Proposal for a slow positron facility at Jefferson National Laboratory

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Abstract. One goal of the JPos-17 International Workshop on Physics with Positrons was to ascertain whether it would be a good idea to expand the mission of the Thomas Jefferson National Accelerator Facility (JLab) to include science with low energy (i.e. “slow”) spin polarized positrons. It is probably true that experimentation with slow positrons would potentially have wide-ranging benefits comparable to those obtained with neutron and x-ray scattering, but it is certain that the full range of these benefits will never be fully available without an infrastructure comparable to that of existing neutron and x-ray facilities. The role for Jefferson Laboratory would therefore be to provide and maintain (1) a dedicated set of machines for making and manipulating high intensity, high brightness beams of polarized slow positrons; (2) a suite of unique and easily used instruments of wide utility that will make efficient use of the positrons; and (3) a group of on-site positron scientists to provide scientific leadership, instrument development, and user support. In this note some examples will be given of the science that might make a serious investment in a positron facility worthwhile. At the same time, the lessons learned from various proposed and successful positron facilities will be presented for consideration.

I. INTRODUCTION

Positrons are the antiparticles of the electrons that are part of all the matter we observe in daily life. Slow positrons are positrons produced in vacuum with a few eV energy by moderating energetic (greater than a few 100 keV) positrons produced by beta decay or pair production. Slow positrons may be accelerated to any desired energy and focused and manipulated in phase space as needed. A positron interacts with ordinary matter in many ways, including scattering, annihilating with electrons, and forming bound states such as the hydrogen-like electron-positron atom positronium (Ps). These interactions can be used to study fundamental physics as well as the properties of matter in ways that are complementary to the more usual methods that probe matter using neutrons, electrons, X-rays and so forth. About 25 years ago the US Department of Energy (DOE) decided that positron spectroscopy had become sufficiently important to justify the initiation at Lawrence Livermore National Laboratory (LLNL) of a high intensity positron source and user facility based on their working 150 MeV electron LINAC. Unfortunately, the non-completion of a complex initial flagship instrument [1] after more than five years of effort led to the cancellation of the project, which otherwise would likely have gradually grown into a valuable enterprise with many instruments and users. Today the case for establishing an intense positron source and user facility in the USA has become even stronger than before with the development of several new types of positron spectroscopies and more advanced theories that would be very valuable to US science and industry given a positron source of sufficient intensity and a suite of instruments that could be easily employed by outside users. Briefly described here are some of the capabilities that would be possible with a new slow positron facility at Jefferson National Laboratory (JLab). This facility would be the best of its kind in the world by at least an order of magnitude in all respects, including providing beams of more than 10⁸ polarized or 10⁹ unpolarized positrons emanating from 1 mm diameter areas with initial energies of less than 1 eV. In this document we are concentrating on the new science and useful materials analysis that could be done at JLab and the reasonably achieved characteristics of the proposed intense slow positron sources that would make it possible.
II. WHAT ARE SLOW POSITRONS?

Energetic positrons are produced in beta decay and pair production interactions. Typical beta-decay radioactive sources like $^{22}\text{Na}$, $^{13}\text{N}$, $^{79}\text{Kr}$, and $^{68}\text{Ge}$ are produced via reactions such as $^{27}\text{Al}(p,X) \rightarrow ^{22}\text{Na}$, $^{12}\text{C}(d,n) \rightarrow ^{13}\text{N}$, $^{79}\text{Kr} + n \rightarrow ^{80}\text{Kr}$, etc. These particular nuclei emit positrons with energies ranging from 0.54 to 1.95 MeV. The positrons have a continuous distribution of velocities $v$ because the total radioactive decay energy is shared with a neutrino. The positrons are emitted with helicities $\hat{s} \cdot \hat{v} = v/c$ [2], where $\hat{s}$ is the positron’s spin angular momentum, due to the non-conservation of parity in the weak interaction [3]. If a restricted solid angle of the directions of the emitted particles is collected into a beam, the beam will be spin-polarized along the average emission direction. A typical polarization for a positron beam from the most common isotope, $^{22}\text{Na}$, has a polarization of about 30% [4, 5], which can be increased by filtering out the lower energies and restricting the positrons to those emitted more closely to the beam direction.

