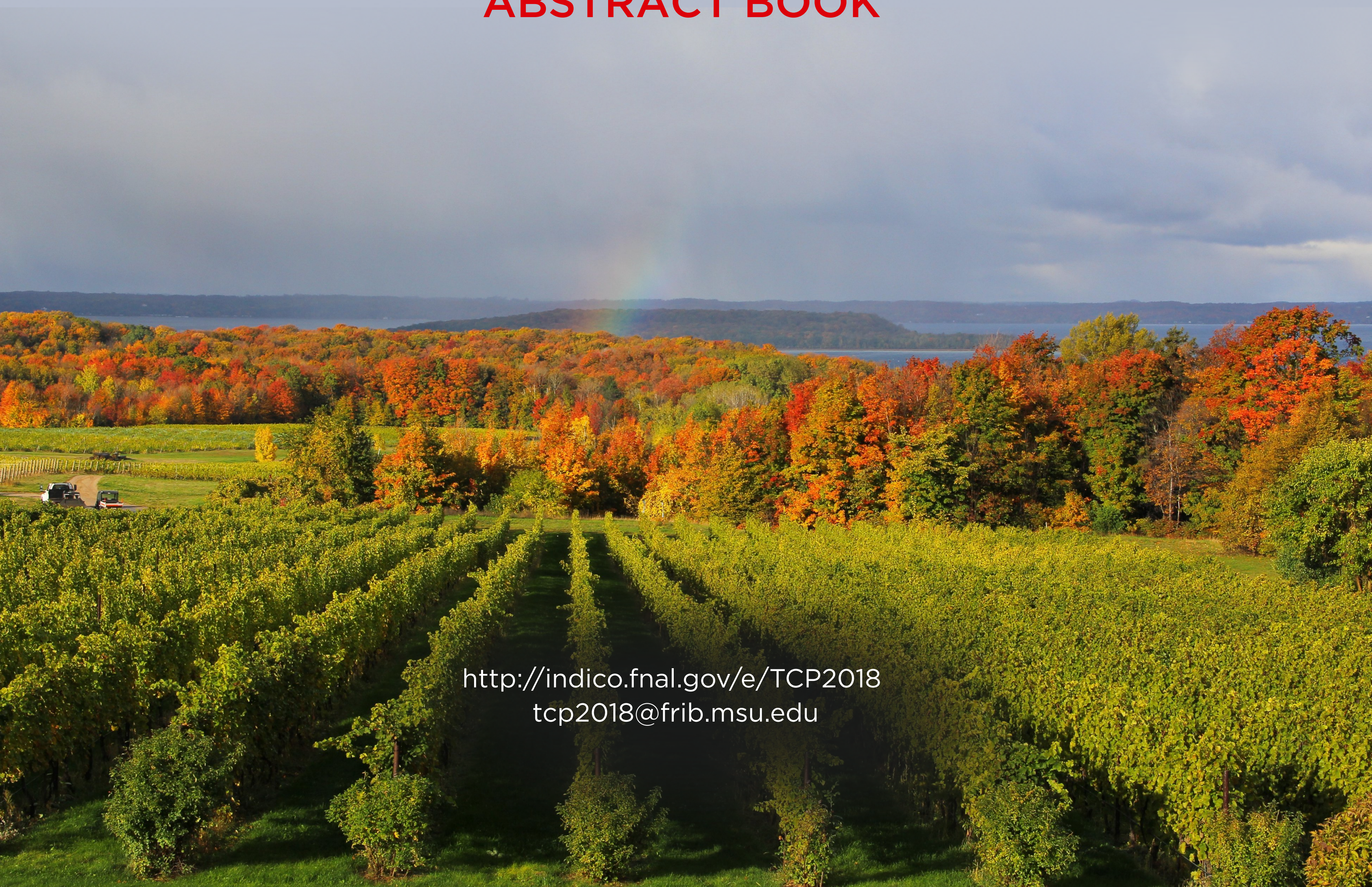
7th International Conference on Trapped Charged Particles and Fundamental Physics

TCP 2018

TRAVERSE CITY | MICHIGAN

SEPTEMBER 30 - OCTOBER 5, 2018

ABSTRACT BOOK



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TCP2018

7th International Conference on Trapped Charged Particles and Fundamental Physics 2018

Park Place Hotel
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Welcome!

The **7th International Conference on Trapped Charged Particles and Fundamental Physics (TCP2018)** is being held in Traverse City, Michigan from 30 September to 5 October 2018.

This conference belongs to the series of conferences started in Lysekil (Sweden) in 1994, followed by conferences in Asilomar (USA, 1998), Wildbad Kreuth (Germany, 2002), Parksville on Vancouver Island (Canada, 2006), Saariselkä (Northern Finland, 2010), and Takamatsu (Japan, 2014). The conference in Traverse City focuses on recent developments and highlights in scientific fields using trapped charged particles with a particular emphasis on:

1. Fundamental Interactions and Symmetries
2. QED Effects
3. Quantum State Manipulation and Quantum Information
4. Precision Spectroscopy and Frequency Standards
5. Highly Charged Ions in Traps
6. Radioactive Isotopes in Traps
7. Plasmas and Collective Behavior
8. Storage Ring Physics
9. Trapped Antimatter
10. Applications of Charged Particle Trapping

CONFERENCE VENUE

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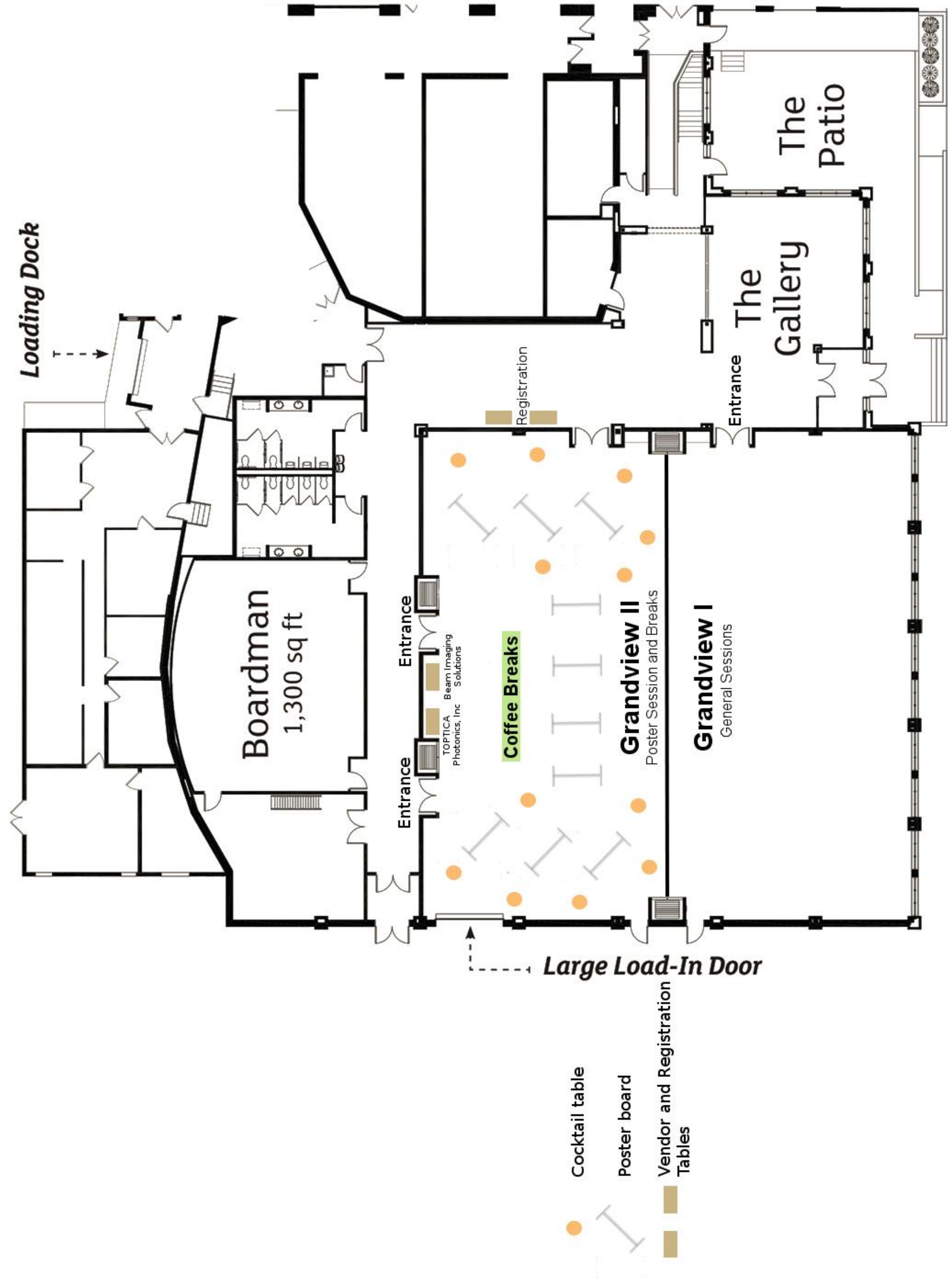
VENUE MAP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TCP 2018
ORAL PRESENTATIONS

As of 10 September 2018

Monday Session 1

1

Quantum Information Using Trapped Ions – Status and Perspectives

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2

Ground-state Cooling and Coherent Control of Ions in a Penning Trap

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We have demonstrated the first optical sideband cooling of the axial motion of a single calcium ion and Coulomb crystals of two calcium ions in a Penning trap. Due to the low oscillation frequencies typically available in a Penning trap, the cooling starts from well outside the Lamb-Dicke regime. For a single ion, this means that it is not sufficient to cool using the first red motional sideband, since after Doppler cooling there is a significant part of the population left in Fock states that are above the first zero of this sideband. A sequence of pulses tuned to different motional sidebands is required to reach the ground state of the motion [1].

For a two-ion axial crystal, this problem gets worse as the trapping voltage has to be reduced (otherwise the axial crystal is not stable). Furthermore, the interaction of the two vibrational modes with each other leads to more possibilities for trapping of parts of the population in high- lying Fock states. We have developed complex pulse sequences to overcome these problems and have successfully cooled two-ion crystals to the ground state of both axial modes simultaneously, in both axial and radial configurations of the crystal [2].

With the ground-state cooled ion, we demonstrate long motional coherence times (of the order of 1 s) and low heating rates. We can also prepare a variety of superpositions of the motional states by applying pulses on low-order optical sidebands, including an equal superposition of $n = 0$, 1 and 2. This is equivalent to an optical triple-slit interference experiment.

By driving a single ion on the first blue sideband in a “sideband heating” process, we can prepare the ion in a narrow range of Fock states around the first minimum of this sideband (where $n \sim 150$). Plots of the visibility of interference fringes for this system clearly show the loss of optical coherence after about 1 ms and the loss of motional coherence only after about 100 ms, despite the high values of n.

We will also present our results for sideband cooling of the cyclotron and magnetron radial motions of a single ion in a Penning trap. We achieved this using the axialisation technique, which is closely related to the rotating wall technique used in other Penning trap experiments. We achieve average occupation numbers of less than 1 for both radial modes simultaneously.

These results show not only that ions in a Penning trap can be cooled to the ground state of their motion, but also that their motional state can be manipulated coherently, opening up applications in quantum optics and quantum information science.

[1] J. F. Goodwin et al, Resolved-Sideband Laser Cooling in a Penning Trap, Physical Review Letters 116, 143002 (2016).
[2] G. Stutter et al., Sideband cooling of small ion Coulomb crystals in a Penning trap, Journal of Modern Optics 65, 549-559 (2018).

3

Thermometry of a Single Trapped Ion by Imaging

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Free space approach to interaction between light and a single atom relies on tightly focusing the light onto the atom [1]. In such experiments the temperature of the atom gets particularly important when the focal intensity distribution is comparable in width to the spatial wavefunction spread of the trapped atom [2]. In order to quantify the best achievable coupling, it becomes necessary to measure the absolute temperature of the atom. On the other hand, in experiments with trapped ions, another important thermometric figure of merit, in addition to absolute temperature is its heating rate. Over the years, several experiments to measure heating rates have been performed to better understand the origins of anomalous heating [3].Here, we present a technique based on high resolution imaging to measure the absolute temperature, and the heating rate of a single ion trapped at the focus of a deep parabolic mirror. We collect the fluorescence light scattered by the ion during laser cooling, and image it onto an electron-multiplying charge-coupled device (EMCCD) camera. The image recorded on the camera is a convolution of the point-spread function (PSF) of the imaging system, and the spatial probability distribution of the ion. Accounting for the width of the PSF and the magnification of the imaging system, we determine the spatial extant of the ion, from which we infer the mean phonon occupation number in the trap. Further, we perform similar measurements by varying the power or the detuning of the cooling laser. We determine the heating rate by a fit to a well-known theoretical model for laser cooling in a harmonic trap [4]. In other established schemes [5] for measuring the heating rate, the ion is initially heated up to temperatures a few orders of magnitude above the Doppler limit. In contrast, we measure the heating rate with the ion always maintained in a state of thermal equilibrium, at temperatures close to the Doppler limit.

[1] M. Sondermann, et.al. Applied Physics B, 89 (4), 489-492 (2007)
[2] M. Fischer, et.al. Applied Physics B 123, 48 (2017).
[3] M. Brownnutt, et.al. Rev. Mod. Phys. 87, 1419 (2015).
[4] S. Stenholm Rev. Mod. Phys. 58, 699 (1986).
[5] J. H. Wesenberg, et.al. Phys. Rev. A 76,053416 (2007).

4

A 1.5 Parts-per-billion Measurement of the Antiproton Magnetic Moment

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Comparing the fundamental properties of protons and antiprotons in high-precision measurements in Penning traps challenge the combined charge, parity and time-reversal (CPT) symmetry – which is a cornerstone in the Standard Model of particle physics. Recently, we conducted a 1.5 parts-per-billion measurement of the antiproton magnetic moment [1] by determining the frequency ratio of the Larmor frequency to the cyclotron frequency of single antiprotons in a Penning trap. The measurement was performed in the Penning-trap system of the BASE collaboration at the Antiproton Decelerator of CERN. The result is based on the observation of individual antiproton spin transitions and a novel two-particle multi-trap spectroscopy technique to improve the sampling rate. Compared to previous measurements based on statistical detection of spin transitions, the result is about 3000-fold [2] and 350-fold [3] more precise. Comparing the result to our recent proton magnetic moment measurement [4], which has 0.3 ppb uncertainty, we conclude that our measurements support CPT invariance in the baryon sector up to an energy resolution of 10^{-24} GeV.
In this presentation, I will present the antiproton magnetic moment measurement technique, the results, and the current status of the BASE experiment at CERN.

[1] C. Smorra et al., Nature 550, 371-374 (2017).
[2] J. DiSciacca et al., Phys. Rev. Lett. 110, 130801 (2013).
[3] H. Nagahama et al., Nat. Commun. 8, 14084 (2017).
[4] G. Schneider et al., Science 358, 1081-1084 (2017).

5

PUMA: antiProton Unstable Matter Annihilation

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PUMA: antiProton Unstable Matter Annihilation is a starting project aimed at measuring annihilation of antiprotons with short-lived nuclei. The objective of PUMA is to determine the surface neutron/proton density profile of short-lived nuclei using the annihilation. Although neutron halos and neutron skins are one of the most important aspects of the neutron-rich unstable nuclei, experimental data are limited. PUMA will provide new observables to determine those quantities. An antiproton is initially captured in an atomic orbital, then approaches to the surface of nuclei through a cascade of orbital states to annihilate. Since the total charge of the annihilation is conserved, one can tell if an antiproton annihilated with a proton or neutron by measuring the total charge of the produced pions. Thus the annihilation is sensitive to the surface neutron/proton density. We are developing a mobile device that can store, transport, and annihilate antiprotons with short-lived nuclei, so that we can bring antiprotons from ELENA to unstable nuclei produced at ISOLDE. Those facilities are both located nearby at the CERN main site. The PUMA will consist of a superconducting solenoid, ion traps for the storage and annihilation, and a detection system for the annihilation products. The development status of the PUMA ion traps will be presented.

Monday Session 3

6

Atomic Clocks with Trapped Ions – Status and Perspectives

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The combination of ion trapping and laser cooling provides ideal conditions for precision spectroscopy and frequency standards with small systematic frequency shifts. Optical clocks based on $^{27}Al^+$ and $^{171}Yb^+$ are now evaluated with systematic uncertainties in the low 1E-18 range and other species can be expected to reach this level soon. Apart from the interest in fundamental metrology, frequency comparisons and precise measurements of frequency ratios can be used in quantitative tests of relativity and searches for violations of the equivalence principle. The $^{171}Yb^+$ optical clock that is based on the extremely narrow S-F electric octupole transition possesses a favorable combination of small systematic uncertainty and high sensitivity for such tests because of the strongly relativistic character of the excited state. In comparisons of two $^{171}Yb^+$ single-ion clocks, a ^{87}Sr optical lattice clock and primary Cs clocks at PTB we perform tests for temporal variations of fundamental constants and for violations of local Lorentz invariance. A future nuclear clock based on the low-energy transition in Th-229 may further increase the sensitivity of such tests. Recent results from hyperfine spectroscopy of the Th-229 isomer provide experimental data on fundamental nuclear properties of this unusual system.

