New-physics prospects in hyperon decays

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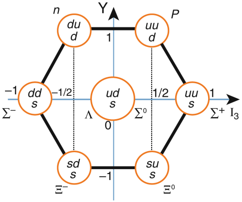
New Physics Searches at Kaon and Hyperon Factories

May 11 2021

Outline

The hyperons

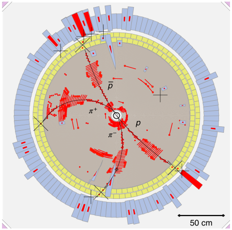
- **Hyperons are the strange siblings of the proton and neutron**



- **Half lifes**: $\tau_Y \sim 10^{-10}$ s
  - Sensitivity loss $\sim 10^3$ w.r.t. to K^+, K_L
- **Rich phenomenology:**
  - Spin $\rightarrow$ sensitivity to various NP structures
  - $SU(3)$-relations to nucleon-structure

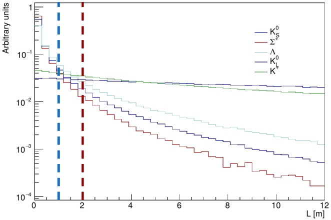
- **Recent experimental "revolution" after 40^+ yrs ...**

- **Polarized-hyperon factories (BESIII&SCTF)**



Nature Physics 15, 631-634(2019)

- **LHCb:** 10^{2-3} more hyps than B's



Alves Junior *et al.* JHEP 05 (2019) 048

The hyperons

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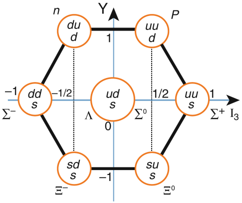

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  - ★ $SU(3)$-relations to nucleon-structure

- **We will use and recast Hai-Bo Li predictions for $B_1 \to B_2 \nu \bar{\nu}$**

Front. Phys. 12(5), 121301 (2017)
DOI 10.1007/s11467-017-0691-9

PERSPECTIVE

Prospects for rare and forbidden hyperon decays at BESIII

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Form factors: Lattice, $SU(3)_F$ and ChPT

- **Predictions require strong form factors** (e.g. LQCD)

$$\langle B_2(p_2)|J^V_\mu|B_1(p_1)\rangle = \bar{u}_2(p_2)\left[f_1(q^2)\,\gamma_\mu + \frac{f_2(q^2)}{M_1}\,\sigma_{\mu\nu}q^\nu + \frac{f_3(q^2)}{M_1}\,q_\mu\right]u_1(p_1),$$

$$\langle B_2(p_2)|J^A_\mu|B_1(p_1)\rangle = \bar{u}_2(p_2)\left[g_1(q^2)\gamma_\mu + \frac{g_2(q^2)}{M_1}\sigma_{\mu\nu}q^\nu + \frac{g_3(q^2)}{M_1}q_\mu\right]\gamma_5 u_1(p_1)$$

$$\langle B_2(p')|J^T_{\mu\nu}|B_1(p)\rangle_{q^2=0} = g_T\,\bar{u}_2(p')\sigma_{\mu\nu}u_1(p)$$

- ***$SU(3)_F$* symmetry** (lacking **direct** LQCD computations)

$$\langle B_a|J_b|B_c\rangle = f_{bac}F_J(q^2) + d_{bac}D_J(q^2)$$

Georgi, Lie Algebras in Particle Physics

  - **Reduced matrix elements** from **data** (axial/vector) or **lattice** (tensor)

$SU(3)_F$ **breaking:** $\delta \equiv (M_1 - M_2)/M \sim 10 - 20\%$

  - **Kinematic expansion:** $q/M_1 \sim \mathcal{O}(\delta)$

- ***$SU(3)_F$*-symmetry is embedded as the LO in ChPT**

Heavy New Physics: $B_1 \to B_2 \nu\bar{\nu}$ Geng, JMC, Xiang, to appear

- **New physics scale of $s \to d\nu\nu$ transitions $\Lambda \gg 1$ GeV**

$$\mathcal{H}_{\rm eff}^{\rm SM} = \frac{G_F}{\sqrt{2}}\lambda_t \left(\sum_{i=1}^{10} C_i O_i + \alpha \sum_{\ell} C^L_{\nu_\ell} O^L_{\nu_\ell}\right)$$

- **Add RH NP**

$$\mathcal{H}_{\rm eff}^{\rm NP} = \frac{G_F \alpha}{\sqrt{2}}\lambda_t \sum_{\ell} C^R_{\nu_\ell} (\bar{d}s)_{V+A}(\bar{\nu}_\ell \nu_\ell)_{V-A}$$

