6th International Conference on

Trapped Charged Particle and Fundamental Physics

TCP2014

December 1st - 5th: Takamatsu, Japan

Welcome

Dear Colleagues,

We warmly welcome all conference participants and accompanying persons to the 6th International Conference on Trapped Charged Particles and Fundamental Physics (TCP2014), now being held at Kagawa International Conference Hall in Sunport Takamatsu Symbol Tower, on the Japanese island of Shikoku.

TCP2014 is organized by the RIKEN Nishina Center for Accelerator-Based Science and is supported by Kagawa Prefecture and Takamatsu Convention & Visitors Bureau.

The TCP conference series was launched with the first meeting in Lysekil (Sweden) in 1994, followed by conferences at Asilomar (USA) in 1998, Wildbad Kreuth (Germany) in 2002, Parksville on Vancouver Island (Canada) 2006 and Saariselkä, northern Finland in 2010.

The conference in Takamatsu focuses on recent developments and highlights in the field of trapped charged particles. In particular, it addresses the following scientific fields:

- Fundamental Interactions and Symmetries
- Quantum and QED Effects
- Precision Spectroscopy and Frequency Standards
- Anti-Hydrogen
- Plasma Effects and Collective Behavior
- Ion Traps for Radioactive Nuclei and Highly Charged Ions
- Storage Ring Physics
- Applications of Particle Trapping: Chemistry, Trace Analysis,

TCP2014 officially starts with TCP School at RIKEN on November 28th and 29th, followed by the registration opening in the evening of December 30th in Takamatsu, and ends on December 5th.

We hope you enjoy discussions in TCP2014 and beautiful nature in Takamatsu.

Michiharu Wada, Chair

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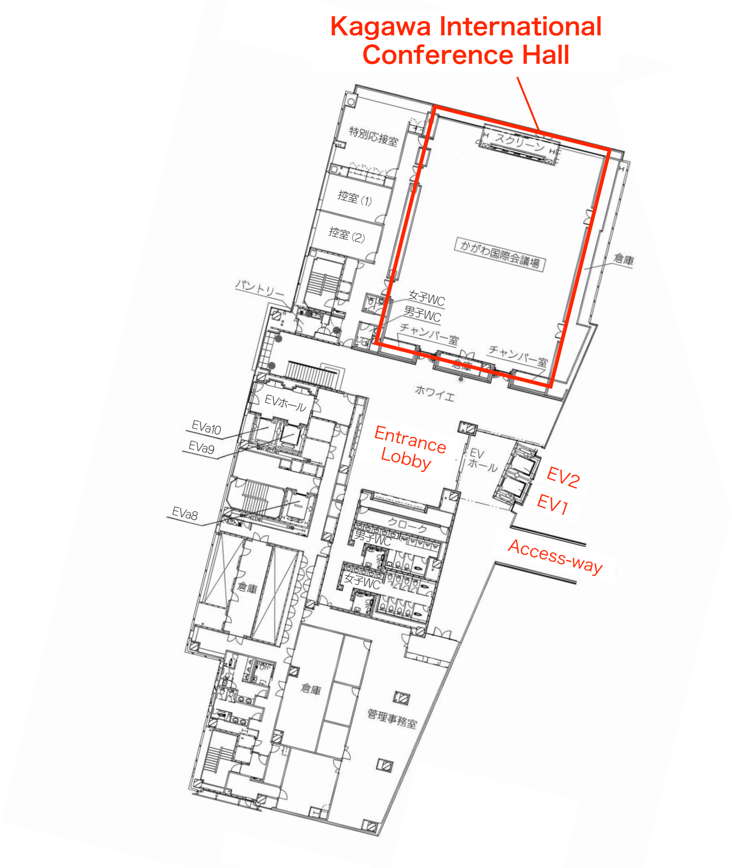
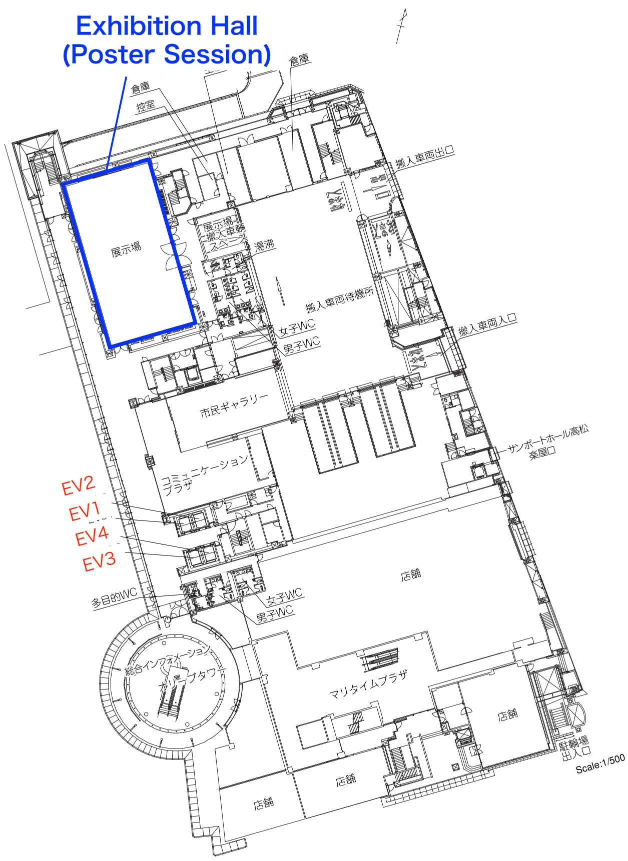
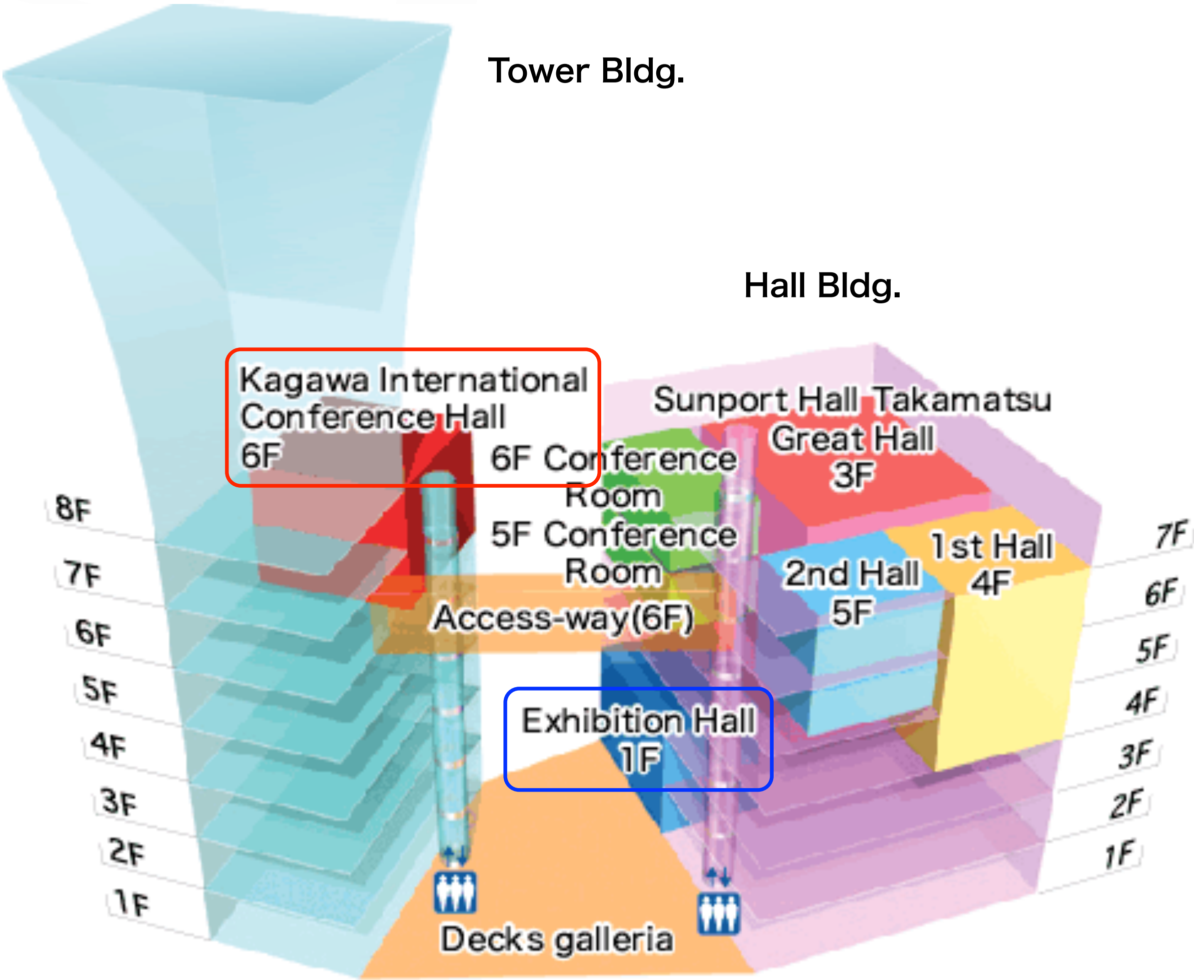
Conference Site

Tower Bldg. 6F



Hall Bldg. 1F





Welcome Reception

CIERO Exhibition Hall in JR Clement Hotel 21F
Sunday, November 30th, 18:00 - 20:00

A welcome cocktail is offered at CIERO Exhibition Hall in JR Clement Hotel 21F at 18:00 for conference participants and accompanying persons.

Poster Session

Exhibition Hall in Takamatsu Symbol Tower, Tower Bldg. 1F
Monday, December 1st, 16:30 - 19:00

Refreshments will be served during the poster session on Monday, 1 December starting from 16:30.
Accompanying persons are welcome to join the reception.
After the poster session, the posters will be exposed during whole conference in the foyer of Kagawa International Conference Hall.
The best posters will be awarded during closing session.

Conference Banquet

Kiyomi Sanso Hanajukai
Tuesday, December 2nd, 19:00 - 21:00

The conference banquet will take place at Kiyomi Sanso Hanajukai.
(http://www.hanajyukai.jp/).
Buses will leave at 18:00 from the conference site.

Excursion

Garden, Food, Culture
Wednesday, December 3rd, 12:25 -

・Ritsurin garden (http://ritsuringarden.jp/)
・Yashima battle field (http://www.my-kagawa.jp/eg/point/point.php?id=17)
・Bonsai garden (Nakanishi Chinshoen) (http://chinshoen.jp/english/)

Conference Proceedings

Peer-reviewed conference proceedings will be published as a volume of the Hyperfine Interactions.
The submission method and deadline will be announced during the conference.

Related Events

・"TCP school": November 28th - 29th, RIKEN Nishina Hall
・"Precision mass measurement with MRTOF and Storage Ring workshop": December 8th, 2F RIBF Hall, RIKEN

Program

	30th, Sunday	1st, Monday	2nd, Tuesday	3rd, Wednesday	4th, Thursday	5th, Friday
8:00		COFFEE & REGISTRATION (International Conference Hall, Takamatsu Symbol Tower Tower Bldg. 6F)	COFFEE Litvinov	COFFEE	COFFEE Yao	COFFEE Toyoda
8:30				Cornell	Nakamura	Vogel Glazov
9:00		Wada En'yo	Zhang Yamaguchi	Drewson	Versolato Fabian	Sternberg
9:30		Yamazaki	Nörtershäuser	Kuroda	Baumann	Lienard
10:00		Hori	Wakasugi	COFFEE & MINGLING	Oreshkina Ali	COFFEE Melconian
10:30		Comparat	COFFEE	Bollinger	COFFEE	Hasegawa
11:00		LUNCH	Schmidt	Fujiwara	Willmann	Ito Ringle
11:30			Azuma	Storry	Brunner Shabaev	Rosenbusch
12:00			Furukawa	*EXCURSION* *(Garden, Food, Culture)*	Kawamura	LUNCH
12:30		Andelkovic Herfurth	Chen *CONFERENCE PHOTO*		Smorra	
13:00		Redshaw	LUNCH		Chupp LUNCH	Nagy
13:30		Eibach				Kwiatkowski
14:00		Mehlman COFFEE				Clark
14:30		Ulmer	Wollnik		Leibfried	COFFEE Eronen
15:00		Perez	Plaß		Roos	Block
15:30		Gutierrez Pusa	Wolf		Kim	*Summary*
16:00		Simon	COFFEE		COFFEE	
16:30		*POSTER SESSION* *(International Conference Hall, Takamatsu Symbol Tower, Hall Bldg.1F)*	Schury Schweikhard		Sturm Eliseev	
17:00			Dickel		Dzuba	
17:30	REGISTRATION (CIERO Exhibition hall, JR Clement Hotel 21F)		Saito		Fujita	
18:00	*RECEPTION* *(CIERO Exhibition hall, JR Clement Hotel 21F)*		LEAVE FOR BANQUET			
18:30						
19:00			*BANQUET* *(Hanajukai)*			
19:30						
20:00						
20:30						
21:00						

Session colour key: Anti-Hydrogen; Ion Traps for HCI; Storage Rings; Applications of Particle Trapping; Fundamental Interactions and Symmetries; Joint Session; Quantum and QED Effects; Precision Spectroscopy and Frequency Standard

1st, Monday

8:00	COFFEE & REGISTRATION	60

Session 1A-1 Chair: Wada, Michiharu

Opening				
9:00	Wada, Michiharu	Opening remarks		15
9:15	En'yo, Hideto	Welcome to TCP in Takamatsu		15
Anti-Hydrogen (1)				
9:30	Yamazaki, Yasunori	What (anti-)matters with antimatter?	P. 13	40+10
10:20	Hori, Masaki	Two-photon laser spectroscopy of antiprotonic Helium and antiproton-to-electron mass ratio	P. 14	20+5
10:45	Comparat, Daniel	Present status of the AEgIS experiment and prospect for cooling antiprotons.	P. 15	20+5

11:10	LUNCH	80

Session 1P-1 Chair: Sakemi, Yasuhiro

Ion Traps for HCI (1)				
12:30	Andelkovic, Zoran	Experiments with highly charged ions at HITRAP	P. 16	20+5
12:55	Herfurth, Frank	Deceleration and storage of highly charged ions and antiprotons at GSI/FAIR	P. 17	20+5
13:20	Redshaw, Matthew	CHIP-TRAP: A high-precision double Penning trap mass spectrometer for stable and long-lived radioactive isotopes	P. 18	15+5
13:40	Eibach, Martin	Mass measurements of rare isotopes with a single ion	P. 19	15+5
14:00	Mehlman, Michael	Current status of the TAMUTRAP facility	P. 20	15+5

14:20	COFFEE	20

Session 1P-2 Chair: Fujiwara, Makoto

Anti-Hydrogen (2)				
14:40	Ulmer, Stefan	First direct high-precision measurement of the magnetic moment of the proton and status of BASE	P. 21	20+5
15:05	Perez, Patrice	The GBAR antimatter gravity experiment	P. 22	20+5
15:30	Gutierrez, Andrea	Antiproton cloud radial compression in the ALPHA apparatus at CERN	P. 23	15+5
15:50	Pusa, Petteri	Antihydrogen annihilation vertex detection in the ALPHA experiment	P. 24	15+5
16:10	Simon, Martin	A spectroscopy beamline for the hyperfine structure of antihydrogen and its characterization with a Hydrogen beam	P. 25	15+5

17:00	POSTER SESSION (Exhibition Hall, Hall Bldg. 1F)	120

2nd, Tuesday

8:00	COFFEE	10

Session 2A-1 Chair: Schuch, Reinhold

Storage Rings				
8:10	Litvinov, Yuri	Beta-decay of highly-charged ions	P. 26	40+10
9:00	Zhang, Yu Hu	Precision mass measurements of short-lived nuclides at storage ring in Lanzhou	P. 27	20+5
9:25	Yamaguchi, Yoshitaka	Rare-RI ring at RIKEN RI beam factory	P. 28	20+5
9:50	Nörtershäuser, Wilfried	Laser-based tests of fundamental symmetries and interactions at the ESR	P. 29	20+5
10:15	Wakasugi, Masanori	The SCRIT electron scattering facility	P. 30	20+5

10:40	COFFEE	20

Session 2A-2 Chair: Uesaka, Tomohiro

11:00	Schmidt, Henning	Low energy storage rings for molecular physics	P. 31	40+10
11:50	Azuma, Toshiyuki	RIKEN's new cryogenic electrostatic ion storage ring for atomic and molecular physics: RICE	P. 32	20+5
12:15	Furukawa, Takeshi	Rapid cooling of isolated small carbon cluster anions	P. 33	15+5
12:35	Chen, Xiangcheng	A new approach to the particle position detection in a storage ring	P. 34	15+5

12:55	CONFERENCE PHOTO	15
13:10	LUNCH	80

Session 2P-1 Chair: Litvinov, Yuri

Applications of Particle Trapping (1)				
14:30	Wollnik, Hermann	High-resolving mass analyzers	P. 35	40+10
15:20	Plaß, Wolfgang	First direct mass measurements with the MR-TOF-MS at the FRS ion catcher	P. 36	20+5
15:45	Wolf, Robert	Multi-reflection time-of-flight mass separation and spectrometry at ISOLTRAP/ ISOLDE	P. 37	20+5

16:10	COFFEE	20

Session 2P-2 Chair: Schwarz, Stefan

16:30	Schury, Peter	High-precision mass measurements of trans-Uranium nuclei by MRTOF-MS: shifting the paradigm in SHE-identification	P. 38	20+5
16:55	Schweikhard, Lutz	Polyanion production in Penning and RFQ ion traps	P. 39	15+5
17:15	Dickel, Timo	The MR-TOF isobar separator for the TITAN facility at TRIUMF	P. 40	15+5
Fundamental Interactions and Symmetries (1)				
17:35	Saito, Naohito	Muon's g-2 experiment at J-PARC	-	20+5

18:00	**LEAVE FOR BANQUET**	60
19:00	**BANQUET (Hanajukai)**	120

3rd, Wednesday

8:00	COFFEE	30

Session 3A-1 Chair: Schweikhard, Lutz

Joint Session				
8:30	Cornell, Eric	Measuring the electron's electric dipole moment in a trapped molecular ion.	P. 41	40+10
9:20	Drewson, Michael	Quantum state preparation of single molecular ions	P. 42	25+5
9:50	Kuroda, Naofumi	The ASACUSA CUSP experiment	P. 43	25+5

10:20	COFFEE & MINGLING	30

Session 3P-1 Chair: Higaki, Hiroyuki

10:50	Bollinger, John	Sensitive detection of modes and quantum simulation ith 2D arrays of trapped ions	P. 44	25+5
11:20	Fujiwara, Makoto	Fundamental physics with the ALPHA antihydrogen trap	P. 45	25+5
11:50	Storry, Cody	A new hydrogenic atom, e^+H^- / Positron systems for antihydrogen and other positronic atom physics	P. 46 P. 47	30+5

12:25	**EXCURSION (Garden, Food, Culture)**	-


Ritsurin Garden


Sanuki Udon


Yashima Battle Field

8:00	COFFEE	10

Session 4A-1 Chair: Azuma, Toshiyuki

Ion Traps for HCI (2)

8:10	Yao, Ke	The high precision mass spectrometer-SMILETRAP meets an EBIT in Shanghai	P. 48	20+5
8:35	Nakamura, Nobuyuki	Spectroscopic studies of highly charged ions at the Tokyo electron beam ion trap facility	P. 49	20+5
9:00	Versolato, Oscar	Coulomb-crystalized highly charged ions	P. 50	20+5
9:25	Fabian, Xavier	Using GPU parallelization to perform realistic simulations of the LPCTrap experiments : from a trapped ion cloud to a time-of-flight measurement	P. 51	15+5
9:45	Baumann, Thomas	Status of the ReA electron beam ion trap charge breeder at NSCL	P. 52	15+5
10:05	Oreshkina, Natalia	Dynamical effects in the X-ray transition strengths of astrophysically relevant Fe^{16+} ions	P. 53	15+5
10:25	Safdar, Ali	High-resolution intensity ratio measurements in EUV spectral wavelength for ions of astrophysical ineterst	P. 54	15+5

10:45	COFFEE	20

Session 4A-2 Chair: Doser, Michael

Fundamental Interactions and Symmetries (2)

11:05	Willmann, Lorenz	Parity violation measurements in trapped single radium ions	P. 55	20+5
11:30	Brunner, Thomas	Ba-ion extraction from high-pressure Xe gas for double-beta decay studies with nEXO	P. 56	20+5
11:55	Shabaev, Vladimir M.	Fundamental physics with highly charged ions at low energies	P. 57	20+5
12:20	Kawamura, Hirokazu	Magneto-optical trapping of radioactive atoms for test of the fundamental symmetries	P. 58	15+5
12:40	Smorra, Christian	BASE - High-precision tests of CPT invariance using antiprotons	P. 59	15+5
13:00	Chupp, Tim	Muon's g-2 experiment at Fermi-lab.	-	20+5

13:25	LUNCH	65

Session 4P-1 Chair: Sugiyama, Kazuhiko

Quantum and QED Effects (1)

14:30	Leibfried, Dietrich	Scalable quantum information processing with trapped ions at NIST	P. 60	40+10
15:20	Roos, Christian	Engineering and observation of interacting quasiparticles in a trapped-ion many-body system	P. 61	20+5
15:45	Kim, Taehyun	Development of the quantum repeater based on trapped Ions	P. 62	20+5

16:10	COFFEE	20

Session 4P-2 Chair: Nakamura, Nobuyuki

Precision Spectroscopy and Frequency Standard (1)

16:30	Sturm, Sven	The g-factor of highly charged ions - Stress test for the Standard Model and access to the mass of the electron	P. 63	20+5
16:55	Eliseev, Sergey	PI-ICR technique for mass measurements on short-lived nuclides and the PENTATRAP project	P. 64	20+5
17:20	Dzuba, Vladimir	Highly charged ions for atomic clocks and search for variation of the fine structure constant	P. 65	20+5
17:45	Fujita, Tomomi	Laser spectroscopy of atoms in superfluid helium for the measurement of nuclear spins and electromagnetic moments of radioisotope atoms	P. 66	15+5

5th, Friday

8:00	COFFEE	10

Session 5A-1 Chair: Schmidt, Henning*

Quantum and QED Effects (2)				
8:10	Toyoda, Kenji	Quantum simulation of the Jaynes-Cummings-Hubbard model using trapped ions	P. 67	20+5
8:35	Vogel, Manuel	Extreme field physics in Penning traps	P. 68	15+5
8:55	Glazov, Dmitry	Quadratic Zeeman effect in highly charged ions	P. 69	15+5
Applications of Particle Trapping (2)				
9:15	Sternberg, Matthew G.	Precision β-decay experiments with the β-decay Paul trap	P. 70	20+5
9:40	Lienard, Ettienne	Precision measurements with LPCTrap at GANIL	P. 71	20+5

