ANTIMATTER IN THE LAB

Chloé Malbrunot
CERN
Content

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

LECTURE # 2
- Antiprotons at low energies : cooling and trapping
- 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?

Quarks:
- $u$ (up)
- $c$ (charm)
- $t$ (top)
- $d$ (down)
- $s$ (strange)
- $b$ (bottom)

Leptons:
- $\nu_e$ (electron neutrino)
- $\nu_\mu$ (muon neutrino)
- $\nu_\tau$ (tau neutrino)
- $e$ (electron)
- $\mu$ (muon)
- $\tau$ (tau)

+ force carriers
What is antimatter?

Quarks

up
charm
top
down
strange
bottom

Leptons

νₑ
νₑ neutrino
νµ
νµ neutrino
ντ
ντ neutrino
e
electron
µ
muon
τ
tau

force carriers

+ force carriers +

force carriers
What is antimatter?

E = mc²
What is antimatter?

\[ E = mc^2 \]

\[ e^- \quad e^+ \]
Matter - Antimatter asymmetry

Matter - Antimatter asymmetry

Matter - Antimatter asymmetry

Afterglow Light Pattern 380,000 yrs.

Inflation

Quantum Fluctuations

Dark Ages

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

1st Stars about 400 million yrs.

Big Bang Expansion 13.7 billion years
Sakharov, 1967:

- “Baryon number violation”, i.e. $n_B - n_{\bar{B}}$ is not constant

- “C and CP violation” : if CP is conserved for a reaction which generates a net number of baryons over anti-baryons there would be a CP conjugate reaction generating a net number of anti-baryons.

- “Departure from thermal equilibrium” : in thermal equilibrium any baryon number violating process will be balanced by the inverse reaction
The “BIG” questions

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 ?

- ...
Frontiers of Particle Physics

courtesy: Fermilab

The Energy Frontier
- Origin of Mass

The Intensity Frontier
- Neutrino Physics
- Proton Decay

The Cosmic Frontier
- Dark Matter
- Dark Energy
- Cosmic Particles
- Origin of Universe
- Unification of Forces
- New Physics Beyond the Standard Model
The first antimatter discovery

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: the Dirac eq.

1928: The Dirac equation (Nobel Prize in 1933)

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

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

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

\[ H \psi = (\alpha \cdot \mathbf{P} + \beta m) \psi \]
Some Bits of History: the Dirac eq.

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

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

\[ = 1 \quad = 0 \quad = 0 \quad = 1 \]
Some Bits of History: the Dirac eq.

1928: The Dirac equation (Nobel Prize in 1933)

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

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

\[
p \rightarrow -i\hbar \nabla
\]

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

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

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

\[
= 1, \quad = 0, \quad = 0, \quad = 1
\]

\[
(i\gamma^\mu \partial_\mu - m)\psi = 0
\]

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

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

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
more antimatter ...

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
more antimatter ...

1932  Discovery of positron
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First measurement of a difference between matter & antimatter
P : Parity transformation. Invert every spatial coordinates

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

fermions and anti-fermions 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 $^{60}\text{Co}$ β-decay when the nuclear spin was aligned up and down

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

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

few particles are C-eigenstates

C is conserved in strong and EM interactions

\[ C|\gamma\rangle = (-1)^n |\gamma\rangle \]
\[ C = (-1)^{l+s} \]

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

\[ \pi^0 \rightarrow 2\gamma \quad \text{is allowed under CC} \]
\[ \pi^0 \rightarrow 3\gamma \quad \text{is not allowed under CC} \]
\[ < 3.1 \times 10^{-8} \]
Discrete Symmetries

CP Violation in Neutral Kaons:

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

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 Violation in Neutral Kaons:

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

Production through $\Delta S=0$

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

Start with a pure $K^0$ beam

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

CP Eigenstates:

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

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

Measured quantity:

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

Interferences: observed in modulation of the 2 pion signal
Discrete Symmetries

Measured quantity:

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

Interferences: observed in modulation of the 2 pion signal

Semi-leptonic mode:

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

Discrimination criteria between matter and antimatter:

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

\[ \Delta \sim 0.3 \times 10^{-2} \]
Discrete Symmetries

\[ \Delta = \frac{\text{rate}(\bar{K}_0 \to K_0) - \text{rate}(K_0 \to \bar{K}_0)}{\text{rate}(\bar{K}_0 \to K_0) + \text{rate}(K_0 \to \bar{K}_0)} \]

TIME-REVERSAL ASYMMETRY $A_T$, the observed difference between the rates for $\bar{K}^0 \to K^0$ and $K^0 \to \bar{K}^0$, divided by their sum, is plotted here as a function of the proper time interval $\tau$ between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of $\lambda_s = 89.3$ ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry, $(6.6 \pm 1.6) \times 10^{-3}$, in good agreement with the theoretical expectation. (Adapted from ref. 2.)
Discrete Symmetries

