Nuclear Decay Anomalies as A Signature of Axion Dark Matter

Tianjun Li

Institute of Theoretical Physics, Chinese Academy of Sciences

Topics of Particle, Astro and Cosmo Frontiers (TOPAC 2023), Tsung-Dao Lee Institute, Shanghai, June 2-4, 2023

Xin Zhang, Nick Houston and TL, arXiv:2303.09865 [hep-ph].

Outline

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The QCD Topological Term

- The topological term

$$\mathcal{L}_\theta = \frac{\theta}{16\pi^2} \mathrm{Tr} F^{\mu\nu} \widetilde{F}^{\mu\nu} , \quad \widetilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} .$$

- The topological term is a total derivative

$$F_{\mu\nu} \widetilde{F}^{\mu\nu} = \partial_\mu K_\mu, \ K_\mu = \frac{1}{16\pi^2} \epsilon^{\mu\nu\alpha\beta} \left(A^a_\nu \partial_\alpha A^a_\beta + \frac{1}{3} f_{abc} A^a_\nu A^b_\alpha A^c_\beta \right) .$$

- Being a total derivative, the θ term does not affect the equations of motion.

Strong CP Problem

- $\overline{\theta} = \theta + \theta_{\rm q}$ parameter is a dimensionless coupling constant and infinitely renormalized by radiative corrections.

$$\theta_{\rm q} \quad = \quad {\rm ArgDet}(Y_U Y_D) \ .$$

- The experimental bound on the neutron EDM is smaller than 3.0×10^{-26} e cm, while the contribution from the $\bar{\theta}$ is

$$d_n \ = \ 2.4(1.0) \times 10^{-16} \overline{\theta} \ {\rm e \ cm} \ .$$

- No theoretical reason for $\overline{\theta}$ as small as 10^{-10} required by the experimental bound on the EDM of the neutron.
- $\overline{\theta}$ may be a random variable with a roughly uniform distribution in the string landscape.

Strong CP problem: why $\overline{\theta}$ is so tiny?

The Possible Solutions to the Strong CP Problem

- Massless quark solution, but not consistent with Lattice QCD.

  If one of the quark fields (say the up quark) was massless, the QCD Lagrangian would have a global $U(1)_u$ axial symmetry, which could be used to rotate the $\overline{\theta}$ term to zero.

- RGE running of $\overline{\theta}$: $\overline{\theta}$ is chosen to be zero at some high scale.

  We can show that all 6-loop diagrams and below cannot generate any RG running.

- Parity: $\overline{\theta} = \theta + \mathrm{ArgDet}(Y_u) + \mathrm{ArgDet}(Y_d) = 0$

$$P : SU(2)_L \leftrightarrow SU(2)_R\,,\ Q_L \leftrightarrow Q_R^\dagger\,,\ H_L \leftrightarrow H_R^\dagger\,,\ L_L \leftrightarrow L_R^\dagger\,.$$

  θ is forbidden, and Y_u/Y_d are Hermitian. The problem arises after a bi-fundamental Higgs is added due to the one-loop contribution to $\overline{\theta}$.

- Soft P (CP) breaking typically called Nelson-Barr models.

  CP is a valid symmetry in the high-energy theory, and is spontaneously broken in such a way that θ naturally turns out to be small. The fine-tuning is still needed.

Peccei–Quinn Mechanism

- The $U(1)_{PQ}$ global symmetry.
- Introducing two Higgs doublets H_u and H_d in the SM, we can consider the following $U(1)_{PQ}$ symmetry [1]

$$Q_i/U_i^c/D_i^c/L_i/E_i^c \longrightarrow e^{i\alpha} Q_i/U_i^c/D_i^c/L_i/E_i^c \ ,$$
$$H_d/H_u \longrightarrow e^{-i2\alpha} H_d/H_u \ .$$

- The Lagrangian is give by

$$\begin{aligned} -\mathcal{L} &= y_{ij}^u Q_i U_i^c H_u + y_{ij}^d Q_i D_i^c H_d + y_{ij}^e L_i E_i^c H_d \\ &+ V\left(H_u^\dagger H_u,\ H_d^\dagger H_d,\ (H_d^\dagger H_u)(H_u^\dagger H_d)\right) \ . \end{aligned}$$

[1] Weinberg; Wilczek.

Peccei–Quinn-Weinberg-Wilczek Axion

- Peccei–Quinn-Weinberg-Wilczek Axion is

$$a \equiv \sin\beta \mathrm{Im} H_d^0 + \cos\beta \mathrm{Im} H_u^0 \ , \quad \mathrm{where} \tan\beta \equiv \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle} \ .$$

- The solution to the strong CP problem: $\overline{\theta} = 0$.

$$V_{\mathrm{Instanton}} \ = \ -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\overline{\theta}}{2}\right)} \ ,$$

$$\overline{\theta} = \theta + \theta_{\mathrm{q}} + a/f_a \ , \quad f_a = \sqrt{\langle H_u^0 \rangle^2 + \langle H_d^0 \rangle^2} \ .$$

- The axion mass

$$m_a \ = \ \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \sim 5.7 \left(\frac{10^{12} \ \mathrm{GeV}}{f_a}\right) \mu\mathrm{eV} \ .$$

Peccei–Quinn-Weinberg-Wilczek Axion

- Weak axion, which has $f_a \sim 246$ GeV and $m_a \sim 25$ keV, is ruled out by $K \to \pi a$ and $J/\Psi \to a\gamma$ experiments.
- Question: can we propose the axion models with the TeV-scale $U(1)_{PQ}$ symmetry breaking and very large f_a?
- Answer: No!
- Point: anomaly argument, and then the only relevant parameter is f_a.
- Solutions: invisible DFSZ and KSVZ axions

Introducing a SM singlet S with intermediate-scale VEV, so $f_a \simeq \langle S \rangle \simeq 10^{10} - 10^{12} \mathrm{GeV}$.

The DFSZ Axion

- The PQWW model with an SM singlet S

$$S \longrightarrow e^{i2\alpha} S \ , \quad -\mathcal{L} = S^2 H_d H_u \ .$$

- In the supersymmetric SMs, we have

$$W = \frac{1}{M_{\rm Pl}} S^2 H_d H_u \ .$$

A natural solution to the μ problem.

- The DFSZ Axion Model

$$a \equiv \frac{1}{f_a} \left(\langle H_u^0 \rangle {\rm Im} H_d^0 + \langle H_d^0 \rangle {\rm Im} H_u^0 + \langle S \rangle {\rm Im} S \right) \ .$$

where $f_a = \sqrt{\langle H_u^0 \rangle^2 + \langle H_d^0 \rangle^2 + \langle S \rangle^2}$.

The KSVZ Axion Model

- A pair of vector-like quarks (XQ^c, XQ) and a SM singlet S

$$XQ^c/XQ \longrightarrow e^{i\alpha} XQ^c/XQ ~, \quad S \longrightarrow e^{-i2\alpha} S ~.$$

- The Lagrangian is

$$-\mathcal{L} = S XQ^c XQ ~.$$

- The KSVZ axion is the imaginary part of S, and $f_a = |\langle S \rangle|$.

Axion Dark Matter Relic Density

- Axion dark matter density is

$$\Omega_a h^2 = 0.15 X \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} .$$

- Pre-inflationary scenario: misalignment mechanism, and $X \sim \sin^2 \theta_{\mathrm{miss}}/2$.
- Post-inflationary scenario: misalignment mechanism and topological defect decays, and $X \subset (2, 10)$.

