HARPO : a TPC as a γ-Ray Telescope and Polarimeter

In the $e^+e^-$ pair creation regime

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SPIE Astronomical Telescopes + Instrumentation,
Ultraviolet to gamma ray,
Palais des congrès de Montréal, Montréal, Québec, Canada ; 22 - 27 Juin 2014

llr.in2p3.fr/~dbernard/polar/harpo-t-p.html
Science Case

- **Non polarized astronomy**:
  - Improve *angular resolution* – crowded sky regions

  \[\text{Fermi/LAT} \quad \text{V. Schönfelder, New Astr. Rev. 48 (2004) 193}\]

  - Solve *sensitivity* gap between Compton and pair telescopes
    - Actually Fermi is publishing mostly in the range \(0.1 - 300\text{GeV}\)
    - Improvement expected from PASS8, [Poster 9144-131] Carmelo Sgrò

- **Polarimetry**: No \(\gamma\) polarimeter above 1 MeV in space ever
  - Astrophysics: understand working mechanism(s) of \(\gamma\) cosmic sources
  - Cosmo / New Physics: LIV: Search for Lorentz Invariance Violation

  [Post-Fermi talk by Eric Charles on Sunday 9144-13]
Science Case: Polarimetry: Astrophysics

- One example: Blazar (AGN with jet pointing to us): decipher leptonic synchrotron self-Compton (SSC) against hadronic (proton-synchrotron) models
  - high-frequency-peaked BL Lac (HBL)
  - X band: 2 - 10 keV
  - $\gamma$ band: 30 - 200 MeV
- SED’s indistinguishable, but
  - X-ray: $P_{\text{lept}} \approx P_{\text{hadr}}$
  - $\gamma$-ray: $P_{\text{lept}} \ll P_{\text{hadr}}$

H. Zhang and M. Böttcher, A.P. J. 774, 18 (2013)
**Way Out : Use a Thin, Homogeneous Detector and Optimal Fits**

**Angular resolution**

- nucleus recoil $\propto E^{-5/4}$
- multiple scattering (optimal fits) $\propto E^{-3/4}$

**point-source differential sensitivity**

limit detectable $E^2dN/dE$, à la Fermi : 4 bins/decade, 5$\sigma$ detection, $T = 3$ years, $\eta = 0.17$ exposure fraction, $\geq 10\gamma$. “against” extragalactic background

- Sampling pitch $l = 1\text{mm}$, point resolution $\sigma = 0.1\text{mm}$

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Polarimetry

- Modulation of azimuthal angle distribution

\[
\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A}P \cos [2(\phi - \phi_0)]),
\]

\[
\sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}},
\]

- \( P \) source linear polarisation fraction
- \( \mathcal{A} \) Polarization asymmetry
- \( \phi \) azimuthal angle
Conversion in a Slab and Multiple Scattering: Dilution of the Polarisation Asymmetry

- \((1 + \mathcal{A} P \cos [2(\phi)]) \otimes e^{-\phi^2/2\sigma^2_\phi} = (1 + \mathcal{A} e^{-2\sigma^2_\phi} P \cos [2(\phi)])\)

\[\Rightarrow A_{\text{eff}} = \mathcal{A} e^{-2\sigma^2_\phi}\]

- Azimuthal angle RMS \(\sigma_\phi = \frac{\theta_{0,+} \oplus \theta_{0,-}}{\hat{\theta}_{+-}}\),

- \(\theta_0 \approx \frac{13.6 \text{ MeV/c}}{\beta p} \sqrt{x/X_0}\),

- Most probable opening angle \(\hat{\theta}_{+-} = 1.6 \text{ MeV}/E\)

\[\Rightarrow \sigma_\phi \approx 24 \text{ rad} \sqrt{x/X_0}\]

- This dilution is energy-independent.