T : Time Reversal @ CPLEAR

The observed difference between the rates for $\bar{K}^0 \rightarrow K^0$ and $K^0 \rightarrow \bar{K}^0$, divided by their sum, is plotted here as a function of the proper time interval $\tau$ between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of $\lambda_s = 89.3$ ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry, $(6.6 \pm 1.6) \times 10^{-3}$, in good agreement with the theoretical expectation. (Adapted from ref. 2.)

$$\Delta = \frac{\text{rate}(\bar{K}^0 \rightarrow K^0) - \text{rate}(K^0 \rightarrow \bar{K}^0)}{\text{rate}(\bar{K}^0 \rightarrow K^0) + \text{rate}(K^0 \rightarrow \bar{K}^0)}$$


\[ \Delta = \frac{\text{rate}(\bar{K}_0 \to K_0) - \text{rate}(K_0 \to \bar{K}_0)}{\text{rate}(\bar{K}_0 \to K_0) + \text{rate}(K_0 \to \bar{K}_0)} \]

\text{Time-reversal asymmetry} \ A_T, \text{the observed difference between the rates for} \ \bar{K}^0 \to K^0 \text{and} \ K^0 \to \bar{K}^0, \text{divided by their sum, is plotted here as a function of the proper time interval} \ \tau \text{between the creation of the neutral kaon in the CPLEAR facility at CERN and its subsequent decay from a state of opposite strangeness. The time is given in units of} \ \lambda_s = 89.3 \ \text{ps, the shorter of the two neutral-kaon lifetimes. The red line is the fitted average measured asymmetry,} \ (6.6 \pm 1.6) \times 10^{-3}, \text{in good agreement with the theoretical expectation. (Adapted from ref. 2.)} \]

CERN PS complex 1996

1982-1996 : AAC
3 separate rings
AC, AA, LEAR

Since 2000 :
all-in-one machine : AD

LEIR

LEP: Large Electron Positron collider
SPS: Super Proton Synchrotron
AAC: Antiproton Accumulator Complex
ISOLDE: Isotope Separator OnLine DEvice
PS: Proton Synchrotron
LEAR: Low Energy Antiproton Ring

CERN SUMMER STUDENT LECTURE - 2019 -
# Discrete Symmetries

## Summary:

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<th>Strong</th>
<th>EM</th>
<th>Weak</th>
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<tbody>
<tr>
<td><strong>P</strong></td>
<td>yes</td>
<td>yes</td>
<td>no</td>
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<tr>
<td><strong>C</strong></td>
<td>yes</td>
<td>yes</td>
<td>no</td>
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<tr>
<td><strong>CP (or T)</strong></td>
<td>yes</td>
<td>yes</td>
<td>~10^-3</td>
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<td>1964 : K0 decay</td>
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<td>1999 (2012) : Direct T Violation</td>
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<td>2001: B decay (BELLE, BaBar)</td>
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<td>2013 : strange B decay (LHCb)</td>
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<td><strong>CPT</strong></td>
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### Summary:

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<th>Interactions</th>
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<td>Strong</td>
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<tr>
<td><strong>P</strong></td>
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<tr>
<td><strong>CPT</strong></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

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. Acta30, 409 (1957);

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

Measurement on H
Recent
Past

CERN (ALICE)

CERN (AD)

Relative precision

$|\bar{H}\text{ GS HFS}|$

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

$|\bar{\text{antiproton } g/\bar{q}/m}|$

$|\text{antiproton } q/m|$

$|\muon g|$

$|\text{positron } g|$

$|\text{kaon } \Delta m|$

$|\text{antideuteron } m/q|$

$|\text{antihelium } m/q|$
Tests of CPT Symmetry

\[
\frac{1}{2} H_{\mu\nu} \sigma^{\mu\nu} + i c_{\mu\nu} \gamma^\mu D^\nu + i d_{\mu\nu} \gamma_5 \gamma^\mu D^\nu \psi = 0
\]

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C. Malbrunot
IS THERE ANTIMATTER LEFT IN THE UNIVERSE?
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.
Results from CAPRICE/BESS

height of flight = 38 km (top of atmosphere)

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


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C. Malbrunot
PAMELA (satellite), AMS (space station)

- SEARCH FOR PRIMARY ANTIMATTER
  e+, p̅, anti-alpha
Note: positrons are difficult to measure/interpret:
  - radiative losses close to sources
  - possibility of primary positron cosmic rays
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
Other sources:
- Modified Propagation of Cosmic Rays, Supernova Remnants, Pulsars
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 $p\bar{p}$ etc., annihilation gamma rays would photodesintegrate etc)

Estimate the baryon density from SBBN and CMB

Photons are final products of annihilation processes

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

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

LECTURE # 2: EXPERIMENTS AND APPLICATIONS OF LOW ENERGY ANTIMATTER