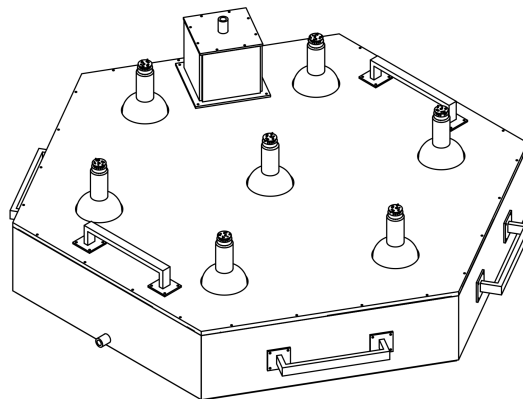

A New Liquid Scintillator Veto System Prototype

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Submitted in partial fulfillment of the requirements for the Research Phase of the
Master's degree in Physics.

June 11, 2026

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Abstract

In the ongoing search for light dark matter, the DarkMESA and NuDoubt⁺⁺ experiments have combined their efforts to probe a new region of parameter space. DarkMESA is a forthcoming electron beam dump experiment to be located in the new MESA accelerator facility in Mainz, designed to detect light dark matter particles using a PbF₂ crystal calorimeter. The NuDoubt⁺⁺ experiment will utilize an opaque liquid scintillator detector to investigate the double beta decay ($2\nu2\beta^+$) and the neutrinoless double beta decay ($0\nu2\beta$). Due to the expected rarity of these interactions, exceptional background rejection is crucial for identifying potential events. Therefore, both experiments plan to use passive and active shielding layers against background radiation.

This thesis will focus on the development of a liquid scintillator veto prototype for use in both experiments. The prototype will feature a hexagonal geometry with an active volume of approximately 351 l, filled with a linear alkylbenzene (LAB) scintillator, loaded with 0.2 wt.% gadolinium for enhanced neutron tagging. The scintillator will be read out by seven 5-inch PMTs mounted on the top surface of the volume. Simulation studies of this prototype veto system will be presented to evaluate the efficiency of the veto system, with particular emphasis on neutron rejection, given its significance as a background in dark matter searches.

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Chapter 1

Introduction

In the search for rare interactions, such as those expected from dark matter (DM) particles, a sensitive detector alone is insufficient to ensure successful detection. Background radiation and cosmic particles can overwhelm the detector with signals, effectively masking the rare events of interest. For this reason, an efficient veto system is required to identify and reject background events, thereby enabling the potential observation of DM interactions.

One such experiment is DarkMESA, a new electron beam dump experiment currently under construction at the MESA accelerator facility in Mainz, aimed at the detection of light dark matter (LDM). DarkMESA is based on the hypothesis that a dark photon, γ' , a massive vector boson, couples both to LDM and to the Standard Model (SM), thereby mediating interactions between the visible and dark sectors. In this scenario, dark photons may be produced in the P2 beam dump and subsequently decay into dark matter particle pairs, $\chi\bar{\chi}$, which can then scatter off electrons in the crystal calorimeter.

To improve detector performance and background rejection capabilities, a collaboration with NuDoubt⁺⁺ was initiated. NuDoubt⁺⁺ is developing an opaque liquid scintillator detector for the search for rare double beta decays. The detector concept incorporates an additional veto layer based on a transparent liquid scintillator. This technology is of particular interest for DarkMESA, since an opaque scintillator medium could enable full topological event reconstruction together with improved particle identification capabilities.

Compared to conventional plastic scintillator veto systems, liquid scintillators offer a significantly higher light yield and can be more easily scaled to larger detector volumes. In particular, loading the scintillator with gadolinium substantially enhances neutron detection efficiency, which is especially important because neutrons constitute one of the dominant background sources in DM searches.

The aim of the present work is the development of such a liquid scintillator veto system prototype. Initial simulation studies were performed using Geant4 to optimize the detector geometry and evaluate the expected efficiency of the prototype. These studies focused on two main scenarios: first, an idealized investigation of neutron interactions across a broad neutron energy spectrum, and second, simulations of the full cosmic-ray spectrum. In both cases, the tagging and veto efficiencies of the prototype were determined. Based on these simulation results, a physical prototype detector was designed and constructed

in order to validate the simulated detector response experimentally. Finally, simulations of a future upscaled veto system were carried out to investigate the resulting performance improvements and to evaluate the suitability of this technology as a potential alternative veto concept for the DarkMESA experiment.

This thesis is structured as follows. Chapter 2 provides a brief overview of the theoretical foundations motivating the DarkMESA and NuDoubt⁺⁺ experiments, including the evidence for dark matter, dark matter candidates, and the theoretical framework of double beta decay processes. Chapter 3 introduces the two experiments in more detail. In Chapter 4, the experimental concepts underlying the development of the veto prototype are presented. The simulation studies and their results are discussed in Chapter 5. This is followed by the design and construction of the physical prototype in Chapter 6. Chapter 7 presents simulation studies of a future large-scale version of the veto system. Finally, the main results and conclusions of this thesis are summarized in Chapter 8.

Chapter 2

Theoretical background

2.1 Astrophysical evidence for dark matter

Over the last century, the idea that an invisible form of matter permeates the universe has attracted increasing attention from the scientific community. Its elusive nature has made it one of the most significant open questions in modern physics.

In 1933, Fritz Zwicky was the first to postulate the existence of dark matter (DM) while observing the galaxies contained in the Coma Cluster. After observing a significant discrepancy in the velocities of individual galaxies, he applied the virial theorem and found that the amount of luminous matter was approximately 400 times smaller than the total mass required to gravitationally bind the cluster [1]. This discrepancy led to the so-called “missing mass” problem, which Zwicky attributed to the presence of large amounts of unseen matter interacting with baryonic matter primarily through gravity.

2.1.1 Rotation curves

In the early 1970s, during her studies of galactic rotation curves, Vera Rubin discovered evidence further supporting the existence of dark matter. She observed a clear discrepancy between the measured rotational velocities of stars and the velocities predicted by Newtonian gravity for their motion around the galactic center:

$$F_c = F_g \Rightarrow \frac{mv(r)^2}{r} = G \frac{mM(r)}{r^2} \Rightarrow v(r) = \sqrt{G \frac{M(r)}{r}} \quad (2.1)$$

Here, the centrifugal force of a star orbiting the galactic center is equated to the gravitational force acting upon it, yielding a relation for the rotational velocity as a function of distance from the galactic center. Under the assumption of a constant enclosed mass, this relation predicts that the velocity should decrease as $\frac{1}{\sqrt{r}}$ with increasing radius.

However, it was observed that the velocities of stars remain relatively constant in the outer regions of a galaxy, as seen in Fig. 2.1. This behavior is inconsistent with the predictions of standard gravitational models based on visible matter alone. To explain this discrepancy, two main possibilities were considered. Either the current understanding of gravity is incomplete and requires modification, or, assuming existing theories to be

correct, there must exist a substantial amount of invisible matter surrounding galaxies. This hypothetical “dark matter halo” would provide the additional gravitational influence needed to sustain the observed flat rotation curves, thereby resolving the disagreement between theory and observation.

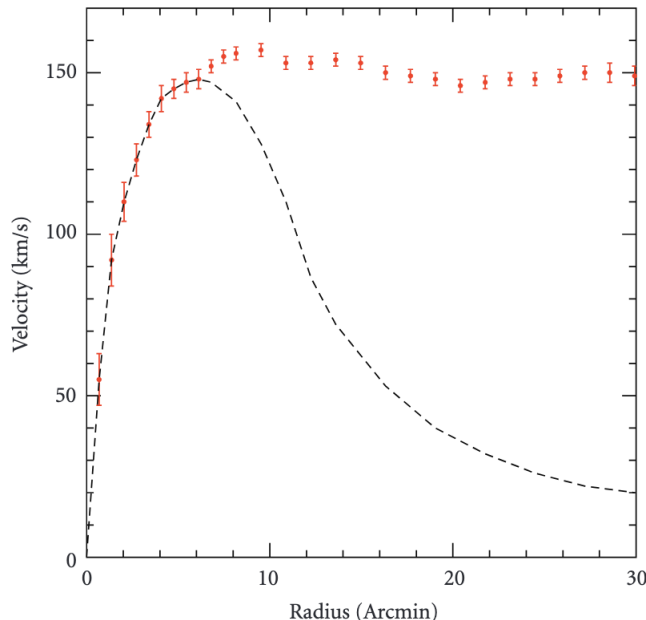


Figure 2.1: In red are the measured rotational velocities of HI regions in NGC 3198 compared to the idealized Keplerian behavior in black. [2]

2.1.2 Bullet Cluster

The Bullet Cluster consists of two colliding clusters of galaxies (see Fig. 2.2). As with multiple other similar observations, gravitational lensing studies claim to provide compelling evidence for the existence of dark matter. [3]

Since the different components of the cluster pair behave differently during the collision, they can be studied separately. Stars and gas are mostly unaffected by the collision, only being slowed to varying degrees due to gravitational forces and electromagnetic interactions in the case of gas. The hot gas, visible in the X-ray spectrum, constitutes most of the baryonic mass in the cluster pair. With the use of gravitational lensing, however, it was discovered that the lensing was strongest in two separate regions near the visible matter, further supporting the idea that most of the gravitation in the cluster pair lies in two areas rich with dark matter. This agrees with the prediction that dark matter interacts both weakly and gravitationally.

The observation of the Bullet Cluster provided a strong argument against modifications of gravity as an alternative to dark matter, in particular against Modified Newtonian Dynamics (MOND). Below a characteristic acceleration threshold, MOND can successfully account for galaxy rotation curves (see Sec. 2.1.1). However, it fails to explain the

observed separation between the baryonic matter and the gravitational lensing signal in the Bullet Cluster. Even relativistic extensions of MOND struggle to reproduce these observations without effectively reintroducing a dark matter component.

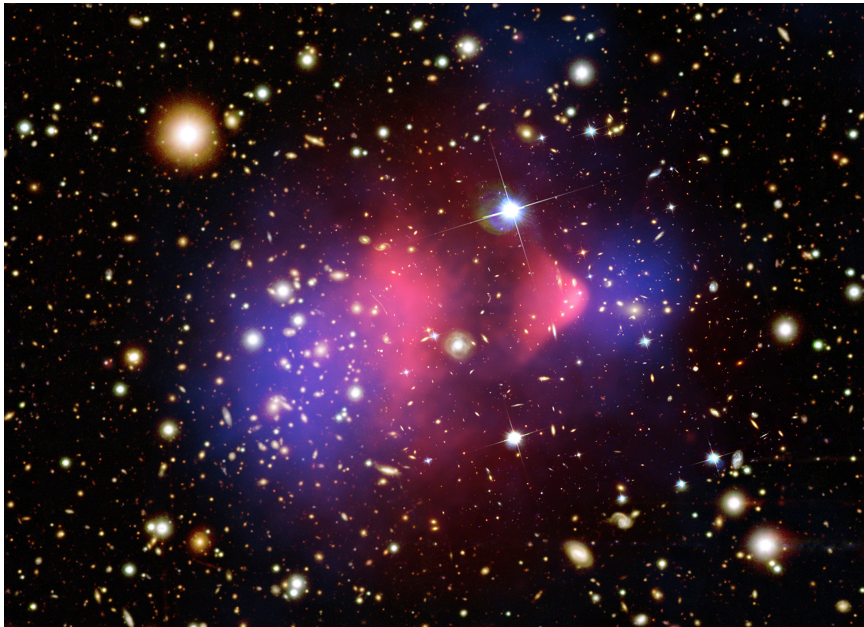


Figure 2.2: Composite image of the Bullet Cluster. The optical image from the Magellan and the Hubble Space Telescope shows galaxies in orange and white in the background. Hot gas, which contains the bulk of the normal matter in the cluster, is shown by the Chandra X-ray image, which shows the hot intracluster gas (pink). Gravitational lensing, the distortion of background images by mass in the cluster, reveals the mass of the cluster is dominated by dark matter (blue). [4]

2.1.3 Cosmic microwave background (CMB)

The discovery of the cosmic microwave background, or CMB, provided strong evidence for the Big Bang and also helped evaluate the matter content of the universe by studying the thermal anisotropies in the microwave spectrum.

The early universe consisted of a hot, dense plasma of electrons and baryons. Photons traveling through the universe could not propagate for any considerable distance before interacting with the plasma via Thomson scattering, rendering the universe opaque. As the universe expanded, the plasma cooled enough to allow protons and electrons to form neutral hydrogen atoms. Following this process, the newly formed atoms could no longer scatter thermal radiation, and photons could travel unhindered through space; the universe thus became transparent. This so-called recombination epoch, which took place approximately 380 000 years after the Big Bang, marks the moment when the universe became transparent, allowing the free-flow of photons through the universe. Due to the universe's expansion, the cosmological redshift has caused the photons to grow less ener-

getic, shifting them towards microwave wavelengths. The CMB has an isotropic thermal black body spectrum at a temperature of 2.725 K [5] and can also be described as a function of redshift z :

$$T = 2.725 \text{ K} \cdot (1 + z) \quad (2.2)$$

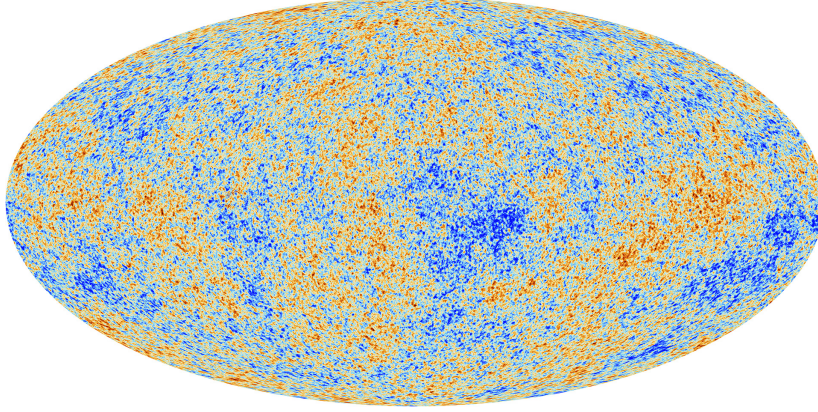


Figure 2.3: Heat map of temperature fluctuations in the cosmic microwave background as observed by the Planck satellite. [6]

The heat map in Fig. 2.3 provides valuable insight into the structure formation and matter distribution of the universe shortly after the Big Bang. In addition to the cosmic microwave background, independent constraints on the matter content of the universe are provided by baryon acoustic oscillations (BAO). These arise from density perturbations in the primordial plasma, which consisted of dark matter, baryons, and photons. In overdense regions, gravitational attraction, dominated by dark matter, pulled matter inward, while the induced radiation pressure, caused by the contraction, pushed matter outward. This competition led to oscillations in the plasma, analogous to sound waves. As a result, spherical waves of baryons and photons propagated outward from the initial overdensities, while dark matter, interacting only gravitationally, remained concentrated at the center. During the recombination epoch, when photons streamed freely through the universe, the radiation pressure opposing gravity was removed. This process left behind a characteristic overdensity of baryonic matter at a fixed radius, known as the sound horizon.

When combined with CMB observations, BAO measurements provide complementary constraints on cosmological parameters and significantly improve the determination of the baryon and dark matter densities. The CMB fluctuation spectrum in combination with BAO measurements can be analyzed with the cosmological Lambda cold dark matter (Λ CDM) model, based on the Friedmann-Lemaître-Robertson-Walker (FLRW) metric:

$$ds^2 = dt^2 - a^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right] \quad (2.3)$$

where $a(t)$ is the scale factor of the universe and k the curvature of space. The curvature parameter k can be assigned the values $+1, 0, -1$ depending on whether the universe is

spherical, flat, or hyperbolic, respectively. By inserting this metric into the Einstein field equations, it is possible to obtain the Friedmann equations:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \quad (2.4)$$

Then, defining the Hubble parameter as:

$$H \equiv \frac{\dot{a}}{a} \quad (2.5)$$

and also introducing the equation of state:

$$\rho_i(a) = \rho_{i,0}a^{-n} \quad (2.6)$$

and the critical density:

$$\rho_c \equiv \frac{3H^2}{8\pi G} \quad (2.7)$$

It is possible to rewrite equation 2.4 as an expression of density parameters to obtain the following relation:

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(a) = H_0^2 [\Omega_{r,0}a^{-4} + \Omega_{m,0}a^{-3} + \Omega_{k,0}a^{-2} + \Omega_{\Lambda,0}] \quad (2.8)$$

Finally, by fitting this model to the data obtained with the Planck satellite, the following density parameters can be obtained:

$$\begin{aligned} \Omega_c + \Omega_b + \Omega_r + \Omega_k + \Omega_\Lambda &= 1, \\ \text{Cold DM density: } \Omega_c &= 0.2589 \pm 0.0057, \\ \text{Baryonic density: } \Omega_b &= 0.0486 \pm 0.0010, \\ \text{Dark energy density: } \Omega_\Lambda &= 0.6911 \pm 0.0062, \\ \text{Radiation density: } \Omega_r &\sim 10^{-4}, \\ \text{Curvature of the universe: } \Omega_k &\sim 0 \end{aligned}$$

These results indicate that the universe is nearly flat ($\Omega_k \sim 0$), and the matter within consists of only approximately $\sim 5\%$ baryonic matter, compared to dark matter, which is about five times more abundant at $\sim 26\%$, while the rest of the universe is made up of dark energy.

