Detection of high-energy particles from the Universe: basic concepts, methods, and challenges

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SpaceX: a revolution in spaceflight is ongoing...

Past/current space experiments costs >10$/g

The cost of the launch has implications in the detector performances/design

NASA goal for 2040: “tens of dollars per kg”

Space elevator: “a few dollars per kg”

0.8T VOYAGER
0.4T ULYSSES
0.5T PAMELA
AMS01 2.4T
AMS02 NUCLEON 7.5T 1.4T 0.4T DAMPE
6T HERD? AMS100? ALADINO?

HOW much does it cost?
Balloons? Not really cheaper now ...

was an option for past experiments

Residual atmosphere is a passive target: the same of 5 cm of plastic

- Fragmentation effects
- Production of secondary particles (problem for antimatter search)

by comparison Galaxy grammage for CR typ. path length is ~2 g/cm²
your kinetic energy during a quiet walking (3km/h) ... but the momentum of just a single eyelash hair ...
GALACTIC SOURCES

(some interesting PeVatron)

EXTRA-GALACTIC

Energy [J]

Energy flux [GeV/m² s sr]

10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^0 10^2

1/cm²/s

1/m²/yr

1/km²/yr

Energy

GeV TeV PeV EeV

AMS02 HAWC AUGER BESS-TeV CALET CREAM I+II DAMPE

FERMI HESS ICECUBE ICETOP KASCADE-Grande PAMELA Tibet-III LHC

ν + ¯ν

IRGB

Knee

Ankle

3 PeV 5 PeV

p e⁺ e⁻ e⁺ e⁻
GALACTIC SOURCES

Direct measurement of cosmic rays with a detector in space are feasible above this line (m² acceptance x year)

EXTRA-GALACTIC

Indirect measurements (next lectures ... )
Cosmic Ray composition:

**NUCLEI composition:**
- particle charge
- particle “Energy”

“High” abundances of “secondary nuclei”
Production by Fragmentation
Cosmic Ray composition:
- particle charge
- particle “Energy”

NUCLEI composition:
- particle charge
- particle “Energy”
Cosmic Ray composition:

NUCLEI composition:
- particle charge
- particle “Energy”

which “Energy”?

Kinetic Energy: calorimeters (ATIC, JACEE, RUNJOB)

E/nucleon: TRD, Cherenkov (CRN-Spacelab, HEAO, CREAM, TRACER, HESS)

Rigidity (P/Z): Spectrometers (AMS02, Pamela, Bess)
Energy vs Energy/nucleon vs Rigidity: Measurement + Physics

RIGIDITY: GV (Giga-Volt)
MEASUREMENT: $P/Z$ is the quantity related to the trajectory in magnetic field (easily converted to Momentum knowing the particle charge $Z$)

PHYSICS:
Different particles with same rigidity follow the same trajectory in magnetic fields (in the Galaxy, in the Heliosphere, in the Earth magnetic field, in the detector field)
Main effects of propagation in the magnetic field (and the main time dependent solar modulation effects) would cancel out in $<\text{Flux Ratio}>$ vs $<\text{Rigidity}>$

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Energy/nucleon: GeV/n (usually average isotopic composition is assumed)
MEASUREMENT: is a quantity related to velocity (ToF, RICH, TRD) (they measure GeV/M and cannot be converted to Energy if mass is unknown)

PHYSICS:
Fragmentation of nuclei roughly conserve $E/n$ in spallation processes (when a relativistic CR nuclei during propagation interacts on a proton of ISM)
$A + p \Rightarrow A_1 + A_2 + p \quad E/A \sim E_1/A_1 \sim E_2/A_2$

high energy CNO ISM gas LiBeB
Flux ratio vs Rigidity: solar modulation

Solar modulation (Voyager is now outside the magnetosphere)

Flux ratio vs R

Solar modulation => time variation

"time-flat"
Particle identification - a summary:

AMS02: 7.5 Tons – 5x4x3m
B=0.15T in space since 2011
able to identify few antinuclei
over 150G events (0.5m² sr)
is shown for PID examples

- Absolute value of charge: VERY SIMPLE
- Particle Mass: easy for E<M, very difficult for E>>M
  (typically evaluated by “velocity” vs Energy)
- Particle Velocity: “easy” at few % (but saturation to β=1)
  (TRD measuring $\gamma = E/M$ to avoid saturation for E>>M)
- Particle direction: VERY SIMPLE
- Particle Momentum: hard to do better than few %, very difficult for P>TV
- Charge sign: (up to now) impossible for R>TV
- Particle Energy: feasible down to few %, but large systematics for E>>TeV
The “easy” measurement: particle CHARGE

