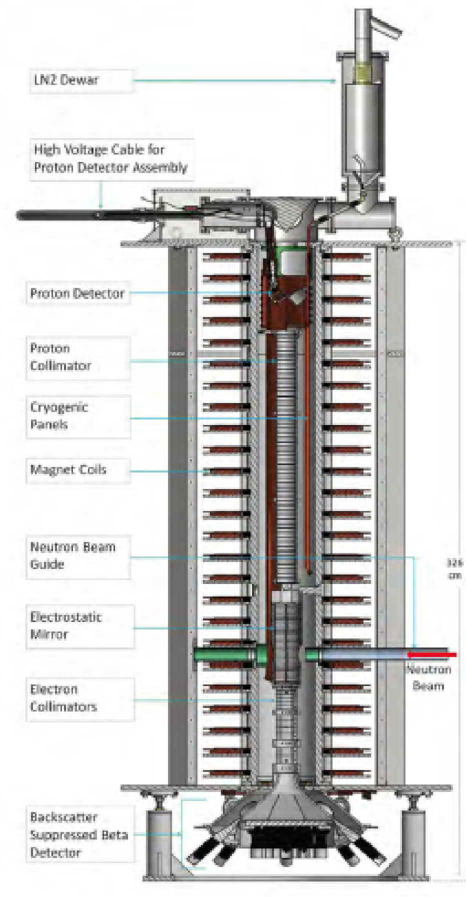
2017 new result: 3.8%

NG-6 data set:
a = -0.1090 ± 0.0030 (stat) ± 0.0028 (sys)
G. Darius, et al. , PRL 119, 042502 (2017)



NG-C data:
collected in 2015-2016 run
10 x larger data set
expect <2% result soon

aCORN B:
Measure B-coefficient
(antineutrino asymmetry)
to ~0.3% using a polarized beam



