Experimental review of high-energy $e^- e^+$ and $p \bar{p}$ spectra

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Measurement of the singly charged component of the cosmic radiation at GeV–TeV energies.

What we measure and what we learn:
- ≈ 10 talks about it in this conference.

Experimental techniques and historical review.
- Bound to be incomplete and not exhaustive.

Prospects for the near future.
Introduction

- **Inclusive spectra:** $e^+ + e^-$ and $\bar{p} + p$
  - Electrons, unlike protons, loose energy rapidly by Synchrotron and Inverse Compton: at very high energy they probe the nearby sources.

- **Charge composition:** $e^+/(e^+ + e^-)$ and $\bar{p}/(\bar{p} + p)$ ratios.
  - $e^+$ and $\bar{p}$ are produced by the interactions of high-energy cosmic rays with the interstellar gas (secondary production).
  - There might be additional (possibly exotic) sources.

- **Different measurements provide complementary information on the origin, acceleration and propagation of cosmic rays.**
  - All the pieces of the puzzles must fit in a coherent interpretative (multi-messenger) framework.
A QUICK LOOK AT THE AVAILABLE DATA

† Data taken from the Cosmic Ray Database maintained by A. Strong and I. Moskalenko

see http://www.mpe.mpg.de/~aws/propagate.html
Experimental techniques and detectors

Imaging calorimeters
- Cannot distinguish the charge sign (inclusive spectra).
- Background rejection mainly relying on the different topologies of electromagnetic and hadronic showers.
- Typically feature larger acceptance and energy reach (measurement of the inclusive electron spectrum at high energy).

Magnetic spectrometers
- Can distinguish the charge sign \((e^+/(e^+ + e^-))\) and \((\bar{p}/(\bar{p} + p))\) ratios).
- Excellent particle identification—typically include an electromagnetic calorimeter and a TRD or a Čerenkov detector.
- Acceptance and energy reach limited by the magnet’s dimensions and bending power (unless operating as an imaging calorimeter).

But that’s not the end of the story (more about this in a moment).
Basic formalism

- Geometric factor (or aperture, or etendue):

\[ G_f(E) = A(E) \cdot \Omega(E) \]

in most cases energy-dependent (effective \( G_f \)), i.e. when:
(i) the acceptance depends on energy (magnetic spectrometers);
(ii) selections are (explicitly or implicitly) energy dependent.

- Exposure factor (or exposure):

\[ E_f(E) = G_f(E) \cdot T_{obs} \]

effectively determining the number of counts through:

\[ N_{E \geq E_0} = \int_{E_0}^{\infty} \frac{dN(E)}{dE \, dt} E_f(E) \, dE \]
The formalism at work... 

The exposure factor determines the statistics. Imaging calorimeters (vs. spectrometers) feature larger $G_f$. Space (vs. balloon) experiments feature longer livetime.
The exposure factor determines the statistics.
The formalism at work...

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Active development for Long Duration and Ultra Long Duration flights ongoing (more than one order of magnitude improvement).
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Complete (multiple) circumpolar trajectories achieved.
Inclusive spectra: $e^+ + e^-$ and $\bar{p} + p$

- $p$ dominate the CR flux, energy measurement is more challenging than background rejection.

- $p$ is the critical source of background for the $e^+ + e^-$ measurement.

\[ \frac{e^+}{(e^+ + e^-)} \] and $\frac{\bar{p}}{\bar{p} + p}$ ratios

- Once the charge sign has been identified, the antiparticle competes with the particle of the same sign...

- ...i.e., $\bar{p}$ with $e$ and $e^+$ with $p$. 
CR measures and backgrounds

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- $e^+ / (e^+ + e^-)$ and $\bar{p} / (\bar{p} + p)$ ratios

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- i.e. $\bar{p}$ with $e$ and $e^+$ with $p$.

