Stored Particles Atomic Physics Research Collaboration

SPARC

Topical Workshop 2017

11-14 September 2017, Caen, France

sparc2017.sciencesconf.org

Program and Abstracts

	Sunday 10th	Monday 11th		Tuesday 12th		Wednesday 13th		Thursday 14th	
08:30 - 09:30		Registration							
09:30 - 10:00		Opening	Rangama Alahari Cassimi Guibellino Schuch/Stoehlker	SPARC Experimental Proposals	Litvinov Bruno Bruno	Theory	Fritzsche Aleksandrov Bondarev Glazov Zubova	SPARC Instrumentation	Brandau Fleischmann Spiellmann
10:00 - 10:30									
10:30 - 11:00		Coffee break		Coffee break		Coffee break		Coffee break	
11:00 - 11:30		Status of GSI and FAIR Facilities	Lestinski Braeuning-Demian Winters Sanchez	SPARC Experimental Proposals for 2018-2019	Brandau Schippers Bernitt Braeuning-Demian Winters Busmann	Astrophysical, Biomolecular ans Surface Applications	Tribedi Agnihotri Lalande Kumar Mattei	International Landscape: Atomic Physics Activities Related to SPARC	Bagnoud Müller Fléchard Juhász
11:30 - 12:00									
12:00 - 12:30									
12:30 - 13:00								Closing speech	Schuch/Stoehlker
13:00 - 14:00		Lunch		Lunch		Lunch		Lunch	
14:30 - 15:00		International Landscape: Atomic Physics Activities Related to SPARC	Santos Indelicato Banas Ullmann	SPARC Experimental Proposals for 2018-2019	Sanchez Hagmann Hagmann Quint Petridis Rothhardt	Excursion to Château Du Breuil		Visit of GANIL/SPIRAL2 Facilities (limited to 45 visitors)	
15:00 - 15:30									
15:30 - 16:00									
16:00 - 16:30	Welcome Cocktail Registration	Coffee break							
16:30 - 17:00		International Landscape: Atomic Physics Activities Related to SPARC	Ringleb Benis Stöhlker	Coffee break					
17:00 - 17:30				SPARC Experimental Proposals	Weber Trassinelli Surzhykov				
17:30 - 18:00									
18:00 - 18:30				Poster session + Cocktail					
18:30 - 19:00		Collaboration meeting : Funding situation				Free Time			
19:00 - 19:30			Schuch			Group Picture			
19:30 - 20:00						Conference dinner			
20:00 - 21:00		SPARC Board Meeting							

Overview

The purpose of the workshop is to present and discuss the current status of the SPARC collaboration, facilities and the related instrumentation at the international FAIR facility. In addition, the workshop aims to provide a forum for the SPARC community for the presentation and discussion of all aspects of atomic physics with highly-charged ions and related fields.

The workshop will cover the following topics:

- Atomic Collisions with Highly Charged Ions
- Critical and Super-critical Fields
- Laser and X-ray Spectroscopy
- Cross-link between Atomic and Nuclear Physics
- CRYRING: Status and Instrumentation
- HESR: Status and Instrumentation
- HITRAP: Status and Instrumentation
- APPA cave: Experiments and Instrumentation
- SPARC Relevant International Facilities
- Status SPARC Collaboration
- Beam times in 2018/2019 and the Research Program FAIR-Phase-0

Organisers

Chairs

- Jimmy Rangama, CIMAP, CNRS (Caen, France)
- Reinhold Schuch, Stockholm University (Stockholm, Sweden)
- Thomas Stöhlker, GSI and Helmholtz Institute Jena (Jena, Germany)
- Angela Braeuning-Demian, GSI and FAIR GmbH (Darmstadt, Germany)

Local Organizing Committee

- Stéphane GUILLOUS, CIMAP, Caen
- Alexandre GUMBERIDZE, GSI, Darmstadt
- Vishant KUMAR, CIMAP, Caen
- Mathieu LALANDE, CIMAP, Caen
- Christiane MALOT, CIMAP, Caen
- Alain MERY, CIMAP, Caen
- Jean-Christophe POULLY, CIMAP, Caen
- Christophe PRIGENT, INSP, Paris
- Hermann ROTHARD, CIMAP, Caen
- Martino TRASSINELLI, INSP, Paris
- Violaine VIZCAINO, CIMAP, Caen

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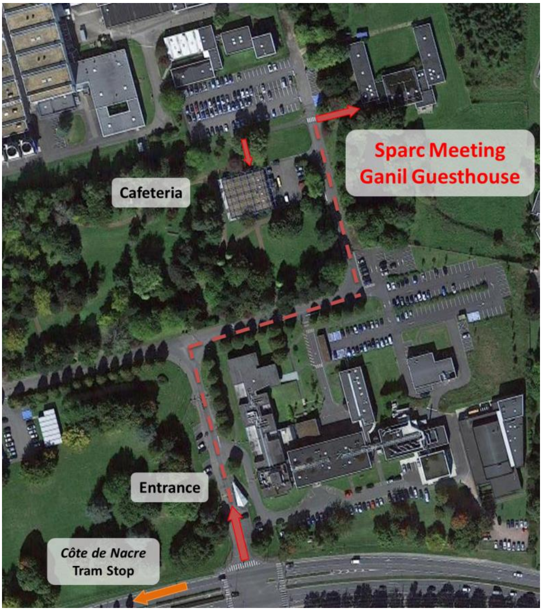
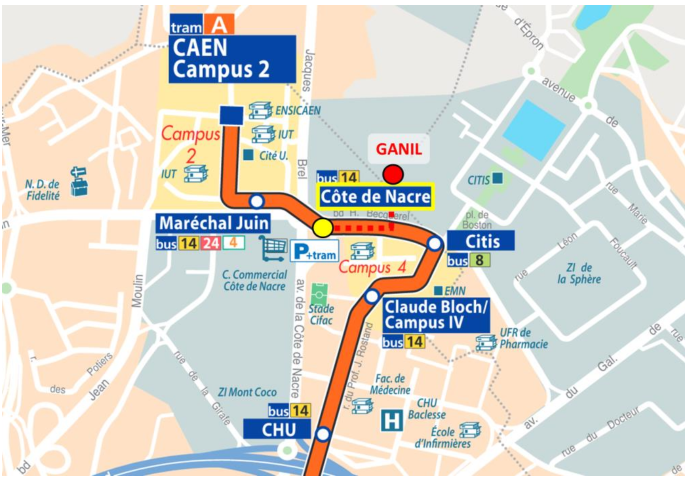
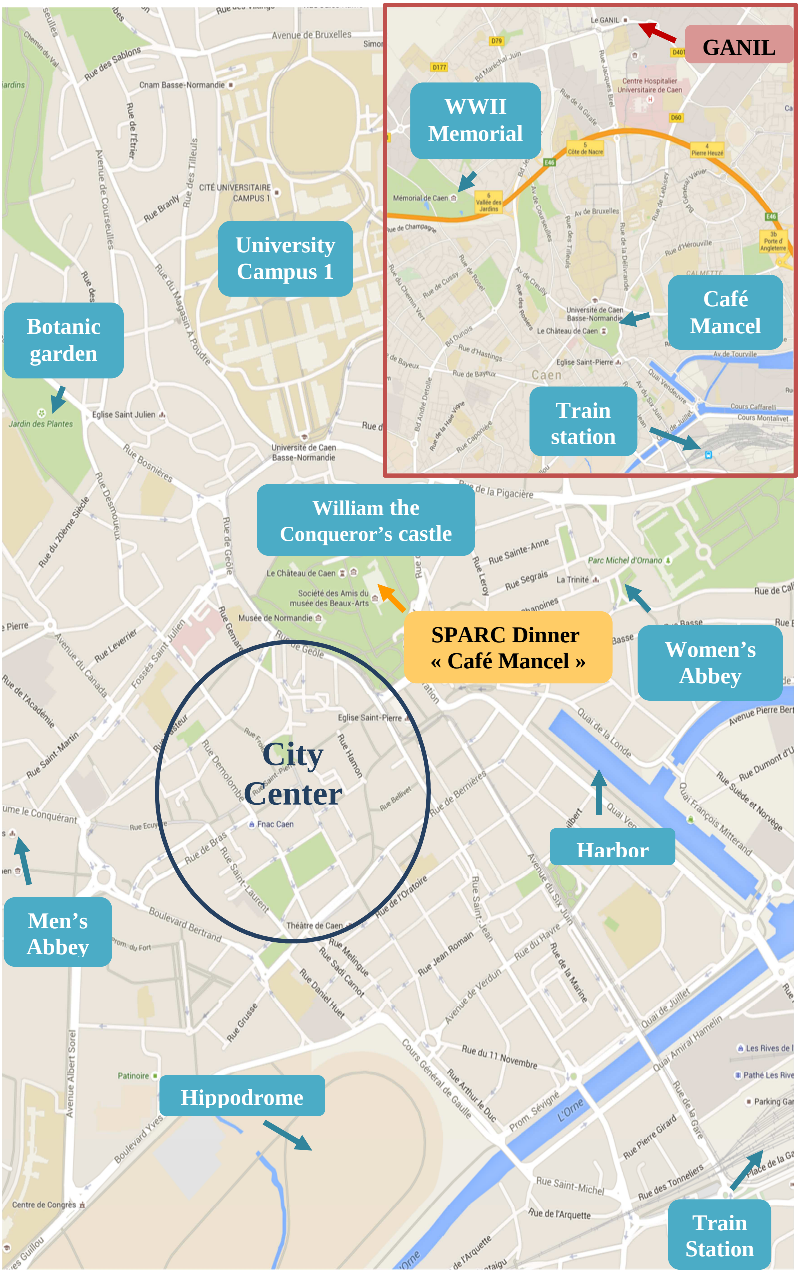




City map


GANIL
WWII Memorial
University Campus 1
Café Mancel
Botanic garden
Train station
William the Conqueror's castle
SPARC Dinner « Café Mancel »
Women's Abbey
City Center
Harbor
Men's Abbey
Hippodrome
Train Station

Social Program

Wednesday 13th September at **14h30**: Visit of Château du Breuil, a Calvados distillery.

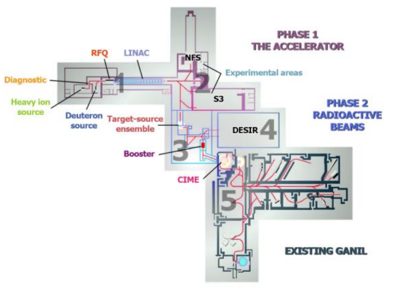
The apple is the basic ingredient to make quality Calvados. The mild and damp weather and clayed soil of the Pays d'Auge give the Château du Breuil ideal growing conditions for its 22,000 apple trees which surround the castle. The Château du Breuil company produces its own cider, coming from a 100% natural fermentation. Their know-how and experience are the strengths of the Château du Breuil which gives priority to high quality rather to quantity. When cider has reached its proper flavour, distillation can start...

Wednesday 13th September at **19h30**: conference dinner at Café Mancel restaurant.

The Café Mancel is located inside the Ducal Castle. It is in a quiet courtyard in front of a delightful garden. Very peaceful surroundings (a simple contemporary setting with a green terrace), a place full of history (it was a princely residence during the reign of William the Conqueror), a dynamic cultural policy (Beaux-Arts Museum and the Museum of Normandy) and above all a creative cookery that reinvents the Norman terroir (foie gras terrine and apples candied with Calvados liqueur).

Thursday 14th September at **14h**: visit of GANIL/Spiral 2 facilities.

SPIRAL2 is the result of the technical and scientific teamwork established between several French, European and international laboratories. Such a large-scale project requires a well-structured, methodical and efficient organization. GANIL works with its partner laboratories in order to achieve a common objective: to delve even further into the mysteries of nuclear physics research. SPIRAL 2 is thus an international project with great promise.



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Scientific Program

Sunday, September 10th

Time	
16h00 – 20h00	Welcome Cocktail - Registration

Monday, September 11th

Time			Duration
8h30	Registration - Inscription for the visit of GANIL/SPIRAL 2 facilities		60’
Opening / Welcome Session Chairperson: J. Rangama			
9h30	Welcome Speech	**J. Rangama** CIMAP	5`
9h35	Welcome Speech	**N. Alahari** GANIL	10+5`
9h50	Welcome Speech	**A. Cassimi** CIMAP	10+5`
10h05	GSI/FAIR	**P. Giubellino** GSI/FAIR	15+5`
10h25	SPARC	**R. Schuch or T. Stöhlker** Univ. Stockholm	15+5`
10h45	Coffee break		
Status of GSI and FAIR Facilities Chairperson:			
11h20	Commissioning of CRYRING@ESR	**M. Lestinsky** GSI, Darmstadt	20+5’
11h45	APPA cave, a multipurpose experimental area for atomic and plasma physics, materials science and biophysics at FAIR: a status report	**A. Braeuning-Demian** GSI, Darmstadt	20+5’
12h10	Status of the SIS100 / Laser cooling	**D. Winters** GSI, Darmstadt	20+5’
12h35	Status of the HESR	**R. Sanchez** GSI, Darmstadt	20+5’
13h00	Lunch		

International Landscape: Atomic Physics Activities Related to SPARC Chairperson:			
14h30	**High-precision measurements of n=2 → n=1 transition energies and level widths in He- and Be-like argon ion**	**J.P. Santos** Univ. of Lisbon	**25'+5'**
15h00	**Tests of QED in few-electrons highly charged ions: status and perspectives**	**P. Indelicato** LKB, ENS, UPMC	**25'+5'**
15h30	**Interaction of slow highly charged Xe^{q+} ions (q = 15 - 40) with metallic surfaces**	**D. Banas** Univ. of Kielce	**20'+5'**
15h55	**Recent developments from hyperfine spectroscopy experiment at the ESR**	**J. Ullmann** GSI	**20'+5'**
16h20	**Coffee Break**		
Chairperson:			
16h50	**HILTE – High intensity laser experiments on stored ions**	**S. Ringleb** Univ. of Jena	**20'+5'**
17h15	**On the production of the 1s2s2p 2,4 P states in collisions of 0.5-1.25 MeV/u He-like mixed (1s2 1S, 1s2s 3S) ionic states with gaseous targets**	**E. Benis** Univ. of Ioannina	**20'+5'**
17h40	**APPA R&D – BMBF collaborative research in Germany**	**T.Stöhlker** Univ. Stockholm	**20'+5'**
Collaboration Meeting			
18h05	**Funding Situation: International and National, Common Funds, Status Reports, "BMBF Verbundforschung"**	**R. Schuch**	**90`**
19h35	**SPARC Board Meeting**		**60`**

Tuesday, September 12th

Time			Duration
SPARC Experimental Proposals for 2018-2019 **Chairperson:**			
9h30	**Measurement of the bound-state beta decay of bare 205Tl ions**	**Y. Litvinov** GSI, Darmstadt	**15`+5`**
9h50	**Nuclear astrophysics & atomic physics techniques**	**C. Bruno** Univ. of Edinburgh	**15`+5`**
10h10	**Measurements of proton-induced reaction rates on radioactive isotopes for the astrophysical p process**	**C. Bruno** Univ. of Edinburgh	**15`+5`**
10h30	**Coffee Break**		
Chairperson:			
11h00	**Dielectronic Recombination of Low-Energy Nuclear Isomers: Towards Storage Ring Studies of the Nuclear Clock' Nucleus 229Th**	**C. Brandau** Univ. of Giessen	**15`+5`**
11h20	**Precision DR collision spectroscopy of Be-like ions at the CRYRING@ESR electron cooler**	**S. Schippers** Univ. of Giessen	**15`+5`**
11h40	**Trapped Highly Charged Ions Interacting with X-rays**	**S. Bernitt** Max Planck Society	**15`+5`**
12h00	**Energy determination of the 1s2 2s1/2 → 1s2 2p3/2 radiative transition in Li-like uranium ions via resonant coherent excitation in crystal**	**A. Braeuning-Demian** GSI, Darmstadt	**15`+5`**
12h20	**Laser spectroscopy of the (1s22s2p) 3P0 - 3P1 level splitting in Be-like krypton**	**D. Winters** GSI, Darmstadt	**15`+5`**
12h40	**Optimizing the laser-ion interaction during laser cooling, using novel pulsed and cw laser systems**	**M. Bussmann** GSI, Darmstadt	**15`+5`**
13h00	**Lunch**		

