Neutrino physics with an opaque detector

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In 1956 Reines & Cowan discovered the neutrino using a liquid scintillator detector. The neutrinos interacted with the scintillator, producing light that propagated across transparent volumes to surrounding photo-sensors. This approach has remained one of the most wide-spread and successful neutrino detection technologies used since. This article introduces a concept that breaks with the conventional paradigm of transparency by confining and collecting light near its creation point with an opaque scintillator and a dense array of optical fibres. This technique, called LiquidO, can provide high-resolution imaging to enable efficient identification of individual particles event-by-event. A natural affinity for adding dopants at high concentrations is provided by the use of an opaque medium. With these and other capabilities, the potential of our detector concept to unlock opportunities in neutrino physics is presented here, alongside the results of the first experimental validation.
The discovery of the neutrino (ν) in the fifties
revolutionised particle physics not only by establishing the existence of this elusive particle, but also by laying the foundations for a technology used in many subsequent breakthroughs. The liquid scintillator detector (LSD) developed by Cowan, Reines et al. for ν detection exploited a well-established radiation detection technique at the time, whereby molecular electrons are excited by the passage of charged particles produced by ν interactions and then emit light upon de-excitation. This light is detected by sensitive photon detectors, typically photo-multiplier tubes (PMTs), that surround the scintillator volume and are often located many metres from the interaction point. Cowan, Reines et al. relied on the inverse-β decay (IBD) reaction, given by \( \bar{\nu}_e + p \rightarrow e^+ + n \), that yields two clear signals: the prompt energy deposition of the \( e^+ \) following the nuclear capture signal of the \( n \) after thermalisation. The close time and space coincidence between these two was exploited as the primary handle to separate the signal from the background (BG). The simplicity and power of this technique, enabled in great part by the abundant light produced by the scintillators, has allowed LSDs to dominate several areas of neutrino physics, particularly at the lower part of the MeV energy scale.

Despite their many advantages, LSDs have limitations. The propagation of light through the scintillator itself makes transparency an essential requirement for efficient light collection, potentially limiting the size of the detector volume. Given the extremely small probability for neutrinos to interact with matter, achieving larger detectors has in fact been a standing challenge throughout the history of ν physics. LSDs have gone from a few hundred kilograms, at the time of Cowan, Reines et al., to today’s 20,000 tons with JUNO4, where a record setting mean attenuation length of greater than 20 m is foreseen. The need for transparency has also set tight constraints on the type and concentration of elements that can be loaded into the scintillator. The physics goals of certain experiments call for detector doping5, where an element other than the scintillator’s native H and C is added to enhance detection capabilities or to search for rare processes. The discovery of the neutrino itself involved doping the detector with \( ^{113}\text{Cd} \) to increase the energy released on \( n \) capture and thus further reduce the BG. However, to this day, doping in LSDs has been limited at high concentrations by transparency and stability constraints.

LSDs typically have a rather poor event-by-event topological discrimination power. It is essentially impossible to distinguish an individual \( e^+ \) from an \( e^- \) or a \( γ \) below 10 MeV, and it is even very difficult to tell whether one or several events have occurred simultaneously. The primary approach to deal with these limitations has been to segment the detector. Here the main volume is subdivided into optically-decoupled compartments, so instead of a single monolithic volume a granular one is used. This allows recovery of topological information from each neutrino interaction, i.e. images of the space and time pattern of an event, and hence enhances a detector’s event identification capability. This technique has been successfully used with GeV-scale neutrinos, where the large physical extent of the events allows imaging of the final state particles using segmentation of a few centimetres. The largest example today is the 14 kiloton NOVA detector7,8, where the resulting images of the neutrino events are crucial for BG rejection and identification of different types of neutrino interactions. The situation is more difficult with MeV-scale neutrino interactions given the smaller physical extent of the resulting energy depositions, although there can still be advantages to segmenting. For instance, the coarsely segmented detector introduced by Cowan, Reines et al.1 exploited the unique anti-matter annihilation pattern of the \( e^+ \), producing two back-to-back mono-energetic \( y’s \), as an aid to event identification. It is difficult however to segment finely enough to resolve the full topological information of individual events at these low energies without introducing certain disadvantages, such as dead material, radioactivity, cost, etc.

