HIM
HELMHOLTZ
Helmholtz-Institut Mainz

HIM ACTIVITY REPORT 2019/2020

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HIM Activities 2019 – 2020

1. HIM Facts & Figures

HIM in numbers

Staff Research & Development 2020
(exclusively funded by HIM-means)

PIs	21
Postdoc	21
Graduate Students (PHD)	40
Staff for Management	8
Admin:	8
Staff for basic infrastructure	18
Nations represented	*17*

PhDs completed

PhD theses at HIM in 2019/20

Measurement of the Cross Section of the Process $e^+ e^- \rightarrow nn$ and the Extraction of the Time-Like Electromagnetic Form Factors of the Neutron at the Beijing Spectrometer III
Samer Nasher Ahmed

Mesospheric Magnetometry and Optimization of Laser Guide Stars
Felipe Pederos Bustos

Tailor-made thin radionuclide layers for targets and recoil ion sources in nuclear applications
Raphael Haas

High-precision mass spectrometry of nobelium, lawrencium and rutherfordium isotopes and studies of long-lived isomers with SHIPTRAP
Oliver Kaleja

Suche nach einem geladenen Charmonium-artigen Zustand in $e^+ e^- \rightarrow \pi^+ \pi^- \chi_{cJ}$ zwischen 4.18 GeV und 4.60 GeV bei BESIII
Patric Kiese

Extraktion des elektromagnetischen Formfaktors des Neutrons aus Daten des BESIII-Experimentes
Paul Larin

Ein Kühlsystem für den $\bar{\text{P}}$ANDA Luminositätsdetektor und Suche nach dem Zerfall $e^+ e^- \rightarrow \gamma \eta \chi_{c0}$ bei der Schwerpunktsenergie von 4.26 GeV an BESIII
Hans Heinrich Leithoff

Digital Signal Processing for the Measurement of Particle Properties with the PANDA Electromagnetic Calorimeter
Oliver Noll

Feasibility studies for the high precision X-ray spectroscopy of heavy Ξ^- hyperatoms at PANDA using the PANda GErmanium Array PANGEA
Marcell Steinen

Entwicklung eines supraleitenden Beschleunigermoduls für den rezirkulierenden Betrieb am Mainz Energy-Recovering Superconducting Accelerator (MESA)
Timo Stengler

Minimal-invasive Strahldiagnose für hoch intensive Elektronenstrahlen
Tobias Weilbach

Novel magnetic-sensing modalities with nitrogen-vacancy centers in diamond
Huijie Zheng

Third party funding

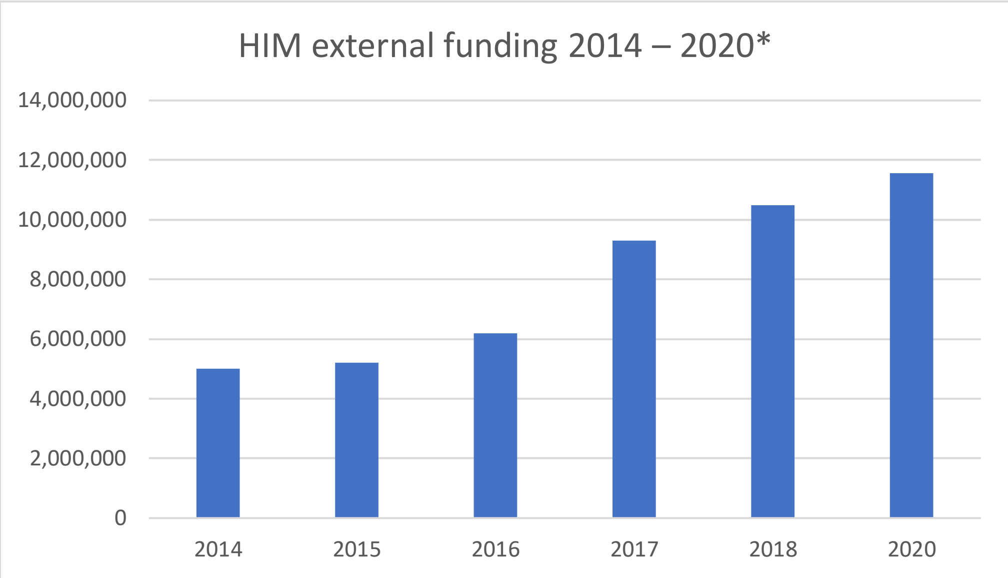

Fig 1: HIM external funding 2014 – 2020
*including HIM-part of the Cluster of Excellence PRISMA+ & SFB 1044

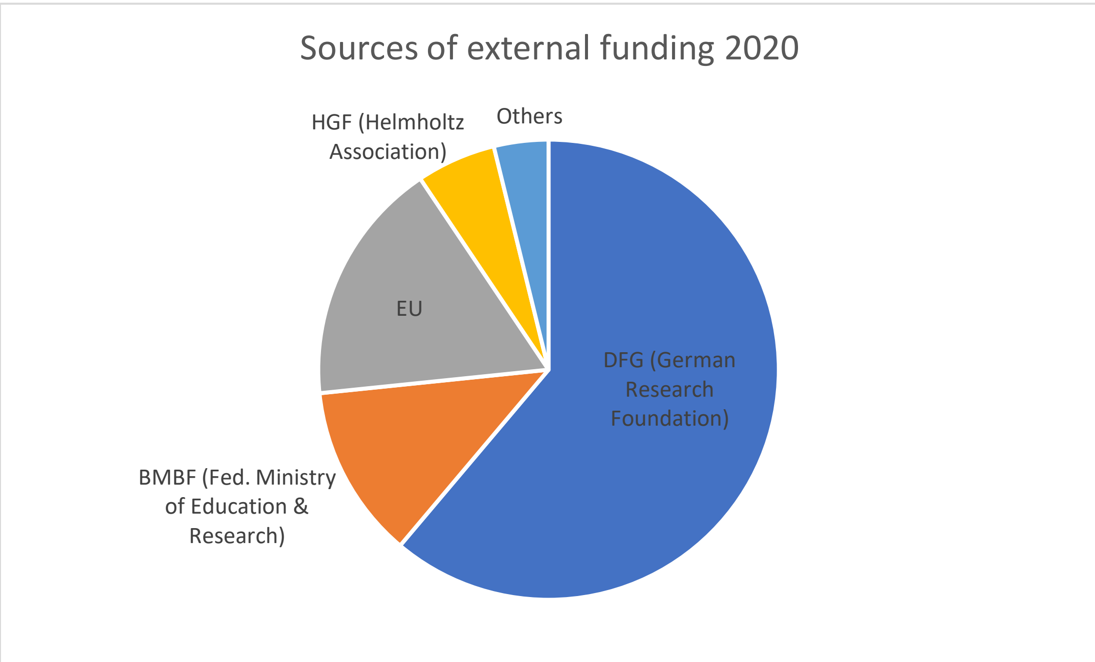

Fig. 2: Sources of external funding 2020

Conference Talks & Conference supports/organized

W. Barth, "Superconducting Proton Accelerators", HBS-Workshop, Runkel, Germany (2019)

W. Barth, "Commissioning of normal and super-conducting LINACs at GSI", ARIES-Workshop, virtual (2021)

M. Block and Ch. E. Düllmann, The 6th International Conference on the Chemistry and Physics of the Transactinide Elements (TAN 19), August 25-30, 2019, Wilhelmshaven, Germany; including the "Special Symposium on Occasion of the "International Year of the Periodic Table""

M. Block, Laser Spectroscopy Studies of the Heaviest Actinides, 10th International Conference on Isotopes (ICI 10), Kuala Lumpur, Malaysia, February 2020

M. Block, Superheavy Element Research at GSI, 13th Latin-American Symposium on Nuclear Physics and Applications (LASNPA), San Jose, Costa Rica, January 2020

M. Block, Perspectives for High-Precision Mass Measurements of Superheavy Nuclides, 4th Superheavy Element Symposium, Hakone, Japan, December 2019

M. Block, Laser spectroscopy of heavy and superheavy elements, Solvay Workshop, Brussels, Belgium, November 2019

M. Block, Status and Perspectives of Superheavy Element Research at GSI, Mendeleev Congress, St. Petersburg, Russia, September 2019

M. Block, Precision measurements of nuclear properties of No, Lr and Rf isotopes at GSI / SHIP, Mazurian Lakes Conference on Physics, Piaski, Poland, September 2019

M. Block, Challenges in Laser Spectroscopy of the Heaviest Elements, International Nuclear Physics Conference (INPC), Glasgow, UK, July 2019

M. Block, Laser Spectroscopy Studies of Superheavy Elements, African Nuclear Physics Conference (ANPC), Kruger Park, South Africa, July 2019

B. Gou, PANDA Collaboration Meeting 2020/1, EMP session, 10/3/2020, "Study of Two-photon exchange | From MAMI-A4 to PANDA"

D. Budker, Co-organizer of online APS Workshop on "Precision-measurement Searches for New Physics", Portland, USA (2020)

D. Budker, Convenor of PANIC2020 – "the 22nd Particles and Nuclei Intl. Conference", Lisbon, Portugal (2020)

D. Budker, Co-organizer of Workshop on "Physics Opportunities with the Gamma Factory" sponsored by the Mainz Institute for Theoretical Physics, Mainz, Germany (2020)

L. Capozza, PANDA Collaboration Meeting 2020/2, 25/6/2020, Report at the Technical Forum

L. Capozza, MAMI PAC Meeting, 13/3/2020, “Measurement of the Electromagnetic Transition Form Factor of the π0 in the space-like region via Primakoff Electroproduction”

L. Capozza, PANDA Collaboration Meeting 2020/2, EMC session, 24/6/2020, “Backward endcap status”

L. Capozza, PANDA Collaboration Meeting 2020/3, EMC session, 28/10/2020, “Status of the backward endcap EMC”

L. Capozza, PANDA Collaboration Meeting 2020/3, 29/10/2020, Report at the Technical Forum

A. Dbeyssi, PANDA Collaboration Meeting 2020/2, EMP session, 23/6/2020, “Study of the ppbar → $e^+ e^- \pi^0$ process in the unphysical region with PANDARoot”

A. Dbeyssi, PANDA Collaboration Meeting 2020/3, EMP session, 27/10/2020, “EMP current activities”

Ch. E. Düllmann, The heavy actinides and transactinides – the radioelements at the end of the periodic table. Invited talk at 10th International Conference on Isotopes (10ICI), February 03-07, 2020, Kuala Lumpur, Malaysia

Ch. E. Düllmann, Superheavy element research at GSI – current status and short-term outlook. Invited talk at 4th International Symposium on Superheavy Elements (SHE 2019), December 01-05, 2019; Hakone, Japan

S. Lauber, “Longitudinal Phase Space Reconstruction for the Heavy Ion Accelerator HELIAC”, IBIC-conference, Malmö, Sweden (2019)

H. Leithoff, “Cooling and Mechanics of the PANDA Luminosity Detector”, International Workshop on Detectors for Colliding Beam Physics (INSTR-20), Novosibirsk, Russia, February 24-28, 2020

C. Motzko, A. Denig, F. Feldbauer, M. Fritsch, R. Hagdorn, R. Klasen, H. Leithoff, S. Maldaner, A. Pitka, S. Pflüger, G. Reicherz und T. Weber für die PANDA Kollaboration, “Ein Spurdetektor zur Luminositätsmessung bei PANDA”, Verhandlungen Deutsche Physikalische Gesellschaft, DPG-Frühjahrstagung München, Deutschland, 17.-21. März 2019

