THE REDTOP

EXPERIMENT

Rare Eta Decays with a Tpc for Optical Photons

Corrado Gatto
INFN Napoli and NIU
For the REDTOP Collaboration
SM is showing its age

- SM matter: Dark matter:Dark energy=5%:25%:70%
- Baryon Asymmetry of the Universe
- Expansion of the universe is accelerating (hint to more forces)

New physics is elusive: probability of processes where new physics is coupled to SM physics is low

LHC found no hint of new physics at high energy so far

Newest theoretical models prefer gauge bosons in MeV-GeV mass range as “…many of the more severe astrophysical and cosmological constraints that apply to lighter states are weakened or eliminated, while those from high energy colliders are often inapplicable” (B. Batell, M. Pospelov, A. Ritz – 2009)

High intensity-low energy experiments are growing in popularity (Fixed target and beam dump)
It is a Goldstone boson

It is an eigenstate of the C, P, CP and G operators (very rare in nature): \( I^G J^{PC} = 0^+ 0^+ \)

All its additive quantum numbers are zero

\[ Q = I = j = S = B = L = 0 \]

All its possible strong decays are forbidden in lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.

EM decays are forbidden in lowest order by C invariance and angular momentum conservation

It can be used to test C and CP invariance.

Its decays are not influenced by a change of flavor (as in K decays) and violations are “pure”

It is a very narrow state (\( \Gamma_\eta = 1.3 \text{ KeV} \) vs \( \Gamma_\rho = 149 \text{ MeV} \))

Contributions from higher orders are enhanced by a factor of \( \sim 100,000 \)

Excellent for testing invariances

\( \eta \) is an excellent laboratory to search for physics Beyond Standard Model
The experiment will yield $2.5 \times 10^{13}$ $\eta$ mesons/year and $2 \times 10^{11}$ $\eta'$ mesons/year.

That is a consequence of a relatively large $\eta/\eta'$ hadro-production cross section (10-20 mbar in the 2 GeV beam energy region and 0.1 mbar at 3 GeV).

Requires a detector blind to protons and slow pions.

Near-4$\pi$ detector can be used with beams of different energy and/or particles.
BSM Physics Program (η and η’ factory)

C, T, CP-violation

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

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \rightarrow \mu^+ e^- + \text{c.c.}$
- Double lepton Flavor Violation: $\eta \rightarrow \mu^+ \mu^+ e^- e^- + \text{c.c.}$
New particles and forces searches

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

Other Precision Physics measurements

- Proton radius anomaly: $\eta \rightarrow \gamma \mu^+\mu^-$ vs $\eta \rightarrow \gamma e^+e^-$
- All unseen leptonic decay mode of $\eta / \eta'$ (SM predicts $10^{-6}$ - $10^{-9}$)
Non-\(\eta/\eta'\) based BSM Physics

- Dark photon and ALP searches in Drell-Yan processes: \(qqbar \rightarrow A'/a \rightarrow l^+l^-\)
- ALP’s searches in Primakoff processes: \(pZ \rightarrow pZ a \rightarrow l^+l^-\) (F. Kahlhoefer)
- Charged pion and kaon decays: \(\pi^+ \rightarrow \mu^+\nu A' \rightarrow \mu^+\nu e^+e^-\) and \(K^+ \rightarrow \mu^+\nu A' \rightarrow \mu^+\nu e^+e^-\)
- Neutral pion decay: \(\pi^0 \rightarrow \gamma A' \rightarrow \gamma e^+e^-\)

Non-BSM Physics Program (\(\eta\) and \(\eta'\) factory)

High precision studies on low energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- \(\pi\pi\) interactions
- Electromagnetic transition form-factors (important input for g-2)
- Lots of other bread&butter physics
Dark photon searches:

Visibly Decaying $A' \rightarrow e^+e^-$

- REDTOP $2 \times 10^{13} \eta$
- 100 evt
- 10 evt

Preliminary

G. Krnjaic
Better limits from Dalitz plot analysis of $\eta \to \pi^0 \gamma \gamma$. Not been done so far.

REDTOP will collect $10^9$ such event: sensitivity is under study.
Experimental Techniques

