NUCLEAR STRUCTURE AND THEORY FOR PRECISION BETA DECAY EXPERIMENTS:
NUCLEAR SHAPE CORRECTIONS
COLLABORATORS

COLLABORATORS IN THIS WORK

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INTRODUCTION

- The standard model is incomplete: dark sector, neutrino masses.
- Finding signatures of beyond the standard model physics in quantum phenomena is one of the heralds of modern physics.
- LHC is the energy frontier.
- Nuclear phenomena are a precision frontier:
  - New techniques allow unprecedented experimental accuracy.
  - Need an accompanying theoretical effort to analyze experimental results and pinpoint new physics.
- It’s not a very rewarding job...
BSM EFFORTS USING NUCLEAR BETA DECAYS

Precision Correlation Studies

- Parity breaking
- V-A structure

Precision spectrum studies

Neutrino hypothesized

KATRIN
BSM EFFORTS USING NUCLEAR BETA DECAYS

\[ \beta \text{ decays} \]

Precision Correlation Studies

Precision spectrum studies

Parity breaking

V-A structure

Neutrino hypothesized

KATRIN
"New Physics" searches using beta decays have been moving back and forth, from spectrum to correlation studies.

Atomic traps acted as the catalyst for precision correlation studies, and many experiments have been constructed since ~2005.

In the last couple of years, the seesaw seems to tilt towards precision spectrum studies again, based on theoretical expectations for the size of the effect.
Differential $\beta$ decay rate

$$\frac{d^5 \omega_{\beta^\pm}}{d\Omega_k/4\pi d\Omega_{\nu}/4\pi d\epsilon} = \Sigma(\epsilon) \cdot \Theta(q, \vec{\beta}, \hat{\nu})$$

Momentum transfer

$$\vec{\beta} = \frac{\vec{k}}{\epsilon'}, \beta \text{ particle momentum to energy ratio}$$

$\hat{\nu}$ neutrino momentum

Nuclear independent part

$$\Sigma(\epsilon) = \frac{2G^2}{\pi^2} \frac{2\Delta J + 1}{\Delta J(2J_i + 1)} (\epsilon_0 - \epsilon)^2 k\epsilon F^{(\pm)}(Z_f, \epsilon) \times (\text{corrections})$$

Classification of $\beta$ decays

$$\Delta J^{\pi} = 0^+ \quad \text{(Super)allowed - Fermi transition}$$

$$\Delta J^{\pi} = 0,1^+ \quad \text{Allowed - Fermi/Gamow-Teller}$$

$$\Delta J^{\pi} = 0,1,2^- \quad \text{Unique First forbidden transition}$$

$$\alpha \propto q^0$$

$$\alpha \propto q^1$$
### WHERE DOES NUCLEAR STRUCTURE ENTER?

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<td>Neutrino mass</td>
<td>Negligible</td>
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Beta Spectrum Generator: High precision allowed \(\beta\) spectrum shapes

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Differential $\beta$ decay rate

$$\frac{d^5 \omega_{\beta^\mp}}{d\Omega_k/4\pi d\Omega_\nu/4\pi d\epsilon} = \sum (\epsilon) \cdot \Theta(q, \vec{\beta}, \hat{\nu})$$

Momentum transfer

$$\vec{\beta} = \frac{\vec{k}}{\epsilon'}, \beta \text{ particle momentum to energy ratio}$$

$\nu$ neutrino momentum

Nuclear dependent part

Assuming V-A structure

$$\Theta(q, \vec{\beta} \cdot \hat{\nu}) = \frac{\Delta J}{2\Delta J + 1} \left\{ \begin{array}{c} 1 - (\hat{\nu} \cdot \hat{q})(\vec{\beta} \cdot \hat{q}) \sum_{J \geq 1} (|\hat{E}_J||^2 + |\hat{M}_J||^2) \\ \pm \hat{q} \cdot (\hat{v} - \vec{\beta}) \sum_{J \geq 1} 2R (|\hat{E}_J||^* |\hat{M}_J||^*) \\ + \sum_{J \geq 0} \left[ (1 - \hat{\nu} \cdot \vec{\beta} + 2(\hat{v} \cdot \hat{q})(\vec{\beta} \cdot \hat{q})) |\hat{L}_J||^2 \\ + (1 + \hat{\nu} \cdot \vec{\beta}) |\hat{C}_J||^2 \\ - 2\hat{q} \cdot (\hat{v} + \vec{\beta}) R (|\hat{C}_J||^* |\hat{L}_J||^*) \right] \right\},$$

(4)

We have similar expressions for Tensor and Scalar structures, and interferences. [Glick–Magid, Gazit, unpublished]
**Differential β decay rate**

\[ \frac{d^5 \omega_{\beta \gamma}}{d\Omega_k/4\pi d\Omega_\nu/4\pi d\epsilon} = \sum (\epsilon) \cdot \Theta(q, \vec{\beta}, \vec{\nu}) \]

**Momentum transfer**

\[ \vec{\beta} = \frac{\vec{k}}{\epsilon}, \beta \text{ particle momentum to energy ratio} \]