Conventional wisdom: \(\gamma\) polarimetry impossible with nuclear conversions \(\gamma Z \rightarrow e^+ e^-\)

\(\text{e.g. Mattox J. R. Astrophys. J. 363 (1990) 270, and refs therein}\)

Very thin Si detectors are being considered though, e.g. PANGU talk by Meng Su on Sunday [9144-130].

**But** Harvard talk: Silicon: 2 single sided SSD of 150 \(\mu\)m each? And how solve the \(x, y\) two track ambiguity?
\textit{\textbf{\gamma Polarimetry with a Homogeneous Detector and Optimal Fits}}

- $\sigma_\phi = \frac{\sigma_{\theta,e^+} \oplus \sigma_{\theta,e^-}}{\hat{\theta}_{+-}}$, azimuthal angle resolution

- $\sigma_{\theta,\text{track}} = (p/p_1)^{-3/4}$, angular resolution due to multiple scattering

- $p_1 = 13.6 \text{ MeV}/c \left( \frac{4\sigma^2 l}{X_0^3} \right)^{1/6}$, Argon ($\sigma = l = 1 \text{ mm}$): $p_1 = 50 \text{ keV}/c$ (1 bar), $p_1 = 1.45 \text{ MeV}/c$ (liquid).

- $\hat{\theta}_{+-} = 1.6 \text{ MeV}/E$, most probable opening angle

- $\sigma_\phi = \left[ x_+^{-\frac{3}{4}} \oplus (1-x_+)^{-\frac{3}{4}} \right] \frac{(p_1)^{\frac{3}{4}}E^{\frac{1}{4}}}{1.6 \text{ MeV}}$, azimuthal angle resolution

- $x_+$ fraction of the energy carried away by the positron,

There is hope .. at low $p_1$ (gas) .. at low energy.

Also need study beyond the most probable opening angle $\theta_{+-} = \hat{\theta}_{+-}$ approximation

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Developed, Validated, Event Generator

- Development of a full (5D) exact (down to threshold) polarized evt generator
- Variables: azimuthal ($\phi_+, \phi_-)$ and polar ($\theta_+, \theta_-$) angles of $e^+$ and $e^-$, and $x_+ \equiv E_+/E$

Uses:
- HELAS amplitude computation
  H. Murayama, et al., KEK-91-11.
- SPRING event generator
- Validation against published 1D distributions (nuclear and triplet conversions)

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Dilution of Polarization Asymmetry due to Multiple Scattering: Optimal Fits and Full MC

- Remember: track angular resolution \((p/p_1)^{-3/4}\), \(p_1 = 13.6\ \text{MeV}/c\left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6}\)

\[ D \equiv \frac{A_{\text{eff}}(p_1)}{A(p_1 = 0)} \]

Energy variation of \(D\) for various values of \(p_1(\text{keV}/c)\)

- Curves are \(D(E, p_1) = \exp \left[ -2(a p_1^b E^c) \right] \) parametrizations, \(a, b, c\) constants
- Liquid: nope \((\text{Ar}, p_1 = 1.45\ \text{MeV}/c)\); gas: Possible! \((1\ \text{bar}, p_1 = 50\ \text{keV}/c)\)

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Polarimetry Performance : 1 : no Experimental Cuts

- Crab-like source, $T = 1$ year, $V = 1 \text{ m}^3$, $\sigma = l = 0.1 \text{ cm}$, $\eta = \epsilon = 1$.
- $A_{\text{eff}}$ (thin line), $\sigma_P$ (thick line);

- Argon, 5 bar, $\sigma_P \approx 1.0\%$, $A_{\text{eff}} \approx 15\%$

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Polarimetry Performance : 2 : Experimental Cuts

- photon-source assignment selection $\theta_{pair} < 10^\circ$
- opening angle $\theta_{+-} > 0.1 \text{ rad}$
- lepton (kinetic) energy cut (5 bar argon, 0.5 MeV $\propto$ path length $\approx 30 \text{ cm}$).
  \[ \sigma_P \approx 1.0\% \rightarrow 1.4\% \]
- expressing the track $E$ cut as a pathlength $\Lambda$ cut (argon):

