Austrian Academy of Sciences

Annual Report 2013

Stefan Meyer Institute (SMI) for subatomic Physics

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Content

1. Mission Statement

The Stefan Meyer Institute (SMI) is devoted to basic research in the field of subatomic physics. Our research focuses on the study of fundamental symmetries and interactions, addressing the following questions:

- What are the properties of the forces that exist in nature?
- What is the origin of the masses of the visible universe?
- Why do the remains of the big bang consist only of matter and not also of antimatter?

We specialize in precision spectroscopy of exotic atoms and exotic meson-nucleus bound states as an integral part of international collaborations at largescale research facilities including

- CERN (Geneva, Switzerland),
- LNF-INFN (Frascati, Italy),
- J-PARC (Tokai, Japan),
- GSI (Darmstadt, Germany) and
- FAIR (Darmstadt, Germany).

These are among the world's leading facilities for subatomic physics and our projects are subject to rigorous annual evaluation to monitor their progress in a dynamic and expanding field. We aspire to perform research that increases the understanding of fundamental physics principles while simultaneously providing opportunities for young researchers in Austria to obtain valuable experience at institutes unavailable to them at home.

The current three main fields of activity at SMI are:

- **Matter-antimatter symmetry**, especially the study of the underlying CPT symmetry. This symmetry is a property of all field theories used hitherto to describe nature, but is in contrast to the observed matter dominance of the visible universe. Furthermore, not all mathematical prerequisites of the CPT theorem are valid in modern theories like string theory or quantum gravity. Experimentally the matter-antimatter symmetry is investigated by precision measurements of properties of the antiproton (mass, charge, magnetic moment) in antiprotonic atoms and antihydrogen, comparing them to known properties of the proton and of hydrogen. A second topic is the study of antimatter gravity, where direct measurements have never been performed before due to the previous unavailability of neutral antimatter.

- **Hadron physics:** here we study the strong interaction and its corresponding theory, quantum chromodynamics (QCD), at low energies in the non-perturbative regime and at intermediate energies. Chiral symmetry and its breaking or restoration plays an important role. They contribute to the origin of the masses of hadrons. The masses of the three current quarks add up to only a few percent of the measured hadron mass, which originates mainly from the dynamic interaction between the quarks and the exchange particles of the strong interaction, the gluons. The underlying mechanism is, to date, not understood at all. The experimental approach is the spectroscopy of meson-nucleus bound states using various reactions, and the measurement of the effect of the strong interaction on the low-lying atomic states of simple exotic atoms by X-ray spectroscopy. In the field of hadron physics new opportunities will be opened by PANDA at FAIR/Darmstadt with antiproton annihilation which provides an elegant way to study hadron physics in the charm quark regime in a rather direct way. It is one of the major experiments at FAIR and our institute participates in the technical development of the complex PANDA detector system. Prior to PANDA our institute takes advantage of experimental data collected by BELLE at KEK/Japan.
- **Advanced instrumentation:** progress in experimental physics needs new or improved instrumentation and methodology. In this field we currently work on three experimental projects funded within the EU FP7 Integrated Activity HadronPhysics3: novel photon detectors (SiPM, silicon photomultipliers) for use in Cherenkov and timing detectors, large size tracking detectors based on GEM (Gas Electron Multiplier) technology, and the development of high-intensity gas jets to be used as internal targets in accelerators. SMI also hosts one site of the PANDA Grid computer network and participates in the development of Grid software.

Further activities include an underground laboratory experiment at Laboratori Nazionali di Gran Sasso (Italy) on a high-sensitivity test of the Pauli principle, in the **VIP** (Violation of the Pauli Principle) experiment. SMI also participates in the analysis of an experiment investigating two-body decays of stored and cooled ions at GSI. A network within the EU FP7 Integrated Activity HadronPhysics3 bringing together experimentalists and theoreticians working on strangeness nuclear physics, **LEANNIS**, is coordinated at SMI.

2. Wissenschaftliche Tätigkeit 2013

Materie-Antimateriesymmetrie

Nach dem Erhalt eines ERC Advanced Grants durch E. Widmann zur Untersuchung der Hyperfeinstruktur von Antiwasserstoff konzentrieren sich die Aktivitäten des SMI nun auf diese Messung, die eine der genauesten Überprüfungen der Materie-Antimateriesymmetrie verspricht. Ein Teil der Aktivitäten während 2013 bestand in der Analyse des Experiments des Jahres 2012 am Antiproton Decelerator des CERN zur Erzeugung eines Antiwasserstoffstrahles, und der Publikation der Resultate. Die erstmalige Beobachtung eines Antiwasserstoffstrahls im Abstand von 2.7 m vom Produktionsort, wo magnetische und elektrische Streufelder verschwindend gering sind, erschien im Januar 2014 in Nature Communications und löste ein starkes Medienecho aus. Aufgrund des Shutdowns des CERN für den LHC Ausbau konnten über 1,5 Jahre keine Messungen mit Antiprotonen gemacht werden. Deshalb konzentrierten sich die Aktivitäten auf Bau und Test einer Apparatur zur Erzeugung eines polarisierten atomaren Wasserstoffstrahls. Nach der Fertigstellung am SMI wurde diese an das CERN transportiert und dort wieder aufgebaut. Nach Verifikation der Funktion wurde die Apparatur mit dem Spektrometer für die Hyperfeinstrukturmessung verbunden, um diese genau zu charakterisieren. Erste Messungen haben im Frühjahr 2014 begonnen.
Eine zweite Säule innerhalb des ERC Projektes ist die AEgIS Kollaboration am CERN-AD, deren Hauptziel die Messung der Gravitation von Antiwasserstoff ist, deren langsamer Antiwasserstoffstrahl aber auch zur einer Messung der Hyperfeinaufspaltung genutzt werden kann. Ein über das ERC Projekt angestellter Postdoc ist verantwortlich für die Erzeugung von Positronium bei AEgIS, und das SMI leitet die Entwicklung eines Interfaces zwischen den verschiedenen Experimentiermodulen (Gravitation, Hyperfeinstruktur).

Hadronenphysik

Unser Interesse ist gegenwärtig auf die starke Wechselwirkung mit Seltsamkeit (strangeness) fokussiert, welche die Dynamik und Phänomene der leichten Quarks (up, down, strange) beinhaltet. Präzisionsexperimente mit Röntgenspektroskopie von exotischen Atomen und die Suche nach Bindungszuständen von Kaonen und Nukleonen mit verschiedenen Reaktionen können Aufschluss über die Hadronenphysik mit Strangeness bei niedrigen Energien geben.

Untersuchungen zur Antikaon-Nukleon Wechselwirkung in kaonischen Atomen

Die Analyse von Daten des SIDDHARTA Experimentes am LNF ergab neue wesentliche Erkenntnisse zur starken Wechselwirkung von Antikaonen mit Nukleonen und Kernen. Nach der besten Bestimmung der Verschiebung und Verbreiterung des Grundzustandes in kaonischem Wasserstoff im Vorjahr wurde 2013 die Ausbeute der beobachteten Übergänge, d.h. der Bruchteil der den Grunzustand erreichenden Kaonen, genau gemessen. Die Analyse einer Messung von in Deuterium gestoppten Kaonen ergab erstmalig eine obere Grenze für die Ausbeute der Röntgenlinien von kaonischem Deuterium. Aufbauend darauf wurde ein Letter of Intent für eine Messung dieser Übergänge, die von größter Wichtigkeit für die Bestimmung der Isospinabhängigkeit der starken Wechselwirkung mit Strangeness sind, am japanischen J-PARC Labor eingereicht.

Hadronenphysik mit Strangeness

Die Suche nach neuen durch Antikaonen vermittelten hadronischen Bindungszuständen wird in verschiedenen Experimenten ausgeführt: DISTO, FOPI, E15 und AMADEUS. Im Jahr 2013 war eine lange Experimentierperiode für das Experiment am J-PARC geplant, diese musste jedoch aufgrund eines Unfalles, bei dem radioaktive Strahlung austrat, nach wenigen Tagen abgebrochen werden. Die Analyse von Daten der Experimente DISTO und FOPI wurden fortgesetzt. Daten mit dem im Vorjahr in den KLOE Detektor eingebauten Kohlenstofftarget wurden ebenso ausgewertet.

Diese Studien haben die Untersuchung der Wechselwirkung negativ geladener Kaonen mit leichten Kernen zum Ziel. Wertvolle Informationen zur Λ(1405) Resonanz können damit gewonnen werden, die extrem wichtig für die Dynamik der Bildung kaonischer Bindungszuständen ist.

PANDA
Das PANDA Experiment wird den Hochenergie-Speicherring von FAIR in Darmstadt zur Untersuchung von stark-wechselwirkender Materie mit Antiprotonenannihilation benutzen. Das Physikprogramm ist sehr vielseitig und beinhaltet Studien exotischer und nicht- exotischer Resonanzen im Charm-Quark Bereich, exotische Objekte wie Gluonbälle, Formfaktoren und Hyperkerne. Das SMI beteiligt sich an der technischen Entwicklung von wichtigen Detektorteilen: Internes Targetsystem und „SciTil“ Detektor. Im Jahr 2013 konzentrierten sich unser Aktivitäten insbesondere auf den Sci Til (Scintillating Tile) Detektor, der zur Zeitmessung dient und daher eine extrem gute Zeitauflösung benötigt. Der teilweise Aufbau des PANDA Detektors in Jülich wurde geplant. SMI ist auch im Bereich der Computersoftware und der Simulationen von PANDA beteiligt.

BELLE
Das BELLE Experiment hat mehr als 10 Jahre lang Daten aus B Meson Zerfällen aufgenommen, die auch sowohl für das PANDA Programm als auch für die Hadronenphysik mit Strangeness wichtige Ereignistypen enthält. Im Jahr 2013 wurde die Analyse dieser Daten intensiviert.

LEANNIS
Das Netzwerk setzt die sehr erfolgreiche Arbeit in HadronPhysics3 fort, welche im vorangegangenen HadronPhysics2 Projekt begonnen wurde. LEANNIS bringt Experimentalphysiker und Theoretiker zusammen, die im Bereich der starken Wechselwirkung mit Strangeness arbeiten. LEANNIS steht in engem Zusammenhang mit unseren experimentellen Aktivitäten. Es hilft Prioritäten in den experimentellen Untersuchungen festzulegen und Interpretationen der experimentellen Ergebnisse im Rahmen der theoretischen Beschreibungen zu finden. Im Berichtsjahr 2013 wurden im Zusammenhang mit LEANNIS Arbeitstreffen in Trento organisiert.

Instrumentelle Entwicklung
Am SMI werden wichtige Teile unserer Experimente entworfen, entwickelt und gebaut, wobei der Bau entweder im Institut oder durch externe Firmen erfolgt. Dies betrifft mechanische und elektronische Teile sowie Detektorkomponenten. Wir nutzen den Vorteil von neuen Technologien wie Gas-Elektronen Vervielfacher (GEM) und neuen Festkörper-Photodetektoren (SiPM). Einige dieser Aktivitäten werden im Rahmen des EU Projekts HadronPhysics3 durchgeführt. Einige Entwicklungen sind für Anwendungen von Interesse wie z.B. Verbesserungen der Zeitnehmung durch neue Photodetektoren in der Flugzeit-Positronen-Emissions- Tomographie. Eine neue Aktivität im Jahr 2013 war die Untersuchung der Emission von prompter Gamma Strahlung beim Eindringen von geladenen Teilchen in Gewebe mittels Computersimulationen, die bei der Bestrahlung mit ionisierender Materie zur Ortsbestimmung genutzt werden könnte.

VIP 2: Test des Pauliprinzips
Im Jahr 2013 wurde ein FWF Projekt zur Fortführung der Untersuchung der Gültigkeit des Pauliprinzips genehmigt. Das Pauliprinzip ist eines der Grundpfeiler der Quantenmechanik und seine Überprüfung stellt einen Test der Fundamente dieser Theorie dar. Die Apparatur wurde entwickelt und getestet, das eigentliche Experiment wird im Untergrundlabor Gran Sasso in Italien stattfinden.

3. Highlights 2013

Ein Meilenstein des vom ERC geförderten Projekts zur Messung der Hyperfeinstruktur von Antiwasserstoff war im Jahr 2013 die Fertigstellung einer Apparatur zur Erzeugung eines monoatomaren, kalten, polarisierten Wasserstoffstrahls. Dieser wird aufgrund der Betriebsunterbrechung des CERN für die Aufrüstung des LHC und der daher nicht verfügbaren Antiprotonen zur Charakterisierung der Messapparatur benutzt. Ein weiteres wichtiges Resultat ergab sich aus der Suche nach Röntgenstrahlen von kaonischem Deuterium. Die Ergebnisses [1] erlaubten es uns, zusammen mit Forschern aus Japan und Italien einen Experimentiervorschlag zur Messung des 2p-1s Röntgenübergangs in kaonischem Deuterium zu verfassen, der an der Beschleunigeranlage J-PARC eingereicht wurde [2].
Im Jahr 2013 wurde der Antrag für ein Doktoratskolleg "DKPI: Particles and Interactions" vom FWF genehmigt, an dem Wissenschaftler des SMI, der Universität Wien sowie der Technischen Universität Wien und des HEPHY beteiligt sind. Dieses DK ermöglichet eine sehr breite Ausbildung von Dissertanten in der Teilchenphysik. Ein Höhepunkt des Jahres war der Besuch des österreichischen Bundesprasidenten Dr. Heinz Fischer am CERN, der auch das ASACUSA Experiment am Antiproton Decelerator besuchte.

[1] Bazzi, M., Beer, G., Berucci, C., Bombelli, L., Bragadireanu, A. M., Cargnelli, M., et al. (2013). Preliminary study of kaonic deuterium X-rays by the SIDDHARTA experiment at DAΦNE. *Nuclear Physics A*, *907*, 69–77. doi:10.1016/j.nuclphysa.2013.03.001

[2] Berucci, C. et al., (2013). *Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium* (KEK/J-PARC-PAC 2013-7). Letter of Intent to J-PARC.

4. Scientific Activity 2013

Matter-Antimatter Symmetry

With the receipt of an ERC Advanced Grant by E. Widmann to study the hyperfine structure of antihydrogen, SMI is now concentrating on theses activities that promise one of the most precise tests of matter-antimatter symmetry. One activity in 2013 was the analysis of data taken in fall of 2012 at the Antiproton Decelerator of CERN aiming at the creation of a beam of antihydrogen atoms and the publication of the results. The first observation of a beam of antihydrogen atoms at a distance of 2.7 m from the production, where magnetic and electric fields are negligible, appeared in January 2014 in Nature Communications, which created a substantial media response. Because of the shutdown of CERN for the LHC upgrade we could not use antiprotons for more than 1,5 years. We therefore concentrated on building a source of polarised atomic hydrogen. After completion at SMI the setup was moved to CERN and reassembled. After verifying its properties it was connected to the spectrometer line for antihydrogen to perform a detailed characterisation. First tests with the full setup started in spring 2014.

