Probing Beyond the Standard Model with Beta Decay and Electron Capture

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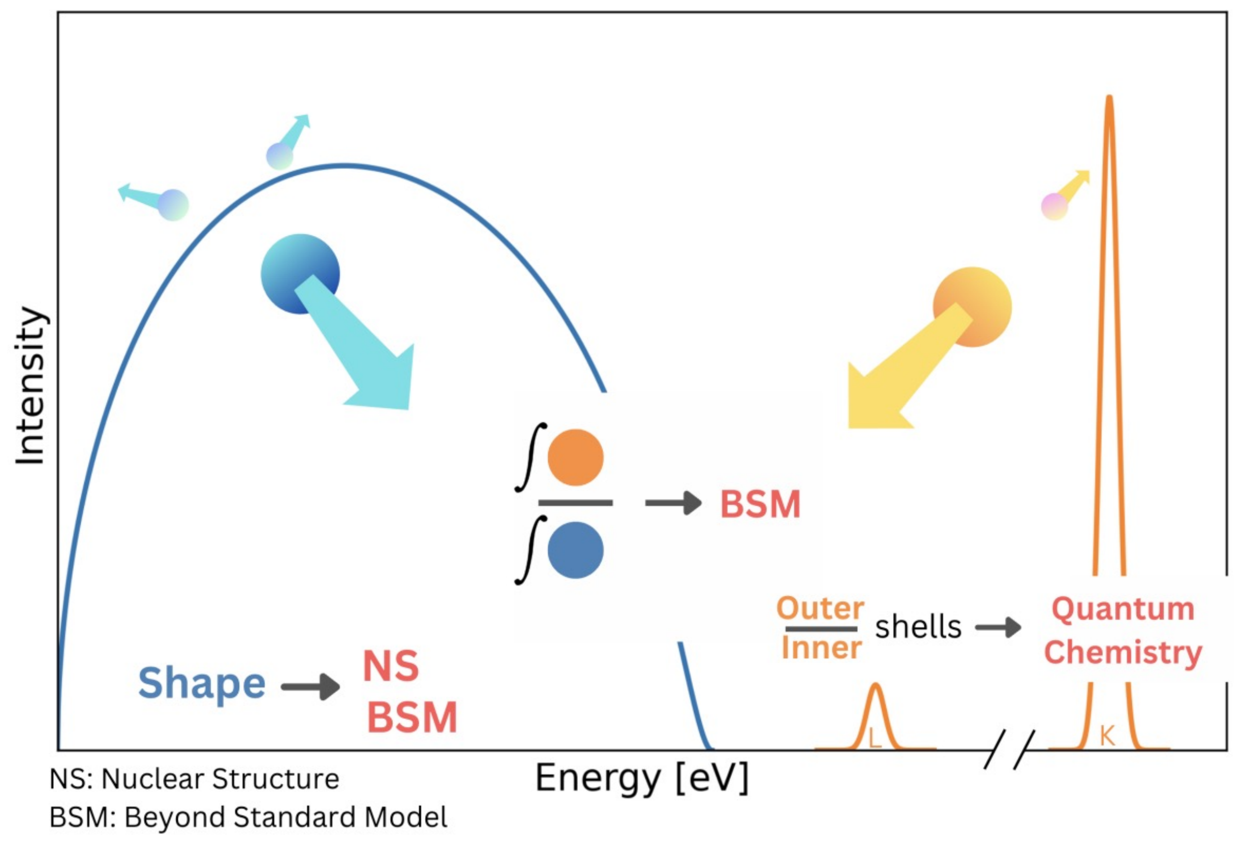
Motivation

Nuclear beta decay and electron capture provide powerful tools to test the Standard Model (SM) and explore new physics. In particular, beta decay can be offers sensitivity to **exotic scalar ε_S and tensor ε_T currents** at the TeV scale.

This sensitivity appears in the **Fierz interference term**, b_F, which depends linearly on these interactions. Beta-plus decay and electron capture (EC) influence b_F in *opposite ways* but probe the same **nuclear matrix element**.

This means the **electron capture to beta-plus branching ratio** is an extremely sensitive probe of new physics with **minimal nuclear structure effects** and able to provide **accuracy of $\sim 10^{-3}$ on b_F**

At the experimental level, **ASGARD/SALER** perform high-precision recoil spectroscopy using **Superconducting Tunnel Junctions (STJ) detectors with eV accuracy.**



Context

Effective field theory is a way to interpreting Beyond Standard Model (BSM) physics at scale $\Lambda_{BSM} \gg LHC$.

$$\mathcal{L}_{\text{eff}} \propto \bar{e}\gamma_\mu \nu_L \cdot \bar{u}\gamma^\mu [C_V - (C_A - 2\epsilon_R)\gamma^5] d + \epsilon_S \bar{e}\nu_L \cdot \bar{u}d$$
$$- \epsilon_P \bar{e}\nu_L \cdot \bar{u}\gamma^5 d + \epsilon_T \bar{e}\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma^5)d \quad \text{at quark level}$$

V – A structure in SM.