10:05	COFFEE	15

Session 5A-2 Chair: Ban, Gilles

10:20	Melconian, Dan	A new correlation Penning trap for fundamental physics at Texas A&M	P. 72	20+5
10:45	Hasegawa, Shuichi	Ion trap and laser cooling spectroscopy for isotope analysis	P. 73	15+5
11:05	Ito, Yuta	Gas-cell beam cooler-buncher for low-energy experiments at SLOWRI	P. 74	15+5
Precision Spectroscopy and Frequency Standard (2)				
11:25	Ringle, Ryan	Penning trap mass spectrometry at the LEBIT facility	P. 75	20+5
11:50	Rosenbusch, Marco	Probing exotic nuclei through mass measurements from ISOLTRAP	P. 76	20+5

12:15	LUNCH	60

Session 5P-1 Chair: Kluge, H.-Jürgen

13:15	Nagy, Szilard	High-precision Penning-trap mass measurements at TRIGA-TRAP	P. 77	20+5
13:40	Kwiatkowski, Ania	TITAN: The ion trapping program at TRIUMF	P. 78	20+5
14:05	Clark, Jason	The Canadian Penning trap mass spectrometer at CARIBU	P. 79	20+5

14:30	COFFEE	15

Session 5P-2 Chair: Kluge, H.-Jürgen

14:45	Eronen, Tommi	On-going developments and measurements at JYFLTRAP	P. 80	20+5
15:10	Block, Michael	Recent developments for investigations of the heaviest elements with SHIPTRAP	P. 81	20+5

15:35	TBA	Summary	25

*: to be confirmed

Poster Session

1	Park, Young-ho	Sympathetic laser cooler for highly charged ions at RAON facility	IT	P. 82
2	Chaudhuri, Ankur	An overview of the high-precision mass measurement system for RAON facility	IT	P. 83
3	Singh, Prithvi	Effect of projectile charge on electron and positron impact single ionization cross section of water molecule	FI	P. 84
4	Im, Kang-bin	Simulation of the sympathetic cooling of highly charged ions using a GPU	IT	P. 85
5	Reponen, Mikael	Optical pumping and resonance ionization of trapped ions at IGISOL	IT, AP	P. 86
6	Fuke, Kiyokazu	Preparation of cold ions in magnetic field and its application to gas-phase NMR spectroscopy	AP	P. 87
7	Jordan, Elena	Towards laser Doppler cooling of negative ions in a Penning Trap	AP	P. 88
8	Takamine, Aiko	Precision measurements of hyperfine structure constants and 2s-2p transition frequencies for laser-cooled radioactive Beryllium isotopes	PS, IT	P. 89
9	Ito, Kiyokazu	Experimental study on dipole motion of an ion plasma confined in a linear Paul trap	PE, AP	P. 90
10	Belov, Nikolay A.	Pair creation and annihilation with atoms and channeling nuclei	FI, PS, QQ	P. 91
11	Fujisaki, Hiroto	Laser-diode-based light source for single-ion spectroscopy of the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition in Ba^+ at 1.76 μm	PS	P. 92
12	Harries, James R.	Compact EBITs with large fields-of-view using permanent magnets and optimized for use at synchrotron and FEL beamlines	IT	P. 93
13	Singh, Rohtash	Effect of an axial magnetic field and ion space charge on trapped charged particle in LBWA	PE	P. 94
14	Okada, Kunihiro	Characterization of ion Coulomb crystals for fundamental sciences	PS, PE	P. 95
15	Sakaue, Hiroyuki A.	EUV spectra of highly charged tungsten ions studied with an Electron Beam Ion Traps	IT	P. 96
16	Delahaye, Pierre	The LPCTrap measurement trap: an open Paul trap for fundamental tests	FI, IT, AP	P. 97
17	Inoue, Takeshi	Development of the optical magnetometer toward the search for the electron electric dipole moment	FI	P. 98
18	Tarlton, James	High-fidelity operations with calcium ion qubits	AP	P. 99
19	Funayama, Chikako	Performance assessment of a new laser system for efficient spin exchange optical pumping in a spin maser measurement of ^{129}Xe EDM	FI	P. 100
20	Masuda, Takahiko	Rate amplification of the two photon emission from para-hydrogen toward the neutrino mass measurement	QQ	P. 101
21	Arai, Fumiya	An ion-surfing RF-carpet gas cell for transuranium nuclei study at GARIS-II	IT	P. 102
22	Numadate, Naoki	Development of a Kingdon ion trap for observation of the forbidden X-ray transitions in solar wind charge exchange	AP	P. 103
23	Hrmo, Pavel	Sideband cooling to the ground state of a Calcium-40+ ion in a Penning Trap	QQ, AP	P. 104
24	Michan, Mario	Towards laser cooling of antihydrogen	AH	P. 105
25	Sternberg, Matthew G.	Cyclotron radiation emission spectroscopy (CRES) with trapped electrons	PS, NNP	P. 106
26	Dupré, Pierre	High-resolution mass separation by phase splitting and fast centering of ion motion in a Penning trap	AP, NNP	P. 107
27	Gutierrez, Andrea	Antiproton cloud radial compression in the ALPHA apparatus at CERN	AH, TCP	P. 108
28	Ito, Yuta	Gas-cell beam cooler-buncher for low-energy experiments at SLOWRI	IT, AP, TCP	P. 109

AH: Anti-Hydrogen AP: Applications of Particle Trapping FI: Fundamental Interactions and Symmetries
IT: Ion Traps for Radioactive Nuclei and Highly Charged Ions PE: Plasma Effects and Collective Behavior
PS: Precision Spectroscopy and Frequency Standard QQ: Quantum and QED Effects
NNP: speaker in NNP TCP: speaker in TCP

What (anti-)matters with antimatter?

Yasunori Yamazaki
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Precision comparisons of the properties of particles and their corresponding antiparticles are highly relevant. Actually, the Standard Model upon which the modern fundamental physics is constructed guarantees the CPT symmetry, which is a very general conclusion of local quantum field theories constructed on a flat space-time which fulfil the condition of Lorentz invariance and unitarity. However in reality, the space-time is curved by the gravitational interaction, and non-local interactions might play a role, which would cause a violation of the CPT symmetry. Further, various phenomena such as finite neutrino masses, strong indications of dark matter and dark energy in the universe, and of course the matter-antimatter asymmetry all point to a new theory beyond the Standard Model, where the CPT symmetry might well be violated.

The CPT symmetry predicts that the properties of antimatter such as the mass, the charge, the magnetic moment, the lifetime, are exactly the same as those of the corresponding matter. In other words, any measured and confirmed violation constitutes a significant challenge to the Standard Model. As the level of CPT violation would be considerably smaller than the CP violation which is already as small as 10^{-17}eV in the case of K^0 and $\overline{K}^0$, high-precision measurements of stable antiparticles are expected to be the potential candidates to attack the CPT symmetry problem. In this respect, antihydrogen atom as well as antiproton itself is best candidates to make stringent tests of the CPT symmetry in the hadron as well as the lepton sectors. Under this general understanding, several groups at CERN have been working on antihydrogen/antiproton research aiming at high-precision spectroscopy of ground state hyperfine and 1S-2S transitions of antihydrogen atoms as well as spin-flip transition of bare antiprotons.

In the present talk, recent developments of different antihydrogen/antiproton studies are overviewed together with a short discussion of other activities such as the gravitational interaction between matter and antimatter.

Two-photon laser spectroscopy of antiprotonic helium and antiproton-to-electron mass ratio

Content :

Antiprotonic helium is a three-body atom consisting of a helium nucleus, an antiproton occupying a Rydberg state, and electron. The ASACUSA collaboration at CERN has carried out sub-Doppler two-photon laser spectroscopy of this atom using two counter-propagating laser beams, thereby measuring the transition frequency of this atom to a precision of 2.5 - 5 parts per billion. By comparing the results with three-body QED calculations, the antiproton-to-electron mass ratio was determined. The PiHe collaboration of PSI attempts to carry out laser spectroscopy of pionic helium, which is an analogous atom consisting of a helium nucleus, electron, and negative pion. We describe the status of these two experiments.

Primary authors : Dr. MASAKI, Hori (MPQ)

Co-authors :

Presenter : Dr. MASAKI, Hori (MPQ)

Present status of the AEgIS Experiment and prospect for cooling antiprotons.

Content :

AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) is an experiment that aims to perform the first direct measurement of the gravitational acceleration g of antihydrogen in the Earth's field [1,2]. A cold antihydrogen beam will be produced by charge exchange reaction between cold antiprotons and positronium excited in Rydberg states. Rydberg positronium (with quantum number n between 20 and 30) will be produced by a two steps laser excitation. The antihydrogen beam, after being accelerated by Stark effect, will fly through a moiré deflectometer. The deflection of the horizontal beam due to its free fall will be measured by a position sensitive detector. In this presentation an overview of the AEgIS experiment will be presented and its current effort toward the determination the gravitational acceleration of antihydrogen will be detailed. Because the final precision relies on the antihydrogen temperature, we will discuss the possibility to lower this temperature by the use of atomic or molecular anions to first cool antiprotons [3].

References:

[1] http://cern.ch/aegis
[2] AEgIS experiment: Towards antihydrogen beam production for antimatter gravity measurements. S. Mariazzi et al. Eur. Phys. J. D.68, 41(2014)
[3] Phys Rev A 89, 043410 (2014) + article in preparation

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Co-authors :

Presenter : Mr. COMPARAT, Daniel (AEGIS collaboration)

Experiments with highly charged ions at HITRAP

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Heavy few-electron ions are relatively simple systems in terms of electron structure which offer unique opportunities for experiments under extremely large electromagnetic fields that exist around their nuclei. This makes them perfectly suited for various experiments including, but not limited to, tests of quantum electrodynamics at the strong field limit, multiple electron transfer or interaction of highly charged ions (HCI) with surfaces.

As an extension of the existing GSI accelerator facility, the heavy ion trap (HITRAP) facility has been conceived as the final deceleration stage for HCI. It is designed to extract HCI at 4 MeV/u from the GSI experimental storage ring and decelerate them in several stages all the way down to the sub-eV range, before distributing them to various experiments. The final deceleration stage of HITRAP employs a Penning trap, designed to capture the incoming HCI with an energy of 6 keV/q and to confine them for a sufficient amount of time to employ electron and resistive cooling techniques. We will present the status of this challenging experimental setup and the results of off-line trapping of ions and electrons.

SpecTrap, a setup designed for precision laser spectroscopy experiments on trapped HCI is being constructed to accept the ions prepared and ejected by the HITRAP cooling trap. It employs a Penning trap located inside a split-coil superconducting magnet which allows direct optical access to the laser-ion interaction region. Laser excitation of the trapped ions with direct observation of their fluorescence can thus be implemented, the ultimate goal being a measurement of the ground state hyperfine splitting in H- and Li-like heavy HCI. Additional measurements on the way to this aim are also planned, like fine-structure spectroscopy of medium-heavy ion species. We will present the status of the setup, the results of laser-cooling of singly charged ions planned for sympathetic cooling of HCI, as well as the first trapping of HCI produced locally by an EBIT. An overview of the supporting infrastructure, such as a 25 m long low-energy beam line for HCI transport, as well as of other experiments associated with HITRAP will also be given.

Deceleration and storage of highly charged ions and antiprotons at GSI/FAIR

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To perform precision experiments it is mandatory to provide means to link high-energy production schemes with low energy storage and measurement schemes. At GSI, heavy, highly charged ions up to bare uranium are produced in large quantities by stripping all electrons at high energies. The FAIR facility will additionally provide antiprotons. While the production of heavy, highly charged ions happens at a few 100 MeV/nucleon it is even at 2 to 3 GeV when it concerns antiprotons. The deceleration down to a few keV/nucleon, an energy that can be handled for instance by ion traps, requires several steps in storage rings and finally in a dedicated linear decelerator.

The linear decelerator HITRAP, is being commissioned with heavy, highly charged ions from the experimental storage ring ESR at GSI. It decelerates ions from 4 MeV/nucleon to 6 keV/nucleon to finally trap them in a Penning trap. For this it employs two different linear accelerator structures operated in inverse, an IH type structure and a RFQ structure. After extensive test and a thorough redesign the RFQ was finally taken into operation during an on-line test beam time in 2014. This was the last step in the deceleration chain from 400 MeV/nucleon production energy, to 4 MeV/nucleon – accompanied by cooling – in the experimental storage ring (ESR), and finally down to 6 keV/nucleon within the linear decelerator.

The CRYRING@ESR project is the early installation of the low-energy storage ring LSR, the Swedish in kind contribution to FAIR, which was proposed as the central decelerator ring for antiprotons at the FLAIR facility. Since the modularized start version of FAIR does not include the erection of the FLAIR building but the continuing operation of the ESR, it was proposed to install the CRYRING storage ring behind the existing experimental storage ring ESR already now. This opens the opportunity to explore part of the low energy atomic physics with heavy, highly charged ions as proposed by the SPARC collaboration but also experiments of nuclear physics background in the NUSTAR collaboration much sooner than foreseen in the FAIR general schedule. Furthermore, since the installation of the ring will be handled mostly by FAIR standards, it will be used to test major parts of the FAIR control system for the first time and well ahead of time before it is needed to run SIS100.

An option for the future that is being evaluated right now is to feed antiprotons back from the production at FAIR into the existing ESR. This would make antiprotons available in CRYRING and hence enable an early realization of at least part of the low energy antiproton program at FAIR, proposed and advanced by the FLAIR collaboration. When finally moving the commissioned decelerator HITRAP into a new spot behind CYRING@ESR, low energy antiprotons could be trapped very efficiently.

CHIP-TRAP: A high-precision double Penning trap mass spectrometer for stable and long-lived radioactive isotopes

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Ultra-high precision atomic mass determinations, to fractional precisions of $\sim 10^{-10}$ – 10^{-11} or better, are required for a number of different applications. In some cases, mass measurements with long-lived radioactive isotopes are required. For example, a measurement of the ^{36}Cl – ^{35}Cl mass difference will provide the ^{36}Cl neutron binding energy, which can be compared with a high-precision γ-ray spectroscopy determination for a direct test of $E = mc^2$ and a determination of the Molar Planck constant. A measurement of the ^{163}Ho – ^{163}Dy mass difference will provide the ^{163}Ho electron capture Q-value, which is required for experiments that aim to determine the neutrino mass via spectroscopy of the de-excitation spectrum from ^{163}Ho electron capture.

At Central Michigan University (CMU), we are developing a high precision Penning trap (CHIP-TRAP), for atomic mass determinations with stable and long-lived radioactive isotopes. CHIP-TRAP will consist of a pair of hyperbolic precision-measurement Penning traps, and a cylindrical capture/filter trap in a 12 T magnetic field. Ions will be produced by external ion sources, including a laser ablation ion source, and transported to the capture trap at low energies enabling ions of a given m/q ratio to be selected via their time-of-flight. This will minimize the amount of radioactive material entering the trap, and will also minimize the amount of material required for the measurement. In the capture trap any contaminant ions will be removed via mass-selective rf dipole excitation and the ion of interest will be transported to the measurement traps. A phase-sensitive image charge detection technique will be used for cyclotron frequency measurements with single ions in the precision traps. Two operating modes will be developed: 1) One trap will be used as a measurement trap while the other will be used as a storage trap. Ions will then be alternately measured and stored to enable quick switching between a pair of ions to account for magnetic field variations; 2) the mass ratio of a pair of ions will be determined by simultaneous cyclotron frequency measurements in the two traps, resulting in a cancelation of magnetic field fluctuations to first order and a reduction in statistical uncertainty. In this presentation we will describe the status and outlook for CHIP-TRAP.

Mass measurements of rare isotopes with a single ion

Content :

High-precision mass data is required for several scientific applications like calculations of the astrophysical r-process, nuclear structure studies, tests of nuclear mass models, and fundamental interactions. Of particular challenge are mass measurements far from stability, where production rates for rare isotopes can be very small.
At the National Superconducting Cyclotron Laboratory (NSCL) rare isotopes are produced by relativistic heavy-ion fragmentation and in-flight separation. This fast, chemically-insensitive production technique provides access to nuclei far from stability. New facilities, like the Facility for Rare Isotope Beams (FRIB) under construction at MSU, will provide even more exotic isotopes.
High-precision mass measurements of rare isotopes are performed at NSCL by the Penning trap mass spectrometer LEBIT using the well-known time of flight ion cyclotron resonance (TOF-ICR) technique. This technique is very universal, requiring minimal effort to change from one ion species to another. However, a single resonance curve requires on the order of 100 detected ions. As one moves further from the valley of beta stability, production rates of the exotic isotopes decline. In order to access rare isotopes being delivered at rates of about 1 ion/hour, or less, a more sensitive technique is required. Thus, the Single Ion Penning Trap project (SIPT) is being developed at NSCL allowing for high-precision mass measurements with a single ion employing the narrow-band Fourier-Transform Ion Cyclotron Resonance (FT-ICR) technique. It aims for mass measurements in the neutron-rich region where half-lives are usually sufficiently long for FT-ICR measurements. SIPT is being implemented in a 7-T superconducting magnet sharing the beam line with LEBIT. An optimal signal-to-noise ratio is ensured by employing a superconducting NbTi resonator coil, and by cooling the trap and detection electronics down to 4.2K with a pulsed-tube cooler.
With this combination of isotope production by fragmentation, and the complementary use of mass measurements with FT-ICR at SIPT as well as TOF-ICR at LEBIT, the reach of Penning trap mass spectrometry will be greatly enhanced at the NSCL now, and at FRIB in the future.

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Current Status of the TAMUTRAP Facility

Content :

The primary goal of the upcoming Texas A University Penning Trap (TAMUTRAP) facility is to test the standard model for the presence of a scalar current in the beta decay of T=2 superallowed beta-delayed proton emitters. By observing the shape of the proton energy spectrum one can deduce the beta-neutrino correlation parameter due to kinematic effects that expose the neutrino momentum. The TAMUTRAP decay station is centered around a unique, compensated cylindrical Penning trap, which is employed to both confine and detect the protons from these decays with high efficiency. This talk will provide a general overview of the TAMUTRAP facility and its current status. In particular, offline tests of the electrostatic ion optic system will be discussed, and preliminary measurements of efficiency and emittance of the phase-space reducing radio frequency quadrupole cooler/buncher will be presented.

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First Direct High-Precision Measurement of the Magnetic Moment of the Proton and Status of BASE

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Recent exciting progress in quantum control of a single isolated nucleus enabled the first observation of spin flips [1], the resolution of single spin flips [2] and the first demonstration of the double Penning trap technique with a single proton. By using these techniques, we performed the first direct high precision measurement of the magnetic moment of the proton μ_p in units of the nuclear magneton μ_N [3]:

$$\mu_p / \mu_N = 2.792\ 847\ 350(7)(6).$$

The achieved fractional precision of 3.3 parts in a billion improves the currently accepted literature value [4] by a factor of 2.5.

Our experiments are driven by the fascination and motivation to compare the properties of matter and antimatter at lowest energies and with greatest precision. Such comparisons provide stringent tests of CPT invariance [5], which is the most fundamental symmetry in the Standard Model of particle physics.
To apply our techniques to the antiproton, we constructed and commissioned the BASE experiment [6], which is located at the antiproton decelerator (AD) of CERN. To implement our apparatus into the present CERN infrastructure a dedicated experiment zone as well as a new antiproton transfer line were constructed. Catching of antiprotons and loss-less preparation of a single particle out of an antiproton reservoir was established, and several advanced charged particle manipulation techniques were implemented.
In the talk I will present the results of our high precision g-factor measurement as well as first data recorded with the BASE apparatus.

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The GBAR antimatter gravity experiment

Content :

The GBAR project (Gravitational Behaviour of Antihydrogen at Rest) at CERN, will measure the free fall acceleration of ultracold neutral antihydrogen atoms in the terrestrial gravitational field. The experiment consists in preparing antihydrogen ions (one antiproton and two positrons) and sympathetically cool them with Be+ ions to a few 10 microK. The ultracold ions will then be photo-ionized just above threshold, and the free-fall time over a known distance measured. I will describe the project, the accuracy that can be reached by standard techniques, and with possible improvements using quantum reflection of antihydrogen on surfaces. I will give the status of our efforts to trap positrons generated by our small electron linac, and using electron cooling.

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Co-authors :

Presenter : Dr. PEREZ, Patrice (CEA/Saclay)

ANTIPROTON CLOUD RADIAL COMPRESSION IN THE ALPHA APPARATUS AT CERN*

Andrea Gutierrez† and the ALPHA Collaboration ‡

University of British Columbia and TRIUMF

The ALPHA experiment aims to study trapped antihydrogen. Based at CERN's Antiproton Decelerator (AD), ALPHA successfully trapped antihydrogen in 2010 [1] and, in 2012, performed the first measurement on the internal structure of the antihydrogen system with microwave radiation [2].

Antiproton cloud compression is crucial for the production of trappable antihydrogen. Antiproton clouds can be radially compressed using a rotating dipolar electric field, also called the rotating wall technique. Antiprotons have previously been indirectly compressed by applying a rotating wall to a dense electron plasma co-located with the antiprotons [3].

We will present new results obtained in the ALPHA apparatus at CERN, in which antiproton clouds are directly compressed at frequencies from 100 kHz – 1 MHz, with a diffuse electron cloud providing a cooling mechanism. We hypothesized that a resonance in the antiprotons motion was responsible for the compression. We performed simulations to determine the distributions of the antiproton bounce frequency and rotation frequency. A simple model can describe qualitative features of the measured antiproton densities. This novel scheme to compress antiproton clouds could have important implications for antihydrogen physics with ALPHA.

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Antihydrogen Annihilation Vertex Detection in the ALPHA experiment

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The aim of the ALPHA experiment at CERN is to trap cold atomic antihydrogen, study its properties, and ultimately to perform precision comparison between the hydrogen and antihydrogen atomic spectra and study gravitational effects on antihydrogen. Recently the collaboration has reached important milestones beginning with demonstrating the ability to trap and confine neutral cold antihydrogen [1] [2], performing the first spectroscopic measurements of antihydrogen [3] and of late through demonstrations of the first application of a new technique to measure the gravitational mass of antihydrogen [4].

The principal diagnostic tool for antihydrogen detection and measurement is a Silicon Vertex Detector (SVD). The detector consists of double-sided silicon strip hybrid modules. Surrounding the ALPHA neutral atom trap, its purpose is to monitor single annihilation events and collective antiproton plasma behavior. A description of the performance and characteristics of this detector [5] and its upgrade [6] will be given, along with methods and results, using spatial and timing data to perform precision measurements on antihydrogen

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A Spectroscopy Beamline for the Hyperfine Structure of Antihydrogen and its Characterization with a Hydrogen Beam

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Recent progress in antihydrogen ($\overline{H}$) research, like long time storage of $\overline{H}$ [1] or sending them along a beamline [2] illustrate that this field is on the verge to first high precision spectroscopy results. If the measured transition frequencies deviated from the corresponding values of hydrogen, CPT (charge conjugation – parity – time reversal) would be a broken symmetry, in contradiction to the standard model.

