Properties of Cosmic Rays $E < 10^{14}$ eV

most important properties:

1) energy spectra are power laws

\[ \frac{dN}{dE} \propto E^{-\gamma} \quad \gamma \approx 2.7 \]

\[ \Rightarrow \text{non-thermal origin} \]

\[ \left( \frac{dN}{dE} \sim e^{-\alpha E} \right) \]

2) below $\sim 1$ GeV/n energy spectra deviate

\[ \text{from power laws} \]
Cosmic-ray energy spectra

Figure 2-7.— Distribution of energies of galactic cosmic rays. This is a graph of the more abundant nuclear species in cosmic rays as measured near the Earth. Below a few GeV/nucleon these spectra are strongly influenced by the Sun. The different curves for the same species represent measurement extremes resulting from varying solar activity. (Taken from Physics Today, Oct. 1974, p. 25.)
Fig. 5: Daily variation in normalized flux. We have observed a gradual decrease in flux in the lower rigid region ($R < \sim 10$ GV) as well as some spikes in the ∼1 GV range which correspond to solar events on 9 August 2011 (X6.9), 27 January 2012 (X1.7), 7 March 2013 (X5.4), and 17 May 2012 (M5.1).

Fig. 6: The average proton flux over the two years of AMS-02 observation as a function of kinetic energy ($E$) multiplied by $E^{2.7}$ together with the previous experimental data [17]–[34].
Helium

\[ \text{He Flux} \left( \text{m}^2 \text{sr sec sec GV}^{-1} \times R^{2.7} \right) \]

Rigidity (GV)

AMS-02(2011-2013)
PAMELA(2006-2008)
CREAM-I(2004-2005)
ATIC-02(2003)
BESS-Tev(2002)
BESS-98(1998)
AMS-01(1998)
CAPRICE(1998)
IMAX(1992)
Baloon(1991)
MASS-91(1991)
Figure 1 | Daily-averaged intensities and streaming of energetic termination shock particles that are accelerated at nearby regions of the shock. Voyager 1 and Voyager 2 crossed the shock and entered the heliosheath on 2004.96 (16 December 2004) at heliographic coordinates of (34.3°, 173°) and on 2007.66 (30 August 2007) at (−27.5°, 216°), respectively. Insets, telescope (A, B and C) viewing directions projected into the R–T plane, where −R is towards the Sun and T is azimuthal. Error bars on black filled circles, ±1s.d.
Solar modulation of the galactic cosmic ray spectra since the Mauner minimum

G. Bonino1, G. Cini Castagnoli1, D. Cane1, C. Taricco1, and N. Bhandari2

1Dipartimento di Fisica Generale, Universitá di Torino and Istituto di Cosmogeofisica, CNR, To rino, Italy
2Physical Research Laboratory, Ahmedabad, India

Fig. 1. Differential cosmic-ray spectra obtained from Eq. (1) for different values of the solar modulation parameter $M = 390, 600, 820, 1080$ MeV corresponding to the measurements performed with balloons or spacecrafts during 1965, 1968, 1980 and 1989 respectively.

Fig. 2. Proton flux $J_p$: a) for the kinetic energy intervals $\Delta T = 100-200$ MeV, 200-400 MeV, 400-800 MeV; b) for $\Delta T = 800-1600$ MeV, 1600-3200 MeV, 3200-6400 MeV, 6400-12800 MeV, 12800-25600 MeV.
Carbon 14 method

formation of $^{14}$C

$^{14}$N + $^1$n $\rightarrow$ $^{14}$C + $^1$p

decay of $^{14}$C

half life time 5730 years

$^{14}$C $\rightarrow$ $^{14}$N + e$^-$
Carbon 14 method

**Formation of $^{14}$C**

$^{14}$N + $^1n$ → $^{14}$C + $^1p$

**Decay of $^{14}$C**

Half life time 5730 years

$^{14}$C → $^{14}$N + e$^-$

Cosmic rays enter the earth's atmosphere and collide with an atom, creating an energetic neutron.

When the neutron collides with a nitrogen atom, a nitrogen-14 (seven protons, seven neutrons) atom turns into a carbon-14 atom.

Plants absorb and incorporate carbon from the atmosphere.

Following death and burial, wood and bones lose C-14 as it changes to N-14 by beta decay.

Gehalt an C-14 nach
0 Jahren: 100%

$^{14}$C → $^{14}$N + e$^-$
Solar flares
**BESS-Polar: Search for antihelium**

### Preliminary

<table>
<thead>
<tr>
<th>Antihelium/helium flux ratio</th>
<th>Rigidity (GV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-3}$</td>
<td>1</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>10</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>100</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>1000</td>
</tr>
<tr>
<td>$10^{-7}$</td>
<td>10000</td>
</tr>
<tr>
<td>$10^{-8}$</td>
<td>100000</td>
</tr>
</tbody>
</table>

**He/He Limit (95% C.L.)**

- Badhwar et al. (1970)
- BESS-TeV
- Golden et al. (1997)
- Buffington et al. (1981)

- [BESS '95] J. F. Ormes et al. (1997)
- [BESS '93 '94 '95] T. Saeki et al. (1998)

- [BESS '93 - '00] M. Sasaki et al. (2002)

- BESS-Polar I
- BESS-Polar II

**ALL BESS Results**

| X 1/100 |

**Search Result**

- Particle Identification using TOF information

- No antihelium candidate was found between -14 and -1 GV after all selection among $4 \times 10^7$ helium events.

- The figure below shows remaining events after all selections applied.