Since the 1950s numerous discoveries have been made using ν’s from reactors, the sun, the interactions of cosmic rays in the atmosphere, accelerator produced beams, one supernova explosion (SN1987A), the earth and other astrophysical sources9, and LSDs have played key roles in many of them. Despite the remarkable progress, the limitations of today’s detector technology constrain our ability to probe the ν beyond our current knowledge and to use it in further exploring the universe.

This article presents a technique for neutrino detection, called LiquidO, that uses an opaque scintillator and a lattice of optical fibres to confine and collect light near its creation point. Extensive studies with simulations have been performed showing that our approach possesses many of the strengths of the existing technology while also giving rise to other capabilities, such as high-resolution imaging and a more natural affinity for doping. The principles of the technique have been demonstrated with a small experimental setup. The result is a detector concept with the potential to break ground in various frontiers of neutrino physics, some of which have remained elusive for decades.

Results and discussion
Detection principle. Our detection technique is based on using an opaque scintillator. Opacity can be achieved in two ways, through light scattering and/or absorption. The LiquidO approach relies on a short scattering length and an intermediate or long absorption length, producing a scintillator that is milky and translucent in appearance. Photons from the scintillator undergo a random walk about their origin, giving rise to stochastic light confinement. While the path of each photon is stochastic, the integral effect is the confinement of the light to a sphere around each ionisation point, resulting in the production of so-called light-balls. This is the principle at the heart of the LiquidO technique.

Scintillators used in modern neutrino experiments typically have scattering lengths of up to tens of metres. Reducing the scattering length down to the scale of millimetres causes the light to be confined to a volume that is much smaller than the typical physical extent of, for example, a 1 MeV γ-ray event whose energy is lost via Compton scattering. To extract the light a lattice of wavelength-shifting fibres runs through the scintillator. With a lattice spacing on the scale of a centimetre, prompt and efficient light collection can be achieved and absorption losses minimised. Many configurations of the fibre lattice are possible, and in principle fibres could run in all three orthogonal directions. In practice, fibres running in one or two directions might suffice. The difference in time of the light detection at the two ends of each fibre can be used as a measure of the event position along the length of each fibre.

The detection principle using the simplest configuration, where the fibres all run along the \( z \)-axis, is illustrated in Fig. 1. The energy depositions in three-dimensional space from a simulated \( e^+ \) with 1 MeV of kinetic energy are shown in Fig. 1b, while Fig. 1a shows the two-dimensional \( x-y \) projection. A simulation of the light propagation is shown in Fig. 1c, d, where the colour of each point represents the number of photons hitting a fibre. An opaque scintillator is simulated in Fig. 1c and in Fig. 1d the scintillator is transparent. The formation of the light-ball around the position of each Compton electron can be seen clearly for the opaque scintillator, whereas that pattern is almost completely washed out in the transparent case. A finely segmented detector would be required to measure this topology using transparent scintillator. In
The energy depositions in a LiquidO detector from a simulated $e^+$ with 1 MeV of kinetic energy plus the associated annihilation gammas are used to illustrate the detection principle and imaging capability. a shows a two-dimensional $x$-$y$ projection of the energy depositions in the scintillator, while b shows the full three-dimensional extent. The green lines running in parallel with the $z$-axis represent the fibres in the simplest configuration of the detector geometry. The energy deposition of the $e^+$ is shown by the orange point and the Compton scatters of the 0.51 MeV back-to-back annihilation $\gamma$'s by light and dark blues. One of the $\gamma$'s (dark blue) turns upwards to run approximately parallel with the fibres and this is reflected by its shorter extent in the $x$-$y$ projection. The simulation of the light hitting each fibre in a 1-cm-pitch lattice is shown in two scenarios: on c an opaque scintillator with a 5 mm scattering length is simulated, whereas on d the scintillator is transparent. The colour of each point represents the number of photons hitting a fibre at that $x$-$y$ location. With a transparent medium the resulting image from the fibre array is almost completely washed out. In stark contrast, the light confinement around each energy deposition with the opaque scintillator allows preservation of the event’s precious topological information and the formation of a high-resolution image.

