Looking Beyond the Standard Model with neutrons and nuclei

GDR Intensity Frontier
2-4 Nov. 2022

G. Pignol
M. Versteegen

Why use n and nuclei ?

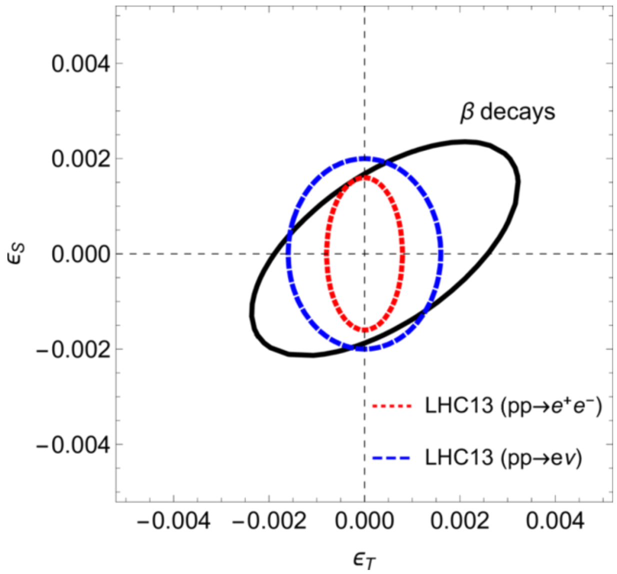
- **Beta decay**
  n and nuclei extensively used to establish the properties of the weak interaction in the framework of the SM

- **Effective Field Theory**
  Model independent approach : no assumption on NP origin
  Wilson coefficients :

$$\epsilon_i \propto \left(\frac{m_W}{\Lambda}\right)^2 \sim 10^{-3}$$

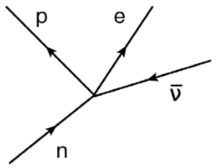
TeV NP scale

➪ Beta decay brings independent and competitive constraints to HEP in the weak sector when going to 0.1% level



M. González-Alonso, O. Naviliat-Cuncic, N. Severijns Prog. Part. Nucl. Phys. (2019)
A. Falkowski, M. González-Alonso, O. Naviliat-Cuncic JHEP04 (2021)

Beta decay



- n beta decay Lagrangian

$$-\mathcal{L}_{LY} = C_V \left(\bar{p}\gamma^\mu n + \frac{C_A}{C_V} \bar{p}\gamma^\mu \gamma_5 n \right) \times \bar{e}\gamma_\mu (1-\gamma_5)\nu_e$$

$$+ C_S\, \bar{p}n \times \bar{e}(1-\gamma_5)\nu_e + \frac{1}{2} C_T\, \bar{p}\sigma^{\mu\nu} n \times \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e + hc$$

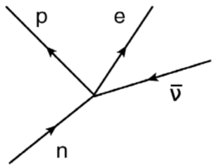
$$+ \; \textit{right-handed} \;\; \textit{neutrinos}$$

SM “V-A” structure

Exotic currents : S and T
P omitted

T.Lee, C-N Yang Phys. Rev. 104 (1956)
M. González-Alonso, Colloque GANIL (2019)

Beta decay



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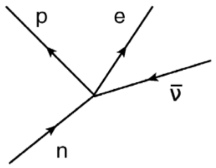

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EFT

$$\bar{C}_V + \bar{C}'_V = 2\, g_V\, (1 + \epsilon_L + \epsilon_R)$$
$$\bar{C}_A + \bar{C}'_A = -2\, g_A\, (1 + \epsilon_L - \epsilon_R)$$
$$\bar{C}_S + \bar{C}'_S = 2\, g_S\, \epsilon_S$$
$$\bar{C}_P + \bar{C}'_P = 2\, g_P\, \epsilon_P$$
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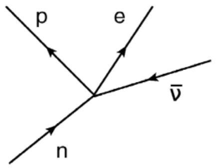

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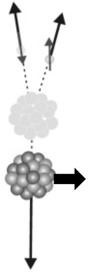
- Decay rate distribution for polarized nuclei



$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = dW_0 \times \xi \left\{ 1 + a\,\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\,\frac{m_e}{E_e} + \frac{<\mathbf{J}>}{J} \cdot \left(A\,\frac{\mathbf{p}_e}{E_e} + B\,\frac{\mathbf{p}_\nu}{E_\nu} + D\,\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right) \right\}$$

β–ν correlation coefficient
CP conserving
Access to C_S and C_T quadratically

Fierz interference term
CP conserving
Access to C_S and C_T linearly

« D » coefficient
CP violating
Acces to C_A, C_A', C_V, C_V' linearly

T.Lee, C-N Yang Phys. Rev. 104 (1956)
M. González-Alonso, Colloque GANIL (2019)
J.D Jackson, S.B Treiman, H.W Wyld Nuclear Phys 4 (1957)

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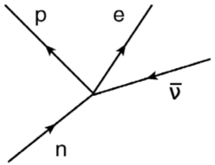

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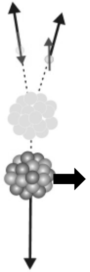

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- Ft values : V_{ud}, b
- Beta spectrum shape : b
- Correlation measurements : a, b, **D**

