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Dark Matter Interpretation of the Neutron Decay Anomaly

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There is a long-standing discrepancy between the neutron lifetime measured in beam and bottle experiments. We propose to explain this anomaly by a dark decay channel for the neutron, involving a dark sector particle in the final state. If this particle is stable, it can be the dark matter. Its mass is close to the neutron mass, suggesting a connection between dark and baryonic matter. In the most interesting scenario a monochromatic photon with energy in the range 0.782 MeV – 1.665 MeV and branching fraction 1% is expected in the final state. We construct representative particle physics models consistent with all experimental constraints.

I. INTRODUCTION

The neutron is one of the fundamental building blocks of matter. Along with the proton and electron it makes up most of the visible universe. Without it, complex atomic nuclei simply would not have formed. Although the neutron was discovered over eighty years ago [1] and has been studied intensively thereafter, its precise lifetime is still an open question [2]. The dominant neutron decay mode is β decay,

$$n \to p + e^- + \bar{\nu}_e \,, \qquad (1)$$

theoretically described by the matrix element

$$\mathcal{M} = [\, G_V \, \bar{p} \, \gamma_\mu n - G_A \, \bar{p} \, \gamma_5 \gamma_\mu n \,] \, [\, \bar{e} \, \gamma_\mu (1 - \gamma_5) \nu \,] \,. \quad (2)$$

Although the vector coupling G_V is measured accurately in superallowed nuclear β decays [3], due to the uncertainty in calculating the matrix elements of axial vector currents the coupling G_A cannot be precisely extracted from other nuclear decays, resulting in a lack of an accurate theoretical prediction for the neutron lifetime.

There are two qualitatively different types of neutron lifetime measurements: bottle and beam experiments. In the first method, ultracold neutrons are stored in a container for a time comparable to the neutron lifetime. The remaining neutrons that did not decay are counted and fit to a decaying exponential, $\exp(-t/\tau_n)$. The average from the five bottle experiments included in the Particle Data Group (PDG) [4] world average [5–9] is

$$\tau_n^{\text{bottle}} = 879.6 \pm 0.6 \,\text{s} \,. \qquad (3)$$

In the beam method, both the number of neutrons N in a beam and the protons resulting from β decays are counted, and the lifetime is obtained from the decay rate, $dN/dt = -N/\tau_n$. This yields a considerably longer neutron lifetime; the average from the two beam experiments included in the PDG average [10, 11] is

$$\tau_n^{\text{beam}} = 888.0 \pm 2.0 \,\text{s} \,. \qquad (4)$$

The discrepancy between the two results is $4.0\,\sigma$. This suggests that either one of the measurement methods suffers from an uncontrolled systematic error, or the theory itself provides inaccurate predictions.

In this letter we focus on the latter possibility. We assume that the discrepancy between the neutron lifetime measurements arises from an incomplete theoretical description of neutron decay and we investigate how the Standard Model (SM) can be extended to account for the anomaly.

II. NEUTRON DARK DECAY

Since in the beam experiments neutron decay is observed by detecting decay protons, the lifetime measured in those experiments is related to the neutron lifetime by

$$\tau_n^{\text{beam}} = \frac{\tau_n}{\text{Br}(n \to p + \text{anything})} \,. \qquad (5)$$

In the SM the branching fraction (Br), dominated by β decay, is 100% and the two lifetimes are the same. The neutron decay rate obtained from bottle experiments is

$$\Gamma_n = \frac{1}{\tau_n} \simeq 7.5 \times 10^{-28} \,\text{GeV} \,. \qquad (6)$$

The discrepancy $\Delta \tau_n \simeq 8.4 \,\text{s}$ between the values measured in bottle and beam experiments corresponds to

$$\Delta \Gamma_n^{\text{exp}} = \Gamma_n^{\text{bottle}} - \Gamma_n^{\text{beam}} \simeq 7.1 \times 10^{-30} \,\text{GeV} \,. \quad (7)$$

We propose that this difference be explained by the existence of a *dark decay* channel for the neutron, which makes $\text{Br}(n \to p + \text{anything}) \approx 99\%$. There are two qualitatively different scenarios for the new dark decay channel, depending on whether the final state consists entirely of dark particles or contains visible ones:

$$n \to \text{invisible} + \text{visible} \,, \qquad (8)$$
$$n \to \text{invisible} \,. \qquad (9)$$

Here the label "invisible" includes dark sector particles, as well as neutrinos. Such decays are described by an effective operator $\mathcal{O} = Xn$, where n is the neutron and X is a spin $1/2$ operator, possibly composite, e.g. $X = \chi_1 \chi_2 ... \chi_k$, with the χ's being fermions and bosons combining into spin $1/2$. From an experimental point of view, channel (8) offers a detection possibility, whereas channel (9) relies on higher order radiative processes. In Sec. III we provide examples of both.

