Double Beta Decay: Status and connections to lattice QCD

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Weak interactions and nuclear physics:

- introduction to double beta decay
- single nucleon g_A and form factor
- two nucleons: neutrino scattering from deuteron
- light $(A \leq 10)$ and heavy nucleon beta decay
- light nuclei and heavy nuclei: neutrino scattering
- double beta decay

Intersections between lattice QCD and many-body Summary and outlook

\mathbb{C} signal that either the neutrino hierarchy is not the neutrino history is or are Dirac particles. And in the event of th

Francisco de Program diagram diagram for 01º Reports on Progress in Physics 2017 **From Engel and Menendez ated by the three light Majorana neutri-in** majorana neutri-in-

of nonperturbative methods to eciently solve the nu-

of the two emitted electrons, *Eⁱ* and *E^f* are the energies

Nucleon Level Muclear Level (neutrinoless) implying the region of an integration of a particles (not the absence of absence of absence of absence of absence of a 0 Signal that is not the neutrino history in the neutrino history is not the new signal to his normal the new s $n_{\rm local}$ ρ , experimental two electrons ρ

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to take place in the next decade have a good chance to take place to the next decade have a good chance to take see the decay, provided the decay, provided the \mathbf{P}_{max}

p

term with */q* vanishes because the two currents are left $\Gamma(T^{0\nu})^{-1} = \sum \int_{\Gamma} \frac{1}{Z_{\delta}(F_{\gamma}+F_{\gamma}+F_{\gamma}+F_{\gamma}-F_{\gamma})} \frac{d^{3}p_{1}}{p_{1}} \frac{d^{3}p_{2}}{p_{2}}$ $\frac{1}{2}$ $\frac{1}{2}$ portional to $m_{\beta\beta}\equiv$ $\begin{array}{c} \begin{array}{c} \begin{array}{c} \end{array} \\ \begin{array}{c} \end{array} \end{array} \end{array}$ $\sum m_k U_{ek}^2$ $\begin{array}{c} \begin{array}{c} \begin{array}{c} \end{array} \\ \begin{array}{c} \end{array} \end{array} \end{array}$ (5) $[T_{1/2}^{0\nu}]^{-1} = \sum_i \int |Z_{0\nu}|^2 \delta(E_{e1}+E_{e2}+E_f-E_i) \frac{d^2 \mathbf{p}_1}{2\pi^3} \frac{d^2 \mathbf{p}_2}{2\pi^3}$, rate the amplitude, the momentum transfer must be on the spins Z $|Z_{0\nu}|^2 \delta(E_{e1}+E_{e2}+E_f-E_i)\frac{d^3p_1}{2\pi^3}$ $2\pi^3$ $d^3{\bm p}_2$ $\frac{1}{2\pi^3}$, of the two emitted electrons, *Eⁱ* and *E^f* are the energies $m_{\beta\beta} \equiv \left| \sum m_k U_{ek}^2 \right|$ (5) where *q* is the 4-momentum of the virtual neutrino. The term with */q* vanishes because the two currents are left rate

$$
= |m_1|U_{e1}|^2 + m_2|U_{e2}|^2e^{i(\alpha_2 - \alpha_1)} + m_3|U_{e3}|^2e^{i(-\alpha_1 - 2\delta)}|.
$$

neutrino mass

 $\qquad \qquad \text{(5)}$ about 100 mass neutrino mass glection the interestation of $\frac{1}{2}$ $\$ \mathbf{i} \overline{D} ma neutrino mass

