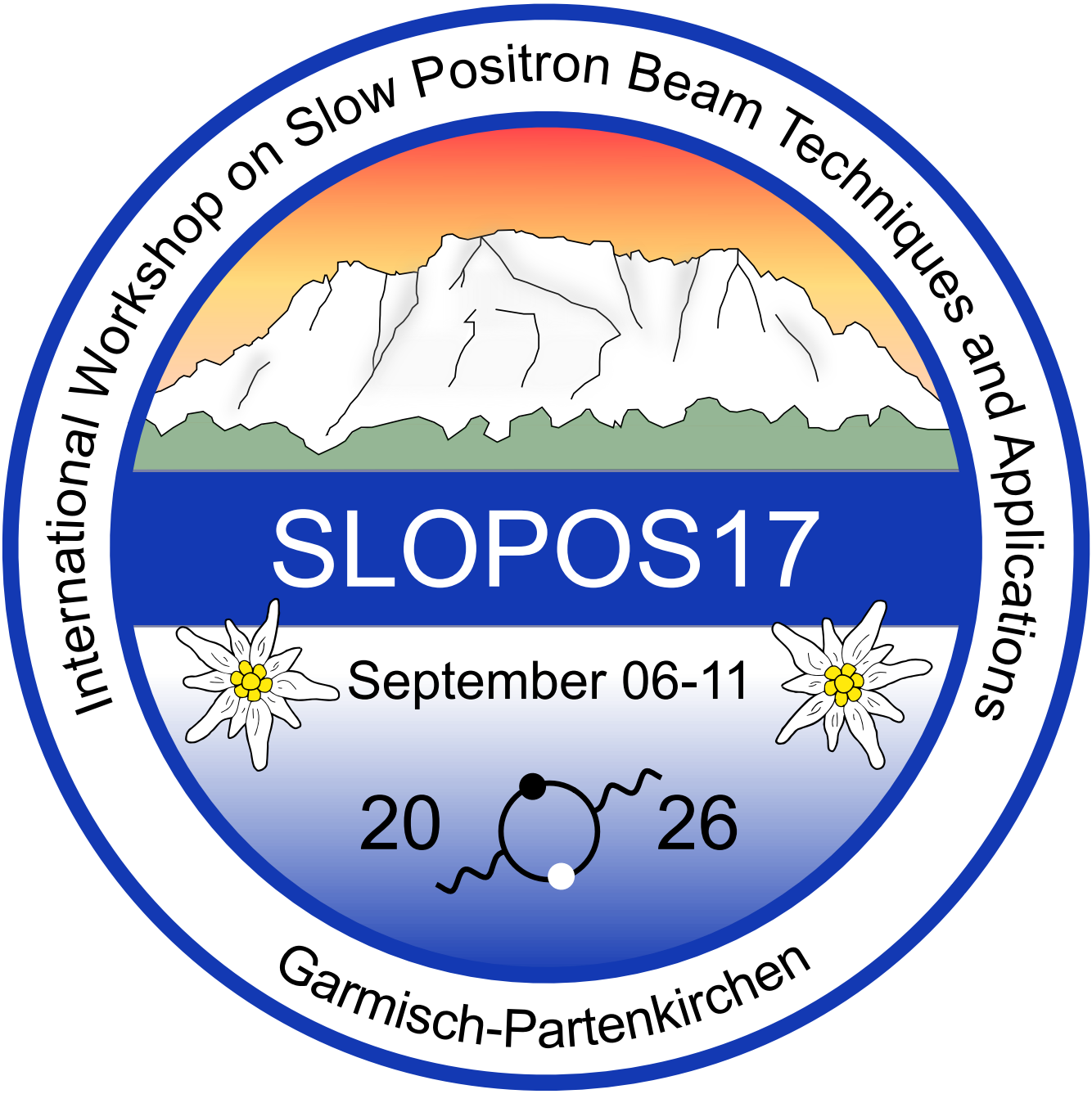
Book of Abstracts

17th International Workshop on Slow Positron Beam Techniques and Applications

Garmisch-Partenkirchen, Germany

September 6–11, 2026



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16:30-18:00	4	Semiconductors & Oxides I	Chair: Jakub Cizek

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Session 1

Instrumentation I – Beamlines & Development

Monday, September 7, 2026, 08:50-10:30 · Chair: Werner Egger

Construction of high-intensity short-pulse slow positron beam at USTC

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To meet the stringent demand of the Super Tau-Charm Facility (STCF) for an ultra-high-brightness positron source, the University of Science and Technology of China (USTC) has designed and constructed an electron-positron beam validation platform [1]. This platform utilizes a 100 MeV photocathode injector to produce high-quality electron beams that bombard a target, systematically collecting experimental data on positron generation via electron-beam-target interactions (as shown in Figure 1). These data are used to benchmark and optimize positron production models. The platform focuses on validating the performance of a magnetic focusing system and a large-aperture S-band accelerating tube in the collection, matching, and acceleration of positrons, thereby providing a solid theoretical and technical basis for the overall design and parameter optimization of the positron source [2]. Currently, the platform employs electron beam parameters of 8 nC at 50 Hz, generating approximately 1.36×10^{12} positrons per second with a pulse width of 30 ps and a repetition rate of 50 Hz, demonstrating extremely high raw positron yield and excellent temporal characteristics. Notably, the platform was designed with foresight to reserve interfaces and capabilities for future upgrade into a positron moderation system. Leveraging its existing technological foundation of positron generation by high-current short-pulse electron beam, future moderation is expected to yield a slow positron beam of up to 10^9 positrons per second.

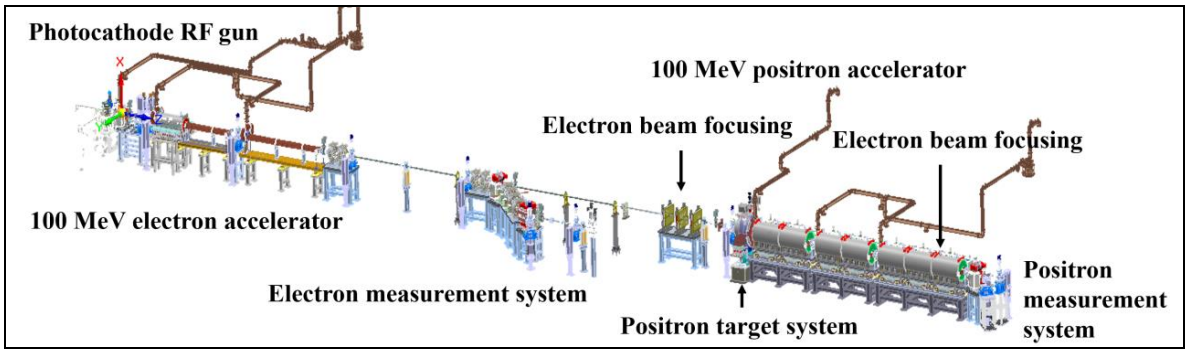


Figure 1: The beam test platform of STCF.

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Low-energy positron diffraction (LEPD) experimental station and experimental procedure at the Slow Positron Facility, IMSS, KEK

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Positron diffraction is a highly surface-sensitive technique for determining the atomic structures of the topmost surface layers. At the Slow Positron Facility (SPF), IMSS, KEK, total-reflection high-energy positron diffraction (TRHEPD) has been actively applied to surface-structure analysis at the SPF-A3 beamline [1]. To expand positron-based surface-structure analysis toward future small-area applications, we have developed a low-energy positron diffraction (LEPD) experimental station at the SPF-A4 beamline [2,3]. LEPD is the positron counterpart of low-energy electron diffraction (LEED) [4,5]. The LEPD station employs a normal-incidence diffraction geometry, complementary to the grazing-incidence geometry used in TRHEPD.

The present SPF-A4 LEPD system enables practical LEPD intensity-voltage (*I*-*V*) measurements. Each LEPD pattern from metal surfaces is now acquired in about one minute, allowing more than 100 patterns to be collected within a few hours [3]. Experimental *I*-*V* curves are obtained by extracting the intensities of selected diffraction spots as a function of incident positron energy. A LEPD *I*-*V* surface-structure analysis code, derived from a LEED multiple-scattering code and modified for positrons, is currently undergoing final verification.

The station consists of two ultra-high-vacuum (UHV) chambers: a LEPD measurement chamber and a sample-preparation chamber, which are connected together through a gate valve. The preparation chamber is equipped with Ar^+ sputtering, electron-beam evaporation, gas-introduction lines, LEED, and Auger electron spectroscopy (AES), enabling preparation and confirmation of clean and well-ordered surfaces. Samples can be heated up to 1200 °C in the preparation chamber and cooled to approximately −180 °C in both chambers using liquid-nitrogen-cooled manipulators.

We have also established a procedure for studying the same sample using LEPD at the SPF-A4 station and angle-resolved photoemission spectroscopy (ARPES) at the Photon Factory (PF) BL-13B, both on the same KEK Tsukuba campus. As a demonstration, LEPD patterns were acquired from a Cu(001) surface prepared at the SPF-A4 LEPD station. After the surface was re-cleaned in the same preparation chamber, the sample was transferred to PF BL-13B using a portable UHV transfer vessel, and ARPES measurements were performed directly [3]. This provides a practical basis for future LEPD–ARPES multi-probe studies using surfaces prepared by the same procedure in the same preparation environment.

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A 325 MHz radiofrequency cavity for the pulsed high energy positron system (PHEPS)

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At previous setups of pulsed low energy positron systems (PLEPS), static accelerators were used to reach beam energies up to 25 keV. Higher beam energies and therefore deeper implantation depths were increasingly difficult to achieve, as a higher potential difference increases the risk of dielectric breakdown. Another challenge was that the target chamber had to be maintained at the static accelerator potential, which further complicated PLEPS operation. To expand the capabilities of the new pulsed high energy positron system (PHEPS), a 325 MHz radiofrequency cavity operating in the TM010 mode will be constructed, allowing for a reduction of the static accelerator voltage, variable positron beam energy between 10 keV and 75 keV and a target chamber on ground potential. In addition, using the cavity in combination with a variable magnetic guiding field enables longitudinal and transverse focusing at the target chamber for all beam energies. This work includes the design process of the cavity, including the evaluation of a cooling concept, a tuning concept, and a multipactor analysis.

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A Compact and Portable Digital Tabletop System for Positron Annihilation Lifetime Spectroscopy

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Due to the complexity of the required instrumentation, Positron Annihilation Lifetime Spectroscopy (PALS) has so far been largely limited to university laboratories and large-scale research facilities. Here, we present the *Life Time Spec*, an entirely digital, compact and portable table-top system designed to make PALS accessible for routine laboratory use, including industrial applications.

Our system is based on miniaturized photomultiplier tubes (PMTs) coupled to plastic scintillators and a four-channel digitizer employing the PSI's DRS4 chip [1], operating at 5.12 GS/s with 14-bit resolution. A digitally controlled high-voltage supply for up to four PMTs is also integrated in the system. Since the trigger implementation of the standard DRS4 evaluation board is not suitable for the rapidly rising nano-second PMT pulses encountered in PALS measurements, a dedicated redesign was implemented. It features a fast trigger architecture and integrated, digitally controlled single-channel analyzers (SCAs). This renders the need for external analog electronics unnecessary.

The detector geometry, including scintillators and PMTs, was modeled as a digital twin [2] and optimized using GEANT4 simulations to achieve a narrow, single-Gaussian resolution function. All components are integrated into a portable system enabling a robust experimental platform that supports flexible configurations with up to four detectors.

All relevant acquisition parameters — including trigger logic, SCA thresholds, and PMT high voltage — are software-controlled via USB. The accompanying software provides a user-friendly interface for configuring both constant-fraction levels and digital filtering.

Instead of storing data for lifetime spectra with fixed binning (ps/channel), our system records parameterized START/STOP pulse pairs, enabling flexible adjustment of bin width and filter parameters during post-acquisition analysis.

This approach significantly simplifies the experimental setup considerably while maintaining a high timing performance, thereby lowering the barrier for the application of PALS in both standard academic and industrial environments.

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Session 2

Metals I

Monday, September 7, 2026, 10:50-12:50 · Chair: Torsten E. M. Staab

PAS application in material studies for safe and long-term operation of nuclear power plants

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The paper focuses on the application of non-destructive methods, including positron annihilation techniques, to selected materials from nuclear power plants with the aim of supporting safe long-term operation (LTO) of VVER-440 and VVER-1000 nuclear reactors. Results obtained within the ongoing H2020-Europe project DELISA-LTO are presented in detail in cumulative form.

Our approach combines the development of the simulation tools, experimental investigations (PALS and CDB analyses), specific in-service and/or non-destructive inspection techniques to develop the effective "early warning" tool for the detection of degradation in VVER reactor materials under LTO conditions.

The paper presents PALS and CDB results for in-service operated steels from primary circuit components (primary piping, surge line piping, etc.), together with complementary mechanical testing. All applied methods indicate only minor microstructural changes induced by long-term thermal exposure. Positron results showed partial microstructural regeneration due to defect recombination and the formation of larger defects, probably associated with precipitates formed during the thermal exposure, which slightly decreased strength and increased hardness.

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Hydrogen-induced vacancy formation and evolution in austenitic stainless steel after hydrogen addition

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Hydrogen embrittlement remains a critical challenge for the implementation of hydrogen-based energy systems, even in austenitic stainless steels (ASS) with high Ni equivalent, which are generally considered highly resistant to hydrogen. While macroscopic degradation has been widely investigated, the atomistic mechanisms—particularly hydrogen-induced lattice defect formation—remain insufficiently understood. In this study, we examine the formation and temporal evolution of hydrogen-related defects in ASS AISI 310S with high Ni equivalent using a combination of conventional ^{22}Na-based bulk positron annihilation lifetime spectroscopy (PALS) and high-intensity positron beam measurements performed with MePS at the HZDR positron ELBE facility.

Hydrogen was added to the near-surface layers by cathodic electrolysis and bulk PALS measurements were carried out during room temperature aging. The results revealed the emergence of a positron lifetime component of ~170 ps, attributed to monovacancy-type defects stabilized by hydrogen (vacancy–hydrogen complexes). Despite the high stability of the austenitic phase, these results provide clear evidence that hydrogen addition alone—without applied stress—induces vacancy formation. Subsequent room-temperature aging leads to a progressive increase of this lifetime component up to ~230 ps after over 48 h, indicating the agglomeration of vacancies into clusters.

Complementary measurements with high temporal resolution of the hydrogen-charged layer using the positron beam (mean implantation depth $\approx$ 400 nm) further corroborate these findings and provide additional insight into the defect structure. In particular, a positron lifetime component consistent with vacancy–hydrogen complexes was detected, alongside a longer lifetime component that increases from ~250 to ~320 ps with aging time, reflecting the growth of vacancy clusters.

The combined results demonstrate that hydrogen-induced vacancies not only form readily in ASS with high-Ni equivalent but also undergo temporal evolution, with hydrogen playing a key role in their stabilization and subsequent clustering behavior. These findings provide direct experimental evidence of hydrogen-induced vacancy formation and growth in ASS in the absence of mechanical loading, offering new insight into the fundamental interactions between hydrogen and lattice defects in nominally hydrogen-resistant materials.

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Positron annihilation study of radiation-induced defects in tungsten under fusion-relevant conditions

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The International Thermonuclear Experimental Reactor (ITER) aims to demonstrate net energy production from nuclear fusion. Tungsten (W) has been selected for ITER's first wall and divertor components owing to its favorable thermophysical and plasma-facing properties [1]. Under reactor operation, W will be subjected to extreme conditions, including 14-MeV neutron irradiation, generating defects such as vacancies and interstitial clusters. No facility produces fusion-relevant neutrons, so defect formation and evolution rely on simulations using input parameters from surrogate irradiations. In this work, 20 MeV W self-ion irradiations are used as a reliable proxy for neutron damage in terms of the nature of the radiation-induced defects (RID) [2], covering multiple damage doses at room temperature (RT) and 500° C. Given the narrow damaged layer (⩽ 2 µm), Doppler Broadening Positron Annihilation Spectroscopy (DB-PAS) measurements with a variable-energy positron beam were performed to probe the annihilation characteristics within this region. In particular, RT-irradiated samples exhibit distinct plateaus in the S(E) and W(E) profiles, reflecting a homogeneous defect distribution over the probed depth. In addition, a saturation of the plateau S and W values is observed as a function of damage dose, indicating that the defect population no longer evolves beyond a dose of ~ 0.65 dpa. Similar behavior has previously been reported for 2 MeV W self-ion irradiations [3].

To further characterize the defect population, the concentration fractions of vacancy clusters were determined using a Quadratic Programming (QP) solver [4], combining experimental DB-PAS data with Two-Component Density Functional Theory (TC-DFT)-derived annihilation characteristics of vacancy clusters [5]. The results reveal an increase in the vacancy cluster fraction with increasing damage dose, as well as a saturation of these fractions, consistent with the aforementioned saturation effect. Positron Annihilation Lifetime Spectroscopy (PALS) measurements on the MePS beamline at the HZDR facility (Dresden, Germany) are ongoing and will be integrated into the trapping model of the QP solver. The PAS results are also complemented by X-Ray Diffraction (XRD) strain measurements and Molecular Dynamics (MD) simulations, providing a comprehensive picture of RID evolution as a function of damage dose.

The authors gratefully acknowledge the staff of the JaNNuS platform for their support during the irradiation experiments. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Program (Grant Agreement No 101052200 — EUROfusion).

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Temperature-Dependent Defect Evolution in Irradiated Tungsten and Tungsten–Rhenium Alloys

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Fusion energy represents a pivotal step toward a sustainable and carbon-neutral future, with Tungsten (W) serving as a primary candidate for plasma-facing materials (PFMs) in the future thermonuclear fusion reactors. During deuterium–tritium (D–T) operations, W-based PFMs will be exposed to 14 MeV neutron irradiation, leading to a significant displacement damage and the transmutation of W into elements such as rhenium (Re)[1]. These processes can degrade the thermo-mechanical integrity of the material, posing serious safety risks.

The present work investigates the temperature-depending microstructural evolution in pure W and W–Re alloys, focusing on the interaction between irradiation-induced defect and Re atoms. To simulate neutron-induced damage, samples were irradiated with 5 MeV W ions at temperatures ranging from 573 to 1073 K, reaching levels up to 30 displacements per atom (dpa) at a steady-state damage region [2,3].

The resulting defect structures were characterized using transmission electron microscopy (TEM) and positron annihilation spectroscopy (PAS)[4], including Doppler broadening spectroscopy (DBS) and positron annihilation lifetime spectroscopy (PALS) performed with a tunable monoenergetic positron beam at the positron ELBE facility of Helmholtz-Zentrum Dresden-Rossendorf (HZDR). These PAS experimental analyses were supported by Two-Component Density Functional Theory (TC-DFT) [5] simulations to determine the positron annihilation characteristics of various potential annihilation states in the system.

Based on the DBS and PALS analysis, vacancy-type defects agglomerate in the temperature range of 573–773 K, followed by a slight decrease at 1073 K. No significant variation in the overall average vacancy defect size is observed up to 30 dpa. Moreover, both PAS and TEM demonstrate that Re addition significantly modifies the nature, size, and distribution of irradiation-induced defects across the investigated temperature range. Furthermore, nanoindentation measurements reveal substantial irradiation-induced hardening. A detailed interpretation and the underlying mechanisms will be presented at the conference.

By combining multi-scale experimental approaches with simulations, these findings provide critical insights into the correlation between microscopic defect evolution and macroscopic material degradation, offering an essential foundation for predicting the long-term performance of W-based PFMs in future fusion devices.

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Radiation Tolerance in Compositionally Complex Alloys

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Compositionally complex alloys (CCAs) represent a new paradigm in alloy design, which is quite distinct from conventional metallurgical approaches. Their complex chemical makeup gives rise to exceptional properties such as high mechanical strength, enhanced radiation resistance, and superior thermal stability, making them promising candidates for structural applications in next-generation nuclear systems [1]. In Generation IV fission and future fusion reactors, materials are required to withstand extreme environments, including high temperatures, high neutron fluxes, and, in fusion systems, embrittlement processes related to the production of helium and hydrogen through transmutation reactions induced by neutrons. These gaseous species play a critical role in the formation and evolution of irradiation-induced defects and require careful studies.

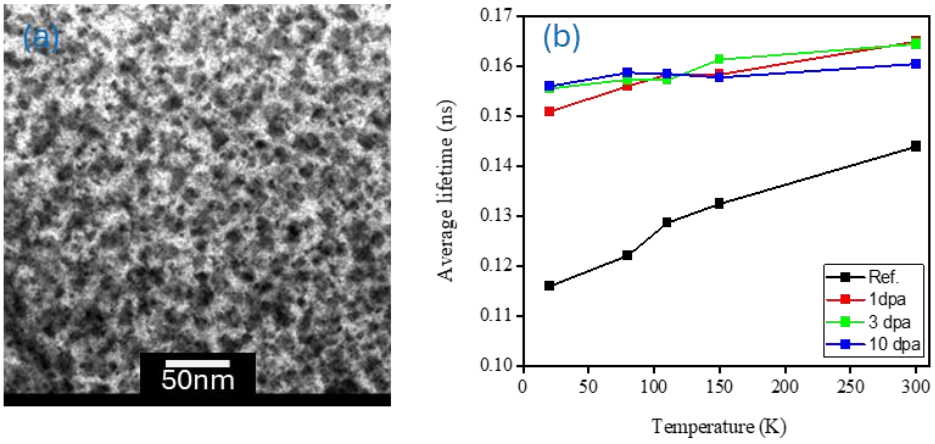


Figure 1(a) TEM image of CrFeMnNi sample after Fe ion irradiation at 300°C **(b)** average positron lifetime as a function of temperature for CrFeMnNi alloy, Fe^{+}-irradiated at 300°C, for a depth of 149 nm.

In this contribution, the radiation tolerance of CrFeMnNi alloys is investigated using Fe^{+}-irradiation at 300 °C to dose equivalents of 1, 3, and 10 displacements per atom (dpa) by means of transmission electron microscopy (TEM) and positron annihilation spectroscopy (PAS). TEM analysis reveals a dense formation of dislocation loops (Fig.1a), whereas PAS provides detailed information on the abundance of point defects, vacancy-dislocation complexes, and their relative concentrations. The observed increase in average positron lifetime as a function of temperature (Fig. 1(b)) indicates the existence of neutral defects (monovacancies) coupled to shallow positron traps (dislocations). The defect landscape evolves from being dominated by more shallow defect states to more neutrally charged positron trapping as the temperature dependence of the average positron lifetime flattens with the increasing ion fluence.

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Session 3

Instrumentation II – Large Facilities

Monday, September 7, 2026, 14:00-15:50 · Chair: Maciej Oskar Liedke

Positron microbeam analysis at the AIST slow positron beam facility

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Positron annihilation spectroscopy (PAS) is a unique analytical technique for evaluating defect and pore structures in materials by detecting gamma rays emitted from electron–positron annihilation. While PAS has been widely used for the characterization of vacancy-type defects and micropores, recent advances in industrial materials and materials processing have led to increasing miniaturization and structural complexity of materials, making it difficult for conventional positron analyses employing spatially extended positron sources (typically a few millimeters in size) to characterize many practical materials. Consequently, there is a growing demand for positron microbeam analysis, in which a focused positron beam selectively probes target regions and spatially resolves defect distributions. To address this need, we have been developing a Positron Probe Microanalyzer (PPMA) capable of positron lifetime imaging.

At the slow positron facility of the National Institute of Advanced Industrial Science and Technology (AIST), an intense slow positron beam is generated using an electron linear accelerator. A 40-MeV electron beam is irradiated onto a Ta converter to produce fast positrons, which are subsequently moderated by a grid-type W moderator to generate a high-intensity slow positron beam. The beamline is equipped with a positron annihilation measurement system using a variable-energy positron beam, a positron trap, and the PPMA, enabling a wide range of positron-beam-based experiments [1]. The PPMA is available to external users through the Advanced Research Infrastructure for Materials and Nanotechnology in Japan (ARIM) program supported by MEXT [2].

