DESIGN, FABRICATION AND COMMISSIONING OF SLOW POSITRON ACCELERATOR AT RADIOCHEMISTRY DIVISION FOR APPLICATIONS IN THIN FILMS

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Abstract
This paper describes the design, fabrication and commissioning of an automated slow positron beam at Radiochemistry Division, BARC. It has primarily three components, namely, slow positron production, focusing and transport, and acceleration of positrons at the target. The positron energy can be varied from 200 eV to 50.2 keV. The estimated beam size and intensity were ~5 mm and $10^4$ positrons/s respectively. The results of preliminary studies are discussed.

Keywords: Positron source, moderator, Einzel lens, solenoid, DC acceleration

Introduction
Positrons have high affinity for atomic scale defects and are sensitive to sub-ppm level concentration which has enabled positron annihilation spectroscopy (PAS) to be a powerful probe in material science. It can identify the size of defects, charge state of defects as found in semiconductors in addition to finding the concentration, the maximum limit being one vacancy in thousand atoms. This has rendered the technique a unique tool for defect spectroscopy. In addition, positron life-time and Doppler broadening of annihilation radiation (DBAR) are sensitive to alteration in electronic environment which makes it possible to characterise phase transition in materials.

Positrons emitted from the radioisotope source (most commonly $^{22}$Na) have a wide energy distribution ranging from practically zero to 500 keV. The implantation of the positrons in the sample is energy dependent and therefore positrons are distributed in the sample over a wide range of depth depending upon the material studied. The positron range in water and metals/alloys are app. 2 mm and less than 1 mm (depends on density) respectively. Due to this reason, PAS (using conventional sources) can not be used for depth selective microstructure characterization of thin films. Slow positron accelerator, that provides a beam of monoenergetic positrons helps in characterising thin films. The most important aspect is depth profiling of defects from surface to bulk by changing the beam energy. Positron beams are also used for study of buried interfaces and a host of other properties in thin films.

Slow Positron Accelerator at Radiochemistry Division

The present beam has three components interconnected under high vacuum viz. slow positron production (Source and moderator), focusing and transport (Einzel lens and magnetic transport), and acceleration of positrons at the target.

Positron Source
Monoenergetic positron beam starts with primary sources having continuous energy distribution. Positrons can be
obtained from radioactive isotopes $^{22}$Na, $^{58}$Co, $^{64}$Cu etc. However, most often used primary source is a radioactive isotope $^{22}$Na. In addition to these natural positron sources, LINAC is also used to generate positrons by pair production. In this case, pulsed electron beam of high energy is stopped in a dense high-Z absorber, creating bremsstrahlung $\gamma$-rays which through pair-production produce positrons. Positrons can also be generated through nuclear reactions.

In our case, $^{22}$Na isotope is used as a positron source. Positrons are obtained from the $\beta^+$-decay of $^{22}$Na isotope according to the decay reaction:

$$^{22}\text{Na} \rightarrow ^{22}\text{Ne} + \beta^+ + n_e + \gamma$$

$^{22}$Na gives a high positron yield of 90.4%. This $^{22}$Na source of 50mCi UHV compatible is mounted on a variable linear mechanism, with a front face of diameter 3mm covered by a thin Ti film and a defect free W(100) single crystal (moderator) of 1\(\mu\)m thickness.

**Moderator**

Positrons generated in the $\beta^+$-decay reaction mentioned above exhibit a broad energy distribution up to an energy of 540keV. These energy distributed positrons can’t be used for depth profiling applications. In order to mono-energize the positrons, moderator is used. Moderation of positrons is a two step process involving thermalisation of positrons and diffusion and emission of these thermalized positrons from the surface of the moderator with energy equal to the work function of positron in moderator material. Positron work function in a material includes bulk contribution which is the chemical potential $\mu$ - and surface contribution known as surface dipole barrier $D^+$. The resultant of the two contributions as shown in fig. … decides the energy of the positron emitted from the surface of the material. Negative work function of positron in the material is required for its emission from the surface. Most of the high efficiency moderators are all negative work function materials with emphasized features such as narrow energy width ($\text{Ni}(100)$) or maximum yield ($\text{W}(100)$). Positrons thus obtained after emission from the moderator surface are emitted preferentially normal to the surface and energy width of the beam is extremely narrow being limited only by the thermal energy of positrons in the lattice, which is advantageous for the beam applications.

We have used W(100) single crystal of 1\(\mu\)m thickness for the moderation. Energetic positrons falling on thin film thermalize in a time scale of few pico-seconds and then diffuse to the surface. These near thermalised positrons (2-3eV equivalent to the work function) are extracted by applying 200eV to the moderator.

**Focusing and transport of the beam**

The positrons extracted from the moderator are focused by an electrostatic lens and are guided towards the sample through a magnetically guided assembly.

Electrostatic lenses are required for extraction, acceleration and focusing of slow positrons emanating from the moderator. An electrostatic lens is an assembly of axially symmetric electrodes (cylindrical), which, are electrically biased to produce equipotential surfaces with shape similar to those of optical lenses. A charged particle passing across these surfaces is accelerated or decelerated, and its path will be curved so as to produce the focusing effect. Direction of force depends upon the curvature of equipotential surfaces. In the region, where curvature is negative, the radial force acting on positrons will point towards the axis leading to the convergence action. On the other hand, positive curvature results in divergent action. Fig.2 shows the equipotential surfaces and resulting particle trajectories.

Focal properties of the electrostatic lens depend upon the diameter of the cylindrical electrodes, the spacing between them and the voltage ratio of the respective electrodes. The three electrode combination is known as Einzel lens, as shown in Fig.1 with operating voltages 195V, 50V and 195V acting in symmetric operation mode. This combination of convergent and divergent lenses produces a resultant convergent beam. Einzel lens can act both in an accelerating as well as decelerating mode depending upon the voltages applied to the electrodes, but the resultant always produces the convergent effect as per light optics.

Positrons thus focused by Einzel lens are transported toward the target position by a magnetically guided system. Focused positrons after extraction from the
moderator are made to travel further via a 90° bent solenoid. This 90° bent section not only acts as an energy filter by which high energy positrons (unmoderated) are eliminated from the beam line but also prevents direct line of sight between the source and the target. Energy selection in this case is simple and effective without the use of complex system like EXB filter. The longitudinal homogeneous guiding magnetic field generated by double layers of solenoid coils made of 1.2mm super-enameled Cu wire is chosen to be around 90 Gauss corresponding to which positrons ejected with energy of 200ev spiral along the guide tube with transverse and longitudinal components of magnetic field providing circular and axial motion respectively as shown in fig…As positrons traverse the bent, they experience a gradient drift velocity $v = \frac{E}{RB}$ where, $R$ is the radius of the bent and $B$ the magnetic field,

$\nu = \frac{E}{RB}$

Monoenergetic positrons thus extracted are made to enter the target chamber mounted at the end of transport tube. The chamber is evacuated by a turbo-molecular and sputter-ion pump to a vacuum level of $10^{-7}$ torr. The magnetic guiding field is extended into the target chamber by Helmholtz coils. The use of helmholtz coils in the target chamber is compelled by geometric reasons. These two coils produce a uniform magnetic field in the chamber so as to focus the positrons to the target. All above beam optics calculations have been carried out using SIMION code and the voltages to moderator, lens assembly have been optimized to get the focused beam. Fig.2 shows simulated beam using SIMION. The voltages applied to the electrodes of the Einzel lens to get the focused beam were optimised 195V, 50V and 195V. The lowest possible positron energy is 200 eV as per the bias of the moderator.

**Acceleration of positrons**

The third component, acceleration of slow positrons is obtained electrostatically by floating the target at variable voltages in the range of 0-50 kV to obtain the positrons having kinetic energy in the range of 200 eV to 50.2 keV at the sample. The voltage at target can be supplied through an automated computerized mechanism at appropriate time difference to carry out the depth resolved defect profiling of the sample. Data acquisition and storage is also carried out using the integrated computer and multichannel analyzer.

**Studies using slow positron beam**

The slow positron beam was commissioned in March 2007. The measured beam intensity on the target was $10^5$ positrons/s. The beam size was estimated ~5 mm (Fig. 3).

Experiments have been carried out in polymers, metals and organic semiconductor thin films to study the behavior of positrons in these different kinds of materials. Positron behavior as depicted from Doppler broadening of annihilation g-rays gives information about the microstructure in terms of pore architecture, porosity, defects, free-volume, voids etc. of the material. DBAR was carried out in nickel metal foil and polymer polyethylene to study the behavior of positron in these
different kinds of materials. S-parameter variation for nickel foil and polythene is shown in Fig. 4. S-parameter decreases with increasing positron’s energy in metals (nickel) but increases in the case of polymers (polythene). Study of positron in metals and polymers shows that decrease of S-parameter in metals is due to the reduction in Ps formation at higher depths as compared to the surface where Ps formation is feasible due to surface states and faults defects near the surface. Increase in S-parameter with depth in polymers shows the presence of more free-volume deep inside the membranes. Above study in metals and polymers shows that Ps formation probability is very low in case of metals than in polymers. The increase in S-parameter observed in polymer is due to the increase of fraction of Ps (p-Ps) in the bulk polymer as compared to the surface. These observations were as per the literature which validated the functioning of the slow positron beam.

Slow positron beam has also been used to study the pore architecture in supported liquid PTFE membranes to understand transport through these membranes. Positron re-emission spectroscopy and Doppler broadening of annihilation $\gamma$-rays has been used to determine the porosity in terms of open and closed porosity as well as the interconnectivity of the pores. Diffusion length of Ps inside the material gives the measure of interconnection and is calculated from the curvature of $3\gamma^22\gamma$ profiles using computer program VEPFIT. Positron re-emission spectroscopy has been used to investigate the surface porosity in these membranes in terms of Ps escaping from the surface of the membranes which is reflected from the $3\gamma^22\gamma$ profiles of virgin and gold coated membranes. Gold coat prevents the Ps to escape and make them coral inside the membrane only and thus give the true picture of pore architecture of the membranes. Permeability of these membranes for uranyl ion transport has been studied and its correlation with the pore architecture of the membranes was tried to be established. Diffusion length of Ps was found to scale inversely with the permeability. Larger diffusion length shows large interconnection and hence large tortuosity which might be responsible for low permeability.

**Summary**

A DC positron beam is designed, fabricated and commissioned which has enhanced the scope of positron research in our laboratory especially characterisation of thin films and devices. It is amongst 20 odd beams being used all over the world. The measured beam size and intensity were ~5 mm diameter and $10^4$ positrons/s respectively. Doppler broadened annihilation radiation measurements have been carried out in different polymer films to reveal the microstructure.

**References**
