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Letter

Searching for axions with kaon decay at rest

Yohei Ema,[1,2,*] Zhen Liu,[2,†] and Ryan Plestid[3,‡]
[1]*William I. Fine Theoretical Physics Institute, University of Minnesota,*
Minneapolis, Minnesota 55455, USA
[2]*School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[3]*Walter Burke Institute for Theoretical Physics, California Institute of Technology,*
Pasadena, California 91125, USA

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We describe a novel search strategy for axions (or hadronically coupled axionlike particles) in the mass range of $m_a \lesssim 350$ MeV. The search relies on kaon decay at rest, which produces a monoenergetic signal in a large volume detector (e.g., a tank of liquid scintillator) from axion decays $a \to \gamma\gamma$ or $a \to e^+e^-$. The decay modes $K^+ \to \pi^+ a$ and $a \to \gamma\gamma$ are induced by the axion's coupling to gluons, which is generic to any model which addresses the strong CP problem. We recast a recent search from MicroBooNE for e^+e^- pairs and study prospects at JSNS^2 and other near-term facilities. We find that JSNS^2 will have world-leading sensitivity to hadronically coupled axions in the mass range of 40 MeV $\lesssim m_a \lesssim 350$ MeV.

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Introduction. The neutron's electron dipole moment (EDM), $d_n \lesssim 2\times 10^{-26}$ e cm [1,2], is 10 orders of magnitude smaller than its naive estimate of 5×10^{-16} e cm. This is unexpected since charge parity (CP) is violated within the Standard Model (SM), and therefore no fundamental symmetry forbids a neutron EDM. This is the strong CP problem, and its microscopic origin can be traced to the minuscule value of the QCD $\bar{\theta}$ parameter, $\bar{\theta} \lesssim 10^{-10}$, which controls the unique CP-violating QCD coupling in the SM. Axions are a popular solution that provide a dynamical mechanism for the relaxation of $\bar{\theta}$ [3–6]; if the axion's potential is generated exclusively by QCD, it naturally aligns the axion's ground state with $\bar{\theta} = 0$.

Axions generically suffer from the so-called quality problem [7–10] wherein high energy contributions to the axion potential can (and often do) displace the minimum away from $\bar{\theta} = 0$. These problem does not arise if the QCD potential is "strenghtened", for instance by introducing a mirror QCD sector. These nonminimal axion models produce a potential that is robust against the high energy corrections discussed above and often predict heavier axions as compared to minimal axion models [11–31].

Recent investigations have reignited interest in these so-called heavy axion models with $m_a \gtrsim 1$ MeV. More generally, there is a broad interest in axionlike particles (ALPs) [32,33], which may serve as IR messengers of UV completions such as a string landscape [34,35]. A wide range of search strategies have been proposed ranging from beam dumps, to flavor facilities, and collider experiments [32,36–60].

In this work, we point out that kaon decay at rest (KDAR) offers a powerful probe of axions (or hadronically coupled ALPs) in the mass range of $m_a = 40$–350 MeV. Unlike previous studies of KDAR [61,62] the axions we consider are naturally coupled to quarks and/or gluons such that the hadronic decays of kaons serve as a powerful axion factory. The signal is a visible decay of either $a \to \gamma\gamma$ or $a \to e^+e^-$. The dominant SM kaon decay modes are $K^+ \to \mu^+\nu_\mu$, as well as $K^+ \to \pi^0 e^+ \nu_e$,[1] and both channels produce a neutrino flux that can be measured [63,64]. In addition to predictions of hadronic cascade simulations, this provides an experiment with an *in situ* measurement of their KDAR population. The axion rate is then calculable, and a counting experiment can be performed.