In the PPMA, the slow positron beam is first converted into ultrashort pulses and then focused onto a Ni thin-film remoderator to enhance its brightness [3]. The reemitted positron beam extracted from the rear surface is subsequently focused by a magnetic objective lens, forming a positron microbeam with a diameter smaller than 100 μm. This microbeam is utilized for positron lifetime measurements of small specimens [4], three-dimensional imaging of positron mean lifetime [5], and local positron lifetime analysis [6]. Recently, we successfully developed a technique for imaging the pick-off annihilation lifetime of ortho-positronium by focusing the positron beam onto polymer and glass-film samples [7]. Furthermore, we are developing a compact two-dimensional angular correlation of annihilation radiation system with a detector separation of 0.4 m by combining the focused positron beam of the PPMA with high-spatial-resolution gamma-ray imaging detectors.

In this contribution, we present an overview of the AIST slow positron facility and report recent advances in positron microbeam analysis at the facility.

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Positron user facilities at ELBE (HZDR): upgrades and outlook

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We present recent developments and planned upgrades for the positron user facilities at the ELBE radiation source [1], including the Monoenergetic Positron Source (MePS) and the Apparatus for In-situ Defect Analysis (AIDA) beamline at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR). As an integral component of ELBE, MePS provides unique capabilities for depth-resolved Positron Annihilation Lifetime Spectroscopy (PALS) based on the ELBE electron accelerator with 35 MeV, 100 µA, and 1.625 MHz repetition rate. The beamline offers a versatile positron implantation energy range from 0.5 to 16 keV and a temperature range from 25 to 750 K. It also supports high-power light illumination experiments and in-situ bias voltage application. This distinctive combination of parameters establishes a comprehensive framework for investigating defect kinetics, electronic properties, and structural transitions across a wide range of material classes. This contribution outlines the general operating principles of MePS, summarizes its current status, and presents a roadmap for planned upgrades in the coming years. Key developments include:

- **Enhanced Automation:** standardization of experimental workflows for non-expert users reduces the likelihood of errors and allows for a "mail-in" operation mode
- **Pulse Synchronization:** synchronization between light and positron pulses for time-resolved studies.
- **Annealing capabilities:** Increasing the maximum sample temperature to 850 K.
- **Real-time Analysis:** Implementation of an on-the-fly **data analysis** pipeline to allow for immediate experimental feedback and quality assessments.

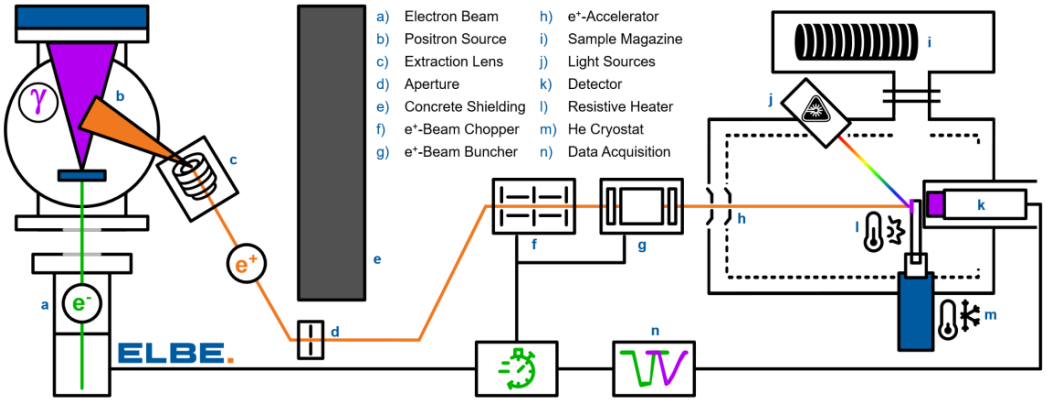


Figure 1: Schematic image of the MePS beam line

Moreover, developments at the AIDA beamline will be briefly given, where the focus is on defect engineering in in-situ magnetron sputtered superconducting heterostructures with positrons as a probe of microstructure quality.

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TU Delft's Positron Annihilation Facilities for Advanced Materials Research - an Update

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The TU Delft Reactor Institute (RID) operates the Netherlands' only research reactor with neutron and positron beamlines, supporting research, education, isotope production, and elemental analysis. Once focused on internal use only, RID now offers access to external academic and industry users through a new organizational structure with dedicated instrument scientists and technicians. The set of investigation methods includes not only various positron facilities but also complementary neutron instruments, e.g. for reflectometry and powder diffraction.
This presentation will give a short general overview of the new possibilities and challenges in Delft with a focus on the positron techniques. Recent developments across all instruments will be presented, along with future perspectives and design upgrades of the reactor-based slow positron beamlines for Positron Annihilation Lifetime Spectroscopy and Coincidence Doppler Broadening Spectroscopy, supported by beam transport simulation studies.

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High-intensity positron sources based on a low-energy electron linac and a buffer-gas trap

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The limited and uncertain availability of radioactive sources for slow positron beam systems is a growing concern for laboratories worldwide. Positron generators based on low-energy electron linacs combined with buffer-gas traps constitute a viable alternative to ^{22}Na-based slow-positron sources. They can provide a sustained positron flux exceeding the maximum achievable with radioactive isotopes while retaining the advantages of dedicated laboratory instruments, independent of large-scale facilities such as nuclear reactors or high-energy accelerator complexes. Although linac-based positron sources inherently produce pulsed beams, this limitation can be effectively overcome through the use of a buffer-gas trap. In addition to enabling quasi-continuous beam delivery, the trap provides a high-quality positron beam with flexible temporal, spatial, and energy characteristics for downstream applications.

We discuss the possibilities and limitations of such sources based on more than 15 years of experience with two positron sources developed for the GBAR experiment [1–3]. A linac operating at an electron energy of 4.3 MeV was used during the initial development phase, while a more powerful 9 MeV electron accelerator was employed in the final production version, both coupled to a buffer-gas trap. Initially, positron capture in the trap relied on nitrogen gas; later, a silicon carbide remoderator was introduced, resulting in significantly higher trapping efficiency. The system was used at the GBAR installation at CERN to fill a high-field (5 T) positron accumulator with a record number of positrons. Such systems can also provide positrons for positron annihilation spectroscopy and a broad range of other applications.

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Session 4

Semiconductors & Oxides I

Monday, September 7, 2026, 16:30-18:00 · Chair: Jakub Cizek

Depth dependence of temperature effect on positron capture in near-surface hybrid perovskites

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More than a decade ago, 3D hybrid perovskites (HPs) have emerged as promising low-cost and efficient materials for a variety of optoelectronic applications [1] such as photovoltaics, light emitting diodes, laser diodes, photodetectors. In addition, more recently, their potential as electromagnetic wave absorbing materials (EMWAMs) has also attracted attention [2]. According to a huge literature, HPs are semiconductors with a high chemical reactivity depending on composition in which various charged species other than electronic carriers can also move during device operation [3]. This leads to several questions concerning the physics of defects in HPs.

This work [4] shows that, depending on preparation type, positrons can annihilate from at least three different annihilation quantum states at room temperature in ≤methylammonium lead iodide ($CH_3NH_3PbI_3$). It also illustrates that the defects in which positrons are captured in HPs can exhibit uncontrolled variations in their near-surface population from one preparation batch to another although the nominal conditions are kept the same.

One key question for the optimization and stability of the optoelectronic [5] or EMWAM [6] performance is whether the defect population in HPs involves neutral vacancies and/or ionized acceptors of the vacancy-type or ion-type. The temperature dependence of the positron capture depends on the type of defects [7]. The consequence is that the fraction of positron annihilating in different type of defects may change with decreasing temperature from 300K to 20K to the benefit of ionized acceptor defects, i.e. either negative vacancies or anions. On the basis of positron lifetime spectra recorded at HZDR versus positron beam energy, this work reports temperature effects depending on the depth in the near-surface of thick HPs. The positron lifetimes for positron energy [0.5-6] keV are lower at 80K than at 150K. This lifetime decrease leads to conclude that lowering the temperature enhances positron capture at negatively charged and smaller open volume defects in the near-surface depth. The depth dependence of the temperature effect is also a fingerprint for the existence of different types of defects capturing positrons. The nature of the defects is discussed [8].

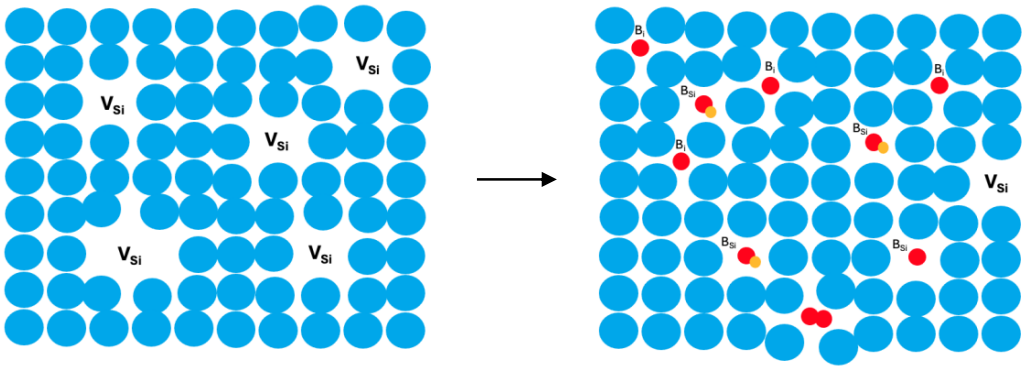
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Evolution of point defects in photovoltaic MBE-grown $BaSi_2$ thin films examined by Positron Annihilation Spectroscopy

Stephan Eijt[a*], Luna Feeke[a], Ana Montes[b], Marcel Dickmann[c,d], Werner Egger[c], Christoph Hugenschmidt[e], Jan Kuriplach[f], Bernardo Barbiellini[g], Maik Butterling[a], Takashi Suemasu[h], Olindo Isabella[b]

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Barium di-silicide ($BaSi_2$) is a promising absorber material for high-efficiency thin-film solar cells, due to its suitable bandgap, high light absorption coefficient, and long minority-carrier lifetime [1-3]. Here, we present Positron Annihilation Spectroscopy (PAS) studies on B-doped and undoped $BaSi_2$ doped thin films grown by Molecular Beam Epitaxy (MBE) on c-Si substrates. We examined the evolution of the nanoscale structure and vacancy-related defects in the $BaSi_2$ thin films as a function of B-doping using Doppler Broadening Positron Annihilation Spectroscopy (DB-PAS) depth profiling, Positron Annihilation Lifetime Spectroscopy (PALS), Raman Spectroscopy (RS) and X-ray Diffraction (XRD). Our PALS studies in combination with ab-initio calculations indicate the presence of Si monovacancies in the undoped MBE-grown $BaSi_2$ films. Diffusion and trapping modelling of the PALS results suggests that, in addition, a very minor fraction of positrons trap and annihilate at grain boundaries in the films. DB-PAS and PALS suggest the formation of boron-oxygen complexes and boron occupation of the Si-vacancies in the B-doped $BaSi_2$ samples. At the highest investigated doping concentration, the formation of open space defects larger than Si mono-vacancies is observed. Photoluminescence and spectroscopic ellipsometry revealed that the opto-electronic properties of the $BaSi_2$ films exhibit trends that clearly correlate with the defect evolution observed by PAS.



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Identification of vacancy-related point defects in inorganic perovskite halide semiconductors

A. Singh[a], J. Wiktor[b], M. O. Liedke[c], K.S. Bayikadi[d], M. G. Kanatzidis[d], Y. Lu[e], T. Kang[e], S.D. Stranks[e], Y. Kominko[f], A. Kanak[f], S. Yakunin[f], A. Wagner[c], D. J. Keeble[a*]

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Wider bandgap inorganic perovskite halides are under development for photovoltaic applications. $CsPbBr_3$ is the material of primary interest. This work focuses on the detection and identification of cation vacancy point defects in $CsPbBr_3$ and $CsPbCl_3$. Single crystal $CsPbBr_3$ and evaporated $CsPbBr_3$ and $CsPbCl_3$ film samples are studied using depth-profiling positron annihilation lifetime spectroscopy.

The results of two-component density functional theory (TC-DFT) studies of positron state lifetimes for the perfect lattice and for the A-site, Cs, and B-site, Pb, cation vacancy defects for $CsPbBr_3$ are reported. Experimental positron lifetime results on the $CsPbBr_3$ samples studied systematically observed a lifetime component with a value of ~352 ps consistent with the TC-DFT calculated lifetime for the Pb vacancy. In addition, in certain samples a second longer, ~ 440 ps, lifetime component was also resolved and is in agreement with the calculated value for Cs vacancies. The results are consistent with previous TC-DFT calculations and experimental positron lifetime studies in $MAPbI_3$ [1] and $MAPbBr_3$ [2] that have observed positron trapping to Pb vacancies, and to A-site vacancies in $MAPbBr_3$ [2]. Measurements were also performed at ~20 K where an increase in trapping to Pb vacancies against Cs vacancies compared to the 300 K, the nominal charge state of Pb vacancies is –2 and –1 for Cs vacancies.

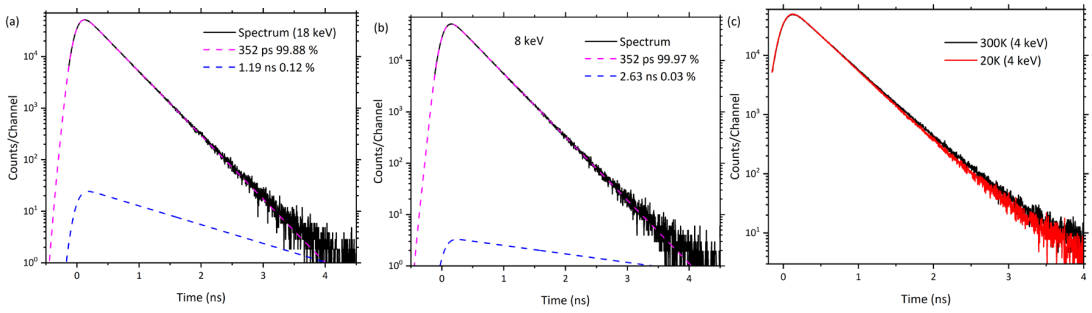


Figure 1 $CsPbBr_3$ (a) Northwestern crystal, (b) ETH crystal, (c) Northwestern crystal measured at 300 K and ~20 K.

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Session 5

Instrumentation III – Detectors & New Devices

Tuesday, September 8, 2026, 08:30-10:10 · Chair: Marcel Dickmann

Positron transport and cooling in a magnetic dipole trap

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APEX-LD (A Positron Electron eXperiment - Levitated Dipole) is designed to trap a low-temperature electron—positron pair plasma [1, 2]. A persistent current flowing in a levitated superconducting coil generates a magnetic field that can simultaneously hold the oppositely charged (anti-)particles. To create and confine a pair plasma, more than 10^{10} electrons and positrons must be injected across the closed magnetic field lines of the device. In preparation for this challenge, we recently demonstrated lossless injection of bunches of e^+ from a buffer-gas trap into a prototype supported-dipole trap [3, 4]. An array of 21 gamma-ray detectors was used to monitor the e^+ annihilation signal during injection and confinement (> 1s) [5]. The primary loss channels were positronium formation via charge exchange with neutrals and radial diffusion across the inhomogeneous magnetic field. Electric-field ramps allowed us to separate the effects of pitch-angle scattering and cooling due to elastic and inelastic scattering. The uninterrupted field lines of APEX-LD are expected to facilitate significantly longer e^+ confinement times (lifetimes of up to ~100 s have been demonstrated with pure electron plasmas [1, 6]). The gamma-ray spectroscopy and tomography techniques that we developed with the supported dipole will soon be exploited to study positrons embedded into a pure electron plasma in APEX-LD [7, 8]. Our improved understanding of the interrelated transport and annihilation processes in strongly inhomogeneous magnetic fields will aid the development of the plasma merging schemes that will ultimately be needed to produce and trap a quasi-neutral pair plasma.

We are grateful to the APEX collaboration for supporting this work. The measurements were performed at the AIST slow positron facility. We thank T. ,Hori for operating the LINAC.

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Refining on novel beam detection methods.

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Michael Berghold[a], Julian Deller-Yee[a],
Robin Prillwitz[a], Dominik Heller[a], Maximilian Suhr[a] and C.P. Hugenschmidt[a]

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In the last few years we have experimented with novel approaches to detect low-energy positrons, with the aim of developing instrumentation to be used at the NEPOMUC beamline and its measurement apparatuses to allow for a faster and more convenient beam setup. The first approach resulted in the development of a fast and precise four-quadrant Faraday cup detector, which was successfully tested at the ELBE facility [1]. The latter saw the development of techniques to modify commercial mobile camera sensors to turn them into particle detectors with extremely high spatial resolution [2]. Since these publications we have worked to bring both technologies to maturity and deploy them in the novel expansion of the NEPOMUC beamline. This contribution will follow up with our latest results.

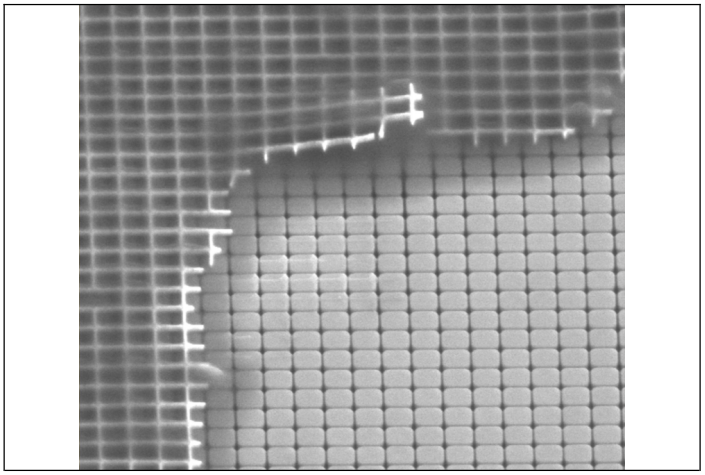


Figure 1: Scanning electron microscope imaging of a camera sensor that is being stripped of one of its passive layers to expose its sensitive area (M. Berghold - Master's thesis, TUM 2026)

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Abstract title centered, capitalizing first word only

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We present the current status of the 2D-Angular Correlation of Electron Positron Annihilation Radiation (2D-ACAR) detector, using an array of 5 × 5 (total size: 125 mm × 125 mm) Multi Pixel Photon Counters (MPPCs) in combination with pixelated LYSO scintillation crystals.
This configuration is planned to replace the current ACAR setup that uses two arrays of 61 photomultiplier tubes in combination with a NaI(Ti) scintillation crystal (Anger Camera). The new setup will drastically improve spatial resolution and count rate by taking advantage of the smaller pixel size, a scintillator with a much better attenuation coefficient, photo-peak-to-total ratio as well as faster digital readout. This leads to a 25 times higher coincidence count rate and an increase in spatial resolution by a factor of 3.5, compared to the present Anger Camera. This setup required less space due to the increase in spatial resolution, but needs a smaller positron spot size on the sample. We therefore designed a beam optimization chamber backed by particle simulations. We designed a correction algorithm for inaccuracies in the resulting detector data which can also be used to determine the origin crystal pixel of the signal and an increased energy resolution of 14.3% [1]. We additionally present some preliminary measurements with the detector with a ^{22}Na source.

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Session 6

Polymers & Organic Materials

Tuesday, September 8, 2026, 10:10-11:20 · Chair: Rafael Ferragut

Search for helicity-dependent positronium formation in biological amino acid molecules

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Homochirality is one of the unsolved mysteries of life. Chirality can be simply described as non-superimposableility of an object and its mirror image. Many molecules exhibit such chiral features. For example, nineteen of twenty proteinogenic amino acids exist in both left-handed (L, levo) and right-handed (D, dextro) forms, i.e., enantiomers; the same applies to sugars, which are key components of DNA. The two enantiomers have identical energies and are therefore produced abiotically in equal amounts. Nevertheless, living systems exclusively select L-amino acids for protein synthesis and D-sugars for DNA formation, resulting in complete polarization toward a single chiral form. This is the homochirality.

In optical activity, molecular chirality is characterized by helical electronic states induced by electromagnetic fields. Garay and Hrasko proposed that interactions between positrons and molecules, and also positronium (Ps) formation, depend on the helicities of both positrons and molecules [1,2]. They further suggested that β-induced radiolysis of molecules might contribute to the homochirality due to parity violation in the weak interaction. Hegstrom developed a more rigorous theory of helicity-dependent Ps formation in molecular systems [3]. Garay actually measured the Ps fraction in some molecular crystals with a ^{22}Na source, i.e., longitudinally polarized positrons, and claimed a dependence on molecular chirality [4]. Subsequently, several groups performed similar experiments for various molecular systems [5–7]; however, chirality-dependent Ps formation was not confirmed. Issues in these experiments would be: (i) positron helicity was not conserved during random walks in the bulk [8]; (ii) the Ps fraction did not directly reflect chirality differences because of variations in the number of voids, where Ps is formed, among different crystals and (iii) instead of Ps formation via the Ore mechanism, it via the spur mechanism was observed. To overcome these issues, a spin-polarized positron beam was employed by the Michigan group, but no positive evidence for helicity-dependent Ps formation was obtained [9].

In the present work, we re-examined this issue using an improved experimental approach. We constructed an in-situ fabrication system for amino acid thin films integrated with an electrostatic positron beam system. Data statistics were improved by performing successive cycles of film deposition and measurements more than 100 times. To date, we have investigated nearly all biological amino acids. Except for four amino acids that could not be evaporated due to thermal decomposition, several amino acids show indications of helicity-dependent positronium formation with an asymmetry on the order of 10^{-3} order.

Acknowledgments This work is financially supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (S) (No. JP23H05462), Challenging Research (Exploratory) (No. JP23H17681) and JST, CREST Grant Number JPMJCR23O3.

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PAL testing of pristine, functionalized and activated hybride membranes

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Hybrid (organic/inorganic) chitosan-based membranes with MCF and SBA-15 mesoporous fillers are successfully applied for selective ethanol dehydration. Here we show that positron annihilation lifetime (PAL) is effective in studies of complex membrane/filler structures and their alteration due to functionalization with amino-groups (NH_2), and activation with glutaraldehyde (GA). We also provide in depth analysis of three different models built-in the Kansy LT 10 [1]: (a) multi-exponential, (b) trapping, and (c) free volume model.

PAL data confirm different topologies, and micro- and meso-porosity structures for both pristine hybrid powders which result in their distinct and different free, positron trapping and positronium lifetimes. All PAL models show an increase in positron trapping rate after adding amino-functionalized groups; the meso-pores size increases with presence of amino-groups and the GA activation, and the change is more pronounced for SBA-15 compared to MCF (Figure 1), and consistent with BET analysis [2]. We postulate that branching caused by amino-groups and a presence of covalent binding between silicates fillers with chitosan walls reduces oxygen radicals, while more interlinking increases positronium formation.

Another PALS study of free volume for pure chitosan membranes compared to membranes filled with MCF and SBA-15 after activation/functionalization during heating indicate systematic increase of free volume with the temperature for all three membranes, and simultaneous decrease in its trapping rate. The initial value of free volume is slightly lower for pure chitosan specimen, but in this case free volume includes micro-pores and meso-pores together, therefore the effect is due to both types of pores that compensate with each other. We are working on extensive physical analysis of these effects by use of the free volume model.