The $\overline{H}$-program of the ASACUSA collaboration aims for a measurement of the hyperfine splitting (HFS) of ground state $\overline{H}$ at the antiproton decelerator at CERN in a Rabi-type beam experiment [3]. The main components of the spectroscopy beamline are a spin-flip microwave cavity, a superconducting sextupole magnet, and an $\overline{H}$ annihilation detector. The first two components have been tested with an atomic hydrogen beam [4] thereby verifying the method on the 10ppb level.

The concept of the HFS spectroscopy (sketch in Fig. 1) and the results from the hydrogen experiments (example resonance in Fig. 2) will be presented in this contribution.

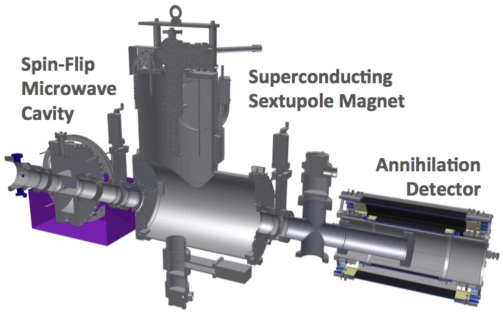

Fig 1. Spectroscopy Beamline

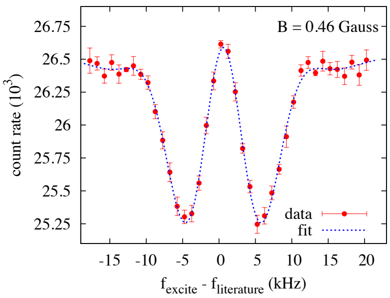

Fig. 2 HFS-resonance of Hydrogen

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Beta-decay of highly-charged ions

Content :

High atomic charge states can significantly influence nuclear decay rates. An obvious example is the electron capture (EC) decay probability, which depends strongly on the number of bound electrons. One of the straightforward motivations for studying the beta-decay of highly charged ions (HCI) is that stellar nucleosynthesis proceeds at high temperatures, where the involved atoms are highly ionized. Furthermore, HCIs offer the possibility to perform basic investigations of beta decay under clean conditions: The decaying nuclei having, e.g., only a single bound electron, represent themselves well-defined quantum-mechanical systems, in which all interactions with other electrons are excluded, and thus the complicated corrections due to shake-off effects, electron screening etc. can be removed.
Largest modifications of nuclear half-lives with respect to neutral atoms were observed in beta decay of fully ionized nuclei. Presently, the ion-storage ring ESR at GSI in Darmstadt is the only tool in the world for addressing radioactive decays of HCIs. There, the radionuclides produced at high kinetic energies as HCIs and purified from unwanted contaminants can be stored in the cooler-storage ring ESR. Due to the ultra-high vacuum of about 10-10 mbar, the high atomic charge states of stored ions can be preserved for extensive periods of time (minutes, hours). The decay characteristics of electron cooled stored HCIs can accurately be measured by employing the highly sensitive non-destructive time-resolved Schottky spectrometry technique.
Recent experiments with stored exotic nuclei that have been performed at the ESR will be discussed in this contribution. A particular emphasis will be given to two-body beta decays, namely bound-state beta decay and orbital electron capture.
As an outlook, the perspectives of future experiments with HCIs at existing storage ring facilities (ESR in Darmstadt and CSRe in Lanzhou) as well as at the planned facilities (TSR@ISOLDE, FAIR, HIAF, RI-RING) will be outlined.

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Precision mass measurements of short-lived nuclides at storage ring in Lanzhou

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Nuclear mass is the fundamental property of a nucleus. The complex interplay of strong, weak and electromagnetic interactions in the nucleus contributes to the difference between its mass and the sum of the masses of its constituent nucleons. Precise and systematic measurements of nuclear masses not only provide information on nuclear structure, but also find their important applications in nuclear astrophysics. Recent commissioning of the Cooler Storage Ring at the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) has allowed us for direct mass measurements at the Institute of Modern Physics in Lanzhou (IMP), Chinese Academy of Sciences (CAS). In the past few years, a series of mass measurement experiments have been carried out using the CSRe-based isochronous mass spectrometry (IMS). Masses of short-lived nuclides of both neutron-rich and neutron-deficient have been measured up to a relative precision of 10^{-6}–10^{-7} via fragmentation of the energetic beams of ^{58}Ni, ^{78}Kr, ^{86}Kr, and ^{112}Sn [1, 2, 3, 4, 5]. In this talk, the experiments and the results will be presented. The implications of our experimental results with respect to nuclear structures and stellar nucleosynthesis in the rp-process of x-ray bursts are discussed. Some disadvantages in the IMS method itself are pointed out and simulated, and further improvement using double ToF detectors are proposed.

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Rare-RI Ring at RIKEN RI Beam Factory

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Co-authors :
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We are constructing the isochronous storage ring named ”Rare-RI Ring (R3)” at RIKEN RI Beam Factory. The target performance of R3 is to determine the mass of extremely short-lived and rarely-generated unstable nuclei by using the isochronous mass spectrometry in an accuracy of the order of 10^{-6}. In order to inject such rare nuclei into the R3 event by event, we adopt the individual injection method[1]. A fast kicker system plays an important role at the time of individual injection. R3 will perform the accurate mass measurements within 1 ms. Here, we introduce the present status of R3, and the prospects.

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Laser-based tests of Fundamental Symmetries and Interactions at the ESR

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Relativistic ion beams in storage rings allow for experimental tests of fundamental theories. I will report on tests of QED in strong magnetic fields and of time dilatation in special relativity that have recently been carried out at the Experimental Storage Ring ESR at the Helmholtzzentrum GSI in Darmstadt.

An experimental comparison between the hyperfine structure (HFS) splitting in hydrogen- and lithium-like bismuth ions allows fundamental tests of the bound-state quantum electrodynamics (QED) in the strongest electromagnetic fields by determination of the so-called specific HFS splitting difference [1]. Even though the ground state hyperfine transition in H-like bismuth was found in 1994 [2], the transition in Li-like bismuth could not be observed until recently [3].
Li-like bismuth ions were stored at 0.71c and the HFS transition was excited by means of collinear laser spectroscopy. Additionally the HFS splitting in H-like bismuth was remeasured. Even though the accuracy of our results are limited by the calibration of the electron cooler voltage, a significant deviation from the previous measurements of H-like Bi was found. The combination of both HFS splittings agrees with the theoretical prediction within the experimental uncertainty.
With the aim to improve the accuracy of our measurement, we repeated this experiment in 2014. This time, we were able to reduce the uncertainties in nearly all relevant parameters. Particularly, the voltage of 214 kV at the ESR electron-cooler was monitored in situ using a PTB (Physikalisch-Technische Bundesanstalt) high-precision high-voltage divider. Results from 2011 and preliminary data from 2014 will be presented.

In the second part of the talk, an Ives-Stilwell experiment using $^7Li^+$ ions at 34% of the speed of light will be presented. It led to a test of time dilation in special relativity with unprecedented accuracy [4].

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The SCRIT Electron Scattering Facility

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The SCRIT Electron Scattering Facility has been constructed at RIKEN RI Beam Factory aiming at electron scattering off short-lived unstable nuclei. This facility consists of an electron accelerator system and an ISOL system (ERIS) equipped with an RI ion source in which uranium fission products are produced by 150-MeV electron beam irradiation on UCx target. The SCRIT (Self-Confining RI Ion Target) system was inserted in a straight section of the electron storage ring (SR2) and connected to ERIS. RI ions injected into the SCRIT are three-dimensionally confined on electron beam axis by transverse focusing force given by electron beam and longitudinal electrostatic potential well provided by the SCRIT device. Circulating electrons are scattered from the confined ions, and the angular distribution is measured. Test experiments for evaluating performance of the SCRIT system were successfully performed using stable ^{133}Cs and ^{132}Xe. The luminosity exceeding 10^{27}/(cm^{2}s) was achieved at the electron beam current of more than 200 mA and the angular distributions of elastically scattered electrons were observed. On the other hand, RI production at ERIS has been started last year. Intensity of the extracted fission product, for instance ^{138}Xe, is currently 10^6 pps with the UCx target including 30-g uranium and the driver electron beam power of 10 W. The power of the driver electron beam will be upgraded. Construction of the scattered-electron detection system consisting of a large acceptance magnetic spectrometer, MWDC's, and trigger plastic schintillators has been almost finished. This is now under testing and the DAQ system is also under development. We present in this paper the status of the SCRIT electron scattering facility.

Low-Energy Storage Rings for Molecular Physics

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When in the early 1990s, magnetic-confinement heavy-ion storage rings were introduced as tools in atomic and molecular physics it was quickly realized that the potential to store ions for an extended time of milliseconds, seconds or even longer was of great importance for studies of molecular ions. For comparisons with theory or in applications in e.g. astrophysics one is in general interested in molecular ions in their lowest ro-vibrational states, while what is formed in most sources of molecular ions are very hot ions populating a wide range of quantum states. With the electron-cooler equipped storage rings large-scale studies of e.g. dissociative recombination for vibrationally relaxed molecular ions was thus made possible for the first time[1].

In these devices, ions are typically stored at MeV energies, but low center of mas energies are reached in merged electron/ion beam configurations. There are, however, other uses of stored beams where the energy is unimportant. If one wants to monitor the decay of a stored beam of metastable ions or in case of laser interaction with the stored particles. Then storage at keV energies is sufficient and this was – beside the principle mass-independence of electrostatic storage – a main motivation behind ELISA, the first *electrostatic* ion-storage ring in Århus[2], and its several followers[3,4,5,6,7].

The DESIREE[8] (Double ElectroStatic Ion-Ring ExpEriment) in Stockholm introduces two rings in a common cryogenically cooled vacuum vessel. Beams of opposite charge polarity are stored in the two rings and overlap over a straight section. DESIREE is now fully operational as a one-ring machine, while optimization of beam overlap and product detection is in progress for the positive/negative ion reaction experiments.
In this review, I will give examples of highlights of the molecular physics experiments performed by means of these machines. I will go into some detail when it comes to the description of the DESIREE facility.

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RIKEN's new cryogenic electrostatic ion storage ring for atomic and molecular physics: RICE

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Electrostatic ion storage rings and ion beam traps are now recognized as quite suitable devices to trace time-resolved slow dynamics of molecular ions by storing them in the time scale from micro-second up to several second and by introducing a laser to control population of their excitation states. For instance, these devices recently have played a crucial role to re-discover the inverse internal conversion (IIC) process of molecular ions, where the conversion of energy from vibrationally excited states to electronically excited states takes place. Martin et.al. reported an evidence for positive anthracene ions (one of polycyclic aromatic hydrocarbons, PAH) using a mini-ring at Lyon [1], while our group showed such a behavior for negative carbon cluster ions of C_6^- using TMU E-ring [2]. This phenomena have been pointed out theoretically, however experimental trials failed to lead a solid conclusion in 1970's due to the lack of the suitable techniques to prepare these ions isolated in vacuum and trace such slow dynamics.

In spite of these successful measurements, they always accompany ambiguity to evaluate the de-excitation process because the initial temperature of molecules is hard to know precisely. It is desirable to prepare very cold ions in the ground or specific vibrational or rotational states as an initial condition. From this context, it is quite natural to prepare cryogenic electrostatic ion storage rings to avoid the black body radiation from a vacuum chamber wall. We can also expect to store the ions much longer than the case at room temperature due to extremely good vacuum. Presently, several new cryogenic ion storage rings are under development. The DESIREE in Stockholm and the CSR in Heidelberg are ready or close to operation. We also developed a new RIken Cryogenic Electrostatic ion ring (RICE) equipped with many unique features.

Configuration of electrodes was basically scaled down from the present TMU E-ring to the total size of about 1m x 3m. All of the electrodes were placed on a single base plate made of Chromium Copper (CrCu) alloy. The plate and electrodes were covered by a half-cylindrical shaped stainless steel lid (inner vacuum chamber, IVC). The IVC was further covered by a cylindrical shaped outer vacuum chamber (OVC) for thermal isolation. The IVC and the radiation shield were cooled down by three GM cryocoolers. We have already finished vacuum and cryogenic tests after assembling works, and succeeded in obtaining the temperature below 5 K, and confirmed that the IVC reached good vacuum bellow 10^{-14} Torr. Using 15 keV Ne^+ ions extracted from an ECR ion source, we confirmed that we succeeded in the stable storage of them. We observed that the storage lifetime of them became drastically longer reflecting the good vacuum condition at the cryogenic temperature.

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Rapid cooling of isolated small carbon cluster anions

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Electrostatic ion storage devices, including ion storage rings or ion beam traps, are powerful tools to investigate slow molecular dynamics because they makes it possible to keep molecular ions in vacuum for a long period up to second or longer. Our group has been studying the dynamics of negatively-charged small carbon cluster ions (C_n^-) stored in the electrostatic ion storage ring at Tokyo Metropolitan University (TMU E-ring). We focus our attention on the energy relaxation process of “hot ions”, i.e. ions with large vibrational energy, prepared by excitation with tunable visible laser irradiation, followed by internal conversion. For the vibrationally excited molecules, radiative cooling is usually a rather inefficient cooling pathway. We have found that even-numbered carbon cluster anions radiate significantly faster than odd-numbered ones, and much faster than by infrared (IR) radiation [1].

The experiments were performed at the TMU E-ring, where we performed the time-resolved observation of thermodynamically-based electron emission from $C_{4\text{-}7}^-$ anions, on the timescale of tens of microseconds and longer after laser excitation. For C_5^- and C_7^-, the time profile of the emission rate in the delayed reaction shows that the anions were cooled slowly by IR radiations (timescale: tens of millisecond). On the other hand, the electron emission rate of laser-excited C_4^- and C_6^- decreased anomalously fast, on less than a few tens of microseconds. The rapid process shows the existence of the electronic transitions *via* low-lying electronic excited states after the inverse internal conversion (IIC) process, i.e., the conversion of energy from vibrationally excited states to electronically excited states. It should be noted that $C_4^-$and C_6^- have low-lying excited states (the excitation energy of first excited states E_{1st} : both approximately 1 eV) but C_5^- and C_7^- do not (E_{1st} : both just below of the electron affinity close to 4 eV). Although this IIC process is usually suppressed due to the small statistical weight of the excited states, it may dominate the cooling dynamics of isolated molecules. Such the process has been suggested in the anthracene cations [2], and our result shows the strong evidence for the existence of the process. Note that this process is general for the molecules with low-lying excited states and then affects many kinds of phenomena arising from the isolated molecules. For example, the IIC process will be more important for the evolution of interstellar molecules, where two-body collisions produce highly excited products and radiative cooling determines whether they survive intact.

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A new approach to the particle position detection in a storage ring

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For the beam position monitoring in a storage ring, physicists sometimes use cavity-based resonators to enhance sensitivity. However such a design is most suitable for machines with smaller apertures. In order to achieve high sensitivity to low current beams in large aperture storage rings such as the CR at FAIR, we propose a novel design utilizing the monopole mode. It is a resonant cavity with the beam pipe placed off-centered, where the field distribution of the monopole mode starts to diminish gradually. Through the RF simulation with CST software, we could confirm the detection potential of such a configuration. In this work, we present bench-top measurements of a model cavity based on this design. The result has in general proven the feasibility of the design, but also shown some limitations.

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High-Resolving Mass Analyzers

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An overview over modern high-resolving mass analyzers will be given with special emphasis on time-of-flight mass analyzers and here especially on multi-pass time-of-flight systems. In this presentation not only applications will be discussed but emphasis will be describe technological development which are essential for the performance of mass analyzers and allow the widespread use of mass analyses in different fields of application.

There will be discussions on very precise laterally dispersive sector-field and Penning trap mass analyzers. Detailed descriptions are planned of time-of-flight mass spectrographs and here especially on multiple pass mass analyzers. This will include descriptions of magnetic sector-field mass analyzers including those of accelerator storage rings used for the investigation of short-lived nuclei, which are important for astrophysics. Described will be also be the use of electric sector field systems including their serial arrangements or their repetitive use of ion flight paths so that very high resolving powers can be achieved.

Furthermore the technologically of – at least in principle – simpler reflector or mirror system mass analyzers will be discussed. This will include multi-reflector mass analyzers and mass separators in which given flight paths are used multiple times so that very long flight paths become possible, which for ion pulses of given length allows higher and higher mass resolving powers.

Points of discussions will also be the formation of short ion pulses as well as their hopefully loss-free cooling, transport and storage.

First Direct Mass Measurements with the MR-TOF-MS at the FRS Ion Catcher

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The FRS Ion Catcher at GSI is a facility for high-precision experiments with stopped and extracted exotic nuclei [1]. It comprises the FRS operated as separator and energy buncher, a cryogenic stopping cell (CSC) and a multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) [2,3,4]. Projectile and fission fragments are produced at relativistic energies at the FRS, separated in-flight, range-focused, slowed-down and thermalized in the CSC. The MR-TOF-MS is used to perform direct mass measurements, to provide an isobarically clean beam to further experiments, and as a versatile diagnostics device to monitor the production, separation and manipulation of exotic nuclei. The FRS Ion Catcher also serves as a test facility for the Low-Energy Branch of the Super-FRS at FAIR, where the CSC and the MR-TOF-MS will be key devices for experiments with stopped projectile and fission fragments at MATS and LaSpec.

The MR-TOF-MS consists of an entrance RFQ for ion cooling and transmission, an injection RF trap for ion bunching, a coaxial TOF analyzer, in which the ions are trapped by electrostatic fields, and an isochronous SEM for mass measurement or a Bradbury-Nielsen-Gate for mass separation. Several novel principles have been implemented to further enhance the performance and versatility of the MR-TOF-MS. For example, temporal focusing of the ions onto the detector plane regardless of the tuning of the analyzer is performed using a post-analyzer reflector. Thus extremely high resolution can be obtained as well as very short flight times. Mass resolving powers up to 600,000 (FWHM) at 50% transmission efficiency have been achieved. A mass resolving power of 130,000 at mass 133 has been reached after only 2.9 ms. Mass measurement accuracies on the level of 0.1 ppm, ion capacities of more than a million ions per second, and cycle frequencies has high as 1 kHz have been achieved. Operation as high-resolution mass separator has been demonstrated using various isobars. For the first time, direct mass measurements of heavy projectile fragments were performed with an MR-TOF-MS, among them the nuclide ^{213}Rn with a half-life of just 19.5 ms; mass determination with only 25 detected ions and at ion rates of four ions per hour has been demonstrated.

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Multi-reflection time-of-flight mass separation and spectrometry at ISOLTRAP/ISOLDE

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Precision mass measurements of radioactive nuclides give direct insight to one of the most fundamental properties of atomic nuclei, their binding energy. Investigating this property as a function of proton and neutron numbers is crucial for advancing theory in describing and predicting the structure of nuclei. Furthermore, knowledge of masses far from stability is necessary for the understanding of nucleosynthesis in supernovae and neutron stars.

Laboratory experiments are often extremely challenging due to the short half-lives and low production rates of the nuclides of interest. At the same time, longer-lived or stable contaminations are produced by orders of magnitude more, demanding a high selectivity and resolving power of the mass spectrometer. ISOLTRAP at ISOLDE/CERN has already investigated over 500 isotopes on an uncertainty level down to dm/m=1x10-8 by use of Penning-trap techniques. To extend the range of accessible nuclides even further, the setup has been upgraded with a multi-reflection time-of-flight mass analyzer [1], see fig. 1. This device can be operated as a mass purifier or a mass spectrometer, which allowed mass measurements for nuclear astrophysics applications [2] and tests of modern nuclear theory, i. e., valence-shell calculations based on three-nucleon forces [3]. The talk will give an overview of these recent developments and further applications of the new MR-ToF device.

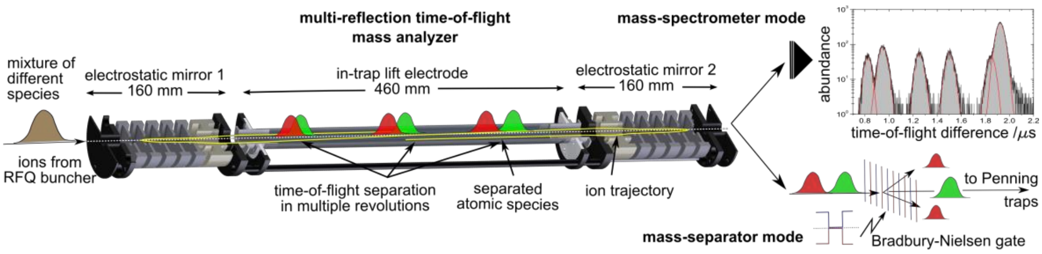

Fig. 1: Sectional view (adapted from [1]) of the MR-ToF device. The mass-separated ions are either detected by a microchannel-plate detector to record a time-of-flight spectrum (right top) or selected by the Bradbury-Nielsen gate (right bottom).

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High-precision mass measurements of trans-Uranium nuclei by MRTOF-MS: shifting the paradigm in SHE-identification

Content :

The SlowSHE project at RIKEN is designed to provide low-energy ions for precision, especially trap-based, studies nuclei produced via fusion-evaporation reactions. Of particular excitement is the possibility to use an MRTOF-MS to change the identification paradigm for SHE nuclei from decay spectroscopy to mass spectroscopy. The importance and technical feasibility of this will be discussed. We will also present the status and outlook of SlowSHE project.

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Polyanion Production in Penning and RFQ Ion Traps

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The charge state of a metal cluster is a crucial parameter as the number of electrons affects many of its properties. Polyanionic clusters are produced by sequential electron-attachment to monoanionic precursors stored in Penning and RFQ ion traps, as developed and investigated at ClusterTrap (Fig. 1).
The range of anionic charge states produced with the electron-bath technique in a Penning trap is restricted by the upper mass limit of this trap. By replacing the hyperbolical 5-Tesla with a cylindrical 12-Tesla Penning trap, the mass and thus cluster-size range has been enhanced by a factor of 20. In a parallel effort, an RFQ-trap-based production method for polyanions has been developed. To this end, an electron beam is guided through a linear RFQ trap, where the clusters are stored in a 3-state digital-ion-trap (DIT) mode.

