Information Letter to the Fermilab PAC

Rare Eta Decays with a TPC for Optical Photons

The REDTOP Collaboration*

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A Rare η Decay Experiment at Fermilab

We are writing this letter to inform you that a collaboration is forming to develop an experiment at Fermilab. Research and development work are underway, and we intend to submit a full proposal late in 2016 for consideration.

The REDTOP experiment is primarily intended to look for new violations of basic symmetry principles and conservation laws in particle physics. Our main focus will be on very rare decays of the η meson. From the Standard Model and other theories, such decays can provide distinct insights into the limits of conservation laws and open unique doors to new ones at branching ratio sensitivity levels typically below 10^{-9}. Notably, current experimental upper limits for η decays are many orders of magnitude larger. The sensitivity goal of our experiment is expected to be better than 10^{-10} for most decay modes, based on an estimated yield of more than 10^{12} η mesons per year. Numerous opportunities for new physics Beyond the Standard Model will become available.

We anticipate that the existing Booster and Delivery rings can be exploited nicely to generate the primary proton beam needed to produce the η mesons from a Be target. Only modest modifications to the accelerator complex will be needed, after including those already planned for the g-2 and Mu2e experiments. The detector will be an optical TPC, already under research and development at Fermilab with project T1059. It includes a totally active dual-readout calorimeter (ADRIANO), under development by a Fermilab-INFN Collaboration (T1015), and an active muon polarimeter under development at KEK for the TREK experiment.

I. MOTIVATION

Conservation laws with their underlying symmetry principles are at the heart of physics, from the classical space-time conservation laws of introductory courses through the symmetries and additive quantum numbers of modern particle physics.

The light pseudoscalar mesons π^0, η, and η' have very special roles for exploring and testing the conservation laws. The π^0 has a long history of such tests and has established tight upper limits of charge (C) and lepton flavor (LF) violations [PDG]. Unlike the isospin $I = 1$ for the π^0, all of the additive quantum numbers for the η and η' are zero, and they differ from the vacuum only in terms of parity. Due to the opposite G parities of the the π^0 and η, couplings via strong interactions are suppressed. Thus, tests of C and CP in electromagnetic interactions are much more directly accessible in η and η' decays, limited mainly by the flux of such mesons [Nef94]. In addition, such decays can provide tests of P, T, CT, PT, and even CPT. Among other possibilities are searches for lepton family violation, leptoquarks, and significant tests of fundamental assumptions underlying chiral perturbation theory.

Almost all searches for symmetry violations in $\eta\,/\,\eta'$ decay are upper limits in the range of 10^{-5} or higher [PDG]. An exception is the decay $\eta \to 4\pi^0$ at $< 6.9 \times 10^{-7}$, based on 3×10^7 η mesons [Prak00]. One-sigma uncertainties have been reported for some asymmetries in the Dalitz distribution of $\eta \to \pi^+\pi^-\pi^0$ (which are consistent with zero at the level of 10^{-2}) [Amb08]. Most models of symmetry violations for various decay processes are at or below the level of 10^{-9}, typically by several orders of magnitude.

The Crystal Ball experiment at the Brookhaven AGS was able to provide a few times 10^7 η mesons (as for the $4\pi^0$ decay study). It was subsequently moved to MAMI, and a goal there is to achieve another order of magnitude in η yield. Other facilities include KLOE (with $\phi(1020) \to \eta\gamma$), WASA at COSY, and GlueX at JLAB, all at the few times 10^7 level. To reach the more exacting levels needed for symmetry violations, the usable η flux must be increased by several orders of magnitude.

To achieve the goal of having a sensitivity level of better than 10^{-10}, the REDTOP experiment is being designed to provide a sea change in the number of η samples to 2×10^{12} or more per year, along with a nearly 4π detector to study a broad range of fore-front physics. The facility will provide vastly reduced upper limits for η and η' decays, as well as studies of processes that can lead to new physics Beyond the Standard Model.

The number of measurements that can be made are too many to describe here and will be described in the proposal. We will mention a few of them briefly here.