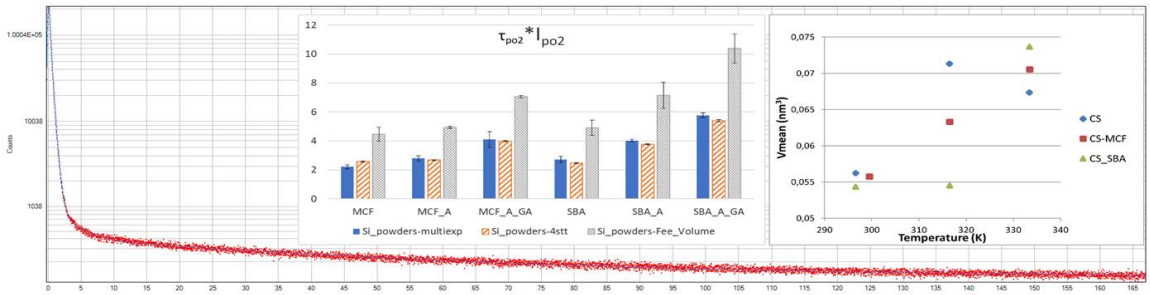


Figure 1: Positron lifetime spectra of SBA_A_GA (activated and functionalized) powder fitted according to the LT10 Free Volume (FV) routine (main panel); product of the longer positronium lifetime and its intensity for all powders fitted with three different models (left inset); temperature dependence of the free volume for pristine and filled membranes (right inset).

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A systematic analysis of free volume distributions across multiple molecular separation polymer membranes using positron annihilation lifetime analysis (PALS)

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Resolving the sub-20 Å diameter free volume elements (FVEs) present within "dense" molecular separation membranes is vital to understanding how microstructure influences their macroscopic transport properties. These analyses, however, are experimentally challenging due to the high spatial resolution required. Here, we use positron annihilation lifetime spectroscopy (PALS) to resolve FVEs within ten commonly studied gas molecular separation membranes (CTA, CA, PSf, PAN, PS, Matrimid 5218, 6FDA-DAM, 6FDA-DAM:DABA(3:2), PTMSP, and PIM-1) to (1) develop a reference list of comparable material standards and (2) elucidate the role data analysis decisions have on the resulting *o*-Ps lifetime components. Instrument resolution functions (IRFs) were determined using a ^{60}Co source and directly from the polymer spectra generated with a ^{22}Na source. IRFs gathered from the polymer spectra showed significant variation between polymer samples, leading to significant changes in the derived *o*-Ps lifetimes. In contrast, when using a ^{60}Co IRF, independent tests of the same polymer provided replicable data. The effect of the number of assumed Gaussian's and their intensities for IRFs was seen to minimally affect the lifetimes. Continuous free volume distributions (FVDs) were mapped from the discrete FVEs determined using PALSfit3 via a χ^2 uncertainty approach and using the MELT program whose results showed qualitative agreement. Analyzing spectra with PALSfit3 was accomplished using an open-source Python wrapper, enabling results for parameter sweeps (*i.e.*, hundreds of PALSfit3 files) to be gathered and reported nearly instantaneously. Overall, this study reports a comprehensive analysis of FVEs within molecular separation membranes and uses these results to provide a best practices framework for future PALS studies within the polymer membrane field.

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Session 7

Instrumentation IV – Applied Beam Methods

Wednesday, September 9, 2026, 08:30-10:10 · Chair: Christoph Hugenschmidt

Transient changes in irradiation-induced defects detected by positron re-emission signals

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Irradiations of energetic particles such as ions and neutrons induce primary knock-on events and form interstitial atoms and vacancies (point defects) in crystalline materials. Such point defects can diffuse and interact with each other, leading to annihilation or clustering. To understand and/or predict defect formation processes, various numerical simulations have been employed. However, it is difficult to perform experiments to confirm the numerical results in short time ranges. In this study, we aim to develop experimental techniques to investigate transient changes in defect kinetics.

A positron-ion simultaneous irradiation system was developed to understand transient behaviors of irradiation-induced defects, where positron annihilation spectroscopy was synchronized with ion beam irradiations [1]. It should be noted that re-emission peaks observed in positron lifetime spectra were used as a measure of defect amounts [2]. Fig. 1 shows the re-emission yields after Ar+ beam irradiations to a pure Ni sample for 1s at 500 °C. Three positron lifetime spectra were sequentially taken for 300 s. Re-emission yields calculated from each spectrum were plotted. The increase in re-emission yields was observed, indicating a reduction of defects near the surface. The experimental results were compared with the calculation results based on rate equations. In this presentation, we will also introduce our new experimental system based on an electron linear accelerator in Kyoto University to perform new experiments using this technique.

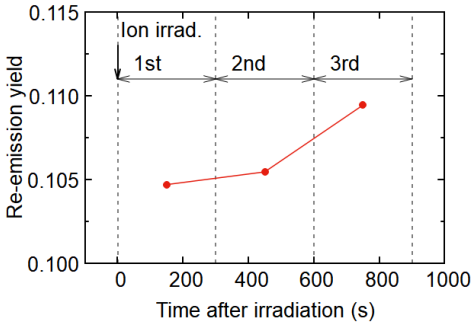


Figure 1: Re-emission yields detected from Ni after 155 keV Ar+ irradiation for 1 s.

Acknowledgement: This study was partially supported by JSPS KAKENHI Grant Number 24310080, 22H02005, 25K08332 and 25H00859.

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Real-time observation of defect production, recovery, and stabilization during ion irradiation and implantation using in-situ positron annihilation spectroscopy

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The ability to characterize defects during irradiation is essential for understanding the dynamic processes that govern microstructural evolution in materials. We present recent developments and applications of the in-situ Positron Annihilation Spectroscopy (iPAS) facility at Los Alamos National Laboratory, which combines a slow positron beam with ion irradiation to enable simultaneous defect generation and positron characterization.

The capability is demonstrated through studies of metallic and semiconductor systems subjected to ion irradiation and implantation. Real-time Doppler broadening measurements provide direct observation of defect evolution during irradiation, revealing transient processes that are not accessible through conventional post-irradiation characterization. The measurements show that defect accumulation depends not only on irradiation conditions and implanted species but also on the dynamic balance between defect production, migration, interaction, and recovery occurring during irradiation.

The results highlight the unique ability of in-situ positron measurements to probe defect kinetics at the atomic scale and to distinguish between defect evolution pathways that may lead to similar final damage states. These studies demonstrate the potential of iPAS as a powerful tool for advancing the understanding of irradiation-induced phenomena in structural and electronic materials.

This work was supported by the U.S. Department of Energy, Office of Science, Energy Frontier Research Center "Fundamental Understanding of Transport Under Reactor Extremes (FUTURE).

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Compact Positron Source as a Source of Entangled Gamma Rays

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We present a compact, ultrafast positron source design for SLAC National Accelerator Laboratory which will provide up to 100,000 e+/s at 30 Hz, with tunable energies from 1 to 5 MeV. A primary near-term application is precision-timed entangled gamma ray pair generation for next-generation PET (Positron Emission Tomography) detector development and calibration. Conventional PET detector testing relies on radioactive sources that cannot provide control over timing or event rates. By using a linac source, we will generate positron beams that, upon annihilation on a thin tungsten target, produce entangled 511 keV gamma ray pairs with precisely defined temporal structure. Beyond medical applications, we explain how this positron source enables time-gated ghost imaging of dense materials, leveraging entangled photon correlations for low signal to noise. Finally, we will discuss longer term positron applications in semiconductor development and basic material studies, highlighting the versatility of a compact positron source.

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Detecting antiprotons with submicrometric spatial accuracy

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The AEgIS experiment at CERN aims to measure the free fall of antihydrogen in Earth's gravitational field with unprecedented precision. This requires determining the vertical deflection of antihydrogen atoms using a Moirè deflectometer. At the end of the deflectometer, the OPHANIM detector allows real-time detection of antiprotons with submicrometric spatial accuracy over a large area. It repurposes commercial smartphone camera sensors, achieving a total resolution of 3.84 gigapixels and a vertexing resolution of ca. 600 nm. Additionally, the detector is inherently sensitive to visible light, which is exploited for precise optical calibration of the deflectometer gratings. The system has been successfully commissioned with an antiproton beam, demonstrating stable performance under experimental conditions. It therefore provides a robust and precise measurement platform for antihydrogen gravity studies.

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Session 8

ErUM DataHub Session – Theory & Simulation

Wednesday, September 9, 2026, 10:30-12:30 · Chair: Francesco Guatieri

Quantum Monte Carlo study on positron binding to atomic anion dimers

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Recently, it was reported that the positronic complex $(H^-)_2$ can form a stable bound state against dissociation into H^- + PsH through a positron-mediated bonding mechanism [1]. This bonding situation, which resembles a well-defined single covalent bond, has been characterized as *positronic covalent bonding*. A similar mechanism may also arise in anion dimers of other alkali species, such as lithium. In this study, we investigate the stability of homonuclear $[X^-; e^+; X^-]$ systems with X = H and Li using quantum Monte Carlo methods combined with multicomponent molecular orbital calculations [2,3].

Figure 1 presents the potential energy curves (PECs) of $[Li^-; e^+; Li^-]$ as a function of internuclear separation, computed using Hartree–Fock (HF), configuration interaction (CI), and diffusion Monte Carlo (DMC) methods. All PECs exhibit a single energy minimum, and the equilibrium internuclear distance becomes significantly shorter as electron–positron correlation effects are more accurately treated. Analysis of the electron and positron densities indicates that the HF-level minimum resembles a positronic covalent bond, whereas the compact structure predicted by DMC suggests strong delocalization of both the excess electron and the positron.

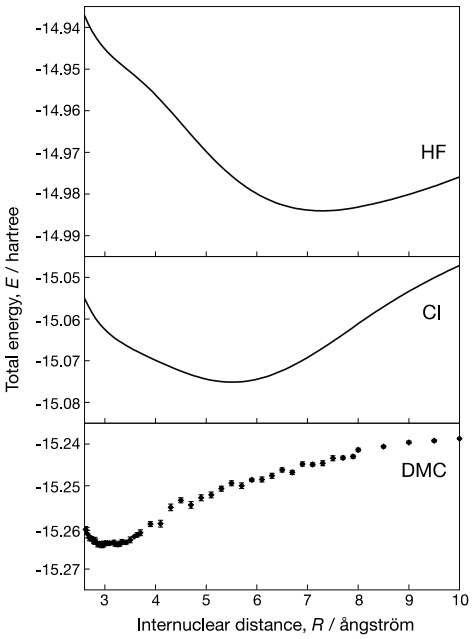


Figure 1: PEC of $[Li^-; e^+; Li^-]$

By evaluating the PECs for the lower-energy dissociation channels Ps + Li_2^- and Ps^- + Li_2, we confirm that the $[Li^-; e^+; Li^-]$ system is stable with respect to both thresholds. Our analysis suggests that the dominant structural motif corresponds to a positronium (Ps) bound to the Li_2^- anion, which contrasts with the $[H^-; e^+; H^-]$ system where a locally stable positronic covalent bond is formed [1,2,4].

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Positron annihilation lifetime calculations in halide perovskites

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Halide perovskites are massively studies since less than two decades for their exceptional properties with regard to photovoltaics and various optoelectronic applications. In spite of their pretended defect tolerance, characterization of point defects in these materials is very important, yet challenging. Positron annihilation lifetime studies on these materials, and in particular on methylammonium lead iodide ($MAPbI_3$), in combination with positron lifetimes calculations, have contributed to the identification of lead vacancies [1], which had previously been predicted as the most stable negatively charged defect in this material [2]. However, defect identification in halide perovskites through positron annihilation lifetimes calculations remains a challenge. Indeed, our results for lifetimes in the lattice and in vacancies, using various approximations for the electron-positron correlation potential, show that the spread of the results are much larger than in conventional semiconductors or in metals. In the case of the methylammonium vacancy, we show that the fully non-local weighted density approximation (WDA) gives results qualitatively different from the semilocal functionals (see Figure 1).
Additionally, we discuss how lattice lifetimes depend on the phase of the material and the role of polymorphism in the high temperature cubic phase.
We analyze our calculated lifetimes on the basis of the size of the voids in the atomic arrangements, estimated in two different ways.

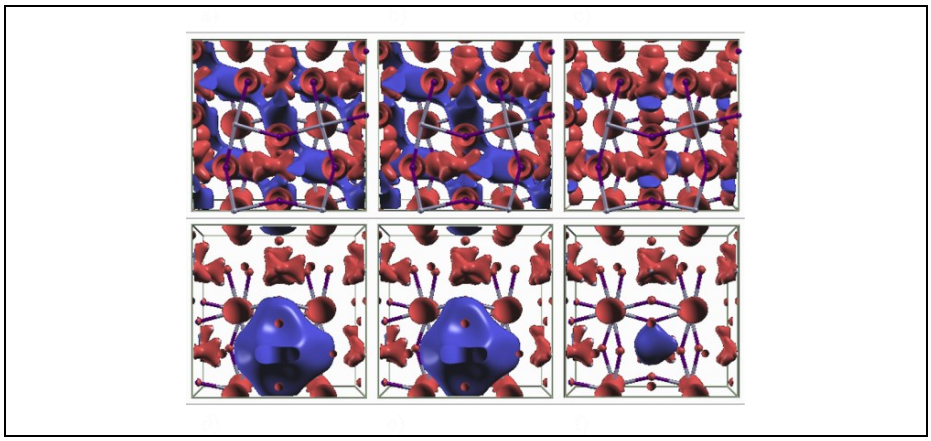


Figure 1: Positron (blue) and electron (red) calculated isosurfaces for the lattice (above) and a methylammonium vacancy (below) for three approximations for the e^+-e^- enhancement factor.

* *corresponding author e-mail: guido.roma@cea.fr*

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Many-body-theory calculations of positron-molecule scattering using the Lippmann-Schwinger equation and Lebedev quadrature

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School of Mathematics and Physics, Queen's University Belfast, University Rd, Belfast BT7 1NN, UK

Many-body theory is a powerful and versatile tool that allows one to study systems with strong correlation effects. It provides reliable and accurate results for low-energy positron-atom scattering and annihilation [1,2,3], positron binding to negative ions [4] and positronium (Ps) scattering and pick-off annihilation on noble-gas atoms [5,6]. More recently, many-body theory achieved unprecedented accuracy in describing positron binding to a wide range of polyatomic molecules [7,8,9]. Analysis of positive-energy positron pseudostates has also enabled extraction of the scattering cross sections and annihilation rates for small polyatomics (H_2, N_2, CH_4) [10]. In this work we show how to calculate positron scattering from arbitrary polyatomic molecules. We find the scattering amplitude $\langle \boldsymbol{k}'|T(E)|\boldsymbol{k}\rangle$ by solving the integral Lippmann-Schwinger equation, using the input of $\langle \boldsymbol{k}'|V_{st} + \Sigma_E|\boldsymbol{k}\rangle$, where $V_{\rm st}$ is the static potential of the molecule in the Hartree-Fock approximation, and Σ_E is the positron correlation potential (self-energy). The self-energy accounts for molecular polarization and virtual Ps formation and is calculated using the diagrammatic approach [7]. The positron momenta $\boldsymbol{k}$ are discretized to form a 3D grid with $|\boldsymbol{k}| \equiv k_i = \alpha(e^{\beta i} - 1)$ and uniform in angle, using Lebedev quadrature on the sphere [11].

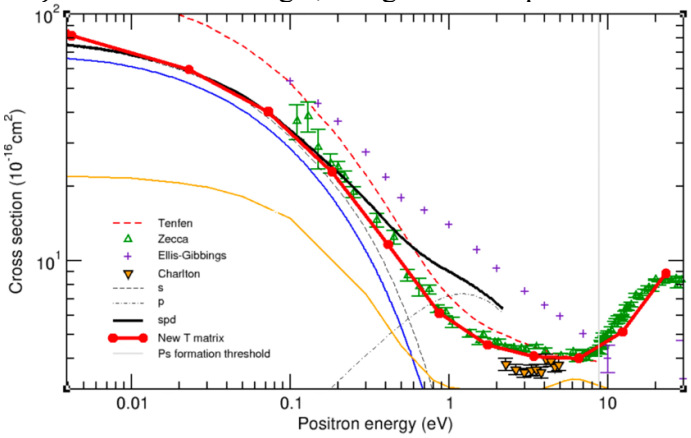


Figure 1: Comparison of the positron scattering cross section for N_2 from the present calculation (solid red line) with earlier calculations (lines) and experimental data, the best being by Zecca *et al.* [12] (green triangles).

We acknowledge support from the European Research Council, grant agreement 101170577.

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LIMPID: an open-source Python framework for positron diffusion analysis in multilayer systems

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Depth-resolved Doppler-Broadening Spectroscopy (DBS) relies on an accurate description of positron implantation, diffusion, and annihilation to extract meaningful material parameters from measured S(E) profiles. This is particularly critical for thin films and multilayer systems, where layer thicknesses, diffusion lengths, surface annihilation, and positron affinities can strongly influence the measured signal.

We present LIMPID (Layer-wise Investigation of Measurements on Positron Implantation and Diffusion*)*, an open-source Python tool for modeling positron diffusion and annihilation in multilayer systems [1]. LIMPID combines material-specific implantation profiles, diffusion parameters, layer thicknesses, surface annihilation, and positron affinities within a flexible layer-based sample description. The diffusion problem is treated in two steps: positrons implanted within a layer either annihilate or reach a layer boundary, after which boundary-to-boundary transport and annihilation are described using a Markov-chain formalism. This yields the annihilation fractions in each layer and at the surface, from which depth-dependent S(E) profiles are calculated.

In addition to forward modeling, LIMPID provides fitting routines for experimental DBS data and includes an optional correction for epithermal positrons at low implantation energies. We demonstrate the method using both artificially generated data and experimental measurements. The resulting fits show excellent agreement with the measured S(E) profiles and illustrate the importance of explicitly including positron affinities when analyzing layered systems.

By providing a transparent, extensible, and freely available implementation, LIMPID aims to improve the reproducibility and comparability of depth-resolved positron annihilation analysis across research groups.

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Positron annihilation in undoped and Ca-doped NFMO sodium-ion cathode materials

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Layered transition metal oxides with intercalated sodium are promising cathode materials for sodium-ion (Na-ion) rechargeable batteries. In this contribution, we investigate the layered P2-type $Na_x[Fe_{1/2}Mn_{1/2}]O_2$ (NFMO) compound with $x = 2/3$, a prospective Na-ion cathode identified in Ref. [1]. The NFMO powder samples were obtained via a coprecipitation route [2] and subsequent calcination with Na_2CO_3. Ca-doped NFMO powders were also examined because Ca doping is expected to have a positive effect on the diffusion properties of Na ions. Positron lifetime and Doppler broadening measurements were performed for a set of samples with different Ca contents, and coprecipitation and calcination conditions. Because sodium in NFMO is sensitive to air moisture, measurements were performed in a vacuum or under a protective atmosphere. The positron lifetime spectra exhibited one or two positron lifetime components and one o-Ps component (p-Ps is also included in the fit). The shorter positron component likely originates from a bulk-like (delocalized) positron state. In contrast, the longer positron and o-Ps components come from larger free volumes. The estimate based on the Tao-Eldrup model (for o-Ps lifetime) gives a pore diameter of 5-6 Å. The changes in the positron and o-Ps lifetimes and intensities in dependence on the sample preparation conditions are discussed in terms of open volumes concentration and size changes as well as possible Ps formation inhibition and quenching. The experimental study was complemented by density functional theory-based simulations employing the SCAN exchange-correlation functional, as recommended in Ref. [3]. Simulations of NFMO are complicated by its partial disorder, i.e., the partial occupancy of Na sites and substitutional mixing of Fe and Mn ions in the transition metal sublattice. In the course of positron calculations, the parameter-free generalized gradient correction [4] for the positron correlation potential and enhancement factor is considered. The positron annihilation results are discussed in the context of the electrochemical parameters (such as capacity and cyclability) of the corresponding NFMO Na-ion cathodes/batteries.

This study is part of the GENSIB project [5]. Technology Agency of the Czech Republic (Project No. TQ17000005) is acknowledged for the financial support.

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Session 9

Surface & Layered Systems

Wednesday, September 9, 2026, 14:00-15:10 · Chair: Jagoda Urban-Klaehn

Light-induced changes of defect states in epitaxial GaN films

Jakub Čížek[a*], Oksana Melikhova[a], Dejan Prokop[a], František Hájek[b], Filip Dominec[b], Alice Hospodková[b], Maciej Oscar Liedke[c], Eric Hirschmann[c], Andreas Wagner[c]

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Gallium nitride (GaN) is a wide-bandgap semiconductor with a bandgap of 3.4 eV, which is widely utilized in short-wavelength optoelectronics. Metal-organic vapor phase epitaxy (MOVPE) is a common technique for depositing high-quality epitaxial GaN films. The electrical and optical properties of these GaN films are influenced by point defects, which introduce electron states within the bandgap. In GaN, cation vacancies (V_{Ga}) form complexes with gas impurities, hydrogen (H) and oxygen (O). These complexes can exist in different charge states, depending on the number of H and O ions attached to the vacancy and the position of the Fermi level. In our study, we investigated the nature and charge states of complexes formed by V_{Ga} with H and O impurities. Our findings revealed that nominally undoped n-type MOVPE GaN films contain electrically neutral complexes of V_{Ga} with three hydrogen atoms $(V_{Ga}+3H)^0$. As illustrated schematically in Fig. 1a, upon light illumination, these electrically neutral complexes become ionized to a positively charged state $(V_{Ga}+3H)^+$, which can no longer trap positrons. This effect is clearly represented in the dependence of the mean positron lifetime on the energy of incident positrons (Fig. 1b). The reduction in positron trapping occurs because some fraction of the $(V_{Ga}+3H)^0$ complexes becomes ionized to $(V_{Ga}+3H)^+$, leading to an increased fraction of positrons diffusing back to the surface. This is observed as an increase in the mean positron lifetime at low energies of incident positrons. The ionization of $(V_{Ga}+3H)^0$ complexes has a distinct threshold: the energy of the incident photon must exceed the energy difference between the electron state of the $(V_{Ga}+3H)^0$ complexes and the conduction band minimum. This threshold can be determined by varying the wavelength of the illuminating photons, as illustrated in Fig. 1c. In this manner, the position of the electron state of the $(V_{Ga}+3H)^0$ complex within the bandgap can be determined experimentally and directly compared with *ab-initio* calculations.

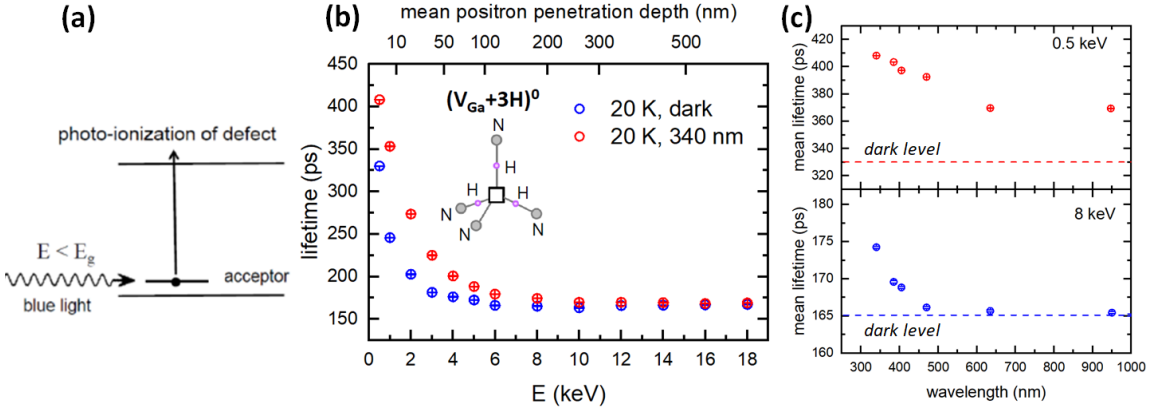


Figure 1: (a) Schematic illustration of light-induced ionization of acceptor-type defects; (b) dependence of the mean positron lifetime on the energy of incident positrons for n-type MOVPE GaN film measured at a temperature of 20 K, both in the dark and when illuminated with near UV light (λ = 340 nm); (c) the mean positron lifetime measured using positrons with energies of 0.5 keV (sub-surface region) and 8 keV (region within the GaN layer) as a function of the wavelength of the illuminating light. The dashed line indicates the mean positron lifetime value measured in the dark.