T.Lee, C-N Yang Phys. Rev. 104 (1956)
M. González-Alonso, Colloque GANIL (2019)
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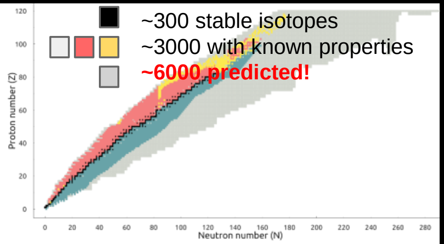
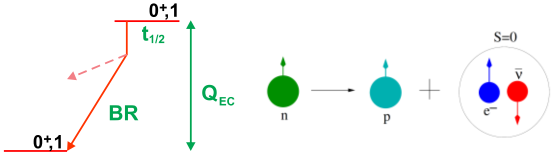
Ft values : total decay rates



- Unitarity test of the CKM matrix 1st row : $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \mathbf{NP}$

$0^+ \longrightarrow 0^+$ superallowed Fermi transition :



JC. Hardy & IS. Towner Phys.Rev.C 102 (2020)

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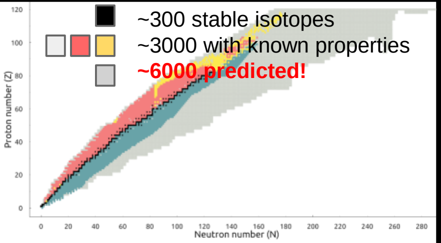

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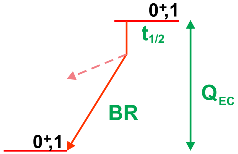
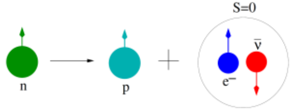
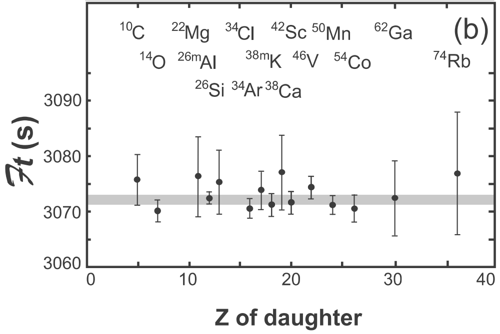




Statistical rate function $f \propto \int dW_0$	$\times$	Partial half-life $t = \frac{t_{1/2}}{BR}(1 + P_{EC})$	$\times$	Corrections: Radiative < 1% Structure < 1%	$=$	$\mathcal{F}t = \frac{K}{2G_F^2\, V_{ud}^2\, (1 + \Delta_R^V)}$
Trap : Q_{EC} $\Delta m \sim 10^{-8}$		Beta counting and Ge with calibrated ε : $t_{1/2}$ and BR $\Delta\varepsilon \sim 0.2\%$		Theoretical Calculations uncertainties < 0.1% (except ^{62}Ga&^{74}Rb)		15 transitions with uncertainties < 0.3%



222 individual measurements from 23 decays : $|\mathbf{V_{ud}}| = \mathbf{0.97373 \pm 0.00031}$

JC. Hardy & IS. Towner Phys.Rev.C 102 (2020)

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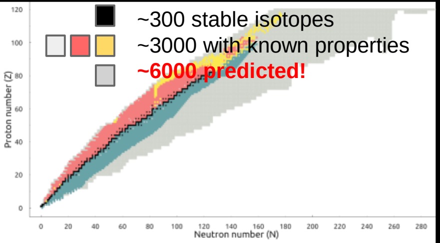

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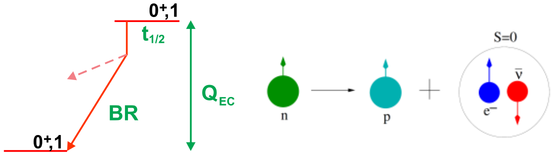

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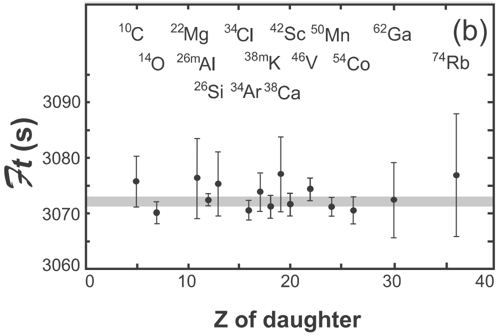

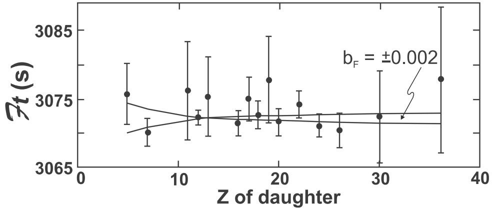

- Sensitivity to exotic scalar currents : b = ± 0.002

If b≠0 then f is affected : $ft' = ft \times \frac{1}{1 + b < \frac{m_e}{E_e} >}$

JC. Hardy & IS. Towner Phys.Rev.C 102 (2020)

Beta spectrum shape

- Beta energy spectrum for non polarized nuclei :

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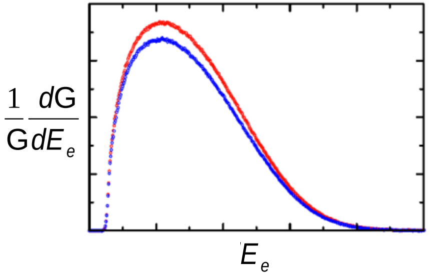
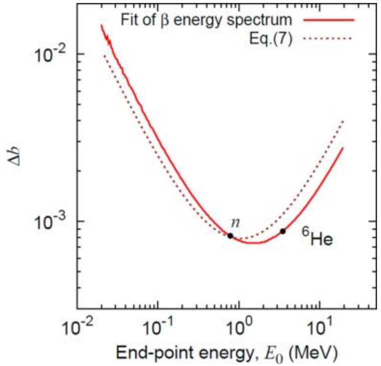
$$dW = dW_0 \times \xi \left(1 + b\frac{m}{E_e} \right)$$