It is the opinion of the investigators that the $e^+$ observation is substantially more difficult than the $\bar{p}$ observation [...] For negatively charged particles one has to distinguish $\bar{p}$ from a 20 times higher flux of $e^-$ and from atmospheric mesons. In the case of $e^+$, however, one must separate the desired particles from protons, which have the same charge and a flux nearly 1000 times as great.

Positron fraction: the early days

<table>
<thead>
<tr>
<th>Year</th>
<th>Detector Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Buffington (1972–73) 4–50 GeV</td>
</tr>
<tr>
<td></td>
<td>Daugherty (1972–74) 20–800 MeV</td>
</tr>
<tr>
<td>1990</td>
<td>MASS (1989) 1.3–26 GeV</td>
</tr>
</tbody>
</table>

Detector concepts

- Magnetic spectrometer (charge sign and momentum).
- Čerenkov detector and shower detector (calorimeter) for background rejection.
- Scintillators (hardware trigger).
- Bremsstrahlung radiator, east-west asymmetry in the geomagnetic cutoff...
THE NATURE OF THE COSMIC-RAY ELECTRON SPECTRUM, AND
SUPERNova REMNANT CONTRIBUTIONS

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Physics Department, Space Physics Laboratory, University of Wisconsin–Madison
Received 1988 October 24; accepted 1988 December 29

ABSTRACT

We examine the observed cosmic-ray (CR) electron spectrum and positron fraction $e^+/\text{(e}^- + e^+\text{)}$ spectrum above 1 GeV, and find that a deconvolution of the total spectrum into three components is necessary because of the increase of $e^+/\text{(e}^- + e^+\text{)}$ above 5 GeV: (1) Secondary electrons $e^\pm$ from the interaction of the CR protons with the interstellar gas provide the total $e^+$ for energies less than 3 GeV, but for energies above 3 GeV these electrons cannot account for the observed positron flux; (2) Electrons $e^-$ generally thought to be primarily from supernova remnants (SNRs), probably via shock acceleration, dominate the total spectrum for more or less for the observed positron flux between 0.1 and 3 GeV.

At energies above $\sim 20$ GeV there is a deficit of primary electrons from SNR's, and other nearby sources must dominate. There are many suggested sources of electrons and positrons at high energy: Type I SN explosions (Colgate and Johnson 1960; Colgate 1983); pulsar magnetospheres (Gunn and Ostriker 1969; Arons 1983); dark matter annihilation (Rudaz and Stecker 1988). Most of the positrons are produced by pair production in these sources.
Positron fraction: the latter days

<table>
<thead>
<tr>
<th>Period</th>
<th>Experiment</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>HEAT (1994–95)</td>
<td>1–50 GeV</td>
</tr>
<tr>
<td>1993</td>
<td>TS93 (1993)</td>
<td>5–60 GeV</td>
</tr>
<tr>
<td>1994</td>
<td>CAPRICE94 (1994)</td>
<td>0.8–14 GeV</td>
</tr>
<tr>
<td>2006–??</td>
<td>PAMELA (2006–??)</td>
<td>1.5–100 GeV</td>
</tr>
</tbody>
</table>

**Detector concepts**

- **TOF** for the measurement of $\beta$ and charge magnitude.
- **TRD** for electron-hadron discrimination.
- **Modern calorimeters**: shower topology, energy measurement, energy-momentum matching.
**Antiproton Fraction**

- **Bogomolov (1972–77)**
  - 2–5 GeV

- **Golden (1979)**
  - 5.6–12.5 GeV

- **MASS91 (1991)**
  - 3.4–19 GeV

  - 150 MeV–4.2 GeV

- **CAPRICE94 (1994)**
  - 620 MeV–3.19 GeV

- **CAPRICE98 (1998)**
  - 3–49 GeV

  - 4–50 GeV

- **BESS-Polar (2004–2007)**
  - 100 MeV–4.2 GeV

- **PAMELA (2006–??)**
  - 1–100 GeV
Anomalous rise in the positron fraction above 10 GeV;
- antiproton fraction consistent with secondary production.
- Several different viable interpretations (> 200 papers over the last year): more data needed!
Emulsion chambers (1968–79)
30 GeV–1.5 TeV [8.2 r. l.]