SPARC Experimental Proposals for 2018-2019 Chairperson:			
14h30	**Dielectronic Recombination-assisted laser spectroscopy: A new tool to investigate the hyperfinepuzzle in $Bi^{80+,82+}$**	**R. Sanchez** GSI, Darmstadt	**15`+5'**
14h50	**Double-differential cross sections for electron emission in collisions of highly-charged ions with gaseous targets**	**S. Hagmann** GSI, Darmstadt	**15`+5`**
15h10	**Electron Emission following 1s Adiabatic Ionization and Quasi-resonant 1s-1s Charge Transfer in Symmetric Heavy-Ion Atom Collisions**	**S. Hagmann** GSI, Darmstadt	**15`+5`**
15h30	**Cooling and precision spectroscopy of 209Bi82+ ion ensembles with the ARTEMIS and SPECTRAP experiments at the HITRAP facility**	**W. Quint** GSI, Darmstadt	**15`+5`**
15h50	**Investigation of novel light phenomena observed for the first time during interaction of highly charged ions with a liquid droplet beam**	**N. Petridis** GSI, Darmstadt	**15`+5`**
16h10	**Photoionization of C+ ions at CRYRING**	**J. Rothhardt** HIJ	**15`+5`**
16h30	**Coffee Break**		
SPARC Experimental Proposals for 2018-2019 **Chairperson:**			
17h00	**The Ground-State Lamb Shift in the Heaviest Hydrogenlike Ion (U91+): High Resolution X-ray Spectroscopy at the CRYRING electron cooler**	**G. Weber** HiJ	**15`+5`**
17h20	**High-resolution differential Measurements Between Two-and Three-Electron Uranium Ions for High-Precision Tests of Strong-Field QED**	**M. Trassinelli** INSP	**15`+5`**
17h40	**Scattering of relativistic vortex electrons**	**A. Surzhykov** PTB	**15`+5**
18h00	**Poster Session + Cocktail**		

Wednesday, September 13th

Time			Duration
Theory **Chairperson:**			
9h30	**Nuclear excitation by two-photon electron transition**	**S. Fritzsche** Univ. of Jena	**15'+5'**
9h50	**Electron-positron pair production in colliding laser pulses**	**I. Aleksandrov** SPSU	**10'+5'**
10h05	**Relativistic approach for calculations of differential ionization cross sections in ion-atom collisions**	**A. Bondarev** SPSU	**10'+5'**
10h20	***g* factor of medium-*Z* lithium-like ions**	**D. Glazov** SPSU	**10'+5'**
10h35	**Relativistic calculations of X-Ray transition energies and isotope shifts in heavy atoms and ions**	**N. Zubova** SPSU	**10'+5'**
10h50	**Coffee Break**		
Astrophysical, Biomolecular and Surface Applications **Chairperson:**			
11h20	**PAH molecules and e-emission enhancement in collisions with halouracil**	**L. Tribedi** TIFR	**15'+5'**
11h40	**Radiation effects in astrophysical ices and biomolecules**	**A. N. Agnihotri** CIMAP	**15'+5'**
12h00	**Irradiation of isolated collagen mimetic peptides and triple-helix models by different ionizing projectiles: keV ions, MeV ions, VUV and X-ray photons**	**M. Lalande** CIMAP	**15'+5'**
12h20	**Studying the fragmentation dynamics and possible geometry of CO molecular clusters**	**V. Kumar** CIMAP	**15'+5'**
12h40	**Investigation of the structural and chemical order in nanomaterial through transmission electron microscopy**	**J.-G. Mattéi** CIMAP	**15'+5'**
13h00	**Lunch**		
14h30	**Excursion to Château Du Breuil**		
18h30	**Free Time**		
19h15	**Group Picture at Cafe Mancel**		
19h30	**Conference Dinner at Cafe Mancel**		

Thursday, September 14th

Time			Duration
SPARC Instrumentation **Chairperson:**			
9h30	**Recent Developments on the CRYRING Transverse Electron Target**	**C. Brandau** Univ. of Giessen	**15'+5'**
9h50	**Magnetic microcalorimeters: status**	**A. Fleischmann** GSI, Darmstadt	**15'+5'**
10h10	**Detector development**	**U. Spiellmann** GSI, Darmstadt	**15'+5'**
10h30	**Coffee Break**		
International Landscape: Atomic Physics Activities Related to SPARC **Chairperson:**			
11h00	**Plasma physics at FAIR**	**V. Bagnoud** GSI, Darmstadt	**15'+5'**
11h20	**Kinetic Energy Release measurements at the electrostatic Frankfurt Low Energy Storage Ring**	**J. Muller** Institut für Kernphysik	**15'+5'**
11h40	**Electron shake-off induced by nuclear beta decay of trapped radioactive ions**	**X. Fléchard** LPC	**15'+5'**
12h00	**Emission of anions from molecular species following cation impact**	**Z. Juhász** MTA Atomki	**15'+5'**
12h20	**Closing speech**	**R. Schuch or T. Stöhlker** Univ. Stockholm	**30'**
13h00	**Lunch**		
14h00	**Visit of GANIL/SPIRAL2 Facilities**		
17h00	**End of the Workshop**		

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Oral Communications

Commissioning of CRYRING@ESR.

M. Lestinsky[1], F. Herfurth[1], Z. Andelkovic[1], A. Bräuning-Demian[1,2], S. Fedotova[1], W. Geithner[1], G. Vorobjev[1], and Th. Stöhlker[1,3,4],

[1] *GSI Helmhotzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*

[2] *FAIR GmbH, Planckstr. 1, 64291 Darmstadt, Germany*

3 Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany

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CRYRING@ESR is the first new installation of the upcoming FAIR facility. The former Swedish low-energy heavy-ion storage ring was transported to Darmstadt, modernized and installed downstream from ESR. The combined facilities give an unprecedented access to intense beams of highly charged ions in isotopically pure, well defined quantum states. This will enable e.g. research on slow collision processes in atomic and nuclear domains and precision spectroscopy in the strong field regime [1]. Furthermore, new materials research and biophysics with very heavy ions in the energy range where the kinetic and the potential energy have equal contributions become feasible using CRYRING@ESR.

Presently, we are commissioning the system using a local 300keV RFQ-injector beamline. First 1.5 turns of ions could be traced on the beam diagnostics elements. We are preparing all systems for regular operation for the upcoming beamtime periods in 2018/19. We will summarize the project goals, the expected future performance, our progress and report on the ongoing preparations for first experiments.

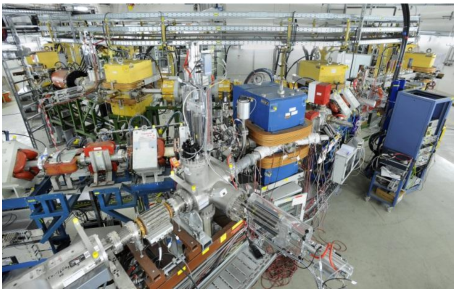

Figure 1: CRYRING@ESR in December 2016 with both injector beamlines.

References:

1 Physics book: CRYRING@ESR: *M. Lestinsky, Y. Litvinov, Th. Stöhlker (eds.) Eur. Phys. J Spec. Top.* 225 (2016), 797-882

APPA cave, a multipurpose experimental area for atomic and plasma physics, materials science and biophysics at FAIR: a status report

A. Braeuning-Demian[1,2]
[1] *GSI-Helmholzzentrum für Schwerionenforschung, Darmstadt, Germany*
[2] *FAIR GmbH, Darmstadt, Germany*
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A dedicated experimental area, the APPA cave was designed and is in construction at FAIR for a board range of single–pass experiments for atomic and plasma physics, materials science and biophysics with highly relativistic heavy ions. The cave will accommodate different experiments using fast and slow extracted ion beams from the two FAIR synchrotrons, SIS18 and SIS100. Beams of all stable elements, from hydrogen to uranium with the highest charge states, highest intensities and energies from 200 MeV/u up to 10 GeV/u will be available for a large variety of experimental investigations committed to give answers to questions related to ion-mater interactions in simple atomic systems, warm dense plasma as well as in macroscopic systems as biological molecules and bulk materials.
This report will give insights into the cave layout, status of the planning, construction and testing of the different installations as well as on the time scale for realization.

Laser cooling and spectroscopy at GSI/FAIR.

D. Winters[1], O. Boine-Frankenheim[1,2], M. Bussmann[3], A. Buß[4], C. Egelkamp[4], L. Eidam[2], V. Hannen[4], Z. Huang[5], D. Kiefer[2], S. Klammes[2], Th. Kühl[1,6], M. Loeser[3,7], X. Ma[5], F. Nolden[1], W. Nörtershäuser[2], R. Sanchez[1], U. Schramm[3,7], M. Siebold[3], P. Spiller[1], M. Steck[1], J. Ullmann[2,6,8], Th. Walther[2], H. Wang[5], W. Wen[5], D. Winzen[4], and Th. Stöhlker[1,6,8]

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[2]*Technische Universität Darmstadt, Germany*
[3]*Helmholtz-Zentrum Dresden-Rossendorf, Germany*
[4]*Westfälische Wilhelms-Universität Münster, Germany*
[5]*Institute of Modern Physics-CAS, Lanzhou, China*
[6]*Helmholtz Institut Jena, Germany*
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Although laser cooling is best known from atom and ion traps, where the particles almost have no kinetic energy at all, it can also be applied to ions traveling at almost the speed of light. There, laser cooling has proven to be a viable technique to reduce the longitudinal phase space volume of bunched ion beams. Moreover, the fluorescence emitted from the ions, due to deexcitation of the laser-excited cooling transition, can serve as a powerful tool for atomic physics, *e.g.* for spectroscopy of fast transitions in highly charged ions, but also as a versatile diagnostic that can be complimentary to standard, charge-based diagnostic techniques. Laser cooling and spectroscopy are planned for the GSI/FAIR facilities: CRYRING, ESR, HESR and SIS100, in order of increasing ion beam energy. We will present the current status of laser cooling, and show some results from beam times at the ESR (GSI, Darmstadt, Germany), and the CSRe, (IMP, Lanzhou, Cina).

References:

1 *D. Winters et al., Phys. Scr. T166 (2015) 014048.*
2 *T. Beck et al., DIO 10.1364/OL.41.004186*
3 *M. Siebold et al., DOI 10.1002/lpor.201600063*
4 *D. Winzen et al., GSI scientific report 2016.*

Laser spectroscopy and status of the SPARC-setup at HESR.

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In this paper I provide a brief overview on the current developments of the infrastructure for the laser spectroscopy experiments and the status of the SPARC setup at the High-Energy Storage Ring (HESR) at FAIR.

High-precision measurements of n=2 → n=1 transition energies and level widths in He- and Be-like argon ions

J. P. Santos[1], J. Machado[1,2], C. I. Szabo[3], P. Amaro,[1] M. Guerra[1], A. Gumberidze[4], Guojie Bian[2,5], J. M. Isac[2], P. Indelicato[2]

[1]Laboratório de Instrumentação, Engenharia Biomédica e Física da Radiação (LIBPhys-UNL), Departamento de Física, Faculdade de Ciências e Tecnologia, FCT, Universidade Nova de Lisboa, 2829-516 Caparica, Portugal
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We present the recent high accuracy transition energies and widths measurements of highly charged ions, using a Double-Crystal Spectrometer (DCS) [1] connected to an Electron-Cyclotron Resonance Ion Source (ECRIS) [2].

We have performed reference-free measurement of the transition energy of the 1s2p $^1P_1$ → $1s^2$ $^1S_0$ line in He-like argon, and of the $1s2s^22p$ $^1P_1$ → $1s_22s^2$ $^1S_0$ line in Be-like argon ions with accuracy better than 3 ppm, using a double flat-crystal spectrometer, without reference to any theoretical or experimental energy. The widths of these transitions have been also measured.

The $1s2s^22p$ $^1P_1$ → $1s^22s^2$ $^1S_0$ transition measurement is the first reference-free measurement for this core-excited transition. On the other hand, the 1s2p $^1P_1$ → $1s^2$ $^1S_0$ transition measurement confirms recent measurements. For both measurements, we find agreement with the most recent theoretical calculations within the combined theoretical and experimental uncertainties. Two Li-like argon transitions have been also measured and its analysis is ongoing.

We intend to extend the performed accurate transition energy measurements [3] to other ions and species (Ar, Kr, K and S) aiming accuracy better than 2 ppm with the improvement of the DCS experimental apparatus, in particular a better control of the crystals temperature and verticality. With an accuracy of few ppm, this experimental method can be used to probe and test QED effects, and provide new and more reliable X-ray standards in the few keV energy region.

References:

1 P. Amaro, et al. Radiation Physics and Chemistry, 98(C), 132–149 (2014)
2 A. Gumberidze, et al. Review of Scientific Instruments, 81(3), 033303 (2010).
3 P. Amaro, et al. Phys. Rev. Lett. 109, 043005 (2012).

Tests of QED in few-electrons highly charged ions: status and perspectives

P. Indelicato[1]
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For 50 years, many experiments have been performed to measure transition energies in few electron ions. The experiment have used laser generated plasma, beam-foil spectroscopy, highly-charged ion sources like Electron-Beam Ion traps or Electron-cyclotron resonance ion source, and storage rings. Emphasis will be made on reference-free measurements[1-6], which provide improved tests. Available experimental results of transition energies in 2, 3 and 4 electron systems, including core-exited ones (dielectronic satellites) are reviewed. Comparison with the most recent theoretical calculations will be shown.

References:

1 P. Amaro, S. Schlesser, M. Guerra, et al., Phys. Rev. Lett. **109**, 043005 (2012).
2 C. I. Szabo, P. Amaro, M. Guerra, et al., in *CAARI* (AIP, Fort Worth, Texas, 2013), Vol. 1525, p. 68.
3 K. Kubiček, P. H. Mokler, V. Mäckel, et al., Phys. Rev. A **90**, 032508 (2014).
4 K. Kubiček, P. H. Mokler, J. Ullrich, et al., Physica Scripta **2013**, 014005 (2013).
5 K. Kubiček, H. Bruhns, J. Braun, et al., Journal of Physics: Conference Series, 012007 (2009).
6 H. Bruhns, J. Braun, K. Kubiček, et al., Phys. Rev. Lett. **99**, 113001 (2007).

Interaction of slow highly charged Xe^{q+} ions (q=15-40) with metallic surfaces

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Slow single charged ions interacting with solid surfaces dissipate their kinetic energy mainly by nuclear collisions which results in, e.g. defect creation and erosion of material from the surface [1]. Slow (in keV energy range) highly charged ions (HCI) are characterized by their additional high, as compared to their kinetic energy, coulombic potential energy, which is the consequence of removing of many or even all electrons from a neutral atom. This conditions provide unique opportunity for formation the so-called "hollow atoms" in the process of fast neutralization of HCI close to surfaces. In these exotic atoms a large part of the electrons are in high Rydberg levels while the inner shells remain empty. Such highly excited atoms quickly decay by Auger electron and x-ray emission. Consequently, their potential energy is deposited in a small volume close to the surface, eventually leading to potential sputtering and nanostructure formation [2].
In this work we present results of experiments performed at the Kielce EBIS facility (Jan Kochanowski University, Kielce, Poland) [3]. In these experiments X-rays emitted in interaction of ~8 keV×q Xe^{q+} ions (q=15-40) with metallic surfaces of Be, Au, Ti and Ta and modifications caused by the Xe^{q+} ions on the Au and Ti surfaces were studied.
The X-rays measured for different charge states of Xe^{q+} ions were interpreted as the M-x-ray transitions corresponding to different multivacancy configurations, including both x-ray satellites and hypersatellites. The energies of these transitions were calculated using the multiconfiguration Dirac-Hartree-Fock (MCDHF) approach by the GRASP2K code [4]. Consequently, predictions of the classical over-the-barrier model (OBM) describing the neutralization of HCI at surfaces were tested experimentally. For Xe^{26+} ions with no M-shell vacancies expected the observed M X-rays may indicate more complex electronic structure of these ions or the internal dielectronic excitation process [5].
We will also present nanostructures (hillocks) created by the HCI on the Au and Ti metallic surfaces [6]. Formation of such structures by HCI on metallic surfaces has not been expected and observed before. The topographic atomic force microscopy (AFM) images of the surfaces unmodified and irradiated by the ion beams will be shown. Statistical analysis of the height and volume distributions of the modifications created by HCI impact will be presented and possible mechanism of the nanostructures creation will be discussed.

