Theory status and experimental opportunities of modern V_{ud} determinations

Leendert Hayen

ISOL-France workshop

4 April 2025

RÉGION NORMANDIE

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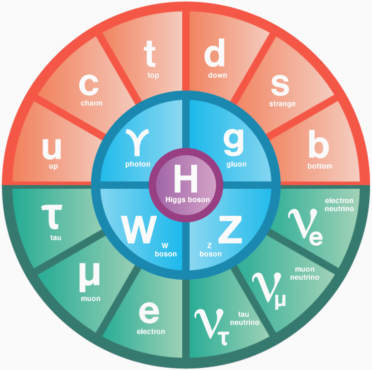
Meet the Standard Model

Three out of four
fundamental forces (no gravity):

Standard Model



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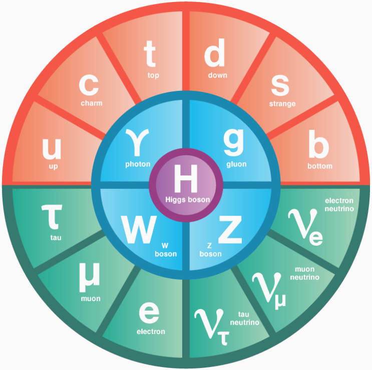

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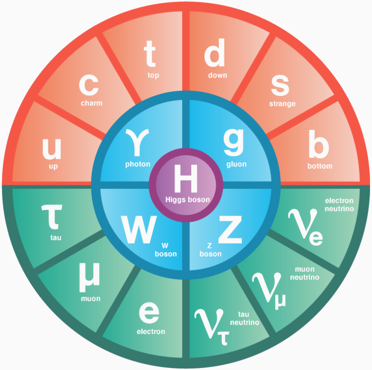
Great (annoyingly so), consistent with constraints at $\sim 10^{0-2}$ TeV



Meet the Standard Model

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18 free parameters

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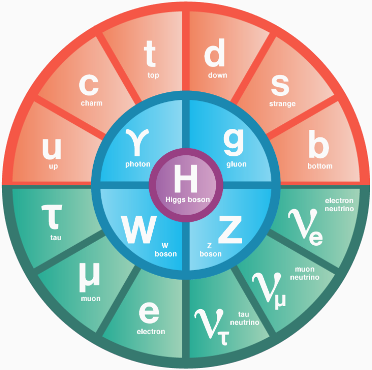
Open questions: dark matter, gravity, neutrino masses, ...



Introduction: Weak interaction & CKM matrix

Cabibbo-Kobayashi-Maskawa matrix relates weak and mass eigenstates

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

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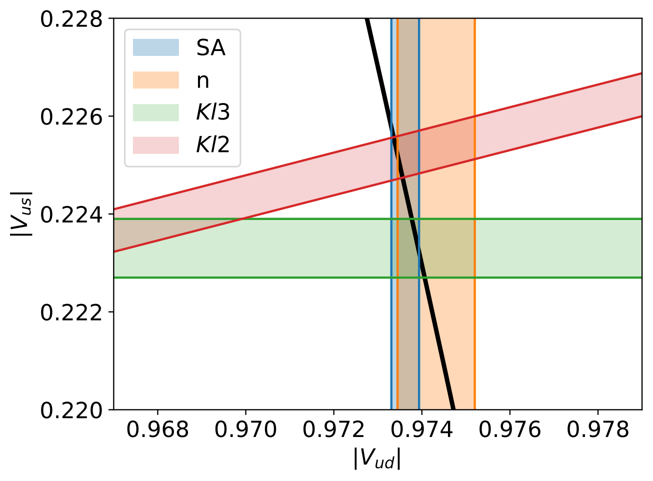
(nuclear) β decay, meson decay (π, K), $|V_{ub}|^2 \sim 10^{-5}$

Violations are sensitive to **TeV scale** new physics!

CKM unitarity: Current status

Signs of non-unitarity at few σ level...

Disagreement between $Kl2$ and $Kl3$ $|V_{us}|$ ‘Cabibbo angle anomaly’



What would new physics look like?

SM has V-A structure, but more generally

$$\mathcal{L}_{\text{eff}} = -\frac{G_F \tilde{V}_{ud}}{\sqrt{2}} \Big\{ \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu [c_V - (c_A - 2\epsilon_R)\gamma^5] d + \epsilon_S \, \bar{e}\nu_L \cdot \bar{u} d$$
$$- \epsilon_P \, \bar{e}\nu_L \cdot \bar{u}\gamma^5 d + \epsilon_T \, \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma^5) d \Big\} + \text{h.c.},$$

at the quark level

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at the quark level

All ϵ_i are proportional to $(M_W/\Lambda_{BSM})^2$, change kinematics

$\epsilon_i \lesssim 10^{-4} \rightarrow \Lambda_{BSM} \gtrsim 15$ TeV assuming natural couplings

CKM unitarity: V_{ud}

Let's break it down: How to obtain V_{ud}?

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Semi-leptonic up-down decay rate

$$\Gamma \propto G_F^2 |V_{ud}|^2 (1 + RC) |\langle O_{\mathrm{hadr}} \rangle|^2 \times \text{phase space}$$

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Things you need to know

- G_F (μ lifetime)
- Radiative corrections
- Hadronic theory
- For each β transition: $t_{1/2}, Q_\beta$, BR, (GT/F mixing)

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Master formula

$$ft(1 + \delta_R')(1 + \Delta_R^V)(1 + \delta_{NS} - \delta_C) = \frac{K}{G_F^2 V_{ud}^2 M_{\mathrm{tree}}^2}$$

CKM unitarity: V_{ud} precision

Nuclear sandbox $\rightarrow$ make hadronic theory easy

- Pion
- Neutron
- Superallowed $0^+ \rightarrow 0^+$
- $T = 1/2$ mirrors

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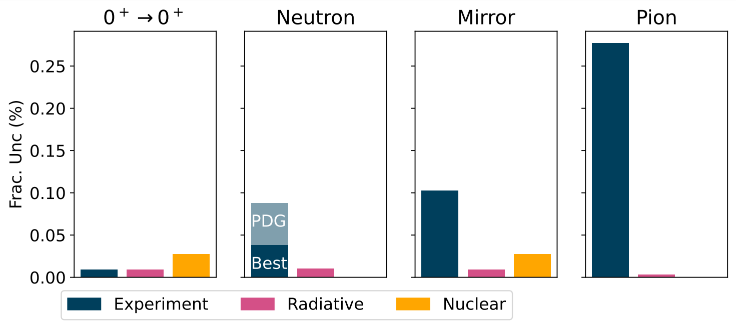

$\pi^+ \rightarrow \pi^0 e^+ \nu_e$ very hard (BR $\sim 10^{-8}$)

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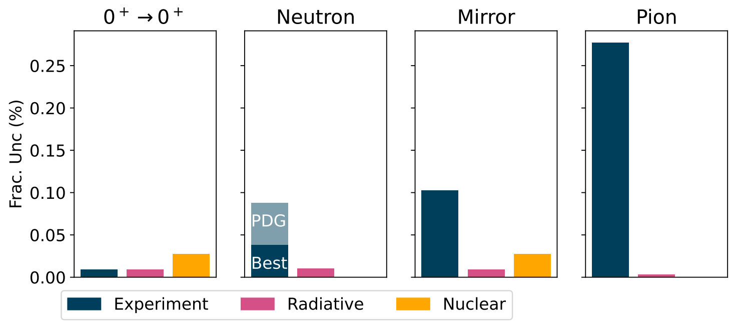

Status of $0^+ \rightarrow 0^+$ **ISOL community triumph for 50+ years!**

LH, ARNPS 74 (2024) 497

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Theory changes overview

Recall master equation:

$$ft(1 + \delta_R')(1 + \Delta_R^V)(1 + \delta_{NS} - \delta_C) = \frac{K}{G_F^2 V_{ud}^2 M_{\mathrm{tree}}^2}$$

Every element has received updates/overhauls.

Theory changes overview

Recall master equation:

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Every element has received updates/overhauls.

Separate into tree level & loop level

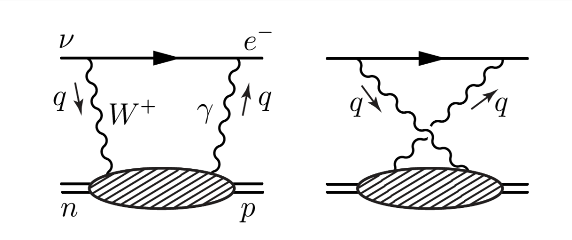
- δ_C: Isospin symmetry breaking of M_F
- f: phase space factor
- δ_R': 'outer' radiative corrections
- Δ_R^V: single-nucleon 'inner' radiative corrections
- δ_{NS}: Changes in Δ_R^V due to nuclear structure

All except for Δ_R^V are **open questions** to this day!