**Limit and Summary**

- BESS-Polar I antihelium upper limit: $4.4 \times 10^{-7}$
- WE set the upper limit of $9.4 \times 10^{-8}$ by using the BESS-Polar II flight data.
- We set the upper limit of $6.9 \times 10^{-8}$ by using all BESS flight data.

- This limit is two orders of magnitude improvement since our first report.
Search for cosmic-ray antideuterons with BESS-Polar

Apply the same selection as deuteron selection.

Box has not be fully opened except the BG-free region yet....

NO Antideuteron was found in rigidity below 2.5 GeV/c.

(K.E. ~ 0.62 GeV/nucleon)
TRACER: Energy spectra for individual elements

P. Boyle et al., ICRC 2011

where $E$ is the energy-per-nucleon (including rest mass energy) and $\alpha \equiv \gamma + 1 = 2.7$ is the differential spectral index of the cosmic ray flux and $\gamma$ is the integral spectral index. About 79% of the primary nucleons are free protons and about 70% of the rest are nucleons bound in helium nuclei. The fractions of the primary nuclei are nearly constant over this energy range (possibly with small but interesting variations). Fractions of both primary and secondary incident nuclei are listed in Table 24.1. Figure 24.1 shows the major components for energies greater than 2 GeV/nucleon.

**Figure 24.1:** Major components of the primary cosmic radiation from Refs. [1–12]. The figure was created by P. Boyle and D. Muller. Color version at end of book.
\( \rightarrow \) Solar modulation of cosmic rays
charged particles of extra solar origin
(galactic origin) drift against solar
wind towards Earth.

3) In first approximation all elements
exhibit about the same slope
spectral index \( \sigma \approx 2.7 \)
\( \propto E^{-\sigma} \)
magnetic rigidity
\[
R = \frac{p \cdot c}{e \cdot E}
\]
e⁻ only
$e^- \& e^+$

Graph showing the relationship between $E^3 \times d(e^+e^-)/dE$ in $m^2 \cdot s^{-1} \cdot sr^{-1} \cdot GeV^2$ and energy in GeV. The graph includes data points from various experiments such as HEAT, Emulsion chambers, AMS-01, PPB-BETS, H.E.S.S. low energy, H.E.S.S. high energy, ATIC, Fermi-LAT low energy, Fermi-LAT high energy, Pamela e-, and MAGIC.
4) electrons: ∼1% of nuclear cosmic rays
   energy spectrum is steeper \( \frac{dN_e}{dE_e} \approx E_e^{-3.3} \)
   reason: losses through synchrotron radiation at high energies

\[
\begin{align*}
\text{\( \frac{dN_e}{dE_e} \approx E_e^{-3.3} \)}
\end{align*}
\]

5) energy density of cosmic rays
   in keV-scale all-particle energy spectrum
   diff. flux \( \frac{d\Gamma}{dE} \left( \frac{\Lambda}{m^2 \cdot s \cdot sr \cdot 1\text{MeV}} \right) \)
\[ I_{CR} = \int dS dE \frac{dI}{dE} \left[ \frac{A}{m^2 \cdot s} \right] \]

*all particle flux*

\[ \nu_{CR} = I_{CR} \cdot \langle E_{CR} \rangle \left[ \frac{eV}{m^2 \cdot s} \right] \]

\[ \varepsilon_{CR} = I_{CR} \frac{\langle E_{CR} \rangle}{\nu_{CR}} \left[ \frac{eV}{cm^3} \right] \]

\[ \approx 1 \frac{eV}{cm^3} \text{ energy density of CRs} \]

comparable with e.g. energy density

of visible star light \[ \varepsilon_{\text{st}} \approx 0.3 \frac{eV}{cm^3} \]

energy density of B-field in galaxy
Relative abundance of elements at Earth

\[ \text{Si} = 100 \]

\( \sim 1 \) GeV/n

\( \text{Si} = 100 \)

\( \rightarrow \) Cosmic rays are „regular matter“, accelerated to extremely high energies

Origin of the Elements

- big bang
- cosmology
- stellar burning
- fusion
- supernova explosions

Relative abundance of elements (Si=100)

Nuclear charge number Z
elemental composition of CRs

\[ \sim 89\% \, P \]

\[ 9\% \, \text{He} \]

\[ 1\% \, \text{heavy nuclei} \]

\[ 1\% \, e^- \]

\[ \leq 0.1\% \, \sigma \]
some remarks

1) even-odd effect
   $\rightarrow$ due to the high binding energy of $ee$-nuclei

2) elements Li, Be, B are more abundant in CRs than in solar system
   $\rightarrow$ propagation in Galaxy

3) same effect for sub-Fe elements ($\sim$ Ca-Fe)

4) \( ^p \) He less abundant in CRs as compared to Sol. syst.
Propagation of Cosmic Rays in the Interstellar Medium (ISM)

Objective: quantitative understanding
start with qualitative picture
\[ \text{ISM in galactic disc} \sim 1 \text{H atom/cm}^3 \]
\[ B \sim 3 \mu G \implies E_B = \frac{B^2}{2 \mu_0} \sim 0.2 \text{ eV/cm}^3 \]

What happens during propagation?

E.g. C nucleus

\[ ^{12}\text{C} \xrightarrow{\text{Li, Be, B}} \rightarrow \text{p, n, }... \]

\( p \) of the ISM

Such nuclear interactions are called spallation reactions.

\( \text{Li, Be, B} \) are rare elements in solar system.

\( \text{(primordial nucleosynthesis)} \)

The production during CR-propagation is significant, they are produced from abundant nuclei: C, N, O.