Expression of Interest

Rare Eta Decays with a TPC for Optical Photons

The REDTOP Collaboration[*]

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A Rare η Decay Experiment at Fermilab

This document is submitted to inform the Fermilab Directorate that a collaboration is forming to develop an experiment at the Laboratory. Research and development work are underway, and we intend to submit a full proposal to the Fermilab Program Advisory Committee 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 $\eta\,/\,\eta'$ decays 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 (for $\phi(1020) \to \eta\gamma$), 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 this goal, 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 reviewed in the proposal. We will instead showcase only a few here, considering both the degree of physics interest and practicality for a meaningful result.

$\pi^+\pi^-\pi^0$ Dalitz Asymmetries

The decay $\eta \to \pi^+\pi^-\pi^0$ has a large decay branching fraction (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 [Amb08, WASA14]. A Dalitz plot can be made in terms of the two variables

$$X = \sqrt{3}\frac{T_+ - T_-}{Q} \tag{1}$$

$$Y = \frac{3T_0}{Q} - 1 \tag{2}$$

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. An alternate kinematic representation is described by Jarlskog and Shabalin [JS02].

The squared amplitude for the Dalitz distribution can be expressed as

$$|\mathcal{A}(X,Y)|^2 = \rho(X,Y) = N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hX^3)$$

where N is a normalization constant. With $m_{\pi^+} = m_{\pi^-}$, the distribution is expected to be symmetric about $X = 0$. Thus non-zero coefficients for the terms with odd powers of X (c,e,h) will indicate violation of C with no isospin constraint 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].

Analysis of the data is complex. Monte Carlo calculations must include adjustments for experimental efficiencies and $\pi\pi$ interactions. The results for the left-right (LR or X), quadrant (Q), and sextant (S) asymmetries for 1.34×10^6 $\eta \to \pi^+\pi^-\pi^0$ decays [Amb08] are:

$$
\begin{aligned}
A_{LR} &= (+0.09 \pm 0.10\,^{+0.10}_{-0.14}) \times 10^{-2} && (3)\\
A_Q &= (-0.05 \pm 0.10\,^{+0.05}_{-0.05}) \times 10^{-2} && (4)\\
A_S &= (+0.08 \pm 0.10\,^{+0.08}_{-0.13}) \times 10^{-2} && (5)
\end{aligned}
$$

More recently, the WASA-at-COSY collaboration has provided data for 1.2×10^7 η decays [WASA14]. Their values for the C-violating parameters are

$$
\begin{aligned}
c &= -0.007 \pm 0.009(\mathrm{stat}) && (6)\\
e &= -0.020 \pm 0.023(\mathrm{stat}) \pm 0.029(\mathrm{syst})\,. && (7)
\end{aligned}
$$

For the other parameters, the differences in the values between the two experiments are

$$
\begin{aligned}
-\Delta a &= +0.054(23) \;\; (+2.5\sigma) && (8)\\
\Delta b &= +0.095(44) \;\; (+1.8\sigma) && (9)\\
\Delta d &= +0.029(28) \;\; (+1.1\sigma) && (10)\\
\Delta f &= -0.025(43) \;\; (-0.6\sigma) && (11)
\end{aligned}
$$

Any definitive asymmetries would be evidence of C and CP violation. REDTOP can vastly improve the accuracy of the measurements and resolve the discrepancies.

$\eta \to \gamma e^+e^-$

This process has a relatively large branching ratio corresponding to $\sim 7 \times 10^{-3}$ [PDG]. Consequently, REDTOP is expecting to detect a number of such final states in excess of 10^8, paving the road for a search of new particles and fields decaying into a two-lepton final state. Among them, the dark photon is an obvious candidate, also quite popular in recent years in the high energy community. Two experiments are pursuing a dedicated dark photon search with e^+e^- colliding beams: the HPS at JLAB [HPS] and PADME at Laboratori Nazionali di Frascati [PADME]. REDTOP, on the other side, will perform a similar search with hadron-produced η mesons, and, consequently, with very different statistical and systematic uncertainties.

