Chemical evolution of antimatter domains in early Universe

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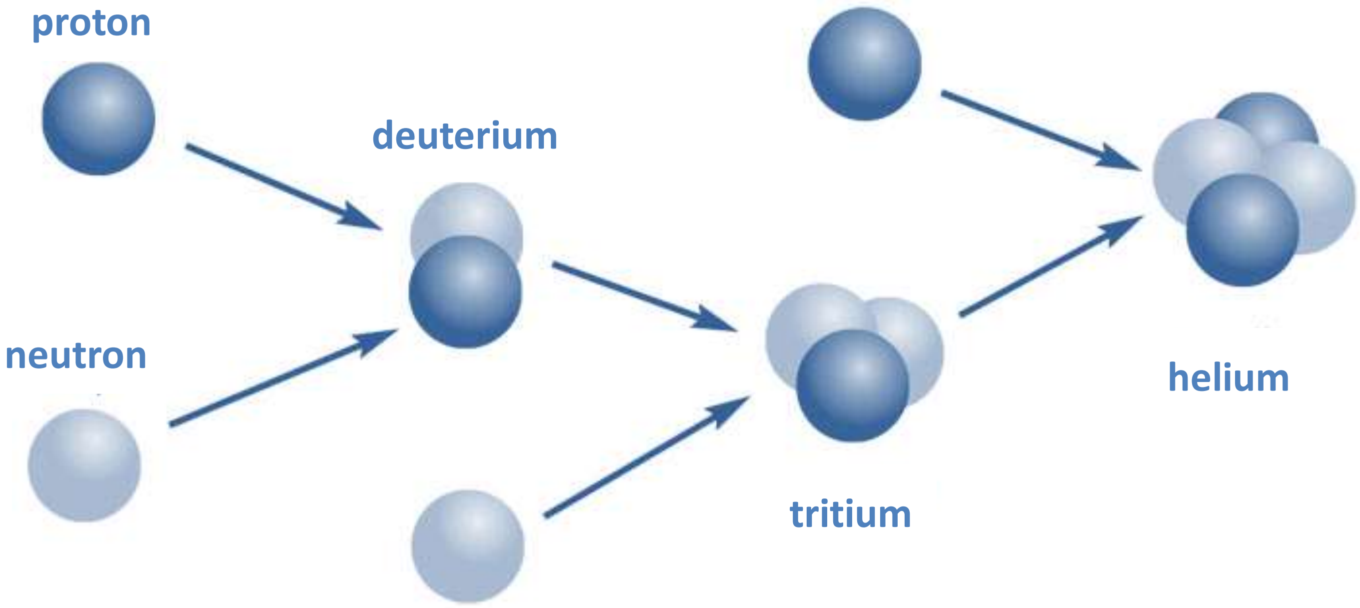
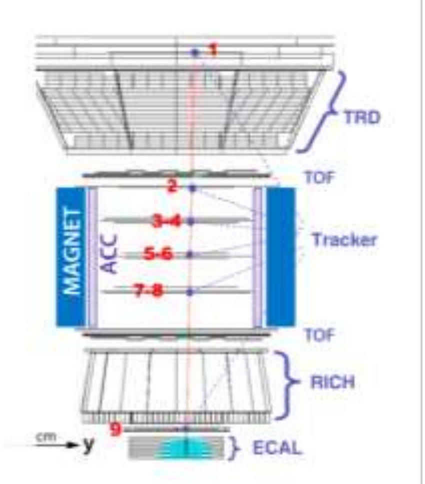
Baryo-asymmetric Universe

Nonhomogeneous baryosynthesis scenario describes the mechanisms of local formation of antimatter domains



AMS-02 experiment



- **Tracker planes 1-9** measure the particle charge, sign and momentum
- The **TRD** identifies the particle as an electron/positron
- The **TOF** measures the charge and ensures that the particle is downward-going
- The **RICH** measures the charge and velocity
- The **ECAL** independently identifies the particle and measures its energy