Vertices of electromagnetic interactions are proportional to particle charge $z$

$\Rightarrow$ detection processes are typically based on EM interaction, thus prop to $z^2$
Energy loss: Bohr classical evaluation

Momentum transferred to an electron:

\[ \Delta P = \int F \, dt = \int eE \frac{dx}{v} = \frac{ze^2}{2 \pi \varepsilon_0 b v} \]

Energy loss in \( dV = 2\pi b \, db \, dx \):

\[ n_e = \rho N_A Z/A \]

\[ -dE = \frac{(\Delta P)^2}{2m_e} n_e \frac{dV}{b} = \frac{1}{(4 \pi \varepsilon_0)^2} \frac{4 \pi Z^2 e^4}{m_e v^2} n_e \frac{db}{b} \, dx \]

\( b_{\text{min}} \): head on collision \( (v_e = 2v) \)

\[ \Delta E_{\text{max}} = 2 \gamma^2 m_e v^2 \quad b_{\text{min}} = \frac{1}{4 \pi \varepsilon_0} \frac{ze^2}{\gamma m_e v^2} \]

\( b_{\text{max}} \): This approach assumes electrons “at rest” that is \( T_{\text{collision}} \ll T_{\text{revolution}} \)

\[ T_{\text{collision}} \approx \frac{b}{(\gamma v)} \quad \text{and} \quad T_{\text{revolution}} \approx 1/\nu \quad \Rightarrow \quad b_{\text{max}} \approx \gamma v/\nu \quad \text{(then integrate over } b) \]

Bohr formula:

\[ -\frac{dE}{dx} = \left( \frac{e^2}{4 \pi \varepsilon_0} \right)^2 \frac{4 \pi N_A Z^2}{m_e} \ln \left( \frac{\gamma n_e v^3}{Z A} \right) \]

Full quantum mechanical: Bethe-Block

\[ -\frac{dE}{\rho dx} = K z^2 Z \frac{1}{A \beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right] \]

Projectile

Target material

\( Z/A \) quite similar in all materials main material effect from density

Gauss th.

\[ \Phi_E = \frac{Q}{\varepsilon_0} \]
The main effect of target material (due to the density) can be factorized out.
Energy loss: Bethe Block – in different materials

\[ -\frac{dE}{dx} = K \rho \left( \frac{Z}{A} \right) \beta^2 \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right] \]

The main effect of target material (due to the density) can be factorized out.

MIPs (Minimum Ionizing Particles) are “calibration sources” for detectors.

MIPs: 1.1-1.8 MeV cm\(^2\)/g for \(Z > 2\) targets
Energy loss: Bethe Block - the Charge measurement

\[ -\frac{dE}{\rho dx} = K \frac{Z^2}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right] \]

to measure dE/dx also some tracking to measure dx is necessary…
(and to get a good charge measurement also some value for velocity is needed)
If charge is known, the energy loss allows a reasonable velocity measurement for $\gamma < 1$ (possible but hard to exploit the relativistic rise for $\gamma$ measurement)

On the other hand correction for this effect is required for precise charge measurements.
Simple spectrometers $\Delta E/E$ (mass for sub-MIPs particles):

**ACE-CRIS evidence for $^{60}$Fe ($\tau \approx 2.6\text{My}$)**

$200 < E < 500 \text{ MeV/n}$

$\Rightarrow$ PRODUCED BY A NEARBY SN
mass above MIPs? (directly measured) Velocity vs Momentum

Isotopes in light cosmic rays:

- Primaries
- Secondaries
- $^6\text{Li}$
- $^7\text{Li}$
- $^9\text{Be}$
- $^{10}\text{Be}$
- $^{11}\text{B}$
- $^{12}\text{C}$
- $^{13}\text{C}$
- $^{14}\text{N}$
- $^{15}\text{N}$
- $^{16}\text{O}$
- $^{17}\text{O}$
- $^{18}\text{O}$

$^{10}\text{Be}$ ($\tau \approx 1.4\text{My})$ is the clock of cosmic rays (propagation times)

\[ M = \frac{RZ}{\gamma\beta} \Rightarrow \frac{\Delta M}{M} = \sqrt{\left(\frac{\Delta R}{R}\right)^2 + \left(\frac{\gamma^2 \Delta \beta}{\beta}\right)^2} \]

