

Conceptual Design of a HANARO-Based High-Intensity Slow Positron Beam Facility: A Positronium Research Platform for Antimatter Gravity, QED Spectroscopy, and Bose-Einstein Condensation

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1. Introduction

Slow positron beams provide a nondestructive probe of open volume defects at the sub-nanometer scale, and they are also the only practical route to laboratory antimatter atoms. The most intense continuous beams available today are produced at research reactors, where high energy photons from (n, γ) reactions generate positrons by pair production. NEPOMUC at FRM-II and the PULSTAR facility at North Carolina State University both operate in the 10^9 e⁺/s range, one to three orders of magnitude above sources driven by accelerators such as KEK SPF at 5×10^7 e⁺/s and above laboratory ²²Na sources at about 10^7 e⁺/s. Korea currently has no slow positron beam facility of any class.

This work presents the conceptual design of a high intensity slow positron beam facility based on the HANARO 30 MW research reactor. The facility is planned not as a single experiment apparatus but as a research platform organized around three fundamental questions in positronium (Ps) physics, together with a suite of material analysis stations. The first question, Q1, asks whether purely leptonic antimatter obeys the weak equivalence principle, and it is tested by Ps matter wave interferometry. The second question, Q2, asks whether bound state QED can be tested at a precision limited by neither hadronic structure nor thermal motion, and it is addressed by two photon 1S-2S spectroscopy of laser cooled Ps. The third question, Q3, asks whether a Ps Bose-Einstein condensate can be formed and whether the condensate annihilates collectively rather than as a collection of independent atoms.

These three questions do not define three independent programs. All of them need the same front end, meaning an intense positron source, accumulation and pulsing in a trap, brightness enhancement, a cryogenic Ps converter, a 243 nm laser system, and fast gamma-ray detection. Roughly 70% of the infrastructure is therefore common

to Q1, Q2 and Q3 and to the material analysis stations such as PALS (Positron Annihilation Lifetime Spectroscopy), CDBS (Coincidence Doppler-Broadening Spectroscopy), PAES (Positron Auger-Electron Spectroscopy), TRHEPD (Total-Reflection High-Energy Positron Diffractometer), PLI (Positronium Lifetime Imaging) and 2D-ACAR (Two-Dimensional Angular Correlation of Annihilation Radiation) (Fig. 1).

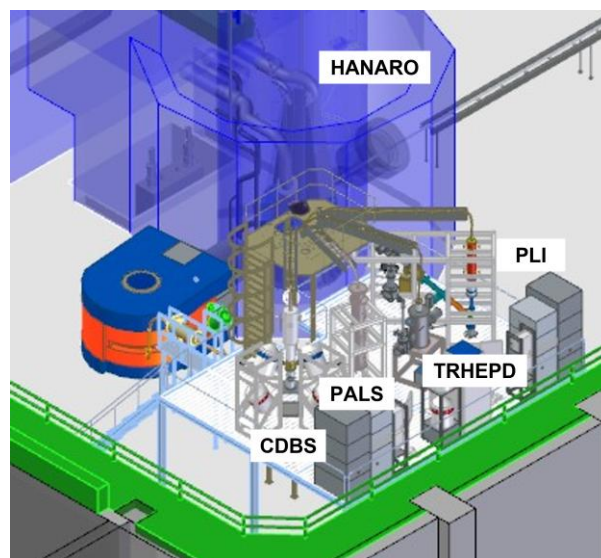


Fig. 1. Conceptual design of the material analysis stations using slow positron beam at HANARO

2. In-Pile Positron Source at HANARO

2.1. Source concept and layout

The proposed source follows the in-pile scheme validated at NEPOMUC. A ¹¹³Cd capsule placed in a high flux region converts thermal neutrons, with a capture cross section of about 2×10^4 barn, into prompt

gamma-rays of up to 9.05 MeV. These photons create pairs of electrons and positrons in a stacked and actively cooled converter of tungsten or platinum, and the fast positrons are moderated in an annealed single crystal W(110) mesh with a reemission efficiency on the order of 10^{-3} . The moderated beam is extracted at 1 to 5 eV and magnetically guided through the shielding wall into the adjacent beam hall, where all Ps experiments and analysis stations are located. This penetration type layout requires no new building. The beamline occupies roughly 60 to 75 m² of existing floor area.

2.2. Expected yield and design verification

Scaling from the HANARO thermal flux distribution, the design target is a continuous slow positron intensity of at least 10^9 e⁺/s, with an optimized design goal of 3×10^{10} e⁺/s. This figure is a design projection rather than a measured value. Coupled MCNP and Geant4 transport calculations against the HANARO core model, thermal and mechanical FEM analysis of the converter, activation and remote handling assessment, and confirmation of beam port availability are therefore defined as Phase I prerequisites. A pre-review of the licensing path with the regulatory body and a survey of vibration and stray magnetic fields in the candidate beam hall area belong to the same phase. The last item is a hard requirement for Q1, because the interferometer demands mechanical stability at the sub-nanometer level.

3. Accumulation, Brightness Enhancement, and Focusing

None of the three experiments uses the continuous beam directly. Q1 and Q2 require a bright and well collimated pulsed Ps source with a narrow velocity distribution, and Q3 requires a large number of positrons delivered into a micron scale volume within the 142 ns ortho-Ps lifetime. A strategy of accumulation followed by fast extraction therefore serves all three. The continuous beam is captured in a three stage Penning-Surko buffer gas trap using inelastic capture in N₂ and cooling in CF₄, compressed radially by a rotating wall, and released as a nanosecond bunch. At 10^9 e⁺/s and a realistic trapping efficiency of 20 to 30%, about 10^8 e⁺ per bunch (goal) are accumulated in roughly 0.3 s, which gives a repetition rate of a few Hz. This is about twenty times faster than a source of comparable class driven by an accelerator. The repetition rate translates directly into statistics, which is the limiting factor for both the interferometric and the spectroscopic measurements.

The bunch is then compressed in phase space by three successive re-moderation stages using W, Ni(100) and isotopically enriched diamond, combined with magnetic and electrostatic lenses. Each stage transmits only 15 to 25%, which gives a cumulative transmission of 0.5 to 1.5%. This loss is close to a physical constant of the technique rather than an engineering defect, and it can be absorbed only by an overwhelming primary intensity.

That is the central argument for a source based on a research reactor. The near-term focusing goal is a spot of 20 to 50 μ m, with less than 10 μ m as a long term objective. Beam expansion limited by space charge at the final focus is quantified by PIC simulation during the preparatory phase.

4. Science Program of the Platform

4.1. Q1, antimatter gravity in a purely leptonic system

The ALPHA-g experiment recently reported the gravitational acceleration of antihydrogen as 0.75 ± 0.21 in units of g , a value consistent with the matter value that rules out repulsive gravity at that precision [1]. Antihydrogen contains an antiproton, however, so the result is not a clean test of a purely leptonic system. Ps consists only of an electron and a positron and carries no hadronic structure, which makes a Ps measurement complementary to the antihydrogen result rather than a duplicate of it.

The reference design is a Mach-Zehnder interferometer driven by laser pulses with large momentum transfer [2]. Ground state ortho-Ps lives only 142 ns, so an interferometer arm of several meters is compatible only with the metastable 2^3S_1 state, whose 1.14 μ s lifetime permits the required propagation time. The 2^3S_1 population is prepared by 1S-2P excitation at 243 nm followed by microwave transfer, and the interferometer output is read out by two color laser photoionization. Field ionization is not an option, because the fields it would require are not attainable in the laboratory for the relevant states. The expected gravitational phase shift is on the order of 10^{-4} rad, so the measurement is limited by counting statistics, and a determination of the gravitational acceleration of Ps at the 10% level is the realistic first target.