7

An $^{27}Al^+$ Quantum-logic Clock with 1.0 x 10^{-18} Systematic Uncertainty

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We report on an optical atomic clock based on quantum-logic spectroscopy of the $^1S_0 \leftrightarrow {}^3P_0$ transition in $^{27}Al^+$ with a systematic uncertainty of 1.0×10^{-18}. A $^{25}Mg^+$ ion is simultaneously trapped with the $^{27}Al^+$ ion and used for sympathetic cooling and state readout during clock operation. The accuracy of previous $^{27}Al^+$ clocks has been limited by uncertainty in the time-dilation shift due to driven ion motion (excess micromotion) and ion temperature (secular motion). Improvements in a new trap have reduced excess micromotion and secular heating, making it possible to operate the clock near the three-dimensional motional ground state, and leading to a reduced time-dilation shift uncertainty. Other systematic uncertainties including those due to blackbody radiation (BBR) and the second-order Zeeman effect have also been reduced. In addition, we present preliminary results from recent optical frequency comparisons between this $^{27}Al+$ clock and the Yb and Sr optical lattice clocks at NIST/JILA.

Work supported by DARPA and ONR. S.M.B. was supported by ARO through MURI grant W911NF-11-1-0400.

Monday Session 4

8

Observation of the Hyperfine Spectrum of Antihydrogen and Perspectives

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Recent progress in antihydrogen spectroscopy has been significant. Measurements of the ground state hyperfine splitting [1,2] and the 1S-2S transition frequency [3,4] have been performed, and transitions between 1S and 2P levels have been induced [5] paving the way for laser cooling. I will describe some of this work, with an emphasis on current status and near-term prospects for increasing the precision to which the ground state hyperfine splitting of trapped antihydrogen is measured.

[1] Amole et.al. (ALPHA Collaboration), Nature 483, 439 (2012).
[2] Ahmadi et al. (ALPHA Collaboration), Nature 548, 66 (2017).
[3] Ahmadi et al. (ALPHA Collaboration), Nature 541, 506 (2017).
[4] Ahmadi et al. (ALPHA Collaboration), Nature 557, 71 (2018).
[5] Ahmadi et al. (ALPHA Collaboration), Nature (advanced online publication Aug. 2)

9

Status of the Antihydrogen Hyperfine Structure Measurement in a Beam by ASACUSA

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The advantage of applying a beam-method for the determination of the antihydrogen hyperfine structure as CPT test is the well-controllable microwave interaction, which takes place outside of the strong fields of the traps required for the mixing of antiprotons and positrons [1,2]. As a trade-off for this opportunity for high precision and small systematic shifts ASACUSA needs to form a sufficiently intense beam of antihydrogen with the right properties regarding quantum states and velocities. Following the first observation of antihydrogen far from the formation region [3] the quantum states have been analysed with the result that antihydrogen atoms with main quantum numbers $n \rightarrow 14$ are unambiguously detected [4]. However, a further rate increase will be mandatory to realize spectroscopy measurements within reasonable acquisition times.
The readiness of the Rabi-type spectroscopy apparatus itself had been tested successfully with a hydrogen beam using the σ-transition (F, M_F : 1, 0 → 0, 0) [5]. The achieved precision of $2.7 \cdot 10^{-9}$ presents the best in-beam measurement of the hydrogen hyperfine splitting to date and by being in agreement with the more precise maser results illustrates that systematic shifts are under control far beyond the initial precision goal for the antihydrogen measurement of 10^{-6} to 10^{-7}. Recent upgrades made it possible to investigate the π-transition (F, M_F : 1, 1 → 0, 0) as well [4]. A second transition opens a couple of new opportunities for the determination of the zero-field hyperfine splitting. Moreover, the potential sensitivity to CPT violations of certain transitions or transition pairs needs to be assessed from a theoretical point of view. To this end the Standard Model Extension by Kostelecky and co-workers [6] appears to be the only available framework for considerations of this type. In this context it will become clear, that a Rabi-type experiment - beyond holding potential for higher precision - is a vital complimentary approach to in-trap spectroscopy on antihydrogen.

[1] A. Mohri and Y. Yamazaki, Europhys. Lett. **63**, 207–213 (2003)
[2] E. Widmann *et al.*, Hyperfine Interact. **215**, 1–8 (2013).
[3] N. Kuroda *et al.*, Nat. Commun. **5**, 3089 (2014).
[4] Malbrunot *et al.*, Philosophical Transactions of the Royal Society A **376**, 2116 (2018).
[5] M. Diermaier *et al.*, Nat. Commun. **8**, 15749 (2017).
[6] V.A. Kostelecky and A.J. Vargas, Phys. Rev. D **92**, 056002 (2015).

Monday Session 4

10

The AEGIS Experiment at CERN: Probing Antimatter Gravity

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The AEGIS experiment at CERN's Antiproton Decelerator is being set up to precisely measure the gravitational interaction between matter and antimatter. For this purpose, antihydrogen will be formed from cold antiprotons and positronium, the hydrogen-like bound state of an electron and a positron. Subsequently, the free-fall acceleration of a cold horizontal beam of antihydrogen will be measured with a deflectometer. In this talk, the present status, recent experimental progress and the medium-term plan of the AEGIS experiment will be presented.

11

Positron Production and Storage for Antihydrogen Production

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Antihydrogen is the simplest stable antiatom which can be produced at low energies. A sample of antihydrogen amenable to precision spectroscopic investigation would provide a stringent test of CPT symmetry and may provide a path to physics beyond the standard model.

The ASACUSA collaboration employs a cryogenic double cusp trap for mixing antiprotons and positrons, which serves as an antihydrogen source for inflight spectroscopy. Antiprotons are provided by the Antiproton Decelerator at CERN. Positrons from a radioactive ^{22}Na source with an activity of currently 0.51 GBq are slowed down to a few eV using a neon rare-gas solid moderator and accumulated in a Surko-type buffer gas trap. Typically, 6×10^6 positrons are accumulated within 30 s and transferred into the double cusp trap for mixing.

We will present our apparatus and methods used to produce, trap, accumulate, and condition positrons will be discussed. Planned new developments in positron temperature measurement and cooling will be shown, which will be important for improving the mixing efficiency. Calculations show that hydrogen production is optimal with a high density, low temperature positron plasma, encouraging recombination via three-body and radiative processes.

Tuesday Session 1

12

Challenging QED with Atomic Hydrogen

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Finding discrepancies between the predictions of fundamental theories and experimental observations is the main driver to develop physics further - the route to more advanced theories ("new physics") that fix the discrepancies. In that sense, quantum electrodynamics (QED) is currently seen as the most advanced fundamental theory, serving as the blueprint for any other quantum field theory. Progress is expected to come from ever more precise testing through comparison of theoretical predictions and experimental data. A good test compares values that can be both computed and measured with high accuracy. Some QED predictions excel in that respect, such as for the transition frequencies of atomic hydrogen [1] and the gyromagnetic ratio of the electron [2].

Most theories, including QED, depend on parameters that have to be adjusted to the experimental data. This means that the number of measurements must exceed the number of parameters, otherwise the theory can always be made correct. The test is passed if the various values for the parameters agree within their respective uncertainties. Precision-spectroscopy determinations and computations of transition frequencies of atomic hydrogen provide the best test for QED. The QED expression for the hydrogen energy levels effectively comes with two parameters: the Rydberg constant R_∞ and the rms proton charge radius r_p. Other parameters, such as the fine structure constant and the electron-to-proton mass ratio, appear as well, but can be better determined from other experiments.

Until 2010, the 15 distinct measurements of transition frequencies in atomic hydrogen as used by CODATA [3] gave 13 value pairs for R_∞ and r_p that were consistent with QED. This situation changed, however, when the frequency of a particular transition (the 2s-2p transition) in muonic hydrogen was measured [4]. Muonic hydrogen is just like regular hydrogen but with the electron replaced by its big brother, the muon. With this replacement the proton-radius term in the theoretical description — and thus the sensitivity to this parameter - is seven orders of magnitude larger than for regular hydrogen. The result was a much more precise but also significantly smaller value of r_p. This meant the QED test failed. The discrepancy between the “small” and “large” charge radius amounts to four combined standard deviations.

In addition to the hydrogen data, the CODATA team uses data for the proton charge radius obtained from electron-proton scattering. This increases the discrepancy to 5.6σ and triggered intense discussions in the community whether or not this should be seen as a hint of new physics. It should be mentioned though that electron-proton scattering experiments are notoriously difficult to evaluate and values for r_p from different groups disagree. The cleaner way to test QED is to compare only quantities that should obey the same physics, namely various transitions in regular and muonic hydrogen.

After publication of the muonic hydrogen results, our group remeasured one of the broader hydrogen lines with better accuracy. Our motivation was that the discrepancy with the muonic value only shows up when all available hydrogen data is averaged. Our latest result for the 2s-4p transition frequency is as accurate as the previous “world data” and supports the “muonic” proton radius. Meanwhile Hélène Fleurbaey and her team at the Laboratoire Kastler Brossel, Paris have remeasured the 1s-3s transition frequency with a significantly improved accuracy and again find the “large” charge radius [5]. At our lab we have also been working on this transition with a different method. We hope to be ready to report some preliminary results. This would provide a unique opportunity to compare two highly accurate measurements obtained at different labs. In case of a disagreement it would strongly hint for a measurement problem causing the “proton radius puzzle”.

[1] A. Beyer *et al.* Science 358, 79 (2017)
[2] G. Gabrielse et al. PRL 97, 030802 (2006).
[3] P.J. Mohr *et al.* RMP 88, 035009 (2014).
[4] R. Pohl *et al.* Nature 466, 213 (2010).
[5] H. Fleurbaey *et al.* PRL 120, 183001 (2018).

Tuesday Session 1

13

The Hyperfine-puzzle of Strong-field Bound-state QED

Author: NÖRTERSHÄUSER, Wilfried[1]
Co-authors: SÁNCHEZ, Rodolfo [2]; KAUFMANN, Simon [3]; KÖNIG, Kristian [3]; LITVINOV,
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A combined measurement of the ground-state hyperfine structure splitting in H-like and Li-like bismuth,the so-called specific difference $\Delta'E = \Delta E_{2s}^{Li-like} - \xi \Delta E_{1s}^{H-like}$ was proposed to be ideally suited for a test of bound−state quantum electrodynamics (BS−QED) in strong fields, where a pertubative description of QED is no longer possible [1]. Here we report on high-precision laser spectroscopy measurements in these few-electron systems that were carried out in the experimental storage ring (ESR) at the GSI Helmholtz-Center for Heavy Ion Research in Darmstadt [2]. The total accuracy of the hyperfine splitting determination was improved by more than an order of magnitude compared to previous measurements. Surprisingly, we found that the experimental value deviates by more than 7σ from the theoretical prediction, giving rise to the so-called *hyperfine puzzle* of BS-QED.

In addition to these results, we discuss possible explanations for the discrepancy and present the latest activities that have been carried out to provide a solution to this conundrum. In particular, we provide evidence that the observed discrepancy is caused by an inaccurate literature value of the nuclear magnetic moment μ_I of ^{209}Bi [3].

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Tuesday Session 2

14

Quantum Simulators with Large Ion Numbers - How to Make Them - What to Learn From Them

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Trapped ions are a promising candidate system to realize a scalable quantum simulator. The naturally long-range Coulomb interactions can be used to tailor laser-mediated coupling terms using the motional modes. Combined with individual addressing and individual readout this opens up a large number of phenomena to be studied. Results from recent experiments on Ising sampling with up to 53 qubits will be presented [1]. Various Hamiltonians can be accessed by going to different interaction regimes, such as the excitation of local phonons [2]. Additionally, gate-based digital quantum simulations can be performed on this platform. As an example, we will show Renyi entropy measurements of simulated Fermi-Hubbard model states. Strategies to scale up these systems [4] will also be discussed.

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Tuesday Session 2

15

Interacting Rydberg Ions

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Trapped Rydberg ions are a novel approach for quantum information processing [1]. By combining the high degree of control of trapped ion systems with the long-range dipolar interactions of Rydberg atoms [2], fast entanglement gates may be realised in large ion crystals [1,3].
Strong interactions between Rydberg ions rely upon using microwave (MW) fields to introduce large oscillating dipole moments to the Rydberg ions. This requires a profound understanding of the properties of the MW-dressed states in the radio-frequency trap. In our experiment [4], we trap $^{88}Sr^+$ ions and coherently excite them to Rydberg states using two UV laser fields [5]. We have observed the Autler-Townes splitting in the MW field, and measured the lifetimes and polarizabilities of the MW-dressed states. Additionally, we recently measured strong interactions between two MW-dressed Rydberg ions in a Coulomb crystal. These are fundamental steps towards a trapped Rydberg ion quantum computer or simulator.

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Tuesday Session 2

16

Production and Study of Polyanionic Metal Clusters

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The properties of atomic clusters – aggregates of few atoms up to several thousand – depend on the geometric arrangement of their atoms and on their electronic structure. Experimentally, one can try to disentangle the geometric and electronic effects by varying both the size, i.e. number n of atoms, and the charge state, z. Whereas in general cluster sources produce only neutral and singly charged species, ion-trap based techniques have been developed at the University of Greifswald to produce metal clusters of higher negative charge states (up to z = -10 in the case of aluminum). These nanoparticles have been investigated with respect to the appearance sizes (minimum atom number) of the different charge states and with respect to their decay behavior upon excitation. This includes the dissociation into smaller clusters by evaporation of neutral atoms or breakup of larger pieces, as well as the emission of electrons.

Recently, the investigations have been extended at the University of Rostock: For the first time, photoelectron spectroscopy (PES) has been applied to multiply negatively charged metal clusters. Singly-charged anionic silver clusters were produced in a magnetron sputter source, size-selected and captured in a linear Paul trap. The trap was operated in the "digital trapping mode" with field-free periods which allowed the attachment of further electrons to the clusters. Depending on the cluster size, charge states up to z = -7 were produced. During the transfer between the trap and the photoelectron spectrometer the ion bunch separates in time of flight according to the different charge states, thus providing a size and charge-state selected cluster target. The photoelectron spectra were obtained with a magnetic-bottle time-of-flight spectrometer.

In general, the electron binding energy increases with cluster size but decreases as a function of (negative) charge state. Thus, for higher charge states and relatively small cluster sizes it becomes negative, i.e. the energetically highest electrons are no longer bound but the polyanion is in a metastable state – a new observation for metal clusters.

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Tuesday Session 2

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The Intense Beam Experiment (IBEX) Paul Trap for Accelerator Physics Studies

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The Intense Beam Experiment (IBEX) is a linear Paul trap designed to replicate the dynamics of intense particle beams in accelerators. Similar to the S-POD apparatus at Hiroshima University, IBEX is a small scale experiment which is located at the STFC Rutherford Appleton Laboratory in the UK. Here we report on the status of recent simulation and experimental results with the IBEX apparatus, including investigations into half-integer resonances relevant to the ISIS Neutron and Muon Source synchrotron. We also describe future upgrade plans for the experiment.

Tuesday Session 3

18

Stringent Tests of Bound-state QED

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High-precision measurements of the gyromagnetic factor (g -factor) of highly-charged ions provide an exceptional opportunity to test the underlying theory of quantum electrodynamics of bound systems (BS-QED) and to determine fundamental constants with highest precision. In combination with prominent improvements on bound-electron g-factor calculations, the bound-electron g-factor experiment located in Mainz performed a variety of highest-precision measurement campaigns, confirming BS-QED theory with unrivalled accuracy: (1) Measuring the g-factor of hydrogenlike silicon with a relative uncertainty of 70 ppt in 2011 the most stringent test of BS-QED has been performed [1]. (2) The ensuing comparison of the measured g-factor of lithiumlike silicon with its theoretical prediction enabled the most stringent test of electron-electron interaction in 2013, which is currently going to be improved [2,3]. (3) In 2014, the atomic mass of the electron has been determined with a relative uncertainty of 30 ppt by the measurement of the bound-electron g-factor of a single hydrogenlike carbon ion [4,5]. In that way, the former literature value recommended by the CODATA (Committee on Data for Science and Technology) 2010 adjustment has been improved by a factor of 13. (4) In 2016, we measured the g-factors of two different lithiumlike calcium isotopes, ^{40}Ca and ^{48}Ca, to test the pure relativistic nuclear recoil effect by measuring the g-factor difference $\Delta g = g\,(^{40}\mathrm{Ca}^{17+}) - g\,(^{48}\mathrm{Ca}^{17+})$ [6]. In our experiment, we determine the bound-electron g-factor of a single ion by a high-precision measurement of the Zeeman splitting in a constant magnetic field. For this purpose, we measure the ratio between the spin-precession frequency (Larmor frequency) of the bound electron to the cyclotron frequency of the singly trapped ion. The spin-state of the bound electron is determined via the continuous Stern-Gerlach effect. The cyclotron frequency is measured by a dedicated phase-sensitive detection technique, working at ultra-low temperatures [7]. In this talk, I will give an overview on our measurement campaigns, have a special focus on our most recent results and present the apparatus including our triple Penning-trap setup as well as all detection techniques. As an outlook, I will also summarize the status and perspectives of our future bound-electron g-factor experiment, ALPHATRAP (located in Heidelberg), which for the first time will be able to study g -factors of heavy highly charged ions.

