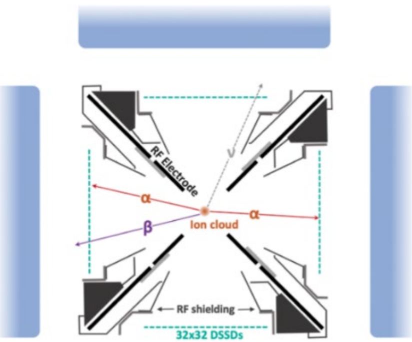
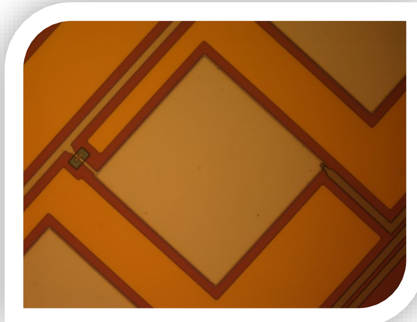
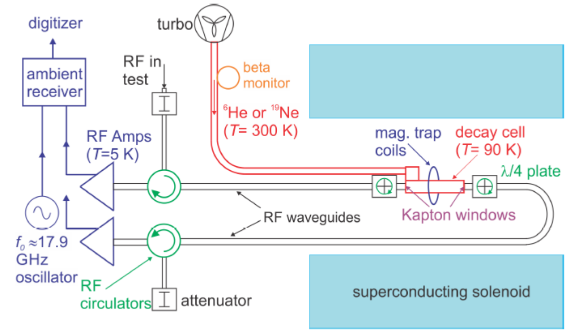
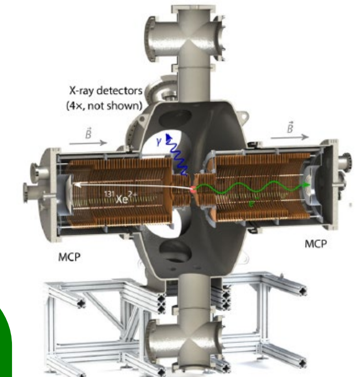
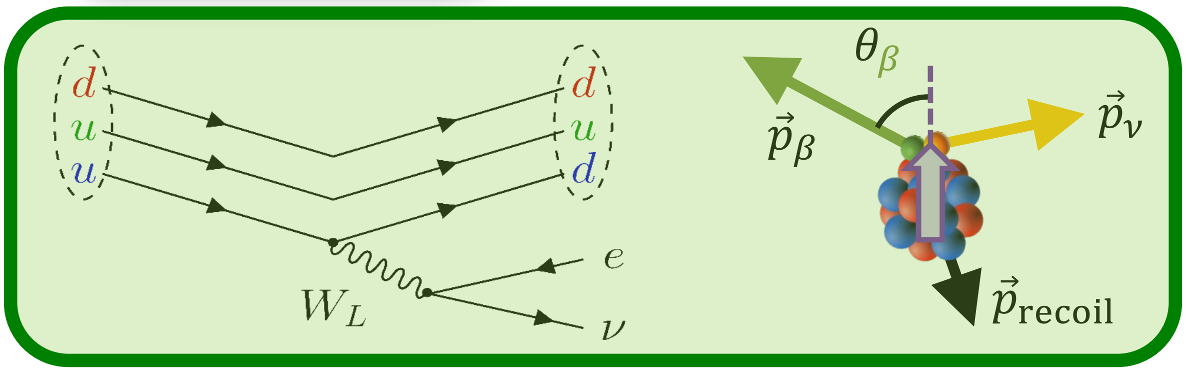
Precision β-decay measurements in nuclei

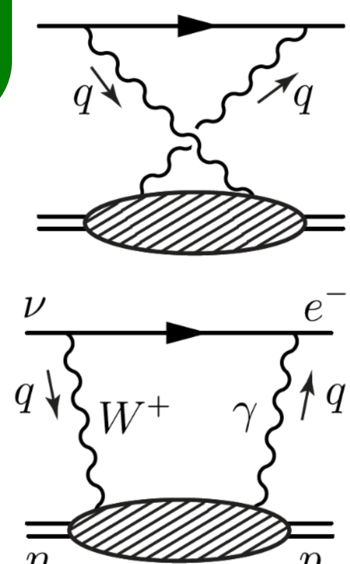


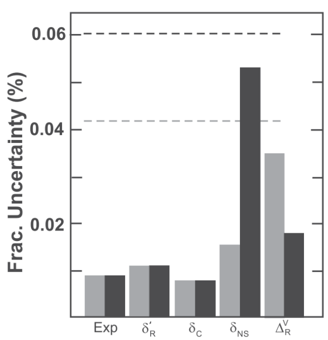


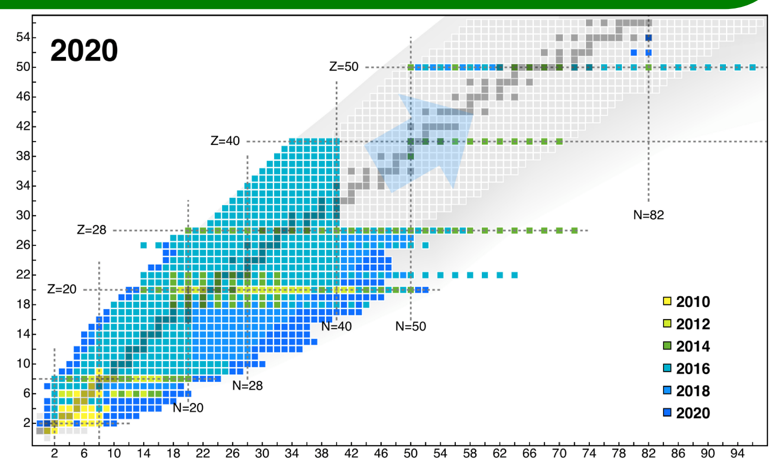


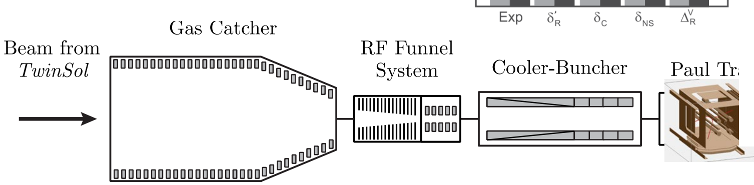












Dan Melconian

Outline

- Not at all dissimilar from what was said at the Town Hall Meetings last fall
- Resulting White Paper is 7 pages of awesome physics (5 pgs of citations)

Nuclear β decay as a probe for physics beyond the Standard Model

M. Brodeur,[1] N. Buzinsky,[2] M.A. Caprio,[1] V. Cirigliano,[3] J.A. Clark,[4] P.J. Fasano,[1] J.A. Formaggio,[5] A.T. Gallant,[6] A. Garcia,[2] S. Gandolfi,[7] S. Gardner,[8] A. Glick-Magid,[2] L. Hayen,[9,10] H. Hergert,[11,12] J. D. Holt,[13,14] M. Horoi,[15] M.Y. Huang,[16] K.D. Launey,[17] K.G. Leach,[18,19] B. Longfellow,[6] A. Lovato,[20] A.E. McCoy,[19,21] D. Melconian,[22,23] P. Mohanmurthy,[5] D.C. Moore,[24] P. Mueller,[4] E. Mereghetti,[25] W. Mittig,[26,19] P. Navratil,[13] S. Pastore,[21,27] M. Piarulli,[21,27] D. Puentes,[26,19] B.C. Rasco,[28] M. Redshaw,[15] G.H. Sargsyan,[6] G. Savard,[4,29] N.D. Scielzo,[6] C.-Y. Seng,[2,19] A. Shindler,[11,12] S.R. Stroberg,[1] J. Surbrook,[26,19] A. Walker-Loud,[30] R. B. Wiringa,[31] C. Wrede,[26,19] A. R. Young,[32,33] and V. Zelevinsky[26,19]

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(Dated: January 11, 2023)

This white paper was submitted to the 2022 Fundamental Symmetries, Neutrons, and Neutrinos (FSNN) Town Hall Meeting in preparation for the next NSAC Long Range Plan. We advocate to support current and future theoretical and experimental searches for physics beyond the Standard Model using nuclear β decay.

Outline

- CKM matrix unitarity tests
  - Theory has made huge progress
  - New experiments targeting low-Z cases, mirror transitions
- Searches for scalar and tensor currents
  - Spectrum-shape for Fierz
  - Ion and atom traps
- β decays for neutrino physics
  - Ultra-low Q-values for direct m_ν measurements
  - Sterile neutrinos via EC
  - Reactor antineutrino anomaly

In case I run out of time (which I will…)

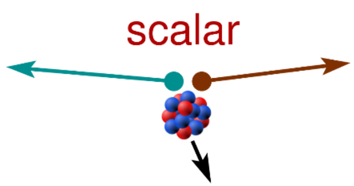
- Start with the White Paper recommendations:
  - Experimental + theoretical alliance for V_{ud} and CKM unitarity
  - Investing in small- and mid-scale projects
  - Establishing support for nuclear theory
  - Developing cutting-edge techniques
  - Promote diverse and inclusive environment, and better support for students

- Thanks for input (apologies to all)
  - Maxime Brodeur, Drew Byron, Jason Clark, Leendert Hayen, Kyle Leach, Charlie Rasco, Matt Redshaw, Nick Scielzo, Chien Yeah Seng, Louis Varrian, and everyone on the nuclear β decay White Paper

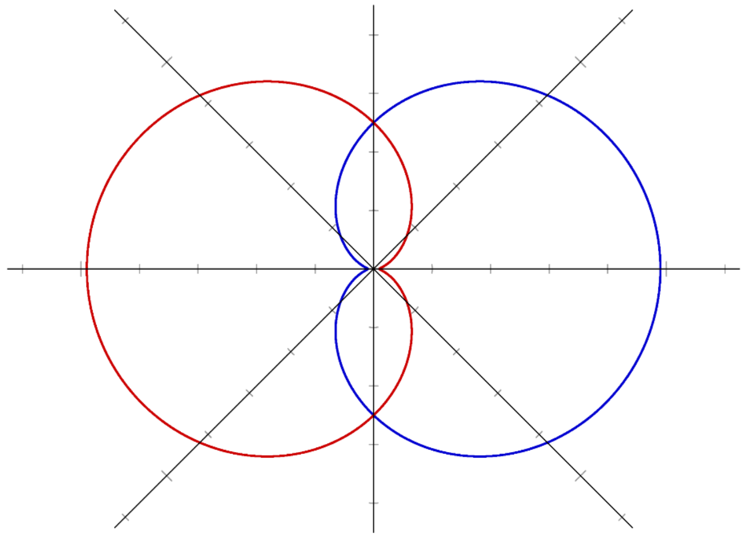
β-decay correlations and ft values

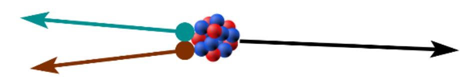
- Quick reminder:

$$dW = dW_0\left[1 + a\frac{\vec{p}_\beta\cdot\vec{p}_\nu}{E_\beta E_\nu} + b\frac{\Gamma m_e}{E_\beta} + \frac{\langle\vec{I}\rangle}{I}\cdot\left(A_\beta\frac{\vec{p}_\beta}{E_\beta} + B_\nu\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\beta\times\vec{p}_\nu}{E_\beta E_\nu}\right) + \cdots\right]$$



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





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

$$a_{\beta\nu} = \frac{|C_V|^2 + |C'_V|^2 - |C_S|^2 - |C'_S|^2}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} = 1??$$

$$b = \frac{-2\Re e(C_S^* C_V + C_S'^* C'_V)}{|C_V|^2 + |C'_V|^2 + |C_S|^2 + |C'_S|^2} = 0??$$

β-decay correlations and ft values

- Quick reminder:

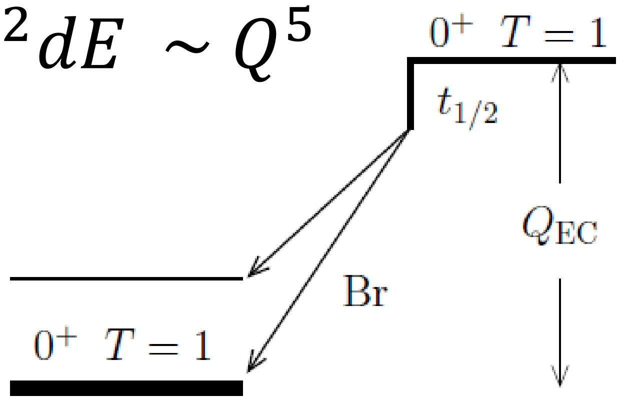
$$dW = dW_0\left[1 + a\frac{\vec{p}_\beta\cdot\vec{p}_\nu}{E_\beta E_\nu} + b\frac{\Gamma m_e}{E_\beta} + \frac{\langle\vec{I}\rangle}{I}\cdot\left(A_\beta\frac{\vec{p}_\beta}{E_\beta} + B_\nu\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\beta\times\vec{p}_\nu}{E_\beta E_\nu}\right) + \cdots\right]$$

