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Observation of Forbush Decreases and GLE-74 Recorded During Ground-Level Neutron Monitoring Survey From Various Sites

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Key Points:

- Forbush decreases and GLE-74 observed over the Northern Hemisphere in Spring 2024
- Cosmic ray count rate trends from N50L subsystems match Compact Neutron Monitor (CNM) and NM-64 monitors at similar geomagnetic cutoff rigidities
- The 4-NM-2023 matches 6-NM-64 count rates with a smaller, lighter, lower-cost design using non-toxic gas-filled counters

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Ground-level neutron monitors (NMs) are essential tools for monitoring space weather events, including the detection and alerting of ground-level enhancement (GLE) events. This study presents findings from a neutron monitoring survey using two compact N50L neutron slab-based subsystems deployed across various field sites in the United Kingdom (UK) with different geomagnetic cutoff rigidities. Data from these N50L subsystems were compared to data from established NM-64 monitors (Dourbes and Oulu) with similar geomagnetic cutoff rigidities and accessed via the Neutron Monitor Database (NMDB). The cosmic ray (CR) count rates measured by the N50L subsystems closely follow NMDB network trends, while absolute count rates differ due to site altitude, geomagnetic latitude, and local environmental conditions in the immediate vicinity of each detector. Key events observed during the campaign include two Forbush decreases and GLE-74. The data collected supported the development and deployment of the NM-2023 design initiative, specifically targeting the site of the first operational 4-NM-2023 in the UK. Additionally, data from the N50L subsystems were compared with the University of Surrey's Compact NM setup and the Lancaster University and Mirion Technologies developed NM-2023, enhancing GLE monitoring capabilities across UK geomagnetic cutoff rigidities. The preliminary measurements from the NM-2023 prototype conducted at the Warrington site suggest it can achieve performance comparable to the 6-NM-64 monitor but with a reduced footprint, volume, mass, and cost, utilizing environmentally friendly, non-toxic gas-filled counters. A full 4-NM-2023 system has been deployed at Met Office Camborne Observatory near Cornwall, with a 1-NM-2023 unit installed at Lancaster University.

Plain Language Summary Space weather events pose a great risk to critical infrastructures such as radio communication, satellite operations, electrical power grids, and aviation technology. The UK has registered severe space weather events as a potential risk to critical infrastructure. The UK designed and built a new standard ground-level neutron monitor called NM-2023 for severe space weather radiation assessment. A 4-NM-2023 matches the performance of a 6-NM-64 design but with a reduced footprint, volume, mass, and cost, utilizing environmentally friendly, non-toxic gas-filled counters. We present neutron monitoring survey results from N50L neutron slab-based subsystems (from now on referred as N50L subsystems) deployed across several UK sites and the University of Surrey's Compact Neutron Monitor (CNM). The N50L subsystems and CNM provide data that have similar trends to the data from DRBS and Oulu, despite both being significantly smaller. The count rate measurements are influenced by altitude, latitude, and objects around the NM. The N50L subsystems, 2-NM-2023, DRBS, and Oulu were able to observe the Forbush decrease which occurred over the 2024 spring. However, only Oulu registered sufficient cosmic ray counts to be classified as GLE-74, classified as a weak GLE.

1. Introduction

Ground-level neutron monitors (NMs) provide continuous measurements of the galactic cosmic ray (GCR) field at the Earth's surface. NMs complement satellites and other ground-based instruments by providing data for nowcasting space weather events (Baker, 2002; Fang et al., 2022; Mishev and Usoskin, 2020; Poluianov et al., 2015; Simpson, 2000; Strauss et al., 2020). Primary GCRs are highly energetic particles caused by

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explosive events such as supernovae, and space weather events (Blanco et al., 2015; Carmichael, 1968; Cordaro et al., 2012; Hnatyk and Voitsekhovskiy, 2021; Medina et al., 2013; Poluianov et al., 2015; Simpson, 2000; Strauss et al., 2020). GCRs interact with the Earth's atmosphere which leads to the production of secondary CRs. The CRs' activities depend on the solar cycle (solar minimum and solar maximum; a solar cycle is roughly every 11 years) (Blanco et al., 2015). NMs respond mainly to the secondary neutrons produced, with smaller contributions from protons, muons, and pions (Clem and Dorman, 2000).

The basic NM comprises an array of gas-filled (^3He or BF_3) proportional counters, moderator (paraffin or high-density polyethylene (HDPE)), producer (lead (Pb)), reflector (paraffin or HDPE), and computer system. The reflector shields thermal neutrons from entering the detector and reflects neutrons produced by the Pb producer (when CR interacts with the Pb, the Pb produces neutrons via the spallation process) through spallation back toward the moderated array of counters. The fast neutrons produced in the Pb producer are thermalized by the moderator prior to interaction with the counters. This results in the production of countable electrical signals (Cordaro et al., 2012; Medina et al., 2013; Poluianov et al., 2024; Simpson, 2000; Strauss et al., 2020).

The Sun occasionally produces severe space weather events, including solar flares and coronal mass ejections (CMEs), which accelerate solar energetic particles (SEPs) and can lead to substantial increases in the atmospheric radiation environment. A global network of ground-level NMs detects the impact of SEP at ground level. Such events are seen in the NM count rates as enhancements over the background, called ground-level enhancements (GLEs) (Forbush, 1946; Klein and Dalla, 2017; McCracken et al., 2012; Reames, 2013). These space weather phenomena pose a risk to infrastructures such as satellite operations and aviation via single event effects in aircraft electronics and ionizing dose to passengers and crew. Models utilize data from NMs to drive nowcasts of the aviation radiation environment both during GLEs and the quiescent GCR background (Hands et al., 2022).