Imaging and particle identification. The intrinsic high-resolution imaging capability of our technique is one of its main advantages. Using the information on the quantity of light collected from each fibre, the position of a point-like energy deposition can be reconstructed to within a few millimetres in the transverse direction to the fibres. This level of precision enables discrimination between point-like events such as MeV-scale $e^-$'s and events with spatially dispersed energy depositions such as $e^+$'s and $\gamma$'s. This is illustrated in Fig. 2a, where the topology of a $\gamma$ and an $e^-$ with 2 MeV of kinetic energy can be compared. The $e^-$ deposits all its energy within a centimetre whereas the $\gamma$ Compton scatters over many tens of centimetres. The discrimination power of LiquidO is quantified in Fig. 2c where the probability that a $\gamma$ is misidentified as an $e^-$ is shown versus the $e^-$ selection efficiency. A simple reconstruction algorithm quantifying the spatial spread of the hit fibres is used for these studies. The results indicate that 2 MeV $e^-$'s can be feasibly distinguished from $\gamma$'s with a contamination factor better than $10^{-2}$, which is unprecedented for LSDs at these energies. Similarly, the topology of an $e^+$ annihilation event, with its back-to-back $\gamma$'s as illustrated in Fig. 1c, stands in stark contrast to the point-like energy deposition of an $e^-$.

Charged particles with enough kinetic energy to travel several cm or more in the detector will produce sequences of point-like energy depositions. Such track-like signatures would arise from, for example, muons, allowing their path through the detector to be naturally opaque ideal, opening up a whole landscape of substances to explore. Known scintillators with substantially higher light output present promising avenues of research, alongside the possibility of finding new materials that have simply not been carefully studied yet due to their poor transparency.

The energy resolution of our 1 cm-pitch detector with a light yield of 400 photo-electrons per MeV is estimated from simulations to be $5%/\sqrt{E}$(MeV) as expected where Gaussian statistics dominate. The position-dependent response of our baseline detector is very uniform after attenuation in the fibres is calibrated out. It varies by less than 1% across more than 95% of the volume and has a negligible effect on the energy resolution.
Fig. 2 Discrimination of electrons from gammas. An image of a γ (a) and an e− (b) with 2 MeV of kinetic energy simulated using the default LiquidO detector configuration with fibres arranged in a 1-cm-pitch lattice running along the z-axis. The spatially dispersed Compton-scattering pattern of the γ clearly sets it apart from the e−. c shows the probability of misidentifying a γ as an e− vs. the efficiency of selecting e−’s estimated with a simple reconstruction. The scintillator is assumed to have a conventional light yield and a mean scattering length of either 1 mm or 5 mm, which is well-matched to the 1 cm fibre pitch. The photon detection efficiency ε of 3% accounts for all losses of light at the various stages and is dominated by the fibre trapping efficiency (around 10%) and the Si-based photo-sensor (SiPM) quantum efficiency (around 50%). The grey curve shows the probability of misidentifying a 2 MeV γ as an e− is estimated to be at the 10−2 level with an efficiency of 87% for λs = 5 mm. The red curve illustrates how the γ contamination decreases by an order of magnitude for the same efficiency when the light is more tightly confined (λs = 1 mm). The blue curve shows the improvement that can be obtained when fibres with the same 1-cm-pitch run along 2 orthogonal axes instead of a single one. Finally, the green curve illustrates how much hypothetical improvement could be obtained in the limit of 100% efficiency or equivalently 30× more light, some of which might be achieved through novel scintillators and/or improved photon detection efficiency. No timing information has been used and more sophisticated spatial reconstruction techniques could likely improve the e− vs. γ separation further. A photofraction scale is shown on d, which quantifies the fraction of γ’s that interact via the photo-electric effect and thus provides a floor to detector performance. Linear-Alkylbenzene (LAB) has a low photofraction of 6 × 10−6, compared to 2.9% for liquid xenon and 0.17% for LAB doped with 10% indium by weight.

Precisely reconstructed. Track-like patterns would also be formed from many other particle interactions such as νμ charged current (CC) above about 10 MeV and νe CC events at higher energies above the μ production threshold. In this way, LiquidO combines some of the advantages of tracking detectors with those of LSDs.