- Comparative half-life:

$$f = \int F(Z',E)C(E)pE(E-E_0)^2 dE \sim Q^5$$

and

$$t = \frac{t_{1/2}}{\text{Br}}(1+P_{\text{EC}})$$

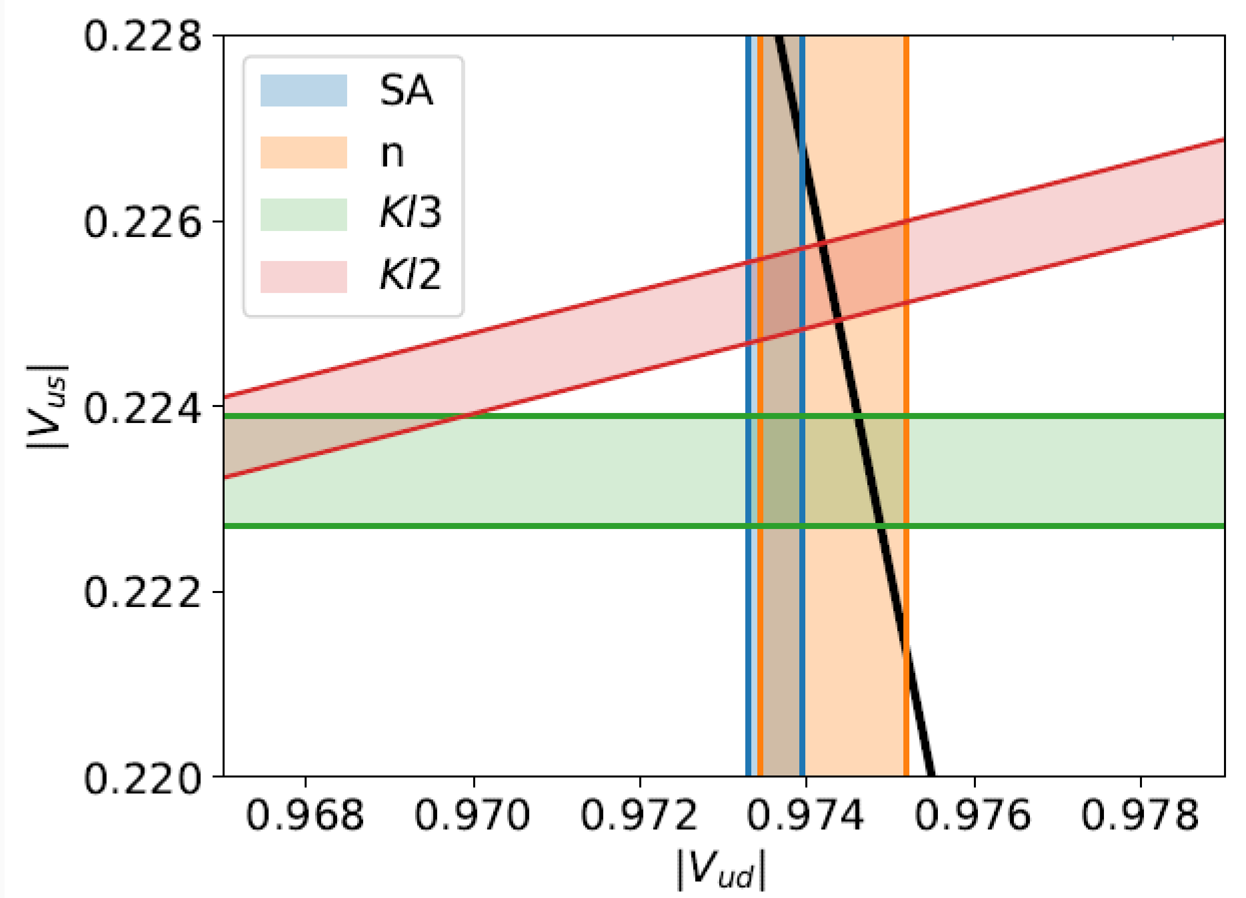


$$Ft \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

$$= \frac{K/G_F^2}{|V_{ud}|^2 M_F^2(1+\Delta_R^V)}$$

CKM Unitarity

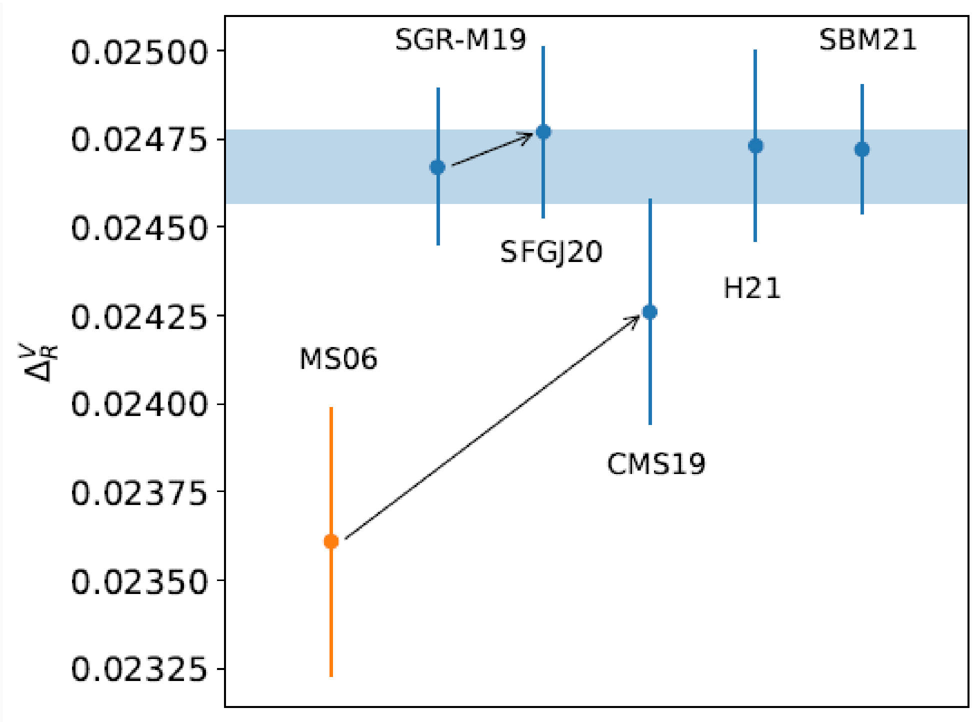
- There are currently indications of non-unitarity at a few σ level

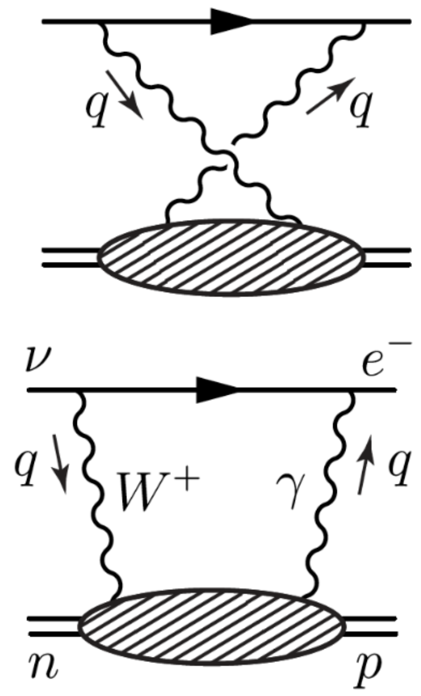


$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9982(6)$$

Recent development: theory

- Hint of new physics due largely to new calcs of Δ_R^V

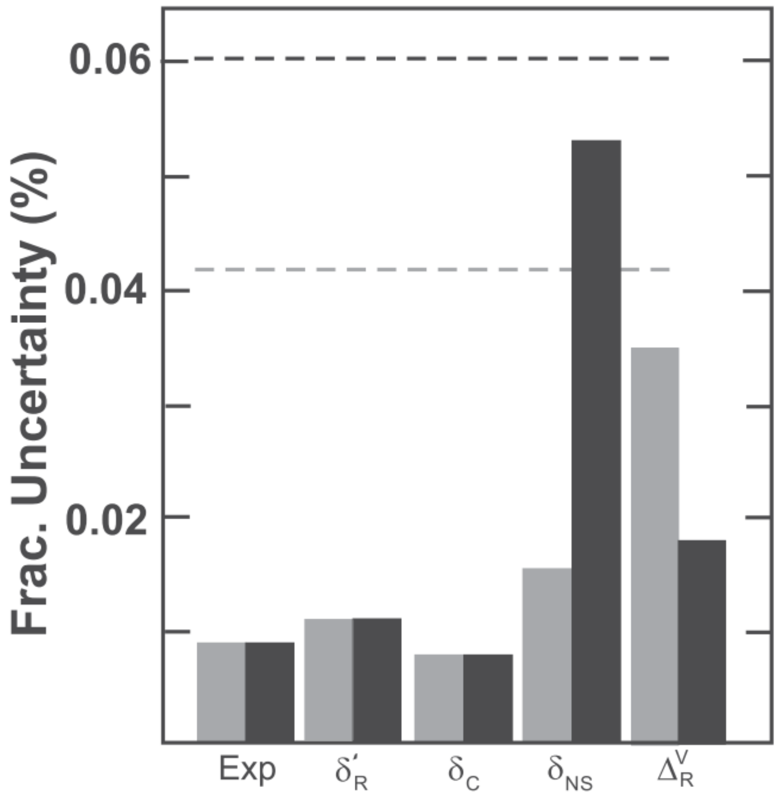




Smaller uncertainty *and* a shift

Recent development: theory

- Hint of new physics due largely to new calcs of Δ_R^V
- New effects to δ_{NS} from quasi-elastic contributions and nuclear polarization effects (1812.03352, 1812.04229): $\delta_{\mathrm{NS}}(E)$
  - Now the (by far) dominant theoretical uncertainty
  - Rigorous theory framework based on dispersion relation to compute the NS effects (2211.10214)
  - New collaborations are formed to compute δ_{NS} with ab-initio methods for light nuclei



Recent development: theory

- Hint of new physics due largely to new calcs of Δ_R^V
- New effects to δ_{NS} from quasi-elastic contributions and nuclear polarization effects (1812.03352, 1812.04229): $\delta_{\mathrm{NS}}(E)$
  - Now the (by far) dominant uncertainty: SM theory input
- New connections are found between experimental measurements of charge radii and the isospin breaking correction, δ_C (2208.03037, 2304.03800)

F16.00008
(Sun 9:54am)

Electroweak nuclear radii constrain the isospin breaking correction to V_{ud}

Chien-Yeah Seng[1,2,3] and Mikhail Gorchtein[4,5]
[1] *Helmholtz-Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn, 53115 Bonn, Germany*
[2] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*
[3] *Department of Physics, University of Washington, Seattle, WA 98195-1560, USA*
[4] *Institut für Kernphysik, Johannes Gutenberg-Universität, J.J. Becher-Weg 45, 55128 Mainz, Germany and*
[5] *PRISMA Cluster of Excellence, Johannes Gutenberg-Universität, Mainz, Germany*
(Dated: January 13, 2023)

We lay out a novel formalism to connect the isospin-symmetry breaking correction to the rates of superallowed nuclear beta decays, δ_C, to the isospin-breaking sensitive combinations of electroweak nuclear radii that can be accessed experimentally. We individuate transitions in the superallowed decay chart where a measurement of the neutron skin of a stable daughter even at a moderate precision could already help discriminating between models used to compute δ_C. We review the existing experimental situation and make connection to the existing and future experimental programs.

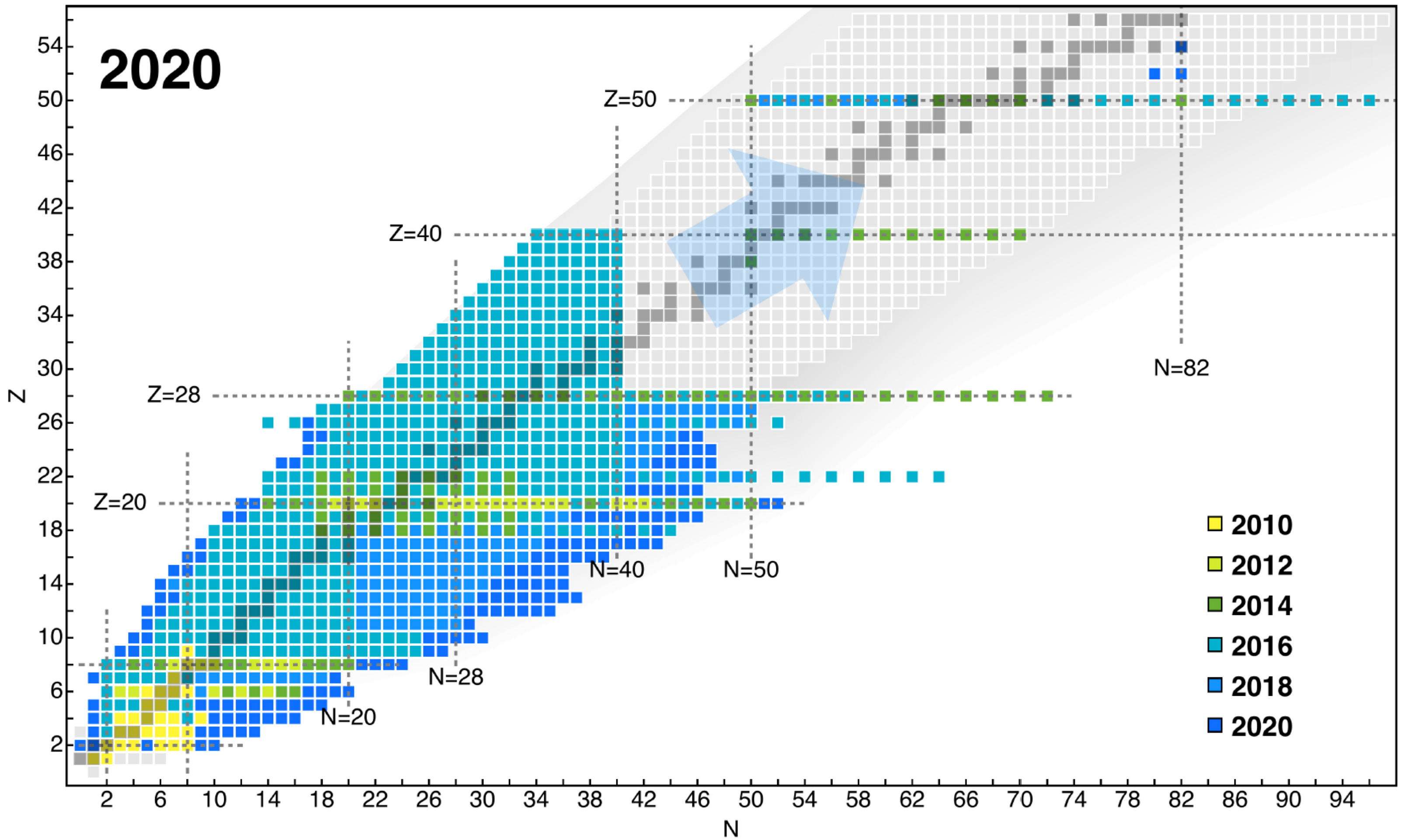
Towards *ab-initio* nuclear theory calculations of δ_C

