Neutron decay, muon capture, and g_A

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Outline

Muon capture: brief overview

- theoretical prediction needs the axial-vector coupling g_A

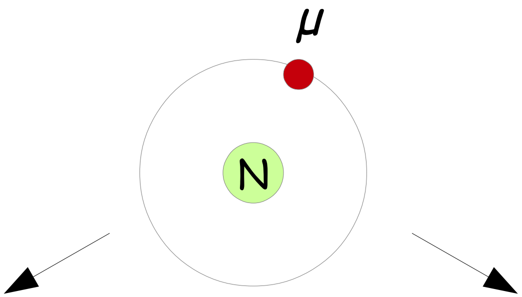
Neutron decay puzzles: lifetime and g_A

Standard Model prediction:

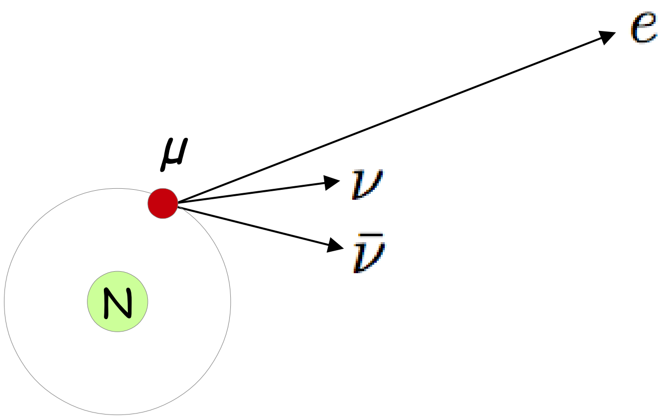
connection between the lifetime and the g_A

Muon capture

Fate of a muon bound in an atom:



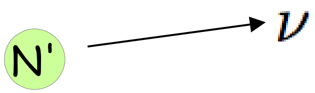
Decay in orbit (DIO)



Rate very close to the free-muon decay,
τ_μ = 2 196 980.3(2.2) ps (1.0 ppm) MuLan
PRL 106, 041803 (2011)

rate ~ $5 \cdot 10^5$ / s

Nuclear capture



Capture rate ~ Z^4

$\Lambda_S(H)$ = 714.9(7.4) / s MuCap
PRL 110, 012504 (2013)

about 1 per mille.

Measurement of the muon capture: MuCap

MuCap led by Peter Kammel (talk next week).
World-record measurement of the capture rate in hydrogen.

$$\Gamma(\mu^- N \to \nu_\mu N') = \frac{1}{\tau_\mu^{\text{bound}}} - \frac{1}{\tau_\mu^{\text{free}}}$$

MuCap

UNIVERSITY *of* WASHINGTON

MuLan

$$\begin{aligned}\Gamma(\mu^- p \to \nu_\mu n)\big|_{\text{singlet}} \;=\; & |\psi(0)|^2 \frac{G_\mu^2 |V_{\text{ud}}|^2}{2\pi} \frac{E_\nu^2}{M^2} (M - m_n)^2 \\ & \cdot \left\{ \frac{2M - m_n}{M - m_n} F_1 + \frac{2M + m_n}{M - m_n} g_A - \frac{g_P}{2} + (2M + 2m_n - 3m_\mu) \frac{F_M}{4m_N} \right\}^2\end{aligned}$$

least well-known form factor;
best determined by MuCap

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MuCap

MuLan

$$\Gamma(\mu^- p \to \nu_\mu n)\big|_{\text{singlet}} = |\psi(0)|^2 \frac{G_\mu^2 |V_{\text{ud}}|^2}{2\pi} \frac{E_\nu^2}{M^2}(M - m_n)^2 \cdot \left\{ \frac{2M - m_n}{M - m_n} F_1 + \frac{2M + m_n}{M - m_n} g_A - \frac{g_P}{2} + (2M + 2m_n - 3m_\mu) \frac{F_M}{4m_N} \right\}^2$$

Form factors are needed at
a significant momentum transfer:

IOP Publishing — Reports on Progress in Physics

Rep. Prog. Phys. 00 (2018) 000000 (22pp) — UNCORRECTED PROOF

Review

Nucleon axial radius and muonic hydrogen—a new analysis and review

Richard J Hill[1,2,3], Peter Kammel[4], William J Marciano[5] and Alberto Sirlin[6]