C. Motzko, “Coolings and Mechanics” PANDA Collaboration Meeting June 2020, Report in the Luminosity Detector Session

M. Miski-Oglu, “Progress in SRF CH-Cavities for the HELIAC CW Linac at GSI”, SRF-conference, Dresden, Germany (2020)

O. Noll, PANDA Collaboration Meeting 2020/1, 12/3/2020, Report at the Technical Forum

D. Rodríguez, PANDA Collaboration Meeting 2020/2, EMC session, 24/6/2020, “Backward endcap cooling”

N. Scahill, Response time measurements of GaAs and K2CsSb. Talk at the European Workshop of Photocathode Applications for Accelerators (EWPAA 2019, Paul Scherrer Institute 11-13 September 2019)

T. Stengler, MESA: The Mainz Energy-Recovering Superconducting Accelerator. Talk at the 19th International Conference on RFSuperconductivity, (SRF2019, Dresden, Germany, June, 30 – July, 5 2019)

A. Wickenbrock, Co-organizer of “WOPM 2019”, 7th Workshop on Optically Pumped Magnetometry, Mainz Germany (2019)

S. Wolff, PANDA Collaboration Meeting 2020/1, EMC session, 11/3/2020, “Status Backward Endcap EMC”

HIM – Visiting Scientists 2020

Prof. Thomas C. Blum
University of Conneticut

HIM Guest Scientist Program
01 – 03/2020

Ms. Dudari Burueva
Novosibirsk State University
02/2020

Prof. Henryk Czyz
University of Silesia
10 – 12/2020

Prof. Jens Erler
Universidad Nacional Autonoma de Mexico

HIM Guest Scientist Program
04/2019 – 12/2020

Prof. Victor Flambaum
University of New South Wales, Australia

Gutenberg Research Fellowship by JGU
2019 – 2020

Prof. Kai-Mei Fu
University of Washington
03 – 05/2020

Dr. Miroslav Ilias
Matej Bel University, Slovakia
06 – 09/2020

Prof. Igor Koptyug
International Tomography Center, Novosibirsk

HIM Guest Scientist Program
01 – 03/2020

Awards for HIM Researchers

Dr. Klaus Götzen and Ralf Kliemt
PANDA Outstanding Achievement Award 2019

MSc. Raphael Haas
Giersch Excellence Award

PD Dr. Stefan Knecht
2020 Nernst-Haber-Bodenstein-Prize

Prof. Dmitry Budker
Norman F. Ramsey Prize of the American Physical Society

Dr. Danila Barskiy
Sofja Kovalevskaja Award, Alexander von Humboldt Foundation

Dr. Dionysis Antypas
ERC Starting Grant, EU

Roman Picazo-Frutos
Poster prize of the First ZULF NMR Conference (2020)

Pavel Fadeev
Poster prize of the First ZULF NMR Conference (2020)

2. Highlight Publications of the HIM Research Sections

EMP – ElectroMagnetic Processes

G. Barucca et al. [PANDA]
"PANDA Phase One"
[arXiv:2101.11877 [hep-ex]]. (submitted in Jan 2021)

G. Barucca et al. [PANDA]
"Feasibility studies for the measurement of time-like proton electromagnetic form factors from $\bar{p}p \to \mu^+\mu^-$ at PANDA at FAIR"
Eur. Phys. J. A 57 (2021) no.1, 30; [arXiv:2006.16363 [hep-ex]]

Y. M. Bystritskiy, V. A. Zykunov, A. Dbeyssi, M. Zambrana, F. Maas and E. Tomasi-Gustafsson
"Radiative corrections in proton--antiproton annihilation to electron-positron and their application to the PANDA experiment: Radiative corrections to $\bar{p}p \to e^+e^-$"
Eur. Phys. J. A 56 (2020) no.2, 58; [arXiv:1911.04137 [hep-ph]]

M. Ablikim et al. [BES-III]
"Measurement of proton electromagnetic form factors in the time-like region using initial state radiation at BESIII"
submitted to PLB, [arXiv:2102.10337 [hep-ex]]

M. Ablikim et al. [BES-III]
"Measurement of proton electromagnetic form factors in $e^+e^- \to p\bar{p}$ in the energy region 2.00 - 3.08 GeV"
Phys. Rev. Lett. 124 (2020) 4, 042001

SPECF – Spectroscopy and Flavor

PANDA Collaboration, G. Barucca et al.
Precision resonance energy scans with the PANDA experiment at FAIR
Eur. Phys. J. A55 (2019) 42

BESIII Collaboration, M. Ablikim et al.
Observation of a Near-Threshold Structure in the K^+ Recoil-Mass Spectra in
$e^+e^- \to K^+(D_S^- D^{*0} + D_S^{*-} D^0)$
Phys. Rev. Lett. 126 (2021) 102001

PANDA Collaboration, G. Barucca et al.
PANDA Phase 1
arXiv:2101.11877

Observation of a Be Double-Lambda hypernucleus in the J-PARC E07 Experiment
E07 Collaboration, H. Ekawa et al.
Prog. Theor. Exp. Phys. 021D02 (2019)

Observation of Coulomb-assisted nuclear bound state of Ξ^- -^{14}N system
E07 Collaboration, S. H. Hayakawa et al.
Phys. Rev. Lett. 126 (2021) 062501

MAM – Matter-AntiMatter Asymmetry

D. F. Jackson Kimball, S. Afach, D. Aybas, J. W. Blanchard, D. Budker, G. Centers, M. Engler, N. L. Figueroa et al.
Overview of the Cosmic Axion Spin Precession Experiment (CASPEr)
In: Carosi G., Rybka G. (eds): Microwave Cavities and Detectors for Axion Research. Springer Proceedings in Physics, vol. 245. Springer, Cham; arXiv:1711.08999

H. Zheng, Z. Sun, G. Chatzidrosos, Ch. Zhang, K. Nakamura, H. Sumiya, T. Ohshima, J. Isoya, J. Wrachtrup, A. Wickenbrock, and D. Budker
Microwave-free vector magnetometry with nitrogen-vacancy centers along a single axis in diamond
Phys. Rev. Applied 13, 044023 (2020), arXiv:1904.04361

A. Banerjee, D. Budker, J. Eby, H. Kim, and G. Perez
Relaxion Stars and their detection via Atomic Physics
***Communications Physics* 3, Article number: 1 (2020); arXiv:1902.08212**

Y. Hu, G. Z. Iwata, M. Mohammadi, E. V. Silletta, A. Wickenbrock, J. W. Blanchard, D. Budker, and A. Jerschow
Sensitive magnetometry reveals inhomogeneities in charge storage and weak transient internal currents in Li-ion cells
PNAS (2020); arXiv:1905.12507

C. Dailey, C. Bradley, D. F. Jackson Kimball, I. A. Sulai, S. Pustelny, A. Wickenbrock, and A. Derevianko
Quantum sensor networks as exotic field telescopes for multi-messenger astronomy
Nature Astronomy (2020); https://doi.org/10.1038/s41550-020-01242-7

SHE – Superheavy Elements

H.M. Albers et al.
Zeptosecond contact times for element Z=120 synthesis
10.1016/j.physletb.2020.135626
Phys. Lett. B 808, 135626 (2020)

J. Khuyagbaatar et al
Search for Electron-Capture Delayed Fission in the New Isotope ^{244}Md
10.1103/PhysRevLett.125.142504
Phys. Rev. Lett. 125, 142504 (2020)

J. Khuyagbaatar et al.
Search for elements 119 and 120
10.1103/PhysRevC.102.064602
Phys. Rev. C 102, 064602 (2020)

P. Mosat et al.
K isomerism in ^{255}Rf and total kinetic energy measurements for spontaneous fission of ^{255,256,258}Rf
10.1103/PhysRevC.101.034310
Phys. Rev. C 101, 034310 (2020)

S. Rau et al.
Penning trap mass measurements of the deuteron and the HD^+ molecular ion
10.1038/s41586-020-2628-7
Nature 585 (2020) 43

A. Samark-Roth et al.
Spectroscopy along Flerovium Decay Chains: Discovery of ^{280}Ds and an Excited State in ^{282}Cn
10.1103/PhysRevLett.126.032503
Phys. Rev. Lett. 126 (2021) 032503

B. Seiferle et al.
Energy of the ^{229}Th nuclear clock transition
10.1038/s41586-019-1533-4
Nature 573 (2019) 573

T. Sikorsky et al.
Measurement of the ^{229}Th isomer energy with a magnetic micro-calorimeter
10.1103/PhysRevLett.125.142503
Phys. Rev. Lett. 125 (2020) 142503

ACID I – Accelerator and Integrated Detector

M. Miski-Oglu
“PROGRESS IN SRF CH-CAVITIES FOR THE HELIAC CW LINAC AT GSI”
Proceedings of SRF2019, Dresden, Germany, p.1206-1212

M. Schwarz et al.
Reference beam dynamics layout for the SC CW heavy ion HELIAC at GSI
Nucl. Instr. Meth. Phys. Res. Sect. A, 163044 (2019)

W. Barth et al.
“LINAC developments for heavy ion operation at GSI and FAIR”
Journal of Instrumentation, Volume 15, December 2020 ICFA Beam Dynamics Newsletter #80 – Medium Energy Heavy Ion Facilities, published 30 December 20, *JINST* 15 T12012

S. Lauber et al.
“Longitudinal phase space reconstruction for a heavy ion accelerator”
Phys. Rev. Accel. Beams 23, 114201, published 13 November 2020
https://doi.org/10.1103/PhysRevAccelBeams.23.114201

ACID II – Accelerator and Integrated Detector

J. Winter, M. Galek, C. Matejcek, J. J. Wilkens, K. Aulenbacher, S. E. Combsa, S. Bartzsch
Clinical microbeam radiation therapy with a compact source: specifications of the line-focus X-ray tube
Physics and Imaging in Radiation Oncology 14 (2020) 74–81

R. Kempf, J. Diefenbach, F. Fichtner, K. Aulenbacher
Beam parameter stabilization for the P2 experiment at MESA
Nuclear Inst. and Methods in Physics Research, A 982 (2020) 164554

T. Beiser, M. W. Bruker, K. Aulenbacher, J. Dietrich
Preliminary studies of beam-induced fluorescence and status of the beam-current upgrade of the electron-cooler-test-bench at HIM
12th Workshop on Beam Cooling and Related Topics COOL2019, Novosibirsk

K. Aulenbacher, J. Dietrich, W. Klag
Status of the turbine-driven HV-Generator for a relativistic electron cooler
12th Workshop on Beam Cooling and Related Topics COOL2019, Novosibirsk, Russia JACoW Publishing

THFL – Theory Floor

I. Danilkin, D.A.S. Molnar, and M. Vanderhaeghen
Simultaneous description of the $e^+e^- \to J/\psi\,\pi\pi\ (KK)$ processes
Phys. Rev. D102 (2020) 016019

J. Erler, M. Gorchtein, O. Koshchii, C.-Y. Seng and H. Spiesberger
Reduced uncertainty of the axial $\boldsymbol{\gamma Z}$-box correction to the proton's weak charge
Phys. Rev. D100 (2019) 053007

D. Djukanovic, T. Harris, G. von Hippel, P.M. Junnarkar, H.B. Meyer, D. Mohler, K. Ottnad, T. Schulz, J. Wilhelm and H. Wittig
Isovector electromagnetic form factors of the nucleon from lattice QCD and the proton radius puzzle
arXiv:2102.07460, submitted to Phys. Rev. D

J.R. Green, A.D. Hanlon, P.M. Junnarkar and H. Wittig
Weakly bound H dibaryon from SU(3)-flavor-symmetric QCD
arXiv:2103.01054, submitted to Phys. Rev. Lett.