Topological defects are mainly strings and domain walls associated with the axion field.

- Axion dark matter density is [2]

$$\Omega_a h^2 \simeq 0.12 \left(\frac{28\,\mu\mathrm{eV}}{m_a} \right)^{7/6} = 0.12 \left(\frac{f_a}{2.0 \times 10^{11}\,\mathrm{GeV}} \right)^{7/6} .$$

[2] L. Di Luzio, M. Giannotti, E. Nardi and L. Visinelli, [arXiv:2003.01100 [hep-ph]].

Axion Mass

- The axion mass is [3]

$$m_a \simeq 5.70(7)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)~.$$

- The more precise calculations give $m_a = 60 - 150~\mu\text{eV}$ [4], and $m_a = 26.5 \pm 3.4~\mu\text{eV}$ [5].
- The axion mass is around 50 μeV.

[3] G. Grilli di Cortona, E. Hardy, J. Pardo Vega and G. Villadoro, JHEP **01**, 034 (2016).

[4] T. Hiramatsu, M. Kawasaki, K. Saikawa and T. Sekiguchi, Phys. Rev. D **85**, 105020 (2012); M. Kawasaki, K. Saikawa and T. Sekiguchi, Phys. Rev. D **91**, no.6, 065014 (2015).

[5] V. B. Klaer and G. D. Moore, JCAP **11**, 049 (2017).

Remarks

- In general, the relation between the axion decay constant and mass for QCD axion can be modified.
- The θ angle is space-time dependent due to the misalignment mechanism.
- For Axion-Like-Particles (ALPs), no relation between its decay constant and mass.

The QCD Axion Models with Light and Heavy Axions

- The QCD axion models with heavy axions [6].
- The QCD axion models with light axions [7]
- The $\mathcal{N}$ copies of the SM are interchanged under a $Z_{\mathcal{N}}$ symmetry, which is non-linearly realized by the axion field

$$Z_{\mathcal{N}}: \quad \mathrm{SM}_k \longrightarrow \mathrm{SM}_{k+1(\mathrm{mod}\ \mathcal{N})}\ , \quad a \longrightarrow a + \frac{2\pi k}{\mathcal{N}} f_a\ .$$

$$\mathcal{L} \;=\; \sum_{k=0}^{\mathcal{N}-1} \left[\mathcal{L}_{\mathrm{SM}_k} + \frac{\alpha_S}{8\pi}\left(\theta_a + \frac{2\pi k}{\mathcal{N}}\right) G_k \tilde{G}_k\right] + \ldots\ .$$

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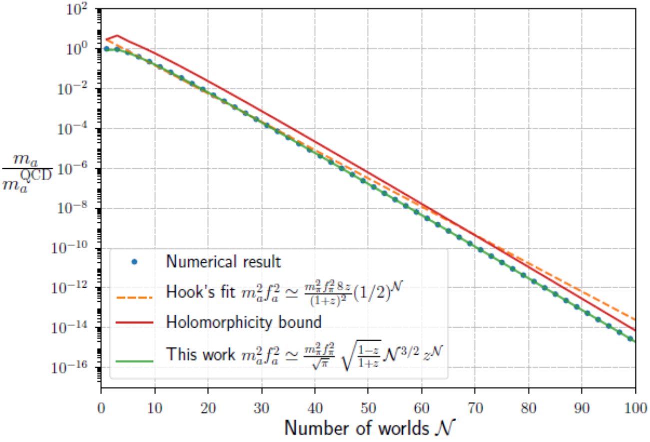
[6] A. Hook, S. Kumar, Z. Liu and R. Sundrum, Phys. Rev. Lett. **124**, no.22, 221801 (2020); C. Csáki, M. Ruhdorfer and Y. Shirman, JHEP **04**, 031 (2020); T. Gherghetta and M. D. Nguyen, JHEP **12**, 094 (2020) doi:10.1007/JHEP12(2020)094.

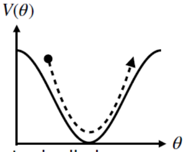
[7] A. Hook, Phys. Rev. Lett. **120**, no.26, 261802 (2018); L. Di Luzio, B. Gavela, P. Quilez and A. Ringwald, JHEP **05** (2021), 184.



Reference: L. Di Luzio, B. Gavela, P. Quilez and A. Ringwald, JHEP **05** (2021), 184.

Recall: the misalignment mechanism

$$\mathscr{L}_\theta = -\,\theta \frac{\alpha_S}{8\pi} G^i_{\mu\nu} \tilde{G}^{\mu\nu i} \longrightarrow \theta \equiv \frac{a}{f_a} \longrightarrow$$



- For QCD axions, with initial condition $\theta_{a,i}$ we typically have

$$\Omega_a h^2 \sim 2 \times 10^4 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}}\right)^{7/6} \langle \theta^2_{a,i} \rangle \,, \quad \theta \simeq \sqrt{\frac{2\rho_{DM}}{m_a^2 f_a^2}} \cos(\omega t + \vec{p} \cdot \vec{x} + \phi)$$

- Many aspects of nuclear physics depend on θ, for example:

$$d_n = \frac{g_{\pi NN}}{4\pi} \left(\frac{e}{m_p f_\pi}\right) \ln\left(\frac{m_\rho}{m_\pi}\right) \left(\frac{m_u m_d}{m_u + m_d}\right) \theta, \quad m_n - m_p \simeq \left(1.29 + 0.37\,\theta^2\right) \mathrm{MeV}$$

- By modifying nuclear binding energies, θ changes decay rates

The Experimental Constraints due to the Axion Oscillation Effects

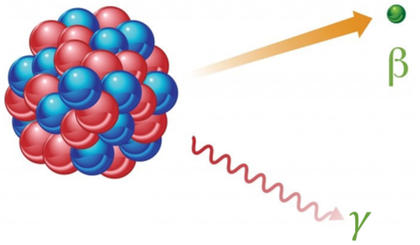
- The neutron EDM and spin precession experiments [8]
- The Big Bang Nucleosynthesis [9].
- Questions: how about nuclear decays?

[8] C. Abel, N. J. Ayres, G. Ban, G. Bison, K. Bodek, V. Bondar, M. Daum, M. Fairbairn, V. V. Flambaum and P. Geltenbort, *et al.*, Phys. Rev. X **7**, no.4, 041034 (2017); T. S. Roussy, D. A. Palken, W. B. Cairncross, B. M. Brubaker, D. N. Gresh, M. Grau, K. C. Cossel, K. B. Ng, Y. Shagam and Y. Zhou, *et al.*, Phys. Rev. Lett. **126** (2021) no.17, 171301; D. Aybas, J. Adam, E. Blumenthal, A. V. Gramolin, D. Johnson, A. Kleyheeg, S. Afach, J. W. Blanchard, G. P. Centers and A. Garcon, *et al.*, Phys. Rev. Lett. **126** (2021) no.14, 141802; I. Schulthess, E. Chanel, A. Fratangelo, A. Gottstein, A. Gsponer, Z. Hodge, C. Pistillo, D. Ries, T. Soldner and J. Thorne, *et al.*, [arXiv:2204.01454 [hep-ex]].

[9] K. Blum, R. T. D'Agnolo, M. Lisanti and B. R. Safdi, Phys. Lett. B **737** (2014), 30-33.