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{Graph showing the relationship between $\sigma_P$ and $\Lambda$ for liquid and 5 bar gas.}
\end{figure}

- polarimetry with a dense detector (liquid / solid TPC, scintillator cube) would imply efficient trigger / tracking / selection of cm long tracks.
- A stack of hyper-thin Si wafer could be considered homogeneous, and if spaced far enough .. low density .. enough?
HARPO : the Demonstrator

- Time Projection Chamber (TPC)
- (30 cm)$^3$ cubic TPC
- Up to 5 bar.
- Micromegas + GEM gas amplification
- Collection on $x$, $y$ strips, pitch 1 mm.
- AFTER chip digitization, up to 50 MHz.
- Scintillator / WLS / PMT based trigger

- micromegas + (1 or 2) GEM
  55Fe & cosmics characterization
  Ph. Gros, TIPP2014
Event Reconstruction

raw “maps” track time spectra \((x, y\) matching)

- Evt reco of a cosmic ray traversing the TPC, emission of a \(\delta\) ray
- Track pattern recognition by combinatorial Hough transform
- \(x, y\) two track ambiguity solved by track time spectra matching
- 2 bar (Ar :95 Isobutane 5 %), shaping 100 ns.
Conclusion

A thin active target such as a gas TPC is THE detector for $\gamma$ astronomy in the $e^+e^-$ with utmost performance in the [MeV - GeV] photon energy range,

- Angular resolution improvement by $\approx 1$ order of magnitude w.r.t. the Fermi LAT within reach.
  @ 100 MeV, 5 bar argon, recoil $\approx$ MS, 0.4° in total
  Therefore, powerful Background rejection
  And rejection of atmospheric photons and of cosmic rays is straightforward

- Full sky, $4\pi$ acceptance
  ( .. if on a high orbit)

- Huge sensitivity improvement, closes the sensitivity gap between (Compton and W/Si pair) telescopes

- Provides, for the first time, polarimetry above 1 MeV!

- The HARPO demonstrator built and characterized with cosmic rays.

Preparation of data taking @ NewSUBARU Japan in Nov 2014 is in progress.
((almost) fully polarized $\gamma$ beams 2 – 76 MeV)
3 layers, each layer of 2 back-to-back modules, each module a \((2 \text{ m})^2 \times 0.5 \text{ m}\) TPC with an endplate segmented into \((33 \text{ cm})^2\) micromegas and charge collection blocks. 432 chips, \((12 \text{ m})^3\) : 100 kg gas at 5 bar.

Conversions of a 100 MeV (left) and of a 10 MeV (right) photon in the TPC gas

\textit{Je vous remercie de votre attention.}
Back-up Slides
**Thin / Thick Detectors, Effective Area**

<table>
<thead>
<tr>
<th></th>
<th>Thick</th>
<th>Thin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion prob.</td>
<td>$p \approx 1$</td>
<td>$p \ll 1$</td>
</tr>
<tr>
<td>Effective area</td>
<td>$\approx S \times \epsilon$</td>
<td>$\approx H \times M \times \epsilon$</td>
</tr>
<tr>
<td>Conversion proc.</td>
<td>compete</td>
<td>don’t compete</td>
</tr>
<tr>
<td>(pair, triplet, Compton)</td>
<td></td>
<td>with each other</td>
</tr>
</tbody>
</table>

- $H$ photon attenuation, $M$ detector mass, $S$ surface, $\epsilon$ reconstruction efficiency
- Thin techno prevents $\gamma$ loss due to Compton in low $Z$ material at low $E$
- High $E$ asymptote $A_{\text{eff}} = 3.6 \text{m}^2/\text{ton}$ (Nuclear, Argon)

$A_{\text{eff}} / M (\text{cm}^2 / \text{g})$ vs $E (\text{MeV})$: Compton, Nucl., Triplet, Xe, Ar, Ne
Which Pressure?

