A positron moderator using porous metal

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Abstract Two types of porous metal moderators (i.e. porous nickel layer and multi-wire tungsten layer) are proposed and tested on a slow positron beam line. A moderation efficiency of about 2×10^{-4} has been achieved, which is higher than that for W vane geometry moderator by a factor of 4.

Keywords Slow positron beam, Moderator, Porous metal

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1 Introduction

Positron annihilation techniques are powerful tools in the study of point defects in metals and alloys.[1,2] As a development of the techniques in the last two decades, the variable-energy positron annihilation spectroscopy has been proven to be a unique tool for investigating the near-surface defects distribution in solids.[3] However, the intensity of positron beam, or say, the efficiency of positron moderation is an important parameter for developing new methods such as positron annihilation lifetime measurement. In 1980s, the condensed metal moderators and polycrystalline W foil moderator annealed at about 2000 ℃ in high vacuum were discovered, and the obtained efficiencies were in the order of 10^{-4}.[4,5] Nowadays, the well-annealed W is still the most robust and widely used moderator material in most of the slow positron beam facilities for its long-term stability and easy treatment, though the solid-state rare-gas moderators described in Ref.[6,7] have the highest efficiency up to 10^{-2}. It was postulated that the future development may be the use of field-assisted positron moderator, such as SiC.[8,9] Improvement of positron moderation efficiency by either using new moderation materials or modifying the moderator assembly is still attractive in developing intense slow positron beam and advancing the technique research.[8] In this work, two new moderators of porous metal materials, which have much larger surface to volume ratios than the bulk metals, were tested and compared with the widely used W vane moderator.

2 Experimental

The specimens are the bubbling treated nickel layer (SEM image of its porous structure is shown in Fig.1) and multi-wire tungsten layer, both of which are with a thickness of 2 mm and a surface density of 40 mg/cm^2. The tungsten layer was fabricated by irregular arrangement of 15 μm diameter of W wires, and the characteristics of micro-holes in this layer were determined by the freely crossed wires. Each layer was annealed at 1100 ℃ in a vacuum of 5×10^{-4} Pa for 1 h before the measurement of moderation efficiency.

The experimental apparatus consisted of a magnetically guided slow positron beam line equipped with a $\boldsymbol{B}\times\boldsymbol{B}$ energy filter,[10] a tungsten vane geometric moderator and a 18.5 MBq ^{22}Na isotope source. The tungsten vane geometry moderator, containing 15 pieces of 50 μm polycrystal W foil, had been calibrated to maintain a moderation efficiency of 5×10^{-5}. In the present study, it was replaced by the porous nickel layer or multi-wire tungsten layer during each measurement. The slow positrons emitted from moderators were extracted out by a bias voltage of about 100 V. After being energy-filtered and transported to a target, the positrons annihilated with electrons and gave out two 0.511 MeV gamma rays. The annihilation count rates, measured by a NaI(Tl)

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detector system, were used to calculate the positron moderation efficiency and the energy spread.

Fig.2 shows the variation of annihilation count rates for the two porous metal moderators as a function of the retarding voltage applied to an electrode located between the energy filter and the target. For comparison, annihilation count rate for the original W vane-geometry moderator was also shown in this figure. As we see, the annihilation count rates are different for these three moderators when the applied retarding voltages were lower than the positron energies, which indicates that the moderation efficiencies are different and the two new moderators have higher efficiency than that of tungsten vane geometry moderator. The moderation efficiencies of 2.1×10^{-4} and 2.0×10^{-4} can be calculated for multi-wire tungsten and porous nickel, respectively, both are larger than that of W vane moderator by a factor of about 4. After a differential transformation to the curves in Fig.2, the energy spreads or work functions of positron of -2.5 eV and -1.0 eV for multi-wire tungsten and porous nickel, respectively, were estimated.

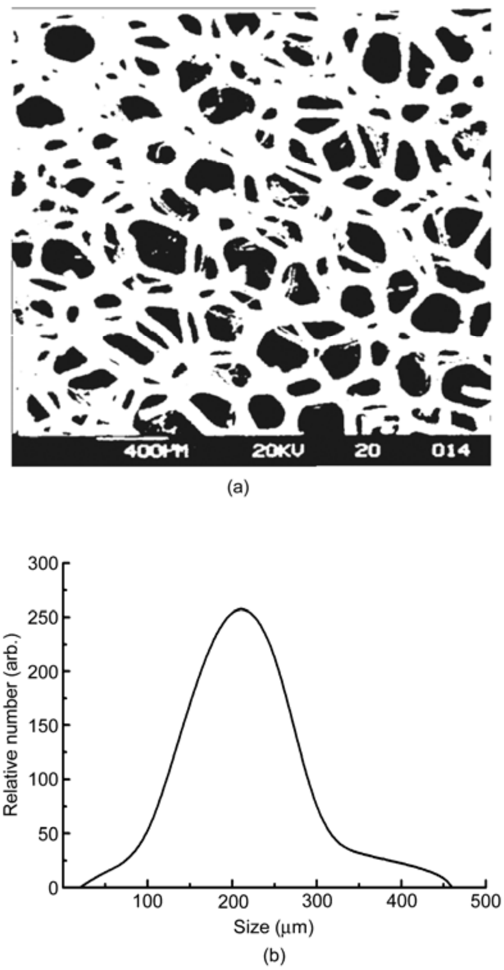

Fig.1 The SEM image (a) and the size distribution for micro-holes (b) in porous nickel.