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Monte Carlo Modelling of Low Energy Positron Annihilation in Few Layer Graphene on Copper: Implications for Surface Sensitive Coincidence Doppler Broadening Spectroscopy

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Doppler broadening spectroscopy with low energy positron beams has been proposed as a method to study surfaces and porous materials [1]. However, at low implantation energies and in ultrathin structures, separating annihilations occurring at the surface from those occurring in the near surface bulk becomes challenging. While positrons trapped in the image potential surface state annihilate at the surface, a fraction of implanted positrons may diffuse into the bulk and annihilate there, producing a Doppler signal containing contributions from both regions. Determining the extent of this mixing is essential for establishing the energy range over which Doppler measurements may be considered truly surface sensitive.

In this project, we develop a Monte Carlo random walk model similar to that proposed by Eichler et al. [2] to simulate positron diffusion in 6-8 layer graphene on copper and investigate the fractions of positrons annihilating at the surface and in the bulk. Positron implantation depths are generated using a multilayer Makhov profile [3], followed by stochastic diffusion determined by region-dependent diffusion coefficients, lifetimes and trapping time. The model includes defect trapping, positronium formation, reflection and transmission at interfaces arising from positron affinity differences and tunneling. The simulated surface and bulk annihilation fractions are compared with experimental values obtained from analysis of the Doppler-broadened annihilation spectra using the full spectrum fitting procedure as described by Mahdy et al. [1], as well as with results obtained using the diffusion model VEPFIT. This microscopic approach provides insight into the probability of surface return for low energy positrons and the conditions under which bulk annihilation must be considered in the interpretation of Doppler measurements. It also enables the study of systems containing extremely thin overlayers, such as few layer graphene, which are difficult to describe accurately using conventional approaches such as VEPFIT.

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Multi-Electron Time-of-Flight Spectroscopy of Positron-Annihilation-Induced Auger Decay from the TiO_2(110) surface

B. Dhar[a], A.J. Fairchild[a], R.W. Gladen[a], N. Hancock[a], S. Yadgeer[a], H. Mahdy[a], A.R. Koymen[a], V.A. Chirayath[a,*], A.H. Weiss[a]

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We report, to our knowledge, the first multi-stop coincidence measurement of a positron-annihilation-induced Auger (PAES) electron together with correlated additional electrons emitted from the same annihilation event at TiO_2 surface. The measurements were performed using the low-energy positron beam system at the University of Texas at Arlington, where slow positrons from a ^{22}Na source are guided to the sample by an axial magnetic field. Data were acquired for incident positron energies of 1.5, 3, and 6 eV. Emitted electrons were detected by a microchannel plate detector at the end of a 1 m time-of-flight spectrometer, while the associated 511 keV annihilation gamma photons were detected using a NaI scintillation detector [1]. The NaI and MCP signals were digitized [2,3], allowing multiple MCP pulses associated with a single gamma-tagged annihilation event to be recorded. Attention is given to events in which two electrons are detected in coincidence, and representative energy spectra of the first and second electrons obtained with a 6 eV positron beam are shown in Fig. 1. At the low incident positron energies used here, primary-beam-induced secondary-electron production is strongly suppressed; therefore, correlated two-electron emission events provide a background-free probe of annihilation-induced core-hole decay that involves multielectron emission from the surface. In such processes, the energy released during the filling of a sufficiently deep annihilation-induced hole may be shared between more than one emitted electron through Auger cascades, or multielectron-Auger-decay channels. Because multi-electron emission can leave a surface atom or local bonding environment in a highly charged state, these measurements may also help clarify positron-stimulated surface processes such as O^+ desorption from TiO_2 (110), whose microscopic mechanism remains unresolved [4]. More broadly, the results demonstrate that multi-stop TOF-PAES can directly access correlated electron-emission processes and surface-localized multi-hole states that are inaccessible to conventional single-electron PAES measurements.

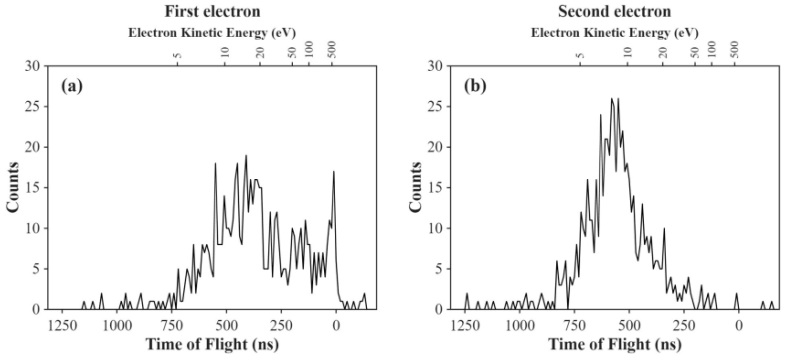


Figure 1. (a) First-arriving and (b) second-arriving electron time-of-flight spectra for coincidence two-electron events from TiO_2(110), obtained with a 5 V sample bias. The corresponding electron kinetic energy scale is shown on the top axis.

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Session 10

Positronium I – Beams & Many Positrons

Thursday, September 10, 2026, 08:30-10:10 · Chair: Ricardo Helm

Measurement of the spatial distribution of Ps^- beam using a laser-wire scanning method towards absolute measurements of photodetachment cross-sections of Ps^-

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The Ps^-, a state in which one positron and two electrons are bound solely by Coulomb interactions, is characterised by the fact that all three particles have equal masses. Numerous theoretical studies on Ps^- have been conducted to understand the effect of each particle's mass on the three-body bound state and calculations of the photodetachment cross-sections have also been performed [1–5]. However, there exists only one measurement, where a lower limit of the cross-section at 1064 nm was estimated [6].

Recently we have started an absolute measurement of the photodetachment cross-sections of Ps^-. We use an energy-tunable Ps beam system developed at Tokyo University of Science [7]. In this system, Ps^- ions are generated using a Na-coated tungsten thin foil and are accelerated by an electric field. They are photodetached by crossing with an Nd:YAG laser (1064 nm) and obtained Ps atoms are detected with a micro-channel plate.

To determine the absolute photodetachment cross-sections, we need to know the spatial distribution of Ps^- in the region where it intersects with the laser. To measure the distribution, we employ a method known as laser-wire scanning, in which the laser is focused using a plano-convex lens to reduce the diameter and changes in the Ps count are recorded as the irradiation position is shifted perpendicular to the Ps^- beam.
In this presentation, we report on the results of spatial distribution measurements obtained using this method.

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Advances towards the first measurement of the gravitational free-fall of a pulsed antihydrogen beam

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The AEgIS (Antimatter Experiment: Gravity, Interferometry, Spectroscopy) experiment, based at CERN's Antiproton Decelerator/ELENA facility, aims to perform the first measurement of the gravitational free-fall of a cold, pulsed beam of neutral antihydrogen propagating in the absence of external fields. The measurement combines a sub-microsecond, velocity-tunable pulsed antihydrogen source with a moiré deflectometer, first demonstrated with antiprotons in 2014 [1], coupled to a high-spatial-resolution annihilation-vertex detector.

Antihydrogen is produced through a charge-exchange reaction between trapped antiprotons and Rydberg-excited positronium atoms, a scheme that demands cold and dense Rydberg positronium cloud interacting with a high number of cold, trapped antiprotons. Since the first pulsed production of antihydrogen in 2021 [2], the pulsed positronium source has been redesigned to greatly enhance antihydrogen production, and the mesoporous silicon/silica positron-positronium converter has been optimized to lower the mean emission temperature from about 1300 K to below 300 K; laser cooling of positronium has further been demonstrated as a route to the colder Rydberg samples required to enhance the charge-exchange cross section. Together with efficient antiproton catching and storage in record-high numbers from AD/ELENA, these advances support antihydrogen production with an enhanced yield by more than two orders of magnitude with respect to the 2021 result [2].

In parallel, the Optical Photon and Antimatter Imager (OPHANIM) detector, built from commercial CMOS image sensors, has achieved real-time antiproton annihilation vertexing with a spatial resolution of about 600 nm, a 35-fold improvement over the previous state of the art [3]. Its sensitivity to visible light enables in-situ optical cross-calibration of the moiré deflectometer, substantially reducing systematic uncertainties. The commissioning of the integrated gravity detector (MEDUSA) is discussed, together with its implications for the gravitational free-fall measurement.

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Current advancements in antihydrogen production and positron purification in the ASACUSA Cusp apparatus

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[b]*University of Vienna, Vienna doctoral school in physics, Vienna, Austria*

The goal of the ASACUSA Collaboration is to measure the ground-state hyperfine splitting of antihydrogen in a beam [1]. Achieving a high yield of ground-state antihydrogen requires dense, low-temperature positron plasma [2], where three-body recombination is maximized.

In strong magnetic fields, positrons can cool efficiently via cyclotron radiation [3]. However, interactions with residual gas lead to ionization, introducing positive ions that drive plasma expansion. Reducing ion contamination therefore is imperative for controlling plasma expansion and by extension temperature and density.

To ensure optimal conditions, reducing ion production is not enough. Active purification of the positron plasma is necessary. The presence of antiprotons and electrons in the trap puts further constraints on the applicable techniques. This talk will discuss the new techniques for ion purification developed in ASACUSA's Cusp trap, as well as recent advancements in antihydrogen production in tandem with higher numbers of usable positrons [4].

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A novel inertial probe of the WEP at AEgIS: The MEDUSA Gravity Module

R.C. Ferguson[a,b], M. Grosbart[c], R. Caravita[b], R.S. Brusa[a,b], on behalf of the AEgIS collaboration[d]

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The interest in whether gravity affects all systems equally regardless of composition is the foundation of the WEP and by performing precision measurements on the free-fall of $\bar{H}$, the gravitational acceleration observed could determine further limits on the WEP [1]. Some results probing WEP using antimatter have been reported [2] but were performed in a dynamic magnetic field rather than a region free of magnetic field gradient. This is one of the primary goals of the Antimatter Experiment: gravity, Interferometry, Spectroscopy (AEgIS) collaboration at CERN, and to achieve this the new MoirÉ Deflectometer for Universality and Symmetry of Antimatter (MEDUSA) Gravity Module has been recently deployed. This module will receive pulsed $\bar{H}$ from the AEgIS apparatus [3] and pass it through an internal moiré deflectometer, consisted of two gratings, that is monitored with three primary detectors. As $\bar{H}$ pass through each grating, annihilation from losses is precisely timed and some vertex reconstructed using SARA [4] and J-PET [5], respectively. The moiré fringe pattern is observed using the OPHANIM [6] detector and is compared to incoherent light for any inertial shifts [7]. The MEDUSA is designed for unprecedented measurements on magnetically induced inertial forces as it can distinguish any radial force acting within the apparatus, via remote controlled rotation of the internal apparatus.

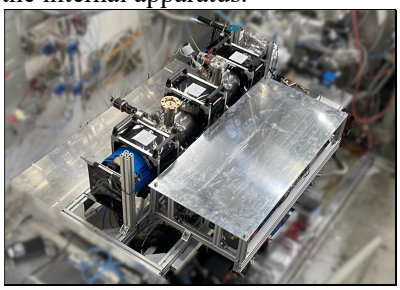


Figure 1: An overhead picture of the MEDUSA Gravity Module as it looks when deployed into the AEgIS zone at CERN.

This report will detail the design and relevant physics pertaining to MEDUSA, as well as the results from incoherent light and antiprotons. Future developments and goals are discussed within this report, as well.

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Session 11

Metals II

Thursday, September 10, 2026, 10:30-12:10 · Chair: Marie-France Barthe

Direct evidence of vacancy-type defects beneath intergranular fracture surfaces in hydrogen-embrittled high-strength steel by a positron microprobe

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Hydrogen embrittlement in high-strength steels is a critical issue for the realization of a hydrogen-based society, yet the microscopic mechanism responsible for intergranular fracture, particularly within the elastic regime, remains controversial. While stress-induced hydrogen accumulation at grain boundaries has been widely discussed, the possible involvement of vacancy-type defects has not been experimentally verified near actual fracture surfaces. In this study, we directly investigated nanoscale defects immediately beneath H-embrittled intergranular fracture surfaces of tempered martensitic steel using a positron probe microanalyzer (PPMA), installed in AIST. A mono-energetic positron microbeam with a diameter of 200 μm was injected onto the fracture surface, enabling localized positron lifetime measurements with a mean implantation depth of approximately 140 nm.

Two-dimensional mapping of the mean positron lifetime revealed remarkably prolonged lifetimes of approximately 220 ps at intergranular fracture regions, even for specimens fractured within the elastic range in a hydrogen environment. This observation provides direct experimental evidence for the presence of vacancy-type defects beneath hydrogen embrittlement fracture surfaces, strongly suggesting that vacancies play a significant role in intergranular fracture under elastic loading conditions. To the best of our knowledge, this is the first experimental visualization of vacancy-type defects directly beneath hydrogen embrittlement fracture surfaces in high-strength steel.

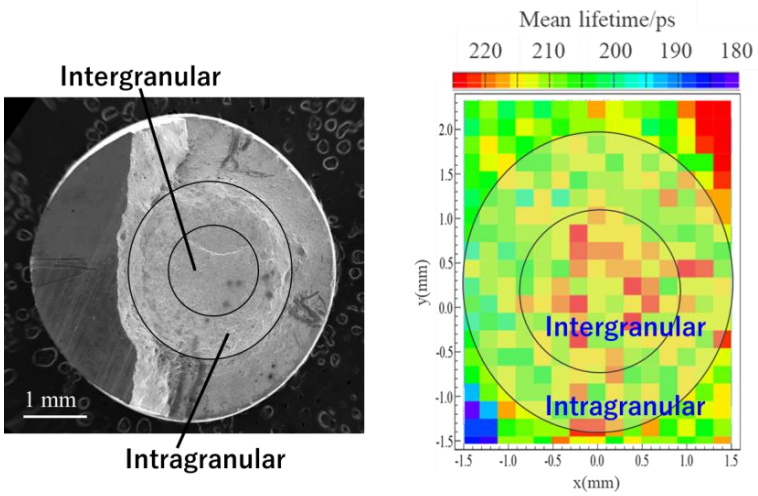


Figure 1 Mean positron lifetime map of the intergranular fracture surface of the H-embrittled tempered martensitic steel by PPMA (the beam energy 8 keV).

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Near-surface hydrogen-filling levels of radiation defects determined by depth-resolved positron annihilation spectroscopy

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In order to improve the understanding of the mechanisms underlying the retention of hydrogen (H) isotopes in tungsten (W), the H trapping characteristics of defects need to be understood. Density functional theory (DFT) calculations predict that a single-vacancy (V_1) in W can trap multiple H atoms, with the binding energy decreasing with increasing number of trapped atoms [1]. However, these predictions are difficult to verify experimentally. Mason et al. [2] calculated the V_1 density using combined creation-relaxation algorithm (CRA) and molecular dynamics (MD) modeling of displacement cascades, then compared it with the deuterium (D) concentration in displacement-damaged W measured by Schwarz-Selinger [2]. The ratio of D to the V_1 concentration suggested 5 D atoms trapped per V_1 at 370 K. This was found to be in agreement with DFT predictions [1].

In positron annihilation lifetime spectroscopy (PALS) the measured lifetime is directly related to the type of defect and to the number of H atoms present in the defect. Comparing the measured lifetime to the values calculated by two-component DFT enables an estimation of the number of trapped H atoms per defect. However, the results depend heavily on the fidelity of the calculations. This method has first been demonstrated on H_2 gas-loaded, MeV-electron irradiated W samples characterized by conventional (non-depth-resolved) PALS [3].

This work further improves the method by using depth-resolved PALS. It also shows its applicability to self-ion irradiated samples. Two recrystallized, polycrystalline W samples were irradiated with 20.3 MeV W-ions to 0.023 dpa (7.87×10^{12} W cm^{-2}) at 290 K. Then one of the samples was exposed to a low-flux ($<10^{20}$ D m^{-2}s^{-1}) D plasma at 370 K up to a fluence of $<3\times10^{23}$ D m^{-2}. PALS depth-profiles of these samples after D-loading indicate the filling of the defects with D. The dominating lifetime component reduces from (201.2±3.0) ps to (178.4±2.0) ps after D loading. The value in the unexposed sample is close to the 195 ps to 200 ps given in literature for a V_1 [4,5,6]. Comparing the value from the D-loaded sample with the calculated lifetimes of two-component DFT for H in a V_1, one obtains an estimate of either 0.5 D per V_1 [7] or 1.9 D per V_1 [5], depending on the literature value used. This is substantially lower than the currently accepted literature estimate of 5 D per V_1 [1,2].

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Atomic-scale characterization of irradiation damage and lattice disorder in refractory Multi-principal Element Alloys

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Advanced fission and fusion reactor systems require structural materials with high stability under extreme temperatures and intense irradiation. Refractory multi-principal element alloys (RMPEAs), including refractory high-entropy alloys (RHEAs), are promising candidates because of their excellent thermal stability and potential irradiation tolerance. [1,2]. However, the atomic-scale mechanisms of irradiation damage accumulation and the role of chemical complexity remain unclear.

In this study, a series of equi-atomic MoNbTa, MoNbTaW and MoNbTaVW RMPEAs were prepared by arc melting and subjected to heavy W ions irradiation to fluences up to 1×10^{15} ions/cm^2. Variable-energy positron annihilation Doppler broadening spectroscopy was used to characterize early-stage irradiation damage, particularly vacancy-type defects. Compared with pure metal references, the unirradiated RMPEAs alloys showed evident positron trapping, indicating that lattice distortion and chemical complexity strongly affect the defect-sensitive positron response. After irradiation, MoNbTa and MoNbTaW exhibited a dose-dependent increase in the *S* parameter, while this trend was suppressed in MoNbTaVW, suggesting that V addition promotes rapid damage saturation. Additionally, synchrotron-based X-ray absorption spectroscopy (XAS) revealed element-specific local disorder and its irradiation-fluence dependence. These results provide atomic-scale insight into irradiation damage evolution in RMPEA alloys.

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Dose and temperature dependent irradiation damage in a novel Co-free high entropy alloy

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High-entropy alloys (HEAs) have emerged as promising candidate materials for advanced nuclear energy systems because of their exceptional mechanical properties, thermal stability, and superior irradiation resistance compared with conventional alloys. Among them, Co-free HEAs have attracted increasing attention due to their reduced activation characteristics and potential advantages for irradiation environments[1].

The defect evolution of NiMnFeCrAl high-entropy alloy under 5 MeV Ni-ion irradiation was investigated using variable-energy Doppler broadening spectroscopy based on a slow positron beam. The S–W parameter analysis showed that room-temperature (RT) irradiation introduced significant vacancy-related open-volume defects, while increasing irradiation dose promoted defect aggregation and evolution. In contrast, the sample irradiated at 350 °C with a high dose exhibited defect characteristics closer to those of the unirradiated alloy, indicating thermally activated defect recovery, although residual irradiation defects still remained.

Nanoindentation measurements were further performed to evaluate the irradiation-induced hardening. The results revealed highest hardness in high-dose irradiated sample at room temperature, while the high-temperature irradiated sample showed partial hardness recovery.

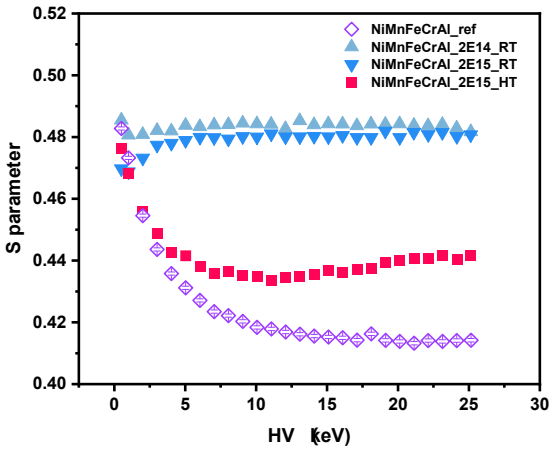


Figure 1: S parameter as a function of positron incident energy obtained from slow positron annihilation spectroscopy for NiMnFeCrAl high-entropy alloy under 5 MeV Ni-ion irradiation with different temperatures and dose, including room-temperature irradiation at 2×10^{14} cm^{-2} and 2×10^{15} cm^{-2}, and high-temperature irradiation at 350 °C with a dose of 2×10^{15} cm^{-2}.

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Session 12

Positronium II – Antihydrogen

Thursday, September 10, 2026, 14:00-15:30 · Chair: Laszlo Liszkay

Rydberg positronium diagnostics for antihydrogen beam formation at AEgIS

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The AEgIS experiment at CERN produces antihydrogen via charge exchange between Rydberg positronium (Ps*) and cold antiprotons, with the goal of measuring the gravitational free-fall deflection through a moiré deflectometer [1]. In the latest apparatus configuration the positron-to-Ps converter is placed only ~2 mm above a 1.5 mm-diameter antiproton cloud. Antiprotons are transferred ballistically to this position and synchronised with Ps formation and laser excitation; during charge exchange they retain a small downstream momentum, which defines the boost direction of the resulting $\bar{H}$ beam. This geometry maximises the spatial overlap and eliminates flight-time losses of Ps* before the interaction region. The $\bar{H}$ formation cross-section scales as n^4, making knowledge of the Ps n-distribution and of the competing self-ionisation losses [2] central to optimising beam production.

For characterizing Ps*, we excite ground state Ps to Rydberg states via two-photon absorption at 205 nm + 16XX nm (XX ≈ 60–80). Ps* then flies ~10 cm towards a high-voltage electrode maintained at a constant field. The neutral Rydberg Ps is ionised in the inhomogeneous electric field near the electrode, which has been mapped radially using finite-element simulations. Recording the field-ionization signal as a function of radial position in the mapped field yields the differential ionisation spectrum, from which the n-distribution of the Rydberg laser excited Ps is extracted.

We also achieved for the first time a Doppler scan of the Ps velocity distribution inside the cryogenic 1T solenoid of the AEgIS main apparatus, using the 205 nm + 1064 nm two-photon photo-ionisation system with MCP detection of the resulting photo-positrons. Scanning the frequency across the resonance yields the one-dimensional velocity distribution along the laser axis. With a room-temperature converter target, $v_{rms} = 6\times10^4$ m s^{-1} ($T_{Ps} \approx 475$ K) while operating at cryogenic temperature (~200 K) reduces this to $v_{rms} = 4\times10^4$ m s^{-1} ($T_{Ps} \approx 211$ K). Combined with the field-ionisation data, these measurements define the optimal Rydberg excitation range: at the cryogenic v_{rms}, the motional Stark effect in the 1T solenoid sets an upper limit of $n \leq 25$ from the self-ionisation criterion, constraining the useful excitation window.