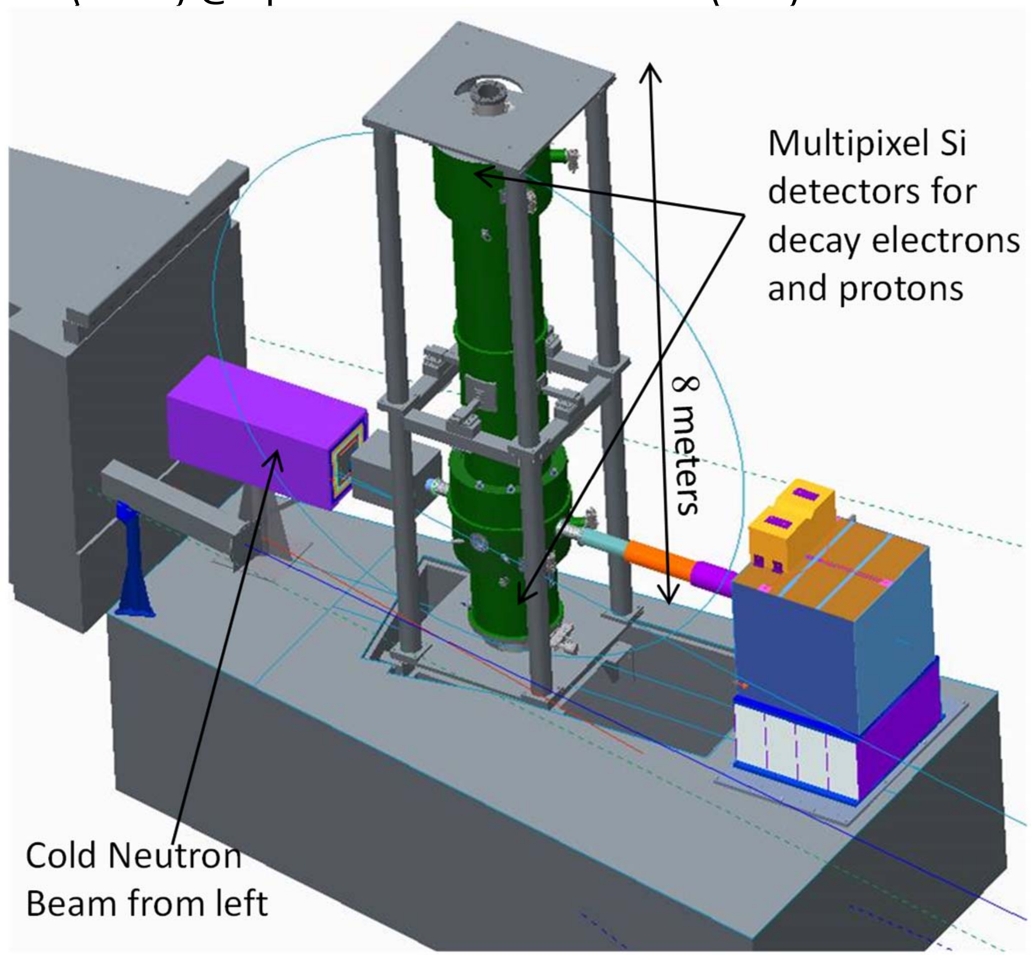
Thanks: Fred Wietfeldt

The Nab experiment

Nab @ Fundamental Neutron Physics Beamline (FNPB) @ Spallation Neutron Source (SNS)

$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

$a = a(\lambda)$ $b \neq 0$ indicates S,T



Measurement of electron energy spectrum gives b.

Goal: $\Delta b \leq 3 \cdot 10^{-3}$

Measurement of a from measurement of proton time of flight and electron energy.

Goal: $\Delta a/a \leq 10^{-3}$

Experiment is being installed right now, and is supposed to be running at SNS until end of 2021.

General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)

Thanks: Stefan Baessler

Followup: Nab polarized (abBA / PANDA)

Not yet funded or scheduled.

$$d\Gamma \propto \varrho(E_e)\left(1 + A\frac{p_e}{E_e}\cos(\vec{\sigma}_n, \vec{p}_e) + B\cos(\vec{\sigma}_n, \vec{p}_\nu)\right)$$

$A = A(\lambda)$ $B \neq B(\lambda)$ may indicate S,T,V+A

Only major modification: Addition of a neutron beam polarizer

Main uncertainties in previous best experiments: statistics, detector, background, polarization

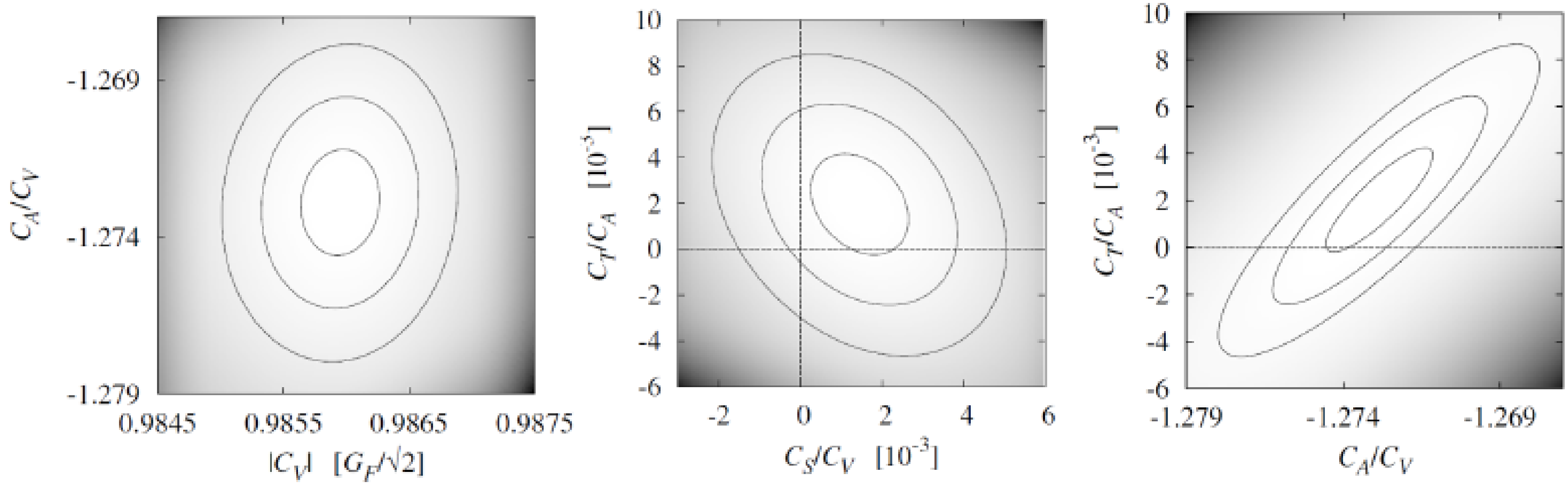
- Statistics @ SNS or NIST is sufficient for a competitive measurement of A, but could be better
- Superior detector energy resolution, good enough time resolution
- Keep coincidence detection (electrons and protons) to improve background
- Polarization measurement seems manageable (Crossed supermirrors or He-3)

