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Electron spectroscopy with a diamond detector

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Abstract

An electronic grade single crystal chemical vapour deposition diamond was investigated as a prototype high temperature spectroscopic electron (β\textsuperscript{-} particle) detector for future space science instruments. The diamond detector was coupled to a custom-built charge-sensitive preamplifier of low noise. A \textsuperscript{60}Ni radioisotope source (endpoint energy 66 keV) was used to provide a spectrum of β\textsuperscript{-} particles incident on the detector. The operating temperature of the detector/preamplifier assembly was controlled to allow its performance to be investigated between +100 °C and -20 °C, in 20 °C steps. Monte Carlo modelling was used to: a) calculate the β\textsuperscript{-} particle spectrum incident on the detector; b) calculate the fraction of β\textsuperscript{-} particle energy deposited into the detector; and c) predict the β\textsuperscript{-} particle spectrum accumulated by the instrument. Comparison between the model and experimental data suggested that there was a 4.5 µm thick recombination region at the front of the detector. The spectrometer was demonstrated to be fully operable at temperatures, \( T_{\text{op}} \), with \( -20 \, ^\circ\text{C} \leq T_{\text{op}} \leq 80 \, ^\circ\text{C} \); the results suggested that some form of polarisation phenomenon occurred in the detector at \( T_{\text{op}} > 80 \, ^\circ\text{C} \). This article presents the first report of an energy calibrated (≤ 50 keV) spectroscopic β\textsuperscript{-} particle diamond detector.

1. Introduction

Electron spectrometers are key instruments in space science. The distributions of charged particles following magnetic field lines are used to map the topology of magnetic fields and measure plasma densities in space environments [1]. Electron energy spectra, spatial distributions, and directions of travel allow absorption and acceleration processes to be understood in planetary magnetospheres, and the understanding of electron populations at icy moons, asteroids, and comets, is essential for exploring radiolytic processing and chemistry on the surface of those bodies [2, 3]. The radiolytic chemistry of comets is most easily studied when they are around perihelion; a temperature of 87 °C was measured at 1P/Halley at 0.8 AU [4]. The temperature at Mercury, where study of the electron radiation environment is also interesting, can be > 400 °C [5]. As such, the development of instrumentation which can operate in high temperature (>> 20 °C) environments is beneficial in order to simplify thermal design of the spacecraft.

Electron spectrometers have been an integral part of numerous space missions to study the interactions between the solar wind and magnetospheres and atmospheres. The Backward Facing Electron Spectrometer (BESA) on board Mariner 10 [6] as part of the Scanning Electrostatic Analyser and Electron Spectrometer (SESA) instrument, established that Mercury possessed a magnetic field, and later the Energetic Particle Spectrometer (EPS) designed to measure composition, energy, and angular distribution of electrons (> 20 keV) and ions (> 5 keV nucleon\textsuperscript{-1}) was included in MESSENGER’s suite of instruments on the most recent mission to visit the planet [7]. The EPS instrument [8], with minor modifications, flew on the New Horizons mission to Pluto and trans-Neptunian object Arrokoth, as the Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI) [9]; the EPS/PEPSSI electron spectrometer featured an array of Si solid-state detectors. An Electron Spectrometer (ELS) on the Cassini mission to the Saturn system was part of the Cassini Plasma Spectrometer (CAPS); it was capable of detecting electrons with energies from 0.58 eV to 26.04 keV [1] with a field of view in excess of ± 60 degrees in elevation and azimuth [10]. The ELS used a micro-channel plate (MCP) detector coupled with an electrostatic analyser to collect energy spectra [10].

Solid state detectors made from Si must be kept cool (≤ 20 °C) to limit their thermally generated leakage currents because of the material’s relatively narrow bandgap (\( E_g = 1.12 \, \text{eV} \)) [11]. Furthermore, in harsh radiation environments, they must be shielded in order to avoid degraded
performance through radiation damage [12]. MCP detectors coupled with electrostatic analysers are an alternative but they require high voltage and high vacuum to operate and are more complex.

As such, an electron spectrometer that could operate unshielded, uncooled, and with modest power supply requirements would be very attractive for future space missions. Wide bandgap solid state detectors may provide such benefits. Wide bandgap radiation detectors that have been proposed for spectroscopic electron detection for space applications include GaAs [14, 15], SiC [16], AlGaAs [17, 18], and InGaP [19]. Each offers particular advantages and trade-offs in terms of radiation hardness, temperature tolerance, and electron detection efficiency. Single crystal chemical vapour deposition (CVD) diamond has previously been shown to be responsive to $\beta$ particles at high temperatures [20] and spectroscopic to $\beta^+$ particles within the estimated energy, $E$, range, $50 \text{ keV} < E \leq 820 \text{ keV} [21]$. Recently a single crystal CVD diamond detector has been reported to be spectroscopic to soft X-rays ($< 10 \text{ keV}$) at $20 \degree \text{C} [22]$.

