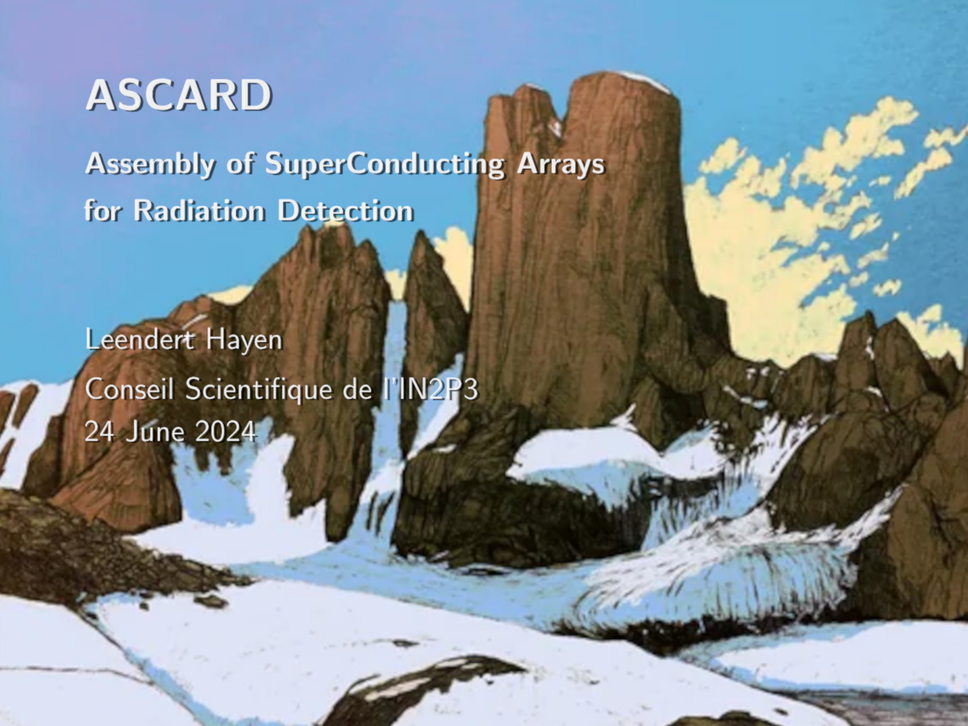

ASCARD

Assembly of SuperConducting Arrays for Radiation Detection

Leendert Hayen

Conseil Scientifique de l'IN2P3

24 June 2024

Fundamental symmetries & RIBs

Fundamental symmetries*: Precision measurements and symmetry tests of the Standard Model and Beyond*

Fundamental symmetries & RIBs

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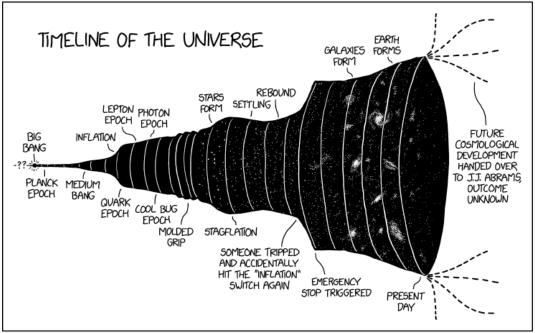


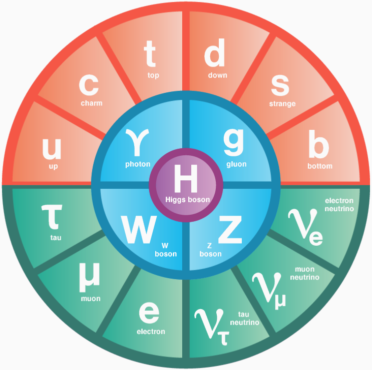
Extremely rich field with connections to

- Nature of neutrino's
- Dark matter
- Big bang nucleosynthesis
- Cosmology

Meet the Standard Model

Three out of four
fundamental forces (no gravity):