Goal: $\Delta A/A \leq 10^{-3}$, $\Delta B/B \leq 10^{-3}$

Thanks: Stefan Baessler

Summary of present limits

Gonzalez-Alonso, Naviliat-
Cuncic, Severijns
hep-ph 1803.08732



Summary of experimental aims

Table 3 of Gonzalez-Alonso, Naviliat-Cuncic, Severijns hep-ph 1803.08732

Invited review article for Prog. Part. Nucl. Phys.

Several experiments reaching 10^{-3} uncertainties.

Coefficient	Precision goal	Experiment (Laboratory)	Comments
τ_n	1.0 s; 0.1 s [209]	BL2, BL3 (NIST) [209]	In preparation; two phases
	1.0 s; 0.3 s [213]	LiNA (J-PARC) [210, 213]	In preparation; two phases
	0.2 s [214]	Gravitrap (ILL) [202, 214]	Apparatus being upgraded
	0.3 s [200]	Ezhov (ILL) [200]	Under construction
	0.1 s [221]	PENeLOPE (Munich) [221]	Being developed
	$\lesssim$ 0.1 s [222]	UCNτ (LANL) [187, 188, 222, 223]	Ongoing
	0.5 s [224]	HOPE (ILL) [187, 224, 225]	Proof of principle Ref. [225]
	1.0 s; 0.2 s [187]	τSPECT (Mainz) [187, 226]	Taking data
β-spectrum	$\mathcal{O}(0.01)$ [260]	Supercond. spectr. (Madison) [260]	C_1 in Eq. (51). Ongoing
β-spectrum	$\mathcal{O}(0.01)$ [257]	Si-det. spectr. (Saclay) [257, 258]	C_1 in Eq. (51). Ongoing
b_{GT}	0.001	Scintill. detectors (NSCL) [115, 264]	Analysis ongoing (^{6}He, ^{20}F)
	$\mathcal{O}(0.001)$ [274]	miniBETA (Krakow-Leuven) [267–269, 274]	Being commissioned
	$\mathcal{O}(0.001)$ [280]	UCNA-Nab-Leuven (LANL) [275, 276, 280]	Analysis ongoing (^{45}Ca)
b_n	0.003 [285]	Nab (LANL) [187, 285, 350, 351]	In preparation
	0.003 [289]	PERKEO III (ILL) [289]	Possible with A_n data
	0.001 [287]	PERC (Munich) [287, 288]	Planned
a_F	0.1% [299]	TRINAT (TRIUMF) [299, 303]	Planned (^{38}K)
	0.1% [336]	TAMUTRAP (TA&M) [336]	Superallowed βp emitters
	0.1% [78]	WISArD (ISOLDE) [78, 176]	In preparation (^{32}Ar βp decay)
a	not stated	Ne-MOT (SARAF) [304, 305]	In preparation (^{18}Ne, ^{19}Ne, ^{23}Ne)
a_{GT}	$\mathcal{O}(0.1)$% [308]	^{6}He-MOT (Seattle) [306, 308]	Ongoing with ^{6}He
	not stated	EIBT (Weizmann Inst.) [309–311]	In preparation (^{6}He)
	0.5% [181]	LPCTrap (GANIL) [181, 314, 316, 317]	Analysis ongoing (^{6}He, ^{35}Ar)
a_{mirror}	0.5% [277]	NSL-Trap (Notre Dame) [277, 337, 338]	Planned (^{11}C, ^{13}N, ^{15}O, ^{17}F)
$\tilde{a}_n$	1.0% [343]	aCORN (NIST) [343, 345–347]	Data taking ongoing
a_n	1.0 − 1.5% [344]	aSPECT (ILL) [227, 228, 344]	Analysis being finalized
	0.15% [187, 351]	Nab (LANL) [187, 285, 350, 351]	In preparation
A_n	0.2% [384]	UCNA (LANL) [384]	Data taking planned
	0.18% [289]	PERKEO III (ILL) [289]	Analysis ongoing
$\tilde{A}_{mirror}$	$\mathcal{O}(0.1)$% [77]	TRINAT (TRIUMF) [77]	Planned
B_n	0.01% [390]	UCNB (LANL) [390]	Planned
A_n (a_n, B_n, C_n)	0.05% [287]	PERC (Munich) [287, 288]	In preparation
$\tilde{A}_n$ (a_n, B_n)	$< \mathcal{O}(0.1)$% [392]	BRAND (ILL) [392, 393]	Proposal
D	$\mathcal{O}(10^{-4})$ [411]	MORA (GANIL / JYFL) [411]	In preparation (^{23}Mg)
R	$\mathcal{O}(10^{-3})$ [420]	MTV (TRIUMF) [420–422]	Data taking (^{8}Li) ongoing
D, R	$\mathcal{O}(0.1)$% [392]	BRAND (ILL) [392, 393]	Proposal