Based on L.H. ARNPS 74 (2024) 497 and Gorchtein, Seng ARNPS 74 (2024) 23

Recent changes: Δ_R^V

Rescaling of coupling constant $g_V^2 \rightarrow g_V^2(1 + \Delta_R^V)$



Specifically, axial-vector contribution $\rightarrow$ symmetries don't save you & QCD at intermediate effects

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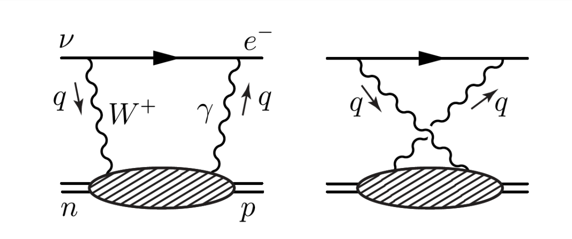
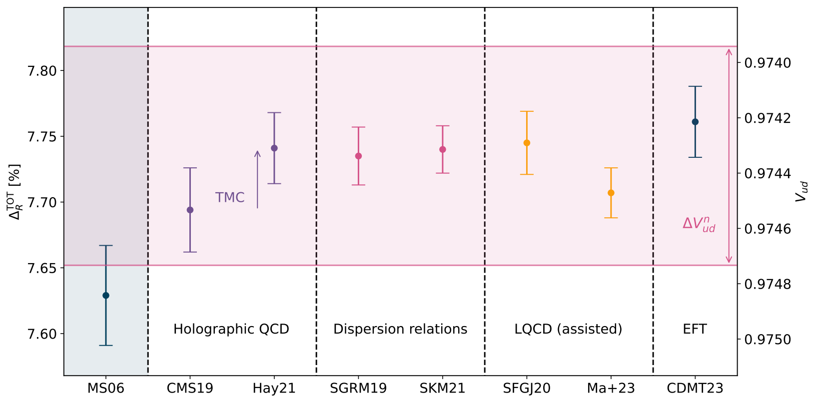


Specifically, axial-vector contribution $\to$ symmetries don't save you & QCD at intermediate effects

$+50$ years of research to improve it

Δ_R^V updates

After 2018 jump different calculations performed: convergence

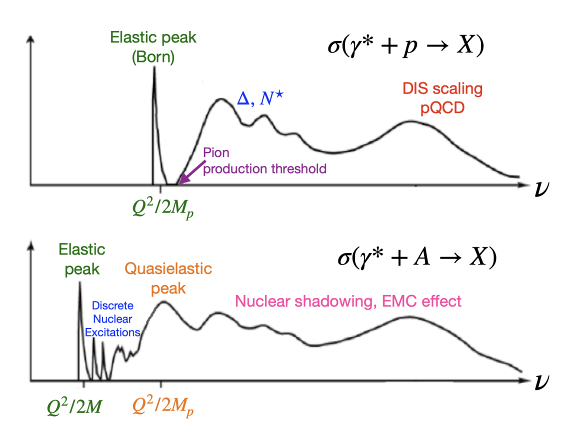


Small differences remain, neutron experimental uncertainty too large to distinguish

LH, ARNPS 74 (2024) 497

Current status on δ_{NS}

V_{ud} currently limited by nuclear structure in radiative corrections

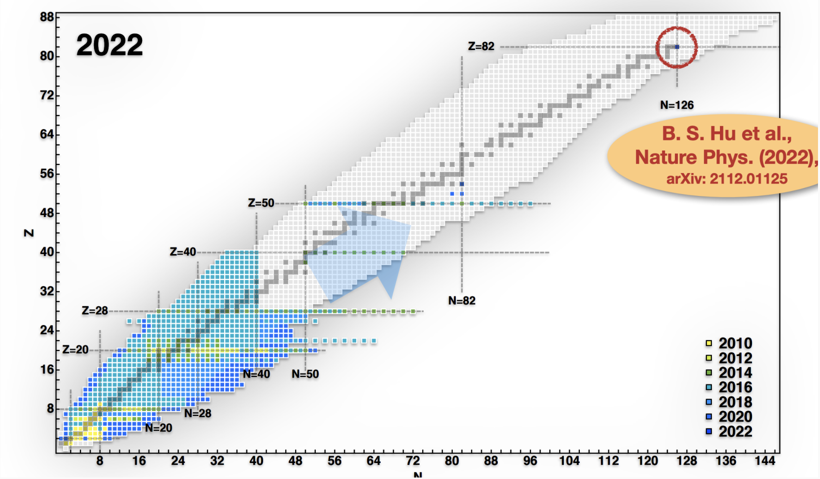


More sophisticated picture, first ab initio calculations emerging

Gorchtein & Seng ARNPS 74 (2024) 1

Progress in nuclear ab initio theory

Field is charging full steam ahead on nuclear ab initio



H. Hergert, Frontiers in Physics (2020)

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Role of charge radii made simple

Schematic description of β decay matrix element

$$M_{fi} \sim \int d^3x \psi_\nu^* \psi_e^* \psi_f^* \mathcal{O}_\beta \psi_i$$

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depends on charge radius: solution in central potential $\rightarrow$ Fermi function

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Schematic description of β decay matrix element

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depends on charge radius: solution in central potential $\rightarrow$ Fermi function

$$F(Z, E_e) \sim |\psi_e(r = R)|^2$$

and weak charge radius

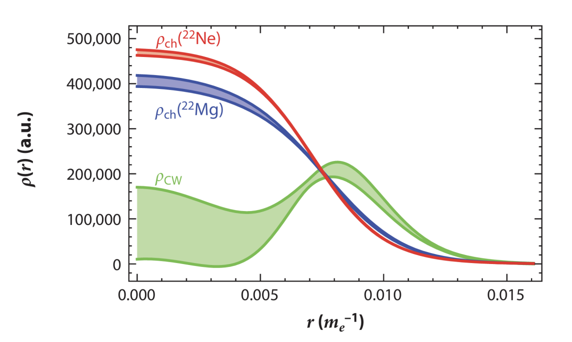
$$\rho_{wc}(r) \sim \psi_f^*(r) O_\beta(r) \psi_i(r)$$

where $\rho_{wc}(r) = \rho_{ch}(r) + \delta\rho(r)$, usually **nuclear (shell) model**

Weak charge from charge radii

Isospin symmetry: ρ_{wc} from 2 out 3 charge radii in $T = 1$ triplet

$$\rho_{wc}(r) = \rho_{ch,1}(r) + \frac{Z_{-1}}{2}[\rho_{ch,-1}(r) - \rho_{ch,1}(r)]$$



Seng, Gorchtein PRC 109 (2024) 045501

Nuclear charge radii: Current data set

Experimentalists: pay attention to **last column** (NA means go)!

Table 1 Determinations of $\langle r^2_{CW} \rangle$ based on available data of nuclear charge radii for isotriplets in measured superallowed decays

A	$\langle r^2_{ch,-1} \rangle^{1/2}$ (fm) [Ref.]	$\langle r^2_{ch,0} \rangle^{1/2}$ (fm) [Ref.]	$\langle r^2_{ch,1} \rangle^{1/2}$ (fm) [Ref.]	$\langle r^2_{CW} \rangle^{1/2}$ (fm)
10	${}^{10}_{6}$C	${}^{10}_{5}$B (ex)	${}^{10}_{4}$Be: 2.3550(170) [59]	NA
14	${}^{14}_{8}$O	${}^{14}_{7}$N (ex)	${}^{14}_{6}$C: 2.5025(87) [59]	NA
18	${}^{18}_{10}$Ne: 2.9714(76) [59]	${}^{18}_{9}$F (ex)	${}^{18}_{8}$O: 2.7726(56) [59]	3.661(72)
22	${}^{22}_{12}$Mg: 3.0691(89) [61]	${}^{22}_{11}$Na (ex)	${}^{22}_{10}$Ne: 2.9525(40) [59]	3.596(99)
26	${}^{26}_{14}$Si	${}^{26m}_{13}$Al: 3.130(15) [65]	${}^{26}_{12}$Mg: 3.0337(18) [59]	4.11(15)
30	${}^{30}_{16}$S	${}^{30}_{15}$P (ex)	${}^{30}_{14}$Si: 3.1336(40) [59]	NA
34	${}^{34}_{18}$Ar: 3.3654(40) [59]	${}^{34}_{17}$Cl	${}^{34}_{16}$S: 3.2847(21) [59]	3.954(68)
38	${}^{38}_{20}$Ca: 3.467(1) [62]	${}^{38m}_{19}$K: 3.437(4) [63]	${}^{38}_{18}$Ar: 3.4028(19) [59]	3.999(35)
42	${}^{42}_{22}$Ti	${}^{42}_{21}$Sc: 3.5702(238) [59]	${}^{42}_{20}$Ca: 3.5081(21) [59]	4.64(39)
46	${}^{46}_{24}$Cr	${}^{46}_{23}$V	${}^{46}_{22}$Ti: 3.6070(22) [59]	NA
50	${}^{50}_{26}$Fe	${}^{50}_{25}$Mn: 3.7120(196) [59]	${}^{50}_{24}$Cr: 3.6588(65) [59]	4.82(39)
54	${}^{54}_{28}$Ni: 3.738(4) [64]	${}^{54}_{27}$Co	${}^{54}_{26}$Fe: 3.6933(19) [59]	4.28(11)
62	${}^{62}_{32}$Ge	${}^{62}_{31}$Ga	${}^{62}_{30}$Zn: 3.9031(69) [61]	NA
66	${}^{66}_{34}$Se	${}^{66}_{33}$As	${}^{66}_{32}$Ge	NA
70	${}^{70}_{36}$Kr	${}^{70}_{35}$Br	${}^{70}_{34}$Se	NA
74	${}^{74}_{38}$Sr	${}^{74}_{37}$Rb: 4.1935(172) [61]	${}^{74}_{36}$Kr: 4.1870(41) [59]	4.42(62)

Gorchtein, Seng ARNPS 74 (2024) 23-47

Phase space updates

Integrating over β spectrum for Γ

$$f = m_e^{-5} \int_{m_e}^{E_0} dE \ pE(E_0 - E)^2 F(Z,E) C(Z,E) K(Z,E)$$

contains charge radius and weak charge effects.