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Advances on positronium cooling at the AEgIS collaboration

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The first successful demonstration of Doppler cooling of positronium (Ps) via the 1S-2P transition has introduced a novel technique to narrow its velocity distribution [1, 2], unlocking new possibilities in antimatter research [3] and possibly in tests of fundamental physics principles [4] and theories [5]. Building on this achievement, we have introduced a preliminary step of collisional cooling by maintaining the nanochanneled silicon e^+\Ps converter at cryogenic temperatures as described in ref. [6]. We obtained a source of positronium which velocity spread can be tuned by controlling the temperature of the converter. At the lowest temperature, with the converter set at 155 K, a source of Ps at 157(61) K was obtained. Subsequently, Doppler cooling was applied for 70 ns lowering the temperature of the Ps cloud down to at least 103(43) K [7]. The latter result is limited by the resolution of the velocimetry diagnostics based on the measurement of the Doppler broadening of the 1S-3P line. Further improvements in the technique, such as a finer temperature probe and multi-dimensional Doppler cooling, as well as promising applications for fundamental physics experiments of the presented cooling scheme will be discussed.

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Measurement of positron spin precession via Quantum Oscillations

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We aim to develop a method for measuring the spin precession of polarized positrons in magnetic fields via the observation of modulations in quantum oscillation amplitudes. It is known that with the introduction of magnetic fields, the degeneracy amongst the positronium (Ps) $^3S_1$ substates will be broken. Interference between these non-degenerate energy eigenstates will, thus, exhibit oscillatory behaviour, known as quantum oscillations or quantum beats [1]. In the past, the primary purpose of measuring these oscillations was to determine the ground-state Ps hyperfine splitting between the $^1S_0$ – $^3S_1$ states through the oscillation frequency [2 – 5]. Often overlooked is that, since the positron polarisation is arranged to be transverse to the applied magnetic field in such measurements, the positron spins will precess, and, hence, the angular distribution of the Ps quantum oscillations would be altered accordingly. We, therefore, propose a spin rotation method for positrons based on the measurement of this angular displacement in quantum oscillation amplitudes. Preliminary results obtained with a ^{22}Na source will be presented alongside discussions on the prospects of performing a monoenergetic measurement using positron beamlines. Furthermore, this spin precession is expected to cover the time range from when the positron enters the field to the formation of the electrically neutral Ps atom. A measurement on the total spin precession should then reflect the time scale of processes such as thermalisation and positron trapping in defects in solid state materials. Given the large Larmour frequency of positrons, picosecond-level time precision could potentially be achieved by a degree-level angular measurement.

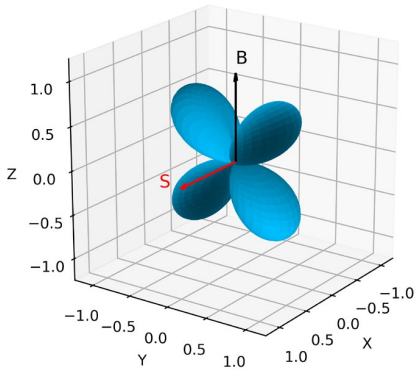


Figure 1: Angular distribution of Ps quantum oscillation amplitude, where S indicates the positron polarisation and B shows the magnetic field.

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Experimental setup for continuous positronium beam formation via Ps^- production and laser photo-detachment

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The QUPLAS (Quantum interferometry and gravitation with Positrons and LASers) experiment seeks to perform the first ever measurement of Earth's gravitational acceleration on positronium (Ps), a purely leptonic matter-antimatter bound state. This constitutes a crucial test for the Einstein Equivalence Principle and the CPT (Charge, Parity, Time) symmetry, whose violation could point toward physics beyond the Standard Model [1].

To achieve this, QUPLAS designed a Mach-Zehnder interferometer to detect gravitationally-induced phase shifts in the positronium beam [2]. This technique requires a continuous-wave Ps beam, produced through a two-step approach. First, a high-intensity beam of positronium negative ions (Ps^-) is generated following the method pioneered by Nagashima et al. [3]. This charged intermediate enables efficient electrical acceleration and focusing before annihilation. The Ps^- ions are generated by bombarding a sodium-coated polycrystalline tungsten target with a positron beam, a method yielding the highest known production efficiency [4]. Second, the focused Ps^- beam is photo-detached to neutral Ps inside a high-power (200 kW) Fabry-Pérot cavity, where a circulating 1560 nm laser interacts with the ions through single-photon absorption. This wavelength optimally balances the maximum photo-detachment cross-section with the availability of commercial high-power lasers.

This contribution outlines the overall design of the QUPLAS gravitation experiment, detailing the Na/W conversion target characteristics, via photoelectric analysis, and the photo-detachment Fabry-Pérot cavity. Furthermore, we report on recent hardware milestones that bring the setup close to the Ps^- production: the successful restoration of the positron beam's operation and the conditioning of the experimental chamber, which has now reached the critical vacuum levels required for the Na/W surface preparation. The next step will be to optimize the Ps^- production to target the highest efficiency and to perform the photo-detachment.

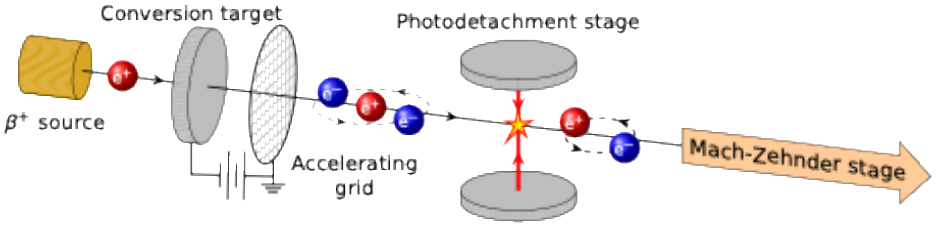


Figure 1: Scheme of QUPLAS Ps beam formation

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Session 13

Semiconductors & Oxides II

Thursday, September 10, 2026, 15:50-17:10 · Chair: Jonatan Slotte

Effect of lanthanum doping on vacancy defects in uranium dioxide

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Irradiation damage in actinide oxides, such as UO_2, significantly impacts fuel performance in fission reactors. Among defects that are created under irradiation are vacancies, and these affect fission gas transport, thermal conductivity, stoichiometry, swelling, and mechanical properties of the fuel. Understanding the behavior of vacancies and their interactions with constituent elements of the fuel and fission products is therefore essential for designing radiation-tolerant fuels and predicting their lifespan.

Positron Annihilation Spectroscopy (PAS) is a proven technique for studying defects in uranium oxide, including under irradiation. Evans et al. [1] used Slow Positron Beam Doppler Broadening (SPBDB) to observe damage recovery in Kr-irradiated UO_2 samples during heating. Later studies with SPBDB and Positron Annihilation Lifetime Spectroscopy (PALS) identified small vacancy defects in electron- and ion-irradiated UO_2 [2-4].

The present work focuses on the effect of lanthanum on the annihilation characteristics and the behavior of vacancy defects in uranium dioxide. For this, we characterized $(La_yU_{1-y})O_{2\pm x}$ with y= 1, 5 and 15, using both PALS and SPBDB facilities at CEMHTI (Orléans).

First, we observed that the positron lifetimes in $(La_yU_{1-y})O_{2\pm x}$ are similar to the values calculated via TC-DFT (Two component-Density Functional Theory) for doped [5] and pure [4] UO_2. A new lifetime component (~ 240 and 200 ps) was observed in $(La_{0.15}U_{0.85})O_{2\pm x}$ after high-temperature annealing in Ar/H_2. This could be linked to the formation of oxygen vacancy clusters due to hypo-stoichiometry. Uranium vacancy defects (Schottky/double Schottky) were detected due electron irradiation in La-doped $UO_{2\pm x}$.

Defect evolution during annealing in Ar/H_2 atmosphere was studied using SPBDB in La-doped samples that were implanted with $1x10^{16}$ cm^{-2} of 1 MeV ^3He . It strongly depends on La content (y=1–15%) and compared to the one in pure UO_2 [6]. The S-parameter reduction observed at 264°C in pure UO_2 [6] disappears for y(La) ≥ 5% while peaks in S-values at 800–900°C (y(La) =5 and 15%), indicate larger vacancy defects, with similar trend expected at 1300°C for y(La) = 1%. The effect of different factors, such as the defect distribution before annealing, changes in stoichiometry, helium release and its presence in the region probed by positrons on the temperature vacancy defects evolution will be discussed.

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Microstructure and defect recovery in ion irradiated Ga_2O_3

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Ion irradiation is an effective tool to engineer defects in wide bandgap semiconductors, e.g. β-Ga_2O_3. We have evidenced a peculiar effect of material exfoliation upon Cr^+ implantation into (100)-oriented *β*-Ga_2O_3. Irradiation of β-Ga_2O_3 with ions, e.g., Ne^+ between 25 keV and 140 keV trigged a phase transformation from the β- to the γ-phase [1]. Although, the resulting material modification was quite different for both study cases, a similar signature in Doppler broadening characteristics has been observed, indicating a substantial raise of positron back diffusion to surface at a critical ion fluence. For the former, a slower decay of the annihilation line parameters as a function of depth, at the very moderate fluence of $1 \cdot 10^{14}$ cm^{-2}, was linked to a detachment and rolling-up of the damaged material exposing the less defected region beneath (see Fig. 1). The exfoliation process has been related to the interplay between vacancy agglomerates and developing stress/strain in the damaged layer with increasing ion fluence. Typically, defect complexes are stabilized by compressive stress/strain and effectively prevent the material from relaxing in absence of grain boundaries. For the latter, the ion-induced defective spinel γ-phase of Ga_2O_3, containing intrinsic vacancies within the unit cell which exhibit strongly delocalized positron trapping, has been deciphered from the apparent reduction of defect density at a fluence of about $3.5 \cdot 10^{16}$ cm^{-2} [1].
Moreover, we have assessed the removal of the introduced defects under thermal annealing in both studied cases, implanted with a fluence close the critical thresholds. The evolution of point defects as a function of temperature will be discussed in detail.

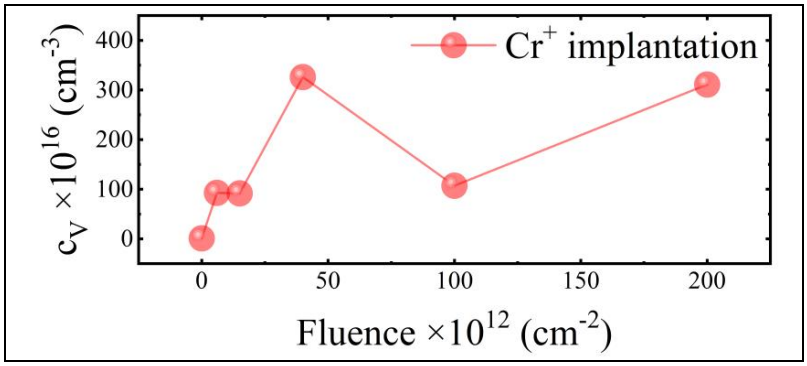


Figure 1: Measured relative defect density as a function of ion fluence for Cr^+ implanted (100)-oriented *β*-Ga_2O_3.

Parts of this research were carried out at ELBE and IBC at HZDR within ReMade@ARI project. The M-ERA.NET Program and GOFIB project are acknowledge.

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Positron Annihilation Study of Frequency-Bias Dependent Defect Dynamics in SiO_2/Si MOS Structures

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Defect states at semiconductor interfaces play a critical role in determining the reliability and performance of devices. Conventional deep-level transient spectroscopy (DLTS) is widely used to study electrically active defects in semiconductors and is primarily based on the measurement of electrical signals, such as capacitance transients, providing limited direct spatial and structural information [1][2]. In this study, the frequency-bias dependent positron annihilation technique [2][3][4] is further developed to investigate bias-dependent defect dynamics in SiO_2/Si metal–oxide–semiconductor (MOS) structures, subjected to ion implantation. The approach combines slow positron Doppler broadening spectroscopy with periodic electrical bias modulation and temperature-dependent measurement, allowing defect charge-state changes to be monitored through variations in the positron annihilation *S*-parameter.

The samples consist of an Al/SiO_2/Si MOS structure, with Si ion implantation used to introduce defects at (and below) the oxide/semiconductor interface. A square-wave voltage was applied between the Al gate and the Si substrate, switching the sample between two bias conditions. The annihilation signal was measured using a HPGe detector with bias-synchronized gating, allowing Doppler broadening spectra to be obtained separately for each of the bias states. At various modulation frequencies, the *S*-parameter contrast between the two bias states was extracted and used as the frequency-dependent response signal. The frequency dependence of the *S*-parameter response was analyzed using a low-pass filter model, from which a characteristic cut-off frequency and corresponding time constant were extracted. Temperature-dependent measurements further allowed the cut-off frequency to be used in an Arrhenius analysis to estimate the activation energy of the underlying positron trapping process.

Acknowledgments: This works was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

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Session 14

Thin Films

Friday, September 11, 2026, 08:30-09:50 · Chair: Stephan W. H. Eijt

Identification of vacancy-type defects in low-T epitaxial films engineered as hosts for Si-based colour centres

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Recently, an all-epitaxy synthesis route for Si-based colour centres has been proposed [1-2]. This opens new opportunities for nano- and heterostructure designs for this up-and-coming class of quantum emitters/spin qubit centers. A key enabler of this technology is the ability to deposit thin films as a matrix for the colour centres at lower temperatures. Low-temperature deposition, however, increases the susceptibility of epitaxial layers to contamination by residual gases in the deposition chamber which must be prevented by being more attentive to the atmosphere during deposition. While many epitaxy studies downplay the effect of chamber pressure, often merely reporting base pressure prior to deposition, this study shows the impact of chamber pressure during deposition, particularly at low temperatures.

50nm layers of Si were deposited by Molecular Beam Epitaxy (MBE) on Si substrates (with 50nm Si buffer layer) at 5E-11, 1E-08 and 5E-08 mbar. Corresponding samples of Ge, with Ge substrates and capping layers were also produced. These pressures respectively correspond to the pressure detection limit, an environment where the predominant impurity is hydrogen, and an environment containing significant other impurities (CO, CO2, etc.). Deposition temperatures ranged from 200 to 600°C. DBPAS results indicate a significant drop in the S parameter with increasing deposition temperature. Significantly, the onset of the S parameter reduction occurred at lower temperature when deposition occurred at lower pressure. VEPFIT [3] analysis is currently underway to identify and quantify specific impurity-related point defects. *This work is being supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Discovery Grants (Grant No. RGPIN-2025-06031) program.*

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A new paradigm for positrons? Charge-transfer orbitals and internal fields at buried interfaces in energy materials

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For decades the positron has served our community as a probe of open-volume defects: a thermalized positron traps at a vacancy, its lifetime reporting the open volume and its coincidence Doppler broadening signature the chemical environment of the trap. Our recent work on energy materials suggests that, in functional and electrically active systems, the positron does considerably more, and this raises a new question worth posing to the slow-positron-beam community.

The question grew from experiment. In carbon-coated Li-ion battery cathodes, positron lifetime spectroscopy showed that the interfacial surface-state component scales with the carbon additive, while broadband electrical spectroscopy on the same samples tied this positron signal directly to the Li^+ diffusion coefficient; rather than trapping, the positron was transported anomalously over micrometric distances toward the cathode/carbon interface [1]. These observations generated the hypotheses later confirmed by first-principles studies: a Schottky-like junction localizes the positron at the interface [2], and orbital-resolved CDB with momentum-density calculations separates oxygen 2p from carbon $2p_z/\pi$ contributions, reading the charge-transfer orbitals that govern transport [3].

The same defect sensitivity, used rigorously, can steer device design. In $MAPbI_3$ and $MAPbBr_3$ single crystals, saturation-trapping lifetimes and halide-dominated momentum distributions identify the lead vacancy V_{Pb}^{2-} unambiguously, yet only ab-initio calculations including positron-induced lattice relaxation reproduce them, exposing the limits of standard theory in soft lattices [4,5]. In turn, passivation of such vacancy-type defects underpinned a novel, solvent-free, rapidly annealed $FAPbI_3$ perovskite solar cell exceeding 20% efficiency and retaining over 90% of it after thousands of hours, compatible with industrial-scale production [6]. We are now extending this to the buried solid–solid interfaces of these all-solid-state devices.

The frontier is to move positrons from ex-situ identification toward depth-resolved, in-situ/in-operando metrology [7,8] of interface electronic structure, co-developing slow-beam methods and electron–positron theory, so that positron spectroscopy can guide the fabrication of next-generation energy devices, not only characterize them afterwards.

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Defect landscape in Nb_3Sn thin films for superconducting radio frequency cavity applications

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Using bulk niobium is the state-of-the-art approach to realize the technology of superconducting radio-frequency (SRF) cavities. However, in order to improve performance and to lower operational costs, the latter resulting from the necessity of cooling to cryogenic temperatures of ~2 K, thin film coatings with superconductors have been proposed as a remedy. Especially Nb_3Sn is of high interest because of its high superconducting transition temperature of up to ~17 K. Moreover, magnetron sputtering is a very suited method which provides a large spectrum of deposition parameters for adjustments. Most relevant are substrate temperature, deposition pressure and sputtering power. During the growth, different defects are formed in the films. Maximizing transition temperature could be correlated to the structure and point defects in thin films like vacancies, their agglomerations and pores. To study this effect, positron annihilation spectroscopy (PAS) is utilized.

a) b)

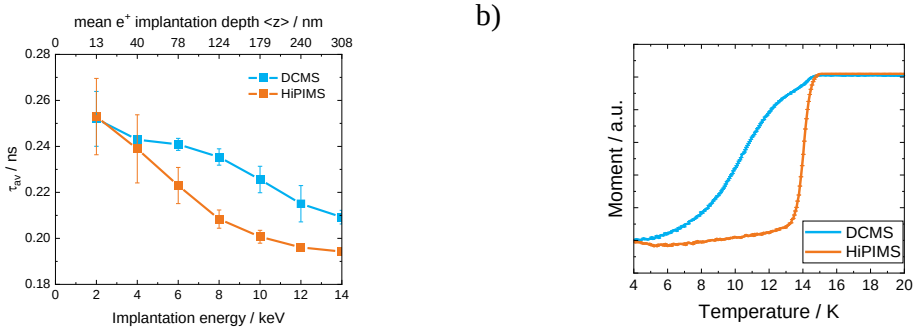


Figure 1: a) Depth-dependent average positron lifetime and b) superconducting transition of Nb_3Sn with DCMS and HiPIMS recipes.

In this contribution, investigations on magnetron sputtered Nb_3Sn will be presented. Aside from depth-resolved PAS, X-ray diffraction, atomic force microscopy and vibrating sample magnetometry are used for structural and superconducting characterization. The results show significant improvement of film quality with the method of high power impulse magnetron sputtering (HiPIMS) compared to direct current magnetron sputtering (DCMS). HiPIMS-Nb_3Sn shows a significant smoother surface with an RMS roughness below 1 nm and good phase development at lower deposition temperatures. For both, there are mainly two lifetime components. Supported by ATSUP and ab-initio calculations, one can estimate the defects to be monovacancies and their agglomerations between 5 to 15 vacancies. HiPIMS shows a general reduction of lifetime components, resulting in a decrease of average positron lifetime (Fig. 1a). The superconducting transition region is significantly sharper for HiPIMS (Fig. 1b), proving the enhancement of superconducting performance due to increased film quality.

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Session 15

Positronium III – Spectroscopy & Diagnostics

Friday, September 11, 2026, 10:10-11:40 · Chair: Ruggero Caravita

A new bunched positron beam for studies on positronium collected in laser-written microcavities

Sebastiano Mariazzi[a,b*], Ahmad Chehaimi[a,b], Erika Socal[a,b], Federico Pozzi[a], Sara Bolzoni[a,b], Marco Bettonte[a,b], Luca Penasa[a,b] , Roberto S Brusa[a,b]

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A new bunched positron beam called PsICO (Positronium Interferometry and Correlation Observation) is under commissioning at the Antimatter Laboratory (AML) of the University of Trento [1, 2]. The primary aim of the positron beam is to generate positronium (Ps) clouds through positron implantation in nanostructured positron/Ps converters [3-6] for fundamental experiments [7-8]. One of these experiments consists of the collection of Ps atoms in buried microcavities for future investigation of laser spectroscopy [9] and tests of laser cooling [10, 11] on confined Ps. Silicon targets with a network of nanochannels connected to laser-written buried microcavities [12] have been developed for this purpose [13].
In this talk, the status of the new positron beam will be presented and the results in the collection of Ps in the nanochannel-connected-buried microcavities will be illustrated. The next planned steps will be indicated.

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Laser spectroscopy of positronium $1^3S_1 \rightarrow 2^3S_1$ interval

Evans Javary[1,†], Edward Thorpe-Woods[1], Lucas de Sousa Borges[1] and Paolo Crivelli[1]

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As purely leptonic atom free from nuclear finite-size effects, positronium constitutes an ideal system for high-precision tests of bound state quantum electrodynamics (QED) and searches for new physics [1]. We report our results on the $1^3S_1 \rightarrow 2^3S_1$ transition in positronium, measured via two-photon optical spectroscopy using a continuous-wave laser. Analysis has been done using both Monte Carlo simulations and a semi-analytical lineshape tool that we developed to extract the resonance. Our measurement with an uncertainty of 6 MHz (4.9 ppb) [2] is consistent with the most precise measurement reported to date (2.6 ppb) [3]. Combining these two results reduces the tension with the theory to the 1.4σ level. With ongoing upgrades of the experimental setup, we expect to improve the measurement in the near future, aiming for a precision of 500 kHz (~0.4 ppb) to match the current theoretical precision (0.47 ppb) [1]. Moreover, we present future long-term directions for positronium spectroscopy, particularly the implementation of an innovative scheme [4], combining optical Ramsey spectroscopy [5] with a relativistic Doppler correction applied on an atom-by-atom basis [6]. This technique has the potential to outperform the current state-of-the-art by at least two orders of magnitude.

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Measurements of positronium compound binding energies

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Positronium (Ps) can form a variety of exotic molecular systems. Although theoretical studies predict the existence of more than thirty Ps compounds [1], experimental observation remains limited to the simplest systems, positronium hydride (PsH) [2] and deuteride (PsD) [3]. Ps compounds are relevant in multiple fields, including many-body quantum calculations [1], materials studies [3], and antihydrogen ion formation [4], but the lack of experimental results means calculations are unvalidated. We report a renewed experimental effort to search for and characterise these molecules, such as PsH, PsO and PsF, by measuring their binding energy with a precision of approximately 50 meV.

To this end, we have constructed a dedicated positron beamline based on a ^{22}Na source, a Surko buffer-gas trap, and a 1 amu resolution time-of-flight mass spectrometer. The trap produces positron bunches characterised by a narrow energy spread of 59 ± 1 meV. Ps compounds are formed via collisions between the positron beam and an effusive gas-jet target $e^+ + AB \rightarrow A^+ + PsB$, employing a methodology analogous to that used in Ref. [2]. The ion produced in the collision is identified in a time-of-flight mass spectrometer using a microchannel plate detector (MCP), its appearance below the threshold for Ps production indicating if the Ps compound is made.

We present the first measurements of this experiment and compare them to the available theoretical models.



Figure 1: Binding energies of Ps compounds, adapted from [1].

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Towards a high precision ortho-Positronium lifetime measurement with a PET-like detector

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Positronium, as a purely leptonic system, provides a unique laboratory for precision tests of bound-state QED. Among its measurable observables, the ortho-positronium decay rate is an interesting quantity. Including all two loop diagrams, second-order corrections of the decay rate have been calculated, leading to a theoretical prediction at the 1 ppm level [1]. In contrast, the most precise experimental results remain two orders of magnitude less accurate [2] [3], limited by both systematic and statistical uncertainties.
At ETH Zurich we are developing a new precision experiment to measure the ortho-positronium decay rate in vacuum, combining and refining established techniques. A key improvement is a novel method to determine and subtract the time-dependent pick-off contribution. That is, the decay of ortho-Positronium into two photons prior to the intrinsic three-photon vacuum decay, arising from interactions of ortho-Positronium with the surrounding matter. The new approach relies on a PET-like detector with high spatial granularity, excellent timing and energy resolution. In addition, a dedicated confinement cavity has been designed and tested to retain ortho-Positronium within a region of uniform detection efficiency, which is expected to further reduce systematic uncertainties related to extrapolation procedures. Together with the ETH slow CW positron beam and a dedicated tagging system, the experiment is expected to achieve the statistics required for a measurement below 10 ppm.
The experimental concept, the validation of parts of the methodology, and the current status of the experiment will be presented.

