Detecting physics beyond the Standard Model with the REDTOP experiment

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Abstract. REDTOP is an experiment at its proposal stage. It belongs to the High Intensity class of experiments. REDTOP will use a 1.8 GeV continuous proton beam impinging on a fixed target. It is expected to produce about $10^{13} \eta$ mesons per year. The main goal of REDTOP is to look for physics beyond the Standard Model by detecting rare $\eta$ decays. The detector is designed with innovative technologies based on the detection of prompt Cherenkov light, such that interesting events can be observed and the background events are efficiently rejected. The experimental design, the physics program and the running plan of the experiment is presented.

1. Introduction
Rare Eta Decays with a TPC for Optical Photons (REDTOP) is a new proposed experiment to search for physics beyond the Standard Model [1]. The experiment will have a branching ratio sensitivity level better than $10^{-10}$, an estimated production of $2 \times 10^{13}$ $\eta$ mesons per year using a continuous proton beam with an average intensity of about $10^{11}$ protons per second impinging on fixed beryllium targets. These are the necessary requirements to produce enough statistical information about $\eta$ decays. This experiment is expected to study C and CP violation as well as C, T, CP and CPT violations, lepton flavor violation; in addition, it will search for new scalar particles, new baryonic forces and new gauge bosons.

2. Why $\eta$ meson?
The $\eta$ meson is a pseudo Goldstone boson and an eigenstate of the C, P, CP and G operators, making it a very special particle and a good option to test C and CP invariance of the strong and electromagnetic interactions. Most of the symmetry violations in $\eta$ and $\eta'$ decays can be detected at a level of $10^{-5}$ or higher; in consequence, REDTOP will increase the $\eta$ flux to reach the essential levels needed to detect interesting events.

3. Experimental apparatus
The detector
The REDTOP detector consists of the following components: the Optical Time Projection Chamber (OTPC), the ADRIANO Dual-Readout Calorimeter, the Muon Polarimeter and Photon Polarimeter. It will be sensitive to electrons, positrons, muons, photons and charged pions, all of them above the Cherenkov thresholds.
The beam and target system

The target system is composed of ten beryllium foils with a thickness of 1/3 mm and 1 cm of diameter, it is located at the center of the beam pipe which is composed of carbon fiber or beryllium. The probability of a proton with an energy of 1.8 GeV interacting by inelastic scattering in any foil of beryllium is 0.5% and the probability to produce a $\eta$ meson is of approximately 0.4%. Monte Carlo (MC) simulations show that the $\eta$ decays are not affected by the beryllium foils. The experiment will use a beam with an energy of 1.8 GeV, provided by a cavity added to the Delivery Ring (DR) which will decelerate the beam coming from the Booster synchrotron.

The Optical Time Projection Chamber

The Optical Time Projection Chamber will measure the momentum and position of a charged track using the Cherenkov effect instead of the gas ionization. The momentum is reconstructed from the detection of the photons radiated and the photo sensors will detect them. The OTPC will be very sensitive to leptons and fast pions while hadrons and slower pions will not be recorded. Two Cherenkov radiators are present: a double aerogel cylinder of about 3 cm thick at the inner wall formed by an innermost and outermost aerogel with $n_D = 1.22$ and $n_D = 1.35$, respectively and a low-pressure nitrogen gas will fill the rest of the volume; in consequence, pions and muons will be discriminated by dual refractive system while electrons and positrons with large momentum will radiate in the aerogel as well as in the gas.

The ADRIANO Dual-Readout Calorimeter

The ADRIANO (A Dual-Readout Integrally Active Non-segmented Option) calorimeter is based on two simultaneous measurements of the energy deposited by a hadronic or electromagnetic shower into two media with different properties. The first is a plastic scintillation, in which any charged particle going through it will generate scintillation. The second medium is a heavy glass with a refractive index of $n_D \geq 1.8$ and a density of $\rho > 5.5 \text{ g/cm}^3$, it will record signals of charged particles and absorb all the particles impinging on the detector. The measurements of scintillation and Cherenkov signals will provide the total energy and by comparing them, identify the initial particle. The main advantage of using a dual readout calorimeter to detect the photons from the $\eta$ decays is that a large amount of background can be easily rejected.