Chien-Yeah Seng[1,2] and Mikhail Gorchtein[3,4]
[1] *Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI 48824, USA*
[2] *Department of Physics, University of Washington, Seattle, WA 98195-1560, USA*
[3] *Institut für Kernphysik, Johannes Gutenberg-Universität, J.J. Becher-Weg 45, 55128 Mainz, Germany and*
[4] *PRISMA Cluster of Excellence, Johannes Gutenberg-Universität, Mainz, Germany*
(Dated: April 11, 2023)

We propose a new theory framework to study the isospin-symmetry breaking correction δ_C in superallowed nuclear beta decays, crucial for the precise determination of $|V_{ud}|$. Based on a general assumptions of the isovector dominance in ISB interactions, we construct a set of functions F_{T_z} which involve nuclear matrix elements of isovector monopole operators and the nuclear Green's function. Via the functions F_{T_z}, a connection of δ_C to measurable electroweak nuclear radii is established, providing an experimental gauge of the theory accuracy of δ_C. We outline a strategy to perform ab-initio calculations of F_{T_z} based on the Lanczos algorithm, and discuss its similarity with other nuclear-structure-dependent inputs in nuclear beta decays.

Ab initio nuclear theory

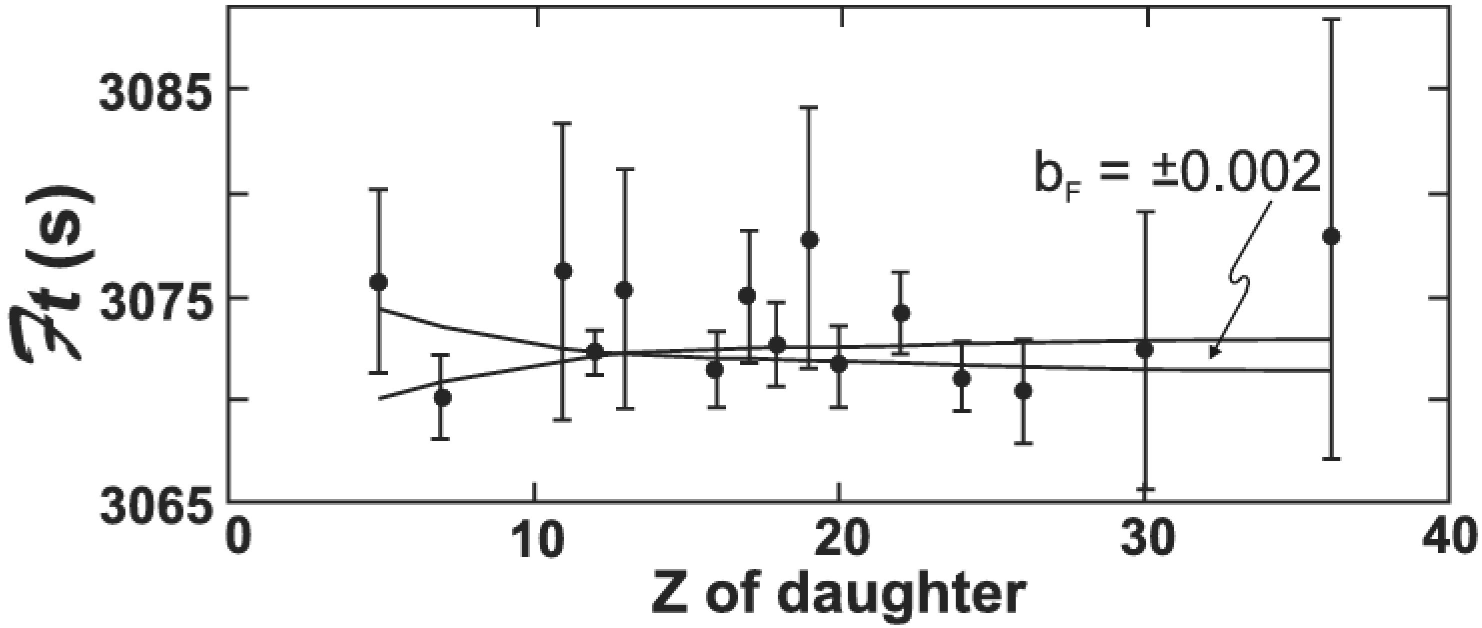
- ***Amazing*** progress in just 10 years!!



H. Hergert, Frontiers in Physics (2020)

Experimental efforts

- Being low-Z, ^{10}C and ^{14}O are the most interesting regarding scalar currents



Hardy and Towner's last survey
PRC **102**, 045501 (2020)

Experimental efforts

- Being low-Z, ^{10}C and ^{14}O are the most interesting regarding scalar currents

SALER: Superconducting Array for Low-Energy Radiation

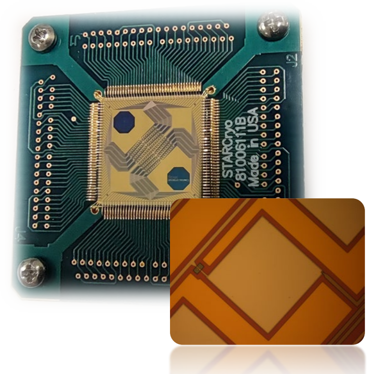
Direct implantation and measurement of eV-scale radiation from short-lived ($T_{1/2}$ > 1 ms) rare isotopes for BSM physics searches (CKM unitarity, exotic weak currents, etc.)

SALER

FRIB

GORDON AND BETTY MOORE FOUNDATION

U.S. DEPARTMENT OF ENERGY | Office of Science

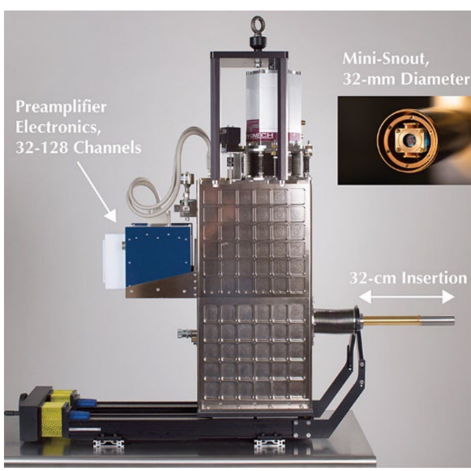


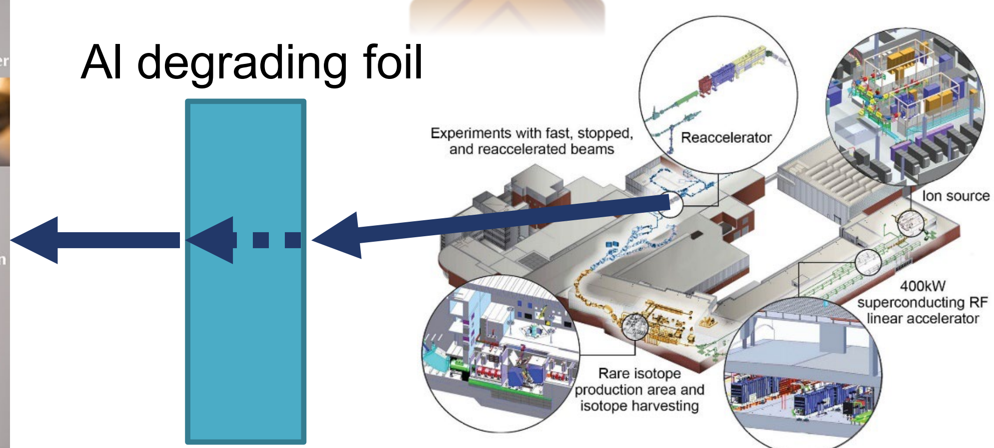
COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

STAR CRYOELECTRONICS

NC STATE UNIVERSITY

eV-scale nuclear recoil spectroscopy for BSM physics studies





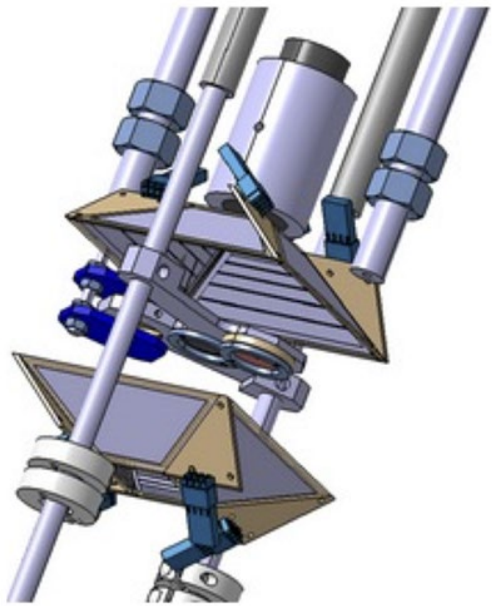
G15.00003
(Sun 11:33 am)

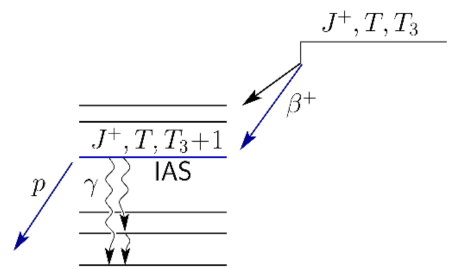
Experimental efforts

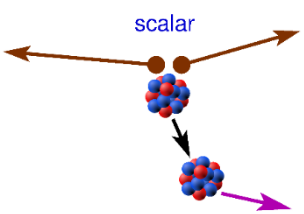
- Being low-Z, ^{10}C and ^{14}O are the most interesting regarding scalar currents

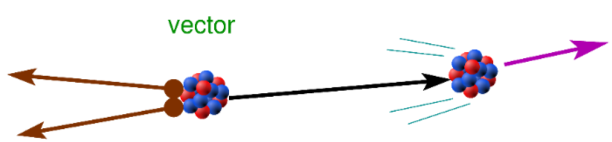
PRC **101**, 055501 (2020)

- Proton-rich cases to be studied with WISArD and TAMUTRAP via the kinematic shift of β-delayed proton decays









Experimental efforts

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PRC **101**, 055501 (2020)

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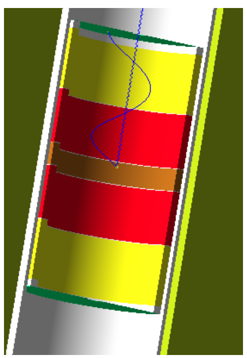
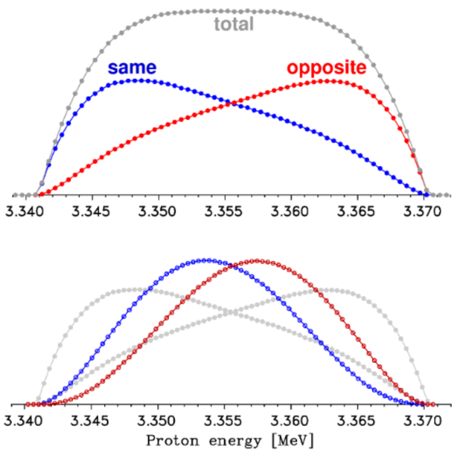
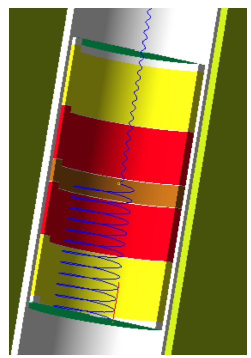
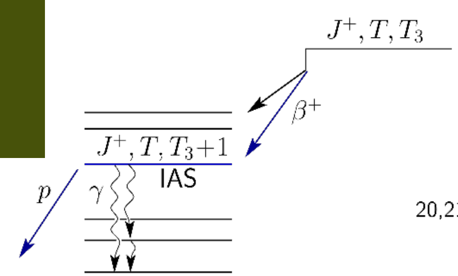
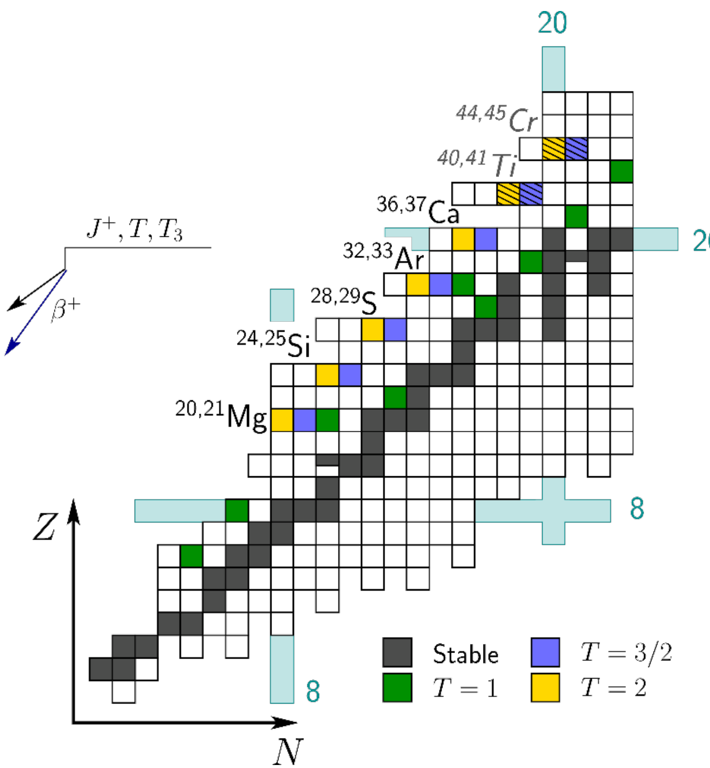
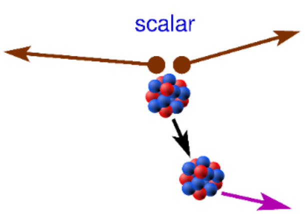