Prominent CR intensity changes recorded by ground-level NMs are Forbush decreases and GLEs (Badrudin and Kumar, 2015; Blanco et al., 2015; Gil et al., 2018; Poluianov et al., 2017, 2024). Forbush decreases are associated with a rapid drop in GCR intensity accompanied by a slow recovery which lasts up to a few days. GLEs are a sudden large increase in CR intensity over a wide area of the Earth's surface for a period of about 15 min or longer followed by a relatively gradual drop to the quiescent level (Badrudin and Kumar, 2015). Seventy-seven GLEs have been observed by NMs to date (<https://gle oulu.fi/#/>). A global network of NMs made up of about 60 stations dating back to the early 1950s are used to monitor the GLEs and Forbush decreases and provide data for modeling and nowcasting (<https://www.nmdb.eu/>). The NM-64 type of NM was standardized by Carmichael in 1964 (Carmichael, 1968). The NM-64 design is based on Chalk River lab BP28 BF_3 gas-filled proportional counters or soviet SNM-15 BF_3 filled counters. Since BF_3 is toxic, this led to some NM deviating to ^3He gas-filled proportional counters (Cordaro et al., 2012).

The United Kingdom (UK) has been without an operational NM since the mid-1980s, limiting the accuracy of nowcasting the atmospheric radiation environment from a UK context. Severe space weather events have been registered as a potential risk to critical UK infrastructure (<https://www.gov.uk/government/publications/national-risk-register-2023>). In preparation to respond to such events, the UK has designed and built a new ground-level NM (the NM-2023) (Aspinall et al., 2024a). The goal of the new design was to reintroduce ground-level neutron monitoring in the UK for the first time since ca. 1984 with a new monitor design to match the performance of a 6-NM-64 design while being a smaller, more cost-effective, and highly stable structural design, using proven modern components for reliable, flexible, and long-term operation. The NM-2023 description is given in Section 2.2.

This paper presents the results of a neutron monitoring survey undertaken using a pair of N50L neutron slab-based subsystems deployed at different UK sites. The N50L neutron slab-based subsystem consists of an N50L detector surrounded by antimony-free lead bricks and a data acquisition system. The data acquisition is the same as that used in the NM-2023. The N50L detector has a similar design concept to the NM-2023. This provided a means to test how the full-scale NM-2023 will work ahead of the production schedule. From now on, the N50L detector surrounded by lead bricks will be referred to as the N50L subsystem. The N50L subsystem is described in detail in Section 2.1. The data from two N50L subsystems, a 4-NM-2023, a 2-NM-2023, and a 1-NM-2023, are compared to data from established NMDB instruments with similar geomagnetic cutoff rigidities. The survey aimed to support the development of the NM-2023 instrument and understand the variation of CRs over the UK.

2. Methodology

2.1. UK Neutron Survey Experiment

A UK survey of count rates using two N50L subsystems has been conducted at Warrington (54.43°N, 2.52°W), Surrey (51.24°N, 0.59°W), Camborne (50.22°N, 5.33°W), and Lerwick (60.14°N, 1.18°W). The survey started on 15 January 2024 and continued until 30 April 2024. Count rates were acquired by using two N50L subsystems. Figure 1 shows the location of the measurement sites (top panel), and the two N50L subsystems used to collect the count rate data (bottom left and right panels). One N50L subsystem was situated in a Maxus Deliver van (https://en.wikipedia.org/wiki/Enterprise_Rent-A-Car) (Figure 1, bottom-left panel), which recorded the count rates from Surrey, Camborne, and Lerwick, whereas the other N50L subsystem was permanently located at Warrington (Figure 1, bottom-right panel) coinciding with the Camborne, Surrey, and Lerwick campaigns. The yellow dots on the map show the locations of the NMs situated at Oulu (65.05°N, 25.47°E), Finland, and Dourbes (DRBS) (50.10°N, 4.60°E), Belgium that provide data to compare against for this study. The UK sites are denoted by the red dots on the map. The map was obtained from Google Earth (<https://earth.google.com/>). The N50L subsystem in the Maxus Deliver van (from now on only referred to as a “the van”) collected data at the Surrey, Camborne, and Lerwick sites for approximately a month at each site.

The arrangements shown in Figure 1 (bottom left and right panels) are made up of N50L neutron slab-based monitors encased in antimony-free Pb bricks, and computer systems (CAEN R7780 device shift register (<https://www.caen.it/>) and PC). The N50L monitors comprise four 4-atm ^3He and ArCH_4 quench gas-filled stainless-steel tubes with 0.71 m active length and 25.4 mm diameter. The tubes were mounted in a moderator (HDPE), wrapped in a 0.5 mm thick cadmium, and encased in stainless steel. The four ^3He tubes are connected to a single Canberra Harwell type 950,120-1 charge amplifier. The N50L monitor measures $910 \times 300 \times 114$ mm and has a mass of 29 kg. The signal output from the amplifier was connected to the CAEN R7780 device shift register. The two N50L monitors were each operated inside a Pb sarcophagus, positioned on a wooden pallet. The CAEN device R7780 device shift register supplied 1600 V to the ^3He tubes and 5 V power to the amplifier. The Pb-sarcophagus was made up of 90 antimony-free pure Pb bricks (8 in \times 4 in \times 2 in dimension). Antimony-free Pb bricks (99.9% pure Pb) were used to avoid the antimony, typically used to improve durability, from capturing thermal neutrons. The N50L subsystem did not have an additional external HDPE reflector to suppress the environmental influence on count rate measurements. An Extech RHT50 USB datalogger connected to the laptop was used to collect the air pressure alongside the N50L subsystem inside the van (Aspinall et al., 2024b). A Bosch BME280 sensor operated using Arduino was used to collect air pressure measurements alongside the N50L subsystem at the Warrington site.