Now, in this article, a diamond detector has been investigated as a potentially temperature, $T$, tolerant ($-20 \degree \text{C} \leq T \leq 100 \degree \text{C}$) electron spectrometer using lower energy electrons from a $^{60}\text{Ni}$ radioisotope $\beta^+$ particle source (endpoint energy 66 keV).

2. Electrical characterisation and $^{60}\text{Ni} \beta^+$ spectroscopy

2.1. Diamond detector

An Element Six UK Ltd. electronic-grade single crystal CVD diamond (area 2.0 mm by 2.0 mm; thickness 0.5 mm) was used [23]. A single square 1.4 mm × 1.4 mm contact (50 nm Ti, 200 nm Ag) was sputtered onto the centre of the front face and rear face of the detector. The detector was mounted in a custom TO-39 style package with the detector’s rear contact connected to the package by silver-loaded epoxy [24] and the top contact connected to a pin of the package by wirebond.

2.2. Leakage current and capacitance of the packaged detector

The leakage current of the detector was measured as a function of electrical potential difference and temperature. For this, the packaged detector was positioned inside a light shielded test harness. Once the detector was positioned, the test harness was sealed and purged with dry $\text{N}_2$ to displace environmental moisture. The test harness holding the packaged detector was then placed in a TAS Micro MT Climatic Cabinet. Once sealed inside, dry $\text{N}_2$ was continually fed into the climatic cabinet to ensure the test environment remained dry (relative humidity < 5%). To commence measurement, the climatic cabinet’s temperature was raised from ambient ($\approx 20 \degree \text{C}$) to $100 \degree \text{C}$ with a 30 minute pause in the temperature climb imposed every 20 °C. This allowed the test harness and the packaged detector to reach thermal equilibrium inside the cabinet without undue thermal stress. At $100 \degree \text{C}$, the temperature inside the climatic cabinet was held constant for 1 hour before leakage current measurements were commenced. The electrical potential difference was applied across the detector in 5 V increments up to 100 V in both polarities. This procedure was repeated in 20 °C decrements until a temperature of -20 °C was reached; for the temperature descent, a 30 minute waiting time was imposed at each temperature to allow the test harness and detector to reach thermal equilibrium. A Keithley 6487 picoammeter/voltage source, controlled by National Instruments LabVIEW software, was used to apply the potential difference and measure the leakage current. The results of the measurements are presented in Figure 1.

The maximum packaged detector leakage currents recorded with $+100 \text{V}$ of electrical potential applied across the detector were $63.4 \text{ pA} \pm 0.6 \text{ pA} (T = 100 \degree \text{C}), 7.5 \text{ pA} \pm 0.4 \text{ pA} (T = 80 \degree \text{C})$, and $1.0 \text{ pA} \pm 0.4 \text{ pA} (T = 60 \degree \text{C})$. At $T \leq 40 \degree \text{C}$, the leakage current remained below the noise floor of the Keithley 6487 picoammeter ($\pm 0.4 \text{ pA}$). A portion of the larger leakage current measured at higher temperatures was attributed to the thermal excitation of electrons into the diamond’s conduction band [25]. The detector’s leakage current density was $3.23 \text{ nA cm}^{-2} \pm 0.03 \text{ nA cm}^{-2}$ at $100 \degree \text{C}$ and $100 \text{ V}$ applied potential difference (field strength 2 kV cm$^{-1}$); this assumed that the leakage current was constrained to the volume under the detector’s electrical contacts and that surface leakage current...
pathways were negligible. Such a leakage current density is more than that reported by other researchers using single crystal CVD diamond. As an example, two electronic grade single crystal CVD diamond detectors, grown by Element Six UK Ltd [23], had leakage current densities of 110 pA cm$^{-2}$ and 220 pA cm$^{-2}$ at 100 °C and a field strength of 2 kV cm$^{-1}$ [26]. However, Kumar et al. [27] reported a much larger leakage current density ($\approx 40$ nA cm$^{-2}$ at an electric field strength of 2 kV cm$^{-1}$) at 100 °C, for a single crystal CVD diamond detector grown by IIa Technologies Pte. Ltd., Singapore. The leakage currents reported by Tchouaso et al. for their $\beta$-particle diamond detector (also grown by Element Six UK Ltd) were approximately 6.4 pA cm$^{-2}$ and 12.7 pA cm$^{-2}$ at an electric filed strength of $\pm$ 2 kV cm$^{-1}$ [21]. Those leakage current measurements were made at ambient laboratory temperature. The asymmetry of leakage current between polarities (Figure 1) for the presently reported detector have been reported for other CVD diamond detectors [28, 29]; asymmetric leakage current and leakage current hysteresis in diamond detectors has been shown to depend upon the surface treatment employed prior to metallisation and the type of metallisation used [30].