DETECTOR COMPLEXITY INCREASES

Velocity direct measurement:
- Time of Flight
- Cherenkov Detector

Momentum measurement: ($R = P/z$)
- Magnet + tracker
Velocity measurement using Time Of Flight

- Plastic scintillator:
  - $\approx 10000$ photons/MeV
  - $\tau \approx \text{ns (but } N \text{ photons} \Rightarrow \sigma T \approx \text{ns}/\sqrt{N} \approx 50-100 \text{ ps}$

- PhotoMultiplier Tubes

- $c = 30\text{cm/ns}$ (speed of light)
- $n \approx 1.6$ (plastic scint. refr. index)

- $t_1 = t_A + L_{A1} n/c$
- $t_2 = t_A + L_{A2} n/c$
- $t_A = (t_1 + t_2)/2 + L n/(2c)$
- $t_B = (t_3 + t_4)/2 + L n/(2c)$
- $\text{ToF} = t_B - t_A = (t_3 + t_4 - t_1 - t_2)/2$
- $\beta = \Delta x/(\text{ToF} \times c)$

Some “self tracking” capability:

- $t_2 - t_1 = (L_{A2} - L_{A1}) n/c = \Delta L_A n/c$
- $t_3 - t_4 = (L_{B4} - L_{B3}) n/c = \Delta L_B n/c$

- $(\Delta x)^2 = H^2 + (\Delta L_A - \Delta L_B)^2/4$

Velocity resolution:
- $\Delta \beta/\beta \approx \Delta \text{ToF}/\text{ToF} \approx 100 \text{ ps c/H}$
- Energy up to $\approx \text{GeV/n}$

Position resolution (along the bar) from time difference $\approx \text{few cm}$
Example: AMS02 - Deuteron flux

Preliminary: please refer to forthcoming PRL publication
Velocity measurement using Cherenkov Ring Imaging

Basic equations:
1) \( \cos \theta = 1/(n\beta) \) [Cherenkov]
2) \( n \sin \theta = \sin \theta_v \) [Snell]
3) \( N_{ph} \approx \epsilon d \frac{2 \pi \alpha Z^2 \sin^2 \theta}{\lambda_2 - \lambda_1} \)

Typically \( K \) 500-1000 photons/cm:
Typ. photon coll. eff. 0.01-0.3

Example of AMS02 RICH: \( L = 45 \) cm
AeroGel \( n = 1.05 \quad \beta_{\text{min}} = 0.95 \quad \sin \theta = 0.3 \quad d = 2.5 \) cm
NaF: \( n = 1.33 \quad \beta_{\text{min}} = 0.75 \quad \sin \theta = 0.65 \quad d = 0.5 \) cm

\( \sigma_{\beta} = \sigma_r \frac{d \beta}{dr} = \frac{s}{\sqrt{12 (N_{ph} - 2)}} \frac{d \beta}{dr} \sim \frac{d \beta}{L n \sqrt{12 (N_{ph} - 2)}} \)

AMS02: \( <N_{ph}> \approx 3xz^2 \); 
\( \frac{\sigma_{\beta}}{\beta} \approx \frac{1.2 \times 10^{-3}}{z} \Rightarrow 10 \text{ GeV}/n \)

Some tracking helps a lot to find the ring center
Momentum measurement: magnetic spectrometers

Lorentz force
\[ \frac{dP}{dt} = z e v \times B \]

Helix trajectory: \( R = \frac{P}{z} \)

\[ \rho = \frac{P}{zeB} \Rightarrow \rho[m] = \frac{R[GV]}{0.3B[T]} \]

Rigidity resolution:
\[ \sigma_{1/R} = \frac{\sigma_{1/\rho}}{0.3B} = \frac{8\sqrt{3}/2 \sigma_y}{0.3BL^2} \]

\[ \frac{\sigma_R}{R} = R \sigma_{1/R} = \frac{R}{MDR} \]

Maximum Detectable Rigidity

Sagitta:
\[ y_2 - \frac{(y_1 + y_3)}{2} \]

\[ s = \rho(1 - \cos \frac{\theta}{2}) \approx \frac{L^2}{8\rho} \]

For a Tracker with \( N \gg 3 \) layers:

\[ \frac{1}{MDR} \approx \sigma_{1/R} = \sqrt{\frac{720}{N+4}} \frac{0.3BL^2}{\sigma_y} \]

AMS02: \( z=1 \quad \sigma_y = 10\mu m \quad MDR(z=1) = 2 \text{ TV} \)
\( z=2 \quad \sigma_y = 5\mu m \) (larger S/N)
Momentum measurement: charge sign identification

Tracker MDR = 2 TV for Z=1 particles

Charge confusion = probability of wrong charge sign measurement

<1% up to 300 GeV
<10% up to TeV

Reduction/identification by MC based multivariate analysis.