Acknowledgements
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RECENT DEVELOPMENTS FROM HYPERFINE SPECTROSCOPY EXPERIMENT AT THE ESR

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While quantum electrodynamics (QED) is usually referred to as the most accurately tested theory, its validity for electrons in very strong fields is still not tested with high accuracy. The strongest magnetic fields available in the laboratory are experienced by electrons in the ground-state of highly charged heavy ions which can be probed by hyperfine spectroscopy. Even though the ground state hyperfine transition in hydrogen-like bismuth was observed already in 1994 [1], the significance of the experiment as a test for QED was limited by the unknown magnetic moment distribution inside the nucleus. However, it was suggested that a so-called specific difference between the hyperfine splittings in hydrogen-like and lithium-like ions of the same isotope can be used to cancel nuclear structure effects and provide an accurate test of QED [2]. The transition in Li-like Bismuth was observed for the first time in 2011 at the Experimental Storage Ring ESR located at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt [3]. Yet the accuracy of the result was limited by the calibration of the electron cooler voltage, determining the ion velocity. Here, we report on improved laser spectroscopic measurements of the hyperfine splittings in hydrogen- and lithium-like bismuth ions ($^{209}Bi^{82+}$ and $^{209}Bi^{80+}$) at the ESR. The accuracy was improved by about an order of magnitude compared to the first observation in 2011 [3]. The most important new feature was an *in-situ* high voltage measurement system with an accuracy at the 10-ppm level provided by German metrology institute Physikalisch-Technische Bundesanstalt. We will present the experimentally determined value for the specific difference in ^{209}Bi, which deviates by more than 7σ from theory. A possible cause for this might be a wrong nuclear magnetic moment. The preliminary results of a remeasurement of the nuclear magnetic resonance in bismuth will be presented as well.

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On the production of the 1s2s2p ^{2,4}P states in collisions of 0.5-1.25 MeV/u He-like mixed (1s^{2} ^{1}S, 1s2s ^{3}S) ionic states with gaseous targets.

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Single electron capture (SEC) observed in collisions of fast He-like ions delivered in mixed (1s^{2} ^{1}S, 1s2s ^{3}S) states with gaseous targets has recently received attention. Various secondary processes, such as dynamic Pauli exchange mechanism[1] and/or selective cascade feeding[2], have been proposed to explain the measured ratio R_m=σ(1s2s2p ^{4}P) / σ(1s2s2p ^{2}P) of transfer cross sections which has been reported to be 3-4 times larger than the expected spin statistics value of 2[2,3]. An important parameter in the evaluation of R_m is the accurate determination of the effective solid angle for the detection of the long-lived ^{4}P state, which is crucial in the interpretation of the data. Recently, we have published a study on the effective solid angle, based on Monte Carlo simulations within the SIMION8.1 ion optics simulation package, for our zero-degree Auger projectile spectroscopy (ZAPS) experimental setup[4]. At the heart of the setup is our hemispherical spectrograph which is equipped with an entry zoom lens and a 2-D position sensitive detector. In addition, we have also reported on a new technique for obtaining R_m that utilizes two independent measurements of the *same* projectile Auger spectrum, but having different 1s2s ^{3}S metastable fraction[5]. Typical spectra obtained using this method are shown in Fig. 1. Our new technique allows for the determination of R_m even in cases when it is not possible to obtain a *pure* ground state He-like ion beam, as required in older methods[1].

Our final results are not in agreement with earlier reports on C^{4+} ions[1] and indicate that our R_m values are close to the statistical value of 2. Details of our calculations and measurements will be presented.

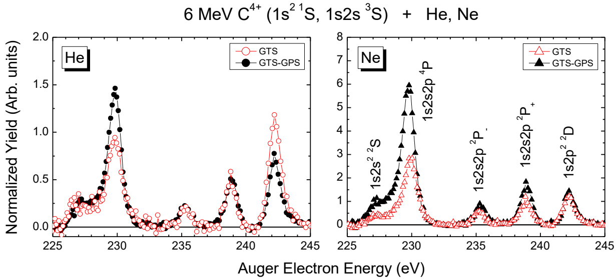

Figure 1: C^{4+} (1s2l2l′) Auger electron spectra obtained in collisions of mixed state 6 MeV C^{4+} (1s^{2} ^{1}S, 1s2s ^{3}S) ion beams with He and Ne gas targets. The ionic beam state can be delivered in different mixture percentage depending on the stripping method, i.e. direct gas terminal stripping (GTS) inside the Tandem Van der Graff accelerator or GTS followed by post-stripping in gas targets (GTS-GPS). The latter results in a higher percentage of the 1s2s ^{3}S metastable component, as evident from the enhancement of the 1s2s2p ^{4}P peak for both He and Ne targets.

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Dielectronic Recombination of Low-Energy Nuclear Isomers: Towards Storage Ring Studies of the 'Nuclear Clock' Nucleus ^{229}Th

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An application for beam time at the storage ring ESR of GSI has been submitted to the General Program Advisory Committee (G-PAC) of GSI. In the application we propose to investigate the radioisotope $^{229(m)}$Th and its low-lying nuclear isomer utilizing the resonant atomic process of dielectronic recombination (DR) [1]. The presence of the isomer will be detected due to a change of the hyperfine structure in the DR resonance pattern. The present proposal is part of an accepted GSI Letter of Intent that describes a full research program with ^{229}Th using DR. Parts of the program can be found in [2].^{229}Th is an exceptional nucleus as it is the only known candidate with a nuclear transition that might be accessed with standard table-top lasers. According to the most recent result [2] the nuclear transition is E_γ = 7.8eV but the value is debated. After more than 30 years of heavily disputed and failed attempts (cf. [3-5] and references therein) to prove the existence or to deduce stringent boundaries on the properties of the ^{229}Th, only recently the transition was directly observed by means of detection of conversion electrons [3]. Yet, besides the sheer existence of the state not many of its properties are known. The outstanding feature of such a low lying nuclear excitation energy renders $^{229(m)}$Th the key ingredient for a long list of striking experiments and applications. In particular, ^{229m}Th is considered as a new nuclear optical frequency standard [4,5]. Such a precision 'nuclear clock' can be exploited in many ways, e.g. for improved length and time standards, but also for very fundamental experiments at the limits of our present understanding of physics. More than 100 publications (cf. e.g. [2–5], and references therein) propose such applications or suggest new effects for ^{229m}Th that could not be observed so far. With the proposed experiment at the ESR we pursue several goals:

- Evidence the isomer signature ^{229m}Th in the hyperfine structure of the DR resonance spectra and thus to establish storage ring studies of the isomer.
- Explore fundamentals properties of the isomer such as the nuclear radius, hyperfine splitting or the lifetime of the undisturbed γ-transition using DR as a detector
- Pave the way for second generation experiments that use the DR signature as a detector or intensity monitor, e.g., for studies of laser excitation or with a gas-target, of electron bridge processes, or nuclear excitation by electron capture, of DR-assisted separation of isomers and/or the extraction to the HITRAP or CRYRING facility [1].

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Precision DR Collision Spectroscopy of Be-like Ions at the CRYRING@ESR Electron Cooler

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In this talk our joint proposal on beamtime for a dielectronic recombination (DR) experiment with heavy Be-like ions at the CRYRING@ESR electron cooler will be presented. The proposal has been submitted to the next GSI's General Program Advisory Committee (G-PAC) that decides on the experimental program at GSI/FAIR in the years 2018/19.
It is planned to perform high-resolution dielectronic recombination (DR) collision spectroscopy of heavy Be-like ions with $Z \geq 54$ at CRYRING@ESR. The ultra-cold beam of the CRYRING@ESR cooler promises very high experimental resolution and precision for DR collision spectroscopy that is unprecedented for such very heavy few-electron ions [1,2].
CRYRING@ESR will be one of first new experimental installations that will become operational at FAIR. This new storage ring features an ultra-cold electron-cooler which we will use as a target for electron-ion collision studies [1,2]. The very low temperature of electron beam [3] allows one to measure DR resonances with a resolving power that is an order-of-magnitude higher as compared to the conditions at the ESR electron cooler [1, 3-5]. Such high-resolution studies have been performed at the CRYRING at its original installation at the Manne-Siegbahn-Laboratory in Stockholm [4,5] as well as at the TSR storage ring in Heidelberg [6] albeit with much lower-charged ions than available at GSI/FAIR.

With the proposed experiment we pursue several goals:

- Commissioning and performance tests of the new DR collision setup at the CRYRING@ESR cooler with few-electron heavy ions from the ESR.
- Precision spectroscopy of Be-like heavy ions as test of bound-state strong-field QED and relativistic atomic theories.
- Preexaminations and development towards a measurement of the two-photon E1M1-lifetime associated with the $1s^2\ 2s\ 2p\ ^3P_0 \rightarrow 1s^2\ 2s^2\ ^1S_0$ transition [7-9]

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Energy determination of the $1s^2\ 2s_{1/2} \rightarrow 1s^2\ 2p_{3/2}$ radiative transition in Li-like uranium ions via resonant coherent excitation in a crystal

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A poof of principle of spectroscopic measurements in relativistic, heavy, highly-charged ions using the technique of resonant coherent excitation (RCE) in crystals has been demonstrated with Li-like uranium ions delivered by the GSI accelerator facility. Using Si-crystals of different thicknesses (7µm, 2.5µm and 1µm effective thickness) and cooled ion beams delivered by the ESR, the resonance spectrum was measured with improved shape and width. The resonance profile is a symmetric Lorenzian with a width of 1.4 eV at a transition energy of 4.459 keV. The precise determination of the transition energy was limited in the previous measurements mainly by the uncertainty in the determination of the initial beam velocity. Based on the electron energy measurement in the ESR electron cooler, made with a precision of $1x10^{-4}$, the value of the measured transition energy could be determined with a systematic uncertainty of about 0.5 eV. Our beam time application for the FAIR phase-zero program, proposes a new measurement of the same transition with the goal to improve the accuracy of the transition energy to a few ppm by a more precise determination of the ion beam energy. To realize this goal we will use a new voltage divider with a precision in the range of 10 ppm for an in situ measurement of the ESR electron cooler voltage and we will apply a direct measurement of the value of the space charge effect of the e-cooler current on the ion velocity.

In addition, for a quantitative understanding of the resonance process and excitation probabilities we propose to try the non-channeling RCE (3D-RCE) which has the great advantage of removing the dependence of the channeling trajectory on the different physical phenomena in the target.

Dielectronic Recombination-assisted laser spectroscopy: A new tool to investigate the hyperfine-puzzle in $Bi^{80+,82+}$

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We propose to establish dielectronic recombination (DR)-assisted laser spectroscopy to improve the sensitivity of hyperfine structure measurements in lithium-like heavy ions by orders of magnitude and make it also applicable for more species. In a first step we want to establish the new detection scheme using the stable isotope ^{209}Bi. After a test of production and injection of $^{208}Bi^{80+;82+}$ into the ESR, the technique will be applied to this isotope. Measuring the hyperfine splitting in both charge states will provide a value for the so-called specific difference, where we have recently reported a discrepancy between QED calculations and experiment by 8-σ, which constitutes a hyperfine puzzle.

Electron Emission following 1s Adiabatic Ionization and Quasi-resonant 1s-1s Charge Transfer in Symmetric Heavy-Ion Atom Collisions

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In very heavy symmetric and highly adiabatic collisions the dynamics of excitation and ionization of electrons in innermost molecular orbitals is best studied by measuring the impact parameter (b) dependence of projectile electron continua and characteristic target K-Auger electron emission and target K-x ray emission following K- shell to K- shell charge transfer. This powerful technique is highly attractive, first, because differential transfer cross sections are even comparable to the elastic cross sections, and second, because the strong oscillations observed in the impact parameter dependent K-vacancy production probability P(b) for lower Z quasi-symmetric collision systems[1,2] are related to the energy difference $E_{1s\sigma}(R)$-$E_{2p\sigma}(R)$, R=internuclear separation, for innermost molecular orbitals |1sσ> and |2pσ> during the collisions.

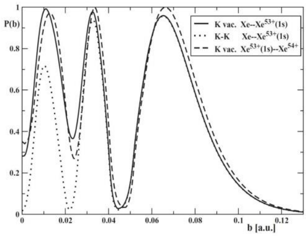

Figure. 1 Comparison of fully relativistic ab-initio calculations [3] for K vacancy production and 1s to 1s charge transfer in 3.6 AMeV Xe^{53+}(1s) + Xe.

Motivated by recent ab initio fully relativistic calculations of K-shell to K-shell charge transfer and K- vacancy production in high Z and very high Z symmetric collision systems by the Shabaev group [3] we will measure the resonant K-shell to K-shell charge transfer in the ESR storage ring for the first time for H-like and bare projectiles like $Xe^{53+, 54+}$, i.e. in collision systems Xe^{q+}+Xe with Z_{UA}>100, Z_{UA}= Z_{proj}+Z_{target}.and compare with theoretical calculations. We discuss the experimental procedure to be used in the storage ring and will also show how this technique can be applied to observe indirectly supercritical fields in transient superheavy quasimolecules.

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Cooling and precision spectroscopy of $^{209}Bi^{82+}$ ion ensembles with the ARTEMIS and SPECTRAP experiments at the HITRAP facility at GSI/FAIR

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The magnetic moment of the electron bound in the extreme field of a highly charged ion is the ultimate litmus test of bound-state quantum electrodynamics (QED). It is a highly fruitful object of high-precision studies due to the existence of both highly precise experiments and of similarly precise predictions in the framework of quantum electrodynamics in the presence of extreme fields almost up to the Schwinger limit, and with the stringency for tests of QED even beyond the Furry picture. We propose to perform sub-meV cooling and precision optical and microwave spectroscopy of confined hydrogen-like bismuth $^{209}Bi^{82+}$ ion ensembles with the ARTEMIS and SpecTrap experiments at the HITRAP facility, to the end of measuring the hyperfine transition energy, lifetime, and the magnetic moments of the bound electron and the nucleus with unprecedented accuracies, providing a test of bound-state QED with highest stringency. As preparatory steps, we propose to investigate the dynamics of highly charged ion clouds under resistive and sympathetic cooling, such that spectroscopy can be performed with the highest spectral resolution possible[1].

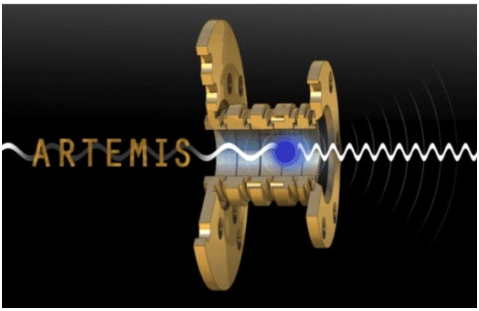

Figure 1: Laser-microwave double-resonance spectroscopy on highly charged ions stored and cooled in the cryogenic Penning trap ARTEMIS at the HITRAP facility.

Reference:

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Investigation of light phenomena observed during interaction of highly charged ions with a liquid droplet beam target

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The introduction of a novel liquid microdroplet target beam technique at the Experimental Storage Ring (ESR) allowed for a significant increase of the achievable area densities, especially for the light gases hydrogen and helium[1].
The interaction of a stored ion beam with microdroplets was thoroughly investigated in the course of numerous atomic and nuclear physics experiments carried out in the ESR[2,3,4]. During the experiments, the light emitted from the interaction region between ion and target beam was monitored by two independent sensitive electron multiplying CCD (em-CCD) cameras and led to the recording of a puzzling observation. Occasionally, bright light traces appeared on the pictures exhibiting a much higher photon intensity than the light emitted from the interaction region. An example of such a bright trace is shown in Figure 1. Unfortunately, no systematic measurements could be performed in order to further investigate in detail these unexpected observations.
An experiment at the ESR was proposed in order to conduct a systematic investigation of the observed effects. Fast detectors will be applied in order to measure the onset of the light effects in correlation with charged particles emitted from the target interaction region. Some preliminary analysis based on the already available, but sparse, data and more details of the experimental setup will be given in this presentation.

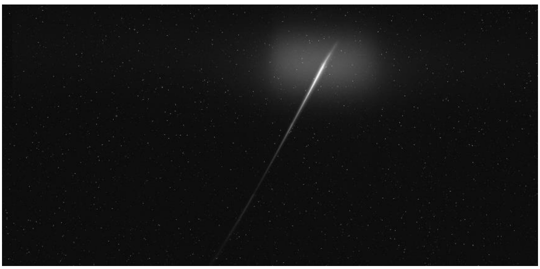

Figure 1: Image of the interaction point recorded with an em-CCD camera during the interaction of a U^{91+} beam with a hydrogen microdroplet target beam.

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High-resolution differential Measurements Between Two-and Three-Electron Uranium Ions for High-Precision Tests of Strong-Field QED

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We propose a highly accurate differential measurement of the Δn=0 x-ray transition energies in the L shell of He- and Li-like uranium ions by Bragg spectroscopy. With an anticipated accuracy of ±0.2 eV on the absolute energy of He-like U transition and ±0.08 eV on the relative energy difference between the transitions in He- and Li-like U, this experiment will deliver a sensitive test of quantum-electrodynamic (QED) and electron correlation effects in few-body systems in the extremely strong field provided by the uranium nucleus. The ESR storage ring at GSI is the only place where the ionic states of interest can be efficiently prepared and the spectroscopic measurements carried out with high accuracy.

