The REDTOP experiment: an η/η' factory

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Abstract

REDTOP is a η/η' factory which aims at detecting small deviations from the Standard Model by collecting a large event set from protons impinging on fixed targets. The proposed experiment will produce about 10^{13} η mesons or 10^{11} η' mesons corresponding to an increase of the existing world sample by four order of magnitude. Decays of the neutral and long-lived η and η' mesons could shed light on New Physics from a theoretical and experimental standpoint. All their electromagnetic and strong decays are suppressed at first order and weak decays have branching ratios of order $\leq 10^{-11}$. Therefore, they provide an excellent laboratory for precision measurements and a unique window to search for Physics Beyond the Standard Model in the MeV-GeV mass range. The η meson has a simple symmetric quark structure which is conducive for fast triggers and online analysis. The detector requires fast and precise timing and should be sensitive only to those particles being produced in the processes of interest. The REDTOP experiment will exploit novel detector technologies aimed at a highly granular, nearly hermetic apparatus, with fast timing (~ 30 *ps*) and excellent particle identification. This will offer the opportunity for a broad physics program, exploiting different beam energies and beam configurations along with the world's leading facility to search for physics BSM in flavor-conserving processes.

The Physics Program of the REDTOP experiment

The peculiarity of the η and η' mesons is that all their quantum numbers are zero. This is a very rare occurrence in nature and strongly constraints the dynamics of those particles. Therefore their decays offer many opportunities for exploring Physics Beyond the Standard Model (BSM). REDTOP will investigate with large statistics violations of discrete symmetries[8, 7] and will search for new weakly-coupled light particles in the MeV-GeV mass scale. They also provide an opportunity to investigate Standard Model predictions with high precision[6]. The most important physics processes that REDTOP experiment[1, 10] intends to study are summarized below, with the golden modes highlighted in blue.

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^0\pi^+\pi^-$
- CP Violation (Type I - P and T odd , C even): $\eta \to 4\pi^0 \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to 4\pi^0 l^+ l^-$ and $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
- Test of CP invariance via γ^* polarization studies: $\eta \to \pi^+\pi^- e^+ e^-$ and $\eta \to \pi^+\pi^-\mu^+\mu^-$
- Test of CP invariance in angular correlation studies: $\eta \to \mu^+\mu^- e^+ e^-$
- Test of T invariance via μ transverse polarization: $\eta \to \pi^0\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polarization in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ and γ polarization in $\eta \to \gamma\gamma$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \to \pi^0 H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$
- Dark photon searches: $\eta \to \gamma A'$ with $A' \to l^+ l^-$
- Protophobic fifth force searches: $\eta \to \gamma X_{17}$ with $X_{17} \to e^+e^-$
- New leptophobic baryonic force searches: $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^0$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma\, e^+e^-$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+ e^- + c.c.$
- Double lepton Flavor Violation: $\eta \to \mu^+\mu^+ e^- e^- + c.c.$

Other Precision Physics measurements

- Proton radius anomaly: $\eta \to \gamma\,\mu^+\mu^-$ vs $\eta \to \gamma\, e^+e^-$
- All unseen leptonic decay mode of η/η'(SM predicts $10^{-6} \div 10^{-9}$)

Non-η/η' based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: $q\bar{q} \to A'/a \to l^+ l^-$
- $p + D \to {}^3\text{He}^+ + X_{17}$ with $X_{17} \to e^+e^-$
- ALP's searches in Primakoff processes: $pZ \to pZa \to l^+ l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi^+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K^+ \to \mu^+\nu A' \to \mu^+\nu\, e^+e^-$
- Neutral pion decay: $\pi^0 \to \gamma A' \to \gamma\, e^+e^-$

High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

Experimental Technique and Beam Requirements

The Collaboration has identified three staged physics runs corresponding to different production mechanisms of η and η' mesons:

Run I - Untagged η/η' factory

In this stage, η and η' mesons are produced from a proton beam scattered on a target made of multiple thin Lithium foils. The production mechanism is based on the formation and decay of intra-nuclear baryonic resonances. Monte Carlo studies have indicated that beam energies of $\sim 1.8\ GeV$ ($\sim 3.0\ GeV$ for the η' meson) are optimal. At such energies the production cross-section is relatively large (of order of several mbarn) and a low-power beam ($30 \div 50\ W$) is sufficient to generate the desired statistics. To cope with large background from hadronic inelastic scattering, a Continuous Wave beam is required.

