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The status of the positron beam facility at NEPOMUC

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Abstract. The NEutron induced POsitron source MUniCh NEPOMUC provides a high intensity positron beam with $9 \cdot 10^8$ moderated positrons per second with a primary beam energy of 1 keV. After remoderation, the positron beam is magnetically guided to five experimental setups: a coincident Doppler-broadening spectrometer (CDBS), a positron annihilation induced Auger-electron spectrometer (PAES), a pulsed low-energy positron system (PLEPS) as well as an interface for providing a pulsed beam with further improved brightness. An apparatus for the production of the negatively charged positronium ion Ps^- is currently in operation at the open multi-purpose beam port, where additional experiments can be realized. Within this contribution, an overview of the positron beam facility NEPOMUC with its instrumentation at the research reactor FRM II is given.

1. Introduction

At nuclear reactors, the absorption of high energy γ radiation can be used to generate positrons by pair production. Besides the γ radiation released during the fission process, one can profit from γ cascades emitted by the de-excitation of excited nuclear states after capture of thermal neutrons. At the research reactor in Delft, the γ radiation from nuclear fission is absorbed in an assembly of thin tungsten tubes for the electron-positron pair production [1]. At NEPOMUC, the positrons are generated by pair production from absorption of high-energy prompt γ-rays after thermal neutron capture in ^{113}Cd (see e.g. [2]). For mounting such an in-pile positron source close to the fuel element of a reactor, several aspects have to be taken into account, e.g. fast and thermal neutron flux, burn-up of the absorbing isotope ^{113}Cd, neutron flux depression, and γ heating. Based on the principle of the NEPOMUC source, two further positron sources have been designed at research reactors. The first one with a large positron emitting area of 900 cm^2 delivered recently about $5 \cdot 10^8$ positrons per second at the PULSTAR reactor, USA [3]. Another new project has been funded in order to install a reactor based positron source in Hamilton, Canada [4].

From the beginning in 1998, NEPOMUC was planned and built as a user-dedicated facility at the *Forschungs-Neutronenquelle Heinz Maier-Leibnitz* FRM II. The reactor is in operation for typically 240-260 days per year according to at least four fuel elements with the commissioned lifetime of 60 days each. Hence, the positron beam facility including several spectrometers is available and open for all external scientists which propose experiments with the need of a high-intensity low-energy positron beam. Besides the experiments at the multi-purpose open beam port and first high-resolution Auger studies at PAES a large variety of positron experiments have

been carried out at PLEPS and CDBS. Up to now, among more than 130 submitted external proposals 95 experiments have been accepted and carried out at NEPOMUC.

2. The High Intensity Positron Beam at NEPOMUC

2.1. In-Pile Positron Source

In summer of 2004 the first setup of NEPOMUC delivered positrons with an intensity of up to $5 \cdot 10^8$ moderated positrons per second at a beam energy of 1 keV. In 2008, a new in-pile γ converter and Pt moderator was installed inside the NEPOMUC beam tube. This change lead to the unprecedented intensity of about 10^9 moderated positrons per second at a beam energy of 1 keV. For details of NEPOMUC, see [5] and references therein.

The positron source is mounted as an in-pile component of the inclined beamtube SR 11 inside the moderator tank of the reactor. An important advantage of the position of the source at FRM II is the high flux ratio of thermal to fast neutron of better than 10^4 which leads to a relatively small amount of irradiation induced defects compared to the previous source at the former reactor FRM where this ratio was close to unity.

A cadmium cap (natural abundance of ^{113}Cd: 12.2%) inside the tip of the beam tube absorbs thermal neutrons very efficiently, and hence, the binding energy of 9.05 MeV of the additional neutron in ^{114}Cd is released as γ cascade. The lifetime of the source setup is limited by the burn-up of the ^{113}Cd and amounts to 1250 days of reactor operation at the nominal power of 20 MW with the presently used thickness of 3 mm cadmium. For this reason, the beamtube SR11 with the in-pile positron source will be replaced by a new one in November 2010 The lifetime of the new positron source is extended to 25 years by using Cd enriched with 80% ^{113}Cd.

A structure of Pt foils is used for the conversion of the high-energy γ radiation into positron-electron pairs and for positron moderation. The energy of the primary positron beam is set to 1 keV. Its band width, i.e. the positron energy distribution, is given by the spectrum of the moderated positrons at the Pt surface with a width of about ΔE=1 eV and the potential differences of the Pt foils of typically 3 V. Consequently, the maximum width of the energy spectrum of the primary positron beam is assumed to be not higher than ΔE$\approx$4 eV.

2.2. Positron Beam Facility

The moderated positron beam is magnetically through three bends in the biological shield in order to eliminate background of fast neutrons as well as γ radiation from the reactor core and the cadmium cap in the tip of the beam tube. The beam line leads from the biological shield of the reactor pool via a remoderation unit to the experimental platform in the experimental hall of the FRM II. The energy of the remoderated beam can be adjusted between 20 and 200 eV and is presently set to 20 eV for most experiments. The total efficiency of the setup is about 5%, and the beam diameter of the remoderated beam is less than 2 mm (FWHM) in a 6 mT guiding field [6]. The beam switch on the experimental platform can be turned to five different outgoing ports. At several experiments such as CDBS and PAES, a purely electrostatic beam guidance is required. For this purpose, magnetic field terminations of μ-metal are mounted at the entrances of those devices as well as at the remoderator unit in order to release the low-energy positron beam non-adiabatically from the magnetic guiding field.