Standard Model



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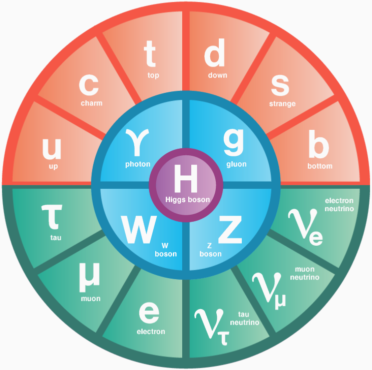

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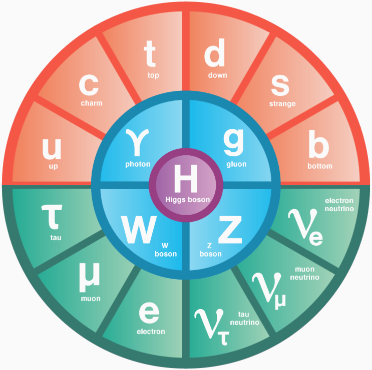

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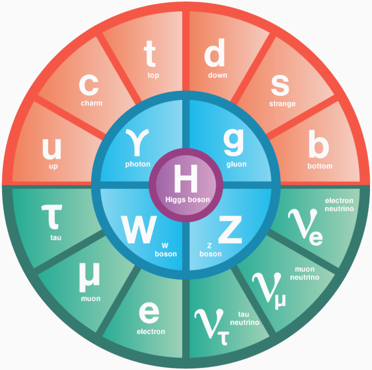
Open questions: dark matter, gravity, neutrino masses, ...



Introduction: Standard Model

What to do?

SM tests @ low energy: sensitive to off-shell exotic physics
(footprints rather than actual beast)

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Besides precision QED ($a_{e,\mu}, r_p, \ldots$), weak interactions probe

- (C)P violation
- CKM unitarity
- Lorentz structure

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- (C)P violation
- CKM unitarity
- Lorentz structure

All of these can be probed using **(nuclear)** β **decay** with RIBs!

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

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

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

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

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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$$- \epsilon_P \, \bar{e}\nu_L \cdot \bar{u}\gamma^5 d + \epsilon_T \, \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma^5) d \Big\} + \text{h.c.},$$

at the quark level

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} precision

Nuclear sandbox $\to$ make hadronic theory easy

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

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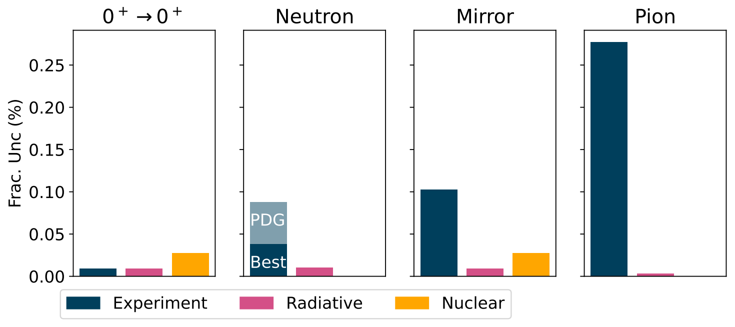
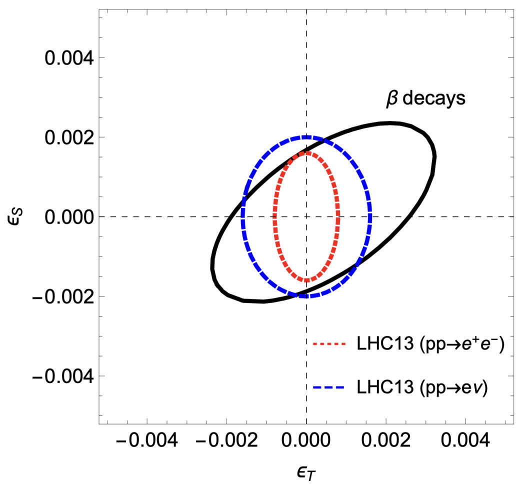


L.H. arXiv:2403.08485

$\pi^+ \rightarrow \pi^0 e^+ \nu_e$ very hard (BR $\sim 10^{-8}$), SA new nuclear corrections!