The leakage current of the packaged detector at $T > 40$ °C and at an applied electrical potential difference of 100 V in both polarities reduced as a function of time, see Figure 2. The maximum leakage current after 30 minutes with 100 V potential difference continuously applied across the packaged detector was 39.1 pA ± 0.5 pA, 6.3 pA ± 0.4 pA, and 0.6 pA ± 0.4 pA at $T = 100$ °C, $T = 80$ °C and $T = 60$ °C, respectively.

Figure 1. a) The leakage current of the packaged detector as a function of electrical potential, in both polarities, up to 100 V, and at temperatures, $T$, 40 °C ≤ $T$ ≤ 100 °C. $T = 100$ °C (open squares), $T = 80$ °C (open diamonds), $T = 60$ ° C (open triangles), and $T = 40$ °C (crosses). At $T < 40$ °C, the detector’s leakage current was below the noise floor of the picoammeter (± 0.4 pA). Error bars are omitted for clarity; at +100 V, the uncertainties in leakage currents were ± 0.6 pA and ± 0.4 pA at $T = 100$ °C and $T = 60$ °C, respectively.

Figure 2. The leakage current of the packaged detector as a function of time at applied electrical potential differences of (a) +100 V and (b) -100 V, at temperatures of 100 °C (open squares), 80 °C (open diamonds), and 60 °C (open triangles).
The capacitance of the packaged detector and an identical device with its bondwires removed, were measured as functions of applied potential difference, in 5 V steps up to 100 V in both polarities. The packaged detector and the device with bondwires removed were separately placed in a test harness, which was purged with dry N₂ and subjected to the same environmental regime as had been used for the leakage current measurements. A HP 4275A Multi Frequency LCR meter, with test signal set to 50 mV rms magnitude and 1 MHz frequency, was used to record the capacitance of the packaged detector and the device with bondwires removed. The packaged detector’s capacitance was independent (within the LCR meter’s uncertainties) of applied potential difference and temperature; it was 870 fF ± 20 fF and 840 fF ± 20 fF at 100 °C and -20 °C, respectively. The capacitance of the device with bondwires removed was 540 fF ± 20 fF and 520 fF ± 20 fF at the same temperatures. The capacitance of the bare die detector was therefore invariant and 320 fF ± 30 fF at all reported temperatures and electrical potential differences.

2.3. $^{63}$Ni $\beta$ particle spectra

The packaged detector was connected to a custom-built low-noise charge-sensitive preamplifier with a Vishay 2N4416A Si input Junction Field Effect Transistor (JFET) [31] at its input. The preamplifier is unconventional in that it did not have a feedback resistor installed in parallel with a feedback capacitor to discharge charge pulses collected from $\beta$ particle interactions. Instead, the feedback capacitor is discharged through the gate-to-source channel of the Si JFET. The design of the preamplifier was similar to that reported by Bertuccio et al. [32]. The detector and preamplifier were co-located in a light shielded test harness. Charge pulses (in the form of voltage pulses) from the preamplifier’s output were shaped and amplified by an Ortec 572A shaping amplifier. An Ortec EASY 8k multi-channel analyser (MCA) subsequently sorted the voltage pulses from the shaping amplifier into appropriately distributed bins. The electrical potential difference across the detector was applied by a Keithley 6487 voltage source. The $\beta$ particle spectrum was provided by a $^{63}$Ni radioisotope $\beta$ particle source (activity 179 MBq; endpoint energy 66 keV). The $^{63}$Ni $\beta$ particle radioisotope source was a 7 mm by 7 mm by 3 µm thick $^{63}$Ni layer with a 1 µm Ni overlayer, electroplated onto a Ni foil substrate. It was held in a cylindrical stainless-steel holder with a 6 mm diameter open aperture. The $^{63}$Ni $\beta$ particle source was positioned ≈ 10.5 mm above the detector, inside the light shielded test harness.

