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ABSTRACT

The spectral response of a $100 \times 100 \mu\text{m}^2$ tantalum based superconducting tunnel junction to 5.9 keV X-ray photons from a ^{55}Fe source has been studied. In full illumination the energy resolution for the Mn- K_{α} line complex is 56 eV, dominated by spatial nonuniformity in the response of the detector. When illuminating selectively a 5-10 μm diameter spot in the centre of the detector, the energy resolution improves to 22 eV, corresponding to 15.7 eV for the individual Mn- $K_{\alpha 1}$ and Mn- $K_{\alpha 2}$ lines. This exceeds the predicted theoretical energy resolution of 7.3 eV for this type of device by only a factor ~ 2 .

Superconducting tunnel junctions (STJs) are investigated extensively as photon and particle detectors because of their predicted high energy resolving power¹. This high energy resolution arises from the much lower energy necessary to generate detectable electronic excitations, compared to semiconductor- or gas-based detectors. In the case of a superconductor these excitations (quasiparticles) are produced by the breaking of Cooper pairs, which typically requires $\sim$ meV. For a common superconductor as Nb, the number of quasiparticles produced by the absorption of a photon with energy E is:

$$N_o(E) = \frac{E}{\epsilon} \pm \sqrt{\frac{E}{\epsilon} F} \quad (1)$$

Here $\epsilon \approx 1.74\Delta$ (with 2Δ the energy gap of the superconductor) is the average energy required to generate one quasiparticle and $F=0.22$ is the Fano factor^{2,3}. The quasiparticles can be detected through tunneling across the thin insulating barrier of a STJ. The amplitude of the signal pulse measured after the absorption of a photon will, in a first approximation, be proportional to the number of generated quasiparticles and, thus, to the energy of the photon. The fundamental limit for the energy resolution is set by the Fano factor and would be $\Delta E_{Fano} \approx 3$ eV (Full Width at Half Maximum) for a 6 keV X-ray photon in a tantalum STJ, assuming the values for F and ϵ are similar to the those calculated for Nb. In a practical STJ detector additional statistical fluctuations occur in the number of tunnelled electrons. For a symmetrical STJ as used for this work, the limiting energy resolution arising from statistical fluctuations is given by^{4,5}:

$$\Delta E_{stat} = 2.355 \sqrt{\epsilon E (F + 1 + \frac{1}{\langle n \rangle})} \quad (2)$$

with $\langle n \rangle$ the average number of tunnel processes per quasiparticle. Typically, the statistically limited energy resolution of a Ta based STJ with $\langle n \rangle \geq 10$ will be $\Delta E_{stat} \approx 7$ eV for 6 keV X-rays. Further degradation of the energy resolution can be envisaged due to electronic noise and to spatial non-uniformities in the response of the detector^{6,7}. Eq. 2 has been shown to be fully valid for Ta-based devices illuminated with lower energy optical photons⁸. At these energies the additional contribution due to spatial nonuniformities is negligible. The best results for energy resolution at $E=5.9$ keV for a STJ are 29 eV for a Nb-based device with 200 nm thick Al trapping layers⁹, and 27 eV for an Al device¹⁰. While these results are impressive they are still inadequate for practical applications in astrophysics where a resolution below 15 eV is required to resolve satellite lines from highly ionised iron, such as He-like Fe XXV.

The STJs used for the present work have been fabricated by Oxford Instruments Scientific Research Division (Cambridge, UK). They are Ta-Al-AlOx-Al-Ta multilayers deposited on polished sapphire substrates. The leads are 3 μm wide and made of niobium, in order to prevent diffusion of quasiparticles from the lower energy gap tantalum into the leads. The tantalum layer thicknesses for base and top electrodes are 110 nm and 95 nm, respectively. The aluminium layers are 5 nm thick on either side of the barrier. The base film tantalum is epitaxial, with a residual resistance ratio of 48, whereas the top electrode is polycrystalline. The AlOx barrier has an estimated thickness of <1 nm and a resistance of $\sim 2.5 \times 10^{-6} \text{ Ohm cm}^2$. The energy gap of the devices at the barrier, as derived from the I-V curves and assuming equal gaps in top and base electrode, is $2\Delta = 1.31 \text{ meV}$, close to that of bulk Ta. Leakage current densities, as measured at $T = 0.30 \text{ K}$, are typically $\sim 30 \text{ fA}/\mu\text{m}^2$. The available device sizes range from $10 \times 10 \mu\text{m}^2$ to $100 \times 100 \mu\text{m}^2$. The work described in this letter has been performed on a $100 \times 100 \mu\text{m}^2$ STJ.

The experiments have been performed in a ^3He cryostat at its base temperature of 0.30 K. A superconducting magnet provides the magnetic field of $\sim 8 \text{ mT}$ required to suppress the STJ's Josephson current and Fiske steps. The X-ray source is a radioactive ^{55}Fe sample emitting the Mn- K_α ($E = 5895 \text{ eV}$) and K_β ($E = 6490 \text{ eV}$) line complexes. The energy¹¹ and relative strength^{12,13} of the individual lines of this complex are listed in Table I. About 5% of the photons incident on the detector are absorbed in each of the two electrodes, while 90% are absorbed in the underlying sapphire substrate. A collimating pinhole with a diameter of $\sim 2 \mu\text{m}$ at a distance of $\sim 60 \mu\text{m}$ from the detector chip is used to selectively illuminate a small fraction of the total detector area. The diameter of the illuminated spot in this configuration is estimated as 5-10 μm (FWHM). The pinhole is aligned to the centre of the STJ at room temperature with an accuracy¹⁴ of $\pm 3 \mu\text{m}$. From previous experience with smaller STJs, the misalignment with respect to the centre of the STJ after cooldown is estimated $< 10 \mu\text{m}$. The rate of events detected in either of the two electrodes is $\sim 1 \text{ cts/minute}$. A separate experiment on the same STJ without the collimating pinhole was performed in order to measure the detectors energy resolution in full illumination mode, thereby assessing the overall contribution from spatial non-uniformities.

