The Intense Slow Positron Beam Facility at the NC State University PULSTAR Reactor

Ayman I. Hawari\textsuperscript{1}, David W. Gidley\textsuperscript{2}, Jun Xu\textsuperscript{3}, Jeremy Moxon\textsuperscript{1}, Alfred G. Hathaway\textsuperscript{1}, Benjamin Brown\textsuperscript{1}, and Richard Vallery\textsuperscript{2}

\textsuperscript{1}Nuclear Engineering/Nuclear Reactor Program, North Carolina State University, P.O. Box 7909, Raleigh NC 27695, USA
\textsuperscript{2}Physics Department, University of Michigan, 450 Church Street, Ann Arbor MI 48109, USA
\textsuperscript{3}Chemical and Analytical Sciences Division, Oak Ridge National Laboratory, Oak Ridge TN 37831, USA

Abstract. An intense slow positron beam is in its early stages of operation at the 1-MW open-pool PULSTAR research reactor at North Carolina State University. The positron beam line is installed in a beam port that has a 30-cm \times 30-cm cross sectional view of the core. The positrons are created in a tungsten converter/moderator by pair-production using gamma rays produced in the reactor core and by neutron capture reactions in cadmium cladding surrounding the tungsten. Upon moderation, slow (~3 eV) positrons that are emitted from the moderator are electrostatically extracted, focused and magnetically guided until they exit the reactor biological shield with 1-keV energy, approximately 3-cm beam diameter and an intensity exceeding 6\times 10^6 positrons per second. A magnetic beam switch and transport system has been installed and tested that directs the beam into one of two spectrometers. The spectrometers are designed to implement state-of-the-art PALS and DBS techniques to perform positron and positronium annihilation studies of nanophases in mater.

Keywords: Slow Positron, Nuclear Reactor, PULSTAR, Intense Positron Beam, PALS, DBS

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INTRODUCTION

The use of positrons as a material probe has proven to be a powerful nondestructive technique to characterize the properties of materials at the nanometer scale. The utilization of low energy beams of positrons wherein the positron’s implantation depth can be controlled vastly expands the possible applications by enabling the study of thin films, surfaces, interfaces, and depth-dependent phenomena. In particular, beam-based positron spectroscopies have demonstrated great utility in characterizing nanoporous thin film materials and nanocomposites. Understanding and controlling nanometer-sized pores is a rapidly developing area in nanotechnology with wide-ranging implications from H storage and CO\textsubscript{2} catalysis to next-generation interlayer dielectrics in microchips and polymer electrolytic membranes in fuel cells.

Despite this promising potential, positron spectroscopies have not achieved the stature of more traditional techniques such as x-ray and neutron scattering. Positron beam rate and poor accessibility to beams have limited its widespread adoption. To address these issues we have constructed a new high rate positron beam attached to two different positron/positronium lifetime spectrometers at the PULSTAR nuclear reactor on the campus of North Carolina State University.

THE PULSTAR INTENSE SLOW POSITRON BEAM

The PULSTAR reactor, for which a schematic of the floor plan can be seen in Fig. 1, is a swimming pool type research reactor. The reactor core is composed of uranium dioxide enriched to 4% in uranium-235 and is placed inside a 15000 gallon open tank of water. The maximum power of the PULSTAR is 1-MWth. The light water surrounding the core acts as both a neutron moderator and a coolant. Beryllium and graphite reflectors are placed on two sides of the core to enhance the neutron economy and therefore maximize fuel usage. Six beam ports are positioned within the pool, with five extending radially from the core. A unique aspect of the PULSTAR core is its...
highly under-moderated design, which allows the thermal neutron flux to peak at the core edges near the entrance of the beam tubes. This characteristic of the PULSTAR design allows generating neutron and gamma-ray intensities, at ex-core experimental locations, that are comparable to reactors of higher power. Therefore, the production of positrons using the core neutrons and gamma-rays (as is the case in this work) can benefit highly from a core that is designed in this fashion.

Figure 1. Layout of the of PULSTAR reactor bay showing the positron beam. Slow positrons created approximately 30 cm away from the core surface are electrostatically extracted and focused into a solenoid for magnetic guidance through the biological shield and into one of the spectrometers. BT 2 (the radial port) is not shown.

The design of the positron beam was initiated based on Monte Carlo radiation transport simulations to establish estimates of positron production in two to four tungsten moderator structures that are placed approximately 30 cm away from the PULSTAR reactor core. The simulations were performed using the transport code MCNP. Using this approach, the pair production reaction rate of the energy dependent photon flux in the moderators and the positron production rate were calculated. Electrostatic lenses were optimized, using the ion optics toolkit from the AMaze series of software, to extract the positrons from the moderators and to focus them into a solenoid for magnetic transport out of the biological shield of the reactor. The final design calculations produced a 1 keV positron beam at the exit of the solenoid with a diameter of 3 cm. The positrons are emitted with a bimodal energy distribution (due to having two moderator arrays held at potentials different by nearly 30 volts) with an overall spread of approximately 50-60 eV. The predicted positron rate was found to vary between $5 \times 10^8$ and $1 \times 10^9$ e$/s$.

Based on the design simulations, the PULSTAR reactor beam currently implements two tungsten arrays as positron converters and moderators. Each array is 22 cm in diameter and 2.5 cm in length and is comprised of interlocking tungsten strips (with 1-cm pitch) that are 0.25 mm thick. In addition, each individual array underwent four hours of annealing at 2200 K. The moderators are placed within an aluminum vacuum chamber that is located at the end of a magnetic solenoid tube and inserted into the 30-cm x 30-cm square beam port. Gamma-rays produced by the core interact in the moderators producing positrons via pair production reactions. In addition, thin sheets of cadmium, which shroud the tungsten moderator portion of the vacuum chamber, are used to harden and intensify the gamma-ray spectrum by generating gamma-rays through thermal neutron capture n-$\gamma$ reactions. Positrons extracted from the moderators are focused and accelerated by a six element electrostatic lens system to an energy of 1 keV. Subsequently, the positrons are injected into a 60 Gauss (0.006 T) magnetic solenoid for transport outside the reactor biological shield.

The positron beam went through a variety of bench-top tests before insertion into the designated beam port of the reactor. The moderator banks were replaced with electron guns to test the optics of the lenses and the resulting electron beam was imaged to demonstrate successful focusing and transport. The effectiveness of the moderator was tested using a Na-24 source. The Na-24 source, which $\beta^-$ decays with the emission of two prompt gammas with energies of 1.37 MeV and 2.75 MeV, was placed as close as possible to the moderator arrays and yielded a count rate of approximately 6.8 slow positrons per second per mCi. Scaling of this measured result using the calculated gamma-ray energy spectrum and intensity of the PULSTAR reactor yielded a rate of $5 \times 10^8$ e$/s$, which is comparable to the value predicted by the simulations described above.

Reactor testing of the positron beam was recently performed. The beam was inserted into the 30-cm x 30-cm square beam port of the PULSTAR reactor. To do so, the beam was attached to a cart placed on a track, which allows the beam to be easily inserted and retracted from the beam port. The positron count rate was measured at the end of an s-shaped bend outside of a borated polyethylene shield. At low reactor power, the positron rate was determined using a micro-channel plate detector mounted at the end of the beam line. At higher power, the rate was inferred based on measurements of the 511 keV annihilation gamma-ray line using a BaF$_2$ scintillation detector. To perform the measurement, the detector was calibrated in-situ using...
a Na-22 source. Initially, the measurements indicated rates approaching $1 \times 10^7$ e$^{-}$/s. However, a sudden deterioration in vacuum was observed that was followed by a decrease in the positron rate to approximately $6 \times 10^8$ e$^{-}$/s. The results of these runs can be seen in Fig. 2. The slow positron count rate is shown to vary linearly with the reactor power and stabilizing at approximately $6 \times 10^8$ e$^{-}$/s.

Ps-PALS Spectrometer

There is a great deal of interest in new materials with controlled porosity and Ps-PALS has demonstrated unique strengths that can provide new insight to characterizing these engineered nanopores. This spectrometer requires a 1-2 mm diameter beam spot on target at beam energies from 0.5 keV to $\sim$10 keV in a zero magnetic field. Two stages of brightness enhancing moderators are used. In the first stage, the beam is extracted from the guiding magnetic field, accelerated to 6 keV and electrostatically focused to 20 mm diameter on a thin tungsten transmission foil remediator (the small reduction in beam diameter from 30 mm to 20 mm owes to the large 500 eV spread in the longitudinal beam energy in the 0.006 T guiding field). After re-acceleration to 6 keV the beam can be focused to 1-2 mm on a second transmission foil remediator such that the final beam on target can be $\sim$1 mm diameter at even the lowest beam implantation energies. The predicted on-target positron rate is $5 \times 10^5$/s, which is still sufficient for the spectrometer to be dead-time limited in the individual pulse-counting mode. Random background rates further limit the overall coincidence data rate to $\sim$10$^3$ events/s. A typical lifetime spectrum can be acquired in less than one minute.