\( \eta/\eta' \) production

- \( \eta/\eta' \) hadro-production from inelastic scattering of protons on Be targets
- Use multiple thin targets to minimize combinatorics background

charged tracks detection

- Use Cerenkov effect in an Optical-TPC for tracking charged particles
- Baryons and most pions are below \( \tilde{\chi} \) threshold
- Electrons and most muons are detected and reconstructed

\( \gamma \) detection

- Use ADRIANO calorimeter for reconstructing EM showers
- \( \sigma_E/E < 5%/\sqrt{E} \)
- PID from dual-readout to disentangle showers from \( \gamma/\mu \)/hadrons
- 96.5% coverage
- Use tiles for high granularity and PFA reconstruction
Beam Requirements

- Assume: $1 \times 10^{11}$ POT/sec – CW
  - Beam power for $\eta$ factory: @ 1.9 GeV: $10^{11} \text{ p/sec} \times 1.9 \text{ GeV} \times 1.6 \times 10^{-10} \text{ J/GeV} = 30 \text{ Watts}$
  - Beam power for $\eta'$ factory: @ 3 GeV: $10^{11} \text{ p/sec} \times 3 \text{ GeV} \times 1.6 \times 10^{-10} \text{ J/GeV} = 48 \text{ Watts}$

- Target system: 10 x 0.33mm Be foils, spaced 10 cm apart
  - $\text{Prob}(p + \text{target} \rightarrow X) = 0.5\%$

- Power dissipated from target:
  - Heat produced for $\eta$ factory: 150 mW total - 15 mW per target foil
  - Heat produced for $\eta$ factory: 240 mW total - 24 mW per target foil

- $p$-inelastic interaction: $5 \times 10^8 \text{ evt/sec}$ (1 interaction/2 nsec in the targets)
- $\eta$ production: $2.5 \times 10^6 \eta/\text{sec}$ or $2.5 \times 10^{13} \eta/\text{yr}$
- $\eta'$ production: $1.5 \times 10^4 \eta'/\text{sec}$ or $1.5 \times 10^{11} \eta'/\text{yr}$
Accelerator complex for REDTOP Fermilab Option: AP50 hall

- Use delivery ring and extract beam at AP50
- Decelerate the 8 GeV beam to desired energy
Acceleration Scheme (M. Syphers)

- Single p pulse from booster ($\leq 4 \times 10^{12}$ p) injected in the DR (former debuncher in anti-p production at Tevatron) at fixed energy (8 GeV)

- Energy is removed by adding 1-2 RF cavities identical to the one already planned for mu2e (J. Dey)

- Spare RF cavities already existing (owned by mu2e and AD)

- Debunching occurs adiabatically inside the DR

- Slow extraction to REDTOP over ~40 seconds.

- The 270$^\circ$ of betatron phase advance between the Mu2e Electrostatic Septum and REDTOP Lambertson is ideal for AP50 extraction to the inside of the ring. **A DEDICATED SEPTUM IS NOT REQUIRED**

- Total time to decelerate-debunch-extract: 51 sec: duty cycle ~80%
Ring Optics through Deceleration (J. Johnstone)

Transition is avoided by using select quad triplets to boost $\gamma_t$ above beam $\gamma$ by 0.5 units throughout deceleration until $\gamma_t = 7.64$ and beam $\gamma = 7.14$ (5.76 GeV kinetic).

Below 5.76 GeV the DR lattice reverts to the nominal design configuration.

8 GeV injection energy (top) and <5.8 GeV (bottom)

- Blue & red circles indicate sites of the $\gamma_t$ quad triplets.