**ν neutrino momentum**

**Nuclear dependent part**

Assuming V-A structure

\[ \Theta(q, \vec{\beta} \cdot \vec{\nu}) = \frac{\Delta J}{2\Delta J + 1} \left\{ \left[ 1 - (\vec{\nu} \cdot \hat{q})(\vec{\beta} \cdot \hat{q}) \right] \sum_{J \geq 1} (|\hat{E}_J|)^2 + (|\hat{M}_J|)^2 \right\} \]

\[ \pm \hat{q} \cdot (\vec{\nu} - \vec{\beta}) \sum_{J \geq 1} 2\Re\langle |\hat{E}_J| \rangle \langle |\hat{M}_J| \rangle^* \]

\[ + \sum_{J \geq 0} \left[ \left[ 1 - \nu \cdot \bar{\beta} + 2(\vec{\nu} \cdot \hat{q})(\vec{\beta} \cdot \hat{q}) \right] |\hat{L}_J| \right]^2 \]

\[ + \left( 1 + \nu \cdot \bar{\beta} \right) |\langle \hat{C}_J \rangle|^2 \]

\[ - 2\hat{q} \cdot (\vec{\nu} + \vec{\beta}) \Re\langle |\hat{C}_J| \rangle \langle |\hat{L}_J| \rangle^* \} \right\}, \quad \text{(4)} \]

We have similar expressions for Tensor and Scalar structures, and interferences.[Glick-Magid, Gazit, unpublished]
\[ \Delta J^{\pi} = 0,1^+ \]

\[
d\omega^{V-A} = \frac{4}{\pi^2} k\epsilon (W_0 - \epsilon)^2 d\epsilon \frac{d\Omega_k}{4\pi} \frac{d\Omega_\nu}{4\pi} \frac{1}{2J_i + 1} \left\{ \frac{|C_V|^2 + |C'_V|^2}{2} \left( 1 + \hat{\nu} \cdot \hat{\beta} \right) \right\} + O(q) \]

Assumptions: vanishing momentum transfer (q=0).
\[ \Delta J^\pi = 0,1^+ \]

\[ d\omega^{V+T} = \frac{4}{\pi^2} k\epsilon (W_0 - \epsilon)^2 d\epsilon \frac{d\Omega_k}{4\pi} \frac{d\Omega_\nu}{4\pi} \frac{1}{2J_i + 1} \cdot \frac{|C_V|^2 + |C'_V|^2}{2} \left( 1 + \hat{\nu} \cdot \vec{\beta} \right) \left| \left\langle J_f \left| \hat{C}_0^V \right| J_i \right\rangle \right|^2 \]

\[ + \frac{|C_T|^2 + |C'_T|^2}{2} \left( 1 + \frac{1}{3} \hat{\nu} \cdot \vec{\beta} \right) \left| \left\langle J_f \left| \hat{L}_1^A \right| J_i \right\rangle \right|^2 \] + \mathcal{O}(g)
V–A WITH T CORRECTIONS:

\[ \Theta \propto (1 + b \frac{m_e}{\epsilon} + a_{\beta v} \vec{\beta} \cdot \hat{v}) \]

\[ a_{\beta v} \approx -\frac{1}{3} (1 - \frac{|c_T|^2 + |c'_T|^2}{|c_A|^2}) \]

and \( b = 2 \frac{c_T + c'_T}{c_A} \)

Caveats:

a) Sensitive to combination of tensor couplings, with spectrum averaging of energy, thus in a specific nucleus — the sensitivity to BSM couplings is QUADRATIC . . .

b) Spectrum, i.e., integration over angle, sensitive to Fierz term, i.e., insensitive to fully right handed couplings.

**Unique first forbidden** $\Delta J^{\pi} = 2^-$

\[
\Theta(q, \vec{\beta} \cdot \hat{v}) = \frac{\Delta J}{2\Delta J + 1} \left\{ \left[ 1 - (\hat{v} \cdot \hat{q})(\vec{\beta} \cdot \hat{q}) \right] \sum_{J \geq 1} |\langle \vec{L}_J \rangle|^2 + |\langle \vec{M}_J \rangle|^2 \right\} \\
\pm \hat{q} \cdot (\hat{v} - \vec{\beta}) \sum_{J \geq 1} 2\Re \langle \vec{L}_J \rangle \langle \vec{M}_J \rangle^* \\
+ \sum_{J \geq 0} \left[ \left[ 1 - \hat{v} \cdot \vec{\beta} + 2(\hat{v} \cdot \hat{q})(\vec{\beta} \cdot \hat{q}) \right] |\langle \vec{L}_J \rangle|^2 \\
+ \left( 1 + \hat{v} \cdot \vec{\beta} \right) |\langle \vec{C}_J \rangle|^2 \\
- 2\hat{q} \cdot (\hat{v} + \vec{\beta}) \Re \langle \vec{C}_J \rangle \langle \vec{L}_J \rangle^* \right\}, \tag{4}
\]

\[
\Theta(q, \vec{\beta} \cdot \hat{v}) \propto 1 \pm 2\gamma_0 \frac{C_T + C'_T}{C_A} \frac{m_e}{\epsilon} \\
- \frac{1}{5} (2(\hat{v} \cdot \vec{\beta}) - (\hat{v} \cdot \hat{q})(\vec{\beta} \cdot \hat{q})) (1 - \frac{|C_T|^2 + |C'_T|^2}{|C_A|^2}) \cdot 1 - (\vec{\beta} \cdot \hat{v})^2
\]