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PHYSICAL REVIEW LETTERS **131,** 222502 (2023)

Editors' Suggestion Featured in Physics

Nuclear Charge Radius of ^{26m}Al and Its Implication for V_{ud} in the Quark Mixing Matrix

P. Plattner,[1,2,3,*] E. Wood,[4] L. Al Ayoubi,[5] O. Beliuskina,[5] M. L. Bissell,[6,1] K. Blaum,[3] P. Campbell,[6] B. Cheal,[4] R. P. de Groote,[5,‡] C. S. Devlin,[4] T. Eronen,[5] L. Filippin,[7] R. F. Garcia Ruiz,[1,8] Z. Ge,[5] S. Geldhof,[9] W. Gins,[5] M. Godefroid,[7] H. Heylen,[1,3] M. Hukkanen,[5] P. Imgram,[10] A. Jaries,[5] A. Jokinen,[5] A. Kanellakopoulos,[9] A. Kankainen,[5] S. Kaufmann,[10] K. König,[10] Á. Koszorús,[4,9,‡] S. Kujanpää,[5] S. Lechner,[1] S. Malbrunot-Ettenauer,[1,11,†] P. Müller,[10] R. Mathieson,[4] I. Moore,[5] W. Nörtershäuser,[10] D. Nesterenko,[5] R. Neugart,[3,12] G. Neyens,[1,9] A. Ortiz-Cortes,[5] H. Penttilä,[5] I. Pohjalainen,[5] A. Raggio,[5] M. Reponen,[5] S. Rinta-Antila,[5] L. V. Rodríguez,[3,1,13] J. Romero,[5] R. Sánchez,[14] F. Sommer,[10] M. Stryjczyk,[5] V. Virtanen,[5] L. Xie,[6] Z. Y. Xu,[9] X. F. Yang,[9,15] and D. T. Yordanov[13]

See also 2502.17070

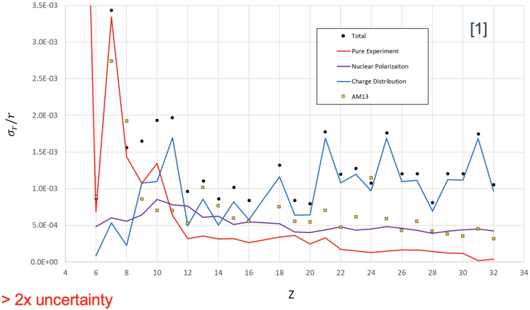
Charge radii for V_{ud}

Absolute charge radii are put into question

The lack of new absolute radii

Both methods faded out in the early '90s

- Data not available
- Not all stables done
- Reliable treatment of errors???



Many absolute radii should have > 2x uncertainty

Ongoing efforts with muonic atoms

Slide by Michael Heines; see also Ohayon 2409.08193

Isospin breaking updates

Isospin breaking ($\sim$Coulomb interaction) means

$$M_F^2 = (M_F^0)^2(1 - \delta_C)$$

with $\delta_C \sim 0.1 - 1\%$ for **nuclei**.

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Isospin breaking ($\sim$Coulomb interaction) means

$$M_F^2 = (M_F^0)^2(1 - \delta_C)$$

with $\delta_C \sim 0.1 - 1\%$ for **nuclei**. Traditional approaches separate into

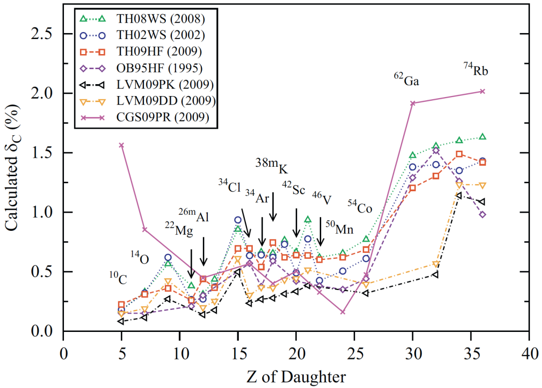
- δ_{C1}: isospin-mixing meaning $\langle \pi | a_{p,\alpha} | \phi_i \rangle^* \neq \langle \phi_f | a^\dagger_{n,\alpha} | \pi \rangle$
- δ_{C2}: radial mismatch, i.e. proton and neutron orbits are not the same

but conceptual issues already noted 15 years ago (Miller & Schwenk)

Same *problem*: strong **theory dependence**

On the radar: δ_C

Proton $\neq$ neutron inside nucleus $\rightarrow M_F^2 = 2(1 - \delta_C)$



It's δ_C that brings V_{ud} from different transitions in line

Grinyer et al., NIMA 622 (2010) 236

Isospin breaking updates

Rewrite δ_C using standard perturbation theory for $H = H_0 + V_{\mathrm{ISB}}$

$$\delta_C \simeq \sum_{T=0,1,2} \frac{\langle a; T || V_{\mathrm{ISB}} || g; 1\rangle^2}{(E_{a,T} - E_{g,1})^2}$$

over all states a and ground state g, **assuming** V_{ISB} is isovector.

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Can charge radii do anything?

PLB 838 (2023) 137654; PLB 846 (2023) 138259

Charge radii for ISB

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Can construct object

$$\Delta M_B^{(1)} = \frac{1}{2}(Z_1 \langle r^2_{ch,1} \rangle - Z_{-1} \langle r^2_{ch,-1} \rangle) - Z_0 \langle r^2_{ch,0} \rangle$$

which is 0 for perfect isospin symmetry

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which is 0 for perfect isospin symmetry

if only 1 intermediate state (isovector monopole dominance) contributes, $\delta_C \sim \Delta M_B^{(1)}$, but generically a theory discriminator

Charge radii for ISB

What we want to know

Transitions	δ_C (%)				
	WS	DFT	HF	RPA	Micro
$^{26m}\mathrm{Al} \to {}^{26}\mathrm{Mg}$	0.310	0.329	0.30	0.139	0.08
$^{34}\mathrm{Cl} \to {}^{34}\mathrm{S}$	0.613	0.75	0.57	0.234	0.13
$^{38m}\mathrm{K} \to {}^{38}\mathrm{Ar}$	0.628	1.7	0.59	0.278	0.15
$^{42}\mathrm{Sc} \to {}^{42}\mathrm{Ca}$	0.690	0.77	0.42	0.333	0.18
$^{46}\mathrm{V} \to {}^{46}\mathrm{Ti}$	0.620	0.563	0.38	/	0.21
$^{50}\mathrm{Mn} \to {}^{50}\mathrm{Cr}$	0.660	0.476	0.35	/	0.24
$^{54}\mathrm{Co} \to {}^{54}\mathrm{Fe}$	0.770	0.586	0.44	0.319	0.28

What we can measure

Transitions	$\Delta M_B^{(1)}$ (fm^2)				
	WS	DFT	HF	RPA	Micro
$^{26m}\mathrm{Al} \to {}^{26}\mathrm{Mg}$	-0.12	-0.12	-0.11	-0.05	-0.03
$^{34}\mathrm{Cl} \to {}^{34}\mathrm{S}$	-0.17	-0.21	-0.16	-0.06	-0.04
$^{38m}\mathrm{K} \to {}^{38}\mathrm{Ar}$	-0.15	-0.42	-0.15	-0.07	-0.04
$^{42}\mathrm{Sc} \to {}^{42}\mathrm{Ca}$	-0.15	-0.17	-0.09	-0.07	-0.04
$^{46}\mathrm{V} \to {}^{46}\mathrm{Ti}$	-0.12	-0.11	-0.08	/	-0.04
$^{50}\mathrm{Mn} \to {}^{50}\mathrm{Cr}$	-0.12	-0.09	-0.06	/	-0.04
$^{54}\mathrm{Co} \to {}^{54}\mathrm{Fe}$	-0.13	-0.10	-0.07	-0.05	-0.05

$$\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_1 R_{p,1}^2 + Z_{-1} R_{p,-1}^2\right) - Z_0 R_{p,0}^2$$

Slide by Ben Ohayon

Charge radii for ISB

What we want to know

Transitions	δ_C (%)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \to {}^{26}Mg$	0.310	0.329	0.30	0.139	0.08
$^{34}Cl \to {}^{34}S$	0.613	0.75	0.57	0.234	0.13
$^{38m}K \to {}^{38}Ar$	0.628	1.7	0.59	0.278	0.15
$^{42}Sc \to {}^{42}Ca$	0.690	0.77	0.42	0.333	0.18
$^{46}V \to {}^{46}Ti$	0.620	0.563	0.38	/	0.21
$^{50}Mn \to {}^{50}Cr$	0.660	0.476	0.35	/	0.24
$^{54}Co \to {}^{54}Fe$	0.770	0.586	0.44	0.319	0.28

What we can measure

Transitions	$\Delta M_B^{(1)}$ (fm^2)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \to {}^{26}Mg$	-0.12	-0.12	-0.11	-0.05	-0.03
$^{34}Cl \to {}^{34}S$	-0.17	-0.21	-0.16	-0.06	-0.04
$^{38m}K \to {}^{38}Ar$	-0.15	-0.42	-0.15	-0.07	-0.04
$^{42}Sc \to {}^{42}Ca$	-0.15	-0.17	-0.09	-0.07	-0.04
$^{46}V \to {}^{46}Ti$	-0.12	-0.11	-0.08	/	-0.04
$^{50}Mn \to {}^{50}Cr$	-0.12	-0.09	-0.06	/	-0.04
$^{54}Co \to {}^{54}Fe$	-0.13	-0.10	-0.07	-0.05	-0.05

$$\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_1 \underbrace{R_{p,1}^2}_{^{38}\mathrm{Ar}} + Z_{-1} \underbrace{R_{p,-1}^2}_{^{38}\mathrm{Ca}}\right) - Z_0 \underbrace{R_{p,0}^2}_{^{38m}\mathrm{K}} = 0.1 \pm 1.0\ \mathrm{fm}^2$$

The only example:

Very high accuracy needed to distinguish models !

