Direct detection of CRs

Thanks to Francesco Cafagna
Bari INFN
A typical CR experiment for PID

Particle id: charge, mass, energy/momentum,

Spectrometer: gyroradius of a particle is proportional to the rigidity and inversely proportional to the magnetic field
Since B is known, Z and p can be measured

The momentum resolution is limited by the position measurement and by the multiple scattering in the magnet
A ToF system (e.g. A,C 2 scintillator counters or proportional counters or spark chambers) provide dE/dx, time, position and trigger.
Hence the time of flight of a particle over a known distance gives the velocity
Hence the particle is fully identified (Z and m)

Occasionally a destructive detector (calorimeter) can be used to have an independent energy measurement

$r_L = \left( \frac{pc}{Z} \right) \frac{1}{Bc}$
$R = \frac{pc}{Ze}$
Searches for anti-matter and primary CR composition

- PAMELA
- AMS
- BESS
- Caprice
- Tiger, Atic, HEAT, Jacee, Runjob, …
Anti-matter in CRs

- Collisions of High Energy Cosmic Rays With the Interstellar Gas
- Cosmic Rays Leaking Out of Antimatter Galaxies
- Annihilation of Exotic Particles
- Evaporation of Primordial Black Holes

Earth
Absolute fluxes

- No clear evidence
- But errors are large
- Ratios are better known
- Flattening at low energy
- Anti-matter from BH evaporation
- Decay of anti-matter at higher energies
Ratios
The Antimatter hunter toolkit

- **Spectrometer:**
  - We need to discriminate the particle charge
  - GOOD Maximum Detectable Rigidity (MDR): we need to push the measured rigidity range up to high energies
  - Magnet (permanent, superconducting at cryogenic T with currents) + Tracker (Gas detectors, solid state detectors)

- **Particle discrimination:**
  - We need to tag very few events out of a large background: positrons out of protons, antiprotons out of electrons
  - Typically we have to catch one antiparticle out of $10^{5\pm6}$ particles
**MDR of a Spectrometer**

- **What is the MDR?**
  - The rigidity for which the error $\Delta p/p = 100\%$

- **Why an MDR of 800 GV could mean a maximum momentum of 190 GeV/c?**
  - **Spillover!** At high energy particle charge is confused due to the finite spectrometer precision
  - Fake antiprotons due to protons “spilling” into the antiprotons spectra
We measure deflection: \( \eta = \frac{1}{R} \propto \frac{1}{p} \)

If \( p \) is high, small deflection, difficult charge determination \( \Rightarrow \) spillover

For this quantity error is gaussian

Spillover is calculated convolving spectra with spectrometer resolution

If gaussian error added, finite resolution changes ‘ideal’ spectra

Exercise 9
Particle discrimination

- Depends on the energy range we are interested in:
  - Low energy: TOF, Cherenkov, Pre Showers
  - High energy: RICH, TRD, electromagnetic calorimeters
The observational objectives of the PAMELA instrument are to:

- measure the spectra of antiprotons, positrons and nuclei in a wide range of energies,
- to search for primordial antimatter,
- to study the cosmic ray fluxes over half a solar cycle.

PAMELA will be able to measure magnetic rigidities (momentum/charge) up to its Maximum Detectable Rigidity (MDR) of 700 GV/c).
Particle ID using:
- TOF
- Em. Calorimeter
- Neutron detector $^3$He n capture to help em/h shower id

Rigidity determination using spectrometer
permanent magnet and silicon tracker
PAMELA: the integration
### PAMELA

