Linear Polarimetry with $\gamma \rightarrow e^+e^-$ conversions

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Polarised Emission from Astrophysical Jets,
12-16 June 2017, Ierapetra, Greece

llr.in2p3.fr/~dbernard/polar/harpo-t-p.html
One Workshop, 3 presentations

- What I had planned
  - **Poster**: High angular-resolution high sensitivity $\gamma$-ray astronomy and linear polarimetry with low density (gas) detectors in the MeV-GeV energy range
  - **Talk**: A Bethe-Heitler 5D polarized $\gamma \rightarrow e^+e^-$ conversion event generator
  - **Poster**: $\gamma$-ray astronomy with magnetic-field-free active targets: Optimal measurement of charged particle momentum from multiple scattering with a Bayesian analysis of filtering innovations
  - **Talk refurbished**: some elements on $\gamma$-ray polarimetry with $e^+e^-$ pairs.
  - $\gamma$-ray polarimetry for jet astrophysics science case: see Haocheng’s talk.
High-energy Polarimetry

- Here photons detected individually (Photo-electric, Compton, pair production)
- $J^{PC} = 1^{--}$:
  $$\frac{d\Gamma}{d\phi} \propto (1 + AP \cos [2(\phi - \phi_0)]), \quad \sigma_P \approx \frac{1}{A} \sqrt{\frac{2}{N}},$$

- $P$ (cosmic source) linear polarisation fraction
- $\phi_0$ (cosmic source) polarisation angle
- $A$ (conversion process) polarization asymmetry
- $\phi$ (event) azimuthal angle

- Polarimetry by analysis of $\phi$ distribution
Compton scattering : Polarisation Asymmetry

Current and past Compton telescopes sensitive below 1 MeV

- Cross section decreasing
- Polarization asymmetry:
  - Exact expression
  - HE approximation
  \[
  \langle A \rangle = -\frac{4(\log 2k_0 - 2)}{k_0(2\log 2k_0 + 1)}.
  \]
  - \(\langle A \rangle \approx -\frac{2}{k_0}\).

\(\langle A \rangle \approx -\frac{2}{k_0}\).

**Pair Conversion: Polarisation Asymmetry**

- **HELAS**: all Feynman diagrams
- **Bethe-Heitler** analytical expression
  (2 dominant diagrams)

Asymptotes:
- **Low energy**
  \[ A = \frac{\pi}{4}. \]
  
  \[ \text{Astropart. Phys. 88 (2017) 30} \]

- **High energy**
  \[ A \approx \frac{4}{9} \ln 2E - \frac{20}{28} \frac{28}{9} \ln 2E - \frac{218}{27} \rightarrow \frac{1}{7} \approx 0.14 \]

Conversion in a Slab and Multiple Scattering: Dilution of the Polarisation Asymmetry

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

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

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

\[ \theta_0 \approx \frac{13.6 \text{ MeV}/c}{\beta_p} \sqrt{\frac{x}{X_0}}, \]

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

\[ \Rightarrow \sigma_\phi \approx 24 \text{ rad} \sqrt{x/X_0} \quad (\text{e.g. } A_{\text{eff}}/A = 1/2 \text{ for } 110 \mu\text{m of Si, } 4 \mu\text{m of W}) \]

This dilution is energy-independent.

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

Yu. D. Kotov, Space Science Reviews 49 (1988) 185,

\[ \gamma \text{ Polarimetry with a Homogeneous Detector and Optimal Fits} \]

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

- \[ \sigma_{\theta,\text{track}} = \left(\frac{p}{p_1}\right)^{-3/4}, \]
  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

- \[ \sigma_{\phi} = \left[ x_+^{-3/4} \oplus (1 - x_+)^{-3/4} \right] \left(\frac{p_1}{1.6 \text{ MeV}}\right)^{3/4}. \]
  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

NIM A 729 (2013) 765
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)

  NIM A 729 (2013) 765
  Astropart. Phys. 88 (2017) 60
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 \(p_1\) (keV/c)

- Curves are \(D(E, p_1) = \exp[-2(a p_1^b E^c)^2]\) 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