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Poster Session & Company Exhibition

Wednesday, September 9, 2026, 15:30-18:30 · P01 - P35

Experiment proposal for the production and characterization of positronic molecules

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The study of positronic compounds – bound systems consisting of one or more positrons interacting with atoms or molecules – has provided novel insights into fundamental matter-antimatter interactions and the limits of molecular binding theory. Nonetheless, many of these systems have remained objects of purely theoretical scrutiny as their synthesis is complicated by their intrinsically short lifetimes and the need for intense, low-energy positron sources [1].

This contribution will explore the few pathways that are available for the production of such systems and present estimations for their reaction cross sections. To that end, the R-Matrix method is applied to positron-molecule interactions and the results fed into an adaptation of a semi-classical model for dissociative attachment. Based on these results, an experimental setup for the production of positronium halides (denoted PsX, where X is any of F, Cl, Br, I) via the process of dissociative positron attachment (DPA) is designed and its performance evaluated via extensive simulation. The device is primarily envisioned for use at the SLOPE positron beam, [2] allowing for source-based positron operation independently of the NEPOMUC beamline. Feasibility studies and projected measurement times for the various modes of operation are presented in detail.

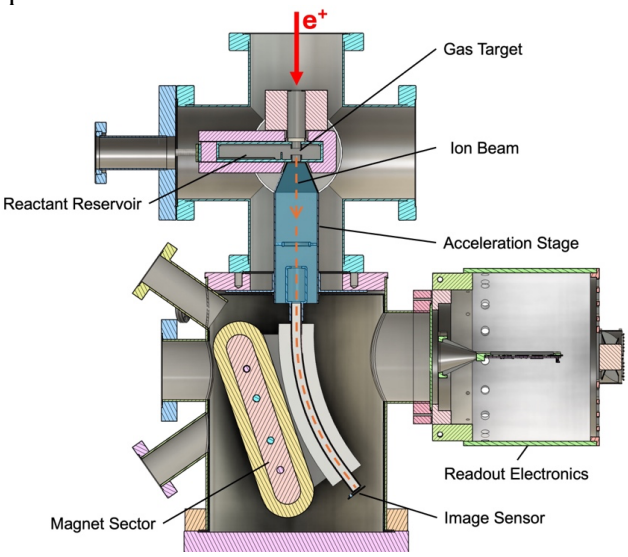


Figure 1: Cross sectional view of the proposed experimental apparatus which has been designed in the Master thesis of Michael Berghold [3]. The positron beam (red) impinges onto the gas target in which the DA reaction occurs, forming the compound of interest and a corresponding signature ion. The signature ions are subsequently accelerated to 20 keV and formed into a beam (orange). The ion beam then traverses a 37 deg magnet sector, selecting for their specific mass-to-charge ratio, before impinging on a modified CMOS image sensor acting as a particle detector.

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Single-electrode diocotron mode Damping for positron plasma recentering

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Multi-cell traps are a promising technique to accumulate large number of positrons [1, 5]. Aiming at overcoming space charge limitations, multi-cell traps present a technical challenge: developing a reliable transfer procedure to load the traps. At present, the most considered technique relies on the excitation and manipulation of a diocotron mode induced in the plasma [3, 4]: the plasma is guided onto the axes of the storage traps by means helical trajectories induced via autoresonance of the diocotron mode in a large cylindrical trap.
Since positional accuracy in the helical trajectory of the injection process and reproducibility of the plasma locking are intrinsic limits of the technique described, an additional procedure to actively axialize the positron plasma after re-catching in the cell traps is likely required to overcome fast expansion dynamics [2].
We present here a procedure to axialize post-recatching positron plasmas via damping of the diocotron motion based on the use of a single segment of a 4-fold segmented rotating wall electrode. This method has been developed by leveraging on the existing small mechanical misalignment between the AEgIS experiment 5T and 1T trap stacks, which provides a reproducible off-axis injection of positrons.
The diocotron signal induced on two opposite segments of the four-fold segmented electrode is fed to a two-stage differential amplification module. Subsequently, the amplified signal, with proper phase, is feed-backed to a third segment to coherently transfer energy to the diocotron motion and realize the axialization.
This technique provides a simple and robust method for recentering off-axis plasma, without requiring exact knowledge of the diocotron frequency.

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<Z_{eff}> Across the Noble Gas Series: Theory, Experiment and Cross-Section Sensitivity

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The thermalization and annihilation of positrons in gases provide a unique probe of low-energy positron–atom interactions. During thermalization, the annihilation rate depends sensitively on the evolving positron energy distribution and therefore on the underlying scattering cross sections. Consequently, measurements of the average effective electron number, ⟨Zeff⟩, contain information not only about annihilation processes but also about positron transport.

In this work, we investigate the relationship between elastic scattering and annihilation dynamics across the noble-gas series using a time-dependent Boltzmann equation treatment of positron transport [1,2]. Simulated ⟨Zeff⟩ relaxation profiles are calculated using recent theoretical cross-section sets [3,4] and compared with available experimental measurements [5]. Particular attention is given to the sensitivity of the annihilation dynamics to variations in the low-energy elastic scattering phase shifts and the corresponding total and momentum-transfer cross sections [6].

Our analysis shows that relatively small variations in the elastic scattering parameters can produce large changes in the predicted ⟨Zeff⟩ relaxation behaviour, especially in heavy noble gases where slow thermalization amplifies the influence of low-energy transport processes [6]. While conventional scattering measurements place useful constraints on the allowable cross sections, the observed annihilation dynamics provide an additional and often more stringent test of their accuracy. By comparing trends across the noble-gas sequence, we determine where annihilation measurements provide the strongest constraints on elastic scattering and discuss the implications for future theoretical and experimental studies.

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High statistics CDBS measurements and TC-DFT calculations on reference materials and Al alloys

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Coincidence Doppler Broadening Spectroscopy (CDBS) uses positrons to detect defects and chemical signatures. Due to the conservation of momentum during annihilation the electron's momentum is transferred to the annihilation radiation and results in a Doppler shift. In conventional DBS this can be used to detect defects with high sensitivity. However, by using the enhanced Coincidence mode of DBS, the signal to noise ratio of the annihilation line is improved, revealing chemical signatures. The annihilation line contains a projection of the electron momentum distribution. This also allows comparisons to theory calculations.
CDBS measurements were first conducted on reference materials and subsequently Two-Component Density Functional Theory (TC-DFT) calculations were performed with ABINIT [1,2]. Measurements on several reference metals and silicon were performed using the recently upgraded CDB Spectrometer at NEPOMUC. A shielded ^{22}Na source setup that contributes *no* source component was used to produce high quality reference data of the bulk electron momentum distribution. This is taken as a baseline and quality check for subsequent measurements and simulations of complex light weight high-strength alloys. Example ratio curves with pure reference samples in relation to aluminum are shown in Figure 1.

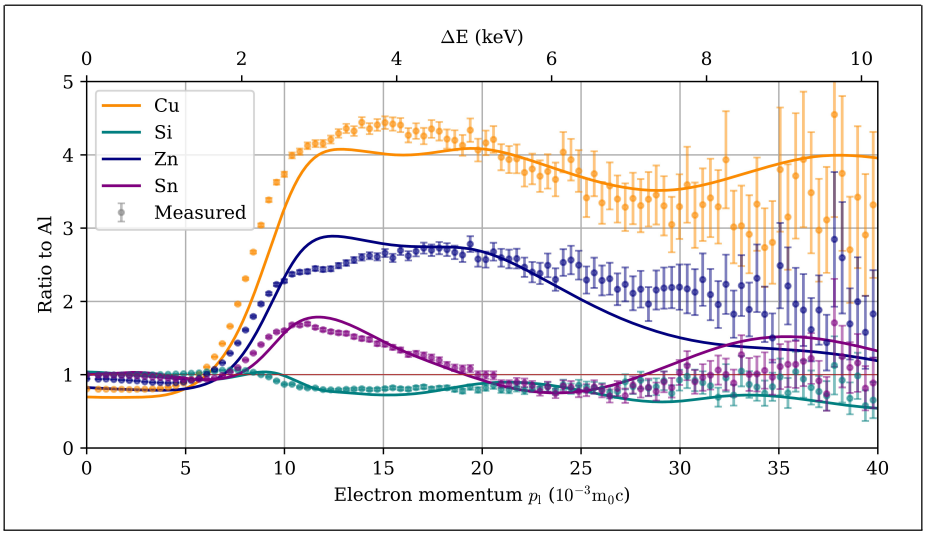


Figure 1: Ratio curves of several pure reference samples in relation to pure aluminum. The simulated data (solid line) shows good agreement with measurements.

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Doppler broadening spectroscopy study of nanostructured FeCr alloy powder produced by mechanical alloying

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Fe-Cr binary alloys are model materials suitable for the study of the processes governing radiation effects in ferritic/martensitic (F/M) steels, as they are important structural material candidates for several components of future nuclear reactors [1]. In this work, the synthesized FeCr nanostructured powders via a high-energy ball milling process are studied as-prepared by Doppler broadening spectroscopy (DBS) of the 511 keV positron annihilation line to estimate the type of defects in sample. The effect of the chromium (Cr) concentration on the structural, S and W parameters of $Fe_{100-x}Cr_x$ (x=2.5, 7.5, 12.5, 17.5, and 20 at.%) nanostructured powders were investigated. For the low Cr concentrations, the nanocrystalline FeCr powder exhibits a pronounced decrease in the S-parameter and a simultaneous increase in the W-parameter relative to the pure Si and commercial Fe powder reference, confirming annihilation in dense regions and near heavy atoms with high core electron momentum of dislocation loops in bcc metals [2]. Beyond 17.5 at.%, the structure shows increase in the S-parameter and decrease in the W-parameter confirming significant open-volume defect accumulation due to a mixture of bcc and fcc phases [3]. Furthermore, *W-S* plot of Doppler broadening spectra found that the (*W*, *S*) points distributed on two different defect species, which qualitatively suggested that the addition of Cr strongly affects the value of S and W parameters and created open volume defects.

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Irradiation induced rhenium segregation in W-Re alloys studied by coincidence Doppler broadening spectroscopy

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The plasma-facing components in a nuclear fusion reactor have to withstand irradiation by 14 MeV neutrons, which are released in the fusion of deuterium and tritium. Tungsten is considered to be the most suitable plasma-facing material, due to its high melting point, high thermal conductivity and low erosion under fusion reactor operating conditions. In addition to radiation damage, like void formation, neutron irradiation of tungsten induces nuclear transmutation reactions. This can result in the formation of further elements such as rhenium. It has been observed that under these conditions rhenium segregates around voids [1,2]. Positrons are likely trapped in such voids. Coincidence Doppler broadening spectroscopy (CDBS) is sensitive to the chemical signature at the annihilation site of the positron and can be used to measure the chemical surrounding of these voids.
We mimicked the radiation damage and the transmutation to rhenium from neutron irradiation. To do so, we irradiated tungsten samples with rhenium ions and tungsten-rhenium alloys with tungsten ions. CDBS measurements were performed on the irradiated samples. In addition, the 3D distribution of rhenium was investigated using Atom Probe Tomography.

Atom Probe Tomography measurements were conducted as part of the GIMRT Program hosted by the Institute for Materials Research, Tohoku University.

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Development of spin-polarized pulsed slow positron beam accumulator

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Positronium (Ps) is a promising system for realizing the first Bose–Einstein condensation including antimatter (Ps-BEC), which is expected to enable studies of matter–antimatter symmetry and applications in next-generation quantum technologies, such as ultra-short-wavelength gamma-ray lasers.

The critical condition for Ps-BEC requires a density exceeding 10^{18} cm^{-3} at a cooling temperature of 10 K. Only long-lived ortho-Ps can contribute to Ps-BEC, however, the lifetime of such high-density positronium generated from spin-unpolarized positrons and electrons is significantly reduced due to spin-exchange collisions and self-annihilations. Thus, most of the positronium (~ 95%) is lost within a few hundred picoseconds [1]. This loss could be suppressed by using spin-polarized positrons.

Spin-polarized positrons can be obtained from radioactive isotopes, however, it is difficult to directly generate the intense pulse required for Ps-BEC. To address this, we have developed a positron accumulator [2,3]. This apparatus accumulates a continuous spin-polarized positron beam for several hundred seconds and releases it as a single intense pulse. Positrons are trapped by electrostatic potential through energy loss caused by collisions with gas molecules. A compact ^{22}Na source (500 MBq, 2 mm diameter) has been newly developed. Positron beam experiments are currently in progress.

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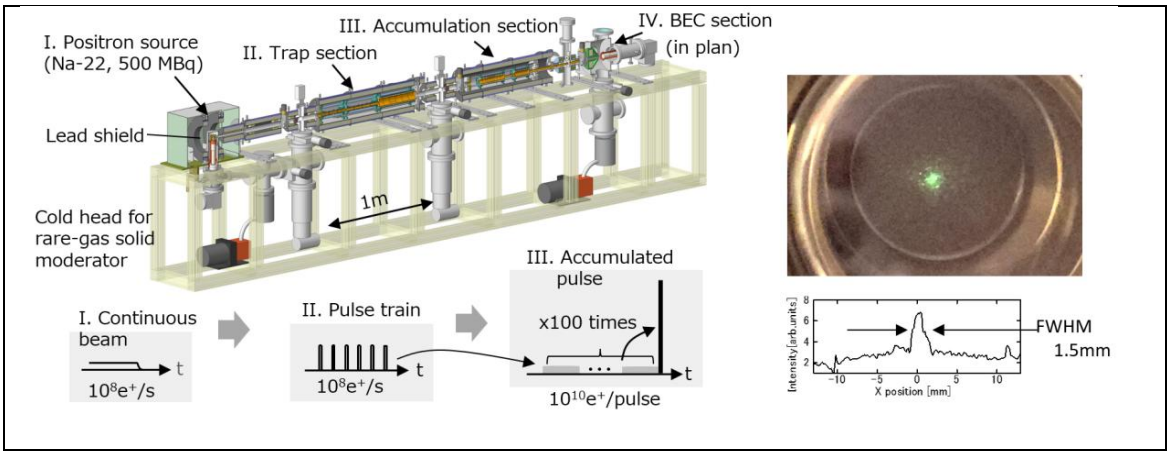


Figure 1: Schematic diagram of a high intensity positronium pulse generating apparatus. Right panel shows a typical positron beam image observed at the trap section.

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The role of vacancy type defects in room-temperature ferromagnetism of TiO_2 films

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Titanium dioxide (TiO_2) primarily exists in two polymorphic forms: rutile and anatase. Both forms have a tetragonal structure, but they differ in symmetry and cell volume. Anatase features a more open structure and has a lower density compared to rutile. Additionally, anatase is a metastable phase that irreversibly transforms into rutile at elevated temperatures. While TiO_2 is generally considered non-magnetic, undoped TiO_2 films can exhibit ferromagnetism at room temperature, which is often attributed to the presence of intrinsic point defects. However, there is ongoing debate regarding the specific nature of these defects.
In this study, we employed variable energy positron annihilation spectroscopy (VEPAS) to characterize open volume defects in rutile and anatase TiO_2 films that were deposited by magnetron sputtering (MS) and by pulsed laser deposition (PLD). We correlated the VEPAS defect studies with the magnetic properties of these films. Our findings revealed that both rutile and anatase TiO_2 films deposited using MS contain large clusters of vacancies, characterized by a positron lifetime of approximately 350 ps. The concentration of these vacancy clusters varies depending on the deposition temperature. Magnetic measurements indicated that films containing vacancy clusters are diamagnetic. In contrast, anatase TiO_2 films deposited using PLD contain Ti monovacancies and exhibit ferromagnetism. Therefore, our results suggest that ferromagnetism in TiO_2 requires the presence of monovacancies. Agglomeration of vacancies into clusters disrupts the ferromagnetic properties of TiO_2 films.

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Micrometer positron beam at the scanning positron microscope for defect analysis

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To investigate inhomogeneous 3D-defect distributions on the micro-meter scale, e.g. close to fatigue cracks or dispersive alloy, with positron annihilation lifetime spectroscopy a monochromatic pulsed positron beam of variable energy with a diameter in the range of 1 µm and a pulse width of 150 ps FWHM is needed.

To this aim the Scanning Positron Microscope (SPM) was developed and built at the Universität der Bundeswehr [1]. To overcome the limit of low count-rates and corresponding exceedingly long measurement times the SPM is transferred to the intense positron source NEPOMUC at the MLZ in Garching. To connect the SPM to NEPOMUC a special interface has been constructed.

A sophisticated beam preparation, including multiple remoderation steps, is needed to reach a lateral resolution in the micro-meter range. An essential component of the interface is the positron elevator which compensates for the energy loss caused by the remoderation process without altering other important beam properties like time structure and brightness [2]. This device allows also keeping both, the source and the sample, at the same electrical potential.

During the long reactor shut down at the MLZ the SPM has undergoes a complete overhaul. The installation of the SPM is now complete and it is ready for first test measurements. We will present technical details of the SPM interface, the positron elevator and the SPM.

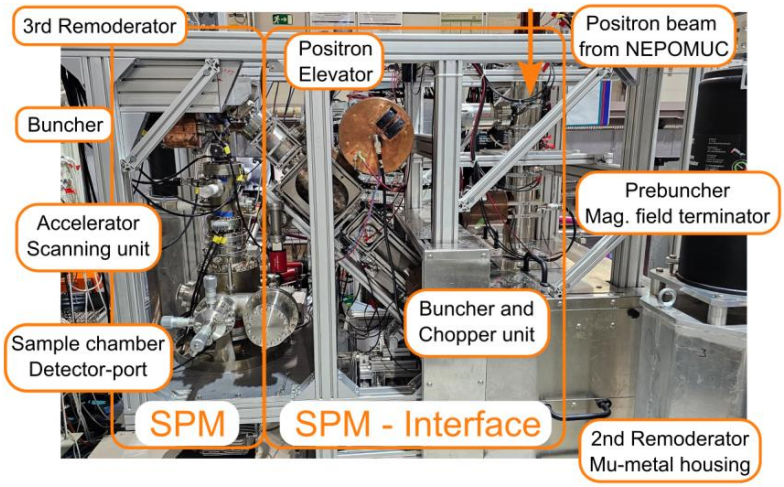


Figure 1: The newly installed SPM at NEPOMUC

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Forward emission of positronium from untreated polycrystalline Au films

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Low-energy positronium (Ps) production in vacuum using slow positron beams is an essential technique for precision tests of fundamental physics and searches for physics beyond the Standard Model. Examples include Ps spectroscopy [1,2], and antihydrogen formation via resonant charge exchange [3]. A reflection geometry has typically been employed in such experiments, in which slow positrons are implanted into a converter and Ps atoms are emitted into vacuum from the same side as the positron implantation surface. This configuration, however, requires positron beam transport through the experimental region and can impose severe geometrical constraints.

Ps production in a transmission geometry can remove these geometrical constraints by spatially separating the positron-beam transport system from the downstream experimental region. This separation facilitates the complex experimental arrangements required for precision Ps spectroscopy and antihydrogen experiments. Previous demonstrations have used single-crystal Ag films under ultra-high vacuum (UHV) [4] or chemically treated porous silica materials [5,6].

Here, we demonstrate Ps production in a transmission geometry using an untreated 100-nm-thick polycrystalline Au film. Under a high-vacuum condition of approximately 4×10^{-6} Pa, low-energy Ps emission via thermal desorption was observed by resistively heating the film to approximately 600 K. We also performed laser spectroscopy to measure Ps velocity distributions parallel and perpendicular to the Au-film surface. The experimental design and the resulting two-dimensional velocity profiles of the emitted Ps will be presented.

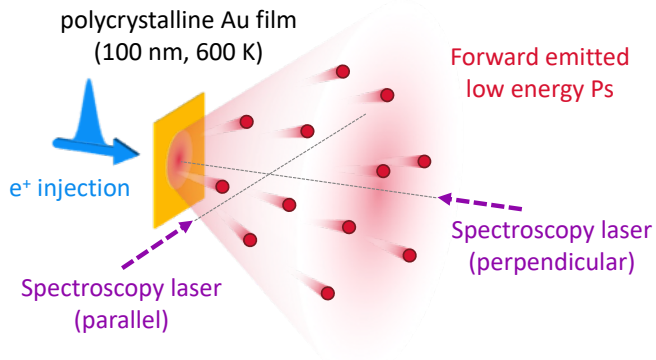


Figure 1: Transmission-geometry Ps production from an untreated polycrystalline Au film. Dashed arrows indicate the spectroscopy laser axes for measuring Ps velocity distributions.

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Positronium diffraction and future developments

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Positronium (Ps) is a particle with unique properties, which are an equal-mass two-body binding system and is electrically neutral. Scattering experiments using Ps beams to investigate the interactions between Ps and molecules have attracted considerable attention [1]. The Ps beams used in this experiment are produced by electron capture process in a gas cell where positron beams are injected. Those energies are less than several hundreds of eV. It has been discovered that Ps scattering has similarities to electron scattering.

In 2017, a high-quality energy-tunable Ps beam based on the photodetachment of Ps^- has been developed [2]. This Ps beam is produced in UHV environment and its energy is keV region, which has not been achieved before.

Recently, we have injected the energy-tunable Ps beam into graphene and measured Ps diffraction pattern for the first time [3]. This indicates that this Ps beam is coherent enough to observe quantum interference in Ps. It is expected to be applied on surface structure analysis using Ps diffraction [4] and gravity experiments using Ps [5]. From the viewpoint of scattering, the experiment shows that the diffraction efficiency for Ps is different from that for electron. This fact differs from the similarities as described above, although the energy region and the targets are different. Further investigation is needed.

We have also been carried out measurements of transmission efficiencies of Ps through graphene, which provide fundamental information on interactions between Ps and graphene [6,7]. To further advance this research, we are planning to investigate the detailed energy dependence of transmission efficiencies of Ps through graphene.

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Design and simulation of an optimized radiation shield for a 1.8 GBq Na-22 positron source

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Designing an efficient radiation shield for a 1.8 GBq Na-22 positron source used in a beamline for Positron Annihilation Lifetime Spectroscopy (PALS) is a core design challenge. A well-designed shield can limit weight and cost while fulfilling regulatory requirements, enabling flexible operation, and preserving upgrade potential.

Because the source-to-sample transmission efficiency in a PALS beamline is only about 10^-6, a high nominal source activity is required. During the β+ decay of Na-22, positrons are emitted together with a prompt 1274.5 keV gamma photon from the de-excitation of Ne-22*. Nearly all emitted positrons annihilate with electrons close to the source or in the moderator, producing pairs of approximately back-to-back 511 keV gamma photons with an isotropic angular distribution. Together, these two photon-production mechanisms lead to a simulated unshielded dose rate of several hundred µSv/h at a distance of 2 m, exceeding the regulatory limit of 3 µSv/h.

The proposed lead-dominated radiation shield uses overlapping modular lead blocks and is designed to achieve a target dose rate of 0.5 µSv/h at 2 m. This shield follows the three design principles of complete enclosure, compactness, and commonality of parts. Feedthroughs and openings required for operation are included and addressed by geometries designed to suppress direct photon streaming by requiring additional scattering events.

