Searching for dark photons in hyperon decays

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Abstract

That massless dark photons could exist and have flavor-changing magnetic-dipole couplings to down-type light quarks is an attractive possibility which may be realized in various new-physics scenarios. It is potentially testable not only in kaon processes but also via two-body hyperon decays involving missing energy carried away by the massless dark photon. We explore the latter within a simplified model approach and take into account constraints from the kaon sector. We find that the branching fractions of some of these hyperon modes are allowed to be as high as a few times $10^{-4}$. Such numbers are likely to be within the sensitivity reaches of ongoing experiments like BESIII and future ones at super charm-tau factories.
Models of new physics (NP) beyond the standard model (SM) may have a dark sector containing a gauge boson associated with an extra Abelian gauge group, U(1)$_D$. This symmetry may be broken spontaneously or unbroken causing the boson, the dark photon, to get mass or stay massless. These possibilities are appealing for various reasons and have been much studied in recent years [1–7]. As SM members do not carry the U(1)$_D$ charge, they do not couple at tree level to the dark photon, $\gamma$, if it is massless [3, 4]. The massless dark photon can interact with the SM fermions via higher-dimension operators generated by loop diagrams involving dark particles if they have some couplings to the SM fermions.

Here we concentrate on flavor-changing neutral current (FCNC) effects arising from massless dark photons coupled to $d$ and $s$ quarks. In the kaon sector, a dark photon with this property and small mass can be probed with $K \to \pi \gamma$ and $K^+ \to \mu^+ \nu \gamma$ [8–10]. However, if $\gamma$ is massless and hence has no direct interactions with SM fermions, the former decay is forbidden by angular momentum conservation and the latter would have a very suppressed rate. Instead, in this case $K^+ \to \pi^+ \pi^0 \gamma$ has been suggested as an avenue to study the $ds\gamma$ coupling [5].

In this paper, we would like to show that the hyperon sector potentially offers a competitive window to access this coupling. The search for the FCNC decays of hyperons with missing energy ($\frac{E}{E}$) carried away by a pair of invisible particles, due to the quark transition $s \to d\bar{\gamma}$, can expectedly be realized in the BESIII experiment [11] and is complementary to quests for kaon decays with missing energy. The forthcoming results would likely be informative regarding possible NP affecting this transition [12, 13]. The prospects for BESIII pursuing two-body hyperon decays with a massless dark photon being invisibly emitted are comparatively better provided that their branching fractions are not too small. As we will see shortly, they can be sizable in some scenarios recently proposed in the literature, implying that they may be testable with the existing hyperon data and upcoming experimental quests.

In the processes under consideration, a massless dark photon is emitted on-shell due to its dipole-type coupling to the $d$ and $s$ quarks generated by loop diagrams involving heavy nonstandard particles. It is described by the effective Lagrangian

$$L_{d\gamma} = -\sigma^{\mu\nu}(C + \gamma_5C_5)s B_{\mu\nu} + \text{H.c.},$$

where $C$ and $C_5$ are constants having the dimension of inverse mass and dependent on the details of the underlying NP model, $\sigma^{\mu\nu} = (i/2)[\gamma^\mu, \gamma^\nu]$, and $B_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the dark photon's field strength.

Our hyperon decays of interest are $B \to B\gamma\gamma$ with $B B' = \Lambda n, \Sigma^+ p, \Xi^0 \Lambda, \Xi^0 \Sigma^0, \Xi^- \Sigma^-, \Omega^- \Xi^-$. All of these baryons have spin 1/2, except $\Omega^-$ which has spin 3/2. To derive the amplitudes for these modes arising from $L_{d\gamma}$, we need to know the matrix elements of $\sigma^{\mu\nu}s$ between $B$ and $B'$. As it turns out, such matrix elements have been estimated a while ago in an investigation of the contributions of the analogous transition $s \to d\gamma$ to hyperon radiative weak decays, $B \to B'\gamma$, involving the ordinary photon [15]. With appropriate changes, we can apply the results derived
therein to the corresponding processes involving the massless dark-photon. Thus, for the latter we have the rate
\[
\Gamma_{B \rightarrow B' \gamma} = \frac{C^2_{B' \gamma} (m_B^2 - m_{B'}^2)^3}{2\pi m_B^4} \left( |C|^2 + |C_5|^2 \right),
\]
(2)
where \(C_{B' \gamma}\) denotes a parameter which is specific to the \(BB'\) pair. The values of \(C^2_{B' \gamma}\) for the aforementioned \(BB'\) pairs were determined in Ref. [15] using quark-model SU(6) wave functions and are listed in Table I, for which we have assumed overlap factors of 1.