- **Total $B_1 \to B_2 \bar{\nu}\nu$ rate**

$$\Gamma = \sum_\ell \frac{\alpha^2 G_F^2 |\lambda_t|^2 f_1(0)^2 M_1^5 \delta^5}{60\pi^3} \cdot \left[\left(1-\frac{3}{2}\delta\right)\left|C^L_{\nu_\ell} + C^R_{\nu_\ell}\right|^2 + 3\left(1-\frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}\left|C^L_{\nu_\ell} - C^R_{\nu_\ell}\right|^2\right] + \mathcal{O}(\delta^2)$$

  - Kinematic expansion ⇒ Only **2 charges** $f_1(0)$ and $g_1(0)$ contribute
  - $f_1(0)$ and $g_1(0)$ determined from **data** ($B_1 \to B_2 e\nu$)
  - Baryon decays sensitive to **axial current** combination

- **SM predictions including NLO corrections in ChPT**

	Λn	$\Sigma^+ p$	$\Xi^0 \Sigma^0$	$\Xi^0 \Lambda$
SM-NLO	$6.0(2) \times 10^{-13}$	$3.8(2) \times 10^{-13}$	$8.4(5) \times 10^{-14}$	$5.7(3) \times 10^{-13}$

Heavy New Physics: Interplay with kaons

- $K \to \pi\nu\bar{\nu}$ is only sensitive to **vectorial** combination

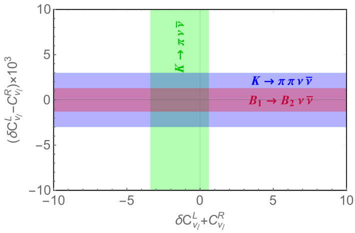
$$\text{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{2\alpha^2 |\lambda_t|^2 \text{BR}(K^+ \to \pi^0 e^+ \nu_e)}{|V_{us}|^2} \sum_{\ell=e,\mu,\tau} |C^L_{\nu_\ell} + C^R_{\nu_\ell}|^2$$

- $K \to \pi\pi\nu\bar{\nu}$ is sensitive to **axial** combination
  - Form factors predicted using **isospin symmetry** and semileptonic $K \to \pi\pi\nu e$ decays

Geng, JMC, Xiang, to appear; see also Littenber&Valencia, PLB385,379 (1996), Chiang, Gilman, PRD62,094026(2000)

$K^+\pi^+\pi^0$	$K_L\pi^0\pi^0$
$7.90(34) \times 10^{-15}$	$3.11(6) \times 10^{-13}$

- **Compare current kaon constraints with BESIII projections** (Hai-bo's paper)



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Can we do much better than this with hyperons or $K \to \pi\pi\nu\bar{\nu}$?

Two body decays with a final dark boson X^0

- **Axions:** $\mathcal{L}_a = \frac{\partial_\mu a}{2f_a}\bar{\psi}_i\gamma^\mu(c_{ij}^V + c_{ij}^A\gamma_5)\psi_j + \frac{1}{2}m_a^2 a^2$

$$\Gamma_a = \frac{\bar{p}\bar{\omega}^2}{8\pi f_a^2}(f_1^2|c_{ds}^V|^2 + (1-\frac{x_a^2}{\delta^2})g_1^2|c_{ds}^A|^2) + \mathcal{O}(\delta^2)$$

  - Only **2 hadronic charges** f_1 and g_1: $SU(3)_F$ + **data**
  - $B_1 \to B_2 a$ sensitive to **axial** current c_{ds}^A (worse for larger $x_a = m_a/\delta$)

- **Massless dark photon:** $\mathcal{L}_{\gamma'} = \frac{1}{\Lambda_{\rm UV}}\bar{\psi}_i\sigma^{\mu\nu}\left(\mathbb{C}^{ij} + \mathbb{C}_5^{ij}\gamma_5\right)\psi_j F'_{\mu\nu}$

$$\Gamma_{\gamma'} = \frac{4\bar{\omega}^3 g_T^2}{\pi\Lambda_{\rm UV}^2}(|\mathbb{C}^{ds}|^2 + |\mathbb{C}_5^{ds}|^2)$$

  - Only **1 hadronic charge** g_T: $SU(3)_F$ + **LQCD** Gupta *et al.* PRD98,091501
  - Best lab limit on $s \to d\gamma'$ stems from $\Xi^0 \to \Sigma^0\gamma'$ and invisible BR of Ξ^0

$$\mathrm{BR_{inv}}(\Xi^0) \leq 2.3\times 10^{-4} \quad \Rightarrow \quad \Lambda_{\rm UV} \leq 3.8\times 10^7 \ \ (95\%\ \mathrm{C.L.})$$