400 GeV protons measured with R<0!

\[
\frac{1}{\text{MDR}} = \sigma_{1/R} 5 \times 10^{-4} \text{ GV}^{-1}
\]

gaussian bulk

CC dominated by "fat" tails

\[
\frac{1}{\text{Rigidity}} - \frac{1}{400} \left[ \text{ GV}^{-1} \right]
\]

\[
\Lambda_{cc} \text{ estimator}
\]

Combines variables based on track fit quality

Rigidity measurement

Charge measurements

Sources of charge confusion
1. Large angle scattering;
2. Production of secondaries.
Well reproduced by the Monte Carlo. Measured directly from data.
Measurement of E/M - TRD detector

Radiated energy/crossing:
\[ W = \frac{1}{3} \alpha \hbar \omega_p \gamma \quad E_{\gamma}^\text{max} \approx \gamma \hbar \omega_p \]

Number of radiated photons/crossing:
\[ N \sim \frac{W}{\hbar \omega} \sim \alpha = \frac{1}{137} \]

Needs a lot of interfaces!

Saturation of number of TRD photons \( \gamma > \gamma_{\text{sat}} \sim 2000 \)
_Not easy to perform isotopic separation… Usually Likelihood technique adopted to do PID_
TRD based Mass measurement at high energy:

\[ N = 20 \text{ layers} \]

\[ P_p = \prod_{i=1}^{n} \frac{1}{P_p^{(i)}}(A) \quad P_e = \prod_{i=1}^{n} \frac{1}{P_e^{(i)}}(A) \]

TRD estimator = \(-\ln\left(\frac{P_e}{P_e + P_p}\right)\)

5.4<|R|<6.5 GV

175<R<211 GV

\( \beta_{\text{RICH}} \)

\( \Lambda_{\text{TRD}} \times \Lambda_{\text{CC}} \)

\( \leq \) TRD: Mass separation for \( E >> M \)
Antiprotons in cosmic rays

**BESS-Polar II (2008-2010)**
- Balloon: ≈ 30gg 4.7×10⁹ events
- Acceptance: 3000 cm² sr 1500kg
- 1T superconducting magnet
- Drift chambers => MDR = 270 GV

**PAMELA:**
- (2006-2016) in space
- 1.3m x 460kg
- Acceptance: 21.5 cm² sr
- 0.43T => MDR = 1 TV

\[\Phi_p = k E^{\Delta \gamma}\]

\[\Delta \gamma = -0.05 \pm 0.06\]

\[\bar{p} = 3.49 \times 10^5\]

\[p = 2.42 \times 10^9\]

Flat antiproton ratio.

“exotic” sources?

Background model still uncertain (next slides...)

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PAMELA

BESS-Polar II
the Mass “of the detector”: Calorimetry

ECAL classifier e/p rejection: shower shapes are different

- **Electron primary**
  - A small fraction produce showers
  - Most of protons remain MIP
  - Wider asymmetric showers

- **Proton primary**
  - Leaks leakage correction increases with E

\[
\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}
\]

\[
t_{\text{max}} = \ln\left(\frac{E}{E_c}\right) \pm 0.5
\]

\[
X_0 = 0.03 \Lambda_i
\]

\[
Fe: X_0 = 0.1 \Lambda_i
\]
AMS02-ECAL: redundancy matters

50,000 fibers, $\phi = 1$ mm
Inside 600 kg of lead

Lead foil (1mm)

Fibers ($\phi = 1$ mm)

ECAL energy resolution $\sim 2\%$ at HE
ECAL energy absolute scale tested during test beams on ground + E/R
MIP ionization used to cross-calibrate the energy scale in flight