Run II - Tagged η factory

In this stage, η mesons are produced on a gaseous Deuterium target via the nuclear process $p + D \to \eta + {}^3\text{He}^{++}$. A minimum of 880 MeV beam energy is required. The smaller η/η' production cross section can be compensated with a larger beam intensity ($\sim 1MW$). By tagging the production of the η via the detection of the ${}^3\text{He}^{++}$ ion, the combinatorics background from non η events is greatly diminished and the sensitivity of the experiment to New Physics is increased. The 4-momentum of the ${}^3\text{He}^{++}$ ion can be measured with the addition of a forward detector. Therefore the kinematics of the reaction is fully closed. Any long-lived, dark particle escaping detection could be identified by measuring the missing 4-momentum. This technique is considerably more powerful than missing p_T or missing energy and it mirrors an analogous technique adopted by B-factories but with the advantage of 4×10^4 larger statistics.

Run III - Tagged η' factory

In this stage, η' mesons are produced with higher beam energy (1.7 GeV) and higher intensity ($> 1MW$), using the same target and detector as in Run II.

The REDTOP Detector

The expected inelastic scattering rate is of the order of 1 GHz (i.e. about 30 times the rate at LHCb experiment). Detailed MC studies indicate a hadronic background[9] with a very low multiplicity ($\leq$ 8 primary particles). Most of the physics processes listed in the table above have leptons and γs in the final state. Furthermore the detection of displaced vertices (not from γ conversion) is an indication of New Physics. Such an environment poses strict requirements on the detector and it portends to an intense *R&D* program:

- **Sub-nanosecond timing detector with ~ 30 *ps* time resolution -** This can be achieved exploiting the prompt nature of the Čerenkov signal combined with the last generation of Si detectors (for example LGAD and 3D digital SiPM).
- **Excellent Particle IDentification (PID) -** Several techniques will be exploited to disentangle final state leptons from the slow baryonic background: threshold Čerenkov, high granularity dual-readout and PFA calorimetry (5D calorimetry), and Time of Flight (ToF) with $\sim$ 30 *ps* time resolution.
- **$\leq 100\ \mu m$ resolution vertexing -** The latter will help rejecting the combinatorics from the γ conversion and with secondary vertices reconstruction of long-lived new particles.
- **Good energy resolution -** for bump-hunting of decaying particles over a continuous background.
- **Forward detector -** for tagging and reconstruction of the $^3\text{He}^{++}$ in Run II and Run III.

The proposed experimental apparatus includes the following detectors:

- **Vertex Fiber Tracker -** Its main purpose is to identify displaced vertexes of long lived particles and to reject e^+e^- pairs from γ conversion. It is based on a mature technology developed by LHCb experiment, achieving a spatial resolution $\leq$ 80 μm. MARS15[17, 5] studies indicate that irradiation doses will be similar to those at LHCb.
- **Central Tracker -** It relies on the threshold Čerenkov effect to separate slower particles (nuclear interactions) from fast leptons associated with New Physics. Fast timing is needed to cope with the large event rate and for input to a Level-1 trigger. Two options are being considered: an Optical-TPC (OTPC)[22] and an LGAD Tracker with $\sim$ 30 *ps* timing[23, 14] surrounded by Quartz bars. An OTPC is blind to most hadronic background while sensitive to faster η decay products. An LGAD Tracker has the granularity to reject multi-hadron events via a 4D track reconstruction. The Quartz bars provide fast input to the Level-0 trigger and complement the LGAD detector for Time (ToF) measurements.
- **5D Calorimeter -** The proposed integrally active ADRIANO2 calorimeter[4, 12, 11] combines the dual-readout and the PFA techniques. It has an excellent energy and position resolution and PID capabilities (5D calorimeter). The scintillation and the Čerenkov lights are read out by on-tile SiPMs[2] or SPAD[16, 20, 21, 18, 19, 15]. The SPAD timing resolution (15 *ps*), based on Single-Photon Avalanche Diode arrays, can be exploited for ToF measurements and as input to the Level-0 trigger.
- **Muon Polarimeter -** It measures the polarization of muons from η/η' decays. A non-zero measurement would be an indication of BSM Physics[6]. Several technologies are being considered. The baseline design is composed by a sandwich of fused silica and Si-pixel extending the technique developed by CALICE[3].
- **Forward Detector for Run II/III -** The tagging $^3\text{He}^{++}$ ions with momentum above 1.24 *GeV* are mostly emitted in a $[3^\circ \div 5^\circ]$ angular range. The very forward region will be instrumented with a fast LGAD pixel tracker and a sandwich of active fused silica and Si-pixel, combining technologies developed for ADRIANO2[4, 11] and CALICE Si/W electromagnetic[3, 13] calorimeters.

Conclusions

We propose an η/η' factory with a meson yield corresponding to an order $O(10^4)$ increase of the present world sample. A very broad physics program can be exploited. Novel detector techniques are required benefiting experiments at future colliders or with high intensity beam.

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