The $\beta$ particle spectra were collected with the test harness located in a TAS Micro MT climatic cabinet for temperature control. The shaping amplifier, MCA, and voltage source were located outside of the climatic cabinet and operated at ambient laboratory temperature. The test harness was purged with dry N₂ before it was placed in the climatic cabinet, and thereafter the climatic cabinet was continually fed with dry N₂ to ensure the test environment remained dry. The temperature inside the climatic cabinet was raised from laboratory temperature (≈ 20 °C) in 20 °C steps to 100 °C. At each 20 °C temperature step, a minimum 30 minutes waiting time was applied to allow the contents of the test harness to reach thermal equilibrium before the climatic cabinet temperature was raised further. $^{63}$Ni $\beta$ particle spectra were accumulated at 100 °C and then in 20 °C decrements, down to -20 °C. Each $\beta$ particle spectrum was accumulated with a live time limit of 1800 s and with the MCA operated in 4096 channels mode. The detector was operated with an applied potential difference of 50 V and the shaping amplifier was set to a shaping time of 2 µs. The potential difference and shaping time were selected in light of preliminary measurements made with the detector and system: when the detector had been previously used as a prototype detector for X-ray spectroscopy, optimum energy resolution was achieved (as measured by the full width at half maximum of a Mn Kα (5.9 keV) photopeak from an $^{55}$Fe radioisotope source) with similar settings [22]. The optimum shaping time occurs when the quadratic sum of series and parallel white noise reach a minimum value [33]. An exposition of the different electronic noise contributions of a non-avalanche X-ray spectrometer can be found in refs. [34, 35, and 36]. At each temperature, a spectrum was collected without an electrical potential difference applied across the detector to check for the presence of any residual electric field sweeping charge in the detector. A characteristic shoulder attached to the so called zero energy noise peak without electrical potential applied externally would have been indicative of such polarisation. When the detector was confirmed to be unpolarised, the potential difference was applied (50 V) and $\beta$ particle spectra were collected. $\beta$ particle spectra were repeated (at constant temperature, applied
potential difference, and shaping time) to check that each spectrum was stable and repeatable. The
turn-around time (the time to save a spectrum and start to acquire another) was < 2 minutes. To
investigate any possible instability in performance, the turn-around procedure was repeated (i.e.
spectra were collected repeatedly) until a second spectrum was obtained which was identical to that
which had been acquired immediately previously. Thereafter, the applied potential difference was
removed and the detector was checked for polarisation effects. If polarisation was detected (by the
presence of a shoulder attached to the zero energy noise peak), the check was repeated until the
apparent polarisation had dissipated.

A series of repeated spectra accumulated at 100 °C are presented in Figure 3. In Figure 3 most of the
counts of the zero-energy noise peak have been removed from the accumulated spectra; a low energy
threshold was set on the MCA after establishing the noise peak’s position, and for clarity, the counts
accumulated below this threshold prior to its implementation are not presented.

![Figure 3](image)

The β\(^{-}\) particle spectra accumulated at 100 °C varied in morphology as a function of time. Two
identical β\(^{-}\) particle spectra at 100 °C were first accumulated 382 minutes after the potential difference
was first applied to the detector. In this time, the endpoint channel number had reduced from channel
1004 to channel 887, and the total number of counts had reduced and from 104,400 to 54,100. It was
hypothesised that polarising effects in the detector were responsible for the changing \(^{63}\)Ni β\(^{-}\) spectrum.

After the applied potential difference was removed from the detector, it was found that a residual
electric field continued to sweep charge in the detector.

The reduction in MCA endpoint channel number and the reduction of counts collected when the
spectrum was repeated, without changing the spectrometer’s settings, was indicative of a
progressively reducing electrical potential across the active region of the detector, as a function of
time. This apparent polarisation of the detector is thought to have been caused by traps in the
material’s bandgap [37] that created space charge regions acting in opposition to the applied field
across the detector; such a phenomenon has been reported previously in both polycrystalline [38] and
single crystal [39] diamond detectors. Polarisation phenomena have previously been shown to
increase as a function of temperature, up to 55 °C, in CdTe radiation detectors [40]. Studies with SiC
radiation detectors radiation damaged by 6.5 MeV protons and 1.0 MeV neutrons have suggested that
high temperatures, up to 580 °C, can decrease the time taken to depopulate charge from deep traps
and thus counter this polarisation effect [41].

The de-trapping lifetime, \(\tau_{d}\), can be expressed as [42, 43],

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\[ r_d = \frac{1}{N_c \sigma \nu_b \exp \left( \frac{-E_i}{kT} \right)} \]  

where \( N_c \) is the density of states, \( \sigma \) is the capture cross section of the trap, \( \nu_b \) is the drift velocity in the applied potential difference, \( E_i \) is the activation energy of the trap, \( k \) is the Boltzmann constant, and \( T \) is the temperature of the detector in Kelvin. **Equation 1** implied that at higher temperatures the de-trapping lifetime increased and consequently trapping lifetime decreased. However, a shorter trapping lifetime implied that there would have been more free traps and that the rate of charge trapping would have been increased causing carrier mobility to decrease and consequently decreased charge collection efficiency. Intrinsic charge carrier concentration is also proportional to \( T^{3/2} \) [44]. At 100 °C, the greater intrinsic concentration of charge may have filled traps at a rate greater than the rate of any trap depopulation, this would have caused the polarisation to build up and disrupt the electrical field across the detector. This would have created a potential barrier for charge carriers transiting the affected regions of the detector. Deep traps also act as recombination centres eliminating charge carriers created in the detector; they are less affected by thermal activation so persist for long periods and are often not easily depopulated. Deep traps in diamond are emptied at 230 °C ≤ \( T \) ≤ 280 °C [45, 46] and were thus thought to less likely to be responsible for the unstable performance exhibited by the presently reported detector at 100 °C. However, shallow traps are emptied at lower temperature (\( T \leq 80 \) °C) [46]; which would account for a continuously evolving trapping population polarizing the detector at 100 °C. Further characterisation of the spectrometer at 100 °C showed that the polarisation effect could be reversed by removing the applied potential difference from the detector for a short period (\( \approx 1 \) hour). After the detector was depolarised in this fashion, when the 50 V potential difference was reapplied, the detector would repolarise as before. Further detailed study of the apparent polarisation phenomenon is warranted. A detailed study of the roles of the contact metallisation and diamond surface preparation in the observed behaviour may reveal that a key role is played by the detector fabrication process.

The \( \beta^+ \) particle spectra collected at \( T \leq 80 \) °C are presented in **Figure 4**. The spectra are shown in their raw form with the MCA scale uncalibrated; i.e. the channel width (in energy and charge terms) of the spectra will have changed with temperature by virtue of variation in the preamplifier’s conversion factor with temperature. At each temperature, the spectra were repeatable and the changing \( \beta^+ \) particle spectra morphology, which was indicative of polarisation, was absent; however, a residual electric field remained in the detector when the applied potential difference was removed. This residual electric field dissipated in less than 30 minutes. The change in position of the apparent endpoint on the MCA’s scale was primarily due to the change in performance of the preamplifier as a function of temperature. However, some contribution may have been from variation of the average electron-hole pair creation energy, which is known to vary as a function of temperature in other materials [47, 48, 49]. The number of counts in each spectrum decreased as a function of temperature. At 80 °C, the total number of counts collected in each spectrum was \( \approx 78300 \) with an endpoint channel of 1080; at -20 °C the total number of counts collected were \( \approx 50300 \) with the endpoint channel of 840. Some of the change in the position of the endpoint channel number will have been due to change in the conversion factor of the preamplifier with temperatures. However, given that the live time limit and shaping amplifier shaping time were unchanged between each spectrum; and given that the apparent endpoint of the lower temperature spectra reduced towards lower channel numbers on the MCA scale, a corresponding increase in the number of counts per channel would have been expected, as each MCA channel would have had to encompass a larger range of \( \beta^+ \) particle energies. However, the opposite was observed; the number of counts per channel remained either relatively constant or slightly reduced when the endpoint channel reduced with temperature (**Figure 4**). The reason for this is not fully understood at present; it may have been caused by the higher temperatures ionising trapping centres which removed space charge. In so doing, the effective volume of material available for electron-hole pair creation leading to detection of the incident radiation through the induction of charge on the contacts of the detector by virtue of the movement of the charge carriers within the detection medium may have been larger at the higher temperatures. Alternatively, or in addition, higher temperatures may have enabled collection of a greater portion of the charge created in the diamond outside of the volume defined by the contact.
metallisation. Based on the change in number of counts, the effective active volume of the diamond
would have had to be 35% greater at 80 °C than it was at -20 °C. Diffusion of charge from low field
regions at higher temperatures may have contributed at least in part to a greater effective active
volume under those conditions but the quantitative extent to which it did is presently unknown; more
evidence would be required to draw definitive conclusions as to the extent of this contribution.
Furthermore, additional investigation of the phenomena reported here is essential if a complete
understanding of the detector is to be achieved.

![Figure 4](image)

**Figure 4.** $^{63}\text{Ni} \beta$ particle spectra accumulated with the diamond detector from -20 °C ≤ $T$ ≤ 80 °C.
$T = 80$ °C (black line), $T = 60$ °C (red line), $T = 40$ °C (orange line), $T = 20$ °C (yellow line), $T = 0$ °C
(green line), and $T = -20$ °C (cyan line). The spectrum live time limit was 1800 s in each case. It
should be noted that the channel width in units of energy (or charge) for each spectrum is not
identical. (The reader is referred to the web version of this article for the colour form of this figure.)

