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To cite this article: E Perotti 2020 J. Phys.: Conf. Ser. 1667 012033

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

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Abstract. The $\Sigma^0$ and $\Lambda$ hyperons are close relatives of the neutron, being related by flavour $SU(3)$ symmetry. This allows to estimate an upper limit for the electric dipole transition moment (EDTM) of the $\Sigma^0$-$\Lambda$ transition, based on the experimental knowledge of the upper limit of the neutron electric dipole moment. The three-body decay $\Sigma^0 \rightarrow \gamma p \pi^-$ could show an angular asymmetry due to the interference of parity violating and conserving amplitudes in both the first and second step of the decay chain $\Sigma^0 \rightarrow \Lambda \gamma \rightarrow \gamma p \pi^-$. This angular asymmetry, which will be measured at e.g. PANDA for both particle and antiparticle decays, is determined in this work from the $\Sigma^0$-$\Lambda$ EDTM, where a CP violating QCD theta-vacuum-angle term has been included. It turns out to be below any experimental resolution that one can expect in the foreseeable future. Any experimental significance would therefore point to physics beyond the Standard Model.

1. Introduction

The amount of charge conjugation parity (CP) symmetry violation predicted by the Standard Model (SM) is not enough to explain the baryon asymmetry observed in our universe. Yet it is one of Sakharov’s conditions[1]. In the SM, CP violation is minimally implemented via weak interactions (Cabibbo-Kobayashi-Maskawa matrix). Here we consider a simple extension by a CP violating QCD theta-vacuum-angle. Moreover, we look for CP violation in the baryonic sector, a choice which is timely considering the large productions of self-analyzing hyperons at ongoing and future experiments.

The decay chain $\Sigma^0 \rightarrow \Lambda \gamma \rightarrow \gamma p \pi^-$ (fig.1) together with its charge-conjugated decay are expected to carry the effects of possible CP violation [2]. The $\Sigma^0 \rightarrow \Lambda \gamma$ decay can be seen as
an interplay between a parity conserving magnetic dipole transition moment \(\kappa_M\) and a parity violating electric dipole transition moment \(d_{\Sigma\Lambda}\). The subsequent \(\Lambda \rightarrow p\pi^-\) decay is weak and therefore also characterized by the interference of a parity conserving and a parity violating amplitude. As a consequence of these features there is the possibility to observe an asymmetry in the angular distribution of the three-body decay \(\Sigma^0 \rightarrow \gamma p\pi^-\). Since the intermediate \(\Lambda\) hyperon is long-lived, the single-differential decay rate can be decomposed as:

\[
\frac{d\Gamma_{\Sigma^0 \rightarrow \gamma p\pi^-}}{d\cos \theta} = \frac{1}{2} \Gamma_{\Sigma^0 \rightarrow \gamma \Lambda} Br_{\Lambda \rightarrow \pi^- p} (1 - \alpha_\Sigma^0 \alpha_\Lambda \cos \theta) \tag{1}
\]

where \(\theta\) is the angle between the proton and the photon in the \(\Lambda\) rest frame. The decay asymmetries are defined by (see, e.g., \[3\])

\[
\alpha_\Sigma^0 := \frac{2 \text{Re}(a^* b)}{|a|^2 + |b|^2} \tag{2}
\]

with \(a\) and \(b\) decay parameters related to the transition moments via

\[
a = \frac{e}{m_{\Sigma^0} + m_\Lambda} \kappa_M, \quad b = i d_{\Sigma\Lambda} \tag{3}
\]

and

\[
\alpha_\Lambda := \frac{2 \text{Re}(s^* p)}{|s|^2 + |p|^2} \tag{4}
\]

with \(s\) and \(p\) proportional to the s-wave and p-wave amplitudes of the \(\Lambda \rightarrow p\pi^-\) decay, properly compensated for phase space differences. The values of the hyperon masses \(m_\Lambda\) and \(m_{\Sigma^0}\) are taken from \[3\]. The elementary charge is denoted by \(e\). According to \[3\] the most recent value of \(\alpha_\Lambda\) is \(0.750 \pm 0.009 \pm 0.004\) \[4\], which compared with \(\alpha_\bar{\Lambda} = -0.758 \pm 0.010 \pm 0.007\) \[3\] is compatible with the assumption of CP conservation in this specific decay channel. The decay asymmetry parameter \(\alpha_\Sigma^0\) is on the other hand still unknown; our goal is to provide an upper limit for it.