The second exotic vector particle accessible with REDTOP is a light gauge boson, mediator of a fifth, milli-weak force. In recent years, several models have postulated the existence of such particles, in an attempt to reconcile anomalies found in experimental observations. In particular, secluded models of WIMP dark matter, characterized by a weak-scale rate for annihilation into light MeV-scale mediators have been proposed [Pospelov08] to explain the excess of positron observed by PAMELA, ATIC, and the WMAP. Such mediators are metastable and will decay into Standard Model states to which REDTOP is sensitive. Another interesting model to challenge has been very recently proposed [Feng16] to explain a 6.8σ anomaly in the invariant mass distributions of e^+e^- pairs produced in ^{8}Be nuclear transitions. The mass of such a gauge boson is determined to be about 17 MeV, which is below the sensitivity of WASA, but accessible to REDTOP thanks to the boost imparted to the η meson in the lab frame. The same fifth force would be able to reconcile the 3.6σ discrepancy between the predicted and measured values of the muon's anomalous magnetic moment. In this respect, REDTOP will be a nice complement to the g-2 experiment under construction at Fermilab [g-207].

$\eta \to \pi^0\mu^+\mu^-$

The mechanism for the $\eta \to \pi^0\mu^+\mu^-$ (or e^+e^-) decay is usually described via a 2-photon intermediate state to conserve C: $\eta \to \pi^0\gamma\gamma$ along with $\gamma\gamma \to \mu\bar{\mu}$ via a triangle diagram. Branching ratios are calculated to be of the order of 10^{-9} [NgP92, NgP93, JS02], which should be well within the sensitivity of REDTOP. In the case of C violation, a 1-photon mechanism ($\eta \to \pi^0\gamma$, with $\gamma \to \mu\bar{\mu}$) is also possible [NgP92, JS02]. A significant enhancement of the branching ratio above the 2-photon model can indicate C violation. Branching ratios of $\sim 5 \times 10^{-6}$ for $\eta \to \mu^+\mu^-$, and $\sim 1 \times 10^{-7}$ for $\eta' \to \mu^+\mu^-$ have been estimated [Pet10].

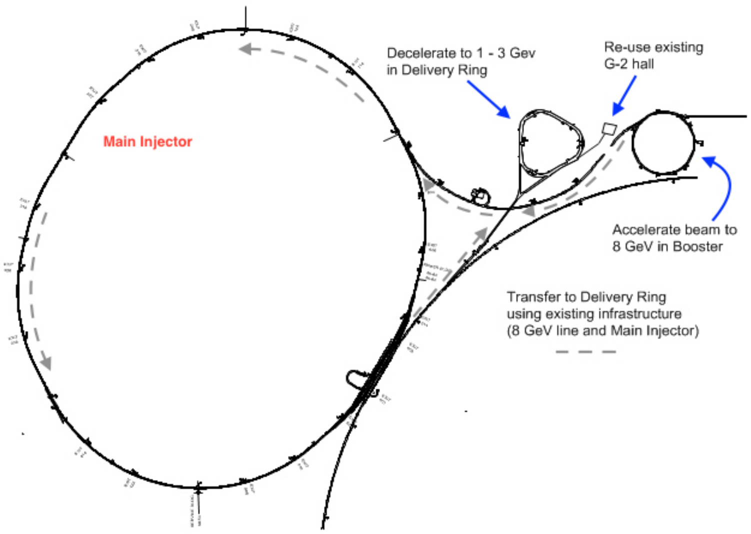

Figure 1: The REDTOP accelerator complex

II. EXPERIMENTAL APPARATUS

Achieving the goals of the experiment will require production and analysis of at least 10^{12} η meson decays. This goal can be met by having a flux of 10^{11} protons per second on target, and a duty factor of over 75%. The Fermilab 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 ∼2 GeV required for REDTOP. The beam-line layout is shown in Fig. 1.