S. Piemonte, S. Collins, D. Mohler, M. Padmanath and S. Prelovsek
Charmonium resonances with $J^{PC} = 1^{--}$ and 3^{--} from $D\bar{D}$ scattering on the lattice
Phys. Rev. D100 (2019) no.7, 074505

M. Cè, T. Harris, H. B. Meyer, A. Steinberg and A. Toniato
Rate of photon production in the quark-gluon plasma from lattice QCD
Phys. Rev. D102 (2020) no.9, 091501

M. Cè, T. Harris, H.B. Meyer and A. Toniato
Deep inelastic scattering on the quark-gluon plasma
JHEP 03 (2021) 035

B. Acharya, V. Lensky, S. Bacca, M. Gorchtein, M. Vanderhaeghen
Dispersive evaluation of the Lamb shift in muonic deuterium from chiral effective field theory
Phys. Rev. C103 (2021) 2, 024001

C.G. Payne, S. Bacca, G. Hagen, W. Jiang, T. Papenbrock
Coherent elastic neutrino-nucleus scattering on ^{40}Ar from first principles
Phys. Rev. C100 (2019) 061304(R)

L. Moschini, J. Yang and P. Capel
^{15}C: From halo effective field theory structure to the study of transfer, breakup, and radiative-capture reactions
Phys. Rev. C100 (2019) no.4, 044615

3. Activities of the HIM Research Sections

Research Section EMP:
Hadron Structure with Electromagnetic Probes

F. Maas

Measurement of nucleon form factors at BES-III and the future PANDA-experiment

The measurement of the proton form factors in the time-like region using the $\bar{p}p \rightarrow e^+e^-$, $\mu^+\mu^-$ annihilation reactions is part of the feasibility studies which we have made for the PANDA experimental program. A manuscript for the publication of this feasibility study was recently accepted for publication (Eur. Phys. J. A **57** (2021) no.1, 30). This is a successor publication to our previous papers on the feasibility measurement of the $\bar{p}p \rightarrow e^+e^-$reaction (Eur. Phys. J. A **52** (2016) no.10, 325) and on the development of a dedicated event generator for this channel (Eur. Phys. J. A 56, 58 (2020)).

In parallel, the collaboration-internal review process for the "PANDA Phase One paper" was completed. This paper outlines the physics program that can be achieved during the first phase of the PANDA operation when antiproton beams will be available at FAIR. A. Dbeyssi from EMP is convener of the working group studying the physics of "electromagnetic processes" within the PANDA collaboration. The results show that PANDA will improve the precision of the proton form factor measurements for $q^2 > 5.1$ (GeV/c)^2. It will be the first measurements of the time-like proton form factors with muons.

These achievements accompanied with the promising presented results allowed us to extend our feasibility studies to the $\bar{p}p \rightarrow e^+e^-\pi^0$ reaction with the aim to achieve complementary measurements of the proton form factors at PANDA in a region that has never been experimentally accessed. PANDA is expected to provide first measurements of the proton electromagnetic form factors in this region. The studies were performed assuming an integrated luminosity of 2 fb^{-1} and show that high statistical precisions on the measurement of R and $\cos(\phi_E - \phi_M)$ of respectively 1% and 11% at q^2=0.6 (GeV/c)^2 (5% and 13% at q^2=2 (GeV/c)^2) can be reached at PANDA. The results are promising and will allow PANDA to perform unique measurements of the proton form factors in the unphysical region.

During the reporting period (2019, 2020, up to today) the analysis work on BES-III data has reached a state where we could finish the BES-III internal review process and publish a number of papers which were the result of the completed PhD-theses in EMP: The result of the analysis of the energy scan data taken in 2015 for the proton form factor in the time like region between 2.0 GeV and 3.08 GeV was published in PRL 124, 042001 (2020) (PhD Christoph Rosner), the result of the ISR-process has been published in PRD 99, 092002 (2019) for the untagged analysis, a further publication has been submitted to the arXiv:2102.10337 (PhD D. Lin). The result of the analysis of the energy scan data taken in 2015 for the neutron form factor in the time like region between 2.0 GeV and 3.08 GeV was submitted and is accepted for publication in Nature physics (arXiv:2103.12486, PhD Paul Larin and Samer Ahmed).

Construction of the backward endcap calorimeter

The collaboration internal experiment readiness review has been passed in early 2020.

The mass production of the backward endcap calorimeter modules has been started and is in full swing as far as the restrictions due to the pandemic allow. This includes the carbon fiber alveoli housing the crystals, the so-called capsules housing the light sensor and preamplifier, the electronics modules of the line driver and HV distributor as well as the mechanical holding structure as well as temperature sensors. We have 700 crystals as well as 1400 fully characterized APDs in hand. Recently the warm holding plate, holding all crystal modules has been delivered so that mounting the full backward endcap can start as soon as the submodule production has been finished. This is foreseen in 2022. The front-end electronics includes the preamplifier ASIC “APFEL” as well as the line drivers, HV-distribution cards, and the Uppsala transient digitizer ADCS. For all modules, several prototypes have been produced and tested with beam. Mass production of all components has been started or can start soon after final small modifications.

Preparation of a FAIR Phase 0 Experiment at the Mainz MAMI accelerator

A modified version of the backward endcap calorimeter will be used at the Mainz MAMI accelerator for a measurement of the pion transition form factor at a finite value of the four-momentum transfer via the Primakoff-process. This form factor is instrumental for hadronic quantum correction to the g-2 factor of the muon. A letter of intent had been sent to the MAMI PAC which has received very encouraging comments (“… a must do experiment …”).

A theoretical model has been developed in collaboration with the theory department in order to estimate cross sections for this process. Based on this, a GEANT4-based simulation of the experiment is in progress in order to optimize the setup and in order to estimate background rates and necessary beam time. Present plan is to complete the backward endcap setup for the phase 0 experiment until the end of the year 2022, have a first Pilot-run in 2023, have a full measurement with about 1000 h of beam time in 2024 before the backward endcap setup has to be prepared for the installation in the PANDA experiment in the year 2025.

Research Section SPECF: Hadron Spectroscopy and Flavour

A. Denig

The research section SPECF (Hadron SPECtroscopy and Flavour) is aiming for world class spectroscopy data of both hadrons and nuclei by a full exploration of the opportunities given by the future PANDA experiment at FAIR. Currently, during the construction phase of PANDA, the section has taken over the responsibility for the design and the construction of three sub detectors of PANDA and is active in the following working packages:

- The **luminosity detector (LUM)**, which is currently set up by researchers from Mainz (Denig) and from Bochum (Fritsch, formerly Mainz), will consist of a setup of four layers of pixel detectors based on the HV-MAPS technology. The detector will measure the elastically scattered antiprotons at small scattering angles and will be located approximately 11 m behind the interaction region of the experiment. The prototype of the luminosity detector will be operated at FZ Jülich as a part of the KOALA experiment (FAIR-Phase 0) before the start-up of PANDA. KOALA will measure the interference between the Coulomb and nuclear part in the elastic proton-proton scattering process, which will reduce the uncertainty of the elastic scattering cross section. More details regarding the progress of the LUM project is given below.
- The **hypernuclei and hyperatom setup (HYP)** will consist of a dedicated primary and secondary target station as well as a high-purity Ge array PANGEA, which is built in cooperation with the NUSTAR collaboration at FAIR. The study of strange nuclear systems (Pochodzalla) is an important pillar for our understanding of the (anti-) hyperon interaction with important relevance for nuclear astrophysics. At PANDA, the focus lies on measurement of hyperon propagation in nuclear medium and the study of hyperatoms and double hypernuclei. Recently, members of the HYP group participated also in successful studies of hyperon systems at J-PARC with kaon beams. More details regarding the progress of the HYP project is given below.
- Researchers of section SPECF (Sfienti) are furthermore planning to become involved in the construction of the **barrel DIRC detector of PANDA**. For this project, a laboratory in the Helmholtz Institute with dedicated long flow boxes will be equipped with the necessary infrastructure to glue the fused silica bars and the lenses to detector boxes, which will then be shipped to GSI for final assembly.
- Furthermore, the research section has been developing an effective selection scheme for a pure **online trigger** for PANDA (Götzen, Peters). Due to the high background rate in pbar-p annihilation and due to the numerous benchmark channels at PANDA, a fast trigger decision will be made online. Modern machine learning tools will be implemented for such an online trigger.
- The section (Denig, Götzen, Peters) is also involved in the **physics analyses of the BESIII collaboration** at the tau-charm factory BEPC-II in Beijing, China. At BESIII, the spectrum of light quark systems, of charmonium and of charmonium-like particles is investigated in electron-positron collision and important discoveries of so-called XYZ particles were made, which do not fit into the classification of ordinary charm-anti-charm states. Recently, with the discovery of a charged strangeness four-quark state, a new class of exotic mesons has

been discovered.

The investigations at BESIII serve as an excellent preparation for the PANDA physics program, where the studies can be continued with a new quality of precision. Recently, the section SPECF (Denig) was also successful in an application for Dr. Nils Hüsken within the highly competitive Marie Curie outgoing fellowship program of the European Union. Nils Hüsken is currently staying for two years at Indiana University and will be coming to Mainz afterwards.

Progress luminosity detector PANDA

For the prototype of the luminosity detector, the readout chain from the sensor to the outside of the vacuum box was designed and most of it produced. The flex cables have now been produced as individual cables per sensor. This makes the bonding of the cables to the sensors much easier. Moreover, the support PCB for the connection of four sensors has also been designed. It will be produced as soon as the tests with a test PCB in Bochum have been successfully completed. Recently, the 60 cm long rigid flex cables were delivered and are ready to be used.

Furthermore, the cooling system for the luminosity detector has been designed (PhD Leithoff) and is also ready to be used. In extensive cooling tests, the predictions by the simulation studies could be confirmed. Recently, in a long test campaign with more than 1000 temperature cycles, it could be shown that the system is operational for the full running time of PANDA.

To ensure safe operation of the vacuum system, a bachelor thesis was carried out on the control with a PLC. The implementation of safety functions during manual control are important features of the program. The final automation and the integration in the EPICS control system is under development.

Finally, the alignment of the box is currently being studied in a master thesis. The deformation under vacuum is measured as well as the position of the capacitive sensors with respect to locations outside of the box. With these measurements it will be possible to determine the position of the sensors with a precision better than 200 µm to the interaction point of PANDA.

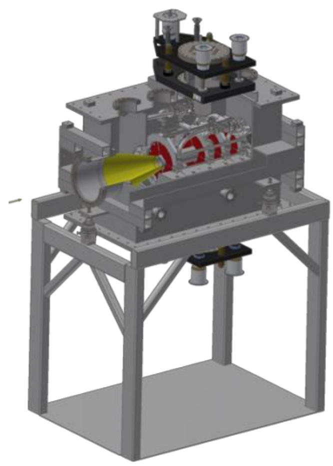

Fig. 3: PANDA Luminosity Detector

Progress hypernuclear physics setup PANDA

The main components of the hypernuclei / hyperatom setup include a dedicated target station, which will be mounted in the backward part of the PANDA detector and the Ge detector array, which is built in cooperation with the NUSTAR collaboration.

The principal design of the target stations is ready. Important features include a radiation-hard design and the selection of new piezo motors. As soon as the Covid-19 situation allows, it is foreseen to carry out dedicated beam tests at the MAMI accelerator for a full test of the setup. In the meantime the slow control system has been designed and is ready to be used.

The high-purity Ge crystals are ordered in a so-called triple cluster, for which the final construction has been finished. An issue with the cooler prototype has been discovered (microphonics) and a solution with the producer has been identified.

Research Section MAM: Symmetry of Matter and Antimatter

D. Budker

The MAM section is addressing fundamental questions in science related to the observed asymmetry of matter and antimatter in the universe. The asymmetry could indicate differences in the observable properties of antimatter with respect to matter but also unknown symmetry-breaking phenomena in the production mechanism of matter and antimatter in the universe that are not described in the standard model. Even though the section focusses mostly on experimental searches, it is also home to a theory division led by Gutenberg Research Fellow and HIM Guest Scientist, Prof. Dr. Victor Flambaum. He was supported by a Humboldt Fellow and 2018-Bragg-medal winner, Dr. Yevgeny Stadnik (now a faculty member at the IPMU, Tokyo), as well as two JGU PhD students. HIM MAM theorists devise novel approaches to tests of the standard model with atoms and molecules and to exotic-physics searches. A recent important result achieved in collaboration with the BASE experiment at CERN used trapped antiprotons to search for possible coupling to ultralight bosonic galactic dark matter. This is the first search for dark matter with an antimatter probe.

