Measurement of the half-life of the $T = \frac{1}{2}$ mirror decay of ^{19}Ne and its implication on physics beyond the standard model

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Reference: L.J.Broussard, et,al. , PRL112 , 212301 (2014)

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Main content

Abstract

Key Findings

The $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ superallowed mixed mirror decay of ^{19}Ne to ^{19}F is suited for high precision studies of the weak interaction:

- New half-life measurement: $T_{1/2} = 17.2832 \pm 0.0051_{\text{(stat)}} \pm 0.0066_{\text{(sys)}}$ s
- Differs from previous world average by 3σ

Physics Implications

- Provides stringent constraints on physics Beyond the Standard Model (BSM)
- Enables precise determination of V_{ud} from mirror decays

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Weak Interaction Tests via β-Decay

Standard Model

- Weak interaction has $V - A$ (Vector minus Axial-vector) structure
- Maximal parity violation

All weak processes are described by a **current-current interaction** with:

- Universal coupling constant G_F (Fermi constant)
- Pure $V - A$ structure: $\gamma^{\mu}(1 - \gamma_5)$

It is natural to hope that all weak interaction phenomena are described by a V–A current–current interaction with a universal coupling G. For example, β-decay of Fig. 12.2 and μ-decay of Fig. 12.4 can be described by the amplitudes

$$\mathfrak{M}(\mathrm{p} \to \mathrm{n e}^+ \nu_e) = \frac{G}{\sqrt{2}}\left[\bar{u}_n \gamma^{\mu}(1 - \gamma^5) u_p\right]\left[\bar{u}_{\nu_e} \gamma_{\mu}(1 - \gamma^5) u_e\right] \quad (12.10)$$

and

$$\mathfrak{M}(\mu^- \to \mathrm{e}^- \bar{\nu}_e \nu_{\mu}) = \frac{G}{\sqrt{2}}\left[\bar{u}_{\nu_{\mu}} \gamma^{\alpha}(1 - \gamma^5) u_{\mu}\right]\left[\bar{u}_e \gamma_{\alpha}(1 - \gamma^5) u_{\nu_e}\right], \quad (12.11)$$

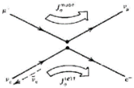

Fig. 12.4 The diagram for μ^- decay: $\mu^- \to \mathrm{e}^- \bar{\nu}_e \nu_{\mu}$.

Figure 1: Weak Interactions: Universal $V - A$ Current-Current Theory

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The transition amplitude for β Decay

amplitudes

The transition amplitude for β+ decay is given by:

$$\mathcal{M} = \frac{G}{\sqrt{2}} \left[\bar{u}_n \gamma^\mu (1-\gamma_5) u_p\right] \left[\bar{u}_e \gamma_\mu (1-\gamma_5) u_{\nu_e}\right]$$

Hadronic Current:

$$J^\mu_{had} = \bar{u}_n \gamma^\mu (1-\gamma_5) u_p$$

- Describes $p \to n$ transition

Leptonic Current:

$$J^\mu_{lep} = \bar{u}_e \gamma_\mu (1-\gamma_5) u_{\nu_e}$$

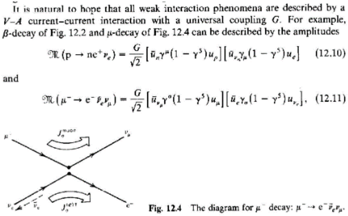
- Creates $e^+ \nu_e$ pair

Feynman Diagram

Standard Model

- $u \to d + W^+$ transition
- $W^+ \to e^+ + \nu_e$ decay

- The process involves the exchange of a virtual W boson, where a u quark inside the proton transforms into a d quark , while emitting $e^+\nu_e$.



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$$\mathcal{M}(p \to n e^+ \nu_e) = \frac{G}{\sqrt{2}}\left[\bar{u}_n \gamma^\mu (1-\gamma^5) u_p\right]\left[\bar{u}_{\nu_e} \gamma_\mu (1-\gamma^5) u_e\right] \quad (12.10)$$

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Fig. 12.4 The diagram for μ^- decay: $\mu^- \to e^- \bar{\nu}_e \nu_\mu$.