A second pillar within the ERC project is the AEgIS collaboration at CERN-AD, whose main goal is the measurement of the gravitation of antihydrogen. For this they develop a slow antihydrogen beam that is also useful to measure the hyperfine structure. A postdoc paid by the ERC project is in charge of the positronium production of AEgIS, and SMI is leading the development of a mechanical interface between different experiment modules (gravitation, hyperfine structure).

Hadron physics

Our current interest focuses on the strong interaction with strangeness, which includes the dynamics and phenomena of the light quarks (up, down, strange). Precision X-ray spectroscopy of exotic atoms and the search for kaon nucleon bound states using different reactions provide important information on hadron physics with Strangeness at low energies.

Studies of the antikaon-nucleon interaction in kaonic atoms

The analysis of data collected in the SIDDHARTA experiment at LNF yielded new significant results on the strong interaction of antikaons with nucleons and nuclei. After the best determination of the strong-interaction induced shift and width of the ground state of kaonic hydrogen in 2012, we could determine the yields of the observed transitions, i.e. the fraction of kaons reaching the ground state, in 2013. The analysis of a measurement of kaons stopped in deuterium provided for the first time ever an upper limit for the yields of X-ray transitions in kaonic deuterium. Based on this result a Letter of Intent to measure these transitions was submitted to J-PARC. The x-ray transitions of kaonic deuterium are of utmost importance to determine the isospin dependence of the strong interaction with strangess.

Hadron physics with strangeness

The search for new hadronic bound states mediated by antikaons is conducted in different experiments: DISTO, FOPI, E15 and AMADEUS. In 2013 a long experimental period was for the experiment E15 at J-PARC, which was stopped after a short period due to an accident in which radioactive material was leaked to the environment. The analysis of the FOPI/GSI data on proton-proton and pion induced reactions was continued. Data taken with a carbon degrader installed in 2012 in the KLOE detector at LNF were also analysed, aiming at studies of negatively charged kaons interacting with light nuclei. Valuable information about the elusive $\Lambda(1405)$ resonance can be deduced which seems to be extremely important for the dynamics of the formation of kaonic bound states.

PANDA

The PANDA experiment will use the high-energy storage ring of FAIR at Darmstadt to study strongly interacting matter with antiproton annihilations. The physics program is very rich including exotic and non-exotic resonances in the charm quark regime exotic objects like glueballs, time-like form factors and hypernuclei. SMI is participating in the technical development of important detector parts of PANDA: Internal target system and the “SciTil” detector. In 2013 our activities concentrated especially on the SciTil (Scintillating Tile Hodoscope) timing detector. The partial setup of the PANDA detector in Jülich is planned. Moreover SMI contributes to the Computer software and simulation framework of PANDA.

BELLE

The BELLE xxperiment has for more than 10 years taken data of B meson decays, which contain events that are also important for our physics interest within PANDA and hadron physics with strangeness. In 2013 we intensified our analysis activities of these data.

LEANNIS

The network, which already started within the preceding HadronPhysics2 project, continues to be very fruitful also in HadronPhysics3. It brings together experimentalists and theoreticians working in the field of strong interaction with strangeness. LEANNIS has to be seen in the context of our experimental activities in hadron physics. It helps to prioritize the experimental studies and to interpret the experimental results in the theoretical framework. In 2013 a meeting in connection with LEANNIS were organized in Trento.

Advanced Instrumentation

At SMI essential parts of our experiments are designed, developed and built either in the institute workshop or made to order by external companies. This concerns mechanical, electronic parts as well as detector components. We take advantage of new technologies like gas-electron multipliers (GEM) and novel solid state photon detectors (SiPM). Some of these activities are performed within the EU project HadronPhysics3. The spin-off of this R&D work is also interesting for applications in medicine like improvements of the timing performance of Time-of-Flight Positron Emission Tomography systems. A new activity in 2013 was the sudy of prompt gamma emission of ionizing radiation when traversing tissue using Monte Carlo simulations, which could be used for real-time range monitoring inion-radiation therapy.

VIP 2: Pauli exclusion principle test

A FWF project was obtained in 2013 to expand our studies of the validity of the Pauli exclusion principle. This principle is one of the pillars of quantum mechanics, and its investigations constitutes a test of the foundations of this theory. A new apparatus was developed and tested and will be installed in Gran Sasso undergraound laboratory in Italy where the experiment itself will take place.

5. Highlights 2013

A major milestone in the ERC project to measure the hyperfine structure of antihydrogen was – in the absence of antiprotons due to the shutdown of CERN – the completion of a source of mono-atomic, cold, polarized hydrogen which is being used to thoroughly characterize the apparatus used for the upcoming measurement with antihydrogen. A further major result came from the first search for x-ray transitions in kaonic deuterium [1]. Based on these results we developed in collaboration with scientists from Japan and Italy a letter of Intent for a precise determination of 2p-1s x-ray transition energy in kaonic deuterium, which was submitted to the J-PARC facility [2].

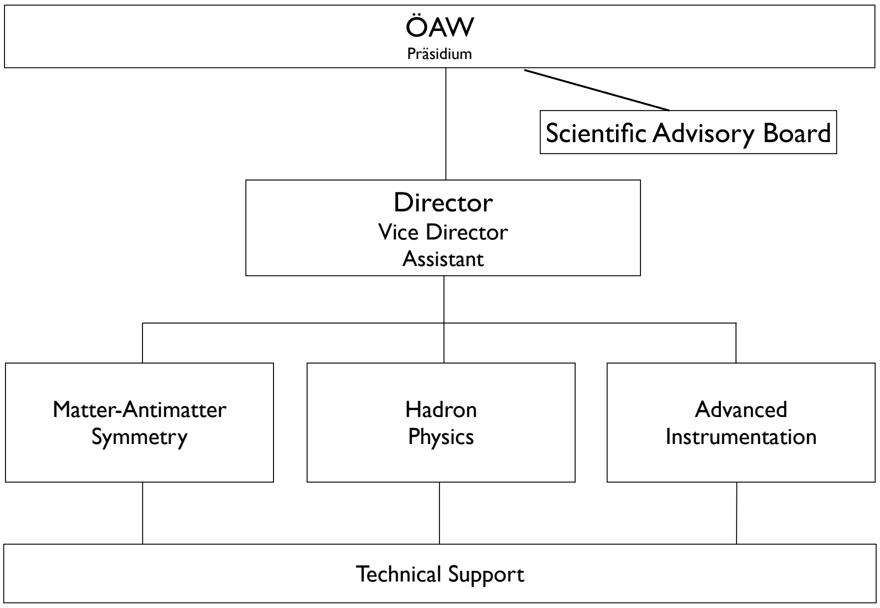
In 2013 an application to FWF was successful for a graduate school "DKPI: Particles and Interactions" which includes scientists from SMI, Vienna University, Vienna University of Technology, and HEPHY, thus offering Ph.D. students a very broad education in many aspects of particle physics. A further highlight was the official visit of Austrian President Dr. Heinz Fischer to CERN who also visited the ASACUSA experiment at the Antiproton Decelerator.

[1] Bazzi, M., Beer, G., Berucci, C., Bombelli, L., Bragadireanu, A. M., Cargnelli, M., et al. (2013). Preliminary study of kaonic deuterium X-rays by the SIDDHARTA experiment at DAΦNE. *Nuclear Physics A*, *907*, 69–77. doi:10.1016/j.nuclphysa.2013.03.001

[2] Berucci, C. et al., (2013). *Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium* (KEK/J-PARC-PAC 2013-7). Letter of Intent to J-PARC.

6. Report on the scientific activity during 2013

The Stefan Meyer Institute has three research foci as shown in the organisational chart below, two scientific ones (matter-antimatter symmetry and hadron physics) and one instrumental (advanced instrumentation). All foci are divided into individual projects, and there are also a few smaller research projects.



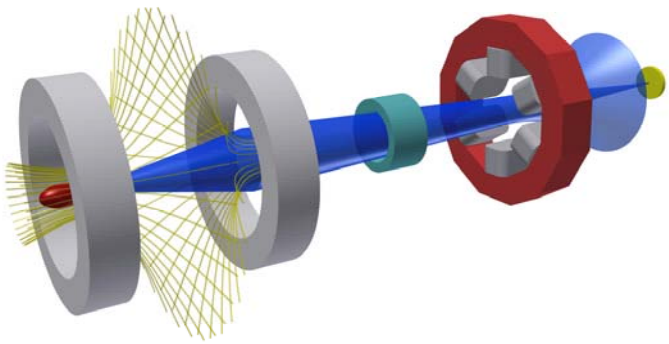
6.1 Matter-Antimatter Symmetry: ASACUSA and AEgIS @ CERN-AD

(Supported by bm_wf, ERC advanced Grant of E. Widmann)

This is one of the main scientific programs at SMI. Physical laws are believed to be invariant under the combined transformations of charge (C), parity (P), and time (T) reversal. This CPT symmetry implies that antimatter particles have exactly the same mass and charge as their particle counterparts. Within the ASACUSA program, SMI is involved in the measurement of the ground-state hyperfine splitting of antihydrogen, supported by the ERC Advanced Grant 291242-HBAR-HFS. The main focus of this experiment is the investigation of the CPT symmetry via precision microwave spectroscopy of antihydrogen, the simplest antimatter atom consisting of a positron and an antiproton. Antihydrogen is a promising tool for testing CPT symmetry, because its CPT conjugate system, hydrogen, has been measured to a precision of $\sim 10^{-14}$ for the 1s-2s two-photon laser transition and $\sim 10^{-12}$ for the ground-state hyperfine structure (GS-HFS). Even if the antihydrogen GS-HFS cannot be measured to this high precision, it can rival the best CPT tests on an absolute scale. This experiment is one of the main topics of the ASACUSA collaboration at CERN-AD of which SMI is a leading member. As part of the ERC Grant project, SMI also joined the AEgIS collaboration which develops an ultra-low energy beam of antihydrogen atoms. The main focus of AEgIS is a measurement of the gravitational interaction of antihydrogen using a slow antihydrogen beam, but this beam is also well suited for a measurement of the hyperfine splitting.

6.1.1 Antihydrogen ground-state hyperfine structure measurement

The experiment aims at a measurement of the ground-state hyperfine structure of antihydrogen by using a Rabi-type atomic beam setup [1] (see Fig. 1 (left)). Within the ASACUSA collaboration, groups from RIKEN and Tokyo University are developing a so-called CUSP trap that is expected to produce a polarized beam of antihydrogen atoms by using an anti-Helmholtz type setup consisting of two ring currents running in opposite direction. SMI is in charge of providing the spectrometer line consisting of a spin-flip cavity, and sextupole magnet for spin analysis, and an antihydrogen detector. All necessary devices had been built and were ready to use for the last beam time in 2012.



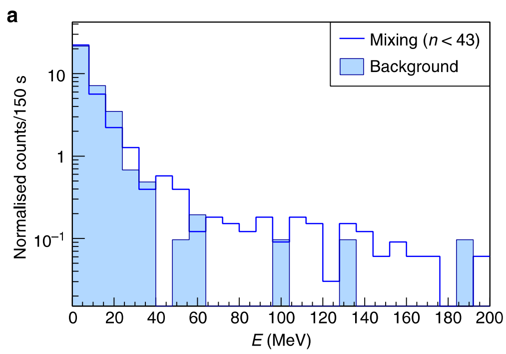


Fig. 1 Left: Schematic view of the Rabi-type atomic beam line for a GS-HFS measurement. From left to right: CUSP trap (yellow: magnetic field lines), cavity (green), sextupole (red), and antihydrogen detector (yellow). In blue the trajectories of antihydrogen are shown. Right: energy deposit in the antihydrogen detector for two conditions (background: trapping of antiprotons with electrons, and mixing of antiprotons and positrons to create antihydrogen atoms). From [2].

During 2013, when no beam at CERN was available because of the LHC Long Shutdown 1, the simulation code based on Geant4 for tracking of (anti)hydrogen atoms through the inhomogeneous magnetic fields as well as the detection of antihydrogen annihilations was continued. A central experimental activity was the development of a mono-atomic polarized hydrogen source to characterize the antihydrogen spectroscopy beam line. The hydrogen source was finished at SMI, transportet to CERN and set up there in fall of 2013, tested and connected to the antihydrogen spectrometer line in early 2014. Studies were made on the homogeneity of the constant magnetic holding field to be applied inside the cavity by finite element simulations of the effect of magnetic shielding and magnetic field measurements.

In parallel data taken during the beam time 2012 were analyzed and submitted for publication in 2013, which appeared early 2014 [2]. By placing an antihydrogen detector 2.7 m downstream of the formation region after the spectrometer beam line we could for the first time unambiguously detect antihydrogen atoms in a region free from stray fields (cf. Fig. 1 (right)). This is an important mile stone towards the in-beam measurement of the antihydrogen GS-HFS. The measured parameters of the antihydrogen beam, intensity (about 20 events per hour) and quantum state (a large fraction of the atoms are in states with principal quantum number $n \leq 29$) still need optimization before a GS-HFS measurement can be done. This is planned to start from 2014, where new schemes of mixing antiprotons and positrons that create colder antihydrogen will be tried and new field ionization electrodes will be installed to be able to ionize atoms in lower states.

[1] Widmann, E., Diermaier, M., Juhász, B., Malbrunot, C., Massiczek, O., Sauerzopf, C., et al. (2013). Measurement of the hyperfine structure of antihydrogen in a beam. *Hyperfine Interactions*, *215*, 1–8. doi:10.1007/s10751-013-0809-6

[2] Kuroda, N., Ulmer, S., Murtagh, D. J., Van Gorp, S., Nagata, Y., Diermaier, M., et al. (2014). A source of antihydrogen for in-flight hyperfine spectroscopy. *Nature Communications*, *5*. doi:10.1038/ncomms4089

6.1.2 Atomic hydrogen beam

(Ph.D. thesis of M. Diermaier and Diploma thesis of M. Wolf)

A systematic characterization of the setup is a premise for a reliable precision experiment. The main components of the Rabi-like hyperfine spectrometer are a spin flip cavity and a spin state selective superconducting sextupole magnet. However, a detailed characterization using anti-hydrogen is hampered by the limited amount of antiproton beam time (interrupted e.g. by the current long shut down LS1 of CERN), and low formation rates for antihydrogen. Fortunately, comprehensive testing is also possible with ordinary atomic hydrogen. To this end a source of modulated atomic hydrogen has been constructed and tested at SMI. It consists of a microwave discharge tube for hydrogen dissociation, a cryogenic PTFE-tubing for beam temperature reduction, and a tuning fork chopper for beam modulation (see figure 2). Hydrogen is then detected by using a quadrupole mass spectrometer and a lock-in amplifier scheme.