<table>
<thead>
<tr>
<th>Particle</th>
<th>Number (3 yrs)</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>$3.10^8$</td>
<td>80 MeV - 700 GeV</td>
</tr>
<tr>
<td>Antiprotons</td>
<td>$&gt;3.10^4$</td>
<td>80 MeV - 190 GeV</td>
</tr>
<tr>
<td>Electrons</td>
<td>$6.10^6$</td>
<td>50 MeV - 2 TeV</td>
</tr>
<tr>
<td>Positrons</td>
<td>$&gt;3.10^5$</td>
<td>50 MeV - 270 GeV</td>
</tr>
<tr>
<td>He</td>
<td>$4.10^7$</td>
<td>80 MeV/n - 300 GeV/n</td>
</tr>
<tr>
<td>Be</td>
<td>$4.10^4$</td>
<td>80 MeV/n - 300 GeV/n</td>
</tr>
<tr>
<td>C</td>
<td>$4.10^5$</td>
<td>80 MeV/n - 300 GeV/n</td>
</tr>
<tr>
<td>Antihelium Limit (90% C.L.)</td>
<td>$7.10^{-8}$</td>
<td>80 MeV/n - 30 GeV/n</td>
</tr>
</tbody>
</table>

*Figure: Schematic diagram of the PAMELA detector system.*
Satellite Mass: ~10 tons
Pamela Container Total Mass: ~750 kg
PAMELA Mass: 470 kg
PAMELA Power: 380 W
Orbit:
- Elliptic (300 ÷ 600 km)
- Inclination: 70.4°
PAMELA in the satellite
Magnetic Spectrometer

- **Permanent magnet**
  - 5 blocks of Nd-B-Fe
  - 0.48 T
  - Magnetic tower = 13.2 x 16.2 cm²
  - 44.5 cm

  20.5 cm² sr
Magnet Construction

Support canister

Ferromagnetic shields
Silicon Planes

- **Double-sided silicon microstrips** (300 µm thick):
  - 25 µm implantation pitch (junction side) / 67 µm (ohmic side)
  - Strips mutually orthogonal on opposite sides
  - Readout pitch 50 µm
Spectrometer Resolution

- SPS Testbeam data: $p_{200 \text{ GeV/c}}$
  - $x$ (bending = orthogonal to B)
    - $\sigma_x = 2.7 \mu m$
  - $y$ (non-bending = parallel to y)
    - $\sigma_y = 12 \mu m$

PAMELA: Magnet

MDR $\approx 1080 \text{ GV (}\Delta p/p = 100\%)$
Si-W Imaging Calorimeter

- 22 planes:
- Alternating layers of Si (380 µm) / W (2.6 mm)
- 96 strips (2.4 mm wide) per Si layer
- X & Y views
- 16 $X_0$ (0.6 $\lambda_N$) deep
- Total number of channels: 4224
- Wide dynamic range $\approx 1 \div 1000$ MIPs (released charge due to a MIP particle)
Calorimeter Energy Resolution

Self trigger mode:
- \( \sim 300 \text{ GeV} \rightarrow 2 \text{TeV} \) ‘electrons’
- Enter one of 1st 4 planes & cross \( \geq 10 \ X_0 \)
- acceptance: 600 cm\(^2\)sr
- \( \text{Eff}(E_e > 300 \text{ GeV}) \) > 99% (sim.)
e-p Separation with the Calorimeter

- SPS Test Beam Data:
  - Proton rejection factor $\approx 3 \times 10^4$

- Electron selection efficiency $\approx 95\%$
The TOF System

- **TOF**: Particle ID / albedo (from below) rejection
  - 3 planes of Scintillators S1, S2, S3
  - Each plane: 2 crossed layers, segmented into X- and Y- strips
  - Hamamatsu PMT R5900 (selected for Q.E. and to match scintillator strips)

- **TRIGGER**: \((S1 \times S2 \times S3)\)
- **dE/dx** measurements (charge)
(Anti)proton/electron discrimination possible up to $\sim 1.5$ GeV/c
Anticoincidence system
Anticounter Purpose

- AC are used offline or in L2 trigger to reduce false triggers
Shower Scintillator & Neutron Counter

