ANTIMATTER IN THE LAB

Chloé Malbrunot
CERN
LECTURE # 1 (This lecture)
  - What is antimatter?
  - Some historical reminders
  - Discrete symmetries
  - Primordial antimatter search

LECTURE # 2
  - Antiprotons at colliders: discovery machines
  - Antiprotons at lower energies: cooling techniques
  - Antiproton trapping techniques

LECTURE # 3
  - Experiments at the AD: exotic atoms made of antimatter
  - Antihydrogen: a tool to study matter-antimatter asymmetry
  - Everyday’s application of antimatter
What is antimatter?

Quote from Angel & Demons (Dan Brown): “Antimatter creates no pollution or radiation... is highly unstable [and] ignites when it comes in contact with absolutely anything”
What is antimatter?

Quote from Angel & Demons (Dan Brown): “Antimatter creates no pollution or radiation ... is highly unstable [and] ignites when it comes in contact with absolutely anything”
What is antimatter?

Quote from Angel & Demons (Dan Brown): “Antimatter creates no pollution or radiation ... is highly unstable [and] ignites when it comes in contact with absolutely anything”
What is antimatter?

Quote from Angel & Demons (Dan Brown): “Antimatter creates no pollution or radiation ... is highly unstable [and] ignites when it comes in contact with absolutely anything”
What is antimatter?

- Quarks: up, charm, top, down, strange, bottom
- Leptons: electron, muon, tau, neutrino, neutrino, neutrino
- Quark colors: red, green, blue
- Lepton flavors: electron, muon, tau
- Neutrino flavors: $\nu_e$, $\nu_\mu$, $\nu_\tau$
What is antimatter?

E = mc²
What is antimatter?

$E = mc^2$
What is antimatter?

E = mc^2

YOU MATTER

Until you multiply yourself by the speed of light squared...

THEN YOU ENERGY
What is antimatter?

E = mc²

YOU MATTER

Until you multiply yourself by the speed of light squared...

THEN YOU ENERGY

and then you can ANTIMATTER!
Excerpt of the list containing the open questions in particle physics:

- Why is the Higgs boson so light (so-called “naturalness” or “hierarchy” problem) ?
- **What is the origin of the matter-antimatter asymmetry in the Universe ?**
- Why 3 fermion families ? Why do neutral leptons, charged leptons and quarks behave differently ?
- What is the origin of neutrino masses and oscillations ?
- What is the composition of dark matter (23% of the Universe) ?
- What is the cause of the Universe’s accelerated expansion (today: dark energy ? primordial: inflation ?)
- Why is Gravity so weak ?
- ...
Matter - Antimatter asymmetry

MATTER: 10 000 000 001

ANTIMATTER: 10 000 000 000
Matter - Antimatter asymmetry

- Afterglow Light Pattern 380,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion 13.7 billion years
1932: Discovery of the positron (Nobel Prize shared with V. Hess in 1936)

C. Anderson

In Cosmic Rays using a Cloud Chamber
Some Bits of History

1928: The Dirac equation (Nobel Prize in 1933)

\[ E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi \]

\[ E \rightarrow i\hbar \frac{\partial}{\partial t} \]

\[ p \rightarrow -i\hbar \nabla \]
1928: The Dirac equation (Nobel Prize in 1933)

\[ E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi \]

\[ E^2 = p^2 + m^2 \rightarrow -\hbar^2 \frac{\partial^2}{\partial t^2} \psi = -\hbar^2 \nabla^2 \psi + m^2 \psi \]

Interlude: playing with equations (best guesses ...)

Einstein:

\[ E = mc^2 \]

\[ E = p^2 + m^2 \rightarrow -\hbar^2 \frac{\partial^2}{\partial t^2} \psi = -\hbar^2 \nabla^2 \psi + m^2 \psi \]
Some Bits of History

1928: The Dirac equation (Nobel Prize in 1933)

\[ E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi \]

\[ E^2 = p^2 + m^2 \rightarrow -\hbar^2 \frac{\partial^2}{\partial t^2} \psi = -\hbar^2 \nabla^2 \psi + m^2 \psi \]

\[ H\psi = (\alpha \cdot \mathbf{P} + \beta m)\psi \]
1928: The Dirac equation (Nobel Prize in 1933)

\[ E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi \]

\[ E^2 = p^2 + m^2 \rightarrow -\hbar^2 \frac{\partial^2}{\partial t^2} \psi = -\hbar^2 \nabla^2 \psi + m^2 \psi \]

\[ H^2 \psi = (\alpha_i P_i + \beta m)(\alpha_j P_j + \beta m)\psi = (\alpha_i^2 P_i^2 + (\alpha_i \alpha_j + \alpha_j \alpha_i) P_i P_j + (\alpha_i \beta + \beta \alpha_i) P_i m + \beta^2 m^2)\psi \]

\[ H \psi = (\alpha \cdot P + \beta m)\psi \]

\[ H^2 \psi = (P^2 + m^2)\psi \]
1928: The Dirac equation (Nobel Prize in 1933)

\[ E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi \]

\[ E^2 = p^2 + m^2 \rightarrow -\hbar^2 \frac{\partial^2}{\partial t^2} \psi = -\hbar^2 \nabla^2 \psi + m^2 \psi \]

\[ H^2 \psi = (\alpha_i P_i + \beta m)(\alpha_j P_j + \beta m)\psi = (\alpha_i^2 P_i^2 + (\alpha_i \alpha_j + \alpha_j \alpha_i) P_i P_j + (\alpha_i \beta + \beta \alpha_i) P_i m + \beta^2 m^2)\psi \]

\[ H\psi = (\alpha \cdot P + \beta m)\psi \]

\[ H^2 \psi = (P^2 + m^2)\psi \]

\[ \gamma^0 = \begin{pmatrix} I_2 & 0 \\ 0 & -I_2 \end{pmatrix}, \quad \gamma^1 = \begin{pmatrix} 0 & \sigma_x \\ -\sigma_x & 0 \end{pmatrix} \]

\[ \gamma^2 = \begin{pmatrix} 0 & \sigma_y \\ -\sigma_y & 0 \end{pmatrix}, \quad \gamma^3 = \begin{pmatrix} 0 & \sigma_z \\ -\sigma_z & 0 \end{pmatrix} \]
Some Bits of History

1928: The Dirac equation (Nobel Prize in 1933)

\[ E = \frac{p^2}{2m} \rightarrow i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi \]

\[ E^2 = p^2 + m^2 \rightarrow -\hbar^2 \frac{\partial^2}{\partial t^2} \psi = -\hbar^2 \nabla^2 \psi + m^2 \psi \]

\[ H^2 \psi = (\alpha_i P_i + \beta m)(\alpha_j P_j + \beta m)\psi \]
\[ = (\alpha_i^2 P_i^2 + (\alpha_i \alpha_j + \alpha_j \alpha_i) P_i P_j + (\alpha_i \beta + \beta \alpha_i) P_i m + \beta^2 m^2)\psi \]
\[ = 1 \quad = 0 \quad = 0 \quad = 1 \]

\[ H \psi = (\alpha \cdot P + \beta m)\psi \]

\[ H^2 \psi = (P^2 + m^2)\psi \]

\[ \gamma^0 = \begin{pmatrix} I_2 & 0 \\ 0 & -I_2 \end{pmatrix}, \gamma^1 = \begin{pmatrix} 0 & \sigma_x \\ -\sigma_x & 0 \end{pmatrix}, \gamma^2 = \begin{pmatrix} 0 & \sigma_y \\ -\sigma_y & 0 \end{pmatrix}, \gamma^3 = \begin{pmatrix} 0 & \sigma_z \\ -\sigma_z & 0 \end{pmatrix} \]

\[ (i \gamma^\mu \partial_\mu - m)\psi = 0 \]
1955: Discovery of the antiproton (Nobel Prize to Chamberlain & Segré in 1959)

Discovery at the Bevatron

Identified 60 events

\( \Delta m/m \sim 5\% \)

Annihilation of an antiproton detected in a emulsion a year later:
first \( \bar{p} - N \) annihilation observed
35 events

\( \rightarrow \) proof of antimatter character

Discrimination against other negatively charged particles via momentum & velocity selection
Some Highlights on a Timeline

- 1932: Discovery of positron
- 1948: Discovery of positronium
- 1955: Discovery of antiproton
- 1956: Discovery of antineutron
- 1965: Discovery of antideuteron
- 1970: Discovery of anti-$^3$He
- 1978: Discovery of anti-tritium
- 1996: First creation of relativistic antihydrogen atoms
**Some Highlights on a Timeline**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1932</td>
<td>Discovery of positron</td>
</tr>
<tr>
<td>1948</td>
<td>Discovery of positronium</td>
</tr>
<tr>
<td>1955</td>
<td>Discovery of antiproton</td>
</tr>
<tr>
<td>1956</td>
<td>Discovery of antineutron</td>
</tr>
<tr>
<td>1964</td>
<td>Discovery of antideuteron</td>
</tr>
<tr>
<td>1970</td>
<td>Discovery of anti-$^3\text{He}$</td>
</tr>
<tr>
<td>1978</td>
<td>Discovery of anti-tritium</td>
</tr>
<tr>
<td>1996</td>
<td>First creation of relativistic antihydrogen atoms</td>
</tr>
</tbody>
</table>

*First measurement of a difference between matter & antimatter*
P : Parity transformation. Invert every spatial coordinates

\[ P(t, x) = P(t, -x) \]

Particles and antiparticles have opposite parity

1956 : Yang and Lee realized that parity invariance had never been tested experimentally for weak interactions

Wu’s experiment: recorded the direction of the emitted electron from a $^{60}\text{Co} \beta$-decay when the nuclear spin was aligned up and down

The electron was emitted in the same direction independently of the spin.

P symmetry is MAXIMALLY violated in weak decays
Discrete Symmetries

C : Charge Conjugaison. C reverses every internal additive quantum number (e.g. charge, baryon/lepton number, strangeness, etc.). Exchange of particle and antiparticle

\[ C |p\rangle = |\bar{p}\rangle \]

Limited use because few particles are C-eigenstates

C is conserved in strong and EM interactions

\[ C|n\gamma\rangle = (-1)^n |\gamma\rangle \]

\[ C = (-1)^{l+s} \]

\[ C|\pi^0\rangle = |\pi^0\rangle \]

\[ \pi^0 \rightarrow 2\gamma \] is allowed under CC

\[ \pi^0 \rightarrow 3\gamma \] is not allowed under CC

\[ < 3.1 \times 10^{-8} \]
Discrete Symmetries

C: Charge Conjugaison. C reverses every internal additive quantum number (e.g. charge, baryon/lepton number, strangeness, etc.). Exchange of particle and antiparticle

\[ C \mid p \rangle = \mid \bar{p} \rangle \]

Limited use because few particles are C-eigenstates

C is conserved in strong and EM interactions

\[ C \mid n\gamma \rangle = (-1)^n \mid \gamma \rangle \]

\[ C = (-1)^{l+s} \]

\[ C \mid \pi^0 \rangle = \mid \pi^0 \rangle \]

\[ \pi^0 \rightarrow 2\gamma \] is allowed under CC

\[ \pi^0 \rightarrow 3\gamma \] is not allowed under CC

\[ < 3.1 \times 10^{-8} \]
Discrete Symmetries

CP Violation in Neutral Kaons:

\[
\begin{align*}
K^0 & : \quad (d\bar{s}) \quad S = +1 \\
\bar{K}^0 & : \quad (s\bar{d}) \quad S = -1
\end{align*}
\]

Production through $\Delta S=0$

Decay through $\Delta S=+/-1$

Start with a pure $K^0$ beam

\[
|K(t)\rangle = \alpha(t)\, |K^0\rangle + \beta(t)\, |\bar{K}^0\rangle
\]
Discrete Symmetries

CP Violation in Neutral Kaons:

\[
\begin{align*}
K^0 : & \quad (d\bar{s}) \quad S = +1 \\
\bar{K}^0 : & \quad (s\bar{d}) \quad S = -1
\end{align*}
\]