Projected sensitivities

Several experiments reaching 10^{-3} uncertainties.

Gonzalez-Alonso,
Naviliat-Cuncic,
Severijns
hep-ph 1803.08732

Invited review article for Prog. Part. Nucl. Phys.

Coefficient	Precision goal	Experiment (Laboratory)	Comments
τ_n	1.0 s; 0.1 s [209]	BL2, BL3 (NIST) [209]	In preparation; two phases
	1.0 s; 0.3 s [213]	LiNA (J-PARC) [210, 213]	In preparation; two phases
	0.2 s [214]	Gravitrap (ILL) [202, 214]	Apparatus being upgraded
	0.3 s [200]	Ezhov (ILL) [200]	Under construction
	0.1 s [221]	PENeLOPE (Munich) [221]	Being developed
	$\lesssim$ 0.1 s [222]	UCNτ (LANL) [187, 188, 222, 223]	Ongoing
	0.5 s [224]	HOPE (ILL) [187, 224, 225]	Proof of principle Ref. [225]
	1.0 s; 0.2 s [187]	τSPECT (Mainz) [187, 226]	Taking data
β-spectrum	$\mathcal{O}(0.01)$ [260]	Supercond. spectr. (Madison) [260]	C_1 in Eq. (51). Ongoing
β-spectrum	$\mathcal{O}(0.01)$ [257]	Si-det. spectr. (Saclay) [257, 258]	C_1 in Eq. (51). Ongoing
b_{GT}	0.001	Scintill. detectors (NSCL) [115, 264]	Analysis ongoing (^{6}He, ^{20}F)

For the left-handed fit with real couplings we obtain the following projected uncertainties:

$$\begin{pmatrix} \delta|C_V| \\ \delta(C_A/C_V) \\ \delta(C_S/C_V) \\ \delta(C_T/C_A) \end{pmatrix} = \begin{pmatrix} 1.9\, G_F/\sqrt{2} \\ 2.2 \\ 7.2 \\ 4.1 \end{pmatrix} \times 10^{-4}\ . \qquad (97)$$