- VHE $e^\pm$, $E \sim 10^{11}$ eV $\div 10^{13}$ eV using a Neutron Detector (ND) (more $n$ in hadronic than EM showers):
  - $n + ^3\text{He} \rightarrow p + ^3\text{H} + 765$ keV
- 2 x 18 $^3\text{He}$ proportional counters (polyethylene / Cd envelope)
- ND triggered by a plastic scintillator: 482 mm x 482 mm x 10 mm
- 6 PMT read-out
- Dynamic range: $1 \div 1000$ MIP
AMS: General

- ISS: 108 m x 80 m, 420 t
- Orbit height: 400 km
- Inclination = 51.57°
- 15.62 revolutions/day
AMS: General

- TRD (e/p)
- Scintillator system (TOF) ($\beta, dE/dx, \text{trigger}$)
- Superconducting magnet ($BL^2 = 0.85 \text{Tm}^2$)
- Silicon Tracker (rigidity, charge)
- RICH ($\beta, \text{charge}$)
- Em. Calorimeter (energy, e/p)
AMS: General

- Large geometrical acceptance: 0.45 m$^2$ sr
- Long exposure: 3 years
- Redundant measurements
- High vacuum
- High radiation levels
- Strong gradients of temperature: -60°C ÷ +40°C
- Weight < 7 Tons
- Power consumption < 3kW
Diameter = 1.2 m, Height = 0.8 m, Weight = 2.3 t
\( B_{\text{dipol}} = 0.860 \, \text{T} \), \( E_{\text{stored}} = 1.15 \, \text{MJ} \), \( I = 459.5 \, \text{A} \)

Cold Heat Exchanger: Superfluid Helium

(-271.35°, 2500 l)

Long Duration Operation without refill
AMS: Tracker

- 2264 Double sided Silicon wafers
- 640 readout strips on implantation or p-side (bending coordinate)
- 384 readout strips on junction or n-side (non-bending coordinate)
- Combined into 192 Ladders of 7-15 sensors
- 1024 readout channels for each ladder, total of ~ 200k channels
- Ladders arranged on 8 layers piled up in 5 planes
- ~ 6.4m² total
AMS: Tracker

MDR = 3000 GeV (Δp/p = 100%)

Spatial resolution ~ 10 µm

120 GeV/c muon beam
Upper ToF

Anti-Coincidence Counter

Lower ToF

ToF & ACC

Fast Trigger$_{\text{prim}}$ \[ \sigma_t \leq 130 \, [\text{ps}] \]

Layers = 4 (2 + 2) \quad Area = 8 \, m^2

ToF : 34 Paddles

ACC : 16 Cylindrical Shell Paddles
AMS: Em. Calo.

- 9 Superlayers (Pb + Fiber Sandwich)
- $16.4 \chi_0$ and $\sim 0.5 \lambda_{nucl}$.
- Standalone Gamma Trigger
- 65x65 cm$^2$, $m=640$ kg, 324 PMTs

$\Delta E/E \sim 3\%$ at 100 GeV $e^\pm$

- Lead foil ($t$:1mm)
- Fibers ($\phi$:1mm)
- Hamamatsu fine mesh PMT
AMS: TRD

- 2.2x 2.2x0.8 m$^3$, 350 kg, 20 layers of straw tubes. Radiator: 2 cm polyethylene/ polypropylene 10 mm fibre fleece. Gas mixture is Xe:CO$_2$ 80:20% (1 bar)
- Conical octagon structure made of aluminum honeycomb with carbon-fibre skins and bulkheads
- Mechanical precision: 100 mm to assure gas gain homogeneity below 2%
- 4 lower and upper oriented parallel to the magnetic field, middle 12 perpendicular to it, for 3D tracking
Tails due to X-rays emission.
High Lorentz factor

AMS TRD Prototype  X7 Beamtest
Data (Symbols) vs Geant3+ MC (Line)