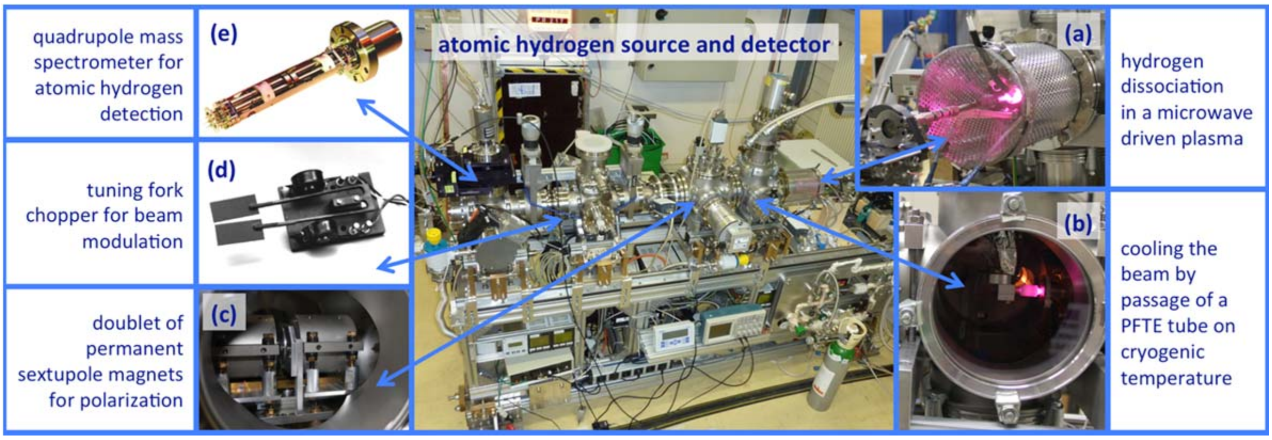


Figure 2: Status of the hydrogen beam experiment at CERN by the end of 2013; the beam goes from the right to the left: (a) molecular hydrogen is dissociated in a microwave driven plasma, (b) the atoms effuse into the evacuated beam line and pass a PTFE-tubing, which is kept at cryogenic temperatures through thermal contact to a coldhead, (c) the beam is polarized by a doublet of permanent sextupole magnets, (d) and modulated at a frequency of 180 Hz by a tuning fork chopper with a 50% duty cycle; (e) a fraction of the atomic hydrogen is ionized and the resulting protons are separated from other ions according to their mass-to-charge ratio by a quadrupole mass spectrometer and registered with single ion counting techniques. In the displayed configuration (without hyperfine spectroscopy components) the detector (e) is directly mounted to the source (a-d).

In the fall of 2013 the source and detector were dismantled at SMI and transported to CERN. There, a permanent sextupole assembly for beam polarization, which was constructed at CERN, was added to the source. The performance of source and detector had to be re-established and subsequently the new component was characterized. Only then the microwave spin flip cavity and superconducting sextupole magnet could be inserted between the hydrogen source and the detector.

At the end of 2013 stable operation of the hydrogen source with dissociation efficiencies around 80% has been demonstrated. Evaluations of the beam velocity suggest beam temperatures below 100 K. This is important, since faster beams can hardly be refocused onto the detector by the superconducting sextupole. Integral rates of the modulated hydrogen beam of up to 50 kHz have been observed at the source exit. Clear indications for the polarization of this beam by the doublet of permanent sextupole magnets have been found. The coupling of the antihydrogen hyperfine spectrometer to the hydrogen source and detector has commenced early 2014 and the characterization of the hyperfine spectrometer is underway.

6.1.3 Antihydrogen detector and simulations

(Ph.D. theses of C. Sauerzopf and Diploma thesis of B. Kolbinger)

During the year 2013 vast improvements on the simulation code for detector and beamline simulations have been achieved. Regarding the simulation of the microwave cavity we managed to implement the use of measured and simulated fieldmaps inside of the cavity volume together with an important improvement in calculation speed and numerical accuracy. For the first time we managed to include the simulation of higher excited quantum states for hydrogen inside the Geant 4 particle physics simulation toolkit. This type of novel simulations also includes the deexcitation of the higher excited states in vacuum as well as in weak and strong magnetic and electric fields, therefore allowing us to produce an accurate tracking simulation for newly produced antihydrogen atoms depending on their initial quantum state distribution. Also during 2013 an evaluation of the antiproton decay processes in Geant 4 has been started and is now under active work. First preliminary results show major differences within the annihilation codes already implemented in Geant 4 (FRITOF and CHIPS) and also in comparison to available annihilation data from crystal ball experiments. Additional effort was invested to develop a model for calculating Majorana transitions of particles traversing a magnetic field gradient. First preliminary simulations with the unfinished model indicate major influences for the polarisation of the antihydrogen atoms due to Majorana transitions. The work on this model is still ongoing.

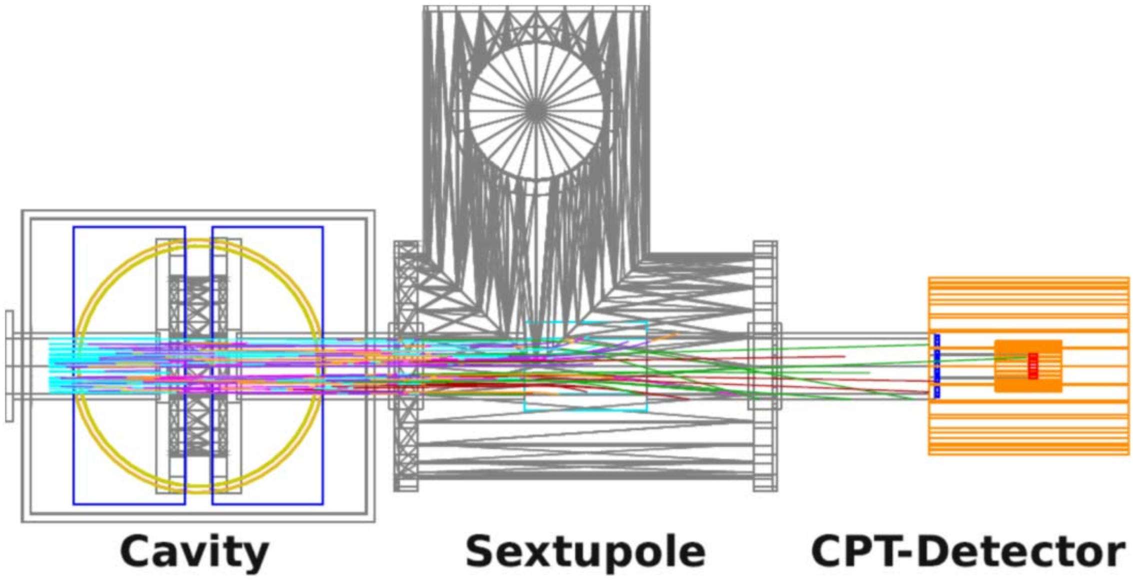


Fig. 3 Geant4 rendering of the trajectories of antihydrogen atoms flying through cavity, sextupole and antihydrogen detector.

Regarding the development of a new antihydrogen detector we developed an analysis framework to test various detector configurations on efficiency in finding real annihilation events and in suppressing the false identification of cosmic particles as antihydrogen annihilation. Distinguishing these two types of events is of great importance as the real event rate is lower than the cosmic rate and due to electromagnetic showers produced by the cosmic rays sophisticated methods for cosmic suppression have been developed. To distinguish these events the detector tracks are separated using a Hough analysis, after that the tracks are fitted with straight lines and statistically tested to their significance, this allows to define timing and multiplicity cuts that allow, together with information on energy deposit, to eliminate most false events while preserving a good efficiency for detecting real antihydrogen annihilations.

Based on the simulation results first ideas for a new antihydrogen detector were finalised and the construction of this detector is currently ongoing effort. On the hardware side new pre-amplifiers for the silicon photomultiplier have been developed and tested, a detailed description of this new devices that allow fine grain control of the amplification gain and self triggering with an onboard discriminator are presented in the advanced instrumentation chapter of this document.

6.1.4 Magnetic shielding and Helmholtz coil design

(Master thesis of N. Dilaver)

The radiofrequency resonator was assembled and tested in preparation of the 2012 beamtime. It was conform to the radiofrequency and vacuum specifications. Although the cavity was not added to the full setup during the 2012 beamtime, measurements of the efficiency of the cavity shielding and field homogeneity inside the cavity were performed in the ASACUSA zone during beamtime. These measurements were also refined in 2013 and compared to simulation in order to assess the level of systematic uncertainties resulting from the use of a pair of Helmholtz coils without correction coils in the experimental environment.

A second cavity, identical to the first one, was manufactured by the CERN main workshop. It has been delivered in November 2012 and was found to be conform with the radiofrequency specifications. This cavity will be added to the hydrogen setup most probably during the shutdown period in 2015 and should improve the measurement precision by a factor 10 compared to a single cavity measurement.

Additional shielding and Helmholtz coils configuration are being developed in anticipation for higher precision measurements and the use of the second cavity.

6.1.5 AEgIS

AEgIS positronium source

In parallel to the work within ASACUSA, SMI has joined since 2013 the AEgIS (Antimatter Experiment: gravity Interferometry Spectroscopy) collaboration with a team of 6 scientists including 3 post-docs and 1 Master student. One postdoc, hired in June 2013, is working full-time on AEgIS and is responsible for the development of its positron apparatus. In the AEgIS experiment, a Surko-trap is used to store and to bunch the positrons (e^+) that will be used for antihydrogen production via the charge exchange reaction $\bar{p} + Ps \rightarrow \bar{H} + e^-$. This system has been assembled and tested in 2012.

Starting from June 2013, SMI has worked on enhancing the performance of the Surko-trap. In particular, cooling gas pressure and rotating wall frequency and amplitude in the Surko-trap have been optimized - increasing the positron lifetime to around 2 minutes. Under optimal conditions more than 4×10^7 positrons are stored and bunched.

In addition to this, a new chamber, which will be used for Positronium formation and laser excitation experiments, has been connected to the positron system. The planned tests aim to investigate cooling and Rydberg excitation of Positronium, which is necessary to maximize antihydrogen production. The chamber has been designed to house a special target for positron/Positronium conversion [3, 4].

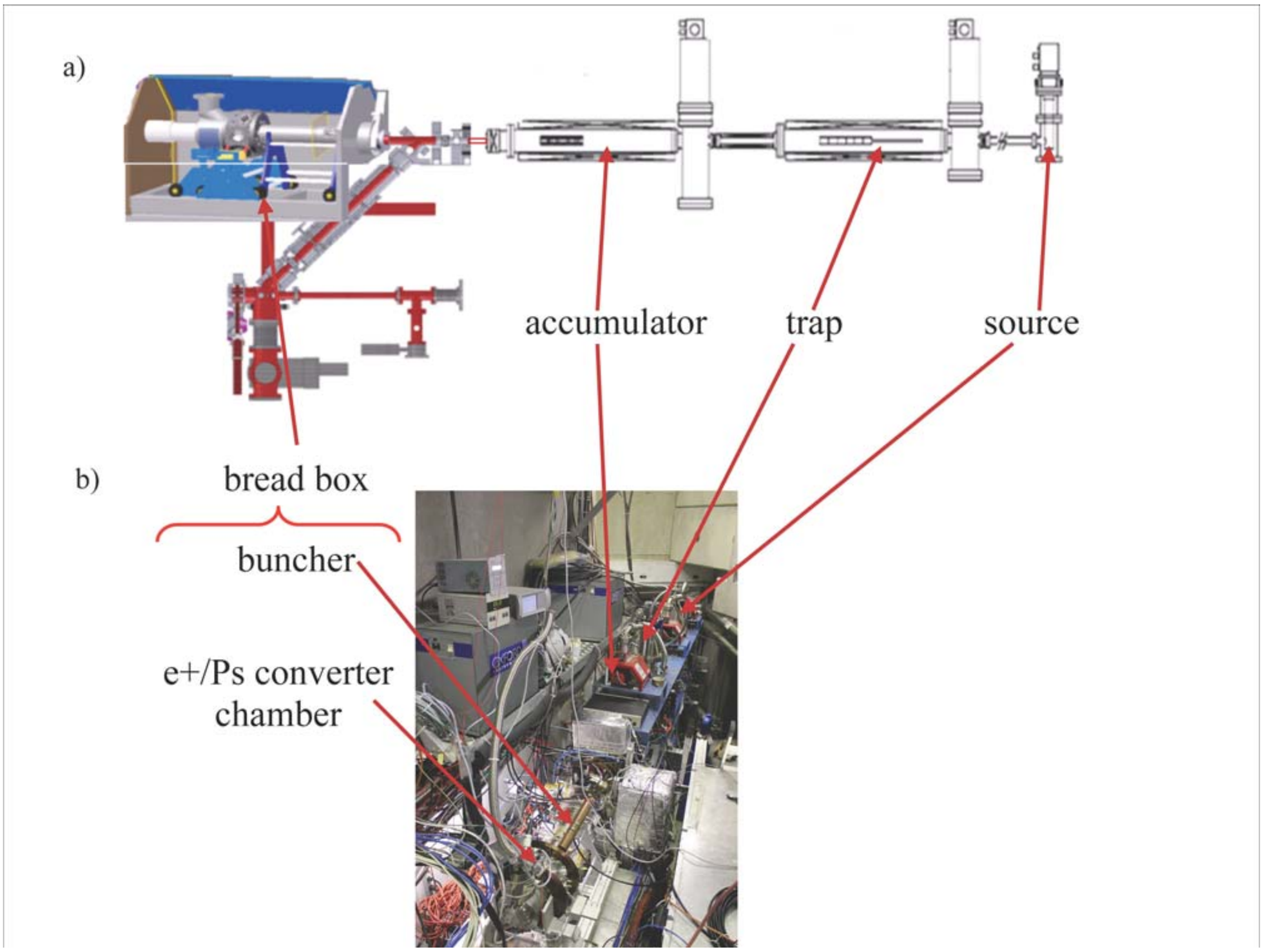


Fig. 4 Overview of the Surko trap and „bread box“ for positronium formation and characterization.

Positron bunches are extracted by magnetic field from the Surko-trap and are then transported by electrostatic lenses. To have the possibility to produce Positronium in the absence of magnetic field, magnetic and electric fields are then uncoupled by a mu-metal field terminator. The positron transport and the uncoupling of magnetic and electric fields with this system have been successfully demonstrated during the last months.

The lenses of the buncher are designed to inject the e^+ into the positron/Positronium converter with energy between 5 and 9 keV in less than 5 ns, to match the laser pulse used for the excitation. The buncher is currently being tested.

