Book of Abstract

Workshop on Physics with Ultra Slow Antiproton Beams

2005 Mar. 14-16
RIKEN

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Workshop on Physics with Ultra Slow Antiproton Beams

March 14 (Monday)	March 15 (Tuesday)	March 16(Wednesday)
9:00-9:30 Registration Opening 9:30-9:40 Y. Yamazaki Opening & Business announcements Session 1. Chair: Y. Yamazaki 9:40-10:20 (35+5 min) J. Ullrich "Sub-Femtosecond Correlated Dynamics Probed with Antiprotons" p.4 10:20-10:50 (25+5 min) J. Cohen "Capture of Slow Antiprotons by Atoms, Molecules, and Ions" p.5	Session 5. Chair: T. Kambara 9:00-9:30 (25+5 min) H. Torii "Production of ultra-slow antiproton beams" p.19 9:30-9:50 (15+5 min) D. Horvath "The Anticyclotron project" p.20 9:50-10:20 (25+5 min) R. Rosowsky "Intense source of slow positrons" p.21 10:20-10:50 (25+5 min) V. Varentsov "ASACUSA gas-jet target: present status and future development" p.22	Session 9. Chair: P. Kienle 9:00-9:40 (35+5 min) S. Wycech "Nuclear structure studies with low energy antiprotons" p.36 9:40-10:10 (25+5 min) A. Trzcinska "Antiprotonic atoms - a tool for the investigation of the nuclear periphery" p.37 10:10-10:40 (25+5 min) D. Gotta "Light antiprotonic atoms" p.38 10:40-11:00 (15+5 min) D. Grzonka "Study of S=-2 baryonic states at FLAIR" p.39
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Session 4. Chair: M. Fujiwara 16:20-17:00 (35+5min) R. Lehnert "Lorentz and CPT tests involving antiprotons" p.15 17:00-17:30 (25+5min) P. Bowe "Anti-hydrogen production conditions in ATHENA. What we (don't) know." p.16 17:30-18:00 (25+5min) P. Perez "A new path toward gravity experiments with anti-hydrogen" p.17	Session 8. Chair: K. Jungmann 16:50-17:30 (35+5min) D. Horvath "The Deepest Symmetries of Nature" p.33 17:30-18:10 (35+5min) J. Eades "The Antiproton and How it was Discovered" p.34	Session 12. Chair: J. Zmeskal 16:00-16:30 (25+5 min) M. Wada "Antiprotonic Radioactive Atoms for Nuclear Structure Studies" p.49 16:30-17:00 (25+5min) K. Nagamine "Muonic Antihydrogen; Production and Test of CPT Theorem " p.50 17:00-17:10 (10min) J. Ullrich "News Topics: " 17:10-17:40 (30min) Y. Yamazaki "Toward the Ultra Slow Antiproton Physics: general Discussion"
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SESSION 1

Sub-Femtosecond Correlated Dynamics Probed with Antiprotons

J. Ullrich, M. Grieser, R. von Hahn, R. Moshammer, C.P. Welsch
Max-Planck Institute for Nuclear Physics, Germany

Abstract: Whereas the three-body Coulomb problem for single excitation and ionization has claimed to be solved for the first time in a mathematically correct way during 1999 until 2004 for electron impact on hydrogen and helium, ion-impact ionization still represents a major challenge for theory. Troubling discrepancies have been observed recently in fully differential cross sections (FDCS) for He single ionization by fast ion impact and even experimental total cross sections are in striking disagreement with the predictions of all state-of-the-art theories for low-energy antiproton collisions.

For antiprotons at energies below about 300 keV down to 1 keV the interaction time between the projectile passing atoms or molecules is on the order of 80 attoseconds (as) up to 1 femtosecond (fs) and, thus, comparable to the revolution time of outer-shell electrons in atoms or molecules. Since ionization or excitation is the only reaction channel that can occur for antiprotons, and electron energies would be below the threshold at similarly low velocities, slow antiprotons provide an unsurpassed, precise and the only tool to study many-electron dynamics in the strongly correlated, non-linear, sub-femtosecond time regime, the most interesting and, at the same time, most challenging domain for theory.

Exploiting and developing many-particle imaging methods – reaction-microscopes – in combination with novel electrostatic storage rings for slow antiprotons we envision to perform, for the first time, single and multiple ionization cross section measurements for antiprotons colliding with atoms, molecules and clusters. Total, as well as any differential cross sections up to FDCS including ionization-excitation reactions will become available serving as benchmark data for theory. Several theory groups world wide concentrate efforts to solve the fundamental few-body Coulomb problem for heavy-particle and antiproton impact. Moreover, the formation of antiprotonic atoms, molecules or of protonium might be explored in kinematically complete experiments at ultra-low energies yielding unprecedented information on (n, l)-distributions of captured antiprotons as well as precise spectroscopic data of the respective energy levels.

In order to achieve these ambitious goals, challenging developments in both, storing and imaging techniques have been launched at MPI-K. A novel ultra-low energy storage ring (USR) to be integrated at the proposed facility for low-energy antiproton and ion research (FLAIR) will be developed for electron-cooled antiprotons in the energy range between 300 keV and 20 keV possibly even approaching the sub keV regime. Low emittance, high luminosity beams can be used for both in-ring and external experiments.

In the talk, the present status of experiments in comparison with theory will be highlighted and the layout of envisioned machines at FLAIR, the USR with an integrated as well as single-pass reaction microscope, will be presented.

Abstract of talk for the Workshop on Physics with Ultra-Slow Antiproton Beams
RIKEN, March 14-16, 2005

Capture of Slow Antiprotons by Atoms, Molecules, and Ions

James S. Cohen
Los Alamos National Laboratory

I will describe the capture of antiprotons by atoms, ions, and molecules to form exotic systems, as well as capture of other heavy negative particles (μ^-, π^-, K^-) that lend insight into the $\bar{p}$ capture problem.* Particular emphasis will be placed on relevance to upcoming ASACUSA experiments and corroboration of critical features. Capture by even the hydrogen atom presents great challenges for theoretical treatment. The wide variety of methods used include perturbative, two-state adiabatic and diabatic, time-independent quantum mechanical, time-dependent semiclassical and quantum mechanical and quasi-classical treatments. A few of these methods, as well as the Fermi–Teller model, have also been applied to heavier atomic targets. Most of the methods, other than the quasi-classical formulations, are not yet up to treating the dynamical electron correlation and multiple ionization found to be important in capture by multi-electron atoms, or the vibronic coupling found to be important in capture by simple molecules. The essential elements of potentially more rigorous quantum-mechanical theories will be characterized. The experimental data on capture states and relative capture probabilities in mixtures will also be discussed. The connection of existing experimental data to the theoretical capture calculations is fairly tenuous, but forthcoming experiments with antiprotons promise direct tests of some of the recent theoretical findings. New analysis of the of the angular and energy distributions of e^- and $\bar{p}$ resulting from antiproton collisions with the noble-gas atoms will be presented to help determine appropriate detector characteristics.

*J. S. Cohen, Rep. Prog. Phys. **67**, 1769-1819 (2004).

SESSION 2

Abstract:

Ionization Dynamics by p and pbar

Horst Schmidt-Böcking, Universität Frankfurt

Measuring in momentum space complete differential ionization cross sections the final-state momentum pattern differ strongly for different projectiles like photons, ions or electrons, particularly if double and multiple ionization processes are considered. Even, when the total momentum transfer from projectile to the target object is negligibly small compared to the initial-state momenta the final-state momentum pattern show characteristic features for the different projectiles. The final-state momentum pattern for photons strongly depend on the photon polarization and on the ratio of photon energy compared to the electron binding energy. The photon absorption process creates a very different pattern than the photon scattering process (Compton).
Going from slow to fast ions the ionization process varies dramatically due to different ionization processes like molecular promotion in slow collisions or ionization by virtual photon absorption processes. Dependent on the collision process the final-state momentum pattern depend on initial- or final-state correlations. In spite of great progress in theory the details of multiple ionization dynamics is not sufficiently well understood. There are many unsolved puzzles. One of the still remaining puzzles is the ratio of double to single ionization of He for fast pbar. It differs by about a factor of two from the proton ratio.
Examples of some ionization pattern are presented and future benchmark experiments are discussed.