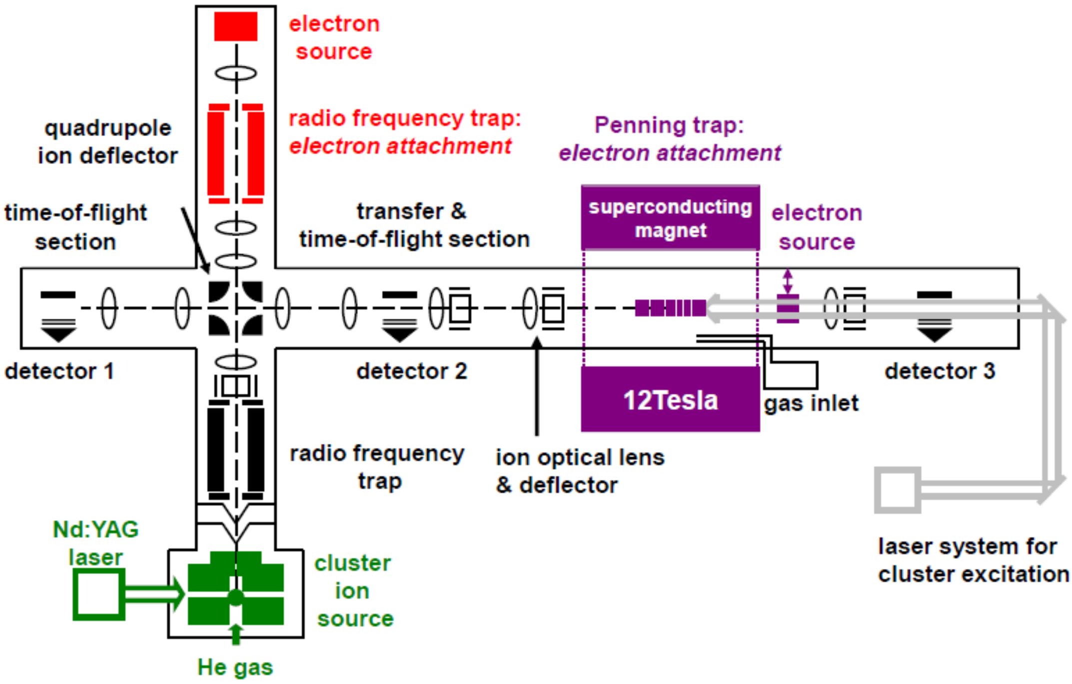

Fig. 1: Overview of the ClusterTrap setup [1].

Recently, gold clusters Au_n^{-1}, n = 330 – 350, have been exposed to the Penning-trap electron bath. As a result, up to hexa-anionic clusters have been observed. For comparison: At comparable trapping voltages the cluster size limit of the previous 5-Tesla hyperbolic Penning trap was about n = 60 and the maximum gold-cluster (negative) charge state was z = -3 [2].
In ClusterTrap's RFQ component, di- and tri-anionic gold clusters have been produced by exposing mono-anions to an electron beam [3]. The introduction of the 3-state DIT allows time slots of zero-volt potentials to be implemented in the guiding-field signal of the RFQ trap [4]. Thus, electrons can pass through the trap at well-defined energies.
We report about the latest results with respect to both methods as well as their combination.
The project is supported by the DFG Collaborative Research Center SFB 652.

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The MR-TOF isobar separator for the TITAN facility at TRIUMF

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At many rare ion beam facilities around the world multiple-reflection time-of-flight mass spectrometers (MR-TOF-MS) have been installed.[1] It has been demonstrated that these systems can achieve outstanding performance, such as high transmission efficiency (<50%), mass resolving power (600,000 FWHM), mass accuracies (~0.1 ppm), repetition rates (400 Hz) and high sensitivity[2]. At TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) an MR-TOF isobar separator will extend TITAN's capabilities and facilitate mass measurements and in-trap decay spectroscopy[3] of exotic nuclei that so far have not been possible due to strong isobaric contaminations[4].This MR-TOF-MS will also enable mass measurements of very short-lived nuclei ($T_{1/2}$ > 1 ms) that are produced in very low quantities (a few detected ions overall).

In order to allow the installation of an MR-TOF-MS in the restricted space on the platform, on which the TITAN facility is located, novel mass spectrometric methods have been developed. Ion transport into and out of the device is performed using an RFQ-based ion beam switchyard. Mass selection is performed using a dynamic retrapping technique after time-of-flight analysis in a isochronous reflector system. Only due to the combination of these novel methods has the realization of an MR-TOF-MS based isobar separator at TITAN become possible. The system will be installed parallel to the existing beamline and which allows for isobar separation in the MR-TOF-MS without requiring changes to the existing ion optics of TITAN. An isobarically clean beam can be provided to the TITAN EBIT and to the Penning trap or eventually in reverse direction back towards the RFQ buncher and the laser spectroscopy setup. In both cases the exotic ions can be merged with ions from several offline ion sources for calibration and optimization of ion transport.

The system has been commissioned in Giessen and installation at the TITAN facility is underway.

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Measuring the electron's electric dipole moment in a trapped molecular ion.

Content :

We discuss an experiment to measure the electron's electric dipole moment (eEDM) with a projected sensitivity of better than ten-to-the-minus-28 electron centimeters. At this level, the eEDM is sensitive to the existence of hypothetical new fundamental particles with masses in excess of one TeV. The experiment will take advantage of the large internal electric fields in a molecule, and the long coherence times possible in an ion trap.

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Controlling Coulomb crystallized strings of ions

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Spatial and motional control of strings of ions is essential for large range of experiments with trapped atomic and molecular ions. For instance, strings of atomic ions are being used for quantum information processing, quantum simulations, quantum memories for light, exploration of energy transport in finite systems and as starting point for studies of symmetry breaking in structural phase transitions. In addition, strings incorporating molecular ions have been exploited in investigations of molecular processes at the single particle level, and in the near future, spectroscopy of highly charged ions are expected to significantly improve the measurement precision through Coulomb crystallization into 1D structures.

In the talk, I will discuss partly new results regarding pinning of identical atomic ions in 1D-configurations within the periodic potential wells of optical lattices, and partly the outcome of a series of experiments focused on sorting two-species ion systems into specific ordered string structures. The latter, includes the nearly deterministically preparation of perfectly interleaved 1D-string with every second ion being of one specific type, and the formation of two parallel strings with each one composed exclusively of atomic and molecular ions, respectively.

The ASACUSA CUSP experiment

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In order to test CPT symmetry between antihydrogen and its counterpart hydrogen, the ASACUSA collaboration plans a high precision microwave spectroscopy of ground-state hyperfine splitting of antihydrogen atom in-flight.
We have developed a cusp trap which consisting of a superconducting anti-Helmholtz coil and multi-ring electrodes, and been successful in producing an antihydrogen beam. A total of 80 antihydrogen atoms were detected at 2.8 m away from the cusp trap. For the preparation of antiproton and positron plasmas, a Penning-Malmberg type traps were utilized. Downstream of the cusp trap a spectrometer line was placed, which consists of a microwave cavity to induce spin flips and a superconducting sextupole magnet for spin-state analysis. At the end of the beamline, an antihydrogen beam detector was located, which was comprised of an inorganic Bismuth Germanium Oxide (BGO) single-crystal scintillator housed in a vacuum duct and surrounding plastic scintillators.
We report recent results of antihydrogen synthesis and production of an anti-atomic beam.

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Sensitive detection of the vibrational modes of 2D trapped ion crystals with spin-dependent forces

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3rd, Wednesday

Trapped ions, when laser-cooled to low temperatures, form crystalline arrays. These arrays have many applications, including quantum computation and simulation [1-3], atomic clocks and precision spectroscopy [4], and in basic studies of strongly coupled plasma physics. In all of these applications, a detailed understanding and characterization of the vibrational modes is important. Here we discuss how a spin-dependent force (that is, a force that depends on the internal electronic state or "spin" of the trapped atomic ion), can be used to excite and characterize the vibrational modes of trapped ion crystals. Specifically we show how a spin-dependent force can entangle the internal "spin" degree of freedom with motional degrees of freedom, enabling spectroscopy and thermometry of the modes through the measured decoherence of the spins [5]. We demonstrate this technique on triangular arrays of several hundred Be^+ ions confined to a single plane in a Penning trap. Through decoherence produced by nanometer-sized spin-dependent displacements, we excite and detect arbitrary modes with wavelengths approaching the interparticle spacing. The decoherence induced by the spin-dependent force can be characterized as spin-dephasing, and by measuring the spin-dephasing directly more detailed information on the motional states is obtained [6]. We apply the technique to measure the ambient heating rate of the axial center-of-mass (COM) mode.

We have completed the design and fabrication of a new Penning trap. We will summarize a few features of this trap, including the possibility of implementing an m=3 rotating wall [7], and report on recent measurements of the qubit coherence and photodissociation of trapped BeH^+ impurities.

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Fundamental Physics with the ALPHA Antihydrogen Trap

Content :

ALPHA is an international project at CERN, whose ultimate goal is to test symmetry between matter and antimatter at highest possible precision via comparisons of the properties of atomic hydrogen with its antimatter counter-part, antihydrogen. After several years of development, we recently achieved significant milestones, including the first stable confinement of antihydrogen [1] for as long as 1000 seconds [2]. ALPHA has also succeeded in performing the first proof-of-principle spectroscopic measurement on antihydrogen atoms by driving its hyperfine transitions with microwaves [3]. Most recently, we reported a precision measurement of charge neutrality of antihydrogen, setting a new limit of the electric charge of the positron [4]. We have recently constructed an entirely new apparatus, ALPHA-2, which will allow laser access to the trapped anti-atoms, and provide improved magnetic field configurations for microwave spectroscopy. For the longer-term, possibilities for a measurement of antimatter-gravity interactions are being explored. This talk will discuss the recent achievements and the future prospects of fundamental physics studies with ALPHA.
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A New Hydrogenic Atom, e+H-

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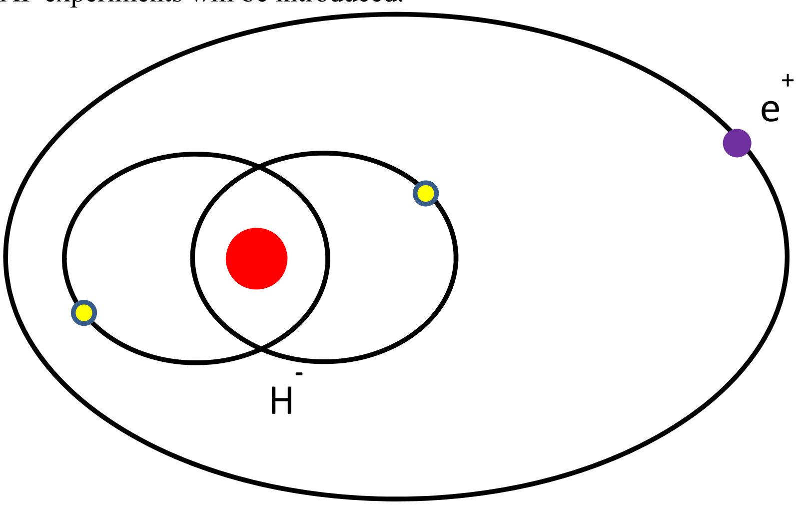
York University

A new atom has been produced and detected for the first time. The system consists of a e+ bound to H^- in a long lived hydrogenic atomic state. 100eV H^- ions are directed through a Penning trap used to hold and cool e^+ from a radioactive source, moderated in frozen neon and captured in this Surko style accumulator. The H^- ions are slowed by the applied trapping potentials of $^-$700Volts providing axial confinement of the e^+. H^- can capture e^+ from the trap, producing forward directed neutrals, e^+H^-, that leave the charged particle trap. The electric fields and the 0.13 Tesla magnetic fields of the e^+ trap result in a challenging problem alignment of ions and e^+ that result in neutrals into the detector aperture. Neutrals pass a high potential region of 900V and travel a 2 meter distance, entering the lead shielded detector system. This system includes a segmented Faraday cup to aid in alignment of the H^- ion beam trajectories. e^+H^- that hit the Faraday cup result in annihilation of the e^+ and emission of back to back gammas photons which pass through the thin vacuum chamber walls. These are detected with external scintillation crystals coupled to photomultiplier tubes. The output current from these detectors are continuously recorded by 10MHz analogue to digital converters and written to computer hard drives for post processing. This processing selects energy resolved coincidence evens from opposing detectors and results in a great reduction in experimentation time because data can be reanalyzed. Detection of coincident gammas indicates e^+H^- that traveled the 2 meter distance and indicates a survival time of 5μs, extremely long for a combined system of antimatter bound to matter. The detected rates of e^+H^- are consistent with those expected for radiative combination. Plans to stimulate this production mechanism with a CO_2 laser will be introduced along with possible extended experiments at the McMaster Intense Positron Beam Facility (MIPBF).

This work was supported by NSERC, CFI and ORS of Canada

Our e+ system at CERN also provides record e+ rates for antihydrogen experiments. With that system we simultaneously load e+ and antiprotons into the cryogenic antihydrogen trapping apparatus. We have achieved the largest ever trapped sample of e+ and maintained a vacuum pressure, measured with antiproton annihilations, of $6x10^{-17}$ torr. These achievements and a brief update of ATRAP experiments will be introduced.



Positron systems for antihydrogen and other positronic atom physics

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Research with positronic atoms requires large numbers of positrons (e^+). Our group at York University has assembled 2 e^+ systems that are based on ^{22}Na radioactive sources. One of these systems, at CERN in Geneva, Switzerland, provides positrons for our ATRAP antihydrogen experiments. The other is in my research labs at York University, providing e^+ for positronic atom experiments (e^+ bound to H^- in Rydberg states (e^+H^-) and Rydberg states of Ps). Positrons from radioactive decay are at high energy. These are slowed (moderated) in frozen neon to make a beam of e^+ with energies of a few eV. Our technique for depositing the neon results in a high efficiency with ~4% of the e^+ that enter the neon being slowed and re-ejected to form the beam. These e^+ are accumulated in a Penning trap by collisions with a nitrogen buffer gas. e^+ are then accelerated by ~10eV out of the Penning trap and into a magnetic guide that transports the e^+ over a distance of ~10 meters to the antihydrogen apparatus. Long term antihydrogen trapping requires extremely low vacuum pressures. A narrow tube at 4 Kelvin (cryogenic pumping restriction) separates the antihydrogen vacuum from the much higher pressures in the e^+ trap system and guide. Positrons that pass through this tube are captured by briefly pulsing open a Penning trap to allow e^+ to enter. These e^+ are cooled to cryogenic temperatures by collisions with cold electrons in this first use of e^- to efficiently trap e^+. Up to 4 billion e^+ are accumulated in this trap, the largest number of e^+ ever held in a Penning trap.

A third e^+ system is being developed by our group for installation at the McMaster Nuclear Reactor. Positrons will be produced by e^-/e^+ pair-production in a platinum foil mounted in the intense gamma flux a few cm from the reactor core. Positrons will be directed to 1 of 4 beam lines that will carry the e^+ to experiments. This system is expected to provide orders of magnitude higher rates of low energy e^+ compared to moderated radioactive source based systems. Our group at York has recently taken the lead role in the McMaster Intense Positron Beam Facility (MIPBF) designing not only the e^+ trap but the e^+ source, switch and beam lines. A brief summary of progress on the MIPBF will also be given.

The High Precision Mass Spectrometer-SMILETRAP Meets an EBIT in Shanghai

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SMILETRAP[1] is a double Penning trap high precision mass spectrometer, see fig. 1. The ions, externally created in an Electron Beam Ion Trap (EBIT) [2], can be re-trapped and cooled in the cooling trap. The coldest ions are then selected and injected into the precision trap where the high precision mass measurements are performed. The SMILETRAP experiment using the merits of highly charged ions by the fact that the precision of the mass determination in a Penning trap increases linearly with their charge state. For this reason, the trap will be connected to an EBIT(see also Shanghai-EBIT [2]) with designed beam energy of 50 keV and beam current of 200 mA in order to produce bare ions up to silver and He-like ions up to uranium.

In order to reach a precision in the mass determination of better than 10^{-9}, cold ions are needed to reduce the influence of imperfections of the fields. Evaporative cooling technique [3] and sympathetic cooling of the HCIs will be employed in the cooling trap. Further improvements of precision will also be implemented, such as the stabilization of the trap temperature [4] and the implementation of the Ramsey excitation technique[5].

Rebuilding of SMILETRAP in Shanghai-EBIT laboratory is ongoing and commissioning is planned in near future. A status report and the planned physics program will be given.

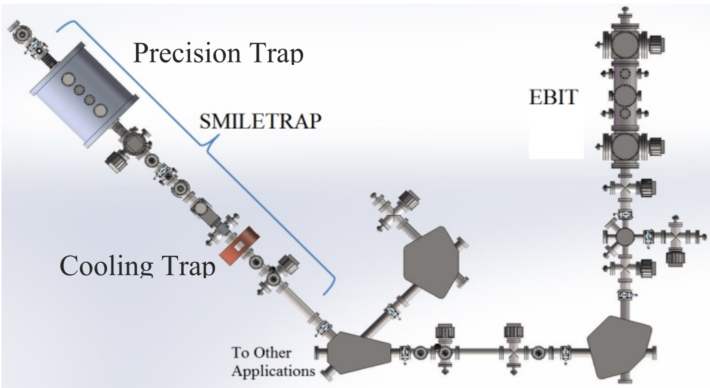

Fig. 1.The experiment setup of SMILETRAP. The most important components are: the EBIT, the cooling trap, and the precision trap.

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Spectroscopic studies of highly charged ions at the Tokyo electron beam ion trap facility

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An electron beam ion trap (EBIT) [1] is one of the most suitable devices for studying spectra of highly charged ions. It consists of a Penning-like ion trap and a high-energy, high-density electron beam going through the trap. It produces highly charged ions through successive electron impact ionization and traps the produced ions for many hours. Emission from the trapped ions excited by the electron beam can be observed for spectroscopic studies through the observation slit opened on the side of the trap.

We have been using two types of EBITs; a high electron energy EBIT called the Tokyo-EBIT [2] and a compact low energy EBIT called CoBIT [3]. Complementary use of them enables us to study highly charged ions over a wide charge state range. It is thus possible to give atomic spectroscopic data required from a wide area of application, such as astrophysics, plasma physics, light source development, fusion reactor engineering, fundamental physics, etc. In this paper, we present our recent spectroscopic studies [4–6] for highly charged ions after brief introduction of the devices.

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COULOMB-CRYSTALLIZED HIGHLY CHARGED IONS

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Coulomb-crystallization of re-trapped highly charged ions (HCI) from an electron beam ion trap (EBIT) has recently been achieved in CryPTEx, a cryogenic Paul trap developed and built at the Max-Planck-Institut für Kernphysik in collaboration with Aarhus University. This accomplishment presents an over six orders-of-magnitude decrease in HCI temperature and provides a platform for unprecedented high-precision spectroscopy of HCI of particular interest for future atomic clocks, and searches for physics beyond the standard model of particle physics. For cooling, $^{40}Ar^{13+}$ ions produced in and extracted from an EBIT are decelerated employing a pulsed time-focusing drift tube and are injected into CryPTEx, where they interact with a Coulomb crystal of laser-cooled $^{9}Be^{+}$ ions. Upon loosing sufficient energy, the Ar^{13+} ions end up implanted as clearly visible defects in the Be^{+} crystal, and thermalized close to the Be^{+} temperature. We studied various configurations of large crystals and fluids, over strings of several ions down to a *single* HCI cooled by a *single* Be^{+} ion – a prerequisite for future quantum logic spectroscopy at an ultimate 10^{-18} level accuracy. Recently, we have performed in-EBIT fluorescence spectroscopy of the two-electron-hole system Ir^{17+}, which features transitions with the largest sensitivity to a possibly changing fine-structure constant of all stable atomic systems so far investigated.

Figure 1: Single Ar^{13+} ion sympathetically laser-cooled by 3 Be^{+} ions in a string configuration: one Be^{+} on the left of the HCI and two on the right. The calculated HCI position is marked with a red cross.

4th, Thursday

Using GPU parallelization to perform realistic simulations of the LPCTrap experiments : from a trapped ion cloud to a time-of-flight measurement.

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The precise measurement of the β-ν angular correlation coefficient, $a_{\beta\nu}$, in nuclear β decay is a sensitive tool to search for exotic couplings presently excluded by the V-A theory of the Standard Model. In the case of a mixed mirror transition, $a_{\beta\nu}$ also allows the access to the mixing ratio ρ. Its measurement constitutes an important input for the database of nuclear mirror transitions, enabling the extraction of the CKM matrix's V_{ud} element with improved precision for such transitions [1]. In a β-ν correlation measurement, the most relevant observable is the energy distribution of the recoiling daughter nuclei. In the LPCTrap device, the radioactive nuclei are confined in a Paul trap, allowing the detection of the recoil ions in coincidence with the β particles [2, 3]. This time-of-flight (TOF) technique allows one to determine not only $a_{\beta\nu}$, but also the shake-off probabilities in the decay of 1+ ions with an excellent precision [4, 5].

In the data analysis, a very precise simulation of the whole experiment is required. In order to correctly generate the position of the decay vertices inside the Paul Trap, one needs to model the effects of the confining electric field, the collisions with the buffer gas and the effects of the space charge of a few hundreds of thousands ions. The achievement of such a simulation with a reasonable amount of resource and high precision is made possible using Graphical Processing Units (GPUs) (see [6]). With a parallel computing logic, even the brute force 2-body interactions (i.e. without approximation) of the space charge effect resolution, an algorithm in O(N^2), is henceforth within reach. Once the decay is correctly modelized, a precise tracking of both the recoil ion and the β particle is required to compute the TOF distribution. The generalizable package developed for this simulation will be presented using our physics case as an example.

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Status of the ReA Electron Beam Ion Trap Charge Breeder at NSCL

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An Electron Beam Ion Trap (EBIT) is used as charge breeder for rare isotope beams at the ReA re-accelerator facility of the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU). At NSCL, radioactive isotopes are produced by in-flight fragmentation, stopped in a He gas-cell, extracted and transported to the EBIT at energies of several tens of keV, where they are trapped for charge breeding. After breeding, the highly charged rare isotopes are extracted into an achromatic Q/A separator for charge-over-mass selection and then re-accelerated to energies of several MeV/u in a room temperature radiofrequency quadrupole accelerator and a subsequent superconducting linear accelerator.

Systematic studies were performed to improve efficient charge breeding and re-acceleration. The current density of the EBIT electron beam is the most crucial factor defining the ion properties in the trap. It was measured to be $j = (454 \pm 83)$ A/cm^2 for an 800 mA electron beam in the 4 T magnetic field by imaging X-ray emissions from the trapped ions using a pinhole camera set-up [1].

It is important to understand the effect of the energy spread of extracted ion beams on the efficiency of the subsequent re-acceleration. The energy spread was measured for stable $^{16}O^{7+}$ and $^{39}K^{15+}$ beams to be 0.3 % of the total ion energy, using the electrostatic bender and a slit assembly in the Q/A separator. This energy spread is mainly influenced by the temperature of the ions in the trapping potential of the EBIT, which can be extracted from these measurements. The ion temperature, normalized on the ion charge state q, was found to be between T/q = 25 and 31 eV/q, depending on the EBIT operation conditions.

Different ion extraction schemes were investigated, that allow for controlling the shape of the ion pulse structure in time. This provides more flexibility in matching the timing requirements for different experiments at the end stations of the re-accelerator. One of the extraction schemes, a slow voltage ramp, provides a further method to investigate the ion temperatures in the trap.