To get sufficient information about Ps formation and excitation, tests have been performed to identify a detector suited for the study of simultaneous annihilations of many positrons (of the order of 10^7 e^+). Several promising candidates with the required time (FWHM of few ns) and saturation characteristics (no saturation in presence of many simultaneous annihilations) have been identified.

The SMI team involved in AEgIS is also working on designing the interface between the AEgIS antihydrogen formation trap and the experimental region as well as the spectrometer line adapted to the AEgIS environment. Significant progress has been made in 2013 on the designs of those parts.

[3] S. Mariazzi, P. Bettotti, S. Larcheri, L. Toniutti, and R. S. Brusa, Phys. Rev. B 81, 235418 (2010)
[4] S. Mariazzi, P. Bettotti, and R. S. Brusa, Phys. Rev. Lett. 104, 243401 (2010)

AEgIS beam line shutter
(Master thesis of S. Lehner)

Electrons and antiprotons in the antihydrogen formation trap will be exposed to thermal radiation from the warmer downstream beam pipe. In order to reduce heating of trapped particles a shutter could be placed in the beam line. It would be opened just before antihydrogen atoms are produced to keep the trap shielded as long as possible. An opening time of several ms is foreseen. Additionally the shutter temperature has to be about 20 K and it must be suited for operation in UHV.
To study the feasibility of such a device a prototype was designed and constructed. Two solenoid magnets are used as actuators to open and close the shutter. The magnets are placed outside the beam pipe vacuum in the Outer Vacuum Chamber (OVC) to reduce the required space and to avoid heat emission when the magnets are operated. A metal rod inside bellows acts as a linear feedthrough from the

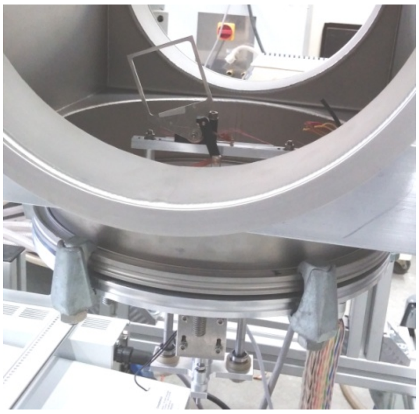


Figure 5: The shutter prototype installed inside a vacuum chamber.

OVC to the beam pipe UHV where it drives the shutter blade. As the blade is heated by absorption of thermal radiation and through the rod, which connects it to the warmer OVC, it is necessary to actively cool it. This is done via a flexible copper tape that has its ends connected directly to the shutter blade and to a cold head at 10 K.

In preliminary tests cooling power was found to be sufficient to keep the shutter blade at 110 K while the magnets and the surrounding vacuum chamber were at room temperature. The time required to open the cold shutter was determined with a photo barrier. Using a standard lab power supply at 60 V an opening time of 15 ms was reached.

<u>Beam Optics Simulations</u>

(Master thesis of S. Lehner)

Effects of a sextupole magnet in the downstream beam line on the antihydrogen count rate of the gravity and hyperfine spectroscopy (HFS) experiments were investigated using the GEANT4 simulation toolkit. Atoms were assumed to be in ground state and to be with equal probability in a hyperfine state that is either focused or defocused by a sextupole magnet. While a sextupole after the source is mandatory for HFS it was studied whether it could also be beneficial for the gravity experiment. In this case the sextupole might be used in both experiments and may be installed before the interface.

Depending on position and field strength of the sextupole and temperature of the atoms (0.1 K – 20 K) it was found that the count rate can be increased by a factor of up to ten. Fig. 6 shows exemplarily how the gain reaches a maximum for an ideal sextupole field strength. In case of HFS the dependence of the count rate on parameters of the polarizing and analyzing sextupole magnet was examined. For both experiments field strengths of up to 1.3 T seem to allow a considerable improvement. Hence a permanent magnet is in principle an option.

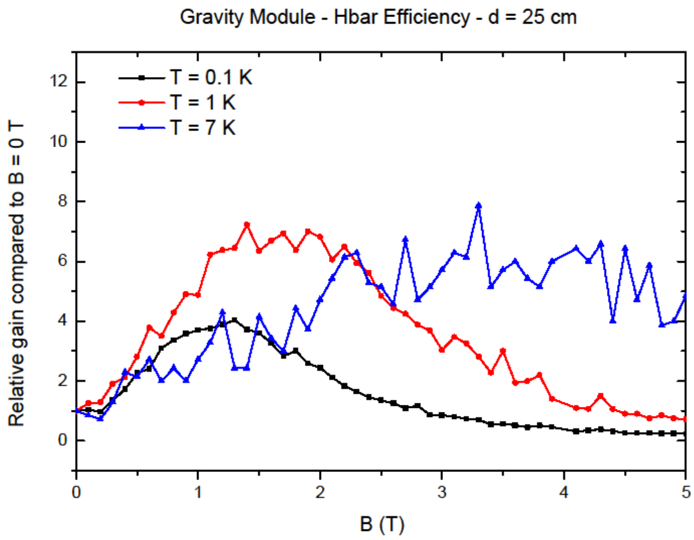


Figure 6: Relative gain in count rate over sextupole field strength shown for the gravity experiment and for three different antihydrogen temperatures. Distance between source and sextupole: 25 cm.

6.2 Hadron Physics

The physics of strongly interacting particles – hadrons – is dealing with topics which have profound consequences for the understanding of basic questions like the generation of the mass of the visible Universe or the structure of exotic objects – e.g. neutron stars – in the Universe. To gain information on how strong interaction works, exotic atoms with strangeness provide a unique insight. For example the low-energy observables of the strong interaction of the negatively charged kaon (K^-) with the proton can be extracted from X-ray spectroscopy of kaonic hydrogen atoms with very high precision. On the other hand, dedicated experiments are devoted to the search of systems bound by the attractive interaction of negatively charged kaons with nuclei. Several experiments are in preparation at different facilities at J-PARC and LNF. Moreover, the strong interaction in the field of charm quarks will be studied in the PANDA experiment at FAIR. As a way to get acquainted with the physics and data analysis techniques and to produce physics results, SMI has joined in a consortium with HEPHY, the high energy physics institute of the Academy, the analysis of BELLE data. The further development of the theory of strong interaction in the field of strange and charm quarks, especially in the low energy regime (low-energy QCD) is promoted within a networking activity, LEANNIS, on the antikaon nucleon and nuclei interaction led by SMI. It was started in the European project HadronPhysics3 - the follow-up project after HadronPhysics2 and bridges the gap between experimental and theoretical studies in hadron physics with strangeness.

6.2.1 LEANNIS

(Networking Activity in EU-HadronPhysics3, Spokesperson J. Marton)

LEANNIS (**L**ow **E**nergy **A**ntikaon **N**ucleon and **N**uclei **I**nteraction **S**tudies) is a networking activity devoted to frontier studies on the interaction of antikaons with nucleons and nuclei. The LEANNIS topics comprehend precision x-ray studies of kaonic atoms, the nature of resonances with strangeness like Λ(1405), the quest of kaonic nuclear bound states and in-medium modifications of hadrons.

In 2013 the progress in experiment and theory continued. The analysis of the SIDDHARTA data taken with the deuterium gas was performed as well as the first study of kaonic deuterium X-rays. Upper limits for the total yield of K transitions and of the K_α transition were extracted. The values are consistent with the expected yields, about 10 times smaller than the yield of the kaonic hydrogen. These results are very important for the preparation of a kaonic deuterium experiment for determining the hadronic width and shift of the 1s state which will provide the necessary empirical data to extract the isospin scattering lengths.

Refined theoretical studies in the framework of effective field theory with coupled channels were continued. Antikaon nuclear quasi-bound states were calculated on the basis of K-nuclear potentials. It was found that the total decay widths are comparable or larger than the binding energies – thus making searches for isolated peaks indicating kaonic nuclear quasi-bound states more complicated. Due to the bigger level spacing the search for isolated peaks corresponding to antikaon nuclear quasi-bound states seems to be advantageous in very light nuclear systems.

The TUM group in LEANNIS finalized the analysis of the production of the sub-threshold resonances $\Sigma(1385)^+$ and $\Lambda(1405)$ in p+p collisions at 3.5 GeV with the HADES spectrometer. The differential analysis of the $\Sigma(1385)$ decay into Λ-π pairs has allowed the extraction of the angular distribution of the resonance in the analyzed production channel. This analysis was the basis for the further development of the studies that concern the production of the $\Lambda(1405)$ resonance in p+p collisions. The signature of the $\Lambda(1405)$ was extracted by analyzing its decay into Sigma-pion pairs and the pair-invariant mass was studied as the spectral distribution of the resonance. The $\Lambda(1405)$ signal shows a shift of about 20 MeV/c^2 of the peak maximum associated to the resonance towards to lower masses.

Participants of the ECT Meeting in October 2013.*

A special Meeting on the scientific topics of LEANNIS ("Theory and experiment study strangeness in the universe") was organized (J. Marton, co-organizer) at the European Center for Theoretical Studies (ECT*) in Trento (see CERN Courier, Jan. 2014).

6.2.2 Kaonic atoms

Precision X-ray spectroscopy of kaonic atoms represents an excellent tool to study the chiral symmetry breaking scenario. Kaonic atoms are QED bound systems in which the heavier, negatively charged particle replaces an electron, for example a kaonic hydrogen

($K^{-}p$) atom could be formed. In general, studies of exotic mesonic atoms have provided important information on strong interaction (hadron) physics.

Effective field theories (EFTs) provide a crucial framework for analyzing the properties and interactions of hadrons and nuclei. These theories describe low-energy hadron physics implementing the symmetries of the underlying theory, QCD, using effective Lagrangians for the relevant degrees of freedom, which leads to observable effects in the spectrum of exotic hadronic atoms.

Therefore, X-ray spectroscopy of kaonic atoms plays an important role for understanding the low energy $K^{bar}N$ interaction. In particular, we have measured the strong-interaction shifts and widths of light kaonic atoms in SIDDHARTA at LNF Frascati and new experiments are planned to measure ($K^{-}d$) at LNF and J-PARC (Japan).

Kaonic hydrogen X-ray yields from SIDDHARTA

In 2013, we finished the data analyses of all the measurements performed during the beam time of the SIDDHARTA experiment in 2009. The experiment aimed at determining the strong-interaction-induced shift and width for the ground state of the kaonic hydrogen atom with the highest precision. This goal has been achieved as already introduced by a series of publications from the group.

The absolute yields of kaonic hydrogen 2*p* -1*s* transition X-rays and all *K*-series X-rays were determined from the simultaneous analysis of the deuterium target data and carefully selected hydro-

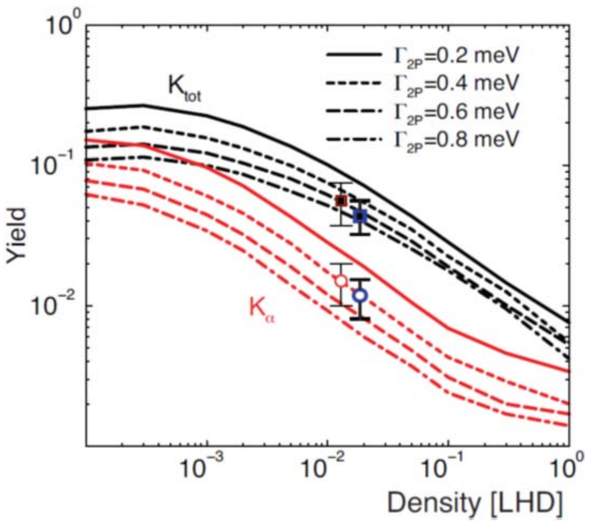


Fig. 7 The absolute yields of kaonic hydrogen K-series X-rays [1]. The density is in the unit of liquid hydrogen density (LHD). The filled dots are the result of SIDDHARTA, and the hollow dots are from KEK E228 experiment in 1997. The lines show the theoretical estimations from cascade model calculation by T. Jensen assuming different width for the kaonic hydrogen 2p state.

gen target data set. For a hydrogen gas target of density 15 ρ_{STP}, we got :

$Y_{K\alpha} = 0.012\ ^{+0.003}_{-0.004}$

$Y_{Ktot} = 0.045\ ^{+0.009}_{-0.012}$

Defined as the number of X-rays for each stopped kaon in the target, the absolute yields are deduced from the comparison between the X-ray detection efficiency estimated from the Monte Carlo simulation assuming a yield of 100%, and the real efficiency obtained from experiment [1,2]. Meanwhile, based on the same analysis, we estimated an upper limit for the yield of $2p$ -$1s$ transition X-rays of kaonic deuterium for reference of a future measurement [3]. Moreover, we obtained the most stringent restriction for the kaonic hydrogen $2p$ width due to nuclear absorption from a comparison of the kaonic hydrogen X-rays yields to the Extended Standard Cascade Model calculation as shown in Fig. 7 (from Ref. [1].)

[1] H. Shi : "Precision spectroscopy of kaonic hydrogen atomic X-rays." Doctoral thesis, 2012, The University of Tokyo.
[2] H. Shi, et al., SIDDHARTA Collaboration: "The yield of kaonic hydrogen X-rays in the SIDDHARTA experiment", Published online: 20 March 2014 DOI: 10.1051/epjconf/20146609016 EPJ66, 09016 (2014)
[3] M. Cargnelli et al., SIDDHARTA collaboration, Nucl. Phys. A 907 (2013) 69.

Monte Carlo simulation for a kaonic deuterium measurement at J-PARC

(Ph.D. thesis of C. Berucci)

A new Monte Carlo code was developed for the kaonic deuterium experiment at the K1.8BR beam line at J-PARC, to improve the setup response in terms of signal over background ratio. The structure and the composition of different materials out of which the setup is build were reproduced with high accuracy, particular attention being given to the low energy detector (SDD) mounting, to the target and to the kaon tracking and degrading devices. The GEANT4 package was chosen for the task, with special care on the low energy tools.

The low energy electromagnetic processes were simulated using the Livermore model, which allows particle tracking down to the few keV range of the experiment and moreover, reproduces well the X-ray fluorescence lines of the setup materials, while the low energy hadronic interaction package was activated for nuclear interactions. For what concerns the nuclear absorption of the stopped kaons as final step of the atomic cascade, the radiative transitions of most of kaonic atoms were included, with tunable yields, to simulate both signal (kaonic hydrogen and deuterium X-rays) and structured background (characteristic X-rays lines of other kaonic atoms).

The simulations start with 660 MeV/c kaons with +/−3% (flat) momentum bite. The kaon beam properties were taken from a measurement at the K1.8 BR beam line at JPARC in June 2012 with a kaon momentum of 1000 MeV/c. For the use as kaon degrader several materials (carbon, polyethylene and iron) were compared in the simulation. The highest stopping rates were obtained with a carbon degrader of about 40 cm thickness.

