Origin and evolution of light elements

Light elements have fragile nuclei, they break up in thermonuclear reactions. High abundance of Li, Be, B in galactic cosmic rays.

CRs are accelerated in strong shock fronts of SNR and propagate in diffusive process through the galaxy close to the Sun: solar modulation.
Table 9.1. *Destruction of light nuclei in stellar interiors*

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>Process</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^2$D</td>
<td>$(p, \gamma)$ $^3$He</td>
<td>$T &gt; 0.5 \times 10^6$ K</td>
</tr>
<tr>
<td>$^6$Li</td>
<td>$(p, \alpha)$ $^3$He</td>
<td>$T &gt; 2 \times 10^6$ K</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>$(p, \alpha)$ $^4$He</td>
<td>$T &gt; 2.5 \times 10^6$ K</td>
</tr>
<tr>
<td>$^9$Be</td>
<td>$(p, \alpha)$ $^6$Li; $(p, D)$ $^8$Be $\rightarrow$ $^4$He</td>
<td>$T &gt; 3.5 \times 10^6$ K</td>
</tr>
<tr>
<td>$^{10}$B</td>
<td>$(p, \alpha)$ $^7$Be ($EC$) $^7$Li</td>
<td>$T &gt; 5.3 \times 10^6$ K</td>
</tr>
<tr>
<td>$^{11}$B</td>
<td>$(p, \alpha)$ $^8$Be $\rightarrow$ $^4$He</td>
<td>$T &gt; 5 \times 10^6$ K</td>
</tr>
<tr>
<td>$^3$He</td>
<td>$(^3$He, $\alpha)$ $^4$He + $^2$H</td>
<td>$T &gt; \sim 10^7$ K</td>
</tr>
</tbody>
</table>
Relative abundance of elements at Earth

cosmic rays - solar system

~ 1 GeV/n

Si = 100

Fig. 9.2. Schematic view of the life history of a cosmic ray from acceleration in the source through propagation in the Galaxy to observation above the Earth's atmosphere. Adapted from Rolfs and Rodney (1988).
Energy spectra of main elements in cosmic rays

The abundances of elements heavier than iron are measured with TIGER.

A new space-based experiment has been launched in June and first data have been published. Main components are a magnet spectrometer, a time-of-flight system, an electromagnetic calorimeter, and a neutron detector.

Measurements indicate that propagation in the Galaxy is energy dependent with the mean path length \( \lambda \) traversed decreasing with increasing energy. The energy \( E \) is the energy and \( z \) the charge of the particle. Current data up to about GeV energy indicate a fall-off in energy with an exponent of 4.

Attention should be paid to not confuse secondary cosmic rays, produced during the propagation process in the Galaxy, with secondary particles, produced in showers inside the atmosphere.
Fig. 9.3. Proton and $\alpha$-particle spectra of primary cosmic rays and their demodulated versions. After Goldstein et al. (1970). Courtesy Reuven Ramaty.
transport equation of cosmic rays through galaxy

"radioactive decays" from $^9\text{Be}$ decay

CRS mean $\sim 10^{-6}$ a through the galaxy

spallation of CNO elements $\rightarrow$ Li, Be, B

$\rightarrow$ path length of CRS in galaxy

B/C ratio decreases with energy

$\rightarrow$ path length decreases with energy

$\rightarrow$ Leaky Box model $\Delta_{\text{esc}}(E) = C \cdot E^{-\delta} + \Delta_0$

path length decreases from $\sim 10$ g/cm$^2$ at 1MeV to a few g/cm$^2$ at $10^3$ GeV/amu
Transport equation for cosmic rays in the Galaxy

\[
\frac{\partial N_i}{\partial t} = \nabla (D_i \nabla N_i) - \frac{\partial}{\partial E} (b_i N_i) - n \nu \sigma_i N_i - \frac{N_i}{\gamma \tau_i} + Q_i + \sum_{j > i} n \nu \sigma_{ij} N_j + \sum_{j > i} \frac{N_j}{\gamma_j \tau_{ij}}
\]

diffusion

energy loss (Bethe Bloch)

loss through interactions with ISM (spallation)

loss through radioactive decay

source term

production through spallation of heavy nuclei

production through decay of heavy nuclei
"Age" of galactic cosmic rays

The age of the galactic cosmic rays derived from the abundance of $^{10}\text{Be}^*$

