Relating CP-violating decays to the neutron EDM

Thomas Gutsche,1 Astrid N. Hiller Blin,2 Sergey Kovalenko,3 Serguei Kuleshov,3 Valery E. Lyubovitskij,1,3,4,5 Manuel J. Vicente Vacas,6 and Alexey Zhevlakov4

1Institut für Theoretische Physik, Universität Tübingen, Kepler Center for Astro and Particle Physics, Auf der Morgenstelle 14, D-72076 Tübingen, Germany
2Institut für Kernphysik & PRISMA Cluster of Excellence, Johannes Gutenberg Universität, D-55099 Mainz, Germany
3Departamento de Física y Centro Científico Tecnológico de Valparaíso (CCTVal), Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile
4Department of Physics, Tomsk State University, 634050 Tomsk, Russia
5Laboratory of Particle Physics, Mathematical Physics Department, Tomsk Polytechnic University, 634050 Tomsk, Russia
6Instituto de Física Corpuscular, Universidad de Valencia –CSIC, Institutos de Investigación, Ap. Correos 22085, E-46071 Valencia, Spain

We use the present upper bound on the neutron electric dipole moment to give an estimate for the upper limit of the CP-violating couplings of the $\eta$($\eta'$) to the neutron. Using this result, we derive constraints on the CP-violating two-pion decays of the $\eta$($\eta'$) mesons. Our results are relevant for the running and planned GlueX and LHCb measurements of rare meson decays.

Keywords: Neutron EDM, CP-violating decays

I. INTRODUCTION

The understanding of CP-violating processes is important from many points of view, both in particle physics, as well as for hadron interactions. On the one hand, the baryon asymmetry in the universe is tightly connected to the existence of CP-violation. In the standard model (SM), this violation has already been confirmed experimentally [1], and it is explained by the explicit symmetry breaking due to a complex phase in the Cabibbo-Kobayashi-Maskawa matrix. However, it is insufficient by several orders of magnitude to explain the size of the baryon asymmetry observed. One expects further beyond-the-SM CP-violating processes to enhance this effect [2–6].

On the other hand, the existence of a permanent electric dipole moment (EDM), both in elementary particles and in hadrons such as the neutron, would point to CP violation as well [7–12]. The neutron, in particular, is a favoured target due to its neutral charge and stability. Currently, only an upper bound on its EDM is known, $|d_n| \leq 2.9 \times 10^{-26}$ e cm with a confidence level (C.L.) of 90% [1].

In view of the extensive experimental programs, by collaborations such as LHCb and GlueX [13, 14], aiming to measure EDMs and searching for rare CP-violating decays, we investigate how to gain further theoretical insight on the size of CP-violating decays, and how to relate them to the permanent EDM of the neutron. We use the framework of fully covariant chiral perturbation theory (ChPT) [15, 16], with the explicit inclusion of vector-meson (VM) [17–20] and $\Delta (1232)$ [21] degrees of freedom. Furthermore, the renormalization scheme used is the extended on-mass shell (EOMS) scheme [22, 23], which is relativistic, satisfies analyticity, and usually converges faster than other relativistic or non-relativistic approaches.

We focus on the process $\eta$($\eta'$) $\rightarrow \pi\pi$. Since it contributes to the neutron EDM, the above-cited current experimental limits on the latter allow for the derivation of indirect upper bounds on the branching ratios of this CP-violating type of decays [24]. The current direct experimental 90% C.L. upper limits [1] are

$$\frac{\Gamma(\eta \rightarrow \pi\pi)}{\Gamma_{\eta}^{\text{tot}}} < \begin{cases} 1.3 \times 10^{-5} & \text{for } \pi^+\pi^- \\ 3.5 \times 10^{-4} & \text{for } \pi^0\pi^0 \end{cases},$$

$$\frac{\Gamma(\eta' \rightarrow \pi\pi)}{\Gamma_{\eta'}^{\text{tot}}} < \begin{cases} 1.8 \times 10^{-5} & \text{for } \pi^+\pi^- \\ 4.0 \times 10^{-4} & \text{for } \pi^0\pi^0 \end{cases}. \tag{1}$$

with $\Gamma_{\eta(\eta')}$ the total decay width.

We proceed as follows: with the help of the experimental upper limit on the neutron EDM, we derive a constraint on the CP-violating couplings of the $\eta$($\eta'$) to the neutron. By describing these couplings via an intermediate pion loop, we can thus extract an estimate of the upper limit of the CP-violating $\eta$($\eta'$) decay into two pions, which turns out to be much more stringent than those given by the experiment so far.
II. RELATING THE NEUTRON EDM TO THE CP-VIOLATING COUPLINGS

The neutron EDM is extracted from the CP-violating piece of the vector current $J^\mu$ of a virtual photon coupling to the neutron, which reads:

$$\langle B(p') | J^\mu_{\text{CPV}} | B(p) \rangle = \bar{u}(p') i\sigma^{\mu\nu}\gamma_5 q_\nu F_{\text{EDM}}(q^2) u(p),$$

(2)

where $q_\nu$ is the momentum of the virtual photon, $\epsilon_\mu$ its polarization, and $\sigma^{\mu\nu} = \frac{i}{2} [\gamma_\nu, \gamma_\mu]$. At the point where $q^2 = 0$, the form factor reduces to the electric dipole moment $F_{\text{EDM}}(0) = \tilde{d}_N$. In our model, we consider the contributions to the CP violation that arise through the loops of Fig. 1.