Proton decay constraints
The operator $\mathcal{O}$ violates baryon number and generically gives rise to proton decay via

$$p \to n^* + e^+ + \nu_e \,, \qquad (10)$$

followed by the decay of n^* through the channel (8) or (9) and has to be suppressed [12]. Proton decay can be eliminated from the theory if the sum of masses of particles in the minimal final state f of the neutron decay process, say M_f, is larger than $m_p - m_e$. On the other hand, for the neutron to

decay, M_f must be smaller than the neutron mass, therefore the following condition is required:

$$m_p - m_e < M_f < m_n \ . \tag{11}$$

Nuclear physics bounds

In general, the decay channels (8) and (9) could trigger nuclear transitions from (Z, A) to $(Z, A - 1)$. If such a transition is accompanied by a prompt emission of a state f' with the sum of masses of particles making up f' equal to $M_{f'}$, it can be eliminated from the theory by imposing $M_{f'} > \Delta M = M(Z, A) - M(Z, A - 1)$. Of course $M_{f'}$ need not be the same as M_f, since the final state f' in nuclear decay may not be available in neutron decay. For example, $M_{f'} < M_f$ when the state f' consists of a single particle, which is not an allowed final state of the neutron decay. If $f' = f$ then f' must contain at least two particles. The requirement becomes, therefore,

$$\Delta M < \min\{M_{f'}\} \le M_f \ . \tag{12}$$

The most stringent of such nuclear decay constraints comes from the requirement of ^{9}Be stability, for which $\Delta M = 937.900$ MeV, thus Eqs. (11) and (12) give

$$937.900 \text{ MeV} < \min\{M_{f'}\} \le M_f < 939.565 \text{ MeV} \ . \tag{13}$$

The condition in Eq. (13) circumvents all nuclear decay limits listed in PDG [4], including the most severe ones [13–15].

Dark matter

Consider f to be a two-particle final state containing a dark sector spin $1/2$ particle χ. Assuming the presence of the interaction χn, the condition in Eq. (13) implies that the other particle in f has to be a photon or a dark sector particle ϕ with mass $m_\phi < 1.665$ MeV (we take it to be spinless). The decay $\chi \to p + e^- + \bar{\nu}_e$ is forbidden if

$$m_\chi < m_p + m_e = 938.783 \text{ MeV} \ . \tag{14}$$

Provided there are no other decay channels for χ, Eq. (14) ensures that χ is stable, thus making it a DM candidate. On the other hand, if $\chi \to p + e^- + \bar{\nu}_e$ is allowed, although this prevents χ from being the DM, its lifetime is still long enough to explain the neutron decay anomaly. In both scenarios ϕ can be a DM particle as well.

Without the interaction χn, only the sum of final state masses is constrained by Eq. (13). Both χ and ϕ can be DM candidates, provided their masses are smaller than $m_p + m_e$. One can also have a scalar DM particle ϕ with mass $m_\phi < 938.783$ MeV and χ being a Dirac right-handed neutrino. Trivial model-building variations are implicit. The scenarios with a Majorana fermion χ or a real scalar ϕ are additionally constrained by neutron-antineutron oscillation and dinucleon decay searches [16, 17].

III. MODEL-INDEPENDENT ANALYSIS

Based on the discussed experimental constraints, the available channels for the neutron dark decay are: (A) $n \to \chi \gamma$, (B) $n \to \chi e^+ e^-$, (C) $n \to \chi \phi$, (D) all of the above with additional dark particle(s) and/or photon(s). We analyze the possibilities (A) – (C) below.

(A) Neutron → dark matter + photon

This decay is realized in the case of a two-particle interaction involving the fermion DM χ and a three-particle interaction including χ and a photon, i.e., χn, $\chi n \gamma$. Equations (13) and (14) imply that the DM mass is

$$937.900 \text{ MeV} < m_\chi < 938.783 \text{ MeV} \tag{15}$$

and the final state photon energy

$$0.782 \text{ MeV} < E_\gamma < 1.665 \text{ MeV} \ . \tag{16}$$

There are no experimental constraints on such single photons. The only related search measures photons from radiative β decays in a neutron beam [18]. However, photons are recorded only if they appear in coincidence with a proton and an electron, which is not the case here.