Large leakage for P
DAMPE: $31 X_0 (1.6 \Lambda)$ size matters

Electron: Test Beam up to 243 GeV
MC extrapolated to 5 TeV

Proton: Test Beam up to 400 GeV
MC extrapolated to 100 TeV

Proton energy:
MC based

Proton Energy resolution:
100 GeV $=>$ 10 TeV
25% $=>$ 35%

No redundancy of Energy scale :(
NUCLEON: size does not matter ... if you have a clever idea (and a good MC)

Kinematic Lightweight Energy Method (KLEM)

\[ S = \sum N_i \eta_i^2 \approx \sum E_i \ln^2 \left( \frac{x_i}{2H} \right) \]

Thin Calorimeter 12 \( X_0 \) 350kg 0.2m\(^2\)sr (2017)

Large \( E \) => smaller pseudorapidity

\[ n = -\ln \tan(\theta/2) \]

<table>
<thead>
<tr>
<th>Projectile</th>
<th>( a, \text{ GeV} )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>1651</td>
<td>1.36</td>
</tr>
<tr>
<td>He</td>
<td>2556</td>
<td>1.27</td>
</tr>
<tr>
<td>C</td>
<td>3514</td>
<td>1.18</td>
</tr>
<tr>
<td>S</td>
<td>4163</td>
<td>1.14</td>
</tr>
<tr>
<td>Fe</td>
<td>4362</td>
<td>1.12</td>
</tr>
</tbody>
</table>

\[ E_{\text{primary}} \approx aS^b \]

\( \pi^- \) beam test @ CERN
60% energy resolution

Flight data
P & He spectrum

propagation or source populations?

hardening

AMS02 (spectrometric measurement) has smaller syst. err. (precise information)
Cosmic Rays & DARK MATTER

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

\[ p + p \rightarrow \bar{p}, p, \pi^±, ... \]

\[ \pi^± \rightarrow \mu^± \rightarrow e^± \]
Measurement of secondary/primary nuclei is important to define effects of propagation/interaction in ISM. This allows a precise evaluation of the antimatter background.
AMS02 Positrons

MINIMAL MODEL:
- **quantitative** information about the Positron source
- **minimal assumptions** on the underlying physics

Evidence for a cutoff energy:
\[ E_s = 810 \text{ GeV} @ 99.99\% (4 \sigma) \]
Detailed information on the positron source e.g. “excess” is compatible with Dark Matter J. Kopp, Phys. Rev. D 88, 076013 (2013).

Dark Matter is just an “intriguing” example, also nearby astrophysical positron sources (pulsar) could account for the excess...

“next point” (1-1.5 TeV, AMS02@2026) will help to solve degeneracy ...
Electrons + Positrons

EVIDENCE FOR TeV BREAK

Some tension in results:
- DAMPE compatible with Fermi-LAT
- CALET compatible with AMS02
- All of them within 2.5 $\sigma$ considering syst. uncertainties in calorim. E scale

HESS
(indirect detection see next lecture)

Example of source fit
arXiv:1903.07271
Some excess in Antiprotons?


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

There is room for DM 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)

=> expected signal in low energy antideuteron?

AMS02@2026
Can just add a new point up to 550-600 GeV
Charge confusion is dominated by gaussian “spillover” (MDR bulk)
AMS: primary & secondary break

AMS02 accuracy & new evidence:
- Both show hardening above 200 GV
- Primary => common behavior
- Secondary => common behavior
- Nitrogen is a mixture
AMERICAN NITROGEN

In the Solar System:

In the Cosmic Rays:

\[
\begin{align*}
\text{N/O} &= 0.14 \pm 0.05 \\
\text{N/O} &= 0.090 \pm 0.002 \\
\text{C/O} &= 0.46 \pm 0.09 \\
\text{C/O} &= 0.91 \pm 0.02
\end{align*}
\]
If the hardening in CRs is related to the injected spectra at their source, then similar hardening is expected both for secondary and primary cosmic rays.

If the hardening is related to propagation properties in the Galaxy then a stronger hardening is expected for the secondary with respect to the primary cosmic rays.

An hardening of 0.13±0.03 at 200 GV is observed combining the six secondary/primary ratios. This observation favors the flux hardening as an universal propagation effect.
Probing Non-Homogeneous Diffusion:

- B/C is a probe for only “local” propagation
- $p, D$ and $p$ come from much further
- Light secondary like $D, ^3He$ investigate better the $p$ secondary production

Spectral index for $^3He/^4He$ is the same obtained for B/C and B/O at high R. May indicate the effect of a different diffusion coefficient in non local regions.
AMS: Be/B clock

$^{10}\text{Be} \ (\tau \approx 1.4\text{My}) \Rightarrow ^{10}\text{B} + e^- + \bar{\nu}$ sensitive to residence time of CR in the Galaxy => halo size $H$.