We have simulated the kaonic deuterium X-ray spectrum, assuming 30 kW primary beam power with a kaon rate of about 5.5 kHz, 30 days of data taking, and 300 cm^2 detector area. The yield ratio of the K_α K_β:K_{total} events was taken from the kaonic hydrogen data, with an assumed K_α yield of 10^{-3} for the gaseous target. For the strong interaction induced shift and width theoretical predictions were used: shift = −800 eV and width = 750 eV.

Assuming this kaon intensity and rejecting the kaon-correlated background using various cuts, especially a fiducial volume cut and a charged particle veto, it will be possible to achieve a signal to background ratio of 1:3 for the kaonic deuterium K_α-line with a target gas density of 5%.

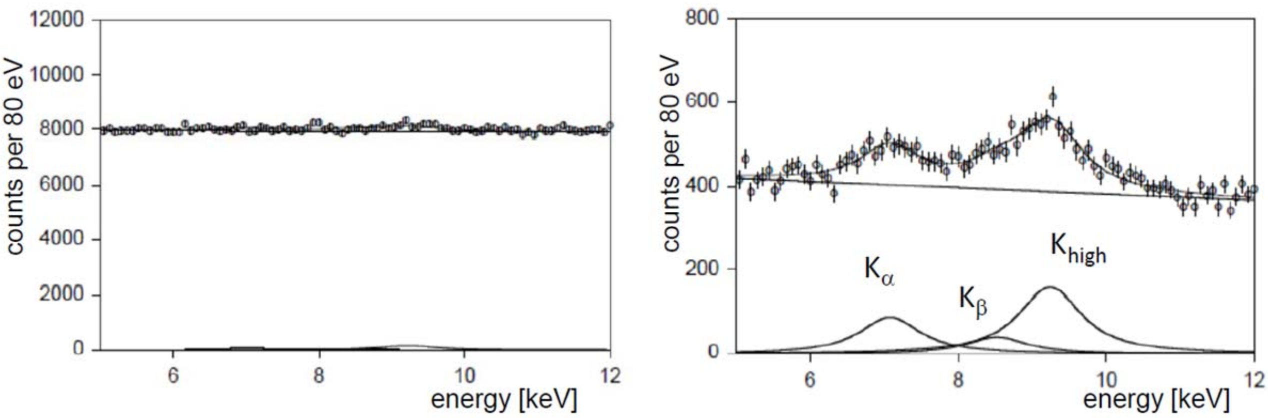


Figure 8: Simulated kaonic deuterium x-ray spectrum, assuming a 30 kW beam power, 30 days of data taking and a detector area of 300 cm2. Left: Demanding only appropriate K signal on the beam counter after the degrader. Right: Beam counter condition same as before but additionally vertex cut and charged particle veto for tracks passing SDDs.

Within 30 days of beam time, using a gas density of 5% LDD, we will be able to collect 1500 K_α events, which will allow a determination of the strong interaction induced shift and width of the 1s state of kaonic deuterium with a precision of 60 eV and 140 eV, respectively. Based on these results a Letter of Intent was submitted to the J-PARC PAC, which was well received. The PAC asked to submit a full proposal, which is currently being prepared [1].

[1] Berucci, C. et al., (2013). *Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium* (KEK/J-PARC-PAC 2013-7). Letter of Intent to J-PARC.

6.2.3 Strangeness Hadron Physics

(Supported partly by FWF grant P21457, Ph.D. thesis of P. Müllner and I. Carević (guest from University of Split))

Strangeness hadron physics tries to reveal the complex dynamics and phenomena of quarks and gluons, e.g., hadron properties in nuclear medium, symmetry breaking pattern and hadron mass generation, new forms of hadrons, which are described by the Quantum Chromodynamics (QCD). The "strong" QCD interaction is characterized by color confinement and asymptotic freedom, namely the interaction becomes weak at short distances (at high energies) and can be treated perturbatively, on the contrary at long distances (at the temperature of the present universe) the interaction stays strong and color charges are confined. The chiral symmetry and the heavy quark symmetry play a role in the QCD at the light quark sector (m_u, $m_d \ll \Lambda_{QCD}$) and at the heavy quark sector (m_c, m_b, $m_t \gg \Lambda_{QCD}$), respectively. At the energy scale of the strange quark mass ($\approx\Lambda_{QCD}$), however, neither of the symmetries is good enough and the dynamics of the strange quark is thus very sensitive to the dynamics of QCD.

The exotic kaonic nuclear few body bound states are predicted to exist by various calculations although the predictions of their masses and widths are rather scattered. Some theories predict that such kaonic nuclei might have significantly higher density than the normal nuclear density. This could be understood with a picture that the quark composition of the antikaon ($s\bar{u}$) are different of the one of the nucleon (ud) and therefore a quark level Pauli excursion principle is suppressed.

The so-called X(2265) state has been found in an exclusive data set of $pp\rightarrow p\Lambda K^+$ at T_p = 2.85 GeV of DISTO data with a mass of 2267 MeV/c^2 and a width 118 MeV and has a baryon number 2 and strangeness S=−1. The X state is possibly a candidate of the long-searched $(\bar{K}NN)_{S=0,\ I=1/2}$ kaonic nuclear dibaryon system, often called K^-pp. An energy dependence study of the production rate of the X(2265) in the DISTO $pp\rightarrow p\Lambda K^+$ data taken at T_p = 2.5 GeV indicated that the Λ(1405) plays an important role as a door way to the high density kaonic nuclear systems [1]. In 2013, many new data on the kaonic nuclei became available. Among them notably the E27 experiment at J-PARC reported a positive result from their preliminary data analysis in their search for K^-pp. Our activities on the theme of kaonic nuclei is described below.

[1] P. Kienle, M. Maggiora, K. Suzuki *et al.*: “Formation of the S=–1 resonance X(2265) in the reaction $pp\rightarrow X+K^+$ at 2.5 and 2.85 GeV”, Eur. Phys. J. **A 48** (2012) 183.

Study of the strange dibaryon K^-pp in the $pp\rightarrow p\Lambda K^+$ reaction at T_p=2.85 and 2.5 GeV (DISTO)

DISTO has investigated the formation of kaonic states in the 3-body final state $pK\Lambda$. A binary process $pp\rightarrow XK^+$ in which an exotic kaonic state is produced could in fact lead through this decay chain to the pKΛ final state. DISTO has a very large and pure statistics. The observation of the X(2265) resonance and the energy dependence study of its production have been performed using what-we-call the deviation method, that was very powerful, however, with a certain limitation. We worked in 2013 for a reanalysis making use of a full acceptance matrix. This allows to investigate further the nature of the X(2265) and to study the Σ decay channel as well.

Study of the strange dibaryon K^-pp in the $pp \rightarrow p\Lambda K^+$ reaction at T_p=3.1 GeV (FOPI)

FOPI as well has been investigating the kaonic states in the same reaction as DISTO, i.e. $pp \rightarrow p\Lambda K^+$ but at the proton incident energy of 3.1 GeV. The FOPI data provides an independent check of the X(2265) found by DISTO, as well as an extended energy dependence study. That could be a vital clue to link the X(2265) resonance to the K^-pp state. The data analysis made a great step forward [2].

[2] R. Münzer *et al.*: "Status of the $pK^+\Lambda$ analysis in pp collisions with the FOPI spectrometer", GSI Annual Report 2013.

E15 Experiment at J-PARC

The E15 experiment is located at J-PARC, Tokai, Japan [3], that aims at searching for the K^-pp state with $^3He(K^-, n)$ reaction, complementary to the *pp* reaction at DISTO/FOPI, using a newly

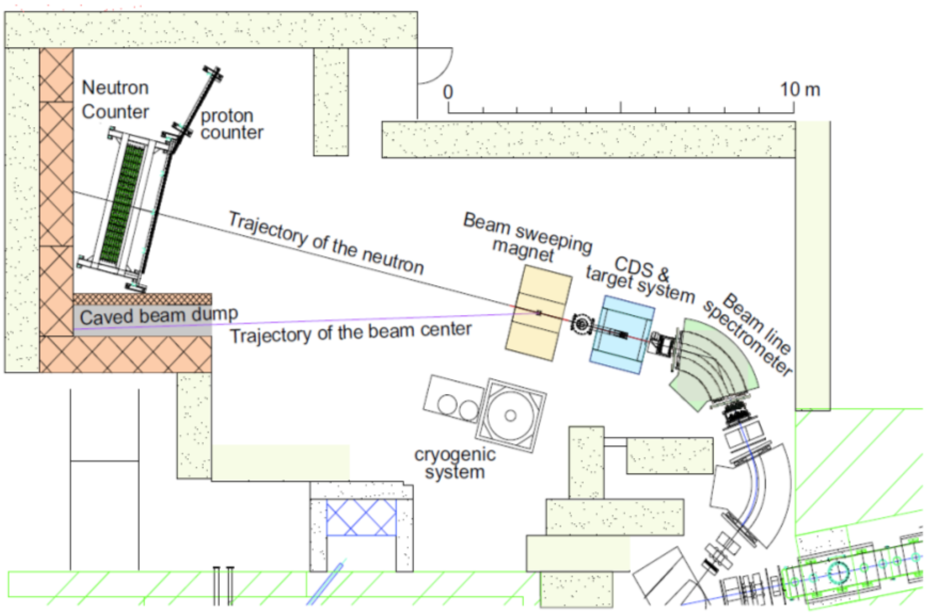


Figure 9: The J-PARC K1.8BR spectrometer. The setup consists of a beam line spectrometer, a cylindrical spectrometer system (CDS), a beam sweeping dipole magnet, a caved beam dump equipped with beam monitor hodoscopes, a neutron counter made of an array of plastic scintillation counters equipped with charged veto counters and a proton counter hodoscopes.

available high intensity, high quality kaon beam. The accelerators and the experimental areas came back in operation with a colossal effort from the substantial damage by the Great East Japan Earthquake on 11.3.2011. The data taking in May 2013 was terminated by an abrupt fast extraction and an eventual leak of radioactivity to the environment. The 1/10 of anticipated statistics has been collected. The analysis of the already taken data set has been started.

[3] K. Agari *et al.*: “The K1.8BR spectrometer system at J-PARC”, Prog. Theo. and Exp. Phys. (2012) 02B011.

The BELLE Experiment

(Master thesis of M. Berger)

The BELLE experiment was built primarily to study the CP violation in B meson system. The e^+e^- collider machine was tuned at Y(4S) resonance that falls into a dominant decay channel of B meson pair production. In order to obtain a firm evidence oft the tiny CP violation, the BELLE experiment had been running with the world highest luminosity for nearly 10 years, accumulating an enormous statistics of high quality data. In 2003 the so-called X(3872) state was discovered in the BELLE data. This exotic hadron, reminded us that the constituent quark model does not prohibit the existence of hadrons with four quarks, besides the firmly established baryon (qqq) and meson ($q\bar{q}$). This discovery has created a whole new field and the BELLE data turned out to be the treasure island for hadron physicist.

SMI has joined the BELLE collaboration in 2011 to analyze the data for the following two major interests.

One focus is related to the PANDA experiment. Although distinct in their primary conceptions and goals, BELLE and PANDA cover common physics topics. The energy range of the antiproton beams at PANDA will be up to 5.5 GeV/c^2 in the *NN* c.m. frame, thus covering the region of hadrons containing the charm quark. Indeed, precision spectroscopy of charmonia and the study of open charm is one of the key issues of the PANDA physics program. The BB^{bar} as well as the 'continuum' events at KEK-BELLE provide a rich opportunity to perform these types of analyses. In fact a big fraction of the more recent publications in the sector of hadron physics with charm comes from B-factories, like KEK-BELLE. Thus analysis activities on BELLE data are very interesting by themselves but in addition an excellent chance to gain more experience in hadron spectroscopy analysis techniques, from which we will profit later on with PANDA.

According to these ideas we recently started to search in BELLE data for the existence of the charmonium state η_{c2}. This state has a predicted mass of 3750 - 3850 MeV/c^2, thus lies slightly above the DD^{bar} threshold and was not observed yet, neither with BELLE nor with other experiments. η_{c2} is predicted to decay by emission of two gammas to h_c and further to η_c. The search is performed with an invariant mass analysis (reconstruction of the four-momentum of η_{c2} from the measured four-momenta of the daughter particles). This analysis shall be finished within 2014.

The other focus is related to the existing activity of the institute on strangeness nuclear/hadron physics, and we extend it to the charmed sector. The search for kaonic nuclei is one of the major themes in hadron physics since its possible existence was predicted. The $\bar{K}N$ interaction is the fundamental theoretical input to the study of few-body systems with antikaons. The scattering lengths of the $\pi\Sigma$ systems are key quantities in understanding the subthreshold behaviour of the $\bar{K}$ N interaction and the structure of the Λ(1405) resonance which is a quasi-bound $\bar{K}N$ state embedded in the $\pi\Sigma$ continuum, and hence are essential to understand the kaonic nuclei. The $\pi\Sigma$ scattering lengths can be extracted from the threshold cusp phenomena in the weak $\Lambda_c \to \pi\pi\Sigma$ decays [PRC 84 (2011) 034201], in analogy with Cabibbo's method for determination of the $\pi\pi$ scattering length. Such kind of study is feasible at BELLE where a huge amount of Λ_c is produced through the B-meson decay.

AMADEUS project and KLOE analyses.

The strangeness sector of the non-perturbative regime of the low energy region of QCD is of capital importance for the understanding of the hadron interactions and structure, and its in-medium modifications. The kaon-nucleon interaction, and specially the study of the antikaon-nucleon potential in nuclear matter is a current hot topic, and it is the main ingredient for understanding how a state of kaon condensate could appear in conditions of extreme density (being the most immediate example the core of the neutron stars) and its influence in the nuclear equation of state.

The AMADEUS project (setup shown in Fig. 10) aims to extract new information from the most accurate available data from kaonic absorption by light nuclei, with the interpretation of the results from the analysis of the KLOE experiment data, where low momentum and stopped kaons are absorbed in the various components of the KLOE spectrometer, being of special interest those produced in the solid ^{12}C of the drift chamber entrance wall, and those from the ^{4}He gas filling the chamber. Missing masses, momenta distributions, etc., are available for different channels ($\Sigma^0\pi^0$, $\Sigma^+\pi$, Λp, $\Lambda\pi^-$), in order to search for signals of exotic kaonic bound states and to study the formation of the $\Lambda(1405)$ resonance.