Hartman (1977)
9–300 GeV [8 r. l.]

Tang (1980)
4–280 GeV [18.5 r. l.]

PPB-BETS (2004)
10 GeV–1 TeV [9 r. l.]

1970
Meegan (1969–73)
6–100 GeV [33.7 r. l.]

1980

2000
BETS (1997–98)
10–100 GeV [7.3 r. l.]

Detector concepts
- Imaging calorimeters (energy measurement and background rejection).
- Many different implementations explored.
**All electron inclusive spectrum**

**ATIC (Advanced Thin Ionization Calorimeter)**
- Si matrix + C target + BGO calorimeter.
- Primary goal: CR hadronic component.

**H.E.S.S. (High Energy Stereoscopic System)**
- Array of Čerenkov telescopes.
- Primary goal: study of VHE $\gamma$-ray sources.

**Fermi LAT (Large Area Telescope)**
- Pair conversion telescope (Si tracker + CsI calorimeter + ACD).
- Primary goal: survey of the HE $\gamma$-ray sky.

- All electrons inclusive spectra published by the three experiments in 2008–09.
- None of the experiments specifically designed to detect electrons.
All electron inclusive spectrum

F. Aharonian et al., arXiv:0905.0105v1

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Future and perspectives I

**AMS-02 (Alpha Magnetic Spectrometer)**

- Three years on the ISS, starting in 2010.
- Positron fraction up to 300 GeV, antiproton fraction up to 450 GeV, all electrons up to 1.5 TeV.
- Silicon tracker and superconducting magnet; background rejection achieved with a combination of ToF, TRD, RICH and ECAL.
- Precursor flight (AMS-01) in 1998.

**PEBS (Positron Electron Balloon Spectrometer)**

- Positron fraction (and all electrons) up to 2 TeV.
- Scintillating fiber tracker with SiPM readout and superconducting magnet; ToF, TRD and ECAL for background rejection.
- PEBS-1 (with a permanent magnet, $e^+$ fraction up to 20 GeV) planned from 2012.
Future and perspectives—II

**CALET (CALorimetric Electron Telescope)**

- Three years on the ISS, starting in ≈ 2013.
- All electrons up to 20 TeV.
- ACD, double layer Si array, IMaging Calorimeter (IMC), Total Absorption Calorimeter (TASC).
- CALET-Polar to be flown on a LDBF in ≈ 2010 (3 technical flights before that).

**ECAL (Electron CALorimeter)**

- Two Long Duration Balloon Flights from Antarctica.
- All electrons up to a few TeV.
- Double-layer Si matrix, Scintillating Optical Fiber Track Imager (SOFTI), BGO calorimeter, neutron detector.
- Based on the ATIC heritage.
Future and perspectives—III

CREST (Cosmic Ray Electron Synchrotron Telescope)

- Two Antarctic LDBFs planned for 2010-2012.
- All electrons from 2 TeV to 50 TeV.
- Detect synchrotron radiation of primary electron as it passes through Earth’s magnetic field: 1024 BaF$_2$ crystal with hermetic ACD.
- Signal: line of photons arriving nearly simultaneously (mean energy 10 keV–5 MeV, related to the primary electron energy).

CTA, AGIS

- Planning for the next-generation ground-based gamma-ray observatories started.
- Efforts currently ongoing in the U.S., Europe, and Japan may unify into a world-wide collaboration.
- Sensitivity improved by one order of magnitude.
- All electrons up to $\approx 10$ TeV.
Conclusions

- Long (at least four decades old) and fascinating story.
  - Many many experiments, huge body of knowledge obtained.
- Last two years have been particularly exciting:
  - Data of unprecedented quality and energy reach published by Pamela, ATIC, Fermi, H.E.S.S.
  - We can expect more from Pamela (positron and antiproton fraction, all electrons) and Fermi (anisotropies in the arrival directions).
- More exciting years to come:
  - Many experiments (in space, on balloons and on the ground) planned for the near future.