Slide by Ben Ohayon

70% summary

Takeaways

- Significant reevaluation following CKM non-unitarity, major opportunities/challenges for nuclear ab initio

70% summary

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- Precision charge radii needed for data-driven uncertainties

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- Precision charge radii needed for data-driven uncertainties

Now, let's talk experiment

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V_{ud} and mirror extraction

If mixing ratio ρ is known, get V_{ud}

$$V_{ud}^2(1+\rho^2) = K \times (1+\delta_{\mathrm{corr}})$$

V_{ud} and mirror extraction

If mixing ratio ρ is known, get V_{ud}

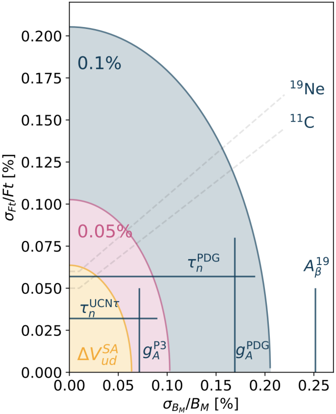
$$V_{ud}^2(1+\rho^2) = K \times (1+\delta_{\mathrm{corr}})$$

Typically, need to measure angular correlations.

Either

- Polarized nuclei (A_β)
- measure 2 final states ($a_{\beta\nu}$)

but significant experimental difficulties (backscattering, cuts, ...)



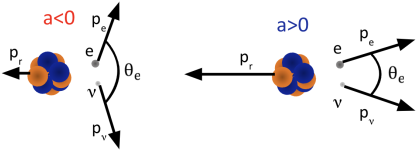
LH, ARNPS 74 (2024) 497

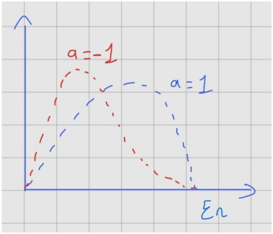
Continuous recoil spectroscopy

Can instead recover ρ from recoil spectrum alone!

Beta-neutrino angular correlation:

$$a_{\beta\nu} \approx \frac{1 - \rho^2/3}{1 + \rho^2}$$





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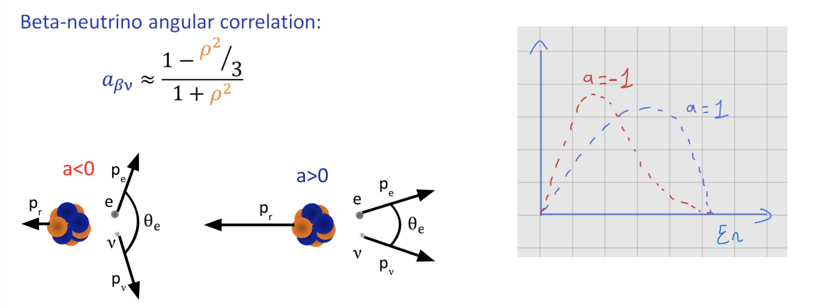

..but recoil energies are <keV, and so far only indirect methods (ToF) at percent-level

Continuous recoil spectroscopy

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Beta-neutrino angular correlation:

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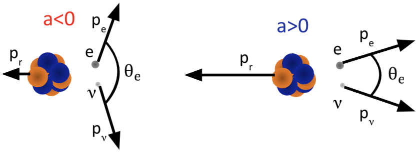
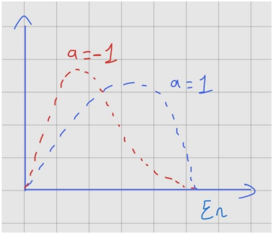




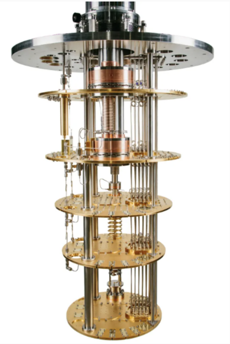
..but recoil energies are <keV, and so far only indirect methods (ToF) at percent-level

and interesting isotopes are **short-lived**

Novel detection challenges

'Conventional' detection technologies become insufficient, need

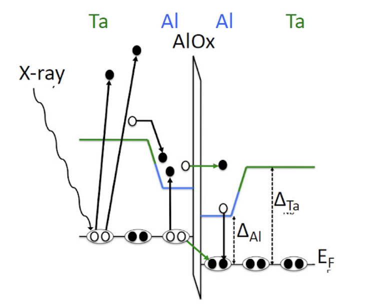
- Low detection threshold (< 1 keV)
- High ($\sim$ eV) resolution
- High acceptance



Want to detect athermal *phonons*
$\rightarrow$ cryogenic systems

Introducing Superconducting Tunnel Junctions

Biased Josephson junction



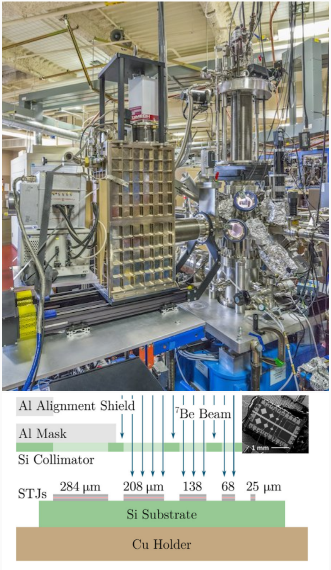
Number of key advantages

- Low threshold energy ($\sim$ 1.5 eV)
- High energy resolution
- High count rate (up to kHz)

Combination is unique

Allows for the first time energy spectroscopy of recoiling nuclei from β decay!

BeEST@TRIUMF



^{7}Be electron capture

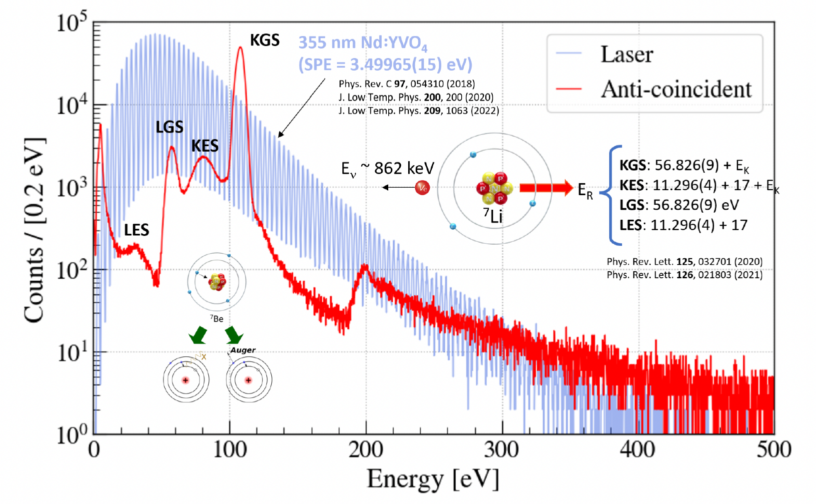
- Responsible for ^{7}Li creation in stars
- Essential contribution to solar neutrino spectrum

Measurement campaign

1. Implantation at ISAC (TRIUMF)
2. Ship to LLNL
3. Cool down and measure

BeEST@TRIUMF

Most precise ^{7}Be L/K capture measurement



PRL 126 (2021) 021803; PRL 125 (2020), 032701

BeEST neutrino wave packet size limits

Probe ν size from $\Delta x \Delta p \geq \hbar/2$ in ^{7}Li spectrum

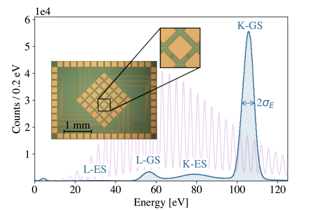
nature

Article | Open access | Published: 12 February 2025

Direct experimental constraints on the spatial extent of a neutrino wavepacket

Joseph Smolsky, Kyle G. Leach, Ryan Abells, Pedro Amaro, Adrien Andoche, Keith Borbridge, Connor Bray, Robin Cantor, David Diercks, Spencer Fretwell, Stephan Friedrich, Abigail Gillespie, Mauro Guerra, Ad Hall, Cameron N. Harris, Jackson T. Harris, Leendert M. Hayen, Paul-Antoine Hervieux, Calvin Hinkle, Geon-Bo Kim, Inwook Kim, Amii Lamm, Annika Lennarz, Vincenzo Lordi, ... William K. Warburton + Show authors

Nature 638, 640–644 (2025) | Cite this article

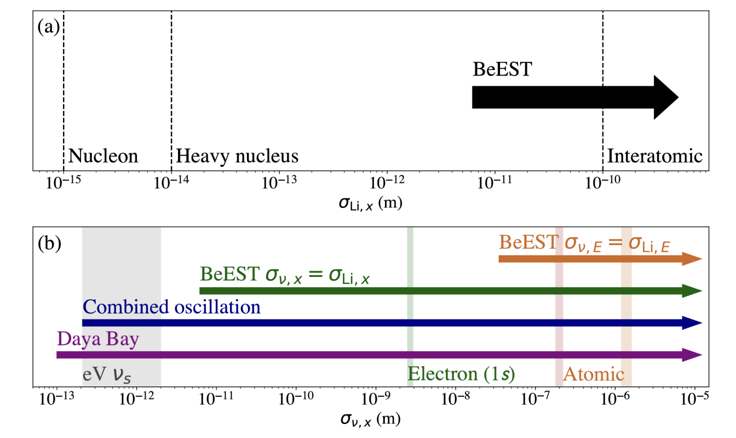


First **direct** constraint on neutrino wave packet size!

Open question: $\sigma_E^{Li} = \sigma_E^{\nu}$ or $\sigma_p^{Li} = \sigma_p^{\nu}$? unresolved!

