The Bristol HIDAC 2D-ACAR Spectrometer

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Abstract. We describe the Bristol spectrometer for positron annihilation Fermi surface studies utilising high-density avalanche chambers (HIDACs) as position sensitive detectors. Measurements on α-SiO$_2$ show, through the momentum distribution of para-positronium, the substantial improvement in resolution compared to Anger cameras. Measurements of the Fermi surface of V are used to determine the resolution. The new spectrometer is found to have an efficiency of 12.5 ± 0.6 % and a (coincidence) contribution to the position resolution of 0.96 ± 0.1 mm.

Introduction

Together with the closely related technique of Compton scattering [1, 2, 3], positron annihilation has established itself as a powerful probe of the Fermi surface (FS) of a variety of materials [4]. With its ability to deliver a direct image of the occupied momentum states (through the Lock-Crisp-West (LCW) folding of the measured momentum distribution back into the first Brillouin zone [5]), and hence the FS, two-dimensional angular correlation of positron annihilation radiation (2D-ACAR) experiments have been able to reveal Fermi surfaces whose particular shapes are thought to be responsible for a wide range of phenomena from the magnetic ordering of $f$-electron magnetic moments in Gd-Y alloys [6] and ferromagnetic shape-memory alloys such as Ni$_2$MnGa [7], through weak ferromagnets close to quantum critical points [8, 9] to borocarbide superconductors with nested FS sheets [10, 11]. The unique properties of the positron have even been exploited to uncover the FS of nanoscale precipitates in Al-Li alloys [12].

Position Sensitive Detectors

The 2D-ACAR technique utilises the positron as a probe and relies on the coincidence measurement of the two annihilation photons’ positions [4]. Thus the angular deviation, which is directly related to the electron momentum, is resolved and the momentum density can be mapped out. Experimentally, the spectrometer assembly comprises two position sensitive detectors (PSDs) (almost) symmetrically positioned with respect to the source/sample chamber. The four main objectives a detector system for 2D-ACAR needs to meet are good spatial resolution (if instrument resolution function deconvolution is to be avoided [13, 14]), high detection efficiency for ~ 511 keV photons, sufficient resolving time for the coincidence measurement and long term stability, as normal acquisition times are of the order of weeks. These technological requirements are, however, hard to meet simultaneously and a trade-off between them usually forces compromise.
Historically, different detector technologies have been used, but three types have emerged. The first 2D-ACAR machine built by Berko [15] utilised multi-element scintillation counters and such an approach has been followed recently by others [16]. The second type of PSDs are so-called Anger Cameras, which have been adapted from medical imaging and use a Tl-activated NaI crystal optically coupled to a hexagonal closed-packed array of photomultiplier tubes [17]. Pioneered by West, the first spectrometer was built in the late 1970s [18], and a similar setup was in operation in Bristol for nearly two decades. Anger cameras offer modest resolution (< 4 mm, although some recent approaches should improve on this [19]), exceptional electronic stability, good resolving times of the order of nanoseconds (∼ 50 ns) and coincidence efficiencies of ∼ 10%. Amongst all PSDs the last type, namely the High Density Proportional Chambers (HDPC), stands out due to its excellent resolution. The concept of HDPCs being a Multi-Wire Proportional Chamber (MWPC) embedded in Pb photon-electron converters is due to Jeavons [20, 21, 22]. However, although the resolution of 1.0 mm was exceptional, the weak point resided in relatively long coincidence resolving times (> 100 ns) causing appreciable background contributions due to accidental coincidences. Moreover, the comparatively low coincidence efficiencies (∼ 8%) demanded more technological developments in order to compete with the Anger Camera [18, 22, 23].

In recent years the HDPC has mostly been applied to the medical imaging technique of Positron Emission Tomography (PET), which stimulated further developments and culminated in various technological improvements tackling its efficiency [24]. In particular the newest generation of the so-called HIDAC (where the acronym stands for HHigh Density Avalanche Chamber) provides sub-millimetre position resolution combined with nanosecond coincidence timing and a high efficiency of ∼ 11% [24, 25]. Consequently, such a system is ideally suited for application in a 2D-ACAR spectrometer, since it does not only result in shorter acquisition times than the older versions, but also permits FS investigations with unprecedented precision, and will allow systems with small Brillouin zones (e.g. complex systems with large unit cells such as Lu₅Ir₄Si₁₀ [26]) to be studied.

Figure 1. The current HIDAC design as utilised in the Bristol spectrometer includes a stack of seven modules with an active area of 290 × 280 mm².

Figure 2. (a) One HIDAC module consists of a gas-filled MWPC with electron-photon converters either side. The converters constitute alternating layers of Pb-Sb alloy and insulation, drilled with a matrix of holes. (b) The HIDACs operate by incident photons releasing electrons which enter an adjacent hole and avalanche towards the MWPC in which they are detected. The position information is then extracted via the printed cathode tracks.

MWPCs possess a dense 2D wire grid, where each wire acts as a proportional chamber resolving the position of the incident particle [27]. The use of gas-filled MWPC for γ-rays has been proven useful up to energies of 8 keV, above which the photoelectric capture cross-section in the gas becomes strongly suppressed and the detection efficiency drops dramatically. The
logical consequence of such behaviour led to the introduction of a denser medium in order to increase the capture efficiency. These so-called converters serve to convert the non-(gas-)ionising photons to ionising particles which can subsequently be detected by the MWPC. The (2.5 mm) converters comprise 12 stacked sheets of a Pb-Sb alloy (50 µm) separated by fibre-glass reinforced epoxy-resin interlayers (140 µm). A hole-matrix with 0.4 mm diameter and 0.5 mm pitch is drilled into the converter, which would ideally deliver sub-millimetre intrinsic spatial resolution while providing a greater surface area and thus higher efficiency. Fig. 2a depicts a HIDAC module (comprising MWPC and converters). Photons interact with the Pb-Sb alloy and liberate fast electrons via the photoelectric (or Compton) effect. The free electrons (Fig. 2b) then escape via an adjacent hole, where in order to guarantee efficient extraction an additional electric field focuses the photo-electrons onto the centre of the hole and the gradient accelerates them resulting in an avalanche effect from gas ionisation as they travel to the MWPC. More details can be found in Ref. [28].

The Bristol HIDAC spectrometer

The HIDAC system utilised in the Bristol 2D-ACAR spectrometer has been developed, constructed and installed by Oxford Positron Systems and the design follows broadly their most recent 3D HIDAC-PET [24, 25]. In the current 2D-ACAR version, one detector consists of seven stacked individual HIDAC modules. Each module constitutes an individual unit including its own MWPC and set of two solid converters. The sensitive area is rectangular in shape and the dimensions of (290 x 280) mm$^2$ give an acceptance angle of ±14 mrad at a sample-detector distance of 10 m. In order to minimise any resolution degradation due to small misalignments of individual modules relative to each other within one HIDAC detector and relative to the other detector, an iterative post-processing procedure is applied to the list-mode data.

Spectrometer Resolution

The characteristic spectrum of $\alpha$-SiO$_2$, featuring thermalised para-positronium (p-Ps) peaks at $p = 0$ and ‘Umklapp’ (higher-momentum components) at the reciprocal lattice points, provides the most obvious way to compare resolution functions, since these peaks are assumed to be $\delta$-functions convoluted with the experimental resolution. Fig. 3a shows such spectra measured with the new HIDAC spectrometer at low temperature (20 − 35 K) and a sample-detector distance of 10 m. For comparison, Fig. 3b shows the equivalent spectrum measured in the old Anger Camera system at similar temperature and a sample-detector distance of 12 m. The difference in the resolution underlying these two spectra is clearly evident in the respective widths of the p-Ps peaks in the $p_x$ direction (where the only additional contribution to the intrinsic detector resolution is due to the temperature broadening). The substantial improvement in resolution is also clearly evident in the ratio of the central peak height to the broad background coming from electron-positron (rather than p-Ps) annihilation.

When the intrinsic detector resolution only provides a small contribution to the total angular resolution, this kind of measurement is governed by various difficulties. For example, at the level of resolution expected for the new HIDAC system, many-body effects may start to broaden the p-Ps peaks (e.g. [29]). In order to gain a more accurate picture of the coincidence resolution an alternative method based on the momentum distribution of a metallic system was employed. Here a well studied and simple metal with strong FS features that are well described by first-principles calculations serves as a reference measurement for the new, high-resolution 2D-ACAR apparatus. Such an approach then allows the resolution to be modelled by electronic structure calculations. The ideal candidate for such a reference measurement is the [100]-projection 2D-ACAR spectrum of V. The projected FS along this direction is dominated by the strong features due to the projected $N$-hole pockets [30, 31], and the electronic structure is well described by theoretical predictions from first-principles calculations [32, 33].
Figure 3. SiO$_2$ spectra measured with the (a) HIDAC and (b) Anger Camera spectrometers.