Highest sensitivity candidates due to kinematics : endpoint energy 1-4 MeV
All theoretical corrections under control at 0.1% level





- Experimental Challenges
  - Electron backscattering
  - energy loss in source
  - Detector dead layer

- Set-ups : 4π, MWDC, CRES...
  Ongoing programs with ^{6}He@LPC, ^{114}In@Leuven, ^{20}F...

M. González-Alonso, O. Naviliat-Cuncic Phys. Rev. C 94 (2016)
L. Hayen et al, Rev. Mod. Phys. 90 (2018)

Correlation measurements : WISArD

- Decay rate for non polarized nuclei

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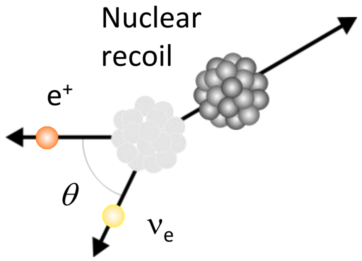
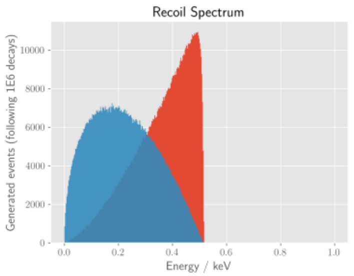


- Correlation measurement = recoil

a > 0 : θ=0° favored and large recoil
a < 0 : θ=180° favored and small recoil

access to : $\tilde{a} \sim \frac{a}{1 + b < \frac{m_e}{E_e} >}$

Beta nuclear recoil < 1 keV



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⬇

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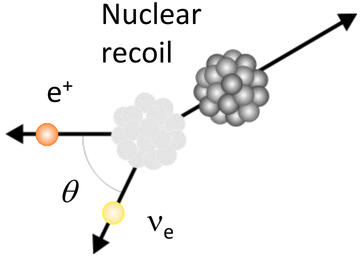

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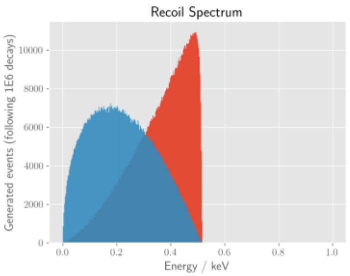
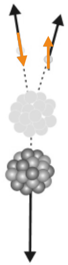




Pure Fermi transition ΔJ=0 S=0

$$a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2} \quad = 1$$

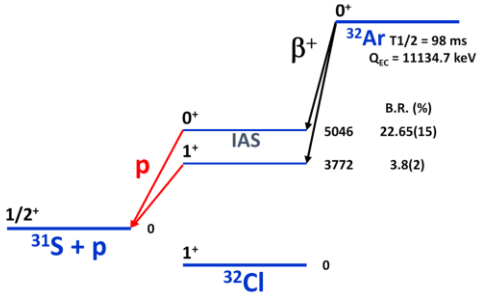
$$b_F \approx \pm Re\left(\frac{C_S + C'_S}{C_V}\right) \quad = 0$$

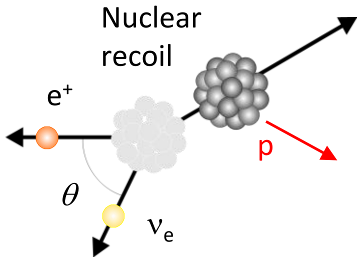
➪ Best measurement a_F at 0.48%

Gorelov, A. et al, Phys. Rev. Lett. 94, 1425 (2005)

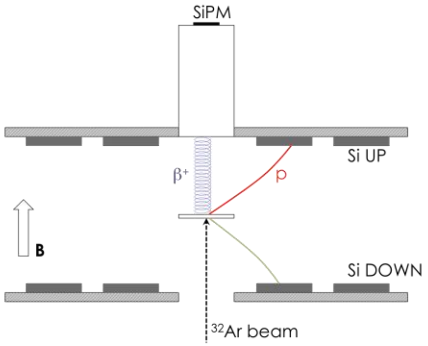
Correlation measurements : WISArD

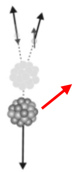
- β-delayed p emission in ^{32}Ar
  - Fermi $0^+ \longrightarrow 0^+$ transition from GS to IAS
  - Recoil energy ~100s eV
  - Beta delayed p emission ~ 3 MeV
  - IAS : $\Gamma \sim 20$ eV ⇔ $T_{1/2} \sim 10^{-17}$ s
  - ➪ p emission in flight from the recoil