The count rate data collected by the N50L subsystem at the Warrington site were used as a control reference for comparing count rates from Surrey, Camborne, and Lerwick sites, unperturbed by the frequent disassemble/re-assemble of the N50L subsystem transported to the three different sites. The count rate data from the Oulu and DRBS ground-level NMs, which are part of the NMDB network (<https://www.nmdb.eu/>), are compared to the data recorded by the N50L subsystem from the UK sites. The Oulu and Lerwick sites are situated at similar geomagnetic cutoff rigidities. Likewise, the DRBS, Surrey, Camborne, and Warrington are located at similar geomagnetic cutoff rigidities. The N50L subsystem data from Surrey is also compared to the data collected by the University of Surrey's Compact NM (CNM). The CNM uses the same sensors employed by CR Soil Moisture Observing System (COSMOS) networks. However, the CNM is operated indoors to isolate it from soil moisture fluctuations as intended use of the COSMOS network. The COSMOS UK network is a national soil moisture monitoring capability operated by the UK Centre for Ecology and Hydrology. The COSMOS UK network consists of 50 sensors operating throughout the UK. Their detectors are made up of BF_3 gas-filled Hydroinnova CRS-1000/B and Hydroinnova CRS-2000/B counters surrounded by HDPE moderator. The Hydroinnova CRS-1000/B detector and Hydroinnova CRS-2000/B detector have different dimensions (Cooper et al., 2021; Hands et al., 2021). The ^3He gas-filled equivalents are the CRS 1000/He and CRS 2000/He. The CNM uses 3 CRS 2000/B. Two are moderated, and one is not.

The local environment and the presence of snow can affect the count rate measurements (Kataoka et al., 2022). Oulu experienced snowfall during most of the observation (13/01/2024–27/04/2024), varying from 2 to 66 cm. DRBS experienced snowfall from 7/01/2024 until 21/01/2024, varying from 0.4 to 4 cm. No snowfall was observed at Lerwick and Camborne during the observation periods. The snowfall of 1 cm was observed at

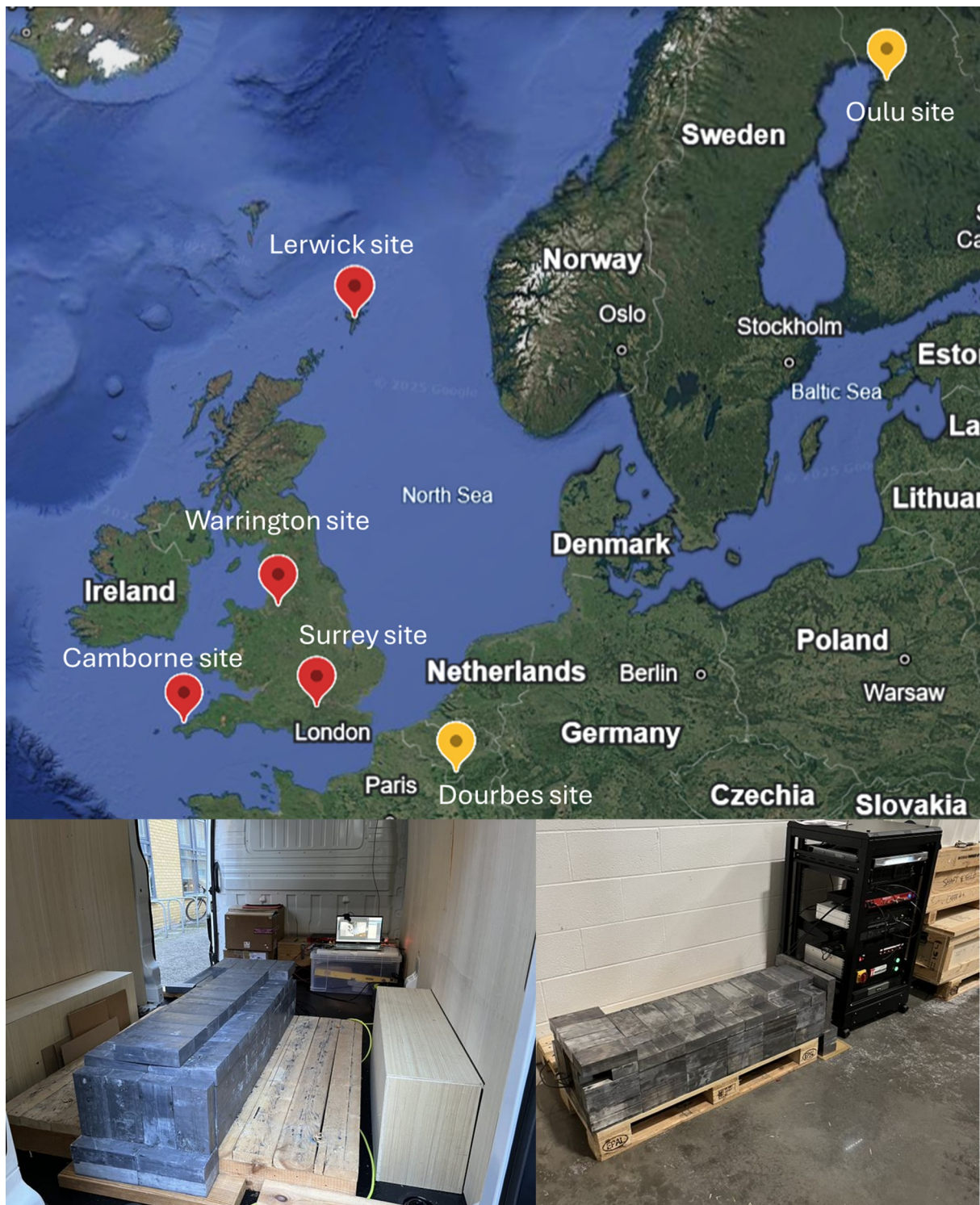


Figure 1. Locations used for neutron monitoring measurements (top panel). The red dots show Surrey, Camborne, and Lerwick locations and the yellow dots denote Oulu and Dourbes (DRBS) locations. The map was obtained from Google Earth (<https://earth.google.com/>). The fixed setup at Warrington (bottom right panel). The setup in a Maxus Deliver van (bottom left panel) was used to collect data at the Surrey, Camborne, and Lerwick sites. The setups in the bottom left and right pictures consist of an N50L neutron slab-based monitors encased in an antimony-free Pb brick sarcophagus, and computer system (CAEN R7780 device shift register (<https://www.caen.it/>) and PC). The setups are referred to as N50L subsystems in this paper.

