論　文　の　要　旨

氏　　名　　　加賀　千翔人

論 文 題 目　Studies on the mixing processes of particles with different signs of charges in a magnetic field
（磁場中での異符号荷電粒子混合過程についての研究）

In this thesis mixing processes of particles with different signs of charges in a magnetic field are described. There are two main topics. One is the mixing an electron plasma with a positron plasma in a magnetic mirror trap to investigate an electron-positron plasma. Three dimensional (3D) particle-in-cell (PIC) simulations were performed to check the feasibility of mixing electrons and positrons in a compact magnetic mirror trap and the experiments were conducted. The other is the PIC simulations on the mixing an antiproton cloud with a positron plasma in a nested Penning trap for the production of low energy antihydrogen atoms.

An electron-positron plasma is an example of pair plasmas composed of the oppositely charged particles with equal masses. Relativistic electron-positron plasmas have been investigated in astrophysical objects such as pulsars, neutron star magnetospheres, and so on. Laboratory experiments for electron-positron plasmas have been also pursued. It was planned to confine relativistic electron-positron plasmas in a magnetic mirror. And high energy positrons emitted from radio isotopes (RI) and moderated positrons were confined in a magnetic mirror. Although low energy electron-positron plasmas have been studied theoretically, the simultaneous confinement of low energy electrons and positrons has never been realized yet. In the case of ordinary electron–ion plasmas, different masses of components result in complicated dispersion relations and the rich phenomena observed so far. For a pair plasma, the dispersion relation becomes simpler. However, much theoretical research suggests that unique features can be observed in pair plasmas.

Currently, there are projects to confine low energy electron-positron plasmas in a magnetic dipole field and a stellarator with the use of low energy positrons from a nuclear reactor in Germany. Also, the simultaneous confinement of low energy electrons and positrons with a compact magnetic mirror trap has been planned at Hiroshima University. Since the magnetic configuration is much simpler, the plasma oscillation measurement becomes easier. Here, 3D PIC code named Warp is used for particle simulations. In case of particle simulations, it is easy to understand charged particle distributions in phase space, particle trajectories, and so on, which are much more difficult to investigate in experiments.

Simulation results revealed that the adiabatic changes of harmonic potentials reduce the temperature of confined particles and enhances the confinement of lower energy electrons and positrons. As a result, it was confirmed that a compact magnetic mirror trap with harmonic potentials inside a magnetic mirror can be used to confine low energy electron-positron plasmas under the condition that collisions between charged particles and back ground neutrals can be ignored.

To perform the experiments, the low energy positron accumulator was constructed at RIKEN. 5 mCi ^{22}Na RI source with a solid Ne moderator and a N_2 buffer gas cooling system were used to accumulate positrons in 120 s by applying a rotational electric field. Similar positron accumulators are used for the production of antihydrogen atoms in the Antiproton Decelerator at CERN. Then, the accumulated low energy positrons were transferred into the compact magnetic mirror trap connected to the accumulator.

As a result, more than 10^7 electrons and 10^5 positrons with energy less than a few eV were confined simultaneously for the first time in a compact magnetic mirror trap with plugging potentials. The exponential decay time constant of the confined positrons exceeded 70 ms at the beginning of the simultaneous confinement. Particle simulations in the early stages of the mixing process were also conducted. The results obtained in the experiments and simulations suggested that an improved setup would make it possible to investigate the unexplored field of low-energy electron–positron plasmas experimentally.

Low energy antihydrogen atoms have been produced in a nested Penning trap, where low energy antiprotons held in a side well are injected into a high density positron plasma in the middle well. A part of synthesized antihydrogen atoms can be trapped in an Ioffe-Pritchard trap for the laser spectroscopy or extracted to a field free region for the hyperfine spectroscopy. In addition to the ongoing experiments, various simulation studies have been conducted to understand the antihydrogen formation processes and related issues. Some of them are concerned with the effects of positron plasma parameters (temperature, density, length, etc.) on the production rate and level population of produced antihydrogen atoms. Some others are concerned with the production points of antihydrogen atoms inside a positron plasma during the mixing process. So far, little attention has been paid for a plasma related effect, i.e., diocotron motions excited during the mixing process.

In fact, it is observed in ASACUSA experiments that a radius of a positron plasma in the middle well expands after a mixing process, which results in a lower density positron plasma. Therefore, it is necessary to apply a rotating electric field to compress the positron plasma to reproduce the higher density state, if the positron plasma is used again for the next mixing process. Of course, the collisions between positrons and antiprotons might be the main reason for the radial expansion of positrons. However, the plasma effect like diocotron oscillations should be also evaluated to understand the mixing process more carefully.

Here, the PIC code Warp is employed, which has been used to study various phenomena in non-neutral plasmas. Since collisions between charged particles are neglected in PIC simulations except numerical collisions, the plasma effect without collisions can be evaluated during a mixing process. Due to the restriction on the calculation time, protons are used instead of positrons. As far as diocotron motions are concerned, it is thought that the difference does not affect the results. Because the diocotron motion is independent of the mass of charged particles. The obtained results show that a slight off axis injection enhances diocotron motions, which should be avoided for the effective production of antihydrogen atoms.