4.2. Q2, QED spectroscopy free of hadronic uncertainty

Ps is a bound state of two point-like leptons, so its energy levels are calculable in QED without the proton structure uncertainty that limits hydrogen. The benchmark measurement of the 1S-2S interval by continuous wave two photon excitation reached 2.6 ppb [3], and the dominant systematic contributions are the second order Doppler shift and the limited interaction time. The motivation here is not to resolve an existing discrepancy in the 1S-2S interval. The well-known 4.5σ tension between theory and experiment belongs to the ground state hyperfine interval near 203 GHz, which is a separate quantity. The aim is instead to push the precision far enough to test higher order QED terms of order $m\alpha^8$ for the first time.

The enabling development is laser cooling. A chirped pulse train system has been demonstrated to cool Ps to a velocity distribution near 1 K within 100 ns [4]. The second order Doppler shift scales linearly with temperature, so cooling from room temperature to about

1 K suppresses it by a factor of roughly 300. It should be noted that the natural linewidth of the transition, on the order of MHz, is not itself reduced. What improves is the determination of the line center, which can be pushed to the kHz level given sufficient signal. Statistics again set the limit, and the reactor source is what supplies them.

4.3. Q3, condensation and coherent 511 keV emission

The interest of a Ps condensate reaches well beyond the demonstration of a new quantum state. Every Ps atom annihilates into 511 keV photons, whose wavelength is 2.4 pm. If the annihilation of a condensate can be made to proceed collectively, the emitted radiation would be coherent at a wavelength roughly twenty times shorter than the shortest wavelength delivered by hard X-ray free electron lasers operating today, which reach photon energies near 25 keV. A Ps condensate is the only physical system for which a source in this regime has been formulated concretely, through the self-amplified gain mechanism proposed for annihilation in a condensate [5]. Opening a path toward coherent radiation more than an order of magnitude beyond the present short wavelength frontier of laser physics is the reason this question sits at the center of the platform rather than at its margin.

Whether such a source can actually be realized remains open, and the proposal does not claim otherwise. A recent analysis argues that the gain of coherent gamma sources based on a condensate has been overestimated by many orders of magnitude [6]. What this program promises is not a gamma-ray laser but the first experimental access to the regime in which the question can be decided, because the measurable quantity is the departure of the annihilation of a dense Ps ensemble from independent decay. Observing such collective annihilation is a meaningful result whether it supports or refutes the optimistic gain estimates, and either outcome fixes a number that theory alone has not been able to settle.

The route to the required density does not rely on beam focusing alone. Positrons are implanted into a micro cavity machined by focused ion beam in isotopically pure diamond, or alternatively into cryogenic nanoporous silica aerogel, where Ps is emitted into the cavity and thermalized by ballistic phonon emission. Residual translational energy is removed by the same 243 nm laser cooling used for Q2. The critical temperature is about 14 K at a density of 10^{18} cm^{-3} [7]. A staged density roadmap is adopted, with 10^{16} cm^{-3} in Phase I, 10^{17} cm^{-3} in Phase II and 10^{18} cm^{-3} in Phase III. The first milestone alone would exceed the highest Ps densities reported to date, and the intermediate stages already give access to annihilation physics that depends on density, so the value of the program does not rest on reaching the final figure. Verification is triplicated. The primary signal is a departure of the annihilation time spectrum from a single exponential ortho-Ps decay as density is raised, supported by narrowing of the momentum distribution in

2D-ACAR with an angular resolution below 0.1 mrad and by PALS measurements as a function of density.

4.4. Material analysis stations

In parallel with the frontier axes, PALS, CDBS, PAES, TRHEPD, PLI and 2D-ACAR stations are served from the same source. These techniques are mature and provide defect characterization at the vacancy level for semiconductors, quantum materials, and nuclear and space materials, none of which is currently possible domestically at this beam intensity.

5. Conclusions

An in-pile positron source at HANARO, combined with accumulation in a trap, multi-stage brightness enhancement, laser cooling and a cryogenic micro cavity target, defines a credible path toward a positronium research platform that addresses antimatter gravity, bound-state QED and quantum condensation from a single shared front end, and that opens the only concrete experimental route toward coherent radiation at 511 keV. Because the analysis stations and the frontier experiments share the same infrastructure, the facility delivers immediate and quantifiable industrial value regardless of the outcome of any single frontier axis, while giving Korea its first access to a class of antimatter research that is currently impossible domestically.

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