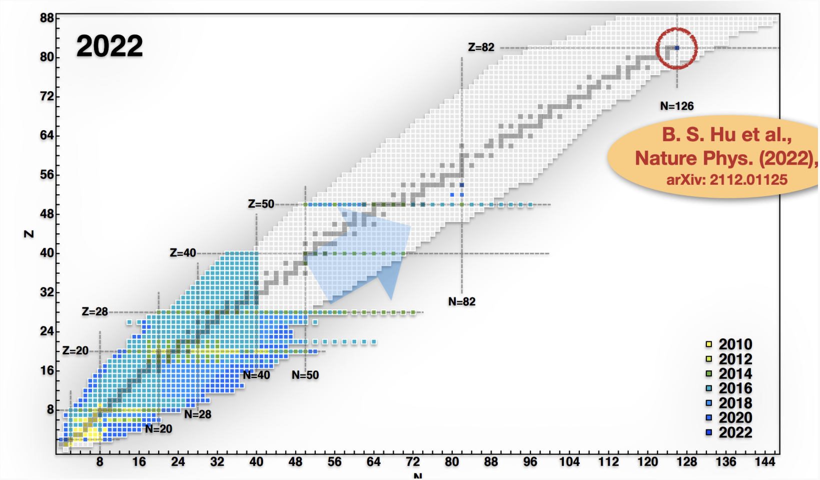
Exotic currents

Competitive searches for scalar (ε_S) and tensor (ε_T) currents



Falkowski et al., JHEP 2021(4):126

Progress in nuclear ab initio theory



H. Hergert, Frontiers in Physics (2020)

Nuclear theory impact

Major advances in last decade, Effective Field Theory come into its own

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

Nuclear theory impact

Major advances in last decade, Effective Field Theory 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)

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

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

Path forward for $0^+ \rightarrow 0^+$ & Mirror V_{ud}

V_{ud} and mirror extraction

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

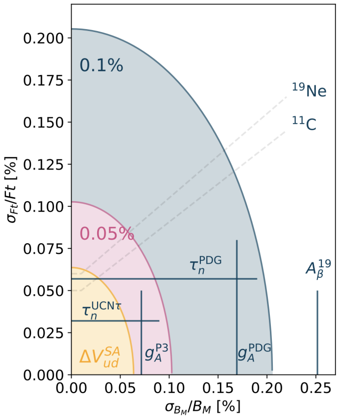
$$V_{ud}^2(1+\rho^2) = K \times (1+\delta_{\text{corr}})$$

Typically, need to measure angular correlations.

Either

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

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



L.H. arXiv:2403.08485

Fierz interference: Spectrum shape

Allowing exotic interactions (ϵ_S, ϵ_T) modifies β spectrum

$$P(E_e) = \text{Standard Model} \times \left(1 + b_F \frac{m_e}{E_e}\right)$$

Fierz interference

$$b_F = \pm 2\gamma \frac{1}{1+\rho^2} \text{Re}\left\{ \frac{g_S \epsilon_S}{g_V(1+\epsilon_L+\epsilon_R)} + \rho^2 \frac{4 g_T \epsilon_T}{-g_A(1+\epsilon_L-\epsilon_R)} \right\}$$

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Promising to directly measure spectra, but also tricky

- Detector linearity, energy losses, pile-up,. . .
- Theory spectrum calculation

Naviliat-Cuncic, Gonzalez-Alonso PRC 94, 035503

LH *et al.*, RMP 90 015008

Recoil spectroscopy

Measuring recoil kinetic energies has substantial benefits

- Strong spectral dependence on $a_{\beta\nu}$ in $\beta^{\pm}$
- Mono-energetic lines in electron capture

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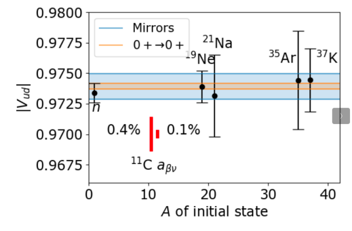
V_{ud} from mirrors