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

- With experimental cuts: $\epsilon = 45\%$, $A_{\text{eff}} \approx 16.6\%$, $\sigma_P \approx 1.4\%$,

NIM A 729 (2013) 765
Polarization sensitivity in a nut shell

- Effective area $A_{\text{eff}} = H \times M$, $V = 1 \text{ m}^3$, 5 bar argon, $M = 8.3 \text{ kg}$

- Crab-like source, $\Gamma = 2$, $E^2 \frac{dN}{dE dtdS} = F = 10^{-3} \text{ MeV cm}^{-2} \text{ s}^{-1}$.

- Exposure duration $T = 1 \text{ year}$, exposure fraction $\eta = 1$

- Polarimetry sensitive for bright sources: zero background assumption

- $N = \eta T M F \int \frac{H(E)}{E^2} dE \approx 830 000 \text{ events}$, $A \approx 0.2$, $\sigma_P \approx \frac{1}{A} \sqrt{\frac{2}{N}} \approx 0.01$.

- Reasonable $\eta \approx 1/7$, (7 year, 1 m$^3$) or (1 year, 7 m$^3$) $\rightarrow$ $\sigma_P \approx 0.01$.

- year $\rightarrow$ day, 0.01 $\rightarrow$ 0.20
Pair conversion: circular polarimetry?

- $\gamma$-ray circular polarization does not take part in the electron-polarization-averaged differential cross section
  (to first order Born approximation)

- $\gamma$-ray circular polarization transferred to electron and positron polarization

- Polarization analysis would need magnetized detectors

On a space mission: nope, IMHO.
The HARPO (Hermetic ARgon POlarimeter) instrument project

• France: the detector

Denis Bernard, Philippe Bruel, Mickael Frotin, Yannick Geerebaert, Berrie Giebels, Philippe Gros, Deirdre Horan, Marc Louzir, Frédéric Magniette, Patrick Poilleux, Igor Semeniouk, Shaobo Wang

LLR, Ecole Polytechnique and CNRS/IN2P3, France

David Attié, Pascal Baron, David Baudin, Denis Calvet, Paul Colas, Alain Delbart, Patrick Sizun, Ryo Yonamine

IRFU, CEA Saclay, France

Diego Götz

AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/SAp, CEA Saclay, France

• Japan: the beam.

S. Amano, T. Kotaka, S. Hashimoto, Y. Minamiyama, A. Takemoto, M. Yamaguchi, S. Miyamoto

LASTI, University of Hyōgo, Japan

S. Daté, H. Ohkuma

JASRI/SPRING8, Japan
HARPO: the Demonstrator

- Time Projection Chamber (TPC)
- $(30\text{cm})^3$ cubic TPC
- Up to 5 bar.
- Micromegas + GEM gas amplification
- Collection on $x$, $y$ strips, pitch 1 mm.
- AFTER chip digitization, up to 100 MHz.
- Scintillator / WLS / PMT based trigger

Data Taking Nov. 2014 NewSUBARU, LASTI, Japan

- Linearly polarized $\gamma$ beam from Laser inverse Compton scattering, $e^-$ beam 0.6 – 1.5 GeV.

- 0.532 $\mu$m and 1.064 $\mu$m 20 kHz pulsed Nd:YVO$_4$ (2$\omega$ and 1$\omega$), 1.540 $\mu$m 200 kHz pulsed Er (fibre) and 10.55 $\mu$m CW CO$_2$ lasers

- $\Rightarrow$ 1.7 - 74 MeV $\gamma$ beam

- Monochromaticity by collimation on axis

- Fully polarized or random polarization beams ($P = 0$, $P = 1$)

- 2.1 bar Ar:isoC$_4$H$_{10}$ 95:5 (+ a 1-4 bar scan).