Production through $\Delta S=0$

Decay through $\Delta S=\pm 1$

Start with a pure $K^0$ beam

\[
|K(t)\rangle = \alpha(t) |K^0\rangle + \beta(t) |\bar{K}^0\rangle
\]

CP Eigenstates:

\[
\begin{align*}
|K_S\rangle &= \frac{1}{\sqrt{2}} (|K^0\rangle + |\bar{K}^0\rangle) \quad CP = +1 \\
|K_L\rangle &= \frac{1}{\sqrt{2}} (|K^0\rangle - |\bar{K}^0\rangle) \quad CP = -1
\end{align*}
\]

\[
\begin{align*}
|K_S\rangle &\rightarrow 2\pi, \quad CP = +1, \quad \tau \sim 0.9 \times 10^{-10} \text{ s} \\
|K_L\rangle &\rightarrow 3\pi, \quad CP = -1, \quad \tau \sim 0.5 \times 10^{-7} \text{ s}
\end{align*}
\]
Discrete Symmetries

Measured quantity:

\[ |\eta_{+-}| = \frac{\text{amplitude}(K_L \rightarrow \pi^+\pi^-)}{\text{amplitude}(K_S \rightarrow \pi^+\pi^-)} \sim 2.3 \times 10^{-3} \]

Interferences
Discrete Symmetries

Measured quantity:

\[ |\eta^{+-}| = \frac{\text{amplitude}(K_L \rightarrow \pi^+\pi^-)}{\text{amplitude}(K_S \rightarrow \pi^+\pi^-)} \sim 2.3 \times 10^{-3} \]

Interferences

Leptonic mode:
Discrete Symmetries

Measured quantity:

\[ |\eta_{+-}| = \frac{\text{amplitude}(K_L \rightarrow \pi^+\pi^-)}{\text{amplitude}(K_S \rightarrow \pi^+\pi^-)} \sim 2.3 \times 10^{-3} \]

Leptonic mode:

- \( K_L \rightarrow e^+ + \nu_e + \pi^- \)
- \( K_L \rightarrow e^- + \bar{\nu}_e + \pi^+ \)

Interferences
Discrete Symmetries

Measured quantity:

\[ |\eta_{+-}| = \frac{\text{amplitude}(K_L \rightarrow \pi^+\pi^-)}{\text{amplitude}(K_S \rightarrow \pi^+\pi^-)} \sim 2.3 \times 10^{-3} \]

Leptonic mode:

\[ K_L \rightarrow e^+ + \nu_e + \pi^- \]
\[ K_L \rightarrow e^- + \bar{\nu}_e + \pi^+ \]

\[ \Delta = \frac{\text{rate}(K_L \rightarrow e^+ + \nu_e + \pi^-) - \text{rate}(K_L \rightarrow e^- + \bar{\nu}_e + \pi^+)}{\text{rate}(K_L \rightarrow e^+ + \nu_e + \pi^-) + \text{rate}(K_L \rightarrow e^- + \bar{\nu}_e + \pi^+)} \]
Discrete Symmetries

Measured quantity:

\[ \left| \eta_{+-} \right| = \frac{\text{amplitude}(K_L \to \pi^+\pi^-)}{\text{amplitude}(K_S \to \pi^+\pi^-)} \sim 2.3 \times 10^{-3} \]

Leptonic mode:

\[ K_L \to e^+ + \nu_e + \pi^- \]
\[ K_L \to e^- + \bar{\nu}_e + \pi^+ \]

\[ \Delta = \frac{\text{rate}(K_L \to e^+ + \nu_e + \pi^-) - \text{rate}(K_L \to e^- + \bar{\nu}_e + \pi^+)}{\text{rate}(K_L \to e^+ + \nu_e + \pi^-) + \text{rate}(K_L \to e^- + \bar{\nu}_e + \pi^+)} \]

Interferences

Discrimination criteria between matter and antimatter:
Measured quantity:

$$|\eta_{+-}| = \frac{\text{amplitude}(K_L \rightarrow \pi^+\pi^-)}{\text{amplitude}(K_S \rightarrow \pi^+\pi^-)} \sim 2.3 \times 10^{-3}$$