During 2013, detailed calculations in the Lambda direct formation processes has been performed. The couple hyperon-pion can be originated in non-resonant absorptions as well in resonant reactions with the intermediate formation of $\Sigma(1385)$ or $\Lambda(1405)$ states. Both resonant and non-resonant processes can arise in different K-mesic atom angular momentum states, and K-nucleon angular momentum states, as a consequence of the three-body structure of the system. Various angular momentum combinations can enhance or prevent the resonant formation, and are characterized by different $P_{\Lambda\pi}$ distribution shapes. Those simulations are being now fitted to the obtained data, and this procedure will be performed as well in the case of the $\Sigma\pi$ analyses.

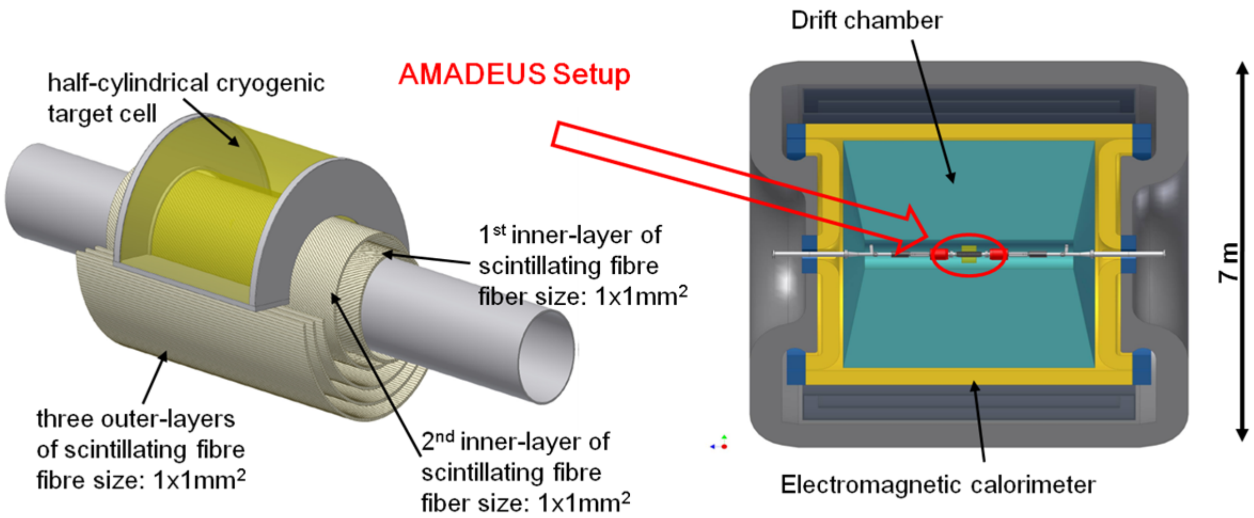


Fig. 10: Sketch of the AMADEUS setup (left) to be inserted into the KLOE detector (right) at DAΦNE.

Pushed by the obtained results a high purity Carbon target (graphite) was realized in summer 2012 and installed inside the KLOE drift chamber, between the beam pipe and the DC entrance wall. The target was realized with the main aim to obtain an almost pure sample of absorptions of K^- stopped. The data collected with this target was analysed during 2013 and used as well for check possible effects of contamination of aluminium present in the top and bottom of the DC wall. In the case of the study of the $\Lambda(1405)$, the opportunity opened by the analysis of the carbon target data is even more obvious: a pure sample of stopped kaon events is available to complement the 2.2 fb^{-1} collected by the first KLOE run, with in-flight absorptions at a momentum of around 120 MeV/c.

6.2.4 The PANDA Experiment

(Partly supported within the 7th EU Framework Programme – HadronPhysics3)

The PANDA Experiment is one of the large scale projects at FAIR. It will study antiproton annihilations on nucleons and nuclei in the energy range of strange and charmed hadrons. A synchrotron and storage ring (HESR) will provide an antiproton beam with very small momentum spread ($2\cdot 10^{-5}$) or high luminosity ($2\cdot 10^{32}$ $cm^{-2}s^{-1}$). The commissioning of the experiment at FAIR is planned to start in 2018. The SMI activities in the PANDA project are contributions to the software framework and simulations/analysis, involvement in the development of the PandaGrid computing network and maintenance of a PandaGrid site, as well as R&D for different detector parts.

The activities in 2013 concentrated on the development of a prototype sensor for the SciTil detector (Scintilation Tile Hodoscope). The SciTil is a timing detector and is planned to be mounted in front of the Electromagnetic Calorimeter (EMC). It is made of ~ 3 x 3 x 0.5 cm^3 scintillator tiles matching the front face of the EMC crystals, and will be read out by 3 x 3 mm^2 Silicon Photo Multipliers (SiPMs). The presence of a large magnetic field due a solenoid magnet prohibits the use of PMTs. At SMI a prototype of a scintillating tile with SiPM readout was investigated and it was demonstrated to provide a time resolution below 100 ps. Figure 10 shows the central tracker system of PANDA, highlighting the position of the SciTil detector.

The activities in the PANDA related R&D are described in more detail in section 6.3.1. In 2013 also the Technical Design Reports for the Muon Detectors has been reviewed and released by the collaboration.

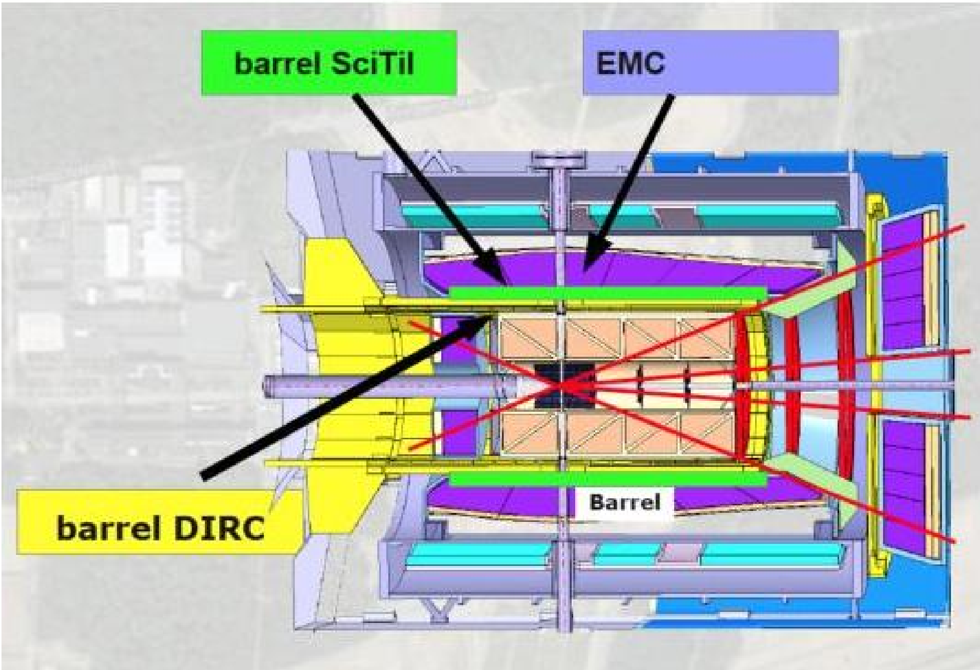


Figure 11: Sketch of the PANDA central tracker highlighting the position of the SciTil detector.

6.3 Advanced Instrumentation

6.3.1 Detector development within Integrated Activity HadronPhysics3

(Supported by EU-FP7 HadronPhysics3)

The Stefan Meyer Institute has well equipped mechanic and electronic workshops, suited for the needs when doing experimental work in the field of subatomic physics. Together with the design and construction employee we are able to produce important parts for our experiments at foreign accelerator facilities: CERN-AD, Switzerland; GSI, Germany; LNF, Italy and J-PARC, Japan.

R&D work is performed mainly in the framework of the “Joint Research Activities”, within the HadronPhysics3 project of the 7th Framework Programme of the EU which started in January 2012 and runs for three years. The Institute participates in 3 work packages: WP20: FutureJet - Cryogenic jets of nano- and micrometer-sized particles for hadron physics, WP24: JointGEM - Ultralight and ultra-large tracking systems based on GEM technology and WP28: SiPM - Avalanche Micro-Pixel Photo-Diodes for Frontier Detector Systems. WP24 is led by SMI.

In addition, to study the anti-hydrogen production and extraction at the CERN-AD with the CUSP trap a central pion tracking detector was built and successfully used, using a hodoscope read out by SiPMs. Because of the success a new two layers system is now in the design phase.

The VIP-2 apparatus was designed and constructed at SMI, with a novel SDD cooling scheme. A veto system surrounding the SDDs is made of plastic scintillator bars, read out by SiPMs with a special amplifier/trigger board designed at SMI (the process for obtaining a patent is ongoing).

WP20 – FutureJet

Within WP20 FutureJet our Institute contributes to studies of the (hydrogen) cluster-jet target of PANDA. A continuous working of the cluster-jet beam, without blocking due to freezing of impurities in the nozzle, is essential for the use in PANDA. Therefore, a gas purification system in the sub-ppm region is a must. SMI is performing R&D work to develop a system which has to work at high gas throughput and at high pressure to achieve the required cluster-jet density for PANDA. In addition first studies have been started for the design of a closed-cycle deuterium gas system.

WP24 –JointGEM

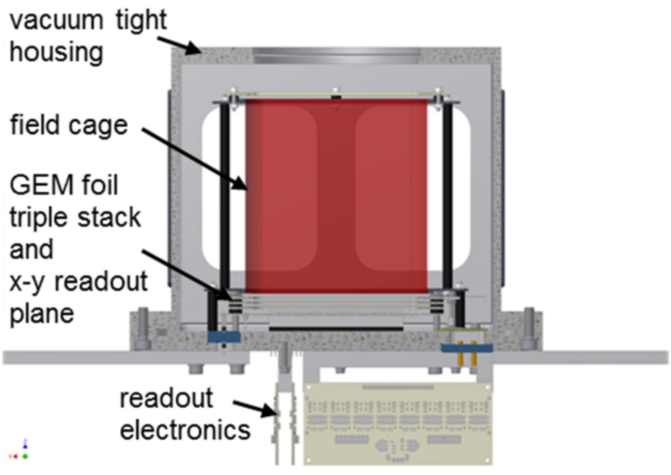
(Spokesperson J. Zmeskal)

The Gas Electron Multiplier (GEM) detector has been introduced by Fabio Sauli in 1997. Characterized by high rate capability and position accuracy, flexibility in shape and lightness, the detector has been successively developed by many research groups, used as tracker and fast triggering system in particle and nuclear physics experiments. The future applications of such a very promising technology require for large area covering with full efficiency, low material budget and high spatial resolution, together with a new simplified and cost effective detector design, which will allow to reduce as much as possible the assembly time and will be suitable for mass production.

A GEM-TPC with more than 10.000 channels has been built and implemented in the FOPI spectrometer, where the GEM-TPC was used during a 3-week physics campaign to study pion-induced reactions on different nuclear targets. The GEM-TPC significantly improved the vertex processing selection capability of the experiment, and provided particle identification via the measurement of the specific energy loss. This is the first application of such a device in a physics experiment.

The idea of an un-gated, continuously running TPC is of interest for example for the upgrade of the ALICE TPC, which is only possible by using one of the key features of a GEM-TPC, the excellent ion backflow suppression.

Simulation and design studies using hydrogen as counter gas in a TPC with GARFIELD and GEANT programmes have been performed in order to investigate the use of such an active target TPC-GEM as inner tracker for the AMADEUS experiment at DAΦNE. A prototype has been designed and is under construction, which will allow first test measurements with pure gases like helium and hydrogen.



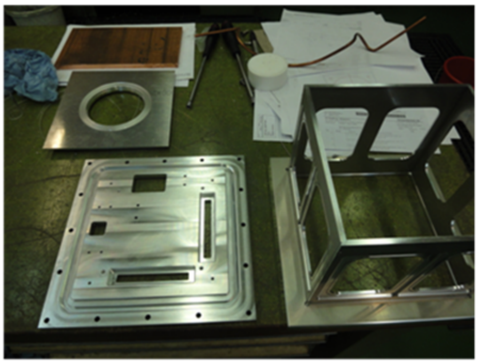


Fig. 12: Sketch of the active target TPC prototype (left); parts of the vacuum tight TPC housing (right).

WP28: SiPM

(Ph.D. theses of L. Gruber)

SiPM provide unique features in terms of single photon detection and are used for several photon detectors at SMI, with the outstanding time resolution being one of them. As Silicon photomultipliers are offered by many vendors differ in many parameters such as cell capacitance and photon detection efficiency which influences the time resolution of the decives. Although, SiPM are used for many timing applications, no systematic measurements for comparison of the time resolution of SiPM have been published, so far. Therefore, a semi-automatic stand including a pico-second laser and waveform sampling for characterisation of the time resolution has been set up and allows measurements at various temperature and voltage conditions. So far devices of AdvanSiD, Ketek and Hamamatsu have been tested and first results already have been published. Furthermore, the time resolutions of the Philips digital SiPM (digital photon counter) has been determined using a slightly different setup (due to the already implemented electronics).

The IFES board for SiPM detectors

(Patent application in progress)

As a consequence of deficiencies discovered during the 2012 ASACUSA antihydrogen beamtime at CERN we decided to redesign and improve our frontend electronics for silicon photomultipliers. The newly developed IFES (Intelligent Frontend Electronics for Silicon photo detectors) modules combine an easy to use pre-amplifier with remote fine grained control over the amplification gain with an onboard discriminator that provides a time over threshold (ToT) signal and a full differential signal way.

The differential signal is generated at the active detector and amplified by an 2.2 GHz differential amplifier, the resulting signal is split into a small fraction that is fed to an leading edge discriminator that provides energy information encoded as length of the digital pulse. The other part of the signal is provided to the user in form of a differential analogue signal. The digital ToT signal is provided as a LVDS (Low Voltage Digital Signal) pulse. The main advantages of using a fully differential signal way is that the noise pickup on long signal lines is suppressed and that the connection itself is ground free. In big experiments earth loops introduce lots of noise pickup which is usually a big problem. The design of the new modules helps circumventing the grounding problem.

The IFES modules can be remotely controlled by a computer, the control bus is an SPI interface driven by LVDS. Therefore even small low-cost microcomputers as an Arduino are capable of controlling the modules and therefore providing and easy to use end user interface that can be integrated into various slow-control and DAQ systems.