To describe this case in a quantitative way, we consider theories with an explicit baryon number violating interaction χn, and an interaction $\chi n \gamma$ mediated by a mixing between the neutron and χ. An example of such a theory is given by the effective Lagrangian

$$\mathcal{L}_I^{\text{eff}} = \bar{n} \left(i\slashed{\partial} - m_n + \frac{g_n e}{2m_n} \sigma^{\mu\nu} F_{\mu\nu} \right) n$$
$$+ \bar{\chi} \left(i\slashed{\partial} - m_\chi \right) \chi + \varepsilon \left(\bar{n}\chi + \bar{\chi}n \right) \ , \tag{17}$$

where $g_n \simeq -3.826$ is the neutron g-factor and ε is the mixing parameter with dimension of mass. The term corresponding to $n \to \chi \gamma$ is obtained by transforming Eq. (17) to the mass eigenstate basis and, for $\varepsilon \ll m_n - m_\chi$, yields

$$\mathcal{L}_{n\to\chi\gamma}^{\text{eff}} = \frac{g_n e}{2m_n} \frac{\varepsilon}{(m_n - m_\chi)} \bar{\chi} \sigma^{\mu\nu} F_{\mu\nu} n \ . \tag{18}$$

Therefore, the neutron dark decay rate is

$$\Delta\Gamma_{n\to\chi\gamma} = \frac{g_n^2 e^2}{8\pi} \left(1 - \frac{m_\chi^2}{m_n^2} \right)^3 \frac{m_n \, \varepsilon^2}{(m_n - m_\chi)^2}$$
$$\approx \Delta\Gamma_n^{\text{exp}} \left(\frac{1+x}{2} \right)^3 \left(\frac{1-x}{1.8\times10^{-3}} \right) \left(\frac{\varepsilon \, [\text{GeV}]}{9.3\times10^{-14}} \right)^2, \tag{19}$$

where $x = m_\chi/m_n$. The rate is maximized when m_χ saturates the lower bound in Eq. (15).

The testable prediction of this class of models is a monochromatic photon with an energy in the range specified by Eq. (16) and a branching fraction

$$\frac{\Delta\Gamma_{n\to\chi\gamma}}{\Gamma_n} \approx 1\% \ . \tag{20}$$

A signature involving an $e^+ e^-$ pair with total energy $E_{e^+e^-} < 1.665$ MeV is also expected, but with a suppressed branching fraction of $\sim 10^{-6}$.

If χ is not a DM particle, the bound in Eq. (14) no longer applies and the final state monochromatic photon can have an energy in a wider range:

$$0 < E_\gamma < 1.665 \text{ MeV} \ . \tag{21}$$

A particle physics realization of this case is provided by model 1 in Sec. IV.

(B) Neutron → dark matter + e^+e^-

We now investigate the case where e^+e^- is the dominant signature, as opposed to case (A) where such a process was suppressed compared to the photon signal. We assume a four-particle interaction $\chi n \bar{e} e$. A two-particle interaction χn may also be present, but, if that is the case, we assume its effects are subdominant. The requirement on the DM mass from Eq. (13) is

$$937.900 \text{ MeV} < m_\chi < 938.543 \text{ MeV} . \quad (22)$$

The allowed energy range of the e^+e^- pair is

$$2m_e \leq E_{e^+e^-} < 1.665 \text{ MeV} . \quad (23)$$

Denoting the effective term for $n \to \chi e^+ e^-$ by

$$\mathcal{L}^{\text{eff}}_{n \to \chi e^+ e^-} = \kappa \, \bar{\chi} n \, \bar{e} e , \quad (24)$$

the neutron dark decay rate is

$$\Delta\Gamma_n = \frac{\kappa^2 m_n^5}{128\,\pi^3} \int_{4z^2}^{(1-x)^2} \frac{d\xi}{\sqrt{\xi}} \left(\xi - 4z^2\right)^{\frac{3}{2}} \left[(1+x)^2 - \xi\right]$$
$$\times \sqrt{(1-x^2-\xi)^2 - 4\,\xi\,x^2} , \quad (25)$$

where $x = m_\chi/m_n$ and $z = m_e/m_n$. It is maximized for $m_\chi = 937.9$ MeV, in which case it requires $1/\sqrt{\kappa} \approx 670$ GeV to explain the anomaly. We will not analyze further this possibility.