Finally, the performance is simulated with the TOol for PArticle Simulation (TOPAS), with GEANT4 as the underlying Monte Carlo engine. The simulated dose rate is scored on a spherical water phantom divided into 1° bins in phi and theta at a radius of 1.9 to 2.0 m from the source. In the simulation, the shielding attenuates the dose rates below the design target of 0.5 µSv/h at 2 m in all angular scoring bins.

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Geant4 simulation of modular J-PET detector response to antihydrogen annihilation products in the AEgIS experiment

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The **AEgIS** experiment at CERN aims to test the Weak Equivalence Principle (WEP) by measuring the gravitational acceleration of antihydrogen atoms using a moiré deflectometer [1-3]. Antihydrogen is produced via the charge-exchange reaction between cold antiprotons and positronium atoms excited to Rydberg states [1,4]. During transport through the setup, antihydrogen may annihilate on the deflectometer's silicon gratings or other internal surfaces. The annihilation of an antiproton at rest yields on average three charged pions [5], and the annihilation of a positron yields two back-to-back gamma photons. The reconstruction of annihilation vertices of resulting products allows the determination of the beam characteristics. Modular J-PET detection modules, each comprising 13 closely packed plastic scintillator strips with dimensions of 500 × 24 × 6 mm³ [6,7], are proposed for the vertex reconstruction. Four modules arranged in a dual-head configuration are placed around the expected particle trajectories emerging from annihilation events on the gratings. Although the modules are sensitive to both photons and charged pions, the present geometry is primarily optimized for vertex reconstruction using pions, which traverse plastic scintillators as minimum-ionising particles along approximately straight trajectories [8].

We present a Geant4 simulation study of the modular J-PET detector's response to annihilation products from a meV-scale antihydrogen beam. The initial antihydrogen beam is sampled from the Maxwell-Boltzmann velocity distribution and propagated through the deflectometer until annihilation. All particles resulting from the annihilation of the antiproton, from the positron annihilation photons and from subsequent interactions in the surrounding materials within the detector acceptance are then tracked within the detector. The energy deposited, hit multiplicity, interaction position, hit time together with other hit-characteristics are recorded for each strip of the scintillator material. In the presentation, the results of the simulation studies will be discussed.

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Pre-Bunching and Bunching System of the PsICO Pulsed Positron Beam

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A pulsed positron beam apparatus consisting of a 22Na source, a cryogenic solid noble-gas moderator [1], a Surko trap [2], and a buncher [3,4] has been designed and built at the Antimatter Laboratory (AML) [5] of the Department of Physics at the University of Trento. The beam, called PsICO (Positronium Inertial and Correlation Observations), has been designed [6] to implant bunches of up to 10^5 positrons per pulse, with repetition rates in the 1-10 Hz range, into a nanochannelled silicon target in a field-free region. This enables the production of a positronium cloud in both reflection [7] and transmission [8] geometries for fundamental studies [9]. In this contribution, we present the commissioning tests of the pre-bunching stage implemented in the Surko trap which allows the extraction of a positron bunch from a 700 G magnetic field with a time width of $\sigma < 5$ ns and of the main buncher which acts as a second bunching and variable elevator stage allowing to implant positrons in the positron-positronium converter up to 13 keV energy. The associated control and electronics system is also described.

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Performance Comparison of a DRS4 Evaluation-Board-based PALS Setup and the Integrated *Life Time Spec* Tabletop Spectrometer

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Over the last two decades, the development of fast digitizers has stimulated the transition from conventional analog positron annihilation lifetime spectroscopy (PALS) toward digital acquisition concepts. In particular, digital PALS enables software-based pulse timing, pulse-height selection and filtering of unwanted events prior to lifetime spectrum generation. However, conventional high-speed digitizer cards providing both sufficient sampling rate and vertical resolution remain technically demanding and therefore expensive. The PSI *DRS4* evaluation board, first introduced to PALS by Petriska et al. [1], provided a substantially more cost-effective alternative by combining high sampling speed (5 GHz) with high digitization depth (14 bit) at a tiny fraction of the cost of conventional high-end digitizer cards. Based on this concept, we developed the open-source Software *DDRS4PALS* allowing user-friendly pulse acquisition, filtering and offline reprocessing of lifetime spectra [2].
In the present work, we compare a digital PALS setup based on the *DRS4* evaluation board [3] with the newly developed commercial *Life Time Spec* system available from Aero-Laser GmbH. Both systems employ plastic scintillators but differ fundamentally in the implementation of event discrimination. In the DRS4-evaluation-board setup, the internal trigger and readout architecture are not optimized for the fast nanosecond detector pulses and coincident-event rates required in PALS. Therefore, coincident events had to be preselected by an external NIM-based branch consisting of constant-fraction discriminators and a coincidence unit which then provided the external trigger for the *DRS4* evaluation board [3]. *Life Time Spec* resolves this limitation by integrating the corresponding coincidence discrimination and trigger logic into the *DRS4*-chip-based acquisition board specifically developed for PALS. This removes the need for the external NIM trigger chain and turns the *DRS4* concept into a compact, method-specific digital PALS platform.
Both systems are evaluated using spectra acquired from in-situ 22-Na source configurations on selected high-purity metals (Al, Cu, Sn, …). The comparison focuses on spectral quality, analyzability, count rate performance and the practical robustness of the acquisition workflow. Particular emphasis is placed on the influence of software-defined filtering and post-acquisition optimization, since both approaches allow unwanted events to be rejected after pulse acquisition rather than fixing all discrimination conditions during measurement.
This comparison shows that both *DRS4*-based systems provide high-quality positron lifetime spectra suitable for reliable analysis. While the evaluation-board setup with *DDRS4PALS* represents a transparent open-source approach to digital PALS, the *Life Time Spec* offers a more integrated and user-friendly implementation. By reducing the need for external nuclear electronics, it lowers the technical entry barrier for routine PALS measurements in academic and industrial laboratories.

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Installation and tests of a laser system for excitation experiments of positronium

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A new laser system for PsICO (Positronium Interferometry and Correlation Observation) experiment has been developed at the Antimatter Laboratory (AML) of the University of Trento. The laser system is based on a pulsed nanoseconds laser with fundamental harmonic at 1064 nm. The aim of the laser system is to excite the positronium (Ps) atom from the ortho-Ps ground state 1^3S to the excited state 2^3S with well-controlled magnetic quantum number, using a two-step transition [1]. Initially, the Ps is excited from the 1^3S state to the 3^3P using a 205 nm laser beam [2, 3], then a subsequent stimulated relaxation of the Ps from the 3^3P to the 2^3S state using a 1312 nm laser beam is performed [1]. A laser beam at 1064 nm is also implemented for the photoionization of the Ps in the 3^3P state. The 205 nm and 1312 nm wavelengths are provided starting from the fundamental harmonic at 1064 nm and using non-linear crystals. In particular, the 205 nm production in a SFG (Sum Frequency Generator) crystal has been obtained in a collinear configuration. In this work, the properties of the laser beams produced will be presented and will be also compared to the required saturation fluences [1, 4] for the Ps spectroscopy.

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Defects in Novel Thermoelectric Complex Nitride Thin Films Prepared by Magnetron Sputtering

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Transition metal nitrides represent a versatile class of materials exhibiting attractive electronic, optical, and mechanical properties, making them promising candidates for thermoelectric devices based on the coupling processes between heat and charge transport via Seebeck, Peltier and Thomson effects. Their thermoelectric properties can be effectively tuned due to their ability to form solid solutions and accommodate dopants within their common crystalline structures, which simultaneously introduces various types of open-volume defects. Among these, we investigated n-type ScN- and HfN-based as well as p-type CrN-based thin films prepared by reactive DC magnetron sputtering on MgO(100) substrates. The systematic variation of deposition parameters, controlled doping and the fabrication of multilayered heterostructures, we enhanced their thermoelectric performance through modifications of their stoichiometry, microstructure, and defect structure. Since electrical conductivity, carrier concentration and mobility are significantly influenced by electron scattering on the crystal lattice defects, the defect studies are crucial for understanding the relationship between defect structure and resulting thermoelectric properties. Depth-resolved PAS revealed the presence of Sc and Hf vacancies, vacancy clusters and nanoscopic voids, which contribute to the enhancement of thermoelectric performance, while nitrogen vacancies promote p-type conductivity. These findings were further supported by ab initio DFT calculations and correlated with microstructural characterization performed by SEM, AFM, and XRD, as well as chemical composition analysis using EDX, WDS, and XPS. This combined approach enabled optimization of the deposition process and fabrication of thin films with improved thermoelectric performance.

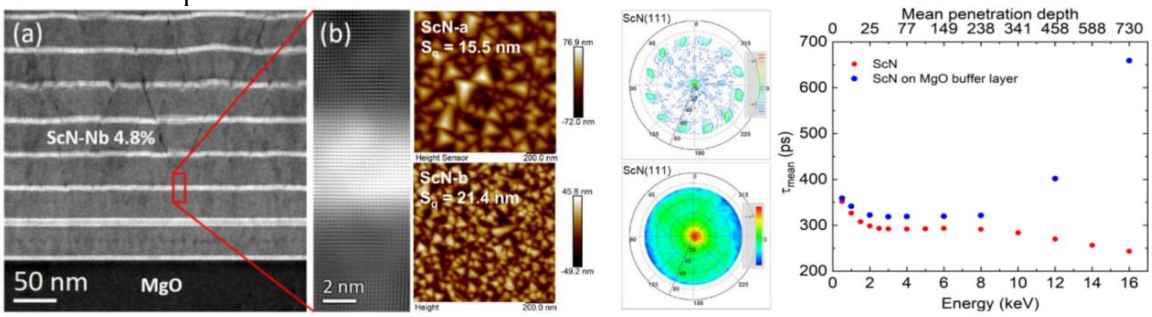


Figure 1: Leftmost figure: (a) STEM HAADF image of the Nb-doped ScN multilayered films prepared by magnetron sputtering (b) high-resolution image of the Nb-rich region [1]. Middle figure: AFM images and XRD pole figures of the ScN films deposited on MgO(100) substrate (upper one) and MgO buffer layer on FS substrate (bottom one). Rightmost graph: the mean positron lifetime of the ScN-a and ScN-b thin films as the function of incident positron energy.

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Various defects in AlGaN with varying Al content

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We recorded Doppler broadening of positron annihilation radiation [1] in AlGaN layers grown by metal-organic vapor phase epitaxy on AlN/sapphire as shown in Fig. 1. Two sets of samples with varied aluminum content in the range of 66-100% were grown at low V/III ratio of 200 at a reactor pressure of 50 mbar to be comparable with earlier studied samples. [2, 3, 4] In series A, we observe cation vacancies increasing in the range of 10^{16}–5×10^{18} cm^{-3} in line with increase in Al content, which appears to be the main factor lowering formation energy in these samples. The observed increase in $[V_{III}]$ correlates with the decrease in quantum efficiency in these samples. In series B, AlGaN layers exhibit defect free behavior with the cation vacancy concentration below 10^{16} cm^{-3} despite the Al% variation. In both series, 100% AlN samples contain around 3×10^{17} cm^{-3} of V_{Al}. Interestingly, our results indicate a non-random ordering of vacancies with respect to Ga in AlGaN and overall overrepresentation of Ga signal. We further study the effect of local Ga clustering on annihilation parameters with two component density functional theory calculations.

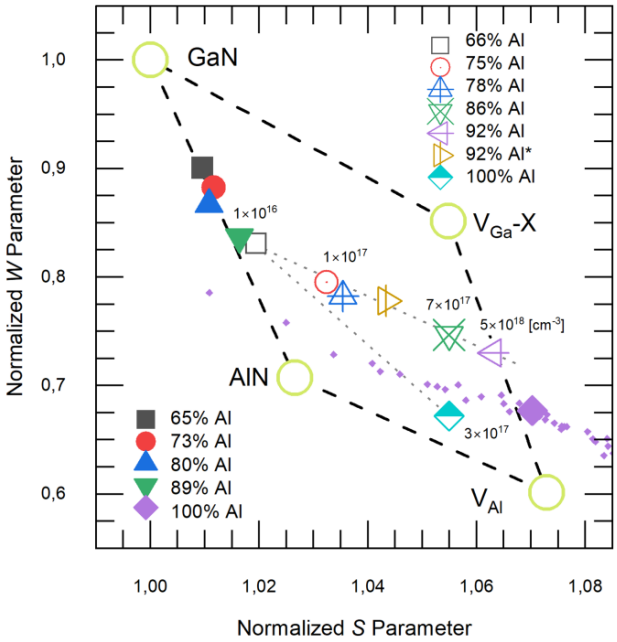


Figure 1: Relative (S,W) parameters measured in AlGaN layers with varying Al content. The light green circles mark the values for the GaN lattice, AlN lattice, V_{Al} in AlN and V_{Ga}-X in GaN. [4] The values given above the data markers show the evolution of the cation vacancy concentrations. Dashed lines are to guide the eye only.

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Dependence of the Ps^- yields emitted from Na-coated W on the electron work function of the surface

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When slow positrons are incident on tungsten (W), Ps^- ions are emitted from the surface [1]. Although the efficiency of this process is extremely low, at less than 0.01%, the emission efficiency increases dramatically when alkali metals are deposited onto the surface [2,3]. This phenomenon is being utilised in research into Ps^- ions [4-6], as well as in the generation of an energy-tunable Ps beam through acceleration and photodetachment of the ions and in its application studies [7-10].

The increase in Ps^- yields is thought to be due to the change of the electron work function of the surface. In this study, we measured the work function of a Na-coated W surface using the photoelectric effect and investigated the relationship between the work function and the Ps^- yields.

In order to observe the photoelectric effect, excitation light with 439 nm (2.82 eV) was irradiated onto a W target while Na was supplied. Photocurrent was measured by applying -110 V between the W target and a grounded mesh placed in front of the W surface. After stopping Na supply, we measured the photoelectron emission spectra by sweeping wavelength from 330 nm to 650 nm and determined the electron work function [11]. Subsequently, slow positrons with the energy of 100 eV were injected into the surface biased at a voltage -3kV through a grounded grid. The Doppler-shifted γ-rays emitted from Ps^- self-annihilation were measured with a Ge detector and the Ps^- yields were obtained [1-3].

Figure 1 shows the Ps^- yields plotted against the electron work function of the surface. The number of Ps^- increased drastically as the electron work function decreased.

In order to create the optimal surface for conducting Ps^- experiments, we plan to apply a Na -coating using the work function as a guide.

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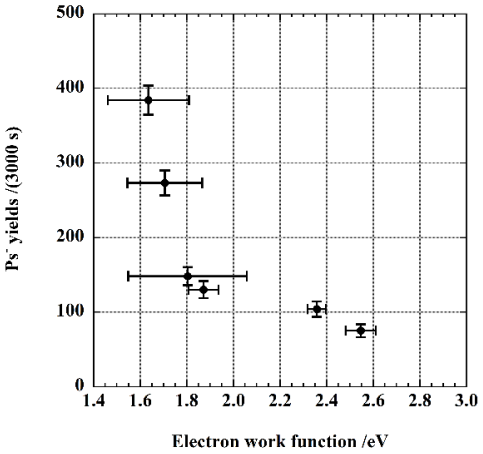


Figure 1. Ps^- yields plotted against the electron work function of the Na-coated W surface.

Positron annihilation spectroscopy characterization of monolayer graphene on 4H-SiC

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Monolayer (ML) epitaxial graphene with high thickness uniformity was synthesized by high-temperature thermal decomposition of Si and C-face 4H-SiC substrates (nominally on-axis) in argon atmosphere [1]. Due to the unintentional misorientation of the SiC substrate and a natural step bunching, epitaxial graphene on the SiC template has terrace-stepped morphology. According to reflectance mapping [2], the SiC surface is up to 97% covered by monolayer graphene. Bilayer patches are rarely observed. After initial characterization with Raman and Positron annihilation spectroscopy, a 2 nm and 18 nm thick Au layer was deposited on top of the graphene.

To study the defect evolution at the graphene interfaces, Doppler broadening spectroscopy with a monoenergetic positron beam was conducted on the samples. The main aim of this study was to determine if slow positrons can be utilized for defect characterization in such structures with overall thicknesses of the order of 10 nm and several interfaces for future projects. Initial results suggest that differences between sample and interface qualities can be quantified.

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Development of a Target Chamber for the pulsed high energy positron system (PHEPS)

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A new pulsed high-energy positron system (PHEPS) is currently under development at the University of the Bundeswehr Munich. The system will enable the characterization of atomic defects in bulk materials using beam energies of up to 1 MeV.
This work focuses on the development of a new target chamber for PHEPS. The chamber must meet several technical requirements, including beamline integration, sample manipulation, and vacuum compatibility. In addition, its geometry must be designed to reduce unwanted background signals and noise, for example those caused by positron backscattering, while ensuring suitable detection conditions.
For the preliminary dimensioning of the chamber, backscattering simulations are performed using Geant4. Based on these simulations and the defined technical requirements, a target chamber concept for PHEPS is developed.

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Development of an additively manufactured 1.3 GHz cavity for PLEPS

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A compact 1.3 GHz linear particle accelerator (linac) is currently under development to extend the range of applications of the pulsed low-energy positron system (PLEPS) located at the Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II). The linac is based on a side-coupled radio-frequency (RF) cavity (SCC) geometry to reduce footprint and power consumption. However, conventional fabrication of SCCs faces significant thermal and mechanical limitations which influence the linac's performance. Laser Powder Bed Fusion (L-PBF) has already demonstrated the ability to produce monolithic pure copper cavities, enabling a complex integrated cooling system and reducing manufacturing time and costs. We aim to transfer this potential to the required 1.3 GHz SCC, making this the first fully additively manufactured SCC developed for a real experimental application. This work presents the first fundamental design of the required SCC geometry. The electromagnetic field distribution, thermal management, and mechanical properties were optimized using simulation tools such as CST Studio. Beam dynamics studies conducted using TraceWin code demonstrate capabilities of the proposed linac concept.

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The pulsed positron laboratory Munich

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The *A P*ositron *E*lectron e*X*periment (*APEX*) Collaboration aims to create and study quasi-neutral, low-temperature, matter-antimatter pair plasmas, using positrons and electrons [1]. For this aim, we built an array of non-neutral plasma (NNP) traps for the generation of bright positron pulses [2]. These pulses will be mixed with electrons in our neutral-plasma traps: a levitated dipole trap (LD) [3], which is complete and being used for studies of pure-electron plasmas, and an optimized tabletop stellarator (EPOS) [4]. For the diagnosis of the positron-electron plasmas, a dedicated system of up to 48 gamma-ray detectors will enable fast, spatially resolved annihilation measurements [5].

In 2026, the NNP and the LD traps will finally be integrated into the positron beamline at the Research Neutron Source Heinz Maier-Leibnitz (FRM2). The NEutron-induced POsitron source MUniCh (NEPOMUC) at FRM2 is the brightest cold positron source worldwide, delivering a moderated beam of 5×10^7 positrons per second [6]. With this positron source and our NNP traps we expect to create well-defined pulses of $\sim 10^8$ positrons every 30s.

We will present the details of the new positron laboratory, its mode of operation, expected capabilities and preliminary experiments with electrons. In addition to our NNP traps and the LD, it is designed to allow for the introduction of additional future components, e.g., a high-field trap as a second accumulation stage or other experiments. APEX's pulsed positron laboratory is planned as a versatile platform for positron-based experiments. With its diagnostic capabilities and source of well-defined positron pulses it presents a novel opportunity for the development of plasma diagnostics using positrons - in addition to the study of fundamental plasma phenomena in pair plasmas.

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UV illumination induced positron trapping in β-Ga_2O_3

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The stable beta phase of gallium oxide (β-Ga_2O_3) is a focus of international research interest due to its potential for the development of lower loss high-power electronics, capable of enhancing the efficiency of electrical energy distribution, and for deep ultraviolet optoelectronic devices. The monoclinic structure results in two inequivalent Ga sties and three O sites, this contributes to a quite complex defect physics and chemistry. Theoretical and experimental evidence has been presented that the high symmetry isolated Ga vacancies are metastable and that lower energy configurations result when an adjacent Ga relaxes to an interstitial site intermediate between the two original Ga sites forming what is commonly termed a split Ga vacancy [1]. The positron state lifetimes for the possible split Ga vacancy configurations result in positron state lifetimes that are approximately 10 to 20 ps lower that then high symmetry isolated vacancy [1]. Gallium vacancy related defects are normal present at high concentrations. In addition, previous studies have observed a longer lifetime component attributed to vacancy cluster defects [2].

Here we report variable energy positron annihilation lifetime measurements on β-Ga_2O_3 substrates, MOCVD films and an HVPE layer. The results are consistent with the presence of a range of Ga vacancy defects giving lifetimes in the region of ~170 – 195 ps and clearly observe multi-vacancy clusters resulting in lifetimes in the range ~360 – 380 ps. Measurements at ~20 K observe an increase in the mean lifetime by up to ~60 ps compared to 300 K, see Figure 1. Illuminating samples cooled to ~20 K in the dark with 240 nm radiation results in a reduction in the mean lifetime by up to ~40 ps. These results are discussed in terms of the possible changes in positron trapping to the observed vacancy-related defects.

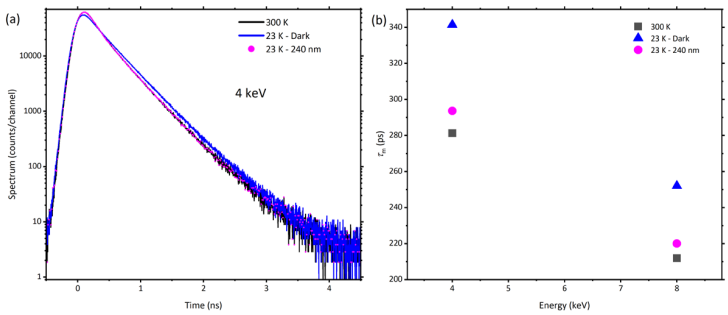


Figure 1 HVPE β-Ga_2O_3 (a) 4 keV PALS spectra (b) mean lifetimes. Showing 300 K (black), 23 K dark (blue) and 23 K 240 nm illuminated (magenta) results.

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Study of positronium lifetime in microcavities connected to a network of nanochannels

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The collection of a large amount of positronium in microcavities connected to a network of nanochannels produced in (100)-crystalline p-type silicon by combination of Ultrafast Laser Direct Writing [1], Inductively Coupled Plasma - Reactive Ion Etching [2], and Electrochemical Etching [3] has been recently observed [4].
PALS (Positron annihilation Lifetime Spectroscopy) measurements were performed at the ELBE facility at the Helmholtz-Zentrum Dresden-Rossendrof.
In this work, the lifetime analysis of positronium atoms confined in the nanostructures, at different implantation energies and temperature of the target, is presented. The emission of positronium into the vacuum was prevented by deposition on the surface of a 20 nm-thick layer of SiO_2. The deposition was performed via non-reactive RF-sputtering [5].
Positron Annihilation Lifetime Spectroscopy measurements, analyzed with PALSfit3 software, reveal the presence of a positronium lifetime component of ~50 ns independent from the dimension of the open volumes in which positronium is trapped, as observed in Ref.[6]. The evolution of this positronium lifetime component is studied and discussed between 20 K and 300 K. In addition, the effect of 515 nm wavelength laser light on such a positronium lifetime is investigated.