Outline

The big picture



Fundamentally, we believe that nuclear decay is **random** and **spontaneous**

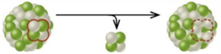
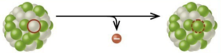
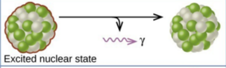
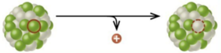
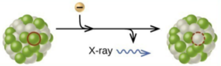
However, we also expect QCD axion DM will lead to an oscillating θ-angle

As θ modifies nuclear physics, this can lead to non-random decay behaviour

What is nuclear decay?

- “Nuclear decay is the process by which an unstable atom loses energy by emitting radiation, generally changing the number of protons and neutrons in the nucleus”

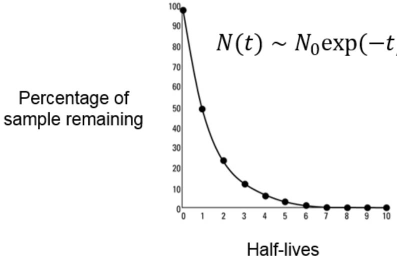
We focus here on beta decay

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	${}^A_ZX$ ${}^4_2He + {}^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	${}^A_ZX$ ${}^0_{-1}e + {}^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	${}^A_ZX$ ${}^0_0\gamma + {}^A_ZY$		A: unchanged Z: unchanged
Positron emission	${}^A_ZX$ ${}^0_{+1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1
Electron capture	${}^A_ZX$ ${}^0_{-1}e + {}^{A}_{Y-1}Y$		A: unchanged Z: decrease by 1

What is nuclear decay?

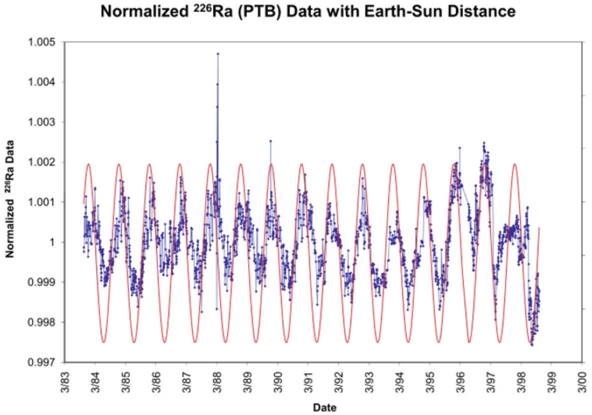
- "Nuclear decay is the process by which an unstable atom loses energy by emitting radiation, generally changing the number of protons and neutrons in the nucleus"

- We can only predict how often this will happen on average



$$N(t) \sim N_0 \exp(-t/t_{1/2})$$

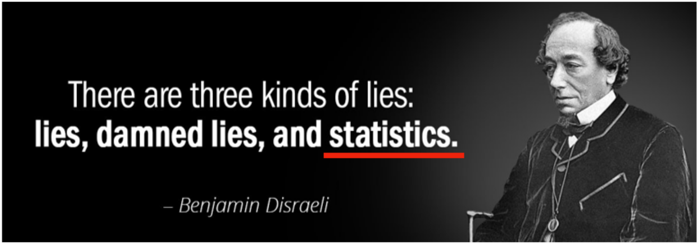
- This is well established science, why should we question this?



- Should we believe this?

"Time-dependent nuclear decay parameters: New evidence for new forces?", *Space Sci.Rev.* 145 (2009) 285-335
"Anomalies in Radioactive Decay Rates: A Bibliography of Measurements and Theory", arxiv: 2111.03149

Reasons to be skeptical: 1



- The data analysis here is quite subtle
- Is it possible these anomalies are due to incorrect statistics?

Reasons to be skeptical: 2

- Can we explain these anomalies without rewriting the laws of physics?
- Did seasonal variations in temperature influence the experiment?
- Is there any possible explanation in terms of fundamental physics?

References: Explanations for the Periodic Variations in the Observed Nuclear Decay Rates

J. H. Jenkins and E. Fischbach, Astropart. Phys. **31**, 407-411 (2009); T. Mohsinally, S. Fancher, M. Czerny, E. Fischbach, J. T. Gruenwald, J. Heim, J. H. Jenkins, J. Nistor and D. O'Keefe, Astropart. Phys. **75**, 29-37 (2016); E. Fischbach, V. E. Barnes, N. Cinko, J. Heim, H. B. Kaplan, D. E. Krause, J. R. Leeman, S. A. Mathews, M. J. Mueterthies and D. Neff, *et al.* Astropart. Phys. **103**, 1-6 (2018); S. Pommé, H. Stroh, J. Paepen, R. Van Ammel, M. Marouli, T. Altzitzoglou, M. Hult, K. Kossert, O. Nähle and H. Schrader, *et al.* Phys. Lett. B **761**, 281-286 (2016); S. Pommé, H. Stroh, J. Paepen, R. V. Ammel, M. Marouli, T. Altzitzoglou, M. Hult, K. Kossert, O. Nähle and H. Schrader, *et al.* Metrologia **54** (2017) no.1, 1; S. Pommé, H. Stroh, J. Paepen, R. V. Ammel, M. Marouli, T. Altzitzoglou, M. Hult, K. Kossert, O. Nähle and H. Schrader, *et al.* Metrologia **54**, no.1, 19 (2017); S. Pommé, H. Stroh, J. Paepen, R. V. Ammel, M. Marouli, T. Altzitzoglou, M. Hult, K. Kossert, O. Nähle and H. Schrader, *et al.* Metrologia **54** (2017) no.1, 36;

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Explanations for the Periodic Variations in the Observed Nuclear Decay Rates

- The result of random noise, unaccounted-for systematic effects, and incomplete uncertainty analysis.
- The influence of seasonally varying environmental conditions
- Conclusion: No concrete framework within which these anomalies can be understood consistently with other observations.
- Question: can we explain it via the QCD axion dark matter?

The Environmental Conditions

- The solar and cosmic neutrinos due to the solar interior dynamics and solar rotations.
- The solar irradiance and rainfall.
- Gravitational wave.

Intuition: the super light mediator which is a dark matter candidate, and whose density arises from misalignment mechanism.

The Nuclear Beta Decay Rate

- For small perturbations to the decay rate, the decays with smaller $Q \equiv M_i - M_f - m_e$ results in a larger fractional change in the beta decay rate.
- Two options: ^{187}Re ($Q \simeq 2.6$ keV) and ^{3}H ($Q \simeq 18.6$ keV).
- The high quality datasets for ^{3}H decay already exist.

We shall use the tritiun beta decays to probe the QCD axion dark matter: can we explain the nuclear decay anomalies via the QCD axion dark matter? Or what is the experimental constraints on the QCD axion from nuclear decays?

Outline

The θ-Dependence of the Nuclear Beta Decay Rates

- The fractional change in the beta decay rate $\Gamma(\theta)$ as a function of θ

$$I_0(\theta) \equiv \frac{\Gamma(\theta) - \Gamma(0)}{\Gamma(0)}\,,\ \Gamma(\theta) = \int_{m_e}^{E_{\rm max}+\delta E(\theta)} dE_e\, \frac{d\Gamma}{dE_e}\,,$$

where $E_{\rm max} = (M_i^2 + m_e^2 - (M_f + m_\nu)^2)/2M_i$.

- The fractional change in the beta decay rate $\Gamma(\theta)$ as a function of θ

$$I(\theta) \equiv \frac{\Gamma(\theta) - \langle\Gamma\rangle}{\langle\Gamma\rangle} = \frac{\Gamma(\theta)}{\Gamma(0)}\left(\frac{\Gamma(0)}{\langle\Gamma\rangle}\right) - 1\,,$$

where $\langle\Gamma\rangle$ is the average value of $\Gamma(\theta)$.