Input into the capture prediction: g_A

Connection with the neutron lifetime,

$$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{\rm ud}|^2}{2\pi^3} m_e^5 (1 + 3g_A^2)(1 + \mathrm{RC}) f$$

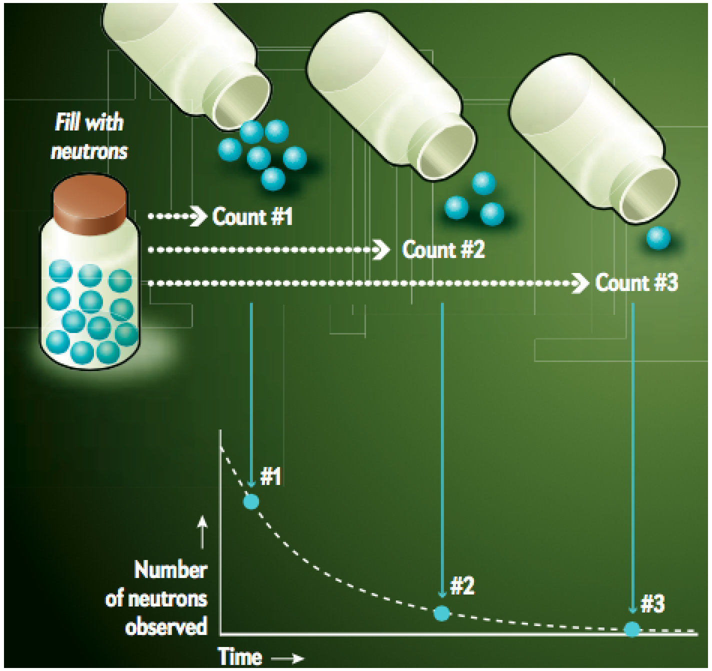
and the electron's correlation with the neutron's spin,

$$A_0 = \frac{2g_A(1 - g_A)}{1 + 3g_A^2}$$

Neutron lifetime measurement: two approaches

Trap:
- count surviving neutrons
- challenge: leaks;
- UCN, varying size and energy
- traditional: material traps
- recently also magnetic traps

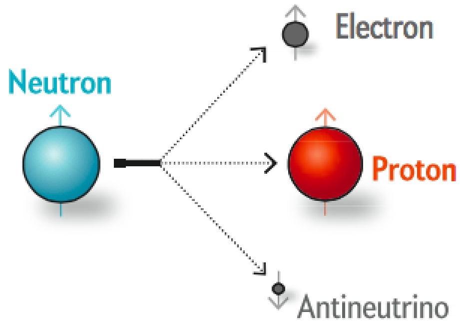
- inclusive: sensitive to all n decays!

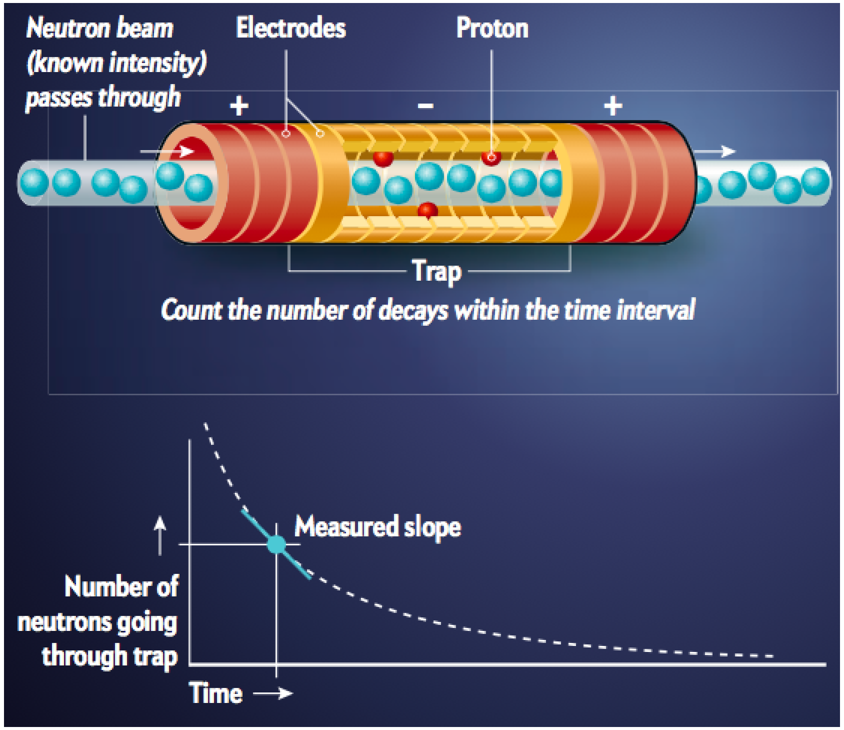


Greene and Geltenbort 2016

Neutron lifetime: the beam approach

Beam:
- daughter protons collected
- and nearly-perfectly counted
- exclusive: sensitive only to n -> p decays
- future: all n -> electron decays