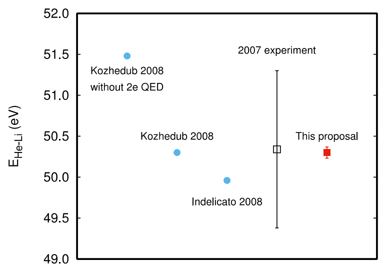

Figure 1: Theoretical predictions of the He-like U $1s_{1/2}2p_{3/2}$ J=2 → $1s_{1/2}2s_{1/2}$ J=1 intra- shell transition relative energy with respect to Li-like U $1s^2_{1/2}2p_{3/2}$ J=3/2 → $1s^2_{1/2}2s_{1/2}$ J=1/2 transition compared to the result of the experiment performed by our collaboration in 2007 [1] and the accuracy goal of the present proposal (the value is just an indication).

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Nuclear excitation by two-photon electron transition

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A new mechanism of nuclear excitation via two-photon electron transitions (NETP) has been proposed and studied theoretically [1]. In such a NETP, a nucleus may resonantly absorb the photon and gets excited due to the two-photon emission of some higher-lying electronic state of the ion. A key advantage of the NETP process is that such resonant nuclear excitations may occur for all nuclear levels with an access energy smaller than the total transition energy. The NETP process is displayed in a more picturesque way in Figure 1. Detailed calculations are performed, in particular, for the E1E1 $1s2s\ ^1S_0 \rightarrow 1s^2\ ^1S_0$ two-photon decay of He-like $^{225}Ac^{87+}$ ion with resonant excitation of the $3/2^+$ nuclear state at energy 40.09(5) keV. The probability that the two-photon decay will happen via the nuclear excitation is found to be $P_{NETP} = 3.5 \times 10^{-9}$. The possibility for the experimental observation of the proposed mechanism will be thoroughly discussed in this talk.

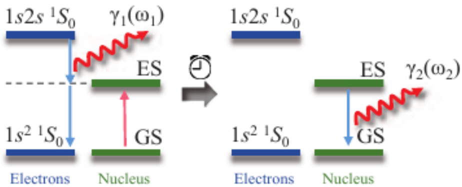

Figure 1: Scheme of the NETP mechanism.

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Electron-positron pair production in space-time-dependent colliding laser pulses

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We investigate the pair-production process in the collision of two counter-propagating linearly polarized short laser pulses. By means of a non-perturbative numerical technique, we take into account the full coordinate dependence of the external field going beyond the previously used dipole and standing-wave approximations. In particular, we study the momentum distribution of particles created. It is demonstrated that the spatial variations of the laser pulses play a crucial role. The more accurate treatment reveals a number of prominent features: the pair-production probabilities become substantially smaller, the quantitative behavior of the momentum spectra changes drastically, and the pulse shape effects become much less pronounced. The results of our study are expected to be very important for future theoretical and experimental investigations devoted to pair production in the non-perturbative regime.

Relativistic calculations of differential ionization cross sections in ion-atom collisions

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Recent progress in experimental technique of the recoil-ion and electron momentum spectroscopy [1] stimulates theoretical studies of the fully differential cross sections (FDCS) for ionization in ion-atom collisions. A unique combination of a reaction microscope and heavy ions available in CRYRING@ESR opens up possibilities for studying ionization processes at the differential level in an unexplored domain [2]. In this region, the relativistic effects are important and have to be taken into account by theory.

Here we present a semiclassical relativistic method for calculation of the FDCS for ionization in ion-atom collisions. The method can be applied to collisions involving light as well as heavy targets, since the relativistic Dirac equation is used to describe electron dynamics. The one-active-electron approximation is implied for the target description, where one electron of the target is assumed to be active, while the others provide a screening potential. The method is based on the finite-basis-set expansion of the wave function of the active electron. The Fourier transform is employed to extract the FDCS for a given projectile momentum transfer.

As the first application, the method is utilized to calculate FDCS for antiproton-impact ionization of atomic hydrogen. This collisional system is very convenient for theoretical study, since it is a pure three particle system without charge-exchange and many-electron processes. An experimental investigation of the FDCS in this collision is not possible at the moment. Nevertheless, the ionization cross sections have already been extensively studied theoretically by various non-perturbative methods [3-6]. Their results are in overall agreement. However, several ionization cross sections, predicted by these methods, considerably differ. Within our independent calculation [7], we can give preference to the results of certain approaches.

Next, the impact-parameter dependencies of the total ionization probabilities from the *K*- and *L*-shells have been calculated for the 100 MeV/u C^{6+}-Xe^{53+} collision. In order to explore the relativistic effects induced by a large target charge, we as well carried out the calculation in the non-relativistic limit, where the standard value of the speed of light *c* was multiplied by a factor of 1000. Comparing the results of both calculations, one can estimate the role of the relativistic effects.

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g factor of medium-Z lithium-like ions

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During the last two decades experimental and theoretical investigations of the *g* factor of highly charged ions have reached an accuracy of ppb and better. In particular, these studies have lead to the most precise up-to-date determination of the electron mass [1]. The stringent tests of the various bound-state QED effects in the presence of magnetic field [2,3], including the relativistic nuclear recoil effect [4], have become possible. Furthermore, it was proposed to determine the fine structure constant α from the *g* factors of light [5] and heavy [6] few-electron ions. Apart from the corresponding high-precision measurements, these proposals demand significant improvement of the theoretical accuracy. Presently, for low- and medium-*Z* lithiumlike ions it is limited by the higher-order interelectronic-interaction and QED screening effects [3,7]. In this work, we improve the accuracy of these contributions by calculating the higher-order terms in the Breit approximation within the recently developed approach based on the recursive formulation of the perturbation theory. The leading-order terms are evaluated within the rigorous QED approach. Application of this method to the binding energies of lithiumlike and boronlike systems has been presented in our recent papers [8,9].

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Relativistic calculations of X-Ray transition energies and isotope shifts in heavy atoms and ions

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Precision calculations of the energies of the X-Ray lines and the related isotope shifts are needed due to growing number of experiments. The energies of X-Ray K-L-M lines in heavy neutral atoms have been measured using the methods of X-Ray emission spectroscopy (XES)[1]. The first measurements of the X-Ray isotope shifts were carried out for neutral U and Mo atoms[2,3]. The measurements of the isotope shifts in Li-, Be-, B-like uranium ions have been performed for odd-even pairs of isotopes[4,5] using the electron beam ion trap (EBIT). Later, precise measurements of the isotope shifts in highly charged ions have been carried out employing other methods[6,7,8] .

From the theoretical side the binding energies of the levels with vacancies in the inner-shells can be calculated very accurately using the multiconfiguration Dirac-Fock method (MCDF) or configuration interaction Dirac-Fock-Sturm (CI-DFS) method. In the present paper the approximation of the center of the gravity of nonrelativistic configuration for the CI-DFS method is used. In this approach the energy is averaged over all atomic terms of the nonrelativistic valence configuration. The validity of this approximation is demonstrated by calculations of the binding energies and the isotope shifts of X-ray lines.

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Radiolysis of water ice and biomolecules

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Radiation interaction with ices causes fragmentation of the ice forming molecules, along with the synthesis of new products such as radicals and even complex molecules and clusters. Similarly, irradiation of biomolecules can destroy the molecules as well as produce new species in a suitable environment. In our group, we study ices of astrophysical relevance[1,2] as well as the stability of biomolecules[3] under ionizing radiation and their evolution at varying temperatures and environment (water matrix). The experiments were performed at the GANIL facility in Caen/France and at GSI, Darmstadt/Germany.
The secondary ion sputtering from water ices was studied using a Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS) setup[4]. The water ices of varying thickness, deposited at different temperatures (10-150 K) were irradiated with 45-90 keV Oxygen ions produced at the ARIBE facility of GANIL. As a result of projectile ion impact, secondary ions such as protonated water molecules and large clusters are produced. The cluster production yields were studied as a function of the thickness and the temperature of the ice. Also, pyridine was studied with and without water environment.Recently, a Quartz crystal microbalance was incorporated in the setup for the in-situ measurement of the total sputtering yield of ices.
The destruction cross-sections of biomolecules such as Adenine were studied using a FTIR setup[3]. The experiments were performed at the high energy ion beam lines at GANIL and GSI. The destruction of the molecules was studied with and without water environment as a function of the projectile fluence. The destruction cross-sections follow a power law as a function of the electronic stopping power of the projectiles. This allows to estimate survival times of biomolecules exposed to cosmic rays.

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Irradiation of isolated collagen mimetic peptides and triple-helix models by different ionizing projectiles: keV ions, MeV ions, VUV and X-ray photons.

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The radiobiology of cartilage has been studying for many years by the LARIA team, from our laboratory. They recently focused on bystander effects such as cellular stress, induced by radio- and hadrontherapy. This stress might be caused by the formation of molecular fragments after irradiation of the cartilage extracellular matrix. To test this hypothesis, we aim at identifying ionic fragments produced after gas-phase irradiation of collagen, a structural protein whose triple-helix structure brings the special mechanical properties of cartilage. Recently, we studied the isolated $[(PPG)_{10}]_3$ and $[(PHypG)_{10}]_3$ (P is proline, G is glycine, and Hyp is hydroxyproline) peptide trimers, two well-known models of the collagen triple-helix. In the condensed phase, these peptide trimers have a triple-helix structure stabilized by proline hydroxylation [1]. However, to our knowledge, they had never been investigated in the gas-phase before our very recent work [2].

Comparisons between ion mobility collision cross-section measurements and simulations have been performed in collaboration with the ILM laboratory (Lyon, France), to probe their gas-phase structure. Our results show that both model peptides keep that particular triple helix shape in gas phase for high protonation states (6 and 7). Irradiations by photons were made by coupling the Paultje set-up [3] with the VUV and X-ray beamlines of the BESSY-II synchrotron (Berlin, Germany), which allowed scanning a range of energies from 14 to 288 eV. Our single photon absorption results [2] show that a smooth transition occurs from photoexcitation to photoionization when increasing the photon energy, for both monomers and trimers. Photoabsorption by the triple helix models first cause intermolecular, and then intramolecular fragmentation. The absence of intramolecular fragmentation for the $(PHypG)_{10}$ trimer indicates a stabilization of the triple helix structure by hydroxyprolines, probably via stereoelectronic effects as suggested earlier [4]. This set-up was also very recently coupled with the IRRSUD beamline at GANIL (Caen, France), and the irradiation of the triply protonated collagen peptides by a C^{4+} beam at 12 MeV, induced both ionization and proton detachment. The latter process has only been observed once before, for collisions between a Xe^{8+} beam at 96 keV and cytochrome C [5]. In Caen, we are currently working on the irradiation of collagen peptides, in a crossed beam configuration, by a high intensity ($\approx$ 100 μA) He^{+} beam at 7 keV. Preliminary results for the irradiation of $(PPG)_{10}$ show non-dissociative ionization of this peptide.

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Studying the fragmentation dynamics and possible geometry of CO molecular clusters

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The analysis of ion-molecule/cluster interactions in low energy collisions using a COLTRIMS (COLd Target Recoil Ion Momentum Spectrometer) setup provides insight in the dynamics of cluster dissociation. In the past few years our group has investigated the systems ranging from atomic clusters [1] to monoatomic molecular clusters [2]. In other terms we moved from systems having only covalent bonds to a system having covalent and van der Waals bonds [1, 2 & 3]. Recently, we have investigated the structure and fragmentation dynamics of diatomic molecular clusters ionized by low-energy highly charged ions produced in ARIBE beamline of GANIL. Weakly bound gas phase targets produced by a supersonic gas jet helps us to study the molecules in a simple environment and it also makes it easier to determine the basics for further condensed states. The projectiles used are Ar^{9+} & Xe^{25+}, both with the 15 keV/q energy. We observe the difference in dissociation of a N_2 dimer and CO dimer in 3-body fragmentations [2, 4]. On the other hand we also obtain the geometrical arrangements of target clusters using Newton and Dalitz plots. We will present the results following the detailed analysis of four fragmentation channels: $CO^{2+} \rightarrow C^+ + O^+$, $(CO)_2^{2+} \rightarrow CO^+ + CO^+$, $(CO)_2^{3+} \rightarrow CO^+ + C^+ + O^+$ & $(CO)_3^{3+} \rightarrow CO^+ + CO^+ + CO^+$ which should give more information about the geometry of the clusters.

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Investigations of the structural and chemical order in the nanomaterials via Transmission Electron Microscopy.

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Transmission electron microscopy is a powerful tool to probe the atomic scale and allow to describe the structural order in the nanomaterials, such as for instance, nanoparticles. It is well established that associated two or several metals in one nanoparticle could produce synergistic effect on properties such as catalysis, optical and magnetism. The use of magnetron sputtering inert gas condensation enable to generate trimetallic nanoparticles from three independent neighboring targets of Au, Pd and Pt. A combination of several techniques as XPS and High-resolution STEM-TEM were used to investigate the chemical and structural order in these nanoparticles.
Other studies are related to the analyses of nitride semiconductors via TEM technique, so as to describe the structure and the chemical environment as well. The nitride semiconductors, GaN and InN, display optical and electronic properties which can be modified by swift heavy ions irradiations[1]. InN and GaN specimens were irradiated at Ganil facility with 950 MeV Pb while InGaN samples were irradiated gsi facility.
Disorder induced in the InN and GaN layers was observed by transmission electron microscopy technique[2]. High resolution TEM investigations were performed in order to identify the structural order of ions tracks and the strain induced in the lattice neighboring the ions tracks. Chemical investigations were carried out by STEM - Electron Energy Loss Spectroscopy and Energy Dispersive X-ray Spectroscopy techniques so as to localize element in the materials and to check the fluctuation rate of each element across an ion track.
InN is the most sensitive and displays partial decomposition inside the track. High resolution TEM evidences a strong oxidation inside the tracks with the formation of In2O3. Discontinuous tracks are observed in GaN sample and a density fluctuation around the track was evidenced by STEM haadf analysis. Chemical profiles plotted across the tracks reveal a decrease of nitrogen and gallium rate within the ion track while higher density of gallium is clearly observed outside the track.

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Recent Developments on the CRYRING Transverse Electron Target

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As outlined in the CRYRING@ESR Physics Book of the SPARC collaboration [1] it is planned to install a ribbon-shaped free-electron target in the experimental section YR09 of CRYRING at ESR. The electron beam interacts with the ion beam under a collision angle of 90°. This allows for an open access to the interaction region for spectroscopic purposes.
In the last year a new 12.5-keV electron gun with multi-electrode configuration has been developed that advances the designs of similar earlier electron targets [2-5]. The present electrode layout has been specifically tailored towards operation at CRYRING@ESR. It has been optimized in several respects: (i) The possibility to set the electrode potentials to a large extent independently from each other, thus allowing for flexible adjustments of electron beam parameters such as electron density, electron energy and beam size, (ii) a homogeneous electron density (n_e) in the interaction region, (iii) minimization of angular misalignments with respect to the ion beam, (iv) clearing/shaping electrodes in the interaction region for the control of the space-charge potential, (v) a collector design foreseeing deceleration of the electron beam yielding lower heat dissipation, (vi) a large interaction gap to provide space for the circulating ion beam, and, (vii) the realization of a high density mode with $n_e > 1\cdot 10^9$ cm^{-3}.
The design of the mechanical and the vacuum layouts of the electron target station (Fig. 1) is presently being finalized. The setup facilitates a concurrent installation with the gas-jet target or other setups in the experimental section YR09. This allows for more flexible usage of test and experimental beam times since fewer vacuum-breaking changes of setups need to be performed. Additional synergies such as for diagnosis or instrumentation or even combined experiments are currently being investigated.

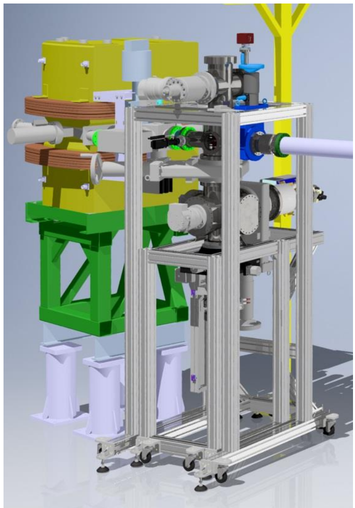

Figure 1: Transverse electron target at the beginning of the experimental section YR09 according to the current status of planning.