**Unique first forbidden** $\Delta J^\pi = 2^-$

$$\Theta(q, \vec{\beta} \cdot \hat{v}) \propto 1 \pm 2\gamma_0 \frac{C_T + C_T'}{C_A} \frac{m_e}{\epsilon}$$

$$- \frac{1}{5} \left( 2(\hat{v} \cdot \vec{\beta}) - (\hat{v} \cdot \hat{q})(\vec{\beta} \cdot \hat{q}) \right) \left( 1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2} \right).$$

$$\propto 1 - \left( \hat{\beta} \cdot \hat{v} \right)^2$$

**Spectrum, i.e., integration over angle:**

$$\frac{d\omega_{\beta^\pm}}{d\epsilon} \propto \Sigma(\epsilon) \left( 2 + 4\gamma_0 \frac{C_T + C_T'}{C_A} \frac{m_e}{\epsilon} + \frac{\beta}{5} \frac{(a^2 - 1) \tanh^{-1}(a) + a}{a^2} \right)$$

$$\times \left( 1 - \frac{|C_T|^2 + |C_T'|^2}{|C_A|^2} \right),$$

where $a = 2k\nu/(k^2 + \nu^2)$.

Unique first forbidden $\Delta J^{\pi} = 2^-$

Unique possibility to separate between left and right-handed couplings!

\[ C_T = C_T' = 0 \]
\[ C_T/C_A = C_T'/C_A = 0.005 \]
\[ C_T/C_A = -C_T'/C_A = 0.2 \]

SHAPE CORRECTIONS

These are **nuclear structure dependent** corrections.

Needed accuracy of the calculation ≈ $10^{-4} - 10^{-3}$

This dictates the number of corrections needed to be calculated explicitly.

\[
\begin{align*}
\hat{C}_{JM}(q) &= \int d\tilde{x} j_J(qx) Y_{JM}(\tilde{x}) \hat{J}_0(\tilde{x}) \\
\hat{E}_{JM}(q) &= \frac{1}{q} \int d\tilde{x} \tilde{\nu} \times [j_J(qx) \tilde{Y}_{JM}(\tilde{x})] \cdot \hat{\mathcal{J}}(\tilde{x}) \propto q^{J-1} \\
\hat{M}_{JM}(q) &= \int d\tilde{x} j_J(qx) \tilde{Y}_{JM}(\tilde{x}) \cdot \hat{\mathcal{J}}(\tilde{x}) \\
\hat{L}_{JM}(q) &= \frac{i}{q} \int d\tilde{x} \tilde{v} [j_J(qx) Y_{JM}(\tilde{x})] \cdot \hat{\mathcal{J}}(\tilde{x}),
\end{align*}
\]

\[
\frac{qR}{\hbar c} \approx 0.005 - 0.1
\]
SHAPE CORRECTIONS

These are nuclear structure dependent corrections.

Needed accuracy of the calculation \(\approx 10^{-4} - 10^{-3}\)

This dictates the number of corrections needed to be calculated explicitly.

\[
\begin{align*}
\hat{C}_{JM}(q) &= \int dx j_j(qx) \mathcal{Y}_{JM}(\hat{x}) \hat{J}_0(\hat{x}) \\
\hat{E}_{JM}(q) &= \frac{1}{q} \int d\hat{x} \hat{v} \times [j_j(qx) \mathcal{Y}_{JJM}(\hat{x})] \cdot \hat{J}(\hat{x}) \propto q^{J-1} \\
\hat{M}_{JM}(q) &= \int dx j_j(qx) \mathcal{Y}_{JM}(\hat{x}) \cdot \hat{J}(\hat{x}) \propto q^J \\
\hat{L}_{JM}(q) &= \frac{i}{q} \int d\hat{x} \hat{v} [j_j(qx) \mathcal{Y}_{JM}(\hat{x})] \cdot \hat{J}(\hat{x}), \propto \frac{1}{J+1} \hat{E}_{JM}
\end{align*}
\]

\[
\frac{qR}{\hbar c} \approx 0.005 - 0.1
\]
SHAPE CORRECTIONS

These are nuclear structure dependent corrections.

Needed accuracy of the calculation $\approx 10^{-4} - 10^{-3}$

This dictates the number of corrections needed to be calculated explicitly.