BeEST neutrino wave packet size limits

Probe ν size from $\Delta x \Delta p \geq \hbar/2$ in ^{7}Li spectrum

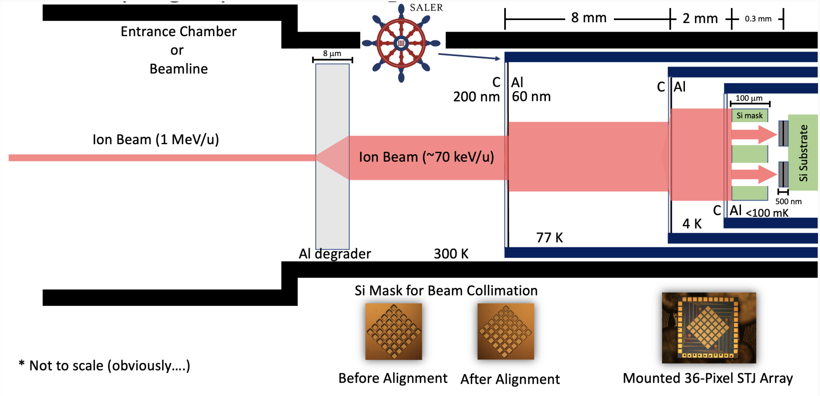


At least 2 orders of magnitude more stringent than global limits!

Smolsky et al., Nature 638 (2025) 640

SALER prototype: First STJ online measurements

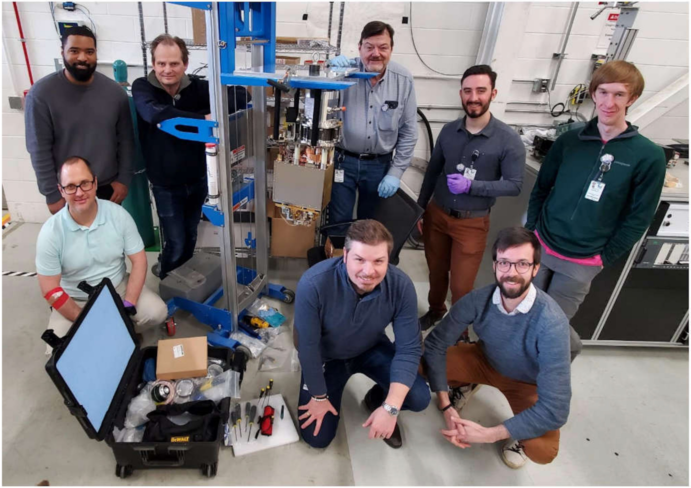
Use same detector and fridge as BeEST, but online at RIB!



first demonstration, but thermal windows mean difficult and imprecise implantation ultimately limiting precision

SALER@FRIB: First STJ online measurements

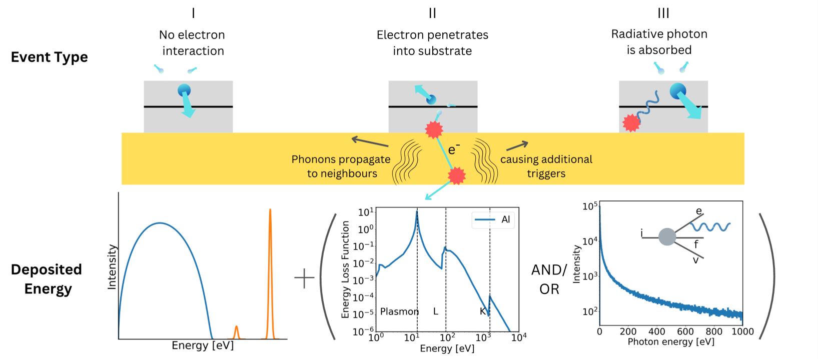
Commissioning and first light in April 2024



Hot off the press: FRIB PAC proposal accepted for Fall 25

Anticipated systematic effects

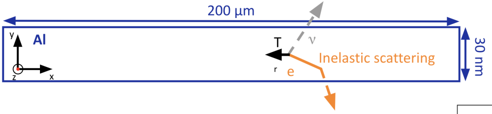
Detector measures *all* deposited energy



Low energy threshold ($\sim$ eV) means strong overlap with condensed matter physics

SALER limitations

SALER is necessary first step, but can't reach high precision. Even after implantation, substantial systematic effects anticipated

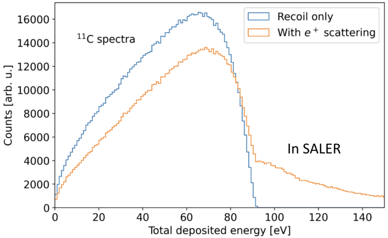


Beta decay energy deposited in STJ:

Full recoil energy deposition

+ Partial beta energy deposition

- → Distortion in the obtained recoil spectrum (influence on extracted $a_{\beta\nu}$)
- → Induced background beyond the recoil spectrum endpoint



Scattering anticipated to enter at percent-level

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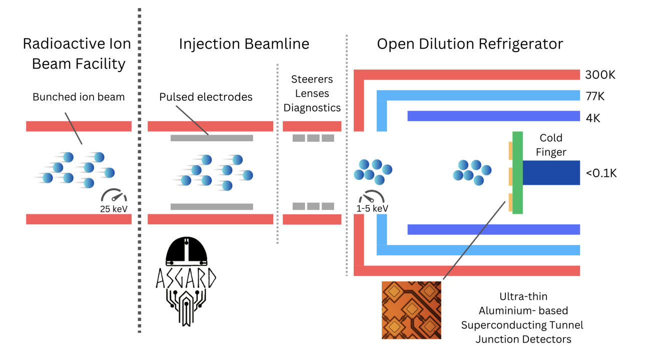
Introducing ASGARD

Open STJs up to all ISOL beams, **precision spectroscopy**



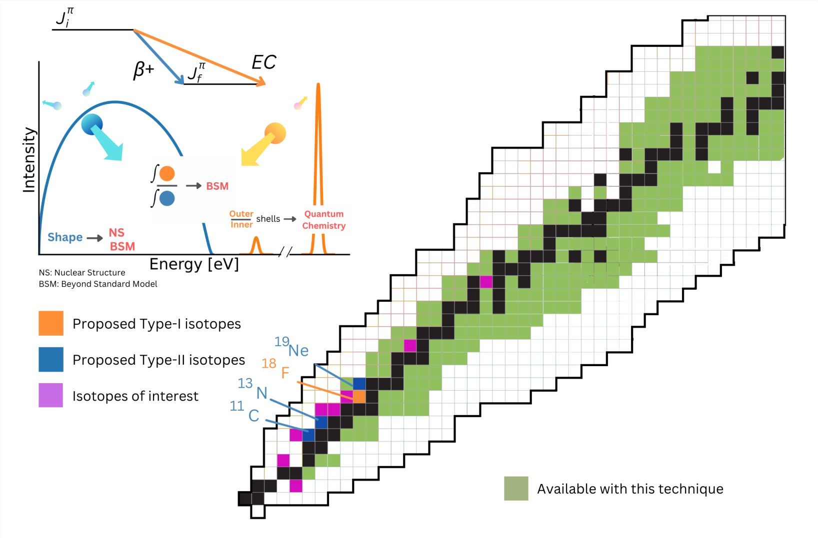
RÉGION NORMANDIE

European Research Council
Established by the European Commission

Aluminium **S**uperconducting **G**rid **A**ssembly for **R**adiation **D**etection

Installation at DESIR facility in GANIL anticipated 2028

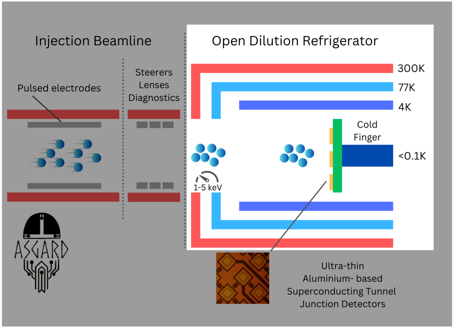
ASGARD overview

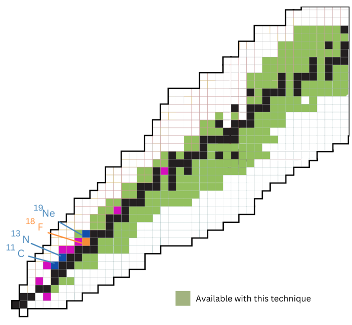


Both V_{ud} (Type-II) and exotic currents (Type-I)!

ASGARD: Key aspects

1: Windowless dilution fridge allows direct implantation

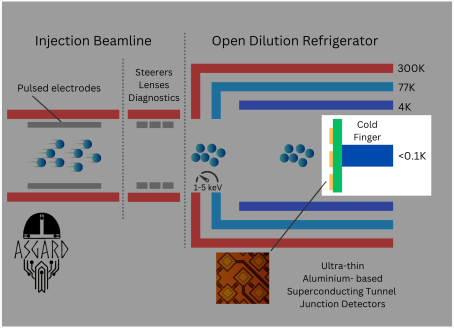




Now **all ISOL isotopes** become available at 100% efficiency

ASGARD: Key aspects

2: Novel, ultra-thin Al-based STJ detectors

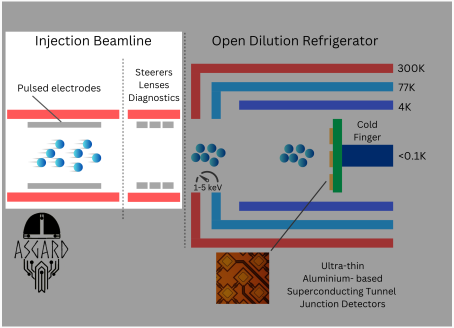


30-nm geometry **reduces scattering effects by two orders of magnitude**

Increased resolution, mitigated material-dependent effects

ASGARD: Key aspects

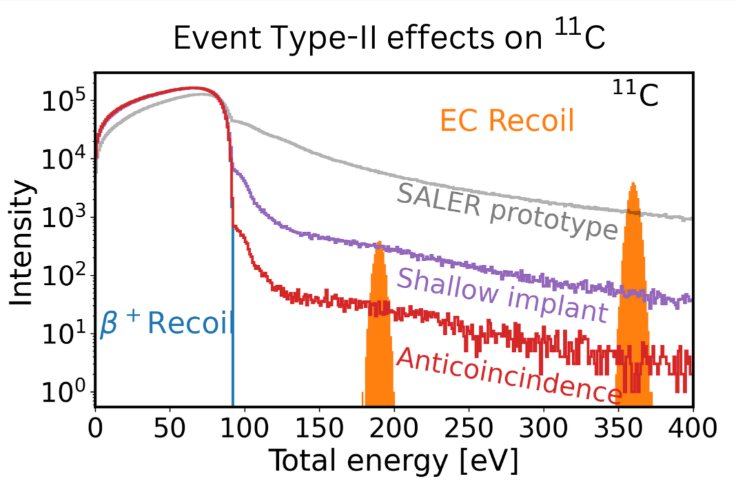
\# 3: Precision injection beam line



Custom implantation of all ISOL isotopes

Shallow implantation further **reduces scattering by another order of magnitude**

ASGARD: Scattering systematic uncertainty



Uncertainties due to scattering on $V_{ud} \lesssim 0.01\%$!