Table I: Energy and relative strength of the individual lines in the Mn-K complex.

line	energy (eV)	relative strength
Mn-K $_{\alpha 1}$	5898.75	100
Mn-K $_{\alpha 2}$	5887.65	51
Mn-K $_{\beta 1}$	6490.45	12
Mn-K $_{\beta 3}$	6490.45	6
Mn-K $_{\beta 5}$	6535.20	0.0053

The STJs are read-out with room temperature electronics, consisting of a charge sensitive preamplifier at ~ 1 m from the STJ, and a shaping stage. The total electronic noise of the combination of STJ and electronics can be measured as the width of the pulse height distribution from electronic pulser signals which are regularly fed into the electronics during data acquisition. For each detected photon the charge output, which corresponds to the total number of tunnelled electrons $N(E) = \langle n \rangle N_0(E)$ and the rise time of the charge pulse, which corresponds to the decay time of the current pulse from the STJ, are stored on a PC.

The typical signal measured for a 5.9 keV X-ray photon absorbed in the base electrode is 1.4×10^8 tunnelled electrons, corresponding to an average number of tunnel processes per initial quasiparticle $\langle n \rangle \approx 28$. The $1/e$ decay time of the pulses, as derived from the rise time of the pulses from the charge sensitive amplifier is typically 20 μ s. Variations of $\pm 10\%$ in measured charge and rise time occur between different cooldown cycles. The signal from the top electrode is usually within a few percent of the base electrode signal amplitude. The measured energy resolution in full illumination is $\Delta E \approx 56$ eV (FWHM) for the base electrode and slightly more for the top electrode. The noise level, as measured from the electronic pulser signal, is $\Delta E_{noise} \approx 12$ eV (FWHM) in this measurement.

The spectrum obtained with the collimated source is shown in figure 1. The assignment of the peaks to top and base electrode is based on the difference of $\sim 10\%$ in the number of counts, which is in agreement with the thickness ratio of the electrodes. The measured ratio of the pulse heights for the Mn-K $_{\alpha}$ and Mn-K $_{\beta}$ lines ($Q_{\alpha}/Q_{\beta} = 1.092$) is smaller than the ratio of the corresponding energies ($E_{\alpha}/E_{\beta} = 1.101$). This indicates some degree of energy non-linearity in the detectors response which is attributed to self-recombination of quasiparticles¹⁵. All derived energy resolutions have been

corrected for this energy non-linearity. The measured energy resolution (FWHM) for the base electrode Mn-K $_{\alpha}$ line complex is $\Delta E=22.0\pm2.0$ eV (see insert in figure 1), while the top polycrystalline Ta electrode gives 29 eV. However, when fitting the measured line profile to two Gaussians corresponding to Mn-K $_{\alpha 1}$ and Mn-K $_{\alpha 2}$, with their relative intensities and energy separation fixed to the values in Table I, the single line energy resolution for the base electrode is found as $\Delta E=15.7\pm2.3$ eV. The noise level in this measurement is $\Delta E_{noise}=5.7$ eV. The estimated contribution from the statistical noise (eq.2), using $\langle n \rangle=28$, is $\Delta E_{stat}=6.9$ eV, and the natural line widths^{16,17} of the K $_{\alpha}$ lines are $\Delta E_{nat}=2-3$ eV. Therefore, the residual broadening of the single Mn-K $_{\alpha 1}$ line, obtained after subtraction of electronic noise, natural line width and statistical noise, is $\Delta E_{res}=12.5\pm2.0$ eV. This residual broadening seems too large to be explained simply by spatial variations over a ≤ 10 μm spot near the centre of the device, compared to the 56 eV resolution measured in full illumination of the 100×100 μm^2 STJ. However, it is estimated that fluctuations in the bias voltage, induced by the voltage noise of the input FET of the charge sensitive preamplifier might provide an additional contribution of the right order. Generally, the gain of the device depends on the applied bias voltage and thus, variations in the bias voltage will give rise to variations in the measured pulse height.

In summary, by constraining the illuminated area of the detector to a small spot near the centre, we have demonstrated the capability of STJs to operate at 5.9 keV photon energy with an energy resolution of 15.7 eV. This exceeds the limit set by statistical fluctuations and natural line width by only a factor ~ 2 .

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Figure 1:

Part of the pulse height spectrum from a $100 \times 100 \mu\text{m}^2$ STJ illuminated with a ^{55}Fe source emitting the Mn-K_α ($E=5.9 \text{ keV}$) and Mn-K_β ($E=6.5 \text{ keV}$) line complexes. The source is collimated to the centre of the STJ. The insert shows the base electrode K_α line in detail. The solid line is the result of a least squares fit to two Gaussians representing the Mn-K_{α1} and Mn-K_{α2} (dashed lines) .