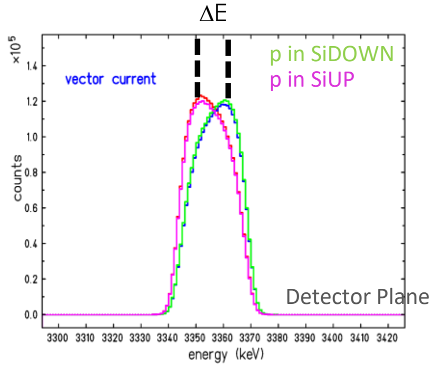




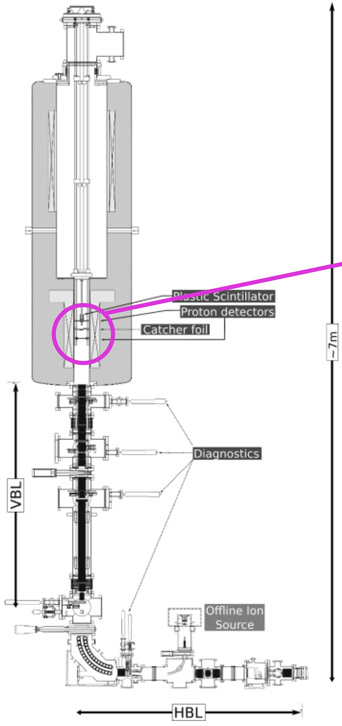
- β-p coincidence measurement
  - Beta detector with detection threshold below 10 keV
  - Strong magnetic field
  - 2 symmetrical p detectors with resolution < 15 keV and high solid angle

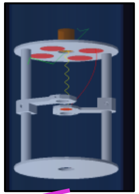


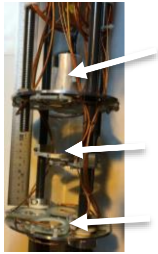




WISArD at ISOLDE







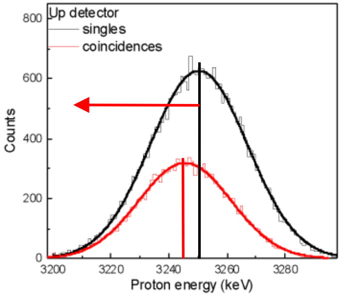
β detector: plastic scintillator and SiPM

6 μm mylar Catcher

2 x 4 proton detectors
(300 μm Si Detectors)

in B = 4 T
(WITCH magnet)

+ FASTER DAQ



Proof-of-principle (2018)

- Readily available β and p detectors
- ~ 1700 pps of ^{32}Ar instead of 3000 nominal
- ~ 35h of beamtime

$$\Delta E_F = 4.49(3)\ keV$$
$$\tilde{a}_F = 1.007(32)_{stat}(25)_{syst}$$

➪ **3rd best result**

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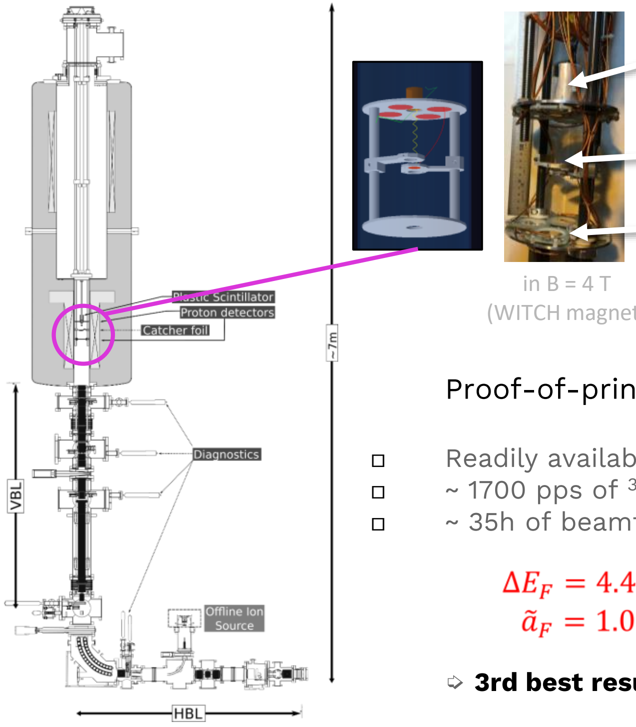

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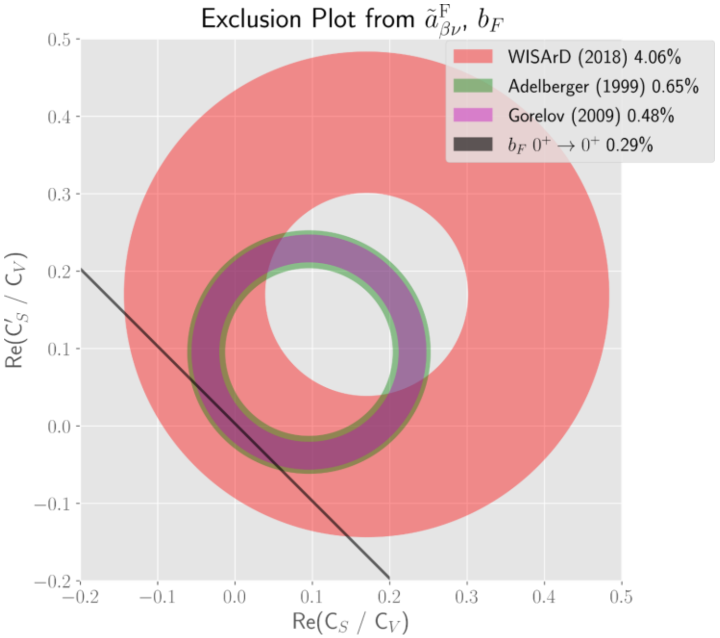
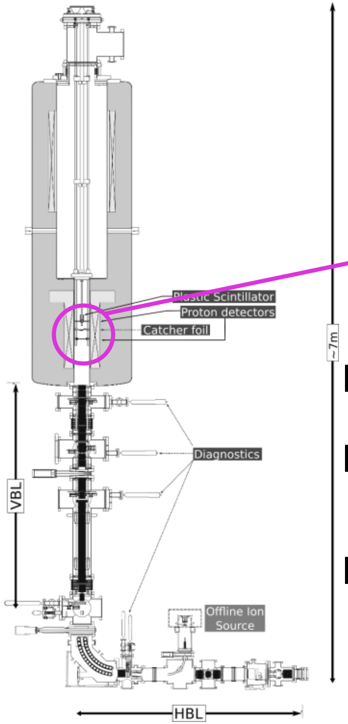
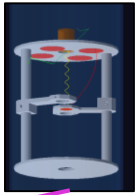
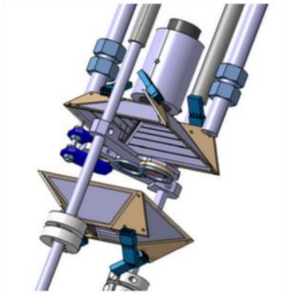