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Summary & Outlook

Theory very active, all inputs are being reevaluated. Significant opportunities/challenges for nuclear ab initio

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Summary & Outlook

Theory very active, all inputs are being reevaluated. Significant opportunities/challenges for nuclear ab initio

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Mirror isotopes continue to be promising due to large enhancements

New spectroscopy techniques incoming, recoil spectroscopy with quantum sensors is highly promising!

BeEST & SALER

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TRIUMF

NOVA
NOVA SCHOOL OF SCIENCE & TECHNOLOGY

THE BeEST

Lawrence Livermore National Laboratory

STAR CRYOELECTRONICS

NC STATE UNIVERSITY

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FRIB

caen

SALER

STAR CRYOELECTRONICS

NC STATE UNIVERSITY

Lawrence Livermore National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

The Standard Model

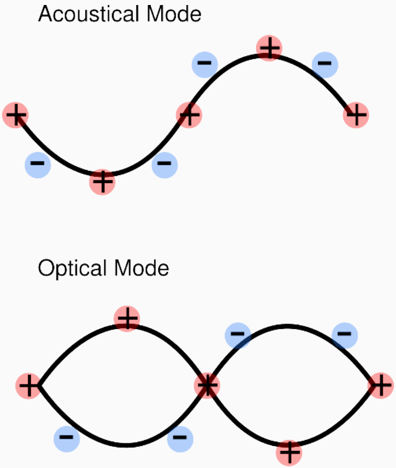
To ~~Infinity~~ and Beyond!

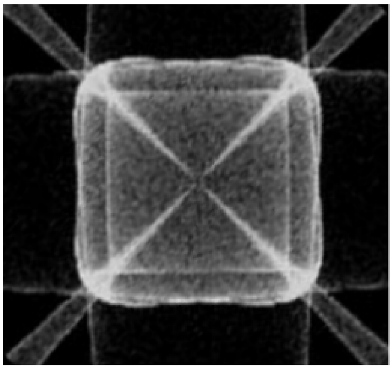
"One should be prepared for further surprises with beta decay"

Niels Bohr, 1933

Phonon detection

Phonons are lattice vibration quanta





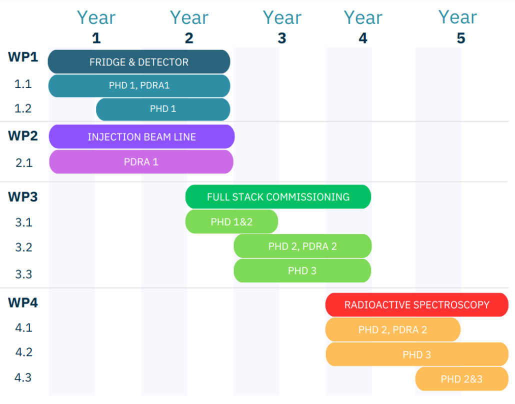
Typical energy scale of (tens of) meV $\rightarrow > 100$ lower than *e*-*h* in Si, Ge

ASGARD Timeline

ERC submitted in 2024

Anticipated installation at DESIR@GANIL facility

Currently ongoing systematic effect simulations, theory support & design



Aside: recent progress on Δ_R^A

First $\mathcal{O}(\alpha)$ calculation of Δ_R^A, follow-up with dispersion relations and lattice QCD

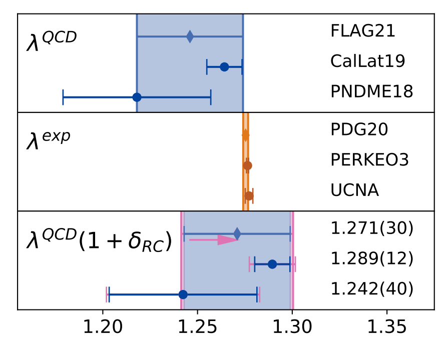
$$\Delta_R^A - \Delta_R^V = 0.13(13) \times 10^{-3}$$

Aside: recent progress on Δ_R^A

First $\mathcal{O}(\alpha)$ calculation of Δ_R^A, follow-up with dispersion relations and lattice QCD

$$\Delta_R^A - \Delta_R^V = 0.13(13) \times 10^{-3}$$

but only first half of the story... also here large ISB effects



First time: $\delta_{\rm RC}^{(\lambda)} \in \{1.4,\, 2.6\} \cdot 10^{-2}$ LH, PRD 103 113001; Seng, Particles 2021, 397; Gorchtein & Seng, JHEP 10 53; PRL 129 121801

Open questions for mirror δ_{NS}

Situation is analogues but **more complicated** than $0^+ \to 0^+$.
Significant questions on:

- How do energy-dependent terms enter for axial transitions?
- What about nuclear shadowing for spin-dependent transitions?

Mirror decays extract $\rho = g_A M_{GT}/g_V M_F$ from angular correlations ($a_{\beta\nu}$, A_β), but both effects may mean $\rho^{\mathrm{corr}} \neq \rho^{\mathrm{Ft}}$.

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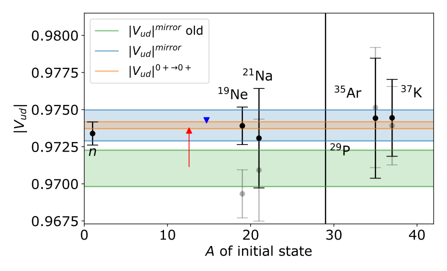
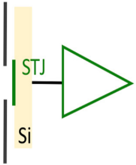
Happened before:

double counting was resolved and V_{ud}^{mirror} now agrees with $V_{ud}^{0^+\to 0^+}$

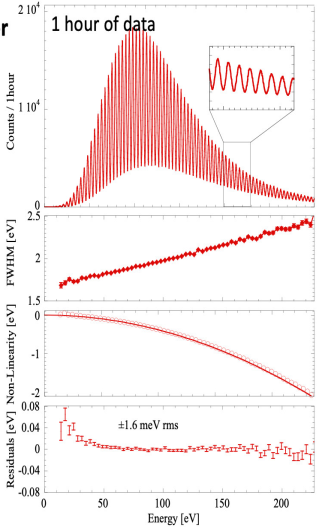
LH, PRD 103, 113001; LH, ARNPS 74 (2024) 497



Superconducting tunnel junctions (Slide by Kyle Leach)



Adiabatic Demagnetization Refrigerator (ADR) – Base Temp ~70 mK



S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)

- Pulsed 355 nm (3.49965(15) eV) laser at 5 kHz fed through optical fiber to 0.1 K stage
- Illumination of STJ provides a comb of peaks at integer multiples of 3.5 eV
- Intrinsic resolution of our Ta-based devices is between ~1.5 and ~2.5 eV FWHM at ~10 – 200 eV
- Stable response and small quadratic non-linearity (10^{-4} per eV)

The BeEST experiment (Slide by Kyle Leach)

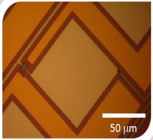
TRIUMF

Rare-isotope implantation at TRIUMF-ISAC

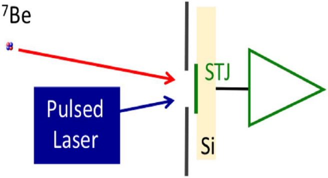
THE BeEST

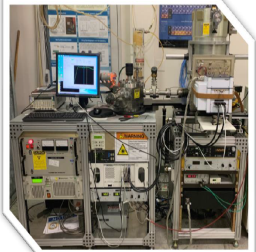
A. Samanta *et al.*, Phys. Rev. Mat. (*in press*) (2022)
S. Friedrich *et al.*, J. Low Temp. Phys. (*in press*) (2022)
C. Bray *et al.*, J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach and S. Friedrich, J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)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

Ta, Al, and Nb-based STJ Sensors



STAR CRYOELECTRONICS





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EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Lawrence Livermore National Laboratory

Introduction: Weak interaction & CKM matrix

Cabibbo-Kobayashi-Maskawa matrix relates weak and mass eigenstates

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

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Unitarity requires

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

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Unitarity requires

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

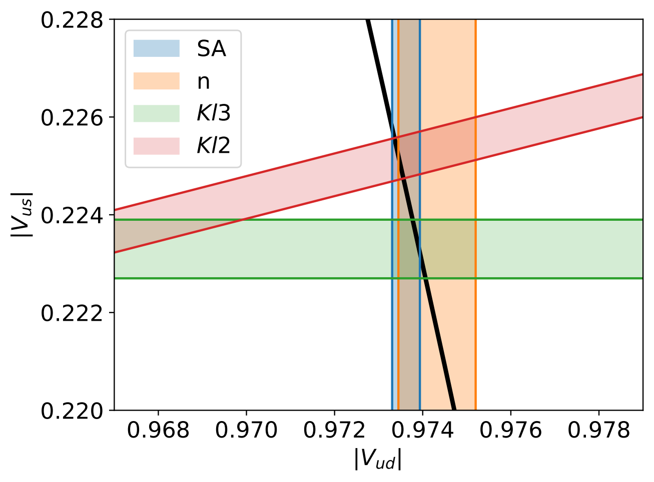
(nuclear) β decay, meson decay (π, K), $|V_{ub}|^2 \sim 10^{-5}$

Violations are sensitive to **TeV scale** new physics!