Table 1

Summarized Ground-Level Neutron Monitor Information, Including Latitude, Longitude, Altitude, Geomagnetic Cutoff of Sites (<http://maire.uk/maire/>), and Detector Type

	DRBS (Belgium)	Oulu (Finland)	Surrey (UK)	Surrey-CNM (UK)	Warrington (UK)	Camborne (UK)	Lerwick (UK)
Latitude (°)	50.10	65.05	51.24	51.24	53.43	50.22	60.14
Longitude (°)	4.60	25.47	-0.59	-0.59	-2.52	-5.33	-1.18
Altitude (m)	225	15	60	62	19	90	80
Geomagnetic Cutoff (GV)	3.2	0.8	2.9	2.9	2.3	3.1	1.0
Detector model/type	9 BF ₃ 9-NM-64 type LND, inc. Type LND 2061	9 BP28 BF ₃ 9-NM-64 type	4 ³ He Canberra UK Ltd., type NRD/25.4/710/4/A	BF ₃ CRS-2000/B	4 ³ He Canberra UK Ltd., type NRD/25.4/710/4/A	4 ³ He Canberra UK Ltd., type NRD/25.4/710/4/A	4 ³ He Canberra UK Ltd., type NRD/25.4/710/4/A

Warrington only on 16/01/2024, and 1 cm of snowfall was observed at Surrey during the respective observation periods.

The Oulu detector, which has been in operation since 1964, is a 9-NM-64 (Chalk River Lab BP28 BF₃-filled tubes), and the DRBS detector has been in operation since 1965, a similar 9-NM-64 (Sapundjiev et al., 2014; Usoskin et al., 2009). Information about the sites is summarized in Table 1. The results are discussed in Section 3.

2.2. NM-2023 Description

The 4-NM-2023 aims to achieve comparable neutron counting performance of 6-NM-64, with 64% smaller footprint, 80% smaller volume, 55% of the mass, and reduced cost using non-toxic gas-filled counters. The leading number of NM-64 denotes the number of BP28 BF₃ gas-filled counters. Using a similar notation, the leading number of NM-2023 denotes the number of banks comprised of three pairs of ³He gas-filled counters. The 4-NM-2023 will be utilized to monitor GLE events and provide data to the NMDB and Model for Atmospheric Ionizing Radiation Effects. Model for Atmospheric Ionizing Radiation Effects is used to nowcast the aviation radiation environment based on the kp-index (the global auroral activity indicator on a scale from 0 to 9), sunspot number, NM data, and geostationary proton flux (Hands et al., 2022). The 4-NM-2023 operates on the fundamental principles of the production of spallation neutrons in a target with high atomic weight (a pure Pb producer), the moderation of these fast neutrons in an HDPE, and the detection of the thermal neutrons indirectly by ionizing particles that are produced in a neutron-induced nuclear reaction inside ³He gas-filled proportional counters. Influences from fluctuations in the ambient environment are suppressed using an outer layer of pure HDPE as a reflector material to reflect and moderate the evaporation of neutrons that are produced in the Pb and to shield and absorb the low energy neutrons that are produced by high energy nucleons in interactions with the materials in the general vicinity surrounding the monitor. Figure 2 shows a picture of 4-NM-2023 composed of 24 2-m long, 4-atm ³He counters surrounded by a HDPE moderator, encased in an antimony-free Pb sarcophagus constructed of bricks, and surrounded by outer reflector material. The 12 boxes are amplifiers (combined charge amplifier, discriminator and digital output driver). The instrument is supported on a steel table to reduce ground effects and to ease maintenance.

The counting chain consists of 12 junction boxes, connecting the ³He counters in pairs, with each counter pair connecting to its preamplifier. Signals from the 12 preamplifiers are fed into a signal aggregator and de-randomizer and two CAEN R7780 shift registers. The CAEN R7780 feeds a high voltage (HV) junction box for HV routing to each preamplifier. The primary data feed from the CAEN R7780 is fed into a rack-mounted PC serviced with an ethernet switch, uninterruptible power supply, power supply units, power distribution, and interconnecting cables. The preliminary data measurements done by the 4-NM-2023 and 1-NM-2023 instruments at the Warrington site are compared to data collected by DRBS and Oulu instruments in Section 3. Aspinall et al. (2024a) provided more information on the NM-2023 design. A 4-NM-2023 has been installed at the UK Met

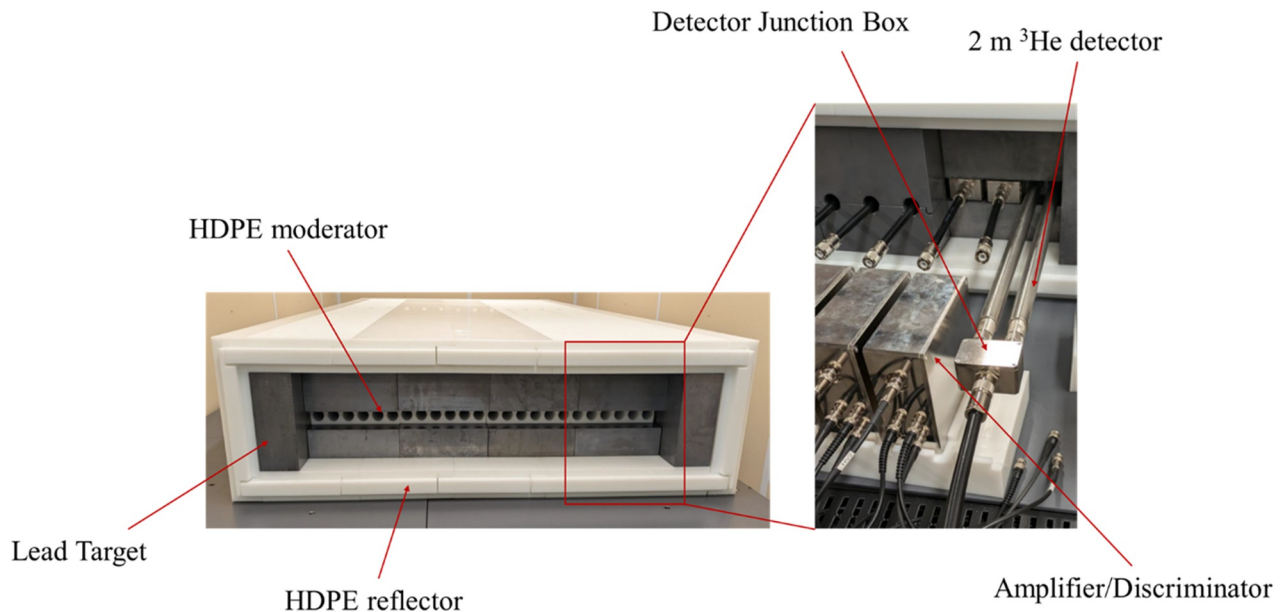


Figure 2. 4-NM-2023 detector composed of 24 2-m long, 4-atm ³He counters surrounded by a HDPE moderator, encased in an antimony-free Pb sarcophagus constructed of bricks, and surrounded by outer reflector material.

Office Camborne Observatory near Cornwall. A 1-NM-2023 instrument, a quarter of the size of the 4-NM-2023, is installed at Lancaster University. The 4-NM-2023 and 1-NM-2023 provide count rates with 1 min resolution.

3. Results and Discussion

3.1. UK Survey

The results of count rate measurements over the UK sites, Oulu, and DRBS during the period of study (15 January to 30 April 2024) are presented in Figure 3. Two Forbush decreases and one GLE were observed and are analyzed in Section 3.2. Since the ambient atmospheric pressure influences count rate measurements, the data presented in Figure 3 (bottom panel) are corrected for atmospheric pressure influences and a moving average of 1 hour was applied to aid the interpretation of the figure. The atmospheric pressure measurements were taken alongside count rate measurements. Where gaps in atmospheric pressure data exist using the Bosch BME280 sensor at the Warrington site, atmospheric pressure measurements from the UK Rostherne no.2 station, located 12 km away from the Warrington site, were used. The measurements from the Oulu and Lerwick sites followed a similar trend whereas DRBS, Warrington, Surrey, and Camborne sites followed a similar trend since they are located at regions of similar geomagnetic cutoff rigidities, see Figure 3 (top panel). We noticed that Oulu and DRBS have similar count rate measurements despite the difference in geomagnetic cutoff rigidities, similar systems and operation settings. This may be due to lots of snowfall at Oulu, local environments, and albedo neutrons (Hubert et al., 2016; Kataoka et al., 2022). From Figure 3 (bottom panel), one can see that count rate data from different locations follow similar trends after applying atmospheric pressure correction. The data gaps in Figure 3 are due to the instrument being transported between locations, utilized for other activities, or data acquisition failing. The interpretation of Figure 3 is summarized in Table 2.

It was found that the N50L subsystems at the Surrey site and the Warrington site recorded a 34% difference in average count rates during the same period (01/02/2024–19/02/2024), with the average count rate lower at the Surrey site. We assume the difference was influenced by the van's location since it was surrounded by tall buildings at the Surrey site. The average count rate data for Camborne were found to be about 3% higher than what was recorded at the Warrington site over the same period. A difference in average count rate of 11% was observed between Lerwick and Warrington, with a greater average count rate at the Lerwick site due to its lower geomagnetic cutoff rigidity.