The decay $\eta \to \pi^+\pi^-\pi^0$ has a large branching ratio (22.7%). It violates G parity, but can occur because isospin symmetry is broken by the non-zero up-down quark mass difference. Recent data exist for this process. A Dalitz plot can be made in terms of the two variables $X = \sqrt{3}(T_+ - T_-)/Q$ and $Y = (3T_0/Q) - 1$, where the pion kinetic energies in the η rest frame are (T_+, T_-, T_0), and $Q = T_+ + T_- + T_0$ is the decay Q-value.

The Dalitz distribution can be expressed in a power series of X and Y, and their products. With $m_+ = m_-$, it is expected to be symmetric about $X = 0$. Non-zero coefficients for terms with odd powers of X will indicate violation of C with no constraint on isospin ΔI. Moreover, an analysis of the partial wave amplitudes contributing in the decay of a C-even, $J = 0$ meson state to $\pi^+\pi^-\pi^0$ reveals that terms of odd X in η decay are both C and CP odd [Gard04]. Other asymmetries between quadrants or sextants in the distribution can test C violation with $\Delta I = 1$ or 2 [Lay72].

Results for two recent experiments are available: Ref. [Amb08] for 1.34×10^6 η decays, and Ref. [WASA14] for 1.2×10^7 η decays. At the 10^{-2} level of sensitivity, no significant asymmetries are seen. However, there are $\sim 2\sigma$ differences between the two sets of results for the coefficients of the Dalitz parameterization. REDTOP can vastly improve the accuracy of the measurements and resolve the discrepancies. Any definitive asymmetries would be evidence of C and CP violation.

REDTOP offers many opportunities for New Phenomena. Possible lepton family number non-conservation can be explored in $\eta \to \mu^\pm e^\mp$ decays. Other topics of high current interest include the possible existence of a new vector gauge photon X, conjectured as indicative of a fifth force and which decays into e^+e^- pairs with an invariant mass of $m_{e^+e^-} \simeq 17$ MeV [Kra16, Feng16]. Our yields and sensitivities from the $\eta \to \gamma e^+e^-$ decay will exceed those of other planned experiments. The observations of this final state will allow us also to perform a search for the dark photon in a region of parameter space still poorly explored. In addition, we will study $\eta \to \pi^0\mu^+\mu^-$ decays to search for a scalar particle that is postulated to be responsible for the proton radius anomaly.

Finally, the flexibility of an upgraded and modified DR will provide opportunities for REDTOP to run at a variety of energies or to use other beams such as K^+.

II. EXPERIMENTAL APPARATUS

In contrast to the complexity and cost of modern multi-purpose experiments, the REDTOP beamline and experimental apparatus will be optimized for detection of mesons, especially the η meson. A simple proton beam along with a detector that is sensitive to only the physics processes of interest will be used. We intend to rely extensively on the Cherenkov process for particle detection. In fact, all the hadrons and the majority of charged pions produced in the p-Be interactions at the chosen beam energy would be under the Cherenkov thresholds that correspond to the refractive indices of the materials employed. A smart trigger, associated with a fast-response detector, would guarantee that the interesting events are efficiently acquired while the expected pile-up from background processes is kept under control.

Achieving our goals will require production and analysis of at least 10^{12} η decays. This goal can be met by having a flux of 10^{11} protons per second on Be targets, and a duty factor >75%. The Fermlab Booster routinely delivers 4×10^{12} protons per cycle at up to 15-Hz repetition rate. Thus, there is in principle an abundance of protons to meet the REDTOP goal. However, the Booster extraction kinetic energy is 8 GeV, well above the $\sim$2 GeV required for REDTOP. The beam-line layout is shown in Fig. 1.

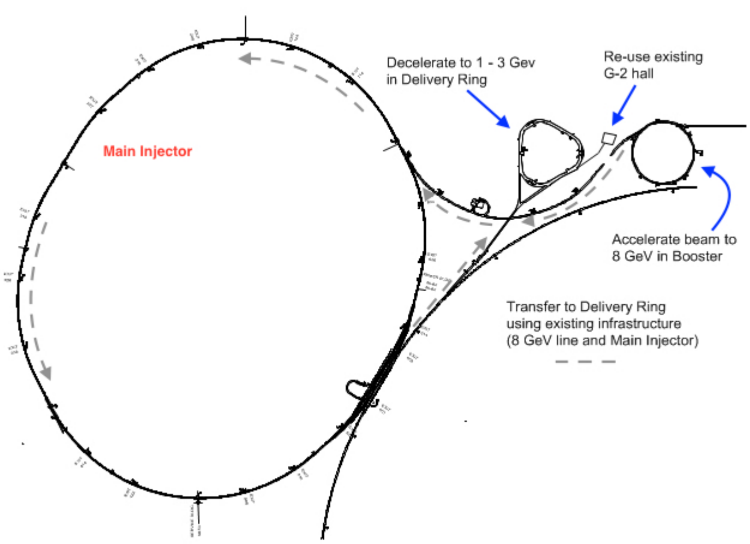

Figure 1: The REDTOP accelerator complex.

