Present and future experiments using bright low-energy positron beams

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Abstract. Bright slow positron beams enable not only experiments with drastically reduced measurement time and improved signal-to-noise ratio but also the realization of novel experimental techniques. In solid state physics and materials science positron beams are usually applied for the depth dependent analysis of vacancy-like defects and their chemical surrounding using positron lifetime and (coincident) Doppler broadening spectroscopy. For surface studies, annihilation induced Auger-electron spectroscopy allows the analysis of the elemental composition in the topmost atomic layer, and the atomic positions at the surface can be determined by positron diffraction with outstanding accuracy. In fundamental research low-energy positron beams are used for the production of e.g. cold positronium or positronium negative ions. All the aforementioned experiments benefit from the high intensity of present positron beam facilities. In this paper, we scrutinize the technical constraints limiting the achievable positron intensity and the available kinetic energy at the sample position. Current efforts and future developments towards the generation of high intensity spin-polarized slow positron beams paving the way for new positron experiments are discussed.

1. Introduction
Mono-energetic positron beams are widely applied in various experiments for fundamental research as well as in materials science, condensed matter and surface physics. As the SLOPOS conference series is devoted to slow positron beam techniques and applications the applied experimental techniques can be subdivided into two categories.

The first category comprises established ”bulk” methods of positron annihilation spectroscopy (PAS) which are carried out with low-energy positron beams in order to gain near surface or depth and/or laterally resolved information on lattice defects. Doppler-broadening spectroscopy (DBS) of the positron electron annihilation line as function of positron implantation energy can simply be applied by using a single high-resolution Ge detector. Additional scanning of the beam allows for imaging defect distributions in order to analyze e.g. the spatial variation of the oxygen deficiency in single crystalline YBa$_2$Cu$_3$O$_{7-\delta}$ thin films [1]. Coincident DBS (CDBS) provides additional information on the chemical surrounding of open volume defects or the presence of precipitates in thin layers or near the surface. Although it is challenging to achieve a sufficient high timing resolution several facilities are in operation world-wide for depth dependent positron annihilation lifetime spectroscopy (PALS) in order to e.g. characterize the free volume in thin polymers [2] or to identify the species of vacancies in thin oxide films [3]. Only a few measurements of the age-momentum correlation (AMOC), where the positron...
lifetime and the Doppler-shift are detected simultaneously for each annihilation event, have been performed so far, since a high beam intensity is crucial for this technique. The same holds for the determination of the angular correlation of annihilation radiation (ACAR) in order to study the electronic structure of matter with low energy positron beams [4].

The second group of experiments includes specifically surface and fundamental studies, where positron beams with narrow band width are absolutely required. In surface science positron annihilation induced Auger-electron spectroscopy (PAES) is applied for element selective surface studies of the topmost atomic layer [5], and (total) reflection high-energy positron diffraction ((T)RHEPD) allows surface structure determination with outstanding accuracy [6]. Bright beams are used in atomic physics for positron and positronium (Ps) scattering experiments, and in fundamental research for the production of a neutral positron electron pair plasma [7] and bound leptonic systems such as cold Ps, the positronium negative ion Ps− [8] or the Ps2 molecule [9]. An overview of the slow positron beam techniques and recent applications are presented in detail in a comprehensive review on positrons in surface physics [10].

In the past all these techniques have benefited from the development of evermore intense mono-energetic positron beams. On the one hand most experiments profit from a high beam intensity which leads to a drastically reduced measurement time and to a considerably enhanced signal-to-background ratio. In particular, a high positron intensity is beneficial for all kinds of coincidence techniques applied in solid state physics. On the other hand high intensity positron beams with high brightness have enabled the development of novel techniques in fundamental research and new positron applications such as time-dependent PAES, e.g. for the observation of surface segregation in situ [11]. In addition, intense positron beams are desired for the realization of micro-beams using multiple remoderation for brightness enhancement.

