

# Muonic Anti-Hydrogen -Formation and Test of CPT Theorem-

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**Abstract.** With a completion of high intensity hadron accelerator in the near future, there will be a realization of high intensity as well as high quality beam of secondary particles like positive muons, anti-protons, etc. Here, it is suggested that a formation of Muonic Anti-Hydrogen is not unrealistic at all. Once it is formed, a new type of testing of CPT theorem will be realized by comparing with Muonic Hydrogen; much powerful testing for a short-range CPT violating interaction in contrast to the case of usual Hydrogen versus Anti-Hydrogen comparison.

**Keywords:** Anti-Hydrogen, CPT, Muonic Atom

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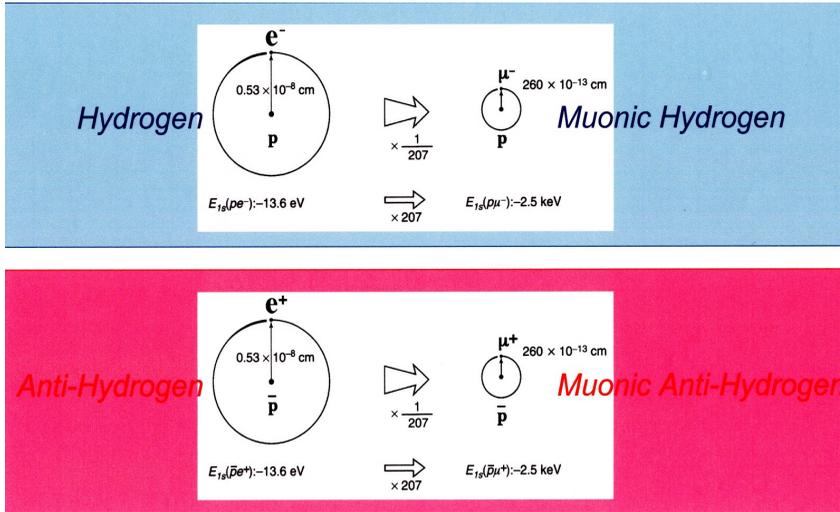
## INTRODUCTION

Including anti-proton  $\bar{p}$ , as seen in Fig. 1, there are four types of hydrogen atoms with  $e^+$ ,  $e^-$ ,  $\mu^+$  and  $\mu^-$ ; these are the conventional H atom ( $e^-p$ ), the corresponding antiparticle  $e^+\bar{p}$  (known as anti-Hydrogen,  $\bar{H}$ ), and the two muonic counterparts  $\mu^-p$  and  $\mu^+\bar{p}$ . As it is well recognized, when a method of generating anti-hydrogen  $\bar{H}$  ( $e^+\bar{p}$ ) is established, a high precision spectroscopic measurement on  $\bar{H}$ , in comparison with the corresponding results for H, may contribute to the verification or falsification of the CPT conservation law (where CPT refers to the product of the three symmetry operations of charge transformation, parity-inversion, and time-reversal). In order to do the test of the CPT theorem, as it is already indicated in the earlier publication ( p.185 of [1] ), there is an obvious advantage for the use of the  $\mu^-p$  and  $\mu^+\bar{p}$  pair, in comparison with the use of usual H and  $\bar{H}$  pair. Although a correct theory does not exist to the knowledge of the present author, when the CPT-violating interaction has a short-range nature with an extremely massive exchange boson, such an effect can more easily be seen in the ( $\mu^-p$ ,  $\mu^+\bar{p}$ ) comparison than in the ( $e^-p$ ,  $e^+\bar{p}$ ) comparison, since the atomic size becomes smaller by a factor of 1/207.

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**FIGURE 1.** The possible four hydrogen atoms which are formed by proton, anti-proton, with electron and muon.

## POSSIBLE FORMATION

Since intense slow  $\mu^+$ /Mu (Muonium, hydrogen-like atomic state of  $\mu^+$  and  $e^-$ ) production as well as intense slow anti-proton beam will soon become available at the future high intensity hadron accelerator, it will be possible to produce  $\mu^+ \bar{p}$  through e.g. the following transfer reaction:

$\text{Mu} + \bar{p} \rightarrow \mu^+ \bar{p} + e^-$ , through a collision reaction by using a cloud target of thermal Mu and slow  $\bar{p}$  projectile with the energy of  $\bar{p}$  optimized for a capturing process to the new atomic state  $\mu^+ \bar{p}$  whose ground state has the binding energy of the  $E_{g.s.}(\mu^+ \bar{p}) \sim 2.528 \text{ keV}$ . The exact transfer-reaction cross section has not been calculated yet. Some indication can be obtained by the similar reactions such as  $\text{H} + \bar{p} \rightarrow p \bar{p} + e^-$  [2, 3], where the value of more than  $10^{-16} \text{ cm}^2$  was indicated for the capturing stage at the c.m. energy of close to 1 eV. Correct theoretical studies for the transfer reaction including a population distribution of the initial states as well as the succeeding cascade transitions are called for.