Title: Stopping and ionization at few keV

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Abstract:
A charged particle gradually slows down while penetrating matter. In a wide range of beam velocities, from that of the atomic electrons to velocities approaching that of light, a penetrating particle primarily loses energy to the electrons of the target, i.e. the main cause of energy loss originates from excitation and ionization.
To produce new insights into these processes, we have at CERN studied the energy loss and ionization probability for antiprotons in a number of solids and gases. Recent results for the ionization cross section of He indicate a substantiation of expectations based on earlier results. This indicates that the probability of releasing an electron drops to very low values for sufficiently low velocities of the antiproton projectile. If this can be confirmed in future measurements, it is a surprise which shows a lack of understanding of simple collision processes at low energies.
Furthermore, measurements of the stopping power of antiprotons in a range of solid targets, metals as well as insulators, shows an absence of an expected threshold effect in the case of an insulator. This threshold effect is due to the presence of a finite band-gap which transforms into a restriction on the momentum transfers, which in turn leads to a reduced stopping power as compared to the velocity-linear behaviour observed in metals. The absence of such a threshold effect - formerly observed for protons - can not be explained by band-gap reduction due to the formation of molecular orbitals for antiprotons.

Antiproton-nucleus annihilation at very low energies down to capture

E. Lodi-Rizzini

ABSTRACT

The dynamics of the antiproton-nucleus interaction and the structure of the nucleus appear to affect in an unexpected way the behavior of the $\bar{p}A$ annihilation cross section (σ_{ann}) at low energies. Antiproton annihilation on light nuclei at momenta below 100 MeV/c seems to be very weakly dependent on the mass of the target nucleus against any naive expectation of a scaling law with the number of nucleons in the target. A set of measurements of antiproton-proton and antiproton-nucleus annihilation and of widths and shifts of antiprotonic atoms, together with several model analyses have demonstrated that huge saturation effects dominate the $\bar{p}$ -nucleus interaction, both in the negative energy bound state domain and in the positive energy reaction sector. Measurements of the total annihilation cross sections for antinucleons on light nuclei are also relevant for fundamental cosmology. Moreover in presence of more complete sets of data, well-tested few-body techniques exist that would permit to relate data on light nuclei to subnuclear interactions (at least in the case of D, ^{3}He and ^{4}He). The recent results on deeply bound meson-nuclear states reinforce for a better knowledge on inelastic $\bar{p}$ reactions in these elements.

SESSION 3

Low Energy Antiproton Experiments – A Review

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Low energy antiprotons offer excellent opportunities to study properties of fundamental forces and symmetries in nature. They can contribute substantially to deepen our fundamental knowledge in atomic, nuclear and particle physics. Searches for new interactions can be carried out by studying discrete symmetries. Known interactions can be tested precisely and fundamental constants can be extracted from accurate measurements.
Among the pioneering experiments have been the trapping of single antiprotons in a Penning trap, the formation and precise studies of antiprotonic helium atomcules and recently the production of antihydrogen. These experiments have led to precise values for antiproton parameters, accurate tests of bound three-body QED, tests of the CPT theorem and better understanding of atom formation. Future experiments promise more precise tests of the standard theory and have a robust potential to discover new physics.
Precsision experiments with low energy antiprotons share the need for intense particle sources and the need for time to develop novel instrumentation with all other experiments, which aim for high precision in exotic fundamental systems. The experimental programs – carried out mostly at the former LEAR facility and at present at the AD facility at CERN – would benefit from intense future sources of low energy antiprotons.
Examples of key antiproton experiments will be given and compared with other experiments in the field. Among the central issues will be their potential to obtain important information on basic symmetries such as CPT and to gain insights into antiparticle gravitation as well as the possibilities to learn about nuclear neutron densities.

Project ALPHA and the Future of Antihydrogen Physics

Following the success of ATHENA and ATRAP at producing antihydrogen atoms from cold plasmas of trapped positrons and antiprotons, it is natural to contemplate the prospect for trapping the anti-atoms. The ALPHA (Antihydrogen Laser PHysics Apparatus) collaboration has been formed to design and construct a next-generation antihydrogen apparatus at the CERN Antiproton Decelerator (AD). In this talk I will present the design, physics goals, and status of the ALPHA project. The heart of the device is a superconducting magnet system comprising a transverse multipole and mirror coils for trapping antihydrogen. An annihilation vertex detector based on silicon strip modules will diagnose antihydrogen formation and trapping. The collaboration intends to begin antihydrogen production and trapping studies with this device in mid-2006.

J.S. Hangst on behalf of the ALPHA Collaboration:

ATRAP - on the way to trapped Antihydrogen

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The ATRAP experiment at the CERN antiproton decelerator AD aims for a test of the CPT invariance by a high precision comparison of the 1s-2s transition between the hydrogen and the antihydrogen atom.

Antihydrogen production is routinely operated at ATRAP [1] in a nested Penning trap configuration. It is built by a stack of ring electrodes located in a uniform magnetic solenoid field which allows to prepare the required potential structure for the trapping of antiprotons and positrons.

Detailed studies have been performed in order to optimize the production efficiency of useful antihydrogen. The shape parameters of the antiproton and positron clouds, the N-state distribution of the produced Rydberg antihydrogen atoms [2] and the antihydrogen velocity [3] have been studied. Furthermore an alternative method of antihydrogen production via two subsequent charge exchange processes was sucessfully applied [4]. Cs Rydberg atoms prepared by laser excitation pass through a positron cloud were Rydberg Positronium is produced which subsequently interacts with antiprotons resulting in the production of Rydberg antihydrogen in well defined Rydberg states.

For high precision measurements of atomic transitions cold antihydrogen in the ground state is required which has to be trapped due to the low number of available antihydrogen atoms compared to the cold hydrogen beam used for hydrogen spectroscopy. The trapping of neutral antihydrogen atoms works via the force on the magnetic moment in a magnetic field gradient which drives the atoms towards the minimum of the magnetic field for a state with spin orientation parallel to the field direction.

To ensure a high antihydrogen trapping efficiency a magnetic trap has to be superposed the nested Penning trap. A basic question in such a configuration is the possibility to keep the charged particle clouds, the antiprotons and the positrons, in the stabilizing solenoid field which is strongly distorted by the varying field of the magnetic trap.

First trapping tests of charged particles within a combined magnetic/Penning trap have started at ATRAP. The Penning trap was surrounded by a permanent quadrupole magnet. Due to space limitations only a relatively low magnetic field gradient of about 15 T/m was possible. Studies with varying electron densities and different solenoid fields down to 1T were performed where stable trapping of Electron clouds could be achieved.

References:

[1] G. Gabrielse et al., Phys. Rev. Lett. 89, 213401 (2002).

[2] G. Gabrielse et al., Phys. Rev. Lett. 89, 233401 (2002).

[3] G. Gabrielse et al.,Phy. Rev. Lett. 93, 073401 (2004).

[4] C.H. Storry et al., Phy. Rev. Lett. 93, 263401 (2004).

SESSION 4

Lorentz and CPT tests involving antiprotons

Ralf Lehnert
Physics and Astronomy Department, Vanderbilt University, Nashville, Tennessee 37235

Perhaps the largest gap in our understanding of nature at the smallest scales is a consistent quantum theory underlying the Standard Model and General Relativity. Substantial theoretical research has been performed in this context, but observational efforts are hampered by the expected Planck suppression of deviations from conventional physics. However, a variety of candidate models predict minute violations of both Lorentz and CPT invariance. Such effects open a promising avenue for experimental research in this field because these symmetries are amenable to Planck-precision tests.