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maXs: Micro-calorimeter Arrays for High Resolution X-Ray Spectroscopy in Atomic Physics

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We recently started the development of 2-dimensional arrays of metallic magnetic calorimeters (MMCs) for x-ray spectroscopy on highly charged heavy ions stored in EBITs and storage rings. MMCs are energy dispersive particle detectors operated at temperatures below 50 mK, which use a paramagnetic temperature sensor to convert the temperature upon the absorption of a single x-ray photon into a change of magnetic flux in a SQUID.
The detector system maXs uses a dry dilution refrigerator with long side arm as common cryogenic platform for 3 detector arrays, each consisting of 8x8 x-ray absorbers with optimized size and thickness for 20/30/200 keV x-rays having an energy resolution below 2/5/50eV. The detector geometry shares many details with the successful one-dimensional predecessors maXs-20/200, where the one for soft x-rays has an instrumental linewidth of 1.6 eV(FWHM) in the investigated energy range up to 6 keV.
We believe to be able to further enhance this energy resolution and push the resolving power of MMCs beyond 10000 by implementing: i) overhanging absorbers on small cross-section stems to reduce the loss of hot phonons and to eliminate position dependencies, ii) paramagnetic sensors made of Ag:Er instead of Au:Er to eliminate the hanging heat capacity carried by Au nuclei in the vicinity of Er ions, iii) a novel fast high resolution susceptibility thermometer to stabilize the operating temperature of the detector platform and allow for unprecedented total gain stability.
We discuss the physics of MMCs and the considerations that went into the design of our 2d-arrays. We present recent results on first maXs-30 arrays, including the linearity, the crosstalk between pixels and the improvement of the signal shapes introduced by the new sensor material Ag:Er. In addition, we show our first measurements done at the experimental storage ring ESR at GSI (Darmstadt, Germany), where we used the linear 1x8 pixel array maXs-200, optimized for hard x-rays, for the high resolution x-ray spectroscopy of H- and He-like xenon. The demonstrated combination of stopping power, energy resolution, linearity and dynamic range will trigger numerous novel approaches in high precision atomic physics experiments with stored ion beams.

Status report on selected detector developments in SPARC

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The experiment program of the SPARC collaboration plans experiment campaigns at GSI, FAIR and other accelerator facilities. Covering the whole range of ions from the lightest to the heaviest elements, from neutral to full ionized, trapped ions to highly relativistic velocities, electrons, positrons, x-rays and XUV to visible light raises a demand for a diversity of detector technology and systems.
The talk presents a short overview on selected detector related activities and topics related to SPARC without the claim of completeness. Developments in x-ray spectroscopy and polarimetry will be addressed as well as detection schemes for ions involving scintillation and diamond detectors.
Also some general remarks with respect to future developments and the operation of detector systems in the FAIR environment will be made.

Plasma physics at FAIR

One of the major improvements, which will happen in the coming years at the SIS-18 and SIS-100 synchrotrons of GSI and FAIR, will be the generation of ion bunches with unprecedented intensities. This is of particular interest for the plasma physics community that has traditionally used the ultra-high ion bunch intensities to volumetrically heat matter to high temperatures at near solid-state densities. These states of matter, which one finds mostly in giant planets, are particularly challenging for theory; and experimental data is very scarce.

With the development of the FAIR phase-0 program, the renewed interest of the community can be seen in the creation of a new collaboration named HEDatFAIR, which will exploit the capabilities of GSI SIS-18 and FAIR SIS-100 to explore HED science on the mesoscopic scale. In the near future, the intensities available at GSI will be sufficient to study ionization potential depression effects in warm dense matter, an actual subject of controversy, because of the inconclusive experimental data available. In the long term, super-earth-like conditions for iron or states of water and hydrogen found in giant planets will be accessible using the FAIR beams. These experiments will make use of the current developments in laser-based diagnostics in pump-probe setups, which lay up the requirements for a high-energy high-repetition-rate laser capability at FAIR.

Kinetic Energy Release measurements at the electrostatic Frankfurt Low Energy Storage Ring.

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The Frankfurt Low Energy Storage Ring (FLSR) [1] is designed for the storage of ions with a total energy of up to 50 keV. It has racetrack geometry with a circumference of 14.7 m. A sketch of the elements of FLSR is given in Figure 1. The four-fold super symmetry of FLSR provides four straight sections with regions of enhanced ion density (interaction points (IP)) for carrying out experiments and/or beam diagnostics [1].

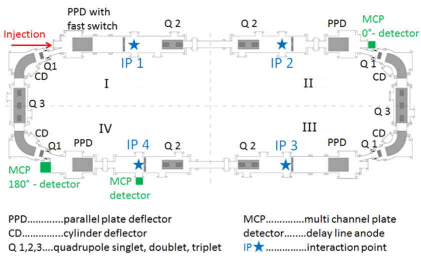

Figure 1: Schematic view of FLSR

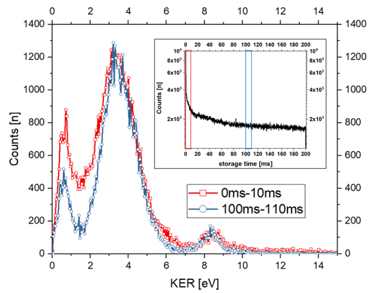

Figure 2: 20 keV HeH^+

In continuation of a first experiment on dissociative recombination of HeH^+-ions by electron impact [2], we have studied the process of dissociation after charge transfer for the molecules HeH^+ and H_3^+. The ions neutralize by charge transfer with the residual gas, which consists mainly of H_2. The fragments dissociate and are detected by a position and time sensitive MCP-detector. In order to determine the Kinetic Energy Release (KER), the exact reaction vertex has to be reconstructed. For this purpose a residual gas spectrometer has been installed into the FLSR at IP4.

As shown in Figure 2 the KER distribution changes over storage time until after approximately 10 ms a constant KER distribution is measured. This is a hint of the depopulation of the vibrational excited levels of HeH^+. After 10 ms all HeH^+ molecules are in the vibrational ground state.

To investigate the depopulation of the vibrational levels of HeH^+ over storage time the Q value must be known. In order to measure Q values with sufficient precision, a cold gas target [3] is needed at IP4 and will be installed as a next step.

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Electron shake-off induced by nuclear beta decay of trapped radioactive ions

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Precision measurements of the recoil-ion energy spectra in nuclear β decay constitute useful probes to test the Vector-Axial vector structure of the weak interaction. With this purpose, experiments using modern trapping techniques coupled to radioactive beams with high production rates have been developed during the last decade. They allow the detection of β particles and recoil ions in coincidence, providing a precise recoil-ion energy measurement with time of flight techniques.
The LPCTrap setup[1,2] installed at GANIL, provides the simultaneous measurement of both the charge-state and the energy of the recoil-ion. Fundamental atomic processes such as electron shake-off resulting from the sudden change of the central potential can thus also be addressed through a measurement of the charge-state distribution of the recoiling daughter nuclei. With a single active electron, the β decay of $^{6}He^{+}$ ions provides a unique textbook case to test simple quantum mechanical calculations[1]. By contrast, heavier systems such as $^{19}Ne^{+}$ and $^{35}Ar^{+}$ ions involve more subtle shake-off dynamics with several active electrons and subsequent relaxation processes such as Auger emission. The experimental ion-charge branching ratios obtained for ^{35}Cl were found in very good agreement with theoretical calculations[2]. The latter were based on an independent electron model (IPM), the use of the sudden approximation, and Hartree-Fock computations of the wave functions. Similar calculations applied to ^{19}F show significant deviations with the experimental data. We trace back the root of this discrepancy to the IPM approximation, which is known to overestimate the probabilities associated to multielectron ionization processes. This does not lead to noticeable deviations from experiments in the case of ^{35}Cl where single and multiple Auger decays play the major roles in the formation of highly charged states.

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Emission of anions from molecular species following cation impact

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It has been recently shown that besides positive ions negative ions are also ejected from gas-phase molecular species in a variety of collisions involving positive ions at a few keV impact energies [1-3]. These findings are relevant for studies of interstellar media and ionospheres, as well as for radiolysis and radiobiology since slow anions are efficient agents for charge transfer and chemical reactions.

We have observed that an H^- ion can be formed from an OH^+ ion when the H center is removed by collision on an Ar target atom [1-2]. The angular distribution of the so-created H^- ions has been found to be proportional to the one calculated for H scattering on the target atom. A similar result is found for the emitted H^+ ions. Also, the kinetic energy distribution of the H^+ fragments shows strong similarities with that of the ejected H^- ions. These findings indicate that the final charge state distribution of the emitted H centers does not depend on how closely the atomic centers approach each other during the collision. Rather, it seems to follow a simple statistical law.

Also, in 6.6-keV $^{16}O^+ + H_2O$ collisions, emission of both H^- and heavier (O^- and OH^-) anions has been observed, with a larger yield for H^- [3]. The experimental setup allowed separate identification of the anions formed in soft collisions with many-body dynamics from those created in hard, binary collisions occurring at small impact parameters. The spectra show that significantly more anions are emitted with low kinetic energies originating from soft collisions. But anions formed in hard collisions are also clearly visible as pronounced peaks at higher energies at emission angles below 90°. These spectral features are well reproduced by model calculations that include a kinetic energy release due to electronic excitation and ionization processes. This indicates that these processes play a decisive role in H^- formation.

For the quantity of produced positive and negative ions in the different collisions, a statistical model is developed in which the excited states of the collisional quasi molecule are populated according to a thermal distribution. The obtained results show a good agreement with the observed charge state distributions of the emitted fragment ions.

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Stored Particles Atomic Physics Research Collaboration

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Posters

Third-order Zeeman effect in boronlike ions

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The numerous experimental and theoretical studies of the Zeeman splitting in hydrogen- and lithium- like ions are of great importance for the test of the many-electron QED effects in the presence of magnetic field [1], the most accurate up-to-date determination of the electron mass [2] and the future independent determination of the fine structure constant [3,4,5]. In these investigations, the nonlinear effects in magnetic field can be neglected at the present and foreseeable level of experimental accuracy. The higher-order contributions in the magnetic field become significant in the case of boronlike ions due to the mixing of the closely spaced $2p_{1/2}$ and $2p_{3/2}$ levels [6,7]. Recently we have performed accurate relativistic calculations of the quadratic [8] and cubic [9] Zeeman effect in boronlike ions. In Ref. [9] the third-order contribution has been calculated with the different screening potentials to account approximately for the interelectronic interaction. In the present work, we rigorously evaluate the one-photon-exchange correction to increase significantly the theoretical accuracy. The calculations are carried out within the framework of a new approach that facilitates the treatment of the higher-order contributions. This method is based on the numerical determination of the electron wave functions taking into account the magnetic field up to the desired kth order. To evaluate these functions we use the basis of the DKB-splines [10] and the recursive representation of the perturbation theory [9,11]. These functions are used to calculate the required matrix elements and finally the correction to the kth-order Zeeman effect is obtained by taking the kth derivative with respect to the magnetic field at zero. Within such approach, we have no individual diagrams for consideration that is an essential simplification of the higher-order investigation.

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Measurement of the linear polarization of K-REC radiation

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The radiative electron capture (REC) is one of the most significant interactions of highly charged heavy ions with matter. As REC can be approximated as the time inversed process of photoionization, it has attracted considerable interest both from experiment and theory [1]. Owing to the development of highly segmented detector systems within the last decade, beside the studies of the total and angular distributions also the determination of the degree of linear polarization of the emitted photons has become possible [2,3,4]. This detection method is also usable for the diagnosis of spin polarized ion beams [5]. An interesting feature of the REC radiation is the very high degree of linear polarization of the emitted photon. Therefore, by changing the particle energy and the ion species, one can achieve a tunable source of photons with a well defined energy and near to full linear polarization [6].
With a new and improved 2D Si(Li) Compton polarimeter, see [7] for more information on the detector, an experiment was carried out at the ESR storage ring at GSI, Darmstadt to investigate this matter. Thererin bare xenon ions at the relatively low energies of 31 MeV/u were used together with a hydrogen target while examining the dominant capture process into the K-shell of the projectile ions. As can be seen in figure 1, the degree of linear polarization turned out to be near to 100%, as expected. Further results of this measurement will be shown in comparison to theory and previous experiments.

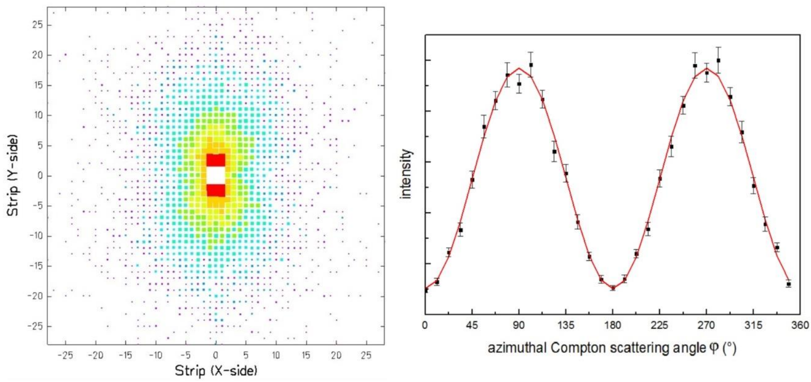

Figure 1: Compton scattering distribution (left) and converted azimuthal scattering distribution (right) of the K-REC peak of bare xenon at 31 MeV/u. The high anisotropy indicates a high degree of linear polarization.

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Scattering of relativistic vortex electrons

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Studies on the scattering of relativistic electrons by atoms and ions have a very long tradition both in theory and experiment. During the recent years, special emphasis in these studies has been placed on the so-called twisted (or vortex) electrons. The beams of twisted electrons, that carry a *nonzero* projection of the orbital angular momentum (OAM) upon their propagation direction, serve today as a valuable tool for probing the magnetic properties of materials at the nano- and even atomic scale. In this contribution, therefore, we re-visit two fundamental processes involving vortex beams: electron-atom and electron-electron scattering. We derive the differential cross sections for both processes and discuss how these cross sections differ from those obtained for the usual plane-wave electrons. Based on this analysis we will show how vortex electrons may shed more light on the relativistic and magnetic effects in Mott and Møller scattering [1,2], and can provide access to the Coulomb phase; a quantity which plays an important role in various collision processes but which cannot be observed in usual, plane-wave-experiments [2].

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P04

PEGASUS
– A versatile spin-polarized electron target –

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We present PEGASUS, a versatile and mobile spin-polarized electron target designed, constructed and build at GSI. It consists of a near-infrared laser-driven bulk GaAs photocathode[1] from which electron currents with a *transversal polarization of 25%* and *currents up to 30 µA* were extracted as a *cw beam 2 mm in diameter*. Spin-polarization measurements were conducted with a mini MOTT polarimeter[2]. After the extraction, the electrons are accelerated to energies between *100 eV and 10 keV*. An electrostatic bender[3] separates the electron beam from the laser beam and changes the polarization vector from longitudinal to transversal[4]. In the following section, diagnostical measurements concerning the beam properties, such as beam intensity, beam size and energy distribution can be carried out. Additionally to the experimental setup, some ideas for future experiments will be discussed, such as the search for electron dichroism in chiral molecules[5,6] or the polarization transfer in bremsstrahlung experiments[7].

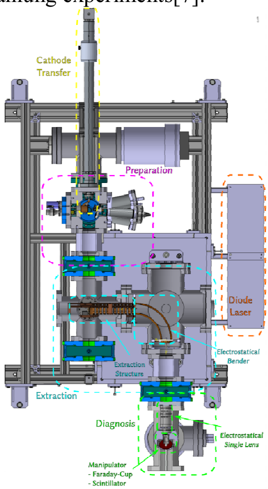

Figure 1: Schematical drawing of the experimental setup

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P05

Recoil effect on the g factor of highly charged Li-like ions

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Recently[1] the isotope shift of the g-factor of Li-like Ca with A=40 and A=48 has been measured. The precision of this measurement is presently limited by an uncertainty of the A=48 atomic calcium mass which is expected to be strongly reduced by a new experiment at MPIK in Heidelberg.

The theoretical value of the g-factor isotope shift is given by a sum of the nuclear recoil (mass shift) and nuclear size (field shift) contributions. For Li-like Ca it is mainly determined by the mass shift, which in the case of the s states is of pure relativistic origin. In Ref.[1] the theoretical mass shift of the g factor of Li-like calcium was evaluated combining the QED calculation of the one-electron recoil contribution and the extrapolation of the two-electron recoil contribution obtained earlier within the Breit approximation[2,3]. Combined with the nuclear size effect, the theoretical prediction for the isotope shift under consideration was found to be in agreement with the experimental one but at the edge of the experimental error bar.