<table>
<thead>
<tr>
<th>$p$ (GeV/c)</th>
<th>8.89</th>
<th>8.33</th>
<th>7.76</th>
<th>7.20</th>
<th>6.63</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE (GeV)</td>
<td>8.00</td>
<td>7.45</td>
<td>6.88</td>
<td>6.32</td>
<td>5.76</td>
</tr>
<tr>
<td>$\gamma_{beam}$</td>
<td>9.53</td>
<td>8.93</td>
<td>8.33</td>
<td>7.74</td>
<td>7.14</td>
</tr>
<tr>
<td>$\gamma_{transition}$</td>
<td>10.03</td>
<td>9.43</td>
<td>8.83</td>
<td>7.74</td>
<td>7.64</td>
</tr>
<tr>
<td>$\beta_{max}$ (m)</td>
<td>94.9</td>
<td>72.5</td>
<td>49.5</td>
<td>30.1</td>
<td>15.1</td>
</tr>
<tr>
<td>$q$ (m$^{-1}$)</td>
<td>.0697</td>
<td>.0573</td>
<td>.0416</td>
<td>.0236</td>
<td>0.0</td>
</tr>
<tr>
<td>$3\sigma$ (mm)</td>
<td>15.0</td>
<td>13.6</td>
<td>11.6</td>
<td>9.4</td>
<td>6.9</td>
</tr>
</tbody>
</table>

Variation of $\gamma_t$, $\beta_{max}$ and the 15$\pi$ 99% beam envelope through deceleration

"J. Johnstone, M. Syphers, NA-PAC, Chicago (2016)"
The REDTOP Detector (baseline)

- **Optical TPC**
  - ~ 1m x 1.5 m
  - CH$_4$ @ 1 Atm
  - 5x10$^5$ Sipm/Lappd
  - 98% coverage

- **Solenoid**
  - 0.6-0.8 T

- **10x Be targets**
  - 0.33 mm thin
  - Spaced 10 cm

- **ADRIANO-NIU Calorimeter (tiles)**
  - Scint. + heavy glass sandwich
  - 20 $X_0$ (~ 64 cm deep)
  - Triple-readout +PFA
  - 96% coverage

- **Aerogel**
  - Dual refractive index system

- **$\mu$-polarizer**
  - Active version (from TREK exp.)

- **Fiber tracker being investigated**
  - (for rejection of $\gamma$-conversion and vertexing)
REDTOP detector

ADRIANO calorimeter

Ilcroot simulation

8/3/2017

C. Gatto - INFN & NICT
n_D(N_2@2.7\text{psi})=1.000145

Č threshold for e- in N_2: P=40 mev

n_D(aerogel1)=1.12

n_D(aerogel2)=1.22

Slic/lcsim simulation
Muon/pion Detection

- $n_D(\text{aerogel}) = 1.22/1.12$
- Č threshold for muons: $P = 160 \text{ mev}$
- Č threshold for pions: $P = 200 \text{ mev}$

Dual-readout: Č vs $S$ for $\mu$ and $\pi$ with $P = 500 \text{ MeV}$
ADRIANO PID @ 100MeV

Ilcroot simulation

pions

p/n

e/γ

muon
Phase I: \(\eta\)-factory
- Beam: protons
- \(T_{\text{beam}}\): 1.8-2.1 GeV
- Detector: baseline

Phase II: \(\eta'\)-factory
- Beam: protons
- \(T_{\text{beam}}\): 3.0-4.0 GeV (to be optimized)
- Detector: baseline (change O-TPC gas pressure, probably the Aerogel section)

Phase III: Muon Scattering Experiment (optional)
- Beam: muons
- \(T_{\text{beam}}\): 0.2< \(\leq\) 0.8 GeV (to be optimized)
- Detector: baseline + front graphite target

Phase IV: Rare Kaon Decays: \(K^+ \rightarrow \pi^+ \nu \bar{\nu}\)
- Beam: kaons
- \(T_{\text{beam}}\): from 8 GeV protons
- Detector: might need upgrade target and central tracker, add range stack
The $\eta/\eta'$ meson is an excellent laboratory for studying rare processes

Existing world sample not sufficient for breaching into decays violating conservation laws or searching for new particles

REDTOP goal is to produce $>2 \times 10^{13}$ $\eta$ mesons/yr in phase I and ($\sim 2 \times 10^{11}$ $\eta'/\text{year}$) in phase II