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Tuesday Session 3

19

Status of the HITRAP Decelerator and Ion Trapping Experiments

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HITRAP is a facility for deceleration of large bunches of highly charged ions (HCI) produced online by the GSI accelerator. It consists of two linear stages for deceleration down to several keV/q and an ion trap for ion cooling down to sub-eV energies. After preparation in the cooling trap, the ions are ejected towards different experiments.

Recently, a new design for the HITRAP cooling trap was proposed in order to improve its stability and voltage rigidity [1]. The goal was to reduce the number of electrodes and sensitive cables, while preserving the basic function of the trap which is capturing and cooling of extended bunches of HCI with large incoming dispersion. Based on this concept, seven new electrodes were machined, gold plated and installed. Novel materials, such as BIN_{77} ceramics, were used in the process. The trap is currently being tested and awaits together with HITRAP the continuation of GSI beamtime after the FAIR upgrade. We will report on the status of the HITRAP decelerator, the new cooling trap concept as well as the first results from tests with ions.

On the road towards trapping and cooling of highly charged ions at HITRAP, properties of two-species ion Coulomb crystals were investigated in the SpecTrap experiment. To this end, ions with a range of charge-to-mass ratios were injected into a previously confined and laser-cooled cloud of magnesium ions. Formation of two-species ion crystals was observed and imaged with a CCD camera [2]. This process will in the future allow rapid cooling of highly charged ions which are themselves not suitable for laser cooling because of comparably slow transitions. We will present the results as well as the new design of the setup after the recent approval of a new superconducting magnet system.

As a local ion source at HITRAP, the SPARC-EBIT (Electron Beam Ion Trap) can routinely deliver up to 10^6 HCI produced either from inert gasses or from externally injected singly charged ions [3]. In order to extend the gas based procedure to metallic ions we investigated the so-called MIVOC (Metal Ions from VOlatile Compounds) method [4], which takes advantage of large vapor pressure of organic compounds with weakly bound metal atoms. Using this method it was possible to produce Fe^{21+}, Sb^{35+} and B^{5+}. We will present the method and the results which significantly increase the number of elements and charge states possible to produce and deliver to experiments at the HITRAP facility.

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Tuesday Session 3

20

The Penning-trap Mass Spectrometer PENTATRAP

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The Penning-trap mass spectrometer PENTATRAP [1] is currently performing first mass ratios measurements using highly charged ions with a relative uncertainty in the 10^{-11} regime. This allows, among others, contributions to electron binding energy determination in highly charged ions and thus test of QED theory. After a successfully first proof-of-principle mass-ratio measurements of the xenon isotopes recent high-precision mass-ratio measurements of $^{132}Xe^{17+}$ and $^{132}Xe^{18+}$ and in the near future $^{132}Xe^{25+}$ and $^{132}Xe^{26+}$ allowed for the first time a direct precise measurement of the binding energy of the open shell electron to perform a stringent test of QED-calculations [2].

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Tuesday Session 4

21

Progress Toward Creating Electron-positron Plasmas in a Magnetic Dipole Trap for Basic Plasma Science and Astrophysics

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The large mass imbalance between ions and electrons produces a separation of the two species' length and time scales that is a cornerstone of traditional plasma physics. To consider the behavior of a "pair plasma", comprising particles with opposite charge but equal mass, is to revisit much of plasma physics from the ground up. To date, on the order of 1000 papers have explored this topic via a variety of analytical and computational treatments, but the experimental side of the investigation is still in its nascence. Laboratory studies of electron/positron plasmas will enable the first tests of many simulation and theory predictions — e.g., the stabilization of anomalous transport mechanisms — with implications for our understanding not only of pair plasmas and astrophysical phenomena in which they play a role but also of traditional electron/ion plasmas. Toward these ends, the goal of the APEX (A Positron Electron eXperiment) collaboration is to create and study pair plasmas confined in the magnetic field of a levitated dipole. This talk will describe how significant milestones to date — as well as ongoing and upcoming activities — move the project closer to pair plasma creation.

Tuesday Session 4

22

Evaporative Cooling of Atomic and Molecular Ions by Autoresonance in an Electrostatic Ion Beam Trap

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Translational cooling of atomic and molecular ions is a requisite in several research areas. An Electrostatic Ion Beam Trap (EIBT) can trap any ion with any mass or charge using the same tuning conditions; therefore, it is an ideal ion trap for ion beam cooling. An external chirp sinusoidal electric field is applied on one of the EIBT mirror electrodes. In this procedure, called autoresononace (AR), a bunch of ions is accelerated out of the rest of the ion beam population. Depending upon the chirped field intensity and rate, one can cool such a bunch of ions. A cooling process has been demonstrated in the EIBT that, by using an autoresonance procedure, reduced the temperature of ions from an initial value of ˜40 K down to about 0.15 K in 80 ms and with ion-ion interaction [1]. Figure 1 shows the calculated bunch internal temperature as a function of the AR voltage using the measured ion bunch velocity distributions. The AR threshold field for an ion bunch acceleration is about 0.052 V. The arrow in the figure indicates the initial temperature of the ions in the trap before the AR process.

Fig 1: The temperature of the ion bunch after the autoresonance dragging process. The arrow represents the initial temperature of the ions in the EIBT

During the process, it has been shown [1] that the ion-ion collisions transfer kinetic energy from the cold population to the hotter population, which in turn is evaporated from the ion bunch, hence reducing the temperature and increasing the phase-space density. Further experiments and theoretical models are ongoing to improve the cooling efficiency and to achieve lower temperatures.

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Tuesday Session 4

23

Studying Proton-capture Reactions on Stored Radioactive Ions for Nuclear Astrophysics

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Radiative proton-capture reactions play a crucial role in explosive nucleosynthesis. In the corresponding stellar scenarios, e.g. supernovae or X-ray bursts, the nuclear reaction flow predominantly proceeds in the domain of radioactive nuclei, making reactions studies in the laboratory challenging. The most promising approach to cross section measurements on radionuclides is to prepare them in inverse kinematics at a rare ion beam facility like GSI/FAIR [1]. After production at higher energies in the fragment separator the secondary beam can be injected into the ESR storage ring, where it is decelerated to the Gamow window and used efficiently for reaction studies.

In this contribution the experimental method will be outlined with a focus on the challenges of particle detection in ultra-high vacuum and the storage of low-energy ions in a ring. Additionally, an extended overview of the proton-capture studies at the ESR will be given. This will include a discussion of results for the ^{96}Ru(p,γ) pilot experiment [2], the ongoing analysis of the ^{124}Xe(p,γ) reaction [3] as well as the technical improvements achieved in the meantime.

Finally, an outlook to future experiments at storage rings will be given, including the CRYRING@ESR facility [4] and the successor of the TSR@ISOLDE project [5].

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Wednesday Session 1

24

What Did We Learn by Mass Spectroscopy Use of Storage Rings or Traps Since TCP14?

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The N = 32 Neutron Shell Closure Viewed Through Mass Measurements with TITAN's MR-TOF-MS

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TRIUMF's Ion Trap for Atomic and Nuclear science (TITAN) is a multiple ion trap system for high precision mass measurements and in-trap decay spectroscopy of singly and highly charged exotic ions. The system is installed at the ISOL facility with the highest beam power on target, the Isotope Separator and Accelerator (ISAC), TRIUMF, Vancouver, Canada.

ISAC delivers the highest yields for some of the most exotic species, but many measurements suffer from strong isobaric background. In order to overcome this limitation an isobar separator based on the Multiple-Reflection Time-Of-Flight Mass Spectrometry (MR-TOF-MS) technique has been developed at the Justus-Liebig University, Giessen, Germany and was recently installed at TITAN. Isobar separation is achieved using dynamic re-trapping of the ions of interest after a time-of-flight analysis in an electrostatic isochronous reflector system. After commissioning with stable beams from ISAC in spring-2017 the MR-TOF-MS is now routinely in operation and being used for real-time determination of the radioactive beam composition and optimization of the ISAC mass separator, for precision mass measurements and soon for isobar separation.

The first measurement campaign with the MR-TOF-MS aimed to investigate the evolution of the N = 32 neutron shell closure. This shell closure forms several neutrons away from stability and had been established in neutron-rich K, Ca and Sc isotopes, where as in V and Cr, no shell effects can be found, thus leaving the intermediate Ti isotopes as the ideal test case for state-of-the-art ab-initio shell model calculations. Accurate, high-precision mass measurements with TITAN's mass spectrometers (Measurement Penning Trap and MR-TOF-MS) were able to prove the existence of a weak shell closure in Ti and quenching of the shell in V. These findings challenge modern ab initio theories, which over predicted the strength and extent of this weak N= 32 shell closure. Recent mass measurements as well as technical upgrades of the new device and perspectives for future mass measurements of short-lived isotopes with the TITAN MR-TOF-MS will be presented.

Wednesday Session 2

26

Precision Measurement of the Electron’s Electric Dipole Moment Using Trapped Molecular Ions - Status and Perspectives

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Precision measurements of fundamental symmetries provide a parallel path in the search for new physics beyond the Standard Model (SM) to that of high-energy collider experiments. Among these are measurements of permanent electric dipole moments in elementary particles that constitute a source of charge-parity (CP) symmetry violation, with very low background within the SM. I will discuss our first measurement of the electron’s electric dipole moment (eEDM) with HfF+ molecular ions, which has produced a value consistent with zero with an upper bound of 1.3x10^{-28} e cm (90% confidence)[1]. The next generation experiment will aim to increase the statistics that dominated the uncertainty despite the 360 hours of data taken. The increased trapping volume and field uniformity, enables ten times as many ions to be interrogated with spin precession times longer than 2 seconds due to the higher polarizing fields applied. I will also briefly discuss the progress towards a generation 3 measurement with ThF+ molecules where the molecular state of the spin precession experiment is the ground state, paving the way to significantly longer coherence times.

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Ba-ion Extraction from High Pressure Xe Gas for Double-beta Decay Studies with nEXO

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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 Gd-148-driven Ba-ion source or a Cf-252-fission source placed in the high pressure gas. The ion transmission has been studied in detail for various operating parameters. A mass spectrometer has been used for mass-to-charge identification of the extracted ions. This identification is being improved 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 Xe-136 neutrino- less double-beta decay (0νββ) experiment. The technique aims to extract the double beta-decay product, Ba-136, from the xenon gas and detect it unambiguously and efficiently. This individual identification of the decay product allows for an ideally background-free measurement of 0νββ vetoing naturally occurring backgrounds. This identification enables a higher level of sensitivity to the onbb decay half-life and thus is a more sensitive probe of the nature of the neutrino.

Wednesday Session 2

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muCool: A Novel Low-energy Muon Beam for Future Precision Experiments

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Experiments with muons and muonium atoms (μ^+e^-) offer several promising possibilities for testing fundamental symmetries. Examples of such experiments include the search for the muon electric dipole moment, measurement of the muon g-2 and muonium laser spectroscopy. These experiments require high-quality muon beam with low energy, small transverse size and high rate. At the Paul Scherrer Institute, we are developing a novel device that reduces the phase space of a standard μ^+ beam by a factor of 10^{10} with 10^{-3} efficiency. The phase space compression is achieved by stopping a standard μ^+ beam in cryogenic helium gas. The stopped μ^+ are manipulated into a small spot with complex electric and magnetic fields in combination with gas density gradients. Finally, muons are extracted into the vacuum and into a field-free region. Various aspects of this compression scheme have been demonstrated. In this talk, the current status will be reviewed.

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Search for the Electric Dipole Moment of the Muon

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Searches for electric dipole moments (EDM) of fundamental particles are considered one of the most sensitive approaches to physics beyond the Standard Model of particle physics (SM). The known violation of the combined symmetry of charge and parity conjugation (CPV) is tiny in the SM, while a common and natural feature of many beyond SM theories. In particular in the light of current results in B decays and the deviation of the muon g-2 experimental result from SM theory a dedicated search for a muEDM is attractive. . It will be complementary to searches for baryonic EDMs (neutron, proton, deuteron, 199-Hg) and the electron EDM by being mostly insensitive to the CP- violating term of QCD and testing an (anti)particle of the second generation. We discuss measuring the muEDM with a compact storage ring at the Paul Scherrer Institute using the frozen spin technique using muons with a momentum of 125 MeV/c, a magnetic field of 1.5 Tesla and a radial electric field of approximately 10kV/cm, similar to the proposal in [Adelmann et al., JPG37(2010)085001].

Wednesday Session 2

30

Precision Mass Measurements with Light Ions: Tritium Q- value, the He-3/HD Puzzle and Resolving Ro-vibrational Energy

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In 2015 we reported mass ratios for $HD^+/^3He^+$ and HD^+/T^+ which yielded a precise value for the tritium beta-decay Q-value, M [T] - M [^{3}He] = 18 592.01(0.07) eV [1]. The uncertainty is more than a factor of 10 smaller than the previous most precise result [2], and enables an important test of systematics in KATRIN and future tritium-beta decay end-point spectrometers that set limits on electron neutrino mass. Our result for $HD^+/^3He^+$ gave a mass difference (expressed with respect to the respective nuclear masses) $m(p) + m(d)—m(h)$ that was smaller, by 0.79(18) nu, than the result obtained from the last values for $m(d)$ and $m(h)$ from the University of Washington (UW) group [3], and the then current CODATA value for $m(p)$ [4] (which also mainly derived from the UW group). This motivated us to re-measure $HD^+/^3He^+$ with an improved apparatus. Our new result agreed with our previous result, but reduced the uncertainty by a factor of 2 [5]. In the meantime, a new result for $m(p)$ was obtained at Mainz [6], which was 3 standard deviations below the CODATA2010 value. With the new value for $m(p)$ the discrepancy for $m(p) + m(d) - m(h)$ was discrepancy is now still more than 4 standard-deviations. In order to provide further information on the cause of the discrepancy, and then provide an improved value for the proton to deuteron mass ratio, we have also measured HD^+/H^+_3 [7], and recently, D^+/H^+_2. For these mass ratios involving homonuclear molecular ions, it is necessary to allow for rotational and vibrational energy of very-long-lived metastable levels, which we can partly resolve, and, in some cases, Stark-quench.

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Electron Scattering from ^{208}Pb and ^{132}Xe Ions at the SCRIT Facility

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We have constructed the SCRIT (Self-Confining Radioactive Ion Target) electron scattering facility to realize electron scattering off short-lived unstable nuclei at RIKEN in Japan. Electron scattering is one of the most powerful tools to investigate the structure of atomic nuclei as demonstrated for stable nuclei in the latter half of the 20th century. It has, however, never been applied for short-lived unstable nuclei with few exceptions due to difficulties of preparing thick targets. The SCRIT is a novel technique to achieve the high luminosity of more than 10^{27} [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$] with a small amount of target ions, typically 10^8, by trapping the target ions on the electron beam. Our facility consists of a 150-MeV racetrack microtron, an electron storage ring equipped with the SCRIT, an electron-beam driven RI separator, a luminosity monitor, and a scattered electron spectrometer. After completion of the construction of the facility, a series of commissioning experiments of the whole facility with several stable targets have been performed. In this talk, the results from the ^{208}Pb and ^{132}Xe targets, the present status of the facility, and a future plan toward electron scattering off unstable nuclei will be presented.

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Laser Cooling of Relativistic Lithium-like ^{16}O^{5+} Ion Beams at the Heavy Ion Storage Ring CSRe

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Laser cooling of lithium-like ^{16}O^{5+} ion beams with an relativistic energy of 275.7 MeV/u was achieved for the first time at the heavy-ion storage ring CSRe in Lanzhou, China. In order to match the energy levels of ^{16}O^{5+} ions at the beam energy, a CW laser system with a wavelength of 220 nm was used while the ion beams were bunched by applying a few tens volts sinusoidal voltage to the RF-buncher system. With laser cooling, the relative longitudinal momentum spread of laser cooled ^{16}O^{5+} ions have reached $dp/p \approx 1 \times 10^{-7}$, the coolest heavy ion beams in storage rings up to now. The successful laser cooling of ^{16}O^{5+} ion beam demonstrates the highest charge state and highest energy of ions that have ever been cooled by lasers. We will present the very recent experimental results at the conference.