![Loops that can contribute to the neutron EDM. The solid line represents the neutron, the dotted line the $\eta(\eta')$, the dashed lines are vector-meson contributions, and the wavy line corresponds to the photon. Again, the black box stands for a CP-violating vertex.](image)

The standard ChPT Lagrangians that describe the CP-conserving couplings appearing here are detailed in Ref. [24]. These include all the couplings involving photons, pseudoscalar and vector mesons, nucleons, and the $\Delta(1232)$ resonance. As for the CP-violating coupling of the $\eta(\eta')$ to the neutron, it is given by

$$\mathcal{L}_{\text{HNN}}^{CP} = g_{\text{HNN}}^{CP} H \bar{N} N,$$

(3)

with $H = \eta, \eta'$. The unknown couplings $g_{\text{HNN}}^{CP}$ can thus be related to the size of the neutron EDM $F_{\text{EDM}}(0)$, thus leading to a constraint on their size.

However, the goal of this work is to set constraints on the size of the CP-violating coupling of the $\eta(\eta')$ to two pions, $f_{H\pi\pi}$. Thus we need to relate $g_{\text{HNN}}^{CP}$ to $f_{H\pi\pi}$, which is done via the ansatz shown in Fig. 2: there, the $\eta(\eta')$ couples to the neutron via an intermediate pion loop. These loops, that include the coupling $f_{H\pi\pi}$, when contracted to one point give precisely the coupling $g_{\text{HNN}}^{CP}$. With this approach, one can thus relate the unknown coupling $f_{H\pi\pi}$ to $g_{\text{HNN}}^{CP}$, which was extracted from the size of the neutron EDM.

The effective Lagrangian describing this CP-violating $\eta(\eta')\pi\pi$ coupling is given by

$$\mathcal{L}_{H\pi\pi}^{CP} = f_{H\pi\pi} M_H H \bar{\pi}\pi,$$

(4)

where $M_H$ is the mass of the $\eta(\eta')$ meson and $f_{H\pi\pi}$ is the coupling constant of $\eta(\eta')$ to the pions. Considering the current experimental upper limit of $2.9 \cdot 10^{-26} e\,\text{cm}$ on the neutron EDM, the constraint on the CP-violating couplings $f_{H\pi\pi}$ is eight orders of magnitude lower than experimentally measured so far, as shown in Eq. 1.
FIG. 2: Loops that can contribute to the $CP$-violating coupling of the $\eta(\eta')$ to the nucleon. The single solid lines stand for nucleons, the double lines for the $\Delta$, the dashes for pions and the dotted lines for the $\eta(\eta')$. The black box at the $H\pi\pi$ vertex indicates the $CP$-violating coupling.

It is important to keep in mind that the sources considered here to originate the neutron EDM included only the $CP$-violating coupling of $\eta(\eta')$ mesons to the neutron. In the future, our goal is to extend this work by considering additional contributions, such as vertices where a photon couples directly to the $CP$-violating meson-nucleon vertex. The contributions from the additional loops that arise from this kind of vertex are expected to give even larger contributions, since they are of a lower chiral order, thus constraining the $\eta(\eta') \to \pi\pi$ branching ratio even further. These vertices can be estimated through contributions similar to those in Fig. 2, but with additional external photon lines, i.e. by pion and $\eta(\eta')$ photoproduction with one $CP$-violating vertex.

III. SUMMARY

We related the neutron EDM to the $CP$-violating decay of the $\eta(\eta')$ mesons into two pions, with the help of fully covariant ChPT. In particular, since the experimental upper limit of $2.9 \cdot 10^{-26}$ e cm for the neutron EDM is very small, it sets a very strong constraint on observables related to it. Therefore, here the goal was to give an estimate of the size of the $CP$-violating branching ratio.

In total, we obtained a constraint on the $CP$-violating $\eta(\eta') \to \pi\pi$ decay ratio roughly eight orders of magnitude smaller than measured in the experiment so far. This is a very instructive result, since it gives an estimate in a region where experimental results are not yet achievable.

It is important to keep in mind that the constraints given in this work are mere estimates, since other processes than those considered here give additional contributions to the neutron EDM. Nevertheless, due to the very large discrepancy between the experimental constraint on the $CP$-violating decays of the $\eta(\eta')$ and those calculated from the current upper limit for the neutron EDM, the results are still rigorous enough for the conclusions to persist, even if other processes are to be additionally considered.

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