Experiments performed in the section involve high-precision measurements to compare the fundamental properties of matter and antimatter, precision measurements of symmetry-breaking phenomena within the standard model, and searches for new symmetry-breaking mechanisms not described in the standard model. In addition, we are engaged in a range of applied research, where we use the techniques and devices developed for fundamental physics to advance the fields having immediate practical impact.

Within the reporting time frame, the section contributed to more than 90 peer-reviewed articles and received 3rd party support, including an ERC starting Grant (to Dr. Dionysis Antypas), and two awards from the Alexander von Humboldt Foundation (AvH): the Sofja Kovalevskaja Award to Dr. Danila Barskiy and a Bessel Award to Prof. Gilad Perez, another of our close collaborators.

Some of the main results to be highlighted since June 2019 are:

Cosmic Axion Spin precession Experiment (CASPEr)

CASPEr is a multipronged approach to shed light on novel particles extending the standard model and potentially to understand the composition of dark matter. We are constructing and running experiments in Mainz and at the Boston University that are sensitive to the presence of dark-matter axion, axion-like-particles, dark photons and other proposed particles. The experiments look for resonant effects using (hyper)polarized nuclear spins as probes for the feebly interacting particles. The first significant physics results from CASPEr Mainz were published already in 2019, while major results from Boston were reported in 2021 in a Physical Review Letter, immediately following the paper reporting the celebrated FNAL muon g-2 result in the same issue of the journal.

Global Network of Optical Magnetometers for Exotic physics searches (GNOME)

GNOME is the first global magnetometer network designed as a dark matter observatory. The GNOME is a worldwide network searching for correlated signals heralding beyond-the Standard-Model physics which currently consists of more than a dozen optical atomic magnetometers, with stations in Europe, North America, Asia, the Middle East, and Australia. A schematic of a domain-wall encounter with the GNOME with stations used in this study is presented in Fig. 4.

The measurements from the magnetometers are recorded with data-acquisition systems, synchronized to the Global Positioning System (GPS) time, and uploaded to servers located in Mainz, Germany, and Daejeon, South Korea. In a paper submitted to Nature Physics, results are reported from the first full-scale search for transient signals from exotic fields of astrophysical origin using data from GNOME obtained in the second out of four completed coordinated runs. We searched for patterns of signals propagating through the network consistent with exotic fields composed of ultralight bosons such as axion-like particles (ALPs). Analysis of data from a continuous month-long operation of the GNOME found no statistically significant signals consistent with those expected due to encounters with topological defects (axion domain walls), placing new experimental constraints on such dark matter scenarios.

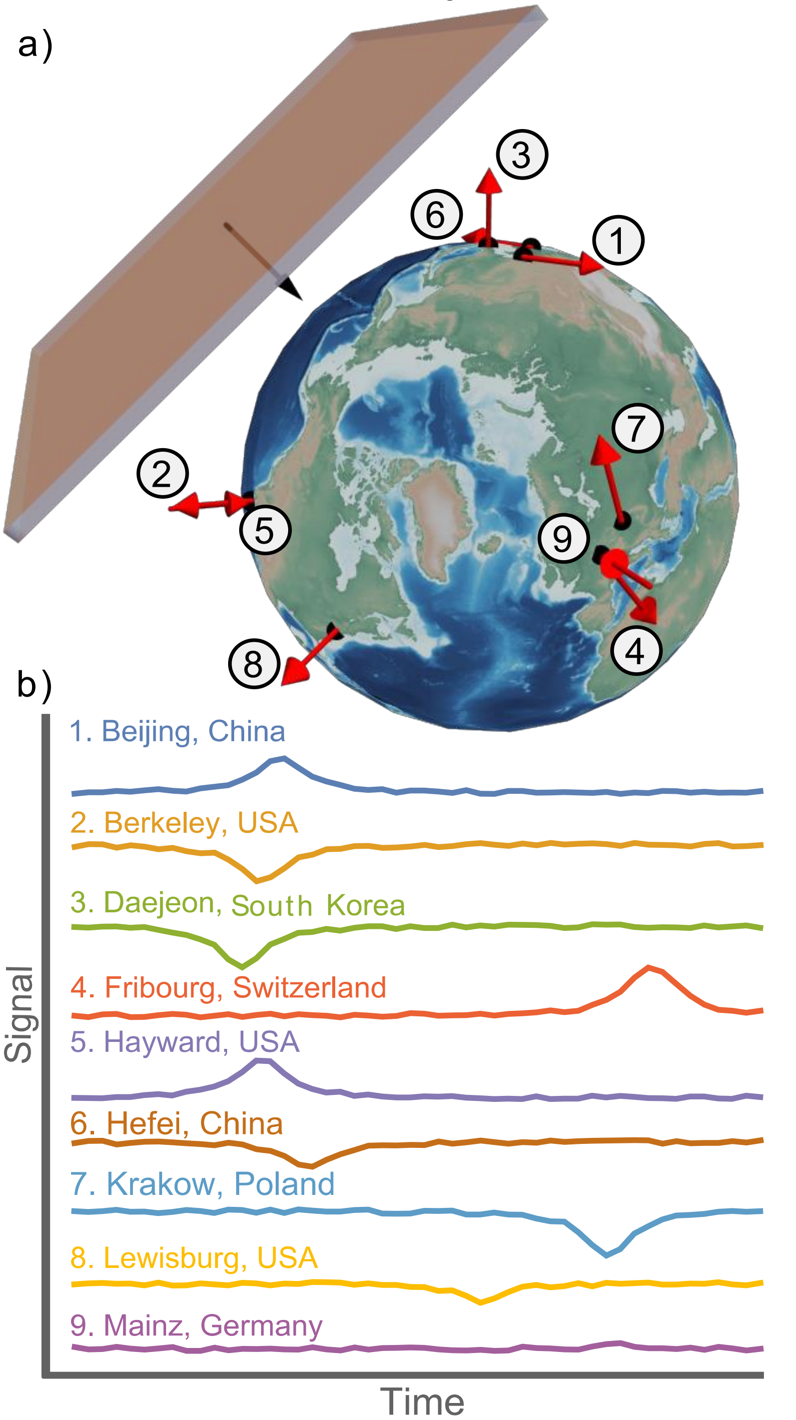

Fig. 4: (a) Visualization of an ALP domain wall crossing the Earth. The red arrows indicate the position and sensitive axes of the GNOME magnetometers during Science Run 2. (b) Simulation of the signals expected to be observed from a domain-wall crossing.

Production of polarized nuclear "targets" and zero-to ultralow-field NMR.

One of the prominent research directions of the HIM MAM section is unconventional nuclear magnetic resonance (NMR). NMR experiments are conventionally performed in large magnetic fields in order to increase chemical shift resolution and to maximize signal via higher nuclear spin polarization and improved inductive detection sensitivity.

Zero- to ultralow-field (ZULF) NMR is an alternative magnetic resonance modality where measurements are performed in the absence of a strong applied magnetic field. Unlike conventional NMR, in which "external" spin interactions – couplings to fields originating from the experimental apparatus – are dominant, zero-field NMR presents a regime dominated by "internal" spin interactions – couplings to fields originating from the sample itself. The ZULF platform has proven to be extremely productive, with results ranging from new limits on ultralight bosonic dark matter to monitoring catalytic chemical reactions inside metal containers. We are currently running a Marie Curie Innovation Training Network (ITN) that will train about a dozen PhD level scientists for Europe, Fig. 5.

Fig. 5: HIM MAM is one of the partners in the Marie Curie Innovation Training Network in ZULF NMR and hosted a ZULF NMR conference.

Biomagnetic measurements. The techniques of sensitive magnetometry that we develop for fundamental-physics experiments can be immediately used to detect field from human and animal bodies that produce strong enough magnetic fields to be detected by such modern magnetometers. We have recently explored, in collaboration with doctors at the University clinic, such fields produced by nerve signals propagating in the arm of a human subject following transcranial magnetic simulation (TMS). The challenge is making such measurements following the strong-field TMS pulse applied to the patient's head. We addressed this challenge by asking the subject to insert their hand into a magnetic shield that also contains an array of sensors.

In another line of research, in collaboration with PTB Berlin, we have successfully detected magnetic fields produced by a plant, the carnivorous Venus fly trap. We discovered that plants also produce detectable fields that accompany the firing of electric "action potentials".

Battery diagnostics. Another application of sensitive magnetometry is nondestructive diagnostics of batteries, a topic the practical importance of which at this time cannot be overestimated. We have collaborated with researcher from NYU (USA) and the Japanese company TDK to devise robotic battery scanners (installed at our laboratory at HIM and NYU) incorporating advanced magnetic sensors and have published several articles describing the novel diagnostic techniques.

Research Section SHE:
Stability and Properties of Superheavy Elements

Ch. E. Düllmann and M. Block

As all activities of the HIM section Superheavy Elements (SHE) are carried out jointly with the GSI Departments on Superheavy Element Chemistry and Physics, we include here also some of the activities led by the GSI departments “Superheavy Element Physics” and “Superheavy Element Chemistry”. In 2020, activities at GSI focused on the UNILAC beamtime within the FAIR Phase-0 program, comprising decay spectroscopy of Fl, chemistry studies of Nh, and laser spectroscopy of Fm and Lr. In addition, the analysis of data obtained in prior beamtimes was continued. At HIM, the advancement of technical and methodological developments, for example for applications in laser spectroscopy and mass spectrometry as well as radionuclide layer production for various applications was most central. In addition, preparations for the beamtime 2021 have been performed.

Synthesis

The search for new elements beyond Og (Z=118) is currently a hot topic in superheavy element research. Attempts to produce the elements 119 and 120 in the ^{50}Ti+^{249}Bk and ^{50}Ti+^{249}Cf reactions were carried out in 2011/2012 at the gas-filled recoil separator TASCA. These reached low cross-cross sensitivities, however, did not result in the discovery of new elements, likely due to aspects of the nuclear reaction mechanism [J. Khuyagbaatar et al., Phys. Rev. C 102, 064602 (2020)]. The reached sensitivity levels are very valuable to enhance the understanding of the nuclear reaction mechanism occurring in beyond-^{48}Ca induced heavy-ion reactions on actinide targets, which did not lead to the production of SHE to date. While the search for new elements is not currently pursued at GSI, studies of the nuclear reaction mechanism continue, in collaboration with Australian National University in Canberra, Australia. We investigated various deep-inelastic reaction channels in four different reactions potentially suitable for the discovery of element 120 [H.M. Albers et al., Phys. Lett. B 808, 135626 (2020)]. The measured deep-inelastic channels show quasi-fission to be the dominant reaction outcome, however, at different contact timescales. The longest interaction time was found for ^{50}Ti+^{249}Cf, which suggests this reaction to be the most promising one in the entrance channel. This result confirms that the choice to synthesize elements 119 and 120 at TASCA in ^{50}Ti-induced reactions was correct [J. Khuyagbaatar et al., Phys. Rev. C 102, 064602 (2020)].