REDTOP would utilize beam sent from the Booster to the Delivery Ring (DR), which is being configured for both the Muon g-2 and the Mu2e experiments. Operationally, an 8-GeV proton beam would be provided to the DR in the same way as for Mu2e, and then decelerated to the desired energy (2 GeV) and slow extracted over the next ∼40 s to produce REDTOP's desired rate on target. Allowing for deceleration and re-setting of the magnetic fields, this process would be repeated every ∼50 s to provide a duty factor of ∼80%. The impact on the accelerator operational time line and on the neutrino program would be less than that for Mu2e or Muon g-2. The DR power supply system will need to be reconfigured to allow appropriate ramping of the magnets down and up in a suitable amount of time, and 1–2 additional RF cavities will be required to perform the deceleration.

A schematic rendering of a detector design being considered is shown in Fig. 2. The proton beam passes through ten thin Be targets that are surrounded by an aerogel ring. The red region is the dual-readout optical TPC. The orange regions represent the ADRIANO calorimeter. The detector will also include a muon polarimeter and, optionally, a photon polarimeter. We note here that all three major components of the detector: the Optical-TPC, ADRIANO, and the active muon polarimeter, are novel technologies under active development. Alternatives with more conventional detector techniques are also being investigated. The advance in detector technologies will pave the way for similar experiments in the future.

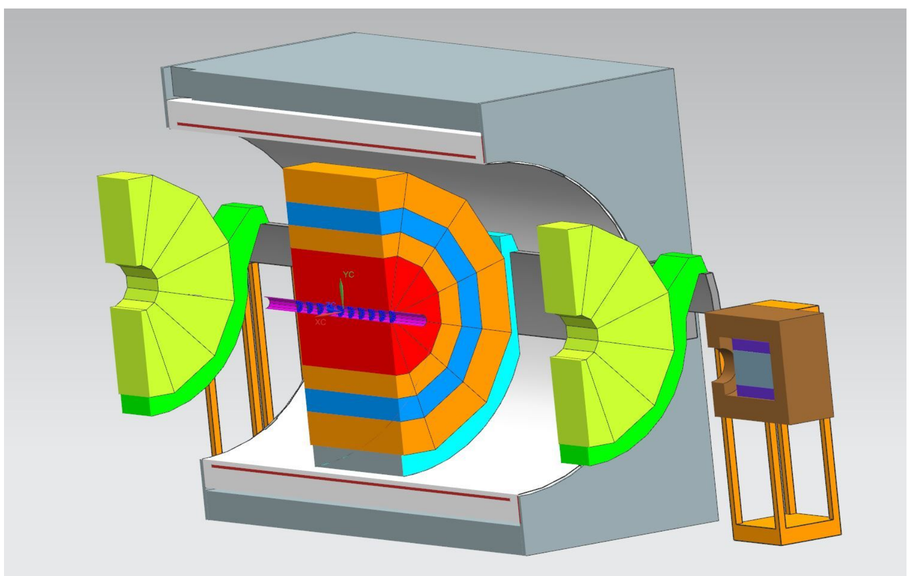

Figure 2: The REDTOP experimental apparatus. See the text for a description.

III. STATUS AND PLANS

We have initiated the formation of a formal "REDTOP" collaboration, and work is actively underway on the design of the beam line and detector components. Extensive computer simulations are planned. The collaboration currently consists of scientists and engineers from Fermilab, other laboratories, and universities. New collaborators are being actively recruited.

In addition to being able to push the realm of new physics to better sensitivities, REDTOP will provide an abundance of opportunities for students to pursue theses, including work involving physics, beams, and detectors of new capabilities. The ability to serve as an "η-factory" by having multiple runs at different energies, along with pursuing fundamental issues in physics will enrich the community for many years.

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