The timing information of the light pulses coming from each fibre is expected to further enhance the particle identification capabilities of LiquidO. Our simulations show that e+’s and γ’s have distinct energy-flow patterns, in that the e+ event typically develops outwards from a central light-ball while the γ consists of several light-balls forming in sequence. Work is ongoing to quantify the ability of LiquidO to perform dynamic imaging of energy depositions in time and the consequent improvement over the static imaging used in Fig. 2a, b. If successful, this could allow single-e+ events to be efficiently identified below 3 MeV, where most gamma backgrounds from natural radioactivity lie. Above this energy, we expect the timing information would typically be much less important and that the static images alone are likely to enable single-e+ identification.

The particle identification capability of our technique builds on the low density of organic scintillator, typically 0.9 g cm−3, and its high fraction of hydrogen with H-to-C ratios typically in the range 2–3. Its low average atomic number favours a long radiation length, around 0.5 m, a minimal photo-electric effect and energy losses by bremsstrahlung that do not start to dominate until e−’s have an energy of around 100 MeV. The extremely low cross-section for the photo-electric effect in scintillator, such as Linear-Alkylbenzene (LAB)17, means that an MeV-scale γ is highly unlikely to interact that way. On the rare occasion that this does happen an e− of the same energy is produced, which sets a limit to the level at which e−’s and γ’s can be distinguished. In scintillators, the fraction of 2 MeV γ’s that
interact via the photo-electric effect (the photofraction) is only $6 \times 10^{-6}$ whereas in a heavy liquid such as xenon it is 2.9%. Doping a scintillator with a metal causes the photofraction to increase. For example, if indium at 10% by mass is used the photofraction rises to 0.17%. These numbers are illustrated in Fig. 2d, allowing comparison of the probability of the event reconstruction misidentifying a $\gamma$ as an $e^-$ with the floor to performance set by the detector material.

**Elemental doping.** A particularly promising avenue for exploiting the LiquidO approach is where doping of the scintillator opens up the possibility of new physics measurements. One of the major challenges usually associated with doping LSDs is maintaining the optical properties, including transparency, while achieving the desired concentration of the dopant. In contrast, our technique actually requires opacity to confine the light and therefore allows for consideration of more possibilities, be it to load new materials or to achieve higher levels of doping. Examples of what can be achieved with a doped scintillator are wide and varied. The original Cowan, Reines et al. experiment used cadmium to increase the neutron capture cross-section and the LENS experiment concept involved using an indium-doped liquid scintillator\textsuperscript{18–20}. Several neutrino-less double beta decay experiments use or propose doped scintillators\textsuperscript{21–25} as the way forward to realise higher isotopic masses. The strong precedent set by LENS with indium suggests that loading at more than 10% for neutrino-less double beta decay searches is a reachable objective.

**First experimental proof of principle.** An experimental proof of principle has been successfully completed with a small detector prototype. The setup focused on demonstrating the primary feature of our technique, which is the stochastic confinement of light. The test was done with point-like $e^-$ energy depositions to demonstrate the formation of the characteristic light-ball.

Well-established technological solutions were used in the prototype for both the readout and the scintillator base. The latter was formulated from transparent LAB with a PPO wavelength-shifter at 2 g l$^{-1}$. The opacity was obtained by mixing in a paraffin polymer at 10% to give a uniform, waxy consistency\textsuperscript{15}. Like in many waxes, the resulting scintillator was observed to transition from a transparent liquid phase at $>30^\circ$C to an opaque white solid phase at $<15^\circ$C. This temperature dependence was exploited in the demonstration, as explained below. The scintillator was poured into a prototype detector that consisted of a small (0.25 litre and 5.0 cm height) cylindrical vessel with internally reflecting surfaces. Three identical Kuraray B-3 wavelength-shifting fibres were run along diametrical lines at different heights, as shown schematically in Fig. 3a, and read out with Hamamatsu S12572-050 SiPMs. The detector was exposed to a mono-energetic 1 MeV $e^-$ source\textsuperscript{26} impinging from the bottom through a thin 25 µm aluminised Kapton sheet. The $e^-$’s deposited their energy in the first few millimetres of scintillator.