The development of future high-intensity positron beams, however, is challenging in many respects: a spin-polarization to a high degree is desired, the positron energy at the sample should be variable within 0-30 keV, the strength of the positron source should be improved and the beam brightness should be as high as possible, preferably simultaneously. The improvement of positron moderators, in fact, would lead to beams with enhanced brightness as well [12] but is not subject of this paper. In the following the limitations of present positron beam setups will be briefly reviewed before the focus will be put on recent progress at current beam facilities and on developments of future positron sources enabling new positron beam experiments.

2. Coping limitations of beam intensity and brightness

2.1. Limits of positron source strengths

Positrons are basically generated either via $\beta^+$ decay or by pair production. In conventional (bulk) PAS and in tabletop beam setups the achievable positron yield is limited by the positron self-absorption in the $\beta^+$ source. For this reason, positron beams of high intensity, i.e. $>10^7$ moderated positrons per second [13], are produced by pair production at large scale facilities. In the last decades great efforts have been made to generate positrons by pair production using intense $\gamma$ sources in order to develop low-energy positron beams with high intensity. Such positron sources use either bremsstrahlung emitted from decelerating electrons or $\gamma$ radiation released from nuclear processes.

At research reactors, positrons can be generated by the absorption of high energy $\gamma$ radiation released either from nuclear fission processes or from the de-excitation of excited nuclear states after neutron absorption. The first process is applied at the Delft reactor, where an assembly of thin W foils inside a beamtube is located close to the reactor core in order to absorb the $\gamma$ radiation from nuclear fission for pair production [14]. The other approach was pursued at the NEutron induced POSitron source MUniCh (NEPOMUC) where the nuclear reaction $^{113}\text{Cd}(n,\gamma)^{114}\text{Cd}$ generates high-energy prompt $\gamma$ rays, which are absorbed in Pt foils to provide $10^9$ moderated positrons per second (see [15, 16] and references therein). The brightness of the
primary 1 keV positron beam is enhanced by a positron remoderator using a W single crystal ($\Phi^+ = -3.0$ eV [12]) in back reflection geometry yielding a total efficiency of about 5% and a beam diameter of less than 2 mm (FWHM) in a 6 mT guiding field [17]. The variable kinetic energy of the remoderated beam is usually set to 20 eV for most experiments. It is noteworthy that the brightness of the primary beam at NEPOMUC is similar to that of a realizable $^{22}$Na based beam (using a high activity of 50 mCi and efficient moderation) but the remoderation leads to a brightness enhancement of at least two orders of magnitude.

For positron production at electron linear accelerators (linacs), high energy bremsstrahlung is released by decelerating electrons in heavy targets (typically Ta or W) in order to convert the $\gamma$ radiation into positron-electron pairs [18, 19, 20, 21]. Since a linac is intrinsically pulsed the produced positron beam shows a pulsed structure too. At linacs releasing bremsstrahlung up to around 20 MeV the largest fraction of the bremsstrahlung spectrum is absorbed due to the photo and Compton effects. Therefore, elaborate cooling devices have to be applied to dissipate the heat at the converter. For example, at the positron source at the ELBE facility a stack of W plates has to be cooled by a high-pressure water cycle [22].

It has to be emphasized that at both, linacs and reactors, the maximum positron yield is mainly limited by the maximum allowed temperature of the conversion target and the supporting structure caused by the so-called $\gamma$-heating. In positron sources based on pair production most of the energy of the $\gamma$ radiation is dissipated by the photo effect and Compton scattering due to their high cross sections, particularly at lower energy. According to the behavior of the pair production cross section, $\sigma_{pp} \propto Z^2 \ln E$, the crossover from energy loss by Compton scattering to pair production is at a photon energy of $E=5$ MeV for W with atomic number $Z=74$. As an example, figure 1 shows the product of the relative $\gamma$ intensity [23] and the respective energy of the $\gamma$ cascade emitted by the de-excitation of $^{114}$Cd. Even assuming complete absorption in W, the maximum fraction of $\gamma$'s contributing to pair production is only of secondary importance, i.e. > 75% of the deposited energy does not contribute to pair production.