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Performance of the Newly Developed *LifeTimeSpec* for Multi-Component Spectra Analysis in Positron Lifetime Spectroscopy (PALS)

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We have been testing the reliability of multi-component decompositions with our recently developed *LifeTimeSpec*. This fully digitized, portable, and compact positron lifetime spectrometer is designed for high quality non-destructive testing (NDT) of materials. By a clever combination of inhouse developed trigger electronics for the DRS4-chip and cutting-edge Hamamatsu metal package photomultiplier tubes R11265U combined with uniquely shaped plastic scintillation crystals (BC-422: cubes with rounded edges), we obtain the following unique features: a minimised time spread of the created photons, an instrumental resolution function being a single Gaussian with a width of 135ps (FWHM). This is a significant improvement over current PALS spectrometers.
The first prototype has been presented recently at the ANALYTICA fair in Munich [1]. Short measurement times are essential for NDT applications. Therefore, we aligned the detectors in-line for a high efficiency (optimal solid angle), while the occurrence of, thus, unavoidable corrupted coincidences [2] is mitigated by employing a 3.5mm tungsten shield for the START detector. This shield offers a significant attenuation of unwanted 511keV gammas in the START channel. As shown recently, this enables high quality data analysis employing the trapping model [2]. We report measurements on both polymers (natural rubber), sandwiched foils, and deformed metals using DDRS4PALS for data acquisition [3]. We finally analyse the data by the common Levenberg-Marquart algorithm implemented in DQuickLTFit [4].

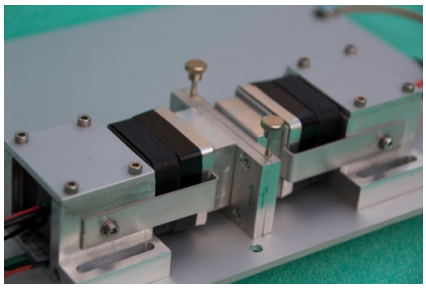


Figure 1: The compact design of the *LifeTimeSpec* (20cm x 6cm x 5cm – length x width x height) with the sample holder in between the detectors.

The results show the potential of the new spectrometer setup, which could as well be used in slow positron beamlines to improve the resolution function (shape and width) for better data analysis.

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Investigation of positronium formation in solids at the low-energy threshold

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Positronium (Ps), the bound state of an electron and a positron, serves as a unique probe for material analysis and is the subject of ongoing fundamental research. We have used the Setup for Low-Energy Positron Experiments (SLOPE) [1] at TUM to investigate the dependence of Ps formation on a material's surface when bombarded with a monoenergetic positron beam implantation energy in the regime below 33 eV, where it is known to vary strongly with positron energy [2]. The estimated relative Ps yield as a function of the positron implantation energy is shown for a selection of insulating materials in Figure **1**.

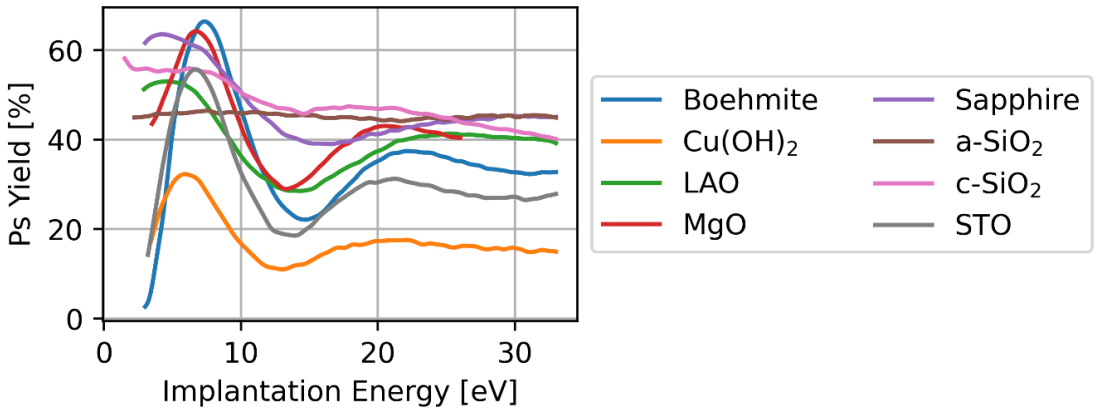


Figure 1 Relative Positronium yield as a function of the positron implantation energy for different insulating materials. The intrinsic features in the data are a result of the Ore process for Ps formation [4].

A Monte-Carlo model has been developed in the 1980s [3, 4] that successfully explains the features in the data in the framework of the Ore model for Ps formation. However, this model has, to our knowledge, only been tested quantitatively on ice. We have investigated a variety of other solids to better understand the dependence of Ps formation on material properties. Fitting the model to experimental data enables us to estimate quantities such as the positron and Ps affinities. Furthermore, we find that, in contrast to crystalline matter, many amorphous solids appear to lack the specific energy-dependent Ps formation mechanism, a fact already realized in the experiments on ice [2, 3].

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Measurement of the correlation between the radial and axial velocity components of positronium by time-resolved Doppler spectroscopy

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In precision spectroscopy of the positronium (Ps) 1S–2S transition, the transition frequency is determined by fitting the measured spectrum with a Monte Carlo-simulated [1] or quasi-analytically-constructed [2] line shape that incorporates the spatial diffusion of Ps. Therefore, precise knowledge of the three-dimensional velocity distribution of Ps atoms emitted from the converter is essential. Although the in-plane velocity components of Ps emitted from silica aerogel, a promising converter material for our spectroscopy experiment, are known to follow a thermal distribution, the velocity distribution normal to the surface deviates significantly from a thermal one [3]. Consequently, whether correlations exist between the in-plane and surface-normal velocity components remains an open question. To address this issue, we propose a laser-based method for measuring the velocity correlation between these two directions.

As illustrated in Fig. 1, a pulsed positron beam and a large-diameter excitation (243 nm) and photoionization (532 nm) laser pulses are incident coaxially and normal to the silica aerogel surface. The photoionized positrons are detected using a microchannel plate (MCP). By scanning the delay between the positron pulse and the laser pulses, the temporal evolution of the ionization signal reflects the in-plane velocity distribution of Ps. Furthermore, scanning the excitation laser frequency enables velocity-selective excitation along the surface-normal (z) direction. Combining these measurements allows the in-plane velocity distribution to be determined for a selected z-velocity class.

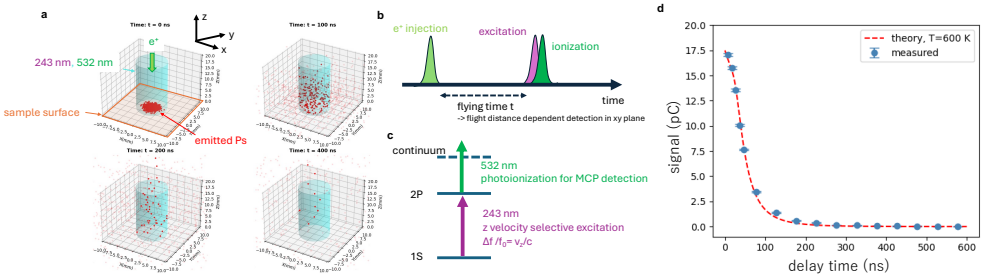


Fig 1: (a) Schematic illustration of the time-resolved Doppler spectroscopy (b) Experimental timing sequence (c) Level diagram for the excitation scheme (d) Delay-time dependence of the photoionization signal. The dashed curve shows the analytical 600 K Maxwell–Boltzmann model.

In this presentation, we report measurements of the delay-time dependence of the ionization signal for the zero-velocity component along the z direction, obtained using a 9-mm-diameter 1S–2P excitation laser and the pulsed slow-positron beam at KEK (Fig. 1(d)). The in-plane velocity distribution of z-velocity-selectively-excited Ps that is reconstructed from these measurements will be discussed.

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Surface Spectrometer for Structure and Element Analysis with Topmost Layer Selectivity Using Positron Beams

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At the neutron induced positron source Munich (NEPOMUC) at the MLZ, two analytical setups are being combined into a single system to enable positron surface studies with top-most layer sensitivity. The positron annihilation induced Auger-electron spectroscopy (PAES) instrument is being merged with the total reflection high-energy positron diffraction (TRHEPD) setup. The combination of those two positron techniques will enable highly surface sensitive elemental and structural analysis of the same sample under ultra-high vacuum (UHV) conditions. The PAES technique uses focused low-energy positrons that induce Auger-electron emission due to annihilation processes from the surface state. The corresponding Auger spectrum – without secondary electron background – provides elemental information on the top-most atomic layers and enables conclusions on fundamental as well as application-based research questions in surface science. As a highlight, atomic surface segregation was observed in situ with topmost layer sensitivity [1]. The TRHEPD technique [2] utilizes positron total reflection to enable surface sensitive diffraction [3]. Due to the high surface sensitivity, this technique allows for the study of surface reconstruction of the topmost atomic layers. With the combination of PAES and THREPD chemical as well as structural surface analysis will be possible on the same sample without exposing them to atmospheres.

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Testing the Newly Developed *LifeTimeSpec*'s Performance with Commonly used Analysis Software for Positron Lifetime Spectroscopy (PALS)

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A prototype of the newly developed *LifeTimeSpec* was officially introduced in Spring 2026 at the Analytica Munich fair [1]. This fully digitized, portable, and compact positron lifetime spectrometer is designed for non-destructive testing. Notably, its lifetime resolution has been enhanced to 135ps FWHM being a single Gaussian, a significant improvement over other PALS spectrometers, which typically report resolutions no better than 170 ps [2]. Our improvements are driven by a clever combination of newly developed trigger electronics for the DRS4-chip and cutting-edge Hamamatsu metal package photomultipliers R11265U combined with uniquely shaped plastic scintillation crystals (BC422 cubes with rounded edges) minimizing the time spread of the created photons. Although, for a high counting efficiency (optimal solid angle) the detectors are aligned in-line, the occurrence of, thus, unavoidable corrupted coincidences is mitigated by inserting a 3.5mm tungsten shield for the START detector (comparable to 4-5 mm of lead, without its associated drawbacks). This shield offers a significant attenuation of unwanted 511keV gammas in the START channel. To assess the performance of the spectrometer, we conducted measurements of diverse materials including metals, semiconductors, polymers and porous specimens using DDRS4PALS [6]. We analyzed the data sets by widely recognized positron lifetime software programs: PALSFIT [3], Kansy's LT 9.2 [4], and DQuickLTFit [5]. A new user-friendly software, being under development, should ensure superior performance relative to other software alternatives.

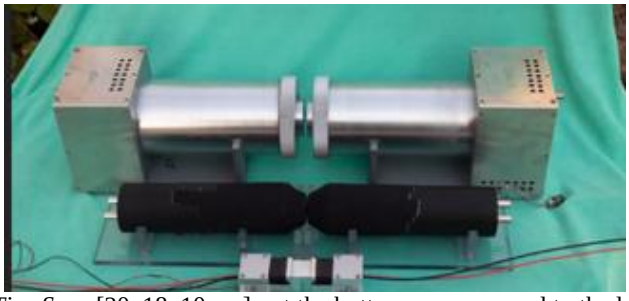


Figure 1: The *LifeTimeSpec* [20x18x10 cm] - at the bottom, as compared to the legacy spectrometers

The results of a double-blind comparative analysis of positron lifetime data across all three software programs will be presented and discussed in this contribution.

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Numerical dosimetry of low-energy positron beams for non-destructive spectroscopy of living biological samples

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Positron annihilation spectroscopy (PAS) probes the nanoscale free volume and electronic environment of matter via positronium formation and decay. Applying PAS to living tissues and cells, from bulk drop-cast sources to intravital measurements, requires moderated, monoenergetic beams for depth-resolved analysis, yet the delivered dose remains unquantified [1,2]. We herein present a preliminary numerical framework coupling positron transport to a radiobiological model to estimate cellular viability during PAS. Using the Berger–Seltzer formulation, we computed the mass collision stopping power and dose rate for a liver endothelial cell. Cell survival is assessed with an extended Linear–Quadratic model incorporating sub-lethal damage repair and ultra-high-dose-rate sparing as a function of the irradiation time. We compared continuous, pulsed, and trap-based bunched delivery regimes (5–100 keV). Our preliminary results highlighted that cellular viability is primally governed by the time-averaged flux delivered to the cells. Because the lowest implantation energies, also give the highest stopping powers, fine axial resolution and a low damage rate are physically anti-correlated. Considering a 50 mCi ^{22}Na source, both the continuous and the pulsed beam cross the 90% survival fraction within seconds in the 5–20 keV range (Figure1 a-c). The bunched regime activates oxygen-depletion sparing and partial repair across ~100 s inter-bunch interval, roughly doubling the effective survival [3, 4].

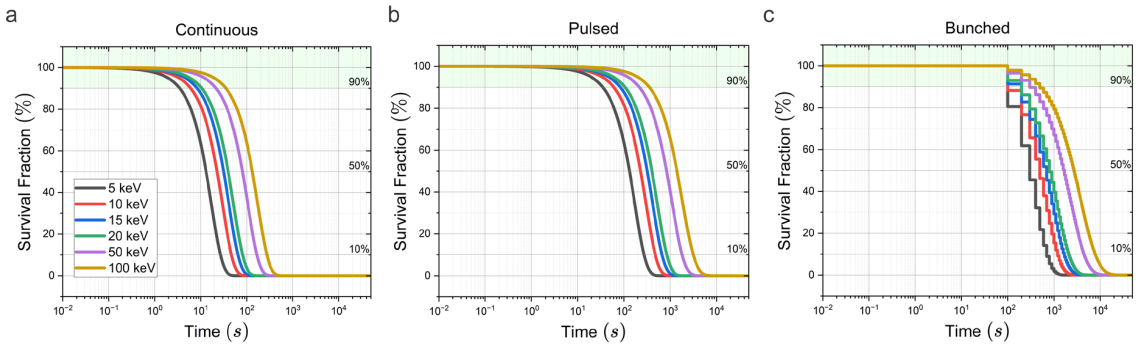


Figure 1: Survival fraction as a function of irradiation time for the continuous (left), pulsed (centre), and bunched(right) beam configurations.

In conclusion, intravital PAS of cells emerges as an instrumental challenge for slow-positron systems as to obtain complete lifetime spectra before compromising biological viability.

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Towards direct detection of halide vacancy defects and photo-ionic effects in halide perovskites by positron annihilation spectroscopy: a proposal

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Photo-ionic effect refers to the ionic response (e.g. ionic defects formation or enhanced ionic defects transport) upon above–bandgap photo excitation. This effect has been firstly discovered in $MAPbI_3$ (architype material of halide perovskites), showing an enhancement of apparent ionic conductivity upon illumination, possibly related with an increase in iodide defect concentration and enhanced iodine transport.[1] Later work focusing on the discrepancies in defect formation pathways and light effects between iodide and bromide perovskites,[2, 3] pointing to an ionic contribution to the driving force for photo de-mixing(reversible phase separation upon photo excitation in mixed bromide - iodide perovskites). Fundamentally, photo de-mixing involves significant ion transport, is a direct result and evidence of photo induced ionic effect.[4-7]A recent defect chemical model of mixed conductors under optical bias predicts that illumination directly modifies the concentration of ionic defects through their coupling to photo-generated electrons and holes via the halogen chemical potential and electroneutrality, implying that halide vacancy populations can be enhanced (or even reduced) by light.[8, 9] Direct, defect-specific experimental evidence for these predictions is still missing. Besides halide perovskites, recently there are also recent activities on the photo–ionic effects in oxides materials.[10] Clarifying the underlying defect chemical mechanisms involved in the photo-ionic effects in these materials are essential to not only providing guidelines to optoelectronic devices but also further utilize such effects in novel devices for energy and information conversion and storage.

Here in this contribution, I would also like to cover both my research activities relevant to photo–ionic effects and invites discussions and collaborations on these topics. Specifically, I propose two sets of samples, including 2D Dion–Jacobson iodide and bromide perovskites and vertical aligned metal oxides composite thin films, toward a depth-resolved positron study in the pristine state and after controlled illumination. Variable-energy positron lifetime spectroscopy and Complementary (coincidence) Doppler broadening spectroscopy targets identification of the vacancy species, their depth distribution and local halide redistribution.[11-13]

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Defects in GaN grown under different growth conditions

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We present a slow positron beam study of defects in GaN samples prepared under various growth conditions. This work aims to study how growth stoichiometry, substrate polarity, substrate growth methods including ammonothermal and halide vapor phase epitaxy (HVPE), and layer thickness influence the depth-dependent positron annihilation parameters in GaN, and thereby gain insight into defect formation under different growth conditions.
Figure 1 shows preliminary results, comparing the defect behavior of 2-µm GaN samples. For the Ga-ammono samples, the N-rich growth condition leads to saturated positron trapping with vacancy concentration above 5×10^{18} cm^{-3}, whereas the Ga-rich condition gives an estimated vacancy concentration of 1.6×10^{17} cm^{-3}. Similar trend is observed in Ga-HVPE samples under N- and Ga-rich conditions respectively. Annihilation parameters in N-ammono samples suggest the presence of defects around the level of 2×10^{18} cm^{-3}. Interestingly, the positron data in the N-HVPE samples suggests a spatially-dependent distribution of vacancy-type defects under N- and Ga-rich conditions. Preliminary results indicate strong effects of growth parameters on formation of point defects in studied GaN samples.

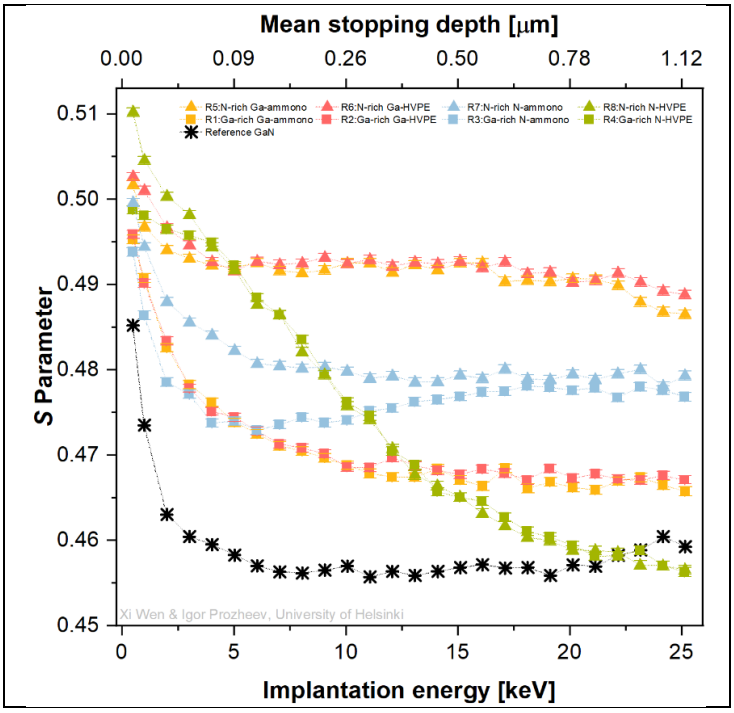


Figure 1: Measured *S* parameter as a function of positron implantation energy in different GaN samples.

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Additive manufacturing of an optimized 1.3 GHz single-cell cavity for high-gradient tests

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A compact continuous-wave (CW) 1.3 GHz linear accelerator (linac) is currently under development as the core component of a pulsed positron annihilation lifetime spectroscopy (PALS) setup. Conventional manufacturing restricts the thermomechanical management required for the CW operation of radio-frequency (RF) cavities. The ability to integrate conformal cooling channels motivates the utilization of pure copper-based laser powder bed fusion (PBF-LB/Cu), enabling monolithic cavity fabrication. However, while fully PBF-LB/Cu-fabricated RF structures have shown promising low-power performance, evaluating their behavior under high-power operation (high-gradient) remains largely unexplored. We aim to investigate the high-gradient performance of the planned linac using 1.3 GHz single-cell cavities. High-power tests will be performed using the Mainz Energy-Recovering Superconducting Accelerator (MESA) RF system at the Johannes Gutenberg University Mainz (JGU). We present the additively manufactured 1.3 GHz single-cell cavity geometry designed for the planned high-gradient tests. Specialized numerical simulation tools, such as CST Studio Suite, were utilized for cavity optimization and the evaluation of its RF, thermal, and mechanical characteristics. Furthermore, to monitor RF breakdown and cavity behavior under high power, a comprehensive detection and analysis framework will be implemented.

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Applications of electron-positron correlation-polarization potential method to molecular systems

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Positron interactions with finite-size systems, such as molecules and clusters, have been extensively studied with particular focus on their chemical and biomedical significance [1-3]. To address these related issues, we have utilized a density functional theory (DFT)-based approach combined with the electron-positron correlation-polarization potential (CPP) [4]. The method is constructed in the generalized-gradient approximation (GGA) framework, combining with the asymptotically polarization potential.

Based on these calculations, we developed a GGA correction model through benchmark calculations for experimentally measured positron affinities, and applied it to several case studies, including hydrocarbon-based molecules, biomolecules, and water-based systems, with their conformations [5]. As an example, the size-dependence of the positron affinities for cage structures of water clusters, together with positronic wavefucntions of the excited states obtained by the calculations, are shown in Figure 1.

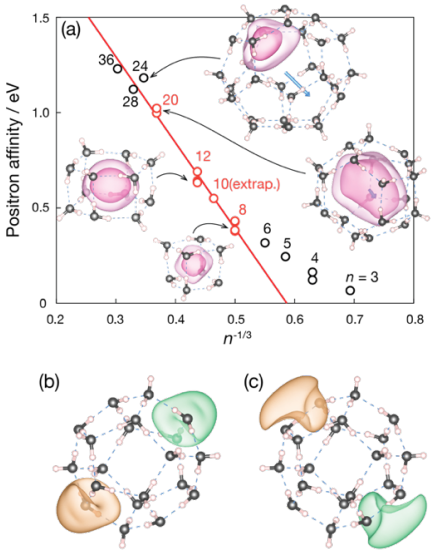


Figure 1. (a) Dependence of the calculated positron binding energy on the cluster size (n) for water clusters $(H2O)_n$; (b) and (c) positronic excited states for n = 20.

Furthermore, recently, we have constructed a method combined with the position-dependent dielectric DFT, to modify the long-range interaction described using the atomic-decomposed polarizability influenced by atomic rearrangements [6]. This approach improved the dependence of the positron affinities on the molecular size and conformational structure in chain alkanes, cycloalkanes, and aromatic molecules. These results and their implications will be presented and discussed.

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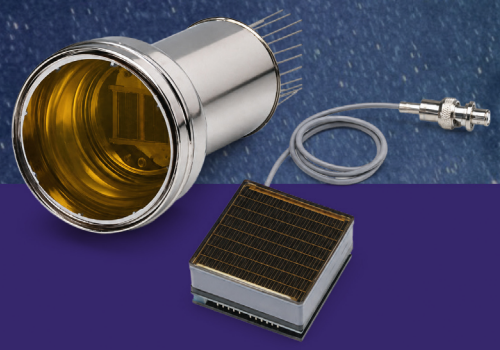
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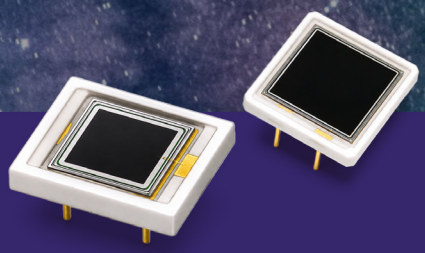
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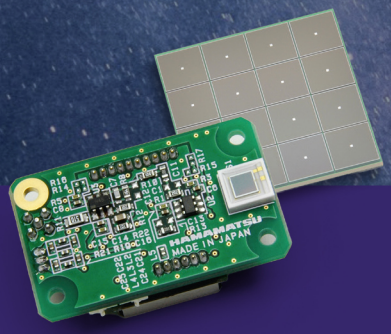
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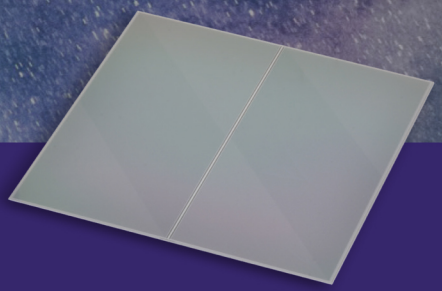
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