The θ-Dependence of the Nuclear Beta Decay Rates

- We shall assume that the leading order contributions arise specifically from modifications of the phase space, while the modifications of the underlying nuclear couplings $g_{A/V}$, etc, can be neglected [10].

[10] D. Lee, U. G. Meißner, K. A. Olive, M. Shifman and T. Vonk, Phys. Rev. Res. **2** (2020) no.3, 033392 [arXiv:2006.12321 [hep-ph]].

The Tritiun Beta Decay

- The Tritiun beta decay is

$$^{3}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e \ .$$

- The Hamiltonian density is

$$\mathcal{H}(x) = \frac{G_F \cos\theta_C}{\sqrt{2}} \bar{e}(x)\gamma^{\mu}(1-\gamma_5)\nu_e(x) j_{\mu}(x) + h.c. \ .$$

- The strangeness-conserving free nucleon charged current is

$$j^{\mu}(x) = \bar{p}(x)\gamma^{\mu}(g_V - g_A\gamma_5)n(x) \ .$$

The Total β-Decay Rate

- The total β-decay rate is [11]

$$\Gamma = \frac{1}{2\pi^3} m_e \left(G_\beta m_e^2\right)^2 \left(B_F(^3H) + B_{GT}(^3H)\right) \; I^\beta(^3H) \;\; .$$

- The Fermi and Gamow-Teller beta strengths are respectively

$$B_F(^3H) = g_V^2 \, |M_F|^2 = g_V^2 \, \tfrac{1}{2} \, |_{^3He}\langle (1/2)^+ \parallel \textstyle\sum_n \tau_n^+ (1/2)^+ \rangle_{^3H}|^2 \;,$$
$$B_{GT}(^3H) = g_A^2 \, |M_{GT}|^2 = g_A^2 \, \tfrac{1}{2} \, |_{^3He}\langle (1/2)^+ \parallel \textstyle\sum_n \tau_n^+ \sigma_n (1/2)^+ \rangle_{^3H}|^2$$

- The phase space integral is

$$I^\beta = \frac{1}{m_e^5} \int_{m_e}^{E_{\rm max}} F_0(Z+1, E_e) p_e E_e (E_{\rm max} - E_e)^2 dE_e \;\; .$$

[11] A. Faessler, R. Hodak, S. Kovalenko and F. Simkovic, "Tritium and rhenium as a probe of cosmic neutrino background," J. Phys. G **38** (2011), 075202.

The Non-QCD Parameters

- All that parameters, which belong to non-QCD sectors, such as m_e, G_F, and θ_C are assumed to be θ-independent.
- The PMNS matrix elements responsible for neutrino oscillations and the neutrino masses themselves should also presumably have no such dependence.

Nucleon Masses

- For free nucleons, $(m_n - m_p)$ is

$$m_n - m_p = (m_n - m_p)^{\rm QED} + (m_n - m_p)^{\rm QCD} \ ,$$

where $(m_n - m_p)^{\rm QED} = -(0.58 \pm 0.16){\rm MeV}$ is the QED correction to the mass difference.

- With QCD corrections, we have

$$\begin{aligned} m_n - m_p &\simeq -0.58{\rm MeV} + 4c_5 B_0 \frac{M_\pi^2}{M_\pi^2(\theta)} (m_u - m_d) \\ &\simeq (-0.58 + 1.87 + 0.21\theta^2){\rm MeV} \\ &\simeq (1.29 + 0.21\theta^2){\rm MeV} \ , \end{aligned}$$

where $c_5 = (-0.074 \pm 0.006)\text{GeV}^{-1}$ is a low energy constant, $B_0 = M_\pi^2/(m_u + m_d)$, and we assume two degenerate quark flavours [12].

[12] D. Lee, U. G. Meißner, K. A. Olive, M. Shifman and T. Vonk, Phys. Rev. Res. **2** (2020) no.3, 033392 [arXiv:2006.12321 [hep-ph]].

Nuclear Binding Energies

- For $n = 3, 4$ nucleon systems, the binding energies B_n satisfy [13]

$(\overline{B}_n(\theta)/\overline{B}_4(0))^{1/4} - (\overline{B}_2(\theta)/\overline{B}_4(0))^{1/4} = (\overline{B}_n(0)/\overline{B}_4(0))^{1/4} - (\overline{B}_2(0)/\overline{B}_4(0))^{1/4}.$

Here the bar indicates an average over states which become degenerate in the limit that the approximate Wigner $SU(4)$ symmetry of low energy nuclear physics becomes exact.

- For $n = 3$ we have

$$\overline{B}_3(\theta) = \left(\overline{B}_2(\theta)^{1/4} + \overline{B}_3(0)^{1/4} - \overline{B}_2(0)^{1/4}\right)^4 ,$$

where averaging over the physical ^{3}H and ^{3}He states gives $\overline{B}_3(0) \simeq 8.1\,\mathrm{MeV}$, and $B_4(0) \simeq 28.3\,\mathrm{MeV}$ is given by the physical ^{4}He binding energy.

[13] D. Lee, U. G. Meißner, K. A. Olive, M. Shifman and T. Vonk, Phys. Rev. Res. **2** (2020) no.3, 033392 [arXiv:2006.12321 [hep-ph]].

Nuclear Binding Energies

To find $\overline{B}_2(\theta)$, we average over the physical deuteron and the spin singlet (dineutron and diproton) channel, with θ dependence parameterised via

$$B_2(\theta) = \left(B_2(0) + \sum_{i=1}^{3} c_i (1 - \cos\theta)^i \right) \text{ MeV} \,,$$

with $B_2(0) \simeq 2.22, -0.072, -0.787\,\text{MeV}$ for the deuteron, dineutron and diproton respectively, which then yields $\overline{B}_2(0) \simeq 1.03\,\mathrm{MeV}$.

For the c_i numerical coefficients we use the (more conservative) choice of parameter set II in Ref. [14], assuming isospin conservation, ($c_1 = 3.25$, $c_2 = 2.55$, $c_3 = 0.47$). Inserting these values we find

$$\overline{B}_3(\theta) \simeq (8.1 + 7.63\,\theta^2)\mathrm{MeV} \,.$$

[14] D. Lee, U. G. Meißner, K. A. Olive, M. Shifman and T. Vonk, Phys. Rev. Res. **2** (2020) no.3, 033392 [arXiv:2006.12321 [hep-ph]].

Nuclear Binding Energies

Since we only know the (averaged) $\overline{B}_3(\theta)$, rather than the individual initial and final state binding energies $B_i(\theta)$ and $B_f(\theta)$, we will assume in the following that for small θ

$$B(\theta)_{i/f} \simeq B(0)_{i/f} \frac{\overline{B}_3(\theta)}{\overline{B}_3(0)} ,$$

which is equivalent to assuming that for small θ the individual binding energies scale in proportion to their average.