The low-energy signatures of Lorentz and CPT breaking are described by an effective field theory called the Standard-Model Extension (SME). In addition to the body of established physics (i.e., the Standard Model and General Relativity), this framework incorporates all Lorentz- and CPT-violating corrections compatible with key principles of physics. To date, the SME has provided the basis for the analysis of numerous tests of Lorentz and CPT symmetry involving protons, neutrons, electrons, muons, and photons. Discovery potential exists in neutrino physics.

A particularly promising class of Planck-scale tests involve matter-antimatter comparisons at low temperatures. SME predictions for transitions frequencies in such systems include both diurnal variations and matter-antimatter differences. For example, in hydrogen-antihydrogen spectroscopy, leading-order effects in a 1s-2s transition as well as in a 1s-Zeeman transition could exist that can be employed to obtain clean constraints. Similarly, tight bounds can be obtained from Penning-trap experiments involving antiprotons.

Anti-hydrogen production conditions in ATHENA.

What we (don't) know.

Paul D. Bowe (for the ATHENA collaboration)
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Antihydrogen was produced in large quantities in the ATHENA experiment at CERN over a three-year period. The usefulness of the anti-atoms so produced and the feasibility of future experiments with antihydrogen depend on the quantum state and momentum distribution of the anti-atoms. For beam-like experiments ground state anti-atoms should emerge from the interaction region in a preferential direction with both low divergence and velocity spread. Experiments aimed at trapping antihydrogen require low velocity anti-atoms and states with low quantum number. I will report on experiments which attempted to elucidate these matters.

A summary of the antihydrogen production efficiency over the three-year period will be given[1]. I will present the results of experiments which attempted to measure the production rate as a function of positron temperature[2,3] as well as the onset time of antihydrogen production[4]. Recent analysis of the spatial distribution of antihydrogen[5,6] indicates that antihydrogen is produced before the antiprotons and positrons have reached thermal equilibrium, meaning that the antihydrogen is moving too fast to be trapped. Time permitting; various mixing techniques will be presented which might overcome this difficulty in the future. A preliminary report on an attempted stimulated recombination experiment will be given.

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[1] M. Amoretti *et al*. Phys. Lett. B 578, 23-32 (2004)
[2] M. Amoretti *et al*. Phys. Rev. Lett. 91, 055001 (2003)
[3] M. Amoretti *et al*. Phys. Lett. B 583, 59-67 (2004)
[4] M. Amoretti *et al*. Phys. Lett. B 590, 133-142 (2004)
[5] M. C. Fujiwara *et al.* Phys. Rev. Lett. 92, 065005 (2004)
[6] N. Madsen *et al*. Phys. Rev. Lett. 94, 033403 (2005)

A new path toward gravity experiments with anti-hydrogen

Patrice PEREZ
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Abstract:
We propose to use a 13 KeV antiproton beam passing through a dense cloud of positronium (Ps) atoms to produce an Hbar+ ``beam''. These ions can be slowed down and captured by a trap. The process involves two reactions with large cross sections under the same experimental conditions. These reactions are the interaction of antiprotons with positronium to produce the anti-hydrogen atom and the positron capture by this atom reacting on positronium to produce Hbar+. Once decelerated with an electrostatic field and captured in a trap the Hbar+ ions could be cooled and the e+ removed with a laser to perform a measurement of the gravitational acceleration of neutral antimatter in the gravity field of the Earth.

SESSION 5

Production of ultra-slow antiproton beams

Hiroyuki A. Torii*, N. Kuroda†, M. Shibata†, Y. Nagata*, D. Barna‡, M. Hori§, J. Eades§, A. Mohri†, K. Komaki* and Y. Yamazaki*†

*Institute of Physics, University of Tokyo,
†Atomic Physics Lab., RIKEN, ‡KFKI (Budapest), §CERN

In the study of atomic physics, exotic particles with negative charge have played an important role in revealing atomic capture processes as well as structures of formed exotic atoms. Among them, antiprotons with its infinite lifetime can be a best-suited probe, especially if they can be cooled to (sub-)atomic energies and become available as a mono-energetic beam at 10–1000 eV. With the aim of decelerating and cooling the antiproton beams delivered from the AD facility (at 5.3 MeV), ASACUSA collaboration prepared a sequential combination of an RFQD (Radio-Frequency Quadrupole Decelerator; down to 50–120 keV), degrader foils (to less than 10 keV) and a Multi-Ring electrode Trap (MRT) installed in a superconducting magnet of 2.5 T. Here the antiprotons were cooled by preloaded electrons to energies less than an electronvolt.

In order to extract the antiprotons out of the strong magnetic field and transport them to a field-free region for atomic physics experiments, a 3 m beamline was designed [1], where the antiproton beam was refocused three times by sets of Einzel lenses at the position of apertures. These variable apertures of diameter 4–10 mm allow differential pumping of 6 orders of magnitude along the beamline, which was necessary to keep the trap region at an ultra-high vacuum better than 10^{-12} Torr so as to avoid antiproton annihilation, while the end of the beamline will be exposed to atomic or molecular gas jets of upto 10^{-6} Torr in our near-future experiments.

We have so far achieved efficient confinement of millions of antiprotons in the MRT [2], and recently succeeded in producing an ultra-slow monoenergetic antiproton beam by extracting the trapped antiprotons and transporting them at a typical energy of 250 eV.

The MRT, the superconducting solenoid and the eV-beam transport line are jointly known as "MUSASHI", or the Monoenergetic Ultra-Slow Antiproton Source for High-precision Investigations. A variety of physics experiments will become possible using the unique beam from MUSASHI, ranging from atomic physics to nuclear physics [3]. The ultra-low energy of the beam allows single collision experiment with atomic targets, while the continuous aspect of the slowly extracted beam of 10 s duration per each spill allows event-by-event data acquisition associated with each single antiproton extracted.

Especially, we are preparing a supersonic gas-jet target to study atomic formation and ionization processes under single collision conditions. The target is aimed to achieve a density of 3×10^{13} cm^{-3} with a gas-jet cross section of 5 mm $\times$ 1 cm [4], which will be crossed with the beam of 10^5 antiprotons to produce 10^2 antiprotonic atoms per spill.

The overview of the project will be presented with an enphasis on the key points for efficient extraction from the strong magnetic field.

References

[1] K. Yoshiki Franzen *et al.*, Rev. Sci. Instrum. **74** (2003) 3305.
[2] N. Kuroda *et al.*, Phys. Rev. Lett. **94** (2005) 023401.
[3] Y. Yamazaki, Nucl. Instrum. Methods **B154** (1999) 174.
[4] V. Varentsov, Contribution to this conference. Refer to his abstract.

The Anticyclotron Project

Dezso Horvath, Budapest

Abstract for the Workshop on Physics with Ultra Slow Antiproton Beams

RIKEN, 14-16 March 2005

For trapping large numbers of antiprotons one needs an intermediate stage between the main source of antiprotons (like the Antiproton Decelerator or the former LEAR at CERN) of typically a few MeV energy and the trap which requires 10-100 keV antiprotons.

The anticyclotron project was started at CERN in 1990 based on the cyclotron trap developed at Karlsruhe and PSI/SIN for studying the pbar X-ray cascades in low-pressure gases. The anticyclotron is a small superconducting cyclotron with no RF field, operating in an inverse way: radial injection and --- after deceleration in a low pressure gas --- axial extraction. It was proposed to serve as a basic apparatus to provide an ultra-low energy antiproton beam at LEAR with a predicted transmission efficiency up to 20% using 0.3 mbar hydrogen as moderator gas [1-3].