In the present paper, the nuclear recoil effect on the g factor of highly charged Li-like ions is studied. The precise fully relativistic calculation of the one-electron recoil contribution to first order in the electron-to-nucleus mass ratio is performed. The two-electron recoil contribution is evaluated within the Breit approximation using a new four-dimensional approach. This leads to new results for the two-electron recoil part which disagree with the previous calculations performed using an effective two-dimensional Hamiltonian approach[2,3,4,5]. The obtained value for the recoil effect is used to calculate the isotope shift of the g-factor of Li-like Ca.

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Recombination processes in highly charged ions observed via x-ray emission in an EBIT

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In the advanced student laboratory, of the Institute of Physics of the Jagiellonian University, a compact commercial electron beam ion trap (Dresden EBIT[1,2], DREEBIT Co.) was installed a few years ago for teaching purposes. Very recently, this compact room-temperature HCI-trap was equipped with an x-ray detector (XFlash 5030, Bruker Co.) which opens a wide range of possibilities for studies of radiative atomic processes associated with ion production and trapping in an EBIT[2]. Presently, preliminary experiments are focused on radiative recombination (RR). Here, details to be observed in resonant processes like dielectronic recombination (DR)[3] or higher-order resonant electronic recombination[4] are of particular interest. In Figure 1 a part of the DR resonances concerning K shell (K-LL structures), just measured, is shown. These resonances were observed in the EBIT running with Ar while scanning the electron beam energy. The basic background pressure in the EBIT was in the region of 10^{-10} mbar. In order to obtain the highest charge states of the Ar ions, which fill the trap, the pulsed trap mode was applied. In addition, to support this effect, the conditions which are favourable to the "evaporative cooling"[2,4] were chosen. The emitted Ar x-rays were

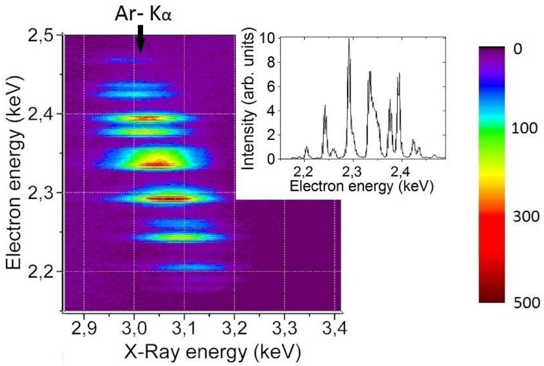

Figure 1: DR K-LL resonances observed in the EBIT, inset shows projection of the spots on the electron-energy axis.

registered, with the resolution of about 100 eV (FWHM), perpendicular to the electron-beam axis at the distance of about 10 mm from the trap centre. A very good resolution of the resonances (inset in Figure 1) helps to reveal details of the transitions mainly in He- to O-like Ar ions present in the EBIT plasma.

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A YAP:Ce-Based Scintillator Detector for High-Energy Ions

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With the commissioning of the CRYRING facility at the novel FAIR accelerator and ion storage complex, the availability of reliable detectors for high-energy ions is of fundamental importance for both standard instrumentation and experiments such as the Franco-German Fit-FISIC project (***F****irst steps* ***t****owards atomic physics of* ***F****ast* ***I****on–****S****low* ***I****on* ***C****ollisions*[1]). These sensors will need to cope with count rates of some MHz and ion energies ranging from sub-MeV/u to 15 MeV/u, while also being able to sustain the radiation damage imparted by the energetic ions. Under these restrictions, scintillation detectors provide an attractive solution, not least from an economical point of view[2]. Unfortunately, common plastic scintillators usually suffer from fatal radiation damage due to the localized energy deposition of the ions – the so-called *Bragg peak*. However, crystalline substances such as YAP:Ce have been known to possess a significant degree of radiation hardness[3].

A robust, UHV-capable prototype detector based on this material is currently under construction at Helmholtz Institute Jena. The setup features a 1 mm scintillator slab mounted on a fused silica vacuum window which separates it from a photomultiplier tube (PMT) that registers the scintillation light generated by impinging ions. To gauge the sensitivity of the assembly as well as its long-term performance (i.e. after continued ion irradiation), a characterization measurement was recently conducted at the 3 MV tandem accelerator *JULIA* operated at the University of Jena's Institute of Solid State Physics. There the detector was found to work reliably for ion energies between 100 keV/u and several MeV/u, even after sustaining ion fluences of several 10^{13} cm^{-2}, yielding pulses of about 50 ns FWHM that can be readily analyzed with stock electronics.

The contribution will present the detector design and explore the results obtained in the characterization experiment.

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Two-loop virtual light-by-light scattering corrections to the bound-electron *g* factor

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We report on advances in the computation of a set of two-loop corrections to the bound-electron *g* factor. Diagrams belonging to this set involve the light-by-light scattering process (which represents the lowest nonvanishing order of the so-called magnetic loop[1]) for which analytical results in the case of the scattering of a low energy magnetic field in the Coulomb field of the nucleus are available[2]. We have looked at the electric loop+magnetic loop diagram and the self-energy+magnetic loop diagrams, taking inspiration for the latter from the approach followed by Yerokhin *et al.*[3] in their investigation of the simpler case of the self-energy correction to the *g* factor. We restrict ourselves to the *1S* ground state, and our approach is also valid for highly charged, high *Z* ions. Our approach is restricted, so far, to H-like ions, but can be extended to multi-electron (*e.g.* Li-like) ions with the inclusion of photon exchange diagrams.

We announce full results on the electric loop+magnetic loop diagram, with a correction scaling as $\Delta g=\alpha^2(Z\alpha)^6\, s(Z)$ with *s* a slowly increasing numerical function of the proton number *Z*, of order 10^{-2}. We also announce partial results on the vertex (analytical and subsequent numerical results for the zero-potential term) and the non-vertex (full contribution from the energy-type (or reducible) correction) self-energy+magnetic loop diagrams. The numerical values obtained so far indicate corrections to the *g* factor of order 10^{-8} and even 10^{-7} for the largest contribution (electric loop+magnetic loop), in the case of Pb (*Z*=82), values that could be observed in principle in upcoming experiments such as ALPHATRAP[4] and HITRAP[5].

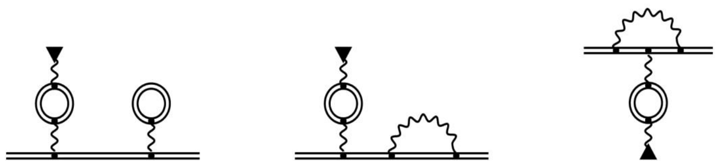

Figure 1: light-by-light scattering diagrams contributing to the two-loop correction to the *g* factor of a bound electron. The leftmost diagram is the electric loop+magnetic loop diagram, the other two diagrams are the non-vertex (centre) and vertex (right) self-energy+magnetic loop diagrams. The double line represents the bound electron and the full triangle is the external magnetic field.

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P09

Electron emission mechanisms in ion-induced ionization of small molecules

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The ion-impact ionization of atom and small molecules is of fundamental interest for decades. Although several applications are based on this fundamental process (industrial irradiations, radiotherapy) the proper theoretical treatment is still in progress. Here we report experimental and theoretical study of ion-impact induced ionization of water and methane.
The gas phase molecules were bombarded by 46-1000 keV/u H^+, He^+ and N^+ ions. Electron energy spectra were taken by an energy-dispersive electrostatic spectrometer in the 20°-160° observation angle range. Absolute double-differential electron-emission cross sections (DDCS) have been determined.

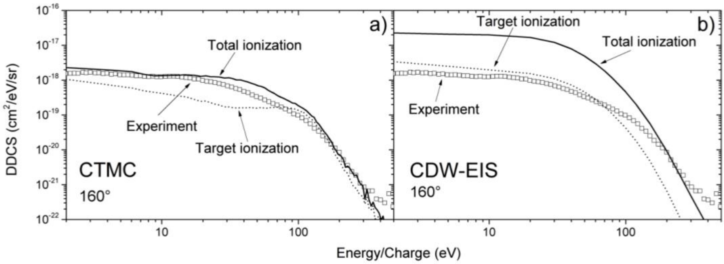

Figure 1: Comparison of the experimental electron spectrum with the results of CTMC (a) and CDW-EIS (b) calculations at 160° observation angle for 650 keV N^+ + H_2O collisions.

The experimental results were compared with the predictions of the extended CDW-EIS and CTMC models [1]. Both theoretical methods were extended for dressed projectiles and for molecular targets with multi-center potentials. Our CTMC model is very similar to that of Illescas *et al.* [2] except that, the full three-body dynamics was considered. In the CDW-EIS model the initial state of the molecule is described by multi-center wave functions (Gausian Program Package), while the continuum state of the emitted electron is evaluated on an averaged spherical potential.
In Figure 1 we compare the energy spectrum of the electrons ejected in 46 keV/u N^++H_2O collisions at 160° observation angle with CTMC (figure 1a) and CDW-EIS (figure 1b) calculations. The pure target and total (sum of target and projectile) ionization are also shown. Good overall agreement was found between the experimental data and the CTMC results. However, the agreement between experiment and the CDW-EIS data is pure: it highly overestimates the measurements below c.a. 80 eV for both target and total ionization. Above this energy the theoretical cross sections fall off significantly faster than the experimental data. By comparing the CTMC results with the 1st order Born reference calculations, we attributed the main component of the electron emission yield above c.a. 100 eV to higher order scattering processes, i.e. the Fermi-shuttle mechanism [3]. Furthermore the CTMC results reveal that these electrons originate from the ionization of the target molecule.

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Relativistic calculations of ionization probabilities in hydrogenlike ions exposed to intense laser pulses

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In the nearest future, experimental facilities will be able to produce short pulses with a peak intensity of 10^{21} W/cm^2 or even higher. Novel facilities will allow us to carry out investigations of heavy atoms and ions exposed to extremely intense laser fields. High photon energies and intensities of laser pulses enable to study relativistic effects of an ion-laser interaction. The progress in laser technologies has triggered the theoretical investigations of one-electron ions exposed to extremely intense fields[1-6].

Previously, we have considered the time-dependent Dirac equation within the dipole approximation, in which the laser vector potential depends only on time variable and spatial dependence is neglected. The aim of the present research is to extend the method by inclusion in calculations non-dipole effects. This extension makes possible to incorporate earlier forbidden magnetic types of interaction, electric quadrupole interaction, etc. Beyond the dipole approximation the ion-laser interaction potential depends on time and spatial variables. This potential is represented by the multipole expansion, and dependence on the spatial coordinates is expressed through the spherical Bessel functions.

The relativistic calculations of the ionization probability have been performed within the dipole approximation and beyond it. The hydrogenlike tin ion ($Z = 50$) has been considered as an example. The laser field has been characterized by a 20-cycle pulse with the carrier frequency of 100 keV and peak intensity of 1.56×10^{22} W/cm^2. The results obtained in this work demonstrate the importance of the non-dipole effects when ionization of heavy hydrogenlike ions by fields of high photon energies and intensities is considered.

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Application for a VUV-VIS-Spectrometer at CRYRING@ESR for Laboratory Astrophysics

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Since the detection of X-ray and EUV emissions from the Moon[1] and comet Hyakutake[2], and shortly after the identification of charge transfer reactions with solar wind ions as their origin[3], charge exchange (CX) reactions have become a thoroughly studied field of interest in astrophysics both theoretically and experimentally[4]. Today, CX-induced X-ray emissions are known from various stellar objects, mostly comets as well as the outer atmospheres of i.e. the Earth or Jupiter. These studies however focus dominantly on the capturing ion and the states the electrons are captured to, whereas the species acting as targets, usually light gases such as Ar, CO_2, CH_4 H_2O, N_2 and others[5] are often disregarded, with the exception of hydrogen.

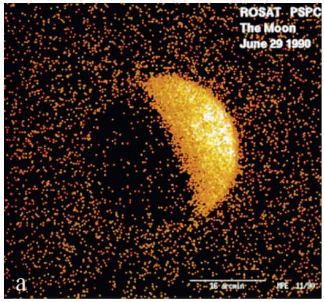

Figure 1 : ROSAT X-ray image of the half-lit moon[1].

The energy of solar wind ions, mainly H^+ and He^{2+}, followed by $O^{(6\text{-}8)+}$, $C^{(5\text{-}6)+}$ and N^{5+} is typically in the range of 0.8—3.0 keV/u[4], but can also reach up to several MeV/u in solar energetic particle events[6]. Within this energy range, the dominant interaction mechanism from the ions with their targets change from charge exchange towards excitation and ionization. The effects of impinging highly-charged ions from the solar wind on composition and stability of these gas mixtures have been investigated scarcely at best.

Excited small molecules, molecular ions and dissociation products show a distinct and well-known fluorescence from the visible to vacuum-ultraviolet spectral range that can be used for identifying their electronic states after an energetic interaction with highly charged ions. The application of a VUV-VIS Spectrometer at the gas target at CRYRING@ESR and its use in conjunction with particle- and X-ray detectors would allow systematic studies of the interaction between solar wind and the atmospheres of planets and the gas halos of comets.
Knowledge of the electronic orbitals where electrons are typically being caught from by the ions can also give more insight into the process of charge transfer, which is still being investigated theoretically[7] and experimentally[8] for fully differential p- and He^{2+}—He collisions.

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Ground-state ionization energies of boronlike ions

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Rigorous QED calculations of ground-state ionization energies are performed for all boronlike ions with nuclear charge numbers in the range $16 \leq Z \leq 96$ [1]. *Ab initio* QED calculations are performed within the extended Furry picture without any expansion in powers of interaction with the effective potential and include all many-electron QED effects up to the second-order of the perturbation theory. Third- and higher-order electron-correlation effects are accounted for within the Breit approximation. The nuclear recoil and nuclear polarization effects are taken into account as well. The accuracy of the theoretical predictions is improved drastically compared to previous evaluations of the ground-state ionization energies of boronlike ions.

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High-precision X-ray spectroscopy of highly-charged ions at storage rings using silicon microcalorimeters

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High precision X-ray spectroscopy of hydrogen-like heavy ions provides a sensitive test of quantum electrodynamics in very strong Coulomb fields which is one of the established subjects within the program of SPARC. However, one limitation of the current accuracy of such experiments is the energy resolution of available X-ray detectors [1]. To improve this accuracy, a novel detector concept, namely the concept of microcalorimeters, is now exploited for such measurements. With this kind of detectors and affixed X-ray absorbers appropriate to the desired energy range, a relative energy resolution of about 1 per mille is obtained in the energy regime of 1 - 100 keV [2].
The application of microcalorimeters for hard X-rays, based on silicon thermistors and tin absorbers, for the determination of the 1s Lamb Shift in hydrogen-like heavy ions has been pursued by our collaborating groups for more than two decades. Two detector arrays have been successfully applied in two experiments at the Experimental Storage Ring (ESR) of the GSI Helmholtz Center for Heavy Ion Research to determine the 1s Lamb Shift of hydrogen-like lead and gold [3]. An excellent agreement with theory has been obtained.
In order to improve the statistical uncertainty and lateral sensitivity, a larger detector array with three times the active detector area in a new, cryogen-free cryostat is currently in preparation. Due to space limitations within the sidearm of the cryostat, a re-design of the detector was necessary for the next generation detector. The new detector design is a more compact version of the design of Bleile et al. [2]. In 2016 this new design was tested at the ESR storage ring of the GSI facility using a hydrogen-like Xenon and a lithium-like Uranium beam. This test was an important benchmark on the way to the larger detector array. Preliminary results of these tests were presented at the last SPARC Meeting. In our current contribution, we will present the final results as well as the next steps since taken to realize the larger detector array. Perspectives for further improvements will also be discussed.

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The magnetic toroidal sector as broad-band electron-positron pair spectrometer in a storage ring

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At the future relativistic storage-ring HESR at FAIR the study of electron-positron pairs from non-nuclear, atomic processes will be one of the goals of the experimental program with kinematically complete experiments focusing on momentum spectroscopy of coincident emission of electrons and positrons from free-free pairs and corresponding recoil ions. The underlying production mechanisms belong to central topics of QED in strong fields.
We present first results on the electron-optical properties of a magnetic toroidal sector configuration enabling coincident detection of free-free electron-positron pairs; this spectrometer is suitable for implementation into a storage ring with a supersonic jet target and covering a wide range of lepton emission into the forward hemisphere. The simulation calculations are performed using the OPERA code [1].

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2 .