Since \(C\) and \(C_5\) are generally independent of each other, for simplicity hereafter we assume that the latter is absent, which is also the case in the examples we examine below. For each of the hyperon modes, we can then evaluate the corresponding branching fraction \(B(B \rightarrow B' \gamma)\) once \(C\) is numerically given. Thus, employing the measured masses from Ref. [14], we arrive at the numbers, in units of \(|C|^2\), collected in Table II. In light of the successful quark-model predictions of other baryonic quantities which rely on the same assumption of a single-quark operator transforming like a component of the quark spin [15], we may expect that the estimates displayed in this table are good to within factors of 2.

To see what values of \(B(B \rightarrow B' \gamma)\) are currently possible, we now consider, as benchmarks, different upper bounds on \(|C|\) in two scenarios recently discussed in the literature. Although they are variations of the same simplified model of NP, the two different sets of predictions which they make can serve to illustrate how hyperon and kaon measurements together could help distinguish various NP scenarios. Thus, similar analyses could be performed for other models. In both of these scenarios, proposed in Refs. [5, 6], the \(ds\gamma\) interaction is induced by loop diagrams involving new particles comprising massive fermions which are SM singlets as well as heavy scalar bosons which are triplets under color SU(3) and some of which are doublets under the SM SU(2)_L. The new fermions and bosons are all charged under \(U(1)_D\) and have Yukawa-like interactions with the \(d\) and \(s\) quarks, allowing the dimension-5 operator for \(ds\gamma\) to arise. Since our aim here is to examine the implications of this coupling for the hyperon modes, once it has been subject to

| \(B'B\) | \(n\Lambda\) | \(p\Sigma^+\) | \(\Lambda\Xi^0\) | \(\Sigma^0\Xi^0\) | \(\Sigma^-\Xi^-\) | \(\Xi^-\Omega^-\) |
|---|---|---|---|---|---|---|
| \(C^2_{B' \gamma}\) | \(\frac{3}{2}\) | \(\frac{1}{9}\) | \(\frac{1}{6}\) | \(\frac{25}{18}\) | \(\frac{25}{9}\) | \(\frac{4}{3}\) |

TABLE I: Values of \(C^2_{B' \gamma}\) in eq. (2) for \(BB' = n\Lambda, p\Sigma^+, \Lambda\Xi^0, \Sigma^0\Xi^0, \Sigma^-\Xi^-, \Xi^-\Omega^-\) from ref. [15].

| Decays | \(B\) | \(\frac{B}{|C|^2}\) (GeV^2) |
|---|---|---|
| \(\Lambda \rightarrow n\gamma\) | \(\Sigma^+ \rightarrow p\gamma\) | \(\Xi^0 \rightarrow \Lambda\gamma\) | \(\Xi^0 \rightarrow \Sigma^0\gamma\) | \(\Xi^- \rightarrow \Sigma^-\gamma\) | \(\Omega^- \rightarrow \Xi^-\gamma\) |
| \(\frac{B}{|C|^2}\) (GeV^2) | \(2.75 \times 10^{12}\) | \(1.54 \times 10^{11}\) | \(4.95 \times 10^{11}\) | \(1.12 \times 10^{12}\) | \(1.32 \times 10^{12}\) | \(5.18 \times 10^{12}\) |

TABLE II: The branching fractions \(B\) of \(BB'\) divided by \(|C|^2\).
constraints from other sectors, we will not dwell further with the details of the underlying NP model. Rather, we will simply take most of the relevant results provided in Refs.\[5, 6\] at face value and employ them to calculate the hyperon rates.

In the first scenario the $d_s\gamma$ coupling constant is given by \[5\]

$$C = \frac{e_D \xi}{64\pi^2 \tilde{\Lambda}},$$

(3)

where $e_D$ parameterizes the dark photon’s interaction strength, $\xi$ is a product of two common Yukawa couplings between the new particles and SM quarks, and $\tilde{\Lambda}$ is the effective heavy mass scale of the dark sector. The Yukawa interactions give rise to box-diagram contributions to the kaon-mixing quantity $\Delta m_K$. The latter is connected to the ratio $\xi/\tilde{\Lambda}$ by \[5\]

$$\Delta m_K^{\text{np}} = 8.47 \times 10^{-13} \text{TeV}^3 \frac{\xi^2}{\tilde{\Lambda}^2},$$

(4)

which is dominated by the contributions of four-quark operators yielding chirally enhanced $K^0-\bar{K}^0$ matrix elements. To constrain $\xi/\tilde{\Lambda}$, this NP contribution is required to be less than 30% of its experimental counterpart, $\Delta m_K^{\text{exp}} < 0.3\Delta m_K^{\text{np}}$, where $\Delta m_K^{\text{exp}} = 3.484 \times 10^{-15} \text{GeV}$ \[14\]. The value of $e_D$ follows from the choice $\alpha_D = e^2_D/(4\pi) = 0.1$ \[5\]. Putting things together, from Eq. (3) we then obtain

$$|C| < 2.0 \times 10^{-9} \text{ GeV}^{-1}.$$ 

(5)

Incorporating this with the entries in Table III we arrive at the maximal branching fractions $B_{\text{max}}$ of the hyperon modes shown in the second row of Table III and labeled [I].