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.

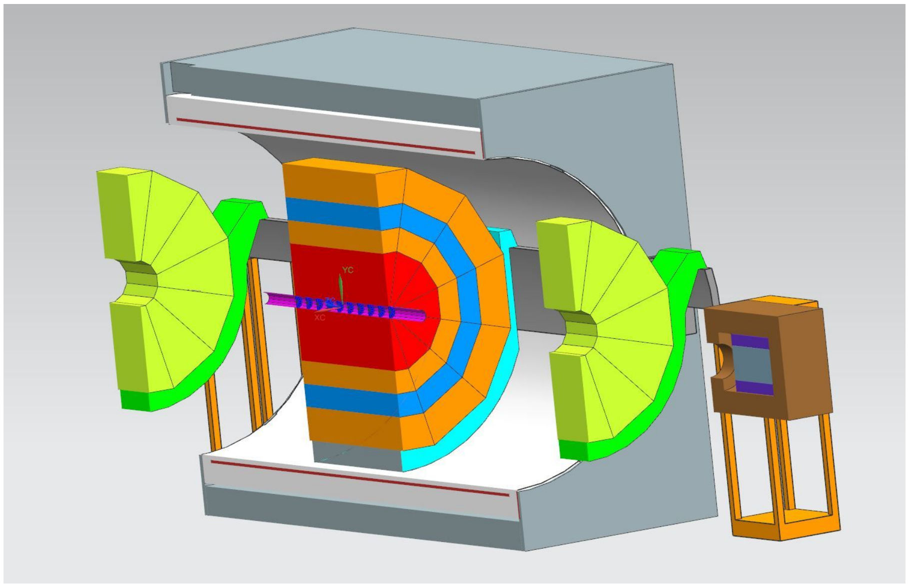

Figure 2: The REDTOP experimental apparatus.

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. Therefore, REDTOP will not only challenge several physics limits, but represent a step-up in detector technologies, paving the way for similar experiments in the future. In particular, we foresee that most of the technologies developed for REDTOP will be applied and/or extended to future experiments in the PIP-II era where events rates and pile-up are expected to be much higher than at REDTOP. A schematics of the detector is shown in Fig. 2. A description of the main components of the experimental apparatus follows.

A. Proton Beam Line

To meet the requirements, it has been recommended that 8-GeV protons be sent from the Booster to the Delivery Ring (DR), which is to be used for both the Muon g-2 and the Mu2e experiments. For the Muon g-2 experiment, the ring will be operated in DC mode and tuned to accept muons with a total energy of approximately 3 GeV. When used for Mu2e, the ring will operate with protons at a constant kinetic energy of 8 GeV and will also employ slow resonant extraction of the proton beam for delivery to the Mu2e experiment. For REDTOP, an 8-GeV beam can be provided to the DR in the same way as for Mu2e, then the protons can be decelerated to the desired energy (2 GeV) before passing through the resonant extraction system (also to be used for Mu2e).

A suggested scenario for REDTOP would be to send a single 15-Hz pulse from the Booster to the DR, decelerate, de-bunch, and then slow extract over the next ∼40 s. Repeating this process every ∼50 s would provide a duty factor of approximately 80%. This scenario is currently being actively considered, although alternatives may also be explored. By using one Booster pulse every ∼40 s, the impact on the accelerator operational time line and on the neutrino program appears to be minimal, but would have to be verified.

