An Helium calorimeter for Anti-Deuteron identification in cosmic rays (ADHD)

(Anti Deutron Helium Detector)

Technology and Instrumentation in Particle Physics (TIPP 2021)

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Evidences & search for Dark Matter

- Rotational velocity of galaxies
- Lensing of galaxy clusters
- Colliding galaxy clusters
- CMB observations
- Dark matter annihilation and scattering
- Production at LHC
e⁻ and p are produced and accelerated from SNR
Collision of “ordinary” Cosmic Rays produce secondary e⁺, e⁻, p⁻
Among many possible mechanisms:
Collisions of Dark Matter will produce additional e⁺, e⁻, p⁻
Positron in Cosmic Rays

Evidence for a common source of $e^+$ and $e^-$ from AMS02 data

- Dark Matter?
- Astrophysical source?
- “Exotic” secondary production?

It is MANDATORY to search for DM annihilation also in all the other possible channels

AMS02:

28.1 million electrons
1.9 million positrons
A bump in the Antiproton flux?

Phys. Rev. Lett. 118, 191102

“A Robust Excess in the Cosmic-Ray Antiproton Spectrum”

“AMS-02 antiprotons are consistent with a secondary astrophysical origin” arXiv:1906.07119

There is room for “vanilla” Dark Matter but…
It is necessary to decrease uncertainty in the background model:
- cross sections knowledge (new measurements in lab)
- propagation models (flux of other secondary cosmic rays)
- solar modulation models (low energy time dependence)

IF TRUE => expected excess of low energy antideuterons

AMS02@2026 would add a new point up to 550-600 GeV

4σ “excess” (>100GeV)

3σ “excess” (15GeV)
THE BACKGROUND: anti-D coalescence production

\[ \bar{D} \]

- \[ M = 1875.6 \text{ MeV} \]
- \[ Z = -1 \]
- \[ A = -2 \]
- \[ \Delta E = -2.2 \text{ MeV} \]

\[ \bar{D} \] flux from spallation (background, B)

- Coalescence is a very rare process
- Low energy, secondary (bkg) anti-D are suppressed by
  Production threshold + center of mass boost
Anti Deuterons in Cosmic rays

Anti Deuterons have been proposed as an almost background free channel for Dark Matter indirect detection.

The Anti Deuterons Flux is < $10^{-4}$ of the Antiproton Flux. Additional background rejection needed.
The current “best-limit”: BESS-Polar II

- 3000 cm² sr (≈ 7 x AMS-02 e⁺)
- 1 T superconducting mag. Field

- TOF: β, Z (dE/dX)
- Solenoid + drift chamber: R
- Cherenkov: PID (identifies and rejects e⁻, μ⁻)

- Data taking at ~40km, ~5 g/cm² residual atmosphere

- $\overline{D}$ limit provided using 4 ~1day flights 11
1997-2000. BESS-Polar II results not yet official

30 days flight
4.7 x 10⁹ events recorded

11th Flight: 2008
Recovery: 2010
BESS-Polar II : still waiting for a published limit

(plots from K.Sakai @ Antideuteron-2019 conference UCLA)

selection: energy deposited + cherenkov veto

Time of Flight velocity vs \(R/P/z\)

\[
M = \frac{R Z}{\gamma \beta}
\]

\(\times 1/300\) for positive rigidity

Antideuterons

\((\sim 10^3 \text{p})\)

Flux < \(5.9 \times 10^{-5} \text{ (m}^2\text{sr sec GeV/n)}^{-1} [0.1-1.2] \text{ GeV/n}\)
a coming-soon improvement in sensitivity: AMS-02

Status of AMS02 anti-D search: already exceed the sensitivity of BESS

S. Ting: https://cds.cern.ch/record/2320166
Atomic-transitions:
additional signatures for low energy anti-D

For low energy additional signature wrt magnetic spectrometer:
- Charge sign is detected by formation of Exotic Atom
- anti-D recognized by distinctive radiative transition energy
- anti-D recognized by larger multiplicity of charged pion star

Exotic Atom

3 pions ($\bar{p}$) vs 6 pions (anti-D)
planned: GAPS (General Anti Particle Spectrometer)

Combination of time-of-flight + depth-sensing, X-ray, and π detection yield rejection > $10^6$
a possible “new” signature: He metastable states

Why He is a special target?