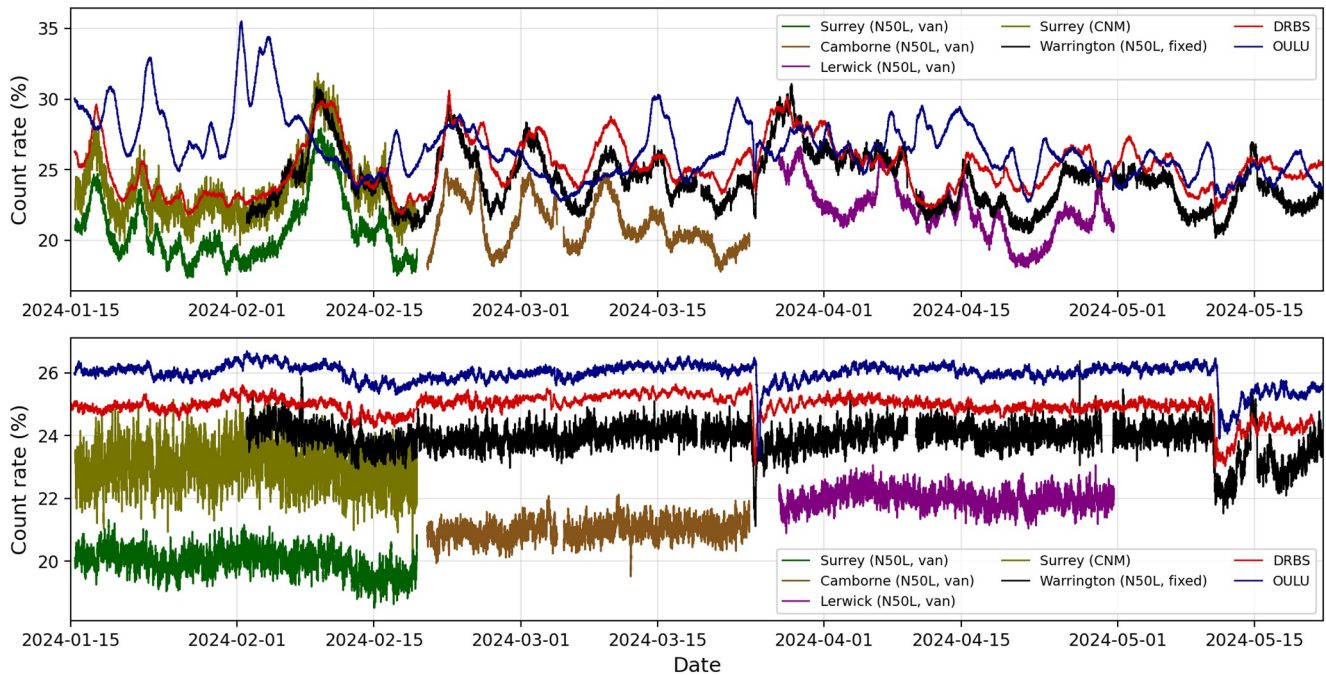


Figure 3. Neutron monitor count rates (relative count rates) from Warrington, Surrey, Camborne, Lerwick, Oulu, and DRBS sites from 15 January to 30 April 2024. No atmospheric pressure correction (top panel) and atmospheric pressure correction applied (bottom panel). A moving average of 1 hour was applied to aid the interpretation of the figure. N50L subsystem at Warrington is referred to as Warrington (N50L, fixed).

The results confirm that altitude, latitude, and objects around the NM influence count rates. The count rate measurements from different UK sites show increases with altitude and latitude, except for the Surrey site which might have been influenced by the built-up urban environment surrounding the van and N50L subsystem. Despite being small relative to the respective NM-64s and having lower count rates compared to DRBS and Oulu instruments, the N50L subsystem and CNM arrangement provided similar count rate trends. This suggests that an N50L-like monitor may be used to detect threats imposed by space weather events. However, the 6-NM-64 or 4-NM-2023 are necessary since the N50L subsystem and CNM are less sensitive in comparison. Less sensitive NMs have a high chance of missing modest GLEs, especially sub-GLEs. Sub-GLEs are GLEs that are only detected by high-altitude polar NMs, while there is no major response from the near-sea level NMs (Poluianov et al., 2017, 2024). The CNM sensor is aimed at detecting only strong GLEs (Hands et al., 2021).

Table 2

Summarized Ground-Level Neutron Monitors Data Analysis, Including Measurement Durations at DRBS, Oulu, Surrey, Warrington, Camborne, and Lerwick, and Average Count Rates

	DRBS (Belgium)	Oulu (Finland)	Surrey (UK) (N50L, van)	Surrey- CNM (UK)	Warrington (UK) (N50L, fixed)	Camborne (UK) (N50L, van)	Lerwick (UK) (N50L, van)
Measurements duration	15/01/ 2024–22/05/ 2024	15/01/ 2024–22/05/ 2024	15/01/ 2024–19/02/ 2024	15/01/ 2024–19/02/ 2024	01/02/ 2024–22/05/ 2024	20/02/ 2024–24/03/ 2024	27/03/ 2024–30/04/ 2024
Count rate range (counts/min)	2,412–9,180	4,242–8,274	90–240	3.6–48	120–372	144–360	150–318
Count rates average (counts/min)	6,156	5,592	144	24	198	210	222
Warrington's Count rates average (N50L, fixed) relative to other N50L subsystems (in a van) at their respective sites (counts/min)			198			204	198

Note. The averaged count rates for the data collected from Surrey, Lerwick, and Camborne are compared with the averaged count rate data from Warrington, these can be found in the average count rates row. The last rows denote Warrington's averaged count rate relative to other N50L subsystems at their respective sites. Count rates are in counts per minute (counts/min). The count rates are not corrected for atmospheric pressure influence.

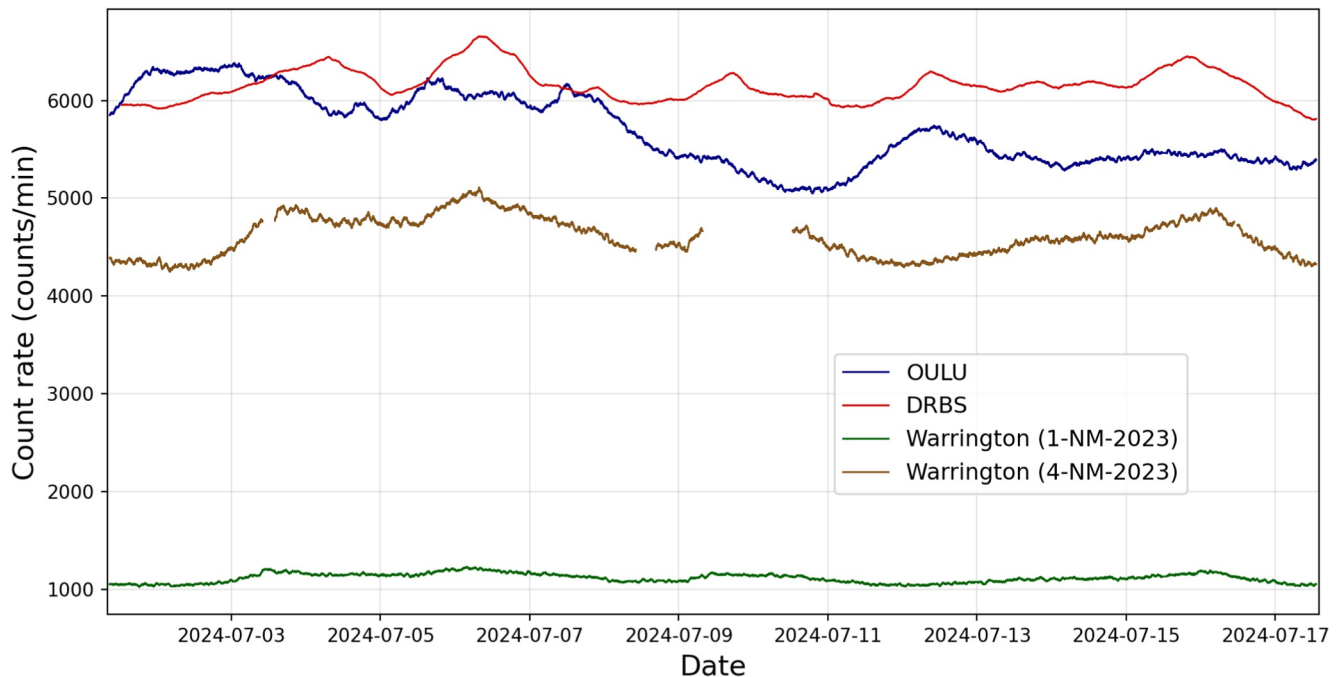


Figure 4. Neutron monitor count rates observed at Warrington (1-NM-2023, 4-NM-2023), Oulu, and DRBS sites from 1 July 2024 until 17 July 2024. No atmospheric pressure applied on the data and the measurements are in counts per minute (counts/min).