Recent progress in the beam technology for the production of the ultra-slow  $\bar{p}$  in the energy range of eV to 100 keV has been reported in the present workshop. In fact, a production of the intense slow  $\bar{p}$  beam in the level of  $10^8/\text{s}$  is under planning at the new accelerator complex at GSI, where beam power of the primary proton is at the level of kW. Thus, if we install the same beam producing device at more intense

hadron accelerator such as J-PARC (50 GeV x 15  $\mu$  A), it is quite natural that one can expect the slow  $\bar{p}$  beam at the level of  $10^{10}/s$ .

At the same time, the production method of intense thermal Mu has been taking a significant progress. At KEK-MSL, the project of ultra-slow muon has been initiated in 1985, on the occasion of the discovery of the thermal Mu production from hot tungsten [4]. The work has been extended, via an initiation of the laser resonant spectroscopy of thermal Mu [5], to the generation of ultra-slow positive muon by laser resonant ionization of the Mu produced from tungsten placed at the position of primary proton beam line [6] and later placed at the secondary beam of intense 4 MeV surface muon at RIKEN-RAL [7]. At the same time, progress has been taken for the method of thermal Mu production; a series of experiments on SiO<sub>2</sub> powder [8] and systematic studies on noble metals [9] and recently on a porous tungsten [10]. As a summary of all of these historical developments, one can say that we have a method to convert a single MeV positive muon to thermal energy Mu in vacuum with a conversion efficiency of close to or more than 10 %.

In addition, in the fields of both the low-energy muon science and the particle physics of muon colliders and neutrino factories, the idea of a large acceptance pion and muon collection has recently become popular. One distinguished example is the Dai-Omega project at KEK-MSL, which is a large-acceptance axial-focussing superconducting surface muon channel and successfully collected 4 MeV surface muon with a solid angle of 1 Str [11]. Similar concept has been introduced at PSI by using a normal-conducting coil at the front-end [12]. More drastic improvement, close to a full-capture of all the produced muons, is employed for the forthcoming rare-decay measurement at BNL [13], based upon the design works on e.g. neutrino factories.

Combining all of these factors, as shown in Table 1, with a realization of 1 MW proton driver, one can expect at the level of more than  $10^{10}/s$  thermal Mu production in the vacuum space near e.g. hot porous tungsten. In the earliest stage of the formation experiment, a full stopping of the MeV positive muons in a multi-layer of the tungsten foil with optimized spacing will be applicable.

Thus, by injecting slow  $\bar{p}$  beam to the cloud of thermal Mu which are produced e.g. from the surfaces of a stack of hot porous tungsten foils, the formation of  $10^4/s$  muonic anti-hydrogen can be expected. The formation can easily be monitored by detecting the characteristic X-ray of 2 keV, a 2p-1s transition. At the discovery stage, in order to eliminate background due to annihilation gamma-rays, an employment of pulsed time structure for both Mu and anti-proton beam might be helpful.

Since the formation experiment is essentially a crossed beam experiment, depending upon the method of the ultra-slow anti-proton beam production, a space compression like a micro-beam in addition to a time-compression like a pulsed beam for the positive muons will contribute to the increase of the formation rate of the muonic anti-hydrogen.

**Table 1.** Intensity estimation for thermal muonium.

	Expected Numbers (s <sup>-1</sup> )	Conditions & Remarks
$N_p$	$7.6 \times 10^{15}$	1 GeV $\times$ 1mA (1 Mw)
$N_{\pi^+}^{tot}$	$4.8 \times 10^{13}$	$\sigma_{\pi^+}^{tot} : 28\text{mb}$
$N_{\mu^+}$	$4.8 \times 10^{12}$	Pion Capture 2.9 T 20 cm Bore $\times$ 1.5m Pion Decay 3.0 T, 25 cm Bore $\times$ 10 m Full Reflection
$N_{\text{Th Mu}} \simeq 10^{12}$		Full Stopping(100 $\times$ 10 $\mu\text{m}$ Poruns W) 20 % Conversion