The results from the prototype are shown in Fig. 3b. Three scintillator configurations were utilised: transparent (no added polymer), low opacity, and high opacity. The former was a control sample and the latter two were obtained by setting the temperature of the same sample of opaque scintillator to 26°C and 10°C respectively. We note that studies of an LAB-based scintillator showed only percent-level effects on the light yield from a similar temperature change\textsuperscript{27}. Direct comparison of the relative fibre response between the transparent and opaque scintillators allowed common systematic uncertainties to cancel, making the use of simulations unnecessary. In the transparent case, the PMT saw the most light and the fibres saw different light levels consistent with their respective solid angle acceptance as the dominant effect. When the opaque scintillator was used the light seen by the PMT and the top fibre was predictably reduced by a large factor. This light was not simply lost. The remarkable increase in light collection by the middle and bottom fibres ruled out an absorption-only scenario and showed that the light was stochastically confined around the point-like energy deposition at the bottom. The measurements at different heights sampled the longitudinal profile of the corresponding light-ball, confirming the LiquidO detection principle.

An interesting byproduct of this measurement was the observation of temperature controlled solidification of the waxy material. This could open the door to several possibilities, such as doping scenarios not bound by chemical stability constraints. The solidification also grants additional mechanical support for the fibre lattice and protection against leaks.

**Neutrino physics with LiquidO.** The LiquidO approach is likely to open up opportunities in neutrino research. Here, we highlight a few measurements at the MeV scale where LiquidO could have a significant impact. This energy range alone provides a rich landscape of challenging physics with a wide potential for discovery.

The performance of a LiquidO detector in terms of its position, timing and energy resolution as well as its light level and particle identification capability, depends on configurable parameters such as fibre pitch and scintillator formulation (scattering length, light yield). These parameters must be optimised for each experimental scenario by balancing all the factors at play, from the physics case to site-specific constraints (shielding, over-burden) and even cost limitations. Prospects for specific detector implementations in concrete experimental scenarios will be studied in subsequent publications.

**Physics potential with antineutrinos.** Above 1.8 MeV $\bar{\nu}_e$’s can undergo an IBD interaction resulting in a prompt $e^+$ signal followed by a delayed $n$ capture as the observable. This is the primary channel to detect $\bar{\nu}_e$’s emitted by nuclear reactors\textsuperscript{28}, supernovae\textsuperscript{29}, and the earth\textsuperscript{30}, as well as to search for these particles in decay-at-rest beams\textsuperscript{31–33}.

In current LSDs, single $e^+$ events are largely indistinguishable from naturally occurring $e^-$’s and $\gamma$’s with the same visible energy. Neutron backgrounds, originating mainly from the nuclear interactions initiated by cosmic-ray muons, are largely unavoidable. Furthermore, a correlated, prompt and point-like energy deposition can precede the capture of some of these neutrons and mimic a $e^+$ in an LSD. The unique signature of a $e^+$ event in a LiquidO detector, as shown in Fig. 1c, provides a powerful handle to reject some of these backgrounds. As shown in Fig. 2c, $e^-$’s or other particles giving point-like energy deposition are estimated to be misidentified as a $\gamma$ with probability of at most $10^{-2}$, which gives a reasonable estimate on the probability of misidentifying them as a $e^+$. Thus, all backgrounds whose prompt-like signals consist of $e^-$, $\alpha$ or recoil-$p$ can be reduced by a factor of at least a hundred in comparison to the latest LSDs\textsuperscript{34}. This includes all correlated backgrounds of cosmogenic origin, which typically bear the largest impact on the background systematic uncertainty, as well as the accidental backgrounds involving a $\beta^-$. Any remaining accidental backgrounds dominated by $\gamma$’s can be reduced by the spatial coincidence requirement that can be tightened by exploiting the more precise mm-scale vertex reconstruction. On top of those BG reductions, a decrease in the radioactivity present within the detector is possible through the elimination of the need for PMTs. As a case in point, the overall signal to background ratio of the Double Chooz near detector\textsuperscript{34}, with an overburden of barely 30 m
Radio-purity of their detection volumes. With LiquidO the by experiments that went to enormous efforts to improve the radioactivity, and has been up to about 4× larger in volume.