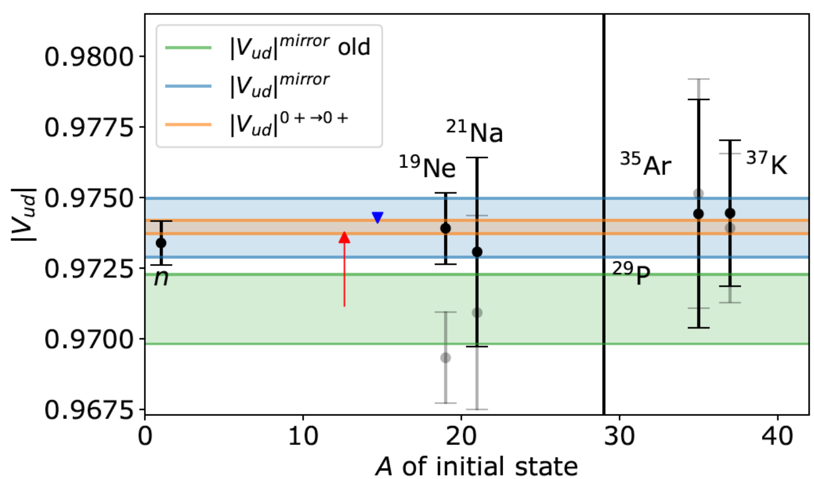


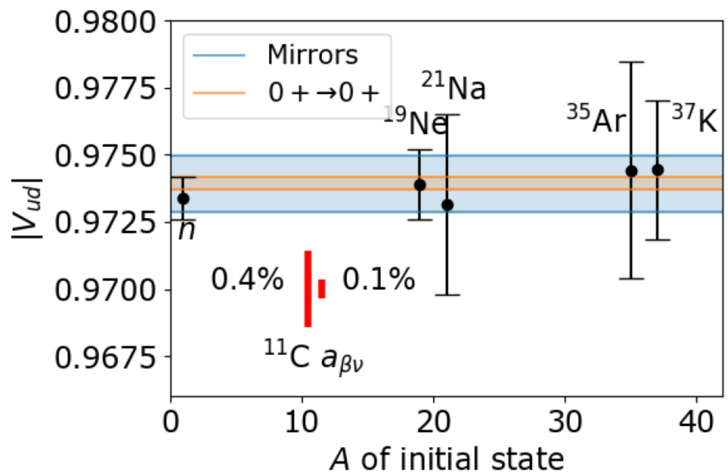




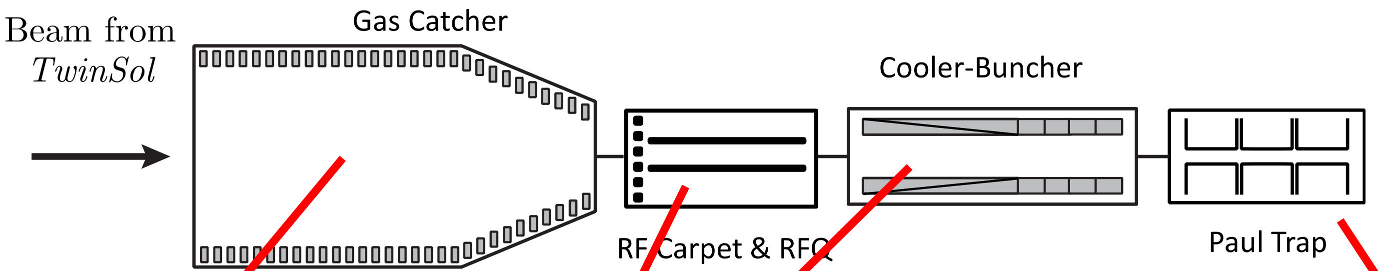
Experimental efforts

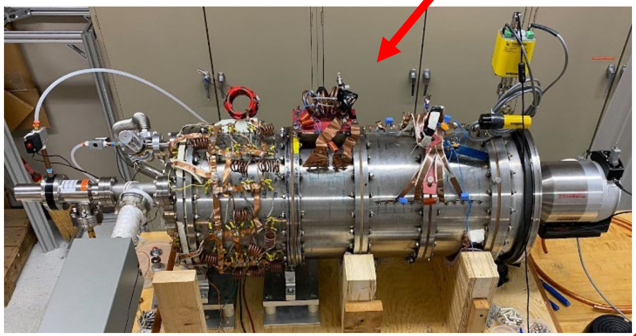
- Being low-Z, ^{10}C and ^{14}O are the most interesting regarding scalar currents)
- Proton-rich cases to be studied with TAMUTRAP via the kinematic shift of β-delayed proton decays
- Mirror nuclei continue to be improved as an alternate to $0^+ \rightarrow 0^+$ (and of course the neutron, next talk)
  - Lifetimes, β-ν correlations with St. Bendict @ Notre Dame

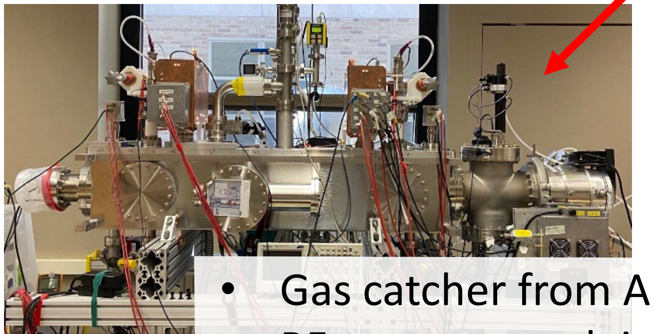


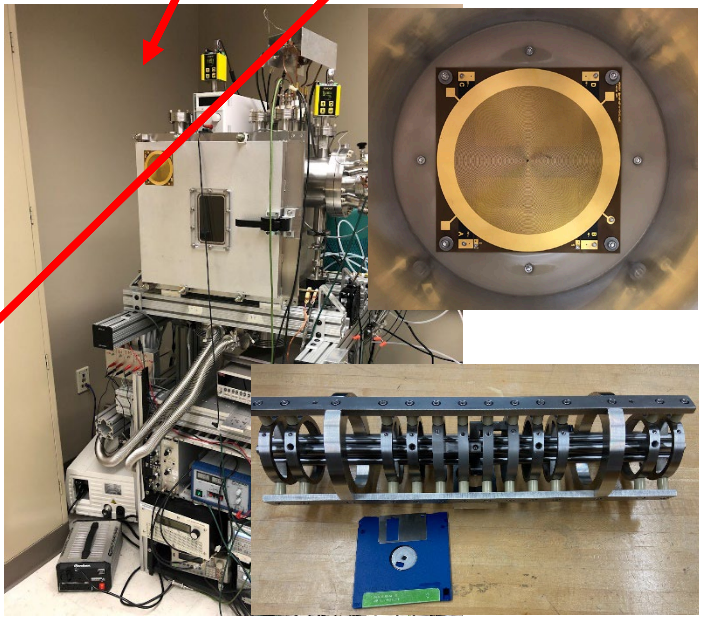


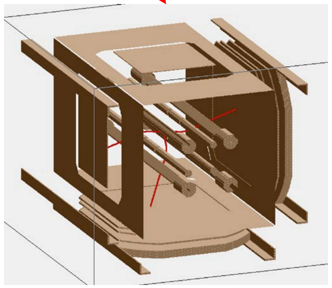
Superallowed Transisiton Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict)











- Gas catcher from ANL: RF/DC & vacuum tested; transport tests underway
- RF carpet tested; ion guide assembled and RF circuit being tested
- Cooler/buncher commissioned
- Paul trap has been simulated and manufactured

Experimental efforts

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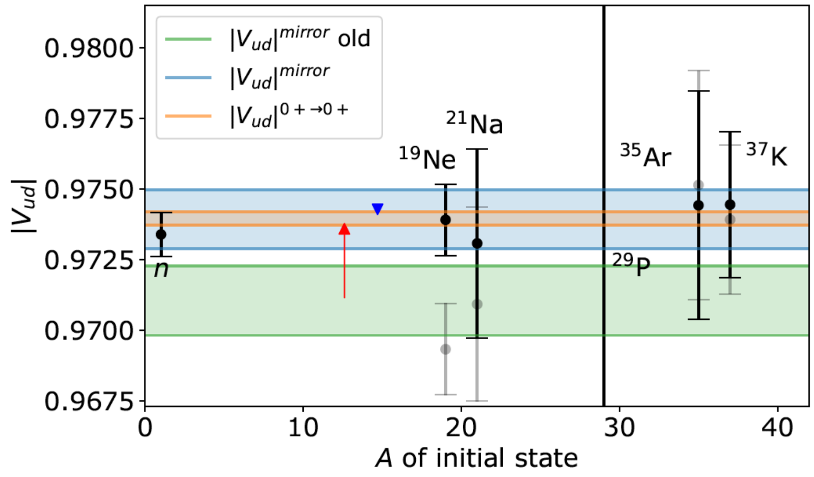
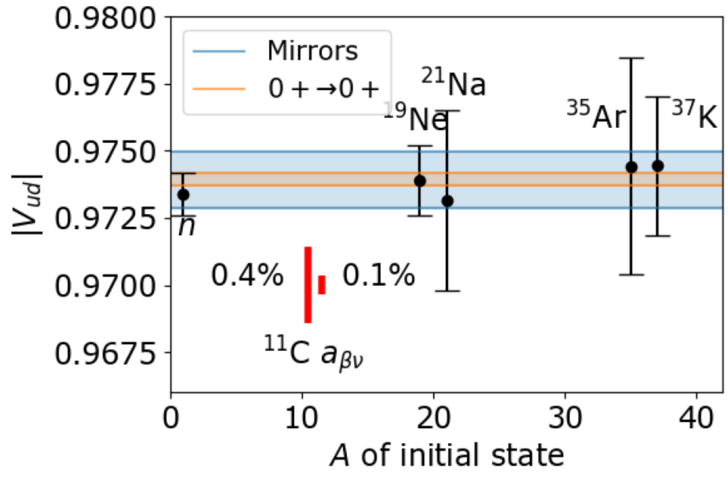
  - Lifetimes, β-ν correlations with St. Bendict @ Notre Dame
  - Lifetimes, branching ratios (fast-tape + HPGe), β-ν correlations (TAMUTRAP) at the Cyclotron Institute



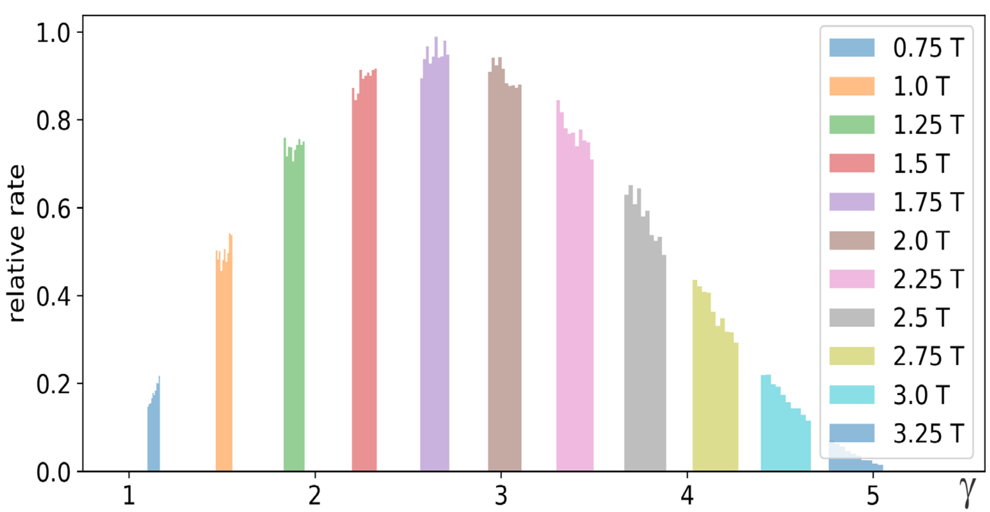


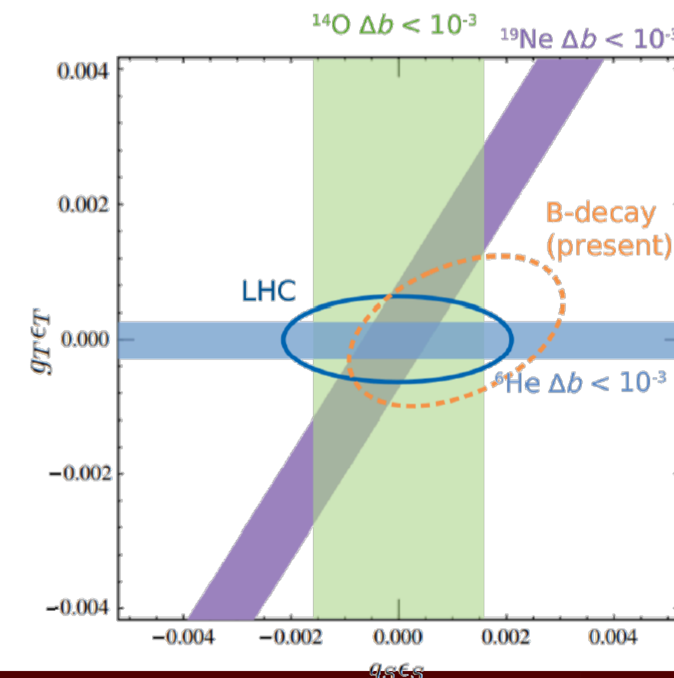
Outline

- CKM matrix unitarity tests
  - Theory has made huge progress
  - New experiments targeting low-Z cases, mirror transitions
- Searches for scalar and tensor currents
  - Spectrum-shape for Fierz
  - Ion and atom traps
- β decays for neutrino physics
  - Ultra-low Q-values for direct m_ν measurements
  - Sterile neutrinos via EC
  - Reactor antineutrino anomaly