 $\sum_{i=1}^{\lceil (f \mid I^{\mu}(a)|_p) / p \mid I^{\nu}(-a)|_q}$ (fi $I^{\nu}(a)|_p / p \mid I^{\mu}(-a)|_q$) $\sum_{\vert a\vert (E_{+}+|a|+|E_{+}|-E_{+})} \frac{\vert b\vert^{2}E_{+}(1)\vert^{2}\vert^{2}+E_{+}(1)\vert^{2}\vert^{2}}{\vert a\vert (E_{+}+|a|+|E_{+}|-E_{+})}$ $\begin{array}{ccc} n & L & | \mathbf{1} | \mathbf{1} | & | \mathbf{2} | & | \mathbf{2} | & | \mathbf{2} | \end{array}$ $\times 2\pi \delta (E_f + E_{e1} + E_{e2} - E_i),$ (7) $\overline{}$ $\left[\frac{\langle f|J_L^{\mu}(\boldsymbol{q})|n\rangle\langle n|J_L^{\nu}(-\boldsymbol{q})|i\rangle}{|\boldsymbol{q}|(E_n+|\boldsymbol{q}|+E_{e2}-E_i)} + \frac{\langle f|J_L^{\nu}(\boldsymbol{q})|n\rangle\langle n|J_L^{\mu}(-\boldsymbol{q})|i\rangle}{|\boldsymbol{q}|(E_n+|\boldsymbol{q}|+E_{e1}-E_i)} \right.$ $|q|(E_n + |q| + E_{e1} - E_i)$ $\mathcal{L}\left[\langle f|J_f^{\mu}(\boldsymbol{q})|n\rangle\langle n|J_f^{\nu}(-\boldsymbol{q})|i\rangle\right]\qquad\langle f|J_f^{\nu}(\boldsymbol{q})|n\rangle\langle n|J_f^{\mu}(-\boldsymbol{q})|i\rangle\right]$ $\sum_{n} \left[\overline{|q|}(E_n + |q| + E_{e2} - E_i) + \overline{|q|}(E_n + |q| + E_{e1} - E_i) \right]$ interaction Lagrangian, it contains a lepton part that de-

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(7). This approximation avoids the explicit calculation of excited states of the internet states of the internet states of the internet states of the internet states o to high energies, a nuclear structure calculation that is computationally much more involved than obtaining the Here is the so-called Dirac phase, and ↵1*,* ↵² are Majonuclear matrix h element

n

νM

Nuclear Matrix Element

from Engel and Menendez Reports on Progress in Physics 2017

 $\boldsymbol{\Sigma}$ \bullet ν

Theory Methods:

QRPA Radial Excitations Radial Excitations Shell Model many-body excitations (low hbar omega) Everything seems to matter: deformation, n-p pairing, … Combining methods should be very valuable

Why is this difficult?

• momentum dependence (light neutrino): Fermi matrix element: $(\tau_i^+ \tau_j^+ / r_{ij})$ Gamow-Teller: $(\sigma_i \cdot \sigma_j \tau_i^+ \tau_j^+ / r_{ij})$

short-range (high-energy) correlations, which are not in-energy) correlations, which are not in-energy are not
In-energy

- low-energy transition to/from explicit states with moderate momentum transfer Though are Thomehorican matrix elements p is that about two thirds of the spin-isos
	- low-energy modes (deformation, etc.) important $\mathcal{O}(\mathcal{O})$ $\frac{1}{2}$ ently, such a superior that because \mathcal{L}
	- very small fraction (<< 1%) of the relevant sum rules Ref. [217] (shell model) and Ref. [218] (QRPA). $\frac{1}{2}$ a use $\frac{1}{2}$ and $\frac{1}{2}$ f suit funcs

First look at a single weak vertex:

- neutrino-nucleon scattering
- nuclear beta decay
- muon capture
- low-energy neutrino scattering
- quasi-elastic neutrino scattering

Not a lot of data on weak interactions at moderate q

- LSND (stopped pions) on Carbon
- muon capture
- more data would be very valuable

Scattering from a single nucleon

Gonzalex-Jiminez, Caballero, Donnelly, Phys. Reports 2013

Axial Form Factor: Deuterium analysis

Nucleon axial form factor in lattice QCD same as in Fig. 8. Same as in Fig.
The same as in Fig. 8. Same as in

FIG. 9. The 8-point fit using Eq. (23) without the finite volume correction (*c*⁴ = 0) to the data for the axial radius h*rA*i. The

phenomenological estimates of the axial mass, *M^A* = 1*.*026 GeV and with our best estimate *M^A* = 1*.*39 GeV corresponding

A/g

Nuclear Beta Decay Calculations vs. Experiment

 m ehing optome on $4th$ pouvoir RR doesn't \sum free-nucleons as the power in pp accay. up to a factor of $(1/1.27)^4 \sim 0.38$ Quenching enters as 4th power in $\beta\beta$ decay:

Moments

EM **Transitions**

Nuclear Beta Decay: Light Nuclei VMC Calculations Nuclei GFMC calculations

from S. Pastore's talk at this program

- moderate quenching in light nuclei: 10-25%
	- significant reduction from correlations
- modest enhancement from 2N currents much smaller effects than magnetic moments, transitions
	- •good reproduction of experimental results

Nuclear Beta Decay: Heavy Nuclei

G. Hagen (talk at this program)

- •significant quenching from 2N currents (different resolution in calculation)
- normal-ordering approximation (effective 1-body operator)
- •need a consistent picture across momentum, A

Higher momentum transfer: neutrino scattering Quasielastic Scattering: Sum Rules Constructive Interference between 1- and 2-body

Large enhancement from combination of initial state

 $\propto \sigma_i \cdot \mathbf{k} \sigma_i \cdot \mathbf{q} (\sigma_j \cdot \mathbf{k})^2 (\tau_i \cdot \tau_j)^2 v_\pi^2(k)$

Transverse response

the quenching noted in (ii) in the quasi-elastic peak.

² e(*E^f E*0)*/*⌧

,

Quasi-elastic electron scattering: 12C

Lovato, et al, PRL 2016

Neutral current: sum rules in ¹²C

Single Nuclean currents (anon Single Nucleon currents (open symbols) versus Full currents (filled symbols)

0.002

0.04

Double Beta-Decay: test cases in light nuclei

• Standard light neutrino plus other possible mechanisms Emanuele Mereghetti & Dekens & Cirigliano & Graesser & Wiringa *et al.* •note large cancellations in standard axial matrix element

Double Beta Decay: Heavy Nuclei

- •compute effective operators in restricted spaces
- •extending shell model spaces
- add correlations to DFT and QRPA approaches
- •compare to calculations in light nuclei

Improved inputs at higher scale from lattice QCD

- many things can be-compared/contrasted
- strong interactions w/ 2- and 3-nucleons
- electroweak form factors of the nucleon
- inelastic scattering $(\pi$ production, ...)

PERIODIC BOUNDARY CONDITIONS

Two Nucleons: beta decay

pion mass dependence may be important:

- •binding (momentum) of the system
- •D-state in the deuteron (analogous to tritium beta decay)

Two Nucleons: double beta decay (2-neutrino)

pion mass dependence nuclear interaction less important •binding (momentum) of the system •nn & pp states essentially s-wave

Inject momentum (neutrino scattering)

- •charge and neutral current processes
- moderate momentum transfers (1 to 2 lattice units)
- •exclusive final states (?)
- •inclusive final states (?)

LQCD analogue of Euclidean response ? $\tilde{R}(q,\tau) = \langle 0 | \mathbf{j}^{\dagger} \exp[-(\mathbf{H} - \mathbf{E_0} - \mathbf{q^2}/(2\mathbf{m}))\tau] \mathbf{j} |0\rangle >$

Double beta decay

- nn to pp different than for real case
- useful to have the matrix element for different q
- want to understand pion light neutrino matrix elements $A=6$

Summary and Outlook

- gA quenching should be quantitatively understood
- g_A enhancement (quasi-elastic) is solvable
- requires consistent treatment of interactions & currents and reliable matching to experiment and LQCD

- neutrinoless double beta decay more difficult
- involves multiple length scales that interfere
- quenching likely different in 0 and 2 neutrino cases
- more information needed from theory/lattice (2 weak vertices at NN level)
- more information at different q required
- significant progress by refining and combining methods