For concreteness, we consider an axion coupled to Standard Model (SM) gauge bosons via

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 - \frac{m_a^2}{2}a^2 + c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f}W_{\mu\nu}\tilde{W}^{\mu\nu} + c_{BB}\frac{\alpha_Y}{4\pi}\frac{a}{f}B_{\mu\nu}\tilde{B}^{\mu\nu}, \quad (1)$$

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[*] ema00001@umn.edu
[†] zliuphys@umn.edu
[‡] rplestid@caltech.edu

[1] Negatively charged K^- decays are subdominant to K^- capture on nuclei. This cannot occur for K^+ because it does not form bound states with nuclei.

at a high scale, where a is the axion, and $\alpha_s = g_s^2/4\pi$, $\alpha_2 = g^2/4\pi$ and $\alpha_Y = g'^2/4\pi$. The coupling c_{GG} can be absorbed into f, and we define the axion decay constant as $f_a = f/2c_{GG}$. As two useful benchmarks, we focus on the so-called "gluon dominance" ($c_{GG} \neq 0$, $c_{WW} = c_{BB} = 0$) and "codominance" ($c_{GG} = c_{WW} = c_{BB} \neq 0$) scenarios following [65–67] (using the relative normalization of c_{BB} in [66,67]). We do not consider, e.g., axion couplings to quarks, though their inclusion is straightforward. In what follows, we discuss the theory of $K^+ \to \pi^+ a$, and project sensitivities for JSNS^2 and a MicroBooNE $\gamma\gamma$ search.

Kaon decay at rest. In models with a hadronically coupled axion, $K^+ \to \pi^+ a$ serves as a powerful axion production channel. Since axions are long-lived, they decay in flight to visible final states. The resulting signal is a monoenergetic peak at an energy of

$$E_a = \frac{m_K^2 + m_a^2 - m_\pi^2}{2m_K}. \tag{2}$$

This indicates that the heavier axion carries more energy and its minimal value is given by setting $m_a = 0$ as $E_a > 227$ MeV. The branching ratio for $K^+ \to \pi^+ a$ can be reliably predicted in chiral perturbation theory [68], with the result [neglecting terms of $\mathcal{O}(m_a^2/m_K^2)$ and $\mathcal{O}(m_\pi^2/m_K^2)$],

$$\mathrm{BR}(K^+ \to \pi^+ a) = \frac{\tau_{K^-}}{\tau_{K_S}} \frac{f_\pi^2}{8f_a^2} \times \mathrm{BR}(K_S \to \pi^+\pi^-). \tag{3}$$

Equation (3) receives corrections from finite axion and pion mass effects in both the matrix element and phase space, both of which are taken into account in our numerical estimates (see Ref. [68] for the complete expression). In the codominance case, the axion coupling to the W-boson induces an extra contribution [46]. However, this contribution is negligible for $c_{WW} = c_{GG}$, and we do not consider it further in what follows.

Axions produced from KDAR can decay inside nearby detectors, either to $\gamma\gamma$ or e^+e^-. The number of axions produced at a KDAR source is given by

$$N_a = \frac{\mathrm{BR}(K^+ \to \pi^+ a)}{\mathrm{BR}(K^+ \to \mu^+ \nu_\mu)} N_{\nu_\mu}, \tag{4}$$

where N_{ν_μ} is the number of muon neutrinos from KDAR that are produced in the beam stop. In the limit of a long decay length, $\lambda_a \gg L$ where L is the distance from the KDAR source to the detector, the number of axions that decay in the detector is given by[2]

$$N_{a\to\mathrm{vis}} = N_a \times \frac{1}{4\pi L^2} \frac{V}{\lambda_a(m_a)}, \tag{5}$$

where V is the volume of the detector, $\lambda_a = \beta_a \gamma_a \tau_a$ is the decay length of the axion in the lab frame, and we have assumed all final states of the axion decay are visible. Our energy range of interest is given by

$$227\ \mathrm{MeV} < E_{ee}, E_{\gamma\gamma} < 354\ \mathrm{MeV}, \tag{6}$$

where the lower bound (upper bound) is given by setting $m_a = 0 (m_a = m_{K^+} - m_{\pi^+})$ in Eq. (2).