(C) Neutron → two dark particles

Denoting the final state dark fermion and scalar by χ and ϕ, respectively, and an intermediate dark fermion by $\tilde{\chi}$, consider a scenario with both a two- and three-particle interaction, $\tilde{\chi} n$, $\chi n \phi$. The requirement in Eq. (13) takes the form

$$937.900 \text{ MeV} < m_\chi + m_\phi < 939.565 \text{ MeV} . \quad (26)$$

For χ to be a DM particle, Eq. (15) additionally applies. The only condition $\tilde{\chi}$ must fulfill is

$$m_{\tilde{\chi}} > 937.900 \text{ MeV} . \quad (27)$$

If $m_{\tilde{\chi}} > m_n$, the only neutron dark decay channels are $n \to \chi\phi$ and $n \to \tilde{\chi}^* \to p + e^- + \bar{\nu}_e$, with branching fractions governed by the strength of the $\chi n \phi$ interaction. Even if this coupling is zero, the lifetime of $\tilde{\chi}$ is long enough for the anomaly to be explained.

In the case 937.9 MeV $< m_{\tilde{\chi}} < m_n$, the particle $\tilde{\chi}$ can be produced on-shell and there are three neutron dark decay channels: $n \to \tilde{\chi}\gamma$, $n \to \chi\phi$ and $n \to \tilde{\chi}^* \to p + e^- + \bar{\nu}_e$ (when $m_{\tilde{\chi}} > 938.783$ MeV), with branching fractions depending on the strength of the $\chi n \phi$ coupling. The rate for the decay $n \to \tilde{\chi}^* \to p + e^- + \bar{\nu}_e$ is negligible compared to that for $n \to \tilde{\chi}\gamma$. In the limit of a vanishing $\chi n \phi$ coupling this case reduces to case (A).

An example of such a theory, in which baryon number violation originates exclusively from the coupling $\tilde{\chi} n$, is

$$\mathcal{L}^{\text{eff}}_{III} = \bar{n}\left(i\slashed{\partial} - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\tilde{\chi}}\left(i\slashed{\partial} - m_{\tilde{\chi}}\right)\tilde{\chi}$$
$$+ \bar{\chi}\left(i\slashed{\partial} - m_\chi\right)\chi + i\partial_\mu\phi^*\partial^\mu\phi + m_\phi^2|\phi|^2$$
$$+ \varepsilon\left(\bar{n}\tilde{\chi} + \bar{\tilde{\chi}}n\right) + \left(\lambda_\phi \, \bar{\tilde{\chi}}\chi\,\phi + \text{h.c.}\right) . \quad (28)$$

The term corresponding to $n \to \chi\phi$ is

$$\mathcal{L}^{\text{eff}}_{n \to \chi\phi} = \frac{\lambda_\phi\,\varepsilon}{m_n - m_{\tilde{\chi}}} \, \bar{\chi} n \, \phi^* . \quad (29)$$

This yields the neutron dark decay rate

$$\Delta\Gamma_{n \to \chi\phi} = \frac{|\lambda_\phi|^2}{16\pi} \sqrt{f(x,y)} \, \frac{m_n \varepsilon^2}{(m_n - m_{\tilde{\chi}})^2} , \quad (30)$$

where

$$f(x,y) = \left[(1-x)^2 - y^2\right]\left[(1+x)^2 - y^2\right]^3 , \quad (31)$$

with $x = m_\chi/m_n$ and $y = m_\phi/m_n$. A particle physics realization of this scenario is provided by model 2 in Sec. IV

For $m_{\tilde{\chi}} > m_n$ the missing energy signature has a branching fraction $\approx 1\%$. There will also be a radiative process involving a photon in the final state, suppressed by $\sim g_n^2 e^2/(16\pi^2)$, thus with a branching fraction $\sim 0.01\%$.