During commissioning runs in 2013, first radioactive $^{76}Ga^{24+,\,25+}$ [2] and $^{37}K^{17+}$ ion beams have been charge bred and re-accelerated successfully. The $^{37}K^{17+}$ beam was then delivered to the ANASEN detector array [3] for a first experiment on re-accelerated rare isotopes [4].

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DYNAMICAL EFFECTS IN THE X-RAY TRANSITION STRENGTHS OF ASTROPHYSICALLY RELEVANT Fe^{16+} IONS

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Line strengths and oscillator strengths for the controversial 3C and 3D transitions in neonlike Fe^{16+} are calculated. These lines, arising from the excitation of $2p \to 3d$ electric dipole transitions by x-rays with photon energies around 800 eV, are used in astrophysical line diagnostics to determine plasma temperatures of celestial objects. Therefore, an accurate knowledge of the line strengths is indispensable. These atomic data may be obtained from experiments or from theoretical calculations; however, a recent measurement [1] uncovered discrepancies between predicted and measured data. In an attempt to resolve this issue, we perform large-scale relativistic configuration [2] calculations of the oscillator strengths to accurately evaluate relativistic electron correlation effects, and also calculate QED screening corrections to the transition energies [3,4]. We furthermore investigate dynamical effects due to driving with intense pulsed x-rays by solving the time-dependent master equation for the density matrix of the involved ionic states, and calculating the spectral line shapes [5,6]. The dynamical effects give a possible resolution of discrepancies of theory and experiment found by recent measurements [1], which motivates the use of light-matter interaction models also valid for strong light fields in the analysis and interpretation of astrophysical and laboratory spectra.

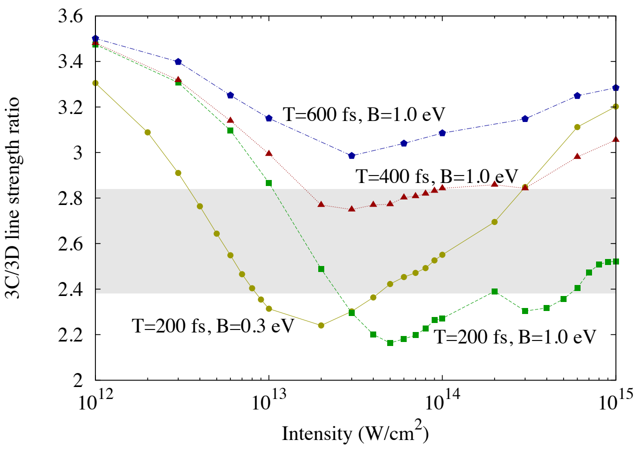

Figure 1. *The line strenght ratio as a function of the intensity, duration and bandwidth of incoherent pulses. The gray shaded area shows the experimental ratio 2.61 with its error bar of 0.23. Each point is obtained by averaging over 10 independent realizations of a chaotic pulse. For the shortest pulses, results with two different XFEL bandwidths B are shown.*

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4th, Thursday

High-resolution intensity ratio measurements in EUV spectral wavelength for ions of astrophysical interests

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Spectroscopic investigations of density sensitive lines emitted from Fe ions play an important role to measure the temperature and density of astrophysical and laboratory plasmas. In particular, emission in the extreme ultraviolet (EUV) spectral region provides an essential tool to study the most violent phenomena-taking place in different astrophysical objects. In the coronal temperature range (1−3 MK), Fe ions are considered to be the main source of density sensitive lines, which originate mainly below 300 Å, the wavelength region well covered with the EUV Imaging Spectromer (EIS) on board the Hinode satellite.

To extend our ongoing efforts to derive Fe spectroscopic data [1], we present high-resolution density sensitive intensity ratio measurements for Fe IX-XII and Fe V ions in EUV spectral wavelength. In the present study, a compact electron beam ion trap called CoBIT developed at the University of Electro-communications was used [2]. EUV emission from the trapped ions was observed with a concave grating having a larger radius of curvature (Hitachi 001-0660) to obtain higher dispersion. Although the average groove number is the same as that of the flat field grazing incidence spectrometer grating used in previous studies [3], but the larger radius of curvature (13450 mm) and the larger distance from the grating to the focal plane (563.2 mm) makes the dispersion on the focal plane higher as 2.6 Å/mm. The derived intensity ratio for several density sensitive lines of Fe IX-XII and Fe V will be compared with the calculations and with the data extracted from the EIS on board the Hinode satellite.

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Parity violation measurements in a single trapped radium ion

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Searches for violations of the fundamental discrete symmetries parity (P), time reversal (T) and charge conjugation (C) provide guidelines for model building beyond the Standard Model of the electroweak interactions (SM). At low energies searches for permanent electric dipole moments (EDMs) have a robust discovery potential while measurements of atomic parity violation (APV) test the electroweak interactions.
These symmetry violating effects are strongly enhanced in heavy atomic systems and they can be determined in precision atomic physics experiment. The technology of single ion trapping for optical clocks and the choice of the most sensitive atomic system, the radium ion, open the pathway to a new determination of atomic parity violation. The design and the progress towards the exploitation of the radium ion potential will be discussed. The precision determination of the weak charge can be used to extract the weak mixing angle (Weinberg angle) with an anticipated five-fold improvement over best existing experiment performed with neutral ceasium. The progress of the experimental efforts will be discussed.

Ba-ion extraction from high pressure Xe gas for double-beta decay studies with EXO

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An RF-only ion funnel has been developed to efficiently extract single Ba ions from a high-pressure (10 bar) xenon gas into vacuum. Gas is injected into the funnel where ions are radially confined by an RF field while the neutral gas escapes. Residual gas flow alone (without any DC drag potential) transports the ions longitudinally through the funnel. In the downstream chamber the ions are captured by a sextupole ion guide and delivered to an ion detector. The xenon gas is captured by a cryopump and then recovered back into storage cylinders for future use.

With the current setup ions were extracted from xenon gas of up to 10 bar and argon gas of up to 7.8 bar. These are the highest gas pressures ions have been extracted from so far. The ions were produced by a ^{148}Gd-driven Ba-ion source placed in the high pressure gas. The ion transmission has been studied in detail for various operating parameters. A mass-to-charge identification is currently being developed to further investigate the properties of the funnel and to measure the Ba-ion extraction efficiency of this setup.

This approach of ion extraction is intended for application in a future large-scale ^{136}Xe neutrinoless double-beta decay ($0\nu\beta\beta$) experiment. The technique aims to extract the $\beta\beta$-decay product, ^{136}Ba, from the xenon volume of a gaseous time-projection chamber and detect it unambiguously and efficiently. This individual identification of the decay product allows for an ideally background-free measurement of $0\nu\beta\beta$ by vetoing natural occurring backgrounds. This identification enables a higher level of sensitivity to the $0\nu\beta\beta$ decay half-life and thus is a more sensitive probe of the nature of the neutrino.

Fundamental physics with highly charged ions at low energies

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QED calculations of highly charged ions are considered. The theoretical predictions for the binding energies, the hyperfine splittings, and the bound-electron g-factors are compared with available experimental data. Special attention is focused on tests of quantum electrodynamics at strong coupling regime within the Furry picture and beyond. Electron-positron pair creation, charge transfer, and x-ray emission in low-energy heavy-ion collisions are also discussed.

MAGNETO-OPTICAL TRAPPING OF RADIOACTIVE ATOMS FOR TEST OF THE FUNDAMENAL SYMMETRIES

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Laser-cooling and trapping techniques are useful for precision measurements such as tests of fundamental symmetries. Heavier elements, such as francium (Fr, $Z = 87$), are predicted to enhance greatly the effect of the symmetry violation and are candidates for discovery of physics beyond the standard model. Besides, it is said that the studies of nuclear structure and weak interaction can be performed by precisely observing behaviors of the decay of radioactive isotopes.

We make researches of magneto-optical trapping of Fr toward the application to various of precision experiments. Since Fr is a radioactive element, we produce it using a cyclotron accelerator. Some artifices are required in order to capture a limited number of the atoms in a magneto-optical trap. The ability to observe very little atoms in the trap is helpful to search for the resonance frequency of Fr. If the Fr ion beam is purified by a Wien filter, collisions with impurities will be suppressed and the trapping efficiency should be improved. At the conference, we report the status of the developments for Fr trapping.

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BASE - High Precision Tests of CPT Invariance Using Antiprotons

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For a high-precision measurement of the antiproton's magnetic moment, the BASE (Baryon-Antibaryon Symmetry Experiment) collaboration has commissioned a new four Penning-trap system. It is located at the Antiproton Decelerator (AD) at CERN and dedicated to measure the antiproton magnetic moment with high precision. A comparison of this value to our recently obtained result for the proton magnetic moment with a precision of 3.3 parts in a billion, we aim at a highly-sensitive test of the CPT invariance with baryons.

The proton result was obtained using the double Penning-trap method, where we measure the ratio of the spin-precession frequency ν_L and the cyclotron frequency ν_C in a trap with homogeneous magnetic field, and in a second trap with a strong inhomogeneous magnetic field $B(z)=B_0 + B_2 z^2$, with B_2 = 30 T / cm^2, we apply the continuous Stern-Gerlach effect, which allows to determine non-destructively the spin-state of a single proton/antiproton. By measuring the spin-flip probability as function of the spin-flip drive excitation frequency, we obtain $\nu_L / \nu_C = g/2 = \mu/\mu_N$ from the resonance curve, which yields the magnetic moment directly in units of the nuclear magnetron.

To apply this technique to the antiproton, the double Penning-trap system has been extended by two additional traps. In the catching trap, antiprotons are captured between two high-voltage electrodes and cooled to thermal equilibrium with the cryogenic apparatus using electron and resistive cooling. Furthermore, it serves as a reservoir to suspend single antiprotons to the measurement cycle. The fourth trap called cooling trap is included in the measurement cycle and enables fast and efficient cooling of the modified cyclotron motion. This reduces significantly the preparation time of the particle for the spin-state read out, which lasted on average two hours per data point in the proton experiment. Further improvements have been made to the detection systems, which outperform the sensitivity of the detectors used at our proton experiment by almost a factor of 10.

The BASE apparatus has been commissioned in the AD, and first particle signals with protons have been recorded to commission the traps and the detection systems. The first injection of antiprotons into the Penning trap system was successful shortly after the start of the AD physics run in 2014. The four Penning trap system of BASE, the design of the detection systems, results from the commissioning with protons and antiprotons in the AD 2014 physics run will be presented.

Scalable quantum information processing with trapped ions at NIST

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This talk will provide an overview of the progress in quantum information processing and quantum simulation with trapped ions at NIST.

Most basic requirements for quantum information processing and quantum simulation have been demonstrated for trapped ions, with two big challenges remaining: Improving operation fidelity and scaling up to larger numbers of qubits. In the last few years, operation fidelities have steadily increased with single qubit rotation errors per π-pulse close to 10^{-6} for microwave operations and 10^{-4} for laser-based Raman-transitions on hyperfine ground state qubits. Laser-based two-qubit entanglement schemes have demonstrated fidelities of deterministically produced Bell states of larger than 0.99. Entanglement operations with microwaves in miniaturized surface electrode traps have demonstrated Bell state fidelities of 0.76. At NIST, scaling towards larger systems is based on moving ion-qubits through a multi-zone trap array and sympathetically cooling them with a second ion species. Micro-fabrication approaches to ion-trap-arrays have yielded structures that should be capable of holding and manipulating large numbers of ions.

After a brief overview of the current status, one recent experiment where the internal states of ions held in separate trapping wells are entangled will be discussed in particular. The experiment demonstrates the basic building block of a potentially scalable approach to analog quantum simulation using two-dimensional surface trap arrays.

This work has been supported by IARPA, DARPA, ONR, and the NIST Quantum Information Program.

Engineering and observation of interacting quasiparticles in a trapped-ion many-body system

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Strings of laser-cooled trapped ions are an attractive system for quantum information processing due to available techniques for encoding quantum information in superpositions of long-lived atomic states, manipulating superposition states with coherent laser pulses and measuring the states with low error rates. The possibility of entangling ions with each other by laser light coupling internal and motional degrees of freedom opens up the possibility of turning an ion string into an interacting quantum many body system.
I will report on our recent work [1] where we used state-dependent forces and single-ion addressing to engineer a 1D transverse Ising Hamiltonian with a tunable interaction range in a linear chain of up to 20 ions and study non-equilibrium dynamics of quantum states subjected to this Hamiltionian. We observe the propagation of quasi-particles in our system and demonstrate that the quasi-particles distribute entanglement between the ions.
In an extension to this work, we make use of a spin-wave description of the system's excitations and directly extract a dispersion relation from the dynamics of superpositions of quasiparticles and observe signatures of quasiparticle interactions by a kind of generalized Ramsey spectroscopy [2].
The entangled states, created at various times during the laser-driven dynamics, are no longer accessible to full state tomography nor can they easily be characterized by a simple entanglement witness. Based on tomographic measurements of subsets of the full chain, we are currently investigating the use of matrix product states and operators [3,4] in the efficient representation of the system's full quantum state. I will report on preliminary results that we have obtained in this manner.

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Development of the Quantum Repeater based on Trapped Ions

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One of the critical challenges in commercialization of quantum key distribution (QKD) technology is the attenuation of a single photon during transmission. To overcome this limitation, we are developing quantum repeater system using ion trap. Trapped ion is a good candidate for quantum memory to maintain entangled state due to its long coherence time, and also a good platform to implement quantum repeater thanks to its relatively easy interface to the photonic quantum bit (qubit) which is necessary to establish long-distance entanglement. Especially, entangled state stored in two remote (ionic) quantum memories was already demonstrated by Olmschenk *et al*. [1] using a scheme shown in Figure 1.

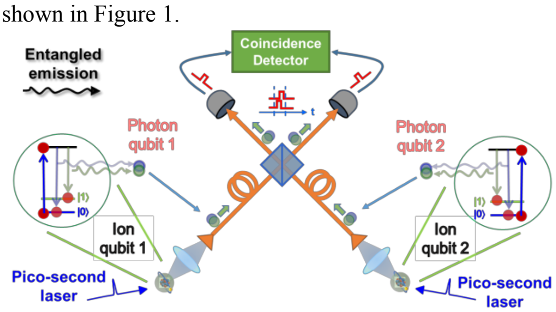

Figure 1: Schematic of entangled state generation [1].

To implement a scalable quantum repeater which can hold many individual ions, we developed our own micro-fabrication process based on micro-electro-mechanical system (MEMS) technology and fabricated an ion trap chip as shown in Figure 2. We used electrode layout similar to the trap chip fabricated by Sandia National Laboratory [2] for initial development and trapped both 171 and 174 isotopes of Yb ions in separate experiments.

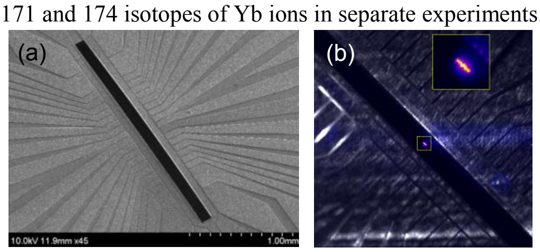

Figure 2: (a) SEM image of the ion-trap chip. (b) Six $^{174}Yb^{+}$ ions trapped on the micro-fabricated MEMS chip.

The image of the surface trap electrode structure was taken separately and overlaid for clarity.

We use two hyperfine ground states of $^{171}Yb^{+}$ ion as qubit. To demonstrate that we can manipulate qubit state, we first applied microwave corresponding to the hyperfine splitting frequency and detected the final quantum state of the ion by counting the fluorescence photons from cycling transition [3]. Figure 3 (a) shows the Rabi flopping result as we vary the detuning of the microwave and Figure 3 (b) shows that the coherence time is at least more than 50 msec. In this talk, I'm going to present our recent progress towards quantum repeater development.

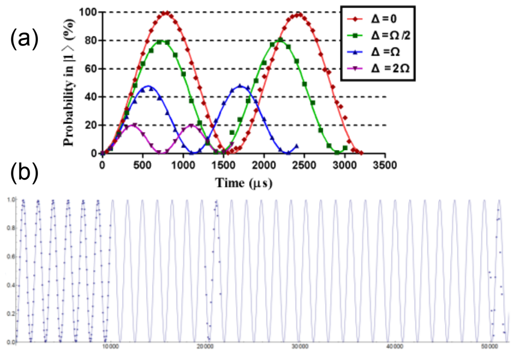

Figure 3: Rabi oscillation measurement. (a) Comparison of theoretical calculation and the measured data as we increase the detuning of the microwave frequency. (b) Data for coherence time measurement. Up to 50 msec, visibility of Rabi oscillation is above 90%.

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The *g*-factor of highly charged ions – Stress test for the Standard Model and access to the mass of the electron

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The ultra-precise measurement of the g-factor of highly-charged ions provides a unique possibility to probe the validity of the Standard Model under extreme conditions. The bound electron is exposed to electric fields of up to 10^{16} V/m, yielding a high sensitivity for higher-order contributions and hypothetical physics beyond the Standard Model. We have determined the *g*-factor of hydrogen- [1] and lithiumlike [2] silicon by measuring the Larmor- and cyclotron frequencies of single ions in a Penning trap with previously unprecedented precision [3]. The comparison of these values with the prediction of theory yields the most stringent test of quantum electrodynamics and relativistic inter-electron interaction in strong fields. Furthermore, the developed techniques open an access to fundamental constants. Recently [4], we have determined the atomic mass of the electron with a relative uncertainty of 30 parts-per-trillion, more than an order of magnitude better than the current CODATA literature value. This result enables future ultra-high precision tests of the Standard Model, *e.g.* the determination of the fine-structure constant and bound-state QED tests. Currently, we are setting up a next-generation apparatus which will be able to study even the heaviest highly-charged ions and thus explore the validity of the Standard Model at the strongest fields.

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PI-ICR technique for mass measurements on short-lived nuclides and the PENTATRAP project

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The talk is devoted to two independent projects: (1) Development of the PI-ICR technique and (2) the PENTATRAP project.

(1) The PI-ICR technique - a novel approach based on the projection of the Penning-trap ion motion onto a position-sensitive detector - opens the door to very accurate mass measurements on the sub-ppb level even for short-lived nuclides with half-lives well below a second. In addition to the accuracy boost the new method provides a superior resolving power by which low-lying isomeric states with excitation energy on the 10-keV level can be separated from the ground state. Recent measurements of the mass differences of, e.g., ^{132}Xe and ^{131}Xe, and ^{187}Re and ^{187}Os with a relative uncertainty of a few parts in 10^{10} have demonstrated the great potential of the new approach.

(2) A novel cryogenic Penning-trap mass spectrometer PENTATRAP has been designed and is now under construction at the Max-Planck Institute for Nuclear Physics (MPIK), Heidelberg, Germany. It aims for high-precision mass-ratio measurements with a relative accuracy of better than 10^{-11} on highly-charged stable and long-lived single ions of nuclides up to uranium. The physics addressed by PENTATRAP will be fundamental symmetries and constants as well as neutrino physics. The apparatus is planned to be coupled to the H-EBIT at MPIK and later to the HITRAP facility at GSI. The current status of the project will be presented.

Highly charged ions for atomic clocks and search for variation of the fine structure constant.

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Optical transitions in highly charged ions (HCI) are not sensitive to external perturbations due to compact size of the ions. This makes them good candidates for optical clocks of exceptionally high accuracy. Optical transitions in HCI can be most easily found between states of the same configuration. In particular, electric quadrupole transitions between ground $^3H_6$ and first excited $^3F_4$ states of the $[Pd]4f^{12}$ and $[Cd]4f^{12}$ configurations of the isoelectronic sequences of Os^{18+} and Hf^{12+} look very promising [1, 2].

Optical transitions between states of different configurations have extra useful feature. They are sensitive to the time variation of the fine structure constant α ($\alpha = 2^2/\hbar c$). The possibility for variation of fundamental constants is suggested by theories unifying gravity with other interactions. Evidence of the space/time variation of the fine structure constant is found in the quasar absorption spectra. To check the finding in terrestrial studies sensitivity to time variation of the fine structure constant on the level 10^{-20} per year is needed. This sensitivity can be achieved with optical clock transitions between states of different configurations in HCI. A number of such transitions have been recently found and studied [3].

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Laser spectroscopy of atoms in superfluid helium for the measurement of nuclear spins and electromagnetic moments of radioisotope atoms

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We have been developing a new laser spectroscopy technique named OROCHI (Optical RI-atoms Observation in Condensed Helium as Ion-catcher) for the investigation of nuclear spins and electromagnetic moments of low yield exotic nuclei [1]. Using this method, we observe atomic Zeeman and hyperfine structure (HFS) with the combination of optical pumping and laser-microwave/radio frequency (MW/RF) double resonance method. From the atomic structures, nuclear spins and electromagnetic moments are derived independently. Superfluid helium (He II) is not only a stopping material of the energetic RI beam but also interesting host material of atoms. The characteristic properties of implanted atoms in He II, for example, widely broadened and blue shifted absorption spectra, enable us to perform the optical pumping efficiently [2].

In our previous study, we performed the observation of atoms injected as energetic (up to 66 MeV/u) $^{84-87}$Rb beams produced by the projectile fragmentation in RIKEN Nishina center and confirmed the feasibility of the OROCHI method [1]. Recently, we have successfully performd OROCHI for stable atoms, for alkali Rb and Cs atoms as well as alkali-like atoms, introduced into He II by the laser spattering technique [3]. We succeeded in producing large atomic spin polarization (>80%) of ^{197}Au with optical pumping in He II by using the fourth harmonics of a LD-pumped pulsed Nd: YLF laser (wavelength: 263.5 nm, repetition rate: 3 kHz, power: typically 10 mW) as pumping laser. The success was based on the incidental coincidence of wavelength between this pulsed laser and the absorption line of Au atoms in He II. Then, we performed HFS measurement of stable ^{197}Au atoms in He II produced by laser sputtering technique. The measured value of HFS splitting in this study was slightly shifted from the literature value in vacuum [4]. It is same as the cases of ^{133}Cs and ^{85,87}Rb. The difference is due to the pressure from surrounding helium atoms. This slight shift (<1%) is of course negligible for the discussion of the structure of nuclei.

In this presentation, we will introduce our OROCHI method, mainly with focusing on the recent measurement of stable ^{197}Au.

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Quantum Simulation of the Jaynes-Cummings-Hubbard Model Using Trapped Ions

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Recent advances in quantum technology enabled us to simulate a certain quantum system with another well-controlled system (*quantum simulation* or *analog quantum computation*). Systems of trapped ions are among the best suited for that purpose. We report here an experiment on quantum simulation of the Jaynes-Cummings-Hubbard (JCH) model [1-3] using two ions in a linear Paul trap.