Leptonic mode:

$$K_L \rightarrow e^+ + \nu_e + \pi^-$$
$$K_L \rightarrow e^- + \bar{\nu}_e + \pi^+$$

Discrimination criteria between matter and antimatter:

$$\Delta = \frac{\text{rate}(K_L \rightarrow e^+ + \nu_e + \pi^-) - \text{rate}(K_L \rightarrow e^- + \bar{\nu}_e + \pi^+)}{\text{rate}(K_L \rightarrow e^+ + \nu_e + \pi^-) + \text{rate}(K_L \rightarrow e^- + \bar{\nu}_e + \pi^+)}$$

$$\Delta \sim 0.3 \times 10^{-2}$$
**Discrete Symmetries**

**T : Time Reversal**

\[ t = -t \]

---

**EDM :**

[Diagram of EDM process]

---

J. P. Lees et al. (The BABAR Collaboration)  
[arXiv:1207.5832 [hep-ex]]

B meson oscillations  
J. Bernabeu (Valencia)
### Discrete Symmetries

**Summary:**

<table>
<thead>
<tr>
<th></th>
<th>Strong</th>
<th>EM</th>
<th>Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strong</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>EM</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Weak</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P</th>
<th>yes</th>
<th>yes</th>
<th>no</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
</tbody>
</table>
| CP (or T)| yes | yes | ~$10^{-3}$
|         |     |     | 1964: K0 decay
|         |     |     | 2001: B decay (BELLE, BaBar)
|         |     |     | 2012: Direct T Violation
| CPT     |     |     |     |
## Discrete Symmetries

### Summary:

<table>
<thead>
<tr>
<th>Interactions</th>
<th>Strong</th>
<th>EM</th>
<th>Weak</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P</strong></td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td><strong>CP (or T)</strong></td>
<td>yes</td>
<td>yes</td>
<td>~10^-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1964 : K0 decay</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2001: B decay (BELLE, BaBar)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2012: Direct T Violation</td>
</tr>
<tr>
<td><strong>CPT</strong></td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Observation of C, P, T, CP violation, what about CPT?
In the SM, CPT is conserved. So, if T is violated, CP is violated & vice-versa

CPT Theorem:
A local, Lorenz invariant theory with canonical spin-statistics relation must be invariant with respect to CPT-transformation

Implication: properties of matter & antimatter particles should be the same

J. Schwinger, Phys. Rev. 82, 914 (1951);
G. Lüders, Ann. Phys. 2, 1 (1957);
W. Pauli, Nuovo Cimento, 6, 204 (1957);
R. Jost, Helv. Phys. Acta 30, 409 (1957);
# Tests of CPT Symmetry

<table>
<thead>
<tr>
<th>Component</th>
<th>Relative Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{H} , 1S/2S$</td>
<td>$10^{-21}$</td>
</tr>
<tr>
<td>$\bar{H} , GS$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>$\bar{H} , HFS$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>Positron $g$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>Muon $g$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Antiproton $q/m$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Antiproton $g$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Antideuteron $m/q$</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Antihelium $m/q$</td>
<td>$10^{-3}$</td>
</tr>
</tbody>
</table>

The measurements are categorized into:

- **Planned**
- **Recent**
- **Past**

These measurements are conducted at CERN (ALICE) and CERN (AD).
Tests of CPT Symmetry

Planned
Recent
Past

kaon $\Delta m$

$\bar{H}$ 1S/2S

$\bar{H}$ GS HFS

$10^{-21}$ $10^{-18}$ $10^{-15}$ $10^{-12}$ $10^{-9}$ $10^{-6}$ $10^{-3}$ $10^0$

relative precision

antideuteron m/q
antihelium m/q

CERN (ALICE)

CERN (AD)

Standard Model Extension

$$\left( i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu \right)$$

$$-\frac{1}{2} H^{e}_{\mu\nu} \sigma^{\mu\nu} + i c^{e}_{\mu\nu} \gamma^\mu D^\nu + i d^{e}_{\mu\nu} \gamma_5 \gamma^\mu D^\nu \psi \right) = 0$$
IS THERE ANTIMATTER LEFT IN THE UNIVERSE?
Search for Primordial Antimatter