ϵ_i are proportional to $(M_W/\Lambda_{BSM})^2$ → $\epsilon_i \leq 10^{-4}$ → $\boldsymbol{\Lambda_{BSM} \geq 15\,TeV}$ assuming natural couplings.

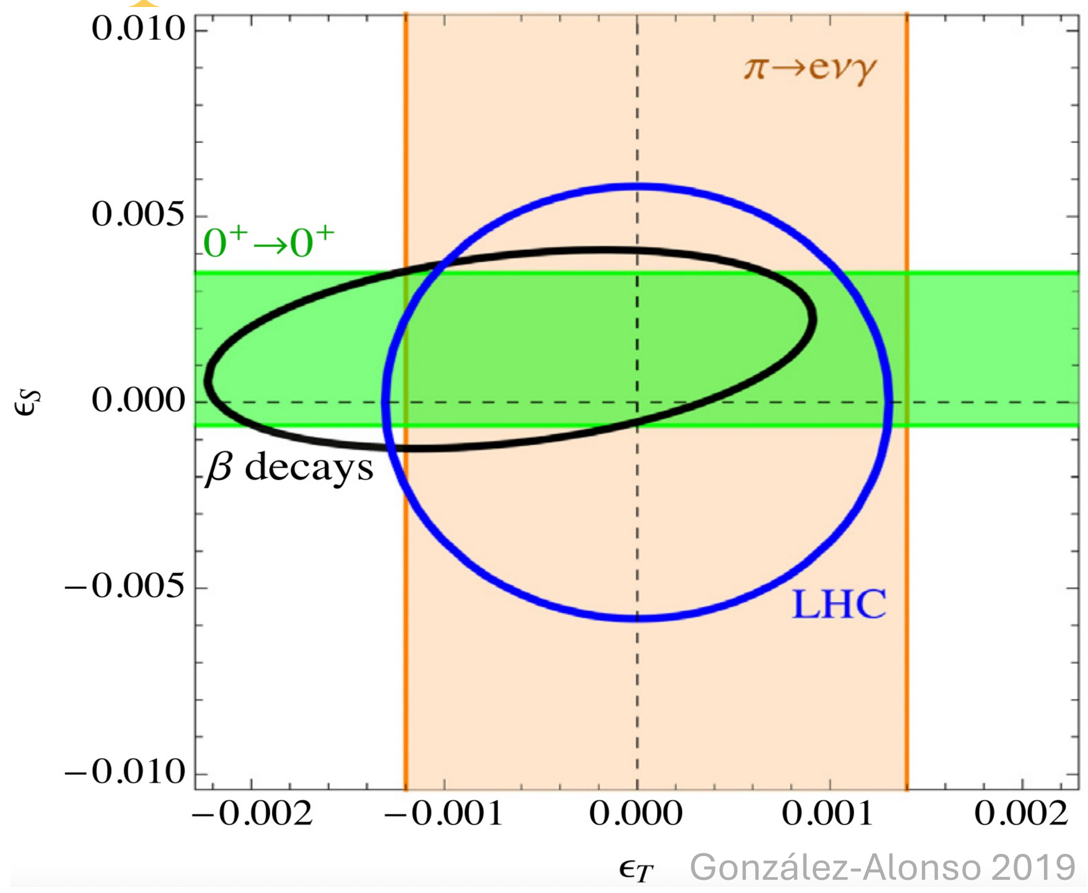
Fierz interference term b_F comes from an interference between the SM and BSM : $\mathcal{M}_{SM} \times \mathcal{M}_{BSM} \approx \mathcal{O}(\epsilon_S, \epsilon_T)$.

$$b_F = \pm \frac{2\gamma}{1+|\rho|^2} \mathrm{Re}\left(\frac{\epsilon_S g_S}{g_V} + |\rho|^2 \frac{8 g_T \epsilon_T}{-2 g_A}\right)$$

This term allows the SM to be probed at low energies. b_F depends linearly on the **scalar** and **tensor exotic currents** (**$\epsilon_S = \epsilon_T = 0$ in SM).**

There are currently **several methods** for constraining the value of scalar and tensor couplings.

With recent results, β-decay is **competitive** with the LHC in the search for exotic currents.