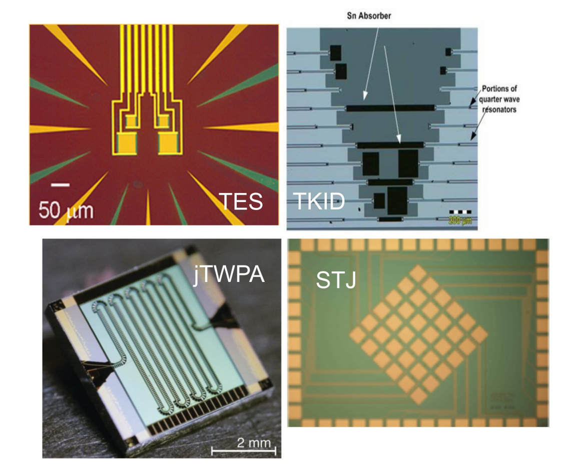
Fierz with **counting experiment**

$$\frac{\lambda_{EC}}{\lambda_{\beta+}} = \sum_{x=K,L,\ldots} \frac{f_x}{f_{\beta+}} \left[\frac{1 + b_F m_e/E_x}{1 - b_F m_e/\overline{E}}\right] \times (1 + 0.001 \times \delta_{\text{theory}})$$

Need **novel technology**

Quantum sensors

Many kinds of quantum-based sensors developed and in-use

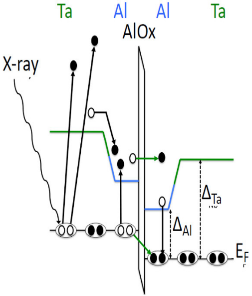


Low-gap materials → high (eV-scale) resolution

Meet superconducting tunnel junctions

- Two electrodes separated by a thin insulating tunnel barrier
- Superconducting energy gap Δ is of order ~meV
  → High Energy Resolution (~1 eV)
- Timing resolution on the order of 10 μs, making it among the fastest high-resolution quantum sensors available
  → "High" Rate (10^4 s^{-1} per pixel)

↖ *Ideal for RIB experiments at ISAC*



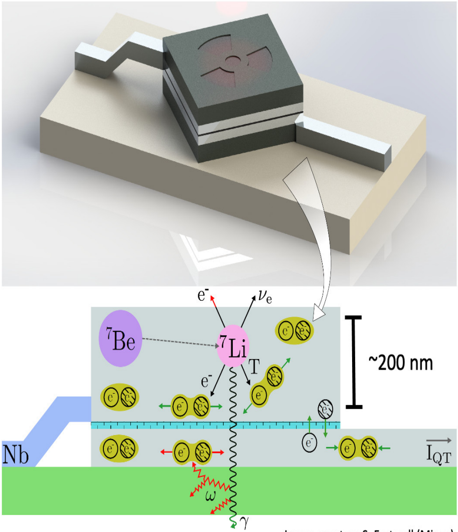
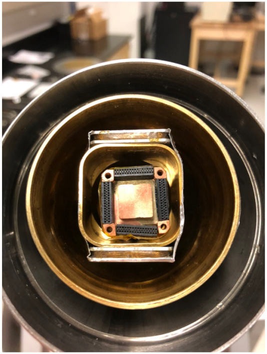
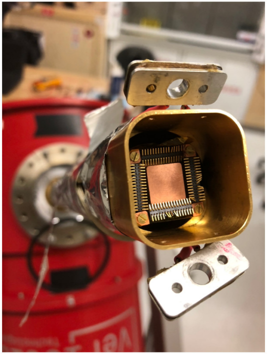
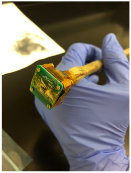


Image courtesy S. Fretwell (Mines)