The JCH model was originally proposed for a system of coupled cavity arrays, each containing a two-level atom [1]. Photons naturally hop between adjacent cavity sites, while coupling with two-level atoms leads to effective photon-photon repulsion. The model has a similarity to the Bose-Hubbard model, which was introduced in relation to studies on strongly-correlated electron systems and later extensively studied with cold neutral atoms in optical lattices. Quantum phase transition between conducting and insulator phases, which is common in these systems, is also expected to be observed for the JCH model.

We performed quantum simulation of the JCH model using an ion chain based on a proposal by Ivanov et al. [2], where each ion in a linear ion crystal represents a cavity in the coupled cavity system, and the single-mode electric field in each cavity is simulated with radial phonons in each ion site. The Jaynes-Cummings (JC) interaction arising from radial red sideband excitation offers effective on-site repulsion, and inter-site hopping of radial phonons is naturally incorporated from the Coulomb coupling.

We observed quantum dynamics derived from the JCH Hamiltonian of a two-ion system, and adiabatic transfer of population from a localized state to a delocalized state [3]. Observation of a polaritonic Mott insulator ('frozen phonons') and the possibility of scaling up the system to several ions will be also discussed.

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EXTREME FIELD PHYSICS IN PENNING TRAPS

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The physics of extreme fields holds two interesting yet distinct regimes: on the microscopic scale there are the extreme electric and magnetic fields in the vicinity of an atomic nucleus which significantly alter the properties of bound electrons. With field strengths almost up to the Schwinger limit, contributions from quantum electrodynamics play an important role in electronic structure, state lifetimes, and magnetic moments, and corresponding calculations can be tested with utmost accuracy. In turn, this allows access to fundamental constants and symmetries. This field can superbly be studied in highly charged ions when confined in a Penning trap and cooled close to rest. We present the ARTEMIS experiment for precision optical and microwave spectroscopy of confined and cooled highly charged ions, aimed at measurements of electron magnetic moments (g-factors) on the ppb level of accuracy, nuclear magnetic moments on the ppm level of accuracy, and of higher-order Zeeman effects [1,2]. We present the concept, status, and first results.
The macroscopic counterpart of extreme field physics are atoms and ions subjected to highly intense laser light. The electromagnetic fields in and close to the laser focus evoke strongly non-linear optical effects such as multi-photon ionization to high charge states. We present the HILITE experiment which features a Penning trap for the preparation and positioning of well-defined ion targets, as well as for non-destructive detection and confinement of reaction products in studies with various high-intensity and / or high-energy lasers [3].

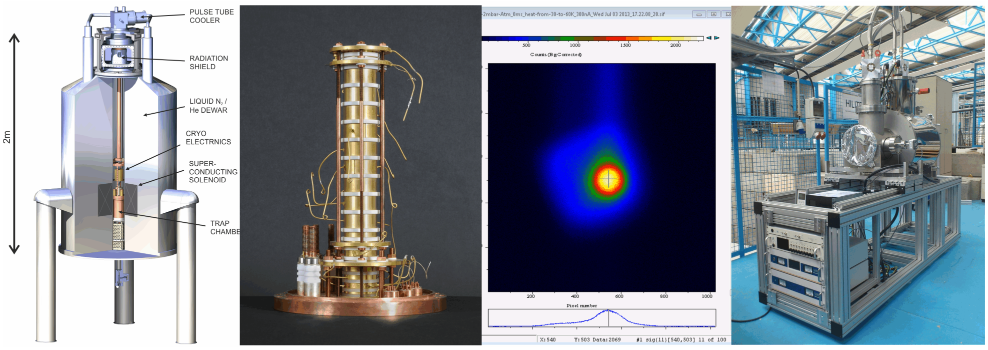

Figure 1: Left to right: setup and trap of the ARTEMIS experiment, fluorescence light emitted from confined highly charged ions, and the setup of the HILITE experiment for laser reaction studies.

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Quadratic Zeeman effect in highly charged ions

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Simultaneous experimental and theoretical study of the g-factor of light hydrogen-like ions provided the best up-to-date determination of the electron mass [1]. Corresponding investigations for heavy hydrogen-like and boron-like ions will lead to independent determination of the fine structure constant [2, 3]. As an important step towards this goal, ARTEMIS experiment presently implemented at GSI aims at high-precision measurement of the Zeeman splitting in boron-like argon for both ground ($2P_{1/2}$) and first excited ($2P_{3/2}$) states. Apart from the g-factors of these states it will be sensitive to the non-linear contributions in magnetic field [4]. In particular, the relative contributions of the second and third order in magnetic field amount to 10^{-4} and 10^{-8}, respectively, at the field of 7 Tesla [5]. The theoretical study of the second-order Zeeman effect in highly charged ions is presented. First-order corrections - one-photon exchange, self-energy, and vacuum polarization - are evaluated within the framework of bound-state QED with local screening potential. Observation feasibility of the second- and third-order effects in the ARTEMIS experiment is discussed.

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Precision β-decay experiments with the β-decay Paul Trap

Abstract

Precision measurements of angular correlations from nuclear β decay provide information on possible exotic couplings in the weak interaction. In the β decay of ^{8}Li, the delayed-α breakup of the ^{8}Be* daughter provides enhanced sensitivity to possible tensor couplings. We report a limit on the ratio of the tensor to axial-vector coupling from the ^{8}Li $\beta - \alpha - \nu$ correlation experiment performed using the β-decay Paul Trap (BPT) at Argonne National Laboratory. We will discuss our continued work on angular correlation measurements as well as other additional precision β-decay experiments being performed with the BPT such as β-delayed neutron spectroscopy.

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Precision measurements with LPCTrap at GANIL

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The LPCTrap setup, presently installed at the low energy beam line (LIRAT) of the SPIRAL facility at GANIL, was designed to perform precise beta-neutrino correlation measurements in nuclear beta decay [1]. The radioactive nuclei are confined in a transparent Paul trap, allowing the detection of the recoil ions in coincidence with the beta particles. The beta-neutrino angular correlation parameter is deduced from the time-of-flight distribution of the recoil ions. A recoil spectrometer was recently added to separate the different charge states of the ions, making this setup unique in the determination of the shake-off probabilities in the decay of 1+ ions.

Several experiments with ^{6}He, ^{35}Ar and ^{19}Ne were successfully performed. The study of the shake-off probabilities has enabled to illustrate the sudden approximation in a text book case [2] and it has also revealed the importance of the Auger emission in complex systems such as ^{35}Ar [3]. The final data analysis is ongoing, based on the development of new simulation tools [4]. The statistics recorded during the experiments should enable the determination of the beta-neutrino correlation coefficients with unprecedented precision in these decays. These coefficients constitute sensitive observables to search for new physics beyond the Standard Model or to test its consistency. The precise measurement of such a coefficient in a pure transition (GT or F) enables to probe the existence of exotic couplings in the weak interaction, while in a mirror transition it allows the accurate determination of the mixing ratio [5]. The matrix element V_{ud} can be deduced from the latter with a high precision to test the unitarity of the CKM matrix, if the masses of the involved nuclei, the half-life and the branching ratio of the transition are also well known.

This presentation will review the experiments performed with LPCTrap and describe future perspectives.

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A new correlation Penning trap for fundamental physics at Texas A&M

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Nuclear β decay has a long-standing history of shaping and testing the standard model of particle physics, and it continues to this day with elegant, ultra-precise low-energy nuclear measurements. Experiments observing the angular correlations between the electron, neutrino and recoil momenta following nuclear β decay can be used to search for exotic currents contributing to the dominant $(V-A)$ structure of the weak interaction. Precision measurements of the correlation parameters to $\lesssim 0.1\%$ would be sensitive to (or meaningfully constrain) new physics, complementing other searches at large-scale facilities like the LHC.

The Cyclotron Institute at Texas A&M University is nearing completion of an upgrade to recommission our K150 cyclotron and couple it to our K500 cyclotron, allowing the two to either work in parallel or in concert for reacceleration of exotic ions. One of the end-stations being constructed to take advantage of the high intenstities available from the K150 is TamuTrap: a large (180-mm inner diameter) cylindrical Penning trap. The unprecedented open-area of TamuTrap is ideal for 4π collection of the delayed protons following the superallowed β decays of very proton-rich nuclei. In particular, observation of the β-delayed proton in coincidence with the β can be used to determine the $\beta-\nu$ correlation parameter, the value of which can be used as a sensitive probe of possible scalar currents contributing to the weak interaction.

An overview of the correlation experiments planned at TamuTrap as well as the status of the facility will be presented.

Ion trap and laser cooling spectroscopy for isotope analysis

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Techniques of laser cooling of trapped ions advance a variety fields of physics such as quantum information, frequency standard, nuclear, atomic and molecular spectroscopy and so on. One of the reasons of the progress is ascribed to high energy resolution of lasers, which can resolve isotope shifts and hyperfine levels of atomic and molecular ions. Laser cooling enhances the resolution because of the suppression of Doppler broadening, which would lead the drastic increase of photoreaction rates with precise control of laser frequencies. We have developed a novel apparatus to apply the techniques to perform isotope analysis because photoreaction selectivity can complement mass spectrometers which cannot resolve isobars [1]. Additionally, high sensitivity and selectivity can be expected when individual ions can be observed in a Coulomb crystal. As ion source, Inductively Coupled Plasma Mass Spectrometer (ICP-MS) was adopted, to which a liquid sample can be directly injected. The experimental apparatus is shown in Fig. 1. We have demonstrated the performance of the apparatus with Ca ions [2, 3]. The results will be discussed in the presentation.

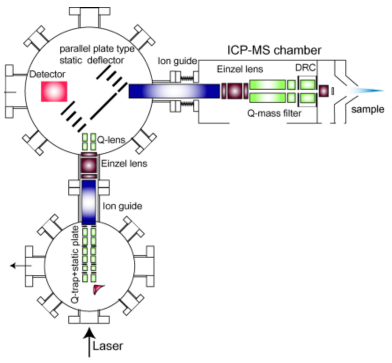

Figure 1: Ion trap and laser cooling spectroscopy (ITLECS) with Inductively Coupled Plasma Mass Spectrometer (ICP-MS)

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Gas-cell beam cooler-buncher for low-energy experiments at SLOWRI

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For future experiments at SLOWRI, ion preparation, e.g. cooling and bunching, are indispensable for various experiments such as collinear laser spectroscopy and all ion trap experiments. The ion beams from SLOWRI gas cells will be continuous with a beam energy of $\lesssim$30 keV/q. Ions must be decelerated and cooled in an ion trap to bunch ions.

Generally, segmented linear Paul traps using He gas at a pressure of $\sim 10^{-2}$ mbar have been used for this purpose. They are typically ∼1 m in length with no more than a few centimeter aperture. The typical efficiency of such cooler-bunchers is limited by the Paul traps's acceptance to a few ten percent [1, 2] when the ions need to be decelerated by a few ten keV. Additionally, the finite length of each segment can lead to small field-free regions in which ions may be inadvertently trapped. Using shorter segments requires ever increasing numbers of segments, leading to complicated mechanical structures.

In order to achieve higher efficiency with much simpler solutions, we are developing new ion preparation systems. One is a new windowless gas-cell cooler-buncher (GCCB) for capture and deceleration of the $\lesssim$30 keV/q continuous beams from the SLOWRI gas cells. The GCCB consists of a gas cell (GC) with an 80-mm diameter RF-carpet (RFC) followed by a flat trap [3]. The GCCB will be filled with He gas at up to 2 mbar, cryogenically cooled to $\lesssim$77 K. According to calculations with TRIM, a stopping efficiency of 100% can be obtained for any $\lesssim$30 keV/q beams with $Z > 3$ if the GCCB is at least 420 mm long. The large radial geometry provides a larger effective acceptance than any conventional Paul trap cooler-buncher, allowing for higher efficiency.

A resistive RFQ ion guide is also being tested. The resistive RFQ uses a traditional four rod structure, made from ceramic rods coated with resistive ink. The resistive rods produce a smooth axial potential, allowing for improved ion transmission in a poor vacuum region. Additionally, by applying a third potential at a midpoint, it can function as a Paul trap with very simple mechanical design. It will be used to transport ions from the GCCB to the flat trap and as a cooler-buncher for lower-energy ion beams.

These new ion preparation schemes will provide us much simpler configurations while achieving higher efficiency. This will allow further reach into exotic nuclei.

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Abstract TCP2014

Penning trap mass spectrometry at the LEBIT facility

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The Low-Energy Beam and Ion Trap (LEBIT) facility at the National Superconducting Cyclotron Laboratory (NSCL) remains the only facility that employs Penning trap mass spectrometry for high-precision mass measurements of rare isotopes produced via projectile fragmentation. Prior to delivery of the rare isotopes to LEBIT, they are first thermalized in a gas stopper and formed into a low-energy, high-quality beam. This powerful combination of a fast, chemically insensitive rare isotope production method with a high-precision Penning trap mass spectrometer has yielded mass measurements of short-lived rare isotopes with precisions below 10 ppb across the chart of nuclides.

From 2004-2009, LEBIT was used to perform mass measurements of over 40 rare isotopes, contributing to nuclear structure, nuclear astrophysics, and fundamental interactions studies. In 2009, due in part to LEBIT's success, an expansion of the NSCL's thermalized beam program was begun, and the experimental science program has recently resumed. However, LEBIT has not remained idle while waiting for beam. The time has been used to implement several upgrades, such as a laser ablation ion source, advanced in-trap beam purification, and a miniature Penning trap magnetometer for continuous magnetic field monitoring using FT-ICR. In addition, the new Single Ion Penning Trap (SIPT), currently under construction, will use narrowband FT-ICR to perform mass measurements of high-impact candidates, delivered at rates as low as one ion per day, with only a single detected ion. LEBIT has also recently been used to measure the Q-values of several neutrinoless double beta decay candidates produced offline using local ion sources.

Probing exotic nuclei through mass measurements from ISOLTRAP

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Numerous physics topics can be addressed by studying nuclei, ranging from their structural evolution to fundamental interactions and even questions related to astrophysics. Experimentally, complementary observables are available to ameliorate our understanding of the nucleus, its mass being the most fundamental property. Together with the known mass of the individual constituents of the nucleus, the mass delivers the binding energy, which in turn reflects all underlying interactions of the nucleons. In many cases, only precision measurements can give insight into structural effects throughout the nuclear chart from the lightest to the heaviest elements.

The precision mass spectrometer ISOLTRAP is such a versatile tool to investigate short-lived nuclei far from the valley of ß-stability, which are produced by the isotope separator ISOLDE at CERN. The system has studied nuclides with half-lives below 50ms and production yields of roughly 100 ions per second reaching relative uncertainties on the order of 10^{-8} [1]. In this contribution, it will be discussed how results from masses enhance our understanding of nuclear structure and even astrophysics. Among the discussed examples, is the structural evolution and establishment of the neutron magic number N=32 in the calcium isotopic chain [2]. The role of models describing the nuclear interaction through three-body forces in this context will be shown. Furthermore, it will be illustrated how the mass measurement of 82Zn impacts our understanding of nucleosynthesis in neutron stars [3].

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Title: High-precision Penning-trap mass measurements at TRIGA-TRAP
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TRIGA-TRAP [1], located at the TRIGA research reactor in Mainz, will access thermal neutron-induced fission products of ^{235}U, ^{239}Pu or ^{249}Cf. The on-line commissioning at the research reactor is ongoing. In parallel, we have developed a laser-ablation ion source featuring a buffer-gas-filled miniature radio-frequency quadrupole trap structure. A number of high-precision off-line mass measurements have been carried out at TRIGA-TRAP employing this ion source. Recently, the absolute masses of four long-lived transuranium nuclides, ^{241}Am, ^{243}Am, ^{244}Pu, and ^{249}Cf have been measured with TRIGA-TRAP [2]. Our measurements confirm the AME 2012 mass values of ^{241}Am, ^{243}Am and ^{244}Pu within one standard deviation, which were indirectly determined by decay spectroscopy studies. In the case of ^{249}Cf a discrepancy of more than three standard deviations has been observed, affecting absolute masses even in the superheavy element region. Additional mass measurements are planned in this region of the chart of nuclides to study further the deformed N=152 neutron shell closure, recently investigated at SHIPTRAP [3].
Our new ion source is capable to operate with relatively small samples, down to 10^{15} atoms deposited on a target. The achieved performance enabled us to employ our ion source in the ^{163}Ho - ^{163}Dy *Q*- value determination relevant for neutrino physics.
In the future extremely rare isotopes of all elements up to uranium will be available at the FAIR facility behind Super-FRS, where TRIGA-TRAP will be installed as MATS [4] within NUSTAR.
The present status of the TRIGA-TRAP experiment will be given focusing on recent mass measurement results and technical developments.

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TITAN: The Ion trapping program at TRIUMF

Content :

The Penning trap mass spectrometer at TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) facility is unique in its demonstrated capabilities for mass measurements of singly and highly charged, very short-lived ions. Recent mass measurements in the island of inversion near N = 20 include nuclides with half lives as low as 13 ms for Na-32. Charge breeding in the EBIT has been used to measure the mass of the shortest-lived superallowed beta-emitter Rb-74 (T1/2 = 65 ms), to resolve an isomer in Rb-78, and to improve beam purity for investigations of the gallium anomaly. To best leverage the benefits of highly charged ions simulations of the charge-breeding process are performed before each experiment, which reduces the setup time required on-line and have been compared to experimental data.

These simulations are also relevant for determining the best trapping settings for in-trap decay spectroscopy in the EBIT. The magnetic field eliminates background due to electrons, and the electron beam improves the trap confinement, thereby increasing storage times. In preparation for branching-ratio measurements relevant to the double-beta-decay problem, the detector array has been commissioned, and multiple-ion injection or "ion stacking" has been demonstrated. The current status of the TITAN facility and recent highlights will be discussed as well as an outlook, including a multi-reflection time-of-flight mass spectrometer and an additional Penning trap to cool highly charged ions.

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Presenter : Dr. KWIATKOWSKI, Ania (TRIUMF)

The Canadian Penning trap mass spectrometer at CARIBU

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More than half of the elements heavier than iron are thought to be created in the astrophysical r process, where nucleosynthesis is primarily achieved through a rapid series of neutron capture reactions during supernovae or merging neutron stars. In an attempt to reproduce the observed distribution of element abundances in the universe, models are generated which inherently rely upon many nuclear physics inputs, with the masses of the nuclides involved being key ingredients. However, the uncertainties in the masses of the relevant nuclei are often too large and limit our understanding of heavy-element nucleosynthesis. More precise mass measurements are difficult to obtain since a large number of the nuclides involved in the astrophysical r process are often too challenging to produce at accelerator facilities. Recently the CARIBU facility, an upgrade to Argonne National Laboratory's ATLAS facility, has started to provide intense beams of a number of these previously elusive neutron-rich nuclei. A program of mass measurements at CARIBU is now underway with the Canadian Penning trap (CPT) mass spectrometer, with more than 130 neutron-rich nuclides measured with a precision of ~ 15 keV/c^2. These measurements will be highlighted, the implications on the astrophysical r process will be discussed, and plans to increase the reach of the CPT to more exotic neutron-rich nuclei will be presented.

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On-going developments and measurements at JYFLTRAP

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The JYFLTRAP setup [1] was recently moved to a new location along with the IGISOL [2] facility. Beams not just from the K130 cyclotron but now also from high-intensity K30 proton/deuteron cyclotron are available. The experimental program utilizing the setup is now in full swing.

JYFLTRAP is essentially the same setup as it used to in the old IGISOL3 facility [3]. The mass measurement program extends to both neutron deficient and rich side of the nuclide chart covering studies for fundamental physics, neutrino physics, nuclear structure and nuclear astrophysics. Additionally, purified beams of various elements (mostly neutron rich fission fragments) are provided for nuclear decay studies.

Currently the JYFLTRAP setup is undergoing several upgrades. The two most significant ones are a construction of a multireflection time-of-flight separator/spectrometer (based on device described in Ref. [4]) and installation of a 2D-MCP detector to enable the new PI-ICR (Phase-Imaging Ion-Cyclotron-Resonance) measurement technique [5]. Coupling of both of them to the existing setup will require significant changes to some parts of the system.

My presentation will contain glimpses of the current measurement program and details of the on-going upgrades.

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RECENT DEVELOPMENTS FOR INVESTIGATIONS OF THE HEAVIEST ELEMENTS WITH SHIPTRAP

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Atomic masses provide information on the interactions inside the atom. For example, binding energies obtained from experimental masses reveal the nuclear structure of nuclides far off stability. The region of superheavy nuclei that owe their existence solely to nuclear shell effects is of particular interest. Accurate experimental data are crucial for a deeper understanding of their structure and to benchmark nuclear models. Mapping the location and the strength of shell closures around N=152 and N=162 with mass measurements will yield information to improve predictions of the location and extension of the long-sought island of stability.

A combination of buffer gas stopping and advanced ion-beam manipulation techniques has paved the way to extend Penning trap mass measurements to the region of nobelium and lawrencium isotopes around N=152 with SHIPTRAP at GSI. In order to extend the reach to ever-heavier elements, whose production rates drop steeply with increasing atomic number, several developments are underway at SHIPTRAP. A cryogenic gas-stopping cell has been set up to increase the efficiency of slowing down the reaction products for trapping and the novel phase imaging ion cyclotron resonance method allows precise mass measurements in shorter measurement times.

In my contribution I will present recent developments and selected results from SHIPTRAP.

Sympathetic laser cooler for highly charged ions at RAON facility

Content :

Our strategy for enhancing mass accuracy of Penning trap is to exploit highly charged ions (HCI). Since buffer gas cooling technique is not viable for HCI, we are developing sympathetic laser cooler where the coolant is not neutral gas but positive ions. Extended cavity diode lasers with wavelength of 397 nm and 866 nm were installed for the Doppler cooling of Ca^+ ions. Frequency locking system was composed of a wavelength meter and an analog output module in PXI platform. For the feasibility experiment, we chose Ca^+ ions as the coolant due to the handiness of the light sources. Prototype chamber with segmented linear Paul trap is being built for testing rf trap and laser cooling. In this presentation we will talk more about our progress in the development of sympathetic laser cooler, which is one of the key subsystems of high precision mass measurement system of RAON.