In the second scenario \[6\]

$$C = \frac{e_D D_M}{2\tilde{\Lambda}},$$

(6)

where $D_M$ contains a product of a couple of Yukawa couplings between the new particles and $d$ and $s$ quarks and is related to the kaon-mixing parameter by $\Delta m_K^{\text{np}} = 32\pi^2 D_M f_K^2 m_{K^0}^2/(3\tilde{\Lambda}^2)$, with $f_K = 159.8 \text{MeV}$ being the kaon decay constant and $m_{K^0} = 497.6 \text{MeV}$ \[14\]. In this case, unlike the preceding one, the $K^0-\bar{K}^0$ matrix elements of the contributing four-quark operators are not chirally enhanced. To be consistent with the previous scenario, we demand $\Delta m_K^{\text{np}} < 0.3\Delta m_K^{\text{exp}}$.

| Decay mode | $\Lambda \rightarrow n\gamma$ | $\Sigma^+ \rightarrow p\gamma$ | $\Xi^0 \rightarrow \Lambda\gamma$ | $\Xi^0 \rightarrow \Sigma^0\gamma$ | $\Xi^- \rightarrow \Sigma^-\gamma$ | $\Omega^- \rightarrow \Xi^-\gamma$ |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $B_{\text{max}}$ [I] | $1.1 \times 10^{-5}$ | $6.0 \times 10^{-7}$ | $1.9 \times 10^{-6}$ | $4.3 \times 10^{-6}$ | $5.1 \times 10^{-6}$ | $2.0 \times 10^{-5}$ |
| $B_{\text{max}}$ [II] | $6.7 \times 10^{-4}$ | $3.8 \times 10^{-5}$ | $1.2 \times 10^{-4}$ | $2.7 \times 10^{-4}$ | $3.3 \times 10^{-4}$ | $1.3 \times 10^{-3}$ |

TABLE III: Maximal branching fractions of $B \rightarrow B'\gamma$ with the $|C|$ values from [I] Eq. (5) and [II] Eq. (6).
leading to

\[
\frac{D_M^2}{\Lambda^2} < 7.8 \times 10^{-16} \text{ GeV}^{-2},
\]

which is smaller than that found in Ref. [6] from the condition \( \Delta m_K^{np} < \Delta m_K^{exp} \). With \( \alpha_D = 0.1 \) as before, we then get

\[
|C| < 1.6 \times 10^{-8} \text{ GeV}^{-1}.
\]

This translates into the maximal branching fractions \( B_{max} \) of the hyperon modes listed in the last row of Table III and labeled \([II]\).

As indicated above, the differences between the two sets of predictions in Table III reflect mainly the fact that the underlying NP in the two cases influence kaon mixing differently. It follows that quests for the hyperon modes could yield information pertinent for testing NP models. As pointed out in Ref. [5], the future measurement on \( K^+ \rightarrow \pi^+\pi^0\gamma \), which arises from the same \( s \rightarrow d\gamma \) transition, is also important.

The hyperon decays may be searched for in the BESIII experiment, which has produced copious \( \Lambda, \Sigma, \Xi, \) and \( \Omega \) hyperons [11]. For their decays with missing energy (\( \bar{E} \)) carried away by a pair of invisible particles, the proposed BESIII sensitivity levels for the branching fractions of \( \Lambda \rightarrow n\bar{E}, \Sigma^+ \rightarrow p\bar{E}, \Xi^0 \rightarrow \Lambda\bar{E}, \Xi^0 \rightarrow \Sigma^0\bar{E}, \) and \( \Omega^- \rightarrow \Xi^-\bar{E} \) are \( 3 \times 10^{-7}, 4 \times 10^{-7}, 8 \times 10^{-7}, 9 \times 10^{-7}, \) and \( 2.6 \times 10^{-5} \), respectively [11]. Since our decays of concern, \( \mathcal{B} \rightarrow \mathcal{B}\gamma \), are two-body ones, BESIII would have better sensitivity to them, being able to probe them more efficiently than the three-body ones. This is especially consequential for NP models which could yield predictions similar to those displayed in Table III.