González-Alonso 2019

Methodology

EC/β+ ratio shows a dependence of **opposite sign** on the **Fierz interference term** while probing the **same nuclear matrix element**, making it **extremely sensitive to new physics**.

$$\frac{\lambda_{\text{EC}}}{\lambda_{\beta+}} = \frac{f_x}{f_\beta}(1+\delta_{\text{NS}}) \cdot \frac{1 + b_F \frac{m_e}{E_x}}{1 - b_F \left\langle \frac{m_e}{E_e} \right\rangle}$$

Nuclear structure effects, ...

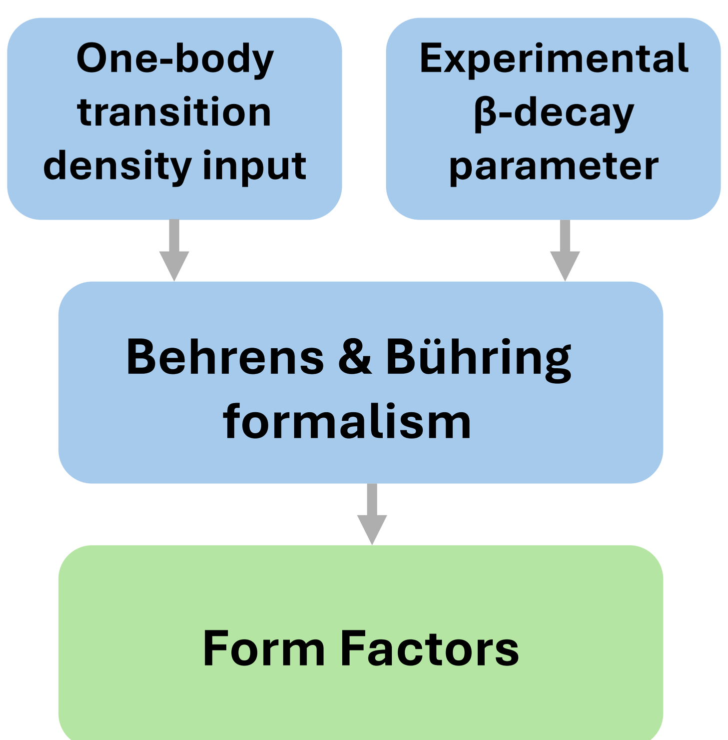
Nuclear Structures (NS) are calculated using the **shell model calculation** and **H.Behrens & W.Bühring formalism [1]** based on a multipole expansion.

$$< f|H_0^{\text{hadr}} L_{\text{lep}}^0|i > \propto \sum_{L,M} j_L(qR) Y_M^L(\hat{q}) F_L(q^2)$$

Form factor

The advantages of this decomposition allows all observables **to be expressed in terms of form factors** for **all types of transitions.**

The aim of my work was to create a code that would **reproduce the calculation of form factors** and **link them to different observables**.



Possible outputs :

- $\lambda_{EC}/\lambda_{\beta+}$ **ratio**
- Shape factor $C(E)$
- β-spectrum, half-life
- Angular parameters
- Testing the CVC hypothesis
- g_A quenching

Results

NS calculations for 2 data sets: X.Mougeot 2019 [3] & W.Bambynek 1977 [2].

Isotope	ρ_{exp}	ρ_{th}^{I}	ρ_{th}^{II}	$\delta_{NS}^{exp}(\%)$	$\delta_{NS}^{I}(\%)$	$\delta_{NS}^{II}(\%)$	$(\lambda_{EC}/\lambda_{\beta+})_{exp}$	$(\lambda_{EC}/\lambda_{\beta+})_{th}$
$^{11}C^{a,c}$	-0.7544(8)	-0.7728	-0.6927	0.23	0.30	0.26	0.00225(15)	0.00211(6)
$^{22}Na^{b,c}$	-	-	-	-2.0	-1.08	0.32	0.1083(9)	0.1097(9)
$^{57}Ni^{d}$	-	-	-	-	0.03	-	1.460(47)	1.447(11)
$^{58}Co^{d}$	-	-	-	-	0.03	-	5.61(8)	5.63(8)
$^{65}Zn^{e}$	-	-	-	-	0.37	-	30.1(5)	29.6(7)
$^{13}N^{a,c}$	-0.560(1)	-0.5480	-0.5077	0.01	0.03	0.01	0.00168(12)	0.00176(5)
$^{15}O^{a,c}$	0.630(2)	0.5555	0.5185	0.01	0.02	-0.02	0.00107(6)	0.00091(2)
$^{17}F^{b,c}$	1.296(1)	1.1572	1.1376	0.48	0.66	0.64	-	0.00135(2)
$^{18}F^{b,c}$	-	-	-	-	0.61	0.59	0.030(18)	0.0310(5)
$^{19}Ne^{b,c}$	-1.602(1)	-1.6338	-1.6197	0.50	0.70	0.69	0.00096(3)	0.00093(1)