A first look at the magnet and RF requirements for the DR to perform the above manipulations suggests that a reconfiguration of the power supply system is needed to ramp the magnets down and up in a suitable amount of time (as the ring is run DC for both Muon g-2 and Mu2e). The inductance of the magnet system has a natural time constant of approximately 7 s. If inverting power supply components were to be installed, a ramp time of 5 s should be achievable. For deceleration, the existing 2.4-MHz cavity being installed in the DR for Mu2e would be insufficient for REDTOP, mainly due to the inherent frequency shift that would occur in going from 8-GeV to 2-GeV kinetic energy. However, if a second RF cavity of the same kind were installed, but tuned to a slightly lower frequency, the combination of the two could be used for the required deceleration. A third cavity would provide even more latitude in the operation, but may not be necessary. Further studies on the cavities would be required, but the DR has space for either of these scenarios. It should be noted that a spare cavity is already being produced for Mu2e, which is also the same style cavity being installed in the Recycler for its upgrade.

Other accelerator physics issues that require examination would be (a) the deceleration through the "transition energy" of the DR (∼6 GeV) at the ramp rates envisioned above; (b) an evaluation of the performance of the slow resonant extraction system at 2 GeV where the beam will be roughly 1.8 times larger than at 8 GeV and where the magnet field quality will be different as well, and (c) a determination of the adequacy of the DR vacuum system for maintaining the beam for tens of seconds at 2 GeV energy. Re-tuning of the DR-to-REDTOP beam lines from 8 GeV to 2 GeV and impacts due to the apertures of these system elements will also require attention.

B. The Target System

The target system (corresponding to the blue circles in Fig. 2) is composed by ten round foils of beryllium, each about 240 μm thick. The diameter of the foil is about 1 cm. The target system is held in the center of the beam pipe, made of either carbon-fiber or beryllium, by thin AlBeMet wires. The pipe will also help in maintaining the vacuum and in supporting the aerogel attached to its external wall. A proton with 1.8 GeV of kinetic energy has a 0.5% probability to make an inelastic scattering in any of the foils. The probability that one such scattering would produce an η meson is about 0.4%. Because the average intensity of the beam is of the order of 1×10^{11} protons/sec, the expected number of η mesons produced in one year in the target systems is about 2×10^{12}.

The proposed approach departs from most similar experiments that utilize a gaseous target (cf., for example, [WASA14]). The rational is that the distributed targets will help in disentangling the η events from the background, the latter being mostly constituted by protons inelastically scattered by the target matter. The distance between foils is sufficient to identify the location of the primary vertex without ambiguities, while the tracking systems will provide $r\varphi$ coordinates. Finally, preliminary Monte Carlo simulations have indicated that the decay products of the η meson are minimally affected when traversing the beryllium foil, the latter being less than 1/4 mm thick. The fraction of the beam absorbed by the target system is about 5%. Consequently, each beryllium foil will need to dissipate only 15 mW, easily achievable by thermal radiation and by conduction through the supporting metal wires.

C. The Optical TPC

The OTPC (marked in red in Fig. 2) is based on the same principles as a conventional TPC. Namely, it will measure the momentum and the position in space of a charged track through their deflection in a solenoidal magnetic field. However, rather than detecting the tracks via a ionization process in the gas, the Cherenkov effect is employed. The momentum of that particle is, then, reconstructed from the detection of the photons radiated inside the OTPC using an array of photo-sensor surrounding the radiator. About 100,000 SiPMs are needed to cover the entire inner walls of the device. The pattern of detected photons will provide also the position in space of the initial particle. The advantage of an OTPC over a conventional TPC is that it will be sensitive only to the fast particles (leptons and fast pions) entering the volume of the detector. On the other side, hadrons and slower pions will be below the Cherenkov threshold and, therefore, will not be detected. A prototype of an OTPC has been built and tested by the T1059 Collaboration at Fermilab [T1059].

