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# Development of a spin-polarised positron beam

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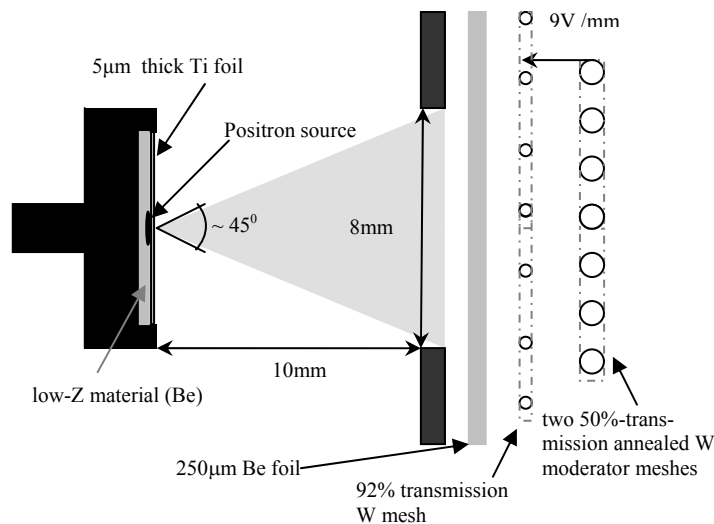
**Abstract.** The development stages of a system for variable-energy spin-polarised positron beam spectroscopy are described. Methods for achieving maximum practical beam polarisation include a Na-22 source configuration with a low-Z backing to reduce positron backscattering, and positioning a 250 $\mu\text{m}$  beryllium foil in front of the source to absorb the slower and decelerate the faster beta positrons, the latter suffering significantly less depolarisation during moderation than the former. To switch the direction of spin polarisation of electrons in the target sample the direction of the positron guiding field was reversed, and strong rare earth magnets were placed behind the sample. Systematic problems associated with low beam intensity and electronic drifts are discussed. Results for single-crystal iron compare well with those expected from theory, but suggest a beam/target polarisation of  $\sim 5\%$  of that expected. Prospects for future beam development and application are outlined.

## 1. Introduction

Variable-energy spin-polarised positron beam spectroscopy (VESPAS) has the potential for application in areas of current scientific and industrial interest such as in depth profiling nano-magnetic structures or of dilute magnetic species in a semiconductor layer developed for spintronics. The principle of the technique is that positrons are  $\sim 10^2$  times more likely to annihilate electrons with opposite spin than with parallel spin [1]. Thus, if the incident positron beam is spin-polarised and the spin orientation of the polarisable electrons in a sample is reversed from the parallel to the anti-parallel direction, then the change in the shape of the two-photon annihilation gamma energy line centred at 511keV is essentially due only to the annihilation events involving the spin-polarised electrons. The magnitude of the lineshape change is reduced by partial beam/target polarization and by the non-negligible probability of three-photon annihilation events (originally discussed by Berko [2]). In a series of papers thirty years ago the Michigan group showed that beta positron polarisation survives the moderation process [3], and there have been programmes to develop polarised positron beams in the intervening years [4]. Recently Cassidy *et al* [5] found that their solid-neon-moderated beam had a polarisation of 22%.

A development programme aimed at maximizing both the beam and target polarisation, both of which are described in the following sections, has led to an understanding of the many problems attached to the implementation of VESPAS as a routine tool. While systematic problems such as those associated with electronic instabilities can be overcome, the fundamental problems of low signal rates and the consequences of the need for high magnetic fields at the target remain a challenge. Trial measurements have been made on a variety of samples, including iron in different states (high purity, annealed, single crystal), mu metal and solid oxygen (alpha phase) [6]. Experimental results for iron are compared with calculations.

## 2. Polarising the Positron Beam



**Figure 1:** Sketch of source-moderator setup to maximise positron beam polarisation.

In order to obtain significant positron beam polarisation a number of modifications have been made to the standard source-moderator geometry [7], represented in Fig. 1. It is more probable that beta positrons emitted from the  $^{22}\text{Na}$  source with higher energies retain their polarisation throughout their lifetime. Unfortunately it is the *lower-energy* beta positrons which are preferentially moderated to form the beam. To combat this, a thin Be foil was positioned in front of the source to absorb the slower beta positrons and slow down the faster, more highly polarised positrons. The foil thickness -  $250\mu\text{m}$  - was chosen with reference to the results of ref. [3]. As beta positrons are spin-polarised in the emission direction the  $^{22}\text{Na}$  source capsule was modified; the source is deposited on a  $0.5\text{mm}$ -thick Be backing plate to minimise the backscattering of positrons (a Ta plate is usually used to maximize backscattering and thus positron flux) [3]. Positrons are polarised in their initial direction of emission.

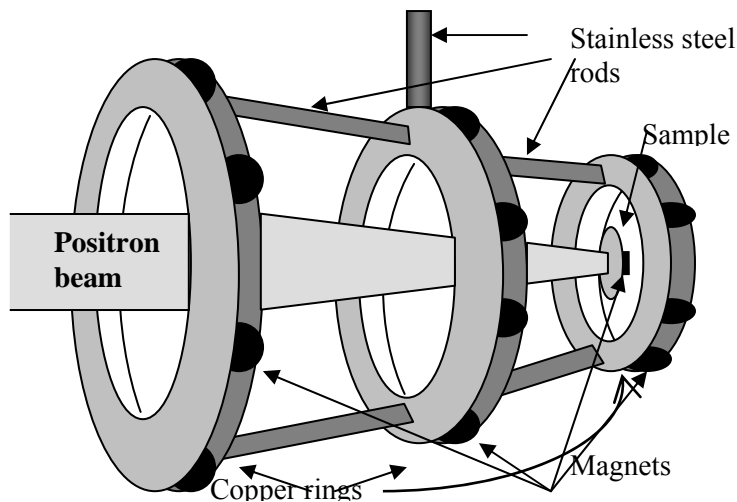
The source was positioned at  $\sim 10\text{mm}$  from the moderator (normally at  $\sim 1\text{mm}$ ) to decrease the angle of acceptance to  $45^\circ$ , which is well within the range suggested by Major [8]. As a result of installing the Be absorber and repositioning the source the positron beam intensity fell to below 5% of its original value, but the beam polarisation is expected to have increased to more than 50% [3].

## 3. Polarising the Sample

Various methods of orienting target electron spin directions have been investigated. Neodymium Grade N42 magnets [9] have been used behind or around the sample target to create a localised field in the direction required; magnetic lensing (Fig. 2) and an in-vacuum electromagnet were also trialled. The positron magnetic guiding field (100G) was also reversed. This rendered the operation of the curved-plate  $\mathbf{ExB}$  filter [7] ineffective, a problem overcome by disconnecting the plates and using external permanent magnets to effect the required beam deflection.

Iron and mu-metal samples were expected to be 100% spin-polarised when placed immediately in front of a Nd N42 magnet, while only partially polarised by the other methods attempted. In the case of iron, the ferromagnetism is associated with the polarization of the 3d electrons. Antiferromagnetic  $\alpha$ -phase solid oxygen, chosen because it is an insulator and because the polarisable electrons are in the outermost shell, could only be magnetised by the guiding field for practical reasons associated with rotating magnets and regrowing the sample; it was therefore expected that, while potentially interesting as a positron target, this sample would give a very small response.

Positrons of incident energy  $30\text{keV}$  were used for these first measurements, to probe the well-known bulk magnetism of the samples and avoid any near-surface effects.



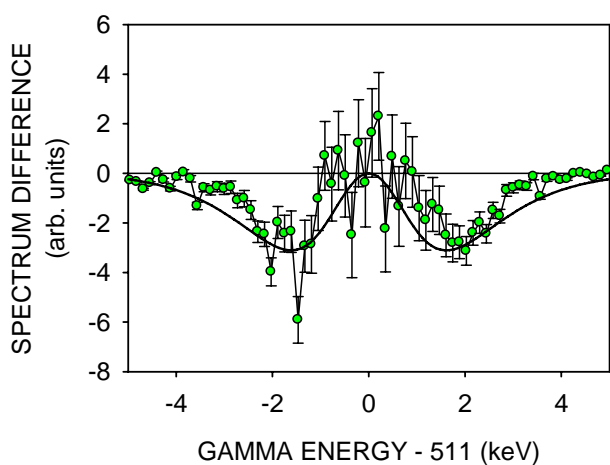
**Figure 3:** Experimental setup for polarising a sample using magnetic focusing.

The annihilation gamma photon count changed by up to 10% when the field direction and magnet orientation were reversed, mostly due to losses in the ExB plates. Careful subtraction of the background, which is not negligible in these low-signal-rate measurements, was therefore required to eliminate any consequent systematic effect on the results.

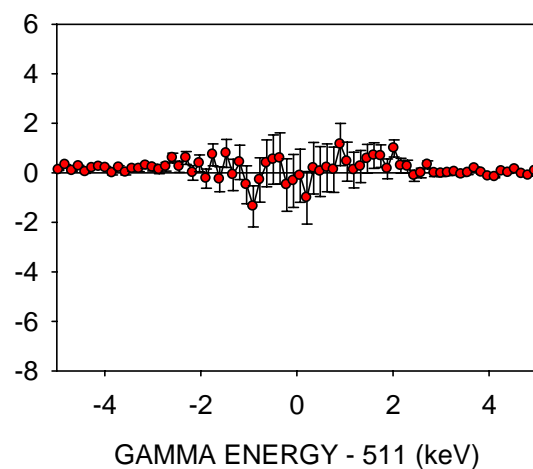
Measurements on Al and Si – of dimensions similar to the magnetic targets studied - were taken in order to investigate the stability of the system. False positive results were obtained when the detector resolution (and thus measured lineshape) was affected by variation in electronic noise, the use of very small samples and/or the presence of high magnetic field gradients in the vicinity of the sample (when positrons could proceed to, or be deflected into, annihilation sites other than the intended target).

#### 4. Results and Discussion

Samples studied included pure Fe (99.999%) – both as-supplied and annealed – single-crystal Fe,  $\mu$ -metal, and solid oxygen, in order to test the effectiveness of the system with samples of varying electronic structure.



**Figure 3:** Normalised spectrum difference for a single crystal Fe in front of a Nd magnet. Solid line: theoretical result using the program MIKA-Doppler [10].



**Figure 4:** Normalised spectrum difference for  $\alpha$ -phase solid oxygen (same scale as for Fig. 3).

Only single-crystal Fe held in front of a Nd magnet (field  $\sim 0.6$ T) gave a signal of the type expected when annihilation line spectra recorded with the external field in the two directions were background-subtracted, normalised and subtracted (Fig. 3, in which data points have been added in groups of 10). The solid line in Fig. 3 is the scaled difference calculated using the MIKA-Doppler package [10] – essentially the contribution to the annihilation line of 3d electrons – after convolution with the experimental detector resolution of 1.4 keV. While the shape of the difference is in reasonable agreement with the observation, the scaling factor of 0.025 suggests that the combined effective polarisation of the beam and target is about 5% of that expected.

No significant results were observed for any other samples, as exemplified by null result shown for  $\alpha$ -phase solid oxygen (Fig. 4). The sample was grown in situ and was thought to be crystalline, with plenty of vacancies and lattice imperfections but essentially no free electrons; therefore polarisable electrons should make a significant contribution to the annihilation spectra. However,  $\alpha$ -phase solid oxygen is anti-ferromagnetic [11] with a very small magnetic susceptibility, and it is concluded that the sample magnetisation was not sufficient for observation by the spin polarised positrons in the current system. For the pure Fe, pure annealed Fe and  $\mu$ -metal samples, the failure to see an effect may be explained by the dominance of annihilation from vacancies and other trapping sites.

## 5. Conclusion

The results shown in Fig. 3 demonstrate that a spin polarised positron beam can be generated using a modified ‘standard’ magnetic-transport positron beam system, and that it can probe spin-polarised samples in magnetic targets. However, the very small response – 5% of that expected – suggests that either (a) the beam polarisation is only a few %, or (b) the magnetic field in the vicinity of the target is not strong enough. Having followed the recipe of Rich *et al* [3] it is felt unlikely that (a) is the case; a polarisation closer to 50-60% is expected. The recent observation of Cassidy *et al.* [5] suggests that a rare gas moderator, or any other moderator which does not rely on thermalisation and work function emission, may have a smaller depolarisation effect on the primary beta positrons. Increasing the magnetic field at the sample is problematic with the current system, and would require a complete redesign of the target chamber to accommodate a strong electromagnetic or, perhaps, a superconducting magnet. The transition between the 100G guiding field and a  $\sim 1$ T target field would, however, have to be carefully controlled. An appropriate choice of moderator, an intense positron source, and a strong (reversible) magnetic field would seem essential if VESPAS is to succeed as a valuable probe of magnetic films of current technological importance.

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