1) the Auger decay is suppressed as well due to large level spacing of the remaining electron (~25 eV) compared to the small (~2 eV) n→n-1 level spacing of \( \bar{p} \rightarrow \) metastability is unexpected and excluded for Z>3 (metastability for Li\(^+\) target? → still not found by expt.)

2) the remaining electron in \( \bar{p}\text{He} \) suppresses the collisional Stark effect (the main de-excitation channel for \( p\bar{p} \) system) 

\[
(p \bar{p})_{nl} + H \rightarrow (p \bar{p})_{nl}' + H
\]

Not really new: similar effect already proven, and used, by the ASACUSA experiment

- In matter lifetime of stopped \( \bar{p} \) is \( \sim \)ps
- In liquid/gas He delayed annihilation: few \( \mu s \) (~3% of the \( \bar{p} \))(discovered @ KEK in 1991)
  The ele is on 1s ground state, while the \( \bar{p} \) (or also \( \pi, k, d \)) occupies a large \( n \) level (~38 for \( \bar{p} \)) (~same bounding energy of the ejected e-)


prompt annihilation

delayed annihilation

a signature for Z=-1 antimatter capture in He is a \( \sim \mu s \) delayed energy release (in \( \sim 3\% \) of cases)
Lifetime & fraction vs pressure vs particle mass

Phys Rev A 53 (1996) 3129  He @ room Temperature

NOT a pure exponential:
Fast and Slow components
Increasing Pressure → Fast component increase

Isotope effect:
expected lifetime increase as squared of the reduced mass => expected for antideuterium
Anti Deuteron He Detector (ADHD)

**Concept:** HeCalorimeter (scintillator) 3xTime of Flight (compact) layers

Status: preliminary Geant4 simulation

Detector size: External ToF L = 1.5m;
Vessel R=45cm Thick=3cm “thermoplastic”
He pressure 400bar (typ. He bottle 130bar)
(“commercially” feasible space qualified)
Detector mass: He = 20 kg  Vessel = 100kg
ToF = 110 kg (4mm scintillator thickness)
Kinetic energy range: 0.06-0.15 GeV/n
(threshold due to energy loss in vessel/ToF)

Particle identification by:
1) timing of tracks
2) dE/dx on ToF
3) Beta ToF
4) Prompt HeCal Energy
5) Delayed HeCal Energy
6) event topology
GEANT4

$\bar{d}$ (65MeV/n)  $\bar{p}$ (230MeV)  Carbon (600MeV/n)

4 charged outgoing (+ pair production)  3 charged outgoing  0 charged outgoing

Negative  Positive  Neutral charges
\[ \bar{d} \text{ (65MeV/n)} \]
\[ \bar{p} \text{ (230MeV)} \]
\[ \text{Carbon (600MeV/n)} \]

… ok it is slow …
prompt HeCal signal
3 hits in ToF

prompt HeCal signal
3 hits in ToF

prompt HeCal signal
10 hits in ToF
stopped by HeCal
small tail in prompt
HeCal signal

stopped by HeCal
small tail in prompt
HeCal signal

...nothing
Antideuteron orbiting He

Antiproton orbiting He

...nothing
Antideuteron annihilation

Antiproton annihilation

...nothing

\[ \bar{d} \text{ (65MeV/n)} \quad (\text{[60-70] ns}) \quad \bar{p} \text{ (230MeV)} \quad \text{Carbon (600MeV/n)} \]
\[ \bar{d} \ (65\text{MeV/n}) \quad [70-\text{XXX}] \text{ ns} \quad \bar{p} \ (230\text{MeV}) \quad \text{Carbon} \ (600\text{MeV/n}) \]

small nuclear processes  
small nuclear processes  
...nothing
Typical HeCal signature for $\bar{p}$ and $\bar{d}$

- **S1**: prompt
  - $\bar{p}$ or $\bar{d}$
  - kinetic energy
  - (- energy loss)

- **S2**: delayed
  - Charged $\pi/\mu$
  - Typ. S2 > S1
  - S2 and Ek not related

- Width: few ns
- Expected S2 ampl. for $\bar{p}$
- Up to few $\mu$s
p/d separation: prompt signal