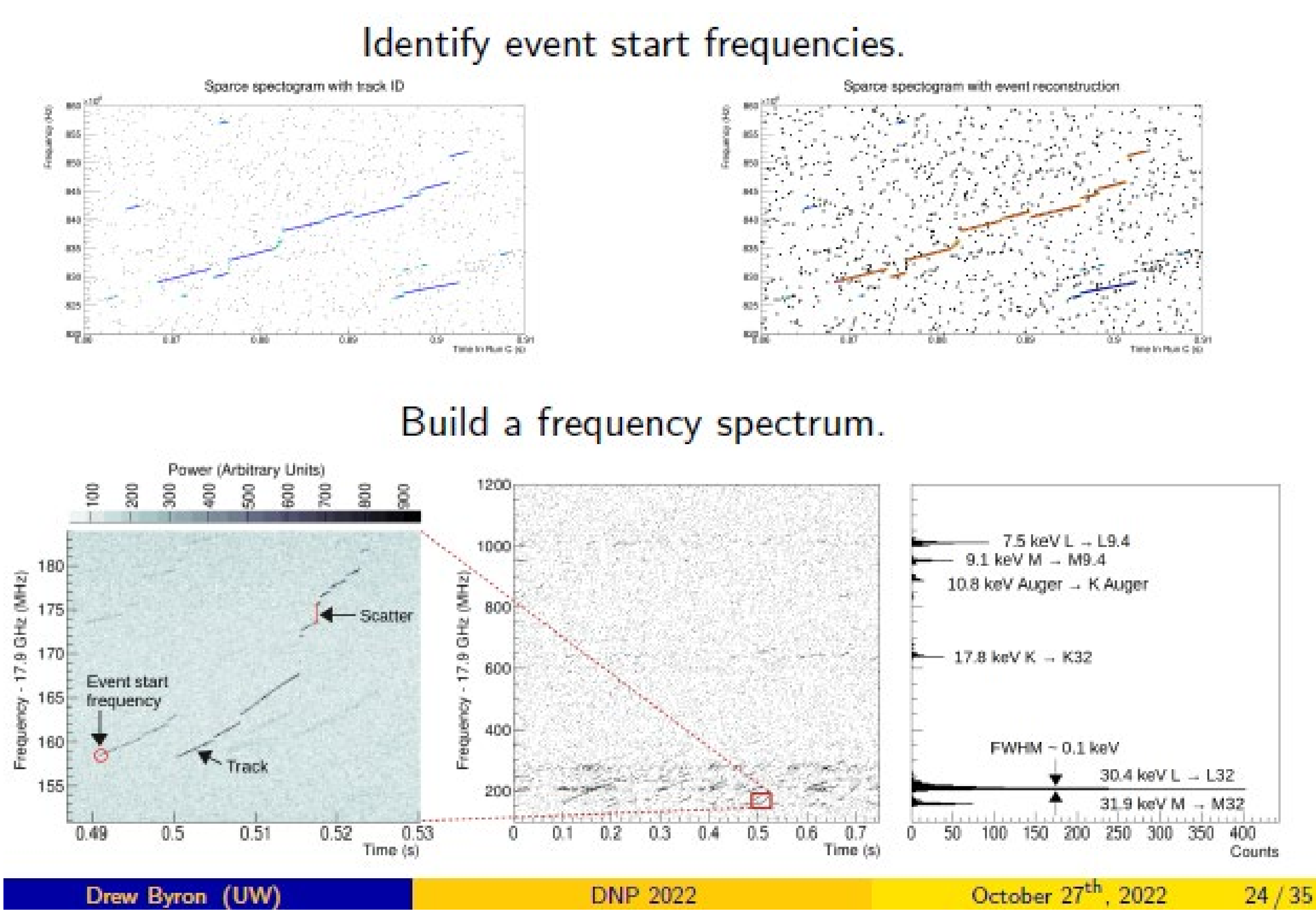
Searches for Scalar/Tensor currents

- Most sensitive probe is b_{Fierz} – linear in exotic couplings
- Cyclotron radiation emission spectroscopy (He6-CRES)
  - ^{6}He (GT), ^{19}Ne (F/GT) and ^{14}O (F); $\beta^{\pm}$ opposite sign in b_{Fierz}
  - Much larger bandwidth needed compared to Project 8
  - Other challenges: other modes, harmonics, wall effects



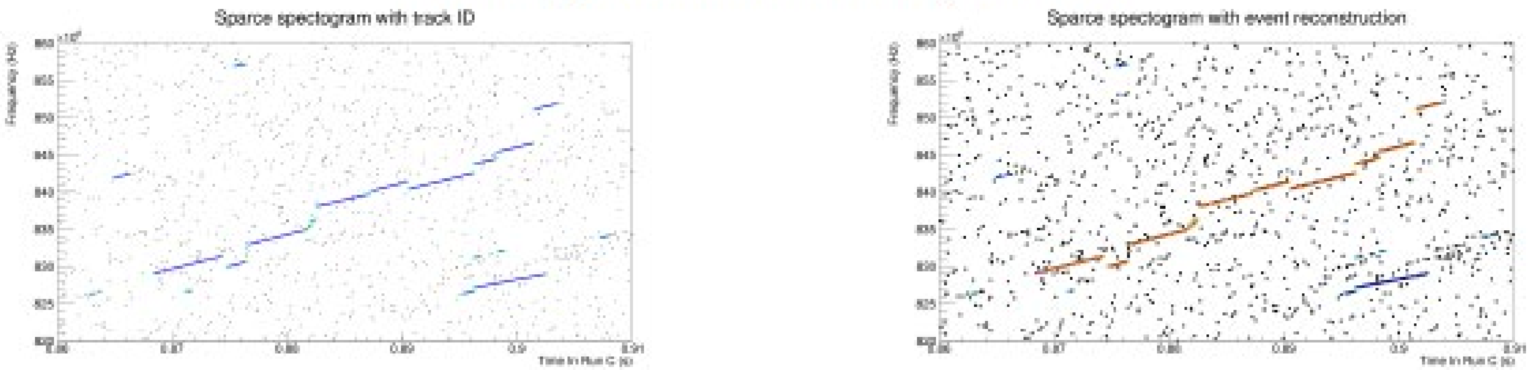


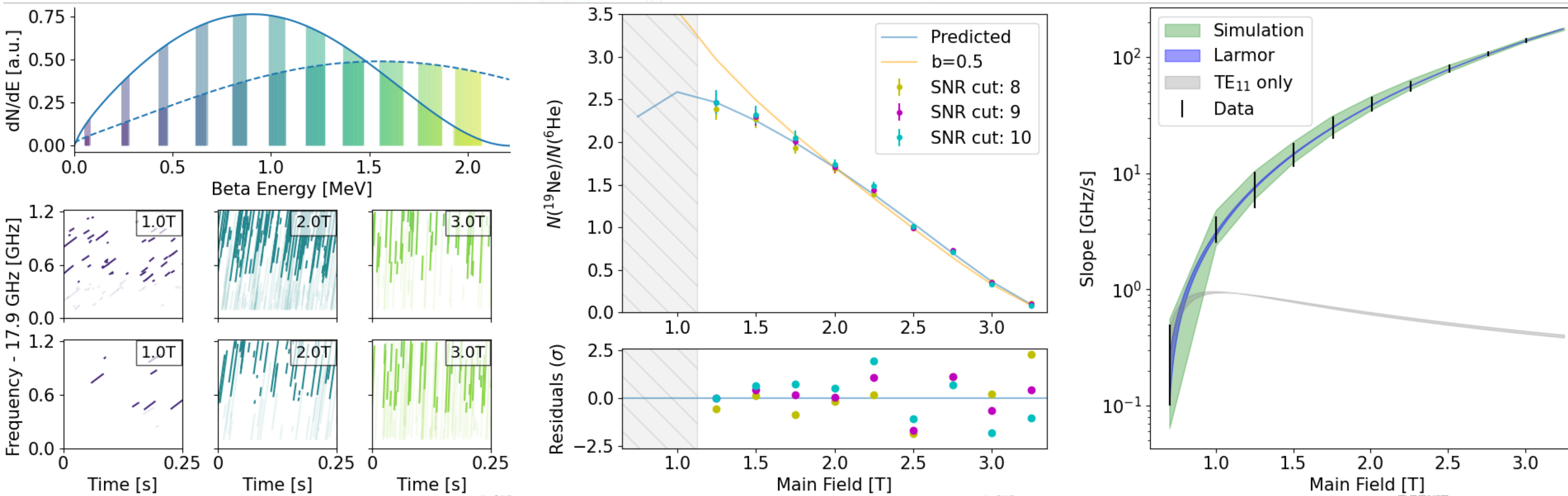
First CRES signals seen



First CRES signals seen

Identify event start frequencies.



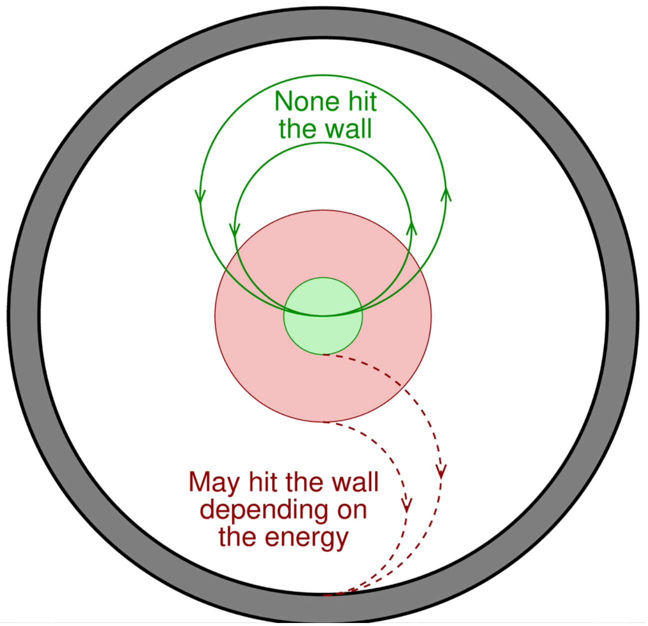


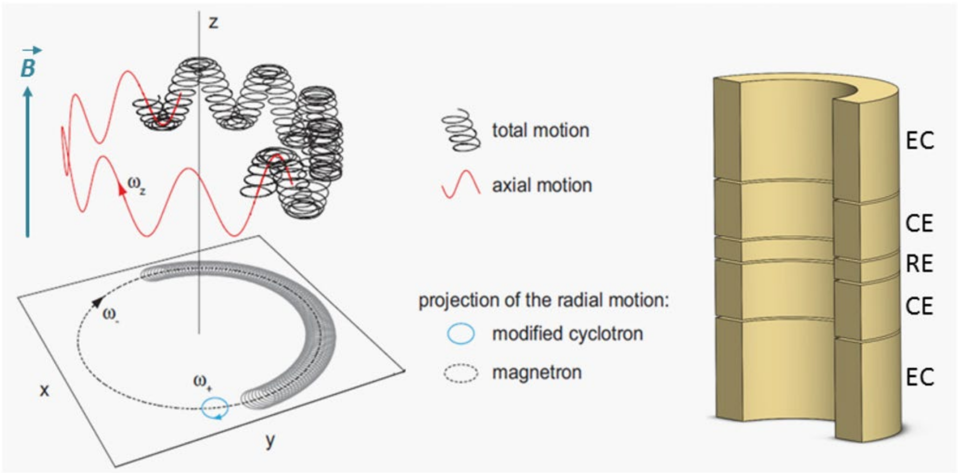
Drew Byron (UW) | DNP 2022 | October 27th, 2022 | 24 / 35