In beta decays, shape corrections are few per-milles, thus the first correction should be calculated explicitly to reach needed accuracy.
SHAPE CORRECTIONS

\[ \frac{d\omega^{V-A}}{d\epsilon d\Omega_{\text{h}} d\Omega_{\nu}} = \frac{4}{\pi^2} (Q - \epsilon)^2 k \epsilon F^2 (Z_f, \epsilon) \frac{1}{2J_i + 1} \cdot \left\{ \begin{array}{l} \frac{|C_V|^2 + |C'_V|^2}{2} \left( 1 + \delta_1^{0+} + \left( 1 + \delta_{\beta\nu}^{0+} \right) \hat{\nu} \cdot \hat{\beta} \right) \left| \langle J_f \| \hat{C}_V \| J_i \rangle \right|^2 \\
+ \frac{|C_A|^2 + |C'_A|^2}{2} \left( 1 - \delta_1^{0+} - \frac{1}{3} \left( 1 + \delta_{\beta\nu}^{0+} \right) \hat{\nu} \cdot \hat{\beta} \right) \left| \langle J_f \| \hat{L}_1^A \| J_i \rangle \right|^2 \end{array} \right\} \]

\[ \begin{align*}
\delta_1^{0+} &= -\frac{\nu + \frac{\epsilon^2}{q}}{2} 2 \text{Re} \left\langle J_f \| \hat{L}_0^V \| J_i \right\rangle \\
\delta_{\beta\nu}^{0+} &= -\frac{\epsilon + \nu}{q} 2 \text{Re} \left\langle J_f \| \hat{C}_0^V \| J_i \right\rangle \\
\delta_1^{1+} &= -\frac{2}{3} \left[ \frac{\nu + \frac{\epsilon^2}{q}}{q} 2 \text{Re} \left\langle J_f \| \hat{C}_0^A \| J_i \right\rangle + 2 \sqrt{2} \frac{\nu - \frac{\epsilon^2}{q}}{q} 2 \text{Re} \left( \frac{C_V^* C_A + C_V^* C_A'}{\left| C_A^2 + |C_A'|^2 \right|} \left\langle J_f \| \hat{M}_1^V \| J_i \right\rangle \right) \right] \\
\delta_{\beta\nu}^{1+} &= 2 \left[ \frac{\epsilon + \nu}{q} 2 \text{Re} \left\langle J_f \| \hat{L}_1^A \| J_i \right\rangle + 2 \sqrt{2} \frac{\epsilon - \nu}{q} 2 \text{Re} \left( \frac{C_V^* C_A + C_V^* C_A'}{\left| C_A^2 + |C_A'|^2 \right|} \left\langle J_f \| \hat{M}_1^V \| J_i \right\rangle \right) \right] \\
\end{align*} \]
SHAPE CORRECTIONS

Unique first forbidden $\Delta J^{\pi} = 2^-$

\[
\frac{d^5 \omega_{\beta^+}}{d\Omega_k/4\pi d\Omega_\nu/4\pi d\epsilon} = \frac{2G^2}{\pi^2} \frac{1}{2J_1 + 1} (\epsilon_0 - \epsilon)^2 k\epsilon F^\pm(Z_f, \epsilon) \times \left\{ \frac{5}{2} \left[ 1 + \delta_1 - \frac{2}{5} (1 + \delta_0, \bar{\beta}) \nu \cdot \bar{\beta} \right] \frac{1}{5} (\nu \cdot \hat{a})(\bar{\beta} \cdot \hat{a}) \right\} \langle ||\hat{L}_2^A||^2 \rangle,
\]

with

\[
\delta_1 = \frac{4}{5} \left\{ \pm \sqrt{\frac{3}{2} \frac{\nu - k^2}{q} \text{Re} \langle ||\hat{M}_2^Y|| \rangle - \frac{\nu + k^2}{q} \text{Re} \langle ||\hat{L}_2^A|| \rangle} \right\},
\]

\[
\delta_{0, \bar{\beta}} = 2 \left\{ \pm \sqrt{\frac{3}{2} \frac{\epsilon - \nu}{q} \text{Re} \langle ||\hat{M}_2^Y|| \rangle - \frac{\nu + \epsilon}{q} \text{Re} \langle ||\hat{L}_2^A|| \rangle} \right\},
\]

Pre-conditions for a precision prediction:

Need to know ratios to 10%.
What about currents?
How to systematically predict and assess uncertainties in reaction rates, from high energy theory to QCD to nuclei?

How to predict the nuclear response to a probe governed by an unknown fundamental theory?
How to systematically predict and assess uncertainties in reaction rates, from high energy theory to QCD to nuclei?

Ultraviolet physics

unknown high energy physics – a calculation for each candidate high energy theory is tedious

probe–quark interaction

Unknown couplings, multiple possible channels.

Probe–nucleus interaction

Going from quark to nucleon demands solving QCD at low–energies.

Many body calculation of nuclear structure

LOW ENERGY REACTION OF A SPIN $\frac{1}{2}$ PARTICLE WITH A NUCLEUS

Effective Lagrangians

$$e.g., \, \frac{\mu}{2} \bar{\chi} \sigma_{\mu\nu} \chi F^{\mu\nu}$$

Couplings:

U(1): anapole, E/M dipole

Scalar, Pseudo-scalar

Vector, Axial-vector

Tensor, Pseudo-tensor

$$\bar{\chi} \chi \langle \Psi | \bar{q} q | \Psi \rangle$$

$$\bar{\chi} \gamma_5 \chi \langle \Psi | \bar{q} \gamma_5 q | \Psi \rangle$$

$$\bar{\chi} \gamma_{\mu} \chi \langle \Psi | \bar{q} \gamma^\mu q | \Psi \rangle$$

$$\bar{\chi} \gamma_{\mu} \gamma_5 \chi \langle \Psi | \bar{q} \gamma^\mu \gamma_5 q | \Psi \rangle$$

$$\bar{\chi} \sigma_{\mu\nu} \chi \langle \Psi | \bar{q} \sigma^{\mu\nu} q | \Psi \rangle$$

$$\bar{\chi} \sigma_{\mu\nu} \gamma_5 \chi \langle \Psi | \bar{q} \sigma^{\mu\nu} q | \Psi \rangle$$

$$\bar{\chi} F^{\mu\nu}$$

$$l$$

$$k^\mu_i$$

$$P^\nu_f = (E_f, P_f)$$

$$k^\mu_i$$

$$P^\nu_i = (E_i, P_i)$$
LOW ENERGY REACTION OF A Spin-1 PARTICLE WITH A NUCLEUS

Effective Lagrangians

\[ e.g., \frac{\mu}{2} \bar{\chi} \sigma_{\mu\nu} \chi F_{\mu\nu} \]

\[ \bar{\chi} \langle \Psi | \bar{q} q | \Psi \rangle \]

\[ \bar{\chi} \gamma_\mu \chi \langle \Psi | \bar{q} \gamma^\mu q | \Psi \rangle \]

\[ \bar{\chi} \gamma_\mu \gamma_5 \chi \langle \Psi | \bar{q} \gamma^\mu \gamma_5 q | \Psi \rangle \]

Couplings:

U(1): anapole, E/M dipole

Scalar, Pseudo-scalar

Vector, Axial-vector

Tensor, Pseudo-tensor

This is the Weak Interaction

\[ P_i = (E_i, P_i) \]

\[ l \]

\[ k_1^\mu \]

\[ k_2^\mu \]
SIZE OF “NEW PHYSICS” BEYOND STANDARD MODEL

\[ L_{ud}^{\text{eff}} = -\frac{G_F^0 V_{ud}}{\sqrt{2}} \left[ (1 + \epsilon_L) \bar{e}_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d + \bar{\epsilon}_L \bar{e}_\mu (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \\
+ \epsilon_R \bar{e}_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d + \bar{\epsilon}_R \bar{e}_\mu (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d \\
+ \epsilon_T \bar{e}_\sigma_{\mu \nu} (1 - \gamma_5) \nu_e \cdot \bar{u} \sigma^{\mu \nu} (1 - \gamma_5) d + \bar{\epsilon}_T \bar{e}_\sigma_{\mu \nu} (1 + \gamma_5) \nu_e \cdot \bar{u} \sigma^{\mu \nu} (1 + \gamma_5) d \\
+ \epsilon_S \bar{e}(1 - \gamma_5) \nu_e \cdot \bar{u} d + \bar{\epsilon}_S \bar{e}(1 + \gamma_5) \nu_e \cdot \bar{u} d \\
- \epsilon_P \bar{e}(1 - \gamma_5) \nu_e \cdot \bar{u} \gamma_5 d - \bar{\epsilon}_P \bar{e}(1 + \gamma_5) \nu_e \cdot \bar{u} \gamma_5 d + \ldots \right] + \text{h.c.}, \]
SIZE OF “NEW PHYSICS” BEYOND STANDARD MODEL

\[ \mathcal{L}_{\text{off}}^{\text{eff}} = -\frac{G_F^0 V_{ud}}{\sqrt{2}} \left[ (1 + \epsilon_L) e\gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u}\gamma^\mu (1 - \gamma_5) d + \bar{e}_L e\gamma_\mu (1 + \gamma_5) \nu_e \cdot \bar{u}\gamma^\mu (1 - \gamma_5) d \ight. \\
+ \epsilon_R \bar{e} e\gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u}\gamma^\mu (1 + \gamma_5) d + \bar{e}_R \bar{e} e\gamma_\mu (1 + \gamma_5) \nu_e \cdot \bar{u}\gamma^\mu (1 + \gamma_5) d \\
+ \epsilon_T e\sigma_{\mu\nu} (1 - \gamma_5) \nu_e \cdot \bar{u}\sigma^{\mu\nu} (1 - \gamma_5) d + \bar{e}_T \bar{e} e\sigma_{\mu\nu} (1 + \gamma_5) \nu_e \cdot \bar{u}\sigma^{\mu\nu} (1 + \gamma_5) d \\
+ \epsilon_S \bar{e} (1 - \gamma_5) \nu_e \cdot \bar{u}d + \bar{e}_S \bar{e} (1 + \gamma_5) \nu_e \cdot \bar{u}d \\
\left. - \epsilon_P \bar{e} (1 - \gamma_5) \nu_e \cdot \bar{u}\gamma_5 d - \bar{e}_P \bar{e} (1 + \gamma_5) \nu_e \cdot \bar{u}\gamma_5 d + \ldots \right] + \text{h.c.} \]