Initial/Final State Energies

Knowing the dependence of free nucleon masses and nuclear binding energies then allows us to calculate M_i and M_f, the masses of the initial and final nuclear states. This is defined in terms of the sum of the masses of their constituent (free) nucleons N and their associated binding energies,

$$M_{i/f}(\theta) = \sum_N m_N(\theta) - B_{i/f}(\theta)\,,$$

Combining the previous results we then find

$$M_i(\theta) - M_f(\theta) = (m_n - m_p)(\theta) - B_i(\theta) + B_f(\theta) \simeq 0.53 - 0.51\,\theta^2 \mathrm{MeV}\,.$$

Integral Endpoint

Modifications to $M_{i/f}$ enter into the beta decay rate via the phase space integral, through the upper limit $E_{\max}$, where

$$E_{\max} = \frac{M_i^2 + m_e^2 - (M_f + m_\nu)^2}{2M_i} ,$$

where m_ν is the neutrino mass. To calculate the leading order modification to $E_{\max}$ we can perturb $M_{i/f}$ by $\delta M_{i/f}$ (representing a θ-dependent correction) and expand to lowest order, finding

$$E_{\max} \simeq E_{\max}\Big|_{\delta M_{i/f}=0} + \delta M_i \frac{M_i^2 - m_e^2 + (M_f + m_\nu)^2}{2M_i^2} - \delta M_f \frac{M_f + m_\nu}{M_i} ,$$

Since $M_{i/f} >> m_e, m_\nu$ we can further neglect terms proportional to products of $\delta M_{i/f}$ and m_e/m_ν to then find

$$E_{\max} \simeq E_{\max}\Big|_{\delta M_{i/f}=0} + \delta M_i \frac{M_i^2 + M_f^2}{2M_i^2} - \delta M_f \frac{M_f}{M_i} ,$$

Integral Endpoint

The latter terms can be calculated exactly here, but we also can notice that since $Q = M_i - M_f - m_e \simeq 18.6$ keV is also much less than $M_{i/f}$, we then have

$$\delta M_{i/f} M_f = \delta M_{i/f}(M_i - m_e - Q) \simeq \delta M_{i/f} M_i \, ,$$

which then leads simply to

$$E_{\max} \simeq E_{\max}\Big|_{\delta M_{i/f}=0} + \delta M_i - \delta M_f \, ,$$

From the previous discussion, we can then calculate:

$$E_{\max}(\theta) \simeq E_{\max}(0) + \delta E(\theta) \simeq 0.53 - 0.51\,\theta^2 \mathrm{MeV} \, .$$

Fermi Function

Before calculating the phase space integral we need to examine the relativistic Fermi function [15], given by

$$F_{k-1}(Z, E_e) = \left(\frac{\Gamma(2k+1)}{\Gamma(k)\Gamma(1+2\gamma_k)}\right)^2 (2p_e R_0)^{2(\gamma_k - k)} |\Gamma(\gamma_k + iz)|^2 e^{\pi z},$$

where $k = 1, 2, 3 \ldots$, Z is the atomic number, $\gamma_k = \sqrt{k^2 - (\alpha Z)^2}$, $R_0 = 1.2 \times 10^{-15}$m is the nuclear radius, and $z = \alpha Z E_e / p_e$. In principle θ-dependence may enter via R_0: as nucleons become more tightly bound we can expect the effective nuclear radius to decrease. However, given that $I^\beta \propto F_0(2, E_e) \propto R_0^{-4\alpha^2}$ it is straightforward to see that modification of the Fermi function need not be considered.

[15] A. Faessler, R. Hodak, S. Kovalenko and F. Simkovic, "Tritium and rhenium as a probe of cosmic neutrino background," J. Phys. G **38** (2011), 075202; R. Dvornicky, K. Muto, F. Simkovic and A. Faessler, "The absolute mass of neutrino and the first unique forbidden beta-decay of 187Re," Phys. Rev. C **83**, 045502 (2011); M. Doi, T. Kotani and E. Takasugi, "Double beta Decay and Majorana Neutrino," Prog. Theor. Phys. Suppl. **83**, 1 (1985).

Phase Space Integral

These points established we can now add the small perturbation δE to $E_{\max}$ and evaluate the phase space integral for a given choice of Fermi function:

$$\frac{\delta I^{\beta}}{I^{\beta}} = \frac{\int_{m_e}^{E_{\max}(0)+\delta E} F_0\left(Z+1, E_e\right) p_e E_e \left(E_{\max}(0) + \delta E - E_e\right)^2 \, \mathrm{d}E_e}{\int_{m_e}^{E_{\max}(0)} F_0\left(Z+1, E_e\right) p_e E_e \left(E_{\max}(0) - E_e\right)^2 \, \mathrm{d}E_e} - 1\,,$$

$$F_0\left(Z, E_e\right) = \left(\frac{\Gamma(3)}{\Gamma(1)\Gamma\left(1 + 2\sqrt{1^2 - (\alpha)^2}\right)}\right)^2 \left(2p_e R\right)^2 \left(\sqrt{1^2 - (\alpha)^2 - 1}\right)$$

$$\times \left|\Gamma\left(\sqrt{1^2 - (\alpha)^2} + i\alpha\frac{E_e}{p_e}\right)\right|^2 e^{\pi\alpha\frac{E_e}{p_e}}\,,$$

R is the average radius of a nucleus, a good approximation for the average radius of a nucleus with A nucleons is

$$R \simeq 1.2 \text{ fm } A^{1/3}\,.$$

Phase Space Integral

In the Primakoff-Rosen (non-relativistic) approximation [16], we have

$$F_{k-1}(Z, E_e) \simeq F_{k-1}^{\mathrm{NR}}(Z, E_e) = F_0^{\mathrm{PR}}(Z, E_e)[(k-1)!]^{-2} \prod_{j=1}^{k-1} \left[(k-j)^2 + y^2\right] ,$$

where $F_0^{\mathrm{PR}}(Z, E_e) = 2\pi y / [1 - \exp(-2\pi\alpha Z)],\ y = \alpha Z E_e / p_e$. We can find the result exactly, expanding for small $\delta E / E_{\mathrm{max}}$ to give

$$\frac{\delta I^\beta}{I^\beta} = \frac{\int_{m_e}^{E_{\mathrm{max}}(0)+\delta E} F_0^{\mathrm{PR}}(Z+1, E_e)\, p_e E_e \left(E_{\mathrm{max}}(0) + \delta E - E_e\right)^2 \, \mathrm{d}E_e}{\int_{m_e}^{E_{\mathrm{max}}(0)} F_0^{\mathrm{PR}}(Z+1, E_e)\, p_e E_e \left(E_{\mathrm{max}}(0) - E_e\right)^2 \, \mathrm{d}E_e} - 1 ,$$

[16] M. Doi, T. Kotani and E. Takasugi, "Double beta Decay and Majorana Neutrino," Prog. Theor. Phys. Suppl. **83**, 1 (1985).

