Compact positron beam for measurement of transmission moderator efficiencies and positron yields of encapsulated sources

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Abstract

We have constructed a simple positron beam for measuring both the efficiencies of positron moderator foils and the positron yields of encapsulated positron beam sources. The slow-positron emission rate from the moderator is determined from the positron annihilation radiation. This technique is also applied to measure source yields. In addition to the coincidence technique, the source yield is determined by measuring electric currents generated by the annihilating positrons. The performance of the system is demonstrated with different tungsten moderator foils before and after heat treatments, and several ^{22}Na sources with primary activities in the range 1–50 mCi.

Key words: Positron beam, positron moderator, positron source
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1 Introduction

The measurement times with monoenergetic slow-positron beams that utilize β^+-active nuclides in the production of positrons are determined primarily by the net positron yield of the source and the conversion efficiency of fast-to-slow positrons of the positron moderator. The practical advantages of ^{22}Na favour its use as a positron source in slow-positron beam applications. A common combination in the production of monoenergetic positrons is an encapsulated ^{22}Na source with a primary activity of 1–100 mCi together with a transmission-type moderator, e.g. W(100) foil. Positron moderator foil efficiencies have previously been studied in Refs. [1–8]. The primary activity (i.e. decay rate) of a ^{22}Na source can be measured to a high accuracy with a coincidence setup by utilizing the 1.27 MeV gamma photon emitted in the decay process [9]. Unfortunately, however, this simple technique cannot be

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applied to determining the net positron yield of the source. To our knowledge, only two studies have been made on measuring yields of encapsulated sources [10,11]. In this work, we present an apparatus for determining both the conversion efficiencies of transmission-type positron moderators, and the net positron yields of encapsulated β^+-active positron beam sources.

2   Setup & Methods

The system consists of i) a vacuum tube with guiding coils and solenoids for performing coincidence measurements to determine moderator efficiencies and source yields (Fig. 1), and ii) a small separate vacuum chamber for determining source yields by electric current measurements. A suitable vacuum level of 10^{-6}–10^{-5} mbar is maintained with turbomolecular pumps to ensure a sufficient positron mean-free-path.
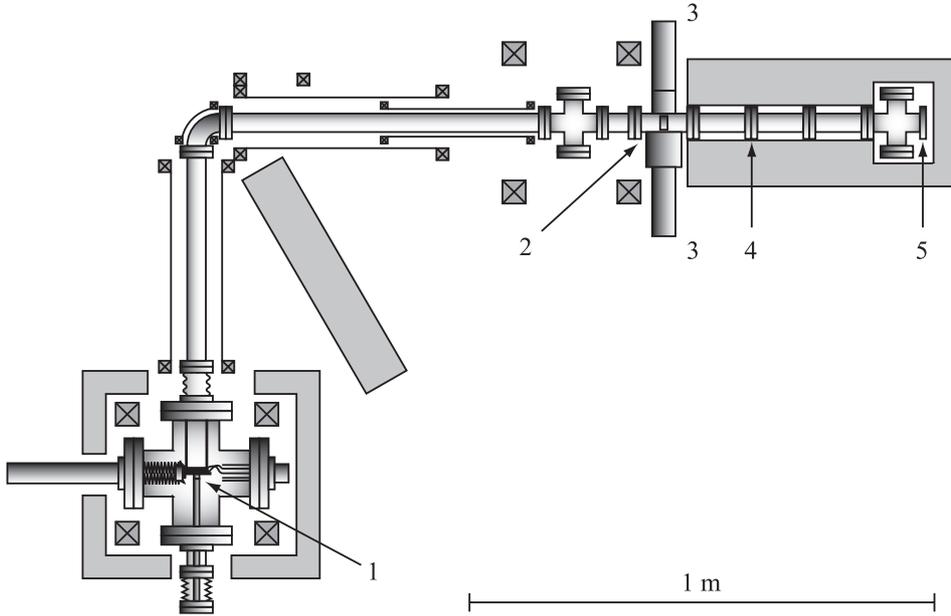

Fig. 1. *Positron beam for determining moderator efficiencies and source yields: 1) 1 mCi ^{22}Na positron source, moderator holder and extraction voltage plates, 2) target, 3) detectors, 4) collimator, 5) flange for positron source. The crossed squares represent the coils and solenoids, and the shaded boxes represent radiation shielding lead bricks.*

2.1   Determining moderator efficiency

For measuring the conversion efficiency of a moderator foil, the foil is attached to a holder and placed in front of a ^{22}Na source capsule with a primary activity of 1 mCi (see Figure 1). In this work, the moderator efficiency is defined as the ratio of slow positrons emitted from the moderator per time unit to the positron yield of the source. The slow positrons are extracted from the moderator by biasing the source–moderator assemblage and using a set of equipotential plates. The positrons are magnetically guided along the beam line by the coils and solenoids. A 90-degree bend in the beam line eliminates

the remaining fast positrons, allowing only the slow positrons to reach the target. The target is made of aluminum to minimize positron backscattering, and biased at -2 kV to prevent the positrons from escaping the target. The positron rate at the target is determined by measuring the rate of annihilation gamma photons with a coincidence setup using two NaI(Tl) scintillation detectors. Care is taken to measure all the possible non-true coincidence events (i.e. chance coincidence, non-moderated positrons etc.) and take them into account when determining the true slow-positron rate at the target. The detection efficiency, including the effects of the measurement geometry, is determined by performing a calibration with a ^{22}Na source of a known activity.

2.2   Determining source yield with coincidence technique

The net yields of positron sources are determined with two separate methods. The first is a similar coincidence measurement as described above. The source under investigation is mounted on the opposite end of the beam line. A copper collimator is situated in the beam between the source and the target, with an aperture spanning a small ($\sim 10^{-5}$ sr) solid angle at the source, to keep the positron rate at the target tolerable for the detector system. It is stressed that in this case the positrons are not guided to the source. Instead, the yield can be calculated when the collimator solid-angle and the spatial distribution of the positron emission from the source are known. To determine the distribution, the source should be rotated with respect to the collimator. At present, this option has not been implemented yet, and the source capsule can only be placed with the window of the source capsule facing the collimator aperture at zero angle. Instead, we use a correction factor based on the results of Massoumi et al. [10] to obtain an estimate of the total yield.

2.3   Determining source yield by electric current measurement

The second method to determine the source yield is by measuring the electric current generated by the annihilation of the emitted positrons. In this method, the source is mounted on a holder which is placed in an aluminum target-tube situated in a vacuum chamber. The source and tube are electrically isolated from each other and from the vacuum chamber, and the source yield is determined by measuring the electric currents between the source, the tube and ground caused by the emitted positrons annihilating in the tube (Figure 2). The decay process leaves the source in a negatively charged state, while on the other hand the target is left in a positively charged state when the emitted positron annihilates with an electron in the target. The electric current is thus directly proportional to the positron emission rate. A vacuum is required to reduce effects such as ionization that could affect the current signal. The end of the target-tube is conical and there is an aluminum foil folded into a spiral to provide additional surface area for positron annihilation and thus to prevent backscattered positrons from returning to the source capsule.

Since typical positron beam sources have an activity level corresponding to electric currents in the picoamper range, care must be taken to protect the
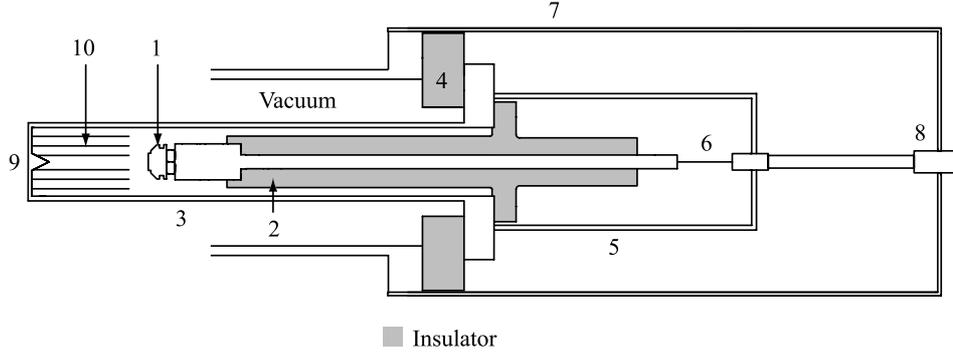
Fig. 2. *Setup for measuring electric current to determine positron yield of source. The source capsule (1) is mounted on a source holder (2) and placed inside the target-tube (3). The holder is made of insulating polyoxymethylene (POM), with a metallic center rod onto which the source is screwed. The target-tube is mounted on a vacuum chamber with a POM flange (4). An inner metallic shielding cylinder (5) is then mounted over the target on the air side, shielding the source holder. A contact probe (6) connected to the center wire of a BNC jack on the cylinder establishes contact with the center rod of the source holder. Finally, an outer metallic shielding cylinder (7) is placed tightly on the vacuum-chamber flange to cover the air side of the entire source–target assembly. The inner conducter and shield of the coaxial cable from the inner shielding cylinder are connected to the inner conductor and inner shield, respectively, of a triaxial jack (8) on the outer cylinder. The construction is designed to minimize electric noise and interference in the current signals between the source and the target. The conical point (9) and folded aluminum foil (10) inside the target-tube are designed to prevent the scattered positrons from returning to the source. Holes were drilled to the back of the target-tube to ensure a good vacuum inside the tube. A picoammeter is further connected via a doubly shielded converter box and triax cable to the jack of the outer shielding cylinder.*

current signal from external electric interference and noise. The assembly is therefore entirely triaxial (see Figure 2). Also, the pumping station is electrically isolated from the vacuum chamber. The current can be measured with a picoammeter in three different ways: between the source and the target-tube (circuit A), between the floating target and ground, while the source is grounded (B), and between the floating source and ground, while the target is kept at ground potential (C).

At present, the current measurement is performed in a separate chamber from the beam line described above, but the two can easily be integrated. Then the current measurement can be performed simultaneously with the coincidence measurement, since the fraction of positrons passing through the collimator aperture is negligible compared to the total positron yield.

3 Results

The slow-positron guidance system was initially tested using an electron gun by monitoring the emitted-to-transmitted ratio of the electron current. In addition, the electron beam was observed visually by replacing the target with a phosphorous screen. The parameters were finally fine-tuned for positrons, using a test moderator foil and by monitoring the coincidence count rate at

the target, to maximize the slow-positron throughput.

3.1 Moderator conversion efficiencies

The conversion efficiencies of a 3 μm thick polycrystalline tungsten foil, purchased from Goodfellow (GF), and two 1 μm thick single-crystal W(100) foils, prepared at the University of Aarhus, Department of Physics and Astronomy (AU), were measured before and after different heat treatments. The heat treatments were performed by electron bombardment under UHV conditions (base pressure $\sim 10^{-9}$ mbar). The single-crystal foils were annealed in a single cycle of less than one hour, at a peak temperature of around 2000°C, whereas the heat treatment of the polycrystalline foil was performed in multiple cycles, lasting several hours in total, reaching a peak temperature of ~ 1800°C. An oxygen treatment was performed on all foils after the annealing to remove carbon traces from the foils. This was done by releasing oxygen into the annealing chamber up to a pressure of 10^{-6} mbar for a few minutes, while maintaining a temperature of around 1000°C. After annealing, the foils were exposed to the atmosphere for no longer than fifteen minutes between transportation from the annealing chamber to the beam.