2.2 Dark matter candidates

Over the years, efforts were made to describe and understand the nature of dark matter. Almost all current models of dark matter use quantum field theory to describe the properties of elementary particle candidates. This means that these candidates can be described by their mass and spin. A few proposed candidates, shown in Tab. 2.1, could claim the title of the elusive dark matter.

Table 2.1: Properties of various dark matter candidates [7].

Type	Particle Spin	Approximate Mass Scale
Axion	0	$\mu\text{eV} - \text{meV}$
Sterile Neutrino	1/2	keV
WIMP	0, 1/2, 1	10 GeV – 100 TeV
LDM	1/2	keV – 1 GeV

DM candidates can be broadly classified into two regimes: **cold dark matter (CDM)**, which drives structure formation on galactic scales, and **hot dark matter (HDM)**, which remains relativistic longer and primarily affects large-scale structures such as galaxy clusters. HDM alone cannot reproduce the observed small-scale structure (e.g. in the CMB), while CDM successfully explains it.

In the early universe, DM particles χ were in thermal equilibrium with SM particles. As the universe expanded and cooled, interaction rates decreased until annihilation and production processes became inefficient. Freeze-out (see Fig. 2.4) occurs when the interaction rate drops below the Hubble expansion rate:

$$n_\chi \Gamma = H \quad \text{with} \quad \Gamma = \langle \sigma v \rangle \quad (2.9)$$

where $\langle \sigma v \rangle$ is the thermally averaged annihilation cross section.

The evolution of the number density is described by the Boltzmann equation:

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\text{eq}}^2) \quad (2.10)$$

The equilibrium number density depends on whether DM is relativistic or not:

- **Relativistic (hot DM, $m_\chi \ll T$):**

$$n_{\text{rel}} \sim T^3 \quad (2.11)$$

- **Non-relativistic (cold DM, $m_\chi \gg T$):**

$$n_{\text{non-rel}} \sim (m_\chi T)^{3/2} e^{-m_\chi/T} \quad (2.12)$$

During the radiation-dominated era ($\rho \sim T^4$), the Hubble rate scales as:

$$H \sim \frac{T^2}{M_{\text{P}}}, \quad (2.13)$$

with M_{P} the Planck mass. Defining $x = m_\chi/T$, the freeze-out condition for cold DM can be approximated as:

$$\sqrt{x} e^{-x} = \frac{1}{m_\chi M_{\text{P}} \langle \sigma v \rangle} \quad (2.14)$$

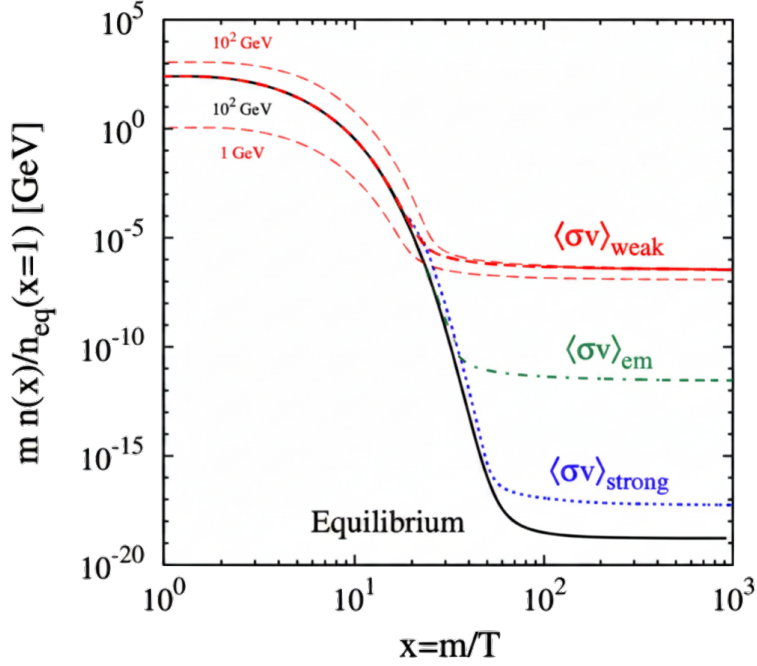


Figure 2.4: Evolution of the cosmological WIMP abundance as a function of $x = m/T$. The thick curves show the WIMP mass density, normalized to the initial equilibrium number density, for different choices of annihilation cross section $\langle\sigma v\rangle$ and mass m . Results for $m = 100$ GeV are shown for weak interactions (dashed red), electromagnetic interactions (dot-dashed green), and strong interactions (dotted blue). For the weak cross section, the thin dashed curves show the WIMP mass dependence for $m = 10^3$ GeV (upper dashed curve) and $m = 1$ GeV (lower dashed curve). The solid black curve shows the evolution of the equilibrium abundance for $m = 100$ GeV. [8]

After freeze-out, the comoving number density becomes constant. This is conveniently expressed using the yield $Y = n/s$ (with entropy density s):

$$\dot{Y} = \langle\sigma v\rangle s (Y_{\text{eq}}^2 - Y^2) \quad (2.15)$$

Once $n_\chi \langle\sigma v\rangle \lesssim H$, annihilations cease, and Y freezes to a constant value.

A key result is that the present-day relic abundance is approximately

$$\Omega_{\text{DM}} h^2 \sim \frac{1}{\langle\sigma v\rangle} \quad (2.16)$$

with weak-scale interactions ($\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3 \text{ s}^{-1}$) naturally reproducing the observed density—this is the **WIMP miracle**.

The requirement that DM be non-relativistic at structure formation sets a lower bound of

$$m_\chi \gtrsim \mathcal{O}(10 \text{ keV}) \quad (2.17)$$

while perturbative unitarity implies an upper bound of roughly 10 TeV for thermal relics.

Prominent candidates in this range include:

- **WIMPs**, typically above ~ 10 GeV,
- **Light dark matter (LDM)** below ~ 1 GeV,
- Specific realizations such as the neutralino (SUSY), Kaluza–Klein excitations, or gravitinos.

For non-thermal production mechanisms, much lighter candidates such as **axion-like particles (ALPs)** can arise, with masses spanning 10^{-22} eV up to the keV scale.

Beyond particle candidates, alternative scenarios include **primordial black holes**, non-luminous compact baryonic objects, or modifications of gravity such as MOND. At the extreme high-mass end, **superheavy dark matter** (“WIMPzillas”, $m \sim 10^{13}$ GeV) may be produced during the inflationary epoch.

2.3 Light dark matter and dark sector models

LDM is considered a product of a hidden “dark” sector. The models that describe the dark sector are classified by the type of mediator (portals) they contain. LDM can exist under the condition that there are still undiscovered light mediators, which are neutral under the standard model gauge groups. Such mediators can be a scalar ϕ , a fermion N , or a vector particle A' . [9]

Higgs portal contains a scalar ϕ mediator. Depending on the mass relation of DM and the scalar ϕ , two different cases can be distinguished. For $m_\chi < m_\phi$ DM particles can directly annihilate into SM fermions via the scalar field ϕ :

$$\chi\chi \rightarrow \phi \rightarrow ff \quad (2.18)$$

For $m_\chi > m_\phi$ a secluded annihilation is also allowed:

$$\chi\chi \rightarrow \phi\phi \quad (2.19)$$

The scalars can then decay into SM particles.

Fermion portal allows the coupling between DM and SM particles via Yukawa coupling with a right-handed neutrino. This is possible only if the mass range of the mediator is very narrow. A sub-GeV fermion mass is required for the thermal origin of DM.

Vector portal contains new vector particles A' . These particles constitute vector mediators of a new gauge group $U(1)_D$ in the dark sector, allowing for interactions between the dark sector and the SM. Such mediators could be Dirac fermions, Majorana fermions, and scalar particles. The dark photon is the most promising vector particle mediator, which is also relevant for LDM production and detection in the DarkMESA experiment.

2.4 The dark photon

The dark photon γ' is a massive vector particle that can mediate interactions between the SM and the dark sector through kinetic mixing with the ordinary photon. The phenomenology of the massive dark photon is discussed in terms of its interaction with SM particles, as given by Eq. 2.20.

$$\mathcal{L} = -\varepsilon e J^\mu A'_\mu \quad (2.20)$$

where J^μ is the electromagnetic current. The strength of this interaction is modulated by the mixing parameter ε . The parameter space for the experimental searches is given by the mass of the dark photon $m_{A'}$ and ε .

Production, decays, and detection

Since the current J_μ in Eq. 2.20 is the same as the usual electromagnetic current, dark photons A' can be produced like ordinary photons. The main production mechanisms are shown in Fig. 2.5.

- **Bremsstrahlung:** An electron scatters off the target nuclei (Z), emitting a dark photon: $e^- Z \rightarrow e^- Z A'$;
- **Annihilation:** An electron-positron pair annihilates into an ordinary and dark photon: resonant $e^- e^+ \rightarrow A'$, and non-resonant $e^- e^+ \rightarrow \gamma A'$
- **Meson decays:** A meson M decays as: $M \rightarrow \gamma A'$
- **Drell-Yan:** A quark-antiquark pair annihilates into the dark photon, later decaying into a pair of leptons: $q\bar{q} \rightarrow A'(\rightarrow \ell^+ \ell^- \text{ or } h^+ h^-)$

At accelerator experiments, dark photons can be searched for through several techniques:

Detection of visible final states targets dark photons above ~ 1 MeV that decay to SM particles, typically requiring high-luminosity colliders or beam dumps; this method is sensitive to larger couplings ($\varepsilon > 10^{-3}$) and benefits from long decay volumes and precise tracking.

Missing momentum/energy techniques detect invisible decays by measuring energy or momentum carried away by undetected particles, offering better sensitivity as the signal scales with ε^2 rather than ε^4 , but requiring highly hermetic detectors and excellent background rejection.

Missing mass techniques look for narrow resonances in reactions with well-known initial states, relying on complete detection of all visible final-state particles and precise knowledge of backgrounds.

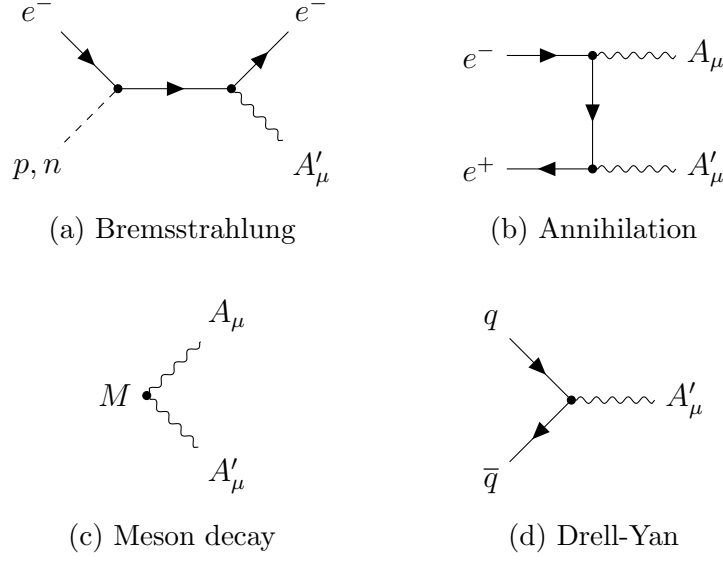


Figure 2.5: Representative Feynman diagrams contributing to dark photon (A'_μ) production: Bremsstrahlung, Annihilation, Meson decay, and Drell-Yan. [10]

Visible and invisible massive dark photon

If the mass of the dark photon is larger than that of dark matter particles, it would most likely decay into a $\chi\bar{\chi}$ pair. Otherwise, it would decay into a pair of SM leptons, as seen in Fig. 2.6.

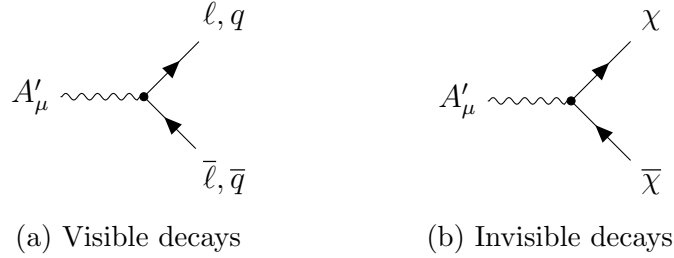


Figure 2.6: Decay of the massive dark photon into visible (SM leptons or hadrons) and invisible (DM) modes. [10]

If $m_{\gamma'} < 2m_\chi$ the DM yield is $Y_\chi \sim \frac{\alpha_D \varepsilon^2}{m_\chi^2}$ and the DM scattering $Y_D \sim \frac{\alpha_D \varepsilon^2}{m_{\gamma'}^2}$, where ε is the weak interaction coupling strength dependent on the weak mixing angle and α_D the dark fine structure constant. The resulting total yield is as follows:

$$Y = Y_\chi \times Y_D \sim \frac{\alpha_D^2 \varepsilon^4}{m_\chi^2 m_{\gamma'}^2} \quad (2.21)$$

If, however, $m_{\gamma'} > 2m_\chi$, the DM yield is $Y_\chi \sim \frac{\alpha_D \varepsilon^2}{m_{\gamma'}^2}$ and the DM scattering Y_D in the

detector scales with the same value, resulting in:

$$Y = Y_\chi \times Y_D \sim \frac{\alpha_D^2 \varepsilon^4}{m_{\gamma'}^4} \quad (2.22)$$

2.5 Double beta decays

Double beta decay is a rare nuclear decay that changes the nuclear charge number Z by two units while keeping the nucleon number A unchanged [11]. It occurs between two even–even isobars when a single beta decay to the intermediate (odd–odd) nucleus is energetically forbidden. This happens because the pairing interaction shifts the mass parabola of even–even nuclei relative to that of odd–odd nuclei within the same isobaric chain (see Fig. 2.7). As a result, the direct transition via two simultaneous beta decays becomes the only allowed process, making double beta decay observable.

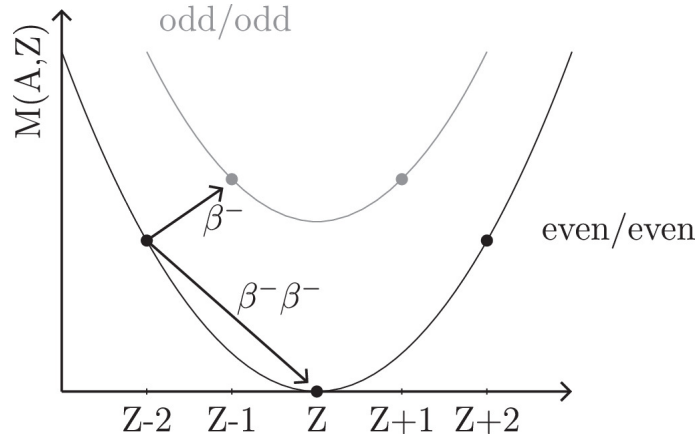


Figure 2.7: Mass parabola of nuclear isobars with even mass number A . Due to the pairing term in the semi-empirical mass formula, β^- transitions of even/even nuclei to their odd/odd isobaric neighbor can be energetically forbidden, whereas, in a second-order process, $\beta^- \beta^-$ decay is allowed. [12]

Double beta decay can occur in different modes, depending on the particles emitted during the decay. The two main modes of interest are two-neutrino ($2\nu 2\beta$) double beta decay, in which two (anti)neutrinos also appear in the final state, and neutrinoless ($0\nu 2\beta$) double beta decay without the emission of any neutrinos [11].

$$\begin{aligned} 2\nu 2\beta^\pm &: (A, Z) \rightarrow (A, Z \pm 2) + 2\beta^\mp + 2\bar{\nu}^{(-)} \\ 0\nu 2\beta^\pm &: (A, Z) \rightarrow (A, Z \pm 2) + 2\beta^\mp \end{aligned} \quad (2.23)$$

The processes where two neutrinos are emitted are predicted by the SM, and $2\nu 2\beta^-$ decay has been observed in several nuclei. The $2\nu 2\beta^+$ (Fig. 2.8a) and $0\nu 2\beta^\pm$ (Fig. 2.8b) decays have not yet been experimentally observed. The latter is a beyond SM (BSM) interaction, which, in most models, violates total lepton number conservation by two units, and its observation would imply Majorana nature of neutrinos.