Phase Space Integral

Using the Primakoff-Rosen approximation, the integral has the analytic expression

$$\frac{\delta I^{\beta}}{I^{\beta}} = \frac{\delta E(5E_{\max}(0)^4 + 15m_e^4 - 20E_{\max}(0)m_e^3)}{(E_{\max}(0)-m_e)^3(6m_e^2+3E_{\max}(0)m_e+E_{\max}(0)}$$
$$+ \frac{\delta E^2(10E_{\max}(0)^3 - 10m_e^3)}{(E_{\max}(0)-m_e)^3(6m_e^2+3E_{\max}(0)m_e+E_{\max}(0)}$$
$$+ \frac{\delta E^3 10E_{\max}(0)^2}{(E_{\max}(0)-m_e)^3(6m_e^2+3E_{\max}(0)m_e+E_{\max}(0)}$$
$$+ \frac{\delta E^4 5E_{\max}(0)}{(E_{\max}(0)-m_e)^3(6m_e^2+3E_{\max}(0)m_e+E_{\max}(0)}$$
$$+ \frac{\delta E^5}{(E_{\max}(0)-m_e)^3(6m_e^2+3E_{\max}(0)m_e+E_{\max}(0)},$$

Phase Space Integral

Expanding around $\delta E = 0$ then gives

$$\frac{\delta I^\beta}{I^\beta} \simeq \frac{\delta E(5E_{\rm max}(0)^4 + 15m_e^4 - 20E_{\rm max}(0)m_e^3)}{(E_{\rm max}(0) - m_e)^3(6m_e^2 + 3E_{\rm max}(0)m_e + E_{\rm max}(0)}$$
$$\simeq 0.162265 \times \left(\frac{\delta E}{\rm keV}\right), \quad |\delta E| \ll 18.6\,{\rm keV}\,,$$

Phase Space Integral

For the fully relativistic Fermi function, we have

$$\frac{\delta I^\beta}{I^\beta} = \frac{\int_{m_e}^{E_{\max}(0)+\delta E} F_0\left(Z+1, E_e\right) p_e E_e \left(E_{\max}(0) + \delta E - E_e\right)^2 \, \mathrm{d}E_e}{\int_{m_e}^{E_{\max}(0)} F_0\left(Z+1, E_e\right) p_e E_e \left(E_{\max}(0) - E_e\right)^2 \, \mathrm{d}E_e} - 1\,,$$

Numerical integration and expanding around $\delta E = 0$ then yields

$$\frac{\delta I^\beta}{I^\beta} \simeq 0.184252 \times \left(\frac{\delta E}{\mathrm{keV}}\right), \quad |\delta E| \ll 18.6\,\mathrm{keV}\,,$$

which agrees to within 12% with the non-relativistic case.

Beta Strengths

Following Refs. [17], on the basis on isospin symmetry and selection rules it can also be shown that

$$M_F = 1\,, \quad |M_{GT}|^2 = 3\,,$$

If we assume isospin symmetry, these results should carry over to the present context, as selection rules are presumably not θ-dependent for small values of θ. The couplings g_A and g_V may also have some θ-dependence, however following Ref. [18] it can also be assumed that their θ-dependence is subleading to phase space modifications.

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[17] A. Faessler, R. Hodak, S. Kovalenko and F. Simkovic, "Tritium and rhenium as a probe of cosmic neutrino background," J. Phys. G **38** (2011), 075202; R. Dvornicky, K. Muto, F. Simkovic and A. Faessler, "The absolute mass of neutrino and the first unique forbidden beta-decay of 187Re," Phys. Rev. C **83**, 045502 (2011); M. Doi, T. Kotani and E. Takasugi, "Double beta Decay and Majorana Neutrino," Prog. Theor. Phys. Suppl. **83**, 1 (1985).

[18] D. Lee, U. G. Meißner, K. A. Olive, M. Shifman and T. Vonk, Phys. Rev. Res. **2** (2020) no.3, 033392 [arXiv:2006.12321 [hep-ph]].

Fractional Decay Rate

These points established we can now combine these results to establish our quantity of interest for comparison to experimental data, the fractional change in the beta decay rate Γ as a function of θ,

$$I_0(\theta) \equiv \frac{\Gamma(\theta) - \Gamma(0)}{\Gamma(0)} \simeq \frac{\delta I^{\beta}(\theta)}{I^{\beta}(0)} ,$$

where we have used the fact that θ-dependence primarily enters through modification of the phase space integral, and dependence on the various other quantities present in Γ cancels.

In the axion dark matter scenario the form of θ is

$$\theta \simeq 2.6 \times 10^{-4} \left(\frac{\rho_{DM}}{0.45\mathrm{GeV/cm^3}}\right)^{1/2} \left(\frac{10^{-21}\mathrm{eV}}{m_a}\right) \left(\frac{10^{13}\mathrm{GeV}}{f_a}\right) \cos(\omega t + \vec{p} \cdot \vec{x} + \phi) ,$$

where ρ_{DM} is the DM density, $\omega = m_a(1 + v^2 + \mathcal{O}(v^4))$, p, v, f_a and m_a are the axion field momentum, velocity, decay constant and mass respectively, and ϕ is an arbitrary phase.

Fractional Decay Rate

This then yields

$$I_0(\theta) \simeq A(\rho, m_a, f_a) \cos(\omega t + \vec{p} \cdot \vec{x} + \phi)^2 \,,$$

where the amplitude A can easily be found via substitution of the above equations. So, we apparently find a fractional change in the decay rate which is strictly positive relative to the ($\theta = 0$) non-axion case. In simple terms, this would mean that the axion-induced effect apparently only creates an excess in the number of nuclear decays, rather than alternating excesses and deficits. However, care is required here.

In a Universe where this mechanism is active the measured values of physical quantities such as decay rates are actually not those at $\theta = 0$, but are instead those at $\langle \theta^2 \rangle$ (since binding energies are $\mathcal{O}(\theta^2)$ at leading order). Therefore when dealing with experimental data, rather than comparing $\Gamma(\theta)$ to $\Gamma(0)$, we should instead consider

$$I(\theta) \equiv \frac{\Gamma(\theta) - \langle \Gamma \rangle}{\langle \Gamma \rangle} = \frac{\Gamma(\theta)}{\langle \Gamma \rangle} - 1 = \frac{\Gamma(\theta)}{\Gamma(0)} \left(\frac{\langle \Gamma \rangle}{\Gamma(0)} \right)^{-1} - 1 \,,$$

where $\langle \Gamma \rangle$ is the average value of $\Gamma(\theta)$.

Fractional Decay Rate

We can calculate $\langle\Gamma\rangle/\Gamma(0)$ by virtue of already knowing $I_0(\theta) = \Gamma(\theta)/\Gamma(0) - 1$ and using $\langle\cos(\omega t + \ldots)^2\rangle = 1/2$. Since $A << 1$ we then find

$$\left(\frac{\langle\Gamma(\theta)\rangle}{\Gamma(0)}\right)^{-1} \simeq \left(1 + A\langle\cos(\omega t + \vec{p}\cdot\vec{x} + \phi)^2\rangle\right)^{-1} \simeq 1 - \frac{1}{2}A\,.$$

Inserting this yields

$$\begin{aligned} I(\theta) &\simeq \left(1 + A\cos(\omega t + \vec{p}\cdot\vec{x} + \phi)^2\right)\left(1 - \tfrac{1}{2}A\right) - 1 \\ &\simeq A\left(\cos(\omega t + \vec{p}\cdot\vec{x} + \phi)^2 - \tfrac{1}{2}\right)\,. \end{aligned}$$

Fractional Decay Rate

Using $2\cos(x)^2 - 1 = \cos(2x)$, we then find

$$I(\theta) \simeq 1.3 \times 10^{-5} \left(\frac{\rho_{DM}}{0.45\mathrm{GeV/cm^3}}\right)\left(\frac{10^{-21}\mathrm{eV}}{m_a}\right)^2\left(\frac{10^{13}\mathrm{GeV}}{f_a}\right)^2 \cos(2\omega t + \dots)\,,$$

which oscillates about zero, as expected, leading to alternating excesses and deficits in the number of nuclear decays per unit time. We can also see that the corresponding shift in the decay energy,

$$\delta E \simeq 3.5 \times 10^{-2}\mathrm{eV} \left(\frac{\rho_{DM}}{0.45\mathrm{GeV/cm^3}}\right)\left(\frac{10^{-21}\mathrm{eV}}{m_a}\right)^2\left(\frac{10^{13}\mathrm{GeV}}{f_a}\right)^2 \cos(2\omega t + \dots)\,,$$