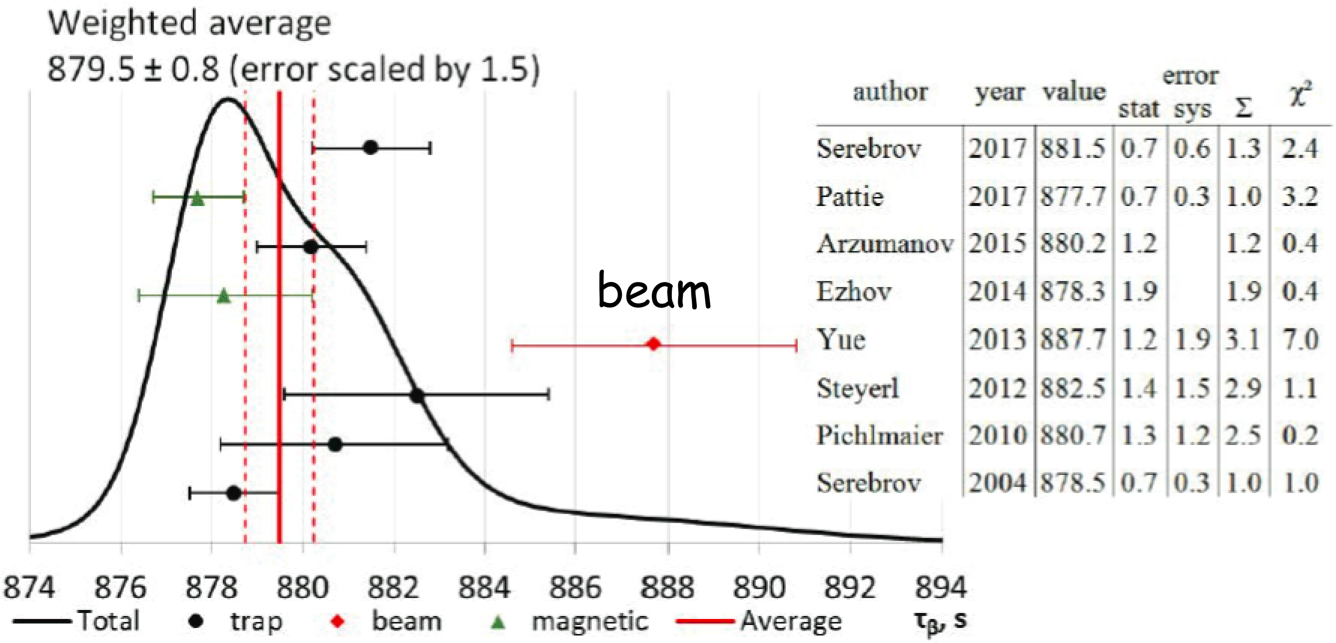




Greene and Geltenbort 2016

Neutron lifetime puzzle

Discrepancy between bottle and beam methods:



author	year	value	error stat	error sys	Σ	χ^2
Serebrov	2017	881.5	0.7	0.6	1.3	2.4
Pattie	2017	877.7	0.7	0.3	1.0	3.2
Arzumanov	2015	880.2	1.2		1.2	0.4
Ezhov	2014	878.3	1.9		1.9	0.4
Yue	2013	887.7	1.2	1.9	3.1	7.0
Steyerl	2012	882.5	1.4	1.5	2.9	1.1
Pichlmaier	2010	880.7	1.3	1.2	2.5	0.2
Serebrov	2004	878.5	0.7	0.3	1.0	1.0

Serebrov 2018, DOI 10.18502/ken.v3i1.1733

Tempting to speculate about exotic decays (inclusive lifetime shorter)