ToF goals (30cm baseline & 4mm thickness):
\( \beta \) resolution 5\% \( \Rightarrow \) \( \sigma_{x/y} \sim \) few cm & \( \sigma_T < 0.1 \) ns
Energy resolution 10\%

Parametrization of \((\beta \text{ vs } E) \) & \((dE/dx \text{ vs } E)\)
2 “independent” classifiers
that can be combined to obtain an overall
“Prompt signal classifier”
p/d separation: delayed signal

delayed signal amplitude is independent from $E_{\text{kin}}$: $\sim 3$ charged pion/antinucleon

- ToF delayed activity classifier = #ToF delayed hits $\oplus$ ToF delayed energy
(can be improved a bit with full track topology)

2 “independent” classifiers
that can be combined to obtain an overall
“Delayed signal classifier”
$p/d$ separation

$p$ rejection 1500 @ 65% $d$ efficiency
$=>$ possibility to detect $1d/1000$ $p$

[50-150] MeV $p$ flux < $2-3 \times 10^{-3}$ (m$^2$s sr GeV)$^{-1}$

Therefore with these ADHD performances
the $p$ background is limiting the sensitivity to:
$d$ flux > $2-3 \times 10^{-6}$ (m$^2$s sr GeV/n)$^{-1}$
These have to be multiplied for the probability to form metastable states $\sim 3.3\%$

Example of sensitivity/new measurements with 5yr data @ $0.2 \times 0.033 \text{ m}^2 \text{ sr}$:
- Antideuteron $[50-150] \text{ MeV}/\text{n}$: $10^{-5} \text{ (m}^2 \text{s sr GeV/n})^{-1}$ ($<0.3 \bar{\text{p}}$ background is expected)
- Antiproton: new measurement in 10 bins in the range $[100-300] \text{ MeV}$ with 5-10% error
planned sensitivity

AMS02-GAPS-ADHD: different techniques, similar sensitivity, complementary Ek regions

Join of all the signatures in a future/ultimate Antideuteron detector?
ADHD

technological readiness level
Vessel (&ToF) sets the energy window: [50-150] MeV/n
Wall thickness $s$ x density (+ToF) => lower Energy threshold
Pressure $P$ & radius $R$ => upper Energy threshold
we need a light/thin vessel + high $P$ + large $R$ ...
… and safety: ADHD gas stored energy is the same as ~ 4kg TNT

For cost reduction on the Ariane 5 launcher, EADS-ST intends to replace the usual and expensive titanium liner of He tank by a plastic one http://www.dtic.mil/dtic/tr/fulltext/u2/a445482.pdf

spherical vessel $P_{burst}$ prop.to $R/s$
COPV for Hydrogen fuel is a commercial product

Example: Faber company in Italy

Faber relies on a unique 40-year track record which includes a very comprehensive range of all Types of Cylinders (Type 1,2,3,4), each one standing out for superior lightness, reliability and safety. The entire production process is controlled by Faber and performed in-house in one of our own dedicated plants. This ensures that Faber is capable of offering the right cylinder at a price that best fits the needs of our customers.
The He Calorimeter

He as scintillator has a strong “fast” component (tens ns, 15000 ph/MeV)

He is scintillating in VUV:
Vessel have to be PTFE coated with an organic phosphor that converted the wavelength of the scintillation light from 80 nm to 430 nm.

High pressure issue:
Most probably PMT cannot be used inside the high pressure vessel => SiPM

(test for a possible use of SiPM in space and their radiation tolerance are currently ongoing @ TIFPA proton beam)
HeCal prototype: ARKTIS B470 test with Muons @ TIFPA

“Near” PMT

μ

“Far” PMT

plastic scint.

h=47cm

209 bar

4He: 0.95L

μ

Ø=5cm

Al$_2$O$_3$

good scint.

