論文の内容の要旨

論文題目

Development of injection scheme of antiprotons and production of antihydrogen atoms in low-lying excited states
(反陽子入射方法の開発と低励起状態反水素原子の生成)

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C, P, and T symmetries are three discrete symmetries which have attracted much attention in modern physics. They are the symmetries of physical laws under charge conjugation (C), parity inversion (P), and time reversal (T), respectively. Although C symmetry, P symmetry, and two-combined CP symmetry are experimentally shown to be broken, and the mechanism of their violations are well-described in the Standard Model, it is widely believed that three-combined symmetry, CPT symmetry, is to be conserved in all laws of physics. When CPT symmetry holds, the mass, the lifetime, the absolute value of charge and magnetic moment of a particle and its antiparticle must be the same. But this brings a big unresolved question, which is called ”baryon asymmetry”. It refers to the fact that there exist far larger amount of baryonic matter compared to antimatter in the observable universe, in contrast to the natural assumption that the universe must have equal amount of matter and antimatter under CPT symmetry. Currently there is no satisfying explanation for this problem. The experimental investigation of CPT symmetry could give a clue to solve the mystery, as well as the fundamental frame work of the theory of particle physics beyond the Standard Model.

The ASACUSA collaboration proposes the spectroscopy of the ground state hyperfine splitting of antihydrogen atoms using its atomic beams. Antihydrogen atom, which was first produced in 1995, is considered as a unique probe for the test of CPT symmetry, partly because many measurements have been done for hydrogen atoms at extremely high precision. If we found any deviation on antihydrogen spectrum from that of hydrogen, it indicates violation of CPT symmetry. The ASACUSA collaboration reported the production of antihydrogen atoms in the cusp magnetic field configuration in 2010. Antihydrogen atoms were produced by injecting antiprotons into a preloaded positron plasma confined in the charged particle trap made of an axial magnetic field and a nested electrostatic potential.

Since then, we have made several advances towards the spectroscopy using atomic beam of antihydrogen for testing CPT symmetry, which are described in this thesis.

First, we have shown that the antihydrogen beams can be extracted toward a detector placed 2.7 m downstream of the production region. The yield of the antihydrogen is increased by a factor of three when the motion of antiprotons is excited by applied RF field. This result confirms the foundation of our proposal that we can extract antihydrogen atoms as an atomic beam to a magnetic-field-free region where we conduct spectroscopy so that the systematic uncertainty of the spectrum due to field inhomogeneity is much reduced.

Then, we have developed a new injection scheme of antiprotons, which is the main work of this thesis. The new scheme ensures the antiprotons have small energy spread when they are injected into positron plasma, resulting production of antihydrogen atoms with small kinetic energy. Small kinetic energy of antihydrogen atoms is essential to the proposed spectroscopy, because it makes antihydrogen atoms highly polarized when extracted, and their population in the ground state larger. There are mainly two steps to be taken to realize the new scheme, one is the extraction of antiprotons from their reservoir with narrow energy spread, the other is the transport of antiprotons from the reservoir to the antihydrogen production region while conserving the narrow initial energy spread.

In the antiproton reservoir, the antiprotons are confined in an electrostatic potential, and its energy spread is known to be small of sub eV. The antiprotons are extracted to downstream by manipulating the potential configuration and removing the potential barrier quickly. Previously the extraction scheme was designed to minimize the pulse length of the extracted antiprotons, but this had resulted rather large potential gradient in the area which affect the energy spread of the extracted antiproton beam. Careful optimization of the potential manipulation process has been carried out so that the potential gradient is as small as possible. The energy distribution of antiprotons is measured to be sub eV. This is compatible with the initial energy spread in the reservoir, and confirms that our new extraction scheme does not broaden the energy spread.

A new adiabatic beam line is designed in order to transport the extracted antiprotons to the antihydrogen production region while keeping the initial energy distribution. The idea of the adiabatic beam line is based on the fact that even when the strength of the magnetic field variates along the trajectory of the charged particle, the particle's velocity distribution is conserved at the same strength of the magnetic field, as far as the change of the field strength the particle experience is slow enough compared to the typical time scale of the particle motion (adiabatic condition). In order to find a feasible design of the new adiabatic beamline, computer simulations are conducted, in which static magnetic field is calculated using finite element method for various configuration of electromagnetic coils, and trajectories of antiprotons with various kinetic energies are calculated by Monte Carlo method. Three transport coils are designed and built according to the requirement obtained by the simulation. In order to generate required strong magnetic field while suppressing Joule heating of the coils, the new coils are energized by a large pulsed current. With the new transport scheme when the injection energy of antiprotons was lowered, it was measured that the energy spread of antiprotons at the entrance of the antihydrogen production region was sub eV. The number of antiprotons trapped in the antihydrogen production region is 6×10^5 per cycle, which is sufficient for antihydrogen production in our experimental procedure. We have successfully developed the new injection scheme of antiprotons.

The small energy distribution of antiprotons would provide several advantages for spectroscopy experiment. First, it is observed that the narrow energy spread of antiprotons reduces the heating of positrons, resulting in a drastic increase of the antihydrogen production rate within 500 ms from the start of mixing of antiproton and positron. This intense antihydrogen production can contribute to improvement of the S/N ratio of detection of antihydrogen atoms, because the backgrounds of the antihydrogen detector are mainly caused by cosmic rays whose rate is a constant. It is roughly estimated that the S/N ratio is doubled than the old scheme. Second, the small relative energy between antiprotons and positrons leads to a production of antihydrogen atoms with small kinetic energy. It contributes to a larger population of antihydrogen atoms in low-lying states at the antihydrogen detector. In order to measure the distribution of atomic states, we installed a field ionizer in front of the detector. By applying a strong electrostatic field, the antihydrogen atoms whose principal quantum number is higher than a threshold are ionized. The threshold can be adjusted by changing the strength of the

electric field. Once antihydrogen atoms are ionized, antiprotons are reflected by the electric field, and cannot reach the detector. By changing the strength of the electric field, and counting the number of antihydrogen atoms detected, we can obtain the distribution of principal quantum number of antihydrogen atoms. Antihydrogen atoms in low-lying excited state were observed. It is an important step for the realization of the spectroscopy.

Further analysis of antihydrogen production process reveals that the space charge potential of positrons plays an important role in determining the number of antiprotons available for antihydrogen production, and that antiprotons and positrons become spatially separated quickly after the mixing starts. Considering these analysis, a new mixing scheme to improve the antihydrogen yield is proposed. Assuming all of the separated and unused antiprotons contribute to antihydrogen production, the number of antihydrogen atoms can be increased. Another proposal is also made in order to increase the population of ground-state antihydrogen atoms by lowering positron temperatures and preparing a long electron plasma through which antihydrogen travels, and cascade down via collisions with electrons. The number of antihydrogen atoms is estimated to reach 1 ppm precision, and shown that it can be accessible utilizing these proposals.