Assuming $a \to \gamma\gamma$ dominates over $a \to ee$, which is generically true for theories without direct axion-electron couplings, the lifetime of the axion is given by[3]

$$\tau_a^{-1} = \frac{\alpha^2 m_a^3}{256\pi^3 f_a^2} |c_{\gamma\gamma}^{\mathrm{eff}}|^2, \tag{7}$$

where α is the electromagnetic fine structure constant. The effective coupling to the photon is given by [32,69]

$$c_{\gamma\gamma}^{\mathrm{eff}} \approx c_{\gamma\gamma} - \left(\frac{5}{3} + \frac{m_\pi^2}{m_\pi^2 - m_a^2} \frac{m_d - m_u}{m_u + m_d}\right), \tag{8}$$

where $c_{\gamma\gamma} = 0$ in the gluon dominance case and $c_{\gamma\gamma} = 2$ in the codominance case, and our constraints are expressible in terms of $1/f_a^4$. Equation (8) assumes a two-flavor approximation, which is reasonably accurate for the masses we consider, $m_a \lesssim 350$ MeV. For these masses, we never approach regions of resonant mixing with η and η'; more complete three flavor expressions can be found in Appendix B of [69]. The constraints can be easily rescaled for other model-dependent choices (e.g., with the axion couplings to the up and down quarks). It is also straightforward to project sensitivities for models where $a \to e^+e^-$ is the dominant decay channel.

For m_a close to m_π cancellations can occur such that $c_{\gamma\gamma}^{\mathrm{eff}}$ vanishes.[4] For our choice of the quark mass ratio, $m_u/m_d = 0.46$, this happens only in the gluon dominance case. We note however that if we instead use $m_u/m_d = 0.56$ motivated from the meson mass spectrum, the cancellation happens around $m_a \simeq 55$ MeV in the codominance case. If the cancellation happens, the decay length of the axion is set by $a \to e^+e^-$. Such a coupling is always generated by radiative effects. For our numerical estimates,

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[2] In our numerical computation, we do not rely on this approximation. Instead, we include the finite axion decay length properly to obtain the upper limit of the sensitivity correctly.

[3] In models with a mirror sector, the axion may have invisible decay modes with $O(1)$ branching ratios.

[4] This is due to a cancellation among the axion direct coupling to the photon and the axion-pion mass and kinetic mixing contributions. Somewhat related to this, Eq. (8) relies on the small mixing angle expansion and hence, is applicable only when $|m_\pi^2/(m_\pi^2 - m_a^2) \times f_\pi/f| \ll 1$, strictly speaking. Since this condition is violated only for the axion mass very close to m_π, we ignore this subtlety.

we include the $a \to e^+e^-$ decay channel, taking $g_{aee} = 0.37 \times 10^{-3} c_{GG}$ [see Eq. (62) of [70]], although the effect of this coupling is almost invisible in our plots. Substantially stronger coupling to electrons is possible if it arises at tree level in the UV or is induced by top quarks [70]; in these cases, our constraints would strengthen. In principle, for $m_a \geq 2m_\mu$, the muon decay channel can also be included, but this only affects the ceiling of our constraint by an $\mathcal{O}(1)$ factor since $\Gamma(a \to \gamma\gamma)$ is comparable to $\Gamma(a \to \mu^+\mu^-)$. If a detector can measure muon tracks, then $a \to \mu^+\mu^-$ would present an additional signal channel with much lower backgrounds. However, since the impact of muon couplings on our results is relatively modest for the codominance and gluon dominance scenarios, and this region can be probed by other experiments [59,60], we do not discuss it further.

Microboone search for heavy scalars. Using the above formulas, we can recast a recent search by MicroBooNE [71]. Their search channel was $K \to \pi h_D$ followed by $h_D \to e^+e^-$ with h_D a dark Higgs boson [62]. If we consider the $a \to e^+e^-$ search, then mapping their result to a heavy axion is an immediate constraint on g_{aee}. Using the induced g_{aee} from gluon couplings mentioned above, we then obtain a limit on f_a. We find that the constraints on f_a obtained in this gluon-dominance scenario are very weak, excluding $f_a \lesssim 1$ TeV, which is already ruled out by other experiments, and so we do not include this in our summary plot (see Ref. [61] for ALPs coupled exclusively to electroweak bosons).