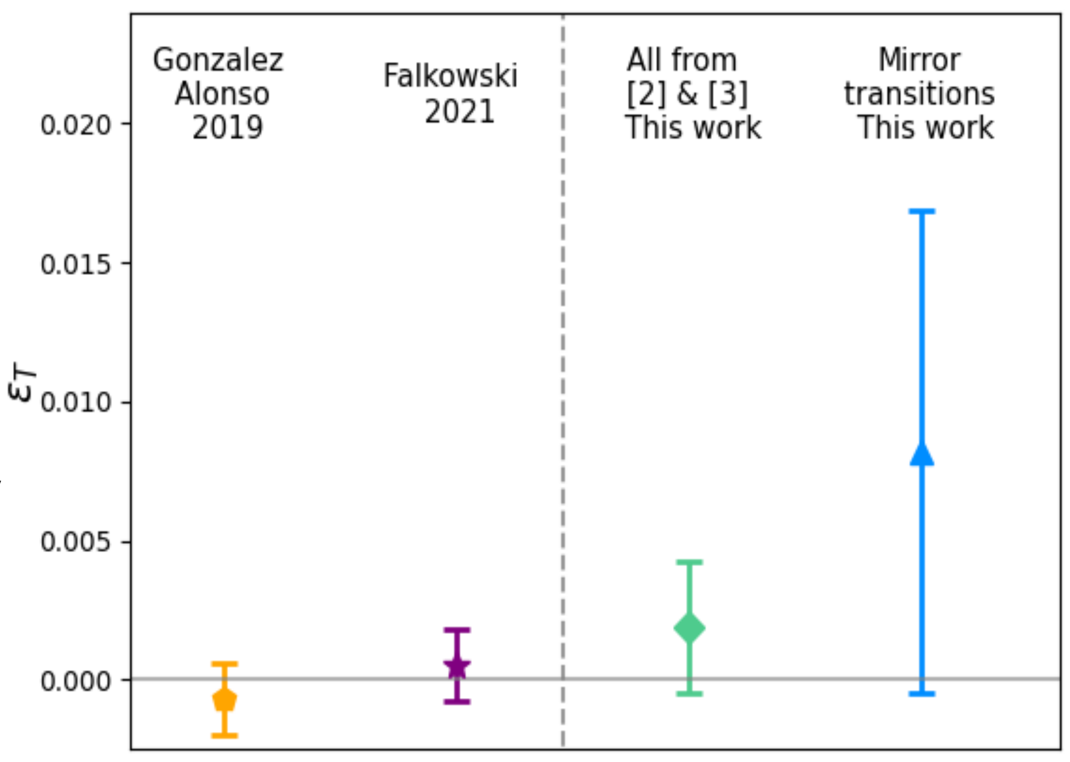
NS corrections are sensitives to the interaction used (I or II).

	CKPOT[a]	USDB[b]	YSOX[c]	HO[d]	JUN45[e]
Model Space	$1p_{3/2}$, $1p_{3/2}$	$1s_{1/2}$, $1d_{5/2}$ $1d_{3/2}$	$1s_{1/2}$, $1p_{3/2}$, $1p_{1/2}$ $1d_{5/2}$, $1d_{3/2}$	N: $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$ P: $1f_{7/2}$	$1f_{7/2}$, $1g_{9/2}$ $2p_{3/2}$, $2p_{3/2}$

For mirror transitions (MT), the **hadronic part is easy** for reasons of symmetry and are **"easily" accessible** for ab initio calculations.

→ Nuclear structure uncertainties **do not play** significant role **in exotic tensor constraints.**

→ **Already competitive** with global dataset.



$\boldsymbol{\epsilon_T^{MT} = 0.0082(82)_{exp}(30)_{atom}(8)_{NS}}$ (90%CL)

$\boldsymbol{\epsilon_T^{All} = 0.0019(24)}$ (90%CL)

Conclusion & Outlook

With nuclear structure corrections at the **$\sim 10^{-3}$ level**, uncertainties are an order of magnitude **lower than typical beta decay searches,** and we are **already competitive with the global dataset in the search for exotic tensor current.**

Experiments aiming to probe the EC/β+ ratio at the 0.1% level are a powerful probe of physics **at the tens of TeV scale with minimal nuclear structure uncertainties.**

Outlook : **ab initio calculations** to appropriately estimate nuclear structure uncertainties in a controlled fashion & **add condensed matter theory** to the Behrens & Bühring formalism to take account of superconducting effects.

[1] : W.Bühring & H.Behrens, Electron Radial Wave Function and Nuclear Beta Decay, 1982.
[2] : W. Bambynek et al. "Orbital electron capture by the nucleus", Reviews of Modern Physics 49.1 (Jan. 1, 1977).
[3] : X. Mougeot, Towards high-precision calculation of electron capture decays, Applied Radiation and Isotopes, 2019.