Sample of $\gamma$-rays from 74 to 1.7 MeV converting to $e^+e^-$ in 2.1 bar Ar:Isobutane 95:5 detected by the HARPO TPC (pre-beam-calibration $\gamma$-ray energy on plots)
Polarimetry : HARPO results

\[
E_\gamma = 11.8 \text{ MeV}
\]

11.8 MeV $\gamma$-rays converting to $e^+e^-$ in 2.1 bar Ar:Isobutane 95:5

Preliminary, publication in preparation
Conclusion

- Gas TPC is THE choice detector for ultimate angular resolution $\gamma \rightarrow e^+e^-$ astronomy and polarimetry

- $4\pi$ acceptance detector, low pile-up, zero deadtime

- Data taken:
  - with a $(30\text{cm})^3$ TPC prototype, mostly @ 2.1 bar, 1-4 bar scan.
  - with a $P = 1$ and $P = 0$, 1.7 – 74 MeV, $\gamma$ beam

- First demonstration of low energy ($E < 1 \text{ GeV}$) $\gamma$-ray polarimetry with pairs

- Cosmic-source polarisation-fraction precision statistics dominated.

Thanks
Back-up Slides
Non polarized astronomy

- Improve **angular resolution** – crowded sky regions

![Contour plot of Fermi/LAT data](image1.png)

- Solve **sensitivity** gap between Compton and pair telescopes
  - Actually Fermi was publishing mostly in the range $0.1 - 300\text{GeV}$
  - Improvement expected from PASS8

![Sensitivity comparison graph](image2.png)

Fermi/LAT

Angular resolution and sensitivity

"Fermi-LAT below 100 MeV (Pass8 data)", Julie McEnery,

"e-ASTROGAM workshop: the extreme Universe", Padova Feb-March 2017
Grey points: dedicated Multiwavelength campaign 2013:

- NuSTAR satellite (3-79 keV),
- the Fermi Large Area Telescope (LAT, 100 MeV-300 GeV)
- (H.E.S.S.) array phase II
Science Case: Polarimetry: Astrophysics

- Blazars: 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)
Pulsars

- Phase-averaged polarization
- Tag transition energy between synchrotron and curvature radiation at 1 – 100 MeV in Crab-like pulsars

LIV: Search for Lorentz Invariance Violation

- Particle (photon) dispersion relations modified in LIV effective field theories (EFT)

- Additional term to the QED Lagrangian parametrized by $\xi/M$, $M$ Planck mass.

- $\xi$ bounds:
  - time of flight from the Crab: $\Delta t = \xi (k_2 - k_1) D/M$, $\xi \leq O(100)$.  
  - birefringence $\Delta \theta = \xi (k_2^2 - k_1^2) D/2M$
    LIV induced birefringence would blurr the linear polarization of GRB emission.
    $\xi \leq 3.4 \times 10^{-16}$ with IBIS on Integral (250 – 800 keV)

- Bound $\propto 1/k^2$!
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 $m_a \leq \sqrt{\frac{2\pi \omega}{L_{GRB}}}$

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

Photon angular resolution

\[ \gamma \ Z \rightarrow e^+ \ e^- \ Z \]

\[ \vec{k} = p_{e^+} + p_{e^-} + p_r \]

Contributions:

- Single-track angular resolution,
- Un-measured nucleus recoil momentum for “nuclear” conversion
- Single-track momentum resolution
Single-track angular resolution

Hypotheses:

• Thin homogeneous detector;
• Tracking with optimal treatment of multiple-scattering-induced correlations (e.g., à la Kalman);
• Low energy, multiple-scattering-dominated, regime

\[ \sigma_{\theta t} = \left( \frac{p}{p_1} \right)^{-3/4} \quad \text{with} \quad p_1 = p_0 \left( \frac{4\sigma^2 l}{X_0^3} \right)^{1/6}, \]

With:

• \( p \) track momentum [MeV/c];
• \( p_0 = 13.6 \text{ MeV}/c \), multi-scattering constant;
• \( p_1 \) detector “multiple-scattering momentum” parameter [MeV/c];
• \( \sigma \) single measurement detector spatial resolution [cm];
• \( l \) track longitudinal sampling (pitch) [cm].