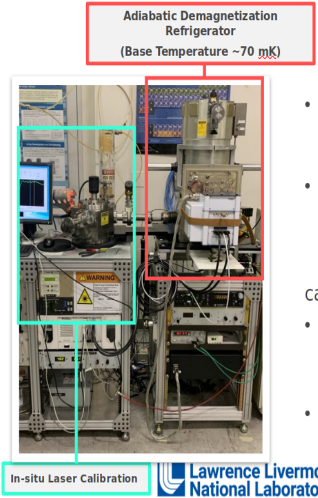
Superconducting tunnel junctions







STJ performance and characterization



Lawrence Livermore National Laboratory

- Pulsed laser (3.5 eV) fed through optical fiber to 0.1 K stage of the ADR
- Illumination of STJs provides a comb of peaks at *integer multiples* of 3.5 eV

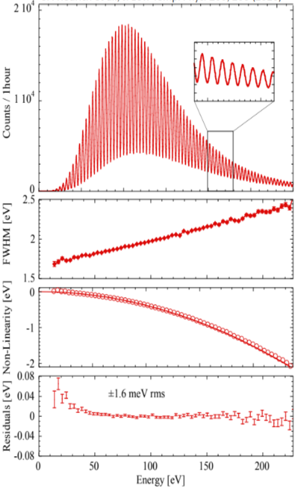
can be used as the in-situ calibration source

- Intrinsic resolution of our Ta-based devices:

  1–2.5 eV FWHM @ 10–200 eV

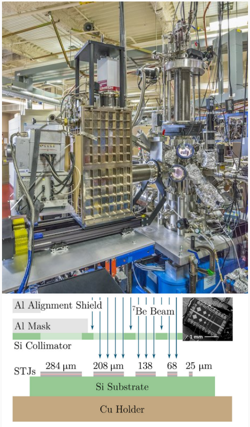
- Stable response and small quadratic non-linearity

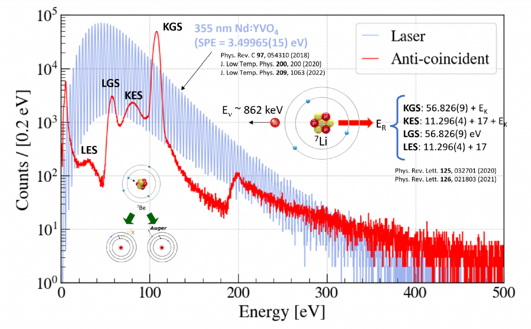
S. Friedrich et al., J. Low Temp. Phys. **200**, 200 (2020)



BeEST@TRIUMF

^{7}Be electron capture





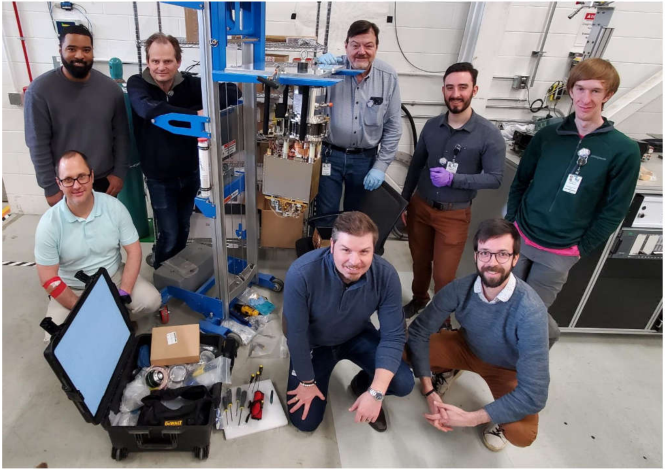
Measure recoil + Auger electrons

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

SALER@FRIB: First STJ online measurements

SALER @ FRIB

- Acceptance testing complete
- Commissioning started
- Will continue through 2024



U.S. DEPARTMENT OF ENERGY | Office of Science

GORDON AND BETTY MOORE FOUNDATION

FRIB

ASCARD

SALER will be very useful prototype, but several challenges

- Complicated energy deposits from $e^{\pm}$ in Ta-STJs
- Complex material-dependent effects for electron capture in Ta
- Awkward implantation scheme