4He: 0.95L

detection volume

9cm of position resolution from signal amplitude asymmetry (for MIPs)

9cm of position resolution from signal amplitude asymmetry (for MIPs)

Good performances also for muons MIP 3-4cm in He(200Bar) = 200-250keV (30MeV-250MeV proton beam test in Trento scheduled for 2020)

Time resolution: 3ns (for lateral crossing MIPs)

Edep $\sim$ 0.25 MeV

Energy resolution:

16% @ MIPs

10 photons/side @ MIPs

$\chi^2$/ndf = 10.08/8

Constant $= 65.4 \pm 5.0$

Mean $= -0.329 \pm 0.175$

Sigma $= 2.963 \pm 0.150$

$\chi^2$/ndf = 10.33/13

Constant $= 29.84 \pm 2.81$

Mean $= -0.04703 \pm 0.01175$

Sigma $= 0.1856 \pm 0.0109$

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a new SiPM array photon detector for proton test beam

- Proton beam pass through center hole (SiPM are shielded by iron collimator)
- Bragg peak $T_b$
- Steel wall thickness 2.5mm
- Plastic scintillator $T_0$
- Hollow SiPM array detector $T_s$
- $1\text{cm Al}_2\text{O}_3$ P3MT $T_1$
- "near" PMT is replaced
- 8xSiPM array Sensl 6x6mm$^2$

Iron collimator shield SiPM array
Vertical Muon calibration @ TIFPA

251 Vertical muons crossing the whole active He volume $L = 50\text{cm} \Rightarrow 3.2 \text{MeV}$

He calorimeter time resolution:
$\Rightarrow 2\text{ns}$
(crossing MIPs)

Top $4 \times 0.8\text{cm}^2$ plastic scint. $T_0$

Bottom $4 \times 0.8\text{cm}^2$ plastic scint. $T_1$

PMT He scintillator (T2)

PMT plastic scintillator (T0)
PROTON Test Beam @ TRENTO Proton-Therapy center

ToF velocity selector
protons 60-75 MeV

collimator

plastic scint. $T_0$

steel wall thickness 2.5mm

Bragg peak $T_b$

hollow SiPM array detector $T_s$

1cm $\text{Al}_2\text{O}_3$

PMT $T_1$

Rear veto

Proton test beam data analysis ongoing ...
ADHD: Summary

ADHD is a new technique for Antideuteron identification in He target 
... a promising tool for Dark Matter search.

https://www.tifpa.infn.it/projects/adhd/

Contact us for:
- PhD project on Anti-deuterons (AMS+ADHD) 

- Post Doc positions in Trento Astroparticle group

ADHD: Attention Deficit: maybe … Hyperactivity Disorder: guaranteed!
Backup
Test of a very thin ToF bar: 15cm x 3cm x 2mm EJ-200
2 x Hamamatsu R9880-210
- proton beam E = 62 MeV
- muons (cosmic) (MIPs)

ADHD goal already fulfilled
10% Energy resolution in MC simulation using 3 layer of 4mm each (test with 2mm).
(17% = 10% \sqrt{3})
=> reasonable to reach 5%
number of readout channel problem: L x 5 cm => 900 ch
3 cm x 15 cm ~ 12000 ch
Test of a ToF bar: Space/Time resolution

\[ \sigma_T = \sqrt{\frac{p_0^2}{E_0} + \frac{p_1^2}{E_0^2} + p_2^2} \]

ADHD goal 0.1ns x 4mm thickness

expected 2x improvements:
EJ200 => EJ232Q factor 4/3
2mm => 4mm: factor \( \sqrt{2} \)

ADC counts

\( \mu \) @ center

\( \mu \) @ 6 cm right

Position resolutions @ %:
Transverse to the bar:
3cm/\(\sqrt{12}\) ~ 1cm
also 5cm bar width is enough
Along the bar:
few cm from side amplitudes
3 cm from timing (0.1ns res)
ADHD goal already fulfilled
<table>
<thead>
<tr>
<th>Beam E (MeV)</th>
<th>-60 MeV</th>
<th>0MeV = 0cm</th>
<th>4.5ns</th>
<th>60 MeV</th>
<th>-45 MeV</th>
<th>20MeV = 13cm</th>
<th>6.0ns</th>
<th>70 MeV</th>
<th>-40 MeV</th>
<th>30MeV = 28cm</th>
<th>7.0ns</th>
<th>75 MeV</th>
<th>-35 MeV</th>
<th>40MeV = 47cm</th>
<th>8.0ns</th>
</tr>
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Energy table: (200bar)