Pair production occurs when an energetic photon is able to turn into an electron and a positron in close proximity to an atomic nucleus which conserves the momentum of the interaction by absorbing a virtual photon. The energetic photons are either obtained from the bremsstrahlung emitted by relativistic electrons passing through a material absorber or Cd(n,$\gamma$) neutron capture gamma rays in a nuclear reactor.

Slow positrons are obtained in vacuum with eV energies when they escape from the surface of a solid moderator that is being bombarded with fast positrons [6, 7]. The usual positron moderators are solid Ne with a fast-positron to slow positron conversion efficiency $\varepsilon \approx 1\%$ for $^{22}\text{Na}$ [8]. For single crystal W [9], which can work at high temperatures, the efficiency is $\varepsilon \approx 0.1\%$ and Ni(111) thin single crystals can be used to efficiently moderate low energy positron beams to increase their brightness [10, 11, 12, 13]. Once produced, slow positrons are accelerated and focused directly onto a target used in an experiment, or manipulated in phase space before being used in an experiment by remoderation, trapping, bunching, etc. A multitude of experiments are done involving $e^+$ interactions with matter, via the annihilation photons, scattering, optical spectroscopy, positronium formation, secondary particle emission, and other mechanisms.

III. OVERVIEW

There is now even more science and probably a greater user base to justify a DOE slow positron user facility unique in the world for intensity and for having polarized positrons. On September 12-15, 2017 a group of scientists met in Newport News, VA to discuss the possibility of JLab being the host for a new US-based positron facility that might include the generation of high energy positrons for study of nuclear structure as well as slow positrons for studying the structure of ordinary materials. The possibility that the same high energy electron LINAC could profitably be used for generating both high energy positron and slow positrons was seriously entertained, especially because of the highly successful facility of this type that has been operated at Dresden for many years [14]. One possibility for having a source of polarized slow positrons was suggested by JLab’s recent demonstrated ability to make 3-6 MeV highly polarized positrons in a small momentum band [15]. The consensus of the group that was considering the possibilities, was that there was more than enough science to be done with unpolarized positrons to justify a facility that would start out with an unpolarized intense bremsstrahlung source, and that a polarized source of lesser intensity based on $^{22}\text{Na}$ should also be made for the facility. This polarized source could in fact be of greater intensity than that of any other existing unpolarized positron facility in the world and it would thus have great utility complementing the main unpolarized source. In addition the polarized source would not be constrained by the schedules of high energy experiments, and maintenance and development that is usual for high energy machines.

The advantages to US Science for developing the slow positron component of the proposed facility are (1) that it would be the best positron facility in terms of available quantity of data anywhere in the world by more than a factor of ten; (2) that it would make available in the US a number of new valuable spectroscopies competitive in sensitivity and precision, and complementary in point of view, to standard methods using neutron and x-ray scattering and photoemission; (3) that it would provide these spectroscopies to our scientists without our scientists having to go overseas; and (4) that the great intensity would mean there will be sufficient beam time for making detailed and precise measurements that could not be done anywhere else. One of the most forceful arguments in favor of the present proposal is that beam
time is scarce at the current best places in the world for this kind of work, namely in Germany at the Munich reactor [16] and at the ELBA LINAC facility in Dresden.

There was some concern expressed by the attendees that there is a long path from 100 MeV to 1 eV and while many have attempted it, none have succeeded in getting $10^{10}$ slow $e^+$s in a useful beam diameter and energy. This concern was met by consideration of the proposal from NCCU [17] of a way to use the highly efficient solid Ne moderator [8] to get slow positron intensities much greater than $10^{10}$ slow $e^+$ per sec. Another concern was that the Jefferson Lab has no onsite history, expertise, or leadership in slow positron physics. This objection would be easily rectified by hiring the right persons. Some worries that there might be competition for space, personnel, and funding between the high and low energy aspects of the project were nullified by the spectacular success of the Dresden LINAC which successfully incorporates both aspects of science into its operations.

IV. SCIENTIFIC ARGUMENT IN FAVOR OF A JLAB LOW ENERGY POSITRON FACILITY

The main argument in favor of a JLab low energy positron Facility is that one could do lots of great experiments with a 1 mm diameter beam of $3\times10^{10}$ unpolarized and $3\times10^{8}$ polarized thermal energy slow positrons per second at Jlab. The following is a list of some of the positron spectroscopies that have been established for studying the electronic structure of solids and surfaces and that would be enormously more useful with the proposed high intensity positron beams.

1. **2D-ACAR** is the two dimensional angular correlation of annihilation radiation spectroscopy that produces a 3D momentum space density profile of the electrons in a solid [18, 19]. This method probes the same information as Compton scattering with much better resolution and detail and with much less unwanted signal from the inner core electrons, but with some distortions due to the positron wave function in the solid. With modern theory, especially the theorem of Biasini and Rusk [20], which shows how to largely remove such probe effects from the measurements, and the Lock-Crisp-West theorem [21], which shows how to remove the effects of the filled electron bands, one could obtain a momentum density map with both $10\times$ better precision and $10\times$ better resolution given a high intensity positron beam and a matching high resolution and high efficiency detector. Measurements of this kind would reveal spectacular detail never before observed in momentum space. At the present time the best 2D-ACAR measurements are obtained with a 50 mCi $^{22}$Na source in close proximity to a sample. The resolution in the direction normal to the crystal surface can be very good, but in the direction parallel to the surface the resolution is determined by the size of the positron illumination spot. As a result of the low intensity and limited resolution, the data being taken today, although useful as far as it goes, is no better than experiments from 25 years ago or more. To really take advantage of the tremendous capabilities of this type of spectroscopy we need both a high intensity source and a detector of high efficiency and high resolution. The latter has never been made because there was never a source that would have justified building it. Nevertheless, the technology for making a great ACAR instrument is available. With the new source and detector, a full 3D image of the momentum density in a crystalline solid at low temperature, with momentum resolution of roughly 1% of the size of the Brillouin zone and statistical precision of the occupation number of the various bands at better than 0.003 out of the maximum value of 1, could be obtained in a few days.

2. **TRHEPD** is total reflection high energy positron diffraction [22], which is like its electron counterpart known as reflection high energy electron diffraction, RHEED. The latter is routinely used to gauge the layer by layer growth of crystals via molecular beam epitaxy or MBE. High energy positron diffraction at grazing angles is predominantly affected by the top monolayer because the positrons are repelled by the inner potential because the attractive polarization potential becomes invisible to the high speed probe particles. This allows one to unambiguously see the precise arrangement of the surface atoms without a theory by a simple Fourier transform of the data. A high intensity version of TRHEPD would permit scanning a large area sample using a small area beam to see details of the surface structure made visible at each location sampled from its local diffraction intensity distribution. For a non-crystalline surface the top layer atom positions could be determined using a microscopic probe beam area even though there are no regularly spaced narrow diffraction spots.

3. **LEPD** is low energy positron diffraction [23], similar to the familiar low energy electron diffraction, LEED, discovered by Davison and Germer at Bell Labs in 1927 [24]. With high intensity a LEPD diffraction pattern could
be obtained in a few seconds rather than over a period of days, allowing one to make a 2D image of a surface with crystal order as the contrast. Although this type of positron diffraction requires a complicated analysis, its interpretation is more reliable than LEED in determining the structure of the first few layers of a crystalline surface [25].

4. **ARPsES** is angle resolved positronium emission spectroscopy [26], which is the analog of angle-resolved photoelectron spectroscopy (ARPES) [27]. A Ps atom is emitted from a metal surface when a thermal energy positron that was implanted within the solid comes up to the surface and tunnels out to the vacuum, having captured one of the electrons from the solid. The momentum parallel to the surface and the total energy of the resulting positronium atom tell us what the parallel momentum and total energy of the electron was when it was inside. ARPsES differs from ARPES in that only the electrons near the Fermi energy are imaged and there are probably less competing processes for the electron leaving the surface to complicate the analysis. While normal emission ARPsES has just been made possible by time of flight detection of Rydberg positronium atoms [28], a full 3D image of the electronic structure near a crystal surface could be made in a few minutes using a high intensity positron source.

5. **PAES** is positron annihilation induced Auger electron spectroscopy [29, 30]. This technique allows one to be free of the defect of ordinary Auger spectroscopy, in which the core hole is created near the surface by bombardment with electrons. As a consequence, the secondary electrons from bombardment are confused with the emitter Auger electrons, and it is difficult to extend the Auger electron energy spectrum to low energies. The positron version of this spectroscopy allows one to see nothing but Auger electrons and would be a much sought-after method of looking at surface atoms if there were a high intensity positron beam.

6. **Positron microscopes or microprobes** can be implemented by bringing a beam of positrons to a tiny focus after the brightness of the beam has been enhanced by repeated stages of acceleration, focusing, and remoderation [10]. The possibilities enabled by a primary positron beam include the following.

7. **Positron reemission microscope.** One could illuminate a 20 µm spot on a metal crystal sample in ultrahigh vacuum with $10^8$ keV $e^+$/s to obtain a reemitted positron immersion optics image able to detect 1% contrast variations with 10 nm resolution in about $10^3$ s. One would be able to see crystal defects, grain boundaries [31], and surface objects larger than 10 nm. With one further stage of brightness enhancement one could illuminate a 150 nm thick single crystal Ni(100) foil such that about $10^6$ $e^+$/s would be emitted from the other side [13] from a half micron diameter spot. With suitable electron optics one could examine single molecules with nm resolution, 1% contrast and 1 h exposure. Ordinarily one would suppose that such a long exposure would completely burn up the molecules, even though the probing re-emitted positrons from the back of the Ni film have only 1 eV of kinetic energy. On the contrary, it has been suggested that the electronic excitations of a molecule in close contact with a metal surface will be transmitted to the electronic degrees of freedom of the metal, thus permitting a long term exposure of delicate protein molecules for example [32, 33].

8. **Variable energy scanning defect positron microprobe.** By scanning a sample surface with a focused positron beam [34] of variable energy one may obtain images with depth resolution of about 50% and with a contrast dependent on the positron lifetime [35] or the S- or W- parameters for detecting vacancies in metals [36], voids in polymers [37], etc.

9. **A positron field emission microscope** is also a possibility but has not been implemented yet [38].

10. **Other applications** of high intensity positrons include fundamental physics studies such as precision 1S-2S spectroscopy of Ps for testing QED, searches for Ps antigravity, production of positron plasmas, and storage of vast quantities of positrons for making portable positron sources or for studies of positron systems at high densities. The latter topic includes studies of the Ps BEC, the e$^+$ superconductor, the e$^+$ FET, the annihilation gamma laser, and density probes of laser fusion capsules and exploding foils.

**Conclusion.** With 10× the count rate of the current best place in the world, a lot of these spectroscopies, which are currently seen as novelties, suddenly become very practical!
V. PROPOSAL FOR A HIGH INTENSITY POSITRON FACILITY

1. Lessons from previous attempts to make a Facility.

Twenty years after the discovery of the first practical slow positron moderator [39] there were already dozens of successful US positron researchers who wanted a high intensity US Positron Facility. Besides numerous Positron meetings, the formal evidence of the need for a facility at that time included:

(1) 1991 Symposium on the need for a US Positron Facility at the Fall Meeting of the Materials Research Society at Boston MA.

(2) 1992 Sept 9-11 (25 years ago) DOE Rancho Mirage CA workshop on the Application of Positron Spectroscopy to Materials Sciences, assessing the need for a US Positron Facility [40].

(3) 1992 DOE BESAC panel on neutron sources requests Report on Positron Spectroscopy [41].

(4) 1994 Proposal for a US positron facility at the ORNL (Oak Ridge National Laboratory) ANS (Advanced Neutron Source) [42].

(5) 1994 Proposal for a US Positron Facility at CEBAF (JLab) [43].