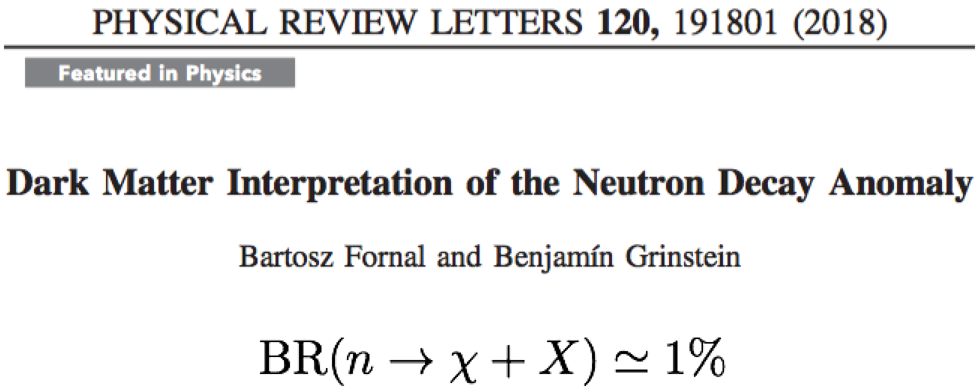
Neutron lifetime puzzle: take-home message

Beam measurements: 888 seconds

World average dominated by storage: about 8 seconds less

About four-sigma discrepancy.

Dark matter solution?



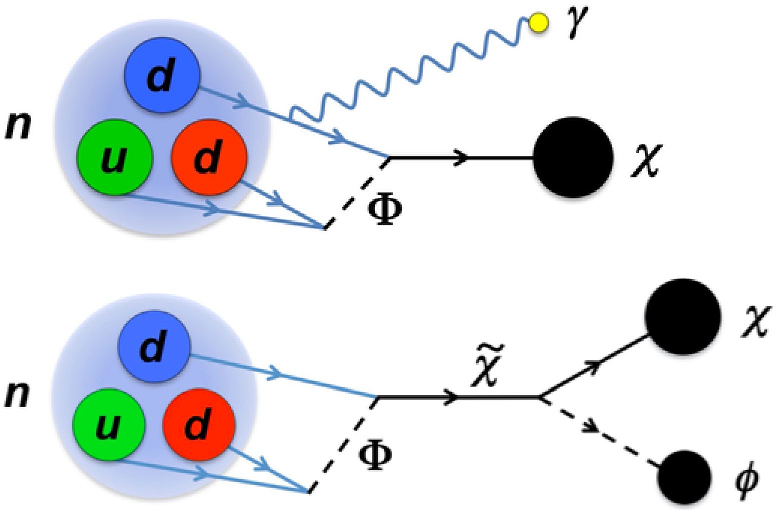
PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Featured in Physics

Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein

$$\mathrm{BR}(n \to \chi + X) \simeq 1\%$$



Mass range for χ, roughly:

$$m_p - m_e < m_\chi < m_p + m_e$$

Mass range, refined:

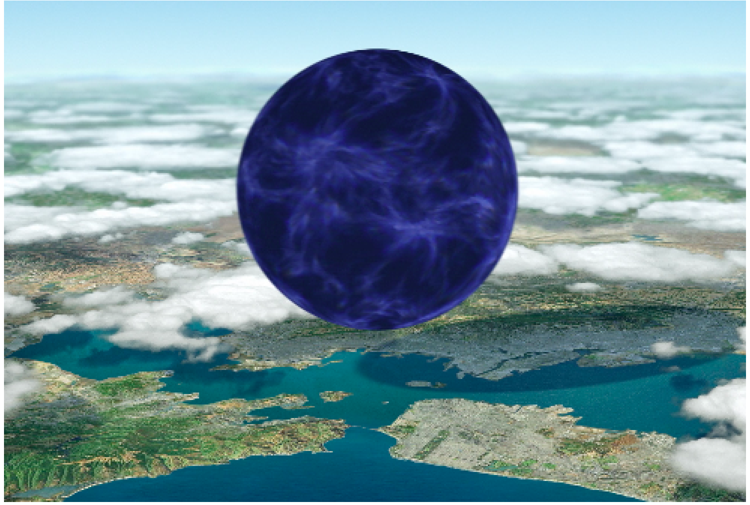
$$937.9\ \mathrm{MeV} < m_\chi < 938.8\ \mathrm{MeV}$$