As we await upcoming direct-search results on \( \mathcal{B} \rightarrow \mathcal{B}\gamma \) from BESIII and other (future) experiments, we can already extract approximate bounds on their branching fractions from the data on the observed channels quoted by the Particle Data Group [14]. To do so, for each of the hyperons, we subtract from unity the sum of the PDG branching-fraction numbers with their errors (at 2 sigmas) combined in quadrature. Thus, for the yet unobserved modes of \( \Lambda, \Sigma^+, \Xi^0, \Xi^-, \) and \( \Omega^- \), we find the upper limits of \( 1.4\%, 8.0 \times 10^{-3}, 3.4 \times 10^{-4}, 8.3 \times 10^{-4}, \) and \( 1.6\% \), respectively. Evidently, they accommodate most of the corresponding predictions in Table III except for the \( \Xi^0 \) ones in the last row, suggesting that the second scenario seems to be already in tension with the available hyperon data. Had we imposed the weaker condition \( \Delta m_K^{np} < \Delta m_K^{exp} \), the second scenario would be disfavored more strongly.

In conclusion, we have entertained the possibility that massless dark photons exist and have nonnegligible flavor-changing magnetic-dipole couplings to down-type light quarks. Such interactions bring about FCNC hyperon decays into a lighter baryon plus missing energy carried away by the massless dark photon. We demonstrate that these hyperon modes can be powerful tools to probe the possible underlying NP, perhaps better than what kaon decays could offer. We illustrate this with a couple of examples from recent studies in the literature which take into account
the existing restrictions from kaon and other sectors. Our findings reveal that one of these two scenarios is already in tension with the indirect bounds on hyperon decays with missing energy inferred from the available hyperon data. Further tests on the hyperon modes will come from ongoing experiments such as BESIII and future facilities such as super charm-tau factories. In the near future, BESIII is likely to be in a position to discover one or more of these hyperon modes or, if not, set stringent constraints on the $ds\gamma$ coupling.

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[1] R. Essig et al., Working Group Report: New Light Weakly Coupled Particles, arXiv:1311.0029 [hep-ph].
[2] J. Alexander et al., Dark Sectors 2016 Workshop: Community Report, arXiv:1608.08632 [hep-ph].
[3] B. Holdom, Two U(1)’s and Epsilon Charge Shifts, Phys. Lett. 166B, 196 (1986).
[4] B.A. Dobrescu, Massless gauge bosons other than the photon, Phys. Rev. Lett. 94, 151802 (2005) hep-ph/0411004.
[5] M. Fabbrichesi, E. Gabrielli, and B. Mele, Hunting down massless dark photons in kaon physics, Phys. Rev. Lett. 119, no. 3, 031801 (2017) arXiv:1705.03470 [hep-ph].
[6] M. Fabbrichesi and E. Gabrielli, Dark-sector physics in the search for the rare decays $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_L \rightarrow \pi^0\nu\bar{\nu}$, arXiv:1911.03755 [hep-ph].
[7] J.Y. Cen, M. He, X.G. He, and G. Li, Scrutinizing a massless dark photon: basis independence and new observables, arXiv:1807.11363 [hep-ph].
[8] M. Pospelov, Secluded U(1) below the weak scale, Phys. Rev. D 80, 095002 (2009) doi:10.1103/PhysRevD.80.095002 [arXiv:0811.1030 [hep-ph]].
[9] V. Barger, C.W. Chiang, W.Y. Keung, and D. Marfatia, Constraint on parity-violating muonic forces, Phys. Rev. Lett. 108, 081802 (2012) doi:10.1103/PhysRevLett.108.081802 [arXiv:1109.6652 [hep-ph]].
[10] J. R. Batley et al. [NA48/2 Collaboration], Search for the dark photon in $\pi^0$ decays, Phys. Lett. B 746, 178 (2015) doi:10.1016/j.physletb.2015.04.068 [arXiv:1504.00607 [hep-ex]].
[11] H.B. Li, Prospects for rare and forbidden hyperon decays at BESIII, Front. Phys. (Beijing) 12, no. 5, 121301 (2017) arXiv:1612.01775 [hep-ex]]; (Erratum) 14, 64001 (2019).
[12] J. Tandean, Rare hyperon decays with missing energy, JHEP 1904, 104 (2019) arXiv:1901.10447 [hep-ph].
[13] G. Li, J.Y. Su, and J. Tandean, Flavor-changing hyperon decays with light invisible bosons, Phys. Rev. D 100, no. 7, 075003 (2019) arXiv:1905.08759 [hep-ph].
[14] M. Tanabashi et al. [Particle Data Group], Review of Particle Physics, Phys. Rev. D 98, no. 3, 030001 (2018). doi:10.1103/PhysRevD.98.030001
[15] F.J. Gilman and M.B. Wise, Radiative Weak Decays of Baryons as Single Quark Transitions, Phys. Rev. D 19, 976 (1979).