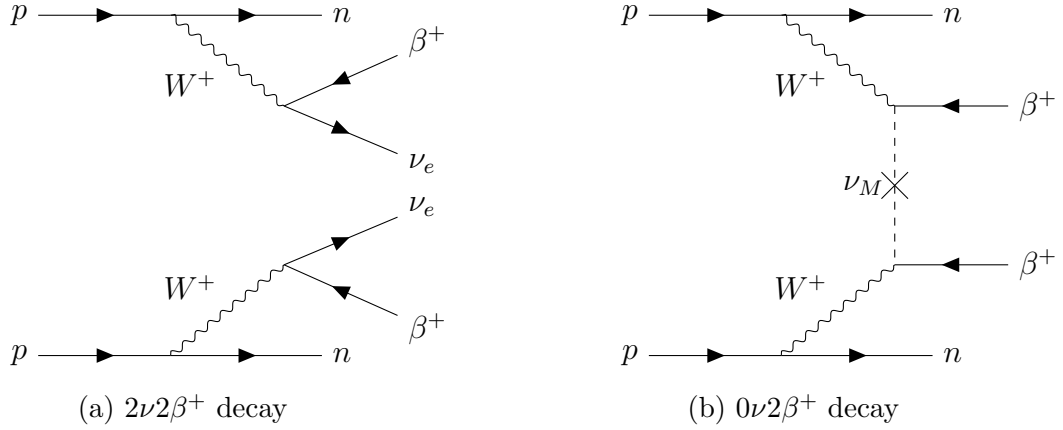


Figure 2.8: Feynman diagram of the SM $2\nu 2\beta^+$ decay (left). Feynman diagram of the $0\nu 2\beta^+$ decay driven by a light Majorana mass exchange (right).

There are two additional decay modes enabled by electron capture in the nucleus, in which the nuclear charge number is decreased. These are the positron emitting electron capture $EC\beta^+$, and double electron capture $2EC$ [11], as seen below:

$$\begin{aligned} 2\nu EC\beta^+ : (A, Z) + e^- &\rightarrow (A, Z - 2) + \beta^+ + 2\nu \\ 2\nu 2EC : (A, Z) + 2e^- &\rightarrow (A, Z - 2) + 2\nu \end{aligned} \quad (2.24)$$

Double beta decays are mediated by the weak interaction, which makes them extremely rare with half-lives in the order of $10^{18} - 10^{24}$ years; however, they are still experimentally detectable. With a sufficiently sensitive detector, including excellent background suppression, it might be possible to study the spectra of these interactions.

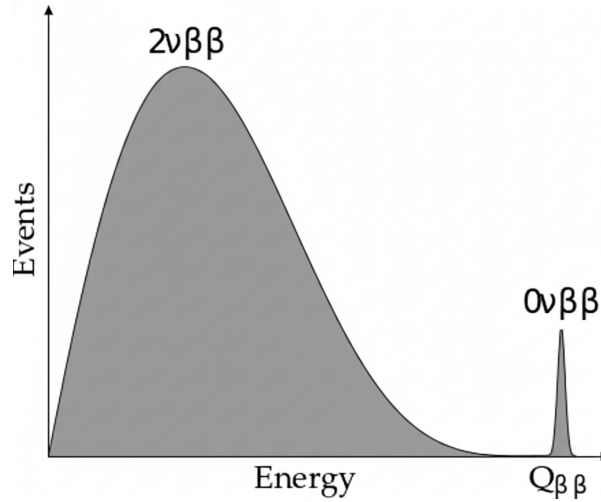


Figure 2.9: Signature of $0\nu 2\beta$ decay in the energy spectrum. The true relative height of the $0\nu 2\beta$ peak is unknown. [13]

In $2\nu 2\beta$ decay, the decay energy $Q_{\beta\beta}$ is shared between two electrons and two neutrinos, so the neutrinos carry away a variable amount of energy. As a result, the summed electron

energy spectrum is continuous, extending from zero up to $Q_{\beta\beta}$, with a broad shape that vanishes at the endpoint. In $0\nu2\beta$, no neutrinos are emitted, so the two electrons carry all the available energy. This leads to a sharp peak at $Q_{\beta\beta}$ in the summed electron energy spectrum (broadened slightly by detector resolution) as shown in Fig. 2.9.

Chapter 3

Experiments at MESA and beyond

3.1 MESA - A new accelerator facility in Mainz

The **M**ainz **E**nergy-recovering **S**uperconducting **A**ccelerator (MESA) is a new accelerator currently under construction at the Institute of Nuclear Physics at the Johannes Gutenberg University of Mainz. The design of MESA is shown in Fig. 3.1. As the world's first superconducting energy-recovering accelerator dedicated to research, it has the potential to pioneer research in elementary particle physics. With its high beam intensity, new high-precision experiments will be achievable. Its two operating modes provide additional variety for potential research fields.

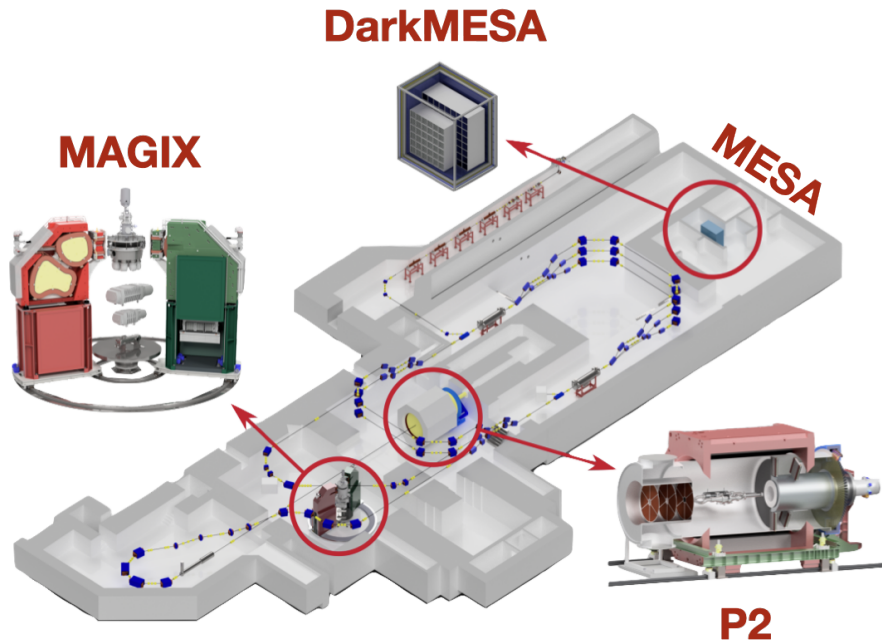


Figure 3.1: Overview of the MESA accelerator facility. Within are contained two main experiments: MAGIX and P2. DarkMESA is a parasitic experiment that utilizes the P2 beam dump. [14]

The **energy-recovering linac (ERL)** mode allows the electron beam to be recirculated twice and gain energy up to 105 MeV with a current of 1 mA. The beam is directed back to the cavities with a 180-degree phase shift after traversing the MAGIX target, decelerating the electrons, and at the same time restoring energy to the accelerator.

The **extracted beam (EB)** mode directs the thrice recirculated beam to the P2 experiment with energy up to 155 MeV and a current of 150 μ A. Due to the high-density targets used in P2, energy recovery is no longer possible, and the beam has to be stopped. The P2 beam dump serves as a target for the third experiment - DarkMESA.

3.1.1 MAGIX

The **Mainz Gas Injection Target Experiment (MAGIX)**, shown in Fig. 3.2, will be operated in the ERL mode. After scattering off the MAGIX windowless gas jet target, the electrons may enter the acceptance of either of the two identical magnetic spectrometers, STAR and PORT, where they are focused on focal plane detectors, which consist of a time projection chamber (TPC) and a trigger veto system for each spectrometer. A silicon strip detector is responsible for detecting recoil particles of the gas jet in addition to the scattered electrons. The windowless target design greatly reduces the background from multiple scatterings inside the chamber.

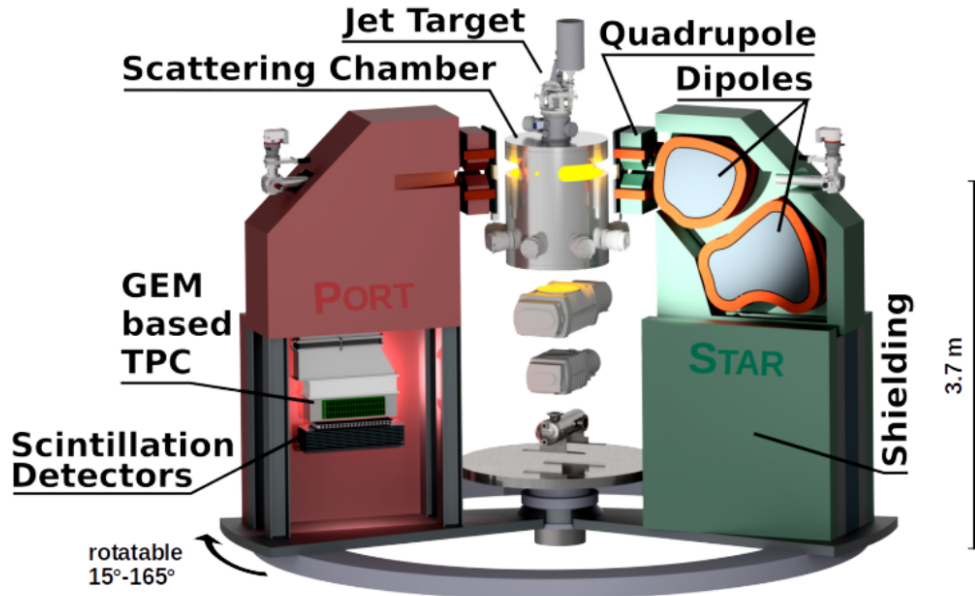


Figure 3.2: Overview of the MAGIX setup. [15]

3.1.2 P2

The P2 experiment, shown in Fig. 3.3, will be operated in the EB mode and intends to measure the weak mixing angle in electron-proton scattering at low momentum transfer with high precision.

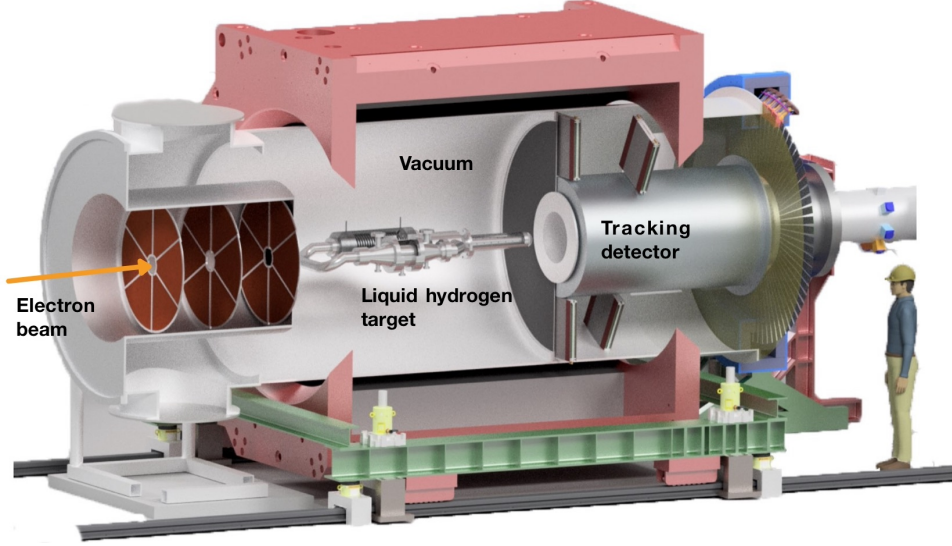


Figure 3.3: Overview of the P2 setup. [16]

Only a small portion of the electrons in the beam are scattered in the liquid hydrogen target, rendering them detectable by P2. Most leave through a beam-exit pipe and are halted by a beam dump after traversing 12 m of vacuum. This beam dump can hinder all MESA beam electrons and all beam-originating particles except for some neutrons and neutrinos.

DarkMESA capitalizes on the P2 beam dump, using it as a target, enabling it to operate parasitically and conduct research in the dark sector.

3.2 DarkMESA - A new beam dump experiment

As mentioned in previous chapters, DarkMESA is the third experiment at MESA and also the subject of this thesis. In an ever-growing effort to discover the elusive dark matter, this parasitic electron beam dump experiment has its gaze turned towards the theorized dark sector, searching for particles such as LDM.

The hypothesis upon which this experiment is founded is that, in the simplest model, LDM can interact with the standard model via a massive dark photon γ' , effectively coupling with strength ε . This dark photon γ' could be produced when the MESA electron beam reaches the beam dump, in a process analogous to the electromagnetic bremsstrahlung (see Sec. 2.4). The dark photon could then invisibly decay into a $\chi\bar{\chi}$ pair of DM particles, with a coupling strength equivalent to the dark fine structure constant α_D . The concept of the DarkMESA experiment is shown in Fig. 3.4.

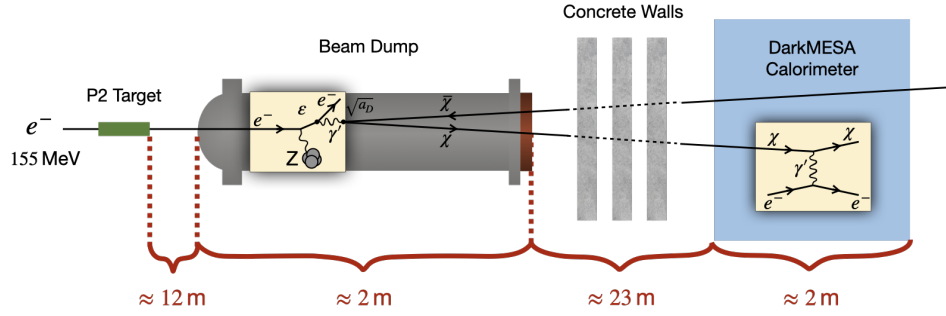


Figure 3.4: Overview of the beam path relevant for DarkMESA (not to scale). The Feynman graphs indicate the production and detection processes, wherein a dark photon γ' is produced in a dark bremsstrahlung process in the P2 beam dump, which decays into a $\chi\bar{\chi}$ pair, which in turn scatters off of SM particles in the DarkMESA detector.

Approximately 23m after exiting the beam dump, having passed through multiple layers of concrete walls and air, the DM particles reach the DarkMESA detector site undisturbed due to their low interaction probability. In contrast, all other SM particles are hindered by the shielding, rendering the detector site almost background-free from secondary particles produced in the electron beam. A fraction of these DM particles may scatter off electrons and nuclei in the calorimeter, potentially enabling their detection.

3.2.1 Prototype detector - Phase A

The DarkMESA experiment is planned to be constructed in several phases with a constantly expanding active volume.

The DarkMESA prototype detector consists of 25 PbF_2 Cherenkov crystals with PMTs individually attached to each one. These crystals are arranged in a 5×5 matrix, resulting in an active volume of 3.6l, as shown in Fig. 3.5. This volume is then surrounded by a veto system comprising two plastic scintillator layers and two lead layers, providing both active and passive shielding properties.

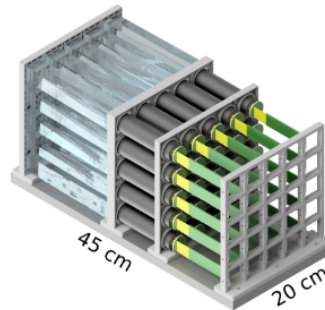


Figure 3.5: DarkMESA Phase A prototype detector without veto system. 25 PbF_2 crystals are arranged in a 5×5 matrix with an active volume of 3.6l. [9]

3.2.2 Upscaled detector - Phase B

After the completion of Phase A, construction of Phase B will be initiated. Phase B will feature one wall consisting of multiple Phase A calorimeters and another wall of Pb-glass detectors to increase the active volume. This consequently increases the probability of detecting DM events. The veto concept will also need to be scaled up to embrace both Phases, but will remain functionally the same. A render of this design is shown in Fig. 3.6.

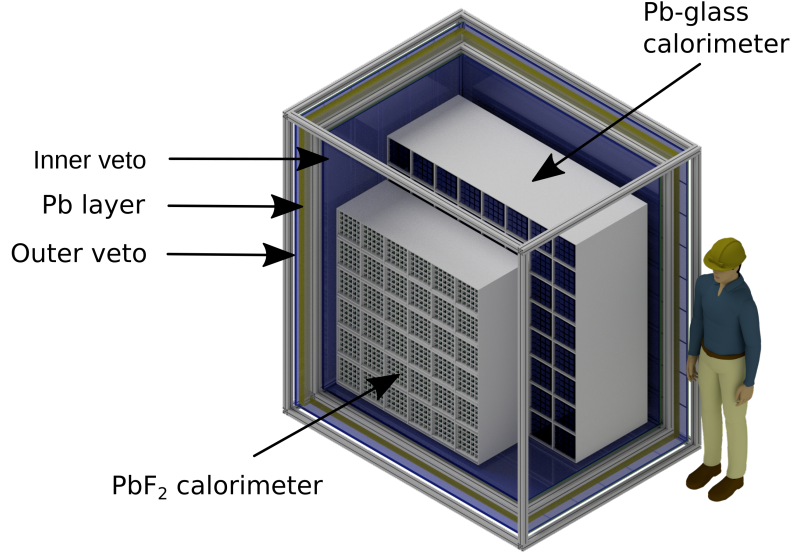


Figure 3.6: DarkMESA Phase B calorimeter and veto detector system. [17]

Due to the expected rarity of dark matter (DM) interactions, efficient background rejection is a central requirement of the experiment. The well-shielded detector hall significantly reduces beam-related backgrounds; however, cosmic radiation remains an important and irreducible source that must be mitigated. To address this, a veto system is foreseen, consisting of two layers of plastic scintillators and two lead layers surrounding the prototype detector.