For the $a \to \gamma\gamma$ channel, it is not possible to interpret the MicroBooNE result as a constraint. The search in [71] made use of a boosted decision tree (BDT) in classifying their events and should reject $\gamma\gamma$ topologies.[5] As a crude estimate of the sensitivity, we may assume that a dedicated analysis for $\gamma\gamma$ final states is performed with comparable BDT performance. Then the sensitivity to f_a (from the same dataset) would be given by equating $\Gamma(K \to \pi h_D) \times \Gamma(h_D \to ee)$, evaluated with the upper bound on the mixing angle in [71], to our $\Gamma(K \to \pi a) \times \Gamma(a \to \gamma\gamma) \times e^{-L/\lambda_a}$ with $L \simeq 100$ m the distance between MicroBooNE and the NuMI absorber (i.e., the KDAR source). This treatment is valid since the decay length of the dark Higgs boson is much longer than L for the mixing angles in [71], and because the MicroBooNE detector is much smaller than L.

In Fig. 1 (gluon dominance) and Fig. 2 (codominance), we plot the sensitivity of MicroBooNE estimated in this way by the orange lines. MicroBooNE may be able to explore certain small regions of parameter space not covered by existing experiments if a dedicated search for $\gamma\gamma$ final states is performed; this is qualitatively similar to the situation with a dark Higgs boson [62,71]. As alluded to above, searches for dimuon final states may also be of interest for $m_a \geq 2m_\mu$ since MicroBooNE can easily reconstruct $\mu^+\mu^-$ pairs.

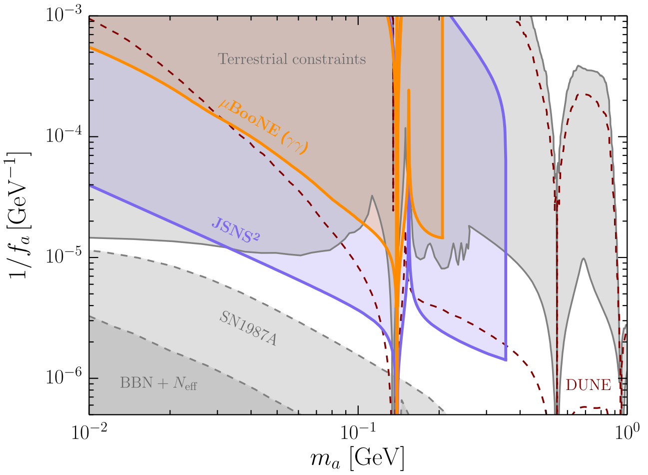

FIG. 1. (*Gluon dominance*) Sensitivities of MicroBooNE and JSNS^2 compared with existing limits and other projected sensitivities when all couplings are induced by a gluon coupling c_{GG} at a high scale. The MicroBooNE sensitivity is cut at 210 MeV because that is the range that appears in [71]. Existing limits include constraints from SN1987A [72,73] and cosmology [74] adapted from [65], Kaon decays (E949 [75] and NA62 [76]), and beam dump searches (CHARM [77] and NuCal [78]), with data adapted from [66]. We also show projected sensitivity of DUNE [65]. Other projected sensitivities not shown here include DarkQuest [69,79,80], FASER [81], KOTO [67,82], and SHiP [83]. We have rederived constraints from E949 and NA62, and our results agree with [67] (but disagree with [73] and therefore, the curves in [65]).