The anticyclotron tests started at LEAR with 2 MeV antiprotons decelerating in a low--pressure gas and continued in the early 90's at PSI with 4 MeV negative muons with a thin Mylar foil in the median plane as a moderator medium, providing a 5-25 keV negative muon beam extracted with a 2% efficiency. Based on the experience with the original apparatus a new anticyclotron was designed [1] and built at PSI. It is used for precision pionic hydrogen measurements [4] as well as a source of low-energy negative muons [3, 5].

[1] L. M. Simons: Hyperfine Interactions 81 (1993) 253.
[2] D. Horvath et al.: Nucl. Instr. Meth. B 85 (1994) 736.
[3] P. DeCecco et al.: Nucl. Instr. Meth. A 394 (1997) 287.
[4] D. Gotta: Prog. Part. Nucl. Phys. 52 (2004) 133.
[5] F. Kottmann et al.: Hyperfine Interactions 138 (2001) 55.

Intense source of slow positrons

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Abstract:
We describe a novel design for an intense source of slow positrons based on pair production with a beam of electrons from a 10 MeV accelerator hitting a thin target at a low incidence angle. The positrons are collected with a set of coils adapted to the large production angle. The collection system is designed to inject the positrons in a Greaves-Surko trap. Such a source could be the basis for a series of experiments in fundamental and applied research and would also be a prototype source for industrial applications which concern the field of defect characterization in the nanometer scale.

ASACUSA Gas-Jet Target: Present Status And Future Development

V.L. Varentsov[2, 3], N. Kuroda [2], Y. Nagata [1, 2], H. A. Torii [1], M. Shibata[2], Y. Yamazaki[1, 2]

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Abstract. A supersonic gas-jet target apparatus that have been prepared to study elementary processes of antiprotonic atoms formation using monoenergetic ultra-slow antiproton beams is described. We investigated an operation of this target with cryogenically cooled nozzle by both gas dynamic simulations and supersonic jet measurements. In result, the helium target density of $2x10^{12}$ atoms/cm^3 has been obtained.
For considerable increasing of the target density, a qualitative modification of the present target setup is suggested. The goal can be achieved by the use of pulsed high-pressure supersonic gas jet that operates in accordance with the pulsed mode of the MUSASHI penning trap. For this purpose an additional stage of differential pumping with a skimmer will be set into the present target setup. To avoid the clusters in the gas-jet target, a sonic nozzle equipped with a solenoid driven pulsed gas valve will be used at room or higher temperatures. The operation of this future version of the gas-jet target apparatus has been studied by means of detailed computer simulations. Results of these calculations for helium, which show availability of the pulsed gas target density of $3x10^{13}$ atoms/cm^3, are presented also.

SESSION 6

Prospects of CPT tests using antiprotonic helium and antihydrogen

R.S. Hayano
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My talk is based on the ASACUSA proposal recently presented to the CERN program committee.

1) Laser spectroscopy of antiprotonic helium atoms, with which we achieved the best baryonic CPT test of $|m_p - m_{\bar{p}}|/m_p < 10^{-8}$ in 2003, will be further pursued to the sub-ppb ($< 10^{-9}$) range. This requires frequency-comb-stabilized lasers, Doppler-width cancellation with the counter-propagating two-photon method, and an order of magnitude improvement in the precision of theoretical calculations.

2) The ground-state hyperfine splitting spectroscopy of antihydrogen is important, because even a modest precision of 10^{-4} can be competitive to the best CPT test available ($K^0 - \bar{K}^0$ relative mass difference of 10^{-18}). After a brief introduction to the theoretical background, requirements for the antihydrogen source, achievable precision, and a possible setup will be discussed.

Non-Neutral Plasma Confinement in a Cusp -Trap and Possible Application to Anti-Hydrogen Beam Generation

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Combination of a magnetic quadrupole (cusp) with an electric octupole (MCEO, or cusp-trap) forms a trap for non-neutral plasmas. Perfect trapping of a single charged particle[1)] and the existence of the equilibrium of cold non-neural plasmas at the Brillouin limit in this cusp-trap[2)] have been proved theoretically. Also, experiments performed so far have shown that electron plasmas with finite temperatures can be confined in the cusp-trap for a long time[3)].

In order to synthesize anti-hydrogen from cold positrons and antiprotons, a positron plasma trapped in the cusp trap should possess an internal electric field to grasp antiprotons for mixing. If cold anti-hydrogen atoms are synthesized, they come out as a focused spin-polarized beam from the trap[4)]. This internal electric field would appear through confinement dynamics of the positron plasma. For studying such an essential problem, a new cusp-trap with a super-conducting quadrupole magnet, which generates the field strength of 3.5 T and the field gradient up to 35 T/m, has been completed at RIKEN. Experiments using this trap are now being performed on electron confinement in a warm bore.

At the workshop, brief explanation of how the cusp-trap confines non-neutral plasma will be given and experimental results obtained in the new device are to be reported.

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A compact setup of fast pnCCDs for exotic atom measurements

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Measurements at particle accelerators suffer from a high beam-induced background. For low-intensity X-ray measurements CCDs can solve this problem due to their pixel structure, which allows to reduce the background by a cluster analysis. Usual CCDs, however, have the disadvantage of only a thin depletion zone and long readout times possibly leading to over illumination. Fast read-out capable CCDs , so called pnCCDs, have been developed at the semi-conductor laboratory of the Max Planck Institute (MPI) for the XMM satellite misson.

One advantage of the chosen CCD setup is, that every channel of the pixel matrix is connected to its own amplifier in a multi amplifier chip (CAMEX). The parallel readout of one line reduces the readout time per frame allowing event rates of more than 100 $K/s{*}cm^2$ without loss in energy resolution. Secondly, the complete detector thickness of 300 μm is depleted and together with a very thin entrance window, the pnCCD reaches a quantum efficiency of better than 80% for energies between 1 and 10 keV. Recently an improved version of pnCCDs was developed. These chips will be available with different pixel size and geometries.

At the ZEL (Central Laboratory for Electronics) of the research center Jülich a dedicated electronics for fast readout was developed in collaboration with the MPI. The aim was toobtain a compact and flexible detector setup with an easily manageable user interface providing computer controlling of all relevant detector parameters. The prototype detector consists of a detector head installed inside a vacuum cryostat, supporting a first generation CCD-chip with its amplifier chip CAMEX and mounted on a ceramic platine attached to a cooling mask, the external electronics with power supplies, ADCs and a digital pulse generator.

The working principle and the present and future performance of pnCCDs, readout chip CAMEX and the external electronics will be demonstrated from first measurements at the high intensity pion beam of the Paul-Scherrer-Institut (PSI).

SESSION 7

Imaging Antimatter: The Challenges and Applications

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Position sensitive detection of antiprotons and positrons was a key feature of the ATHENA experiment in establishing the production of old antihydrogen atoms, and in subsequent physics measurements [1]. After a brief review of the ATHENA detection system, I will discuss a recent example of its applications in trap physics [2]. By reconstructing annihilation vertices, images of antiproton annihilations in a Penning trap are obtained. The capability of antiparticle imaging allows, for the fist time, the observation of the spatial distribution of the particle loss in a Penning trap, a previously unexplored regime in trap physics. The radial loss of antiprotons on the trap wall is localized to small "hot spots," strongly breaking the azimuthal symmetry expected for an ideal trap. Important implications for antihydrogen detection will be discussed.

In a proposed experiment ALPHA [3], we will face new challenges in antihydrogen detection. In particular, the thickness of the materials between the annihilation points and the detector can be up to one radiation length, a condition imposed by the requirements for trapping neutral antihydrogen atoms. This will absorb most of the 511 gamma rays, and increase multiple scattering for charged pions. I will present a preliminary design of the new antihydrogen detector for the Project ALPHA, and discuss how we plan to overcome these challenges.

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Abstract of Workshop on Physics with Ultra Slow Antiproton Beams,
RIKEN, March 14-16, 2005.