As discussed earlier, in the case 937.9 MeV $< m_{\tilde{\chi}} < m_n$ both the visible and invisible neutron dark decay channels are present. The ratio of their branching fractions is

$$\frac{\Delta\Gamma_{n \to \chi\gamma}}{\Delta\Gamma_{n \to \chi\phi}} = \frac{2g_n^2 e^2}{|\lambda_\phi|^2} \frac{(1-x^2)^3}{\sqrt{f(x,y)}} \left(\frac{m_n - m_{\tilde{\chi}}}{m_n - m_\chi}\right)^2 , \quad (32)$$

while their sum accounts for the neutron decay anomaly, i.e.

$$\frac{\Delta\Gamma_{n \to \chi\gamma} + \Delta\Gamma_{n \to \chi\phi}}{\Gamma_n} \approx 1\% . \quad (33)$$

The branching fraction for the process involving a photon in the final state ranges thus from $\sim 0.01\%$ to 1%. A suppressed decay channel involving e^+e^- is also present.

IV. PARTICLE PHYSICS MODELS

Here we present two microscopic renormalizable models that are representative of cases (A) and (C) in Sec. III.

Model 1

The minimal model for the neutron dark decay requires only two particles beyond the SM: a scalar $\Phi = (3, 1)_{-1/3}$ (color triplet, weak singlet, hypercharge $-1/3$), and a Dirac fermion χ (SM singlet, which can be the DM). This model is a realization of case (A) in Sec. III. The neutron dark decay proceeds through the process shown in Fig. 1. The corresponding Lagrangian is[1]

$$\mathcal{L}_1 = \left(\lambda_q \, \epsilon^{ijk} \, \overline{u^c_{Li}} \, d_{Rj}\Phi_k + \lambda_\chi \Phi^{*i}\bar{\chi}\, d_{Ri} + \text{h.c.}\right)$$
$$+ M_\Phi^2|\Phi|^2 + m_\chi \, \bar{\chi}\chi , \quad (34)$$

---

[1] As pointed out in [19–21], adding just the field Φ to the SM triggers rapid proton decay unless the product of its diquark and leptoquark couplings is small. We assume a negligible leptoquark coupling in our analysis. This assumption is not necessary in the framework of the recently constructed grand unified theory with no proton decay [22].
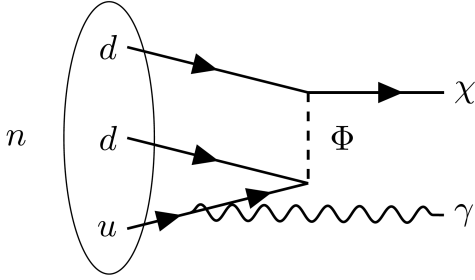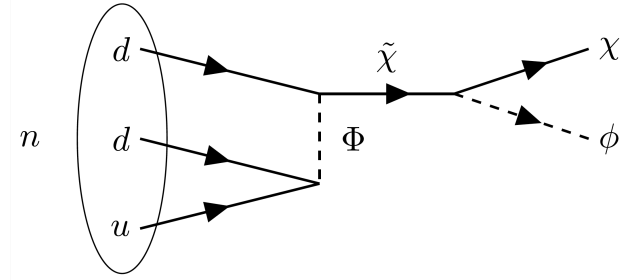
FIG. 1. Dark decay of the neutron in model 1.

FIG. 2. Dark decay of the neutron in model 2.

where u_L^c is the complex conjugate of u_R. The rate for $n \to \chi\gamma$ is given by Eq. (19) with

$$\varepsilon = \frac{\beta \lambda_q \lambda_\chi}{M_\Phi^2} , \qquad (35)$$

where β is defined by [23]

$$\langle 0|\epsilon^{ijk} \overline{u_{Li}^c} d_{Rj} d_{Rk}|n\rangle = \beta P_R u_n , \qquad (36)$$

with the neutron spinor field u_n. Lattice QCD techniques give $\beta \simeq 0.014$ GeV^3. Assuming $m_\chi = 937.9$ MeV to maximize the rate, the parameter choice explaining the anomaly is

$$\frac{|\lambda_q \lambda_\chi|}{M_\Phi^2} \approx 6.7 \times 10^{-6} \text{ TeV}^{-2} . \qquad (37)$$

In addition to the monochromatic photon with energy $E_\gamma < 1.665$ MeV and the e^+e^- signal discussed in Sec. III, one may search directly also for Φ. It can be singly produced through $p\,p \to \Phi$ or pair produced via gluon fusion $g\,g \to \Phi\,\Phi$. This results in a dijet or four-jet signal from $\Phi \to d^c u^c$, as well as a monojet plus missing energy signal from $\Phi \to d\,\chi$. Given Eq. (37), Φ is not excluded by recent LHC analyses provided $M_\Phi \gtrsim 1$ TeV [24–26].[2]

If χ is the DM, due to the lack of an efficient annihilation channel, it has to be non-thermally produced. This can be realized via a late decay of a new heavy scalar, as shown for a related model in [27]. Alternatively, one can introduce a lighter unstable field ϕ which χ could annihilate to.