Stability of beryllium-9

No χ-decay into proton+electron

Objections to the dark-matter decay

Objection 1: existence of large neutron stars



Radius stabilized by Pauli exclusion

If neutrons decay into dark matter, radius decreases -> density increases -> collapse; maximum mass

$$\sim 0.7 - 0.8 M_{\odot}$$

But larger masses have been observed, up to

$$\sim 2 M_{\odot}$$

1802.08244 D. McKeen, Ann E. Nelson, S. Reddy, D. Zhou
1802.08282 G. Baym, D.H. Beck, P. Geltenbort, J. Shelton
1802.08427 T.F. Motta, P.A.M. Guichon, A.W. Thomas

Strong repulsive self-interactions: a way around this bound; but then not a good DM candidate.

1803.04961 Cline & Cornell
1805.03656 Karananas & Kassiteridis

Objection 2: connection between g_A and τ_n

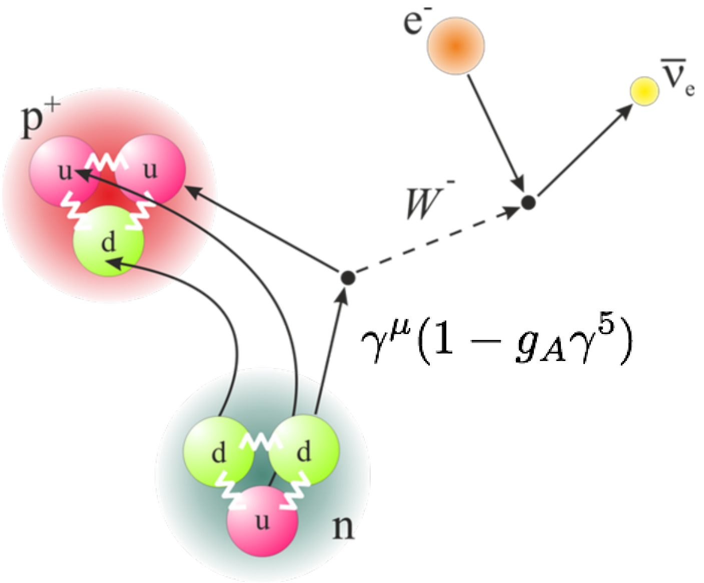
PHYSICAL REVIEW LETTERS **120**, 202002 (2018)

Neutron Lifetime and Axial Coupling Connection

A. Czarnecki, W. J. Marciano, and A. Sirlin

Two neutron puzzles:

$$\left.\begin{aligned}\tau_n^{\text{beam}} &= 888.0(2.0)\ \text{s}\\ \tau_n^{\text{trap}} &= 879.4(6)\ \text{s}\end{aligned}\right\}\ 8.6(2.1)\,\text{s} \simeq 4\sigma$$



$$\gamma^\mu(1 - g_A\gamma^5)$$

https://www.quora.com/What-products-are-formed-due-to-decay-of-neutrons

$$\left.\begin{aligned}g_A^{\text{pre2002}} &= 1.2637(21)\\ g_A^{\text{post2002}} &= 1.2755(11)\end{aligned}\right\}\ 0.0118(24) \simeq 5\sigma$$

Connection: lifetime and g_A

$$\frac{1}{\tau_n} = \frac{G_\mu^2 |V_{\mathrm{ud}}|^2}{2\pi^3} m_e^5 (1 + 3g_A^2)(1 + \mathrm{RC}) f \longrightarrow \tau_n \left(1 + 3g_A^2\right) = \text{SM-predictable}$$