2.4. $^{63}\text{Ni} \beta$ particle spectrum modelling

The CASINO (monte Carlo Simulation of electronTrajectory in solids) computer program [50, 51]
was used to simulate the paths and the energy losses of the $\beta^+$ particles emitted from the $^{63}\text{Ni} \beta$
particle source as they traversed the 1 µm Ni overlayer and the 10.5 mm dry $N_2$ atmosphere between
the $^{63}\text{Ni} \beta$ particle source and the top of the detector. Each simulated $\beta^+$ particle was allocated an
energy between 1 keV and the $^{63}\text{Ni}$ endpoint energy of 66 keV, in 1 keV increments. The simulated
spectrum of $\beta^+$ particles emitted from the $^{63}\text{Ni} \beta$ particle source was dependent upon the emission
probability of each $\beta^+$ particle’s energy when emitted by $^{63}\text{Ni}$ and included the effects of self-
absorption within the $^{63}\text{Ni}$ radioisotope source [52]. A total of 18,549,380 $\beta^+$ particles across the 1
keV to 66 keV $\beta^+$ particle energy range were simulated. The total number of $\beta^+$ particles simulated
was selected in order to provide good counting statistics across the whole of the energy range rather
than to reflect the activity of any specific $^{63}\text{Ni} \beta$ particle source. The density of the 1 µm Ni overlayer
was modelled as 8.908 g cm$^{-3}$ and the density of the $N_2$ atmosphere was modelled as 0.0012 g cm$^{-3}$.
The physical model selected for the $\beta^+$ particle source was ‘Mott’; the developers of CASINO have reported
the associated backscattering coefficients to be in better agreement with experimental results at low
electron energies (< 10 keV). The Mott model has also been found to be more accurate than the
Rutherford cross section for low Z materials [51]. Of the three Mott models available to CASINO
‘Mott by Interpolation’ was selected as this model was computationally faster and known to be more
accurate than the other selectable Mott models [50]. Other pertinent CASINO settings were:

- Ionisation Potential – Joy and Luo [53]; Random Number Generator – the Press et al. [54]; Directing
- Cosine – Drouin et al. [51]; and Effective Section Ionisation – Casnati et al. [55].
- The computed trajectories of the simulated $\beta^+$ particles were used to calculate their residual energy after interacting
- with the 1 µm Ni overlayer and the dry $N_2$ atmosphere above the detector’s face. The simulated $\beta^+$
- particles at the face of the detector were analysed and the distribution of those energies produced the
- spectrum of $\beta^+$ particles incident upon the face of the detector. Both $\beta^+$ particle spectra (i.e. emitted
- from source and incident on detector) are presented in **Figure 5**.
- The endpoint $\beta^+$ particle energy
- emitted from the $^{63}\text{Ni}$ layer of the $\beta^+$ particle source was 66 keV, but after traversing the 1 µm Ni
- overlayer and the dry $N_2$ layer the endpoint energy of the spectrum reduced to 63 keV. It should also
be noted that the temperature range reported here did not change the density of the Ni overlayer or the dry N₂ atmosphere sufficiently to alter the results of the CASINO modelling.

Figure 5. Simulated β⁻ particle spectrum emitted from the $^{63}$Ni layer of the β⁻ particle source including the effects of self-absorption (open diamonds) and incident on the face of the detector having been attenuated by the 1 µm protective Ni overlayer and 10.5 mm of dry N₂ atmosphere (open squares).

The CASINO program was also used to calculate the quantum detection efficiency of the detector (i.e. the fraction of the energy deposited in the detector by β⁻ particles incident upon the face of the detector, as a function of energy up to 66 keV). To do this, 4000 β⁻ particles at each energy from 1 keV to 66 keV in 1 keV steps were simulated as incident upon a) the top metalized contact, and b) the non-metalized portion of the detector’s top face, i.e. 8000 β⁻ particles were simulated at each energy. The number of β⁻ particles simulated was chosen in order to give good counting statistics rather than to reflect any specific individual case of illumination of the detector with β⁻ particles. At each energy, both simulations were combined in the ratio of the areas of the detector’s face covered (49 %) and not covered (51 %) by the contact. As shown in Figure 6, the fraction of β⁻ particle energy deposited in the detector was 0.49 at 1 keV and this rose to 0.97 at 66 keV. However, it should be noted that this was calculated based on the assumption that the entire thickness (i.e. 500 µm) of the diamond usefully contributed to the quantum detection efficiency; this resulted in an overestimate of the detector’s quantum detection efficiency since, as will be shown, the detector actually had a 4.5 µm deadlayer in the diamond at its top. Furthermore, it should be noted that the values stated and presented as part of the figure include backscattering losses.