Figure 2: Weak Interactions: Universal $V - A$ Current-Current Theory

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Beyond Standard Model

Beyond Standard Model Possibilities

BSM may introduce other forms of coupling, such as scalars or tensor, the contribution of these couplings can be probed by experimentally observing the new physics.

- Exotic couplings: Scalar (S) and Tensor (T)

Sensitive Observables

- Fierz term b: Scalar/tensor interference
- β-asymmetry (A): Tensor/axial-vector mixing
- β-ν correlation (a): All couplings

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Polarized ^{19}Ne Decay Kinematics

Angular Distribution Formula

$$\Gamma = 1 + \underbrace{\beta}_{v/c} \underbrace{\langle P \rangle}_{\text{Polarization}} \underbrace{A(W)}_{\text{Asymmetry}} \cos\theta$$

- θ: Angle between nuclear spin $\vec{J}$ and positron momentum $\vec{p}_e$
- Leading-order asymmetry for ^{19}Ne:

$$\bar{A} \approx 0.67 \frac{\rho^2 - 1.73\rho}{1 + \rho^2} \approx -0.039$$

$\bar{A}$ depends on positron energy W

Beyond Standard Model

Gamow-Teller to Fermi mixing ratio:

$$\rho \equiv \frac{g_A M_{GT}}{g_V M_F}$$

Deviations from SM prediction for $A(W)$ may reveal:

$$\rho \to \rho \left(1 + \epsilon_T \frac{g_T}{g_A}\right)$$

where ϵ_T quantifies tensor couplings.

β-Decay as a Precision Lab

- Angular correlations (e.g., β-asymmetry) are sensitive probes
- Nuclear mirrors like ^{19}Ne provide:
  - $T = 1/2$ systems
  - Complementary to neutron decay

Mirror Decay

- Mirror nuclei are a pair of isobars of two different elements where Z1 = N2 and Z2 = N1.
- The $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$ superallowed mixed mirror decay of ^{19}Ne to ^{19}F is excellently suited for high precision studies of the weak interaction

Physical characteristics

- Mixed **Fermi + Gamow-Teller** transitions
- Sensitive to both **vector + axial-vector** currents

Research implications

- Test **CKM unitarity** via V_{ud}
- Probe for **tensor currents** (BSM physics)
- Cross-check superallowed $0^+ \rightarrow 0^+$ results

CKM Matrix

Definition

Links quark mass & weak eigenstates:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Standard Parameterization:

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ \cdots & \cdots & s_{23}c_{13} \\ \cdots & \cdots & c_{23}c_{13} \end{pmatrix}$$

Unitarity Test (1st Row)

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

- Current status: $\Delta = 0.0011(6)$ (1.8σ deviation)
- Most precise input: $|V_{ud}| = 0.97373(31)$ (superallowed β decays)

β-Decay for Measuring $|V_{ud}|$

We can now use this result for $\overline{\mathcal{F}t}$ to determine the vector coupling constant, G_{V}, from Eq. (1). The value of G_{V} itself is of little interest but, together with the weak interaction constant for the purely leptonic muon decay, G_{F}, it yields the much more interesting up-down element of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. The basic relationship is $V_{ud} = G_{\mathrm{V}}/G_{\mathrm{F}}$, which in terms of $\overline{\mathcal{F}t}$ becomes

$$|V_{ud}|^2 = \frac{K}{2G_{\mathrm{F}}^2(1+\Delta_{\mathrm{R}}^{\mathrm{V}})\overline{\mathcal{F}t}} = \frac{2915.64 \pm 1.08}{\overline{\mathcal{F}t}}, \quad (8)$$