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Upgrading the Isochronous Mass Spectrometer by Measuring Velocity of Stored Ions

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The Isochronous Mass Spectrometry (IMS) is one of important tools which is used to measure atomic mass of short lived nuclides at in-flight radioactive ion beam facilities [1]. The nuclides of interest are present as highly charged ions with none or just a very few bound electrons. The IMS is based on a special –isochronous– tuning of a storage ring [1]. The necessary condition for the isochronous mode is that the energy of the ions corresponds to $\gamma = \gamma t$. In this mode, the revolution times of ions with same m/q but with different velocities v are compensated by different lengths of their orbits. However, due to the fixed magnetic rigidity, $B\rho = mv\gamma/q$ of the transport lines and the injection into the ring, nuclides with different m/q values inevitably have different mean velocities. In a realistic experiment, the simultaneously covered $\Delta(m/q)/(m/q)$ range is about 10% thus the treatment of ions with $\gamma \neq \gamma t$ is an essential issue. One effective way to improve the precision of the IMS experiments is through velocity measurement. Therefore, two ToF detectors have been installed in the CSRe at Lanzhou in order to determine the velocity of each ion stored inside CSRe. Preliminary results indicated that the precision of the IMS could significantly be improved with such velocity measurements. The experimental details will be given in this presentation.

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The Heidelberg Cryogenic Storage Ring CSR: Rotational Cooling and Electron Collisions of Molecular Ions

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Presented for the CSR experimental team.

Cryogenic electrostatic ion storage rings were taken into operation recently in Stockholm, Tokyo and Heidelberg. Beams of atomic, molecular and cluster ions with tens to hundreds of keV of kinetic energy are stored in a cryogenic vacuum chamber with a circumference of several meters in a distributed lattice of deflection and focusing elements. The beam storage decay times reach up to the order of one hour. By the high beam velocity, charge or mass changed and neutral products of ionic decays can be observed in event mode, using cryogenic counting and imaging detectors. Processes leading to ionic decay of fragmentation are induced by lasers and by particle beams merged to the circulating ions over storage-ring straight sections.
The Heidelberg cryogenic storage ring CSR started operation in 2015 [1], showing extremely low vacuum along the beams with beam decay constants often exceeding 1000 s. The decay of rotational levels in diatomic hydride ions by far-infrared spontaneous emission has been studied by probing the rotational level populations, using threshold laser photodetachment and laser photodissociation via ro-vibrational resonances as probes for anions (OH^-) and cations (CH^+), respectively [2,3]. This yielded A coefficients for the lowest rotational transitions and probed the radiation field in the CSR near 1 THz. Recently the electron cooler of the CSR has been taken into operation and the first measurements of dissociative recombination on rotationally cold molecular cations were performed.

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Thursday Session 2

35

Penning-Trap Mass Spectrometry of the Heaviest Elements with SHIPTRAP

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The quest for the heaviest elements is at the forefront of nuclear physics. Superheavy elements ($Z \geq 104$) owe their very existence to an enhanced stability resulting from nuclear shell effects. High-precision Penning-trap mass spectrometry (PTMS) is an established tool for investigations of nuclear structure-related properties, such as binding-energy differences, for example two-nucleon separation energies [1, 2]. Although elements up to oganesson ($Z = 118$) have been discovered, detailed studies of the elements with $Z > 110$ are hampered (by low statistics) due to low production cross sections in the order of pb. However, direct high-precision PTMS in the region of $Z > 100$ provides indispensable knowledge like pairing correlations affecting the properties of the heaviest elements. Furthermore, anchor points for alpha-decay chains and benchmarks for theoretical models are obtained.

Pioneering experiments with SHIPTRAP, located behind the velocity filter SHIP at GSI in Darmstadt, Germany, have demonstrated that direct measurements of the heaviest elements are feasible for lowest yields [3,4], in the case of ^{256}Lr ($Z = 103$) with a cross section as low as 60 nb [5]. The recent rearrangement of the system and the implementation of a cryogenic gas-catcher [6] allow us to push these limits to even heavier and more exotic nuclides. In the upcoming beam time periods at GSI we aim at performing direct mass measurements of $^{254-256}$Lr and ^{257}Rf ($Z = 104$), providing additional anchor points of very heavy odd-N and odd-Z as well as odd-A nuclides, affecting the masses up to darmstadtium ($Z = 110$). In addition, employing the novel phase-imaging ion-cyclotron-resonance technique (PI-ICR) [7,8] will among others allow determining the excitation energies of low-lying isomeric states, where only tentative level energies were derived from previous alpha decay spectroscopy experiments [9].

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Thursday Session 2

36

Probing Nuclear Isomers Using Phase-imaging Ion-cyclotron- Resonance Detection with ISOLTRAP at CERN

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ISOLTRAP, located at the radioactive-ion beam facility ISOLDE at CERN, provides high-precision mass values of short-lived nuclides as well as precision β-decay Q-values for nuclear models and fundamental interactions. Previously, the measurements were made using the time-of-flight ion-cyclotron-resonance (ToF-ICR) detection technique, which is limited in accessible half-lives, resolving power and relative uncertainty. More recently, the new phase-imaging ion-cyclotron- resonance (PI-ICR) detection technique [S. Eliseev et al., Phys. Rev. Lett. 110 082501 (2013)] enables complementary experiments, with fewer ions and increased resolving power, providing access to new areas of the nuclear chart and to new physics. This contribution will report on the implementation and further development of PI-ICR mass spectrometry (MS) with ISOLTRAP, including results from first on-line measurements in both the high-resolution and high-precision regimes. In particular, the Q-value of the ^{88}Sr-^{88}Rb β-decay was determined with an uncertainty of < 130 eV. Furthermore, the separation of the low-lying isomeric states in ^{127}Cd and ^{129}Cd was achieved, from which their excitation energies were determined. A mass resolving power $m/\Delta m > 10^6$ was reached for only 100 ms measurement time compared to $m/\Delta m \sim 10^4 - 10^5$ using ToF-ICR MS.

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Mass Measurements of Heavy and Superheavy Nuclei by Multireflection Time-of-flight Mass Spectrograph

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The SHE-mass project at RIKEN utilizes a cryogenic helium gas stopping cell in combination with a multi-reflection time-of-flight mass spectrograph (MRTOF-MS) to measure atomic masses of heavy nuclei produced in fusion-evaporation reactions. The spectrographic nature of the MRTOF-MS allows simultaneous measurement of multiple chains of isobars, resulting in extraordinarily efficient use of online machine time. Additionally, the MRTOF-MS achieves a mass resolving power of R_m˜150,000 within less than 10 ms for even the heaviest of atomic ions, allowing access to even the shortest-lived heavy nuclei. The first mass measurement campaign of the SHE-mass project was completed in January 2017. During that initial mass measurement campaign, over 80 atomic masses were measured. Of particular note were extremely high-precision measurements of neutron-deficient light nuclei which lead to revised masses of ^{67}Ge and ^{81}Br [1], first-time direct mass measurements of several neutron deficient isotopes of Ac, Ra, Fr, Rn, and At [2,3], high-precision measurements of ^{219}Ra ($T_{1/2}$=10 ms) and ^{220}Ra ($T_{1/2}$=18 ms), and first mass measurements of $^{249-252}$Md [4]. We will report on the results of this first mass measurement campaign and the plans for the second measurement campaign which will focus on Z>104 nuclei.

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38

Search for New Physics with Trapped Charged Atoms and Molecules

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I will give an overview of recent developments in the search for new physics with trapped ions and molecules [1] and then focus on selected examples.
In many theories beyond the Standard Model of elementary particles and general relativity dimensionless fundamental constants become dynamic fields. Such theories include string theories, discrete quantum gravity and loop quantum gravity, chameleon models, quintessence (dark energy) models, and others. I will review the current status of searches for the variation of fundamental constants with trapped ions as well as related ultra-light dark matter searches. I will focus on the future perspectives for improved sensitivity with highly-charged ions [2] and a nuclear clock.
A broadly applicable new method to search for the violation of local Lorentz invariance with atomic systems [3] will be discussed. The new scheme uses dynamic decoupling and can be implemented in current atomic clock experiments, with both single ions and arrays of neutral atoms. Moreover, the scheme can be performed on systems with no optical transitions, and therefore it is also applicable to highly charged ions which exhibit a particularly high sensitivity to Lorentz invariance violation.

I will also discuss the perspectives for laser cooling of a negative ion, La^- [4]. A very exciting application of La^- laser cooling includes cooling of antiprotons for antihydrogen formation and subsequent tests of CPT invariance, i.e. combined transformations of charge conjugation, spatial and time reversal, and weak equivalence principle as well as tests of gravity with antimatter.

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A New Concept for Searching for Time Reversal Symmetry Violation Using Pa-229 Ions Trapped in Optical Crystals

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Certain pear-shaped nuclei are expected to have enhanced sensitivity to time-reversal and parity- violating interactions originating within the nuclear medium. In particular, Protactinium-229 is thought to be about 100,000 times more sensitive than Mercury-199 which currently sets some of the most stringent limits for these types of interactions. Several challenges would first have to be addressed in order to take advantage of this discovery potential. First, there is not currently a significant source of Pa-229 (1.5 day half-life); however, there are plans to harvest Pa-229 at the Facility for Rare Isotope Beams at Michigan State University. Second, the spin-5/2 nucleus of Pa-229 limits its coherence time while also making it sensitive to systematic effects related to local electric field gradients. On the other hand, this also give Pa-229 an additional source of signal in the form of a magnetic quadrupole moment (MQM) which violates the same symmetries as an EDM but is not observable in spin-1/2 systems. Third, in order to compensate for the small atom numbers and short coherence times, the Pa-229 atoms would have to be probed with exceptionally large electric and magnetic fields that are only possible if Pa-229 is a part of a polar molecule such as PaO or embedded inside an optical crystal. I will present our plans to test this latter concept using the stable Praseodymium-141 isotope which has the same nuclear spin and similar atomic structure of Pa-229.

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Searching for Tensor Currents in the Weak Interaction Using Lithium-8 Beta Decay

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Nuclear physics remains a powerful tool to search for unobserved phenomena by probing the limits of the Standard Model. The electroweak interaction is well predicted by a pure vector-axial vector structure. However, high-precision measurements of the beta-neutrino correlation coefficient, $a_{\beta\nu}$ in beta decay have long been used as a test for New Physics because of the term's sensitivity to tensor and scalar currents. The beta decay of ^{8}Li is an ideal reaction for probing $a_{\beta\nu}$ due to its high Q-value and delayed alpha emission of the daughter nucleus. By measuring the kinematics of stopped ^{8}Li ions in a Paul Trap surrounded with silicon strip detectors backed with plastic scintillators and comparing to simulation, we can set a limit on tensor contributions from $a\beta\nu$. Upon completing the analysis of a high-statistics dataset obtained in 2016, we are poised to constrain tensor currents in the weak interaction to ~0.2%, the most stringent limit yet achieved in the low energy regime.

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The MORA Project

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Why are we living in a world of matter? What is the reason for the strong matter – antimatter asymmetry we observe in the Universe?
The MORA (**M**atter's **O**rigin from the **R**adio**A**ctivity of trapped and oriented ions) project aims at searching for possible hints. In 1967, A. Sakharov expressed the 3 conditions which should be fulfilled for the baryogenesis process. These conditions are: (i) a large C and CP violation; (ii) a violation of the baryonic number, (iii) a process out of thermal equilibrium. A large CP violation has therefore to be discovered to account for this large matter-antimatter asymmetry, at a level beyond the CP violation predicted to occur in the Standard Model via the quark-mixing mechanism.
MORA aims at measuring with unprecedented precision the *D* correlation in the nuclear beta decay of trapped and oriented ions. There is a large window in which *D* correlation measurements can contribute to the search for other sources of CP violation at a much higher level than predicted by the Standard Model. The *D* correlation offers the possibility to search for new CP-violating interactions in a region that is less accessible by EDM searches, in particular via the Leptoquark model. With sensitivity on *D* close to 10^{-5} , the MORA apparatus should additionally permit a probe of the FSI (Final State Interactions) effects for the first time, which can mimic a non-zero *D* correlation of the order of 10^{-5} to 10^{-4} depending on the beta decay transition which is observed. Technically, MORA uses an innovative in-trap orientation method which combines the high trapping efficiency of a transparent Paul trap with beta-NMR laser orientation techniques. The project will first focus on the proof-of-principle of the in-trap laser orientation technique, before the actual measurement of the *D* correlation in the decay of $^{23}\text{Mg}^{+}$ ions is done firstly at JYFL and then later, at GANIL.
The MORA project is supported by Region Normandie.

Thursday Session 4

42

TAMUTRAP: An Ion trap Facility for Weak Interaction Studies

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In the low-energy regime, precision measurements in nuclear beta decay continue to be a sensitive tool to search for new physics beyond the standard model (SM). The primary goal of Texas A&M University Penning trap facility (TAMTURAP) is to improve the limits on non-SM processes in the weak interaction, in particular scalar currents, by measuring the β-ν angular correlation parameter, $a_{\beta\nu}$, for T=2 super-allowed β-delayed proton emitters. The Doppler energy shift of the β-delayed protons emitted from the isobaric analogue state carries the information about the angular correlation parameter, $a_{\beta\nu}$. The experiment will be performed in a unique large bore cylindrical Penning trap with inner radius of 90 mm, which is larger than any existing Penning trap. This large radius Penning trap will allow to full radial containment of protons (4π acceptance) of interest, as well as less magnetically rigid beta's, for $a_{\beta\nu}$, studies. TAMUTRAP facility will be coupled to T-REX (TAMU-Reaccelerated Exotics) upgrade project of the Cyclotron Institute, Texas A&M University, and, will be the source of low energy radioactive ion beams to the TAMUTRAP facility.

Friday Session 1

43

The Challenge of a Nuclear Frequency Standard: Towards a Precise Energy Determination of ^{229m}Th

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Since the proposal of a nuclear frequency standard based on the first excited nuclear isomeric state of ^{229}Th in 2003 [1], considerable worldwide efforts have been made in order to pin down the isomeric energy (for a recent review see Ref. [2]). The currently most accepted value is 7.8(5) eV, corresponding to about (159 ± 11) nm [3], which is, however, not sufficiently precise in order to allow for nuclear laser excitation in a Paul trap, as required in the nuclear clock concept.

A direct detection of the isomeric decay via the internal conversion (IC) decay channel in 2016 [4] has opened three new paths for a precise determination of the isomeric energy value. These are (1) electron spectroscopy of the IC electrons emitted in the isomeric decay [5], (2) laser-based IC-Mössbauer spectroscopy [6] and (3) a microcalorimetric measurement using a superconducting nanowire single-photon detector (SNSPD). All three paths are currently investigated by our group and the most recent experimental status will be reported. The measurements will be brought in context with other efforts aiming for a precise ^{229m}Th energy determination worldwide.

This work was supported by DFG (Th956/3-2), by the European Union's Horizon 2020 research and innovation programme under grant agreement 6674732 "nuClock" and by the LMU department of Medical Physics via the Maier-Leibnitz Laboratory.

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44

Trapping and Sympathetic Cooling of Single Thorium Ions for Spectroscopy

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Precision spectroscopy of exotic ions reveals accurate information about the excitation frequencies of nuclei, their transition rates and lifetimes. Thorium ions exhibit unique nuclear properties with high relevance for testing symmetries of nature. We report loading and trapping of single $^{232}Th^{+}$ ions in a linear Paul trap, embedded into and sympathetically cooled by small crystals of trapped $^{40}Ca^{+}$ ions. Trapped thorium ions are identified in non-destructive manner from the voids in laser-induced Ca fluorescence emitted by the crystal, and alternatively by means of a time-of-flight signal when extracting ions from the Paul trap and steering them into a detector downstream. We have loaded and handled in total 231 individual Th ions. In the time-of-flight detection we reach an efficiency of 95%, consistent with the detector quantum efficiency. The sympathetic cooling technique is expected to be applicable for other isotopes and various charge states of thorium, e.g. for studies of the ^{229}Th isomer state.