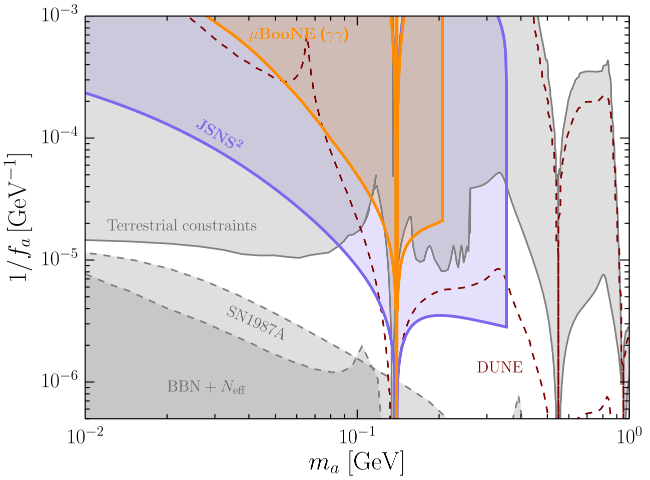

FIG. 2. (*Codominance*) The same figure as Fig. 1 but with $c_{WW} = c_{BB} = c_{GG}$. The sensitivity for $m_a \ll m_\pi$ is worse than the gluon dominance case since $|c^{\text{eff}}_{\gamma\gamma}| \ll 1$ for this specific choice of the parameters.

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[5] In principle, there should be some probability of a $\gamma\gamma$ pair contaminating the BDT-tagged e^+e^- sample, but this would require collaboration input.

Searches at JSNS^2. Next, we consider JSNS^2 [84–86], which is designed to test the excess of events seen at LSND [87]. A crucial difference between JSNS^2 and LSND is the proton beam energy, 3 GeV vs 0.8 GeV, such that JSNS^2 serves as both a πDAR and KDAR facility, whereas LSND had much fewer KDAR events (if any) [88]. We, therefore, find that JSNS^2 offers much more compelling sensitivity to heavy axions and do not consider LSND further in what follows.

To estimate the sensitivity at JSNS^2, we take the number of KDAR neutrinos per proton on target ($N_{\nu_\mu} = 0.0034/\mathrm{POT}$) from [84]. Although the kaon production rate is uncertain (N_{ν_μ} can be twice as large [89]), as we mentioned in the Introduction, in the actual experiment, the KDAR neutrino flux can be measured *in situ*. Using estimates from Fig. 3 of [90], we find that the search will be nearly background free $N_{\mathrm{bkg}} \leq 1$ in three years of operation, except for $E_a \leq 238$ MeV (corresponding to $m_a < 104$ MeV) where muon neutrinos produced from kaon decay-at-rest comes into play and $N_{\mathrm{bkg}} \approx 2.5$ over three years. Reference [90] assumes an additional lead shielding of the detector, which has not been put in place at JSNS^2. Cosmic backgrounds are therefore underestimated in that work. However, the axion signal we consider benefits from the high energy signal region, $E > 227$ MeV [Eq. (2)], where cosmic events are suppressed. Further reductions in the cosmic muon rate can be achieved using coincident tagging with daughter Michel electrons [91]. Since studies of cosmic background mitigation are ongoing, we plot projections using a 5-event contour (corresponding to approximately 95% C.L. exclusion if JSNS^2 observes only one event) assuming 100% efficiency of the detector.[6] Backgrounds will be smooth above 227 MeV, and a sideband analysis can be used to estimate their size *in situ* such that a search will always be statistics rather than systematics limited. As we discuss below, if backgrounds are high at JSNS^2, a search could be performed using their second detector [86,92].

To compute the expected number of axion events, we take $L = 24$ m as the distance between the KDAR source and the JSNS^2 detector, and the detector volume $V = (17\ \mathrm{tonnes})/(0.852\ \mathrm{g/ml}) = 20.35\ \mathrm{m}^3$ [85,93]. We assume 10^{23} POT, corresponding to roughly three years of live time. This results in $\sim 3 \times 10^{20}$ stopped K^+ in total, which is much larger than the 10^{12}–10^{13} K^+ decay events at NA62 [76].

In Fig. 1 (gluon dominance) and Fig. 2 (codominance), we plot the sensitivity of JSNS^2 by the blue lines, together with the existing constraints and future sensitivities. The figures demonstrate that JSNS^2 has excellent sensitivity to heavy axions. Note that the event number scales as f_a^{-4}. Therefore, even if we instead require, e.g., 50 events, the sensitivity only weakens by $10^{1/4} \simeq 1.8$, which does not alter our main conclusion.