To translate these uncertainties to the quark-level parameters, we also assume that the lattice calculation of the axial charge g_A will reach the 0.5% precision, which seems feasible looking at the preliminary result in Ref. [34]. For the remaining theory input (Δ_V^R, g_S, g_T) we use their current values. We obtain

$$\begin{pmatrix} \delta|\tilde{V}_{ud}| \\ \delta\epsilon_R \\ \delta\epsilon_S \\ \delta\epsilon_T \end{pmatrix} = \begin{pmatrix} 2.6 & \\ 41 & (90\%\ \text{CL}) \\ 12 & (90\%\ \text{CL}) \\ 2.2 & (90\%\ \text{CL}) \end{pmatrix} \times 10^{-4}\ . \qquad (98)$$

Summary of theory needs

Nucleon form factors (g_A, g_S, g_T)
A=8, ^{37}K, recoil-order matrix elements
^{6}He, ^{14}O, ^{19}Ne, ^{20}F beta spectra corrections (radiative, recoil)
Radiative corrections in correlations (F. Glueck's work extended)
Mirror transition ratios of f_A/f_V

To be completed during our workshop…

Nuclear beta decay phenomenology: beyond *V-A*?

Standard Model
+ non-SM-LL

Right-handed

$$H_{V,A} = \sum_{i=V,A} \bar{\Psi}_f\, O_i^{\mu} \Psi_0 \left[(C_i + C_i{}')\, \bar{e}^L\, O_{i,\mu} \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^R O_{i,\mu} \nu_e{}^R \right]$$

$$O_i^{\mu} = \begin{cases} \gamma^{\mu} & i = V \\ \gamma^{\mu}\gamma_5 & i = A \end{cases}$$

chirality flipping

$$H_{S,T} = \sum_{i=S,T} \bar{\Psi}_f\, O_i\ \Psi_0 [(C_i + C_i{}')\, \bar{e}^R\, O_i \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^L O_i \nu_e{}^R]$$

Scalar, Tensor

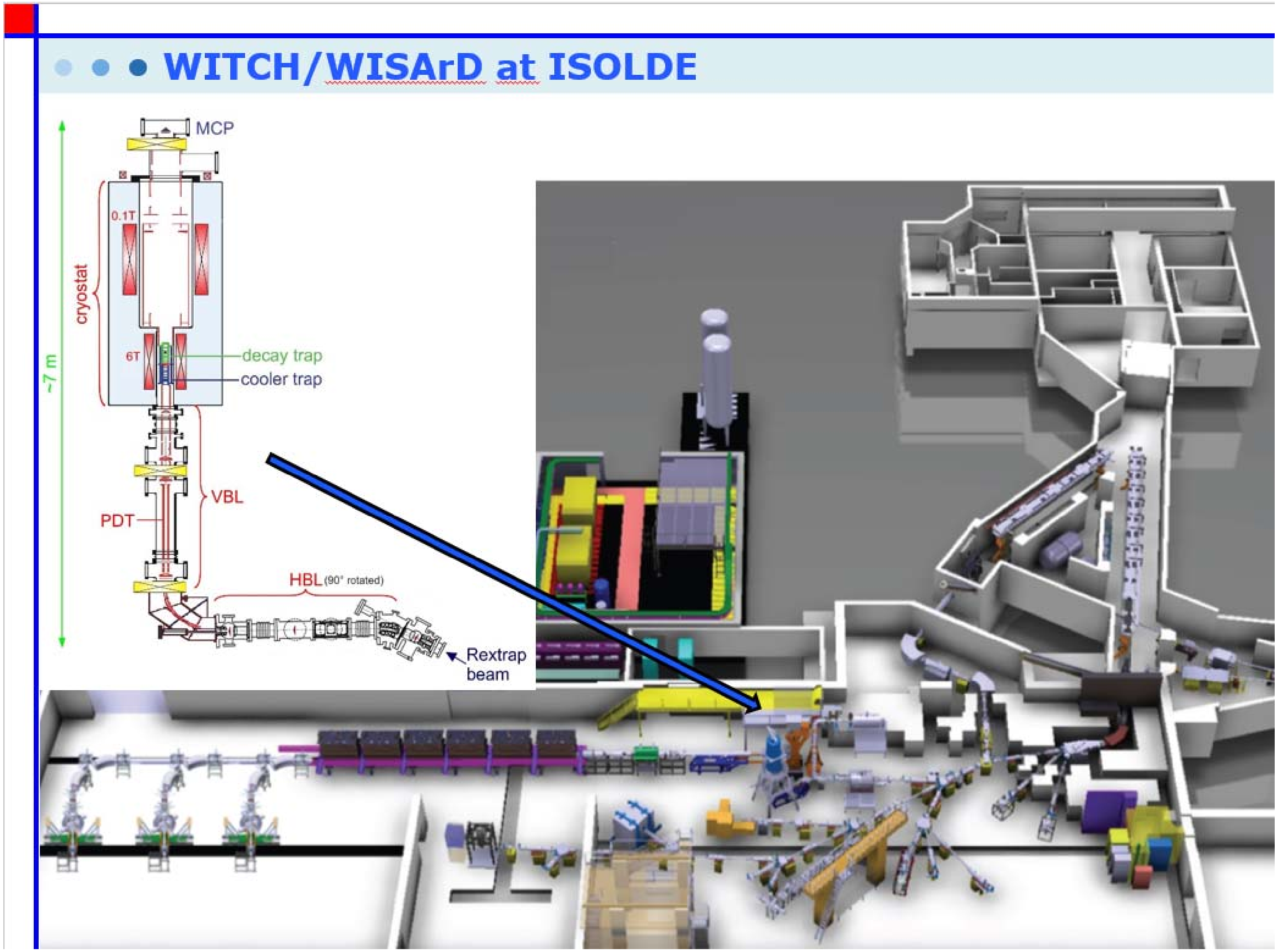
$$O_i = \begin{cases} 1 & i = S \\ \sigma^{\mu\nu} & i = T \end{cases}$$