45

A Lutetium-ion Optical Atomic Clock

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Singly-ionized lutetium has been identified as a promising optical clock candidate with several advantageous properties. It has multiple candidate clock transitions: from the $^1S_0$ ground state to the $^3D_1$, $^3D_2$, and $^1D_2$ metastable states. Overall systematic sensitivities compare favorably with other leading candidates, and, in particular, the $^1S_0$ to $^3D_1$ was recently found to have the lowest blackbody radiation sensitivity of all known candidate transitions. Here we report recent spectroscopy on all three clock transitions and ongoing efforts to evaluate systematic shifts. Long-term prospects for lutetium and progress towards a multi-ion clock are discussed.

46

MIRACLS- the Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy

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Collinear laser spectroscopy (CLS) is a powerful tool to access nuclear ground state properties such as spin, charge radius, and electromagnetic moments with high precision and accuracy [1]. Conventional CLS is based on the optical detection of fluorescence photons from laser-excited ions or atoms. It is limited to radioactive ion beams (RIB) with yields of more than 100 to 10,000 ions/s, depending on the specific case and spectroscopic transition. Consequently, the study of the most exotic nuclides synthesized at today's RIB facilities demands for more sensitive experimental methods.

Complementary to Collinear Resonance Ionization Spectroscopy (CRIS) [2] or more specialized techniques, e.g. [3], we are currently developing the Multi Ion Reflection Apparatus for Collinear Laser Spectroscopy (MIRACLS) at ISOLDE/CERN. This novel approach is determined to enhance the sensitivity of CLS by a factor of 20-600. It is based on an electrostatic ion beam trap (EIBT) or also called multi reflection time of flight (MR-ToF) device in which the ions bounce back and forth between electrostatic mirrors [4]. This scheme allows extended observation times and hence higher experimental sensitivity.

In order to preserve the high resolution of conventional CLS, MIRACLS' MR-ToF device will be operated at a beam energy of 30 keV compared to a few keV in today's instruments [4]. Moreover, CLS requires the ions' energy spread to be ideally < 1 eV to minimize Doppler broadening whereas MR-ToF devices usually work with a focus in the time domain resulting in a much larger energy spread. At MIRACLS these conflicting beam requirements will be addressed by preparing the ion bunch in a cryogenic Paul trap (<50 K) to obtain an improved beam emittance.

From the perspective of mass separation, these advances in beam preparation and MR-ToF beam energy promise mass resolving powers of $R > 10^5$ obtained significantly faster than in state-of-the-art MR-ToF devices. Consequently, the limit on resolving power normally imposed by space charge effects when storing too many ions inside the MR-ToF apparatus is bypassed by keeping the number of ions trapped at a time below this limit but processing the mass separation faster. This opens the path for a high ion-flux MR-ToF mass separator beneficial for a wide range of applications.

This contribution will introduce the MIRACLS concept and will present the current status of the project. This includes MIRACLS' proof-of-principle experiment in an existing, low energy MR- ToF apparatus [5] which has been modified for the purpose of CLS to experimentally demonstrate the potential of the MIRACLS approach.

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Optical Pumping in RFQ Cooler/Buncher for the Determination of Charge Radii and Nuclear Moments of Radioactive Nuclides of Transition Metals

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Collinear laser spectroscopy (CLS) is a powerful technique for determining the differential mean- square charge radii and nuclear electromagnetic moments of rare isotopes [1]. The first and second-row transition metals can provide critical nuclear structure information because they cross the N = 28-50 neutron magic numbers, and surround the debated subshell closure at N = 40 [2]. However, the transition metals have proven difficult to study with CLS. Low production rates, inaccessible wavelengths of electronic transitions, and high electronic level densities that make atomic charge exchange unfavorable [3] present the main challenges to CLS measurements of the transition metals.

One promising technique to overcome these barriers is optical pumping, by which the electronic population is redistributed to favorable electronic states for laser spectroscopy. The laser light for optical pumping is introduced into a RFQ cooler/buncher to irradiate trapped ions, where long ion-laser light interaction time can be obtained for efficient population manipulation. Such optical pumping was first applied to niobium ions [4], and later to other systems [5,6].

A pulsed laser system has been installed at the Beam Cooling and Laser spectroscopy (BECOLA) facility [7] at NSCL/MSU for optical pumping experiments with trapped rare isotopes. A simulation has been developed to evaluate possible optical pumping schemes and estimate expected improvements in electronic state populations for the rare isotopes of interest. Results of the simulations for refractory elements and the status of development for a light transport system will be discussed.

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Friday Session 2

48

RFQ Ion Trap for Laser Spectroscopy Measurements at the BECOLA Facility

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Laser induced fluorescence measurements are commonly used for the measurements of atomic hyperfine structure to deduce nuclear properties [1]. An radio-frequency quadrupole (RFQ) ion trap is now an indispensable component in laser spectroscopy measurements to gain detection sensitivity by way of trapping, cooling and bunching the beam [2, 3]. This is especially critical for rare isotope beams, whose production rate is limited.

A helium-buffer gas filled RFQ ion trap [4] is used at the BECOLA facility [5] at NSCL/MSU for collinear laser spectroscopy. The RFQ has separate cooling and buncing sections not to enlarge the emittance of the extracted ion beam. Typical bunch width is ~1 μs (FWHM) without disturbing the energy resolution of hyperfine spectra. The high sensitivity realized by the RFQ enables determination of charge radius of ^{36}Ca, whose ion rate was ~50/s at the RFQ. The result of the Ca experiments as well as the performance characteristics of the RFQ will be discussed.

An optical pumping technique in the RFQ ion trap is also being developed at BECOLA. Long ion-laser light interaction time can be obtained for efficient electronic population manipulation to favor the following laser spectroscopy measurements [6]. The status of this development is also briefly discussed.

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Friday Session 2

49

Recent Developments and Results at JYFLTRAP

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In this contribution I will give a short overview of the JYFLTRAP Penning trap setup [1], discuss the most recent development work and show some mass measurement results.
The most important recent upgrade at JYFLTRAP is undoubtedly the commissioning of the PI- ICR mass measurement technique [2] in 2017. Since then the technique has been regularly used for mass measurements of exotic nuclei and to identify and separate isomeric states. Precision better than 10^{-9} and also mass resolving power exceeding 10^6 has been demonstrated. Isomerically pure samples of ions separated with the phase-dependent cleaning technique has been also delivered to the post-trap decay spectroscopy station.
Another upgrade being commissioned at JYFLTRAP is the JYFL multi-reflection time-of-flight (MR-TOF) separator/spectrometer. In summer 2018 the ion beam buncher will be modified to provide suitable time-focused bunches of ions for MR-TOF. Later in the year the MR-TOF will be installed. (See contribution by A. de Roubin) Recently we have performed several mass and Q-value measurements relevant for nuclear astrophysics and neutrino studies. I will present some results of measurements which have utilized PI-ICR method.
The phase-dependent cleaning technique can be used to determine isomeric yield ratios (for example in proton induced fission of natural uranium). This has been performed for the first time. The advantage here is that the measurement is done through direct ion counting and the method is universal and fast.

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TCP 2018
POSTER PRESENTATIONS

As of 7 September 2018

P1

Open Shell Ions Mobility in Cooled Helium Gas at 4.3K: Shallow Minimum Appearance

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On the light of the experimental measurements of Matoba et al., [1] and Sandreson et al., with a mass-selected-ion-injected drift tube mass spectrometer, of ionic open-shell systems such as C+, N+ and O+ ions, evolving in a helium gas at very low temperatures, and according to the quantum-mechanical [3] and the classical [1], [4] calculations of the ground and the metastable- excited C+ ions and to the classical calculations of the ground and the metastable-excited N+ and O+ ions mobility in helium at temperatures 77 and 4.3 K, we have aimed to show the effect of the Spin-Orbit and the quantum-mechanical calculations on the shallow minimum in C+ and N+ and O+ ions mobility in a cooled buffer helium gas at 4.3K. For this reason, we use the interaction potentials corresponding to the ground and metastable-excited ions which are performed with MOLPRO. Then we use the computed quantum-mechanical transport cross sections in the Viehland gram-char Fortran code as to get the mobility of open shell ions at 4.3K helium gas temperatures.

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P2

Stopped, Bunched Beams for the TwinSol Facility

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Testing the unitarity of the Cabbibo-Kobayashi-Masakawa (CKM) matrix offers an important avenue for constraining physics beyond the Standard Model. Several methods are used to determine *Vud*, the largest element going into determining CKM matrix unitarity. Thanks to extensive experimental efforts, the superallowed $0^+ \rightarrow 0^+$ pure Fermi transitions provide the most precise value of *Vud* and the most stringent test of CKM matrix unitarity [1]. However, alternate approaches are desirable to test for unknown systematic effects or even new physics; one such approach is to use superallowed mixed mirror transitions [2]. Determining the corrected F*t*-value in these systems is more challenging, as it requires the determination of the Fermi to Gamow-Teller mixing ratio, which has currently been done for only five medium-mass nuclei of interest. A recent program at the University of Notre Dame's Nuclear Science Laboratory has demonstrated the production of radioactive ion beams of several superallowed mixed mirror transition nuclei, including ^{11}C, ^{13}N, ^{15}O, ^{17}F, ^{23}Mg, and ^{25}Al, and the development of St. Benedict (the Superallowed Transition Beta-Neutrino Decay-Ion-Coincidence Trap), which uses a Paul trap to measure the Beta-Neutrino correlation angle $a_{\beta\nu}$, is underway. In order to trap these isotopes, the fast beam of radioactive ions produced by transfer reactions and separated using the *TwinSol* twin solenoid separator must be thermalized using a large volume gas cell. The ions will then be extracted using a unique RF-funnel based ion guide system, followed by a radiofrequency quadrupole (RFQ) to provide cooled ion bunches for capture in the Paul trap. The design and early commissioning of the Argonne National Laboratory gas cell, RF funnel extraction system, and the RFQ buncher, based on the design used at the National Superconducting Cyclotron Laboratory's BECOLA [3] and EBIT cooler-bunchers, will be presented.

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P3

Electron cooling at the Cryogenic Storage Ring CSR

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In the cryogenic electrostatic storage ring CSR ions are stored at keV energies for hundreds to thousands of seconds in a low-temperature radiation field given by the black-body radiation of the beamline wall at less than 10 K. By this, stored molecular and cluster ions can undergo ro-vibrational radiative relaxation. Measurements probing fundamental molecular and cluster dynamics can be performed with good internal state definition. Electron cooling in the electrostatic storage ring was realized yielding small transverse beam sizes and longitudinal bunch compression. In the CSR electron cooler, cold electrons are produced by a LN_2-cooled GaAs photocathode. Merging of the electrons with the stored ion beam in the cryogenic region is realized by a magnetic guiding field, created by a set of high-temperature superconducting solenoids, toroids and racetrack coils. The CSR electron cooler is designed to reach an electron beam energy as low as 1 eV at an energy spread of about 1 meV. It was succesfully taken into operation in beam times of June 2017 and May 2018. Electron cooling was so far studied for HeH^+, HD^+, O^+ and F^{6+} ions at electron beam energies of about 12-40 eV. For the new regime of low electron energy and density, cooling rates of one to several seconds and equilibrium beam sizes in the few-mm range were observed, holding the promise of realizing cooling of even lower beam energies in future experiments. Studies of longitudinal and transverse electron cooling for these atomic and molecular ions will be presented.

P4

Off-line Commissioning of the University of Notre Dame Multi-Reflection Time-of-Flight Mass Spectrograph

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The production of exotic nuclei at the vicinity of the N = 126 peak of the rapid-neutron capture process as for a long time pose a challenge. A new facility currently under construction at Argonne National Laboratory aims at undertaking the challenge by producing these difficult nuclei via deep-inelastic reactions. The facility will first include a large-volume gas cell to collect and thermalize the reaction products. Then, upon extraction from the gas cell and radio-frequency ion guide, the ion beam will be separated by a high-resolution mass separator magnet and a multi- reflection time-of-flight mass spectrometer (MR-ToF) for the removal of isobaric contamination. This MR-ToF has been built and is being commissioned in an offline test setup at the University of Notre Dame. The commissioning results and off-line performance of the MR-ToF will be presented. This work is supported by the National Science Foundation and the University of Notre Dame.

P5

Design of a Multiple-Reflection Time-of-Flight Mass-Spectrometer for Barium-tagging with nEXO

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The search for neutrinoless double beta decay requires increasingly advanced methods of back- ground reduction. A bold solution to this problem, in experiments using Xenon, is to extract and identify, i.e. tag, the daughter Barium ion produced by double beta decay. Tagging events in this manner allows for a virtually background free verification of a potential neutrinoless double beta decay signal. The Barium-tagging process involves multiple methods of ion transport, trapping and identification, in which the Multiple-Reflection Time-of-Flight Mass-Spectrometer (MR TOF) will perform systematic studies of the ion extraction technique, as well as provide further identification of the Barium isotope. The MR TOF has been adapted such that it has a quickly adjustable mass-range and resolution. Simulations show that the mass-resolving power reaches a maximum of approximately 70000. To improve upon this result, the MR TOF mirror geometry is currently being optimized to correct higher-order time-of-flight aberrations. The status and results of this study will be presented along with an outlook on the proposed Barium-tagging scheme.

P6

Towards CPT Tests with the Molecular Antihydrogen Ion

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High precision radio-frequency, microwave and infrared spectroscopic measurements of the molecular antihydrogen ion $\bar{H}_2^-$ ($\bar{p}\bar{p}e^+$) compared with its normal matter counterpart H_2^+ provide direct tests of the CPT theorem [1]. The sensitivity to a difference between the positron/antiproton and electron/proton mass ratios, and to a difference between the positron-antiproton and electron-proton hyperfine interactions, can exceed that obtained by comparing antihydrogen with hydrogen by several orders of magnitude. Methods are outlined for measurements on a single $\bar{H}_2^-$ ion in a cryogenic Penning trap, that use non-destructive state identification by measuring the cyclotron frequency and bound-positron spin-flip frequency using the continuous Stern-Gerlach effect; and also for creating an $\bar{H}_2^-$ ion and initializing its quantum state. Progress towards implementing these concepts with H_2^+ will also be discussed.

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P7

Single-ion Optical Clock Based on a Sympathetically-cooled Indium Ion

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Among the optical clocks based on trapped ions the indium ion (^{115}In+) is characterized by small black-body radiation shift and negligibly small quadrupole shift of the clock transition ($^1S_0$-$^3P_0$, 237nm). Combined with another advantage of direct quantum state detection using the $^1S_0$-$^3P_1$ transition (230 nm, linewidth 360 kHz), a straightforward extension is expected to a multi-ion clock with enhanced stability without sacrificing small fractional inaccuracies.
As the first step toward the implementation of such a novel optical clock we have measured the clock frequency of an In+ sympathetically-cooled with two calcium ions (^{40}Ca+) in a linear trap. The frequency was determined by averaging 36 sets of spectra taken at low magnetic fields. The value of 1 267 402 452 901 049.1 (6.9) Hz resolved the discrepancy of the previously reported values [1]. The main contribution to the inaccuracy was possible shifts of degenerated spectra due to imperfect control on the magnetic sublevels.
The next step includes two major improvements of the measurement scheme. The first is the application of high magnetic fields to resolve the Zeeman components followed by optical pumping to the stretched states at low magnetic field. This has resulted in well-resolved spectra with 80 Hz linewidth which is 5 time narrower than that of first step measurements. The second is locking of the clock laser to the center of the two Zeeman components. Initial attempts have demonstrated continuous clock operation over 15,000 seconds, which enables faster frequency determination as well as evaluation of the stability. The preliminary frequency value agrees to the first step measurement [1] within the statistical uncertainty. With these two improvements, we expect the inaccuracy and the instability in the order of 10^{-16} level.

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P8

High-Precision Mass Measurements of Highly Charged Xenon Isotopes with PENTATRAP

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High-precision mass measurements with relative uncertainties of 10^{-11} and below have applications, among others, in tests of special relativity [1], bound-state QED [2] and neutrino-physics research [3]. This precision can be reached with Penning-trap mass spectrometry, where the mass of a charged particle is determined by measuring its free cyclotron frequency in a strong magnetic field.

With its first proof-of-principle measurements the novel high-precision Penning-trap mass spectrometer Pentatrap [4] at the Max-Planck-Institut fuer Kernphysik in Heidelberg has recently demonstrated a relative mass precision of $3\ 10^{-11}$ using highly charged ions of different xenon isotopes. Unique features of the setup are the use of electron beam ion traps as external ion sources and of five stacked cylindrical Penning traps [5]. This allows for simultaneous storage and measurement of several ion species, reducing systematic errors. Long storage times due to the cryogenic environment and dedicated image-current detection systems [6] with single ion sensitivity allow for high-precision determination of cyclotron frequencies in all traps.

Subsequent measurements are currently aiming at tests of bound-state QED theory [7] by determining electron binding energies through mass ratios of identical xenon nuclides in consecutive charge states. Furthermore, a direct test of special relativity is planned in collaboration with ILL in Grenoble by investigating the neutron capture process of ^{35}Cl. The mass ratio of ^{35}Cl/^{36}Cl will be precisely determined by Pentatrap, whereas the photon wavelength is determined by means of crystal-Bragg spectroscopy at ILL.

