First Observation of a Low-Energy Positron Diffraction Pattern with a Linac-Based Beam

In this study, an experimental station is developed for studying low-energy positron diffraction (LEPD) with a slow-positron beam generated by a linear-electron-accelerator (linac). Diffraction patterns of a Ge(001)-2×1 surface structure are observed with a normal positron incidence. This is the first LEPD observation with a linac-based high-intensity pulsed slow-positron beam. LEPD is expected to be particularly useful for structural analysis of surfaces containing heavy atoms, which are difficult to analyze using low-energy electron diffraction. LEPD can be applied to surfaces of poor flatness and is expected to develop into a method for analyzing local surface structures. It can thus be a complementary method to total-reflection high-energy positron diffraction.

Low-energy positron diffraction (LEPD), which is the positron counterpart of low-energy electron diffraction (LEED), has been evaluated by a LEED theorist as an ideal surface structure analysis method [1]. In 1979, the first LEPD was observed by the Brandeis University group with a channel electron multiplier using a slow-positron beam from a radioisotope (RI) source emitting positrons through β^+-decay [2]. Subsequently they developed a system for observing an LEPD pattern with multiple spots and demonstrated that LEPD experimental results are more closely reproduced by a dynamical diffraction theory than in LEED [3]. Unfortunately, however, LEPD experimental research has been discontinued for about the last two decades because of the difficulty in obtaining a low-energy positron beam with sufficient intensity and adequate quality.

Theoretical works revealed that LEPD has several advantages over LEED [1]. First, LEPD is more surface sensitive than LEED. This is because inelastic scattering cross-sections of the positron are about 1.5 to 2 times larger than those of the electron while elastic backscattering cross-sections are several times to nearly an order of magnitude smaller than those of the electron. This makes the ratio of the inelastic scattering cross-section to the elastic back scattering cross-section, which is a crucial factor for the surface sensitivity, one order of magnitude greater for LEPD than LEED. As a result, LEPD is sensitive to 3 to 5 atomic layers from the surface. Second, positron diffraction suffers less multiple elastic-scattering than electron diffraction for the same reason. Third, scattering factors of positron are simple with a small angular dependence, like those of X-rays. This comes from the fact that the positive charge keeps the positrons away from the inner shell of the atoms, while the electrons are attracted into the core, resulting in complex scattering factors.

Despite the promising properties of LEPD as an ideal technique for studying surface structure, no further experimental LEPD research followed the pioneering work of the Brandeis University group. The difficulty in obtaining sufficient beam intensities, as mentioned above, discouraged researchers from starting LEPD experiments.

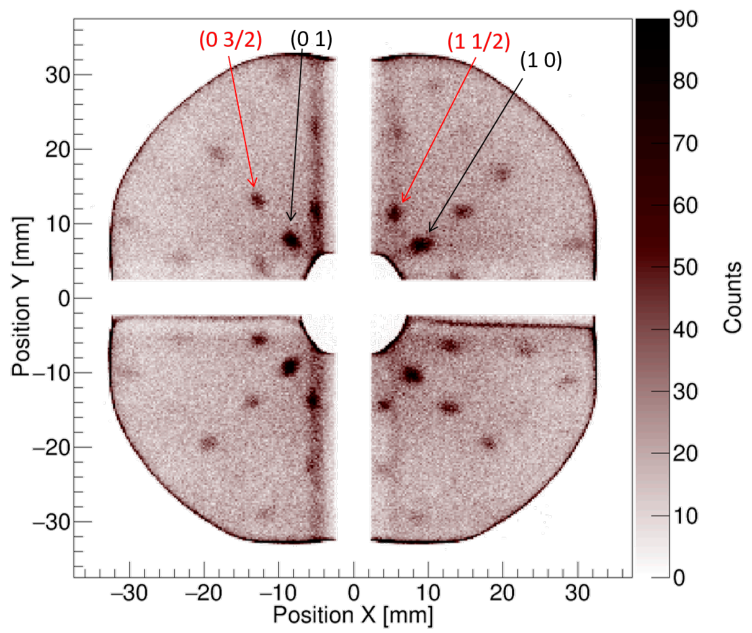

Figure 1: A diffraction pattern of a Ge(001)-2x1 structure observed with a 144.5-eV positron beam generated by a linac [4].