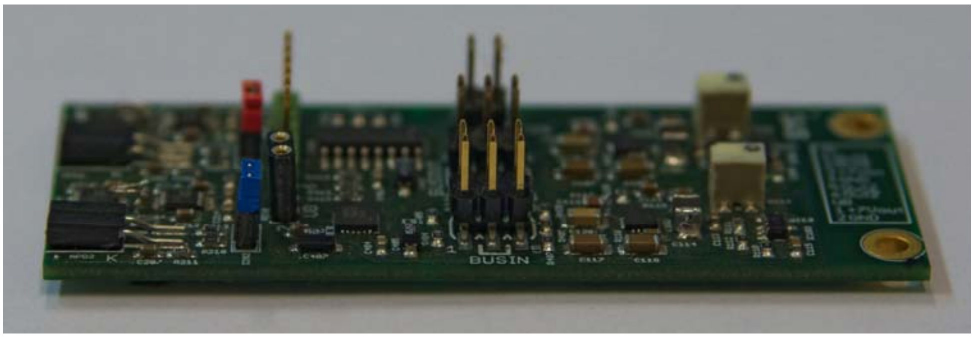


Fig. 13: Foto of the IFES board

6.3.2 Medical applications

The Cherenkov effect for TOF-PET

(Ph.D. theses of S. Brunner)

The Cherenkov effect is a well known effect and is used in many detectors in high energy physics (e.g. PANDA-DIRC). Nevertheless, it has not been used for detection of gamma rays, especially at low energies. We are evaluating the Cherenkov effect for implementation into TOF-PET, in which the electrons, ionized by the impinging 511 keV gamma-quanta, emit Cherenkov photons, when they are propagating faster than the speed of light in the detector medium. As this emission takes place immediately after the photoelectric effect, the Cherenkov photons are promising to improve the overall timing performance of TOF-PET as it bypasses the relatively long lasting scintillation processes in inorganic scintillators [1]. For evaluation of the potential of this effect we performed comprehensive simulation studies using Geant4, in which the improvement of Cherenkov photon detection on the time resolution in PET was determined quantitatively, see figure. Furthermore, a proof of principle measurement using lead glass as Cherenkov radiator and PMTs as photodetectors was performed and has been published in [2]. Based on the outcomes of the simulation studies and the proof of principle new promising Cherenkov radiators have been found and are currently under testing. Using these new materials with a high yield of Cherenkov photons the proof the principle is tried to be repeated using SiPM (analog and digital) in order to profit of their good timing performance and the possibility to arrange them in highly segmented and compact PET detectors which resulting in an improved timing performance and, furthermore, could be implemented in hybrid TOF-PET-MRI systems due to their insensitivity to magnetic fields. This method not only is interesting for TOF-PET but also can be used in fast, low-energy particle detectors in basic research.

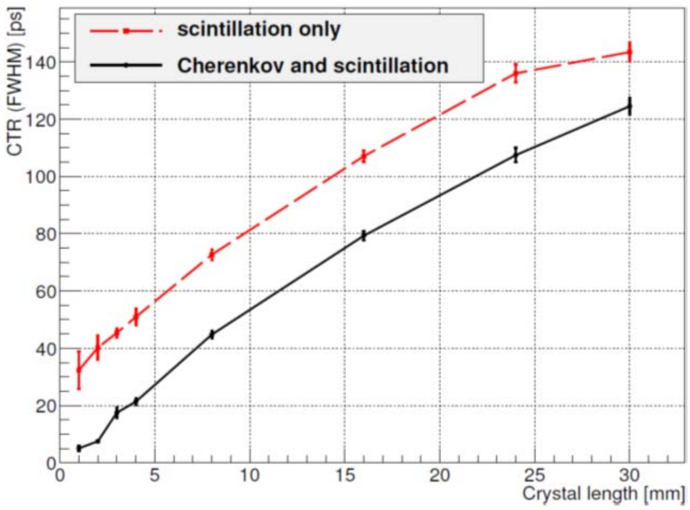


Fig. 14: Improvement of the coincidence time resolution of a basic TOF-PET setup by detecting Cherenkov photons.

[1] S. E. Brunner et al., "New approaches for improvement of TOF-PET," NIM A, 732, (2013) pp. 560–563.

[2] S. E. Brunner et al., " Studies on the Cherenkov effect for Improved Time Resolution of TOF-PET", IEEE TNS, 61 (online 2013), pp. 443–447.

Prompt gamma emission of charged particles

(Master theses of D. Steinschaden and A. Pichler)

In ion-radiation therapy no satisfying method exists for real-time range monitoring. The PET monitoring, which is implemented in a few facilities for this purpose, has its drawbacks like the so-called wash-out effect, which causes excited atoms to be transported away from their original position in the time between excitation and emission of radiation.

This effect can be avoided by using prompt radiation (timescale of 10^{-9} s after their excitation). This radiation can consist of prompt gamma radiation. These photons are emitted by excited target or projectile particles all along the ion path, with a maximum intensity at the end of the ion range, at the Bragg peak. By detecting the emitted photons, the Bragg peak and with that, the range of the ions should be calculated.

The feasibility of the prompt gamma detection was studied with the GATE simulation framework (GEANT 4 based framework for simulating the passage of particles through matter). The study of the prompt photon spectrum shows that the energy range from 2.3 to 6 MeV is promising for getting information about the ion range. At energies lower than 2.3 MeV, the emission of the photons does not exhibit a peak structure in the region of the Bragg peak and scattering effects inside of the target are stronger for lower energies. For higher energies than 6 MeV, a larger part of the photons are produced outside of the beam, which is also an unwanted effect.

The feasibility of detecting the Bragg peak with cylindrical detectors with lead collimators has been investigated. The detectors were aligned in the plane perpendicular to the beam. The produced photons as a function of depth in the target have been calculated from the detected photons. This scheme has been tested with a cylindrical water target and carbon ion projectiles with varying energy. Depending on the energy, an accuracy of the calculation of the depth of the Bragg peak of a few millimeters was achieved. The next steps in this project would be to optimize the detector geometry and to verify the simulations with experiments.

6.4 Smaller Physics Projects

6.4.1 VIP2: Pauli exclusion principle test in an underground laboratory

(Supported by FWF Project P25529-N20)

The Pauli Exclusion Principle (PEP) is one of the pillars of quantum physics and the foundation of modern physics. It is at the basis of our understanding of nature and has consequences for the world of elementary particles up to compact objects (e.g. neutron stars) in the universe - but it has no simple explanation. We know that the Pauli Principle is very well fulfilled leaving still the question open about the limit of validity. A possible (tiny) violation of this principle would point to new physics possibly showing up at the Planck scale but might be present at lower energies. A method to test the PEP experimentally was developed by Ramberg-Snow. PEP is tested for electrons, i.e. elementary particles having no interaction with the studied system thus circumventing the Messiah-Greenberg super-selection rule. These new electrons are provided by a strong electric current which flowing through a piece of solid metal. Pauli-forbidden transitions in this metal exhibit an energy shift in the transition energy resolvable by x-ray spectroscopy. A search for x-ray transition events can be performed with high sensitivity but requires substantial background discrimination. In our previous VIP experiment [29] at the underground laboratory LNGS (Gran Sasso) we used an improved Ramberg-Snow experimental setup exploiting charge coupled devices as x-ray detectors. In this experiment we could deduce an upper limit for the Pauli exclusion principle violation in the order of 10^{-29}. The follow-up VIP2 experiment will be performed in the underground laboratory LNGS in Gran Sasso taking again advantage of the excellent shielding against cosmic rays. A strongly improved compact setup with passive and active shielding will be used. Silicon drift detectors will serve as x-ray detectors providing a timing signal used in anticoincidence with scintillators (veto counters) to suppress actively background events.

A FWF project (P 25529-N20, project leader J. Marton) was approved and started with January 15th, 2013. In 2013 the VIP2 experimental setup was assembled at the Stefan Meyer Institute in Vienna and transported to the Laboratori Nazionali di Frascati/INFN (LNF/INFN) for testing. The final installation of the VIP2 setup in the underground laboratory of LNGS/INFN in the Gran Sasso laboratory – the final destination - will be done after the careful examination and testing of the full

VIP2 setup in Frascati. The active shielding consisting of plastic scintillation detectors with readout by solid-state photo-detectors (SiPMs) was developed at SMI and transported to LNF in Frascati. The lucite housing of the VIP2 setup, which will provide a clean gas surrounding of VIP2, was transported already to LNGS in Gran Sasso.

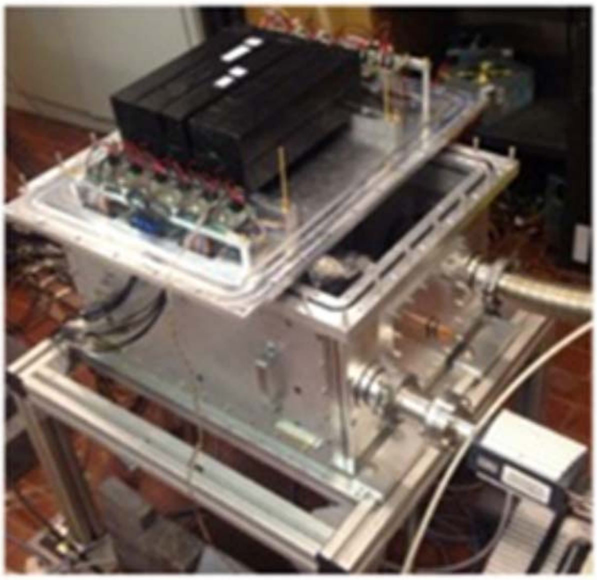


Fig. 15: Test setup of the VIP2 experiment in the laboratory at LNF.

First tests of the vacuum systems and the target cooling system were performed in the first half of 2013. With August 2013 a post-doc, Dr. Hexi Shi, financed by the project started his work. The SiPM readout of the active shielding scintillation detectors was tested with cosmic rays. The efficiency of the scintillators was measured and was found to be better than 95% as anticipated. The timing resolution was measured using the relative timing of a 3-scintillation detector setup. The timing resolution was also studied at the beam test facility (BTF) at LNF employing tagged 500 MeV/c electrons and positrons. The typical time resolution is 2-3 ns FWHM. With the BTF beam the position sensitivity of the detection efficiency was studied but has found to be not significant.

The x-ray detection with silicon drift detectors (SDDs) was setup and tested. A timing resolution of SDDs <600 ns was found. The target system was tested with current flowing through the copper foils. The stability of the vacuum and cooling system were checked.

Therefore, the testing of the VIP2 apparatus made progress with encouraging results.

6.4.2 EC-decay of highly ionized atoms

(Master thesis of Ch. Klaushofer)

At the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany a unique combination of a heavy-ion synchrotron (SIS), a projectile fragment separator (FRS) and an experimental storage ring (ESR) with stochastic and electron cooling of coasting ions allows to produce, separate, store, cool, and study various decay modes of exotic nuclei with well-defined number of bound electrons. Masses and life-times of unstable ions can be measured by using high resolution time-resolved Schottky Mass Spectroscopy (SMS).

Using the sensitivity of SMS to measure the revolution frequency of cooled single ions in the ESR, which is a monotonous function of the specific charge q/M of the ion, the time dependence of the EC-decays of H-like ions was studied in 2008. The rates of the number of the EC-decays of H-like ^{140}Pr and ^{142}Pm ions deviate from the expected exponential decay law. The data were described by adding a modulation term with a modulation period T = 7 s, an amplitude of about 20 %, and a phase which was not well determined. In turn, the analysis of the β^+-decay of the H-like ^{142}Pm ions showed no deviation from the exponential decay law [PLB 664 (2008) 162].

Although the study has triggered a vivid discussion about the cause of this modulation (see e.g. http://www.nu.to.infn.it/Neutrino_Oscillations/) there exists no conclusive explanation so far. The observation, that the modulation exists in the two-body EC decay but not in the three-body β^+-decay could however point to a weak-interaction origin of the modulation which is observed in connection with the mono-energetic electron-neutrinos from EC decays, but not visible for the continuous neutrino spectrum of the β^+-decay branch.

The experiment with ^{142}Pm was repeated in 2010 by using a 245 MHz resonator cavity with much improved sensitivity and time resolution. And again a modulation of the exponential decay was found with a period of 7.11 seconds but this time with a somewhat smaller amplitude of ~12 % [1]. No deviation from the exponential decay law was found for the β^+-decay in agreement with the previous results. The data analysis of these 2010 data has been carried out by two independent groups at GSI and SMI. At SMI an automatic analysis method was developed for this purpose.

During the measuring period in 2008, in addition to the ion species ^{142}Pm and ^{140}Pr, also the decay of ^{122}I has been investigated. From this data set only a preliminary analysis exists. The final analysis is subject of a diploma thesis which is carried out at SMI and which started in October 2013 and is planned to be finished until the end of 2014. Following the positive experience with the analysis of the 2010 data, independent analysis at GSI and SMI will be combined to obtain the final result.

[1] K. Kienle et al., PLB 726 (2013) 638].

6.4.3 Deeply bound pionic atoms

Deeply bound pionic atom state was discovered at GSI, Darmstadt in 1996 using (*d*, ^{3}He) reaction on heavy element (Pb, Sn). The precisely-determined π-nucleus potential lead to a unique determination of a reduction of the quark condensation in a nuclear medium by ~35% [1]. In order to further improve an experimental precision and hence to better constrain the theoretical scenario of the dynamical generation of hadron masses from spontaneously broken chiral symmetry, a new series of experiments is proposed to make use of high intensity deuteron beam which became recently available at the new RI Beam Facility and the fragment separator (BigRIPS) at RIKEN, Japan. In the short pilot experiment in 2010, primarily meant to develop the required special momentum-matching beam optics, we succeeded to collect an equivalent statistics as the preceding GSI experiment and observed deeply-bound *1s*, *2s*, *2p* peaks of ^{121}Sn for the very first time. We also succeeded to observe an angular dependence of the production of the deeply- bound states in the (*d*, ^{3}He) reaction for the first time thanks to the large angular acceptance of the BigRIPS. The successful pilot experiment lead naturally the project to go on for a further systematic study. An isotonic scan on N=68 line as well as an isotopic scan on Z=50 line (Sn) are intended, that will reduce the biggest uncertainty in the analysis of the preceding experiment, the uncertainty of the neutron density distributions of the core nucleus. In 2013 we presented the result of 2010 run at an international conference [2], as well as we worked on a preparation for the main beamtime anticipated in the May 2014.

[1] K. Suzuki *et al.*, Precision Spectroscopy of Pionic 1s state of Sn Nuclei and Evidence for Partial Restoration of Chiral Symmetry in the Nuclear Medium, Phys. Rev. Lett. 92 (2004) 072302.

[2] Hadron 2013, XV International Conference on Hadron Spectroscopy, Nara, Japan.

6.4.4 Spectroscopy of η' mesic nuclei with (*p*, *d*) reaction

The $U_A(1)$ problem is a long-standing question on the low-energy spectrum and dynamics of the pseudoscalar mesons in QCD. The η' meson is, in a naive picture, one of the Nambu-Goldstone bosons associated with the spontaneous breakdown of the $U(3)_L \times U(3)_R$ chiral symmetry to the $U_V(3)$ flavour symmetry. The gluon dynamics, however, plays an important role here. The quantum anomaly effect of non-perturbative gluon dynamics induces the QCD vacuum to be non-trivial, resulting the η' meson to acquire a peculiarly larger mass than other pseudoscalar mesons e.g. π, K, and η. The mass generation of the η' meson is therefore a result of the interplay of quark symmetry and gluon dynamics but quantitative understanding is yet to be achieved.