Confinement of toroidal non-neutral plasma in Proto-RT

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In contrast to linear configurations for non-neutral plasmas, toroidal devices allow us to trap charged particles without the use of a plugging electric field. Thus it has a potential ability to confine high-energy particles or to simultaneously trap multiple particles with different charges. In spite of the relatively long history of the study in pure toroidal magnetic field devices, toroidal non-neutral plasmas are attracting renewed interest with the use of magnetic surface configurations [1, 2]. Possible applications of toroidal trap for non-neutral plasmas are formation of matter-antimatter plasmas [2], investigation on the fundamental properties of exotic plasmas including pair (equal mass) plasmas, and experimental test on the equilibrium and stability of flowing plasmas [3].

As an initial test on non-neutral plasmas in the toroidal magnetic-surface geometry, formation and confinement properties of pure electron plasma have been investigated at Prototype-Ring Trap (Proto-RT) device with a dipole magnetic field [1, 4, 5]. Electrons can be injected by using chaotic orbits near a magnetic null line generated by the combination of dipole and vertical magnetic fields [4]. The confinement time of electrons is limited due to the effects of collisions with remaining neutral gas, and electrons of $\sim 10^{12}$ are trapped for ~0.5s in the typical magnetic field strength of 100G and back pressure of 4×10^{-7}Torr in Proto-RT. Although the present experiment was carried out on the single-component plasma, the result shows that a stable confinement geometry has been realized for toroidal non-neutral plasmas by using the magnetic surface configuration.

Together with the recent experiments on the toroidal pure electron plasma in Proto-RT, preliminary prospects for the injection and trap of anti-protons and positrons in the toroidal magnetic surface configuration, and creation of multi-component plasmas will be described.

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On the possibility of non-neutral antiproton plasmas and antihydrogen plasmas

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A large number of slow antiprotons have been confined in particle traps at Antiproton Decelerator (AD) in CERN. However, a unique feature as a non-neutral antiproton plasma has not been reported. It is thought that the size of the antiproton cloud was smaller than its Debye length. Progresses in accumulating a larger number of low energy antiprotons with AD, Radio Frequency Quadrupole Decelerator (RFQD), and Musashi trap in ASACUSA enables the confinement of a larger antiproton cloud. Further improvement in stacking antiproton pulses will lead to the observation of the plasma oscillations of a non-neutral antiproton plasma. This is also favorable for the effective production of low energy antiproton beams to be used in atomic collision experiments.

The possibility of producing non-neutral antihydrogen plasmas is also considered with a magnetic mirror configuration. Although antihydrogen atoms were created by mixing a positron plasma and antiproton cloud, it was a kind of beam-plasma system. The basic procedure is to accumulate both antiprotons and positrons in a nested Penning trap in a magnetic mirror field. It is assumed here that more positrons are trapped than antiprotons. Adiabatic expansion of particles along the magnetic field by reducing the trapping potential results in an anisotropic energy distribution. Then, the positron plasma can be trapped with the magnetic mirror field and antiprotons can be trapped simultaneously with the magnetic field and the space potential of the positron plasma. A strongly magnetized positron plasma may enhance the confinement time of the non-neutral antihydrogen plasma.

Control of plasmas for production of ultraslow antiproton beams

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Ultraslow antiproton beams in the 10 – 500 eV will be applicable for studies of the elementary processes of production of antiprotonic atoms [1]. ASACUSA collaboration prepared ultraslow antiproton beam source, MUSASHI (Monoenergetic Ultra Slow Antiproton Source for High-precision Investigation), by a combination with the CERN Antiproton Decelerator (AD) and a radio frequency quadrupole decelerator (RFQD) [2]. The MUSASHI is composed of two parts, an electro-magnetic trap (called multiring trap, MRT), and a low energy beam transport line. After the deceleration and cooling by the AD and the RFQD, antiprotons in 10 keV were captured and cooled to sub-eV energy via collisions between simultaneously trapped electrons in the MRT. Such cold antiprotons were extracted out of a strong magnetic field, re-accelerated, and focused into field-free region by using electrostatic lenses [3].
Since charged particles tend to follow magnetic field lines, a cloud of antiprotons should have a small radius in the MRT for better focusing of extracted beams. Without any radial compression, we have observed that the most of extracted antiprotons from the MRT annihilated around the entrance electrodes of the low energy antiproton beam transport line, where the strength of the magnetic field dropped. Therefore we developed a technique to control the radial distribution of antiproton clouds by rotating electric dipole fields.
In the MRT, it is known that cold charged particle clouds behave as non-neutral plasmas. Since electrostatic mode frequencies of non-neutral plasmas depend on the temperature, the observation of their modes allows nondestructive measurement of antiproton cooling process. We realized it by real time monitoring of electrostatic mode frequencies with a real time spectrum analyzer.

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SESSION 8

The Deepest Symmetries of Nature

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Abstract for the Workshop on Physics with Ultra Slow Antiproton Beams

RIKEN, 14-16 March 2005

The structure of matter is related to symmetries on every level of study. CPT symmetry is one of the most important laws of field theory: it states the invariance of physical propoerties when simultaneously changing the signs of the charge and of the spatial and time coordinates of particles. Although in general opinion CPT symmetry cannot be violated in Nature, there are theoretical attempts to develope CPT-violating models. The Antiproton Decelerator at CERN was built to test CPT invariance.

Several observations imply that there might be another deep symmetry, supersymmetry (SUSY), between basic fermions and bosons. SUSY assumes that every fermion and boson observed so far has supersymmetric partners of the opposite nature. In addition to some theoretical problems of the Standard Model of elementary particles supersymmetry may provide solution to the constituents of the mysterious dark matter of the Universe. However, as opposed to CPT, SUSY is necessarily violated at low energies as so far none of the predicted supersymmetric partners of existing particles was observed experimentally. The LHC experiments at CERN aim to search for these particles.

Workshop at RIKEN 14-16 March

ABSTRACT: The Antiproton and How it was Discovered - John EADES

The antiproton celebrates its 50th birthday this year. Although its existence had been suspected since the discovery of the positron in 1932, there was still doubt in some quarters that such a companion particle to the proton could exist. I will try to trace the scientific history of the antiproton from that time to the publication of the definitive paper by Chamberlain, Segrè, Wiegand and Ypsilantis in November 2005. The narrative will be supplemented with thoughts and opinions of some of the main actors, both at the time and in retrospect,

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SESSION 9

Nuclear structure studies with low energy antiprotons

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Abstract

The nuclear capture of stopped $\bar{p}$ has been used to study the neutron density distributions in nuclei. Three well established methods were used for this purpose: the atomic X-rays measurements [1,2], radiochemical detection of residual nuclei [2] and the detection of charged π mesons emitted in the $\bar{p}N$annihilation [3]. The extension of the last method to study trapped, unstable nuclei is proposed by the RIKEN group [4]. An alternative method of $\bar{p}$ capture in flight is proposed by the AIC collaboration [5].

The X-ray measurements offer an advantage of well defined initial states, but cannot distinguish the proton contribution from the neutron one. The other methods can do that, but require additional data: the strengths of the $\bar{p}p$ and $\bar{p}n$ absorption rates and the knowledge of initial capture states.

Few problems that arise in the analysis of the existing and the forthcoming data will be discussed. All, these capture modes test neutron density distributions in different regions of nuclei and yield complementary information on the R_{ms} and higher moments of the neutron density profiles. In particular the radiochemistry tests the highest and the in flight experiments will test the lowest of the available moments. Some advantages and difficulties of these experimental methods are indicated.

The best ratio of $\bar{p}p$ and $\bar{p}n$ absorption rates will be extracted from antiprotonic atoms in particular the $\bar{p}D$, $\bar{p}He$ and CERN chamber experiments. The comparison with theoretical $\bar{N}N$ interaction models will be made.