Novel Approach to High Rate Micro-Calorimeter Signal-Processing for X-Ray Spectroscopy Experiments

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Recent developments in the field of cryogenic microcalorimeters have made metallic magnetic calorimeters – like the maXs-detectors – a particularly promising tool for x-ray spectroscopy experiments as they are proposed within the frame of the SPARC collaboration [1]. Due to their measurement principle requiring very low operation temperatures (< 15 mK), they provide an intrinsically high energy resolution ($E/\Delta E_{FWHM} \approx 3000$), which is mostly independent of the measured particle energy, therefore making them operable in a wide range of energies at the same time ($\approx 0.1 - 100\ keV$) [2]. However, the processing of the detector signals still poses many challenges, as current methods of data analysis – the *optimal filtering approach* in particular – despite providing energy data with almost negligible uncertainties, require offline data analysis – leading to a growing demand for data storage capacities – and are very sensitive to jittering of operation parameters [3]. Therefore, in the frame of this work a new signal processing method is introduced, which relies on *finite response filter* pipelines to trigger, deconvolute and smooth the detector events. The method is optimized for high event rates (up to 10 kHz), supports signal pile-up analysis and is designed for deployment on FPGA or GPU based online signal processing systems.

Data sets captured by the maXs-30 micro-calorimeter detector stemming from collision experiments conducted at the internal target of the ESR at GSI in May 2016 were analyzed to compare the performance of the new processing algorithm with results of the optimal filter. The experiments involved U^{89+} ions with a beam energy of 76 MeV/u on N_2 and Xe gas targets and were observed by the novel 48-pixel detector at an angle of 90°. This contribution will present first results of the currently ongoing data analysis.

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Measurements of transition energies and lifetimes in Li- and Be-like ions with an XUV Laser source at FAIR

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We report on the latest progress in development of a turn-key XUV laser source for experiments with highly charged ions at FAIR. The source is based on high harmonic generation [1] and currently generates 10^{12} photons/s @ 21.6 eV and 26.4 eV. A typical XUV emission spectrum is displayed in fig. 1 a). The spectral bandwidth is currently about ~30 meV and will be further reduced in future. The robust implementation and portable nature of this instrument will enable various experiments at FAIR facilities including CRYRING, ESR, HESR and ion traps.
We will present detailed proposals for first proof of principle experiments to be performed at CRYRING. Moreover we will discuss in detail the feasibility of testing state-of-the art calculations [3,4] with transition energy and excited state lifetime measurements on Li-like and Be-like ions. While transition energies can be measured by tuning across a resonance and simultaneous fluorescence detection [2], lifetime measurements with Femtosecond precision require a more sophisticated setup. To this end a XUV-pump-XUV-probe setup will be developed, which allows driving two transitions with variable time delay as illustrated in fig. 1 b). The recorded fluorescence signal, if adequately filtered, provides a direct measure of the excited state lifetime. These sub-nanosecond lifetimes will be measured with <100 fs precision and thus provide a sensitive and complementary test for theoretical calculations.

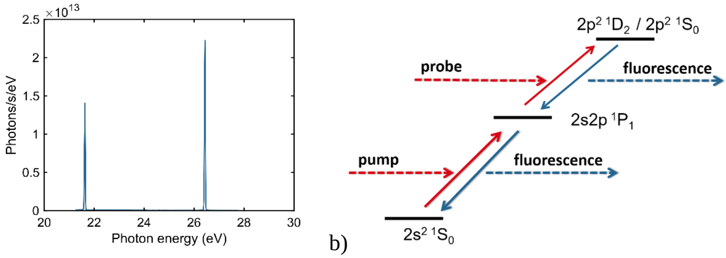
a)


Figure 1: a) XUV spectrum generated by the turn-key XUV source b) schematic of a lifetime measurement experiment with Be-like ions

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HILITE – High intensity laser experiments on stored ions

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Advanced studies of laser-ion interactions in extreme laser fields require well-defined ion target preparation, as well as detection techniques for high-sensitivity measurements of reaction educts and products. Therefore, we have designed and built the HILITE [1] experiment. It features a cryogenic Penning trap located in the center of a superconducting magnet and is designed to be operated at different large scale laser facilities.
In particular, the trap-specific manipulation techniques allow control over the confined ion-ensembles in size, shape, position and density, while destructive and non-destructive detection methods are used to determine number and charge state of stored ions simultaneously.
To cover a large frequency range - and by that a large bandwidth of the charge-to-mass ratio - the resonance circuits for non-destructive detection of ions are tunable. We applied and tested electronics to filter electronic noise and thus enable the application of excitation signals and fast switching of the electrodes. This allows us an efficient capture of ions produced externally by an EBIT source. Those ions will be decelerated by a dedicated deceleration stage, which is implemented inside our setup.
We will present the current status, characterization results of the devices and recent results of our measurements as well as the upcoming steps.

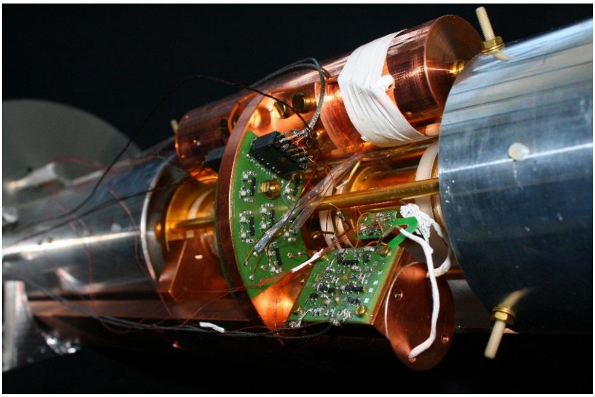

Figure 1: HILITE Penning trap with cryo-electronics and non-destructive detection system

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The model operator approach to relativistic calculations of the QED corrections in the highly charged molecular ions

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The model operator approach [1,2] is applied to evaluate the first-order quantum electrodynamics (QED) corrections to the ground-state energy of the $U^{92+}-U^{91+}$ one-electron quasi-molecule [3]. The two-center calculations of the self-energy and vacuum-polarization corrections are performed for the different values of the internuclear distances (from the chemical distances up to the critical ones). The more simplified evaluation with the use of the monopole approximation is also considered. The results of the calculations are compared with the theoretical predictions obtained previously within the *ab initio* approaches.

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CCC-XD: last measurements & the trinity of inductance.

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The Cryogenic Current Comparator with eXtended Dimensions (CCC-XD) is a new non-destructive particle beam intensity sensor for the nA-range with an inner diameter of 250 mm for larger beamlines [1, 2]. The first CCC-XD is now ready for the integration into a beamline-cryostat (see Fig. 1). Measured basic parameters in a test environment are: white current noise <5 pA/√Hz; small-signal frequency bandwidths ≥200 kHz; slew-rate ≥0.16 µA/µs at 200 kHz [3]. The CCC-XD consists of a main body (meander shielding, magnetic flux concentrator, pickup coil) and a changeable SQUID-cartridge (Superconducting Quantum Interference Device). Three cartridge versions are possible: a direct version without matching transformer with a higher frequency bandwidth, an enhanced version with current-optimized matching transformer and a lower bandwidth, and a moderate balanced version with a transformer current magnification of 2.8x.

This work has been performed in collaboration between CERN, GSI, HI Jena, and U-Jena (collaboration agreement # KE2915/BE) and is supported by BMBF in the framework of the project # 05P15SJRBA.

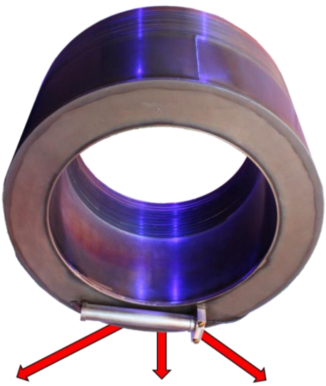

Figure 1: View of the CCC-XD and the three versions of cartridges.

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Dissociative ionization of H_2O molecule impacted by single charged projectiles

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We report measurements on fragmentation cross sections of water. From the yields of the fragments we deduced the multiple ionization cross sections, and compared them with the results of theoretical predictions.

The dissociation pattern of the gas phase water molecule was measured by 1 MeV H^+, He^+ and 650 keV N^+ impact in crossed beam experiments. The energy and angular distribution of the emergent charged fragments were analyzed by a rotatable, energy-dispersive electrostatic spectrometer. Absolute double-differential fragmentation cross sections were determined.

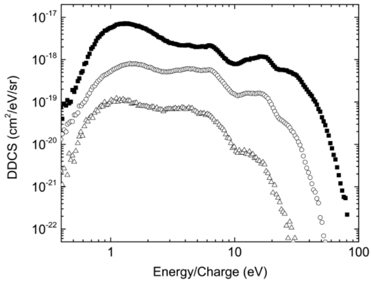

Figure 1: Double-differential fragmentation cross sections for the H_2O molecule. Open triangles stands for H^+ impact, open circles for He^+ and full squares for N^+ projectile.

The total cross section significantly increases from H^+ to N^+ which is attributed to the increasing (average) perturbation strength (see Figure 1). The structure of the spectra is also different: the maximal energy of the H^+ fragments (typically >3 eV) are increasing from ~30 eV to ~90 eV from H^+ to N^+ resulting rising structures in this energy region. These structures are attributed to proton fragments from the triple (16-28 eV), four-fold (30-40 eV) or five-fold (>45 eV) ionized H_2O^{q+} molecules [1]. Accordingly, the maximal ionization degrees were q_{max}= 3, 4, and 5 for H^+, He^+ and N^+ impact respectively. These high values and the increasing multiple ionization yields from H^+ to N^+ is attributed to close collision events, where the effective charge of the projectile is increased, due to the decreased screening effect of the projectile electrons.

From the yields of the fragments we obtained the multiple ionization cross sections for the three projectiles and compared them with the results of the quantum mechanical CDW-EIS and the classical CTMC calculations [2]. The analysis of the theoretical data confirms the rule of close collision event in the high multiple ionization cross sections for He^+ and N^+ impact. However, as the ionization degree increases the theoretical results more and more overestimates the experimental data, which is attributed to the limitation of the independent particle model (IPM), namely that the electron correlation is neglected.

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SPARC meeting 2017

Development and characterization of 2D gaseous detectors for soft X-ray detection

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For a sensitive test of electron correlation effects in few-body systems under extremely strong field provided by the uranium nucleus, high precision X-ray spectroscopy of the $\Delta n=0$ x-ray transition energies in the L shell of two- and three-electron uranium ions is needed. A possible detector setup for X-ray spectroscopy can be: a combination of Si, Ge detectors for high precision energy measurements and gaseous detector for high precision time and position measurements. A possible candidate to meet the latter requirements is the gas electron multiplier detector (GEM), which uses delay-line readout technique. Position and time resolution differ and depend on the geometry of anode and cathode. In general, a GEM detector provides the sufficient position resolution in two dimensions. Time resolution depends on the strength of the drift fields and the fields between anode and cathode. A specific detector design was constructed and tested. Experimentally obtained time resolution prove that the design of this candidate meets requirements of 50 ns time resolution. However, position resolution needs to be improved to meet 200 µm position resolution.

Keywords: gaseous detectors, multiwire detectors, backgammon cathode, gem detectors, soft x-ray detectors

Scattering of twisted electrons on diatomic molecules

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Twisted (or vortex) electron beams are the new tool for studying the Nature on nano- and even atomic scale. These beams have a helical wave front and carry a non-zero projection of the orbital angular momentum (OAM) onto their propagation direction. Vortex electrons have been predicted theoretically only in 2007[1] and produced in experiment just few years ago[2-4] for energies up to few hundreds keV and for the projection of the angular momentum $m\hbar \sim 100\hbar$. Due to such a significant OAM projection, twisted electron beams possess a large magnetic moment and, hence, provide an effective tool for investigations of magnetic properties of atoms, nuclei and solid states[5].

During the few years, a number of studies have been performed for various collision processes involving twisted electrons[6-10]. In all these studies, however, vortex electron beam interacts either with a single counter-propagating beam or with an atomic target. In the present work we study the scattering of vortex electrons by *diatomic* molecules. It is well known for the "usual" plane-wave electrons that the scattering from the two molecular centers gives rise to the interference pattern in the cross section, similar to that observed in the classical Young double-slit experiment. Here we investigate how this Young-type interference picture will be affected by the electron "twistedness". We consider utmost cases of interaction of vortex electrons with a single molecule and with an infinitely large target. In the case of single molecule, two different schemes of the process have been considered. In the first one the vortex beam axis passess between two atoms forming molecule. In the second scheme, one of the molecular centers is placed on the beam axis. All calculations have been performed for hydrogen molecule and for the electron energies of few hundreds eV.

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Study of the K-shell x-ray emission of Kr ionized by 52-200 MeV/u Xe^{54+} ions

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Recently an essential progress was achieved in measuring of radiation spectra in quasi-symmetric highly-charged heavy ion-atom collisions at middle rage of collision energies. Thus an investigation of the Kr, Xe + Xe^{54+} collisions at 52-, 94-, 146, 197-MeV/u collision energies was carried out in IMP (Lanzhou, China) [1]. While the collisions Xe + Xe^{54+}, Xe^{52+} at 50 MeV/u were studied in GSI (Darmstadt, Germany) [2]. The present work is devoted to theoretical calculation of the K-shell satellite and hypersatellite x-ray radiation structure of krypton ionized by impact with 52-200 MeV/u bare xenon ions.

Method of calculations employs an independent particle model, with en effective single-electron Dirac-Kohn-Sham operator [3]. Solving of the single-electron equations is based on the coupled-channel approach with atomic-like Dirac-Fock-Sturm orbitals, localized at the ions (atoms) [4]. Many-particle probabilities are calculated in terms of single-particle amplitudes employing the formalism of inclusive probabilities [5]. The analysis of the post-collisional processes resulting in the target K-shell x-ray emissions is based on the fluorescence yields, the radiation, and Auger decay rates, and allows one to derive intensities of the x-ray emission and compare them with experimental data. The method of calculation takes into account the dynamics of all electrons in the system. The role of relativistic and many-particle effects is analyzed.

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Analysis of the photons twistedness in various atomic processes

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Twisted photons attract tremendous interest and their interaction with various systems is presently widely investigated. Nevertheless, it is still unknown whether the photons emitted in different processes are twisted or not. Here we propose a simple theoretical method which allows to analyze the twistedness of photons emitted in various processes. This method is demonstrated by the evaluation of the twistedness of the pure-state photons, viz., plane-wave, spherical-wave, and twisted photons. We also apply our method for analysis of the photons emitted in the process of the radiative recombination of twisted electrons with ionic targets. It is found that the recombination photons do carry nonzero orbital angular momentum. Additionally, we analyze the purity of the states of the emitted photons.

Elastic scattering of twisted electrons by atomic target: Going beyond the Born approximation

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The twisted (or vortex) electrons being predicted [1] and realized [2, 3, 4] during the last decade presently attract a lot of interest from both the experimental and theoretical sides. In contrast to the plane-wave electrons, the twisted ones possess a nonzero projection of the orbital angular momentum (OAM) $\hbar m$ on the propagation direction. This projection being an additional degree of freedom provides an unique possibility to get a deeper insight in the role of the spin-orbit interaction in different atomic processes and can be utilized for more detailed investigations of various systems.
The application of the twisted electrons for the study of the different systems and structures demands the comprehensive description of the interaction processes of such electrons with target atoms or ions. In the present work we perform a fully relativistic description of one of the basic interaction process; namely, the elastic scattering of the vortex electrons by heavy neutral atoms. This process was studied previously within the framework of the first Born approximation [5]. Here we treat the interaction of the electron with the target atom exactly with the usage of the method analogous to one described in Ref. [6]. It is found that the differential cross section for the scattering of the 1 MeV twisted electron on the iron atom ($Z = 26$) being calculated within the first Born approximation differs from the exact value by 20%.

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Relativistic calculations of ionization probabilities for a many-electron ion exposed to a strong laser field.

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We propose an efficient numerical implementation of the relativistic time-dependent density functional theory (RTDDFT) to study multielectron highly-charged ions subject to intense linearly-polarized laser fields. The interaction with the electromagnetic field is described within the electric dipole approximation. The resulting time-dependent relativistic Kohn–Sham (RKS) equations possess an axial symmetry and are solved accurately and efficiently with the help of the time-dependent generalized pseudospectral method[1]. As a case study, we calculate multiphoton ionization probabilities of the neutral argon atom and argon-like xenon ion. Relativistic effects are assessed by comparison of our present results with existing non-relativistic data.

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Calculations of electron-positron pair creation probabilities in collisions of heavy bare nuclei.