Figure 6. Quantum detection efficiency as a function of energy assuming that the whole thickness (500 µm) of the diamond contributed usefully to the quantum detection efficiency.

In order to predict the $^{63}$Ni β⁻ particle spectrum that would be detected by the spectrometer, the CASINO simulations in Figure 5 and Figure 6 were combined. The resultant spectrum excluded any pulse pile up and detector edge effects, as well as the noise processes (Fano, electronic, and any incomplete charge collection noise) present in the spectrometer. The results for spectra at selected
temperatures (80 °C, 20 °C, and -20 °C) are presented in Figure 7; similar results were obtained for all temperatures but three temperatures were selected for clarity of presentation. For comparison of the simulated spectrum and the experimentally detected spectra, the predicted spectrum and the experimentally detected spectra at each temperature were normalised. For this, the predicted spectrum was normalised to the mean number of counts in the generally constant region between 10 keV and 20 keV. The experimentally detected spectra were normalised to the mean number of counts in the generally constant region between 15 keV and 30 keV; this avoided counts from the zero noise energy peak adding to the averaged count. Experimental spectra were calibrated using the endpoint energy from the simulated spectrum, the position of the zero energy noise peak, and by taking account of the relative probability of detection as indicated by the number of counts that were detected.

![Figure 7](image)

As can be seen from Figure 7, the simulated and experimentally measured spectra had substantially different morphologies. The particular morphological difference shown is evidence of an inactive “dead” layer within the diamond at its front. Electron-hole pairs generated in a deadlayer are not able to move in the normal way so as to induce on the contacts of the detector the charge that they would have induced had they been created in an active region of the detector. Consequently, those charge carriers do not contribute to the accumulated spectrum. Such deadlayers (where generated charge is lost) have been reported at the detector/contact interface of other semiconductor radiation detectors (e.g. ref. [56]). Further modelling in CASINO was used to compute the apparent thickness of the deadlayer in the present diamond detector.

The simulations which led to the production of Figure 6 were rerun to include the presence of a deadlayer within the diamond immediately proximate to the front contact. The thickness of deadlayer was varied from non-existent to 4.5 µm thick, in 0.5 µm increments. This produced new quantum detection efficiency predictions which included the effects of a deadlayer. Each simulation was then
combined with the simulations of Figure 5 to produce a number of predicted spectra for different deadlayer thicknesses.

A match between the predicted and experimentally detected spectra was accomplished when a 4.5 µm deadlayer at the top of the detector was included. The simulated spectrum (with 4.5 µm deadlayer) and the experimentally detected spectra was normalised to the mean number of counts in the generally constant region between 17 keV and 25 keV. The experimental spectra were then energy calibrated using the endpoint energy from the simulated spectrum and the position of the zero energy noise peak.

In positioning the endpoint of the simulated spectrum, the relative probability of detection, indicated by the number of detected counts was also considered. It was recognised that inclusion of a single deadlayer thickness across all temperatures was likely to be an oversimplification (the thickness of recombination regions are known to be temperature dependent in ultraviolet detectors [57]) but the approach employed here was considered adequate for present purposes. In future, synchrotron measurements could be employed to measure the profile and thickness of the dead layer by measuring the X-ray quantum efficiency as a function of X-ray energy [58]. The calculated quantum detection efficiency for the detector, including the 4.5 µm deadlayer, is shown in Figure 8; for comparison, the quantum detection efficiencies which would have resulted had the deadlayer been 1.5 µm and 3.0 µm are also included. With a 4.5 µm deadlayer, the quantum detection efficiency (fraction of β particle energy usefully deposited in the active region of the detector) was 0.02 and 0.79 at 30 keV and 66 keV, respectively, cf. 0.87 and 0.97 without a dead layer. The spectra predicted to be detected when the 4.5 µm deadlayer was included in the simulations are shown in Figure 9 together with the experimentally detected 60Ni β particle spectra; for clarity of presentation, only the spectra at temperatures of 80 °C, 20 °C, and -20 °C are shown. As was the case for Figure 7, the spectra are presented in terms of relative counts, based on the position of the zero energy noise peak, the endpoint energy predicted by the simulation, and by taking account of the relative probability of detection as indicated by the number of counts that were detected.

![Figure 8](image_url)  
**Figure 8.** Quantum detection efficiency for the detector as a function of β particle energy when no deadlayer (open squares), and deadlayers of 1.5 µm (open diamonds), 3 µm (open triangles), and 4.5 µm (open circles) are included.