For the simplest BSM operator \( n=2 \), a 3 TeV scale means \( \epsilon_i, \bar{\epsilon}_i \approx 10^{-3} \)
FROM THE QUARK TO THE NUCLEON

\[ \mathcal{L}_{\text{ud} \nu}^{\text{eff}} = -\frac{G^0_F V_{ud}}{\sqrt{2}} \left[ (1 + \epsilon_L) \bar{e}_\gamma \mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d + \bar{e}_L \bar{e}_\gamma \mu (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d + \epsilon_R \bar{e}_\gamma \mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d + \bar{e}_R \bar{e}_\gamma \mu (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d + \epsilon_T \bar{e}_\sigma \mu \nu (1 - \gamma_5) \nu_e \cdot \bar{u} \sigma^\mu \nu (1 - \gamma_5) d + \bar{e}_T \bar{e}_\sigma \mu \nu (1 + \gamma_5) \nu_e \cdot \bar{u} \sigma^\mu \nu (1 + \gamma_5) d + \epsilon_S \bar{e}_S (1 - \gamma_5) \nu_e \cdot \bar{u} d + \bar{e}_S \bar{e}_S (1 + \gamma_5) \nu_e \cdot \bar{u} d - \epsilon_P \bar{e}_S (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma_5 d - \bar{e}_P \bar{e}_S (1 + \gamma_5) \nu_e \cdot \bar{u} \gamma_5 d + \ldots \right] + \text{h.c.} \]

Taking a matrix element between nucleonic states:

\[ -\mathcal{L}_{n \rightarrow p e^{-} \nu_e} = \bar{p} n \left( C_S \bar{e}_\nu e - C'_S \bar{e}_\gamma \gamma_5 e \right) + \bar{p} \gamma^\mu n \left( C_V \bar{e}_\gamma \mu \nu e - C'_V \bar{e}_\gamma \mu \gamma_5 \nu e \right) + \frac{1}{2} \bar{p} \sigma^\mu \nu n \left( C_T \bar{e}_\sigma \mu \nu \nu e - C'_T \bar{e}_\sigma \mu \nu \gamma_5 \nu e \right) - \bar{p} \gamma_5 \nu e \left( C_A \bar{e}_\gamma \mu \gamma_5 \nu e - C'_A \bar{e}_\gamma \mu \gamma_5 \nu e \right) + \bar{p} \gamma_5 n \left( C_P \bar{e}_\gamma \nu e - C'_P \bar{e}_\gamma \nu e \right) + \text{h.c.} \]

\[ \bar{C}_V + \bar{C}'_V = 2 g_V (1 + \epsilon_L + \epsilon_R) \]
\[ \bar{C}_A + \bar{C}'_A = -2 g_A (1 + \epsilon_L - \epsilon_R) \]
\[ \bar{C}_S + \bar{C}'_S = 2 g_S \epsilon_S \]
\[ \bar{C}_P + \bar{C}'_P = 2 g_P \epsilon_P \]
\[ \bar{C}_T + \bar{C}'_T = 8 g_T \epsilon_T \]
\[ \bar{C}_V - \bar{C}'_V = 2 g_V (\epsilon_L + \epsilon_R) \]
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\[ \bar{C}_P - \bar{C}'_P = -2 g_P \epsilon_P \]
\[ \bar{C}_T - \bar{C}'_T = 8 g_T \epsilon_T \]
FROM THE QUARK TO THE NUCLEON

\(-\mathcal{L}_{n\to pe^{-}\bar{\nu}_{e}} = \bar{p} \, n \ (C_S \bar{e}\nu_e - C'_S \bar{e}\gamma_5 \nu_e) + \bar{p}\gamma^\mu n \ (C_V \bar{e}\gamma_{\mu} \nu_e - C'_V \bar{e}\gamma_{\mu} \gamma_5 \nu_e) + \frac{1}{2} \bar{p}\sigma_{\mu\nu} n \ (C_T \bar{e}\sigma_{\mu\nu} \nu_e - C'_T \bar{e}\sigma_{\mu\nu} \gamma_5 \nu_e) - \bar{p}\gamma^5 \gamma^5 n \ (C_A \bar{e}\gamma_{\mu} \gamma_5 \nu_e - C'_A \bar{e}\gamma_{\mu} \nu_e) + h.c.\)

\[\mathcal{C}_V + \mathcal{C}'_V = 2 g_V (1 + \epsilon_L + \epsilon_R)\]
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\[\mathcal{C}_T - \mathcal{C}'_T = 8 g_T \bar{\epsilon}_T\]

Taking a matrix element between nucleonic states:

\[\langle p(p_p) | \bar{u} \gamma_{\mu} d | n(p_n) \rangle = \bar{u}_p(p_p) \left[ \frac{g_V(q^2)}{2M_N} \gamma_{\mu} + \frac{\tilde{g}_T(V)(q^2)}{2M_N} \sigma_{\mu\nu} q^\nu + \frac{\tilde{g}_S(q^2)}{2M_N} q_{\mu} \right] u_n(p_n),\]

\[\langle p(p_p) | \bar{u} \gamma_{\mu} \gamma_5 d | n(p_n) \rangle = \bar{u}_p(p_p) \left[ \frac{g_A(q^2)}{2M_N} \gamma_{\mu} + \frac{\tilde{g}_T(A)(q^2)}{2M_N} \sigma_{\mu\nu} q^\nu + \frac{\tilde{g}_P(q^2)}{2M_N} q_{\mu} \right] \gamma_5 u_n(p_n),\]