Nuclear structure

Nuclear fission is one of the main issues determining the stability of superheavy nuclei. In the SHE chemistry department the fission process is intensively studied both theoretically [J. Khuyagbaatar, Nucl. Phys. A 1002, 12195 (2020)] as well as experimentally [J. Khuyagbaatar et al., Phys. Rev. Lett. 125, 142504 (2020)]. In a semi-empirical description of all known half-lives of even-even heaviest nuclei [J. Khuyagbaatar, Nucl. Phys. A 1002, 12195 (2020).], it has been shown that fission might be one of the main decay modes for the yet unknown element 120. Accordingly, this decay mode should also be considered in any discovery experiment on element 120. The obtained results also support that a lowering of the outer fission barrier occurs in the superheavy nuclei, which had been inferred previously from the analysis of the electron capture delayed fission. Thus, the new results support the predicted large electron-capture delayed fission (ECDF) branching in the SHN. The ECDF phenomenon is a promising topic for examining fission properties of superheavy nuclei. The occurrence of ECDF has been examined in the new isotope ^{244}Md at TASCA [J. Khuyagbaatar et al., Phys. Rev. Lett. 125, 142504 (2020)]. No ECDF branch was discovered because the new isotope ^{244}Md decays mostly by α-decay. At the same time, we have observed a short-lived fission activity, which could not unambiguously be attributed to a specific physical process and deserves further investigation. This work was included in the list of the few most important achievements in the fields of particle-, nuclear and accelerator physics of pro-physik.

In the wake of the discovery of superheavy elements, nuclear spectroscopy experiments aim at providing anchor points at the upper end of the nuclear chart for nuclear structure theory, which otherwise solely relys on extrapolations. In two runs in 2019 and 2020, such a nuclear spectroscopy experiment was conducted to study α-decay chains stemming from isotopes of flerovium (element Z = 114). One incentive to study flerovium isotopes is that many, but not all, nuclear structure models or model parametrizations favour Z = 114 as the next magic proton number beyond lead, Z = 82. This was studied in an experiment, in which an upgraded TASISpec decay station was placed behind TASCA. The fusion-evaporation reactions ^{48}Ca+^{242}Pu and ^{48}Ca+^{244}Pu provided a total of 32 flerovium-candidate decay chains in effectively 18 days of beam time. Two and eleven decay chains were firmly assigned to even-even isotopes, ^{286}Fl and ^{288}Fl respectively. The – admittedly unexpected – observations include (i) an excited 0^+ state at 0.62(4) MeV excitation energy in ^{282}Cn, and (ii) a Q_α = 9.46(1) MeV decay branch, $b_\alpha \approx 2\%$, from ^{284}Cn into ^{280}Ds [A. Såmark-Roth et al., Phys. Rev. Lett. 126, 032503 (2021)]. Both observations indicate that there is hardly any shell gap at proton number Z = 114. This statement is supported by demanding beyond-mean-field model calculations, which include the necessary triaxial shapes [J.L. Egido and A. Jungclaus, Phys. Rev. Lett. 125, 192504 (2020)]. The existence of the excited 0^+ state in ^{282}Cn requires an understanding of both shape coexistence and shape transitions for heaviest nuclei. Also, using the known Q_α = 10.79(4) MeV for the $^{292}\mathrm{Lv} \rightarrow {}^{288}\mathrm{Fl}$ α decay as well as the now precisely measured Q_α = 10.06(1) MeV for $^{288}\mathrm{Fl} \rightarrow {}^{284}\mathrm{Ds}$, a smooth Q_α sequence across Z = 114 could be established. Hardly any kink is observed at Z = 114, while it is characteristic for any pronounced shell gap. The present results thus reinforce the benchmarking capability of nuclear spectroscopy experiments in the superheavy nuclei.

Atomic physics

The investigation of the heaviest elements by laser spectroscopy at SHIP has been further extended. In the GSI beamtime 2020, the atomic level search in lawrencium was started using the RADRIS method. It was shown that Hf is a suitable filament material for the efficient neutralization and evaporation of Lr with low background level from surface ionization. A significant part of the range, in which atomic transitions were predicted by atomic theory, was scanned using a two-step laser excitation scheme, but no evidence for a transition was observed yet. In addition to the Lr level search, for the first time laser spectroscopy of $^{248\text{-}250}$Fm was performed by a variant of the RADRIS method. These Fm isotopes are inaccessible in a direct production scheme and were produced via α decay of $^{252\text{-}254}$No. A two-step laser excitation scheme was used with the second step populating an autoionizing state. We measured the isotope shift of the 5,112 cm^{-1} transition in $^{248\text{-}250}$Fm. However, the hyperfine splitting of this transition in ^{249}Fm was not fully resolved due to limited statistics. This work extended optical spectroscopy in the Fm isotopes to neutron-deficient isotopes below the N = 152 deformed neutron shell closure complementing recent work at the RISIKO mass separator of Mainz university performed in collaboration with the SHE departments at GSI and HIM. There, the long-lived isotope ^{257}Fm was studied by resonance ionization laser spectroscopy in a hot-cavity ion source offline. The same technique was used to study the einsteinium isotopes $^{253\text{-}255}$Es. In 2020, an injection-seeded laser was used to measure the complex hyperfine structure splitting of three different transitions in ^{254}Es with increased spectral resolution. The obtained data will provide information of the nuclear moments and the changes in the mean-square charge radii in the Fm and Es isotopes.

For future on-line measurements on the heaviest elements with improved spectral resolution, a new setup for in-gas jet laser spectroscopy was commissioned. Different de Laval nozzles were compared to identify the optimum pressure conditions to form a gas jet with a Mach number of 8. A spectral resolution of about 400 MHz was obtained measuring resonances in the stable isotope ^{174}Yb, a chemical homologue of No. This paves the way for a measurement of the K=8^{-} isomer in ^{254}No in the 2022 beamtime at GSI.

Chemical studies: Elements beyond copernicium: nihonium, flerovium, moscovium and perspectives for livermorium

The first chemical study of Nh at TASCA was attempted in 2016. The non-observation of any Nh events in a three-week experiment pointed at losses of Nh atoms on surfaces encountered on the way to the detection system COMPACT due to a high chemical reactivity of Nh. Several preparatory studies with chemically reactive metals (Tl, Pb, Fr) have been performed in 2018 and 2019, aiming at a faster and more efficient extraction of short-lived and chemically reactive species into the gas chromatography and detection setup, extended with a new detector array (16-element miniCOMPACT), which was directly attached to the recoil transfer chamber.

Based on the obtained positive results an advanced 64-element miniCOMPACT detector was built. In 2020, during a beamtime of 20 days, the reaction ^{48}Ca + ^{243}Am was used to produce ^{288}Mc in the 3n exit channel. Reaction products were separated in TASCA, thermalized in a newly designed recoil transfer chamber (RTC) and transferred into the new advanced miniCOMPACT. Seven decay chains, assigned to ^{288}Mc and ^{284}Nh, were observed. The obtained data are under evaluation and will allow to define the interaction strength of Nh towards SiO_2. The observation of two decay chains originating from ^{288}Mc ($T_{1/2} \approx 170$ ms) is promising for the chemical study of Mc, which is scheduled at GSI for 2021.

Complementing the experiments with SHE, off-line studies with Pb and Bi as lighter homologs of Fl and Mc were performed. Short-lived volatile ^{219}Rn, provided from an ^{227}Ac source, was flushed with flowing gas. The daughters ^{211}Pb and ^{211}Bi were flushed through the RTC into the miniCOMPACT array. Chromatograms were recorded as a function of various parameters like carrier gas type, gas flow rate and pressure, thus characterizing the novel detector array and aiding to optimize the conditions for experiments with superheavy elements. Pb and Bi showed the expected high reactivity towards the silicon dioxide surface of the miniCOMPACT.

On the way to even more short-lived elements like Lv, the extraction time to transfer the isotopes from the RTC into COMPACT needs to be reduced, as this is significantly longer than the half-lives of even the most long-lived isotopes of all elements beyond Fl. To overcome this limitation, exploratory experiments to study the performance of a buffer gas cell in combination with a COMPACT array were carried out using short-lived α-decaying Hg, Fr, and At radioisotopes. These were produced in ^{40}Ar- and ^{48}Ca-induced nuclear fusion-evaporation reactions, isolated in the recoil separators MARS at Texas A&M University (USA), and TASCA at GSI and thermalized in a gas-stopping cell. From the latter, the nuclear reaction products were extracted into gas-phase chromatographic systems. The efficiency for transporting chemically reactive Fr radioisotopes into the optimized miniCOMPACT gas-chromatography setup was measured and supports that this technique enables the identification of isotopes of volatile as well as non-volatile elements. These studies guide the path towards chemical investigations of elements beyond flerovium, which are beyond the reach of current setups. However, the presently used gas cell is not efficient enough for experiments with superheavy elements. To overcome this problem, the design of the advanced “UniCell” has started.

Chemical theory supporting experimental work

In assistance to the coming experiments on the study of reactivity and volatility of Mc and its homolog Bi, calculations of adsorption properties of Bi and Mc on the surfaces of gold and quartz have been performed with the use of the ADF BAND relativistic periodic code. The results have shown that Mc will adsorb on the hydroxylated quartz surface similarly to Nh with an energy of 58 kJ/mol. Adsorption of Bi is much stronger.

Both elements will adsorb very strongly on the gold surface with the energy above 200 kJ/mol. With the aim to support gas-phase experiments on the volatility of element 113, Nh, and its homolog Tl, adsorption energy calculations of TlOH and NhOH on the hydroxylated surface of quartz have been performed with the use of the ADF BAND and Quantum Espresso (QE) pseudopotential methods. The preliminary results (-83 kJ/mol with BAND and -69 kJ/mol with QE for TlOH) show that the interaction has a complex nature and that a rearrangement of the surface OH groups occurs. There could also be a formation of H_2O molecules on the surface, from hydrogen atoms and hydroxy groups “ripped” off the surface. This work is ongoing. Further work focuses on the theoretical investigation with molecular ADF on the formation of small molecules of Mc and Ts in COMPACT-type setups. We found that formation of oxides and their reduction with hydrogen is energetically favourable.

Quantum chemical software developments

Quantum chemical studies with a particular focus on molecular properties and reactivities of chemical systems with SHE necessitates treating scalar-relativistic effects, spin-orbit coupling and electron correlation effects on an equal footing. Recently, we presented an implementation of the matrix-product state (MPS) wave function parametrization of the density matrix renormalization group approach within the relativistic quantum chemistry software package DIRAC [T. Saue et al., J. Chem. Phys. 152, 204104 (2020)] which was applied to study electron correlation effects on the valence electronic shell structure of Og [S. Knecht, Nachr. Chem. 67, 57 (2019)]. Since orbital relaxation beyond a mean-field picture often plays a crucial role for a correct description of chemical properties in ground- and electronically excited states we currently develop an ansatz based on a relativistic MPS reference wave function. Moreover, work is in progress to address the issue of dynamical electron correlation along the lines of non-relativistic developments.

Production of improved actinide targets for SHE production

To date, actinide targets for research into superheavy elements are mainly produced using the Molecular Plating (MP) process. Neither the exact chemistry nor the layer modifications induced by heavy-ion irradiation have been fully elucidated so far. For this purpose, MP-produced lanthanide targets were irradiated at different fluences in TASCA and at the M3 branch of the Material Research beamline. Further irradiations with ultra-low-energy particles were carried out at the Offline Deposit Irradiation (ODIn) setup [R. Haas et al., Nucl. Instrum. Meth. A 957, 163366 (2020)] at HIM. The analysis of the irradiated targets with various methods in house and at external partner institutions is ongoing.

To overcome the limitations of classical molecular plating, which is applicable for the production of thin layers with a thickness of at most about 800 $\mu g/cm^2$, a novel, triflate-based electrochemical deposition method for target production is being developed. For this, triflate salts of different lanthanides have been synthesized and were activated in the TRIGA reactor. The lanthanide precursors produced in this way were used for extensive experiments series on the electrodeposition from N, N-dimethylformamide (DMF). Layers with thicknesses up to 2000 $\mu g/cm^2$ were obtained and were characterized by autoradiography. Circular Tm layers were produced and irradiated with ^{48}Ca beam at TASCA. Characterization is currently ongoing, in collaboration with the Materials Research departments at GSI and at TU Darmstadt. As a next step, this process will be adapted to produce layers in the shape of TASCA target.