Exclusion plot from D. Atanasov
V. Araujo-Escalona et al. Phys. Rev. C 101 (2020)

WISArD at ISOLDE



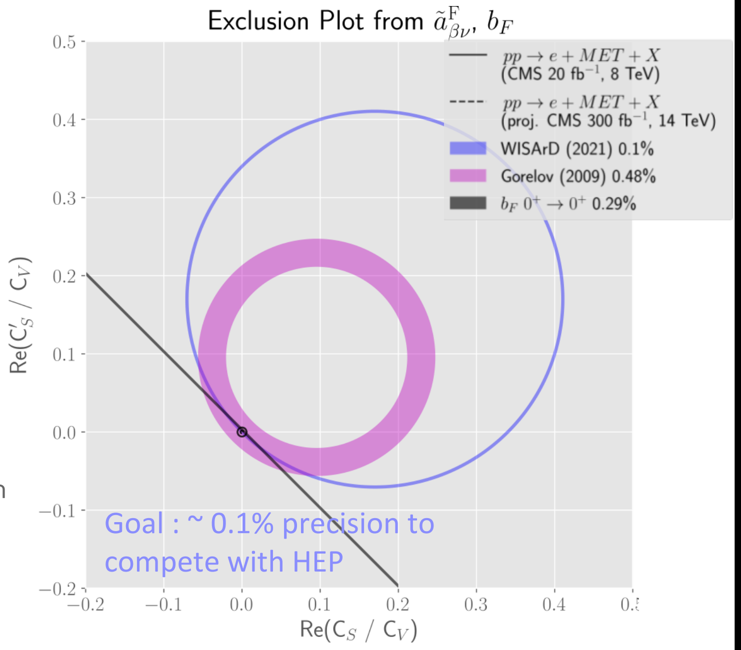




2022 Upgrade

- Ion beam transport
  98% transmission (SIMION)
- p detectors
  40% solid angle + 10 keV resolution + 100 nm dead layer
- Beta detector
  Lower detection threshold + Validation of backscattering (GEANT4)

Next data taking : spring 2023



Goal : ~ 0.1% precision to compete with HEP

Exclusion plot from D. Atanasov

Correlation measurements : many projects

$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} = dW_0 \times \xi \left\{ 1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{< \mathbf{J} >}{J} \cdot \left(A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_\nu}{E_\nu} + D \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right) \right\}$$

^{6}He @ LPC (Paul trap)
^{8}Li @ ANL (Paul trap)
^{6}He @ ANL (MOT)
^{32}Ar @ Texas A&M (Penning)
^{38m}K @ TRIUMF (MOT)
n @ aSPECT
...

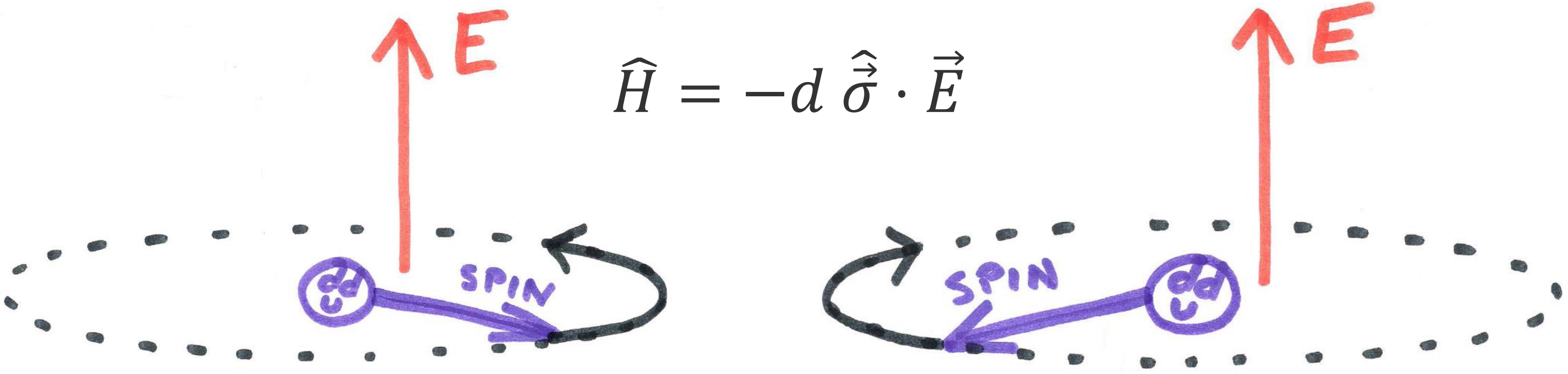
^{114}In @ ISOLDE
^{6}He @ LPC (bSTILED)
^{6}He @ NSCL
...