Figure 1. Transverse view of the detector.
The Muon and Photon Polarimeters
The polarimeters are composed of plastic scintillators inserted in specific areas of the detector. The muon polarimeter is inserted between the inner and the outer shells of ADRIANO calorimeter: it will count the $e^+$ and $e^-$ emitted when a muon is stopped inside the polarimeter while the photon polarimeter is inserted inside the volume of the OTPC: it will count the number of photons decaying to $e^+ e^-$ pairs. The asymmetry of the counting will provide an estimate of the polarization of muons and photons.

4. Physics program
The REDTOP experiment will focus on many areas of research, including: symmetry and conservation laws violations, searches for new particles and forces and searches for new baryonic forces.

Symmetry and conservation violations
- **CP Violation (Type I: P and T odd, C even):** This type of CP violation considers a parity of the final state is reversed while charge conjugation is unchanged. This happens when the $P=-1$ and the $\eta$ meson decays into an even number of pions.
- **CP Violation (Type II: C and T odd, P even):** The charge of the final state is reserved and parity is not. This will just be possible in certain classes of decays:
  \[ \eta \rightarrow \pi^0 \pi^+ \pi^- \quad \text{and} \quad \eta \rightarrow 3\gamma \]
- **CP Violation via the polarization of the muons:** In the $\eta \rightarrow \mu^+ \mu^-$ decay, the CP invariance does not allow the muons to be longitudinally polarized. For observing non-zero longitudinal polarization of the muons, an extra Higgs boson must be considered. The muon polarization would be as high as $10^{-2}$.
- **CP and C Violation with Dalitz plot studies:** The CP invariance has to be present in the $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay considering the dynamics of charged pions are symmetric. Essentially, any mirror-asymmetry in the Dalitz plot would be an indication of CP and C violation.
- **T violation via the polarization of the muons:** Detecting T invariance implies that transverse polarization of the muons be null in the following decays:
  \[ \eta \rightarrow \pi^0 \mu^+ \mu^- \quad \text{and} \quad \eta \rightarrow \gamma \mu^+ \mu^- \]
  Observing any polarization is a direct evidence of violation of T invariance.
- **CPT Violation:** CPT invariance can be test analyzing two processes:
  \[ \eta \rightarrow \pi^+ \mu^- \nu^- \quad \text{vs} \quad \eta \rightarrow \pi^- \mu^+ \nu^+ \]
  In case of CPT violation, the transverse polarization of the $\mu^-$ and $\mu^+$ is reversed. The $\eta \rightarrow \pi \mu \nu$ is not detected yet.
- **CPT Violation with non-hermitian lagrangians:** In the following processes,
  \[ \eta \rightarrow \gamma \gamma \quad \text{and} \quad \pi^0 \rightarrow \gamma \gamma \]
  the CPT invariance of the hermitian lagrangians implies that the photons have null circular polarization. The main reason to verify this case is that if the non-null circular polarization of the photons exist [4], Redtop will observe it.
• **Lepton flavor violation:** Violation of the leptonic number will be detected in the process:

\[ \eta \rightarrow \mu^+e^-\gamma \quad \text{and} \quad \eta \rightarrow \pi^0\mu^+e^- + c.c. \]

where current PDG limits are lower than \( 5.7 \times 10^{13} \) and CL=90%.

• **Double lepton flavor violation:** Double violation of the leptonic number could be observed through the following process:

\[ \eta \rightarrow \mu^+\mu^-e^-e^- + c.c. \]

this event is considered a rare process but it occurs within the sensitivity of the experiment. Its unique signature make it easy to detect.

• **CP Violation with gamma polarization measurements or in \( \eta \rightarrow \pi^+\pi^-e^+e^- \) decays:** For investigating the CP violation we will take a look to the photon in the decay \( \eta \rightarrow \pi^+\pi^-\gamma \), this needs the photon polarization which will be measured with a gamma polarimeter. Furthermore, It is possible study CP violation considering a virtual photon decaying into a \( e^-e^+ \) pair.

\[ \eta \rightarrow \pi^+\pi^-\gamma^* \quad \text{with} \quad \gamma^* \rightarrow e^++e^- \]

The CP invariance vanish the next asymmetry:

\[
A_\Phi = \frac{N(\sin[\Phi] \cos[\Phi] > 0) - N(\sin[\Phi] \cos[\Phi] < 0)}{N(\sin[\Phi] \cos[\Phi] > 0) + N(\sin[\Phi] \cos[\Phi] < 0)}
\]

in which \( \Phi \) is the angle between the decay planes of the electron-positron pair and the two charged pions. The REDTOP experiment will improve on the systematic error by almost two orders of magnitude compared with the best present measurements of such asymmetry performed by WASA collaboration [2].