Production of targets for various collaborators

A multitude of further targets and sources, mostly of actinides were prepared for studies within our groups, e.g., at TRIGA-TRAP, as well as for use in collaborative work, including Am, Cm, and Cf samples provided for laser spectroscopy studies at the RISIKO laser mass separator [N. Kneip et al., Hyp. Int. 241, 45 (2020).], ^{248}Cm sources for spontaneous fission studies at the GSI FRS ion catcher, as well as ^{229}Th samples for UCLA (USA) for studies connected to the low-energy isomer ^{229m}Th.

For MPI-K in Heidelberg, 5 targets of ^{40}Ca, each with a different amount between 10^{12} and 10^{17} atoms, was prepared by drop-on-demand printing. These targets serve as efficiency test candidates to determine the necessary amount of Ca atoms in a laser ablation ion source [Ch. Schweiger et al., Rev. Sci. Instrum. 90, 123201 (2019).] for fundamental physics studies using the full Ca isotopic chain.

A few hundred kBq of ^{169}Yb were produced for Helmholtz Institute Jena by irradiating enriched ^{168}Yb at the TRIGA Mainz. The sample provides γ lines of ^{169}Yb, which serve to calibrate ultra-high resolution micro-calorimeter detectors used for precise X-ray measurements of hydrogen-like uranium isotopes in an upcoming experiment at the GSI ESR.

Publications from collaborative work that was published this year includes the results obtained in the high-precision mass measurement of the HD^+ molecule using DoD-produced deuterium targets provided to MPI-K last year have been published this year [S. Rau et al., Nature 585, 43 (2020).] as well as the determination of the excitation energy of ^{229m}Th using a γ spectrometric approach [T. Sikorsky et al., Phys. Rev. Lett. 125, 142503 (2020)].

To further broaden the set of methods available for the production of thin layers of exotic isotopes, a spin-coater optimized for work with radioactive materials has been constructed. Spin-coating is an established method to produce nanometre-thick layers. Several new precursor synthetic routes for various elements were developed to produce tailor-made actinide targets, e.g., using polymer-assisted deposition (PAD), sol-gel chemistry, etc. The precursor chemistry developed for spin coating also served for layer production by the drop-on-demand (DoD) method [R. Haas et al., Nucl. Instrum. Meth. A 874, 43 (2017).]. The Th targets produced in this way were used for mass measurements at TRIGA-TRAP.

Developments for Mass Measurements of Superheavy Nuclides

At SHIPTRAP, the vacuum system was further improved by the installation of non-evaporable getter pumps to enable longer measurement times while minimizing losses due to charge exchange and molecule formation. As a consequence, the rate of ^{257}Rf ions available in the SHIPTRAP measurement trap was increased in the 2020 beamtime by almost an order of magnitude compared to 2018 in a preparatory experiment for high-precision mass measurements of Rf and Db isotopes with SHIPTRAP in 2021.Developments for single-ion mass measurements of rare exotic nuclides utilizing a non-destructive electronic detection scheme with the Fourier-transform ion-cyclotron-resonance method were continued. Such methods can be applied in mass measurements of superheavy nuclides with SHIPTRAP and on other exotic nuclides with MATS at FAIR. A novel version of a resonant tank circuit with a quartz resonator serving as the inductor was employed to detect trapped ions in the TRIGA-TRAP Penning trap at room temperature. A sensitivity of some ten ions was achieved and a proof-of-principle mass measurement on ^{206,207}Pb ions was performed with TRIGA-TRAP [S. Lohse, J. Berrocal, S. Böhland, J. van de Laar, M. Block, S. Chenmarev, Ch. E. Düllmann, Sz. Nagy, J. G. Ramírez, and D. Rodríguez, Rev. Sci. Instrum 91, 093202 (2020)]. Further improvements are under way to further increase the sensitivity.

Research Section ACID: Accelerator Physics and Integrated Detectors

W. Barth, K. Aulenbacher

ACID-I

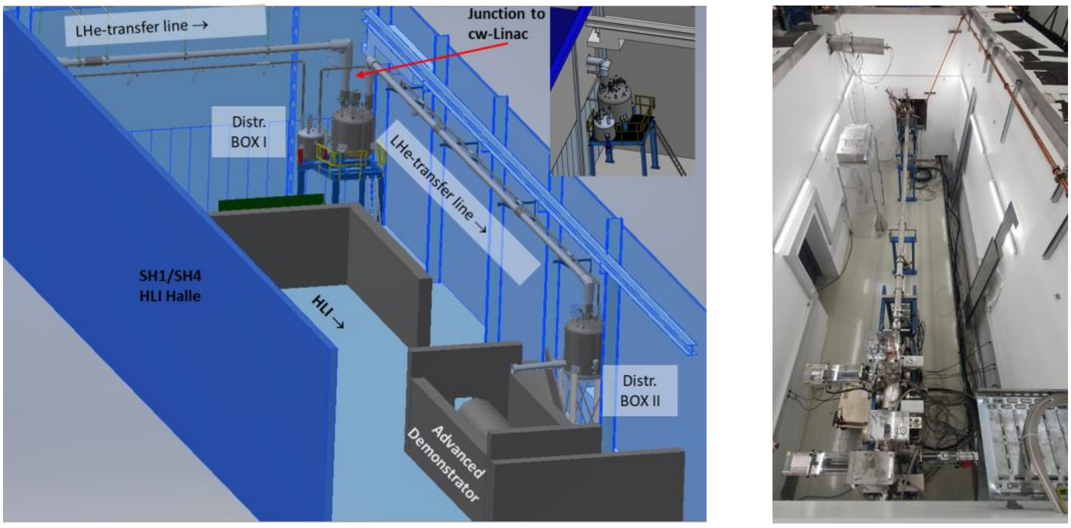

Fig 6: 3D Model of the Helium infrastructure for the cw-Linac and its test area (left). The radiation protection shelter with the newly installed beamline and a beam diagnostic bench is shown on the right side.

The revised cw-Linac layout considering optimized cavity layouts with modified voltage distributions provides three CH-cavities and a rebuncher per cryo module (CM1 – CM4) as well as two sc solenoids for transversal beam focusing. It features high acceleration efficiency with longitudinal and transversal stability and a straightforward energy variation. Highly charged ions will be accelerated from 1.4 MeV/u up to 3.5 - 7.3 MeV/u. The design is sufficient to accelerate light up to heavy ions ($1 \leq A/q \leq 8.5$), this has been confirmed experimentally once again. The advanced cryomodule (CM1) insides are in the final production stage as well as the cryostat, which accommodates all cryogenic components. The delivery of the cryostat is scheduled to May 2021, the rebuncher cavities for CM1 and CM2 are also in the manufacturing process, delivery of the first cavity is announced for the 3rd quarter of 2021 – the superconducting solenoids are going to be delivered in March 2021. All Rf-cavities are already fabricated. Three different test campaigns have been carried out to accomplish Rf testing of CH-cavities with the horizontal test cryostat at the HIM-SRF-lab, vertical Rf-tests of CH1 and CH2 were conducted at Goethe University Frankfurt (Institute of Applied Physics). Another important milestone was the successful rf-performance test of the rf-power coupler prototype. After this the series production of the ceramic rf-windows started, which are scheduled for delivery in the 2nd quarter of 2021. Besides the design of the next generation of CH-cavities CH3 – CH5 sufficient to serve for CM2 and CH6 – CH8 for CM3 was carried out and reviewed – all specifications are prepared to start with purchasing. On the basis of the CM1-cryostat, the CM2-cryostat has been technically specified and already ordered. The newly developed standard cryostat design will be adapted to the higher energy application for the subsequent modules (CM3-4).

For stable 4 K operation of the entire cw-Linac HELIAC (HElmholtz LInear ACcelerator) a cryo plant with 240 W total cooling power@4K is required. The cryo plant of the GSI-Series Test

Facility (STF) with a cooling capacity of 700W is foreseen to supply the HELIAC after the magnet testing will be finished. Figure 6 shows a 3d model of the newly installed Helium transfer lines and the distribution boxes.

The distribution box guides the Helium either to the test area or to the installation site of the HELIAC in the neighbouring hall. The commissioning of the He-supply infrastructure has been accomplished in the 3rd quarter of 2020. In preparation for further beam test activities, the beamline, which connects the “GSI-Hochladungsinjektor” (HLI) with the testing area, was installed. The photograph on the right side of Fig. 6 shows the beamline in the radiation protection shelter, instead of the cryogenic module initially a long vacuum pipe has been installed. The beamline enables transversal and longitudinal matching, provided by a newly installed 4-gap RF-buncher cavity. Furthermore, for beam-based alignment of the cryogenic module new collimating slits in front of the test area were installed. The slits cut out the beam halo and potentially can produce a pencil like beam. The beam diagnostics bench at the end of the beamline (inside the protection shelter) is equipped with current transformers, phase probe pairs for TOF measurement of the outcoming beam energy, a slit-grid device for transversal emittance measurement, a bunch structure monitor (Feshenko monitor) for measurement of the longitudinal beam profile. This setup allows for complete 6d characterization of the beam. The entire beam line together with the beam diagnostic bench was successfully commissioned with beam during the engineering run in November 2020. Altogether, the achievements described above, are important steps toward the upcoming full performance test of the prototype cryo module (Advanced Demonstrator) with beam, scheduled for June 2022.

ACID-II

ACID-II is mainly performing R&D work concerning electron cooling for the PANDA experiment at the upcoming HESR storage ring. The antiprotons in this ring will circulate with a beam energy of almost 15GeV thus requiring an electron beam of nearly 8MeV. Such an energy has so far not been achieved with an electron cooler and the challenge is even increased by the fact that currents of the order of Amperes are required. In addition, the beam has to be immersed in a continuous longitudinal magnetic field. So far, the device which operates at the highest energy under such conditions is the COSY-cooler that was installed by Budker institute Novosibirsk (BINP) and is designed for voltages of 2MV. In cooperation with BINP, ACID-II is aiming to remove a major obstacle for higher energies, namely the potential free powering of the solenoid channel in the several meters long acceleration and deceleration stage.

We have made cooperation agreements with BINP to develop a potentially game changing device for electrostatic accelerators, namely the generation of potential free electrical power via gas turbines. Besides the production of much more electrical power than available with conventional devices, the strongly cooled exhaust gas of the turbines offers improved conditions for thermal management. Turbines were tested successfully at HIM in the past and BINP has developed a prototype stage for 600kV which incorporates a solenoid as load. In 2019 BINP has agreed to produce a second 600kV stage which will serve as demonstrator for the scalability of the turbine concept. It will also comprise acceleration tubes. The production of the stage is on schedule in spite of the pandemic, its delivery is expected in spring 2022.

So far, the absence of a pressure vessel limited the operating voltage. Meanwhile, ACID-II engineers have designed a suitable pressure tank and the order has been placed in autumn 2019. The production of the tank was delayed by the pandemic by about half a year. The tank is ready and has passed the pressure tests by the authorities. Delivery to Mainz is expected in April or May 2021.

By end of 2021 we plan the installation of the available stage in the pressure vessel, which should allow testing turbine powered 600kV operation. Then, we will go for cascading two stages and to equip them with three turbines, the additional turbine will serve for the electron source and collector. This will represent a full “1:6” scale HESR cooler prototype operating with ample electrical power to focus the beam and to generate auxiliary power for the electron source and the collector.