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Motivation

Precision Tests of Weak Interaction

- Current best V_{ud} from superallowed $0^+ \to 0^+$ Fermi decays:

$$|V_{ud}| = 0.97425(22)$$

- Mirror decays ($T = \frac{1}{2}$) provide crucial cross-check:

$$|V_{ud}| = 0.9719(17)$$

The ^{19}Ne Advantage

- Small β asymmetry $\Rightarrow$ sensitive to right-handed currents
- Obtaining complementary limits on tensor couplings

Key Challenges in ^{19}Ne Mixed Decay Studies

Essential Measurements for SM Tests

- **Half-life** ($T_{1/2}$)
- **Angular correlation** (to extract ρ = Fermi/Gamow-Teller mixing ratio)

Discrepancies

- Given the log ft value, the half-life is:

$$t_{1/2} = 10^{\log ft - \log f_0}\ \text{s}. \tag{1}$$

- Large uncertainty in ^{19}Ne half-life dominated the uncertainty in Ft
- It is on par with the contribution of the beta asymmetry parameter to the uncertainty of V_{ud}

This discrepancy has been addressed in the experiment through a novel approach

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Experimental Setup

- Performed at TRIμP facility at KVI
- ^{19}Ne production:
  - ^{19}F(p,n)^{19}Ne reaction
  - 10.5 MeV/A beam energy
- Detection system:
  - Two HPGe clover detectors
  - Coincidence measurement of 511 keV γ rays
  - Low background ($\sim$0.2 s^{-1})

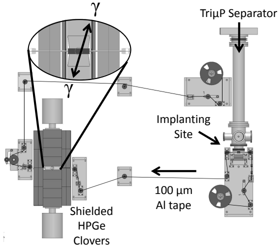

Figure 3: Tape drive system for transporting ^{19}Ne samples

Systematic Effects

Table 1: Main systematic uncertainties

Effect	Uncertainty (%)
Deadtime	0.02
Accidental coincidences	0.002
Energy determination	0.01
Diffusion	8×10^{-5}
Contamination	0.03
Total systematic	0.038

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Results of ^{19}Ne half-life measurements

Key Measurements

- 8 historical experiments(1957–2013)
- New weighted average:

$$\boxed{T_{1/2} = 17.2604 \pm 0.0034\,\text{s}}$$

- χ^2/NDF = 50.3/8 (indicates unresolved systematics)

- Extracted $\mathcal{F}t = 1719.8(13)$ s $\Rightarrow V_{ud} = 0.9712(22)$
- Competitive with neutron decay ($V_{ud} = 0.9774(17)$)
- Tensor coupling limits: $-0.006 < C_T/C_A < 0.034$

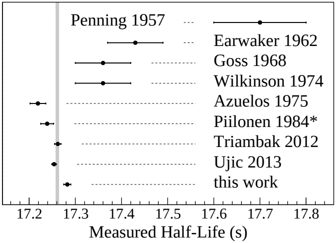

Figure 4: Discrepancy in previous ^{19}Ne half-life measurements

Half-life Results

- Blinded analysis result:
  - $T_{1/2} = 17.2832 \pm 0.0051_{\text{stat}} \pm 0.0058_{\text{sys}}$ s
- Post-blind analysis:
  - $T_{1/2} = 17.2826 \pm 0.0044_{\text{stat}} \pm 0.0064_{\text{sys}}$ s
- Final adopted value:
  - $T_{1/2} = 17.2832 \pm 0.0051_{\text{stat}} \pm 0.0066_{\text{sys}}$ s
- Differs from previous world average by 3σ:
  - New world average: 17.2604 ± 0.0034 s

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Summary

- New precise measurement of ^{19}Ne half-life:
  - $T_{1/2} = 17.2832 \pm 0.0083$ s
  - Differs from previous average by 3σ
- Improved understanding of systematics:
  - Diffusion effects characterized
  - Contamination limits established
  - Rate-dependent effects studied
- Physics results:
  - Precise V_{ud} determination
  - Competitive limits on tensor currents

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Thank you!