$$H_{PS} = \sum_{i=PS} \bar{\Psi}_f\, O_i\ \Psi_0 [(C_i + C_i{}')\, \bar{e}^R\, O_i \nu_e{}^L + (C_i - C_i{}')\, \bar{e}^L O_i \nu_e{}^R]$$

Pseudo-scalar

$$O_i = \{\gamma_5$$

CERN ion trap

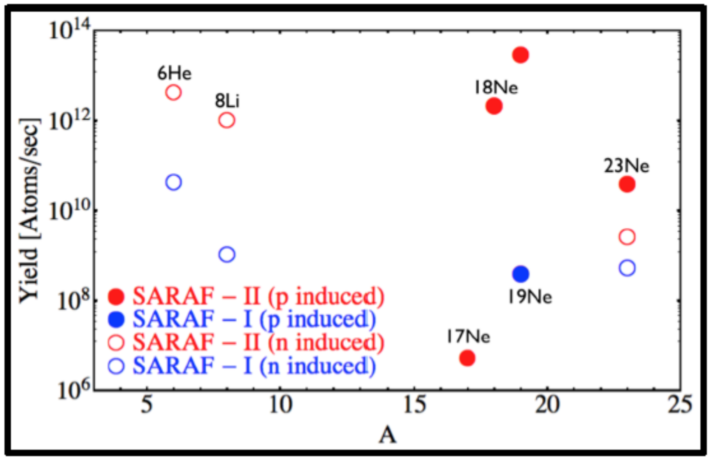


Thanks: Bertram Blank

Ion trap at Hebrew University of Jerusalem and Racah Institute

Production of rare isotopes @ SARAF

Phase (start year)	Beam				Neutron Source	
	Proton		Deuteron			
	E (MeV)	I (mA)	E (MeV)	I (mA)	E (MeV)	Rate (n/s)
I (2013)	1.5-4	0.04-2	3-5.6	0.04-1.2	0.03-20	10^{11}
I+ (2018)	1.5-4	0.04-2	3-5.0	0.04-2	0.03-20	10^{13}
II (2023)	5-35	0.04-5	5-40	0.04-5	0.03-55	10^{15}