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Antiprotonic atoms - a tool for the investigation of the nuclear periphery

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The antiprotonic atoms are useful tool for study of the nuclear periphery. Antiprotons captured onto the atomic orbits cascade down emitting X rays. In the vicinity of a nucleus the strong interaction reveals its presence: antiprotonic levels are shifted compared to the pure electromagnetic energy and are broadened. The width and shift of the levels give an information on the nuclear matter density on the nuclear periphery.

The antiprotonic cascade ends with the annihilation on a peripheral nucleon: a neutron or a proton. Two kinds of residues are produced: with one neutron or one proton less then the target nucleus, respectively. The yields of the products are proportional to the neutron to proton density ratio at the nuclear surface.

Neutron densities in 26 isotopes were studied using antiprotonic X rays. The information on the nuclear matter density at relatively large radii was then converted to rms radii by the use of a two-parameter Fermi-function form factor [1]. The obtained systematics of differences of the neutron and proton rms radii is in a fair agreement with theoretical calculations and results of other experimental methods [2].

A detailed analysis is in progress. In particular the model dependency of the results are studied.

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Light antiprotonic atoms

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The measurement of the characteristic X-radiation emitted from antiprotonic atoms constitutes an antinucleon-nucleus scattering experiment at relative energy zero. The strong interaction manifests in an energy shift and broadening of the low-lying atomic states. Shift and broadening are directly related to the complex antiproton-nucleus scattering length and are sensitive to the medium- and long range part of the antinucleon-nucleus interaction. The hydrogen isotopes allow access to the elementary systems antiproton-proton and -neutron. Light nuclei serve as a testing ground to build up a consistent picture of the antinucleon-nucleus interaction. Furthermore, the study of the atomic cascade and its pressure dependence sheds light on the processes governing the de-excitation of the antiprotonic atoms.

In antiprotonic hydrogen the resolution of hyperfine states, which is equivalent to a double polarisation experiment at threshold, became already possible during the LEAR era. The low precision, however, hinders a sensitive test of the various theoretical approaches. The experimental information on the antiproton-deuteron s-wave interaction urgently needs confirmation from a new measurement and the accuracy of the measurements of the helium isotopes is modest.

For precision studies of the strong-interaction effects high statistics is essential. In order to achieve sufficiently high X-ray yields antiprotonic hydrogen and helium must be formed in dilute gases to reduce the influence of non-radiative de-excitation processes owing to collisions. Therefore, gas targets in the mbar range having both thin entrance and exit windows must be used. Antiproton beams of 100-300 keV are well suited as planned for the low-energy antiproton facility FLAIR at GSI. The possibility to combine an antiproton plasma inside a trap with a gas jet might be considered in context with the improving performance of such devices (e. g., ASACUSA experiment at AD, CERN).

Energies of the low-lying X-ray transitions in hydrogen and helium isotopes are in the range 2-15 keV. For hydrogen, the hadronic effects are of the order of 1 keV and 10-500 meV for the s-wave and p-wave interaction, respectively. Consequently, the measurement requires two different approaches: a direct measurement with semiconductor detectors, e. g., fast CCDs and ultimate resolution by using a Bragg crystal spectrometer. Whereas CCDs allow an efficient reduction of the annihilation induced background by the analysis of the hit pattern, a Bragg spectrometer is self collimating due to the small angular acceptance. Even fast CCDs, processing about 500 frames per second, are limited to a continuous beam of about 10^5 antiprotons per second to avoid over illumination, whereas the crystal spectrometer is not yet rate limited at the design parameters of FLAIR.

Study of S = -2 baryonic states at FLAIR

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At the future FAIR project of the GSI low energy antiprotons will be available at FLAIR, the Facility for Low energy Antiproton and Ion Research. Within the FLAIR LOI [1] it is proposed to study the production of strangeness S = -2 baryonic states based on ideas proposed for LEAR [2].

The study of the baryon-baryon interaction is a basic tool to investigate the strong interaction. Especially in the strangeness S = -2 sector the available data are strongly limited. Most studies in this field were devoted to the search for the H-particle, a $(B = 2, S = -2)$ system with the quark configuration $(uuddss)$ first proposed by Jaffe [1]. The entrance into the S=-2 baryonic systems is mostly the cascade hyperon Ξ produced via K^- or p induced reactions. Slow Ξ particles can go into interacting ΞN systems which can couple to YY or might also directly connect to the H particle.

With stopped antiprotons a very efficient reaction chain for the production of slow Ξ hyperons can be initiated. In a first step a $\bar{K}^*$ "beam" is produced in the annihilation of a stopped antiproton on a nucleon. The production of $S = -2$ systems proceeds then in a second step via the double strangeness and charge exchange reaction $(\bar{K}^*, K)$. Due to the short decay length of a few fm both, $\bar{K}^*$ production and the double strangeness and charge exchange reaction have to take place in the same nucleus. The special feature of this reaction channel is the low momentum of the produced Ξ hyperon. The 'magic' $\bar{K}^*$ momentum at which the Ξ can be produced at rest is at around 200 MeV/c which is very close to the momentum of the produced $\bar{K}^*$ in the first reaction step.

The studies will start with the pure Ξ production via e.g. $\bar{p}d \rightarrow \Xi^- K_s^0 K^{*+}$. To investigate the ΞN , $\Lambda\Lambda$ or H systems a ^3He target has to be used. The slow Ξ hyperons with recoil momenta down to even zero MeV/c have a high probability of producing a (B = 2, S = -2) system. A further extension of the programme may be the production of double hypernuclei. With the technique of recoil-free kinematics the Ξ can also be produced and deposited in more extended nuclei. A highly efficient production of double hypernuclei is expected with this method.

From the experimental point of view the delayed decays of the strange exit particles allows a highly selective trigger on these reaction channels and the event reconstruction is relatively simple. A non magnetic detection system with track reconstruction ability is sufficient for the complete kinematical reconstruction.

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SESSION 10

Muonic Atom of Unstable Nuclei

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For decades, the study of muonic atoms has played an important role in establishing and refining the nuclear structure model, through muonic X-ray measurements that yielded very precise and absolute values for the charge radii and other ground state properties of stable nuclei [1]. New intense muon beams, with fluxes several orders of magnitude higher than at present muon facilities, would allow many novel experimental studies that were statistically not feasible. The investigation of the nuclear properties of short-lived nuclei using muonic atom spectroscopy would become possible. Muonic X-ray measurements of unstable nuclei would be a unique tool to increase our knowledge of the nuclear structure far from stability, in particular the nuclear charge distribution and the deformation properties of nuclei.

We proposed the cold hydrogen film method [2] to extend muonic atom spectroscopy to the use of radioactive isotope (RI) beams to produce unstable muonic atoms. The basic concept of this method is to stop both negative muon and RI beams simultaneously in a solid hydrogen film, followed by the direct muon transfer reaction to higher Z nuclei to form muonic atoms. This method would allow studies of the nuclear properties of unstable nuclei, in particular the nuclear charge distribution, by means of the muonic X-ray method at facilities where both intense negative muon and RI beams would be available. For instance, the neutrino factory concept to produce intense muon beams is very attractive to realize the proposed study, because the same driver beam could also be used for next generation RI beam facilities. This would be a unique opportunity to combine massive amounts of muons with very intense RI beams.

An experimental program is in progress at the RIKEN-RAL Muon Facility to demonstrate the feasibility of this method. An apparatus has been constructed to perform X-ray spectroscopy with muonic atoms formed from stable ions implanted in solid hydrogenous films [2]. Already solid deuterium targets with various concentration of implanted argon ions showed very clearly delayed muonic argon 2p-1s transition X-rays at 644 keV from the muon transfer reaction. Also, as an intermediate step towards muonic spectroscopy with unstable nuclei, an experiment using long-lived isotopes is under consideration. Radium isotopes are of strong interest, since there are no stable isotopes for good measurements of nuclear parameters like the nuclear charge radius. These parameters would be urgently needed to exploit the full potential of the radium atom for atomic parity non-conservation studies [3]. A new surface ionization ion source is now under development with the goal of using later radioactive isotopes. At first, stable barium ions will produced for tuning and optimization, and to test the system safety. The latest experimental developments will be reported at the conference. Future perspective at the new Muon Experimental Facility in the J-PARC project will also be discussed.