The parameter choice in Eq. (37) is excluded if χ is a Majorana particle, as in the model proposed in [28], by the neutron-antineutron oscillation and dinucleon decay constraints [16, 17].

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[2] A similar model with a scalar $\Phi = (3, 1)_{2/3}$ would also work as an explanation of the neutron decay anomaly, again requiring χ to be Dirac. Since the scalar $(3, 1)_{2/3}$ does not couple to two first generation quarks, the rate in Eq. (37) would be suppressed by the strange quark content of the neutron and would require a larger value of $|\lambda_q \lambda_\chi|/M_\Phi^2$. Another viable option for Φ is the vector $(3, 2)_{1/6}$.

Model 2

A representative model for case (C) discussed in Sec. III involves four new particles: the scalar $\Phi = (3, 1)_{-1/3}$, two Dirac fermions $\tilde{\chi}$, χ (where χ can be the DM), and a complex scalar ϕ, the last three being SM singlets. The dark decay of the neutron in this model is shown in Fig. 2. The Lagrangian is given by

$$\mathcal{L}_2 = \left(\lambda_q \, \epsilon^{ijk} \, \overline{u_{Li}^c} \, d_{Rj} \Phi_k + \lambda_\chi \Phi^{*i} \bar{\tilde{\chi}} d_{Ri} + \lambda_\phi \, \bar{\tilde{\chi}} \chi \, \phi + \text{h.c.}\right)$$
$$+ M_\Phi^2 |\Phi|^2 + m_\phi^2 |\phi|^2 + m_\chi \bar{\chi} \chi + m_{\tilde{\chi}} \bar{\tilde{\chi}} \tilde{\chi} . \qquad (38)$$

With a mass in the range specified by Eqs. (15) and (26), χ is a DM candidate in this model. For $m_\chi > m_\phi$ the annihilation channel $\chi \bar{\chi} \to \phi \bar{\phi}$ via a t-channel $\tilde{\chi}$ exchange is open. The observed DM relic density is obtained for $\lambda_\phi \simeq 0.037$.

The rate for $n \to \chi \phi$ is described by Eq. (30) with ε given by Eq. (35). It is maximal for $m_\chi = 937.9$ MeV and $m_\phi \approx 0$. Assuming $m_{\tilde{\chi}} = m_\chi$, the anomaly is explained with

$$\frac{|\lambda_q \lambda_\chi|}{M_\Phi^2} \frac{|\lambda_\phi|}{0.04} \approx 4.9 \times 10^{-7} \text{ TeV}^{-2} . \qquad (39)$$

For $\lambda_\phi \approx 0.04$ this is consistent with LHC searches, provided again that $M_\Phi \gtrsim 1$ TeV. For similar reasons as before, χ and $\tilde{\chi}$ cannot be Majorana particles.

As discussed in Sec. III, in this model the branching fractions for the visible (including a photon) and invisible final states can be comparable, and their relative size is described by Eq. (32). A final state containing an e^+e^- pair is also possible. The same LHC signatures are expected as in model 1.

V. CONCLUSIONS

The puzzling discrepancy between the neutron lifetime measurements has been around for over twenty years. We could not find any theoretical model for this anomaly in the literature. In this letter we bring the neutron enigma into attention by showing that it can be explained by a dark decay channel for the neutron that contains an unobservable particle in the final state. We illustrate the most promising scenarios with simple particle physics models.

Despite most of the energy from the neutron dark decay escaping into the dark sector, our proposal is experimentally verifiable. The most striking and unique signature is monochromatic photons with energies less than 1.665 MeV. Furthermore, if the dark particle is the dark matter, the energy of the photon is bounded by 0.782 MeV from below. The simplest model predicts the neutron decay into dark matter and a photon with a branching fraction of approximately 1%. Another signature consists of electron-positron pairs with total energy less than 1.665 MeV. It would be interesting to perform a detailed analysis of the experimental reach for such signals.