Single layer dE/dX
All layers dE/dX
Rad. NaF (n=1.336) in central region and Aerogel (n=1.035) elsewhere
680 PMT's Array, Spatial Pixel 8.5×8.5 mm²
Velocity Res.: $\Delta \beta / \beta = 0.07\%$ (Z=1)
Charge Measurement: $Z \leq 26$ (w/ Tracker + ToF)
Charge $N_\gamma \sim Z^2 \Delta L \sin \Theta_C$
Mass: $m(\beta,Z,R) = p/c \times \sqrt{n^2 \cos^2 \Theta_C - 1} = (pc/Ze) \times Ze/c^2 \times \sqrt{1-\beta^2}/\beta = RZe \times \sqrt{1-\beta^2}/\beta c^2$
AMS: Rich

Accelerator Measurements
@A/Z=2, 2.25, 10GeV/n
**Charge measurement**

**TOF Tracker**: Sampling of particle energy deposition

\[ \Delta E \propto Z^2 \]

**RICH**: The number of Cerenkov radiated photons when a charged particle crosses a radiator path \( \Delta L \), depends on its charge \( Z \)

\[ N \propto Z^2 \Delta L \left( 1 - \frac{1}{\beta^2 n^2} \right) \]

Their detection on the PMT matrix close to the expected pattern depends on:

- radiator interactions (\( \varepsilon_{\text{rad}} \)):
  - absorption and scattering
- photon ring acceptance (\( \varepsilon_{\text{geo}} \)):
  - photons lost through the radiator lateral and inner walls
  - mirror reflectivity
  - photons falling into the non-active area
- light guide losses (\( \varepsilon_{\text{lg}} \))
- PMT quantum efficiency (\( \varepsilon_{\text{pmt}} \))

\[ N_{\text{pe}} \propto Z^2 \Delta L \left( 1 - \frac{1}{\beta^2 n^2} \right) \varepsilon_{\text{rad}} \varepsilon_{\text{geo}} \varepsilon_{\text{lg}} \varepsilon_{\text{pmt}} \]

\( \varepsilon_{\text{tot}} \left( \theta, \theta', \phi, \phi', P \right) \)
RICH velocity measurement ($\beta$): a prototype (96 PMTs) was tested

Aerogel 1.05 3 cm $C = 0.0055 \, \mu m^4 cm^{-1} H = 33 \, cm$

\[
\left( \frac{A}{Z} \right)^2 + B^2 = 7.774 \times 10^4 \pm 5.079 \times 10^3
\]

\[
B = 7.275 \times 10^5 \pm 1.645 \times 10^5
\]

\[
\chi^2 = 2.76 \quad np = 22
\]

$\theta = 0^\circ$  $\beta \sim 1$

Z selected with scintillator

Lake Louise Winter Institute, 23rd February, 2005
The BESS experiment
Balloon-borne Experiment with Superconducting Spectrometer

Joint project of Japanese and USA Institutions to search for antimatter in the cosmic radiation
http://bess.kek.jp/
http://universe.gsfc.nasa.gov/astroparticles/programs/bess/
Last flight: 8 days from McMurdo (Antartica) in Dec 2004
BESS detector:

- Top and bottom Tof scintillators that also measure the particle energy loss
- Aerogel Cherenkov counter mounted under the top ToF
- 2 inner drift chambers (IDC) inside the magnetic field space
- Central tracking device in magnetic field region made of JET type drift chambers
Finally ..... CAPRICE 98!

- For the first time a GAS RICH together with a Silicon calorimeter.
- Mass resolved $\bar{p}$ for $E > 18$ GeV
- Redundancy and cross-measurements
In flight Performances

Spectrometer
In flight Performances

dE/dx \propto Z^2

vs p

Silicon calorimeter
In flight Performances

$\beta \text{ vs } 1/p \rightarrow \text{mass}$
In flight Performances

\[ \beta \text{ and } p \rightarrow \text{mass} \]
In flight Performances

GAS-RICH

![Graph showing particle distributions](image-url)
Exercise

Find a paper published by one of the described experiments or by another balloon experiment performing primary CR composition/anti-matter measurements and describe a measurement they perform and the detectors used for this purpose.