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Electron-positron pair creation in presence of super strong electromagnetic fields is a fundamental phenomenon of quantum electrodynamics. Low-energy heavy-ion collisions can provide a field of sufficient for this process to appear amplitude and therefore can serve as a great tool for investigation of this effect [1]. Up to date, nonperturbative calculations of electron-positron pair creation probabilities are mainly confined within the monopole approximation [2,3] that takes into account only the spherically symmetric part of the interaction potential. In the present work we performed nonperturbative calculations of electron-positron pair creation probabilities beyond the monopole approximation in the reference frame centred at one of the colliding nuclei. The calculation method is grounded on numerical solution of the two-centre Dirac equation in the one-centre basis set constituted of eigenfunctions of the static one-centre Hamiltonian. The results of this calculations will be presented at the conference.

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QED theory of the quadratic Zeeman effect

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The last two decades have been marked with the significant progress in the study of the g factor of highly-charged ions, which was a result of both experimental and theoretical work. The substantial improvement of the accuracy of the electron mass is one of the most remarkable outcomes of this work [1]. It`s expected that high precision measurements of *g* factor of hydrogen and boronlike ions will give an alternative method of the fine structure constant determination [2]. As an important step on this way, the ARTEMIS experiment is being carried out now at GSI. It aims at high-precision measurement of the Zeeman splitting in boron-like argon [3]. It will be sensitive not only to the linear Zeeman effect (*g* factors) of the ground and first excited states, but also to the non-linear effects in magnetic field. Up to date, the *g* factor has been well investigated theoretically to high accuracy including the QED, interelectronic-interaction and nuclear effects. The second order effect, on the contrary, is known only to the leading order [4]. We present *ab initio* QED calculation of the quadratic Zeeman effect for $2p_{1/2}$ and $2p_{3/2}$ states of boronlike ions including the first-order corrections: one-photon exchange, self-energy and vacuum polarization. As a result, the most accurate up-to-date theoretical values for the quadratic Zeeman effect are presented. In particular, the theoretical background for the ARTEMIS experiment has been significantly improved [5].

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Single-Particle Detector for the CRYRING@ESR

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We present the design of the single-particle detector (SPD) system[1], based on secondary electron emission. The detector is movable within the ultra-high vacuum chamber and planned to be used to measure production rates of a variety of charged and neutral daughter particles during future experiments at CRYRING@ESR. Together with other types of particle detectors, the detectors based on surface secondary-electron emission after interaction with ions and subsequent electrons multiplication in single-channel electron multipliers (CEMs) or micro-channel plates (MCPs), are a powerful and important instrument in many atomic and molecular physics experiments on fast propagating ion beams[2].
Detectors of this type characteristically show efficiencies greater than 90% for kHz count rates. Implementation of the Extended Dynamic Range (EDR) CEMs (with lower wall resistance) in our SPD design improve the performance and longevity for higher count rates up to 10MHz, such as they may be expected e.g. from electron capture reactions in highly charged ions at the electron cooler.
Design, simulations, calibration arrangement and preliminary characterization of SPD are presented.

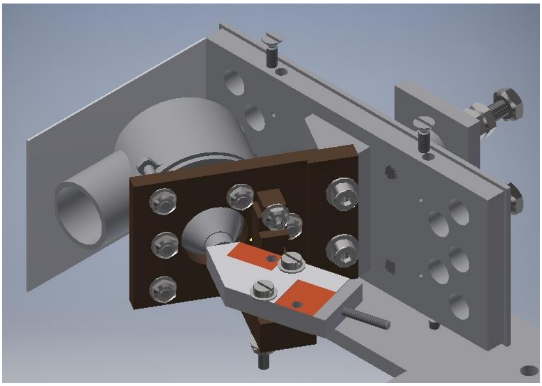

Figure 1: Single-particle detector CAD-Model

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Electron-positron pair creation in slow collisions of heavy nuclei beyond the monopole approximation

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The low-energy collisions of heavy ions can provide an unique opportunity for investigation of QED in supercritical regime [1]. However, to date the non-perturbative calculations of pair creation in such collisions were mainly restricted to the monopole approximation in which only the spherically symmetric part of the full two-center potential is taken into account [2-4]. In present work, we propose the method for calculations of pair-creation probabilities beyond the monopole approximation. The approach is based on propagation of the finite number of initial one-electron states via numerical solving of the time-dependent Dirac equation with the full two-center potential. The wave functions are expanded in a finite basis set constructed using the DKB technique for axially symmetric systems [5]. Employing the developed method the pair-creation probabilities are calculated for low-energy collisions of bare uranium nuclei. The results are compared with the corresponding values obtained in the monopole approximation.

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Nuclear magnetic shielding in boronlike ions

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Investigations of the Zeeman splitting of the hyperfine-structure levels in few-electron ions can serve for precise determination of the nuclear magnetic moments[1,2]. We present the relativistic treatment of the nuclear magnetic shielding effect in boronlike ions. The leading-order corrections to the magnetic-dipole hyperfine interaction is calculated. Along with the standard second-order perturbation theory expression, we use the solutions to the Dirac equation in the presence of magnetic field found within the dual-kinetic-balance approach[3]. These methods are found to be in agreement with each other and with the previous calculations for hydrogenlike and lithiumlike ions[4-6]. The effective screening potential is used to account approximately for the interelectronic interaction. The obtained results extend the theoretical basis for future experiments to boronlike ions.

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Electron loss from highly charged ions in collisions with atomic particles

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In this work we study single electron loss from hydrogen-like and helium-like highly charged ions which occurs in collisions with light atomic particles.

We consider electron loss from a hydrogen-like highly charged ion by the impact of equivelocity electrons and protons and also in collisions with hydrogen and helium. The collision velocity v varies between v_{min} and v_{max} , where v_{min} and v_{max} correspond to the energy threshold ε_{th} for electron loss in collisions with a free electron and to $\approx 5\ \varepsilon_{th}$, respectively. Our results show that for this range of v: i) compared to equivelocity electrons protons are more effective in inducing electron loss (due to a substantially larger volume of the effectively available final-state electron momentum space), ii) the relative (compared to protons) effectiveness of electron projectiles grows with increase in the atomic number of a highly charged ion, iii) the entire volume of the final-state- electron momentum space, kinematically available in collisions with electrons, is much stronger populated in collisions with electrons.

We study single electron loss from the ground state of a helium-like highly charged ion in fast collisions with an atomic particle (a nucleus or an atom) focusing on electron emission energies where the so called excitation-autoionization channel of electron loss becomes of importance. The presence of this channel leads to the appearance of sharp structures in the energy distribution of the emitted electrons and may also noticeably influence the angular distributions of the emission in the vicinity of autoionization resonances. We performed calculations for electron loss from Ca^{18+} ($1s^2$) and Zn^{28+} ($1s^2$) in 100 MeV/u collisions with neon. It is shown that two qualitatively different subchannels (which involve either one or two interactions between the electrons of the ion and the incident atomic particle) contribute to this channel. According to our results, both these subchannels yield substantial contribution to excitation-autoionization and take active part in the interference with the direct channel of electron loss; however, they practically do not interfere with each other. Our consideration also shows that the account of QED corrections is important for an accurate description of electron loss even from relatively light helium-like HCIs.

A Detection System for Laser Spectroscopy Experiments at CRYRING@ESR.

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In order to enable laser spectroscopy experiments at CRYRING, a new general purpose fluorescence detector is being developed at the University of Münster. The design allows detection from ultraviolet wavelengths to the near infrared regime. Thus, the detector can be used to observe a large variety of atomic transitions. Among others Mg- (at 280 nm) and Ca+ (at 854 nm/866 nm) ions have transitions in the wavelength regime covered by the detector.

Geant4 simulations have been performed in order to optimize the detection efficiency of fluorescence photons, while – at the same time – suppressing the detection of background photons.
This is realized by an elliptical detector geometry, which selectively focuses fluorescence photons from the beam axis onto PMTs outside of the vacuum.
In order to achieve a high sensitivity over the complete wavelength range, two sets of interchangable PMTs will be used, one for the UV range and one for the long wavelength part.
The vacuum chamber for the detection setup and suitable mirror materials (Alanod MIRO3) have benn procured, while the support structure for the mirror elements is currently being manufactured in the mechanical workshop of the institute. The poster will present the design and current status of the instrument.

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1 This project is funded by BMBF under contract number 05P15PMFAA.

Commissioning of a detection system for forward emitted XUV photons

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The Institut für Kernphysik in Münster developed a system for in-vacuum detection of forward emitted extreme UV photons created in laser spectroscopy experiments at the ESR[1]. To collect the emitted photons a cathode plate with a slit for the ions is moved into the beam. XUV photons hitting the plate produce mostly low energetic secondary electrons which are guided electromagnetically onto an in-vacuum MCP detector. To optimize the quantum efficiency of the cathode plate for a wavelength range around 10 nm, the plate is coated with a 300 nm CsI-layer. This wavelength region is especially important for a study of electron-electron correlations in Be-like krypton[2], for which the detector was originally developed.
A three day beam time for laser cooling tests and commissioning of the XUV detection system was conducted at the ESR in 2016. In an anti-collinear laser-spectroscopy setup with $^{12}C^{3+}$-ions, the $2s_{1/2} - 2p_{1/2}$ and the $2s_{1/2} - 2p_{3/2}$ transitions at $\lambda_0 \approx 155$ nm were investigated using the XUV detection system. Preliminary results of both transition analyses, as well as currently investigated background reduction concepts, will be presented.
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The S-EBIT Facility at the Helmholtz Institute Jena.

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The Super-EBIT (S-EBIT) [1] plays an important role for accomplishing the mission of Helmholtz Institute Jena (HI-Jena) towards Facility for Antiproton and Ion Research (FAIR). It considerably expands the opportunities for developing new technologies and procedures for novel experiments with highly charged ions (HCI). In the S-EBIT program of HI-Jena the emphasis is put on X-ray spectroscopy and the interaction of intense laser radiation with HCI, including the respective diagnostics. Moreover, the S-EBIT program may be of substantial importance for bridging the gap of the transition time for heavy ion experiments between GSI and FAIR. As an operating source of HCI during the shutdown of GSI accelerator, it will facilitate research and development works indispensable for plasma and SPARC experiments at FAIR. The project will open up further points of contact, e.g. in the fields of X-ray wavelength standards, astrophysics, and material sciences. The S-EBIT is being built for commissioning at the experiment platform of the HITRAP facility, where it will not only be used as a standalone device but also serve as a source of highly charged heavy ions for HITRAP. This is of particular importance for the FAIR related shutdown period, where virtually no beam time will be provided for SIS18/ESR and consequently for the HITRAP facility. The S-EBIT will provide extracted medium Z ions up to about Z=66 with sufficient intensities, allowing to perform a unique physics program and to make use of the available experimental infrastructure of HITRAP as well as of the novel instrumentation provided by the HI-Jena [2].

In addition, the important R&D projects related to FAIR, such as tests of spectrometers, position sensitive detectors operating in UHV environment and so on can be conducted which are of particular relevance for the first available facility of the FAIR project, the CRYRING@ESR [3]. Moreover, first experiments with highly-charged ions in intense laser fields can be carried out (PHELIX) at the HITRAP location.

A status report of the S-EBIT program will be presented.

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Full ion trajectory simulations of the slow ion beam for the FISIC project

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Knowledge of fundamental electronic mechanisms at play in ion-ion collisions can provide a real breakthrough in the understanding of energy transfer in various plasmas such as inertial confinement fusion plasma, stellar/interstellar plasmas and also in material damages.

The Fast Ion (MeV/u) – Slow Ion (keV/u) project [1] aims to measure absolute electronic cross sections in the intermediate velocity regime, a regime in which ion stopping power is maximum and where all the primary electronic processes (electron capture, loss and excitation) reach their optimum. So far, no experiments have been performed in this regime mainly due to experimental issues, like the requirement of very high ion beam intensities of good optical quality and a perfect charge state control of both the ion beams. The forthcoming availability of GANIL/SPIRAL 2 and FAIR/CRYRING facilities opens new opportunities to study such atomic collisions.

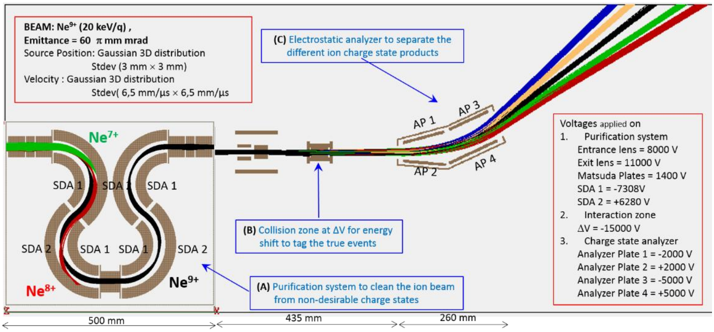

Figure 1: Full ion trajectory simulations of slow ion beam with SIMION

For such a challenging experimental project, many technical barriers have to be overcome. In this workshop, we will present the full ion trajectory simulations of the slow ion beam for the FISIC project starting from the entrance of the ion in the chamber towards the end of detection system i.e. (i) Cleaning of the ion beam in terms of charge state, (ii) Tagging the true events at the interaction zone and (iii) Post collision electrostatic charge state analysis after the collision zone. An Omega-type purification system [2, 3] (never tested for ions) to prevent pollution from electron-capture from the residual gas has been designed and is under construction.

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Crystal Optics for X-Ray Studies at EBIT Devices

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EBIT ion sources are well established devices in basic research [1,2,3] with a broad range of applications allowing to produce ions at high-charge states in rest in the laboratory. Also in case of the international FAIR project, EBIT`s play an important role as test devices for various detector systems of the SPARC collaboration [4,5] but most importantly as ion sources for precursor experiments at HITRAP [6] and possibly also as ion source for CRYRING@ESR [7]. CRYRING@ESR is a Swedish in-kind contribution for the FAIR Facility.

Typically a variety of different charge states of ions is generated in an EBIT. The relative abundance of atomic charge states depends on different charge exchange processes. Among ionization and excitation by electron impact several other processes take place in the interaction zone of the EBIT such as RR-processes. Hence the detection of the X-ray emission pattern is a key-element for getting access to the physical processes in the EBIT and to determine the charge state distribution inside the trap. Here we present a novel approach to enhance the x-ray collection efficiency by utilizing 'the state-of-the-art' X-ray crystal optics in combination with a high energy resolution prototype micro calorimeter [8,9]. Due to the X-ray crystal optic, the effective surface of the detector is substantially increased by matching the Bragg-angle of the used crystal [9]. The resolution for detected photon energies (in keV range) is expected to be at a Full Width Half Maximum of a few eV`s [10].

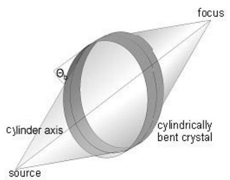

Fig 1: principle set-up of experiment with cylindrically bent crystal [10]

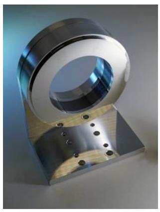

Fig 2: crystal optics [10]

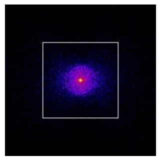

Fig 3: Focus from first measurements with crystal optics [10]

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Calculation of charge state distributions for high energy ion beams using the BREIT code

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Part of the FAIR project at GSI in Darmstadt will be the High-Energy Storage Ring (HESR). While this storage ring was originally solely dedicated to the field of high energy antiproton physics to explore the research areas of hadron structure and quark-gluon dynamics, it is now planned to act in addition as a main experimental facility for the high energy branch of the SPARC‡ research program. For heavy ions the accessible ion beam energy in the HESR will span the range from 0.4 GeV/u to roughly 5 GeV/u [1]. To efficiently prepare ion beams in the charge state of interest, the design of optimized stripper foils is required. For this purpose a reliable model of the charge state distribution emerging from the penetration of high energy ions through matter is desirable. In this context the recently developed BREIT† code [2] is studied to find out if it is suitable to perform this task. Widely used conventional codes like CHARGE, GLOBAL, and ETACHA have built-in cross sections and have some limitations on the number of accounted charge states, ion energy range, approximations used for calculating charge-changing cross sections and others. The BREIT code can be used for calculating the evolution of the charge state distribution with free choice of cross sections and allows to overcome these limitations [2].

As a first consistency check the predictions of the BREIT code were compared to experimental data measured at the SIS†† at GSI [3]. In further steps the BREIT model will be applied for the calculation of the charge-state distribution of many-electron-systems. The results will then be systematically compared to experimental charge distribution data. The status of the ongoing work will be presented.

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‡Stored Particles Atomic Research Collaboration
†Balance Rate Equations for Ion Transportation
††Heavy Ion Syncrotron

Stored Particles Atomic Physics Research Collaboration

SPARC

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11-14 September 2017, Caen, France

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