From a theoretical particle physics perspective, our analysis opens the door to rich model building opportunities well beyond the two simple examples we provided. In particular, we have not investigated how neutron dark decay models address the outstanding problems of the Standard Model other than the dark matter. Perhaps the dark matter mass being close to the nucleon mass can explain the matter-antimatter asymmetry of the universe via a similar mechanism as in asymmetric dark matter models.

Finally, the neutron lifetime has profound consequences for nuclear physics and astrophysics, e.g., it affects the primordial helium production during nucleosynthesis [29] and impacts the determination of the neutrino effective number from the cosmic microwave background [30]. If the dark decay channel of the neutron we propose is the true explanation for the difference in the results of bottle and beam experiments, then the correct value for the neutron lifetime is $\tau_n \simeq 880$ s.

[1] J. Chadwick, "*The Existence of a Neutron*," Proceedings of the Royal Society of London Series A **136**, 692–708 (1932).

[2] F. E. Wietfeldt and G. L. Greene, "*The Neutron Lifetime*," Reviews of Modern Physics **83**, 1173–1192 (2011).

[3] J. C. Hardy and I. S. Towner, "*Superallowed $0^+ \to 0^+$ Nuclear β Decays: 2014 Critical Survey, with Precise Results for V_{ud} and CKM Unitarity*," Phys. Rev. **C91**, 025501 (2015), arXiv:1411.5987 [nucl-ex].

[4] C. Patrignani *et al.* (Particle Data Group), "*Review of Particle Physics*," Chin. Phys. **C40**, 100001 (2016).

[5] W. Mampe, L. N. Bondarenko, V. I. Morozov, Y. N. Panin, and A. I. Fomin, "*Measuring Neutron Lifetime by Storing Ultracold Neutrons and Detecting Inelastically Scattered Neutrons*," JETP Lett. **57**, 82–87 (1993), [Pisma Zh. Eksp. Teor. Fiz.57,77(1993)].

[6] A. Serebrov *et al.*, "*Measurement of the Neutron Lifetime Using a Gravitational Trap and a Low-Temperature Fomblin Coating*," Phys. Lett. **B605**, 72–78 (2005), arXiv:nucl-ex/0408009 [nucl-ex].

[7] A. Pichlmaier, V. Varlamov, K. Schreckenbach, and P. Geltenbort, "*Neutron Lifetime Measurement with the UCN Trap-in-Trap MAMBO II*," Phys. Lett. **B693**, 221–226 (2010).

[8] A. Steyerl, J. M. Pendlebury, C. Kaufman, S. S. Malik, and A. M. Desai, "*Quasielastic Scattering in the Interaction of Ultracold Neutrons with a Liquid Wall and Application in a Reanalysis of the Mambo I Neutron Lifetime Experiment*," Phys. Rev. **C85**, 065503 (2012).

[9] S. Arzumanov, L. Bondarenko, S. Chernyavsky, P. Geltenbort, V. Morozov, V. V. Nesvizhevsky, Yu. Panin, and A. Strepetov, "*A Measurement of the Neutron Lifetime Using the Method of Storage of Ultracold Neutrons and Detection of Inelastically Up-Scattered Neutrons*," Phys. Lett. **B745**, 79–89 (2015).

[10] J. Byrne and P. G. Dawber, "*A Revised Value for the Neutron Lifetime Measured Using a Penning Trap*," Europhys. Lett. **33**, 187 (1996).

[11] A. T. Yue, M. S. Dewey, D. M. Gilliam, G. L. Greene, A. B. Laptev, J. S. Nico, W. M. Snow, and F. E. Wietfeldt, "*Improved Determination of the Neutron Lifetime*," Phys. Rev. Lett. **111**, 222501 (2013), arXiv:1309.2623 [nucl-ex].

[12] K. Abe *et al.* (Super-Kamiokande), "*Search for Proton Decay via $p \to e^+ \pi^0$ and $p \to \mu^+ \pi^0$ in 0.31 Megaton·years Exposure of the Super-Kamiokande Water Cherenkov Detector*," Phys. Rev. **D95**, 012004 (2017), arXiv:1610.03597 [hep-ex].

[13] S. N. Ahmed *et al.* (SNO), "*Constraints on Nucleon Decay via Invisible Modes from the Sudbury Neutrino Observatory*," Phys. Rev. Lett. **92**, 102004 (2004), arXiv:hep-ex/0310030 [hep-ex].