The lead layer serves primarily to attenuate electromagnetic components of cosmic radiation, in particular low- and high-energy gamma rays and electrons. However, several classes of particles remain challenging:

- **Cosmic muons:** Due to their high penetration power, muons can traverse the shielding and reach the calorimeter. They typically produce signals in multiple detector elements along straight trajectories, allowing for their identification through characteristic track-like hit patterns.
- **High-energy photons:** These can initiate electromagnetic showers in the calorimeter. Such events are often accompanied by activity in the veto layers and multiple coincident hits in the calorimeter. While the resulting high multiplicity provides a handle for rejection, it does not guarantee full efficiency.

- **Neutrons:** Both cosmic neutrons and neutrons produced via muon-induced spallation in the surrounding concrete and shielding materials represent a particularly challenging background.

The response of the veto system to neutrons depends strongly on their energy:

- **Thermal neutrons:** These are not efficiently detected by plastic scintillators. Detection relies on neutron capture on hydrogen ($n + p \rightarrow d + \gamma$), which produces a delayed ~ 2.2 MeV γ ray. The resulting signal is weak and inefficient for veto purposes.
- **Fast neutrons (MeV scale):** These can scatter elastically on hydrogen nuclei in the plastic scintillators, producing recoil protons that generate detectable scintillation light. This provides an indirect handle for tagging a fraction of these events.
- **High-energy neutrons (GeV scale):** These can induce hadronic interactions and secondary particle production in the surrounding materials. While secondaries may occasionally trigger the veto, the response is indirect and not fully efficient.

The use of non-scintillating crystals in the calorimeter is advantageous in this context, as neutral particles such as neutrons do not directly produce scintillation or Cherenkov light. Their detection relies instead on secondary interactions, reducing their direct contribution to the signal region.

Despite these limitations, simulation studies [9] indicate that the proposed veto system can achieve a rejection efficiency in the order of $\sim 99.93\%$ for cosmic backgrounds. In practice, the realized efficiency is expected to be lower due to systematic effects, detector noise, and non-ideal geometrical coverage.

For this reason, further improvements are desirable, particularly in the suppression of neutron- and γ -induced backgrounds. This motivates the investigation of alternative or complementary technologies, such as liquid scintillator based veto systems, in collaboration with the NuDoubt⁺⁺ experiment, as discussed in Sec. 3.3.

3.3 NuDoubt⁺⁺ - A new double beta decay experiment

The NuDoubt⁺⁺ experiment is a new project currently under development at the Institute of Physics and the PRISMA Detector Lab at the University of Mainz. It will be the first experiment to utilize a combination of hybrid and opaque scintillators in the search for the $2\nu 2\beta^+$ and $0\nu 2\beta^+$ decay modes.

The detector concept features two active volumes, as illustrated in the render shown in Fig. 3.7. The inner detector vessel is filled with a hybrid slow opaque scintillator composed of 88% linear alkylbenzene (LAB), 10% diisopropylnaphthalene (DIN), and 2% wax, with diphenyloxazole (PPO) acting as a wavelength shifter. The addition of wax renders the scintillator opaque, effectively reducing the light scattering length to approximately 2 mm, while maintaining a high light yield of about 9000 photons/MeV.

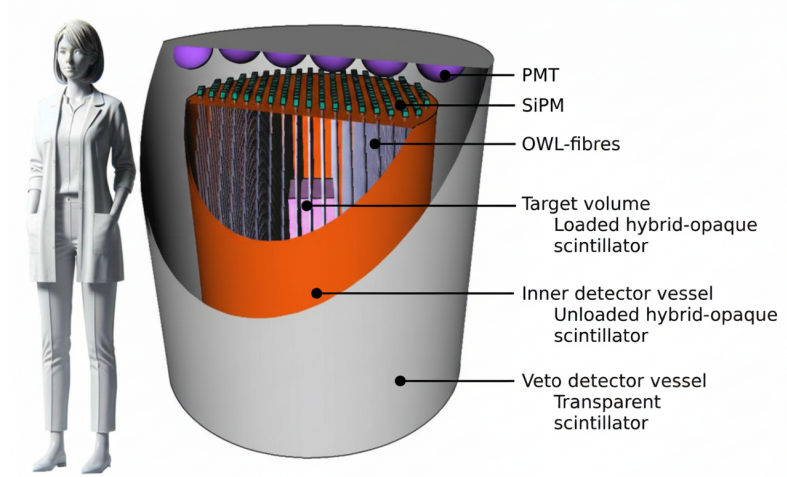


Figure 3.7: Basic detector design. From the outer to the inner layer: the active veto volume (grey) is filled with transparent scintillator and has PMTs (purple) on the top and bottom; the inner detector volume (orange) holds 1 t of unloaded hybrid-opaque scintillator and parallel-running OWL-fibres (light grey). The inner cubical target volume (pink) is filled with about 10 kg of loaded hybrid-opaque scintillator. [11]

The slow scintillation emission (> 10 ns) delays the scintillation light relative to the prompt Cherenkov signal, resulting in a temporal separation of the two components. This makes the Cherenkov peak more distinct, as shown in Fig. 3.8. This separation enables the estimation of the Cherenkov-to-scintillation light (C/S) ratio, which can in turn be used for particle identification.

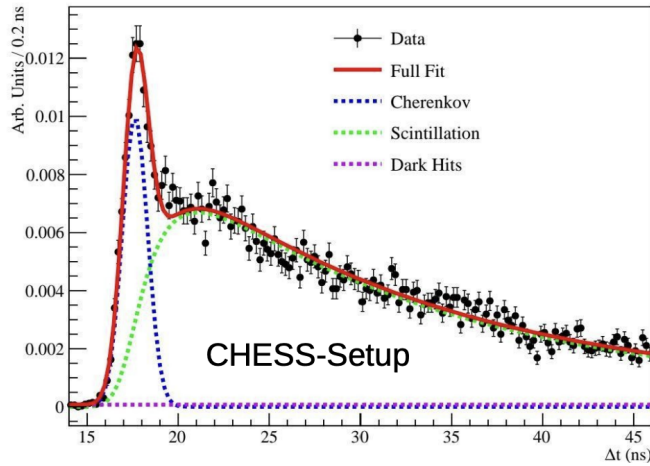


Figure 3.8: Scintillation and Cherenkov peaks emitted in a hybrid-slow liquid scintillator. The Cherenkov peak precedes that of the scintillation pulse by a few ns, allowing for the separation of the peaks. [11]

In addition, the opacity of the scintillator leads to the formation of localized light vertices, as photons cannot propagate far through the medium due to strong scattering (primarily Mie scattering). As a result, the emitted light remains confined near the interaction point. These localized light deposits can be read out using optical fibers. Such an example is shown in Fig. 3.9. Since different particles produce distinct interaction topologies, these spatial patterns can be exploited to further enhance the particle identification capabilities of the detector. Moreover, in this way, it is possible to study the C/S ratio of individual interactions, as seen in the right plot in Fig. 3.9, which makes identification easier.

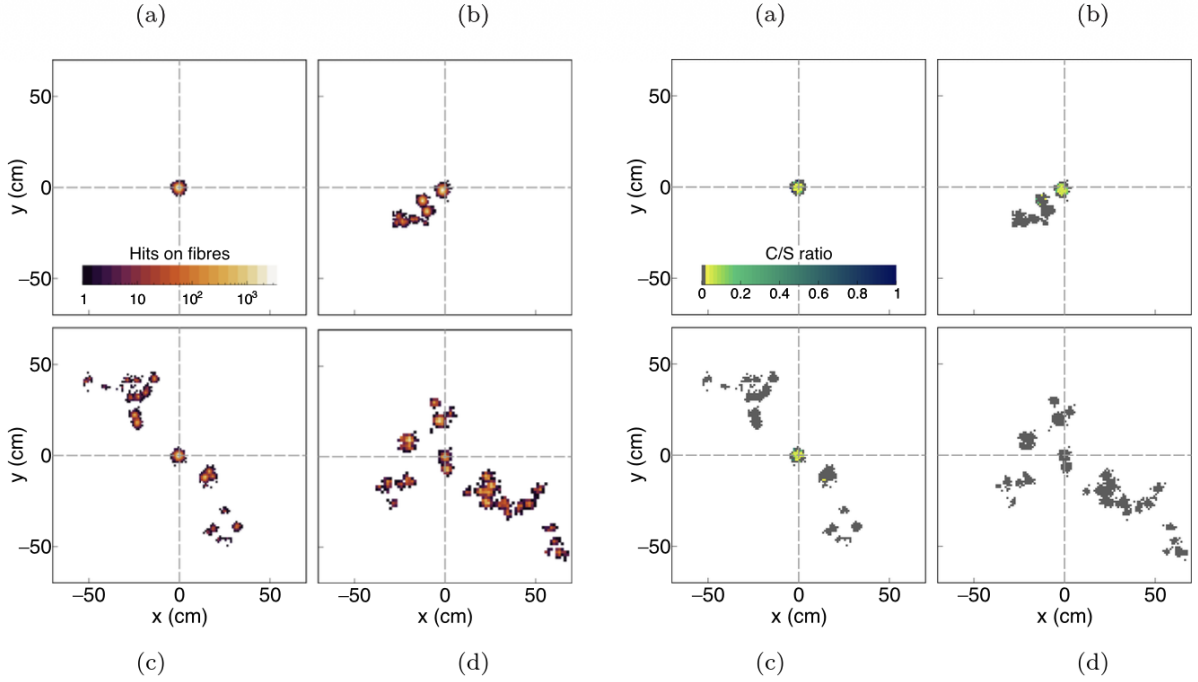


Figure 3.9: Illustration of the proposed strategy of particle discrimination in an opaque scintillator. The left figure displays the fibre hits for different kinds of simulated particles, and the right the C/S hit ratio per fibre. Geant4 simulations of (a) an electron of 2.8 MeV, (b) a gamma-ray of 2.8 MeV, (c) a single positron of 1.78 MeV, and (d) two positrons of 0.38 MeV. [11]

Surrounding the inner detector, there is a veto detector vessel filled with a transparent scintillator. This scintillator is read out by photomultiplier tubes (PMTs) located at the top and bottom of the vessel.

Utilizing this setup, the NuDoubt⁺⁺ detector will primarily investigate the isotopes Kr⁷⁸, Xe¹²⁴, and Cd¹⁰⁶. The experiment aims to perform initial measurements of two-neutrino double weak decay modes such as $2\nu 2\beta^+$ and $2\nu EC\beta^+$, as well as to set limits on the corresponding neutrinoless processes $0\nu 2\beta^+$ and $0\nu EC\beta^+$.

To minimize background from cosmic radiation, the detector has been proposed to be installed in the underground facilities of the SNOLAB laboratory.

Chapter 4

Experimental concepts

As the goal of this thesis is the development and construction of a prototype veto system based on an organic liquid scintillator, several relevant concepts must first be introduced in order to understand both the experimental setup and the associated simulation studies. These include the operating principles of liquid scintillators, as well as the loading of the scintillator with gadolinium to enhance neutron detection efficiency. In addition, the basic concept of photomultiplier tubes (PMTs) will be briefly discussed, since they constitute the primary method for reading out scintillation signals. Finally, cosmic radiation will also be introduced, both as a tool for detector characterization and because of its importance as a dominant background source for the DarkMESA and NuDoubt⁺⁺ experiments.

4.1 Liquid scintillators

Scintillators are a class of materials that exhibit light emission (scintillation) when excited by ionizing radiation. They can be broadly divided into two main categories: inorganic and organic scintillators, with further classification based on their physical form, such as organic and inorganic crystals, inorganic noble gases and liquids, organic liquids, and organic solids such as plastic. In the context of this thesis, only organic liquid scintillators are considered.

A liquid organic scintillator typically consists of an organic solvent, a primary fluor, and often a secondary wavelength shifter. The underlying scintillation mechanism can be illustrated using a Jablonski energy diagram, as shown in Fig. 4.1.

When a charged particle, or a gamma ray via secondary interactions, passes through the liquid, it excites the molecules of the scintillator. These molecules subsequently de-excite, emitting scintillation photons.

In organic scintillators, electrons can be excited through π -electron transitions from the ground state to higher-energy singlet states, of which multiple levels exist. The ground state itself consists of several vibrational sub-levels, typically denoted as S_{0i} , where i labels the individual vibrational states.

After excitation, electrons rapidly relax non-radiatively to the lowest vibrational level of the first excited singlet state, S_{10} . From this state, de-excitation can proceed via two primary pathways. If the electron transitions directly from S_{10} to one of the S_{0i} states,

prompt light emission occurs, known as fluorescence. The decay times associated with fluorescence are typically in the order of a few ns, allowing the emitted light to be clearly associated with individual radiation events. Alternatively, the electron may undergo intersystem crossing to a triplet state T_{1i} before eventually returning to one of the S_{0i} states. This process results in delayed light emission, referred to as phosphorescence. Persistent phosphorescence is generally undesirable in detector applications, as it produces a long-lived afterglow that cannot be directly associated with individual events, particularly in high-rate environments. However, delayed fluorescence or fast phosphorescence is desirable, as it makes it easier to discriminate the delayed neutron signals from the fast electron signals in the scintillator.

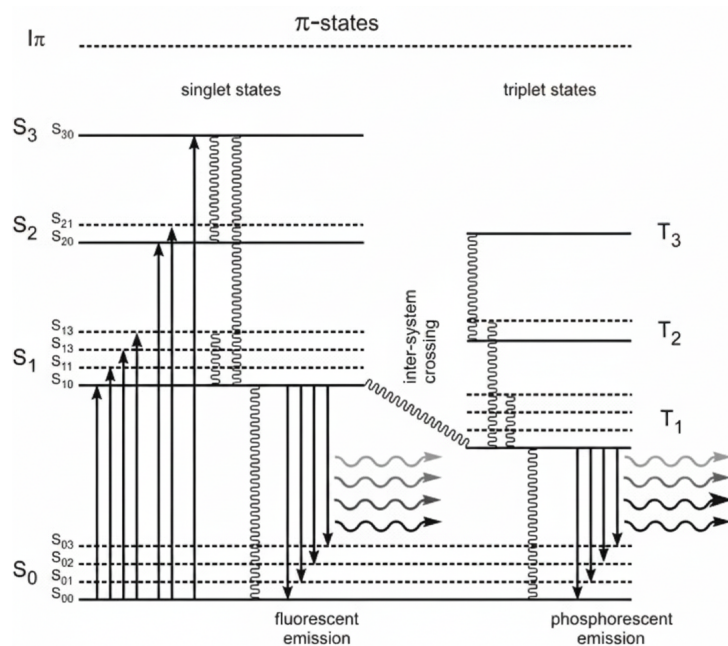


Figure 4.1: Illustration of two basic methods by which an organic scintillator produces light. [18]

The photons emitted by the primary fluor are typically in the ultraviolet range, which is not optimal for detection due to reabsorption in the medium and limited photodetector sensitivity. To address this, a secondary wavelength shifter is often added. This component absorbs ultraviolet photons and re-emits them at longer wavelengths in the visible spectrum, where the medium is more transparent, and photomultiplier tubes exhibit higher efficiency.

The light yield of organic scintillators is proportional to the deposited energy, but it is not linear with respect to the ionization density. Tracks with high ionization density dE/dx produce less light than expected compared to minimum-ionizing particles. This effect is commonly described by Birks' semi-empirical model, which attributes the reduction in light yield to recombination and quenching processes among densely excited molecules. These effects become more significant as the excitation density increases. Birks' law is

given by:

$$\frac{dL}{dx} = L_0 \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}} \quad (4.1)$$

where L is the light yield, L_0 is the light yield at low specific ionization density, and k_B is Birks' constant, which must be determined individually for each scintillator.

Due to their composition, which is mostly hydrogen and carbon, organic scintillators are poor absorbers of gamma rays. Their edge lies mainly in the detection of electrons and other minimum-ionizing particles because of their high light yield. In the case of fast neutrons, a significant fraction of their energy is transferred to recoil protons through elastic scattering on hydrogen nuclei. Organic scintillators are therefore well-suited for fast neutron detection via proton recoils. However, their sensitivity across the full neutron energy spectrum is limited. To enhance neutron detection capabilities, the liquid scintillator can be loaded with gadolinium (Gd).

4.1.1 Gd-loading of scintillator

Of all the elements in the periodic table, Gd has the highest thermal neutron capture cross-section, primarily due to the isotopes ^{155}Gd and ^{157}Gd . As seen in Fig. 4.2, this cross-section varies significantly in the fast-neutron regime, but becomes almost negligible at higher energies. This means that for a neutron to be consistently captured by a Gd nucleus, it should first be thermalized.