THE MORA PROJECT
MATTER'S ORIGIN FROM RADIOACTIVITY

See talk by N. Goyal

EDMs: coupling between spin and E-field

$$\widehat{H} = -d\,\hat{\vec{\sigma}}\cdot\vec{E}$$



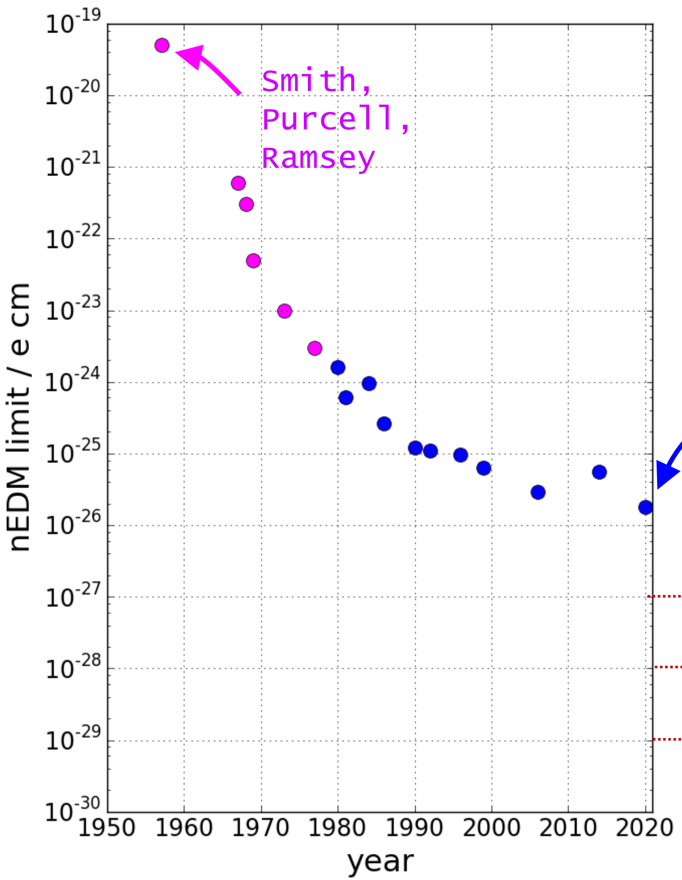
>> PLAY >>

<< REWIND <<

If $d \neq 0$ the process and its time reversed version are different.

Violation of T $\xrightarrow{CPT}$ **Violation of CP**

The neutron EDM is still zero



Best limit (nEDM@PSI)
Abel et al, PRL **124**, 081803 (2020)

$$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$$

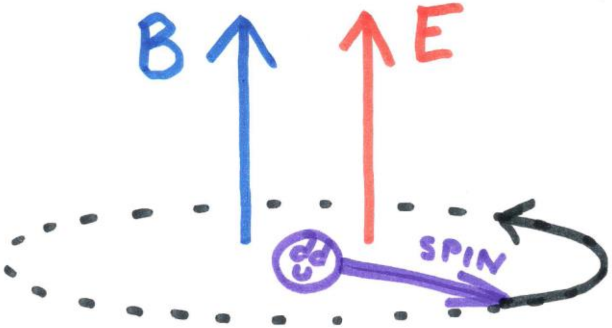
Design sensitivity range of 4 experiments
n2EDM @PSI, panEDM @ILL, LANL EDM, tucan @TRIUMF
under construction now

Design sensitivity EDM@SNS, starting 2028

Possible reach with present neutron sources

CKM background uncertain, possibly 10^{-31} e cm

Basics of nEDM measurement



Larmor frequency
$f = 30\ \mathrm{Hz}\ @\ B = 1\ \mu\mathrm{T}$

$$2\pi f = \frac{2\mu}{\hbar} B \pm \frac{2d}{\hbar}|E|$$

If $d = 10^{-26}\, e\,\mathrm{cm}$ and $E = 11\ \mathrm{kV/cm}$
one full turn in a time

$$\frac{\pi\hbar}{dE} = \mathbf{200\ days}$$

To detect such a minuscule coupling
- Long interaction time
- High intensity/statistics
- Control the magnetic field