In parallel we have continued the work in our test cooler device. The test cooler has been moved from nuclear physics institute to the HIM (experimental) hall and has been re-commissioned. This required considerable resources to provide for safety installations concerning electrical and radiation hazard. By introducing stronger insulators, the HV capability has been increased to 30kV which should allow beam currents of 1 Ampere or even more. A more symmetrical electrode arrangement in the electron source allows increasing the magnetic field at the cathode. By installation of a cooled CCD-camera it has been possible to observe the beam induced fluorescence at a current of 500mA without the need to introduce an additional gas load, i.e. at a vacuum level of $1*10^{-9}$ mbar. Further activities at the test-cooler apparatus concern dynamical effects such as the ion-trapping process by space charge. Other fields of beam diagnostics address stabilization for the P2 beam within the excellence network activity and the development of its polarimeter.

We have also started a new activity which makes use of our experience with high power electron sources. ACID-II is part of a collaboration which tries to realize “Microbeam”-radiation therapy which is based on generating a stripe pattern by collimating the X-rays from a line source with high aspect ratio ($15*0.05\ mm^2$). It turns out that this requirement is helpful to overcome the X-ray flux limitations of conventional X-ray tubes since additional heat transport is achieved along the small axis by the out-scattered electrons in the material. This can increase the flux towards levels which are sufficient for radiation therapy. ACID-II is member of a collaboration headed by TUM with the Helmholtz centers München and Jülich as additional partners. ACID-II is responsible for the design of the electron source and the focusing system. The line focus has to be achieved at a beam energy of 300keV and a current of 300mA. Simulations with the CST software package show that the goals can be reached. First tests of the source are expected in 2022.

Research Section THFL: Theory Floor

Hartmut Wittig

Section THFL addresses a wide range of subjects in hadron and nuclear physics, using state-of-the-art theoretical tool such as QCD factorisation, Lattice QCD and nuclear effective field theory. Activities are focussed on hadron structure, hadron spectroscopy, nuclear effects in muonic atoms, and studies of the QCD phase diagram. Following the appointment of Jens Erler as a new professor at Mainz in January 2021, the activities of the section have been broadened to include electroweak precision tests of the Standard Model in the low-energy domain. Furthermore, the collaborative links between HIM-THFL and the Theory Group at GSI have been strengthened following the appointment of HIM postdoc Daniel Mohler to a permanent scientific staff position at GSI. Below we describe recent research highlights.

In the area of **Hadron Phenomenology**, the group of Vanderhaeghen extended their previous description of the $\pi^+\pi^-$ and $\pi^\pm J/\psi$ invariant mass distribution in conjunction with cross section data on $e^+e^- \to J/\psi\, K^+ K^-$. A key ingredient was the treatment of the $\pi\pi$ and KK final state interactions with the help of the Omnès formalism. This allowed for the first theoretical prediction for the KK invariant mass distribution in $e^+e^- \to J/\psi\, K^+ K^-$, which was found to be significantly different from pure phase space. The constructed amplitudes serve as an essential framework to extract the parameters of the $Z_c(3900)$ exotic state more accurately from forthcoming measurements by the BESIII and Belle II Collaborations.

As part of the Helmholtz Excellence Network, Erler and collaborators published an updated calculation of the γZ-box correction which is required to determine the weak mixing angle at low energies in parity-violating electron-proton scattering. To this end they adopted a Regge parameterisation fitted to neutrino and antineutrino inclusive scattering data to predict the parity-violating structure function $F_3^{\gamma Z}$ via isospin symmetry. The new analysis confirms previous results for the axial contribution to the γZ-box graph and reduces the uncertainty by a factor of two. Furthermore, using constraints on the nucleon anapole moment the associated uncertainty could be estimated. The correction due to γZ-box graphs was determined for the QWeak and P2 experiments.

Activities in **Lattice QCD** focussed on calculations of structural properties of the nucleon, studies of hadron resonances and multi-baryon states, as well as investigations of the properties of the quark-gluon plasma.

Among recent research highlights is a new determination of the isovector electromagnetic form factors of the nucleon, using gauge ensembles that cover a wide range of lattice spacings, volumes and pion masses, including the physical value of m_π. Several methods were applied to control the unwanted contributions from excited states. The nucleon magnetic moment and the charge radii were determined by simultaneously fitting the dependence of the electric and magnetic form factors on the pion mass and the squared momentum transfer Q^2. To this end the expressions of covariant ChPT were used, augmented by terms parameterising the leading discretisation errors and/or finite-volume effects. The estimate for the proton radius was obtained by combining the estimate for the isovector charge radius with the experimental measurement of the neutron charge radius, which yields $\langle r_p^2 \rangle^{1/2} = 0.827(40)\ \mathrm{fm}$. Thus, the results favour the smaller proton radius as measured in muonic hydrogen, while they are in slight tension (2.4 standard deviations) with the measurement in electron-proton scattering by the A1 collaboration.

Another highlight is the first lattice QCD calculation of the H dibaryon, a conjectured bound state of two Λ-baryons, in the continuum limit. To this end Lüscher's finite-volume quantisation condition was applied to lattice spectroscopy data at five different lattice spacings, supplemented by terms that parameterise discretisation effects. Results indicate that lattice artefacts change the results considerably. In SU(3) flavour-symmetric QCD with $m_\pi = m_K = 420\ \mathrm{MeV}$, a binding energy of $3.97 \pm 1.16 \pm 0.86\ \mathrm{MeV}$ was found, which is about one order of magnitude smaller than the results reported at non-zero lattice spacings. A paper describing the results has been submitted to Physical Review Letters.

The Lüscher formalism was also used to study charmonium resonances and bound states near the open charm threshold. In a recent paper, the first lattice investigation of coupled-channel $D\bar{D}$ and $D_s\bar{D}_s$ scattering for $J^{PC} = 0^{++}$ and 2^{++}, at fixed lattice spacing and $m_\pi = 280\ \mathrm{MeV}$ was performed, extending previous work for $J^{PC} = 1^{--}$ and 3^{--}. The results suggest the existence of three scalar charmonium-like states in the region slightly below $2m_D$ up to $4.13\ \mathrm{MeV}$. In addition, an unobserved $D\bar{D}$ bound state just below threshold and a $D\bar{D}$ resonance likely related to the $\chi_{c2}(3860)$ was found. Furthermore, there is evidence for a narrow 0^{++} resonance below the $D_s\bar{D}_s$ threshold, which is possibly related to the narrow states $X(3915)$ and $\chi_{c0}(3930)$ observed by LHCb and BaBar, Belle, respectively.

In the area of strong-interaction matter at non-zero temperature, lattice QCD was used to calculate the rate of real-photon emission from the quark-gluon plasma at a temperature of $T = 254\ \mathrm{MeV}$. The calculation is based on the difference between the spatially transverse and longitudinal parts of the polarisation tensor, which has the advantage of falling off rapidly at large frequencies. This combination has been determined in the continuum limit of two-flavour QCD with a precision of about two parts per million. Surprisingly, the non-perturbative results constrain the photon rate to be no larger than twice the weak-coupling prediction for momenta $k = 1.0 - 1.4\ \mathrm{GeV}$, inspite of the low temperature. Another publication addressed the interpretation of the structure functions of a thermal medium such as the quark-gluon plasma in terms of the scattering of an incoming electron on the medium via the exchange of a spacelike photon. In the deep-inelastic scattering regime, the corresponding moment sum rules obeyed by the structure functions were derived. These moments are given by the thermal expectation value of twist-2 operators, which is computable from first principles in lattice QCD.

The **low-energy nuclear reaction** group led by Pierre Capel has continued their study of nuclear reactions to study the structure of halo nuclei, employing an effective field theory, known as Halo-EFT. This approach describes the interaction between the halo and the nuclear core in a power series of the small core binding energy, with expansion coefficients fitted to physical observables. In a series of papers the group has studied the Halo-EFT description of $^{15}\mathrm{C}$ and other halo nuclei in accurate nuclear-reaction models. By combing the EFT description with accurate reaction models, excellent agreement with data without fitting any parameter was obtained. This included the transfer reaction $^{14}\mathrm{C}(d,p)15^{15}\mathrm{C}$ at $E_d = 17\ \mathrm{MeV}$, and the breakup reaction $^{15}\mathrm{C} + \mathrm{Pb} \to {}^{14}\mathrm{C} + n + \mathrm{Pb}$ at 605 and $68\ \mathrm{MeV/nucleon}$, using experimental data from GSI. A paper on the extension of the Halo-EFT description to the knockout reaction $^{15}\mathrm{C} + {}^{9}\mathrm{Be} \to {}^{14}\mathrm{C} + X$ is in preparation.

The **ab initio nuclear theory group** lead by Sonia Bacca has focussed on the calculation of nuclear structure corrections to the Lamb shift in muonic deuterium. To this end, the deuteron response functions were computed in chiral nuclear effective field theory up to NNNLO and used as input in a dispersive formalism. In this way, the accuracy could be improved significantly, which opens up the possibility of applying this hybrid method to other light muonic atoms with the goal of reducing uncertainties in estimates of nuclear structure effects in atomic spectroscopy. In another project, electroweak properties of medium-mass nuclei such as $^{40}\mathrm{Ar}$ were studied in chiral nuclear EFT. Weak form factors and cross sections were determined, as well as the corresponding systematic uncertainties. Results indicate that nuclear structure uncertainties are small.

4. Helmholtz Excellence Network

During the reporting period, HIM continued its collaboration with the excellence cluster PRISMA+ at Johannes Gutenberg-Universität Mainz, which started operation in January 2019. This is based on funds from the third stage of the Helmholtz excellence network.

Within the network, the TACTICa project was pursued by the Matter and Antimatter (MAM) and the Superheavy-Element (SHE) research groups. Other projects concern precision measurements of the weak mixing angle via parity violating electron scattering (P2-experiment) and dark matter searches in beam dump experiments at accelerators (LOWDASA-project). These activities are supported by physicists from the SPECF and EMP sections as well as the Theory-floor section (THFL).

Section EMP
P2: Precision parity violating electron scattering

The P2 collaboration aims for a high precision measurement of the parity violating asymmetry in the elastic scattering of polarized electrons off unpolarized nuclei. The expected data will be interpreted as a determination of the weak mixing angle, one of the fundamental parameters of the Standard Model, with a precision competitive with measurements at LEP or LHC. During the reported period, preparatory work concerning the assembly and commissioning of the P2-detector and the extension of the measurements towards other targets, like 12C was done. Together was the JINR institute in Dubna we have developed a design for a new type of polarimeter which is based on trapped hydrogen atoms which have an almost complete electronic spin polarization ("Hydro-Möller-Polarimeter").

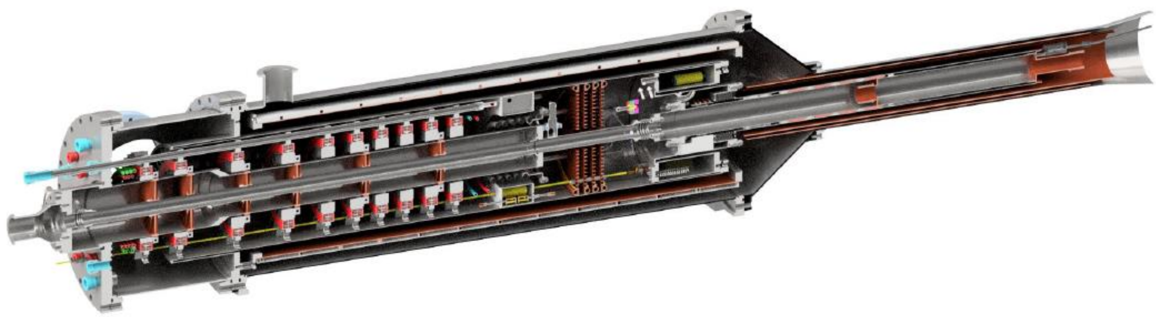

Fig. 7: The Hydro-Möller-Polarimeter of the P2 experiment, design by JINR-Dubna. Polarized Hydrogen atoms are stored in the small diameter part at the right hand side in a 8Tesla field that is generated by an external warm bore solenoid. Size of device is about 2 meters.