## HIGH PRECISION SPECTROSCOPY FOR CPT TEST

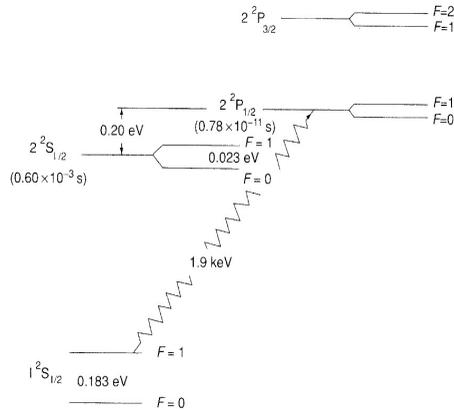
With keeping the aim of the test of CPT theorem in mind, it is somewhat a shame of the present muon physicist that there has been no successful high precision measurement like a laser resonance experiment on muonic hydrogen ( $\mu^-p$ ). At the same time, other than the comparison to ( $\mu^+p$ ) mentioned here, a high precision spectroscopy of the system ( $\mu^-p$ ) presents many other fundamental physics interests such as the questions of QED testing of the vacuum polarization, proton polarizability, etc.

As for the energy levels of ( $\mu^-p$ ) shown in Fig. 3, there have been several proposals for laser resonance spectroscopy.

One distinguished example is the measurement of the 2S Lamb shift ( $2^5P_{3/2} - 2^3S_{1/2}$ ) of muonic hydrogen proposed at PSI [14]. There, laser resonance spectroscopy will be planned to a precision of 30 ppm by employing  $\lambda \sim 6 \mu\text{m}$  laser produced by multiple Raman process of 708 nm laser. The detection of the resonance signal will

be a change of the succeeding cascade X-ray; a missing  $K_{\alpha}$  X-ray. Another example of the similar type of experiment is  $(\mu^-p)$  (3d-3p) with  $\Delta E : 0.006$  eV and  $\lambda : 188$   $\mu\text{m}$  [15]. For this purpose, a variable-frequency free electron laser is required, together with intense  $\mu^-$  stopping in low pressure (below 20 mbar) hydrogen gas. Since 88 % of the splitting is due to the vacuum polarization, one can determine vacuum polarization with an accuracy of 100 ppm which should be compared to the presently available value with an accuracy of 0.1 % from either  $(g - 2)_{\mu}$  or  $(g - 2)_e$ .

The other example is the  $(\mu^-p)$  ( $n = 1$ , hfs) with  $\Delta E : 0.183$  eV and  $\lambda : 6.8$   $\mu\text{m}$ . As described by Kato [16], an appropriate laser source with frequency variability might be available. The major difficulty in this measurement is how to detect the resonance signal. A polarized  $(\mu^-p)$  ( $n = 1$ ) state can in principle be produced by spin-exchange collision between a spin-polarized Kr atom and unpolarized  $(\mu^-p)$  as commonly used to obtain polarized radioactive nuclei, muonium, etc. The conditions, i.e. the Kr concentration in  $\text{H}_2$  gas and the total pressure of the gas mixture, must be optimized so that  $\mu^-$  transfer from p to Kr is minimized and spin polarization transfer maximized. Another possibility might be a brute-force low-temperature nuclear polarization of ortho  $\text{H}_2$  (80% polarization under 15 T at 0.015 K). After generating the spin repolarized  $(\mu^-p)$  in its  $F = 1$  state, the hfs resonance can easily be detected by observing the destruction of the decay electron asymmetry with reference to the spin polarization axis. Also, it is suggested that one can use a difference in the range as well as the interaction time between two hyperfine states in hydrogen [17].



**FIGURE 2.** Energy level of Muonic Hydrogen and that of Muonic Anti-Hydrogen under CPT conservation.

## CONCLUSION

At the time of the beginning of the 21<sup>st</sup> century, the following concluding statements can be drawn.

1) Muonic Anti-Hydrogen is not a dream but a scientific subject to be realized within the 21st century. The technology of high-intensity and high-quality ultra-slow positive muon and  $\bar{p}$  will take a rapid development *independently*, because of the needs of each community: surface-intersurface studies, nano-sciences, life-sciences, further higher energy projects like neutrino factories and muon colliders, etc. for the positive muons; anti-hydrogen spectroscopy and anti-particle gravity etc. for  $\bar{p}$ . Thus, good communications between low-energy muon-science community and anti-proton physics community should only be encouraged at the relevant timing of the future technical development of each community.

2) At the same time, theoretical works on CPT violation effect in Muonic Anti-Hydrogen taking into account the range difference effect in comparison with electronic system is called for.

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