MUONIC ANTI-HYDROGEN

— Possible Production and Test of CPT Theorem —

Workshop on Physics with Ultra Slow Antiprotons
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RIKEN

1. Introduction
2. Ultra Slow $\mu^+$; Recent Progress and Future
3. Towards Production of Muonic Anti-Hydrogen
4. Possible High Precession Spectroscopy for Test of CPT Theorem
5. Conclusion; Future Perspectives
Hydrogen, Anti-Hydrogen with ($e^-, e^+, \mu^-, \mu^+$)

**Hydrogen**
- $E_{1s}(pe^-) = -13.6$ eV
- $r = 0.53 \times 10^{-6}$ cm

**Muonic Hydrogen**
- $E_{1s}(p\mu^-) = -2.5$ keV
- $r = 260 \times 10^{-13}$ cm

**Anti-Hydrogen**
- $E_{1s}(\bar{pe}^+) = -13.6$ eV
- $r = 0.53 \times 10^{-6}$ cm

**Muonic Anti-Hydrogen**
- $E_{1s}(\bar{p}\mu^+) = -2.5$ keV
- $r = 260 \times 10^{-13}$ cm
What is a muon?

Muon is an elementary particle first found in the cosmic ray in 1937. Muon is now produced in large numbers by using accelerators.

<table>
<thead>
<tr>
<th>Charge</th>
<th>Spin</th>
<th>Mass (200 me)</th>
<th>Lifetime (2.2 µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$</td>
<td>$+\frac{1}{2}$</td>
<td>106 MeV (1/9 of Proton)</td>
<td>2.2 µs</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>$-\frac{1}{2}$</td>
<td>106 MeV (207 x Electron)</td>
<td>2.2 µs</td>
</tr>
</tbody>
</table>

Structureless (point-like) particle and interacts mainly electromagnetically with atoms in matters.

Pion ($\pi$) production by accelerated beam:

$p(n) + N \rightarrow \pi^+ + X, \ldots$

Muon ($\mu$) production by $\pi$ decay:

$\pi^- \rightarrow \mu^- + \nu$ (26 ns)

Behavior in Matters:

$\mu^+$ "Light proton"

$\mu^-$ "Heavy electron"

Muonium

Radius: 0.532 Å
Ionization Energy: 13.6 eV
$g$ Factor: $103 \times g_\mu$

Muon trapped to a Nucleus

Radius: 260 fm

Muon for human life

Heavy Electron (200 me-)

Heavy Electron Promotion Of Cyclic Electron Energy

Radioactivity Sensitive Characterization of Polarization Microscopic New Materials & Phenomena Magnetic Probe New Life Science

(2.2 µs)

Heavy Electromagnetic Particle (200 me-, 200 me+)

Heavy Electromagnetic Radiography for Large-scale Natural Disasters Prevention

Phenomena Characterization of Industrial Application

Radiography for Large-scale Prevention

Natural Disasters

Industrial Application
# ULTRA SLOW $\mu^+$

--- RECENT PROGRESS AND FUTURE ---

PROPOSED & REALIZED (★) MUON COOLING METHOD

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Technique</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IONIZATION COOLING</td>
<td>$\mu^+$, $\mu^-$</td>
</tr>
<tr>
<td></td>
<td>PRISM</td>
<td>$\mu^+$, $\mu^-$</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>RE-EMISSION FROM $\mu$CF</td>
<td>$\mu^-$</td>
</tr>
<tr>
<td>$\star$</td>
<td>FRICTIONAL COOLING (PSI)</td>
<td>$\mu^+$, $\mu^-$</td>
</tr>
<tr>
<td>$\star$</td>
<td>COLD MODERATOR (TRIUMF/PSI)</td>
<td>$\mu^+$</td>
</tr>
<tr>
<td>$\star$</td>
<td>THERMAL MUONIUM IONIZATION (KEK)</td>
<td>$\mu^+$</td>
</tr>
</tbody>
</table>
KEK METHOD OF ULTRA SLOW $\mu^+$