CKM unitarity: Current status

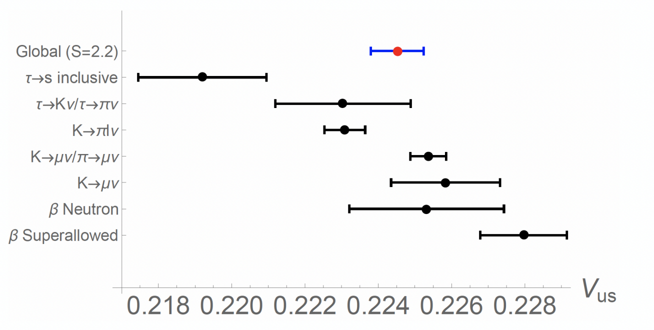
Signs of non-unitarity at few σ level...

Disagreement between $Kl2$ and $Kl3$ $|V_{us}|$ ‘Cabibbo angle anomaly’



CKM unitarity: Cabibbo Angle Anomaly

Signs of non-unitarity at several σ (Falkowski CKM2021)



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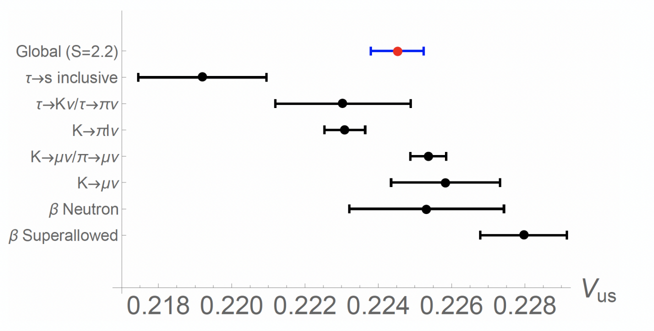

Takeaways assuming Standard Model physics:

- Most precise V_{ud} & V_{us} not consistent with unitarity
- Significant internal inconsistencies within V_{us}
- Taken at face value $\sim 3\sigma$ for new physics

Exotic contributions

A more modern way of interpreting BSM physics

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Effective field theory: new physics at scale $\Lambda_{BSM} \gg$ LHC

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{i=1} c_i \frac{\mathcal{O}_{4+i}}{\Lambda^i_{BSM}}$$

effective operators $\mathcal{O}(i)$. Expansion in parameter $c_i/\Lambda^i_{BSM} \ll 1$

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Phenomenological theories will give different $\{c_i\}$,

but agnostic experimental analysis

Effective β decay

SM has V-A structure, but more generally

$$\mathcal{L}_{\text{eff}} = -\frac{G_F \tilde{V}_{ud}}{\sqrt{2}} \Big\{ \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu [c_V - (c_A - 2\epsilon_R)\gamma^5] d + \epsilon_S \, \bar{e}\nu_L \cdot \bar{u} d \\ - \epsilon_P \, \bar{e}\nu_L \cdot \bar{u}\gamma^5 d + \epsilon_T \, \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma^5) d \Big\} + \text{h.c.},$$

at the quark level

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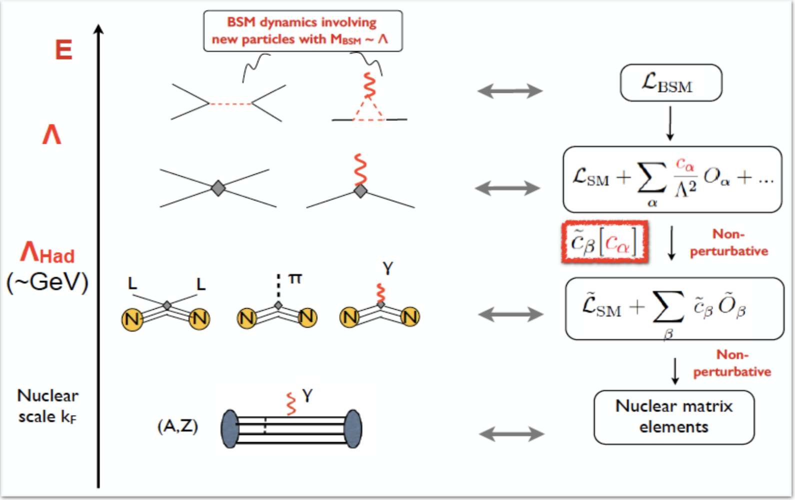
at the quark level

All ϵ_i are proportional to $(M_W/\Lambda_{BSM})^2$, change kinematics

$\epsilon_i \lesssim 10^{-4} \rightarrow \Lambda_{BSM} \gtrsim 15$ TeV assuming natural couplings

Effective field theory tower Slide by V. Cirigliano



Chiral EFT, Lattice QCD

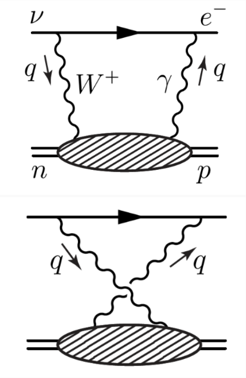
Nuclear many-body methods

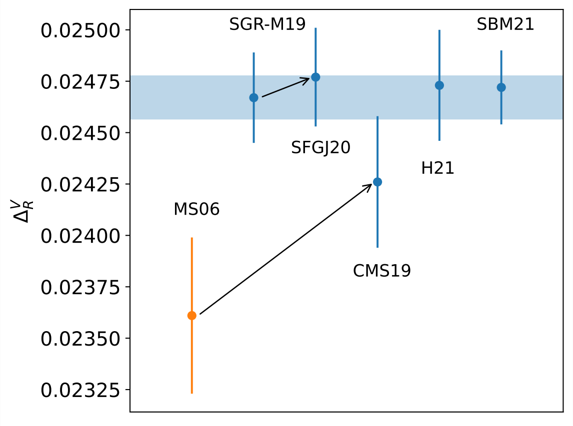
Effective field theory recipe Slide by V. Cirigliano

- In order to build L_{eff}, one needs to specify:
  - ★ Relevant low-E degrees of freedom: *assume* SM field content
    - ★ One Higgs doublet, no light ν_R and no other light fields
  - ★ Symmetries: L_{eff} must reflect symmetries of underlying theory
    - ★ Assume underlying theory respects SM gauge group $SU(3)_c \times SU(2)_W \times U(1)_Y$
    - ★ But not necessarily SM symmetries that result from keeping only terms of dimension ≤ 4
  - ★ Power counting in E/Λ, $v_{EW}/\Lambda << 1$ (recall $v_{EW} = G_F^{-1/2}$): organize analysis in terms of operators of increasing dimension (5,6,...)

Recent changes: Δ_R^V

Number of new calculations performed

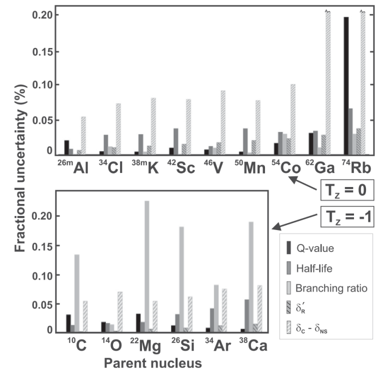


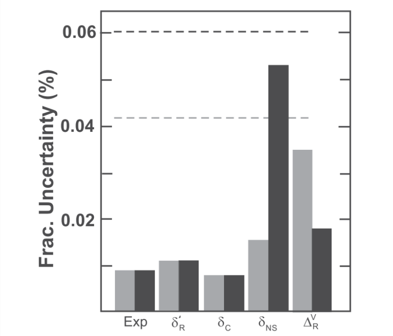


Now good convergence: uncertainty halved but about 3σ shift

Superallowed uncertainties

Experimentally, $T_z = -1$ limited by BR (new ^{10}C welcome)





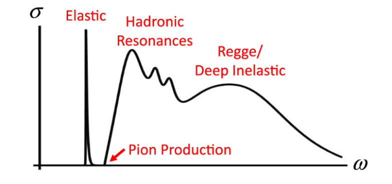
Moving towards mature *ab initio* theory evaluation

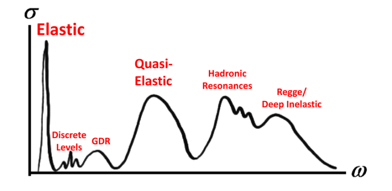
Talk by Bertram Blank

Hardy & Towner PRC 102 (2020) 045501

Recent changes: δ_{NS}

Nuclear medium changes nuclear response, but also spectrum





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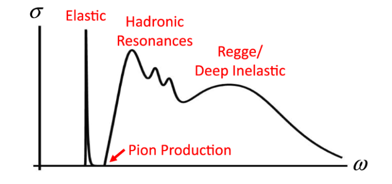

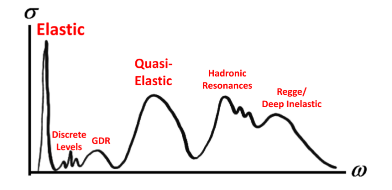

Paradigm shift in analysis, two major effects

Quasi-elastic contributions

$$\delta_{NS}^{A} = \frac{\alpha}{\pi}[-0.47 \pm 0.14]^{\mathrm{QE}}$$

Estimated using free Fermi gas

Nuclear polarization

$$\delta_{NS}^{A}(E) \sim (1.6\pm1.6)\times10^{-4}\left(\frac{E}{\mathrm{MeV}}\right)$$