2.2. Gamma-beam based positron generation
A new approach is the application of a brilliant high-energy $\gamma$ beam for the creation of positron-electron pairs by pair production in a suitable target. Currently large efforts are devoted worldwide to the development of $\gamma$ beams created by inverse Compton scattering of photons from an intense laser with electrons (see [24] and references therein). For this purpose, relativistic electron beams will be applied since the inverse Compton effects basically boosts the photon energy by the Lorentz factor squared. For example, using a green high-power laser with 2.5 eV photons hitting a relativistic electron bunch of 500 MeV would yield in 9.6 MeV $\gamma$'s.

Such a $\gamma$ beam based positron source exhibits several advantageous features. In principle, the energy of the $\gamma$ beam can be varied in the range of several MeV that allows the maximization of the positron production rate and hence the yield of moderated positrons. Due to the narrow band width of the $\gamma$ beam, which can be well below 1%, no $\gamma$'s hit the converter target with an energy below the pair production threshold. Therefore, compared to linac or reactor based positron sources the heat load is intrinsically considerably lower. The low emittance of the $\gamma$ beam allows the adaptation of a converter and positron moderator in an efficient positron source geometry. Hence, the intrinsic small diameter of the $\gamma$ beam can be used to create a high-brightness moderated positron beam. It has to be mentioned that the source area of the $\gamma$ beam is easily accessible which greatly facilitates e.g. the change of the source setup. The time structure of the positron beam is basically provided by the pulsed $\gamma$ beam which might be beneficial for positron beam experiments using coincidence techniques. Moreover, a spin-polarized positron beam can be created using a polarized $\gamma$ beam (see below). A detailed overview of the novel concept of a positron source based on $\gamma$ beams produced via Compton back-scattering can be found in [24]. At present, a $\gamma$ beam based positron source is being
developed at the so-called ELI-NP facility, which is under construction in Bucharest, Romania [25]. As demonstrated most recently the polarization of electrons can be transferred to positrons produced via pair production of polarized bremsstrahlung in a high-Z target [26] that might open up another possibility to generate spin-polarized slow positrons in the future.

3. Variable beam energy

3.1. Present status of low-energy positron beam setups

Mono-energetic positron beams with variable energy are applied for all kinds of depth dependent measurements. Usually, the positron implantation energy is adjusted by biasing the sample or the source-moderator assembly. Hence, the maximal possible potential difference between positron emitter and sample constrains the implantation energy to typically 30-40 keV. The potential of the positron source, however, cannot be raised very high at the positron emitting area at most laboratory setups or in reactor-based sources as well as at positron remoderators. Consequently, in such cases the acceleration voltage has to be applied to the sample stage.

This constraint can be adverse for using remoderation devices or in surface studies. It is especially crucial for positron re-emission measurements where the sample has to be fixed to ground or even to a positive potential to allow for low-energy positrons to reach the grounded detector. For this reason, only an increase of the total energy of the beam between source and sample can bypass this constraint enabling any desired implantation energy. An increase of the potential energy of a positron pulse, without altering its velocity, can be achieved by a so-called positron energy elevator using time dependent fields [27].

3.2. New positron beam elevator

Recently, two novel pulsed setups for positron acceleration based on elevation of the total beam energy have been successfully put into operation within two different projects at the NEPOMUC
Figure 2. Novel acceleration facility including a beam energy elevator at NEPOMUC: (a) continuous positron beam, (b) pre-buncher for pulse generation with low background, (c) chopper for further background reduction, (d) main-buncher for pulse compression to below 2 ns (FWHM), (e) positron elevator for raising the potential energy of the pulse, (f) electrostatic accelerator for conversion of potential into kinetic energy, and (g) beam monitor at entrance of surface spectrometer. Figure from ref. [28].