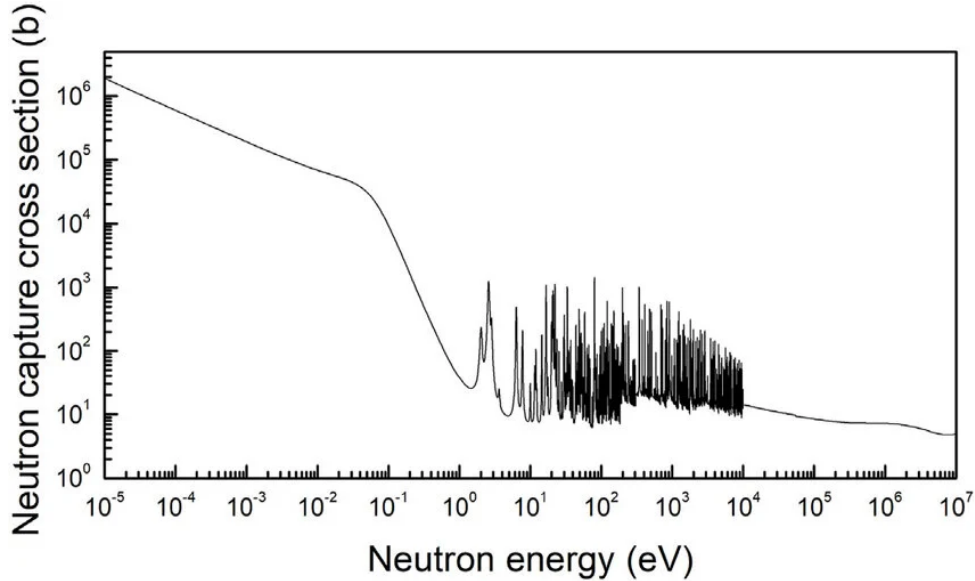
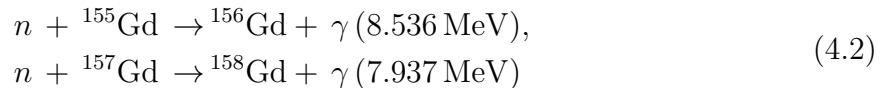


Figure 4.2: Neutron cross-section of Gd as a function of incident neutron energy. [19]

Upon capturing a neutron, the Gd nucleus emits prompt gamma rays with a total energy of $\sim 8\text{ MeV}$:



Due to its characteristic gamma emission, the addition of Gd in a scintillator can significantly enhance the tagging of neutrons. As an extension to that, Gd is commonly used in neutrino detectors both due to its ability to detect the inverse beta decay reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$) and also its excellent self-shielding properties against neutrons as a background source. For this reason, the NuDoubt⁺⁺ experiment is currently planning to implement Gd-loaded LAB as an outer veto detector, which will also be the liquid scintillator investigated in this thesis.

4.2 Photomultiplier tubes (PMTs)

The radiation produced by a scintillator can be converted to an electronic signal using a photomultiplier tube. This is done by exploiting the photoelectric effect. A PMT comprises a photosensitive cathode, multiple dynodes, and an anode; all stored inside a vacuum tube. This is shown in Fig. 4.3. An incoming photon induces the extraction of a photoelectron from the photocathode via the photoelectric effect. The applied voltage accelerates the photoelectron to the first dynode, where the secondary electrons are knocked off, multiplying their initial number. The cascading electrons finally reach the anode, where they are read out. The significant amplification of the signal even allows the detection of a single incoming photon.

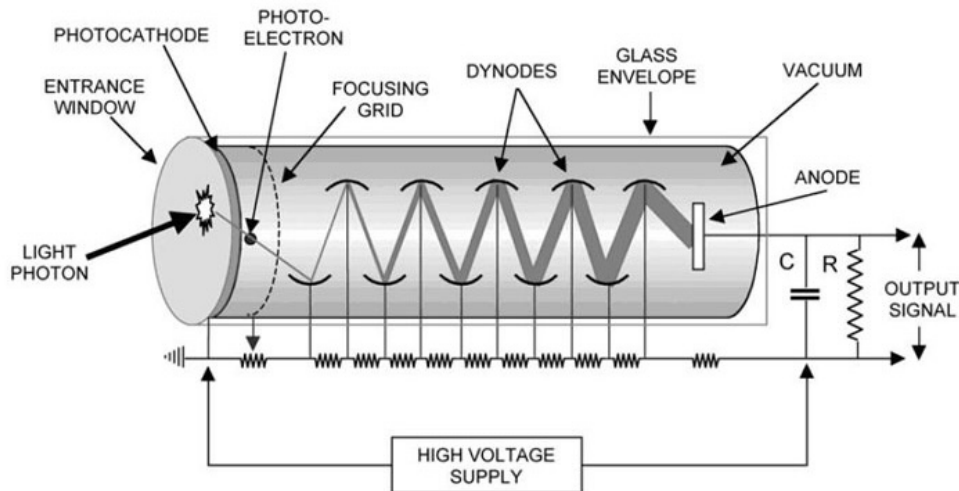


Figure 4.3: Schematic of a photomultiplier tube. [20]

Two important quantities when selecting a PMT are the dark count rate and its spectral response, i.e., the quantum efficiency. Due to thermal effects, PMTs tend to generate false signals known as dark counts. Typical values range from ~ 0.5 to 2 kHz at room temperature. By requiring a coincidence between multiple PMTs, this effect can be made negligible. The quantum efficiency is defined as the ratio of the number of photoelectrons emitted from the photocathode to the number of incident photons, and it depends on the wavelength of the incident photons. This effect can significantly reduce the light collection efficiency if it is poorly matched to the relevant wavelength range.

4.3 Cosmic radiation as a tool to study detectors

When ionization currents were discovered with a bell apparatus, a dark current appeared in the measurements, which, though weakened, persisted even while shielding the device with lead. This alluded to the postulation of earth radioactivity. However, similar experiments were conducted at higher altitudes and discovered that this radiation was caused by high-energy particles from space, thereby giving it the name cosmic radiation.

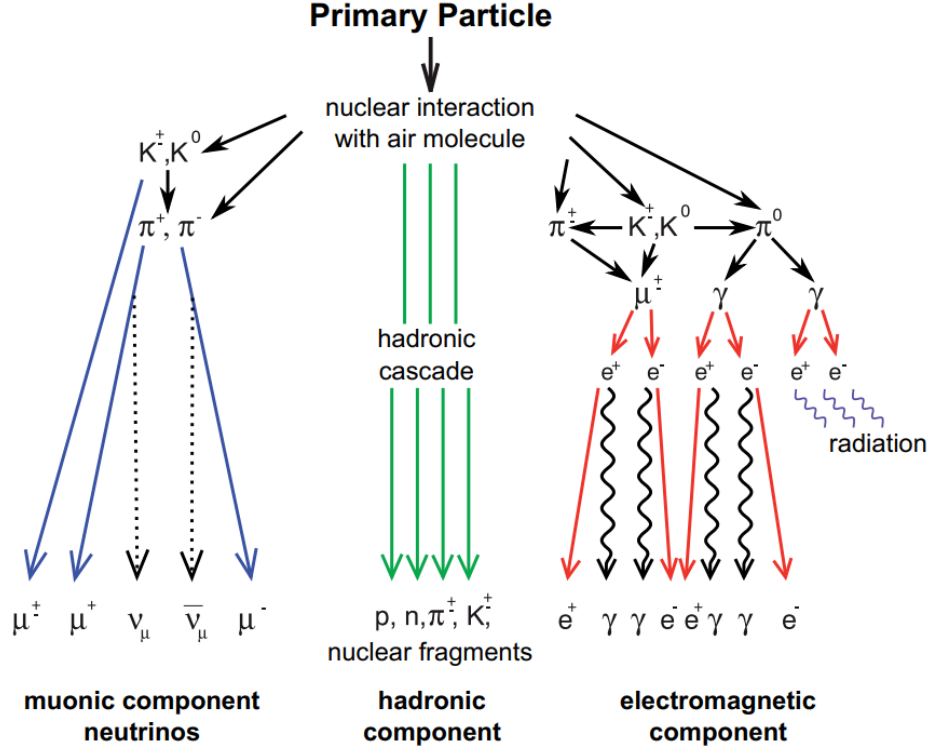


Figure 4.4: The decay chain of cosmic rays in the atmosphere. [21]

4.3.1 Primary cosmic rays

During supernovae, particles tend to be accelerated to very high energies, thereby escaping the star's potential well. These particles can potentially be emitted depending on their mass. Lighter particles, such as electrons, tend to expend their energy due to bremsstrahlung emissions. Protons and heavier nuclei can easily be emitted since energy loss is proportional to the inverse of the square of the particle's mass:

$$E_{\text{Brems}} \propto \frac{1}{m_p^2} \quad (4.3)$$

When primary cosmic rays reach the Earth's atmosphere, they are deflected by its magnetic field via the Lorentz force. This implies that particles require minimal kinetic energy

to penetrate the atmosphere, depending on the entrance latitude. In Mainz (latitude of 50°) the minimal required energy is 3 GeV.

4.3.2 Secondary cosmic rays

When primary cosmic rays enter Earth's atmosphere, they interact with the present electromagnetic fields, producing secondary cosmic rays via multiple interactions, shown in Fig. 4.4. Low-energy photons (< 10 GeV) knock off individual nucleons from nitrogen and oxygen nuclei, whereas higher-energy protons tend to lose their energy mostly due to meson-dominated bremsstrahlung radiation. Pions comprise the majority of mesons, but kaons can also be produced at higher energies. Charged pions decay overwhelmingly into a muon and muon neutrino pair with a lifetime of $2.6 \cdot 10^{-8}$ s, most of which reach the Earth's surface. [5]

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (4.4)$$

4.3.3 Cosmic radiation content

Cosmic radiation is made up of several components:

Nuclear radiation consists of nucleons and atomic nuclei, which lose energy through absorption into the air, while low-energy protons lose theirs through ionization. The proportion of nuclear radiation reaching the Earth's surface is negligible compared to the other sources.

Soft radiation consists of photons, electrons, and positrons, which arise partially from muon decay but mostly from photon pair creation. Electromagnetic bremsstrahlung, Cherenkov radiation, and neutral pion π^0 decay are the most common production methods. Neutral pions decay into photon pairs and then into $e^\pm$ pairs if their energy is $E > 2m_e$. As a result, the pion's energy is distributed over many particles until critical energy is reached. A couple of centimeters of lead offer sufficient shielding from soft radiation.

Hard radiation consists mostly of muons produced in secondary cosmic rays. Due to their high mass, they lose a small amount of energy due to bremsstrahlung and mostly through ionization. The energy loss is described by the Bethe-Bloch formula:

$$-\frac{dE}{dx} = \frac{4\pi n z^2 e^4}{m_e} \left(\ln \left(\frac{2m_e v^2}{I(1 - \beta^2)} - \beta^2 \right) \right) \quad (4.5)$$

where E is the energy, x is the distance, n is the number of electrons per cm^3 in the traversed material, $z \cdot e$ is the electrical charge, v is the particle's speed, and I is the mean excitation potential of an atom in the material. The distribution is minimal for particles with $\beta\gamma \sim 3$, which are known as Minimum-Ionizing-Particles (MIPs) and have an energy loss in the air of $\sim 1.8 \text{ MeV g}^{-1} \text{ cm}^2$.

Muons have a lifetime of $\tau \sim 2.2 \mu\text{s}$, in which case they would only travel an average of 600 m in a vacuum. However, by considering relativistic effects, highly energetic muons will have a dilated lifetime, which allows them to reach the Earth's surface and be detected.

Chapter 5

Simulation studies

As discussed previously, the goal of this work is the development and construction of a veto system prototype filled with a liquid scintillator for use in the NuDoubt⁺⁺ experiment and potentially in DarkMESA. The first step toward constructing such a prototype is to perform simulation studies to determine and optimize the detector geometry, its scintillator composition, its sensitivity, and, ultimately, its efficiency in tagging and vetoing particles. The focus of these simulations is the study of neutrons and cosmic rays as background sources. To carry out these studies, the **Geant4** simulation toolkit was used in combination with **ROOT** for data analysis. Due to the high computational demands of these simulations, they were executed on the **MOGON II** cluster at the University of Mainz.

5.1 Simulation framework

The foundation of the simulation framework is the set of physics lists that define the environment in which the studies are conducted. Selecting appropriate physics lists requires careful consideration of the processes to be simulated and the underlying physical effects that must be included to ensure a realistic description. These processes include standard electromagnetic interactions, decay processes, hadronic interactions, and, since the simulation involves scintillators, the generation and tracking of optical photons. The implemented lists are shown in Tab. 5.1.

Table 5.1: Physics lists implemented in the simulation studies.

Physics processes	Physics lists
Optical physics	G4OpticalPhysics
Electromagnetic physics	G4EmStandardPhysics
Decay physics	G4DecayPhysics
Hadron physics	G4HadronPhysicsQGSP_BIC_HP
Stopping physics	G4StoppingPhysics

A note should be made regarding the selection of the hadronic physics list. Since neutrons are the primary focus of these studies, and the interaction of interest is their capture on Gd, a high-precision model is required. The `G4HadronPhysicsQGSP_BIC_HP` list implements a data-driven approach with high precision for neutron energies below 20 MeV [22]. At higher energies, the list transitions to a model-based approach using parametrizations rather than detailed data, resulting in reduced precision.

5.1.1 Simulation setup

After defining the physics processes governing the simulation, the next step is to specify the materials and their properties. As discussed in Sec. 4.1.1, the scintillator investigated in this work is Gd-loaded LAB. The composition is 99.8 wt.% LAB and 0.2 wt.% Gd. The scintillator light yield is approximately 6000 photons/MeV [23], and the Birks constant is $k_B = 0.096 \pm 0.007$ mm/MeV [24], both experimentally determined by the STEREO experiment. The absorption and emission spectra, as well as the attenuation length and refractive index, are shown in Figs. 5.1, 5.2a, and 5.2b. Detailed data tables for these parameters are provided in Appendix A.1.

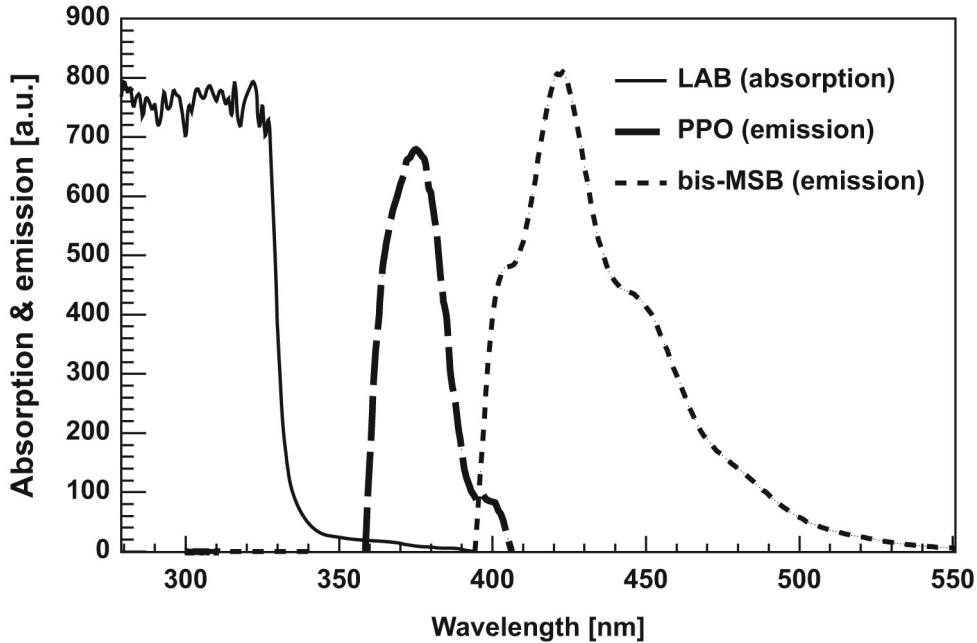
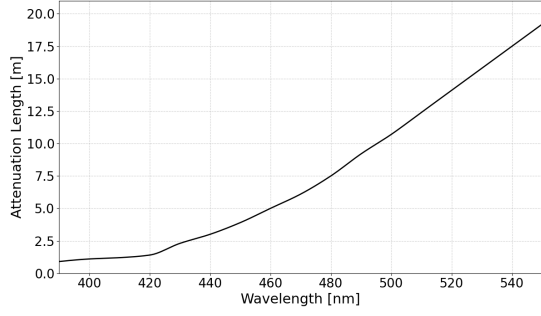
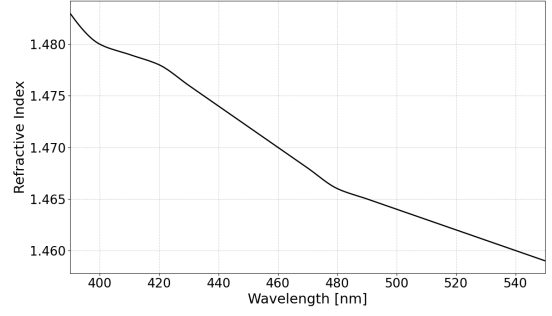


Figure 5.1: Emission spectra of the solvent LAB (linear alkylbenzene), the primary fluor PPO (2,5-Diphenyloxazole), and the wavelength shifter bis-MSB (1,4-Bis(2-methylstyryl)benzol). [25]

The detector vessel containing the scintillator is planned to be made of aluminum, chosen for its low weight, durability, and cost-effectiveness compared to alternatives such as stainless steel. Additionally, polished aluminum can achieve a reflectivity of 88–92%, which is beneficial for optimizing light collection. In the simulation, a mean reflectivity of 90% was assumed. The vessel is modeled as a hexagonal prism with a radius of 775 mm



(a) Wavelength dependence of LAB attenuation length rescaled for 2.3 m at 430 nm from the STEREO target liquid scintillator. [23]



(b) Wavelength dependence of LAB refractive index (adapted from [26]).