M. Garcia-Munoz, G. M. Mason, and J. A. Simpson†

Enrico Fermi Institute, University of Chicago

Received 1977 March 14; accepted 1977 April 21

Residence time in Galaxy

$^{10}\text{Be} \rightarrow ^{10}\text{B} + e^- \quad (\tau = 2.4 \times 10^6 \text{ a})$

$\tau = 17 \times 10^6 \text{ a}$
Composition of Cosmic-Ray Nuclei at High Energies*

Einar Juliusson, Peter Meyer, and Dietrich Müller

Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637
(Received 26 May 1972)

We have measured the charge composition of cosmic-ray nuclei from Li to Fe with energies up to about 100 GeV/nucleon. A balloon-borne counter telescope with gas Cherenkov counters for energy determination was used for this experiment. Our first results show that, in contrast to low-energy observations, the relative abundances change as a function of energy. We find that the ratio of the galactic secondary nuclei to primary-source nuclei decreases at energies above about 30 GeV/nucleon.

spallation

\[ C \rightarrow B + n + p \]

\[ \lambda(E) \propto E^{-0.6} \]

The spallation processes during the cosmic-ray propagation have a decisive influence on the shape of the spectrum. This stems partly from the energy dependence of the spallation cross sections and partly from the fact that the spallation produces a large number of stable nuclides which remain in the Galaxy. During the propagation also radioactive secondary nuclei may be produced (fifth term in the all-particle spectrum to explain the second knee). For protons the escape path length of the particles in the Galaxy has been determined to be \( \lambda_{esc} = (4.0 \pm 0.5) \times 10^{6} \) g/cm\(^2\). For iron nuclei the corresponding value for protons is \( \lambda_{esc} = (0.13 \pm 0.02) \times 10^{6} \) g/cm\(^2\), which is 3.07 times smaller than the value for protons. Indeed, direct measurements of the TRACER experiment yield an upper limit for the constant term of \( 0.15 \times 10^{6} \) g/cm\(^2\).

Relative abundance of elements (Si=100)

\[ \text{primary/secondary-ratio} \]

\[ \lambda = 10 \text{ g/cm}^2 \]

\[ \lambda = 5 \text{ g/cm}^2 \]

\[ (\text{Sc+V})/\text{Fe} \]

\[ B/C \]

\[ \text{Energy [MeV/n]} \]

Fig. 9.4. Reaction cross-sections, as a function of energy per nucleon, for the production of light elements for some typical cases. Adapted from Read and Viola (1984). Courtesy Vic Viola.
Transition Radiation Array for Cosmic Energetic Rays

- **Charge**
- **$dE/dx$**
- **TR**

**Geometric factor:** $5 \text{ m}^2 \text{ sr}$

**1600 proportional tubes total**
TRACER - Mc Murdo, Antarctica, 2003
Cosmic-ray propagation

**B/C ratio**

![Graph of B/C ratio against kinetic energy (GeV/amu)]

- **Leaky-Box Fit**
- **GALPROP**
- $\Lambda \propto E^{1/2}$

**Path length**

![Graph of escape pathlength against kinetic energy (GeV/amu)]

- **Leaky-Box Fit**
- **GALPROP**
- $\Lambda \propto E^{0.6}$

A. Obermeier et al., ICRC (2011)  
Light element production

Two processes: CR's + ISM

- Fusion reactions
  \[ \alpha + \alpha \rightarrow ^{6}\text{Li} + p + n \]
  \[ ^{7}\text{Li} + p \]
  \[ ^{7}\text{Be} (E_c) ^{7}\text{Li} + n \]

- Spallation reactions
  \[ ^{12}\text{C}, ^{16}\text{O} + p, \alpha \rightarrow ^{6}, ^{7}\text{Li}, ^{9}\text{Be}, ^{10}, ^{11}\text{B} \]