[14] T. Araki *et al.* (KamLAND), "*Search for the Invisible Decay of Neutrons with KamLAND*," Phys. Rev. Lett. **96**, 101802 (2006), arXiv:hep-ex/0512059 [hep-ex].

[15] V. Takhistov *et al.* (Super-Kamiokande), "*Search for Nucleon and Dinucleon Decays with an Invisible Particle and a Charged Lepton in the Final State at the Super-Kamiokande Experiment*," Phys. Rev. Lett. **115**, 121803 (2015), arXiv:1508.05530 [hep-ex].

[16] K. Abe *et al.* (Super-Kamiokande), "*The Search for $n-\bar{n}$ Oscillation in Super-Kamiokande I*," Phys. Rev. **D91**, 072006 (2015), arXiv:1109.4227 [hep-ex].

[17] J. Gustafson *et al.* (Super-Kamiokande), "*Search for Dinucleon Decay into Pions at Super-Kamiokande*," Phys. Rev. **D91**, 072009 (2015), arXiv:1504.01041 [hep-ex].

[18] M. J. Bales *et al.* (RDK II), "*Precision Measurement of the Radiative β Decay of the Free Neutron*," Phys. Rev. Lett. **116**, 242501 (2016), arXiv:1603.00243 [nucl-ex].

[19] J. M. Arnold, B. Fornal, and M. B. Wise, "*Simplified Models with Baryon Number Violation But No Proton Decay*," Phys. Rev. **D87**, 075004 (2013), arXiv:1212.4556 [hep-ph].

[20] I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik, and N. Košnik, "*Physics of Leptoquarks in Precision Experiments and at Particle Colliders*," Phys. Rept. **641**, 1–68 (2016), arXiv:1603.04993 [hep-ph].

[21] N. Assad, B. Fornal, and B. Grinstein, "*Baryon Number and Lepton Universality Violation in Leptoquark and Diquark Models*," Phys. Lett. **B777**, 324–331 (2018), arXiv:1708.06350 [hep-ph].

[22] B. Fornal and B. Grinstein, "*SU(5) Unification without Proton Decay*," Phys. Rev. Lett. **119**, 241801 (2017), arXiv:1706.08535 [hep-ph].

[23] Y. Aoki, T. Izubuchi, E. Shintani, and A. Soni, "*Improved Lattice Computation of Proton Decay Matrix Elements*," Phys. Rev. **D96**, 014506 (2017), arXiv:1705.01338 [hep-lat].

[24] M. Aaboud *et al.* (ATLAS), "*Search for New Phenomena in Dijet Events Using 37 fb^{-1} of pp Collision Data Collected*

at $\sqrt{s}$ =13 TeV with the ATLAS Detector," Phys. Rev. **D96**, 052004 (2017), arXiv:1703.09127 [hep-ex].

[25] M. Aaboud *et al.* (ATLAS), "*A Search for Pair-Produced Resonances in Four-Jet Final States at $\sqrt{s}$=13 TeV with the ATLAS Detector*," (2017), arXiv:1710.07171 [hep-ex].

[26] M. Aaboud *et al.* (ATLAS), "*Search for Dark Matter and Other New Phenomena in Events with an Energetic Jet and Large Missing Transverse Momentum Using the ATLAS Detector*," (2017), arXiv:1711.03301 [hep-ex].

[27] R. Allahverdi, P. S. B. Dev, and B. Dutta, "*A Simple Testable Model of Baryon Number Violation: Baryogenesis, Dark Matter, Neutron-Antineutron Oscillation and Collider Signals*,"

(2017), arXiv:1712.02713 [hep-ph].

[28] D. McKeen and A. E. Nelson, "*CP Violating Baryon Oscillations*," Phys. Rev. **D94**, 076002 (2016), arXiv:1512.05359 [hep-ph].

[29] G. J. Mathews, T. Kajino, and T. Shima, "*Big Bang Nucleosynthesis with a New Neutron Lifetime*," Phys. Rev. **D71**, 021302 (2005), arXiv:astro-ph/0408523 [astro-ph].

[30] L. Capparelli, E. Di Valentino, A. Melchiorri, and J. Chluba, "*The Impact of Theoretical Assumptions in the Determination of the Neutrino Effective Number from Future CMB Measurements*," (2017), arXiv:1712.06965 [astro-ph.CO].