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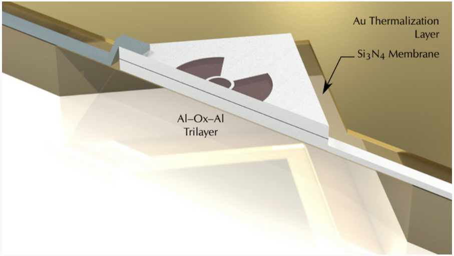
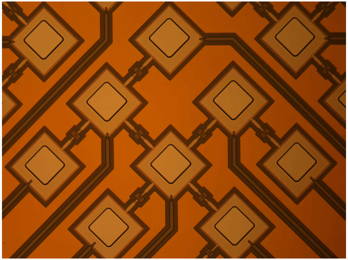
Introducing

Assembly of **S**uper**C**onducting **A**rrays for **R**adiation **D**etection

Al-STJs

Move from Nb/Ta-based STJs to Al

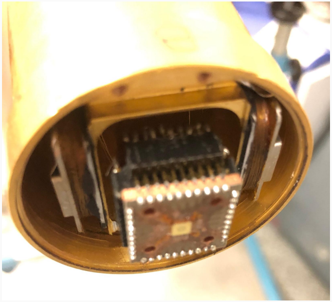


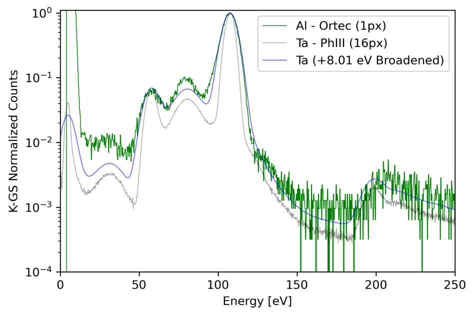


- Much larger electron MFP & well-known material response
- Increased resolution (lower $T_c \propto \Delta$)
- Simplified material effects in electron capture

Al-STJ challenges

Basic Al-STJ configuration functional

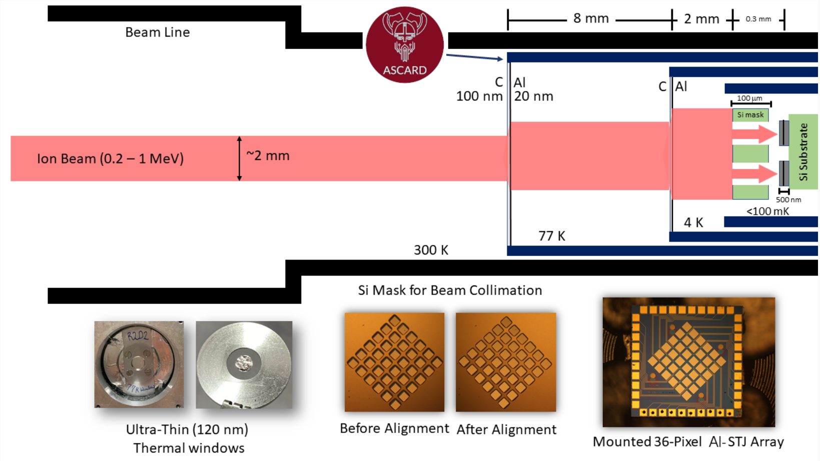




but figuring out poor resolution, wiring, ...

Superconducting tunnel junctions

Concept to couple to beam line



Investigate **eliminating thermal windows** (cryogenic beam line?)