- Long interaction time
- High intensity/statistics
- Control the magnetic field

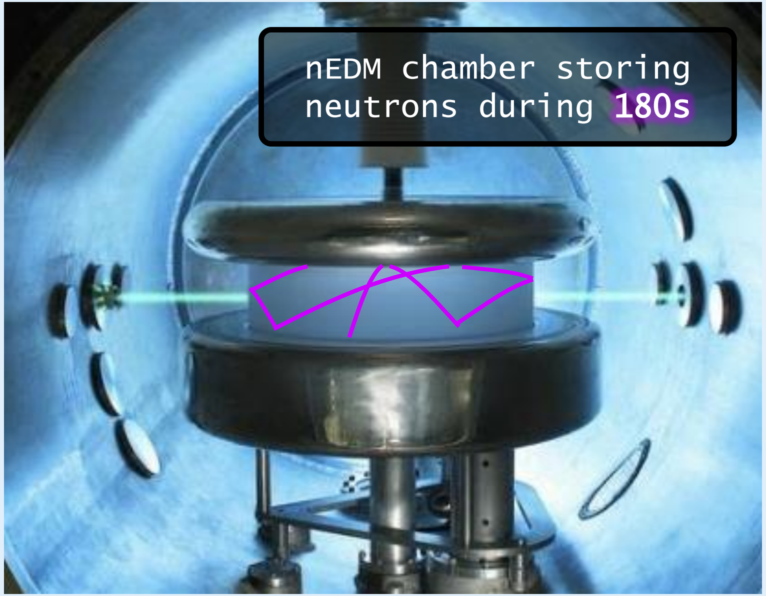
Build colossal magnetic shields

6 layers of mu-metal
Shielding factor 100,000

+ Use quantum magnetometry

Use Ultracold neutrons

Neutrons with velocity <5m/s (E<200neV) can undergo total reflection and be stored in material "bottles"



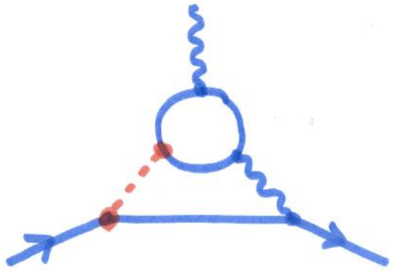
EDMs beyond the SM: modified Higgs couplings

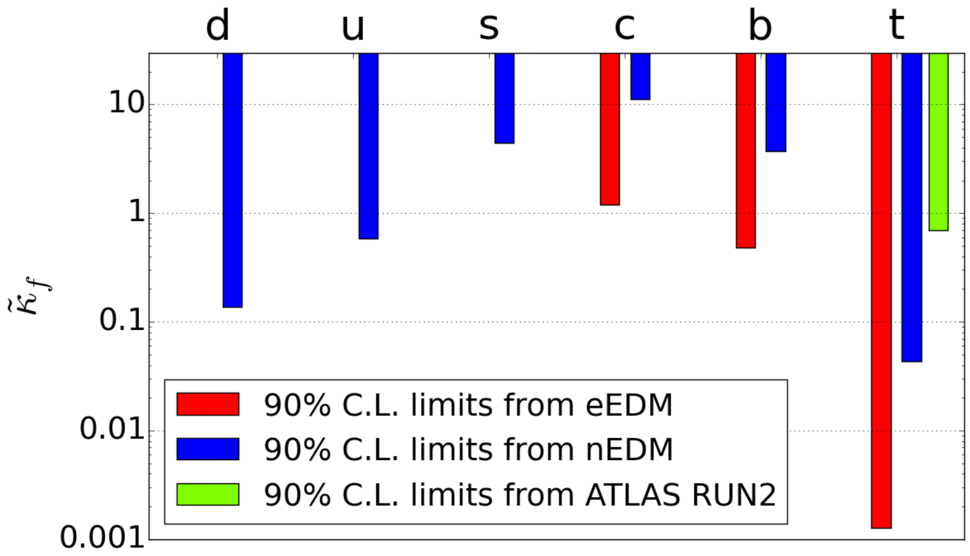
Modified Higgs-fermion Yukawa coupling

$$\mathcal{L} = -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f\, \bar{f}\gamma_5 f h\right)$$

CP

Generates EDM at 2 loops
Barr, Zee, PRL 65 (1990)

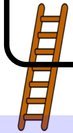


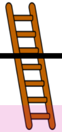


Brod, Haich, Zupan, 1310.1385
Brod, Stamou, 1810.12303
Brod, Skodras, 1811.05480
ATLAS, PRL 125, 061802 (2020)

Concluding view: hunt for forbidden couplings…

Beyond SM physics =
EFT with fundamental degrees of freedom:
quarks & leptons, gauge, Higgs





EFT with nucleons, leptons and photons

Observables

Lee-Yang operators: semileptonic, isospin changing

$$-\mathcal{L}_{LY} = C_V \left(\bar{p}\gamma^\mu n + \frac{C_A}{C_V} \bar{p}\gamma^\mu \gamma_5 n \right) \times \bar{e}\gamma_\mu (1-\gamma_5)\nu_e + C_S\, \bar{p}n \times \bar{e}(1-\gamma_5)\nu_e + \frac{1}{2} C_T\, \bar{p}\sigma^{\mu\nu} n \times \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e + hc$$