As a member of the ECHo collaboration [8] Pentatrap contributes to the determination of a new upper limit of the electron neutrino mass on the sub-eV level. The precise determination of the Q-value of the electron capture process of ^{163}Ho, provided by Pentatrap as a mass-difference measurement of ^{163}Ho and ^{163}Dy, will be of utmost importance to reduce systematic errors in the analysis of the ^{163}Ho spectrum.

The poster will present a description of the experimental setup of Pentatrap and show the most recent results on xenon masses.

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P9

Precision Mass Measurements in the Rare-earth Region at JYFLTRAP

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The astrophysical rapid neutron capture process (r-process) is responsible for the production of around half of elements heavier than iron. The r-process path lies far away from the valley of stability on the neutron-rich side of the nuclear chart making many r-process nuclei challenging to reach via experiments. Recently, several neutron-rich rare-earth isotopes relevant for the formation of the rare-earth abundance peak in the r-process have been measured at the JYFLTRAP double Penning trap mass spectrometer at IGISOL. The ions of interest were produced using the chemically insensitive ion-guide method and proton-induced fission on uranium. The accelerated and mass-separated ions were cooled and bunched in the RFQ cooler and buncher before purification and mass measurements at JYFLTRAP. Several previously experimentally unknown atomic masses were measured at JYFLTRAP using the time-of-flight ion cyclotron resonance technique. Additionally, precision of several experimentally known atomic masses were improved [1]. The phase-imaging ion cyclotron resonance technique has also been applied for identification of long-living isomeric states. In this contribution, precision mass measurements in the neutron-rich rare-earth region at JYFLTRAP along with the used methods, will be presented.

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P10

Towards Commissioning of a Multi-reflection Time-of-flight Mass Spectrometer at JYFLTRAP

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The Penning-trap mass measurements of exotic isotopes at radioactive ion beam facilities are often limited by the low production rates of the ion of interest, their short half-lives and the amount of isobaric contamination. The multi-reflection time-of-flight mass spectrometer (MR-ToF MS) can overcome most of these limitations with its fast operation mode and its resolving power of 10^5, sufficient for most of the isobars. In order to enhance the capabilities of the JYFLTRAP Penning trap at IGISOL a MR-ToF MS is currently being developed. To operate this device at its full potential the ion bunch delivered by the radio frequency quadrupole (RFQ) cooler and buncher should have an energy spread less than 40 eV and a time-of-flight width below 100 ns. Those requirements can be achieved by modifying the RFQ cooler buncher extraction. Two different extraction modes will thus be available at IGISOL; one with a low energy spread for collinear laser spectroscopy experiments and one with a short time-of-flight spread for mass measurements. The new RFQ bunching section and its commissioning will be presented, as well as the status of the whole MR-ToF MS project.

P11

Precision X-ray Spectroscopy of the 1s Lamb Shift in Hydrogen- like Gold

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The study of the 1s Lamb shift in hydrogen-like systems represents one of the most stringent tests of quantum electrodynamics (QED) for the most fundamental atomic systems. Due to the strong dependence of the Lamb shift on the nuclear charge Z, it is of high interest to test the predictions of QED in the regime of very strong electric fields, such as in hydrogen-like gold (Au^{78+}) or uranium (U^{91+}), where approximations relying on $\alpha Z \ll 1$ are not applicable. The present contribution will focus on most recent efforts with respect to high-precision Lamb shift studies in high-Z systems at the heavy-ion storage ring ESR at GSI, Darmstadt. After several experiments on the 1s Lamb shift in U^{91+}, conducted with conventional semiconductor detectors [3], the twin crystal spectrometer FOCAL has been developed [4] which is the result of a well-balanced trade-off between a high resolving power and detection efficiency. Namely, an acceptable efficiency is needed to operate the crystal spectrometer at an ion storage ring with a luminosity which is low compared to other high intensity x-ray sources like synchrotrons or nuclear reactors. The outcome of the first beam time using the complete two-arm FOCAL spectrometer will be presented. In addition, the development of micro-calorimeters for the x-ray regime, that combine the high resolution typical for crystal spectrometers with the good efficiency of conventional solid state detectors, is expected to open a promising route for precision spectroscopy in high-Z systems [5].

P12

SIPT - An Ultrasensitive Mass Spectrometer for Rare Isotopes

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Precision mass measurements of rare isotopes are needed in almost all areas of nuclear physics research. In particular, mass measurements that will have the greatest impact on nuclear structure and astrophysics require access to isotopes far beyond the valley of stability [1,2]. New accelerator facilities, such as the Facility for Rare Isotope Beams (FRIB), will bring many isotopes of interest within reach. In order to make optimal use of the new facilities, sensitive mass measurement techniques must be developed. For over ten years now, the Low Energy Beam and Ion Trapping (LEBIT) facility at the National Superconducting Cyclotron Laboratory (NSCL) has been performing mass measurements using the most precise method known to date, Penning trap mass spectrometry [3]. The original LEBIT Penning trap uses the traditional time of flight ion cyclotron resonance (TOF-ICR) technique to carry out measurements [4]. While this method is very flexible, it requires a significant number of detected ions (≥100 ions). However, the most exotic isotopes may only be delivered at rates on the order of 1 ion per day, so a different technique must be used to perform mass measurements of isotopes with extremely low rates. To this end, we are developing a new single ion Penning trap (SIPT), which makes use of the non-destructive narrowband Fourier transform ion cyclotron resonance (FT-ICR) technique [5]. This technique relies on a superconducting LC circuit with a high quality factor ($Q > 2000$) to detect the image charge produced on the electrodes of the Penning trap by a single ion. SIPT will enable mass measurements using a single ion with a precision ($dm/m \leq 10^{-6}$) compatible with requirements of nuclear structure and astrophysics studies. SIPT is currently being commissioned and will be fully operational by the end of 2018. The development of SIPT and its key features will be discussed in this presentation.

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P13

Development of a Unique Ion Trapping System to Test the Standard Model of Physics at the Nuclear Science Laboratory

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There are various tests of the Standard Model aimed at probing new physics, such as investigating weak couplings with beta decay. One such test is to check the unitarity of the Cabbibo-Kobayashi-Masakawa (CKM) matrix, with the most precise result given by the normalization of the top row. The precision of this result is limited by the uncertainty of the V_{ud} element. The most precise result for V_{ud} is currently derived from the ensemble of superallowed 0+→0+ decays, but the determination is also desirable for other systems to check theoretical calculations and the potential presence of unknown systematic contributions. Other candidates include neutron decay, pion decay, and the ensemble of mirror decays. While the neutron and pion decay present their own experimental challenges, the group of mirror decays also require the precise determination of the Fermi to Gamow-Teller mixing ratio. This value can be extracted from a measurement of the beta-neutrino angular correlation parameter $\alpha_{\beta\nu}$, and is only currently known for five of the mirror decays. The new ion trapping system, ST. BENEDICT (Superallowed Transition Beta-Neutrino Decay-Ion-Coincidence Trap), to be located in the Nuclear Science Laboratory at the University of Notre Dame is currently under construction and will ultimately aim to extract $\alpha_{\beta\nu}$ for more mirror decays. The focus of this presentation will be on the design of the Paul trap which will be used to perform the correlation measurement.

P14

Towards Electron Cooling of Highly Charged Radioisotopes for Improved Resolution of Nuclear Isomers

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The determination of nuclear masses contributes to a wealth of different physics including nuclear structure studies, fundamental symmetry tests and nuclear astrophysics. The TITAN facility [1] at TRIUMF utilizes a series of ion traps to perform precision mass spectrometry on rare isotopes. The unique combination of an electron beam ion trap charge breeder with a Measurement PEnning Trap (MPET) [2] provides certain advantages. In particular, since the mass resolving power increases with the ion charge state z, the use of Highly Charged Ions (HCI) is especially beneficial to the resolution of low-lying nuclear isomers. This has recently been highlighted in precision mass spectrometry on neutron-rich Cadmium [3] and Indium [4] isotopes at TITAN using the time-of-flight ion cyclotron resonance technique. In this measurement campaign, charge breeding ions to z = 13+ enabled to fully separate several isomers with excitation energies of only a few 100 keV from their respective ground states.

The performance gain arising from the use of high charge states may be mitigated by two factors: higher loss rates of the ion of interest due to charge exchange reactions with residual gas atoms and an increased ion energy spread induced by the charge breeding process. Therefore, several upgrades to the TITAN system are currently underway to further strengthen the attainable mass precision and resolving power of Penning trap mass spectrometry on HCI. These include the addition of a Cooler PEnning Trap (CPET) [5] to improve the beam quality prior to mass measurement. The CPET will perform electron cooling of short-lived HCI. In the trap's 7-Tesla magnetic field electrons rapidly thermalize by cyclotron radiation cooling and form a dense room temperature plasma. HCI injected into the plasma are sympathetically cooled in a series of Coulomb scattering events. Currently, the device is undergoing off-line commissioning in a test stand. In future on-line operation, an efficient cooling cycle will require the rapid preparation of an electron plasma. Therefore ˜10^8 electrons have to be accumulated in a timescale of only a few 100 ms. In order to leave the future ion extraction beamline towards MPET unobstructed electrons have to be injected from an off-axis electron source placed in the CPET's magnetic fringe field. We describe the development of a specialized off-axis electron gun adapted to the high magnetic field environment, its characterization in field-free and strong magnetic field regions, and electron cooling.

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P15

Progress Towards Electron Cooling of Highly Charged Ions at TITAN

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TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN) is pioneering the use of an Electron Beam Ion Trap (EBIT) to charge breed the beams of radioactive ions produced by TRIUMF's Isotope Separator and ACcelerator (ISAC) to high charge states in order to enhance the precision achievable with Penning trap mass spectrometry. The EBIT can also increase the purity of the ion beam, and in some cases, can even populate otherwise unavailable nuclear species through decay and recapture.

However, the high energy electron beam in TITAN's EBIT can introduce an energy spread into the ion bunch on the order of 20 eV, which in turn can negatively impact the experiment. Therefore, a Cooler PEnning Trap (CPET) is presently under development to reduce the energy spread in highly charged ion bunches prior to performing a mass measurement. Recent advances towards the very rapid cooling of singly charged ions (offline) using a cold electron plasma will be presented. The electrons cool by emitting synchrotron radiation in the 7 T magnetic field of the trap. We have successfully demonstrated that these electrons can be made to settle into a 'nested' potential minimum within our trap, which will allow for the simultaneous trapping of electrons with positively charged ions in the future. This requires an increasingly sophisticated potential landscape inside the trap that allows for arbitrarily shaped potentials in order to accomplish this. Additionally, a variety of different charged-particle detection strategies have been implemented to address the unique challenges of single-ion and electron plasma detection in this system. Finally the impact on CPET from the latest studies and upgrade of the EBIT will be discussed.

P16

Penning Trap Mass Spectrometry Q Value Determinations for Investigating Ultra-low Q value β-decays

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Over the last several years there has been growing interest in ultra-low Q value β-decays, in which the parent decays to an excited state of the daughter with a Q value of less than ~1 keV. Interest in such decays was sparked by the discovery of the β-decay of ^{115}In to the 3/2+ first excited state in the daughter ^{115}Sn by Cattadori, et al. [1]. This decay branch was confirmed to be ultra-low with a Q value of 155(24) eV using Penning trap mass spectrometry [2,3]. The identification and study of additional ultra-low Q value candidates is motivated by the fact that they can provide a testing ground for atomic interference effects in nuclear β-decay, and the possibility of identifying candidates for direct neutrino mass determination experiments [1,4,5]. Evaluations of atomic mass and nuclear energy level data have identified ^{115}Cd [6], ^{135}Cs [7], and several additional isotopes as potential ultra-low Q value β-decay candidates [4,5]. We have performed additional studies, which revealed that a number of isotopes including ^{112,113}Ag, ^{89}Sr and ^{139}Ba are also potential candidates. Current atomic mass data for the parent and/or daughter isotopes in these cases are not precise enough to determine whether the ultra-low Q value decay branches are energetically allowed. Here we will present preliminary results for the evaluation of ultra-low Q-value β-decays in ^{112,113}Ag, ^{115}Cd, ^{89}Sr and ^{139}Ba using Penning trap mass spectrometry with the CPT mass spectrometer at Argonne National Laboratory and LEBIT at the National Superconducting Cyclotron Facility.

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P17

Schottky Mass Measurements of Neutron-deficient Xe-Eu Isotopes at the FRS-ESR Facility

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Schottky mass spectrometry (SMS) is a storage-ring based technique for accurate mass measurements of short-lived nuclei at radioactive ion beam facilities. Masses of nuclides with half-lives longer than a few seconds and production rates as tiny as a few ions per day can be addressed. At the FRS-ESR facility at GSI, precision mass measurements of neutron-deficient Ba-Tb isotopes were performed employing SMS. Exotic nuclei were produced via fragmentation of relativistic ^{152}Sm projectiles in a thick beryllium target. The reaction products recoils from target were separated in-flight with the fragment separator FRS, and injected into the storage-cooler ring ESR. Typically, less than one thousand ion were stored and measured simultaneously in the ring. Mass resolving power of 8e$_5$ (FWHM) has been achieved thanks to the powerful electron cooler installed in the ESR. Masses for 10 nuclides (^{94n}Rh, ^{114}I, ^{122,123}La, ^{125}Ce, ^{127}Pr, ^{129}Nd, ^{132}Pm, ^{134}Sm, ^{137}Eu) have been determined for the first time. A typical mass uncertainty of 20 keV could be reached finally. The new masses allow us to uncover a part of the previously unknown mass surface. The impact of new masses on nuclear structure in the neutron-deficient Xe-Eu isotopes will be discussed.

P18

Status of CHIP-TRAP: the Central Michigan University High Precision Penning Trap

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At Central Michigan University we are developing the CHIP-TRAP mass spectrometer with the goal of performing ultra-high precision (˜0.1 – 0.01 ppb) mass measurements on long-lived and stable isotopes. Two science cases on which we are focused are measurements of the ^{35}Cl – ^{36}Cl mass difference, and the ^{163}Ho – ^{163}Dy mass difference. The former, along with the mass of the neutron, will provide a determination of the ^{36}Cl neutron binding energy. This can be compared with high-precision gamma-ray spectroscopy determinations of the neutron binding energy for a direct test of $E = mc^2$. The latter will provide a direct, independent determination of the ^{163}Ho electron capture Q value. This quantity is required for experiments that aim to determine the neutron mass via electron capture spectroscopy of ^{163}Ho.

CHIP-TRAP will consist of pair of hyperbolic precision measurement traps and a cylindrical capture/filter trap housed inside a 12 T superconducting magnet. Ions will be produced with a laser ablation ion source (LAS) for solid targets, and a Penning ionization gauge type ion source for gaseous samples. Ions will be transported to the capture trap at low energy using electrostatic ion optics. Before entering the magnetic field, ions of a given A/q will be selected via their time-of-flight using a Bradbury-Nielsen gate. Inside the capture trap ions will be identified using Fourier Transform Ion Cyclotron Resonance (FT-ICR) techniques, and unwanted ions will be removed using mass-selective rf dipole excitation of their cyclotron motion. The ion of interest will then be transferred to one of the precision measurement traps. Cyclotron frequency measurements will be performed using a phase-sensitive image charge detection technique with single ions. We aim to perform simultaneous cyclotron frequency measurements on pairs of ions stored in the two precision measurement traps. This will result in a cancellation of magnetic field fluctuations to lowest order and an associated reduction in statistical uncertainty.

In this presentation will we describe the design, construction and commissioning of the two ion sources and ion transport beamline and on the overall status of CHIP-TRAP.

P19

Electron-ion Recombination Spectroscopy of Highly Charged Ions at the Heavy Ion Storage Ring CSR

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Dielectronic recombination (DR) experiments of highly charged ions at the storage rings have been developed as a precision spectroscopic tool to investigate the topics from the atomic structure to nuclear properties. DR also plays a crucial role for accurate plasma modeling and spectral analysis in astrophysics. We will present the recent DR experimental results of Be-like Ar^{14+} and Ca^{16+} ions at main Cooler Storage Ring (CSRm) at Heavy Ion Research Facility in Lanzhou (HIRFL) accelerator complex. In addition, strong trielectronic recombination (TR) resonances associated with $2s^2 \rightarrow 2p^2$ core transitions were observed. The plasma rate coefficients for DR+TR of Ar^{14+} and Ca^{16+} were deduced from the measured electron-ion recombination rate coefficients, and compared with calculated data from the literature. In addition, the overview of DR experiments by employing an electron cooler and a separated ultra-cold electron target at the upcoming High Intensity heavy ion Accelerator Facility (HIAF) will be given.