In our analysis, we have focused on the JSNS^2 near detector. However, the JSNS^2 Collaboration recently installed another detector at a far location [86,92], 48 m away from the source. This second detector is expected to start taking data soon and contains 32 tonnes of liquid scintillator as a fiducial volume; the larger volume partially compensating for the longer baseline. Together with possibly smaller backgrounds due to its location, the far detector may be better suited for axion searches once it starts its operation.

Conclusions. KDAR provides a clean smoking gun signature of hadronically coupled axions. A K^+ production target, coupled with a large volume detector placed ∼10–100 m away, allows for a powerful probe of visibly decaying particles lighter than the kaon (e.g., dark scalars or heavy neutral leptons [62,94]). In the context of KDAR, axions are particularly compelling due to their well-motivated hadronic couplings, which are necessary in any model that addresses the strong *CP* problem.

We have focused on two benchmark scenarios (gluon dominance and codominance) for ease of comparison with the literature. It is interesting to understand how constraints vary with model-dependent coupling textures. The visible decays we consider here are governed both by $\mathrm{BR}(K \to \pi a)$ and the axion decay length and scale as $1/f_a^4$. By way of contrast, the constraints from NA62 depend only on $\mathrm{BR}(K \to \pi a)$ and scale as $1/f_a^2$. Stronger hadronic couplings will therefore favor NA62 over JSNS^2. Conversely, weaker hadronic couplings and/or a larger $c_{\gamma\gamma}^{\mathrm{eff}}$ will favor JSNS^2 over NA62. Beam dump searches scale the same way as JSNS^2.

We find that JSNS^2 will have world-leading sensitivity to heavy axions. One might imagine a competitive experimental landscape of modern high-intensity low-energy proton beams. Notably, we find that JSNS^2 is likely to provide unsurpassed sensitivity, since other facilities suffer from low K^+ yields (e.g., at a PIP-II beam dump [95], LANSCE [96], or the SNS [97]) or do not have competitive intensity (e.g., the SBN beam dump concept [98]). Experiments with detectors far downstream also suffer from large $1/L^2$ geometric suppressions c.f. Eq. (5). Modified experimental designs, e.g., a PIP-II beam dump with a proton beam energy $T_p \gtrsim 2$ GeV, could allow for competitive KDAR rates. A large volume detector placed near the DUNE hadron absorber or coupled with a high-intensity 8 GeV beam for a muon collider demonstrator would both offer promising future sensitivity. Nevertheless, with JSNS^2 already taking data [86], there is an immediate opportunity to shed light on heavy axion models in currently unprobed regions of parameter space.

We strongly encourage the JSNS^2 Collaboration to incorporate axion searches into their central physics program. The signal we have identified, will generically lie far

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[6] The background rate is expected to be lower for a higher energy bin, and hence, the statistical meaning of the 5-event contour varies depending on the axion mass (which determines the signal energy). However, as long as the background event rate is smaller than unity, this effect is minor.

above the signal windows of interest for neutrino physics. Kaon decay at rest produces a monoenergetic ν_μ with $E_\nu = 236$ MeV; however, the resultant muon signature is very different from the signal we have identified herein. If an axion is produced and decays visibly, the signal is two collimated photons with a total energy between 227 MeV and 354 MeV. Since this lies outside the range of any planned physics goals at JSNS^2, this signal could be easily missed; it should not be, and a dedicated search should be performed. For instance, our background estimate relies on additional lead shielding which is absent in reality as we have mentioned. Therefore, if JSNS^2 Collaboration observes a larger background than the estimate in [90], we believe that our study provides a strong motivation to, e.g., install additional shielding to suppress background and to explore the potential signals coming from the axions.

Note added. Recently, we were made aware of other experiments in the J-PARC facility that could search for axions from KDAR [99]. These include KOTO and ND280. It would be interesting to better understand the capability of these experiments to do searches using the JSNS^2 beam stop.

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