Current $0^+ \to 0^+$ **bottleneck**

Seng et al., PRD 100 013001

On the radar: δ_C

Proton $\neq$ neutron inside nucleus $\rightarrow M_F^2 = 2(1 - \delta_C)$

1. Configuration interaction difference initial $\leftrightarrow$ final
2. Different radial wave function (Coulomb)

$$\delta_C = \delta_{C1} + \delta_{C2}$$

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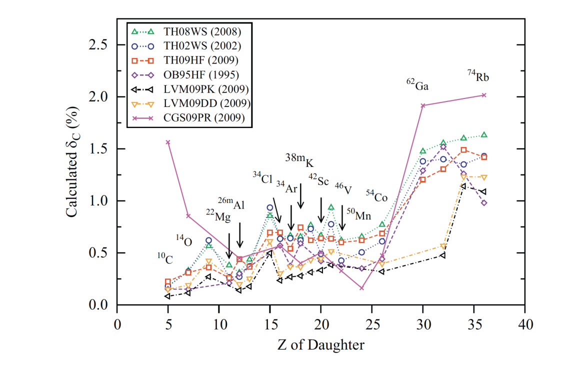
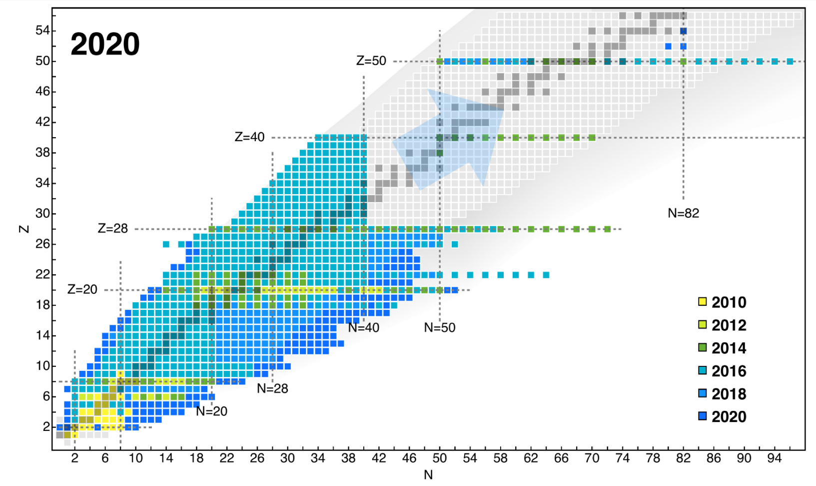


Grinyer et al., NIMA 622 (2010) 236

Progress in nuclear ab initio theory

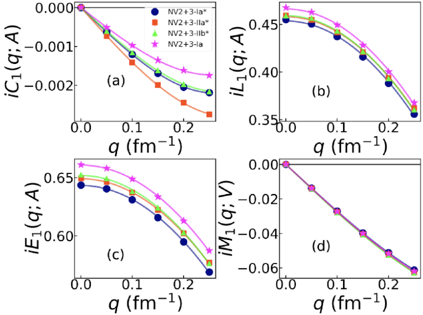


H. Hergert, Frontiers in Physics (2020)

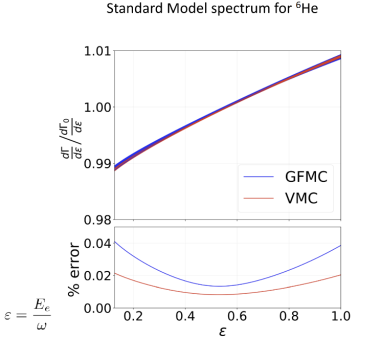
Monte Carlo methods (Slide by Saori Pastore)

Ab initio is providing bottleneck input for spectral measurements

Beta Decay Spectrum



Dominant terms $L_1^{(0)}$ and $E_1^{(0)}$ have model dependence of ~1% to ~2%



τ_{GFMC} = 808 +/- 24 ms

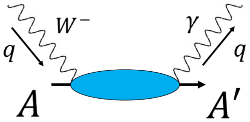
$\tau_{\text{Expt.}}$ = 807.25 +/- 0.16 +/- 0.11 ms

Garrett King et al. arXiv:2207.11179

Looking at implementing δ_{NS} for ^{10}C

No Core Shell Model (Slide by Michael Gennari)

Compton amplitude in the NCSM



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- Nuclear matrix elements for γW-box
  1) Express currents in momentum space
  2) Multipole expansion of current operators
  3) Connect currents to effective one–body operators

Lanczos continued fractions method to compute Green's functions!

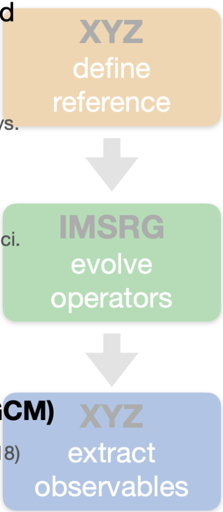
$$T_3(q_0, Q^2) = -4\pi i \frac{q_0}{q}\sqrt{M_i M_f}\sum_{J=1}^{\infty}(2J+1)$$

$$\times \langle A\lambda_f J_f M_f | \Big[T_{J0}^{mag}(q) \boxed{G(M_f + q_0 + i\epsilon)} T_{J0}^{5,el}(q) + T_{J0}^{el}(q) \boxed{G(M_f + q_0 + i\epsilon)} T_{J0}^{5,mag}(q)$$

$$+ T_{J0}^{5,mag}(q) \boxed{G(M_i - q_0 + i\epsilon)} T_{J0}^{el}(q) + T_{J0}^{5,el}(q) \boxed{G(M_i - q_0 + i\epsilon)} T_{J0}^{mag}(q) \Big] | A\lambda_i J_i M_i \rangle$$

Going heavier: IM-SRG type methods (Slide by Heiko Hergert)

- IMSRG for closed and open-shell nuclei: IM-HF and IM-PHFB
  - HH, Phys. Scripta, Phys. Scripta 92, 023002 (2017)
  - HH, S. K. Bogner, T. D. Morris, A. Schwenk, and K. Tuskiyama, Phys. Rept. 621, 165 (2016)
- **Valence-Space IMSRG (VS-IMSRG)**
  - S. R. Stroberg, HH, S. K. Bogner, J. D. Holt, Ann. Rev. Nucl. Part. Sci. **69**, 165
- In-Medium No Core Shell Model (IM-NCSM)
  - E. Gebrerufael, K. Vobig, HH, R. Roth, PRL **118**, 152503
- **In-Medium Generator Coordinate Method (IM-GCM)**
  - J. M. Yao, J. Engel, L. J. Wang, C. F. Jiao, HH PRC 98, 054311 (2018)
  - J. M. Yao et al., PRL 124, 232501 (2020)



+ Coupled Cluster, ...

Nuclear theory impact

Major advances in last decade, EFT come into its own

Quantifiable theory uncertainties are game-changer for precision
FS: paradigm shifts are strong driver of progress in the field

Benefit from 'rigorous' theory overlap at low masses (NCSM, GFMC, QMC)

- $0^+ \to 0^+$:^{10}C & ^{14}O
- Promising isotopes: ^{6}He, ^{11}C, ...

to confidently go higher (CC, IM-SRG, IM-GCM, ...)

Path forward for $0^+ \to 0^+$ V_{ud}

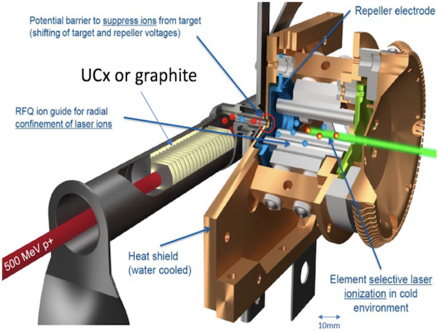
BeEST implantation

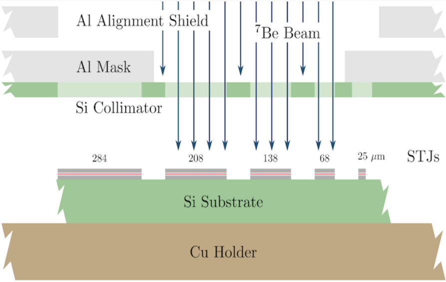
TRIUMF

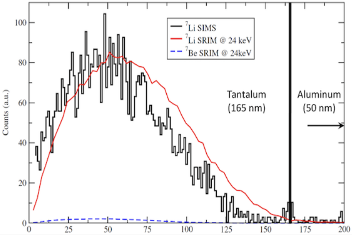
Isotope Separation On-Line (ISOL) Method

Element- and mass-selective delivery of ^{7}Be:

- Purity > 80%
- Rate > 1e8 pps

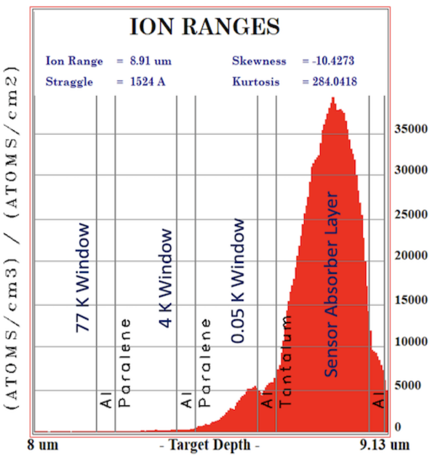






SALER implantation

11 MeV ^{11}C Beam w/ 8μm Al foil



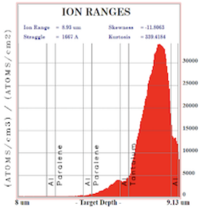
For a given energy, initial beam from ReA can be +/- a few % in spread

1% spread gives ~50 nm width in the depth profile

Total $^{11}C^{+}$ to achieve goal: ~10^7 (< 2 days of beam @ 100 pps)

Purity: 1 part in 10^6

11.1 MeV ^{11}C Beam



10.9 MeV ^{11}C Beam