The detector consists of a small cylindrical vessel with internally reflecting surfaces including a 25 µm aluminised Kapton sheet at the bottom. Light is collected with three fibres (φ = 1 mm) running diametrically at different heights. A 3" photo-multiplier tube (PMT) is placed at the top and serves as a transparency monitor. Mono-energetic 1 MeV e−’s impinge from the bottom and make point-like energy depositions inside the detector as shown by the dashed semi-circular line.

The data collected with three scintillators made from the same base of Linear-Alkylbenzene (LAB) plus a PPO wavelength-shifter at 2 g l−1 are shown with measurement uncertainties illustrated by the pale regions at the top of each bar. These uncertainties correspond to the standard deviation of up to 10 measurements for each sample. The high (dark blue) and low (light blue) opacity formulations are obtained by mixing in a paraffin polymer at 10% and setting the temperature at 12 °C and 26 °C, respectively. The measurements from the prototype obtained with the opaque formulations are compared with those from the transparent scintillator (red), which serves as a control sample. To allow relative changes in light collection between the three fibres and the PMT to be seen easily, the axes of each bar chart were scaled so that the red bars are all the same height (grey dashed line). The high opacity data show a clear increase (around 2.0×) at the bottom of the vessel and a decrease (around 0.5×) at the top, as expected from stochastic light confinement around the energy deposition point. Given that the low and high opacity samples have the same composition and differ only in temperature, these results show that the formation of a light-ball and the corresponding increase in light collection at the bottom fibre are directly linked to the shorter scattering length.

In 1976, the possibility of doping with indium to enable MeV-scale νe CC interactions in a detector was proposed by Raghavan.

An additional factor is that pure organic scintillators provide no νe CC interaction below 15 MeV with a high-enough yield to be useful, except for elastic scattering with e−’s. The ability to dope a LiquidO detector with various elements at concentrations that would be prohibitive in conventional LSDs could enable measurements of electron neutrinos from a variety of sources that include the sun, supernovae and decay-at-rest beams.

### Physics potential with neutrinos

The detection of MeV-scale νe is in general a much greater challenge than νe in LSDs. A νe CC interaction produces an e− in the same way a νe produces a νe, but typically without an accompanying neutron. Measuring those single e−’s in LSDs is extremely hard due to the indistinguishable β’s and γ’s from natural radioactivity. It has, however, been done by experiments that went to enormous efforts to improve the radio-purity of their detection volumes. With LiquidO the dominant gamma backgrounds could be largely rejected by exploiting the difference in event topology.

**Fig. 3 Experimental proof of principle.**

- **a** Diagram of the small prototype detector built to make the first experimental demonstration of our opaque scintillator detection concept. The detector consists of a small cylindrical vessel with internally reflecting surfaces including a 25 µm aluminised Kapton sheet at the bottom. Light is collected with three fibres (φ = 1 mm) running diametrically at different heights. A 3” photo-multiplier tube (PMT) is placed at the top and serves as a transparency monitor. Mono-energetic 1 MeV e−’s impinge from the bottom and make point-like energy depositions inside the detector as shown by the dashed semi-circular line.