The measured efficiencies are presented in Table 1. The efficiencies are in the typical range of 10^{-5}–10^{-4} [3,4,6,8]. Both faces of the annealed single-crystal foils were studied, and they were found to differ by a factor of 1.4. The cause lies perhaps in the growth or annealing procedures of the foils. XPS studies performed on one of the single-crystal foils revealed traces of thoria, emitted from the heating filament during annealing, on one side of the foil. Interestingly, an efficiency by a factor of 4 higher was obtained for the polycrystalline foil than for the single-crystal foils. Two immediate possible explanations for this arise: the difference in the annealing processes and the different thicknesses.

Table 1

Measured fast-to-slow conversion efficiencies and statistical errors of positron moderator foils. The two values for the single-crystal tungsten foils after heat treatment correspond to the two faces of the foils.

Foil	Foil material	Before ann. (10^{-4})	After ann. (10^{-4})
GF	3 μm polycryst. W	≤ 0.004	2.3 ± 0.3
AU #1	1 μm W(100)	–	0.53 ± 0.06 / 0.77 ± 0.08
AU #2	1 μm W(100)	0.18 ± 0.02	0.53 ± 0.05 / 0.73 ± 0.08

3.2 Source yields

The yields of three ^{22}Na source capsules with primary activities in the range 1–50 mCi, purchased from Brookhaven National Laboratory (BNL) and iThemba LABS (iTL), were measured. The results obtained with the coincidence technique are presented in Table 2. Two values for the total yield were calculated:

one assuming isotropic emission in a 2π solid angle from the source, and another using the correction factor to take the anisotropy into account. As for the current measurements, all three circuits yielded virtually identical results (Table 3). Because the emission profiles of the sources was not studied, the corrected values obtained with the coincidence technique are mere estimates. However, in the case of the two iTL sources, they are in good agreement with the yields obtained by electric current measurements. Moreover, the relative yields of the BNL and iTL #1 sources scale with the actual count rates of the Doppler broadening measurement in our slow-positron beams when these sources are used with the same moderator. In addition to the estimative nature of the coincidence measurement results, the difference in the yields of the BNL source may result from the inaccuracy of the picoammeter used for measuring the currents. The current generated by the source was close to the limit of the ammeters range of operation.

Table 2

Positron yields of different encapsulated ^{22}Na positron sources determined with the coincidence technique. The first values were calculated assuming isotropic emission in a 2π solid angle. The second values are corrected to take the emission anisotropy into account. The positron emission probability of 90.5% in the decay of ^{22}Na has been taken into account when calculating the yields.

Source	Primary act. (mCi)	Yield (isotr.) (%)	Yield (corr.) (%)
BNL	1.0	47 ± 2	19 ± 2
iTL #1	51	19 ± 1	8 ± 1
iTL #2	30	74 ± 3	30 ± 4

Table 3

Positron yields of different encapsulated ^{22}Na positron sources determined by electric current measurement. The three values for each source correspond to the different measurement circuits.

Source	Yield (A) (%)	Yield (B) (%)	Yield (C) (%)
BNL	28 ± 2	28 ± 2	28 ± 2
iTL #1	9.2 ± 0.3	8.7 ± 0.2	9.2 ± 0.2
iTL #2	31.8 ± 0.4	30.8 ± 0.3	31.7 ± 0.4

4 Summary

We have constructed and tested apparatuses for measuring efficiencies of transmission positron moderators and net yields of encapsulated positron sources. The slow positrons emitted from the moderator are detected with a coincidence setup using two scintillation detectors. The source yield is measured by detecting the emitted positrons with two individual methods: a coincidence setup and a current measurement. The system was tested with different tungsten moderator foils and ^{22}Na sources. Conversion efficiencies of 10^{-5}–10^{-4}

were obtained for the foils after heat treatment. The positron yields of the tested source capsules were discovered to be between 9% and 31%.

Acknowledgements

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