\section*{2. Electric Dipole Transition Moment}

Following the framework of \[5\] we calculated the \(\Sigma^0\Lambda\) electric dipole transition moment (EDTM) \(d_{\Sigma\Lambda}\) at leading order (LO) in the chiral expansion, where CP violation has been implemented via a QCD theta term. Electric dipole moments (EDMs) for nucleons and hyperons have also been calculated in \[6, 7\]. The coupling of baryons to the electromagnetic current \(J_\mu\) is given by:

\[
\langle B'(p')|J_\mu|B(p)\rangle = e u_{B'}(p') \Gamma^\mu(q) u_B(p) \tag{5}
\]

with \(q := p - p'\) and

\[
\Gamma^\mu(q) = \left(\gamma^\mu + \frac{m_{B'} - m_B}{q^2} q^\mu\right) F_1(q^2) \\
+ i \left(\gamma^\mu q^2 + (m_B + m_{B'}) q^\mu\right) \gamma_5 F_A(q^2) \\
- \frac{i}{m_B + m_{B'}} \sigma^{\mu\nu} q_\nu F_2(q^2) \frac{1}{m_B + m_{B'}} \sigma^{\nu\rho} q_\rho \gamma_5 F_3(q^2) . \tag{6}
\]

Since we deal with spin 1/2 baryons the vertex function \(\Gamma^\mu\) is given in terms of four form factors which are functions of the photon squared momentum: two of them are parity conserving \(F_1(q^2)\)
and $F_3(q^2)$, two of them are not ($F_3(q^2)$ and $F_A(q^2)$). The decay $\Sigma^0 \to \gamma \Lambda$ is only sensitive to the magnetic (dipole) transition moment $\kappa_M := F_{2,\Sigma\Lambda}(0)$, and the electric dipole transition moment $d_{\Sigma\Lambda} := e \bar{\theta}_0 (\alpha w_{13} + w'_{13})$.

(7)

In the following we present the novel $\Sigma$-$\Lambda$ EDTM results [2] besides the neutron ones [5]. The tree-level part is manifestly SU(3) symmetric:

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

(9)

and

$$d_{n}^{\text{tree}} = \frac{8}{3} e \bar{\theta}_0 (\alpha w_{13} + w'_{13})$$

(10)

with low-energy constants $w_{13}$ and $w'_{13}$ from the baryon next-to-leading order (NLO) Lagrangian and $\alpha := 144 V_0^{(2)} V_3^{(1)} / (F_0 F_{\pi} M_{\eta_0})^2$. Here, $F_0$ denotes the pion decay constant while $F_0 (M_{\eta_0})$ is the decay constant (mass) of the singlet eta field. This field is intimately tied to the field $\theta(x)$ that encodes the strong CP violation. In the framework of chiral perturbation theory it is useful to introduce a chirally invariant combination $\bar{\theta}(x)$ of these two fields. The vacuum expectation value of $\bar{\theta}(x)$ can be linked back to the vacuum expectation value of the original $\theta(x)$ field via

$$\bar{\theta}_0 = \left[ 1 + 4 V_0^{(2)} \frac{4 M_K^2 - M_{\pi}^2}{M_{\pi}^2 (2 M_K^2 - M_{\pi}^2)} \right]^{-1} \theta_0$$

(11)

with the masses of pion, $M_{\pi}$, and kaon, $M_K$. Finally, the quantities $V_i^{(j)}$ are the Taylor coefficients of the functions $V_i(\bar{\theta})$ expanded in powers of the field $\bar{\theta}$. These functions appear as coefficients in the chiral expansion of the meson Lagrangian [9, 10]. For technical details we refer to [7, 5].