**THERMAL MUONIUM & ITS LASER IONIZATION**

**Historical Development at KEK-MSL**

1. Thermal Muonium Production in Vacuum from Hot Tungsten (W) Surface
   
   
   *Phys. Rev. Lett. 56(1986) 1463*

2. Laser Resonant Ionization ($1\ s \rightarrow 2\ s \rightarrow$ unbound)
   
   of Thermal Muonium
   
   
   *Phys. Rev. Lett. 60(1988) 101*

3. Laser Resonant Ionization ($1\ s \rightarrow 2\ p \rightarrow$ unbound)
   
   of Thermal Muonium and Ultra-Slow $\mu^+$ Production
   
   *K. Nagamine, Y. Miyake et al.*
   
**THERMAL MUONIUM PRODUCTION IN VACUUM**

—— Activities at KEK-MSL ——

**Original**
Mills et al. (1986)

**Development**
Matsushita et al. (1998)

**Recent Development**
Miyadera et al. (2004)

\[
\frac{N_{\text{Mu}}}{N_{\mu^+}} \sim 0.04 \quad T_{\text{Mu}} \sim T_W
\]

<table>
<thead>
<tr>
<th>Metal</th>
<th>(E_{\text{Mu}}) (eV)</th>
<th>(E_{\text{ad}}) (eV)</th>
<th>(\phi_H) (eV)</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>0.66(4)</td>
<td>2.9</td>
<td>1.6</td>
<td>KEKMSL</td>
</tr>
<tr>
<td>W</td>
<td>1.72(5)</td>
<td>2.9</td>
<td>1.6</td>
<td>KEKMSL</td>
</tr>
<tr>
<td>W</td>
<td>1.3(1)</td>
<td>2.9</td>
<td>1.6</td>
<td>RIKEN-RAL</td>
</tr>
<tr>
<td>Re</td>
<td>2.62(3)</td>
<td>2.8</td>
<td>2.0</td>
<td>RIKEN-RAL</td>
</tr>
<tr>
<td>Ir</td>
<td>1.4(1)</td>
<td>2.7</td>
<td>1.5</td>
<td>KEKMSL</td>
</tr>
<tr>
<td>Pt</td>
<td>2.9(1)</td>
<td>2.5</td>
<td>2.2</td>
<td>KEKMSL</td>
</tr>
</tbody>
</table>

\[N_{\text{Mu}} (\text{Porus W}) \sim 2 \times N_{\text{Mu}} (W)\]
ULTRA SLOW $\mu^+$ PRODUCTION VIA LASER IONIZATION OF THERMAL $\mu$

Original Chu et al. (1989) (KEK-MSL)

Hot $\mu^+$ at Proton Beam Nagamine, Miyake et al. (1995) (KEK-MSL)

Hot $\mu^+$ at 4 MeV $\mu^+$ Beam Bakule, Matsuda et al. (2002) (RIKEN-RAL)

$1/h/10^3$ 4 MeV $\mu^+$

$1/min/2$ µA 500 MeV $p$

$1/s/10^5$ 4 MeV $\mu^+$
INTENSE ULTRA SLOW $\mu^+$
IN THE NEAR FUTHRE (1)

FEFICIENT $\pi/\mu$ COLLECTOR

High Intensity Proton Driver
(1 GeV $\times$ mA $\rightarrow$ MW)

Full $\pi/\mu$ Capture

$\mu^+$ Stopping & Zero-Energy $\mu^+$ Production

FEFICIENT Mu IONIZATION

i) Resonant $e^-$ Transfer in High Density H Plasma
\[ \text{Mu} + \text{H}^+ \rightarrow \text{H} + \mu^+ \]
\[ \sigma_{tr} \approx 5 \times 10^{-15} \text{ cm}^2 \]

ii) Multi-Photon Mu Ionization by femto-sec Laser Pu

iii) Laser Impact Ionization of Mu at Surface
π/μ COLLECTION AND MUON TRANSPORTATION