Figure 4. (a) The LCW of V ([100] projection) as measured on the HIDAC spectrometer (b) The convoluted results of the optimised LMTO calculation (Ref. [33]).

The high-statistics data (300 million counts) were processed as described in Ref.[28] and histogrammed on a (1024 $\times$ 1024) mesh with a calibration of 0.05 mrad/channel. The detectors were located at an average distance of 8 m, with one detector offset by $\Delta z = 0.3$ m with respect to the other which ensures a smooth, flat-topped momentum sampling function [28]. The theoretical result convoluted with the fitted resolution is compared to the experimental data in Fig. 4. The FWHM of the fitted resolution function corresponds to a resolution of $\Gamma_x = 1.25 \pm 0.05$ mm and $\Gamma_y = 8.10 \pm 0.08$ mm, where the $y$-resolution is completely dominated by the finite source spot on the sample. Finally, $x$-resolution can be decomposed into a temperature-dependent part and the intrinsic detector coincidence resolution. The temperature contribution at $T = 4$ K, assuming an effective mass of $m^* \sim 1m_e$, is $\Gamma_x = 0.8$ mm. Thus the intrinsic coincidence contribution to the detector resolution is $\Gamma_c = 0.96 \pm 0.1$ mm (including estimates
of the temperature contribution and the error of the fit), which is very similar to the results obtained in PET applications [24]. Finally, the single detector position resolution is estimated to be $\Gamma_i = 0.68\,\mathrm{mm}$, which is (perhaps unsurprisingly) in close agreement with the converter hole pitch of 0.5 mm, particularly taking into account that the processing electronics and the data treatment itself (e.g. LCW-folding) will contribute some broadening as well. One should also note, that here the coincidence detector resolution is determined by the intrinsic detector resolution in quadrature (i.e. $\Gamma_c = \sqrt{2} \cdot \Gamma_i$). However, as observed for Anger Camera systems, where the intrinsic position resolution is well defined via for instance single camera images of a phantom, in the case of HIDAC such measurements are precluded due to the required accuracy of the phantom at the current level of resolution, and determinations via the coincidence detector resolution in practice result in a factor between $\sqrt{2}$ and 2 [18]. Hence, the estimate given here can be viewed as an upper limit on the intrinsic spatial resolution of the HIDAC. As a result, this number quantifies the last performance characteristic of the new spectrometer and proves the high level of resolution reached in the new 2D-ACAR system utilising HIDAC detectors.

**Detector Efficiency**

In the case of HIDAC detectors the major factors influencing their efficiency are the size and number of modules as well as the converter’s hole matrix. The small hole sizes and the dense hole grid in the converters affect not only the resolution but also provide a larger effective internal surface area for interactions, increasing the probability of electron escape from the Pb-Sb alloy. From measurements of count rates in coincidence and anti-coincidence (the latter corrected for non-sample-related background), the efficiency of a single module was calculated to be $\epsilon_s \sim 2.5 \pm 0.3\%$ [28]. The total detector efficiency, of all seven modules (including the attenuation factor of the converters) was calculated to be $\sim 12.5 \pm 0.6\%$.

**Paramagnetic phase of NbFe$_2$**

Finally, in order to demonstrate the new spectrometer on a ‘new’ material, in Fig. 5 the radial anisotropy of a [01\overline{1}0] projection of NbFe$_2$ is shown alongside theoretical calculations [32]. There is clear agreement in the shape of the anisotropy between experiment and calculation. This

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**Figure 5.** Radial anisotropies (at 20K) for the [01\overline{1}0] direction in NbFe$_2$ from experiment (left) and theory (right).
measurement is part of a wider study to understand the role of electronic structure in governing the magnetic properties of the quantum-critical Nb$_{1-y}$Fe$_{2+y}$ system [34, 35, 36, 37, 38].

Conclusions
The Bristol HIDAC 2D-ACAR spectrometer is a powerful tool for Fermiology. Future work will focus on determining the FS in electronically complex materials, and, for example elucidating its role in driving charge-density waves in materials like RNiC$_2$[39, 40].

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