Two or more phases could extend the lifetime of the experiment considerably

Five golden processes - Many other processes also within reach

Currently the collaboration is forming and working at a proposal

Fermilab is the preferred hosting lab. BNL has, also, expressed some interest

Total cost: $< 40$ M$\$ (depending on re-use of existing infra-structure)
The REDTOP collaboration

8 Countries, 20 Institutions, 60 Collaborators

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For more info see: [http://redtop.fnal.gov](http://redtop.fnal.gov)
Prospects

- **2016-1017**: Collaboration forming and studies for the Proposal
- **Dec. 2017-early 2018**: proposal to Fermilab’s PAC
- **2018-2020**: Detector R&D
- **2021**: Detector construction + engineering run
- **>2022**: Start physics run
- **Successive phases depends from results of phase I, occupancy of the experimental hall and beam request from experiments**
- **More details**: [http://redtop.fnal.gov](http://redtop.fnal.gov)

All schedule contingent to upcoming P5 process (2022)
An exciting phase of detector R&D ahead
Time of facilities

Electrons (FT)
Positrons (FT)
Electrons and positrons (collider)
Protons

Paolo Valente
Stepan Stepanyan
Backup slides
Possible Intermediate Phases

Pre-REDTV TOP with OTPC only

- $p^7\text{Li} \rightarrow ^8\text{Be}^* \rightarrow e^+ e^- X$
  - At 2.5 MeV IOTA proton source (Fermilab)
  - Confirm 17 MeV bump found in Prague experiment

- $p \ D \rightarrow ^3\text{He} e^+ e^-$ (M. Viviani, L. E. Marcucci and A. Kievsky)
  - At 40 MeV Fermilab p linac (Fermilab) or ATLAS facility (ANL)

- $p^9\text{Be} \rightarrow ^8\text{Be}^* + X \rightarrow e^+ e^- X$
  - At MCenter 2 GeV p beam (Fermilab)

- $\mu^+ \ Nucleus \ scattering \ in \ fixed \ target \ mode$
  - 1.5-3 GeV muon campus – Fermilab

- $\mu^+ \ Nucleus \ in \ beam \ dump \ mode$

- $e^- \ Nucleus \ in \ fixed \ target \ mode$
  - 250-500 MeV, 50 mA IOTA facility – Fermilab

- $e^- \ Nucleus \ in \ beam \ dump \ mode$

- OTPC test with 2 GeV protons dumped by g-2 - Fermilab
Present $\eta$ Samples

<table>
<thead>
<tr>
<th>Technique</th>
<th>$\eta \to 3\pi$</th>
<th>$\eta \to e^+e^-\gamma$</th>
<th>Total $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB@AGS</td>
<td>$\pi^- p \to \eta n$</td>
<td>$9 \times 10^5$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>CB@MAMI-B</td>
<td>$\gamma p \to \eta p$</td>
<td>$1.8 \times 10^6$</td>
<td>$5000$</td>
</tr>
<tr>
<td>CB@MAMI-C</td>
<td>$\gamma p \to \eta p$</td>
<td>$6 \times 10^6$</td>
<td>$6 \times 10^7$</td>
</tr>
<tr>
<td>KLOE</td>
<td>$e^+e^- \to \Phi \to \eta \gamma$</td>
<td>$6.5 \times 10^5$</td>
<td>$5 \times 10^7$</td>
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<tr>
<td>WASA@COSY</td>
<td>$pp \to \eta pp$</td>
<td></td>
<td>$&gt;10^9$</td>
</tr>
<tr>
<td></td>
<td>$pd \to \eta^3\text{He}$</td>
<td></td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>CB@MAMI 10 wk (proposed 2014)</td>
<td>$\gamma p \to \eta p$</td>
<td>$3 \times 10^7$</td>
<td>$1.5 \times 10^5$</td>
</tr>
<tr>
<td>Phenix</td>
<td>$d Au \to \eta X$</td>
<td></td>
<td>$5 \times 10^9$</td>
</tr>
<tr>
<td>Hades</td>
<td>$pp \to \eta pp$</td>
<td></td>
<td>$4.5 \times 10^8$</td>
</tr>
<tr>
<td></td>
<td>$p Au \to \eta X$</td>
<td></td>
<td></td>
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</table>