- **b** The data collected with three scintillators made from the same base of Linear-Alkylbenzene (LAB) plus a PPO wavelength-shifter at 2 g l−1 are shown with measurement uncertainties illustrated by the pale regions at the top of each bar. These uncertainties correspond to the standard deviation of up to 10 measurements for each sample. The high (dark blue) and low (light blue) opacity formulations are obtained by mixing in a paraffin polymer at 10% and setting the temperature at 12 °C and 26 °C, respectively. The measurements from the prototype obtained with the opaque formulations are compared with those from the transparent scintillator (red), which serves as a control sample. To allow relative changes in light collection between the three fibres and the PMT to be seen easily, the axes of each bar chart were scaled so that the red bars are all the same height (grey dashed line). The high opacity data show a clear increase (around 2.0×) at the bottom of the vessel and a decrease (around 0.5×) at the top, as expected from stochastic light confinement around the energy deposition point. Given that the low and high opacity samples have the same composition and differ only in temperature, these results show that the formation of a light-ball and the corresponding increase in light collection at the bottom fibre are directly linked to the shorter scattering length.
can be done with the $^{12}$C naturally present in organic scintillators$^{38,39}$. These capabilities would enable important measurements, such as the extraction of spectral information for the high-temperature neutrinos of a supernova burst$^{38}$. Furthermore, the simultaneous detection and identification of $\nu_e$ and $\bar{\nu}_e$ events could enable a measurement of leptonic charge conjugation parity symmetry violation$^{40}$ or other sub-dominant effects to photons reaching the detector sides are negligible: 90% of the photons hit a fibre radius and with an effectively negligible absorption length of 16 m. The outer cladding has a refractive index $n = 1.42$ and the inner cladding has $n = 1.49$. The fibres were modelled as having a maximum wavelength-shifting efficiency of 90% and a trapping efficiency of 10% for the re-emitted photons. Both ends of the fibres were assumed to be read out using SIPMs with a 50% photon detection efficiency. For the photons that hit a fibre, this resulted in a probability of detection of 4.5%. Since 90% of scintillator light hits a fibre, the overall efficiency was 4.05% before attenuation of the fibres to their own light (1 m) was applied, corresponding to a total 405 detected photons per MeV. In some studies, where stated, 300 detected photons per MeV was used, corresponding to an overall efficiency of 3%. This included the attenuation from a 1.5 m average distance travelled in the fibres, corresponding to a 3 m tall detector.

Conclusions

Our detector technique builds upon decades of existing expertise using scintillator detectors, but departs from the ubiquitous transparency-based approach by exploiting an opaque scintillator medium. The result is a detector that preserves many advantages of conventional liquid scintillator detectors while adding detailed imaging of particle interaction topology that enables individual identification of heavy metals. Studies looking at specific scenarios are ongoing and will be presented in future publications.

Methods

The key details of the simulation used for this paper are as follows. We used Geant4 version 4.10.04$^{41-43}$ to produce lists of energy deposits from particle interactions in our detector geometry. In the next step, 10,000 scintillation photons per MeV were generated within Geant4 and propagated through the geometry. A simple detector geometry with a 1-cm-pitch lattice of 0.5 mm diameter fibres running along the z-axis was used, unless otherwise stated. The behaviour of the photons in the opaque scintillator was modelled using a scattering length ($\lambda_s$) and an absorption length ($\lambda_a$). We used $\lambda_s = 5$ mm and $\lambda_a = 5$ m, unless otherwise stated. With the 1 cm lattice, 90% of the photons scatter until they hit a fibre with the remaining 10% being absorbed in the opaque scintillator. The fraction of light hitting the fibres is a weak function of the scattering length: with $\lambda_s$ between 1 mm and 100 cm the collection efficiency changes by only a few percent. Additionally, any edge effects due to photons being absorbed by the wavelength-shifting dye in the core of the fibre was modelled using an absorption length of 0.7 mm. The cladding of the fibre is simulated as 2 layers, each comprising 3% of the total fibre radius and with an effectively negligible absorption length of 16 m. The outer cladding has a refractive index $n = 1.42$ and the inner cladding has $n = 1.49$. The fibres were modelled as having a maximum wavelength-shifting efficiency of 90% and a trapping efficiency of 10% for the re-emitted photons. Both ends of the fibres were assumed to be read out using SIPMs with a 50% photon detection efficiency. For the photons that hit a fibre, this resulted in a probability of detection of 4.5%. Since 90% of scintillator light hits a fibre, the overall efficiency was 4.05% before attenuation of the fibres to their own light (1 m) was applied, corresponding to a total 405 detected photons per MeV. In some studies, where stated, 300 detected photons per MeV was used, corresponding to an overall efficiency of 3%. This included the attenuation from a 1.5 m average distance travelled in the fibres, corresponding to a 3 m tall detector.

Data availability

The data supporting the findings of this study are available from the corresponding author on reasonable request.

Code availability

The code that supports the findings of this study is available from the corresponding author upon reasonable request.

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Author contributions

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Competing interests

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