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Contribution of $\Lambda \to nX^0$ to SN's dark luminosity

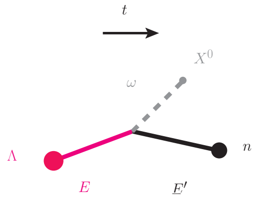
JMC, Pospelov, Vuong, Ziegler, Zupan PRD 102 (2020) 1, 015023, JMC, Terol-Calvo, Tolos & Ziegler, arXiv: 2012.11632 [hep-ph]

- **There are hyperons (Λ's) in proto-neutron stars!**
  - Abundancies sustained by weak processes

$$pe^- \leftrightarrow \Lambda\nu_e, \qquad \Lambda \to pe^-\bar{\nu}, \ldots$$

  - High Temperatures and supranuclear densities

$$\textbf{Thermal effects: } n_\Lambda \simeq n_n \exp\left(-\frac{m_\Lambda - m_n}{T}\right) \simeq 0.01 \times n_n$$



  - **Spectrum of dark cooling rate per unit volume**

$$\frac{dQ}{d\omega} = \frac{m_\Lambda^2 \Gamma \omega}{2\pi^2\bar{\omega}} \int_{E_0}^{\infty} dE\, f_\Lambda (1 - f_n)$$

  - ★ Γ: $\Lambda \to nX^0$ decay rate in vacuum
  - ★ $f_{\mathcal{B}}$ Fermi-Dirac distributions

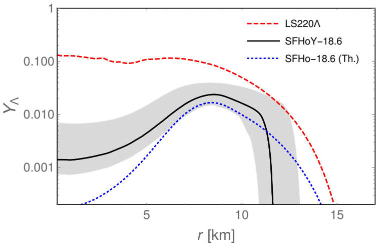
The SN 1987A bound on $\Lambda \to nX^0$

"Raffelt's Criterion" G. Raffelt'95

$$L_d \lesssim L_\nu = 3 \times 10^{52} \text{ erg s}^{-1}$$

- **Recent SN simulations for SN 1987A + EoS from compOSE database**

Bollig *et al.* PRL125(2020)051104

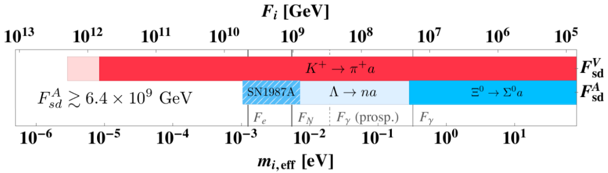


- **Most conservative limit, including reabsorbtion/trapping, medium effects ...**

$$\text{BR}(\Lambda \to nX^0) \lesssim 8.0 \times 10^{-9}$$

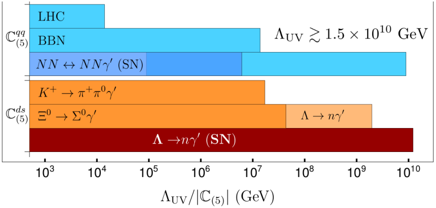
Application of the SN bound

- **Axions**
  - Define $F_{sd}^{V,A} = 2f_a/c_{sd}^{V,A}$



  - Best limit on axion models with **tuned axial couplings**
  - Small change for ALP – **significant less tuning** for the $K \to 2\pi$ region
  - **BESIII projections** (Hai-bo's) lie within 1 order of magnitude from SN bound

- **Massless dark photon**



  - Strongest absolute limit on the quark couplings of the massless dark-photon

How well *should* we do experimentally?

- **If we take the SN bound as a benchmark**

Kaon and Hyperon decays

• SN: $\Lambda/d_M^{sd} = 1.2 \times 10^7$ TeV

Decay	Branching Ratio	Decay	Branching Ratio
$K^+ \to \pi^0\pi^+ A'$	7.8×10^{-11}	$K_L \to \pi^0\gamma A'$	3.4×10^{-11}
$K^+ \to \pi^+\gamma A'$	1.9×10^{-11}	$K_L \to \pi^+\pi^- A'$	3.2×10^{-10}
$K_L \to \gamma A'$	4.0×10^{-8}		
$\Sigma^+ \to pA'$	4.9×10^{-10}	$\Lambda \to nA'$	8.0×10^{-9}
$\Xi^0 \to \Sigma^0 A'$	3.02×10^{-9}	$\Xi^- \to \Sigma^- A'$	3.6×10^{-9}
$\Xi^0 \to \Lambda A'$	1.4×10^{-9}	$\Omega^- \to \Sigma^- A'$	3.6×10^{-8}

- Using current notation in white book
- Predictions for kaons and Ω^- decay from Su & Tandean, PRD101, 035044(2020)

Any projection one order of magnitude short of this would be interesting

How well can we do experimentally?

- **Our recast of Hai-bo's projections** $\mathrm{BR}(B_1 \to B_2 X^0) \simeq \mathrm{BR}(B_1 \to B_2 \nu\bar{\nu})$ **is *wrong***
  - For 2-body with massless X^0 we need to subtract SM's $B_1 \to B_2\gamma$ (missing γ)
- **Idea:** Exploit polarized B_1 and **experimental** α_γ parameter

$$\frac{d\Gamma}{d\cos\theta} = \frac{\Gamma}{2}(1 + P\alpha_\gamma \cos\theta)$$

where

$$\alpha_\gamma = \frac{2\mathrm{Re}(SP^*)}{|S|^2 + |P|^2}$$

measures interference between parity conserving and violating conts. to amplitude

Formulas for axions/Dark photons

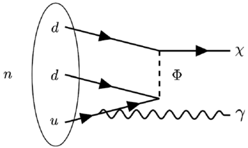
Useful for realistic experimental projections at BESIII & SCTF?

Dark baryons Alonso-Alvarez, Elor, Escudero, Fornal, Grinstein, JMC – WIP

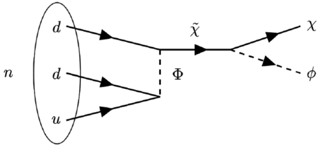
- **Dark particles carrying baryon number $\Rightarrow$ Hyperon BNV signatures**
  - $m_\chi > m_p$ **to avoid proton decay!**

1. **Models addressing *neutron lifetime anomaly*** Fornal&Grinstein, PRL120,191801(2018)

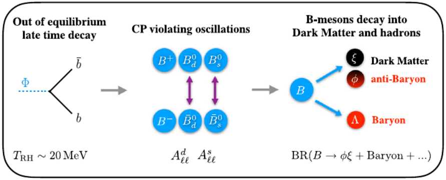
- Expt signature with one SM particle



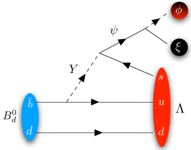
- Expt signature purely invisible



2. ***B*-mesogenesis** Elor, Escudero, Nelson, PRD99(2019)3,035031, Alonso-Alvarez, Elor, Escudero, arXiv: 2101.02706



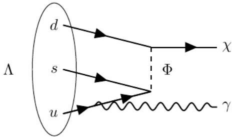
- **Expt signature:** *B* BNV decays



- **Other ideas in this direction:** McKeen&Pospelov arXiv: 2003.09865, McKeen, Pospelov&Raj arXiv: 2012.09865, . . .

The dark baryon - hyperon connection

- **These models can have flavor entries triggering hyperon BNV signatures!**



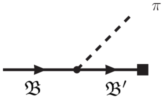
- **However,** there is generally not a one-to-one correspondence ...

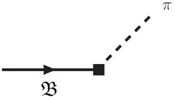
1. **Identify mediators**

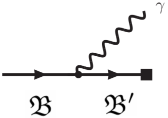
$$\mathcal{L}_1 \supset -y_{d_a d_b}\epsilon_{ijk}\Psi^i d^j_{Ra} d^k_{Rb} - y_{\chi u_c}\Psi^*_i \chi u^i_{Rc} + \text{h.c.}$$
$$\mathcal{L}_2 \supset -y_{u_a d_b}\epsilon_{ijk}\Phi^i u^j_{Ra} d^k_{Rb} - y_{\chi d_c}\Phi^*_i \chi d^i_{Rc} + \text{h.c.}$$
$$\mathcal{L}_3 \supset -y_{Q_a d_b}\epsilon_{ijk}\epsilon_{\alpha\beta} X^{i\alpha}_\mu Q^{j\beta}_{La}\gamma^\mu d^k_{Rb} - y_{\chi Q_c} X^{\dagger i\alpha}_\mu Q^{i\alpha}_{Lc}\gamma^\mu \chi + \text{h.c.},$$

$$\Psi = (3,1)_{\frac{2}{3}}$$
$$\Phi = (3,1)_{-\frac{1}{3}}$$
$$X_\mu = (3,2)_{\frac{1}{6}}$$

2. **Match to $SU(2) \times U(1)$ and $U(1)_{\rm em}$ EFTs**
   - ★ Fierz transformations, RGEs, etc Weinberg PRL43,1566 (1979), Abbot&Wise PRD22,9,22 (1980)
3. **Match low-E EFT to chiral Lagrangian and calculate matrix elements**







- ★ Leading order parameters obtained from LQCD calculations for proton decay!

Experimental hyperon BNV signatures

- **Simplest experimental signatures**

(1) $\mathfrak{B} \to \mathrm{inv}$ **(2)** $\mathfrak{B} \to \gamma + \mathrm{inv}$ **(3)** $\mathfrak{B} \to \pi + \mathrm{inv}$

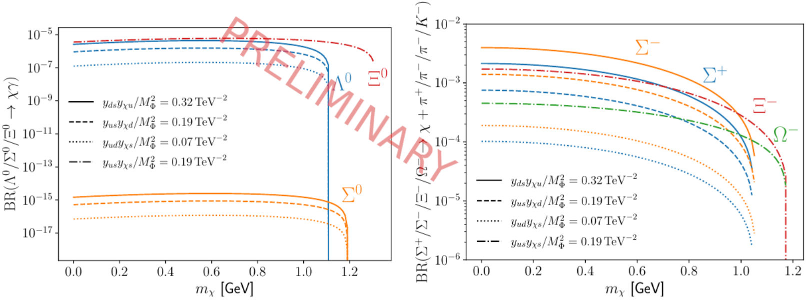
Initial State	Final State	ΔM (MeV)	Operator	$W_{\mathrm{RR}}/\mathrm{GeV}^3$	$\mathrm{Br} \times \left[\frac{M_\Phi^2}{y^2}\frac{1}{5\,\mathrm{TeV}^2}\right]^2$	Br sensitivity
$\Lambda^0\,(uds)$	$\chi + \gamma$	1116	χuds	0.01445	7.2×10^{-7}	
$\Lambda^0\,(uds)$	$\xi + \phi$	1116	χuds	0.01445	$5.0 \times 10^{-3}\, y_{\xi\phi}^2$	
$\Sigma^+\,(uus)$	$\chi + \pi^+\,(\bar{d}u)$	1050	χuds	0.122	4.7×10^{-5}	
$\Sigma^-\,(dds)$	$\chi + \pi^-\,(\bar{u}d)$	1058	χuds	0.122	9.8×10^{-5}	
$\Xi^0\,(uss)$	$\chi + \gamma$	1315	χuss	0.01445	5.2×10^{-6}	
$\Xi^0\,(uss)$	$\xi + \phi$	1315	χuss	0.01445	$1.4 \times 10^{-3}\, y_{\xi\phi}^2$	
$\Xi^-\,(dss)$	$\chi + \pi^-\,(\bar{u}d)$	1182	χuss	0.122	3.1×10^{-4}	
$\Omega^-\,(sss)$	$\chi + K^-\,(\bar{u}s)$	1179	χuss	-0.085	1.4×10^{-4}	

PRELIMINARY

  - Finishing/checking calculation of matrix elements (**to happen soon!**)

- **Other signatures calculable with chiral Lagrangians**
  - **Two pions:** e.g. $\Xi^- \to \pi^0\pi^- + \mathrm{inv}$
  - **Two leptons:** e.g. $\Xi^0 \to e^+e^- + \mathrm{inv}$
  - **Two leptons and one pion:** e.g. $\Xi^- \to \pi^- e^+ e^- + \mathrm{inv}$ (**LHCb!**)

Type of results to appear in the white book



- Interplay with colliders, flavor observables, SN bound will be partially covered

> **Question for experimentalists**
>
> Which BNV modes could be measured and for which could we get **BESIII/SCTF** and **LHCb** projections?

Summary

Solid progress towards completion of baryon pheno section

1. **Heavy New Physics:** Constraining axial currents
   - $B_1 \to B_2 \nu\bar{\nu}$ interesting if order-of-magnitude improvement over Hai-Bo's projections
   - We can provide $K \to \pi\pi\nu\bar{\nu}$ predictions
2. **2-body decays**
   - Formulae and form factors for baryonic decays for **axions** and **massless dark photon**
   - Axial current for **axion** and (possibly) best limits for **dark photon**
   - **SN bound** (should be taken as reference)
   - Decays of polarized baryons to help beating backgrounds?
   - **@Marco** Sprecific proposals to try converge and finish **dark photon section**
3. **Dark baryons**
   - **Only accessible with hyperon decays:** Fullfledged theoretical&experimental program
   - **To be written soon!!**

What is missing?

1. **Selection of experimental projections**
2. Other models in interplay with kaons?