The apparent endpoint energy of the detected spectra (∼ 46 keV) was lower than the endpoint energy of the spectrum illuminating the detector (63 keV) because the detector’s top contact and the 4.5 µm deadlayer attenuated the energy of the β particles before they could reach the active region of the detector. Electronic grade single crystal CVD diamond wafers are scaif polished (a mechanical process where diamond particles are used to abrassively polish the wafer’s surface) [59]. Imperfections caused by the polishing process can reach 10 µm below the polished surface [60]. It is hypothesised that this may have altered the electrical characteristics of the diamond resulting in the 4.5 µm thick deadlayer at the top of the detector.
Figure 9. Comparison of $^{63}$Ni $\beta$-particle spectra predicted when a 4.5 µm deadlayer was included (open squares) and experimentally detected (black line) at temperatures of (a) 80 °C, (b) 20 °C, and (c) -20 °C, as compared with that predicted by the simulation (open squares). To enable morphological comparison, the spectra are presented in terms of relative counts and the energy axis has been calibrated based on the position of the zero energy noise peak, the endpoint energy predicted by the simulation, and by taking account of the relative probability of detection as indicated by the number of counts that were detected.

Given that the front and rear of the detector were substantially similar, the presence of a similar deadlayer immediately proximate to the bottom contact was hypothesised but could not be concluded from the present data. The detector was sufficiently thick that the presence (or absence) of a comparable deadlayer at the bottom would not have changed the quantum detection efficiency within the energy range applicable for the present work; hence, regardless of the presence or absence of a 4.5 µm deadlayer at the bottom of the detector, the detected spectrum would be the same. Further CASINO simulations which included a deadlayer proximate to the bottom contact were performed and showed that the spectra predicted to be detected were identical regardless of the inclusion or exclusion of such a 4.5 µm thick bottom deadlayer.

3. Discussion, conclusions, and further work
An electronic grade single crystal CVD diamond detector was investigated for its performance as part of an electron ($\beta$-particle) spectrometer. The detector was connected to a custom-built low-noise charge-sensitive preamplifier which was itself connected to a standard electronics chain. The detector was illuminated by a $^{63}$Ni radioisotope $\beta$-particle source. The spectrometer was investigated across the temperature range $-20 \degree C \leq T \leq 100 \degree C$. At 100 °C, the detector experienced significant polarisation. Performance was stable at each of the lower investigated temperatures (i.e. $-20 \degree C \leq T \leq 80 \degree C$) and polarisation did not impede the collection of spectra across this temperature range.

The detector’s performance was modelled using CASINO. By comparison between the spectra predicted by the model and those experimentally accumulated, it was determined that the detector had a 4.5 µm thick deadlayer in the material in direct proximity with the front contact. It was hypothesized that imperfections were introduced into this region of material during a polishing process used by the supplier of the diamond from which the detector was fabricated.
These results show that spectroscopic detection of relatively soft (energy ≤ 63 keV) electrons (β-particles) is possible at elevated temperatures (≤ 80 °C) using a single crystal CVD diamond detector. Despite the specific limitations of the detector reported here, the results show that diamond is a promising candidate material for future solid state electron spectrometers which will be required for various terrestrial and space applications. Whilst polarisation limited operation of the detector at 100 °C, the wide bandgap of diamond (5.47 eV [61]) suggests that operation at even higher temperatures is likely to be possible if the present polarisation problem can be eliminated. This potential for operation at extremely high temperatures and the expected radiation hardness of diamond detectors are key motivating factors for its study by researchers developing next generation instrumentation for space science. One key challenge to address is understanding the nature and mechanisms of the apparent polarisation phenomenon: detectors made from different single crystal CVD diamonds should be characterised and it may be advantageous to measure the change in performance of the present detector in detail at temperatures 80 °C < T ≤ 100 °C in order to identify the transitional behaviours between stable and polarised performance. Another potentially valuable avenue of exploration would be in seeking to understand how surface preparation changes the properties of the diamond detector close to its surface; a reduction in thickness (or preferably, elimination) of the deadlayer would improve the quantum detection efficiency at soft energies (≪ 25 keV). It is also informative to compare the diamond detector’s response to β-particles with that for photons of similar energies. The detection efficiency of the diamond detector for β-particles is high because of its thickness. Despite the detector being thick, the detector’s quantum detection efficiency for photons would be low, by virtue of carbon’s low atomic number. For example, at 66 keV the detector’s β-particle detection efficiency was 0.79; however, its quantum detection efficiency for 66 keV photons was computed to be 0.71 × 10⁻⁵. This suggests that this type of detector could find particular utility in detecting electrons or β-particles in mixed electron/photon radiation environments as the need to discriminate or subtract the photon background would be reduced cf. for higher atomic number detectors.

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**Data Statement**

Data underlying this work are subject to commercial confidentiality. The authors regret that they cannot grant public requests for further access to any data produced during the study, however the key findings are included within the article.

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