Figure 5.2: Gd-loaded LAB scintillator optical properties.

and a height of 225 mm, as shown in Fig. 5.3. These dimensions were selected based on the initial design of the NuDoubt⁺⁺ veto system (see Fig. 3.7), specifically the top layer above the inner detector, which served as the reference geometry for the simulations. The relatively large volume is required to allow the gamma rays produced in neutron capture on Gd to propagate sufficiently within the scintillator and generate detectable secondary particles. The hexagonal geometry was chosen to improve light reflection at the vessel walls and reduce dead regions. It was also preferred over a cylindrical design due to its simpler manufacturability in the in-house mechanical workshop.

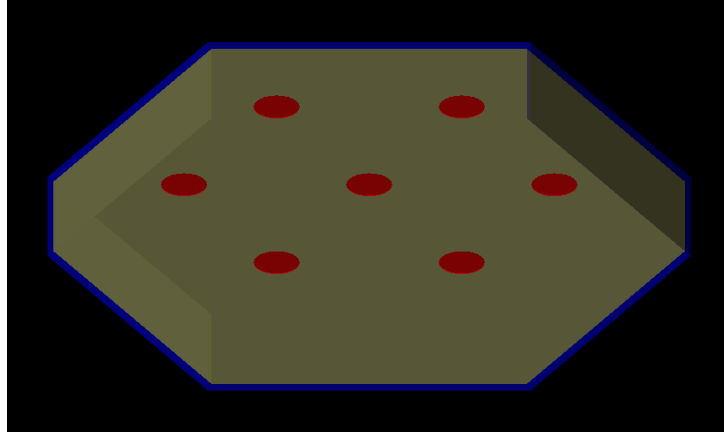


Figure 5.3: Visualization of the physical volume of the veto system prototype in Geant4.

The red disks in Fig. 5.3 represent the PMTs used for scintillator readout. In the simulation, only the glass window of each PMT is treated as a sensitive detector, while the photocathode is modeled through its quantum efficiency. Both the simulation and the prototype use seven 5-inch ET Enterprises 9330B series photomultiplier tubes. Their specifications are provided in App. A.2.

5.1.2 Geometric light collection efficiency

The positioning of the PMTs was the first aspect investigated. As this is a purely geometric study, an optimal symmetric arrangement was identified with one PMT at the center and six distributed evenly along the radius of the circumscribed circle. To evaluate the geometric light collection efficiency, the detector volume was divided into a hexagonal grid with a lattice spacing of 10 mm. At the center of each grid cell, a photon bomb consisting of 6000 photons was simulated. This number corresponds to the light yield per MeV for electrons in the scintillator. The efficiency is defined as:

$$\varepsilon = \frac{N_{\text{detected}}}{N_{\text{generated}}} = \frac{N_{\text{detected}}}{6000} \quad (5.1)$$

Applying this procedure across the full detector volume yields the efficiency map shown in Fig. 5.4.

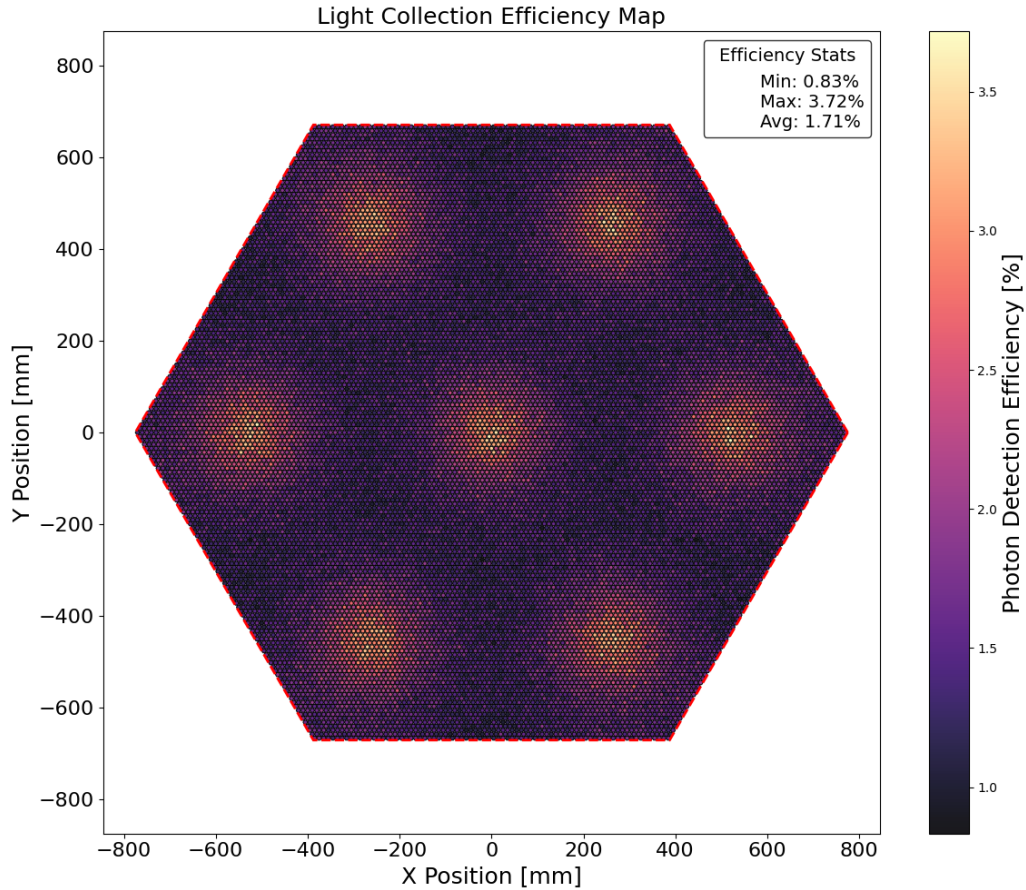


Figure 5.4: Light collection efficiency map of the veto system prototype.

The map clearly shows a higher detection efficiency near the PMTs, with significant reductions in the regions between them. The average efficiency across the detector is 1.71%, with a minimum of 0.83%. These relatively low efficiencies are expected. Photons

not directly incident on a PMT typically undergo multiple reflections at the detector surfaces, reducing their probability of detection. Additionally, the Gd loading further reduces efficiency, as it effectively acts as a photon absorber due to its high atomic number ($Z = 64$), primarily via the photoelectric effect.

Despite these limitations, even in the least efficient regions, at least 50 photons are detected by the PMTs. This indicates that, from a purely geometric standpoint, particle interactions should be detectable throughout the entire detector volume.

5.1.3 Simulation scenarios and goals

With the simulation framework established, detailed studies can now be performed to evaluate the detector's performance. As outlined previously, particular emphasis is placed on neutron detection. In the first simulation scenario, neutrons of varying energies are directed toward the detector to study their interactions and capture signatures. The second scenario focuses on cosmic radiation, enabling comparison with experimental data. The overall objective is to determine the tagging and veto efficiencies of the detector for both types of background.

5.2 Scenario 1: Neutron spectrum

For the study of the neutron spectrum, the simulation setup was modified by introducing an additional sensitive detector volume directly below the veto system. This detector was designed to tag particles and interactions escaping the veto in the downward direction. It serves as an analog of the inner detector shown in Fig. 3.7 and provides a reference for determining the veto efficiency.

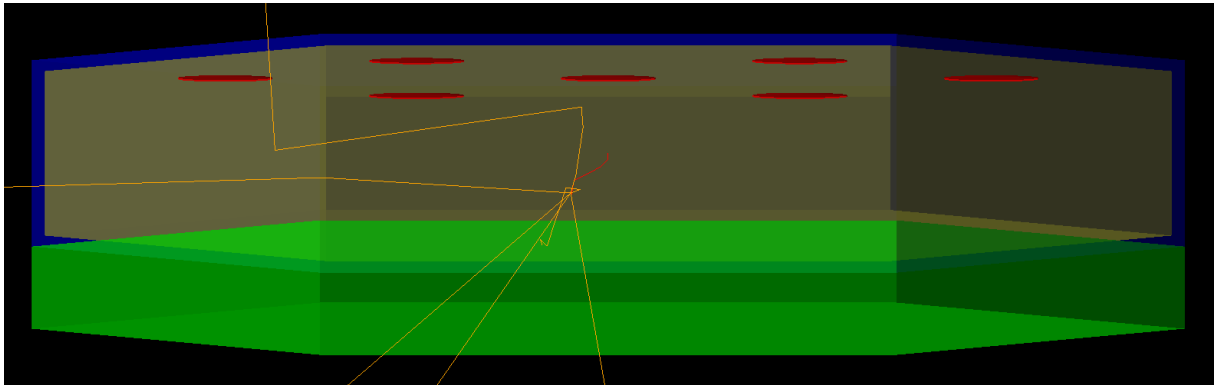


Figure 5.5: Visualization of the modified simulation setup. The veto system is located at the top, while the detector volume, seen in green, is positioned directly below it and covers the entire bottom surface of the veto. Neutrons (red) are generated at random positions in the horizontal plane at half the height of the veto volume, with downward-directed momentum. Optical photons were disabled for visualization purposes. Here is depicted a neutron capture event on Gd. The 8 MeV gamma cascade is shown in orange.

As shown in Fig 5.5, neutrons were generated at random positions in the horizontal plane at half the height of the detector, with downward-directed momentum over an energy range extending from thermal energies up to the TeV scale. Each simulation run consisted of 10^5 neutrons at a fixed initial energy.

By analyzing the photon hits recorded by the PMTs, the spectrum of the resulting interactions can be reconstructed. To account for experimental systematic effects which were not considered in the simulation, such as PMT dark counts, a two-fold coincidence cut was imposed together with a minimum threshold of two detected photons per PMT. In the following, only the 1 eV case will be discussed; additional examples of the energy spectra are provided in App. A.3.

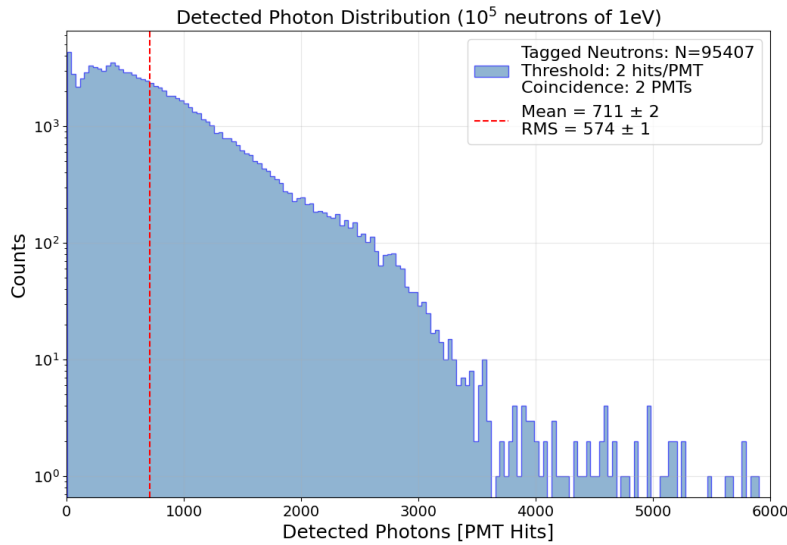


Figure 5.6: Spectrum of detected photons for 10^5 neutrons of 1 eV energy.

If a neutron interaction satisfies the detection criteria, the neutron is considered tagged and contributes to the tagging efficiency. The resulting spectrum in Fig. 5.6 consists of two distinct regions, although the individual peaks are not immediately obvious in the logarithmic representation, and the following interpretation remains preliminary. The first is a low-photon peak extending up to a few hundred detected photons, which originates primarily from neutron thermalization. During this process, neutrons scatter elastically off hydrogen nuclei and can thereby produce a detectable signal. The second, significantly broader peak is associated with neutron capture on hydrogen and gadolinium.

To verify this interpretation, the internal tracking capabilities of Geant4 were used to identify the origin of each interaction and study the corresponding spectra separately. This was achieved by correlating the track ID of each event with neutron capture processes on specific nuclei. The results are shown in Fig. 5.7, where the different interaction channels are separated. Events in which neutrons were tagged without being captured on either hydrogen (green) or gadolinium (blue) were classified separately and attributed to other interaction channels (red), such as elastic and inelastic scattering or decays.

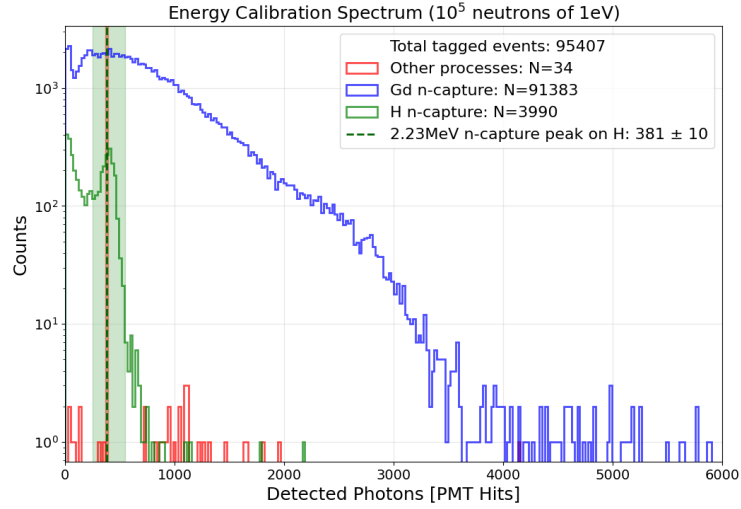


Figure 5.7: Separated spectra illustrating the interaction processes of 1 eV neutrons. Captures on Gd are shown in blue, captures on H in green, and other processes in red.

The separation of the peaks clearly demonstrates the dominance of neutron capture on Gd, which accounts for more than 91% of all tagged neutrons, compared to approximately $\sim 4\%$ for captures on H and $\ll 1\%$ for other processes. This ratio is expected in this energy regime due to the large neutron capture cross-section of gadolinium shown in Fig. 4.2. At higher neutron energies, however, these relative contributions are expected to change significantly, as illustrated in Fig 5.8.

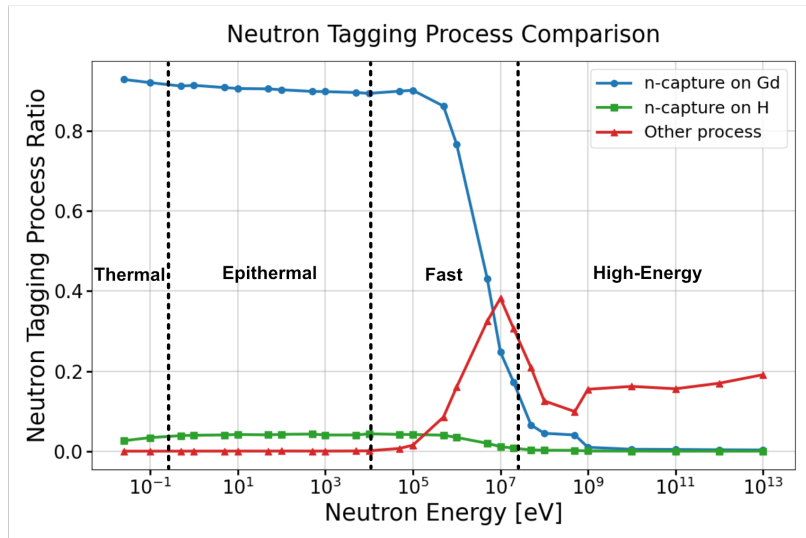


Figure 5.8: Comparison of the relative contributions of different neutron interaction channels in the scintillator.