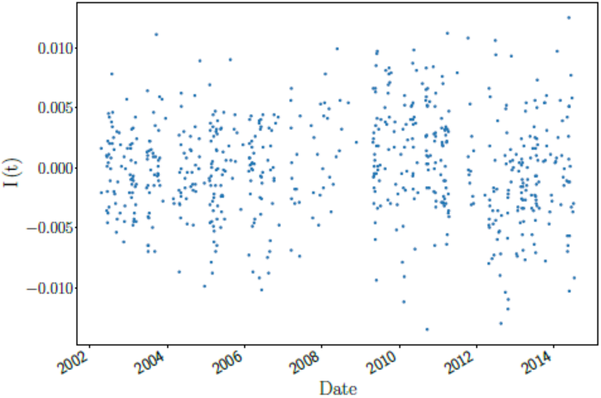
is also a small correction in regions of the axion parameter space we exclude, justifying our previous assumption that $\delta E << Q$. Similarly, $\theta << 1$ in these regions.

Outline

Tritium Decay Dataset

- We make use of a dataset provided by the European Commission's Joint Research Centre (JRC) at the Directorate for Nuclear Safety and Security in Belgium, which spans approximately 12 years of liquid scintillation counter observations of the decay of an $\mathcal{O}(\text{microcurie})$ ^{3}H source [19].
- This time-series data show the fractional change in the ^{3}H beta decay rate $I(t) = (\dot{N} - \langle \dot{N} \rangle)/\langle \dot{N} \rangle$, where $\dot{N}$ is the measured value of decays per second, whilst $\langle \dot{N} \rangle$ is its expected value due to the exponential decay law.

[19] S. Pommé, H. Stroh, J. Paepen, R. V. Ammel, M. Marouli, T. Altzitzoglou, M. Hult, K. Kossert, O. Nähle and H. Schrader, *et al.* Metrologia **54**, no.1, 19 (2017).



Reference: S. Pommé, H. Stroh, J. Paepen, R. V. Ammel, M. Marouli, T. Altzitzoglou, M. Hult, K. Kossert, O. Nähle and H. Schrader, *et al.* Metrologia **54**, no.1, 19 (2017).

Data Analysis Approaces

- The statistical analysis of nuclear decay anomalies has been subject to a number of treatments, with no overall consensus on which approach is optimal [20].
- We broadly follow the approaches of Refs. [21], where searches for oscillatory signals in time-series data were also used to place limits on ultralight axion DM.

[20] S. Pommé, Nucl. Instrum. Meth. A **968** (2020), 163933.

[21] C. Abel, N. J. Ayres, G. Ban, G. Bison, K. Bodek, V. Bondar, M. Daum, M. Fairbairn, V. V. Flambaum and P. Geltenbort, *et al.* Phys. Rev. X **7**, no.4, 041034 (2017) [arXiv:1708.06367 [hep-ph]]; D. Aybas, J. Adam, E. Blumenthal, A. V. Gramolin, D. Johnson, A. Kleyheeg, S. Afach, J. W. Blanchard, G. P. Centers and A. Garcon, *et al.* Phys. Rev. Lett. **126** (2021) no.14, 141802 [arXiv:2101.01241 [hep-ex]]; T. Wu, J. W. Blanchard, G. P. Centers, N. L. Figueroa, A. Garcon, P. W. Graham, D. F. Jackson Kimball, S. Rajendran, Y. V. Stadnik and A. O. Sushkov, *et al.* Phys. Rev. Lett. **122**, no.19, 191302 (2019) [arXiv:1901.10843 [hep-ex]].

Data Analysis

- Because the data points are unevenly spaced in time, we shall estimate their power spectrum using the Least Squares Spectral Analysis (LSSA) method to construct periodograms [22].
- We compute the power spectrum using the `astropy.timeseries.LombScargle` class provided by the `Python astropy.timeseries` package [23], evaluated at a set of 8113 evenly spaced trial frequencies.

[22] N. R. Lomb, Astrophys. Space Sci. **39**, 447-462 (1976); J. D. Scargle, Astrophys. J. **263**, 835-853 (1982).
[23] Jacob T. VanderPlas, ApJS, 236, 16, 2018.

Data Analysis

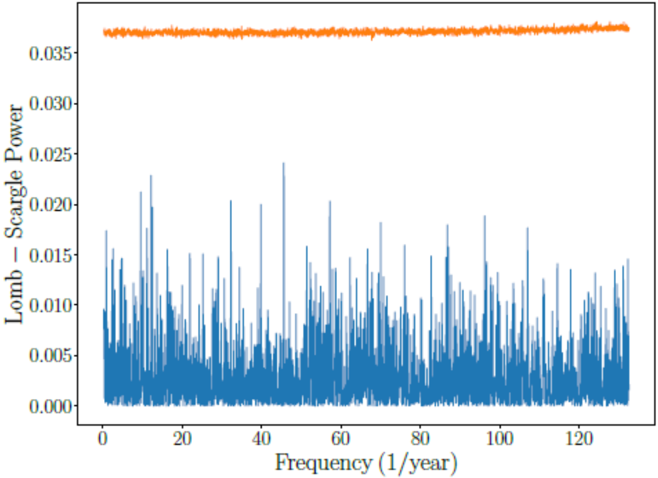
- As the lowest 15 trial frequencies appear to show evidence of uncontrolled systematic effects, possibly long-term drift of the experimental apparatus, we exclude them from our analysis.
- Comments: for these lowest 15 trial frequencies, we do find the axion dark matter induced signal at 4.7σ. However, this parameter space has been excluded by the neutron EDM experimental constraints under the assumption of the isospin conservation. The interesting question is how about the isospin violation scenario?
- The largest frequency in the remaining data, 4.2×10^{-6} Hz, corresponds to a period of ~ 2.8 days, whilst the smallest, 8.0×10^{-9} Hz, corresponds to a period of ~ 4.0 years.

Data Analysis

- Under the null hypothesis that the dataset contains no axion-induced signal, the time-series datapoints should follow a Gaussian distribution about $I = 0$.
- To place limits on the corresponding power spectrum, we perform the Monte Carlo (MC) simulations by generating $N = 50000$ time-series MC datasets, with the same time spacing as the original data. The MC data points themselves are drawn from a zero-mean Gaussian distribution, with width set by the standard deviation of the original dataset.
- For each MC dataset, we calculate a corresponding periodogram, and then use the statistics of these periodograms to construct the Cumulative Distribution Function (CDF) for the power at each frequency.

Data Analysis

- From these CDFs we then determine the false positive (or false alarm) power at 95% confidence level for each frequency.
- We account for the 'look elsewhere effect' by defining these limits with respect to the global trials factor $p_{\mathrm{global}} = 1 - (1 - p_{\mathrm{local}})^{N_f}$, where p_{local} is the corresponding local p-value and N_f the number of trial frequencies.
- Conclusion: the original dataset does not exceed the 95% confidence level threshold, indicating the data are compatible with the null hypothesis that the dataset contains no axion-induced signal.