Constant production rate

\[
\frac{dN_{Li}}{dt} = N_{\text{CNO}} \int \frac{\bar{\sigma}_{\text{CNO}} (E)}{E} \phi (E) \, dE
\]

\[ \sim N_{\text{CNO}} < \bar{\sigma} > \phi \]
abundance relative to H

\frac{L}{H} = \frac{C_{\nu 0}}{H} <\bar{\sigma}> \phi P T = 4.10^{-12} \left( \frac{I}{10 \text{Gy} \text{y}^{-1}} \right) \langle \bar{\sigma} \rangle \nu

T age of the Galaxy

\sigma(E) \approx \text{const, for relevant } E
GALACTIC CHEMICAL EVOLUTION OF LIGHT ELEMENTS

Using instantaneous recycling approximation

\[
\frac{d}{ds} (g_z) = g + \beta R Z - \frac{N_{\text{cusp}} \phi A_{\text{H}} t}{2 \mu F - t_z} \psi
\]

\(0 \leq \beta \leq 1\) allows for oxidation

\(\beta = 0\) for complete destruction

A mass number of light element

\(\alpha - \alpha\) fusion reactions have been neglected

If \(SF = R\) is assumed proportional to mass of gas

\[
\frac{ds}{dt} = \omega g \quad \omega = \text{const.}
\]
\[ \rightarrow \text{abundance of primary element increases linearly with time} \]
\[ z = wt \]

or, general \[ z(t) = \int_0^t w(t') \, dt' = u \]

(1) with \( u \)

\[ \frac{d}{dt} (g z) = g \left( p + \frac{A}{\Delta C_{NO}} \circ \right) 2C_{NO} \frac{\phi}{w} - \frac{z}{\Delta} \right) + \frac{t_E F - t_E G}{w} \]

p yield from stellar production \[ \chi = \frac{\lambda}{1 - \beta (1 - \lambda)} \rightarrow \chi \text{ for complete destruction} \]

\[ \rightarrow 1 \text{ for no destruction} \]
pure CR spallation products $^6\mathrm{Li}$, $\mathrm{Be}$, $\beta$

(2) becomes

$$\frac{d}{du} (g_t + \frac{F}{2}) = \frac{\Phi}{A\omega_0} g_t \epsilon_\nu \sigma \frac{\phi}{\omega} + \frac{\epsilon F - \epsilon_\nu \ell}{\omega}$$

$\phi$ proportional to SN rate $\propto$ SFR $\psi$

$$\frac{\phi/\omega}{(\phi/\omega)_n} = \frac{g}{g_0}$$

$\lambda$ refers to the present epoch

simple model $E = F = 0 \quad g = e^{-u}$

$$\frac{dt}{du} + (\lambda' - 1) t = \frac{\Phi}{A\omega_0} \epsilon_\nu \rho C_{\nu 0} \frac{\phi_1}{\omega_1} u e^{-(u-u_{\nu})}$$

$$= k (\frac{\sigma \phi}{\omega}) u e^{u_{\nu} - u}$$
\[ t = k \left( \frac{\sigma \phi}{\omega} \right) \phi e^{-u} \frac{e^{-u} (e^{-u} - (\alpha u')^1)}{(2 - \frac{1}{\alpha^1})^2} \]

with \( u = \frac{\Pi}{\alpha^N_0} \phi \nu_0 \)

\[ u^1 = (2 - \frac{1}{\alpha^1}) u \approx \frac{u}{2} \text{ for } \alpha^1 = \frac{2}{3} \]

\[ \implies \text{limiting behaviour} \]

\[ t \propto \frac{1}{2} \frac{u^2}{e^{-(u-u^1)}} \quad \text{for } u \to 0 \]

\[ \propto \frac{e^{-u}}{(2 - \frac{1}{\alpha^1})^2} \quad \text{for } u \to \infty \]
Fig. 9.6. Beryllium abundance as a function of oxygen abundance, according to models (curves) and observations (open circles) by Gilmore et al. (1992). (α in the key is actually the quantity called α' in the text.) After Pagel (1994). With kind permission from Kluwer Academic Publishers.