3. The Positron Instrumentation

At present, three experiments are in routine operation at NEPOMUC which use the 20 eV positron beam. In the following, the instruments are listed chronologically according to their commissioning at NEPOMUC.

3.1. Positron annihilation induced Auger electron Spectroscopy — PAES
PAES is a non-destructive technique for element selective surface studies which has several advantages over conventional AES such as suppressed secondary electron background in the range of Auger-transition energies and exceptional sensitivity to the topmost atomic layer. The main disadvantage of PAES of the very long data acquisition time in the range of typically several days per spectrum is overcome with the availability of the strong NEPOMUC positron source. The aim of our own developments was to further improve this exceptional technique in order to profit from its attractive features for high sensitive surface investigations. After upgrading the spectrometer, we succeeded not only to obtain PAES spectra within considerably reduced data acquisition times of several minutes, which is comparable to measurement times with conventional AES, but also to improve the energy resolution and the signal-to-noise ratio.

Within the last year, the surface coverage and island growth in the (sub-)monolayer region were studied in particular in the systems Cu/Pd and Cu/Fe. Moreover, the theoretically predicted segregation process of Cu in Pd was observed, which is the first *time-dependent* PAES measurement reported so far [7].

3.2. Coincident Doppler-Broadening Spectroscopy — CDBS
The CDB spectrometer enables defect studies by DBS and element specific measurements with CDBS in the near surface region and in the bulk of the specimen. A positioning device allows us to scan the sample in two dimensions with a lateral resolution of 300 μm which is currently improved to below 100 μm. Depth dependent measurements up to a few μm are performed by accelerating the positrons up to an energy of 30 keV.

With laterally resolved DBS defects can be mapped in two dimensions (see e.g. [8, 9]) and as function of positron implantation depth [10]. Depth dependent CDBS is particularly suited to study the elemental surrounding of the positron annihilation site in thin layered samples [11].

3.3. Pulsed Low-Energy Positron System — PLEPS
In order to perform depth dependent positron lifetime measurements for the investigation of defect types and concentration, the PLEPS was developed at the Universität der Bundeswehr (UniBW) München and transferred to NEPOMUC. The lifetime spectra are not only recorded within a low measurement time of a few minutes but also show an exceptional peak-to-background ratio of 10^4, which allows one to extract at least three lifetime components according to different positron states reliably (see [12]).

Examples of recent PLEPS experiments are the determination of the free volume in polymer films [13] or in bioadhesive [14]. In particular, positron lifetime experiments with PLEPS and additional DBS were applied to get a deeper insight into the nature of defects. For instance, the annealing of irradiation induced defects after He implantation in InN and GaN [15] or the vacancy defects in a thin film perovskite oxide have been studied [16].

3.4. Scanning Positron Microscope — SPM
The SPM, which allows positron lifetime measurements with a spatial resolution in the μm range, has been developed and operated at the UniBW München [17]. In order to connect the SPM to the NEPOMUC beam line, an interface including pulsing units and an additional remoderator for brightness enhancement was developed [18]. With this interface, which is required to achieve a sufficiently high phase space density to operate a positron micro-beam for lifetime measurements, a triply moderated pulsed positron beam was obtained for the first time.

3.5. Open multi-purpose beam Port — OP
At the OP, where experimental setups can easily be connected to the positron beam line, the following experiments have been performed up to now: The positron moderation by inelastic

scattering in nitrogen was investigated by cooling the beam in a gas-filled drift chamber [19]. Together with the group of A. Dorn from the Max-Planck Institute for Nuclear Physics in Heidelberg first experiments on positron-He scattering were carried out. In addition, the correlated electron-electron and electron-positron emission at surfaces after slow positron impact was studied by the group of J. Kirschner from the Max-Planck Institute of Microstructure Physics in Halle using a coincidence setup for the detection of the ejected particles [20]. An apparatus for the production and lifetime measurements of the negatively charged positronium ion Ps^-, which was developed in the group of D. Schwalm at the Max-Planck Institute for Nuclear Physics in Heidelberg [21], was transferred to NEPOMUC. For the Ps^- experiments at the OP, first the primary positron beam at an energy of 500 eV and later the remoderated 20 eV beam was used. Recently, the whole setup was improved in order to determine the Ps^- decay rate with enhanced accuracy.

4. Outlook

At the CDB spectrometer, a new sample stage was installed recently in order to enable measurements in an temperature range between 110 K and 1000 K, and four additional pairs of Ge detectors will lead to a corresponding reduction in measurement time by a factor of four. In 2010, funding was granted to develop a novel a coincident setup with two segmented high-resolution Ge detectors, which will enable the detection of the electron momentum in three dimension for each annihilation event, in contrast to ACAR or (C)DBS where only projections are measured. In another project, an ACAR spectrometer is planned to be built in collaboration with the group of A. Alam, University of Bristol, which will allow high resolution electron momentum measurements. At the PAES system, a STM is mounted in order to enable the determination of the surface topology, and a X-ray source for XAES and XPS is installed to gain element information of the surface with complementary techniques. Managed by the UniBW München, additional funding was granted in order to upgrade the pulsed beam facilities, e.g. for extending the time window for the measurement of long positron lifetimes with PLEPS or for accelerating the positrons inside the SPM-interface. In 2012/2013, it is planned to move the positron instruments to a new experimental hall located at the east side of the reactor building.

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