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An overview of the high-precision mass measurement system for RAON facility

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Atomic masses provide key input data in the study of the ground-state properties of nuclear structure since the binding energy reflects the net result of all interactions in the nucleus. Also, the masses have a decisive influence on the reaction network calculation in the study of stellar nucleosynthesis. For the study of nuclear structure and stellar nucleosynthesis in astrophysics, a relative mass uncertainty $\delta m/m = 10^{-6} - 10^{-8}$ is necessary. Due to the lack of experimental nuclear mass data when moving away from the valley of stability of the nuclear chart, mass models are used to provide the needed input parameter. However, for these exotic nuclides, the mass values provided by the models disagree significantly with each other. Hence, direct mass measurements for those short-lived nuclides are required.
By now Penning traps are the most accurate tools for high-precision mass spectrometry of atomic nuclides. The coupling of the Penning traps to the rare isotope beam (RIB) facilities revolutionized the field of mass spectrometry of short-lived nuclides. Today most of the RIB facilities worldwide have Penning trap based mass measurement systems. The Rare Isotope Science Project (RISP) aims to construct the new accelerator complex RAON in Daejeon, Korea. RAON will provide high-intensity RIBs near the proton- and neutron-drip line by employing both the Isotope Separation On-Line (ISOL), and In-flight fragmentation (IF) production method. A high-precision mass measurement system at RAON will offer precise mass values of the exotic nuclei with mass accuracy better than 10^{-8}. The essential subsystem for the precision mass measurement system will be RFQ cooler and buncher, multi-reflection time-of-flight mass separator (MR-TOF-MS), EBIT charge-breeder, sympathetic cooling trap, and precision Penning trap. An overview of the planned high-precision mass measurement system for RAON will be presented.

Effect of projectile charge on electron and positron impact single ionization cross section of water molecule

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The charged particle impact ionization studies of fundamental atomic and molecular systems have been of great interest since the early days of quantum mechanics. Extensive theoretical and experimental investigations have been carried out to understand the electron and positron impact single ionization processes of various targets. [1-6]. Such type of studied is important in many areas, such as understanding the processes in the earth's upper atmosphere, in the development of new lasers and novel forms of lighting, as well as in the treatment of cancers that use radiotherapy. Accurate cross sections for Water molecule target ionization by low energy electron and positron impact are very important for the understanding of the radiation damage in biological samples [7].

Triple differential cross section calculations for the ionization of $3a_1$orbitals of the water molecule by low energy electron, and positron impact are reported. The present investigation is done in the modified distorted wave born approximation using post collision interaction and polarization of target with inclusion of second order term (DWBA2). We found a very good agreement with the experimental data of Nixon and Murray [8] in case of the $3a_1$ orbital of water molecule. By changing the projectile's charge, significant differences were observed between the electron and positron impact ionization cross section of water molecules.

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Simulation of the sympathetic cooling of highly charged ions using a GPU

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Sympathetic cooling will be employed to cool down and transport the highly charged ions (HCI) to the Penning trap with better energy spread and emittance which can provide higher resolution in the high-precision mass measurement system of RAON. In our simulation study, a segmented linear Paul trap acts as playground for HCI to be captured and cooled by laser-cooled Ca^+ ions. Two potential wells are formed along the linear trap to initially capture HCI and Ca^+ ions in separate region. An efficient injection of HCI to the trap was achieved by suitable arrangement of voltage sequence to the drift tube and trap electrodes. Once HCI are captured into the first potential well, the bottom of the trap potential is raised gradually. Then, they start to enter the neighboring potential well, where 70,000 $^{40}Ca^+$ ions are laser-cooled and form a Coulomb crystal. The HCI lose their kinetic energy through the Coulomb interaction with the cooled $^{40}Ca^+$ ions and are arranged finally near the center of crystal. By adjusting the voltage of the end electrode of the trap, the HCI can be extracted from the crystal. For high speed simulation of many ions, a graphics process unit (GPU) was used in the parallel computation linked with commercial software SIMION, which enables us to calculate N-body interaction very fast. Furthermore, we successfully adopted the Barnes-Hut algorithm to reduce the number of calculation from $O(N^2)$ to $O(N \log N)$. We show and analyze how HCI are cooled and extracted in the Ca^+ Coulomb crystal.

Optical pumping and resonance ionization of trapped ions at IGISOL

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The constant development of the collinear laser spectroscopy programme at the University of Jyväskylä, Accelerator Laboratory, Finland over the past 15 years has led to new experimental techniques. In particular, the pioneering application of cooled and bunched ion beams of fission fragments for laser spectroscopy utilising a radio-frequency quadrupole cooler [1] has enabled new physics cases to be pursued [2].

More recently, by optically manipulating the ions within the cooler, the reach of collinear laser spectroscopy has been extended to previously inaccessible elements for efficient study [3, 4]. The extended laser–ion interaction time allows metastable states to be populated via spectroscopically weak ground-state transitions, thus enabling collinear laser spectroscopy from these states rather than from the ground state. Such a state may be preferable if the transition from the ground state is either unfavourable for extracting nuclear parameters or beyond the wavelength capabilities of a CW laser. For example, the nuclear spin cannot be determined if the transition takes place from a ground state spin J=0 → J'=1. Likewise, the nuclear spin and the quadrupole moment are indeterminable for $J=\frac{1}{2} \rightarrow J=\frac{1}{2}$ transitions. The method has been demonstrated on both singly [3, 5] and doubly charged ions under on-line conditions.

In the latest development, the optical pumping of ions is being extended to multi-photon resonance ionization. The ion-resonance ionization (IRIS) -technique would allow the charge state of the trapped ions to be selectively increased to 2^+. These doubly charged ions could be then utilized either to access ultra-pure ion bunches through time-of-flight gating and to to enable spectroscopy of more favourable electron configurations.

In addition, a new electrostatic trap is under commissioning at IGISOL. The trap, namely Conetrap [6], consist of two conical and one central cylindrical electrode. The relatively open geometry and long storage times of he device are expected enable efficient optical manipulation of the trapped ions thus providing alternative site or optical pumping and IRIS. We report the current status of the optical manipulation of trapped ions at IGISOL.

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Preparation of cold ions in magnetic field and its application to gas-phase NMR spectroscopy

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Recently, we proposed a new principle to detect a nuclear magnetic resonance (NMR) signal for mass-selected molecular ions. NMR technique is a powerful tool to study the physical and chemical properties of materials in wide area. However, this technique is limited to the materials in condensed phase because of its very low sensitivity. Although this technique is also highly expected to use for mass selected gas-phase ions in both fundamental and applied sciences, the method to extend to the gas-phase ions is not reported yet. In order to break this situation and overcome the sensitivity problem, we adopt a Stern-Gerlach type experiment in a Penning-type trap, in which ultracold molecular ions are introduced in the trap and their magnetic moments are probe by observing the modulation of their time-of-flights induced by a Rf magnetic excitation at both end of the trap.[1)] In the usual Stern-Gerlach experiment such as a molecular-beam magnetic resonance method, [2)] the sensitivity depends on the divergence of molecular beam; a transverse temperature. On the other hand, the sensitivity of our method depends on a translational temperature of the sample ion packets: the method requires the ion packet with a slow velocity and a very narrow velocity width. In order to fulfill the experimental conditions, we are developing the methods to prepare and control cold molecular ions in a strong magnetic field. Here, we discuss the experimental techniques and the results on the formation and manipulation of cold NH_3^+ ions with a kinetic energy of less than 5 meV, which are prepared through deceleration, bunching and slicing of the ion packets generated by the photoionization of supersonically cooled ammonia molecules. We also discuss the subjects on the NMR detection for cold mass-selected ions.

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Towards Laser Doppler Cooling of Negative Ions in a Penning Trap

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We aim at demonstrating the first direct laser cooling of negative ions in a Penning trap. For laser cooling we first trap the ions and then illuminate them with a red-detuned cw laser to cool their radial motion. For this purpose, the hyperfine structure and the Zeeman splitting in the magnetic field of the trap must be known. We have measured the Zeeman splitting, the hyperfine structure and the transition cross-sections of bound-bound transitions in negative lanthanum ions. The studied transition has been suggested for laser cooling both theoretically and experimentally [1,2,3]. Presently, lanthanum is the most promising laser cooling candidate among all atomic anions. Once one species of negative ions is cooled, any other species can be cooled sympathetically. This is a promising technique, among others, for the cooling of antiprotons to ultracold temperatures [4].

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Precision Measurements of Hyperfine Structure Constants and 2s-2p Transition Frequencies for Laser-Cooled Radioactive Beryllium Isotopes

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Halo nuclei were discovered from interaction cross section measurements to have nuclear matter radii that far exceed those of stable nuclei with same mass number [1]. ^{11}Be has been known to be a one-neutron halo nucleus, which is considered to consist of a ^{10}Be core and a valence halo neutron. However a nuclear model is required to deduce nuclear radii from the interaction cross sections so that the resulting radii depend on the model.

Precision atomic spectroscopy enables us to nuclear-model-dependently determine the static properties related to nuclear moments. Recently the nuclear charge radii were measured for halo nuclei such as ^{6}He [2], ^{8}He [3], ^{11}Li [4], and ^{11}Be [5]. On the other hand, a comparison of the ratio of the hfs constant A to the nuclear g-factor among isotopes yields the Bohr-Weisskopf effect [9], which sensitively reflects the structure of the single neutron halo [6]. The theoretical investigation *via* modern atomic physics is also in progress by Puchalski *et al.* [7]. We have performed precision optical spectroscopy of trapped and laser-cooled radioactive Be ions to determine the magnetization radii of ^{11}Be by a reliable pure-electromagnetic probe as well as their nuclear charge radii to identify the extended single neutron halo of ^{11}Be independently of the collinear laser spectroscopy experiments[5, 8].

The experiments were performed at the SLOWRI [10] prototype at the RIKEN RIBF, where relativistic ion beams from the projectile fragment separator RIPS were thermalised and stored in a linear RF trap. Using a weak probe laser alternatively irradiated with the cooling laser, we observed symmetric narrow spectra for the 2s-2p transition of ^{7,9,10,11}Be$^+$ ions. From the spectra the absolute transition energies were precisely measured and the charge radii for the Be isotopes were reliably determined [11]. Using laser-microwave double-resonance spectroscopy, we directly measured the magnetic hyperfine constants of the ground state Be ions with relative precisions of 6×10^{-7} and 3×10^{-8} for ^{7}Be$^+$ and ^{11}Be$^+$, respectively [12]. The higher precision for ^{11}Be than ^{7}Be was achieved from the measurement of the transition frequency of $|F,m_F\rangle = |0,0\rangle \rightarrow |1,0\rangle$, owing to the feature of ^{11}Be, which has a half spin in its ground state, since the transition frequency is independent to the magnetic field strength to the first order. In order to deduce the nuclear magnetization radii, an accurate value of the nuclear magnetic moment is required to be measured independently of the hyperfine constants. We prepare the measurements of the nuclear g-factors of ^{7}Be$^+$ and ^{11}Be$^+$.

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Experimental study on dipole motion of an ion plasma confined in a linear Paul trap

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Linear Paul traps have been used for study of many fields [1, 2]. The dynamics of an ion plasma confined in a linear Paul trap is equivalent in that of a charged particle beam propagating through a beam transport channel. Quadrupole and dipole RF voltages of a linear Paul trap correspond with a focusing and bending magnet system of an accelerator, respectively. Therefore, we can study fundamental aspects of beam dynamics by using the linear Paul trap [2-5].

In this experiment, Ar^+ ions generated by electron impact ionization are confined in the linear Paul trap optimized to study of beam physics. Maximum numbers of confined ions is in the order of 10^7. The radius of quadrupole cylindrical electrodes is 5.75 mm and the distance from axis trap to the electrodes is 5 mm. The rods are cut into five axial sections. The length of trap section rods is 75 mm. The ions are confined axially in the trap section by DC potential and radially by RF voltage (up to 100 V, 1 MHz). Supplemental RF voltage (~ 1 V, f_d~ 0.5 MHz) to excite the dipole motion is also applied to the rods. The total number and the transverse profile of the ion plasma are measured by an ion collector and a micro-channel plate with a phosphor screen.

When the excited dipole motion of ions and the dipole RF filed are resonant, it is observed that the trapped ions decrease with increasing the applying time of dipole RF voltage because the amplitude of dipole motion grow resonantly. A simple particle simulation represent the experimental results quantitatively. The resonance frequency is independent of the number of trapped ions. This result agrees with theoretical prediction. Therefore, we can directly measure frequency of secular motion of trapping ion without space-charge effect from resonance frequency. The space-chargeless secular frequency corresponds to the betatron bare tune in beam physics. It is an important parameter to characterize the stability of beams.

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Pair creation and annihilation with atoms and channeling nuclei

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We theoretically investigate different processes connected with the pair production and annihilation in atoms and highly charged ions. These fundamental features include the nuclear excitation by resonance positron annihilation (NERPA) and the electron-positron pair creation in heavy ion channeling (PC-HIC).

In the annihilation of a positron with a bound atomic electron, the virtual γ photon created may excite the atomic nucleus. We put forward this effect as a spectroscopic tool for an energy-selective excitation of nuclear transitions [1]. This scheme can efficiently populate nuclear levels of arbitrary multipolarities in the MeV regime, including giant resonances and monopole transitions. NERPA constitutes a way to excite nuclei which is alternative to photo- and Coulomb excitation. It has an attractive combination of advantages of the both methods: the resonant character of the excitation and a significant cross section regardless of the multipolarity. Furthermore, in certain cases, it has higher cross sections than the conventionally used Coulomb excitation and it can even occur with high probability when the latter is energetically forbidden. The resonance character of the nuclear excitation by positron annihilation opens a way to investigate a structure of wide nuclear resonances. For instance, it allows to excite efficiently certain energy regions of the Giant Dipole Resonance in heavy nuclei. For certain GDR, our predicted NERPA resonance strengths are 8 orders of magnitude higher than the largest NERPA resonance strengths investigated so far.

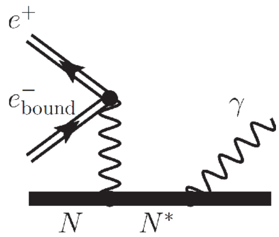

FIG. 1. Lowest-order Feynman diagram for nuclear excitation by resonant positron annihilation (NERPA) followed by γ -emission.

The time-reversed process – the bound-free electron-positron pair production is the channel of monochromatic positron creation in nucleus-nucleus collisions. This channel is important in the experimental investigation of such collisions of heavy highly charged ions. We suggest an alternative way to investigate this phenomenon by the channeling of accelerated ions through a crystal, namely, the electron-positron pair creation in heavy ion channeling (PC-HIC). This scheme increases the pair production rate coherently and allows to provide a more precise investigation of pair conversion [2]. It also allows to depopulate nuclei in metastable states, and convert the nuclear energy stored to electron-positron pairs. Pair creation by channeling ions can be also regarded as an extension of the resonance coherent excitation of highly charged ions to higher frequencies and higher ion velocities, which has been investigated at the GSI before [3]. This novel channel of pair creation can be examined at the upcoming FAIR facility in the nearest future.

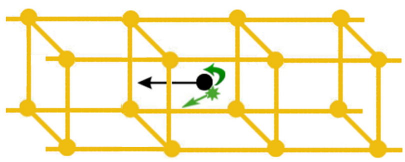

FIG. 2. Schematic view of electron-positron pair creation in heavy ion channeling (PC-HIC).

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Poster Session

Laser-diode-based light source for single-ion spectroscopy of the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition in Ba^+ at 1.76 μm

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We aim at realization of an optical frequency standard with barium ions (Ba^+). Ba^+ has a transition of short lifetime suitable for laser cooling, *i.e.*, the $^2S_{1/2}$ - $^2P_{1/2}$ at 493 nm, and two clock transitions of long lifetime, *i.e.*, $^2S_{1/2}$ - $^2D_{5/2}$ and $^2S_{1/2}$ - $^2D_{3/2}$. The $^2S_{1/2}(F = 2, m_F = 0)$ - $^2D_{3/2}(F = 0, m_F = 0)$ transition in $^{135}Ba^+$ or $^{137}Ba^+$ is insensitive to quadrupole electric field. Therefore, it is possible to improve the frequency stability by increase of the number of ions without degradation of uncertainty.

As a first step, we are developing an optical clock by using the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition at 1.76 μm in $^{138}Ba^+$. We realize a light source based on external-cavity diode lasers (ECDLs) for driving of the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition. This transition has been observed by using other lasers[1-3]. We first construct an ECDL at 881 nm of an output power of 31 mW. We linenarrow the ECDL to the resonance of a reference cavity by using FM sideband technique[4]. We estimate the linewidth of the ECDL to be 5.4 Hz to the reference cavity from the error signal. Then, we construct another ECDL at 1.76 μm of an output power of 20 mW. We generate second-harmonics of the ECDL by using a periodically poled lithium niobate (PPLN) crystal. The power of second harmonics is 250 nW. We detect the beat between the 881 nm-ECDL and second harmonics of the 1.76 μm-ECDL. We achieve a signal-to-noise ratio of 29 dB with a resolution band width of 300 kHz. We phase lock the 1.76 μm-ECDL to the linenarrowed 881 nm-ECDL in order to linenarrow the 1.76 μm-ECDL.

We confine and laser cool single Ba^+ ions in a linear RF trap of which trap region is 0.8 mm $\times$ 1.0 mm. We detect the fluorescence of approximately 200 Hz for single $^{138}Ba^+$ ion. We observe quantum jumps by excitation of $^{138}Ba^+$ ions to the $^2D_{3/2}$ state with irradiation of the light source developed and by spontaneous decay to the $^2S_{1/2}$ state as shown in Fig. 1. We are conducting spectroscopy of the $^2S_{1/2}$ - $^2D_{5/2}$ transition. We so far obtain the spectrum shown in Fig. 2 by using several $^{138}Ba^+$ ions. We will improve the resolution by using single $^{138}Ba^+$ ions.

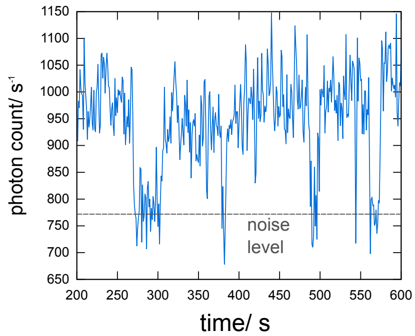

Figure 1: Quantum jumps with driving of the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition

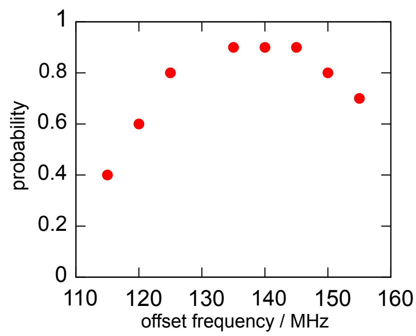

Figure 2: Spectrum of the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition

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Compact EBITs with large fields-of-view using permanent magnets and optimized for use at synchrotron and FEL beamlines

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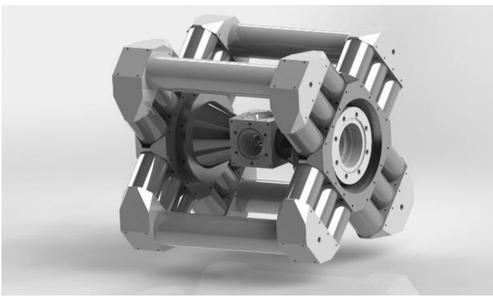
Two new compact electron-beam ion traps have been developed which use NdFeB permanent magnets. Both traps have at their centres a 70 mm cubic vacuum chamber, offering large fields-of view of the trap contents for fluorescence detection. Arrays of NdFeB magnets (see figure) are used to create an axial magnetic field using soft-iron (MPIK trap) and permendur (SPring-8 trap) polepieces. The magnets can be removed for baking, and field strengths at the centre of the trap range from 0.4 T to over 1 T depending on the number of magnets used.

Conventional on-axis electron guns have been used to characterize both traps, with currents of up to a few mA and electron beam energies of up to a few keV. An off-axis electron gun has also been tested, which will allow a secondary beam (synchrotron radiation, free-electron or femtosecond laser, or even molecular or ion beam) to pass through the trap along the axis. Use as an online diagnostic (for example making use of resonances in HCI absorption) is one possible application, and now that EBITs are demonstrating their power for HCI spectroscopy at free-electron lasers [1] and synchrotron beamlines [2] it is hoped that these new traps will facilitate many new exploratory studies.



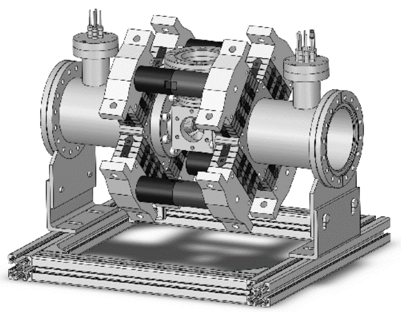


Figure 1: The table-top sized EBITs being developed at MPIK (left) and SPring-8 (right).

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Effect of an Axial Magnetic Field and Ion Space Charge on Trapped Charged Particle in LBWA

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ABSTRACT

The presence of an axial magnetic field in a laser beat wave accelerator enhances the oscillatory velocity of electrons due to cyclotron resonance effect leading to a higher amplitude of the ponderomotive force driven plasma wave, and higher energy of accelerating electrons. The axial magnetic field inhibits the transverse escape of electrons and thus causes a growth of the interaction length. The surfatron acceleration of electrons also shows a similar enhancement. A surfatron transverse magnetic field deflects the electrons parallel to the phase fronts of the accelerating wave keeping them in phase with it. However, the electron continues to move away radially.

Characterization of ion Coulomb crystals for fundamental sciences

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Cold molecular ions and cold highly charged ions are fascinating research objects for studying fundamental sciences, such as cold/ultracold ion chemistry[1), 2)] and the study of the time variation of the fundamental constants via precise optical spectroscopy[3)]. Recently, precision vibrational spectroscopy of cold N_2^+ was proposed for studying the time variation of the electron-proton mass ratio β [4)]. On the other hand, cold highly charged ions (HCIs) are considered to be good candidates for studying the time variation of the fine structure constant α [5)]. In performing these studies, the sympathetic cooling by ion Coulomb crystals in a linear Paul trap is promising method to generate cold molecular ions or cold highly charged ions.

In this work, we performed molecular dynamics (MD) simulations in order to search the optimized conditions for efficient sympathetic cooling of HCIs in a linear Paul trap[6)]. Moreover, the characterization of two-component ion Coulomb crystals was performed using the results of the MD simulations. Here we propose a reliable method to determine micromotion energies of sympathetically cooled ions (SCIs) embedded in ion Coulomb crystals. Then, the results were compared to the adiabatic calculations of the energies[7)]. A reliable method for determination of the relative number of SCIs will be proposed mainly for the application of cold ion chemistry. Figure 1 shows a simulation image of a string crystal including 24 $^{9}Be^{+}$ and 2 $^{141}Pr^{9+}$. The micromotion temperatures of Be^{+} and Pr^{9+} are determined to be 25(9) mK and 43(3) mK, respectively. The simulation details and the other results will be given in the presentation.

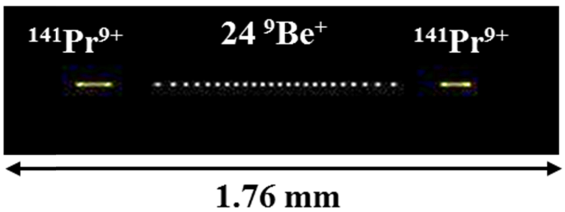

Fig1. A string crystal consisting of 24 $^{9}Be^{+}$ and 2 $^{141}Pr^{9+}$ in a linear Paul trap.