Indeed, the tagging efficiency on Gd remains above 90% across the thermal, epithermal, and fast neutron regimes, before dropping sharply at higher energies to approximately 10%. As indicated by the energy dependence of the capture cross section shown in Fig. 4.2, the probability of neutron capture above the thermal regime is significantly reduced. In order to be captured, higher-energy neutrons must first thermalize by depositing sufficient energy within the detector medium. This process occurs over a timescale of a few μs , corresponding to a total path length of a few cm in the scintillator. The neutron propagation through the medium can be described as a random walk due to successive scattering interactions. As a result, the total path length is given by the sum of the individual step lengths:

$$L = \sum_i \ell_i \quad (5.2)$$

This cumulative path length can then be used to study the energy loss of neutrons as they propagate through the medium until they are ultimately captured by Gd.

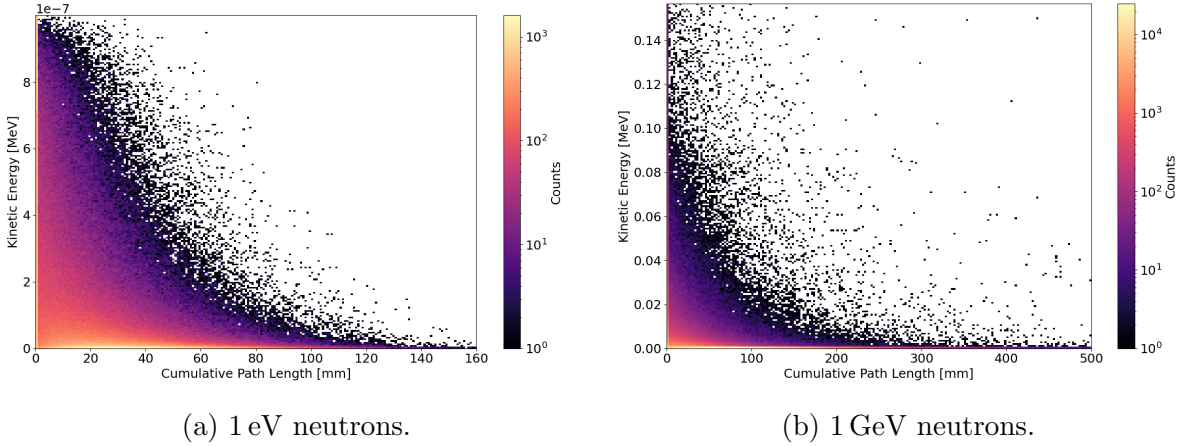


Figure 5.9: Kinetic energy as a function of cumulative path length for neutrons until capture on Gd.

In the thermal regime shown in Fig. 5.9, 1 eV neutrons travel a shorter distance of approximately ~ 150 mm before their energy is fully depleted. This is expected, as lower-energy neutrons require fewer scattering interactions to reach thermal energies and are therefore captured more quickly. In contrast, 1 GeV neutrons undergo many more scattering events before thermalization, resulting in significantly longer propagation paths, with some neutrons traversing distances of up to ~ 500 mm prior to capture.

The cumulative path length as a function of neutron time of flight in Fig. 5.10 illustrates the stochastic moderation and diffusion processes that precede neutron capture on Gd.

Neutrons with an initial energy of 1 GeV traverse significantly larger total path lengths than 1 eV neutrons, reflecting the extended scattering cascade required for thermalization from high initial energies. Despite this substantial difference in total traveled distance, both neutron cases exhibit similar capture timescales, indicating that the overall capture dynamics are primarily governed by the thermal diffusion regime rather than the initial

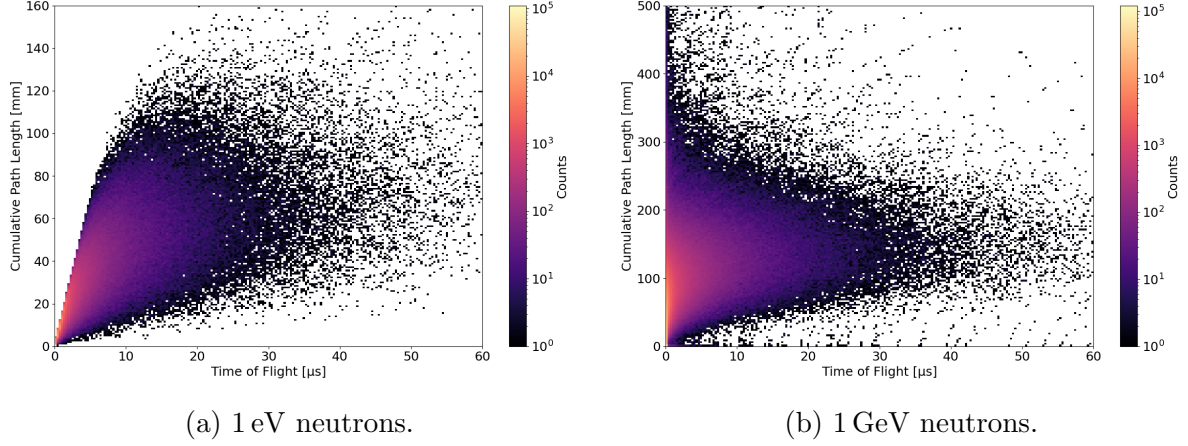


Figure 5.10: Cumulative path length as a function of time of flight for neutrons until capture on Gd.

neutron energy. The progressive broadening of the distributions with increasing time of flight further reflects the increasing variance in neutron random-walk trajectories within the medium.

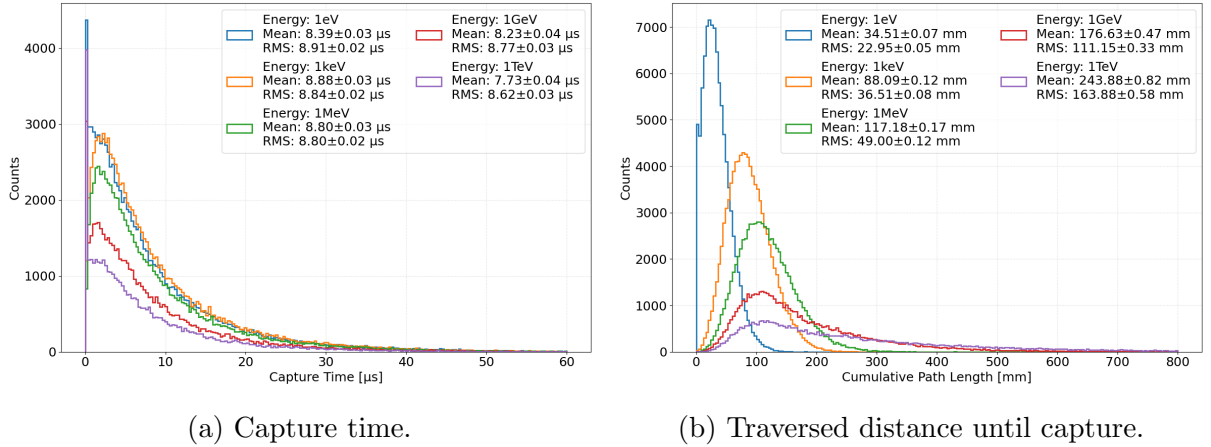


Figure 5.11: Time (left) and cumulative path length (right) elapsed by neutrons until capture on Gd.

As shown in Fig. 5.11, this behavior becomes more evident. The neutron capture time remains relatively constant across several orders of magnitude in initial energy, with an average of approximately $8.5 \mu\text{s}$. In contrast, the distributions of traversed path length vary significantly with energy. As discussed above, lower-energy neutrons are captured after relatively short propagation distances, while higher-energy neutrons undergo extended scattering cascades before thermalization and capture. At the TeV scale, the mean traversed distance reaches approximately $\sim 244 \text{ mm}$. This indicates that the detector volume is sufficiently large to allow high-energy neutrons to thermalize and subsequently be captured to a substantial extent.

Furthermore, in addition to capturing on Gd, neutrons can also be captured on hydrogen, although with significantly reduced probability due to the presence of gadolinium as the dominant capture medium. The probability of capture on hydrogen remains approximately constant at $\sim 5\%$ up to energies of about 1 MeV, after which it drops to nearly zero at higher energies, as shown in Fig. 5.8.

As a consequence of the dominant capture channels on Gd and H, the probability of tagging neutrons via other processes, such as elastic scattering, remains relatively low below the 1 MeV threshold. However, at around 10 MeV, this probability peaks at approximately 40%, since neutrons at this energy are energetic enough that they are not efficiently captured, yet still sufficiently interacting to undergo scattering within the detector volume rather than escaping without interaction. At higher energies, the probability of such non-capture processes stabilizes at approximately 18%. Understanding the response of the scintillator to neutrons is therefore essential for characterizing the overall detection efficiency.

Returning to Fig. 5.7, the measured signals can also be used for energy calibration. In the case of neutron capture on Gd, a higher total gamma energy is released; however, this energy is distributed over multiple gamma rays, making it difficult to reliably reconstruct the full deposited energy. In addition, if the capture occurs near the detector boundaries,

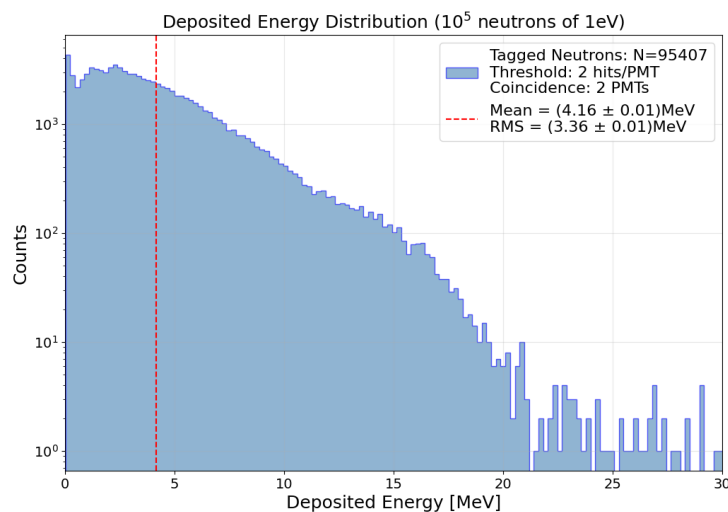


Figure 5.12: Calibrated energy spectrum of tagged neutrons after rescaling Fig. 5.6 for the neutron capture peak on hydrogen.

a fraction of the gammas may escape the scintillator without depositing their energy. To reduce these uncertainties, the hydrogen capture spectrum is instead used for calibration. In this case, a single 2.23 MeV gamma is emitted, which is more likely to deposit its full energy within the detector and thus produces a well-defined peak. The resulting peak (shown in green in Fig. 5.7) is used as the calibration reference by determining its corresponding position in the measured photon spectrum. For peak selection, a boundary

window is defined to isolate the relevant region, and the peak maximum is extracted within this interval. This maximum is then mapped to 2.23 MeV, establishing the energy scale. Applying this rescaling to the full spectrum yields the calibrated energy distribution shown in Fig. 5.12.

Using this calibrated spectrum, it is now possible to extract the mean deposited energy in the PMTs. The number of tagged neutrons is also an important value, as it can be used to compute the tagging efficiency by dividing it by the total number of generated neutrons. The tagging efficiency, therefore, quantifies the active shielding performance of the veto system. However, since the system under study is a veto rather than a primary detector, a more relevant quantity is the veto efficiency, which accounts for both active and passive shielding effects. Here, active shielding refers to the detector's ability to register passing particles, while passive shielding describes its ability to absorb or deflect background particles, thereby preventing them from reaching the inner detector. To determine the veto efficiency, the detector volume placed below the veto system (see Fig. 5.5) is used in conjunction with the following logic: events that are either tagged by the veto system or not detected by either the veto or the downstream detector are counted as vetoed events. In contrast, events that are registered only in the downstream detector and not in the veto are classified as missed events.

All these values are summarized in Fig. 5.13, which illustrates the overall performance of the veto system.

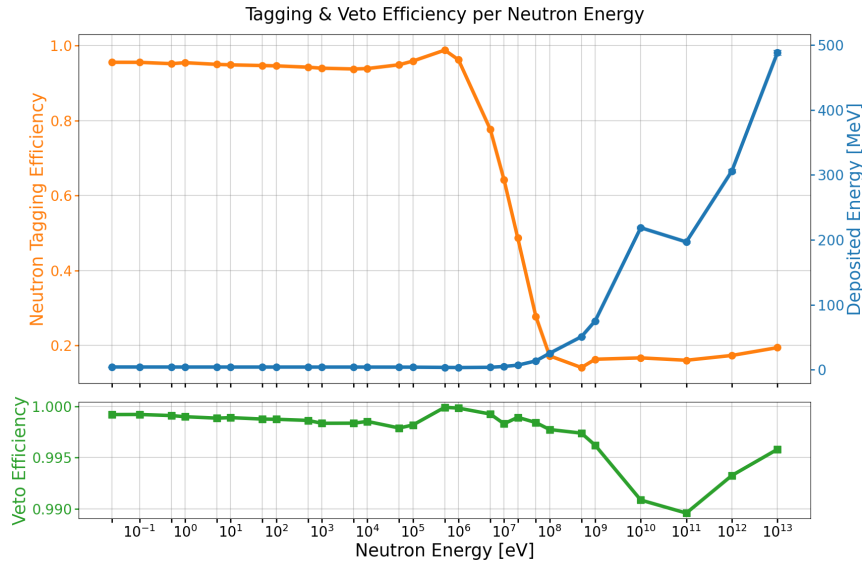


Figure 5.13: Neutron tagging and veto efficiency as a function of initial energy across the full neutron energy spectrum.

Here, the tagging and veto efficiencies are treated as exact within the simulation, since the numbers of generated and interacting particles are known without statistical uncertainty. The same assumption applies to the veto efficiency. For the deposited energy, the uncertainty on the mean value of each histogram was estimated using the standard

error of the mean. These uncertainties are not visible in the plot, as they are negligible compared to the corresponding energy scales.

Figure 5.13 illustrates the performance of the veto system across the full neutron energy spectrum relevant for cosmic rays, spallation neutrons, and radioactive backgrounds. In the energy regime up to 1 MeV, the tagging efficiency remains above 93%, reaching a maximum of approximately 98.7% around 500 keV. As discussed previously, this high efficiency is driven by the dominance of neutron capture on Gd in this energy range. This regime is particularly important, since a large fraction of cosmogenic neutrons are expected to reach the detector with energies in or near this interval, making efficient tagging essential. The mean deposited energy in this regime remains approximately constant at around 4 MeV, reflecting the energy released predominantly through gamma cascades following neutron capture on Gd. Above the 1 MeV threshold, the tagging efficiency decreases rapidly and stabilizes at a level below 20%. In this higher-energy regime, neutron interactions are no longer dominated by capture processes but instead by elastic scattering and spallation reactions.

The reduced efficiency could potentially be improved in a larger-scale detector geometry planned for future implementations. In this regime, the deposited energy increases sharply, as higher-energy neutrons transfer a significant fraction of their kinetic energy to nuclei, producing energetic secondary particles and more complex interaction cascades. This leads to a more distinct and, in some cases, more easily identifiable signal.

Finally, the veto efficiency, which is the most relevant metric for evaluating the system's performance in rejecting background particles, remains above 99.5% up to 1 GeV, decreasing to approximately 99% at 100 GeV and increases back to 99.5% at higher energies. This demonstrates the strong overall capability of the system to suppress neutron-induced backgrounds across a broad energy range.

This idealized neutron study should next be extended to a more realistic cosmic-ray environment, where the full expected cosmic spectrum can be simulated. This follow-up will provide a more comprehensive assessment of the veto system's performance for all relevant cosmic-induced particle backgrounds.

5.3 Scenario 2: Cosmic rays with CRY

For the study of cosmic rays, the Geant4 cosmic-ray shower library CRY was implemented within the simulation framework. CRY generates natural cosmic-ray particles, including muons, neutrons, protons, electrons, photons, and pions, for use within Geant4 simulations. It provides correlated particle showers at three elevations (sea level, 2100 m, 11 300 m), making it well suited for simulating cosmic-ray interactions in detector systems.

An additional modification was introduced to model a more realistic laboratory environment. Specifically, a 20 cm thick concrete ceiling was placed 2 m above the veto system, similar to the ceiling above the detector in the lab, as shown in Fig. 5.14. Cosmic-ray particles were generated on a 1×1 m surface above the concrete ceiling and directed towards the detector. A latitude of 50° was selected to match the location of the experiment in Mainz, and a fixed date of 01-01-2026 was chosen to define the corresponding phase of the 11-year solar cycle.

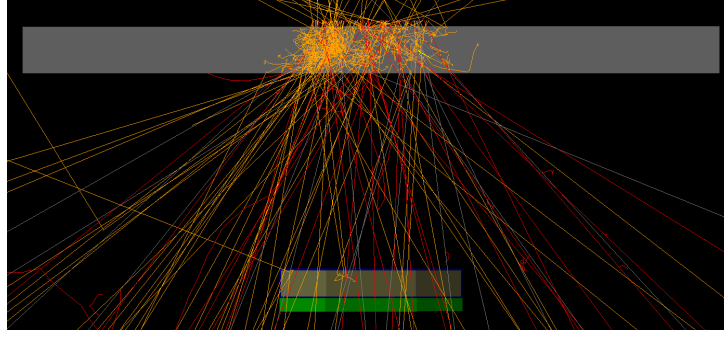


Figure 5.14: Visualization of the simulation setup used for cosmic-ray studies. A 20 cm thick concrete ceiling is positioned 2 m above the veto system. Cosmic rays are generated on a 1×1 m surface above the ceiling with downward-directed momentum and randomized angular distributions. Optical photons were disabled for visualization purposes.