Main parameters

Mass limitation:

1.Mass of the domain must be large enough to survive to the modern era

2.Gamma background from annihilation at the boundaries to exchange should correspond to the observed one

Predicted range of masses of macroscopic antimatter regions:

$$10^3 M_\odot < M < 10^5 M_\odot$$

Baryon/photon ratio describes the number density of baryons, such as protons and neutrons, relative to the number density of photons in the universe

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          Yp              H2/H            He3/H           Li7/H
  low:    2.520e-01       1.066e-05       7.832e-06       1.223e-09
 cent:    2.519e-01       1.016e-05       7.963e-06       1.320e-09
 high:    2.518e-01       9.784e-06       8.078e-06       1.415e-09

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With uncertainties:
          Yp              H2/H            He3/H           Li7/H
value:    2.519e-01       1.016e-05       7.963e-06       1.320e-09
 +/- :    3.218e-04       3.682e-07       1.703e-07       8.863e-11

Correlation matrix:
          Yp              H2/H            He3/H           Li7/H
Yp        1.000000        -0.022184       0.027050        0.036160
H2/H      -0.022184       1.000000        -0.842199       -0.480025
He3/H     0.027050        -0.842199       1.000000        0.443496
Li7/H     0.036160        -0.480025       0.443496        1.000000
Li6/H     0.000876        0.032128        -0.027271       -0.015694
Be7/H     0.036232        -0.487401       0.447933        0.999869
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AlterBBN is a C program which computes the abundances of the elements predicted by Big-Bang nucleosynthesis (BBN)

Density of the domain

$$3 \times 10^{-12} \leq \eta \leq 1 \times 10^{-6}$$

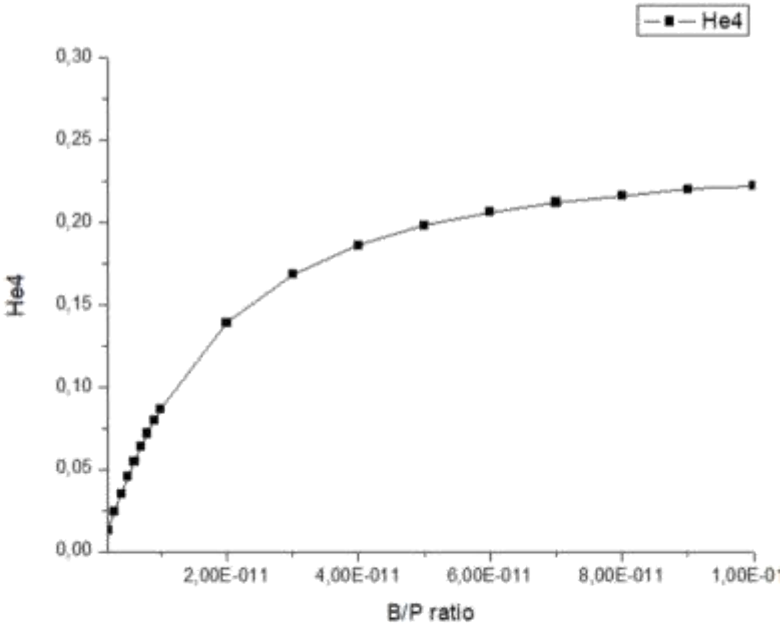


Figure 2. Dependence of the 4He's mass fraction on baryon/photon ratio

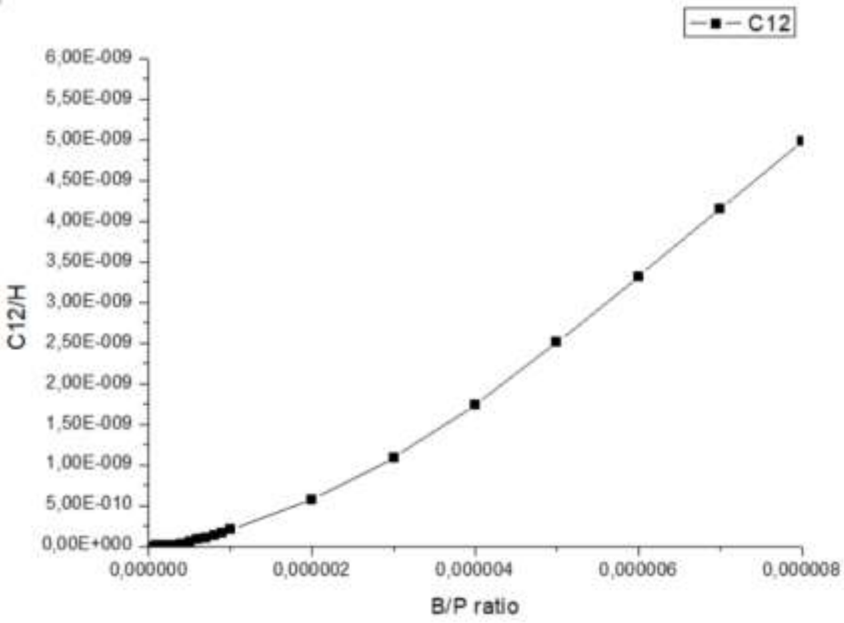


Figure 3. Dependence of the 12C's mass fraction on baryon/photon ratio

Size of the domain

Size of the domain:

$$\boxed{R = \left(\frac{\mathrm{N}}{\mathrm{n}}\right)^{\frac{1}{3}}}$$

- $\mathrm{N} = \frac{\mathrm{M}}{\mathrm{m_p}}$
- $\mathrm{n} = \eta \mathrm{n}_\gamma$
- $\mathrm{n}_\gamma \sim T^3$

Main formula:

$$\boxed{\mathrm{R} \sim \left(\frac{M}{m_p \eta T^3}\right)^{\frac{1}{3}}}$$

Parameters:

$$10^3 M\odot \leq M \leq 10^5 M\odot$$

$$3 \times 10^{-12} \leq \eta \leq 1 \times 10^{-6}$$

Processes at the border

Criterion of annihilation processes at the border of the domain:

$$\boxed{ct \geq R}$$

$$\boxed{t \geq \left(\frac{M}{c^3 m_p \eta 10^{30}} \right)^{\frac{2}{3}}}$$

According to the main parameters:

$$t_{min} = 1,25 \times 10^3 \text{c}$$

Products of annihilation will penetrate the domain

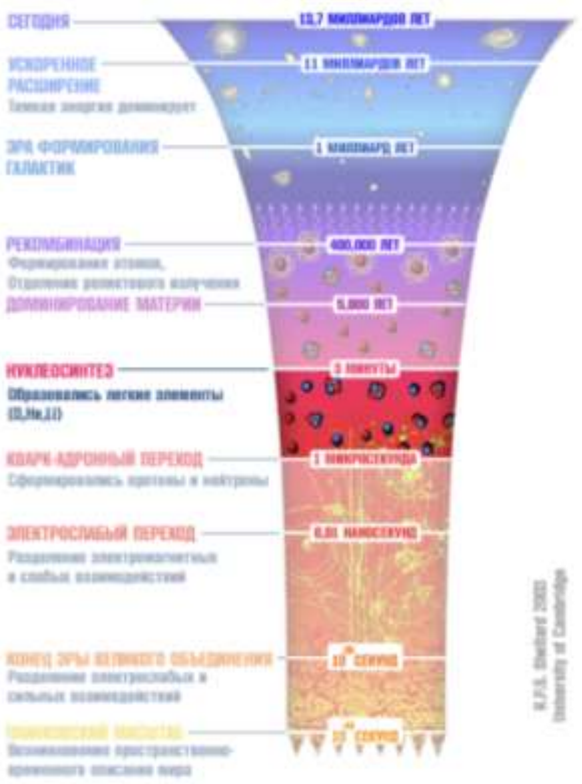


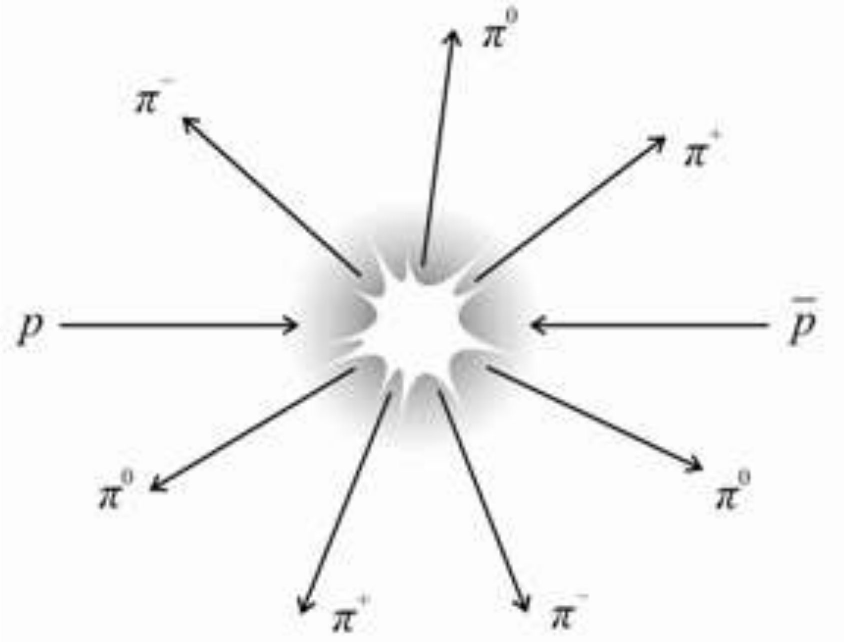
Figure 4. Eras of the Universe

Proton-antiproton annihilation

Main channels:

- Production of photons due to neutral pion decay

- Production of electrons and positrons due to charged pion decay involving muon production



Interaction between thermal and annihilation photon

High energy thermal photon distribution:

$$n_{\gamma\_high} \approx n_\gamma \left(\frac{E_{min}}{kT}\right)^2 e^{\frac{-E_{min}}{kT}}$$

Temperature range:

$$T = 2,83 \times 10^8 \div 10^7 \mathrm{K}$$

Possible result of the reaction: production of electron-positron pair

Breit–Wheeler formula:

$$\sigma_{pp} \approx \frac{2\pi\alpha^2}{s}\left[2\ln\frac{s}{m_e^2} - \frac{3}{2}\right] \approx 2,1 \times 10^{-28}\mathrm{cm}^2$$

Compton scattering

Temperature range:

$$T \leq 10^7 \mathrm{K}$$

Klein–Nishina formula:

$$\sigma = \sigma_T f(x),$$

$$f(x) = \frac{3}{8x}\left(\ln 2x + \frac{1}{2}\right)$$

$$\boxed{\sigma_k = 10^{-26} \mathrm{cm}^2}$$

Energy loss:

$$\boxed{E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - cos\theta)}}$$

Multiple scattering (>2500)

$$\sigma_{eff} = N < \sigma >$$

$$\sigma_{eff} \geq 8.4 \times 10^{-22}\ \mathrm{cm}^2$$

Charged pion decay

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$$

$$\pi^- \to \mu^- + \overline{\nu}_\mu$$
$$\mu^- \to e^- + \nu_\mu + \overline{\nu}_e$$

Energy distribution of the electrons emitted in muon decay:

$$\frac{d\Gamma}{dE} = \left(\frac{g_w}{M_W c}\right)^4 \frac{m_\mu^2 E^2}{2\hbar(4\pi)^3}\left(1 - \frac{4E}{3m_\mu c^2}\right)$$

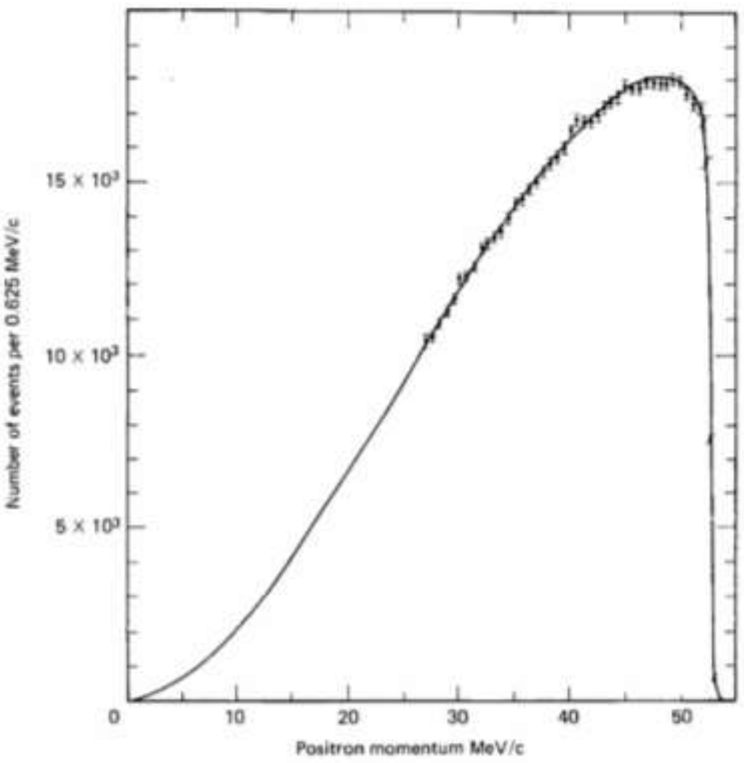


Figure 5. Experimental spectrum of positrons (Source: M. Bardon et al., Phys. Rev. Lett. 14, 449 (1965).)

Penetration depth of photons

$$T = 2,83 \times 10^8 \div 10^7 \mathrm{K}$$

Dominant process: pair production

$$\lambda_{pp} = \frac{1}{T^3 \sigma_{pp}}$$

$$\lambda = \frac{1}{n\sigma}$$

$$\sigma \approx \sigma_{pp}$$

$$2 \times 10^2 \mathrm{cm} \leq \lambda_{pp} \leq 5 \times 10^6 \mathrm{cm}$$

Comparison with the domain's size:

$$R_{min} \approx 10^{13} \mathrm{cm}$$
$$R_{max} \approx 10^{17} \mathrm{cm}$$

Penetration depth of photons is significantly less than domain radius

Penetration depth of photons

$$\boxed{T \leq 10^7 \mathrm{K}}$$

Dominant process: Compton scattering

$$\lambda = \frac{1}{n\sigma} \qquad n_p = \frac{\rho Z}{m_p}$$

$$\rho = n_\gamma \eta m_p = T^3 \eta m_p$$

$$\boxed{\lambda_k = \frac{1}{T^3 \eta Z \sigma_{eff}}}$$

$$\boxed{t < \frac{Z 10^{20} \sigma_{eff} \eta^{\frac{2}{3}} M^{\frac{1}{3}}}{m_p^{\frac{1}{3}}}}$$

Taking into account temperature restrictions:

$$\boxed{\begin{cases} t > 10^6 \mathrm{c} \\ t < \frac{Z 10^{20} \sigma_{eff} \eta^{\frac{2}{3}} M^{\frac{1}{3}}}{m_p^{\frac{1}{3}}} \approx \eta^{\frac{2}{3}} M^{\frac{1}{3}} \times 7 \times 10^6 \mathrm{c} \end{cases}}$$

Conclusion

-Size of the domain has been estimated

-Processes at the border of the antimatter domain were studied and described

-Penetration depth of photons inside the antimatter domain has been estimated

Perspectives:

More accurate and detailed description of processes at the border and inside the antimatter domain over time

Thank you for your attention!

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