The start signal for the lifetime measurement is the detection in a channel electron multiplier array (CEMA) of secondary electrons, emitted when positrons impact the target. The positron beam passes through a co-axial hole in the CEMA and strikes the sample target about 1 cm behind it. A subsequent annihilation gamma-ray is detected in a bank of small, fast-plastic scintillators and a time digitizer measures and records the time interval for each event. Timing using secondary electrons is limited to approximately 0.5 ns due to the energy and angular distribution of the reemitted electrons, but this time resolution is acceptable for measurement of positronium lifetimes in polymers and insulators (>2 ns).

$e^+$/PALS Spectrometer

The lifetime of positrons within metals is on the order of 100s of picoseconds, so a time resolution of 0.5 ns (500 ps) is not suitable for studying defects in such materials. Greatly enhanced timing performance can be achieved by time focusing the positron beam into narrow pulses using radiofrequency (rf) bunching, with a time resolution on the order of 100 ps. Usually, this improved resolution comes at the expense of more complicated electronics where the positron start signal is taken directly from the electronics of the system.

LIFETIME SPECTROMETERS

Two different types of lifetime spectrometers are under construction (see Fig. 1). The positronium-based spectrometer (Ps-PALS) is designed to measure long exponential Ps lifetimes up to 140 ns and requires a clock timing range of 1000 ns. It does not demand ultra-fast time resolution. The second spectrometer ($e^+$/PALS) is focused on measuring fast, 0.15 ns, positron lifetimes in metals and semiconductors where ultra-fast timing is critical and a clock range of only 20 ns is typical. The intense beam can be switched and magnetically guided out of the reactor bay and into either one of the spectrometer laboratories.

Figure 2. Results of the initial in-core positron beam tests. (a) The positron count rate is shown to vary linearly with reactor power. The solid line shown in the figure is intended to guide data observation. (b) The positron count rate (approximately $6 \times 10^8$ e$^{-}$/s) after a few hours of reactor operation.
The designed e\textsuperscript{-}-PALS spectrometer is based on magnetically guiding the positrons to the sample holder with a series of coils. To reduce the background at the detector, the positrons will be transported through internal shielding with applied transverse fields. Coils will be mounted on gimbals to optimize the axial field. An assembly of a transmission positron moderator and grid will act as a pre-buncher for the beam. A time-varying potential in the form of a 50 MHz ramp function will be applied to the moderator, which will in turn set up a time-varying electric field in the region separating the moderator and grid. Positrons emitted at a later time in the waveform will experience a greater electric field, therefore obtaining higher acceleration. This velocity modulation is optimized by changing a DC offset placed on the moderator ensuring that the focal point of the pre-buncher is the entrance of the main buncher. Simulations, performed with a program that is developed using the ion optics code SIMION\textsuperscript{9}, demonstrated that the pre-buncher configuration is capable of producing bunches at the moderator with a width (FWHM) of approximately 2 ns.

The main buncher is a double-gap design with the applied potential in the form of a 50 MHz sine wave produced from rf fields. The length of the bunching electrode is calculated so positrons entering the buncher exit in phase with the applied sine wave using the relationship for classical kinetic energy. SIMION was once again used to test the effectiveness of the buncher. The simulations demonstrated that this configuration could yield a timing resolution on the order of 100 ps (FWHM), as seen in Fig. 3.

![Figure 3. Simulated time-of-flight for positrons arriving at the sample in the e\textsuperscript{-}-PALS spectrometer. The FWHM is determined to be approximately 100 ps with 70\% efficiency. This timing structure is produced using the double-gap buncher design discussed in the text.](image)

In addition, the bunching efficiency of the proposed buncher was found to be approximately 70\%. Eventually, the overall efficiency will be determined based on the linearity of the ramp function produced by an arbitrary function generator.

**CONCLUSIONS**

An intense slow positron beam has been established at the PULSTAR nuclear reactor of North Carolina State University. The beam was demonstrated to have an intensity of nearly 6x10\textsuperscript{8} e\textsuperscript{-}/s, a diameter of 3 cm and an energy of 1 keV with an overall spread of approximately 50-60 eV. Active work is currently underway to complete two state-of-the-art positron/positronium lifetime spectrometers. Doppler broadening techniques can also be performed with each spectrometer. Once completed, this facility will provide a positron beam with an energy up to 50 keV and a millimeter spot size for applications in nanophase characterization of materials.

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I acknowledge that this manuscript is considered to be a representation that it has been neither copyrighted or published, nor submitted for publication elsewhere.

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