The 4-NM-2023 operated from 1 July 2024 until 17 July 2024 at the Warrington site. The 4-NM-2023 measured an average count rate of about 4,620 counts per minute (counts/min). The 1-NM-2023 (also then at the Warrington site) measured an average count rate of about 1140 counts/min. The 1-NM-2023 is the quarter size of 4-NM-2023, that is, six ^3He counters in pairs compared to 24 counters in pairs (see Figure 2). From 12 December 2024, the 4-NM-2023 was sited at the Met Office Camborne Observatory near Cornwall. From 25 February 2025, the 1-NM-2023 was sited at Lancaster University. Oulu and DRBS stations, which are both 9-NM-64 stations, measured average count rates of about 5,700 counts/min and 6,180 counts/min over the same period, see Figure 4. The percentage difference of 4-NM-2023 against Oulu and DRBS were 23% and 34%. For direct comparison, the average count rates for Oulu and DRBS were scaled to that of a 6-NM-64, providing average count rates of 3,780 counts/min and 4,080 counts/min, respectively. This shows that the 4-NM-2023 (4,620 counts/min) can match the counting performance of a 6-NM-64 with a smaller footprint, smaller volume, and less mass, in a cost-effective solution, and while using non-toxic gas-filled counters.

3.2. Forbush Decreases and GLE

The National Oceanic and Atmospheric Administration's Space Weather Prediction Center issued an alert on 23 March 2024 and 9 May 2024 for CMEs heading for Earth (<https://www.swpc.noaa.gov/>). The CME impact on the intensity of secondary CRs near the Earth's surface was recorded by the global NM network, N50L subsystems, and a 2-NM-2023. The components that make a 2-NM-2023 system (i.e., half a 4-NM-2023) were all that were available at that time. Figure 5 shows CME impacts on count rates measured by the N50L subsystem at Warrington, OULU, and DRBS on 23 March 2024 (top panel) and the N50L subsystem and 2-NM-2023 at Warrington, OULU, and DRBS on 9 May 2024 (bottom panel).

In Figure 5, count rate measurements are corrected for atmospheric pressure influences. A one-hour moving average was applied to the count rate data with a one-minute time resolution to aid the interpretation of the figure. On 24 March 2024, the CME struck the Earth's magnetic field at about 14:00 UT (confirmed by magnetic field B_z and solar wind measurements; the graphs are in the Supporting Information S1 (Figure S1)), which disturbed the Earth's magnetic field. A sudden, huge drop in count rate at the Earth's surface for about 9 hr was recorded (a Forbush decrease), see Figure 5 (top panel). The NM instruments at the Warrington, Oulu, and DRBS sites recorded a reduced count rate as a result of the CME impact. A count rate reduction of about 13%, 13%, and 15%