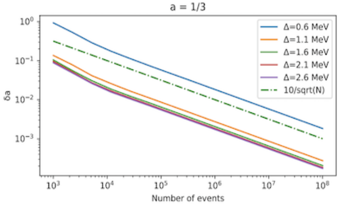
ASCARD statistical sensitivity

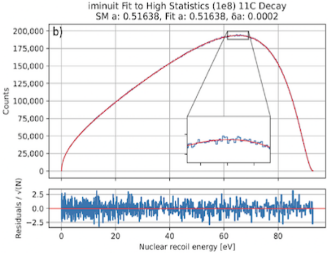
Assuming **10^8 decays**, recoil spectroscopy on all mirrors (except ^{3}H) achieves

$\delta a/a \sim 10^{-4}$

Species	$\mathcal{F}t^{\text{mirror}}$	$\delta a_{\beta\nu}[10^{-4}]$	$\delta V_{ud}[10^{-4}]$
n	1043.58(67)	2.6	3.6
^{3}H	1130.9(10)	49	96
^{11}C	3916.9(19)	2.0	2.8
^{13}N	4681.3(49)	1.6	5.0
^{15}O	4402.5(59)	1.5	6.7
^{17}F	2291.2(19)	1.9	4.8
^{19}Ne	1721.5(10)	1.9	4.0

- **Can reach 10^8 decays in 1 day with ~128 pixels**
- **Systematics budget in progress**





L. Hayen and A. Marino (2023)

Many possibilities at DESIR!

Nuclear Physics

Precision structure and decay measurements of beta decaying "rare" isotopes

Quantum Engineering and Low-Temperature Physics

Superconductors operated at mK-scale temperatures and optical control and manipulation of fg masses

Atomic Physics

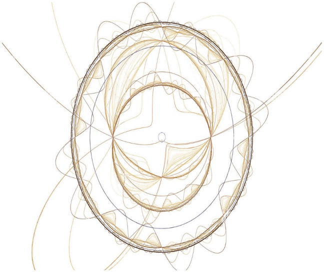
eV-scale atomic screening and rearrangement effects that result from nuclear transmutations

Materials Imaging and Quantum Simulation

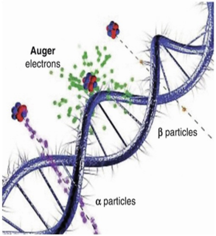
In-medium effects of the electronic states generate a need for an "atom-by-atom" map of superconductors

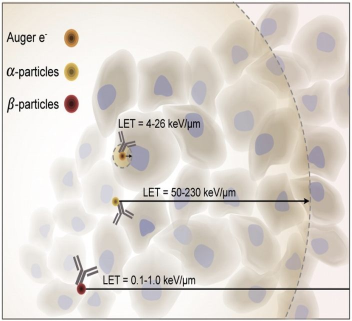
Particle Physics

Precision laboratory searches for new physics and interactions in the sub-GeV domain

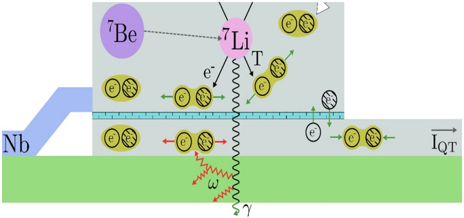


Auger spectroscopy for medical use

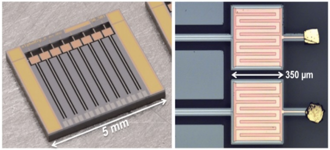




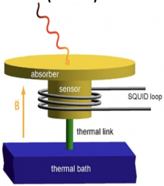
Sadaf Aghevliana, Amanda J. Boyle, Raymond M. Reilly, Advanced Drug Delivery Reviews **109**, 102-118 (2017)



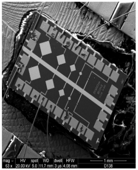
Transition Edge Sensor (TES)



Magnetic Microcalorimeter (MMC)



Superconducting Tunnel Junction (STJ)



Summary & Outlook

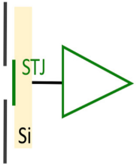
Fundamental symmetries lives at the interface, connections to many different fields

Nuclear β decay searches provide crucial input through variety of experiments, quantum sensors very exciting

ASCARD can become Europe's first STJ@RIB experiment, learn lessons from emerging technology