P20

FRS Ion Catcher: Recent Results and Experiments in FAIR Phase-0

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The FRS Ion Catcher experiment at GSI enables precision experiments with thermalized projectile and fission fragments. The fragments are produced at relativistic energies in a target at the entrance of the fragment separator FRS, spatially separated and energy-bunched in the FRS, slowed-down and thermalized in a cryogenic stopping cell. A versatile RFQ beam line and diagnostics unit and a high-performance multiple-reflection time-of-flight mass spectrometer (MR-TOF-MS) enable a variety of experiments, including high-accuracy mass measurements, isomer measurements and mass-selected decay spectroscopy. At the same time the FRS Ion Catcher serves as a test facility for the Low-Energy Branch of the Super-FRS at FAIR.

The performance of the FRS Ion Catcher has been characterized in five experiments with ^{238}U and ^{124}Xe projectile and fission fragments produced at energies in the range from 300 to 1000 MeV/u. High-accuracy mass measurements of more than 40 projectile and fission fragments have been performed with the MR-TOF-MS at mass resolving powers of up to 450,000 with production cross-sections down to the microbarn-level and at rates down to a few ions per hour. A novel data analysis method for mass measurements of rare nuclides with the MR-TOF-MS has been developed, achieving mass accuracies as good as 6×10^{-8} and determining accurate masses of nuclides from as little as ten detected ions. Access to millisecond nuclides has been demonstrated by the first direct mass measurement and mass-selected half-life measurement of ^{215}Po (half-life 1.78 ms). The versatility of the MR-TOF-MS for isomer research has been demonstrated by the measurements of 15 isomers, determination of excitation energies and the production of an isomeric beam. The isotope-dependence of proton-rich indium isomers has been measured.

The latest results will be presented, and an overview of approved experiments to be carried out with the FRS Ion Catcher during FAIR Phase-0 at GSI in the years 2018 and 2019 will be given, including direct mass measurements of neutron-deficient nuclides below ^{100}Sn and neutron-rich nuclides below ^{208}Pb, measurement of beta-delayed neutron emission probabilities and reaction studies with multi-nucleon transfer.

P21

The Search for a Clock Transition in a Solid-state System

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Optical atomic clocks, based on laser-cooled and trapped atoms and ions, have made great advances in precision and accuracy in recent years. Nevertheless, their complexity has so far restricted them to lab-based applications. We have been investigating the use of samarium ions, doped into a host crystal, in order to develop a simple and portable optical atomic clock. The advantages of basing an optical clock on a solid-state transition include greater simplicity (as laser-cooling or trapping are not necessary to confine ions), and potentially much higher signal-to-noise ratios (due to the large number of trapped dopant ions). The challenge is that optical transitions in solid-state systems are usually strongly perturbed by inevitable solid-state effects such as phonons and impurities.

In this talk, I will describe the motivation for pursuing a program of precision solid-state optical spectroscopy in spite of this challenge, and point out the unique properties of samarium-doped crystals that might allow an optical clock transition to survive in a solid. I will describe our progress to date on isolating and driving a highly forbidden transition in samarium-doped strontium fluoride.

P22

Prospects for Laser Spectroscopy Experiments at HIAF

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The High-Intensity Heavy-Ion Accelerator Facility (HIAF) is a new facility planned in China for heavy ion related researches. At HIAF, the radioactive ion beam line will provide variety of short-lived isotopes which are far away from the valley of nuclear stability. Collinear laser spectroscopy (CLS) and resonance ionization spectroscopy (RIS) are being designed and developed to study the hyperfine structure splitting (HFS) and isotope shift (IS) of the neutral atoms and singly- and highly-charged ions.

P23

ARTEMIS: Measuring the Electron Magnetic Moment in Highly Charged Ions via Laser-Microwave Double-Resonance Spectroscopy in a Penning Trap

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The ARTEMIS experiment in GSI Darmstadt aims to precisely measure the magnetic moment of the electron in highly charged ions with laser-microwave double-resonance spectroscopy as the method of choice. The first major phase of the experiment is a proof of principle to be performed on boron-like Ar^{13+} ions stored in a Penning trap at pressures estimated to be as low as 10^{-16} mbar within a 7-Tesla magnetic field. In the first of two connected Penning traps, ion charge-states up to Ar^{16+} are produced via electron impact ionisation. Subsequently, the ion cloud is cleaned to attain a high relative concentration of Ar^{13+} ions, which are then transported to a second Penning trap dedicated to storing the ions for spectroscopy. Storage times of more than 2 weeks are easily achievable, enabling prolonged studies of ion ensemble properties such as cooling behaviour, ion density and ensemble temperature. The results point towards fluid-like behaviour of the ion ensembles.

Measurements are projected to be performed on much heavier ions, such as hydrogen-like Bi^{82+}, extracted from the HITRAP facility at GSI eventually. Results herein would enable fine assessments of the theoretical propositions of bound-state quantum electrodynamics.

P24

Thermometry of a Single Trapped Ion by Imaging

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Free space approach to interaction between light and a single atom relies on tightly focusing the light onto the atom [1]. In such experiments the temperature of the atom gets particularly important when the focal intensity distribution is comparable in width to the spatial wavefunction spread of the trapped atom [2]. In order to quantify the best achievable coupling, it becomes necessary to measure the absolute temperature of the atom. On the other hand, in experiments with trapped ions, another important thermometric figure of merit, in addition to absolute temperature is its heating rate. Over the years, several experiments to measure heating rates have been performed to better understand the origins of anomalous heating [3].Here, we present a technique based on high resolution imaging to measure the absolute temperature, and the heating rate of a single ion trapped at the focus of a deep parabolic mirror. We collect the fluorescence light scattered by the ion during laser cooling, and image it onto an electron-multiplying charge-coupled device (EMCCD) camera. The image recorded on the camera is a convolution of the point-spread function (PSF) of the imaging system, and the spatial probability distribution of the ion. Accounting for the width of the PSF and the magnification of the imaging system, we determine the spatial extant of the ion, from which we infer the mean phonon occupation number in the trap. Further, we perform similar measurements by varying the power or the detuning of the cooling laser. We determine the heating rate by a fit to a well-known theoretical model for laser cooling in a harmonic trap [4]. In other established schemes [5] for measuring the heating rate, the ion is initially heated up to temperatures a few orders of magnitude above the Doppler limit. In contrast, we measure the heating rate with the ion always maintained in a state of thermal equilibrium, at temperatures close to the Doppler limit.

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P25

A Scheme of High-resolution Selection and Identification of Secondary Beams for Mass Measurements at the Rare-RI Ring

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Strong interest in fast, high-accuracy and high-precision mass measurements for exotic nuclides due to their importance in nuclear astrophysics and nuclear structure studies, has triggered the development of a various of techniques for mass measurement around the world. To achieve high precision and accuracy mass measurements of exotic nuclei at the Radioactive Ion beam factory (RIBF), a new technique of mass measurements by complementary Time-of-flight (TOF) methods: Bρ-TOF by bam-line and in-ring isochronous mass spectrometry, are established in one experiment. To realize high accuracy mass measurements by the TOF methods, a scheme of high resolution particle selection and identification of the secondary beams is employed. Exotic nuclei of interest are produced at relativistic energies of a few hundreds MeV/nucleon through projectile fragmentation or in-flight fission nuclear reactions at F0 target of BigRIPS separator. To achieve the selection and separation of mono-isotopic beams to transport to the Rare-RI Ring, BigRIPS separator combined with High-resolution beam-line of SHARAQ (BigRIPS- HA) as a complex accelerator is served as a two-stage separator: the first stage from F_0 to F_2 is used for separation of the nuclei of interest through a Bρ-ΔE-Bρ selection and the second stage from F_3 to S_0 for identification of the beam with a Bρ-ΔE-TOF-E method. With this scheme, all the secondary ions can be well separated on an event-by-event basis and be utilized for mass measurements by the Bρ-TOF method employing the BigRIPS- HA beam-line to measure a exotic nuclide less than 1μs and via the IMS at the Rare-RI Ring. The scheme of selection and identification of secondary beams has been successfully studied in online experiments of projectile fragmentation (primary beam of ^{48}Ca) and in-flight fission (primary beam of ^{238}U) at the Rare-RI Ring in RIBF.

P26

HILITE - An Ion Trap for High-Intensity-Laser Experiments

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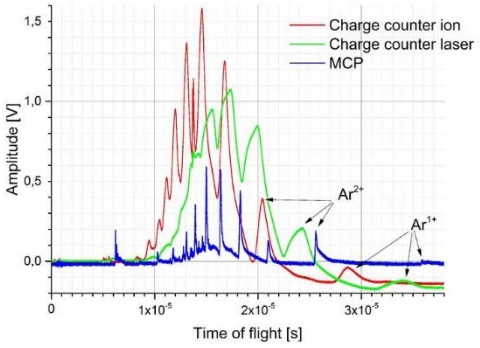
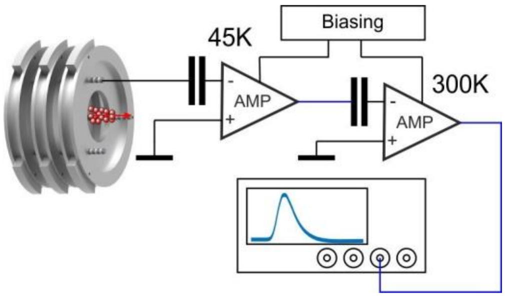
Detailed investigations of high-intensity and high-energy laser-matter interactions require well- defined ion targets and detection techniques for high-sensitivity measurements of reaction educts and products. Therefore, we have conceived, designed and built the HILITE Penning trap [1]. It employs various ion-target formation techniques as well as destructive and non-destructive techniques to analyze the stored species and charge states individually and simultaneously [2]. Our Penning Trap is designed to be transported to different laser facilities in order to cover a wide range of interaction parameters. To be independent from external ion sources we have combined the Penning trap setup with an Electron Beam Ion Source (EBIS), which currently delivers ion species up to He-like ions such as Ar^{16+} with kinetic energies of the order of few thousand electronvolt. For characterization of the incoming and outgoing ion bunches, we use non-destructive single-pass charge-counters optimized for low-energetic ions [3].





We will present the current status of the HILITE experiment and the ion-detection techniques used. We will provide characterization data of the ion deceleration and ion capture, and we will give an outlook to upcoming experiments.

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P27

A Compact RFQ Cooler Buncher for the CRIS Experiment

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The CRIS technique (Collinear Resonance Ionisation Spectroscopy) has been shown to be an efficient method for accessing fundamental nuclear properties of exotic isotopes [1]. It has demonstrated a factor of 100 improvement in sensitivity compared to state-of-the-art fluorescence techniques [2], and achieved an increased resolution and sensitivity compared to existing fluorescence detection based methods [3]. Currently, radioactive ion beams are produced via proton impact with a suitable target at the ISOLDE (Ion separator On-line) facility at CERN. The resulting beam is then trapped, cooled, and bunched using the ISCOOL RFQ cooler buncher following mass separation. The ion bunches are then directed through a charge exchange cell for the purpose of neutralisation via interactions within an alkali vapour. The beam of atoms is then collinearly overlapped with multiple pulsed laser fields. This enables Doppler-free measurements of atomic hyperfine structure, leading to the determination of model-free nuclear properties such as nuclear spins, magnetic and electric quadrupole moments, and isotopic variations in the nuclear mean square charge radii. These measurements are essential for unlocking physics beyond the standard model as precision laser spectroscopy provides robust observables for testing and validation of theoretical models [4]. For example, dark matter detection, neutrino oscillations and neutrinoless double beta decay all require accurate determination of the associated nuclear matrix elements. We envisage significant improvements to the technique following the installation of an independent RFQ cooler buncher as an alternative to ISCOOL. This would reduce set up times prior to time constrained experiments at the ISOLDE facility. It would enable constant optimisation of beam transport and quality. It would also trivialise switching from an exotic beam to a stable reference isotope from our independent offline ion source. Spatial limitations at CRIS require that an alternative RFQ cooler buncher is compact. However, SIMION calculations estimate that our prototype can perform with a comparable efficiency to ISCOOL, in terms of transport efficiency and energy spread reduction. Testing of the device is being conducted using an offline Ga ion source at the University of Manchester and this presentation will cover its progress in addition to the previous highlights of the CRIS experimental program.

P28

Penning Trap Mass Spectrometry at the LEBIT Facility and Measurement of ^{56}Cu to Determine the Redirection of the rp-process flow

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The Low-Energy Beam and Ion Trap (LEBIT) facility [1] at the National Superconducting Cyclotron Laboratory (NSCL) is the only facility that utilizes Penning trap mass spectrometry for precision mass measurements of rare isotopes produced via projectile fragmentation. The 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 for a variety of exotic nuclei. Recent LEBIT measurements have been focused on nuclear astrophysics. One example is the recent mass measurement of ^{56}Cu in order to constrain the reaction rates of the ^{55}Ni(p,γ) ^{56}Cu(p, γ) ^{57}Zn(β+) Cu bypass around the ^{56}Ni waiting point [2]. The new value, ME = 38626.7(7.1) keV, was used to show that the *rp*-process flow redirects around the ^{56}Ni waiting point through the ^{55}Ni(p, γ) route. This route allows nuclei to proceed to higher masses more quickly and results in a reduction in ashes around the ^{56}Ni waiting point and an enhancement to higher-mass ashes.

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P29

Precision Mass Measurements of ^{44}V and ^{44m}V for NN Interaction Studies

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Isospin symmetry is an approximate symmetry between protons and neutrons in atomic nuclei; it offers an elegant framework for nuclear physics calculations and eloquently frames several tests of nuclear structure models. The Isobaric Multiplet Mass Equation (IMME) estimates the nuclear mass excess of isobaric analogue states (of fixed atomic mass number, A) as a function of the isospin projection, $T_Z = (N-Z)/2$, where N and Z are neutron and proton number, respectively. IMME parameters provide a powerful interface between theory and experiment, testing charge- dependent, isospin symmetry breaking (ISB) nucleon-nucleon (NN) interactions. Additionally, these parameters provide empirical mass values of exotic nuclei, often inaccessible by direct measurement, for nuclear reaction rate network codes. Nuclear shell model codes are successful in reproducing the experimental IMME parameters by implementing ISB NN interactions up to A≈40 (*sd*-shell); however, such success has not been reached for heavier multiplet cases (*fp*-shell). ^{44}V is well positioned to offer insight, as its poorly known mass suggests improbable IMME parameters in the A=44 multiplet. ^{44}V is a short-lived radioisotope and ^{44}V production capability must be paired with sufficiently precise mass measurement systems – the most stringent tests of the IMME require $\delta m/m \approx 10^{-8}$. The National Superconducting Cyclotron Laboratory (NSCL) paired with the Low-mEnergy Beam and Ion Trap facility (LEBIT) Penning trap system meet both isotope production and mass precision requirements for a precision measurement of ^{44}V. In April 2018, ^{44}V and its low-lying isomer state ^{44m}V were produced at NSCL and masses measured using the Time-of-Flight Ion-Cyclotron-Resonance method at LEBIT. Results are in preparation, and are anticipated to be presented.

P30

Ion Trapping Developments at the University of Notre Dame

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In the past decades ion trapping technique has been used in a large variety of applications aiming to address questions going from the synthesis of isotopes heavier than iron to the testing of the weak interaction within the Standard Model. Two different ion traps in different phase of developments are being constructed at the University of Notre Dame to address these questions. First, a multi-reflection time-of-flight mass spectrometer (MR-ToF) has been developed for the future N = 126 beam factory of Argonne National Laboratory. This facility will aim at producing exotic nuclei at the vicinity of the N = 126 peak of the rapid-neutron capture process via multi-nucleon transfer reactions. The MR-ToF will be used to remove isobaric contaminants with a resolving power of around 50,000 before sending the beam to various experimental stations including the Canadian Penning Trap for high-precision mass measurements and a decay station for life-time measurements. The off-line commissioning of the MR-ToF at Notre Dame will be presented. The second project is an ion trapping system called St-Benedict (Superallowed Transition Beta-Neutrino Decay-Ion-Coincidence Trap), which will be installed after the TwinSol facility of the Nuclear Science Laboratory of Notre Dame. St-Benedict aims at measuring the beta-neutrino angular correlation parameter in superallowed mixed mirror decays to test the weak interaction. St- Benedict will include a gas catcher to stop the fast beam from TwinSol, followed by an RF funnel system, an RFQ cooler and buncher, and a Paul trap. An update on the development of this project will be given.