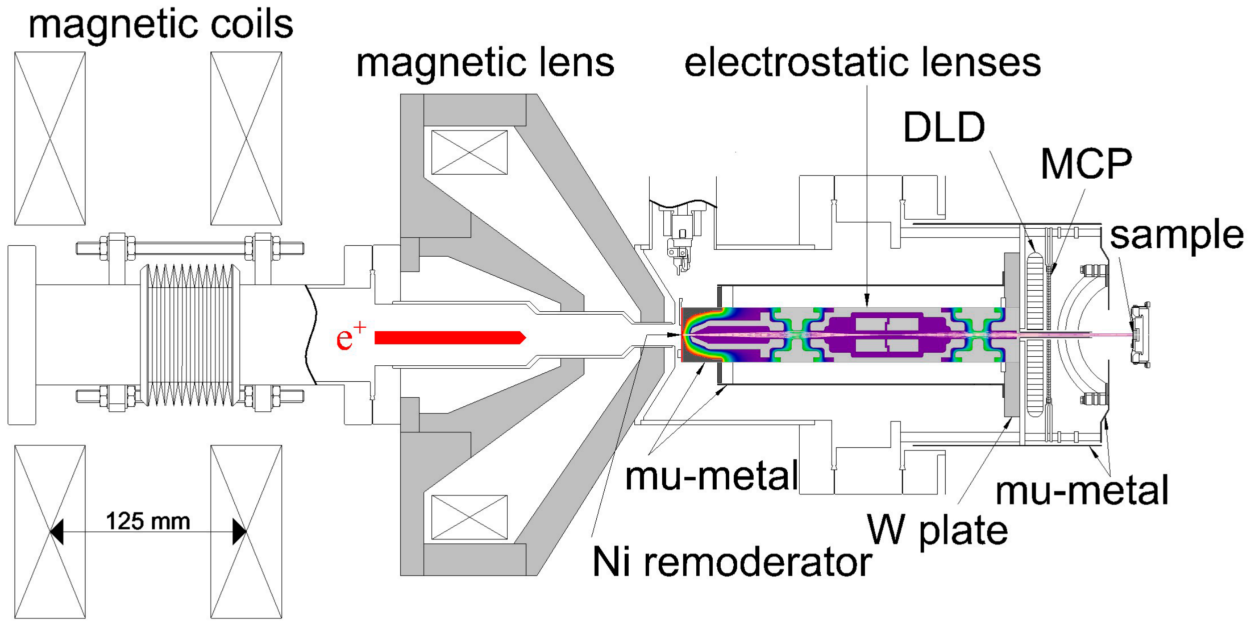

Figure 2: The present LEPD experimental station developed at IMSS-SPF [4]. "DLD" and "MCP" denote delay-line detector and multi-channel plate, respectively.

Slow Positron Facility (SPF) at Institute of Materials Structure Science (IMSS) has overcome this difficulty by utilizing a high-intensity slow-positron beam generated by a linear-electron-accelerator (linac) and succeeded in observing diffraction patterns of a Ge(001)-2×1 surface structure (**Fig. 1**) [4]. This is the first LEPD observation with a linac-based slow-positron beam, and is expected to lead the way in providing another fundamental tool for surface structure analysis for KEK facility users, in addition to total-reflection high-energy positron diffraction (TRHEPD) [5].

There are a number of differences between an RI-based LEPD system and a linac-based one. One difference is the time structure of the beam. While an RI-based system provides a continuous beam resulting from the Poisson random process for positron emission through β^+-decay, a slow-positron beam generated with a normal-conducting linac has a pulsed time-structure reflecting that of the linac beam. A high-intensity pulsed slow-positron beam could cause a multi-hit problem in the detection system with a position-sensitive detector. To address this problem, a pulse stretcher with a Penning-Malmberg trap, approximately 6 m long, has been developed.

Another difference is in the beam transportation methods. The RI-based LEPD system employed electrostatic lenses along the whole beam-line, while linac-based systems transport the beam from a remote positron production unit along the beam-line with a magnetic field. It is more difficult to shield the diffraction observation system from a magnetic field than from an electric field. A new transmission-type brightness-enhancement system with electrostatic lenses has been developed to produce low-energy positron beams, interacting with a sample in a non-magnetic field region, with sufficient intensity and adequate quality (**Fig. 2**).

LEPD is expected to be particularly useful for structural analysis of the surfaces containing heavy atoms, which are difficult to analyze by LEED. As LEPD patterns have properties more suitable for inversion by the Patterson function and holography than LEED, the experimental demonstrations of these are also attractive. LEPD is even applicable to a crystal surface with poor flatness, because of its normal incidence, and is also expected to develop into a method for the analysis of local surface structure.

REFERENCES

[1] S. Y. Tong, *Surf. Sci.* **457**, L432 (2000).
[2] I. J. Rosenberg, A. H. weiss and K. F. Canter, *Phys. Rev. Lett.* **44**, 1139 (1980).
[3] C. B. Duke,"Low-Energy Positron and Electron Diffraction by Solids: Concepts, Models, Calculations and Surface Structure Analyses" in *Positron Spectroscopy of Solids* edited by A. Dupasquier and A. P. Mills Jr. (IOS. Press Ebooks, Amsterdam, 1995.) p. 317.
[4] K. Wada, T. Shirasawa, I. Mochizuki, M. Fujinami, M. Maekawa, A. Kawasuso, T. Takahashi and T. Hyodo*e, e-J. Surf. Sci. Nanotech.* **16**, 313 (2018).
[5] Y. Fukaya, A. Kawasuso, A. Ichimiya and T. Hyodo, *J. Phys. D: Appl. Phys.* **52**, 013002 (2019).

BEAMLINE

SPF-A4

K. Wada[1], T. Shirasawa[2], I. Mochizuki[3], M. Fujinami[4], M. Maekawa[1], A. Kawasuso[1], T. Takahashi[5] and T. Hyodo[3] ([1]QST, [2]AIST, [3]KEK-IMSS-PF, [4]Chiba Univ., [5]Tokyo Gakugei Univ.)