- DIRECT SEARCHES IN COSMIC RAYS
  Creation of Secondaries in IGM: Test source and propagation models for cosmic rays

A large part of positrons and antiprotons impinging on Earth are produced in high-energy interactions between cosmic rays nuclei with the interstellar medium. Their spectra can provide an insight on the origin, production and propagation of cosmic rays in our galaxy. Any observed flux larger than that predicted by the Leaky Box Model (LBM), the “standard” model of cosmic ray propagation, could indicate exotic sources of antimatter. The predictions of the propagation models are different above 10 GeV where more refined measurements are needed.
Balloon experiments
Results from CAPRICE/BESS

height of flight = 38 km (top of atmosphere)

subsidary result (data+propagation model) = \(\tau(\bar{p}) > 1.7\) Myr

Space experiments

PAMELA (satellite), AMS (space station)

- SEARCH FOR PRIMARY ANTIMATTER
  e+, \( \bar{p} \), anti-alpha

Note: positrons are difficult to measure/interpret:
- radiative losses close to sources
- possibility of primary positron cosmic rays
Space experiments

PAMELA (satellite), AMS (space station)

- SEARCH FOR PRIMARY ANTIMATTER
  e+, \( \bar{p} \), anti-alpha

Note: positrons are difficult to measure/interpret:
  - radiative losses close to sources
  - possibility of primary positron cosmic rays
Space experiments

Other sources:
- Modified Propagation of Cosmic Rays, Supernova Remnants, Pulsars

Similar findings with antiprotons -> STAY TUNED!
Cosmological Models

Distortions in the CMB:

- CMB would have been affected by late annihilations (if antimatter would have survived longer than expected) & photons from the annihilation would contribute to the diffuse gamma rays

Dirac Nobel lecture 1933

- $B=0$ universe is mostly excluded by standard cosmology scenarios based on CMB observation (annihilation at boundaries, at least for domains which are smaller than the size of the visible universe)
Cosmological Models

**Big Bang Nucleosynthesis**
Existence of antimatter during nucleosynthesis would have affected the formation of nuclei (annihilation, formation of p̅p etc., annihilation gamma rays would photodesintegrate etc)

Estimate the baryon density from SBBN and CMB

Photons are final products of annihilation processes

\[ \eta = \left( \frac{N_B}{N_\gamma} \right)_{T=3K} \quad \eta = \left( \frac{N_B - N_{\bar{B}}}{N_\gamma} \right)_{T=3K} \]

\[ \eta_{SBBN} = (5.80 \pm 0.27) \times 10^{-10} \]
\[ \eta_{CMB} = 6.160^{+0.153}_{-0.156} \times 10^{-10} \]
Summary of Lecture #1

INITIAL POSTULATION OF ANTIMATTER THROUGH THE DIRAC EQUATION

EXPERIMENTAL CONFIRMATION IN COSMIC RAYS

PUZZLE OF MATTER - ANTIMATTER ASYMMETRY IN THE UNIVERSE

TRIGGERS PRECISE COMPARISON OF MATTER & ANTIMATTER PROPERTIES

THROUGH TEST OF DISCRETE SYMMETRIES IN THE LAB

AND SEARCH OF PRIMORDIAL ANTIMATTER IN OUTER SPACE
Summary of Lecture #1

INITIAL POSTULATION OF ANTIMATTER THROUGH THE DIRAC EQUATION

EXPERIMENTAL CONFIRMATION IN COSMIC RAYS

PUZZLE OF MATTER -ANTIMATTER ASYMMETRY IN THE UNIVERSE

TRIGGERS PRECISE COMPARISON OF MATTER & ANTIMATTER PROPERTIES

THROUGH TEST OF DISCRETE SYMMETRIES IN THE LAB

AND SEARCH OF PRIMORDIAL ANTIMATTER IN OUTER SPACE

NEXT LECTURE : ANTIMATTER AS TOOLS FOR DISCOVERY (IN COLLIDERS & IN LOW ENERGY EXPERIMENTS). TECHNICAL DEVELOPMENTS ALLOWING SM ESTABLISHMENT AND BSM STUDIES