Interestingly one-loop diagrams with various meson-baryon pairs $\{M, B\}$ contribute at the same order as the tree-level terms of eqs.(9, 10)

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

(12)

and

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

(13)

The sum covers the meson-baryon pairs listed in table 1 or 2 respectively. The loop function $J_{MM}$ is essentially the bubble diagram with two meson lines of mass $M$. It is given by

$$J_{MM}(q^2) = \frac{1}{i} \int \frac{d^4 k}{(2\pi)^d} \frac{1}{(k^2 - M^2 + i\epsilon)((k + q)^2 - M^2 + i\epsilon)}$$

$$= 2 L + \frac{1}{16\pi^2} \left( \ln \frac{M^2}{\mu^2} - 1 - \sigma \ln \frac{\sigma - 1}{\sigma + 1} \right),$$

(14)
Table 1. Coefficients for the loop contributions to the EDTM of $\Sigma^0$ to $\Lambda$. The first column shows all possible meson-baryon pairs that can contribute in the loop. The second and third columns contain the respective coefficients $C_{cc}$ and $C_{df}$. The indices c–f refer to the loop diagrams depicted in [5]. The parameters $F (b_F)$ and $D (b_D)$ are low-energy constants from the LO (NLO) baryon Lagrangian.

| $\{M, B\}$  | $C_{cc}$         | $C_{df}$         |
|--------------|------------------|------------------|
| $\{\pi^+, \Sigma^-\}$ | $-4Db_F$         | $4Fb_D$          |
| $\{\pi^-, \Sigma^+\}$ | $-4Db_F$         | $4Fb_D$          |
| $\{K^+, \Xi^-\}$     | $-(3F - D)(b_D + b_F)$ | $(D + F)(3b_F - b_D)$ |
| $\{K^-, p\}$         | $-(D + 3F)(b_D - b_F)$ | $(D - F)(3b_F + b_D)$ |

Table 2. Coefficients for the loop contributions to the neutron EDM. See the caption of table 1 for further details.

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

where $\sigma = \sqrt{1 - 4M^2/q^2}$ and $L$ contains the divergence for space-time dimension $d = 4$. As shown in [5], it can be absorbed into the renormalization of the low-energy constant $w_{13}'$. Note that different combinations of coefficients enter the one-loop contributions of eqs.(12, 13) as a consequence of the explicit breaking of the $SU(3)$ flavor symmetry, which is systematically taken into account by chiral perturbation theory.

3. Results and conclusions
Having used the numerical values of the low-energy constants as spelled out in [2], we obtain:

$$\frac{d_{\Sigma\Lambda}}{d_n} = \frac{d_{\Sigma\Lambda}^{\text{tree}} + d_{\Sigma\Lambda}^{\text{loop}}}{d_n^{\text{tree}} + d_n^{\text{loop}}} \approx -0.88.$$  \hspace{1cm} (15)

Using eq.(15) together with the experimental upper limit of the neutron EDM [11], $|d_{n}^{\text{exp}}| \leq 2.9 \times 10^{-26} \text{ e cm}$, we obtain an upper limit for the $\Sigma^0$-$\Lambda$ EDTM:

$$|d_{\Sigma\Lambda}| \leq 2.5 \times 10^{-26} \text{ e cm}.$$  \hspace{1cm} (16)

Recalling the definition of the angular asymmetry parameter $\alpha_{\Sigma^0}$ of eq.(2), we can relate it to the EDTM:

$$\alpha_{\Sigma^0} \approx -\frac{2d_{\Sigma\Lambda}}{a} \sin \delta_F,$$  \hspace{1cm} (17)

which in turn constraints the angular asymmetry of the $\Sigma^0$ decay to

$$|\alpha_{\Sigma^0}| \leq 3.0 \times 10^{-14}.$$  \hspace{1cm} (18)
In the above estimate we have taken the final state interaction factor \( \sin \delta_F \) to be of order \( \alpha_{\text{QED}} \), being the interaction between the photon and the \( \Lambda \) of electromagnetic nature. Considering also the antiparticle decay, one can construct an observable to test CP symmetry, namely

\[
|O_{\text{CP}}| := |\alpha_{\Sigma^0} + \alpha_{\bar{\Sigma}^0}| \leq 6.0 \times 10^{-14}.
\] (19)

Conservation of CP symmetry would result in \( O_{\text{CP}} = 0 \). The extremely tiny effect of eq. (19) cannot be observed at any experimental facility in the near future. Any experimental significance would therefore point to physics beyond the Standard Model.

Acknowledgments
This work is a follow-up on S. S. Nair’s Master Thesis [12]. It has been supported by the Anna Maria Lundin’s Fund. I thank S. Leupold for his guidance through this work.

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