\[\approx \frac{g_S(0)}{2M_N} \bar{u}_p(p_p) u_n(p_n) + \mathcal{O}(q^2/M_N^2),\]

\[\approx \frac{g_P(0)}{2M_N} \bar{u}_p(p_p) \gamma_5 u_n(p_n) + \mathcal{O}(q^2/M_N^2),\]

\[\approx \frac{g_T(0)}{2M_N} \bar{u}_p(p_p) \sigma_{\mu\nu} u_n(p_n) + \mathcal{O}(q/M_N),\]
FROM THE QUARK TO THE NUCLEON

\[ -\mathcal{L}_{n \to p e^- \nu_e} = \bar{p}_n (C_S \bar{e} \nu_e - C'_S \bar{e} \gamma_5 \nu_e) + \bar{p} \gamma^\mu n (C_V \bar{e} \gamma_\mu \nu_e - C'_V \bar{e} \gamma_\mu \gamma_5 \nu_e) + \frac{1}{2} \bar{p} \sigma^{\mu \nu} n (C_T \bar{e} \sigma_{\mu \nu} \nu_e - C'_T \bar{e} \sigma_{\mu \nu} \gamma_5 \nu_e) - \bar{p} \gamma_5 \gamma_5 n (C_A \bar{e} \gamma_\mu \gamma_5 \nu_e - C'_A \bar{e} \gamma_\mu \nu_e) + \bar{p} \gamma_5 n (C_P \bar{e} \gamma_5 \nu_e - C'_P \bar{e} \nu_e) + \text{h.c.} \]

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Taking a matrix element between nucleonic states:

\[ \langle p(p_p) | \bar{u} \gamma_\mu d | n(p_n) \rangle = \bar{u}_{p}(p_p) \left[ g_V(q^2) \frac{\gamma_\mu}{2M_N} \sigma_{\mu \nu} q^\nu + g_S(q^2) \frac{1}{2M_N} q_\mu \right] u_n(p_n) , \]
\[ \langle p(p_p) | \bar{u} \gamma_\mu \gamma_5 d | n(p_n) \rangle = \bar{u}_{p}(p_p) \left[ g_A(q^2) \frac{\gamma_\mu}{2M_N} \sigma_{\mu \nu} q^\nu + g_T(q^2) \frac{1}{2M_N} q_\mu \right] \gamma_5 u_n(p_n) , \]
\[ \langle p(p_p) | \bar{u} d | n(p_n) \rangle \approx g_S(0) \bar{u}_p(p_p) u_n(p_n) + \mathcal{O}(q^2/M_N^2) , \]
\[ \langle p(p_p) | \bar{u} \gamma_5 d | n(p_n) \rangle \approx g_P(0) \bar{u}_p(p_p) \gamma_5 u_n(p_n) + \mathcal{O}(q^2/M_N^2) , \]
\[ \langle p(p_p) | \bar{u} \sigma_{\mu \nu} d | n(p_n) \rangle \approx g_T(0) \bar{u}_p(p_p) \sigma_{\mu \nu} u_n(p_n) + \mathcal{O}(q/M_N) , \]
The $\epsilon'$s are small, not the nuclear charges!

\[ g_P = g_A(M_n + M_p)/(m_d + m_u) = 349(9) \]
\[ g_S = g_V \frac{(M_n - M_p)_{QCD}}{m_d - m_u} \approx 0.8 - 1.2 \]
How to systematically predict and assess uncertainties in reaction rates, from high energy theory to QCD to nuclei?

Symmetries are dictated by fundamental QCD-probe interactions.

Physics of the nucleus dictates structure of the operators.

Fundamental physics dictates size of coupling constants.

Probe-nucleus interaction

Going from quark to nucleon demands solving QCD at low-energies.

Many body calculation of nuclear structure

**Effective Lagrangians**

\[ e.g., \frac{\mu}{2} \bar{\chi} \sigma_{\mu\nu} \chi F^{\mu\nu} \]

\[ \bar{x}\chi \langle \Psi | \bar{q} q | \Psi \rangle \]

\[ \bar{x} \gamma_\mu \chi \langle \Psi | \bar{q} \gamma^\mu q | \Psi \rangle \]

\[ \bar{x} \gamma_\mu \gamma_5 \chi \langle \Psi | \bar{q} \gamma^\mu \gamma_5 q | \Psi \rangle \]

**Couplings:**

- **U(1): anapole, E/M dipole**
- **Scalar, Pseudo-scalar**
- **Vector, Axial-vector**
- **Tensor, Pseudo-tensor**

**Probe “current” of known Lorentz symmetry**

**Nuclear “current” of the same symmetry**

*Decoupled from probe physics!*

**This is the Weak Interaction**

\[ P_i^* = (E_i, P_i) \]

\[ k^\mu_1 \]

\[ k^\mu_2 \]

\[ l \]
EFFECTIVE FIELD THEORIES OF QCD AT LOW ENERGIES

QCD scales

Probe momentum

$4\pi f_\pi$

$M_N$

$m_\rho$

$\Lambda_{\text{br}}$

$m_\pi$

Chiral EFT: pions and nuclens
**Effective Field Theories of QCD at Low Energies**

**QCD scales**

- $4\pi f_\pi$
- $M_N$
- $m_\rho$
- $\Lambda_{brk}$
- $m_\pi$

**Probe momentum**

- Characteristic momentum $Q$
- Momentum scale in the nucleus
- Momentum scale of the probe

**EFT procedure for a specific phenomenon**

- Identify viable d.o.f.
- Write most general Lagrangian consistent with fund. symmetries.