Ion trap + CRES

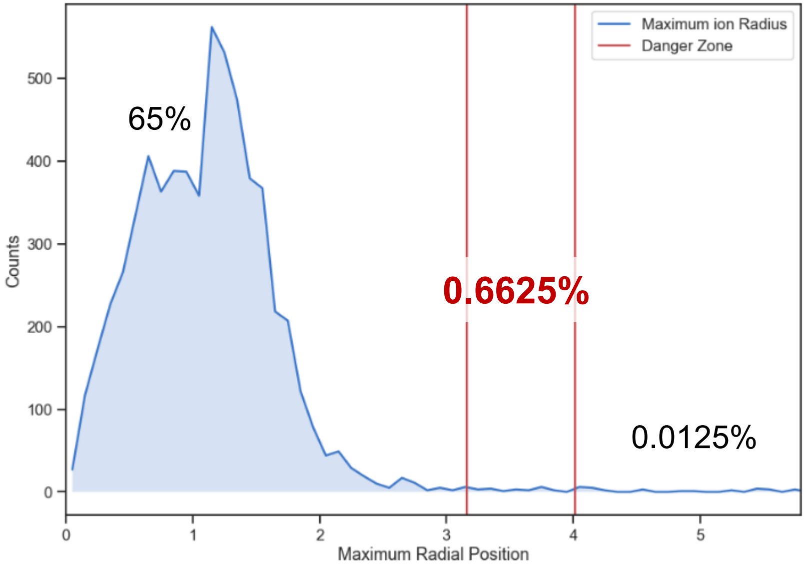
- Wall effects expected to be a limiting systematic

Largest and smallest electron orbits at 2 T





- Simulations indicate the rf signal not degraded, and rates *should* be high enough



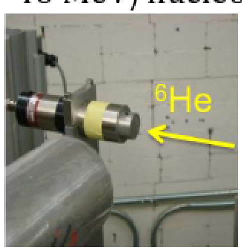
Searches for Scalar/Tensor currents

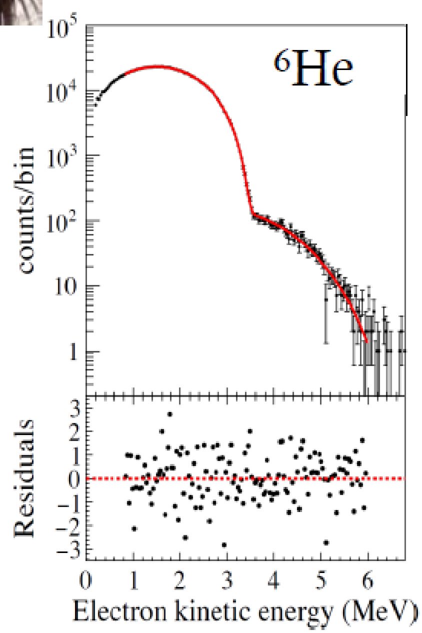
- Most sensitive probe is b_{Fierz} – linear in exotic couplings
- Cyclotron radiation emission spectroscopy (CRES)
- Implantation at FRIB (Naviliat-Cuncic); next ^{26m}Al

Fragmentation reactions enable choosing the most suitable candidates.

X. Huyan, PhD thesis 2019

46 MeV/nucleon

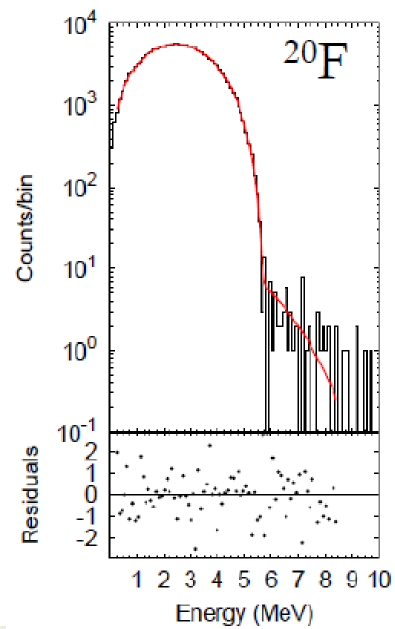


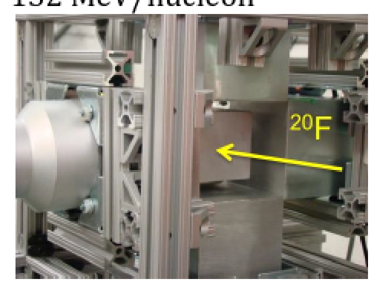


Analysis near completion. Expected $\Delta b_{GT}\sim0.01$

M. Hughes, PhD thesis 2019

132 MeV/nucleon

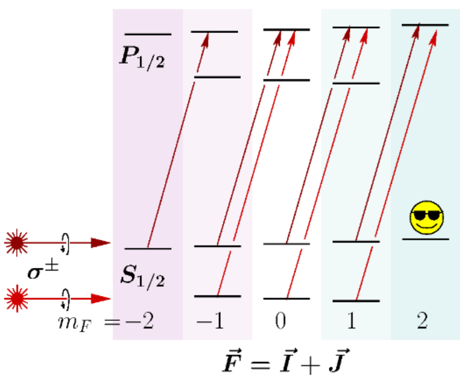




Analysis completed: reached $\Delta b_{GT}\sim0.02$ including systematics

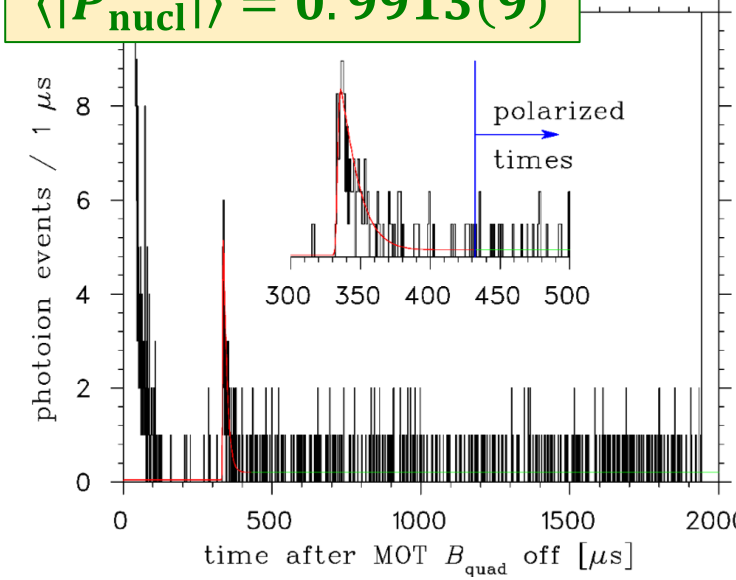
Atom and ion traps for BSM searches

- TRINAT has developed some pretty cool techniques
  - High nuclear polarization

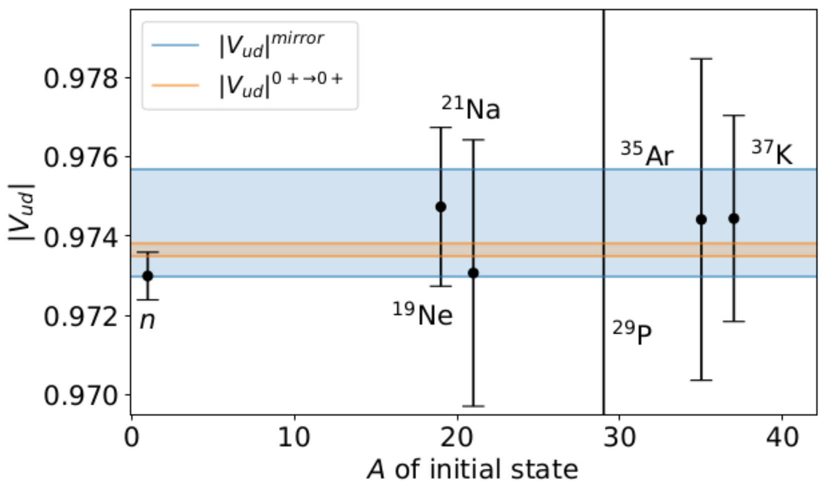


B.Fenker *et al*, New J. Phys. **18** (2016)

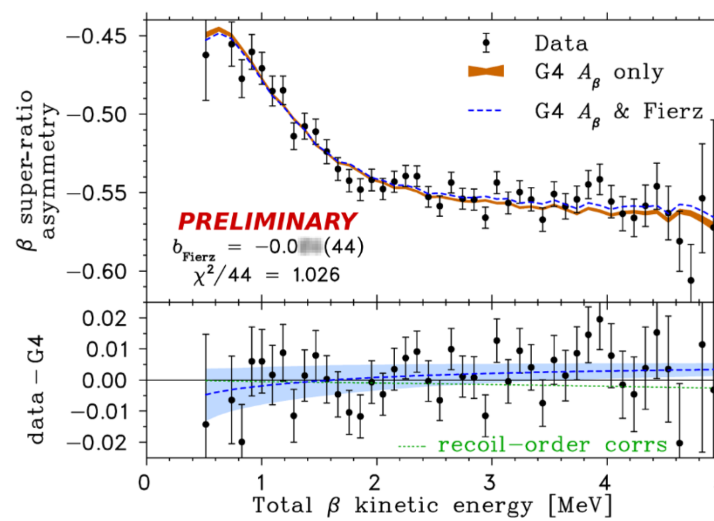
$\langle|P_{\mathrm{nucl}}|\rangle = 0.9913(9)$



  - Physics result: A_β to 0.3%

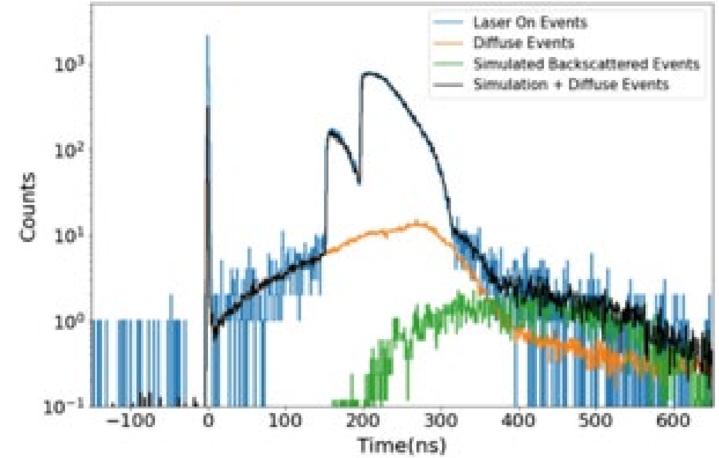


B.Fenker *et al*, PRL **120** (2018)



Atom and ion traps for BSM searches

- TRINAT has developed some pretty cool techniques
  - High nuclear polarization
  - Physics result: A_β to 0.3%
  - $< 0.1\%$ within reach!

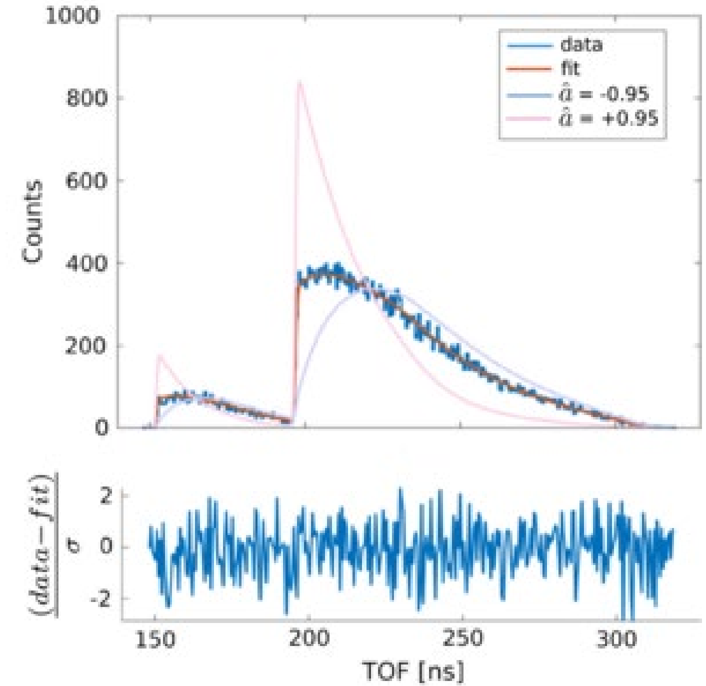


- ^{6}He at CENPA in collaboration with ANL
  - Recently published result:

$$\tilde{a} = -0.3268(46)(41)$$

$$\Leftrightarrow\ 0.007 \leq |C_T/C_A| \leq 0.111 \text{ (90\% CL)}$$

Muller *et al*., PRL **129**, 182502 (2022)

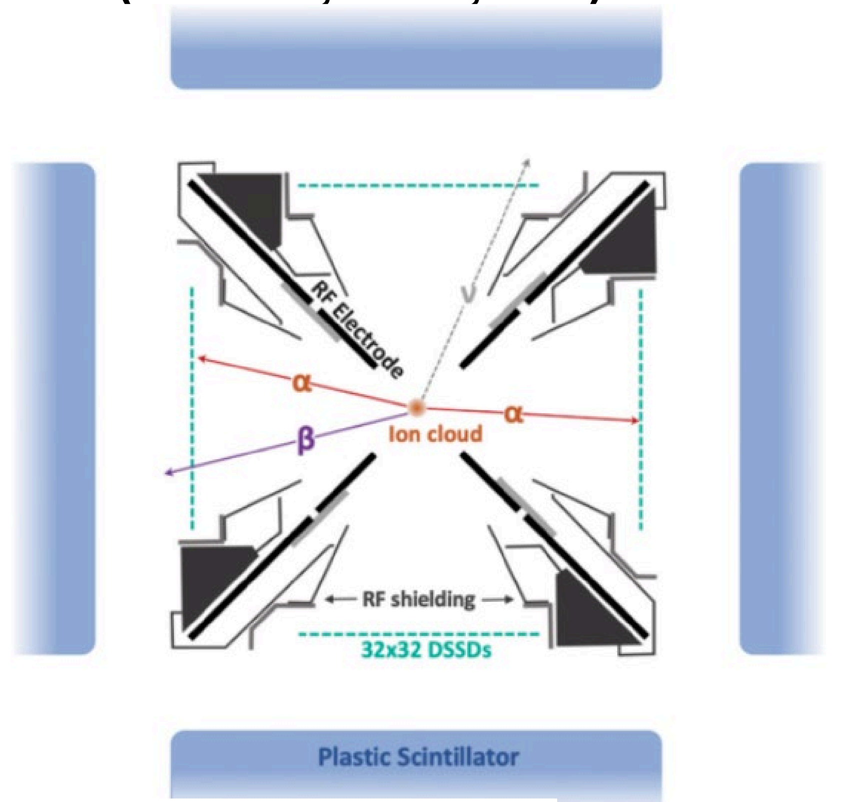


Atom and ion traps for BSM searches

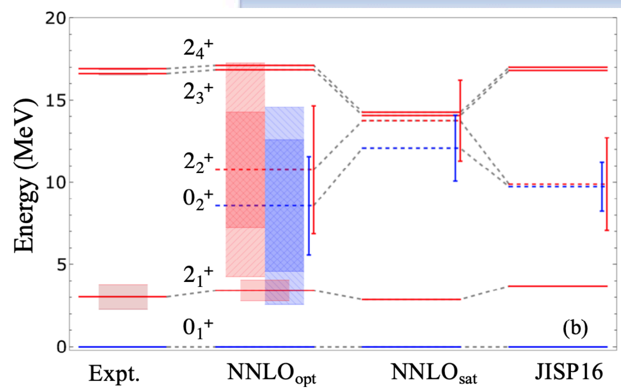
- The beta-decay Paul trap @ ANL (LLNL, ND, …)
  - β-α-α coincidence M.T. Burkey *et al*., PRL **128**, 202502 (2022)

TABLE I. Summary of dominant systematic corrections and uncertainties, listed at 1σ.