**Searches for new particles and forces**

• **The proton radius anomaly:** The processes implicated are

\[ \eta \rightarrow \gamma e^+e^- \quad \text{and} \quad \eta \rightarrow \gamma \mu^+\mu^- \]

This anomaly is a discrepancy of several sigma between the electron and the muon probes, such processes occur mainly through the exchange of one virtual photon. In the case of \( \eta \rightarrow \gamma l^+l^- \) can occur either via one photon or two photons. The existence of a light scalar particle \( S \) coupling differently to electrons and muons could produce this type of \( \eta \) decays and a precise measurement of the branching ratios of the latter might explain the proton radius anomaly.

• **Search for true muonium:** The process implicated is:

\[ \eta \rightarrow \gamma (\mu^+\mu^-)|_{2M_\mu} \rightarrow \gamma e^+e^- \]

The production of true muonium is associated with a \( \mu^+ \mu^- \) pair that determines a mass of about \( 2M_\mu \) [3] and it is hoped to decay into a \( e^+e^- \) pair with a large branching ratio.

• **Indirect searches for dark photons:** The mass of the dark photon particle is expected to be in GeV scale, considering its mass is below the mass of the \( \eta \) meson it can be observed by:

\[ \eta \rightarrow \gamma A' \rightarrow \gamma + l^+l^- \]

where \( A' \) correspond to dark photon is a U(1) vector boson. For two \( \eta \) and \( A' \) mass restrictions will help to reject the background.
• **Searches for new baryonic forces** Following the same sample search for dark photon case, but without the mass constraint on the resonance, shall be deemed the vector boson B (coupling to baryonic matter) mediating that force is below mass of the $\eta$ it can be measured via:

$$\eta \rightarrow \gamma B \quad \text{with} \quad B \rightarrow \gamma \pi^0 \quad \text{and} \quad \eta \rightarrow \gamma B \quad \text{with} \quad B \rightarrow \gamma + l^+ l^-$$

The expected new forces in the Mev-GeV range are associated with dark matter in some models, among them [5], [6], [7] y [8].

**Low and intermediate energy studies**
The studies of energy physics using $\eta$ mesons could lead the next topics:

- Test of nuclear models
- Non-perturbative QCD
- Chiral perturbation theory
- $\pi\pi$ interactions
- Electromagnetic transition form-factors
- Octet-singlet mixing angle
- Isospin breaking due to the u-d quark mass difference

5. **Running Plan**
The experiment REDTOP is expected to do four runs, one of them is still considered as optional.

**Run I - $\eta$ factory**
The $\eta$ meson factory will be the most area focused on REDTOP and will yield $\eta$ mesons by using a proton beam with an energy of 1.8 GeV. The aim is to produce $10^{13}$ $\eta$ mesons per year.

**Run II - $\eta'$ factory**
The REDTOP $\eta'$ factory will use a proton beam with an energy between 3.5 to 4.9 GeV, aiming to collect $10^{11}$ $\eta'$ mesons.

**Run III - $\mu$ scattering experiment (optional)**
The beam required is composed of muons with an energy between 0.2 and 0.8 GeV, aiming to collect $10^{12}$ $\mu$ scattering events. In this stage the proton radius anomaly would be explored but the detector operation is still under investigation keeping Run III as optional. However, the REDTOP detector will need extra requirements, one of them changing the position of the graphite target.

**Run IV - Rare kaon decay experiment**
The main physics topic will be the study of the CP violating process $k^+ \rightarrow \pi^+ \nu \nu$. This run will use a kaon beam provided as a secondary from the primary 8 GeV proton beam with expected $\pi/k$ production radio of 13. Nevertheless, the target has to be replaced with an active plastic target while the rest of the detector will stand unchanged.

6. **Conclusions**
Studying the decays of mesons $\eta/\eta'$ can lead to the discovery of new physics. Using new and innovative technologies the REDTOP experiment aims to reach new levels of intensity and sensitivity for this type of decays obtaining measurements with low background coming from the Standard Model Events.
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