**Power counting:** Find a systematic way to organize diagrams according to their contribution to the observable.

*Weinberg’s Power Counting:* Each Feynman diagram can be characterized by $\left(\frac{Q}{\Lambda}\right)^\nu$

**QCD is strongly interacting** — things are not that simple.

Error assessment: order by order OR cutoff variation.
Low energy QCD has (accidental) scale separation

Low energy EFT — Cutoff $\Lambda_{\text{IR}} \gg Q$ dictates viable deg. of freedom

EFT Lagrangian

Nuclear potential

Nöther current

Wave functions

Nuclear current

Theoretical uncertainty quantification:
Power Counting: systematic expansion
RG invariance: cutoff variation

Nuclear Matrix Element of characteristic momentum $Q$
NUCLEAR CURRENTS FROM CHIRAL EFT

**Couplings:**

- U(1): anapole, E/M dipole
- Scalar, Pseudo-scalar
- Vector, Axial-vector
- Tensor, Pseudo-tensor

**Nuclear currents**

- $J^E_M$
- $\pi N \sigma$ terms
- The weak gauge!
- lattice
How to systematically predict and assess uncertainties in reaction rates, from high energy theory to QCD to nuclei?

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Coarse graining the probe–quark interaction down to probe nucleon and probe–nucleus interaction is accomplished via $\chi^{EFT}$

Many body calculation of nuclear structure

Progress in ab initio calculations of nuclei
dramatic progress in last 5 years to access nuclei up to $A \sim 50$

Progress in ab initio calculations of nuclei
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Ab-initio calculations of $^{100}\text{Sn}$ with $N = Z = 50$ predict it to be doubly magic.
Frontier: Chiral EFT for electroweak currents
consistent electroweak one- and two-body (meson-exchange) currents

magnetic moments in light nuclei
Pastore et al. (2012-)

Gamow-Teller beta decay of $^{100}$Sn
Gysbers, Hagen et al.

two-body currents are key for quenching puzzle of beta decays
In order to probe the weak structure of the nucleon, one has to keep the nuclear effects under control.
RESULTS

\[
\Gamma = \left\{ \frac{2G^2|V_{ud}|^2E_v^2}{2J_{3He}^3} + 1 \right\} \left( 1 - \frac{E_v}{M_{3H}^3} \right) |\psi_{1s}^{av}|^2 \Gamma_N \right\}(1 + RC)
\]

\[
\Gamma = 1499(2)_{\Lambda(3)}^{(3)}_{NM} (5)_{t(6)}^{(6)}_{RC} = 1499 \pm 16 \text{ Hz}
\]

\[
\Gamma_{EXP} = 1496 \pm 4 \text{ Hz}
\]

INDUCED TENSOR:

- From QCD sum rules: \( \frac{g_t}{g_A} = -0.0152(53) \)
  \[ \left| \frac{g_t}{g_A} \right| < 0.36 \text{ at } 90\% \]

- This work:
  \( \frac{g_t}{g_A} = -0.1(0.68) \)

\[ \delta J^{\mu A} = \frac{ig_t}{2M_N} \sigma^{\mu\nu} \gamma_5 q_v \]
**INDUCED SCALAR (LIMITS CVC):**

- Experimentally [Severijns et. al., RMP 78, 991 (2006)]:
  \[ g_s = 0.01 \pm 0.27 \]

- This work: \[ g_s = -0.005 \pm 0.04 \]

\[ \delta J_{\mu V} = \frac{g_s}{m_\mu} q^{\mu} \]
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Many body methods can reach 2% absolute accuracy for light nuclei, 10% accuracy for heavy nuclei ratios are known much better because of the small expansion parameter.
The Soreq Applied Research Accelerator Facility (SARAF): Overview, research programs and future plans

**ON-GOING EXPERIMENTS IN SARAF**

- **${^6}\text{He}:** Production Trap in EIBT and measure kinematics.
- **${^{23}}\text{Ne}:** Production Branching-Ratio Trap in MOT and measure kinematics.
1. Different $\beta-\nu$ correlation properties for GT and unique 1$^{\text{st}}$ forbidden – \textit{BSM test}

2. Unique 1$^{\text{st}}$ forbidden spectrum – \textit{BSM test}
NEON ISOTOPES

$^{23}$Ne Decay to $^{23}$Na

DAMA, DM-ice, ANAIS experiments

$^{19}$Ne Decay to $^{19}$F

PICASSO, SIMPLE, COUPP experiments
Nuclear beta decays are an important front for “new physics” discoveries.

New experiments will have 0.01-0.1% level precision.

Important shape (and radiative) corrections that should be calculated, these are challenging calculations, but seem feasible:

- Worse case: we have great tests for the nuclear interactions.
- Best case: experimentalists are satisfied with theory