Single-track angular resolution

- Dependence of the RMS photon angular resolution on photon energy
- Sampling pitch $l = 1 \text{ mm}$, point resolution $\sigma = 0.1 \text{ mm}$,

For various densities (argon)

For various gases

NIM A 701 (2013) 225
Angular resolution

- Argon-based gas, $P = 10$ bar
  $$X_0 = 1180 \text{ cm}$$

- Sampling pitch $l = 1 \text{ mm}$, point resolution $\sigma = 0.1 \text{ mm}$,
Performances with 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 $E^2 dN/dE$, à la Fermi: 4 bins/decade, $5\sigma$ detection, $T = 3$ years, $\eta = 0.17$ exposure fraction, $\geq 10\gamma$. “against” extragalactic background

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"Nuclear" and "triplet" pair conversion

\[ \gamma Z \rightarrow e^+ e^- Z \]

\[ \gamma e^- \rightarrow e^+ e^- e^- \]

74 MeV \( \gamma \)-rays from NewSUBARU conversions in 2.1 bar Ar:Isobutane 95:5
A 16.7 MeV $\gamma$-ray converting to $e^+e^-$
in 2.1 bar Ar:Isobutane 95:5

- $x$, $y$ two-track ambiguity solved by track time spectra matching
- 1 channel = 1 mm.
- 1 time bin = 30 ns, $v_{\text{drift}} \approx 3.3 \text{ cm/\mu s}$ $\Rightarrow$ 1 time bin $\propto 1 \text{ mm}$
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 \( \sigma^2_P \) minimal;
  - a solution is \( w_{opt} = \frac{\partial \ln p(\Omega)}{\partial P} \); e.g.: F. V. Tkachov, Part. Nucl. Lett. 111, 28 (2002)
  - polarimetry: \( p(\Omega) \equiv f(\Omega) + P \times g(\Omega), \quad w_{opt} = \frac{g(\Omega)}{f(\Omega) + P \times g(\Omega)}. \)
  - 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: Defining the Azimuthal Angle?

- **ω**
- **φₚ**, recoil angle, \( \varphi_p = \varphi_{\text{pair}} \pm \pi \)
- **φ**, bisector of \( e^+ \) and \( e^- \) direction

Polarization asymmetry

\[ \omega = \left( \frac{\varphi_+ + \varphi_-}{2} \right) \]

Polarization angle

\[ \phi = \left( \frac{\varphi_+ + \varphi_-}{2} \right) \]

\( \sigma_{\varphi_0} \times A[\text{rad}] \)

\( E - 2mc^2 \) [MeV]

\( \sigma_{\varphi_0} \times A[\text{rad}] \)

\( E - 2mc^2 \) [MeV]

\( \sigma_{\varphi_0} \times A[\text{rad}] \)

\( E - 2mc^2 \) [MeV]
Gas amplification: micromegas + 2 GEM

Gas Electron Multiplier
50 µm Kapton, copper clad,
pitch 140 µm, Φ70 µm

“bulk” micromegas
gap 128 µm

F. Sauli, NIM A 386, 531 (1997)
I. Giomataris et al., NIM A 560, 405 (2006)
55Fe (dedicated test bench) and cosmic-rays (in TPC)

Ph. Gros et al., TIPP2014, PoS(TIPP2014)133
Anode segmentation

- Avalanche electrons collected on a segmented anode.

- Cu-clad PCB, strip pitch 1 mm, strip width \( \approx 400 \mu m \)
Signal digitization

- 2 directions $x, y$, 288 strips (channels) / direction
- 72 channels /chip
- 4 chips / direction
- 511 time bins, “circular” SCA (Switched Capacitor Array)
- Input: 120 fC to 600 fC
- Up to 100 MHz sampling
- Shaping time 100 ns to 2 $\mu$s
- 12 bit ADC.

Our set-up: $1/(30 \text{ ns})$ sampling, 100 ns shaping time, digitization (dead-time) 1.67 ms.