Source		Correction	Uncertainty
Theory	Intruder state (added linearly)	+0.0005	0.0005
	Recoil and radiative terms		0.0015
Experiment	α-energy calibration		0.0007
	Detector line shape		0.0009
	Data cuts		0.0009
	β scattering		0.0010
Total		+0.0005	0.0028



	j_2/A^2c_0	j_3/A^2c_0	d/Ac_0	b/Ac_0
2_1^+	-956 ± 37	-1547 ± 42	10.0 ± 1.0	6.0 ± 0.4
2_2^+ (new)	-10 ± 10	-80 ± 30	-0.5 ± 0.5	3.7 ± 0.4
2_3^+ (doublet 1)	12 ± 5	-60 ± 15	0.3 ± 0.2	3.8 ± 0.2
2_4^+ (doublet 2)	11 ± 3	-65 ± 11	0.2 ± 0.2	3.8 ± 0.2



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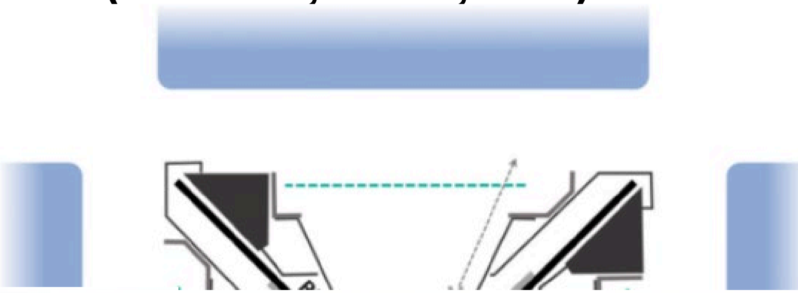

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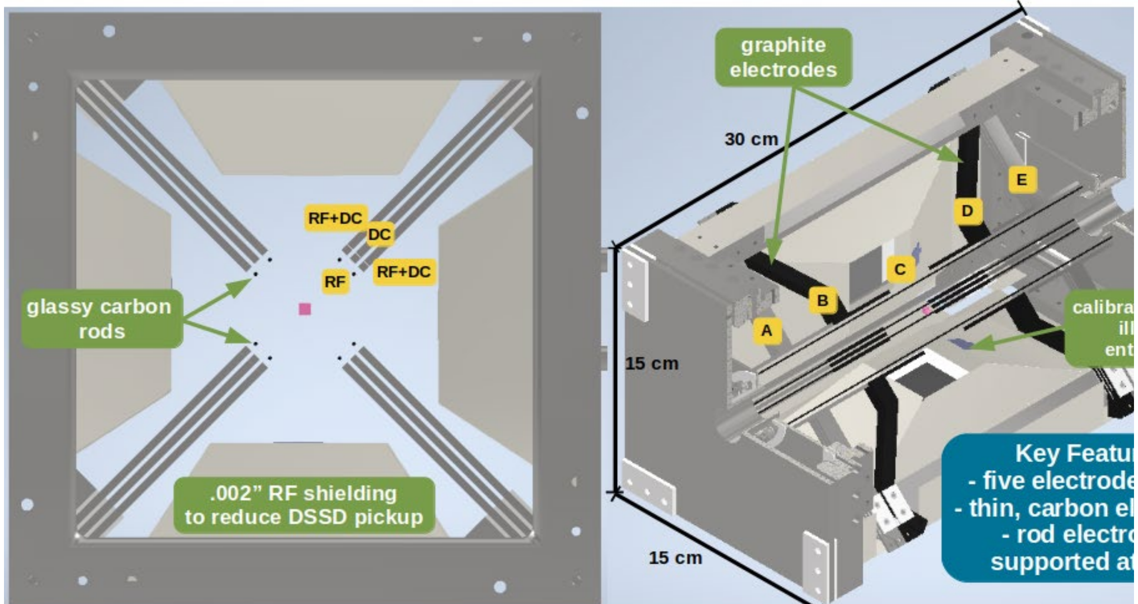
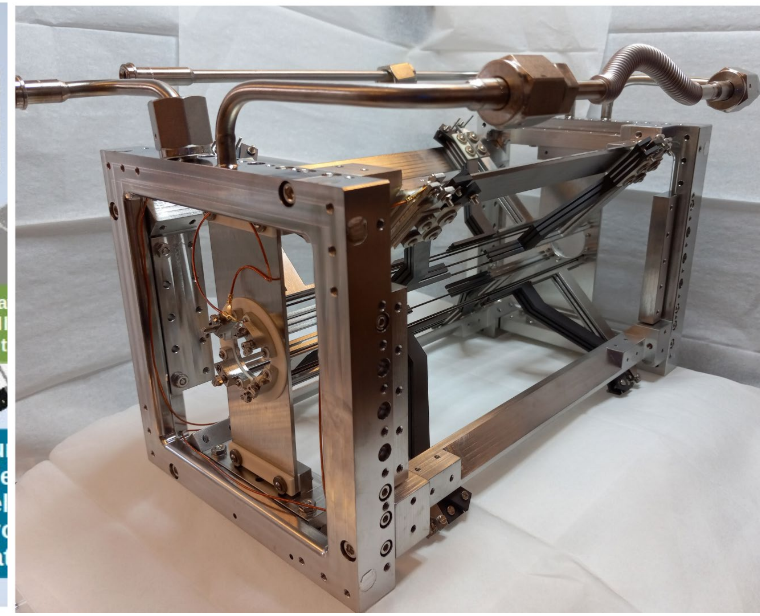


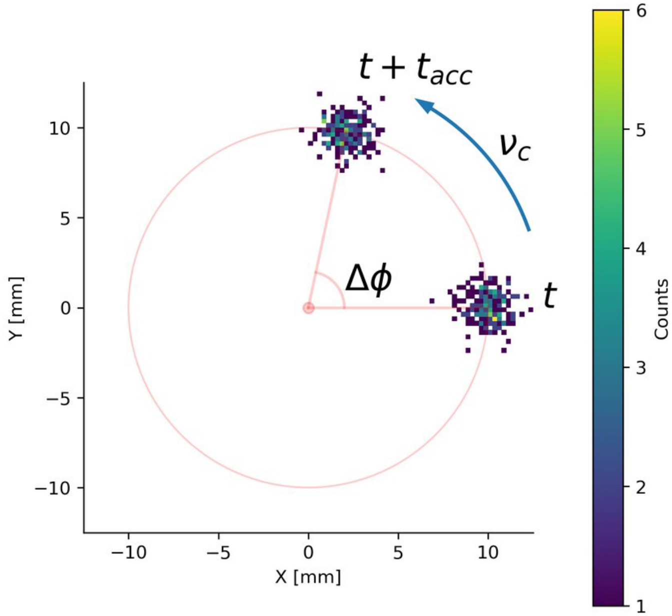


- Upgrade will reduce β scattering by $4\,\times$. Goal is to improve uncertainty by factor of 2 from recently published result.

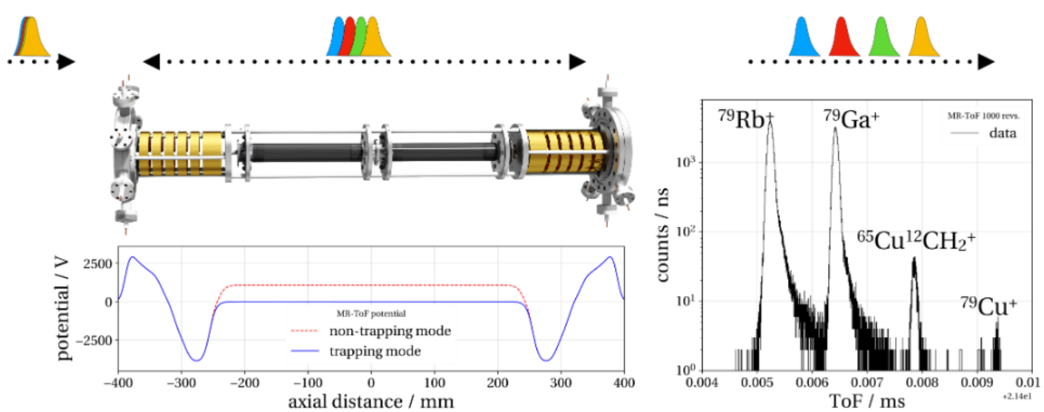
G15.00001 and G15.00002 (Sun 10:45 am)

Mass measurements with Penning traps

- TOF-ICR the workhorse for many years
- Phase-image ion-cyclotron-resonance (PI-ICR) improves precision
  - LEBIT, CPT (TITAN, JYFLTRAP, …)



- MR-TOF has really exploded in recent years; every major lab has one now



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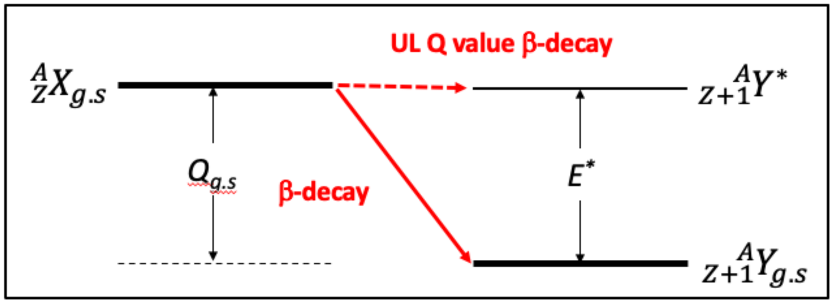
Ultra-low Q value measurements with CHIP-TRAP

Penning traps: Independent β-decay Q value from mass ratio of parent and daughter nuclides

$$Q_{g.s.} = (M_P - M_D)c^2 = (M_P - m_e)(1 - R)c^2 \qquad R = M_D^+/M_P^+$$

Ultra-low Q value β-decay: $Q_{UL} = Q_{g.s.} - E^* < 1$ keV



More precise Q values needed to identify candidates

Some promising potential candidates

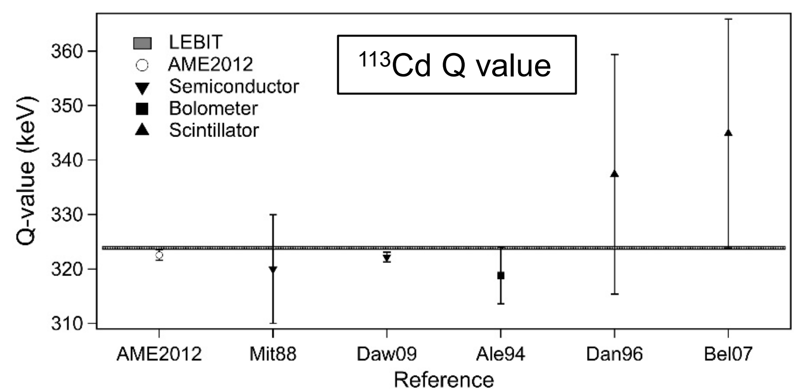
Isotope	Decay	Forbiddenness	Half-life	Q_{ES} (keV)
^{136}Cs	β^-	Allowed	13 dy	3.7(19)
^{188}W	β^-	Allowed	70 dy	-4.6(32)
^{155}Eu	β^-	1st Forbidden	5 yr	0.3(16)
^{156}Eu	β^-	1st Forbidden	15 dy	1.0(37)
^{56}Co	EC	Allowed	78 dy	4.76(55)
^{97}Tc	EC	Allowed	4.2 Myr	-0.1(42)
^{175}Hf	EC	Allowed	70 dy	1.0(26)
^{81}Kr	EC	1st Forbidden	229 kyr	3.2(15)
^{146}Pm	EC	1st Forbidden	6 yr	-0.3(45)
^{157}Tb	EC	1st Forbidden	71 yr	-2.3(14)
^{173}Lu	EC	1st Forbidden	1.5 yr	1.0(18)
^{183}Re	EC	1st Forbidden	70 dy	2.5(81)
^{195}Au	EC	1st Forbidden	186 dy	1.9(12)
^{148}Eu	β^+	Allowed	55 dy	-15(10)
^{105}Ag	β^+	1st Forbidden	41 dy	5.7(47)
^{144}Pm	β^+	1st Forbidden	1 yr	-4.8(32)
^{146}Pm	β^+	1st Forbidden	6 yr	-4.3(45)

2201.08790v2

Q values for forbidden β-decays

High-precision β-spectra provide:
- Possibility to extract g_A via spectral shape method.
- Data for radionuclide metrology (applications in nuclear medicine and nuclear power).
- Improved knowledge of rare decays – potential backgrounds in $0\nu\beta\beta$ and dark matter detectors.
- Improved data for testing theoretical calculations.