(6) 1997 Nov 5-7 DOE Workshop on Applications of positron beam spectroscopy was held at LLNL and gave a positive answer to the questions: (1) Is there a need for a national center for materials analysis using positron techniques and (2) Can the capabilities at Lawrence Livermore National Laboratory serve this need? [44]

By the mid 1990’s there were 3 medium intensity DOE slow positron machines that had been operating in the US for about 10 years [45]:

(1) BNL had a $^{64}$Cu source made in their reactor that produced $6 \times 10^7$ slow e$^+$s from a 5 mm diameter spot [46].

(2) ORNL was using its ORELA LINAC operating at 3 kW to produce $7.8 \times 10^6$ slow e$^+$s [47, 48].

(3) LLNL reported they were developing a 100 MeV LINAC positron microprobe [49, 1]. The measured raw slow e$^+$ intensity was $(5 \pm 1) \times 10^8$ e$^+$s [50] and perhaps could have been more than an order of magnitude higher but for target heating problems.

2. What Happened?

Despite Scientific Justification for there being a US Positron Facility at a DOE Lab, it did not happen. There were several problems that may have prevented going forward to facility status for the three high intensity DOE positron machines. Both the ORNL and LLNL LINAC’s never reached the claimed possible intensities of $10^{10}$ slow e$^+$s because the LINAC’s primary purposes were for producing neutrons and therefore the positron producing target geometries could not be optimized. The $^{64}$Cu source at BNL used a self-moderating $^{64}$Cu single crystal evaporated on a clean W single crystal. The source perhaps could have simplified and reached the desired intensity by using a solid Ne moderator, but before that could be implemented the operation ceased when the reactor was permanently shut down. While the BNL reactor source produced lots of good physics, the LLNL positron microprobe project never worked due to a complicated design and a failure to ever obtain preliminary results along the way.

To prevent this type of failure, the present proposal is based on (1) a noncontroversial facility, and (2) a small group of expert collaborators in the field who will ensure (a) that a reasonable route is taken to the fast and slow positron production and (b) that useful and interesting preliminary and continuing experimental results will unambiguously verify progress.
3. Expectations that there will be a significant user base.

(1) The existing slow positron facilities at the Munich Reactor [16], the Dresden superconducting electron accelerator [14], and the KEK (Japan) electron LINAC [22] between them have ~10 beam lines and a significant and oversubscribed user base. With $10^\times$ higher useful intensity at JLab the user base and data rate could be much larger.

(2) The many new positron techniques that have been developed in the last 50 years using weak positron beams are now ripe for exploitation in hundreds of new applications given sufficient intensity.

(3) Advances in theory and computation speed now make it practical to analyze and understand in detail various new types of measurements with large amounts of data.

(4) A well-staffed and well equipped slow positron facility would allow hundreds of researchers who ordinarily use neutron or x-ray scattering to obtain complementary information using positrons, without having to become experts in positron beam technology.


(1) The primary solid Ne moderated slow positron source will be based on the proposal by S. Golge, B. Vlahovic, and B. Wojtsekhowski [17] and will be implemented by collaborators at JLab.

(2) Positron beam transport to the slow positron experiment hall will implemented be via solenoids, and positron instruments will be set up, starting with the simplest (scanning microprobe) and progressing up to building instruments for PAES and 2D ACAR.

(3) To permit rapid development, testing, and first applications of the instrumentation so that it will be ready when the JLab positrons are available, the UCR polarized positron beam would be moved to the JLab slow positron experiment hall. The three existing beam lines will eventually be set up to accept either the $^{22}$Na beam or the JLab beam. Experiments on the positronium BEC, measuring the positronium 1S-2S interval, and measuring Rydberg positronium gravitational free fall will be set up and continued as they were at UCR.

(4) In order that there will be positrons available with significant intensities for set up and for preliminary experiments when the JLab positron source is not available (availability may only be about 30%) a 1 Ci $^{22}$Na capsule will be prepared at LANL and installed in the UCR beam. Eventual upgrade to 3 Ci will provide $10^9$ polarized 10 keV $e^+$ on a 1 mm spot for bulk magnetic 2D ACAR.

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