Hard to get direct measurement of $^{10}\text{Be}$ content at “high energy”, but Be/B is sensitive to $^{10}\text{Be}$ fraction.
Current - future experiments
Current - future experiments

- AMS-02 Inner - 8ys
- AMS-100 MSOnly - 8ys
- ALADINO MSOnly - 8ys
- HERD - 8ys
- ALADINO - 8ys
- DAMPE - 8ys
- DAMPE - 4ys
- CALET - 8ys
- CALET - 4ys
- AMS-02 Full - 8ys

antideuteron detection

Weight (kg)

Exposure ($m^2 sr s/ton$)

- $10^{11}$ m$^2$ sr s
- $10^{10}$ m$^2$ sr s
- $10^9$ m$^2$ sr s
- $10^8$ m$^2$ sr s
- $10^7$ m$^2$ sr s

(1 m$^2$ x yr)

(the knee)
... and ... anti-nuclei?
**anti-D coalescence production**

\[ \bar{D} \]

- **M = 1875.6 MeV**
- **Z = -1**
- **A = -2**
- **\( \Delta E = 2.2 \text{ MeV} \)**

\[ p \rightarrow \bar{D} \rightarrow \bar{p} + \bar{n} \]

\[ |\Delta(k)| = k_{\bar{p}} - k_{\bar{n}} < p_0 \]

\[ p_0 \sim 180 \text{ MeV} \]

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

- **\( p \) (E > 16 \text{ GeV})**
- **Boosted RF**
- **Steeply falling CR \( p \) flux**

-Coalescence is a very rare process.
-Low energy, secondary (bkg) anti-D suppressed by: threshold (16 GeV) + boost.
-Jet structure (correlation of \( \bar{p}, \bar{n} \)) enhance anti-D production at low energy (i.e. from DM annihilation).
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.
BESS-Polar II: we are still waiting for an “official” limit

- Typical approach: MASS SELECTION

\[ m = \frac{p}{Z} \frac{\sqrt{1 - \beta^2}}{\beta} \]

- dE/dX sampled in many subdetectors and used to select the signal window

Signal Region for Antideuteron

0 \bar{D} ~10^3 \bar{p}

Excluded Region for Antiproton contamination

Z<0

Z>0
a coming-soon improvement in sensitivity: AMS-02

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

\[ \frac{\bar{p}}{p} \approx 10^{-4} \]

\[ \frac{\bar{D}}{p} < 10^{-3} \]

\[ \frac{\bar{D}}{D} < 10^{-5} \]
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

3 pions ($p$) 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 “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 atoms (metastability for Li\(^+\) target? → still not confirmed by expt.)

2) the remaining electron in \( \bar{p} \)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
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)
... a small & light detector ...

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
planned sensitivity

AMS02-GAPS-ADHD: different techniques, similar sensitivity, complementary Ek/n Join of all the signatures in a future/ultimate Antideuteron detector?

Aladino: detector technology almost ready (how to deal with huge trigger rate in L2?)
Currently, AMS observed 8 anti-helium candidates (mass region from 0-10 GeV) rigidity <50 GV with respect to a sample of 700 million He events. The rate in AMS of antihelium candidates is less than 1 in 100 million helium. At this extremely low rate, more data (through the lifetime of the ISS) is required to further check the origin of these events.
Bibliography – some useful links

-Cosmic ray database:
https://lpsc.in2p3.fr/cosmic-rays-db/  (France, user friendly)
https://tools.ssdc.asi.it/CosmicRays/  (Italy, only published data tables)

-Particle Data Book (a lot of review on particle, cosmology, ecc… very very useful):

-Link to homepages of many Cosmic rays experiments:

-AMS02 webpage:
https://ams02.space/

-ADHD webpage:
https://www.tifpa.infn.it/projects/adhd/

-Aladino proposal:
https://www.cosmos.esa.int/documents/1866246/3219248/
BattistonR_ALADINO_PROPOSAL_20190805_v1.pdf

-AMS100 proposal:
https://www.cosmos.esa.int/documents/1866246/3219248/
SchaelS_AMS100_Voyage2050.pdf
arXiv:1907.04168v1