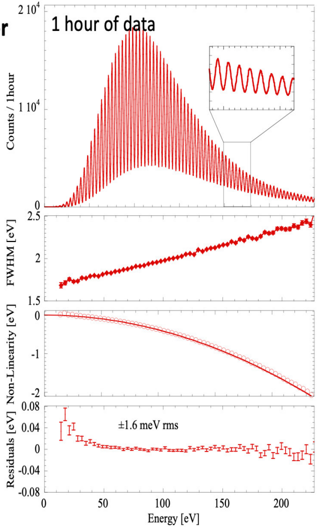
Highly competitive new physics searches using new measurement schemes

Superconducting tunnel junctions (Slide by Kyle Leach)



- 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)

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



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

The BeEST experiment (Slide by Kyle Leach)

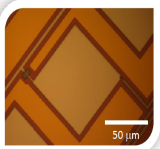
TRIUMF

Rare-isotope implantation at TRIUMF-ISAC

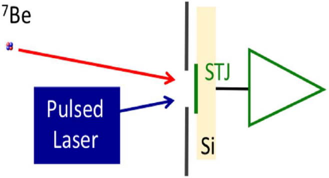
THE BeEST

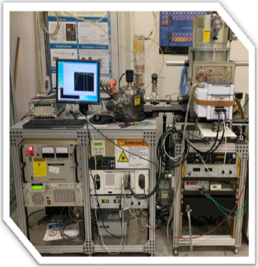
A. Samanta *et al.*, Phys. Rev. Mat. (*in press*) (2022)
S. Friedrich *et al.*, J. Low Temp. Phys. (*in press*) (2022)
C. Bray *et al.*, J. Low Temp. Phys. (*in press*) (2022)
K.G. Leach and S. Friedrich, J. Low Temp. Phys. (*in press*) (2022)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)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

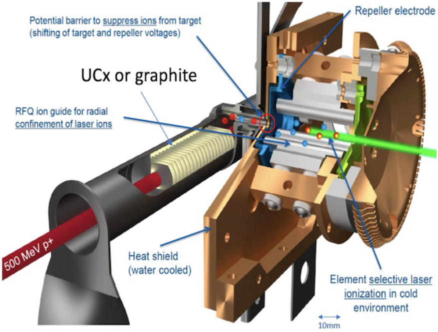
BeEST implantation

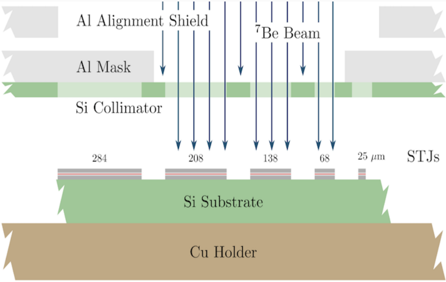
TRIUMF

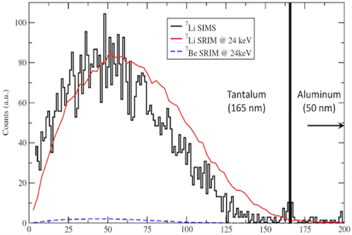
Isotope Separation On-Line (ISOL) Method

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

- Purity > 80%
- Rate > 1e8 pps

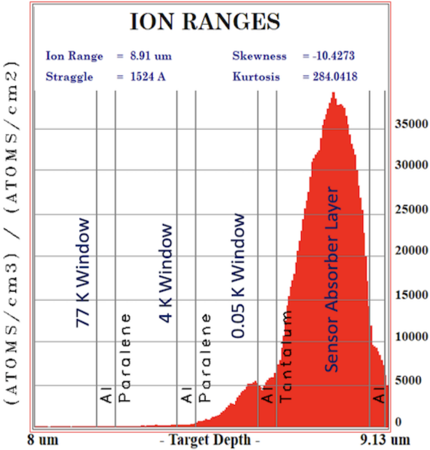






SALER implantation

11 MeV ^{11}C Beam w/ 8µm Al foil



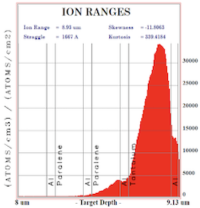
For a given energy, initial beam from ReA can be +/- a few % in spread

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