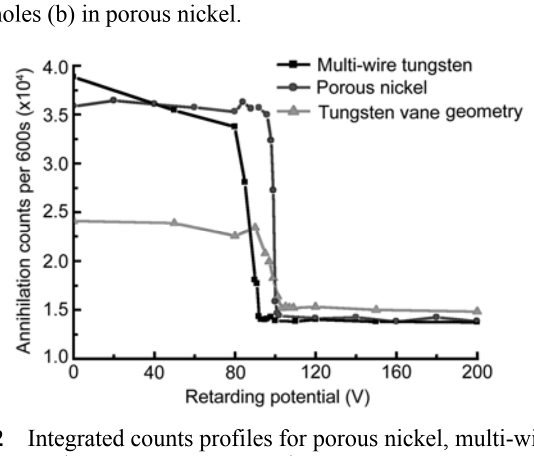

Fig.2 Integrated counts profiles for porous nickel, multi-wire W layer and W vane geometry moderators.

3 Discussion

The moderation efficiency is strongly affected by two factors, i.e. the fraction of fast positrons thermalized down in solid and the probability of these thermalized positrons to be extracted out of the surface. In the case of transmission geometry, usually a thin W foil with thickness much smaller than the positron mean penetration depth is placed directly in front of the source capsule,[11] therefore only a small fraction of fast positrons can be stopped in the foil. For example, a fraction of about 13% fast positrons was stopped in a 2 μm W foil. Another factor determining the efficiency is the emission probability of positrons thermalized in the near-surface region of the moderator. In other words, the amount of effective emission surface is a key factor for the efficiency.

It is known that the positron implantation profiles for a β^+ spectrum are as follows:[12]

$$P(x)=\mu\exp(-\mu x)$$

where $\mu\,(=R^{-1})$ is the absorption coefficient (cm^{-1}) of positrons in the moderator. According to an empirical formula $\mu=17\rho/E_{\max}^{1.43}$, where ρ and $E_{\max}$ are the density of solid ($g\cdot cm^{-3}$) and the maximum energy of positrons emitted from an isotope (MeV) respectively, the mean implantation depth (cm) for fast positrons can be obtained as $R=E_{\max}^{1.43}/(17\rho)$. If the surface density (ρ_s) of a moderator is equal to $2R\rho$, i.e. 48 mg/cm^2 in our case, we have found that $1-(1/e)^2\approx87\%$ of incident positrons can be stopped inside the moderator. Although we didn't obtain an exactly same value as deduced from the above equations, the surface density of 40 mg/cm^2 for the porous nickel layer and multi-wire tungsten was still able to stop about 80% of incident positrons in the porous moderators studied in the current experiment. Meanwhile, due to their porous properties, the two moderators have about 10 times surface area larger than the W vane geometric moderator. Generally speaking, slow positrons emitted out of the porous moderator surface are scattered freely inside the micro-holes and re-injecting into the surface is impossible due to the negative work function of the W or Ni metal. So the probability for positron emission out of the moderator could be linearly proportional to the effective surface area. Considering the moderation efficiency of the W vane moderator equal to 5×10^{-5}, an efficiency as high as 10^{-3} can be roughly estimated for the two porous moderators if all the emitted positrons from the metal surface are extracted out.

Nevertheless, we only obtained a moderation efficiency of 2.1×10^{-4} for the multi-wire tungsten and 2.0×10^{-4} for the porous nickel, by comparing the annihilation counts shown in Fig.2. Although the values are larger than that for the W vane moderator by a factor of about 4, they are significantly lower than the expected value. This can be partially attributed to the relatively low annealing temperature during heat treatments of the moderators, and considerable defects could still exist in the near surface region of the metal and trap positrons. Another reason could be related to the scattering effect between positrons and the surfaces of porous Ni or W wires. Positrons emitted at a deep place of the moderator layers undergo much more collisions before their final emission, and the probability of in-layer annihilation is considerably enhanced. Furthermore, the screening of metal material from electrical field may also be an important factor for the reduction of the number of emitted positrons. In the case of porous Ni and multi-wire W here in Fig.1, the sizes of holes cover a range of 0~500 μm with irregular arrangements. This is probably another disadvantageous factor for increasing efficiency. We expect that further optimization of the size distribution and reduction of the moderator thickness with applying the extraction bias between metal layers may increase the moderation efficiency.

As we know, besides a large value of moderation efficiency, a good positron moderator should maintain its efficiency as long as possible. It is worth mentioning that the porous Ni and multi-wire W moderators used in this study have very stable performance in high vacuum. No observable deficiency was found during several months' operation.

In conclusion, we have found that porous nickel and multi-wire W assemble are valuable positron moderators. Though the measured moderation efficiencies are much lower than the expected, the well designed porous structure may be a hopeful way to improve the moderation efficiency.

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