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Neutron density distributions of the Sn isotopes and Ca isotopebs extracted from the proton elastic scattering

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Cross sections and analyzing powers of proton elastic scattering off ^{58}Ni, ^{40,42,44,48}Ca, and ^{116,118,120,122,124}Sn have been measured up to the angle of 3.5 fm^{-1} in momentum transfer to deduce a systematic change of neutron density distributions. The mean free path of intermediate energy protons in nuclear matter is large enough to penetrate into the nucleus, providing some sensitivity to the nuclear interior. The measurement has been performed at RCNP Osaka University ring cyclotron with the use of the Grand Raiden spectrometer, the focal plane counters.

We used the relativistic impulse approximation (RIA) calculation [1]. Since the shapes of neutron and proton density distributions are supposed to be the same in ^{58}Ni, we have used the proton elastic scattering from ^{58}Ni as a reference to tune the relativistic Love-Franey interaction that the coupling constants and masses of exchanging mesons are depend on nuclear density distributuins [2]. Point proton distributions are unfolded from the existing charge distribution data [3, 4]. After confirming that our interaction is applicable to the scattering off heavier nuclei such as the proton elastic scattering off ^{208}Pb at nearby beam energy [5] by using the same parameters of ^{58}Ni [6], we applied the elastic scattering to deduce the neutron density distributions of Ca and Sn isotopes by using the proton density distributions and the tuned interaction. The result of our analysis shows a clear systematic behavier which shows a gradual filling in the 1f$_{7/2}$ and 3s$_{1/2}$ neuton single particle orbit and a systematic change of neutron thickness.

We have been planning the proton elastic scattering off unstable nuclei experiment at the intermidiate energy by using inverse kinematics. We measure the proton elastic scattering the scattering angles and the energies of the recoiled protons from hydrogen target. We expect to be able to extract the neutron density distributions of not only stable nuclei but unstable nuclei.

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Highly charged ions at rest: The HITRAP project at GSI

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The planned HITRAP facility at GSI in Darmstadt will make highly-charged ions up to bare uranium available at very low energy. Later, HITRAP will be a central part in the low energy section, in the facility for low energy antiproton and ion research (FLAIR), at the planned international accelerator facility for research with ions and antiprotons (FAIR). There, HITRAP will not only provide low energy highly charged ions but also low energy antiprotons. First, the ions or antiprotons will be decelerated after production down to 4 MeV/u using the Experimental Storage Ring (ESR) at the present GSI facility and the New Experimental Storage Ring (NESR) followed by the Low Energy Storage Ring (LSR) at FAIR, respectively. This deceleration will be accompanied by electron cooling in the storage ring, such that the emittance of the beam does not grow. Then a linear decelerator will take over. After rebunching the beam will enter an IH structure and will be decelerated to 0.5 MeV/u. Then it will be rebunched again and sent to an RFQ decelerator. The final energy after the Radio-Frequency Quadrupole will be as low as 6 keV/u. There is no transverse cooling applied in the linear decelerator section, hence the emittance grows considerably. The beam after the RFQ will have about $100\,\pi$ mm mrad transversal emittance and an energy spread calculated to be in the order of 6%. In order to further slow down the antiprotons or highly-charged ions, the beam is captured in a Penning trap. There, electron cooling and subsequent resistive cooling will be applied to cool up to 10^5 charged particles.

A cylindrical Penning trap in a magnetic field of 6 T will be cooled to 4 K. This will ensure the best possible vacuum that is needed to store antiprotons or highly-charged ions long enough for the applied cooling. When injected into the strong magnetic field the ions or antiprotons will be decelerated further to energies below 2 keV/u. The strong magnetic field prohibits the transversal blow up of the beam in this phase. After the dynamic capture by closing the trap right in time, the ions or antiprotons will be first cooled by interaction with a dense electron plasma. After about 1 s the ions or antiprotons will be separated from the electrons and stored in a harmonic electric field region. There, resistive cooling will be applied in order to cool the particles to final temperatures close to 4 K, equivalent to energies below 1 meV. Then the ions or antiprotons will be ejected and sent to experiments in either of two ways. Slowly, that means 10^5 particles distributed over up to 10 s or fast, i.e. all particles within a few microseconds.

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SESSION 11

An Antiproton Ion Collider (AIC) for Measuring Neutron and Proton Distributions of Stable and Radioactive Nuclei

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Abstract

An antiproton-ion collider is proposed to independently determine rms radii for protons and neutrons in stable and short lived nuclei by means of antiproton absorption at medium energies.

The experiment makes use of the electron ion collider complex (ELISE) of the GSI FAIR project with appropriate modifications of the electron ring to store, cool and collide antiprotons of 30 MeV energy with 740A MeV ions in the NESR. Antiprotons are collected, in the RESR and will be cooled and slowed to 30 MeV by an additional electron cooler. Hereafter the 30 MeV antiprotons are transferred to the electron storage ring using a new transfer line.

Radioactive nuclei are produced by projectile fragmentation and projectile fission of 1.5A GeV primary beams and separated in the Super FRS. The separated beams are transferred to the collector ring (CR) and cooled at 740A MeV and transported via the RESR to NESR, in which especially short lived nuclei are accumulated continuously to increase the luminosity.

The total absorption cross-section for antiprotons on the stored ions with mass A will be measured by detecting the loss of stored ions by means of the Schottky method. Cross sections for the absorption on protons and neutrons, respectively, will be measured by the detection of residual nuclei with A-1 either by the Schottky method or by detecting them in recoil detectors after the first dipole stage of the NESR following the interaction zone. With a measurement of the A-1 fragment momentum distribution, one can test the momentum wave functions of the annihilated neutrons and protons, respectively. Furthermore by changing the incident ion energy the tails of neutron and proton distribution can be measured.

Theoretical calculations show that the absorption cross sections are in leading order directly proportional to the mean square radii. Predicted cross sections and luminosities show that the method is applicable to nuclei with production rates down to about 10^{5} s^{-1} or lower depending on the lifetime of the ions in the NESR and half-lives of about down to 1 second.

Nuclear matter radii determined by interaction cross sections

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Experimental studies on nuclear matter radii determined by interaction cross sections (σ_I) will be reviewed. Recently σ_I have been extensively measured at FRS facility in GSI, where RI beams with relativistic energies (~1 *A* GeV) are available. Using Glauber-model analysis, nuclear matter radii of unstable nuclei can be determined from the measured σ_I. We have determined nuclear matter radii in *p*-*sd* shell region and some Cl and Ar isotopes, as shown in Fig.1. In near future, measurements of σ_I will be performed in RIKEN RI beam factory (RIBF), where RI beam energies are around 400 *A* MeV. In RIBF, we will determine the nuclear matter radii for more neutron rich nuclei and much heavier nuclei up to Sn.