- **Science.** Rising the pressure:
  - degrades the angular resolution and (mildly) point like source sensitivity
  - Increases the effective area improves the precision on the polarization

- Maximum **micropattern gas amplification gain** (micromegas, GEM) known to decrease with pressure .. but $dE/dx$ increases ..


micropattern gas amplification above 10 bar a concern, unless very small gap devices can be produced.

- **Vessel Mass** $\propto$ gas mass to 1rst order.
  - For a given mission : which limit will we touch first (volume, mass) ?

In this talk examples were given at 1, 5, 10 bar
Pressure Vessel: a Naive Static Study

\[
P \quad \text{Alloy} \quad 0.2\% \text{ yield} \quad @ \ T \quad \text{safety} \quad \phi \quad t \quad t \quad M \\
5 \text{ bar} \quad 6\text{Al-V4} \quad 750 \text{ MPa} \quad 150^\circ \text{C} \quad 1.6 \quad 3000 \text{ mm} \quad 4 \text{ mm} \quad 5.5 \text{ mm} \quad 1110 \text{ kg}
\]

No re-inforcement of any kind at the moment.

TPC gas 100 kg
outside gas 150
vessel 1110
PCB 142
Scintillator veto 300 ?
electronics ?
support ?
gas system ?
\[
\text{total} \quad \geq \quad 1800 \quad \text{kg}
\]

Behavior upon launch?
A $\gamma$ Nuclear Conversion in a 30 cm 5 bar Argon TPC

$$\gamma \rightarrow Z^{e^+ e^- Z}$$

(10 MeV) (4.3 MeV) (5.7 MeV)

(EGS5)
Search for Axions

- Scalar field associated with $U(1)$ symmetry devised to solve the strong CP problem.
- Couples to $2\gamma$ through triangle anomaly.
- $\gamma$ propagation through $B \Rightarrow$ Dichroism $\Rightarrow E$ dependant rotation of linear polarization $\Rightarrow$ linear polarization dilution.

$$g_{a\gamma\gamma} \leq \frac{\pi m_a}{B \sqrt{\Delta \omega L_{GRB}}}$$

- Saturation over $L = 2\pi \omega/m_a^2 > L_{GRB}$ for $m_a \leq \sqrt{2\pi \omega \Delta \omega L_{GRB}}$

and the limit $g_{a\gamma\gamma}$ reaches a $\omega$-independent constant.

Optimal Track Fit with Multiple Scattering Cross Validation

- 5 bar argon, $\sigma = l = 0.1\text{cm}$; \[ p_1 = 13.6\text{MeV}/c \left( \frac{4\sigma^2 l}{X_0^3} \right)^{1/6} = 112\text{keV}/c \]

- 40 MeV/c electrons, $\sigma_{\theta t} = (p/p_1)^{-3/4} = 12.2\text{mrad}$

Smoothed angle residues RMS for track fits with a Kalman filter.

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Evt Generator : One Example of Validation Plot

- Triplet conversion: cross section for recoil electron momentum larger than $q_0$, $\sigma(q > q_0)$, as a function of $q_0/mc$, for various photon energies $E$;

Compared with:

**Track Momentum Measurement in TPC Alone from Multiple Estimations of Multiple Scattering**

- multiple scattering $\theta_0 \propto 1/p \Rightarrow p \propto 1/\theta_0$ [G. Molière, Zeit. Naturforschung A, 10 (1955) 177.]