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EUV spectra of highly charged tungsten ions studied with an Electron Beam Ion Trap

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Tungsten will be used as material for the divertor plates in ITER because of its higher sputtering threshold energy for light ion bombardment, the highest melting point among all the elements, and less tritium retention compared with carbon based materials. However, since extremely high particle- and heat-fluxes of the intermittent edge plasma transport (e.g. edge-localized-mode) in ITER would cause serious damages to such components, tungsten is considered to be one of the most abundant impurities in the ITER plasma. Impurity tungsten enters the high-temperature plasma and is ionized to highly charged ions, and then highly charged ions emit very strong radiation in the EUV and/or X-ray ranges, which causes serious radiation loss. On the other hand, the radiation from the impurity tungsten has very important information on plasma diagnostics, such as electron and ion temperatures, electron density, impurity ion abundance and impurity transportation. Emission lines of highly charged tungsten ions thus play an important role in the spectroscopic diagnostics of the ITER plasma, and consequently the spectroscopic data of tungsten ions have been studied at several facilities.

An electron beam ion trap is a useful device for the systematic spectroscopic studies of highly charged ions. We have constructed a compact electron beam ion trap, called CoBIT[1-3], and observed extreme ultraviolet (EUV) spectra of highly charged tungsten ions. We have also observed the emission spectra of tungsten injected in LHD plasma, and compared them with the CoBIT spectra as well as the model calculations. In this paper, we present observation of previously-unreported emission lines around 100Å, which are identified from the comparison with theoretical calculations to be the 4f-5s transitions in W^{26+} and W^{27+}.

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The LPCTrap measurement trap: an open Paul trap for fundamental tests

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The LPCTrap experiment [1] makes use of an open Paul trap which was built to enable precision measurements in the beta decay of radioactive ions. The principal goal was the precise measurement of the beta-neutrino angular correlation coefficient in the beta decay of ^{6}He. Its geometry results from a careful optimization of the harmonic potential created by cylindrical electrodes. It supersedes previously considered geometries that presented a smaller detection solid angle to the beta particle and the recoiling ion [2, 3]. In this contribution we describe the methods which were used for its optimization and we present the measured properties in terms of trapping time cloud size and space charge related limits. The open trap shall serve other projects: it is used for commissioning purpose in the TRAPSENSOR experiment [4], and is also considered in tests of the Standard Model involving the beta decay of polarized ^{23}Mg and ^{39}Ca ions. Such tests require in trap polarization of the ions and further optimization of the trapping and detection setup. These optimizations will be additionally discussed.

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Development of the optical magnetometer toward the search for the electron electric dipole moment

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A permanent electric dipole moment (EDM) of a particle, an atom or a molecule is a good probe to test theories beyond the standard model (SM) of elementary particle, since the EDM has the sensitivity to the CP violation in the theories beyond the SM. An experiment to search for the electron EDM by using the laser cooled francium (Fr) atoms is planned at Cyclotron and Radioisotope Center (CYRIC), Tohoku University [1].

The EDM is experimentally deduced from the tiny change of the spin precession frequency induced from a reversal of a direction of an electric field, which couples the EDM, applied along a magnetic field, which define the quantization axis. However, the fluctuation of the magnetic field can easily screen the EDM effect. In our assumed condition, we need to monitor the fluctuation less than 10 fT precision. A magnetometer based on the nonlinear magneto-optical rotation (NMOR) effect of the rubidium (Rb) atom can achieve that precision [2]. One of the key issues to realize the high sensitivity to the magnetic field is the spin coherence time of the Rb atom. The Rb atom utilized for the magnetometer is confined to a glass cell. The collision between the Rb atom and an inner surface of the cell limits the coherence time. We prepared several types of the cell and the wall relaxation time of each cell was measured. Another key issue is a residual field of a magnetic shield. The glass cell is place inside the magnetic shield to suppress effects of environmental field. The residual field also limits the coherence time. We degauss the magnetic shield and observed the NMOR spectrum.

In this presentation, we report the present status of the magnetometer and discuss its sensitivity toward the EDM experiment using the laser cooled Fr atoms..

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High-fidelity operations with calcium ion qubits

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Our recent work on performing high-fidelity qubit operations using calcium ions will be reported.

Using intermediate-field “atomic clock” states in $^{43}Ca^{+}$, we have demonstrated single-qubit preparation, gates and readout each with 99.9% fidelity or better, with operation times much less than the qubit coherence time of T_2^* = 50s [1]. These results were achieved in a room-temperature surface trap incorporating integrated microwave waveguides and resonators, using near-field microwaves to drive the qubit gates [2]. The trap is also capable of using this scalable approach to implement two-qubit gates [3], which we have recently demonstrated. Our latest results will be reported.

We have also designed and fabricated a separate surface trap to implement scalable independent qubit addressing using near-field microwaves [4]. In a pilot experiment, we drive qubit rotations with microwaves in one trap zone while nulling the microwave field in a neighbouring zone (1mm distant), achieving an addressing error below 0.01%.

In a third experiment, which uses a macroscopic trap, we have studied the speed/fidelity trade-off for two-qubit gates driven by Raman laser beams [5]. We achieve gate fidelities between 97% (for a gate time of 3.8μs) and 99.9% (for a gate time of 100μs) [6], representing respectively the fastest and highest-fidelity two-qubit gates reported using trapped ions.

The fidelities of all of these operations exceed the minimum threshold (≈ 99%) required for fault-tolerant quantum computing by a significant margin. Maintaining these fidelity levels in a single system, while scaling to larger numbers of qubits, remains a significant challenge.

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Performance assessment of a new laser system for efficient spin exchange optical pumping in a spin maser measurement of ^{129}Xe EDM

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A permanent electric dipole moment (EDM) violates time-reversal invariance, and serves as a key observable in testing theories beyond the Standard Model. We aim to search for an atomic EDM in ^{129}Xe at the level of 10^{-28} *e*cm beyond the present upper limit, using an active nuclear spin maser that sustains the nuclear spin precession semi-permanently [1,2]. The enhancement of the spin polarization through the improvement of the efficiency in spin-exchange optical pumping process is one of the important factors for stable maser operation.

Previously, a laser system consisting of a distributed feedback (DFB) laser and a spatially separated tapered semiconductor amplifier (TA) was used for the optical pumping. The characteristics of a TA-DFB laser, such as its narrow line width and high frequency stability, enable us to produce a large spin polarization. However, the power of our TA-DFB laser is not sufficient for the stabilized spin-maser operation with ^{3}He which works as a co-magnetometer. Recently, we have been preparing a new laser system containing a self-made external cavity laser diode (ECLD) and a more intense TA for improving the efficiency of spin-exchange optical pumping.

In the presentation, we discuss the polarization of Rb and noble gases achieved with our new ECLD compared to that with the DFB laser used as probe light and TA-DFB laser, and evaluate the advantages gained by employing the ECLD.

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Rate amplification of the two photon emission from para-hydrogen toward the neutrino mass measurement

Takahiko Masuda on behalf of the SPAN collaboration

The SPAN collaboration aims to determine the neutrino absolute mass using atomic processes and laser spectroscopy methods. The process we use is a cooperative de-excitation of atoms in a metastable level emitting a neutrino pair associated with a photon[1]. We call this process RENP (Radiative Emission of Neutrino Pair). Feynman diagrams are shown in Fig. 1. An observable of this experiment is wavelength of the photon which is emitted with a neutrino pair. The spectra of the photon have information on the neutrino properties. One important item of this experiment is the amplification of emission rate using macro-coherence in target media. Although the rate amplification by coherence has been established in case of single particle emission process (i.e. super-radiance[2]), the amplification for plural particles emission process has never been demonstrated. We thus performed an experiment to validate this amplification mechanism in case of plural particles process.

This poster reports the observation of the two photon emission from a para-hydrogen gas target. We have observed that the rate of two photon emission from the target was amplified. The achieved amplification factor of more than 10^{15} [3]. The huge factor suggested that the macro-coherence worked effectively. We used two monochromatic lasers (532 nm and 683 nm) in this experiment to generate coherence in the medium, and two photon emission was automatically generated via the adiabatic Raman process.

For the advanced experiment, we employed one more monochromatic laser (4.55 μm) to trigger the two photon emission. It is important to trigger it because the triggered emission can be controlled externally: for example timing, polarization, and intensity of the trigger laser. It is useful for the detailed study of the amplification mechanism itself. We have recently succeeded in triggering the two photon emission. This poster also reports the current status of the experiment.

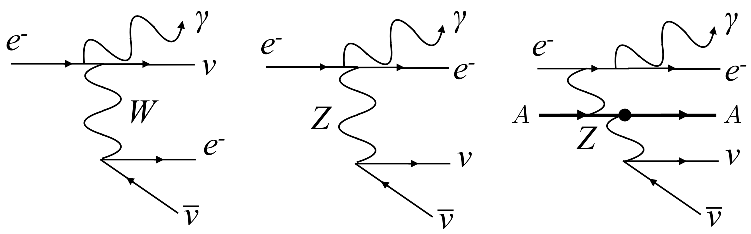

Fig. 1 Feynman diagrams of RENP

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An ion-surfing RF-carpet gas cell for transuranium nuclei study at GARIS-II

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High-energy radioactive isotopes produced in-flight by fragmentation or fission is used in ion trap-based precision experiments after being stopped in a large gas catcher. The stopped ions can be extracted from the large gas cell as a low energy ion beam. In order to transport and extract ions quickly and efficiently, the guidance by electric fields is necessary. In this respect, an rf-carpet (RFC) method utilizing a dc potential gradient has been a standard technique [1]. However, such a method is restricted by the transport time to longer half-life isotopes due to the maximum dc gradient that can be supported before electric discharges occur in the gas catcher. To avoid that limitation, a hybrid technique where-in the dc gradient is replaced by a traveling potential wave was proposed, called "ion surfing" [2]. This technique has recently been experimentally verified with a linear RFC[3].

As in the standard method, rf signals are applied to the electrodes such that adjacent electrodes are 180° out of phase, creating an effective force that repels the ions from the surface. In the "ion surfing" method, in order to keep the ion just above the RFC surface, the repelling force needs to be balanced by a pushing force, created by a pushing electric field. The confined ions can then be transported along the RFC surface by superimposing weak audio-frequency (AF) signals such that adjacent electrodes are 90° out of phase, forming a traveling potential wave. Under the optimal conditions, the ion speed approaches the wave's speed which is proportional to the AF frequency $f_{\rm AF}$ [2, 3].

Recently, we have demonstrated the ion extraction using a circular RFC [4]. Using a Cs ion source in the gas cell, we obtained an extraction efficiency of nearly 100% at proper conditions of He gas. In addition, we have operated the gas cell on line at GARIS -II. We could extracted Fr isotopes from the gas cell with an overall efficiency of 28.7%, even the gas cell was operated at room temperature.

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Development of a Kingdon ion trap for observation of the forbidden X-ray transitions in solar wind charge exchange

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In 1990s, observatory satellites were launched and the soft X-ray emissions from the solar system have been observed. The all-sky map of the soft X-ray background was created and the intensity fluctuation of the soft X-ray was discovered [1]. It was recognized that this fluctuation is related to the activity of the solar wind, and regarded as the result of collisions between highly charged ions in the solar wind and neutral gases in the solar system, i.e., the solar wind charge exchange (SWCX). The forbidden transitions in O^{6+} (1s2s - 1s^2 transitions) are the main emissions in the SWCX [2], but have not been measured yet due to the long lifetimes of the excited states. We have a plan to observe the long lived forbidden transitions by trapping metastable highly charged ions after the charge exchange reactions of O^{7+} $(1s)$ + H_2/He → O^{6+} $(1snl)$ + H_2^+/He$^+$.

The highly charged ions (Ar^{q+}, O^{q+}) produced by a 10 GHz Electron Cyclotron Resonance Ion Source are extracted at 6 - 8 kV acceleration voltage and are injected into a Kingdon ion trap after the charge-state selection. After a pre-determined storage time, the trapped ions are ejected and some of ejected ions are detected by a micro channel plate (MCP). The output pulse signals from the MCP are counted by a fast multichannel scaler. The data aquisitions are typically repeated 10^3 - 10^4 cycles depending on the storage time, which was varied from 5 ms to 3 s.

Fig.1 shows decay curves of the trapped Ar^{q+} (q = 5, 6) ions as a function of the storage time in H_2 gas at the pressure of 1.3×10^{-5} Pa. These data are well fitted by a single exponential function. The decay rates of Ar^{5+} and Ar^{6+} are determined to be 28(6) s^{-1} and 67(5) s^{-1}, respectively. The charge-transfer cross sections are obtained to be $5.2(3.0)\times10^{-15}$ cm^2 and $1.2(0.7)\times10^{-14}$ cm^2. These values are consistent with previous experimental data and theoretical estimations [3,4]. The results, discussions and progress of observations of the forbidden transitions will be presented in the poster presentation.

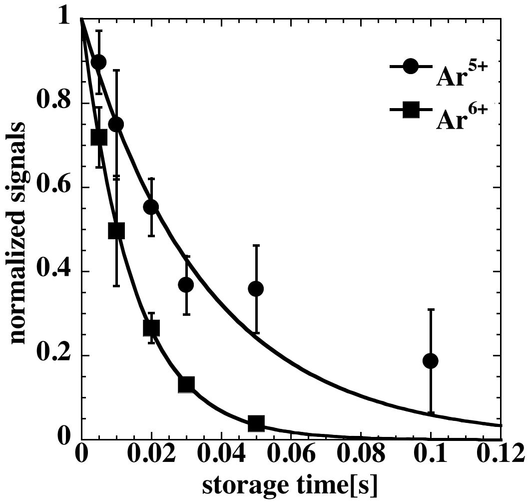

Fig.1 A plot of the extracted Ar^{5+} and Ar^{6+} as a function of the storage time.

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Poster Session

Title: Sideband Cooling to the Ground State of a Calcium-40+ Ion in a Penning Trap

In order to investigate the suitability of Penning traps for use in quantum information processing we have performed one of the first pre-requisites for coherent control – cooling of a single ion to its motional ground state in one dimension. We achieved this by performing resolved motional sideband cooling on the electric quadrupole $S_{1/2} \leftrightarrow D_{5/2}$ transition at 729 nm. We found a minimum average phonon number $\bar{n} = 0.026 \pm 0.009$. We also measured the heating rate for the trap to be $\dot{\bar{n}} = 1.8 \pm 0.2$, which in scaled spectral noise density corresponds to one of the lowest rates measured yet.

Primary authors : Mr. HRMO, Pavel (Imperial College, London)

Co-authors :

Presenter : Mr. HRMO, Pavel (Imperial College, London)

Title: Towards Laser Cooling of Antihydrogen

Primary authors: M. Michan (TRIUMF & Univ. of British Columbia), M.C. Fujiwara (TRIUMF), and T. Momose (Univ. of British Columbia)

Presenter: M.C. Fujiwara (TRIUMF)

Abstract:

Cooling of antihydrogen to mK temperatures has been a dream for some in the field for many years. The ultimate precision of spectroscopy of magnetically trapped antihydrogen will be limited by the magnetic field non-uniformity probed by the trapped anti-atoms (i.e. Zeeman broadening), as well as transit-time broadening. A sample of extremely cold antihydrogen, accessing only a small spatial region of the trap, will minimize these broadenings. Furthermore, at mK temperatures, the gravitational force will become important, providing opportunities to test Einstein's Equivalence Principle with antimatter.

Doppler cooling of antihydrogen can take place via radiation pressure from Lyman-alpha light at 121.5 nm, which drives the 1s-2p transition. Historically, generation of Lyman-alpha radiation has been a challenging task, due to the lack of tunable lasers or non-linear crystals for these wavelengths in the vacuum ultra-violet. Recent realistic simulation studies suggested that antihydrogen laser cooling to the mK regime would be possible with a narrowline pulsed Lyman-alpha laser with a sufficient power [1]. This presentation will report our development of a pulsed Lyman-alpha laser system, and our effort towards laser cooling of antihydrogen.

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Cyclotron radiation emission spectroscopy (CRES) with trapped electrons

Abstract

We report the detection of cyclotron radiation from individually trapped electrons produced by internal conversion of ^{83m}Kr atoms in a gaseous source. Measurement of the relativistic shifts in the cyclotron frequencies yields a precise spectrum of the low-energy conversion electrons. We will discuss possible applications of the technique in precision beta spectroscopy including the determination of the neutrino mass via the tritium decay endpoint.

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High-resolution mass separation by phase splitting and fast centering of ion motion in a Penning trap

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A new technique for fast and effective mass separation of isobaric-contaminant ions will be presented based on the continuous control of the phase and magnetron radius of ions orbiting in a Penning trap. Requiring no ion cooling, the method is inspired by two techniques: Phase Imaging ion cyclotron resonance (PI-ICR) [1] and magnetron-orbit manipulation [2]. First, isobaric species are separated in the radial plane by mass-selective excitations. A radial, position-selective dipole excitation pulse is then applied to re-center only the ions of interest. The theoretical analysis of the process will be described with detailed simulations, highlighting its resolving power. In addition, the results will be compared with another buffer-gas free technique: SImultaneous Magnetron and resonant COnversion (SIMCO) excitation [3]. Despite a lower maximum resolving power, the new process is twice as fast as SIMCO.

Investigations on the deleterious effects of space charge are also presented. Using the SIMBUCA simulation package [4, 5], a model has been constructed that estimates the critical number of ions for efficient separation of trapped contaminant ions.

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Program

DAY 1

09:10 Coffee
09:30 Opening
10:00 LECTURE 1: **Stefan Ulmer (RIKEN)**
"Basics of ion traps"
12:00 Lunch
13:30 LECTURE 2: **Richard Thompson (Imperial College London)**
"Optical sideband cooling of an ion to the ground state of its motion in a Penning trap"
14:30 LECTURE 3: **Ryugo Hayano (Univ. of Tokyo)**
"Basics of antimatter science"
16:30 Coffee
17:00 Facility tour
18:00 Welcome reception

DAY 2

09:30 Coffee
10:00 LECTURE 4: **Hidetoshi Katori (RIKEN, Univ. of Tokyo)**
"Optical lattice clock for fundamental physics"
11:00 LECTURE 5: **Vladimir Dzuba (Univ. of New South Wales)**
"Basics of fundamental physics with stored HCI"
12:00 Lunch
13:30 LECTURE 6: **Yuri Litvinov (GSI)**
"Physics with storage rings"
14:30 Coffee
15:00 LECTURE 7: **Wilfried Nörtershäuser (Technische Universität Darmstadt)**
"Laser spectroscopy of stored ions"
17:00 Closing

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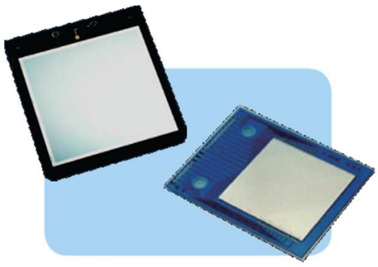

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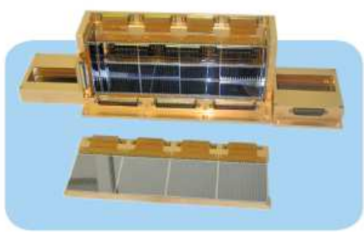

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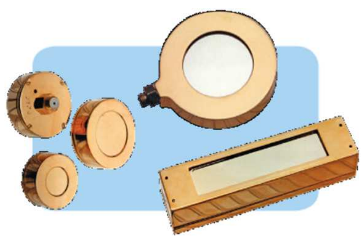

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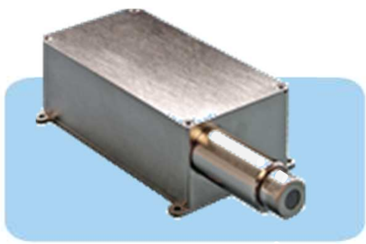

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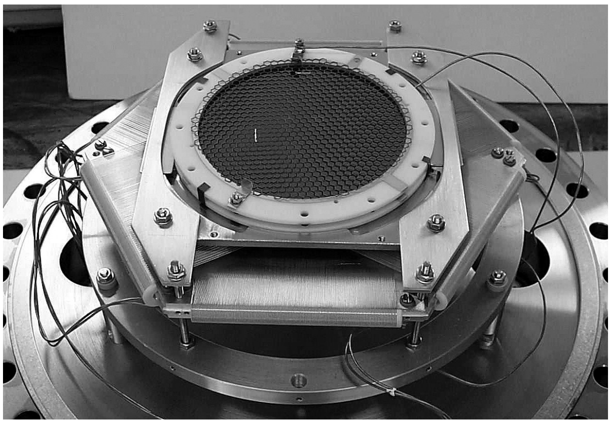

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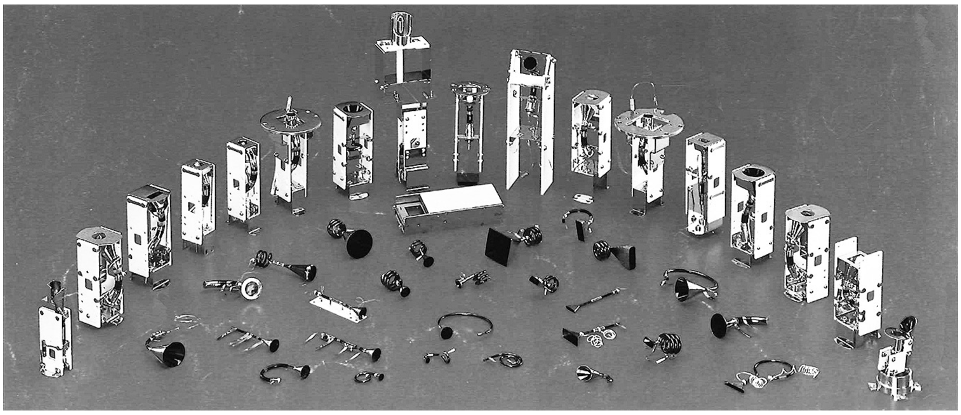

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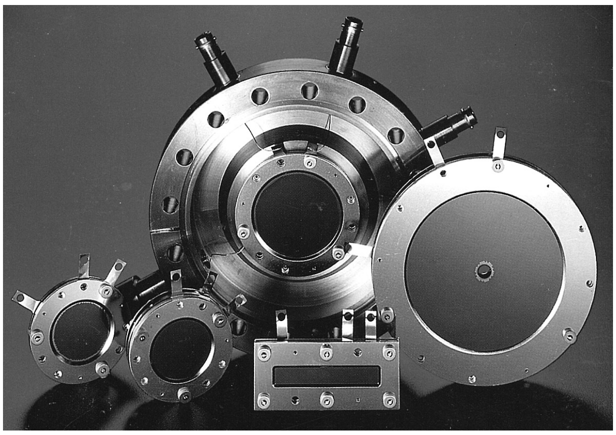

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