Near future $\eta$ Samples

- **GlueX@JLAB (just started)**: $\gamma_{12\text{GeV}} p \to \eta p \to \text{neutrals}$
  - $4.5 \times 10^7$/yr

- **JEF@JLAB (proposing – not approved)**: $\gamma_{12\text{GeV}} p \to \eta X \to \text{neutrals}$
  - $3.9 \times 10^5$/day

- **REDTO@FNAL (proposing)**: $p_{1.9\text{GeV}} Be \to \eta X$
  - $2.5 \times 10^{13}$/yr

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OTPC Thresholds

\( p \) from background

\( \pi \) from background

\( \mu \) from \( \eta \to \pi^0\mu^+\mu^- \)

8/3/2017
ADRIANO Particle ID @ 100MeV

µ vs π

e vs π

µ vs e

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## 15 Prototypes Performance Summary

<table>
<thead>
<tr>
<th>Prototype</th>
<th>Year</th>
<th>Glass</th>
<th>gr/cm$^3$</th>
<th>Cerenkov L. Y./GeV</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 slices, machine grooved, unpolished, white</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>82</td>
<td>SiPM readout</td>
</tr>
<tr>
<td>5 slices, machine grooved, unpolished, white, v2</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>84</td>
<td>SiPM readout</td>
</tr>
<tr>
<td>5 slices, precision molded, unpolished, coated</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>55</td>
<td>15 cm long</td>
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<tr>
<td>2 slices, ungrooved, unpolished, white wrap</td>
<td>2011</td>
<td>Ohara BBH1</td>
<td>6.6</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>5 slices, scifi silver coated, grooved, clear, unpolished</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>64</td>
<td>15 cm long</td>
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<tr>
<td>5 slices, scifi white coated, grooved, clear, unpolished</td>
<td>2011</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>2 slices, plain, white wrap</td>
<td>2011</td>
<td>Ohara</td>
<td>7.5</td>
<td></td>
<td>DAQ problem</td>
</tr>
<tr>
<td>10 slices, white, ungrooved, polished</td>
<td>2012</td>
<td>Ohara PBH56</td>
<td>5.4</td>
<td>30</td>
<td>DAQ problems</td>
</tr>
<tr>
<td>10 slices, white, ungrooved, polished</td>
<td>2012</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>5 slices, wifi Al sputter, grooved, clear, polished</td>
<td>2012</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>30</td>
<td>2 wls/groove</td>
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<tr>
<td>5 slices, white wrap, ungrooved, polished</td>
<td>2012</td>
<td>Schott SF57HHT</td>
<td>5.6</td>
<td>158</td>
<td>Small wls groove</td>
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<tr>
<td>ORKA barrel</td>
<td>2013</td>
<td>Schott SF57</td>
<td>5.6</td>
<td></td>
<td>2500/side molded</td>
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<tr>
<td>ORKA endcaps</td>
<td>2013</td>
<td>Schott SF57</td>
<td>5.6</td>
<td></td>
<td>4000 molded</td>
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<tr>
<td>10 slices – 6.2 mm thick, scifi version</td>
<td>2014</td>
<td>Schott SF57</td>
<td>5.6</td>
<td></td>
<td>338 molded</td>
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<tr>
<td>10 slices – 6.2 mm thick, sci-plate version</td>
<td>2014</td>
<td>Schott SF57</td>
<td>5.6</td>
<td></td>
<td>354 molded</td>
</tr>
</tbody>
</table>

ADRIANO 2015 (for lepton colliders) is currently in the beam at FTBF
BNL hadron complex
Building 912 AGS Experimental Area (1998)
Detector R&D: OTPC

Fnal –T1059 (H. Frisch, E. Oberla)

- Successful proof of principle in 2015 at FTBF
- Instrumented with an MCP photo-detector, three boards each with thirty channels of 10 GSPS waveform digitizing readout

It requires a robust and dedicated R&D
Detector R&D: ADRIANO in T1015
Moving R&D from FNAL to NIU