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P31

A Lutetium-ion Optical Atomic Clock

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Singly-ionized lutetium is a promising optical clock candidate with several advantageous properties [1] and suitable for multi-ion clock schemes [2]. The overall systematic sensitivities compare favourably with other leading clock candidates. Notably, the $^1S_0$ to $^3D_1$ transition was recently found to have the lowest blackbody radiation sensitivity of all active clock candidates [3]. Lu^+ is unique in having multiple high quality clock transitions: from the $^1S_0$ ground state to the $^3D_1$, $^3D_2$, and $^1D_2$ metastable states. A new scheme for clock calibration using the frequency ratios of these transitions is proposed. We report results of recent efforts to evaluate systematic shifts in the Lu^+ clock: specifically, dynamic polarizability measurements, AC-Zeeman shifts, and AC-Quadrupole shifts. In the case of ac magnetic fields, a simple experimental method for their characterization is presented [4], which is of direct relevance to many high precision measurements in ion traps
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P32

Towards Parts Per Trillion Mass Measurements on Light Nuclei at LIONTRAP

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The precise knowledge of the atomic masses of various light nuclei, e.g. of the proton, deuteron, helion and triton are of great importance for several tests of fundamental physics. For example, the mass of the proton itself and the mass ratio of the electron and the proton are important input parameters for a couple of experiments in atomic physics. Furthermore, an essential consistency check of the KATRIN experiment will require an ultra-precise measurement of the mass difference of triton and helion on a so far inaccessible level of precision of 6 meV or smaller [1]. However, five sigma discrepancies between high-precision measurements of these light nuclear masses question their current literature values [2] and give strong motivation for a new and independent experiment: the LIONTRAP (Light ION TRAP) experiment, aiming for relative uncertainties of a few parts per trillion. The new setup contains a cryogenic stack of five cylindrical Penning traps enclosed in a hermetically sealed vacuum chamber. The measurement principle is based on a non-destructive phase-sensitive comparison of the cyclotron frequency of the single particle of interest to the cyclotron frequency of a single bare carbon nucleus. In order to measure both frequencies in the same electric and magnetic field configuration, both single ions are transported alternately into an ultra-harmonic, doubly compensated Penning trap. Using the same electric field configuration for both ions with different charge/mass ratio necessitates two separate, precisely tuned axial resonators for non-destructive frequency detection. To overcome the statistically limiting magnetic field fluctuations, simultaneous phase-sensitive measurements are planned in neighbouring traps. At this conference, the new LIONTRAP setup including a variety of novel techniques and improvements will be introduced. Furthermore, first results on the atomic mass of the proton will be presented. This new proton mass value is 3 times more precise than the current literature value and reveals a disagreement of about 3 standard deviations to it [3].

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Tune-out Wavelength for the 1s2s ^{3}S State of Helium: D-wave and Nite Wavelength Corrections

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At present there is a nearly 2σ disagreement between theory and experiment for the tune-out wavelength of helium near 413 nm. The tune-out wavelength is the wavelength at which the frequency dependent polarizability of an atom vanishes. It can be measured to very high precision by means of an interferometric comparison between two beams 1, and it provides a novel test of QED for an atomic property other than the energy. The 413 nm transition is the one closest to the 1s2s ^{3}S 1s3p ^{3}P transition of ^{4}He.
The purpose of this paper is to present new results for electric quadrupole and finite wavelength corrections to the dominant electric dipole polarizability. Previous high precision calculations [2,3] have taken into account relativistic, QED and finite nuclear size effects, but higher multipole and finite wavelength effects have not yet been taken into account. These are the same α2 order of magnitude as the relativistic corrections, and so may well account for at least part of the discrepancy.
The basic expression for the frequency-dependent polarizability is

$$\alpha_d(\omega) = 2\sum_n \frac{\Delta E(n)|\langle 2\,^3S \mid \hat{e}\cdot\vec{r} \mid n\,^3P\rangle|^2}{\Delta E(n)^2 - (\hbar\omega)^2}$$

where $\Delta E(n)$ is the virtual excitation energy $\Delta E(n) = E(n\,^3P)\ E(2\,^3S)$, ω is the laser frequency, and the sum includes an integration over the continuum. The sum over intermediate states was efficiently accomplished by the use of pseudostates generated by diagonalizing the Hamiltonian in a discrete variational basis set consisting correlated Hylleraas-type functions. The operator is just the leading term in the power series expansion of a plane wave. Assuming that the wave is propagating in the x-direction and polarized in the z-direction, the expansion is

$$ze^{ikx} = z(1 + ikx - (kx)^2/2 + \cdots)$$

where k = ω/c is the wave number of the incident laser. The term $ikxz$ generates quadrupole transitions to intermediate n^3D states in place of the n^3P states in Eq. (1), and the term $z(kx)^2/2$ generates a finite wavelength correction to the leading dipole term of the form $z[1\ (kr)^2/10]$. In addition, there is a relativistic correction to the tensor polarizability due to a mixing of the 2^3S_1 state with n^3D_1 states via the Breit spin-spin interaction [3] This has not been taken into account previously, except in the static field limit.
The results are shown in Table 1 as a series of corrections to the tune-out wavelength. Although the finite wavelength and D-wave spin-spin mixing effects are small, the quadrupole polarizability correction of 0.001 813 nm is substantial, and it significantly decreases the disagreement between theory and experiment to within 1σ. The theoretical value is now 413.091 83(1) nm, in comparison with the measurement 413.093 8(9_{stat})(20_{sys}) [1]. However, all these effects are large compared with the QED corrections of order α3 and higher, and must be taken into account before a precision test of QED can be made.
Comparisons will also be made with previous high-precision calculations for the helium ground state [4,5].
This paper is part of a joint theoretical / experimental project with K. Baldwin et al. (Australian National University) [1] and L.-Y. Tang et al. (Wuhan Institute of Physics and Mathematics) [2] to perform a high precision comparison between theory and experiment as a probe of atomic structure, including relativistic and quantum electrodynamic effects.

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The Line Shape of Time-of-flight ion-cyclotron-resonance Mass Spectroscopy with Highly Charged Ions

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In the time-of-flight ion-cyclotron-resonance (ToF-ICR) technique of Penning trap mass spectroscopy (PTMS) the interaction with residual gas alters the line shape. The most striking effect is an incomplete recovery of the initial state between the central and neighboring conversion extrema. Introducing a drag force (damping) reproduces the observed changes as has been discussed for the case of singly charged ions (SCI) [1,2]. The use of highly charged ions (HCIs) in PTMS offers a variety of new opportunities especially for rare isotopes [3-6] and a similar change of the line shape has been observed. There are clear indications, that the effect originates from residual gas interactions as well (for instance it was not observed at even better vacuum conditions [7]). However, the mechanism must be different in the case of HCIs as they exhibit a much larger charge exchange (CX) probability [8]. Additionally a SCI is neutralized in a CX reaction and escapes the trap, making this process effectively invisible. In contrast a HCI remains trapped with a decremented charge, but at this instant the coherent drive by the quadrupole excitation used in ToF-ICR to convert magnetron into reduced cyclotron motion becomes ineffective. A drag force does not seem adequate to capture this situation in the derivation of the line shape. This contribution describes how a simplified line shape for ToF-ICR with HCIs including the effect of charge exchange can be obtained. The following solution for the ratio of the final reduced cyclotron radius to the initial magnetron radius is obtained when assuming a velocity independent CX cross section and ignoring effects from the Coulomb explosion and the trapped residual gas ions in general:

$$\left(\frac{\mathrm{R}_+(\tau_{int})}{R_-(0)}\right)^2 = \frac{1-e^{-\kappa}[\cos(\pi \mathrm{x})+(\kappa/\pi \mathrm{x})\sin(\pi \mathrm{x})]}{2x^2[1+(\kappa/\pi \mathrm{x})^2]},$$

where $x = \sqrt{1+(\delta/\omega_\mathrm{R})^2}$ is a function of the detune δ in units of the Rabi frequency ω_R and $\kappa = \tau_\mathrm{int}/\tau_\mathrm{CX}$ is the ratio of the interaction time τ_int and the charge exchange lifetime. This equation simplifies to the conventional solution for large τ_CX (or $\kappa \rightarrow 0$): $R_+(\tau_\mathrm{int})/R_-(0) = \sin(\tfrac{1}{2}\pi x)/x$.

The result shows that a mechanism different from a drag force is capable of describing qualitatively the observed effects on the line shape. Remaining deviation from experimental data might result from the simplified assumptions mentioned before. Numerical investigations will be required to include the velocity dependence of the CX cross sections and the energy exchange between the charge decremented HCI and the ionized residual gas.

Finally the consequences for the precision on the central frequency of the resonance obtained from a fit are analysed based on the methods described by Posener [9], thereby setting a more general framework for the definition of a quality factor in ToF-ICR PTMS [10].

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Mass measurements with the Canadian Penning Trap mass spectrometer for studies of the astrophysical r process

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The origin of the elements in the universe is still not clearly understood. About half of the elements, heavier than iron (^{56}Fe) are believed to be produced via the r process (rapid neutron capture process), which is thought to occur during explosive astrophysical events. Due to the short-lived nature of these nuclides and the unique conditions necessary for the occurrence of the r process, our knowledge of this topic is limited. Observations from the recent gravitational wave event (GW170817) and its electromagnetic counterpart at LIGO and VIRGO have reported evidences of neutron star mergers being possible r -process sites. But exactly where the r process occurs in the merging neutron star environment, and whether merging neutron stars can alone account for all the r -process elements are still open questions. Building theoretical models and making reasonable predictions about this r process rely on the availability of nuclear data for nuclides near the expected r -process path like the nuclide masses, binding energies, neutron capture rates and beta-decay characteristics, with reduced uncertainties. Currently there is very little data available for these neutron rich nuclides due to the challenges in producing the rare isotope beams (RIB) necessary for such experiments. With the recent development of a number of advanced RIB facilities, the situation has improved. One such facility is the CAlifornium Rare Isotope Breeder Upgrade (CARIBU), at the Argonne National Laboratory (ANL), which uses the spontaneous fission of a ^{252}Cf source to produce beams of neutron rich isotopes. The fission fragments are collected and stopped in a gas catcher cell and extracted as an ion beam. The beam undergoes initial purification by passing through a magnetic dipole isobar separator and then gets bunched in a Radio-Frequency Quadrupole (RFQ) buncher. Next, the beam passes through a Multi-Reflection Time-of-Flight (MR-TOF) isobar separator, which enables us to achieve a mass resolving power (i.e. $R=m/\Delta m$) in excess of 100,000. The mass resolved beams are then sent to the Canadian Penning Trap (CPT) mass spectrometer located at the low-energy experimental area of CARIBU. An upgrade to the CPT detection system allowed for the implementation of the novel detection technique, Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR), which permits us to make mass measurements faster and with improved resolution, compared to the traditional Time-Of-Flight Ion-Cyclotron-Resonance (TOF-ICR) method. This enables us to measure masses of weakly produced neutron-rich isotopes nearer to the r-process path without loss of precision. Recently, a number of rare-earth, neutron-rich nuclides have been measured to ~12 keV precision. The results are consistent with the masses needed to reproduce the solar abundance pattern in the rare-earth region for a hot, neutron star merger wind scenario, as determined by reverse engineered Markov Chain Monte Carlo simulations.

My poster will describe the production of RIB at CARIBU, the mass measurement technique implemented at the CPT and a status report including some of our recent result

INTERNET

Wireless Internet access is available to all participants in the Park Place Hotel and Conference Center.
In the hotel, connect to “Park-Place-Hotel” – No password is required.
In the conference center, connect to “PPH Conf“ – Password: Traverse300

USEFUL INFORMATION

Transportation

The Park Place Hotel offers a shuttle that can be scheduled by speaking with the hotel front desk.

Bay Area Transportation Authority (BATA) www.bata.net; Local busses with many different routes via a FREE city loop route.

Taxis:

Cherry Capital Cab	+1-231-941-8294
About Time Transportation	+1-231-660-3514
Dan's Airport Transportation	+1-231-645-9696

Emergency Phone Numbers

Police	911
Fire	911
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Hospitals and Urgent Care Facilities in Traverse City

- Munson Medical Center - 1105 6th Street, +1-231-935-5000
  Emergency Room, open 24 hours;
  1.4 miles from conference venue
- Bayside Docs Urgent Care - 400 Munson Ave, +1-231-933-9150
  Open 9 a.m.-7 p.m. Monday -Friday, 10 a.m.-5 p.m. Saturday-Sunday, no appointment needed;
  2 miles from conference venue
- Munson Urgent Care - 550 Munson Ave, +1-231-935-8686
  Open 7 a.m. -10 p.m. daily, no appointment needed;
  2.3 miles from conference venue

Banking and Currency Exchange

The currency used in the United States is the U.S. dollar ($). Exchange offices are located in the airports. Banks and ATMs are well distributed throughout the Traverse City area.

Lost and Found
A lost-and-found service will be available at the conference registration desk as well as the hotel registration desk.

REGISTRATION

Hours and Location
The registration desk will be open at the following times.

Day	Times
Sunday, 30 September	4 p.m.-8 p.m.
Monday, 1 October	8 a.m.-5 p.m.
Tuesday, 2 October	8 a.m.-7:30 p.m.
Wednesday, 3 October	8 a.m.-12 p.m.
Thursday, 4 October	8 a.m.-5 p.m.
Friday, 5 October	8 a.m.-12:30 p.m.

Your registration fee includes entry to all technical sessions of the workshop, morning and afternoon coffee daily, an abstract book, a souvenir, and the following social events:

- Welcome Reception (Sunday, 30 September)
- Poster Session (Tuesday, 2 October)
- Conference Outing (Wednesday, 3 October) – box lunch provided
- Conference Banquet (Thursday, 4 October)
- NSCL/FRIB Tour (East Lansing, Saturday, 6 October)

Security and Insurance
Participants are advised not to leave their belongings unattended. The conference organizers cannot accept liability for personal injuries sustained or for loss or damage to participants’ (or companions’) personal property during the conference.

Conference Nametags
Participants are asked to wear their nametag during all TCP2018-sponsored events.

Luggage Storage
Your hotel may provide luggage storage for their guests on arrival and departure days.

SOCIAL PROGRAM AND FRIB SITE TOUR

Summary of Events

Date	Event	Venue
Sunday, 30 September	Welcome Reception	Top of the Park
Tuesday, 2 October	Poster Session	Grandview II
Wednesday, 3 October	Conference Outings	Varies
Thursday, 4 October	Conference Banquet	City Opera House
Saturday, 6 October	FRIB/NSCL Tour	East Lansing, MI

Transportation will be provided for the Conference Outings and for the FRIB/NSCL Tour from Traverse City to East Lansing one-way ONLY.

Social Events

Sunday, 30 September [6 p.m.-9 p.m.]
Welcome Reception
The welcome reception will be held at the "Top of the Park" located on the 10th floor of the Park Place Hotel. The "Top of the Park" is the perfect place to take in a Traverse Bay sunset.

Tuesday, 2 October [5:30 p.m.]
Poster Session
The poster session will be held in the Grandview II room at the Park Place Hotel. Appetizers and light refreshments will be available.

Wednesday, 3 October [1 p.m.]
Conference Outings
For all outings, a boxed lunch will be provided.
All outings will depart from the Park Place Hotel.

Thursday, 4 October [6 p.m. cocktails, 7 p.m. dinner]
Workshop Banquet
The banquet will be held at the City Opera House (106 East Front Street, Traverse City, Michigan 49684, +1 (231) 941-8082). The City Opera House is a 7-minute walk from the Park Place Hotel. Transportation will not be provided.

Saturday, 6 October
FRIB/NSCL Tour.
Transportion from Traverse City to East Lansing (one-way) can be provided.
Please note the following:

- Photos, videos, bags, food or beverages, high-heel shoes, open-toed shoes and sandals, and minors under the age of 16 are not allowed on the tour route.
- All visitors must wear long pants (no shorts, capris, or dresses).

SCIENTIFIC PROGRAM LOGISTICS

Oral Presentations

Oral presentations will be held in room Grandview I.

Presentation slides should be provided as PowerPoint or pdf files for smooth operation.
Speakers are asked to identify themselves to the chairperson of the session and upload the final version of their talk during the preceding coffee break.
We will not have the capability for speakers to use their own laptop.

Poster Presentations

The poster session will be held on Tuesday, 2 October.
Poster specifications - Poster boards are designed for maximum poster size 48” high x 36” wide. Poster boards will hold two posters per side per board.

The oral presentation and poster listing in this book of abstracts is current as of printing and may not reflect late changes.

INDUSTRIAL EXHIBITION

Hours and Location

The Industrial Exhibition booths are located in the Grandview II room at the Park Place Hotel.

Exhibit hours:

Monday, 1 October	9 a.m.-5 p.m.
Tuesday, 2 October	9 a.m.-5 p.m.
Wednesday, 3 October	9 a.m.-12 p.m.
Thursday, 4 October	9 a.m.-5 p.m.

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