“Beam” trigger system

- $S_{up}$ upstream scintillator
- $O$ one of the 5 other scintillators
- $M_{slow}$: a delayed ($> 1\mu s$) signal on the micromegas mesh
- $L$ laser trigger pulse

“Main line”: $T_{\gamma,\text{laser}} = \overline{S_{up}} \cap O \cap M_{slow} \cap L$

“Beam” trigger system: additional lines

- Additional trigger lines:
  7 \( T_{\gamma,\text{laser}} \quad \overline{S}_{\text{up}} \cap O \cap M_{\text{slow}} \cap L \)
  8 \( T_{\text{noMesh,\text{laser}}} \quad \overline{S}_{\text{up}} \cap O \cap L \)
  9 \( T_{\text{invMesh,\text{laser}}} \quad \overline{S}_{\text{up}} \cap O \cap M_{\text{quick}} \cap L \)
  10 \( T_{\text{noUp,\text{laser}}} \quad O \cap M_{\text{slow}} \cap L \)
  11 \( T_{\text{noPM,\text{laser}}} \quad \overline{S}_{\text{up}} \cap M_{\text{slow}} \cap L \)
  12 \( T_{\text{noLaser}} \quad \overline{S}_{\text{up}} \cap O \cap M_{\text{slow}} \cap L \)

Designed to characterize the performance (signal efficiency, background rejection) of each component of main trigger line

“Beam” trigger system: conversion point distributions

- signal efficiency 51%
- background rejection 99.3%
- incident rate 2 kHz
- signal on disk 50 Hz

Towards a space detector: some elements

- Gas composition
- Gas pressure
- Temperature range
- Gas purity on the long term
- . . .
Towards a space detector: Gas composition: drifting species?

- TPC’s to some extent immune to pile-up
- $2 \times 1D$ orthogonal strips given the (small) available electronic powering (i.e., not pads)
- Proton flux $20\text{kHz/m}^2$ at Fermi/LAT orbit.
- Need “fast gas”:

<table>
<thead>
<tr>
<th>Drifting species</th>
<th>Example</th>
<th>$v_{\text{drift}}$</th>
<th>$t_{\text{drift}}$</th>
<th>Pile-up fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>Ar:isoC$<em>4$H$</em>{10}$</td>
<td>3.3 cm/$\mu$s</td>
<td>10$\mu$s</td>
<td>0.2 proton/m$^2$</td>
</tr>
<tr>
<td>Negative ion</td>
<td>Ar:CS$_2$</td>
<td>3.3 cm/ms</td>
<td>10ms</td>
<td>200 proton/m$^2$</td>
</tr>
</tbody>
</table>
Gas composition: light / heavy Z? Gas pressure?

- \( \rho \times X_0 = \frac{A}{Z^2} b \),  \( \rho = aAP \),  \( M = V \rho = V aAP \),  \( X_0 = \frac{b}{aZ^2P} \)  \( a, b \) constants.

\[ \sigma_\theta \propto X_0^{-3/8} \propto Z^{3/4} P^{3/8} \]

(multiple scattering)

\[ A_{\text{eff}} \propto \frac{V}{X_0} \propto VPZ^2 \]

(asymptotically)

\[ s \propto \frac{\sigma_\theta}{\sqrt{A_{\text{eff}}}} \propto \frac{X_0^{1/8}}{\sqrt{V}} \propto \frac{1}{V^{1/2}Z^{1/4}P^{1/8}} \]

(assuming gaussian stats.)

- Note that  \( M_{\text{vessel}} \propto P \)  and  \( M_{\text{gas}} \propto P \)  so  \( M_{\text{vessel}} \propto M_{\text{gas}} \)

\[ M_{\text{vessel}}/M_{\text{gas}} \approx 0.36 \]  for Ti alloy sphere at elastic limit / Argon.

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Gas composition, quencher

- Gas detectors need limitation of breakdown from UV photoelectric effect on the cathode: add poly($n > 2$)molecular “quencher” gas (alcanes, CO$_2$ ..)

- Mitigates diffusion $\sigma = \sigma_x / \sqrt{z}$, $\sigma_x = 200 \, \mu$m/$\sqrt{\text{cm}}$, ($\sigma \approx 0.6$ mm after $z = 9$ cm drift)

- Diffusion is needed to minimize the TPC spatial resolution! $C_D \equiv \sigma_x$, $w$ strip pitch.