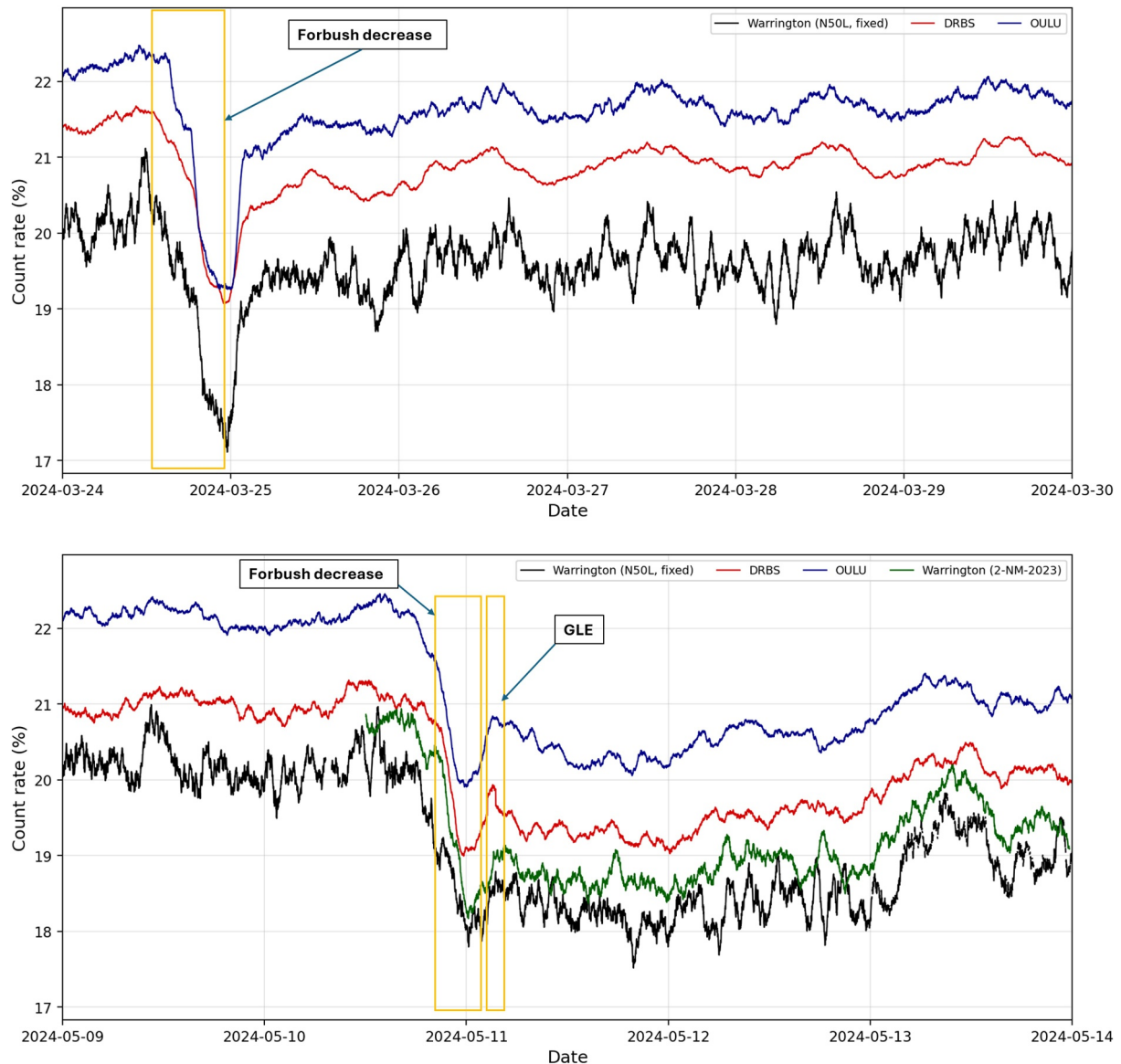


Figure 5. Impact of coronal mass ejection (CME) observed by neutron monitors on 23 March 2024 (top panel) and 9 May 2024 (bottom panel). On 24 March 2024 the CME impact resulted in a Forbush decrease. On 11 May 2024 the CME resulted in a Forbush decrease accompanied by ground-level enhancement. Atmospheric pressure correction and a one-hour moving average were applied to the data. The measurements are presented in count rate (%). The N50L subsystem at Warrington is referred to as Warrington (N50L, fixed).

was observed at Warrington, DRBS, and Oulu, respectively. The recovery phase, which was in several steps, took about 4 hr.

On 10 May 2024, NM instruments at the Warrington, Oulu, and DRBS sites recorded reduced count rates as a result of the CME impact. The CME struck the Earth's magnetic field at about 17:00 UT (confirmed by magnetic field B_z and solar wind measurements; the graphs are in the Supporting Information S1 (Figure S2)), see Figure 5 (bottom). The NM-2023 was partially assembled to form a 2-NM-2023 and was in operation at the Warrington site during that period. A Forbush decrease due to a CME impact on count rate was observed by the N50L subsystem, the 2-NM-2023 (at Warrington), DRBS, and Oulu monitors, with count rate reductions of approximately 11%, 10%, 10%, and 12%, respectively. The count rate decrease lasted approximately 6 hr. A few minutes into the recovery phase (i.e., the count rate observed between the two orange boxes in Figure 5, bottom panel), GLE-74 was observed, resulting in a sudden increase in count rate. The N50L subsystem in the van was not operating during those periods, due to the pre-agreed measured period at Camborne and Lerwick.

For this GLE-74 analysis, the NM count rates were examined at a one-hour time resolution. The backgrounds N_0 for each instrument were determined using standard GLE methodology (Usoskin et al., 2022), that is, the 2 hours of data immediately preceding the event. The magnitude of the enhancement was then computed as the fractional increase $(N_{(t)} - N_0)/N_0$, and uncertainties were estimated assuming Poisson statistics, yielding 1σ confidence intervals and corresponding z-scores. The 2-NM-2023 showed a 4% increase with a 1σ uncertainty of 2% ($z \approx 2$), while the Warrington N50L subsystem showed a 4% increase but with a much larger 1σ of 8% ($z \approx 0.5$). Oulu recorded the largest and only statistically significant enhancement, 5% with a 1σ of 1%, resulting in $z \approx 3$, which exceeds the 3σ threshold commonly used to confirm CR-induced GLE signatures. DRBS produced a 4% rise with $1\sigma = 1\%$ and $z \approx 2.8$, placing it just below significance. Only Oulu registered a statistically significant SEP-associated increase, while the 2-NM-2023, N50L subsystem, and DRBS displayed sub-threshold enhancements that are consistent with minor fluctuations rather than a confidently detectable GLE signature. Thus, the NMs' geomagnetic cutoff rigidity influences the count rate registered by the monitor. The time-integrated GLE increases measured by Oulu and the 2-NM-2023 are similar (8.4% and 8.1%·hr), while smaller values are observed for the N50L subsystem (4.0%·hr) and DRBS (5%·hr). The N50L subsystem and DRBS also peaked an hour earlier than Oulu and the 2-NM-2023 during the GLE. GLE-74 can be categorized as a weak GLE event.

4. Conclusions

The N50L subsystem and CNM provide data that are comparable in trend and analytical capability to those from DRBS and Oulu despite being smaller. However, the count rates are much lower compared to the DRBS and Oulu, as would be expected, because the N50L subsystems have fewer counters and are smaller in size. The count rates at various UK sites indicate that altitude, latitude, and objects surrounding the NM (no reflector) affect count rates. This is essential for the future deployment of NM. The N50L subsystems, and 2-NM-2023, were able to observe the Forbush decrease, which occurred over the spring of 2024. However, did not register enough CR counts to be classified as a GLE-74. This shows the importance of having the 4-NM-2023 for detecting weak GLE in the UK. Initial measurements of 4-NM-2023 demonstrate that it achieves count-rate performance comparable to a 6-NM-64, while benefiting from a smaller footprint, reduced volume and mass, greater cost-effectiveness, and the use of non-toxic gas-filled counters.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Data for OULU are available online at <https://cosmicrays oulu fi/>, data for both OULU and DRBS are available online at <https://www nmdb eu/>. The data used to generate the figures in this article are available at (Mashao, 2025).

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