0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
Lomb − Scargle Power
0
20
40
60
80
100
120
Frequency (1/year)

Experimental Constraints on the Axion Parameter Space

- At each trial frequency, we construct $N = 50000$ MC datasets containing Gaussian background and injected axion-derived signals and calculate their periodograms.
- We incorporate annual modulation of the signal, which enters via the axion velocity [24].
- For a given choice of parameters, we can then construct the corresponding CDF for the power at each trial frequency.
- With the mass fixed by the frequency under consideration, the threshold value of f_a can then be determined following a standard frequentist approach in Ref. [25].

[24] A. Bandyopadhyay and D. Majumdar, Astrophys. J. **746**, 107 (2012) [arXiv:1006.3231 [hep-ph]]; K. Freese, M. Lisanti and C. Savage, Rev. Mod. Phys. **85**, 1561-1581 (2013) [arXiv:1209.3339 [astro-ph.CO]].

[25] G. P. Centers, J. W. Blanchard, J. Conrad, N. L. Figueroa, A. Garcon, A. V. Gramolin, D. F. J. Kimball, M. Lawson, B. Pelssers and J. A. Smiga, *et al.* Nature Commun. **12**, no.1, 7321 (2021) [arXiv:1905.13650 [astro-ph.CO]].

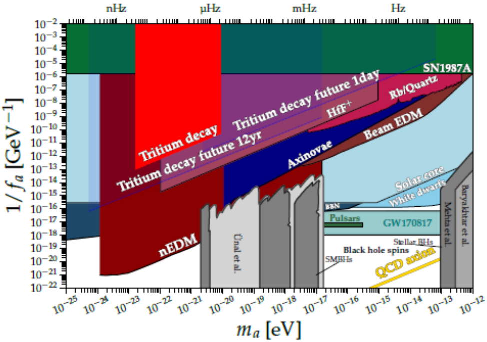
Experimental Constraints on the Axion Parameter Space

- For a given choice of f_a, from the background-only CDF we first find the false positive threshold power at a desired confidence level. From the background plus signal CDF we can also find the false negative threshold power.
- The threshold value of f_a is then determined by the condition that the false positive threshold from the background-only CDF coincides with the false negative threshold from the background plus signal CDF, at the desired confidence level.
- Equivalently, the threshold value of f_a occurs when the false positive rate α is equal to the false negative rate $1-\beta$, where $CL = 1-\alpha$.

Experimental Constraints on the Axion Parameter Space

- We marginalise over the unknown axion phase ϕ assuming a uniform distribution, and account for the 'stochastic vs deterministic' correction factor occurring in the regime where the measurement time is much less than axion field coherence time [26].
- We exclude f_a below $9.4 \times 10^{12} - 1.8 \times 10^{10}$ GeV (95 % confidence level) for masses in the $1.7 \times 10^{-23} - 8.7 \times 10^{-21}$ eV range.

[26] G. P. Centers, J. W. Blanchard, J. Conrad, N. L. Figueroa, A. Garcon, A. V. Gramolin, D. F. J. Kimball, M. Lawson, B. Pelssers and J. A. Smiga, *et al.* Nature Commun. **12**, no.1, 7321 (2021) [arXiv:1905.13650 [astro-ph.CO]].



We show the constraints from oscillating nEDM searches, BBN, the spectroscopy of radio-frequency atomic transitions, pulsars, gravitational waves and black hole superradiance, solar/white dwarf observations, so-called ‘axinovae’, and the parameter space occupied by canonical QCD axion models (yellow). Figure producing using the AxionLimits code.

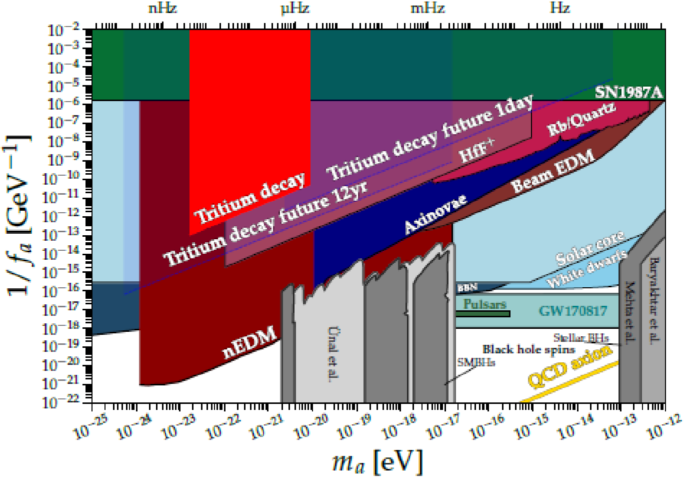
Future Experimental Possibilities

- The first is a long-term experiment designed to search lower frequencies, with 1 measurement per hour over 12 years.
- The second is a short-term experiment to search higher frequencies, with approximately 1 measurement per second over 1 day.
- Both schemes increase the initial quantity of tritium by a factor of 100 relative to the JRC dataset, up to a presumed limit imposed by detector pileup [27].

[27] X. L. Luo, V. Modamio, J. Nyberg, J. J. Valiente-Dobón, Q. Nishada, G. de Angelis, J. Agramunt, F. J. Egea, M. N. Erduran and S. Ertürk, *et al.* "Pulse pile-up identification and reconstruction for liquid scintillator based neutron detectors," Nucl. Instrum. Meth. A **897**, 59-65 (2018).

Future Experimental Possibilities

In the first case we can exclude axion decay constants up to $f_a < 1.5 \times 10^{16}$ GeV (95 % confidence level) and cover masses in the $5.4 \times 10^{-25} - 1.4 \times 10^{-17}$ eV range, while in the latter we can exclude axion decay constants up to $f_a < 4.5 \times 10^{11}$ GeV (95 % confidence level) and cover masses in the $2.4 \times 10^{-21} - 6.3 \times 10^{-14}$ eV range.


nHz
μHz
mHz
Hz
SN1987A
Tritium decay
Tritium decay future 1day
Tritium decay future 12yr
HfF+
Rb/Quartz
Beam EDM
Axinovae
nEDM
Ünal et al.
BBN
Pulsars
GW170817
Solar core
White dwarfs
Mehta et al.
Baryakhtar et al.
Stellar BHs
Black hole spins
SMBHs
QCD axion
$1/f_a$ [GeV^{-1}]
m_a [eV]

Summary

- A number of nuclear decay anomalies have been reported in the literature, which purport to show periodic variations in the decay rates of certain radioisotopes.
- We provide the first mechanism to explain these findings, via the misalignment mechanism of QCD axion dark matter, wherein oscillations of the effective θ angle induce periodic variation in nuclear binding energies and hence decay rates.
- We analyse 12 years of tritium decay data ($Q \simeq 18.6$ keV) taken at the European Commission's Joint Research Centre. Finding no statistically significant excess, we exclude axion decay constants below $9.4 \times 10^{12} - 1.8 \times 10^{10}$ GeV (95 % confidence level) for masses in the $1.7 \times 10^{-23} - 8.7 \times 10^{-21}$ eV range.

Summary

- We do find the axion induced signal at 4.7σ for the lowest 15 trial frequencies, which we exclude them from this analysis.
- This axion parameter space has been excluded by the neutron EDM experiments if we assume the isospin conservation.
- Interesting question: can we evade the constraints from the neutron EDM experiments if we consider the isospin violation?
- Question: Can we explain the nuclear decay anomaies via the super light CP-odd and CP-even dark scalars, as well as dark photons, whose densities arise from misalignment mechanism?

Thank You Very Much for Your Attention!