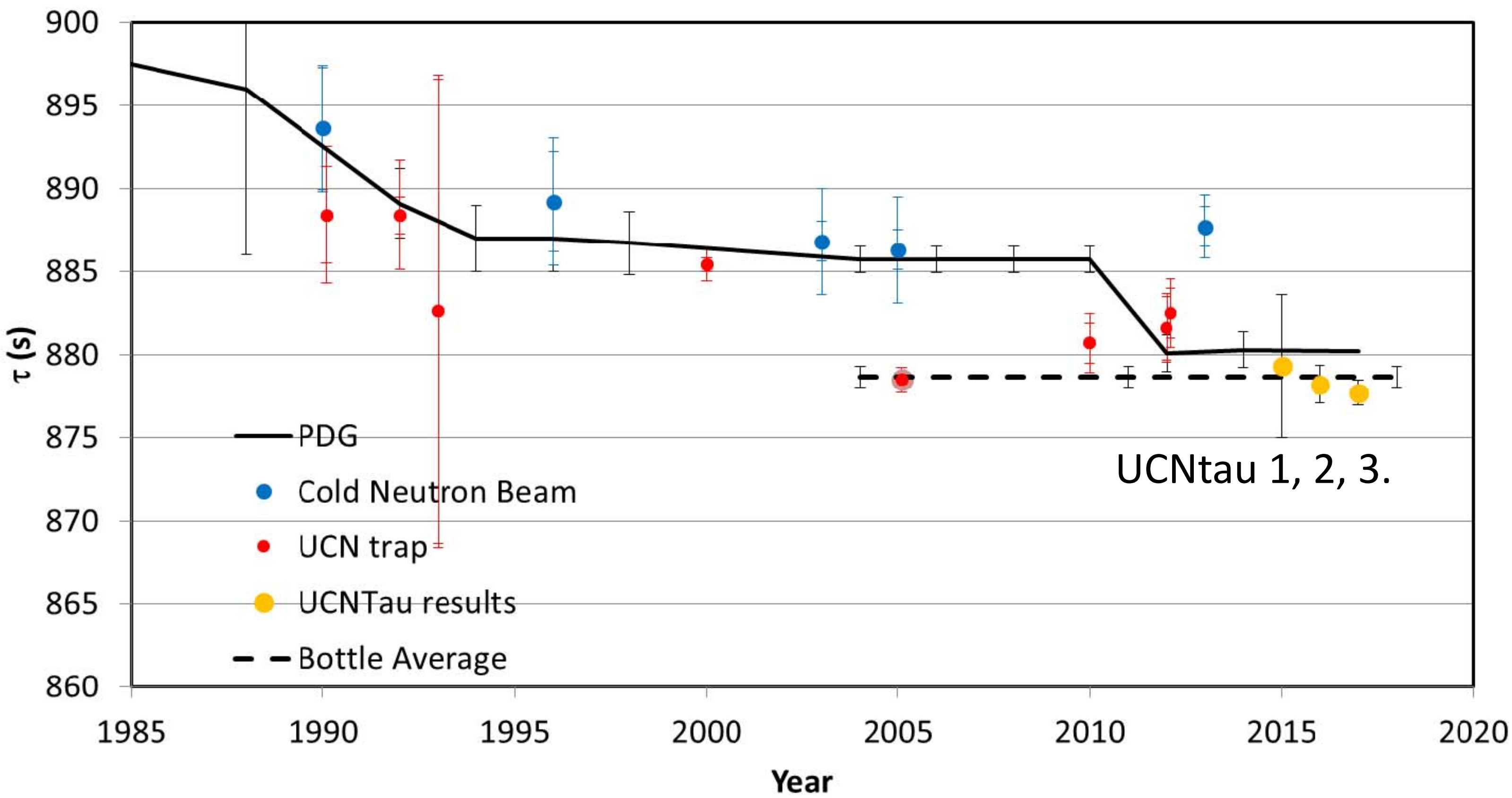
Phase - I experiments:

* ^{6}He measurement in EIBT.
* ^{23}Ne measurement in MOT.

Thanks: Guy Ron

UCNtau results

1. 2015 commission data (RSI)
2. 2015-2016 data
3. 2016-2017 data (Science, 2018)



We have made a measurement of τ_n for the first time with **no extrapolation**: 877.7 ± 0.7 (stat) +0.3/-0.1 (sys) s.

CENPA
Center for Experimental Nuclear Physics and Astrophysics