Section SPECF
LOWDASA: Low-mass particles of the dark sector at accelerators

Within the Excellence Network of the Helmholtz association, SPECF researchers – in collaboration with the PRISMA+ Cluster of Excellence – work on the design and construction of a Beam Dump Experiment at MESA: DarkMESA. The DarkMESA experiment will be located behind the beam dump of the P2 experiment at MESA, where an extraordinarily large number of electrons will be dumped (6×10^{22} electrons on target). This beam dump will be used as a target for the eventual production of dark sector particles, which can be detected in the DarkMESA detector material.

A full simulation of the sensitive parameter space of DarkMESA has been carried out (see Fig. 8), which clearly demonstrates the competitiveness of the experiment in the search for light dark matter particles. For the detector material, PbF_2 crystals (being available from the old A4 experiment at MAMI) as well as lead glass blocks are foreseen.

Recently, the neutron efficiency of the lead glass blocks and crystals have been investigated and the design of a veto system is ongoing. A first prototype of the DarkMESA detector, including a veto system to protect the detector from cosmic radiation, is almost ready.

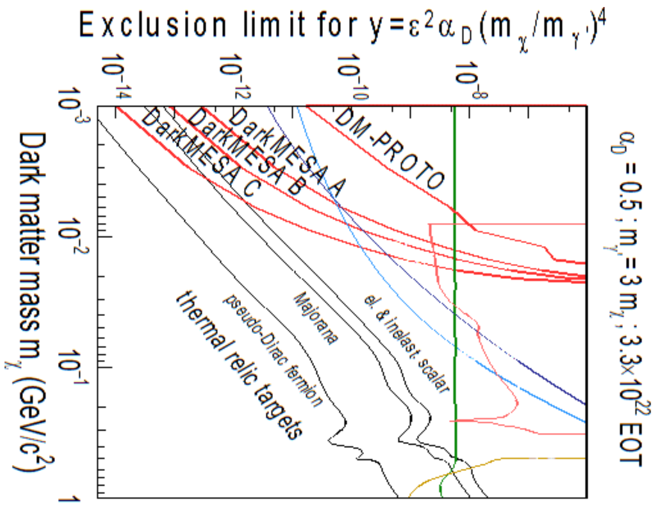

Fig. 8: Sensitivity of the DarkMESA experiment as a function of the parameter y versus dark matter mass, m_χ. The y variable is a function of the parameters ε and α_D, which parametrize the coupling of a dark photon (γ') to standard model matter and dark matter, respectively, and it depends also on the mass ratio $m_\chi/m_{\gamma'}$.

Sections SHE & MAM
TACTICa (Trapping And Cooling of Thorium Ions with Calcium)

The TACTICa Collaboration focuses on laser-based research ^{229m}Th with the aim of new insights in fundamental physics. Th ions produced by laser ablation from macroscopic samples or as α-decay daughters populated in the decay of their U-precursors will be electrostatically decelerated, loaded into a linear Paul trap and sympathetically cooled in a calcium-ion crystal. For a successful loading, the ions' kinetic energy needs to be below 1 keV. For $^{229(m)}$Th, the α-decay recoil energy is 84 keV. To employ the full initial charge state distribution, thermalization without buffer gas cooling is foreseen [R. Haas et al., Hyp. Int. 241 (2020) 25], which coincides with the requirements of the high vacuum atmosphere inside the Paul trap. To obtain a sharp energy spectrum, monolayer-thick ^{233}U sources are required. Several fabrication methods were explored with respect to their potential of producing U monolayers [R. Haas et al., Radiochim. Acta 108 (2020) 923]. These include Molecular Plating, Drop-on-Demand inkjet printing, chelation by functionalized silicon surfaces and self-adsorption on thermally oxidized titanium foils. The obtained α spectra served as a proxy for the energy distribution of recoiling Th daughters and were compared with advanced alpha spectrometric simulations, to gain insights about the deposited source composition. The most promising results were obtained for sources produced by self-adsorption. The daughter recoil efficiency was verified to be close to 100 % by using shorter-lived ^{232}U. Furthermore, the vacuum chamber setup of the TACTICa source section was finished, including a safety system for the 100 kV HV box, programmable logic controller for an autonomous operation of the whole system and online monitoring of the experiment, which is now ready for commissioning.

Fig. 9: Current source part of the TACTICa setup. The recoil ion source is mounted at the end of the vacuum chambersetup in the right-hand side of the photo.

In the meantime, we have demonstrated capture, trapping and sympathetic cooling with ^{232}Th+ ions from a laser-ablation source [K. Groot-Berning et al. Phys. Rev. A 99 (2019) 023420; F. Stopp et al.. Hyp. Int. 240 (2019) 33]. In these experiments, ^{232}Th+ ions became a high-mass defect inside ^{40}Ca+ Coulomb crystals (see Figure 10). From the type of mass defect, we deduce, in-situ inside the trap, the charge state and mass of the dark Th ion. This was independently verified by time-of-flight measurements. We used a segmented Paul trap to find singly-charged ions; additional RF and DC potentials would be used for charge states up to +10. The trap was operated at background pressures of < 10^{-10} mbar, and we observed ion lifetimes exceeding hours.

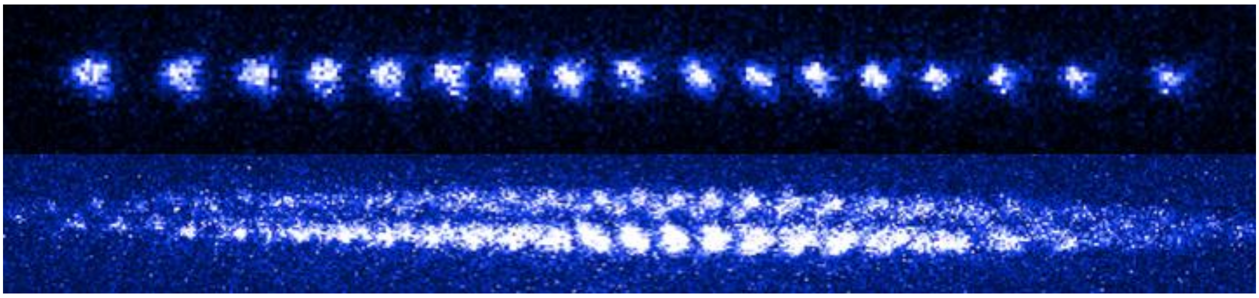

Fig. 10: Top: fluorescence image of a linear Ca^+ ion crystal. Inter-ion distances are about 10 µm, bottom: three-dimensional crystal with >100 ions.

5. Externally Funded Research Groups

End of 2020, HIM comprised three such groups. Mustapha Laatiaoui and Dionysios Antypas hold ERC starting and consolidator grants, respectively. Danila Barskiy has won the Sofja Kovalevskaja Award from the Humboldt foundation which also entitles him to form a research group. These research groups are associated to the MAM section (Barskiy, Antypas) and the SHE section (Laatiaoui). The MAM groups have been established during the second half of 2020, Laatiaoui started in 2018. We give a short summary of the work that has already been started or that is anticipated.

Dionysios Antipas (ERC Starting Grant)
Parity violation in Ytterbium

Comparing the Atomic Parity Violation (APV) effect in different isotopes of the same atomic species is a sensitive tool to study the distribution of neutrons in the nucleus, which in turn is closely related to the structure and size of neutron stars. Indeed, neutron-rich nuclear matter appearing in vastly different sizes, such as the Yb nucleus (of size ≈ 1 femtometer, or 10^{-15} meter) and a neutron star (of size ≈ 10 kilometer), is described by the same physics models.

As part of their earlier measurements, the researchers have also provided information on an additional Z boson. Z bosons mediate the weak interaction and scientists in the field speculate the existence of a further Z boson, referred to as the "Z prime" or Z' with a much smaller mass than that of the established Z boson. For that reason, the new platform to be established in the context of this project is also a probe of additional vector bosons, beyond the Standard Model of particle physics. Finally, the study of nuclear-spin-dependent contributions to the APV effect in isotopes with nuclear spin is a sensitive way to investigate intranuclear weak interactions, which are currently poorly understood.

Danila Barskiy (Sofja Kovalevskaja Award)
New approaches to promote the use of nuclear magnetic resonance spectroscopy for analysis in chemistry, biology, and medicine

Barskiy's new interdisciplinary group will focus on developing miniaturized, portable NMR sensors. These sensors would employ the principle of zero to ultra-low field magnetic resonance, or ZULF NMR for short, using optically pumped magnetometers which would not require any strong magnetic fields. In addition to applications in chemical and biomedical research, such sensors could find use for detecting metabolic disorders at an early stage.

By heading up a work group at Mainz, Barskiy also wants to develop hyperpolarizers for benchtop NMR spectrometers. Hyperpolarization improves the alignment of nuclear spins in a sample, thereby amplifying their NMR signals. The scientist predicts that application-specific hyperpolarizers for tabletop NMR devices may be soon available and that they will be about the size of a coffee machine. And with a tabletop NMR device, it will be possible to perform highly sensitive analyses of fuels, biofluids such as blood or urine, and food extracts.

Mustapha Laatiaoui (ERC Consolidator Grant)
Atomic Physics via Ion-Mobility Studies

This research takes place within the framework of the superheavy elements (SHE) section.

Another way of studying the atomic structure of the heaviest elements and its impact on the ion transport is through ion-mobility spectrometry (IMS) [M. Block, M. Laatiaoui, and S. Raeder, Recent progress in laser spectroscopy of the actinides, Prog. Part. Nucl. Phys. 116, 103834 (2021); G. Visentin, M. Laatiaoui, L. A. Viehland, and A. A. Buchachenko, Mobility of the Singly-Charged Lanthanide and Actinide cations: trends and perspectives, Front. Chem. 8, 438 (2020).]. We operate an IMS setup with the aim of studying the interaction of actinide ions with noble gas atoms. Off-line experiments with macroscopic quantities of various actinides are in preparation [E. Rickert, H. Backe, M. Block, M. Laatiaoui, W. Lauth, S. Raeder, J. Schneider, and F. Schneider, Ion Mobilities for Heaviest Element Identification, Hyperfine Interact. 241, 49 (2020).]. Our systematic ion-mobility measurements include measurements at various gas pressures, temperatures and electric fields. Despite providing anchor points for modern ab-initio calculations, we hope to open a new niche for the development of novel techniques for isobaric purification and elemental identification at miniscule production yields. In a second project, we operate a cryogenic drift tube to enable laser spectroscopy of superheavy elements. This EU-funded project Laser Resonance Chromatography of superheavy Metals (LRC) is in the start-up phase. However, preparatory theoretical work on the electronic structures of Lu+ (Z = 71) and Hf+ (Z = 72) and their heavier homologs, Lr+ (Z = 103) and Rf+ (Z = 104), respectively, was performed using Dirac-Coulomb Hamiltonian and multi-reference configuration interaction methods. First results for Lu+ and Lr+ have recently been published [E. V. Kahl, J. C. Berengut, M. Laatiaoui, E. Eliav, and A. Borschevsky, High-precision ab-initio calculations of the spectrum of Lr+, Phys. Rev. A 100, 062505 (2019).]. In addition, the theoretical proof-of-principle for the LRC method was published and attracted widespread attention [M. Laatiaoui, L. A. Viehland, and A. A. Buchachenko, Laser resonance chromatography of superheavy elements, Phys. Rev. Lett. 125, 023002 (2020)., M. Laatiaoui, L. A. Viehland, and A. A. Buchachenko, Exploiting transport properties for the detection of optical pumping in heavy ions, Phys. Rev. A 102, 013106 (2020).]. This was listed by “pro-physik.de” among the few most important achievements in 2020 in the fields atomic and quantum physics [D. Eidemüller, Quantensprünge auf der Waage und im Zeitraffer, Jahresrückblick Atom- und Quantenphysik 2020, pro-physik.de, 6. Januar 2021].