An in-medium property of η' will give a vital constraint on the theory. At a finite density where chiral symmetry is partially restored, it is expected that the η' mass is reduced. The Nambu–Jona-Lasinio model suggests a mass reduction of 150 MeV/c^2 [3]. This indicates that the interaction between an η' meson and a nucleus is attractive and that an η'-nucleus bound state may exist. While there is no experimental information on the strength of the interaction nor the existence of the bound state, a small absorption width of η' at the normal nuclear density (15-25 MeV) is reported by CBELSA/TAPS [4]. The suggested narrow absorption width stimulates an experimental study of η' mesic nuclei.

We plan a missing-mass spectroscopy experiment at GSI by using a (*p*,*d*) reaction off ^{12}C target [5]. The fragment separator FRS is used as a spectrometer. We finalized the development of detector and data acquisition system. The performance of a special high refractive index Cherenkov detector, which is the key to reduce the expected high background from quasi-free multi-pion production reaction, p+N→d+πs, was also proven. The data taking (S437 experiment) takes place in July 2014.

[3] H. Nagahiro, M. Takizawa, and S. Hirenzaki, Phys. Rev. C 74, 045203 (2006).
[4] M. Nanova et al., Phys. Lett. B 710, 600 (2012).
[5] K. Itahashi et al., Letter of Intent for GSI-SIS (2011).

6.4.5 FLAIR

After reaching an agreement between the Swedish and German funding agencies, GSI and FAIR in 2012, the CRYRING accelerator was moved from the Manne Siegbahn Laboratory of Stockholm University to GSI and installation at the ESR storage ring has started. CRYRING in connection with the ESR offers exciting new physics opportunities particularly in the realm of atomic physics and nuclear physics as it was already anticipated by the physics program with heavy ions for the FLAIR facility at FAIR. Moreover, CRYRING at the ESR can play a very valuable role as a test bench for accelerator relevant developments for FAIR and for R&D related to experimental setups.

CRYRING@ESR has also a strong relevance for the physics with low-energy antiprotons and with beams of rare isotopes. For both, this project is very valuable assuming that a transfer beamline will become possible, connecting the FAIR facilities with the ESR. In this way we can realize rapidly at FAIR the experiments with slow anti-protons as well as with slow rare isotopes. This project will be very stimulating for the whole anti-proton FLAIR community as well as for colleagues interested in nuclear- and hadron physics at FLAIR. This will enable an early start of the highly charged ion program of FLAIR. E. Widmann gave an invited talk on this subject at the LEAP 2013 conference in Uppsala [1].

[1] E. Widmann,(2014). Perspectives for low energy antiproton physics at FAIR. *Hyperfine Interactions* 2014, doi:10.1007/s10751-014-1058-z

6.4.7 Laser photodetachment of negative ions in a RFQ cooler

(Supported by FWF, Project Nr. P22164)

Within this project a gas-filled radio frequency quadrupole cooler for studying laser photodetachment of negatively charged ions is constructed. Laser photodetachment is a non-resonant process where the extra electron of the negative atomic or molecular ion can be removed if the photon energy exceeds the electron affinity of the respective ion. This can be used in mass spectrometry to selectively suppress unwanted isobars provided that the electron affinity of the unwanted isobar is lower than the isobar under investigation. However, being a non-resonant process the cross sections for laser photodetachment are too low and therefore the achieved suppression by overlapping a laser beam with the fast moving ions of energies up to 30 keV is not sufficient. For this reason the ions will be slowed down in the RFQ cooler to increase the interaction time and bring the efficiency to practical values.

Figure 16: The RFQ cooler inside the high voltage cage.

The project is conducted in collaboration with the VERA Laboratory at the Faculty of Physics of the University of Vienna. The setup itself is situated in a laboratory space of the University of Vienna close to the VERA accelerator mass spectrometry facility.

In 2013 the construction of the cooler has been finished and the commissioning has been started. In parallel, a detection beamline for the reaccelerated ions has been assembled. To identify the charged particles emerging from the cooler laser photodetachment will be used. The negative ions will be overlapped with a laser beam in crossed-beams geometry and selectively neutralized. The remaining ions will be bent away by an electrostatic bender whereas the neutrals will continue onto a neutral particle detector. This detector consists of a conductively coated glass plate where the impinging particles create secondary electrons, which are subsequently detected by a channeltron electron multiplier. The commissioning of this beamline has been finished and laser photodetachment of selected negative ions and molecules could be shown.

6.4.8 Theory

The theoretician Steven Bass is a guest scientist at SMI since the second half of 2013, His theoretical work focuses on η'-nucleon and nucleus interactions, proton spin structure and the vacuum energy puzzle with main focus during 2013 on the η'-nucleus system described here.

Measurements of the η - and η'- (as well as pion and kaon) nucleon and nucleus systems are sensitive to dynamical chiral and axial U(1) symmetry breaking in low energy QCD. While pions and kaons are would-be Goldstone bosons associated with chiral symmetry, the isosinglet η and η' mesons are too massive by about 300-400 MeV for them to be pure Goldstone states. They receive extra mass from non-perturbative gluon dynamics associated with the QCD axial anomaly. OZI violation is also expected to enter the η' nucleon interaction. How do the gluonic degrees of freedom that contribute to the mass also contribute to the interaction of these mesons with nucleons and how does this gluonic part change in nuclei?

Several general features can be deduced from QCD about the scattering lengths and possible mass shifts of the η' in nuclear media. η -η' mixing increases the octet relative to singlet component in the η', reducing the binding through increased strange quark component in the η' wavefunction. Without the gluonic mass contribution the η' would be a strange quark state after eta-η' mixing, with the eta a light quark state degenerate with the pion mirroring the situation with isoscalar ω and Φ vector mesons.

To the extent that coupling to nucleons and nuclear matter is induced by light-quark components in the meson, then any observed scattering length and mass shift is induced by the QCD axial anomaly that generates part of the η' mass. With finite gluon anomaly contribution to the η' mass there is no vanishing Weinberg-Tomozawa relation for the η' nucleon scattering length in the chiral limit. General QCD arguments suggest that the gluonic mass contribution to the eta and η' mesons decreases in the nuclear medium and the medium acts to partially neutralise axial U(1) symmetry breaking by gluonic effects.

6.5 Outreach

6.5.1 HbarHFS video joins Fast Forward Science competition

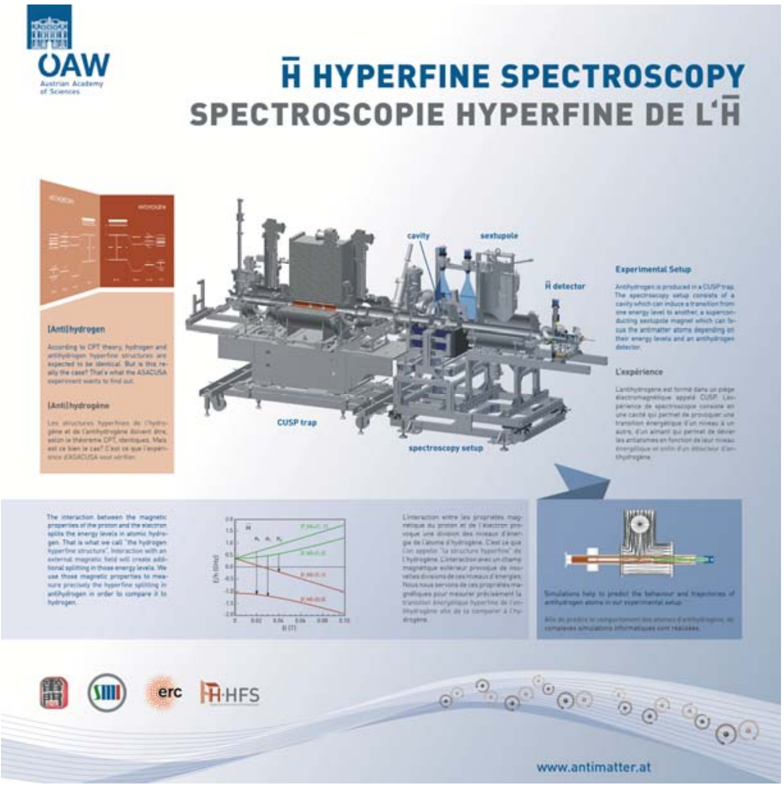
A promotion video was recorded as part of the outreach program of the ERC grant project and took part in the “Fast Forward Science” competition. http://www.youtube.com/watch?v=sC3IJCB7EN0.

6.5.2 Visit of Austrian President Fischer to CERN

During a formal visit to CERN the Austrian President Fischer and the Austrian Minister for Science and Research visited the ASACUSA experiment on June 11, 2013. On that occasion large posters were designed that are also used during the visitors program of CERN on Saturdays and during the open day of CERN.

6.5.3 Internships for university and high-school students

SMI usually offers a summer student program, accepting physics students for about 4 weeks that take part in experimental work either in the lab at SMI or at CERN. In addition high-school students from Austrian schools and the French Lycee located close to SMI are sometimes spending one to four weeks at SMI. The high school student program is sponsored by the “Generation Innovation” program of FFG.



Posters (original size 2 m x 2 m)

6.6 Publications 2013

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Curceanu, C.; Bazzi, M.; Beer, G.; Berucci, C.; Bombelli, L. et al. (2013) Unlocking the secrets of the kaon-nucleon/nuclei interactions at low-energies: The SIDDHARTA(-2) and the AMADEUS experiments at the DAPHNE collider. Nuclear Physics A, Bd. 914, S. 251 - 259

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Nishi, T.; Berg, G. P. A.; Dozono, M.; Fujioka, H.; Fukuda, N. et al. (2013) BigRIPS as a high resolution spectrometer for pionic atoms. NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH SECTION B-BEAM INTERACTIONS WITH MATERIALS AND ATOMS, Bd. 317, S. 290-293

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Berucci, C., Bühler, P., Cargnelli, M., Curceanu, C., Guaraldo, C. et al. (2013) Measurement of the strong interaction induced shift and width of the 1s state of kaonic deuterium, Letter of Intent for J-PARC, KEK/J-PARC-PAC 2013-7

Dissertations:

Muellner, Philipp (2013, online: 2013) GEM-detector development for the study of antikaon nucleon/nucleus interaction., Dissertation, Universität Wien.

Master theses

Pichler, Andreas (2013) Simulation studies fro the Bragg peak determination using prompt gamma ray in ion theraphy. Diplomarbeit, Atominstitut, TU Wien.

Schilling, Florian (2013) Development and testing of a false-event error-compensator for SIDDHARTA-2. Master Thesis, Physikalisches Institut, TU Wien.

6.7 Scientific events

Conferences/Workshops/Meetings

On February 16th, 2013, an international Workshop in connection with the EU project HadronPhysics3 (Workpackage 28 "SiPM) was co-organized by SMI and GSI. About 20 participants from different institutions participating in SiPM (IFN-HH Bucharest, Politecnico Bari, Univ. Torino, INFN-LNFrascati, INR Moscow, INFN Pisa, Univ. Glasgow, Univ. Giessen, JU Cracow, PNPI Gatchina, HIKP Bonn, Univ. Prague and GSI) discussed the progress and the newest developments in SiPM technology and integrated electronics for the readout. Furthermore, the promising application of SiPM in medical applications like time-of-flight tomography was presented.

A two-day collaboration meeting of the ASACUSA collaboration was held at SMI on Dec. 14th and 15th, 2013. It was preceded by a one-day meeting of the CUSP subgroup of ASACUSA which concentrates on experiments with antihydrogen. In total 30 participants of the member institutions took part. During the annual collaboration meeting the status and plans of the experiments are discussed and a report for the CERN SPS committee is prepared.

A midterm workshop of HadronPhysics3 “FutureJet” was held at SMI on April 18-19, 2013. The achievements of the hydrogen cluster-jet source and the compact cryogenic droplet source were presented. The open problems were discussed and an outlook of the work for the next period was given. Related to this topic half a day was devoted to a PANDA Target meeting discussing the responsibilities, time lines, man power and funding issues of the cryogenic hydrogen cluster-jet target for PANDA. 20 participants were participating to this workshop.

6.8 Scientific cooperation 2013

SMI is member of the following cooperations:

ASACUSA@CERN-AD

AEḡIS@CERN-AD

Kaonic hydrogen and deuterium: SIDDHARTA

PANDA: Antiproton Annihilations at Darmstadt

Deeply bound kaonic nuclei with FOPI at GSI

VIP @ Gran Sasso (VIolation of the Pauli Exclusion Principle Experiment) “.

Study of kaon-nucleon interaction @ J-PARC

AMADEUS at DAPHNE2

FLAIR: Facility for Low-Energy Antiproton and Ion Research

BELLE

6.9 Scientific co-workers

Name	Position	Funding
Prof. Dr. Eberhard Widmann	Director	ÖAW
Privatdozent Dr. Johann Marton	Senior scientist, vice director	ÖAW
Privatdozent Dr. Johann Zmeskal	Senior scientist, workshop supervisor	ÖAW
Dr. Paul Bühler	Senior scientist	ÖAW
Dr. Michael Cargnelli	Senior scientist	ÖAW
Dr. Ken Suzuki	Senior scientist	ÖAW
Dr. Tomo Ishiwatari	Senior postdoc	FWF
Dr. Oliver Forstner	Senior postdoc	FWF
Dr. Susanne Friedreich	Postdoc	EU
Dr. Chloé Malbrunot	Postdoc	EU / CERN
Dr. Sebastiano Mariazzi	Postdoc	EU
Dr. Hexi Shi	Postdoc	FWF
Dr. Martin Simon	Postdoc	EU
Dr. Barbara Wünschek	Postdoc	EU
Dr. Steven Bass	Guest scientist	
Carolina Berucci	Ph.D. student	FWF
Stefan Brunner	Ph.D. student	ÖAW
Martin Diermaier	Ph.D. student	EU
Lukas Gruber	Ph.D. student	ÖAW
Philip Müllner	Ph.D. student	FWF
Mariana Rihl	Ph.D. student	CERN
Clemens Sauerzopf	Ph.D. student	EU
Michael Bartel	Master student	EU
Manfred Berger	Master student	ÖAW
Nazli Dilaver	Master student	ÖAW
Sebastian Lehner	Master student	ÖAW
Christoph Klaushofer	Master student	ÖAW
Bernadette Kolbinger	Master student	ÖAW
Oswald Massiczek	Master student	ÖAW
Andreas Pichler	Master student	ÖAW
Dominik Steinschaden	Master student	ÖAW