Penning trap Q values provide:
- Direct test of systematics via comparison of Q value and end point energy.
- Precise Q value for phase space factor calculations.



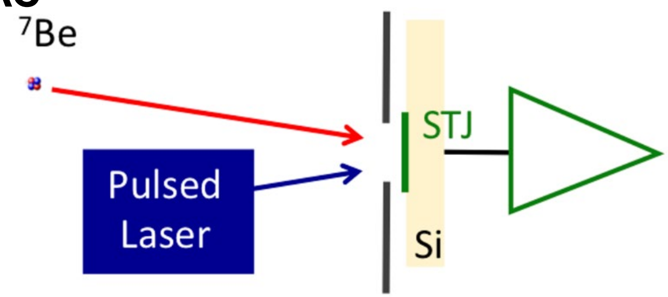
BSM with Rare-Isotope Doped Superconductors

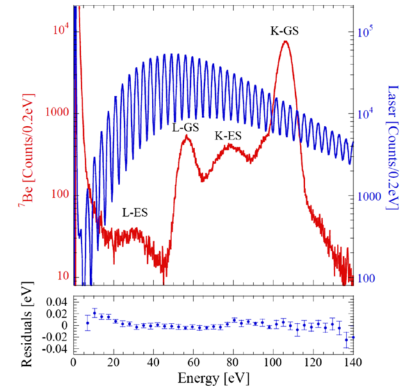
Colorado School of Mines — Earth • Energy • Environment
Lawrence Livermore National Laboratory
TRIUMF

THE BeEST

- Embedding radioactive atoms into superconducting tunnel junctions (STJs)
- Measure eV-scale decay recoils
- Search for keV – MeV sterile neutrinos

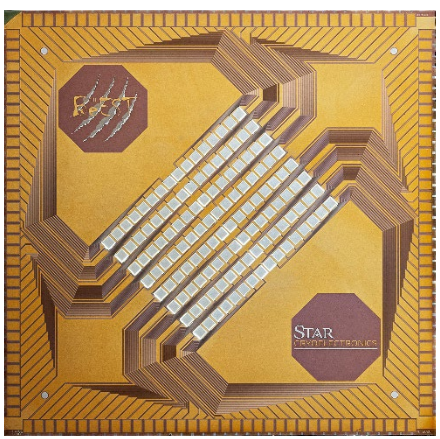
^{7}Be implantation at TRIUMF-ISAC

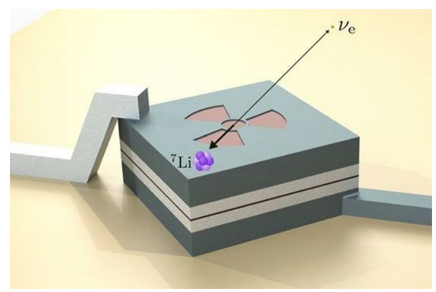


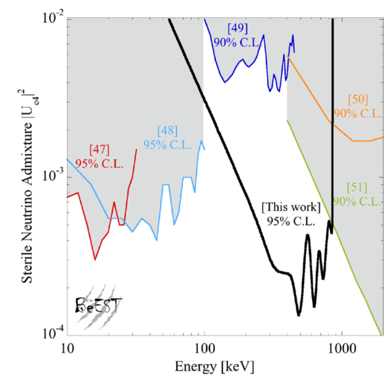


STAR Cryoelectronics

Ta, Al, and Nb-based STJ Sensors







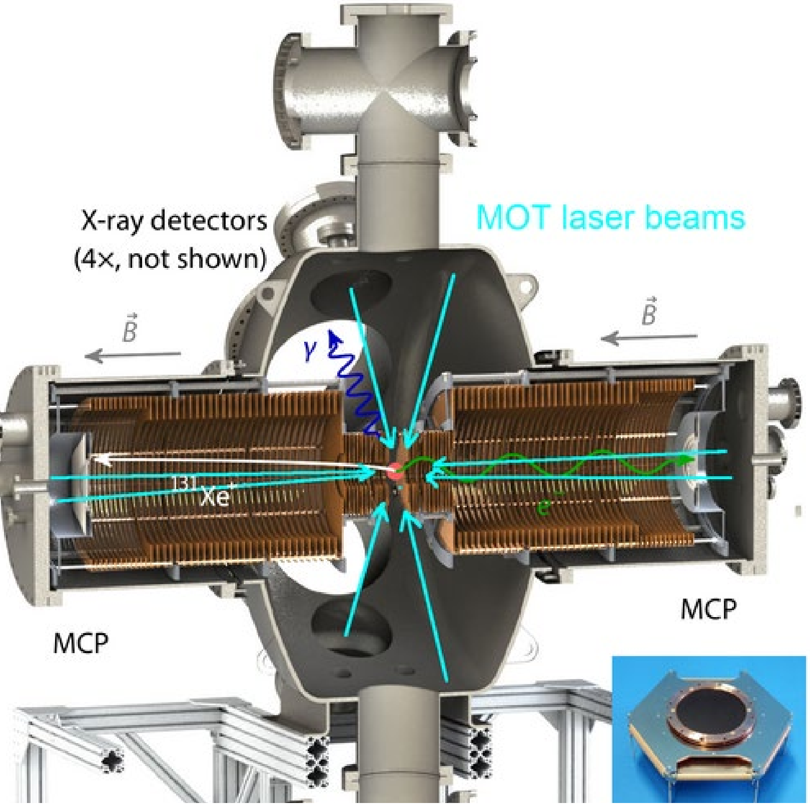
U.S. Department of Energy — Office of Science
Gordon and Betty Moore Foundation
EMPIR — EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

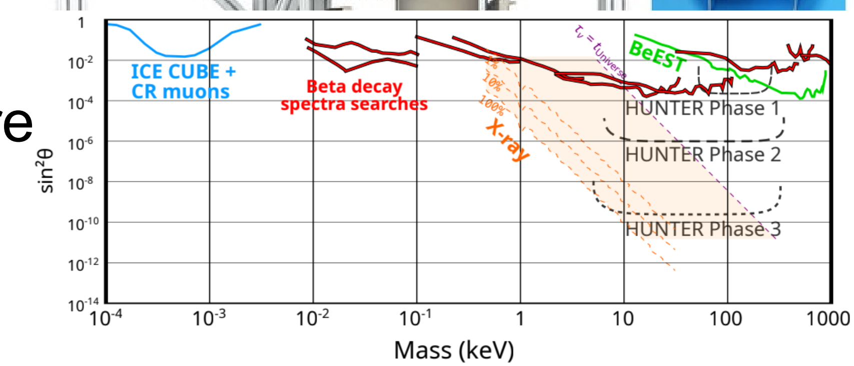
A. Samanta *et al*., Phys. Rev. Applied (*in press*) (2022)
S. Friedrich *et al*., J. Low Temp. Phys. (*in press*) (2022)
C. Bray *et al*., J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach *et al*., J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al*., Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al*., Phys. Rev. Lett. **125**, 032701 (2020)
S. Friedrich *et al*., J. Low Temp. Phys. **200**, 200 (2020)

HUNTER

Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction

- Kinematic reconstruction of m_ν in individual EC decays of ^{131}Cs atoms at rest
  - Kinematic reconstruction - not an oscillation experiment. Measure all decay product momenta & reconstruct missing neutrino mass event-by-event
  - ^{131}Cs is at rest - held in a Magneto-Optical Trap and laser cooled to 20 μK
  - Reaction Ion Microscopes measure recoil nucleus and Auger electron directions & momenta with high efficiency & resolution 0.1-1%





Measuring β Transitions in Complex β Decays

Currently only β energy spectra of ***very*** simple β decays are studied

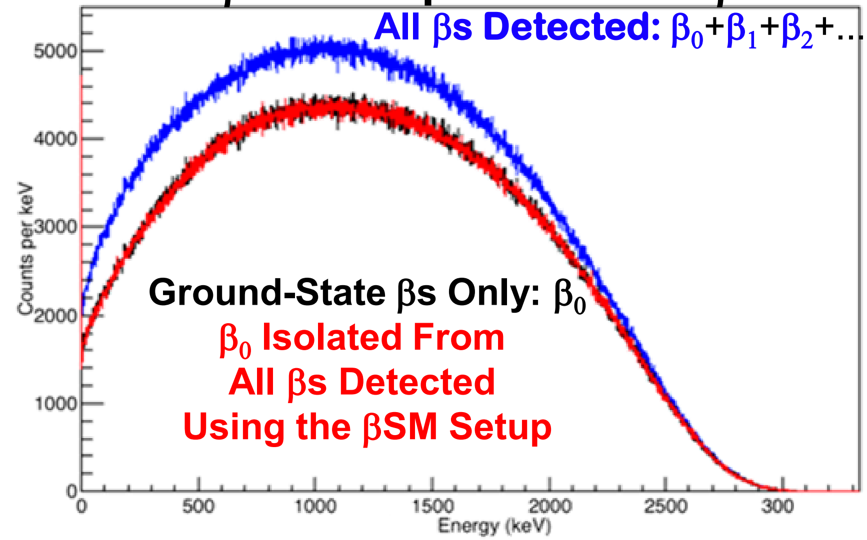
ORNL-LSU collab are developing the
β-Spectrum Module (βSM)
with ORNL's MTAS Detector
to measure entire β-energy spectra for each individual β-decay transition

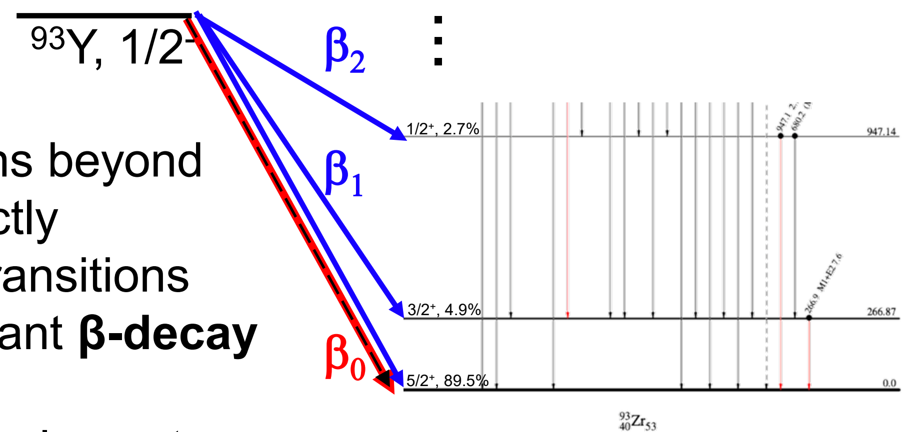
Isolate Individual β transitions with ~99% efficiency

Permits extraction of various allowed and 1st -forbidden β shapes all from the same parent

- Improve reactor antineutrino flux predictions beyond the 5% level down to the ~1% level by directly measuring β-shape factors of individual β transitions
- Expand by hundreds the number of important **β-decay shape factors** that can be studied
- Allows access to g_V and g_A, nuclear matrix elements
- Can minimize systematics by measuring different β transitions from the same β-decaying parent

Simulated βSM Response to ^{93}Y β Decay





Work supported by Nuclear Data FOA-2440, Rasco *et al.*, 2022

Summary

Why are the next few years interesting:

- Increased precision of V_{ud} could confirm CKM unitarity deficit
  - Precision of V_{ud} from neutron decay is gradually catching up. Comparisons between V_{ud} from different determinations could possibly unveil new anomalies.
  - It is possible for the first time to compute quantities such as δ_{NS} and δ_C with rigorously-quantified theory uncertainties
- Cutting-edge technologies opening up new opportunities for significant increase in precision for BSM searches and (sterile) neutrino searches (CRES, quantum sensors, traps, …)

What might get accomplished during this LRP:

- Formation of a topical group (e.g. VudU, "Vud unitarity" alliance) to facilitate collaborations, especially between experiment and theory
- Compute δ_{NS} and δ_C with ab-initio methods for light and medium nuclei; improve recoil-order corrections
- Experimental programs maturing to reach 0.1% and beyond, and orders of magnitude on sterile neutrinos

Poised for great results to come out of this LRP

In case I run out of time (I didn't?!?!)

- Start and end with the White Paper recommendations:
  - Experimental + theoretical alliance for V_{ud} and CKM unitarity
  - Investing in small- and mid-scale projects
  - Establishing support for nuclear theory
  - Developing cutting-edge techniques
  - Promote diverse and inclusive environment, and better support students
- Thanks for input (apologies to all)
  - Maxime Brodeur, Drew Byron, Jason Clark, Leendert Hayen, Kyle Leach, Charlie Rasco, Matt Redshaw, Nick Scielzo, Chien Yeah Seng, Louis Varrian, and everyone on the nuclear β decay White Paper
  - DOE and NSF for support

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