Nuclear Beta decay alphabet:
a, b, A, B, D

$$\frac{dW(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu}$$

Isospin-diagonal, CPV operators

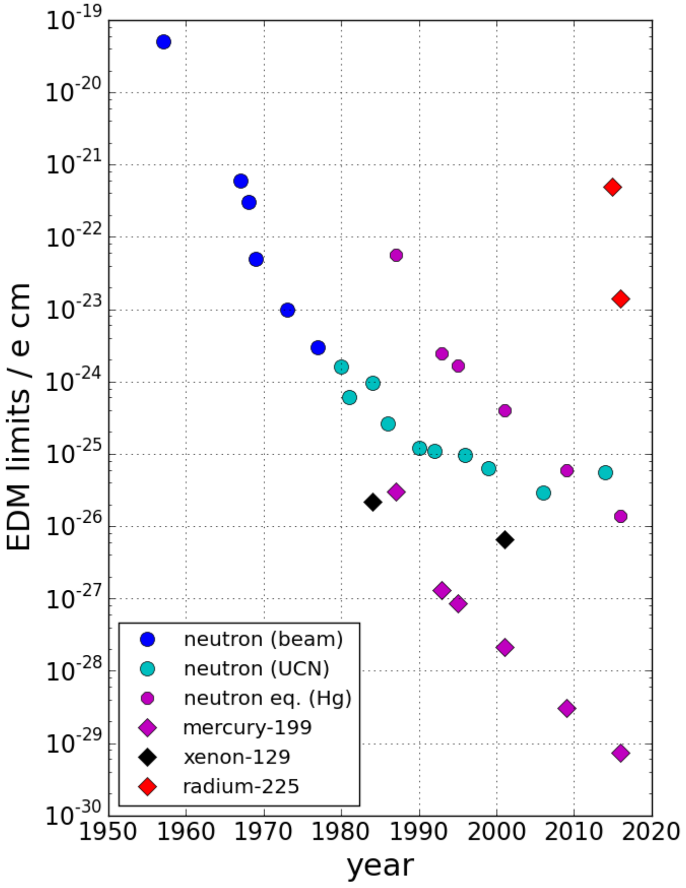
$$-\mathcal{L}_{\mathrm{EDM}} = \frac{1}{2} d_n\, \bar{n}\sigma_{\mu\nu} i\gamma_5 n\, F^{\mu\nu} + \frac{G_F}{\sqrt{2}} C_S^0\, \bar{n}n\, \bar{e}i\gamma_5 e + \cdots$$

EDMs of nucleons and atoms

$$\hat{H} = -d\, \hat{\vec{\sigma}} \cdot \vec{E}$$

Thank you for your attention

Back up



EDMs of diamagnetic atoms

Very stringent EDM limits of diamagnetic atoms with nuclear spin ½ :

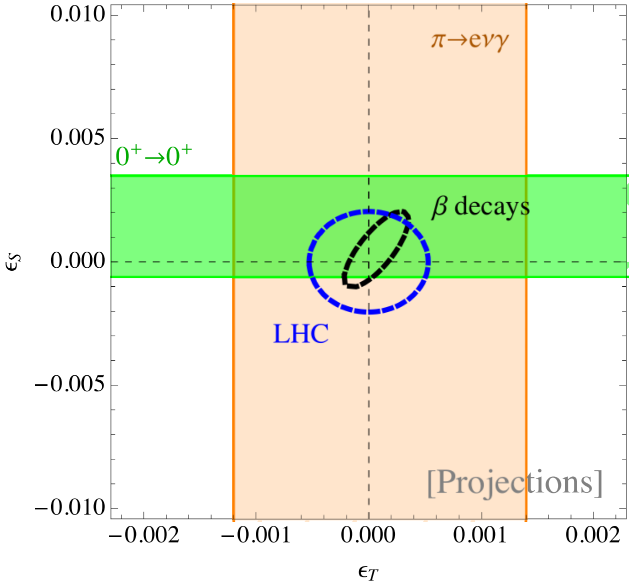
- Mercury-199: atom-light interaction permits super-precise monitoring of the spin precession
- Xenon-129: very long interaction times (many hours)

Due to electron shielding, nuclear EDMs do not generate atomic EDMs.
Instead, atomic EDMs could be induced by

- T-violating e-N interactions
- A T-odd nuclear deformation (Schiff moment)

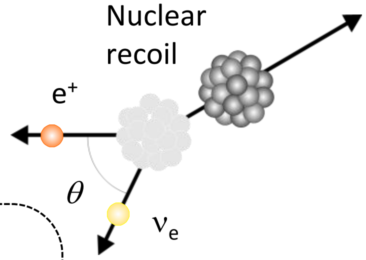
→ generating an E field inside the nucleus
→ pulling the s electrons.
→ atomic EDM

T-violating N-N interactions or nucleon EDM generate a nuclear Schiff moment, the effect is larger in heavy nuclei, and enhanced in octupole-deformed nuclei like radium-225.



0.010
0.005
0.000
−0.005
−0.010
−0.002
−0.001
0.000
0.001
0.002
ϵ_S
ϵ_T
$\pi \to e\nu\gamma$
$0^+ \to 0^+$
β decays
LHC
[Projections]

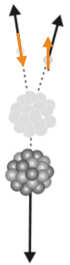
Correlation measurements : WISArD



■ …zed nuclei :

$$dW = dW_0\left(1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e}\right)$$

Pure F transition ΔJ=0 S=0

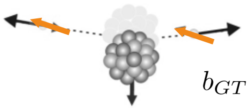


$$a_F \cong 1 - \frac{|C_S|^2 + |C'_S|^2}{|C_V|^2} \quad = 1$$

$$b_F \approx \pm Re\left(\frac{C_S + C'_S}{C_V}\right) \quad = 0$$

➪Best measurement a_F at 0.45%

Pure GT transition ΔJ=0 or 1 S=1



$$a_{GT} \cong -\frac{1}{3}\left(1 - \frac{|C_T|^2 + |C'_T|^2}{|C_A|^2}\right) \quad = -1/3$$

$$b_{GT} \approx \pm Re\left(\frac{C_T + C'_T}{C_A}\right) \quad = 0$$

➪Best measurement a_{GT} at < ~1%

Gorelov, A. et al, Phys. Rev. Lett. 94, 1425 (2005)
Johnson, C.H. et al, Phys. Rev. 132, 1149 (1963)