- optimization of track step size

$$\Rightarrow \frac{\sigma_p}{p} \propto \frac{1}{\sqrt{L}} \left[ \frac{p \sigma \sqrt{X_0}}{13.6\text{MeV}/c} \right]^{1/3}$$

**$E$ range of interest**

**Relative precision**

<table>
<thead>
<tr>
<th>$p$ (MeV/c)</th>
<th>$\sigma_p/p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.03</td>
</tr>
<tr>
<td>10</td>
<td>0.04</td>
</tr>
<tr>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>1000</td>
<td>0.06</td>
</tr>
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</table>

- Ne
- Ar
- Xe

**$H/E^2$ (cm$^2$/g MeV$^2$)**

- Ne
- Ar
- Xe

**Triplet**

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TPC-Based $\gamma$-Ray Telescope Projects

.. Most likely not exhaustive..

AdEPT
NASA
et al.

HARPO
LLR & Irfu CEA/Saclay

$\mu$ PIC
Kyoto U.
et al.

S. D. Hunter
Proc. of SPIE Vol. 7732 773221-7

D.B.
Pisa2012 & NIM A 718 (2013) 395

K. Ueno
Vienna 2010
Polarimetry : Optimal Measurement

- Remember, fit of
  \[ \frac{d\Gamma}{d\phi} \propto (1 + AP \cos[2(\phi)]) \]
  yields
  \[ \sigma_P \approx \frac{1}{A} \sqrt{\frac{2}{N}}, \]

- Optimal measurement ; \(\Omega\)
  - let’s define \(p(\Omega)\) the pdf of set of (here 5) variables \(\Omega\)
  - search for weight \(w(\Omega)\), \(E(w)\) function of \(P\), and variance \(\sigma_P^2\) minimal ;
  - a solution is
    \[ w_{\text{opt}} = \frac{\partial \ln p(\Omega)}{\partial P} \]
    e.g. : F. V. Tkachov, Part. Nucl. Lett. 111, 28 (2002)
  - polarimetry : \(p(\Omega) \equiv f(\Omega) + P \times g(\Omega)\),
    \(w_{\text{opt}} = \frac{g(\Omega)}{f(\Omega) + P \times g(\Omega)}\).

- If \(A \ll 1\), \(w_0 \equiv 2 \frac{g(\Omega)}{f(\Omega)}\), and

- for the 1D “projection” \(p(\Omega) = (1 + AP \cos[2(\phi)])\) :
  \[ w_1 = 2 \cos 2\phi, \quad E(w_1) = AP, \quad \sigma_P = \frac{1}{A\sqrt{N}} \sqrt{2 - (AP)^2}, \]

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Polarimetry : Optimal Measurement

- Full MC, nuclear conversion

- **1D** weight : validation $\sqrt{2}$

- **5D** weight :
  - similar polarization asymmetry $A$ ($\approx 15\%$ asymptotically at high $E$)
  - gain factor $> 2$ on precision $\sigma_P$ w.r.t. 1D weight,
  - ability to measure precisely the 5D final state?

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Polarimetry: Effects of Experimental Cuts

- opening angle, \( \theta_{+-} > 0.1 \text{ rad} \) (easy pattern recognition)
- source selection \( \theta_{\text{pair}} < 10^\circ \)
- kinetic leptons energy \( E_{\text{kin}} > 0.5 \text{ MeV} \), (path length in 5 bar argon \( \approx 30 \text{ cm} \))

- All cuts: \( \epsilon = 45\% \), (1D) \( A_{\text{eff}} \approx 16.6\% \) \( \sigma_P \approx 1.4\% \),

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Polarimetry with Compton Scattering Events at High Energy

Minimum detectable polarization

Compton polarization asymmetry

M. L. McConnell, J. M. Ryan

Long Term Work with Gas Detector in Space

- Our present “ground” demonstrator is rather dirty (scintillator, WLS, PCB, glue ..)
- Sealed operation, no recirculation.
  ⇒ After one month of working, it showed significant absorption over 30 cm drift length
- Obvious cure would be recirculating / purifying the gas.
- An other option is to separate “clean” and “dirty” volumes by a ceramic foil


- Obviously the collecting board is on the “dirty” side
- The signal is then read through capacitive coupling