Two Cherenkov radiators are being considered: a double aerogel shell, about 3 cm thick at the inner wall, supported by the beam pipe (the magenta ring in Fig. 2). The innermost aerogel has $n_D = 1.22$ while the outermost has $n_D = 1.35$; low-pressure nitrogen gas fills the rest of the volume of the OTPC. The pressure is adjusted in order to have $n_D = 1.000145$. Muon particles with momentum larger than 160 MeV will radiate only in the aerogel. The radius, the center and the skewness of the ring will help to determine their velocity. The dual refractive systems has the function of discriminating pions from muons. The electrons and positron will radiate in the aerogel as well as in the gas. The ring produced by such light particles has a radius in almost all cases independent from their velocity and much larger than that of the muons. That feature will provide particle identification for electrons vs. muons. Furthermore, the Cherenkov photons radiated in the gas will generate a characteristic pattern in the photo-sensors. From the analysis of that pattern, one is able to estimate the momentum of the electron and its position in space.

D. The ADRIANO Calorimeter

Dual-readout calorimetry is a novel detector technique which has received considerable attention in the past few years. An implementation, named ADRIANO (A Dual-Readout Integrally Active Non-segmented Option), is currently under development at Fermilab [T1015-1, T1015-2, T1015-3]. It is based on the simultaneous measurements of the energy deposited by a hadronic or electromagnetic shower into two media with different properties.

The first medium is usually a plastic scintillator. Consequently, any charged particle depositing energy in that medium will produce scintillation. The second medium is usually a heavy glass with high refractive index ($n_D \geq 1.8$) and high density ($\rho > 5.5$ g/cm^3). The latter medium will be sensitive only to charged particles above the Cherenkov threshold, which usually happens for the electromagnetic components of the shower (electrons and positrons or photons producing pairs). Furthermore, the high density of the medium will make it an ideal integrally active absorber for all particles impinging on the detector. Summing the Cherenkov (C) and the scintillation (S) signals will provide the total energy of the particle. By comparing the scintillation vs. the Cherenkov signals, one also has information about the ID of the particle that generated the shower. The rationale for employing an ADRIANO calorimeter is that the large background from the vast majority of neutrons entering the detector could be easily rejected. Furthermore, the different behavior in terms of S vs. C for muons and pions will complement the double aerogel systems for identifying the two species. The ADRIANO calorimeter is indicated in orange in Fig. 2.

E. The Active Muon Polarimeter

The muon polarimeter (the blue bars in Fig. 2) is an array of plastic scintillators and wire chambers inserted between the inner and the outer layers of ADRIANO. They will detect the electrons and positrons emitted when a muon is stopped inside the ADRIANO calorimeter. This happens in a short range of depths after the muon has lost all of its energy. The initial polarization of the muon is not lost in this process since the ADRIANO lead-glass is a homogeneous and isoscalar medium. If the muon carries a non-null polarization, the electrons (or positrons) are emitted non-isotropically in the solenoidal magnetic field. The muon polarimeter will count those electrons: any unbalance in the left-right or front-backward counting is associated with a non-null transverse or longitudinal polarization of the initial muon.

F. The Solenoid

The REDTOP detector will be inserted inside the CDF superconducting solenoid (the white cylinder in Fig. 2) where a 0.6-T solenoidal field will be generated. The magnetic field will allow the OTPC to measure the transverse momentum of charged particles, and the Muon Polarimeter to measure the polarization of muons.

III. STATUS AND PLANS

We have initiated the formation of a formal “REDTOP" collaboration, with the goal of generating a much more complete Letter-of-Intent over the next few months, and subsequently a proposal within a year. The collaboration currently consists of scientists and engineers from Fermilab, other laboratories, and universities. New collaborators are being actively recruited. Work is actively underway on the design of the beam line and detector components. Extensive computer simulations are planned.

Cost and resource estimates are in their very early stages and will be under close scrutiny in the next several months. REDTOP is proposing to re-use some of the facilities available at

Fermilab, in particular, the CDF solenoid and a substantial fraction of the Muon Campus. A considerable amount of money will be saved, and we anticipate that most of the cost of the project will be related to the R&D on the detectors and on the construction of the experimental apparatus.

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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