Based Upon Recent Progress in the Studies of Neutrino-Factory and μμ Colliders

Full Solid Angle Capture

1 Str Acceptance for Surface μ⁺, DAI-OMEGA at KEK
Realization of more than $10^{10}$/s Ultra Slow $\mu^+$

<table>
<thead>
<tr>
<th></th>
<th>Expected Numbers</th>
<th>Conditions &amp; Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_p$</td>
<td>$7.6 \times 10^{15}$</td>
<td>$1 \text{ GeV} \times 1 \text{mA (1 Mw)}$</td>
</tr>
<tr>
<td>$N_{\pi^+}$</td>
<td>$4.8 \times 10^{13}$</td>
<td>$\sigma_{\pi^+}^{\pi^+}: 28\text{mb}$</td>
</tr>
<tr>
<td>$N_{\mu^+}$</td>
<td>$4.8 \times 10^{12}$</td>
<td>Pion Capture 2.9 T 20 cm Bore $\times 1.5\text{m}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pion Decay 3.0 T, 25 cm Bore $\times 10\text{m}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Full Reflection</td>
</tr>
<tr>
<td>$N_{\text{ThMu}}$</td>
<td>$\sim 10^{12}$</td>
<td>Full Stopping(100 $\times$ 10 $\mu$m Poruns W)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20% Conversion</td>
</tr>
<tr>
<td>$N_{\text{sp}}$</td>
<td>$\sim 10^{12}$</td>
<td>Full Ionization</td>
</tr>
</tbody>
</table>
TOWARDS PRODUCTION OF MUONIOC ANTI-HYDROGEN

POSSIBLE CROSSED-BEAM EXPERIMENT

\[
\text{Mu} + \bar{p} \to \bar{p} \mu^+ + e^- \\
a_0 \quad \frac{1}{207} \quad a_0 \\
E^e_{ls} \quad 20E^e_{ls}
\]

\[
\sigma_{Tr} \approx 10^{-4} \pi a_0^2 \\
\text{at } E_{\bar{p}} \approx 20E^e_{ls}
\]

cf. \( (\mu^+\mu^-) + p \leftarrow \mu^-p + \mu^+ \)

\[
\frac{2}{207} \quad a_0 \quad \frac{1}{207} \quad a_0 \\
\frac{207}{2} E^2_{ls} \quad 20E^e_{ls}
\]

\[
\sigma_{Tr} \approx 10^{-4} \pi a_0^2 \\
\text{at } E_{\mu^+} \approx 20E^e_{ls}
\]

FURTHER EFFICIENCY INCREASE
— Optimization of Time, Space, Character —

☆ Time Compression/Bunching

☆ Acceleration & Micro-Beam

Yield Estimation

\[
\frac{L_p}{N_{Mu}} \cdot \sigma_{Tr} \approx 1/s
\]

\[
10^{10/s} \quad 10^{10} \quad 10^{-20} \text{ (cm}^2\text{)}
\]
POSSIBLE HIGH-PRECISION SPECTROSCOPY FOR TEST OF CPT THEOREM BY USING MUONIC HYDROGEN/ANTI-HYDROGEN

\[ \mu^+ p \text{ and } \mu^+ \bar{p} \text{ under CPT conservation} \]

\[ e^- p \text{ and } e^- \mu^+ \]
POSSIBLE OBSERVABLES FOR HIGH PRECISION LASER SPECTROSCOPY

1. Hyperfine Splitting at the Ground State
   \[ \Delta E (n = 1, \text{hfs}) = 0.18 \text{ eV (6.89 } \mu\text{m}) \]
   Resonance Signal Detection:
   Range, Polarization, Transfer to H

2. Lamb Shift (Vacuum Polarization at n = 2)
   \[ \Delta E (2^2p_{1/2} - 2^2s_{1/2}) = 0.20 \text{ eV (6.20 } \mu\text{m}) \]
   Resonance Signal Detection:
   Missing K_\alpha X-ray

   Laser is available!
   CdGeAs_2 (K. Kato et al.)

   no (\mu^-p) experiment So far!
CONCLUSION;
FUTURE PERSPECTIVES

1. Muonic Anti-Hydrogen is not a Dream and to be realized in the 21st century
   The technology of intense and high-quality $\mu^+$ and $\mu^-$ beam will take a rapid development independently, because of the needs of each community.
   Good communication between Low Energy Muon Science and Physics Community should be encouraged.

2. Need of theoretical works on CPT violation effect in Muonic Anti-Hydrogen
Proposed accelerator systems for the advanced muon radiography
Surface Physics
Inter-Surface Physics
Nano Materials
Life Science

Bunching & Re-Acceleration
Radiography
Neutrino Factories
Muon Colliders

Ionization Dynamics
Capture Process
Anti-Hydrogen Production
Anti-Hydrogen Spectroscopy
Gravity
LOOKING INNER-STRUCTURE FROM OUTSIDE

—Keeping Objective as it is—

Volcano

Pyramid

Blast Furnace
Proposed accelerator systems for the advanced muon radiography
Ultra-Slow

Surface Physics
Inter-Surface Physics
Nano Materials
Life Science

Bunching & Re-Acceleration
Radiography
Neutrino Factories
Muon Colliders

Ultra-Slow

within 21st Century

\( \mu^+ \)

\( \bar{P} \)

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