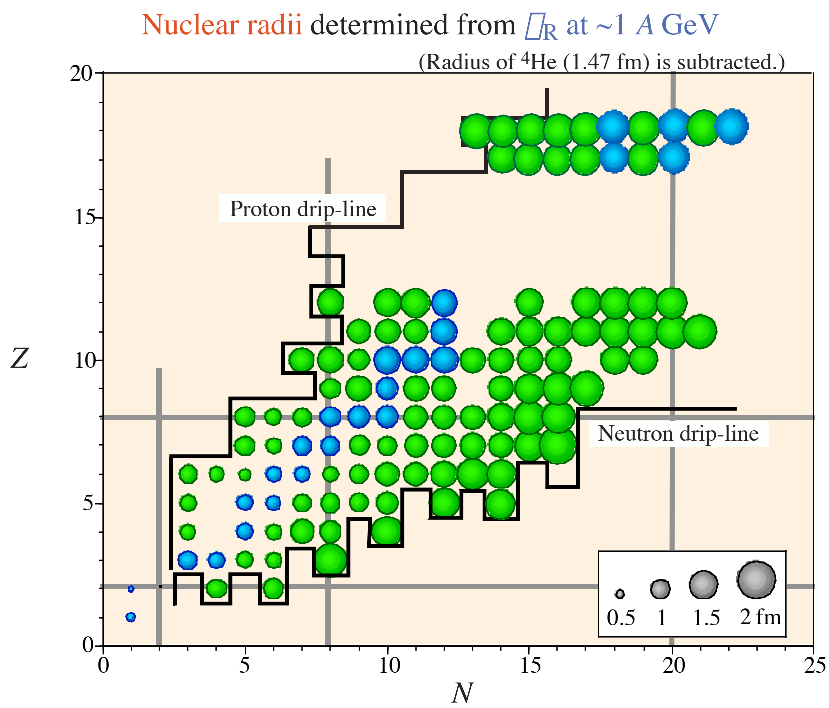

Fig. 1 Nuclear matter radii determined from interaction cross sections. Blue (green) circles show stable (unstable) nuclei, respectively.

Structure studies of unstable nuclei by electron scattering

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Electron scattering provides essential information on the internal structure of atomic nuclei. A new experimental scheme, **SCRIT** (**S**elf-**C**onfining **R**adioactive **I**sotope **T**arget), is proposed to study the internal structure of short-lived nuclei by electron scattering. Using a well-known ion-trapping phenomena at electron storage ring facilities, SCRIT forms a localized RI target on the circulating electron beam at an electron storage ring. Numerical simulations show that SCRIT provides a sufficiently high luminosity [1] for elastic electron scattering experiments to determine the charge form factor of short-lived nuclei, which has been never measured experimentally. A feasibility study of this new SCRIT scheme is now underway at an existing electron storage ring.

In the workshop, I will briefly introduce the electron scattering experiments for the charge form factor measurement, and discuss on the required luminosity. The SCRIT scheme is, then, introduced, and the results of feasibility studies currently on-going at an electron storage ring facility will be discussed.

[1] M. Wakasugi, T. Suda and Y. Yano, Nucl. Instrum. And Method A532 (2004) 216.

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SESSION 12

Antiprotonic Radioactive Atom for Nuclear Structure Studies

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Antiprotonic atom would be a new probe for nuclear structure studies, especially for the different peripheral distribution of protons and neutrons in a nucleus, which is in particular interesting for nuclei far from stability. Exotic properties of nuclei, such as halo and skin, have been investigated in such unstable nuclei.

Antiprotonic atoms have been studied exclusively for stable nuclei with various experimental methods. Antiprotonic atoms were produced by irradiating an antiproton beam on a fixed target material. When an antiproton is captured in an electronic orbital of an atom, it decays to lower levels by radiating auger electrons and X-rays. The lowest X-ray transition level and the shift indicate the matter radius of the nucleus [1]. At a certain level where a sizeable overlapping of the wavefunctions of the antiproton and the nucleons, an annihilation process between the antiproton and a nucleon of the nucleus occurs. The highlight of these studies should be that the annihilation dominantly occurs with a nucleon at the surface of the nucleus where the matter density is as small as 1/1000 of the center and that one can distinguish whether the vanished nucleon is a proton or a neutron by the following phenomena. One is that pbar-n and pbar-p annihilations produce charged pions with a net charge of -1 and 0, respectively. Bugg et al. used a bubble chamber to detect charged pions and identified the annihilated nucleons [2]. The other is the fact that the "cold" residual nucleus becomes ${}^{A-1}_{N-1}Z$ and ${}^{A-1}_{N}(Z-1)$ from the parent nucleus ${}^{A}_{N}Z$, as consequences of pbar-n and pbar-p annihilations, respectively. Warsaw group detected γ-rays from the residues in radio chemical way to identify the cold residues [3].

We proposed a future experiment aiming at investigations of the different abundance of protons and neutrons at the surface of nuclei far from stability by forming antiprotonic radioactive nuclear atoms in a nested Penning trap [4]. Here a cloud of antipronts are trapped in the central part of the trap as a target and slow radioactive ions are bunch injected in the outer well of the trap. If we assume a target density of 5×10^6 antiprotons in 1 mm^2, a slow RI-beam intensity of 10^3 s^{-1}, and a short measurement cycle of 10 ms for short-lived nuclei, an antiprotonic atoms production rate of 1 s^{-1} is expected. Charged pions radiated from the produced antiprotonic atoms are detected by multi-layer position sensitive detectors and the polarity of the charge is identified by the deflection direction in the magnetic field. Even if the detection efficiency is not unity, the annihilated nucleon can be identified statistically simply by accumulating the number of π^+ and π^- events throughout a measurement. If we assume a pion detection efficiency of 50% and a background event rate of 10%, 5×10^5 antiprotonic atoms enable us to determine the relative abundance ratio $\rho_\mathrm{n}/\rho_\mathrm{p}$ with an accuracy of 5%.

Measurements of X-rays from antiprotonic atoms enable us not only to determine the matter radii of the nuclei but also to identify the mean atomic level where annihilation has occurred. However, it is rather hard to realize a sufficiently high detection efficiency for MeV photons in the possible geometry of the experimental setup. This function would be a future option.

The statistical pion detection method would be a universal method. As long as the intensity of the slow radioactive ion beam is sufficiently high, any nuclides including drip-line nuclides can be experimental objects. Note that the "cold residues" of them are particle unbound.

[1] Trzcinska et al., Phys. Rev. Lett. 87 (2001) 82501.
[2] Bugg et al., Phys. Rev. Lett. 31 (1973) 475.
[3] Jastrzebski et al., Nucl. Phys. A588 (1993) 405c.
[4] M. Wada and Y. Yamazaki, Nucl. Instr. Meth. B214 (2004) 196.

Muonic Anti-Hydrogen; Production and Test of CPT Theorem

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Including antiproton $\bar{p}$, there are four types of hydrogen atoms allowing species involving μ^+ and μ^-: these are the conventional H atom (e^-p), the corresponding anti-atom $e^+\bar{p}$ ($\bar{H}$), and the two muonic counterparts, μ^-p and $\mu^+\bar{p}$. If a method of generating antihydrogen $\bar{H}$ ($e^+\bar{p}$) is established, it is widely discussed that 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. The advantage of the use of the μ^-p, $\mu^+\bar{p}$ pair is obvious. If the CPT-violating interaction is short-range (with an extremely massive exchange boson), such an effect can be seen more easily in the (μ^-p, $\mu^+\bar{p}$) case in comparison with that in the (e^-p, $e^+\bar{p}$) case since the atomic size becomes smaller by 1/207.

Since intense slow μ^+ and Mu beams will soon become available, it will be possible to produce $\mu^+\bar{p}$ through, e.g., the following reaction: Mu + $\bar{p}$ $\rightarrow \mu^+\bar{p}$ + e^-, i.e. thermal Mu and $\bar{p}$ reaction with the energy of $\bar{p}$ optimized for the binding energy of the final state $\mu^+\bar{p}$ ($E_{q.s.}(\mu^-\bar{p}) \sim 2.8$ keV). A crossed-beam experiment with a few keV 10^{10}/s $\bar{p}$ beam onto 10^{10} thermal Mu will produce a few $\mu^+\bar{p}$ atom/s. As for the detection of a formation of the $\mu^+\bar{p}$ atom, 1.9 keV 2p-1s transition photon will be an easiest way.

Precise CPT test will be considered to perform comparative measurements of the following energy intervals with the aid of high precision Resonant Laser Spectroscopy; e.g. ΔE (n = 1, hfs) = 0.183 eV or ΔE ($2^2p_{1/2} - 2^2s_{1/2}$) = 0.20 eV.