D. C. Arogancia et al., NIM A 602, 403 (2009)

D. Bernard
Polarised Emission from Astrophysical Jets, June 2017, Ierapetra
Pressure, Quencher fraction, $e^-$ transport properties

- Argon-isoo-butane mixture with (2, 5, 10)% iso-butane and pressure 1, 2, 4 bar

Drift velocity

Transverse diffusion coefficient

Longitudinal diffusion coefficient

\[ v_{\text{drift}} \quad \text{cm/µs} \]

\[ C_{D,T} \quad \text{cm/√cm} \]

\[ C_{D,L} \quad \text{cm/√cm} \]

- $v_{\text{drift}}$ max value does not depend on $P$; $E$ value for $v_{\text{drift}}$ maximum is $\propto P_{C4H10}$.

- $C_{D,T} \propto 1/\sqrt{P_{C4H10}}$.

- $C_{D,L}$ fn of $E$.

Transverse diffusion coefficient determined by quencher partial pressure

Longitudinal diffusion coefficient determined by drift field

garfield.web.cern.ch/
Temperature variation, Temperature range

- TPC parameters depend on gas density $\rho$, not on (pressure $P$, temperature $T$)

- Thermal vessel volume variations corrected by small (drift, amplification) voltages.
  (We operated the same set-up in the range 1-4 bar by simple voltage adjustments)

- Maximal temperature ?
  - check your electronics !

- Minimal temperature ?
  - avoid quencher partial liquefaction

<table>
<thead>
<tr>
<th>gas</th>
<th>Ar</th>
<th>Xe</th>
<th>CH$_4$</th>
<th>C$_2$H$_6$</th>
<th>iso C$<em>4$H$</em>{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>boiling point at 1.013 bar ($^\circ$C)</td>
<td>-185.8</td>
<td>-108.1</td>
<td>-161.5</td>
<td>-89</td>
<td>-11.7</td>
</tr>
</tbody>
</table>

- alcanes have similar quencher properties.
Gas purity on the long term

- HARPO pressure vessel extremely dirty: scintillator, WLS, PVC box, PCB, epoxy, O-rings ..
- We have observed the evolution of the gaz quality in sealed mode [Fev. - Jun.] 2015 (2.1 bar).

![Graph showing cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.]

Cumulative charge drift-length-distribution of one-hour cosmic-rays (through-tracks) runs.

- $O_2$ fraction peaked at 180 ppm on Jul. 08. $O_2/(O_2 + N_2) = 0.225$, compatible with air.
- Then we switched an oxisorb recirculation to operation. $O_2$ fraction disappeared ($< 20$ ppm)

M. Frotin et al., arXiv:1512.03248 [physics.ins-det], MPGD2015, EPJ Web of Conferences
Gas purity on the long term: results

Time evolution of the amplification gain, of the electron capture and of the drift velocity as measured with cosmic-rays through [Fev. - Sept.] 2015.

- Interpreted as air leak or air outgassing, with complete gas cleaning upon purification
- Good prospects to run a TPC for years with a simple oxisorb cleaning

M. Frotin et al., arXiv:1512.03248 [physics.ins-det], MPGD2015, EPJ Web of Conferences
AGET: ASIC for Generic Electronics for TPC

- Input current polarity: positive or negative
- 64 analog channels
- 4 charge ranges/channel: 120 fC to 10 pC
- Shaping: 16 peaking time values: 70 ns to 1μs
- 512 analog memory cells / channel
- Fsampling: 1 MHz to 100 MHz; Fread: 25 MHz
- Auto triggering: discriminator + threshold (DAC)
- Real time (25 MHz) Multiplicity signal: analog OR of the 64 discri Outputs
- Readout:
  - Address of the hit channel(s)
  - 3 readout modes: All, hit or specific channels
  - Predefined number of analog cells / trigger (1 to 512)

AGET → radhard ASTRE: “Asic with SCA & Trigger for detector Readout Electronics”: