Constraining CP violation in the main decay of the neutral Sigma hyperon

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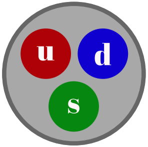
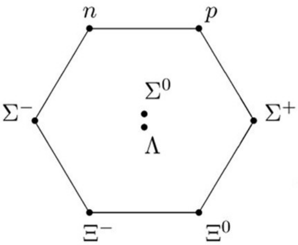
Focus on:

Σ^0 and Λ hyperon

Σ^0 : $\quad I(J^P) = 1(\frac{1}{2}^+)$

Λ : $\quad I(J^P) = 0(\frac{1}{2}^+)$

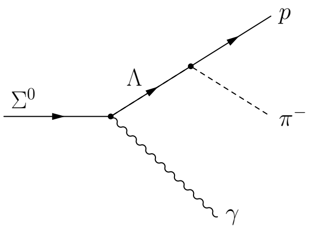




Focus on:

$\Sigma^0 \rightarrow \Lambda\gamma$ BR: 100%

$\Lambda \rightarrow p\pi$ BR: 64%

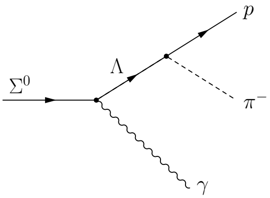


Motivation

- Look for **baryonic** CP violation

  $\rightarrow$ Might give us some insight into the origin of:

  - baryon asymmetry
  - strong CP problem



Strong CP problem in a nutshell

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \bar{q}(i\not{D} - \mathcal{M})q + \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$$

- QCD doesn't seem to break CP symmetry (in contrast to the electroweak theory)
  $\rightarrow$ *i.e.*, no experimental evidence for strong CP violation

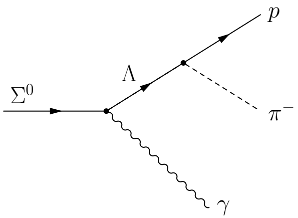
Our conservative approach:

1. allows strong CP violation via θ-term
2. stays faithful to the Standard Model (SM)

Two-step decay chain

Our starting point:

1. $\Sigma^0 \to \Lambda\gamma$
   - electromagnetic decay
   - parity conserving magnetic dipole transition moment κ_M
   - parity violating electric dipole transition moment $d_{\Sigma\Lambda}$



$$\mathcal{M}_1 = \bar{u}_\Lambda \left(a\,\sigma_{\mu\nu} - b\,\sigma_{\mu\nu}\gamma_5\right) u_{\Sigma^0}\,(-i)q^\nu \epsilon^{\mu *}$$

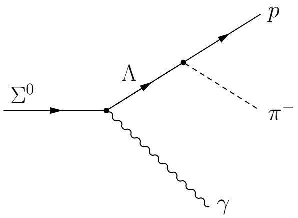
- a and b related to transition moments κ_M and $d_{\Sigma\Lambda}$
- final-state interaction leads to additional phase shift δ_F
- $\alpha_{\Sigma^0} := \frac{2\mathrm{Re}(a^* b)}{|a|^2+|b|^2}$ decay asymmetry parameter

Asymmetry in the angular distribution!

2. $\Lambda \to p\pi$
   - weak decay
   - self-analyzing

$$\mathcal{M}_2 = \bar{u}_p(\mathcal{A} - \mathcal{B}\gamma_5)\, u_\Lambda$$

- $\mathcal{A}$ and $\mathcal{B}$ related to s- and p-wave
- $\alpha_\Lambda := \frac{2\mathrm{Re}(s^* p)}{|s|^2+|p|^2}$



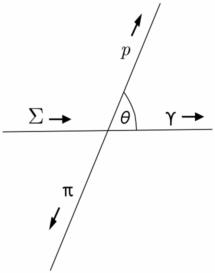
To reveal CP violation compare particle and antiparticle decays

Three-body decay

$$\mathcal{M}_3 = \bar{u}_p \, (\mathcal{A} - \mathcal{B}\gamma_5) \, (\not{p}_\Lambda + m_\Lambda) \, (a\,\sigma_{\mu\nu} - b\,\sigma_{\mu\nu}\gamma_5) \, u_{\Sigma^0} \, (-i) p_\gamma^\nu \, \epsilon^{\mu *} \, D_\Lambda(m_{12}^2)$$

- Λ resonance propagator

  $D_\Lambda(s) := (s - m_\Lambda^2 + i m_\Lambda \Gamma_\Lambda)^{-1}$
- Λ is long-lived → displaced vertex!



in the Λ rest frame

$$\boxed{\frac{d\Gamma_{\Sigma^0 \to \gamma p \pi^-}}{d\cos\theta} = \frac{1}{2} \Gamma_{\Sigma^0 \to \gamma\Lambda} \mathrm{Br}_{\Lambda \to p\pi^-} \left(1 - \boldsymbol{\alpha_\Lambda \alpha_{\Sigma^0}} \cos\theta\right)}$$

How?

- In practice: Compare decay distributions of Σ^0 and $\bar{\Sigma}^0$

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \frac{N}{2}(1 - \alpha_\Lambda \alpha_{\Sigma^0} \cos\theta) \quad \text{Vs} \quad \frac{\mathrm{d}\bar{N}}{\mathrm{d}\cos\theta} = \frac{\bar{N}}{2}(1 - \bar{\alpha}_\Lambda \bar{\alpha}_{\Sigma^0} \cos\theta)$$

- In theory: Exploit $SU(3)_F$ symmetry!

  i.e. from upper limit on neutron EDM $\to$ get upper limit for the angular asymmetry

- Construct an observable to search for CP violation

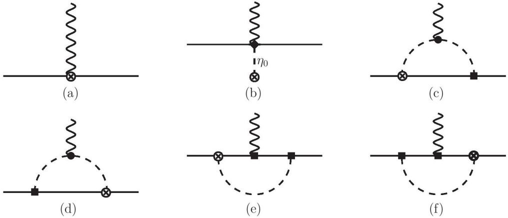
$$\boxed{\mathcal{O}_{\mathrm{CP}} := \alpha_{\Sigma^0} + \bar{\alpha}_{\Sigma^0}}$$

$\to$ vanishes if CP is conserved!

Theory approach

Σ^0-Λ EDM is related to nEDM via $SU(3)_F$ symmetry

- use baryon chiral perturbation theory (incl. θ-term) to connect them
- calculate Σ^0-Λ EDM at LO
  - one-loop diagrams contribute!
  - meson-baryon exchange pairs: $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $K^+\Xi^-$, K^-p



Guo/Meißer, JHEP 12 (2012) 097

Tree-level contribution to EDM

NEUTRON

$$d_n^{\rm tree} = \frac{8}{3}\, e\bar{\theta}_0\, (\alpha w_{13} + w'_{13})$$

Σ-Λ

$$d_{\Sigma\Lambda}^{\rm tree} = -\frac{4}{\sqrt{3}}\, e\bar{\theta}_0\, (\alpha w_{13} + w'_{13})$$

where:

- w_{13} and w'_{13} are low-energy constants from baryon NLO Lagrangian
- $\alpha := 144 V_0^{(2)} V_3^{(1)} / (F_0 F_\pi M_{\eta_0})^2$
- $\bar{\theta}_0 = \left[1 + \frac{4V_0^{(2)}}{F_\pi^2} \frac{4M_K^2 - M_\pi^2}{M_\pi^2 (2M_K^2 - M_\pi^2)}\right]^{-1} \theta_0$

Loop contribution to EDM

NEUTRON

$$d_n^{\rm loop} = -\frac{8e\bar{\theta}_0 V_0^{(2)}}{F_\pi^4} \sum_{\{M,B\}} C_{\rm cd}\, J_{MM}(0)$$

loops	$C_{\rm cd}$
$\{\pi^-, p\}$	$2(D+F)(b_D+b_F)$
$\{K^+, \Sigma^-\}$	$-2(D-F)(b_D-b_F)$

Σ-Λ

$$d_{\Sigma\Lambda}^{\rm loop} = -\frac{4e\bar{\theta}_0 V_0^{(2)}}{\sqrt{3}F_\pi^4} \sum_{\{M,B\}} (C_{\rm ce} - C_{\rm df})\, J_{MM}(0)$$

loops	$C_{\rm ce}$	$C_{\rm df}$
$\{\pi^+, \Sigma^-\}$	$-4Db_F$	$4Fb_D$
$\{\pi^-, \Sigma^+\}$	$-4Db_F$	$4Fb_D$
$\{K^+, \Xi^-\}$	$-(3F-D)(b_D+b_F)$	$(D+F)(3b_F-b_D)$
$\{K^-, p\}$	$-(D+3F)(b_D-b_F)$	$(D-F)(3b_F+b_D)$

where:

$$J_{MM}(q^2) = i\int \frac{d^dk}{(2\pi)^d}\frac{1}{(k^2-M^2+i\epsilon)((k+q)^2-M^2+i\epsilon)}$$
$$= 2L + \frac{1}{16\pi^2}\left(\ln\frac{M^2}{\mu^2} - 1 - \sigma\ln\frac{\sigma-1}{\sigma+1}\right)$$

- L contains a divergence, absorbed into the renormalization of w'_{13}

Parameter estimates

Our calculations give:

$$\frac{d_{\Sigma\Lambda}}{d_n} = \frac{d_{\Sigma\Lambda}^{\text{tree}} + d_{\Sigma\Lambda}^{\text{loop}}}{d_n^{\text{tree}} + d_n^{\text{loop}}} \approx -0.88$$

Use the experimental upper limit for the nEDM:

$$|d_n^{\text{exp}}| \leq 2.9 \times 10^{-26} e\,\text{cm}$$

$$\downdownarrows$$

to get an upper limit for the Σ^0-Λ EDM:

$$\boxed{|d_{\Sigma\Lambda}| \leq 2.5 \times 10^{-26} e\,\text{cm}}$$

Constraining CP violation in $\Sigma^0 \to \Lambda\gamma$

Our result:

$$\alpha_{\Sigma^0} \approx -\frac{2d_{\Sigma\Lambda}\sin\delta_F}{a}$$

$$\boxed{|\alpha_{\Sigma^0}| \leq 3.0 \cdot 10^{-14}} \quad \to \quad \boxed{|\mathcal{O}_{\mathrm{CP}}| \leq 6.0 \cdot 10^{-14}}$$

- far below any experimental resolution!
- observation of CP violating angular asymmetry implies physics beyond the Standard Model

Nair/Perotti/Leupold, Phys.Lett. B788 (2019)

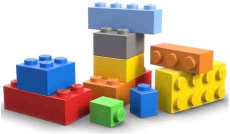
Summary and Outlook

So...What have we learned today?

- $\Sigma^0 \to \Lambda p \pi^-$: Observation of CP violating angular asymmetry would constitute physics BSM

And...What are other related projects?

- $\Sigma^{(*)}$-Λ Transition Form Factors to NLO
- Dalitz decays of decuplet hyperons to octet hyperons + dilepton
- Branching ratios of spin-3/2 decuplet hyperons to octet hyperon + photon



Back-up slides

Electric and magnetic dipole moment

Baryon coupling to the EM current J^μ:

$$\langle B'(p')|J^\mu|B(p)\rangle = e\,\bar{u}_{B'}(p')\,\Gamma^\mu(q)\,u_B(p), \qquad \text{with} \quad q := p - p'$$

and

$$\Gamma^\mu(q) = -\frac{i}{m_B + m_{B'}}\,\sigma^{\mu\nu} q_\nu\, F_2(q^2) - \frac{1}{m_B + m_{B'}}\,\sigma^{\mu\nu} q_\nu \gamma_5\, F_3(q^2)\ + \ldots$$

NEUTRON

$$F_{2,n}(0) = \kappa_n \approx -1.91$$

$$d_n = \frac{e}{2m_n}\, F_{3,n}(0)$$

Σ-Λ

$$\kappa_M := F_{2,\Sigma\Lambda}(0) \approx 1.98$$

$$d_{\Sigma\Lambda} := \frac{e}{m_{\Sigma^0} + m_\Lambda}\, F_{3,\Sigma\Lambda}(0)$$

Decay parameters

The two decay parameters a and b are related to the transition moments via:

$$a = \frac{e}{m_{\Sigma^0} + m_\Lambda} \kappa_M \, , \qquad b = i\, d_{\Sigma\Lambda}$$

For the second decay we have:

$$s := \mathcal{A} \qquad \text{and} \qquad p := \eta \mathcal{B}$$

with $\eta := |\vec{p}_p|/(m_p + E_p)$