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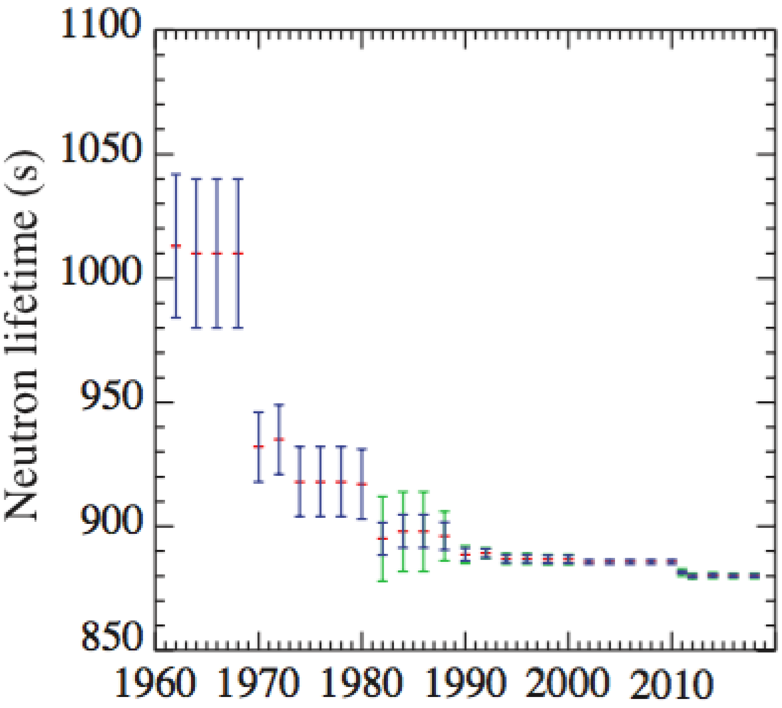
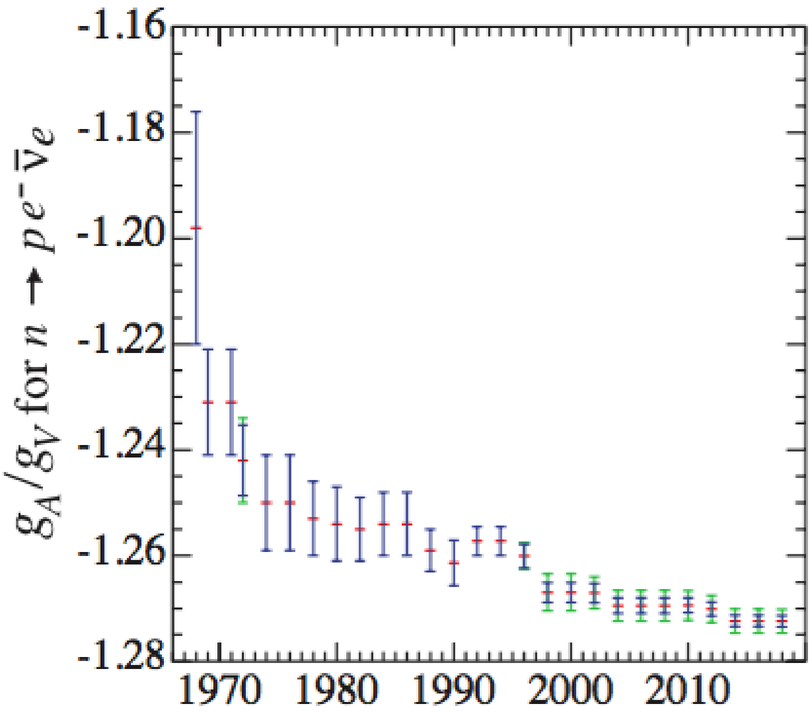
Lifetime and g_A measured separately but (usually) move together,





http://pdg.lbl.gov/2018/

Lifetime and g_A : favored values

Master formula:

$$|V_{\text{ud}}|^2 \tau_n (1 + 3g_A^2) = 4908.6(1.9)\ \text{s},$$

Anti-correlation of RC in V_{ud} and the n-lifetime:

more precise connection, $\tau_n (1 + 3g_A^2) = 5172.0(1.1)\ \text{s},$

Examples:

$$\tau_n^{\text{trap}} = 879.4(6)\ \text{s} \rightarrow g_A = 1.2756(5),$$

$$\tau_n^{\text{beam}} = 888.0(2.0)\ \text{s} \rightarrow g_A = 1.2681(17),$$

$$g_A^{\text{post2002}} = 1.2755(11) \rightarrow \tau_n = 879.5(1.3)\ \text{s},$$

$$g_A^{\text{pre2002}} = 1.2637(21) \rightarrow \tau_n = 893.1(2.4)\ \text{s}.$$

Our recommended values: $\tau_n^{\text{favored}} = 879.4(6)\ \text{s},$

$$g_A^{\text{favored}} = 1.2755(11).$$

AC, W. J. Marciano, A. Sirlin, PRL 2018

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Not much room
for dark decays:

Total exotic neutron decay branching ratio $< 0.27\%$ for $g_A = 1.2755(11)$

AC, W. J. Marciano, A. Sirlin, PRL 2018