Figure 2 exemplarily shows the setup for pulsing the positron beam with subsequent elevation of the total beam energy. It is noteworthy, that this new device is versatile with regard to the species of charged particles to be accelerated, and in principle it can be used for efficient deceleration. The viability of the new concept has been demonstrated by elevating the energy of a 20 eV mono-energetic positron beam to 3.5 keV. After passage through the elevator the time structure is preserved with a pulse width of <1.6 ns (FWHM), and it was shown that the whole device operates with a high efficiency of 88% [28]. Since the new elevator technique is demonstrated to compensate the constraints of source and samples being near ground potential positron re-emission experiments are envisaged within the next beamtimes.

4. Spin-polarized beams
4.1. Spin-polarized positron experiments
Positrons emitted from $\beta^+$ sources are intrinsically right-handed longitudinally spin-polarized due to parity violation in the weak interaction. Polarized positrons can also be generated by pair production either using polarized electron induced bremsstrahlung [26] or via the
The low energy interaction of a circularly polarized $\gamma$ beam with a high degree of polarization [33]. Therefore, it is intriguing to apply the aforementioned technique to produce positrons with a polarized $\gamma$ beam in order to generate a spin-polarized positron beam with high brightness [24]. Since the positron polarization is almost entirely maintained during moderation, spin-polarized positron beam experiments will become feasible at such a $\gamma$ based positron source. At ELI-NP in Bucarest it is envisaged to generate spin-polarized positrons based on the interaction of a circularly polarized $\gamma$ beam with an optimized W converter. Simulations of the low energy $\gamma$ beam ($<3.5$ MeV) with an intensity of $2.4 \times 10^{10} \gamma$/s predict a positron beam intensity of $>10^6$ slow positrons per second. In case of total circular polarization of the $\gamma$ beam the degree of spin polarization of the slow positron beam is expected to be in the range of 33-45% dependent on the thickness of the W foils used in the $\gamma$-positron converter [25]. It has to be mentioned that in the lab-scale spin-polarized positron beams with intensities of $>10^6$ slow positrons per second and a degree of polarization of about 30% are realizable. In the long term, however, $\gamma$ beam facilities as a matter of principle offer the great potential to develop intense positron beams with significant spin-polarization.

5. Conclusion and future positron beam experiments
The availability of new positron sources providing (spin-polarized) positron beams with enhanced brightness would greatly improve all kinds of positron beam applications in material science, solid-state, surface, and atomic physics. In general, a beam with increased intensity and same emittance would immediately lead to a higher quality of the experiments in terms of higher signal-to-noise ratio, shorter measurement time and/or improved statistics. In addition, a higher beam intensity is also advantageous for the generation of remoderated positron micro-beams and for scanning beam applications.

For fundamental experiments, a high intensity of moderated positrons is crucial e.g. for the creation of an energy variable mono-energetic Ps beam by photodetaching an electron from Ps$^-$, spectroscopy of Ps and Ps$^-$, generation of a neutral leptonic plasma, and the future creation of a Ps Bose-Einstein condensate. In materials science and solid-state physics, such scanning micro-beams are highly in demand for spatially resolved defect spectroscopy using PALS and CDBS. For surface studies the maximum available positron intensity is crucial for positron diffraction experiments TRHEPD and for future spatially resolved surface analysis using PAES.
With the new positron beam elevator the kinetic energy of the particle becomes independent on potentials of both the source and the sample. This allows for the spectroscopy of re-emitted positrons and hence the investigation of the material dependent positron work function as well as the determination of depth dependent moderation efficiency. In the future it would be most intriguing to analyze the electronic structure in thin layers and to observe the evolution of the Fermi surface from the bulk to the surface using depth-dependent 2D-ACAR. Moreover, in ferromagnetic materials this could even be done for each spin channel of the electron density of states by using spin-polarized low-energy positrons.

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