The spectrum of the generated cosmic rays is modeled according to experimental measurements and follows the distribution shown in Fig. 5.15.

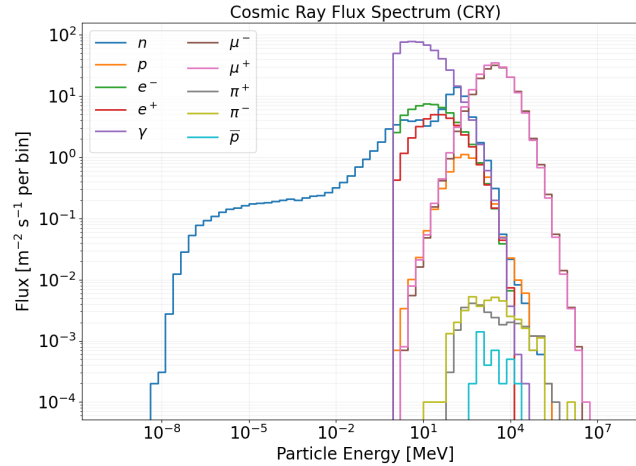


Figure 5.15: Cosmic-ray spectrum simulated with the cosmic-ray shower library CRY for Mainz (sea level) on January 1st, 2026.

A total of 10^7 cosmic particle events were generated, corresponding to approximately one week of real time. To study the response of the veto system to cosmic rays, a different analysis approach was employed compared to the neutron spectrum study. Instead of reconstructing the full PMT photon-hit spectrum, a photon threshold was applied to the PMT signals under a two-fold coincidence condition. Events in which the detected light exceeded this threshold were classified as tagged, and the initial kinetic energy of the corresponding particle upon entering the scintillator volume was recorded. The simulated events were then separated according to particle type using their corresponding PDG identification codes, together with their incident kinetic energies. The photon threshold was introduced primarily to suppress false triggers arising from PMT dark counts.

Since the goal of this study is to characterize the response of the veto system to cosmic rays, a useful metric is the differential detection rate. To determine this quantity, one first evaluates the particle flux generated by the CRY library:

$$\Phi_i = \frac{N_{\text{gen}}}{A_{\text{gen}} \cdot T_{\text{sim}_i}} \quad (5.3)$$

where N_{gen_i} is the total number of generated events per particle type i , A_{gen} the CRY generation area (1 m^2), and T_{sim} the real-time equivalent of the simulation ($\sim 6.2 \times 10^5 \text{ sec}$).

The differential detection rate is then obtained by evaluating the detected event rate per unit energy:

$$\frac{dR}{dE} = \frac{1}{A_{\text{det}} \cdot T_{\text{sim}}} \cdot \frac{dN_{\text{det}}}{dE} = \frac{N_{\text{det}}(E)}{T_{\text{sim}} \cdot A_{\text{det}} \cdot \Delta E} \quad [\text{MeV}^{-1} \text{cm}^{-2} \text{s}^{-1}] \quad (5.4)$$

where $A_{\text{det}} = 1.586 \text{ m}^2$ is the detector area and $N_{\text{det}}(E)$ is the number of detected particles within the energy bin ΔE . The uncertainty on the differential detection rate is given by Poisson statistics:

$$\Delta \left(\frac{dR}{dE} \right) = \frac{\sqrt{N_{\text{det}}}}{T_{\text{sim}} \cdot A_{\text{det}} \cdot \Delta E} \quad (5.5)$$

Using these quantities, the differential detection rates of the various particle species can be plotted as a function of their incident kinetic energy.

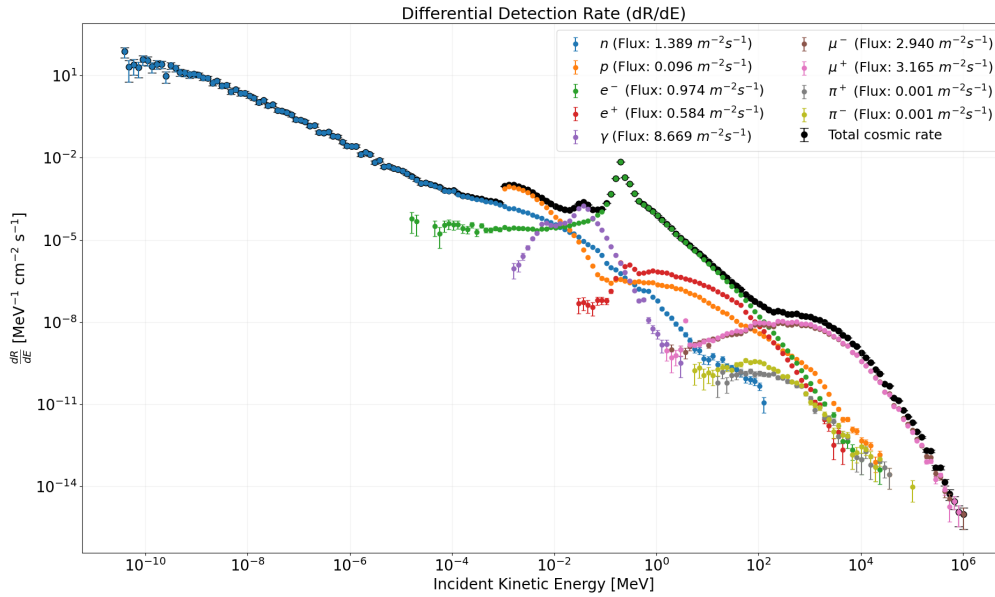


Figure 5.16: Differential detection rate for different particle species.

The differential detection rate in Fig. 5.16 describes how frequently particles of a given type trigger the detector per unit energy, area, and time. The plot shows that low-energy neutrons and gamma rays dominate the secondary cosmic-ray flux at low energies, whereas muons become the dominant component at intermediate and high energies due to their

strong penetrating power. The rapid decrease in the detection rate with increasing energy reflects the power-law nature of the cosmic-ray spectrum, in which high-energy particles are significantly less abundant:

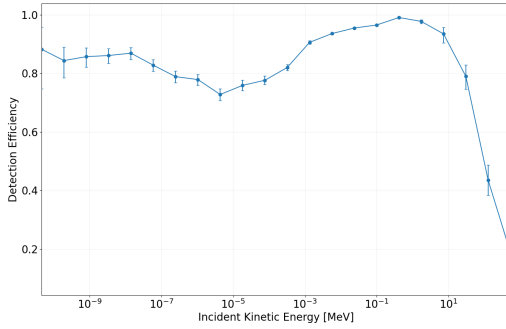
$$\frac{dN}{dE} \propto E^{-2.7} \quad (5.6)$$

The differential detection rate can further be used to determine the detector efficiency, which is defined as the ratio between the detected particle rate and the true incident particle rate above threshold for each energy bin. Following from Eq. 5.4, the efficiency can be defined per energy bin i as:

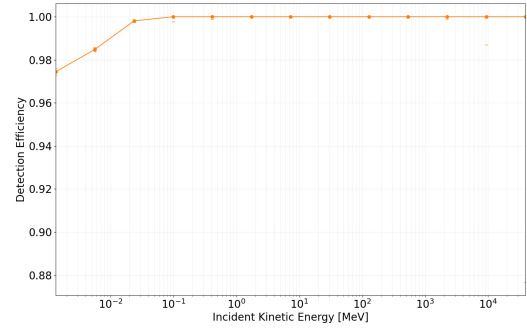
$$\epsilon_i = \frac{\left(\frac{dR_{\text{det}}}{dE}\right)_i}{\left(\frac{dR_{\text{inc}}}{dE}\right)_i} = \frac{\frac{N_{\text{det},i}}{T_{\text{sim}} \cdot A_{\text{det}} \cdot \Delta E_i}}{\frac{N_{\text{inc},i}}{T_{\text{sim}} \cdot A_{\text{det}} \cdot \Delta E_i}} = \frac{N_{\text{det},i}}{N_{\text{inc},i}} \quad (5.7)$$

Binomial statistics are implemented for the calculation of the detection efficiency error $\sigma_{\epsilon,i}$ per energy bin i :

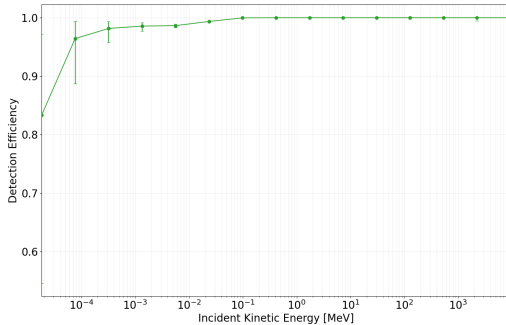
$$\sigma_{\epsilon,i} = \sqrt{\frac{\epsilon_i(1 - \epsilon_i)}{N_{\text{inc},i}}} \quad (5.8)$$



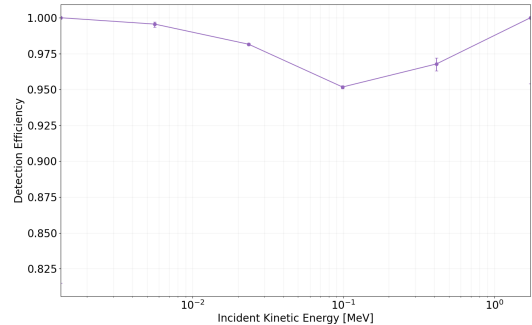
(a) Neutrons.



(b) Protons.



(c) Electrons.



(d) Gammas.

Figure 5.17: Detection efficiency of different particle types.

The detection efficiency was evaluated separately for each particle type and is shown in Fig. 5.17. Only the particle species exhibiting significant energy-dependent variations are discussed here. The remaining results are provided in App. A.4.

This study demonstrates that the veto system achieves high detection efficiency across most of the cosmic-ray spectrum, exceeding 95% over the majority of the investigated energy ranges for the individual particle species, particularly at energies above 1 keV. This high overall efficiency is also evident in the full-spectrum result shown in Fig. 5.18. In the case of neutrons, however, the efficiency exhibits a distribution similar to that observed previously in Fig. 5.13. The efficiency again reaches a maximum around 100 keV before decreasing significantly at higher energies. The comparatively large error bars in these distributions do not necessarily indicate systematic uncertainties. Instead, they primarily reflect the statistical uncertainties associated with the simulated particle energy spectra. Due to the limited statistics in certain energy regions, some bins contain substantially fewer events than others, resulting in larger uncertainties. These fluctuations would be reduced with a larger simulated data set.

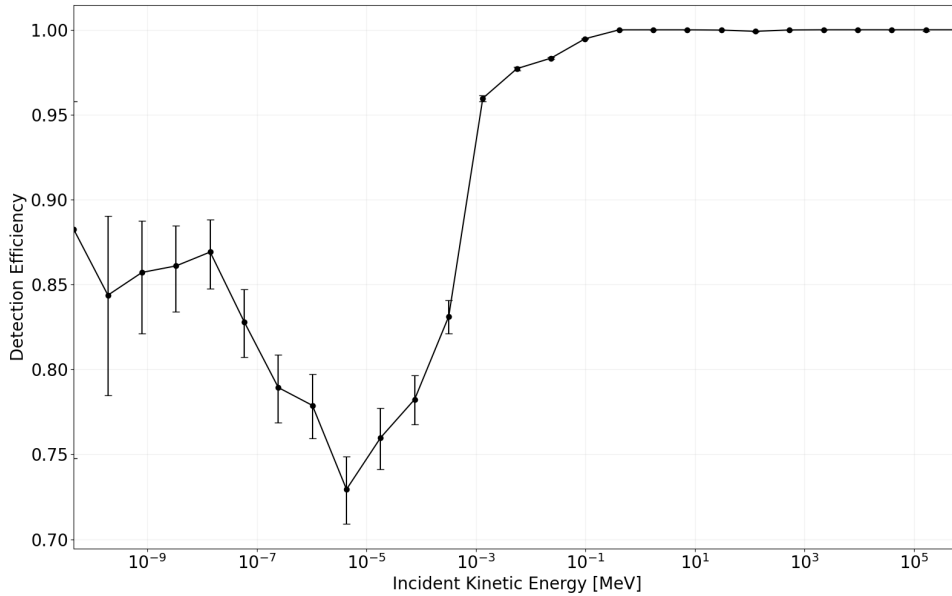


Figure 5.18: Global detection efficiency of cosmic rays.

The distribution shown in Fig. 5.19 reveals a strong dominance of electrons, exceeding the rates of the other primary particle species by at least two orders of magnitude. These electrons consist of both primary particles generated by CRY and secondary electrons produced through interactions of other particles within the veto system, as shown in Fig. 5.20. The electron spectrum peaks in the energy range between 1 MeV and 10 MeV, followed by a long high-energy tail. The positron spectrum peaks within a similar energy range. Given the overlap of these distributions, it is likely that a significant fraction of the electrons and positrons in this region originates from gamma-induced pair production. Overall, the veto system achieves a tagging efficiency of approximately 98.928% for electrons and 99.999% for positrons.

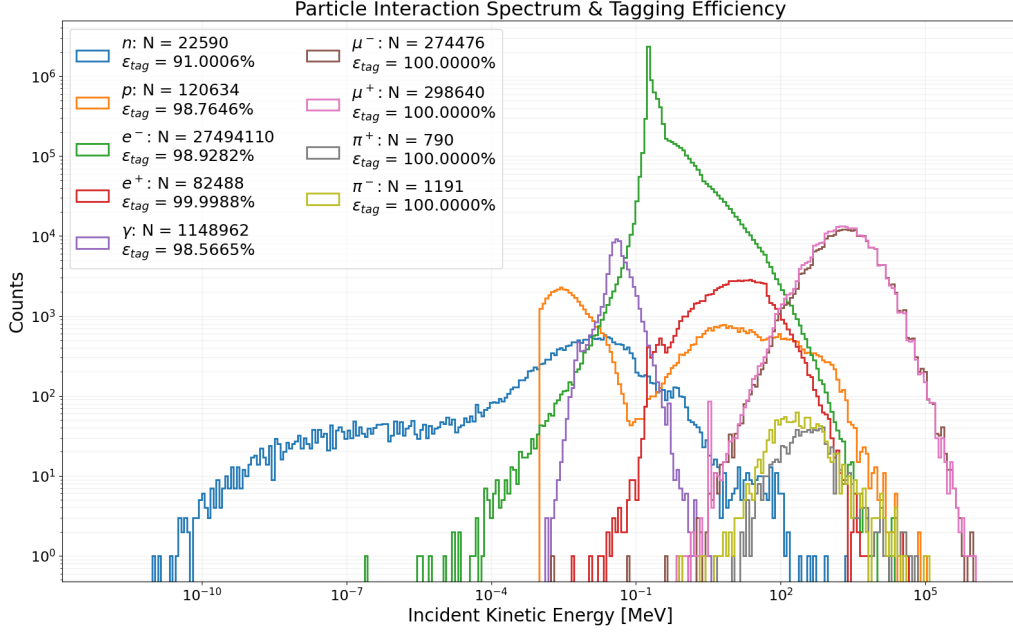


Figure 5.19: Spectrum of interacting cosmic particles inside the veto system using a two-photon threshold per PMT under a two-fold coincidence condition. The tagging efficiency for the different particle species is shown in the legend.

The neutron spectrum produced by cosmic rays extends from thermal energies up to approximately 100 MeV, with a broad maximum between 1 keV and 1 MeV. As discussed in Sec. 5.2, this corresponds to the energy range in which most cosmogenic neutrons are expected. The neutron tagging efficiency is approximately 91%, somewhat lower than the $\sim 93\%$ efficiency predicted in the idealized neutron study. This reduction likely results from the isotropic angular distribution of the incoming particles. Neutrons entering near the detector boundaries may still interact within the scintillator volume but lack sufficient path length to fully thermalize and subsequently be captured.

The gamma spectrum peaks at approximately 100 keV with a tagging efficiency of about 98.6%. A fraction of these gammas are primary particles generated directly by CRY, while most originate from secondary processes such as Compton scattering and e^+e^- annihilation. Gamma rays emitted following neutron capture are not included in this spectrum, since in the analysis, they are associated directly with the parent neutron event. Consequently, tagging a neutron implicitly includes reconstruction of the corresponding capture gamma cascade.

The proton spectrum exhibits a characteristic double-peak structure. The higher-energy peak contains contributions from both primary and secondary protons and is therefore dominated by elastic scattering processes on nuclei. In contrast, the lower-energy peak is likely associated primarily with secondary protons produced through nuclear decay and spallation processes.

By tracking the parent IDs of these particles, it is possible to distinguish between primary and secondary contributions, as shown in Fig. 5.20, clarifying these observations.

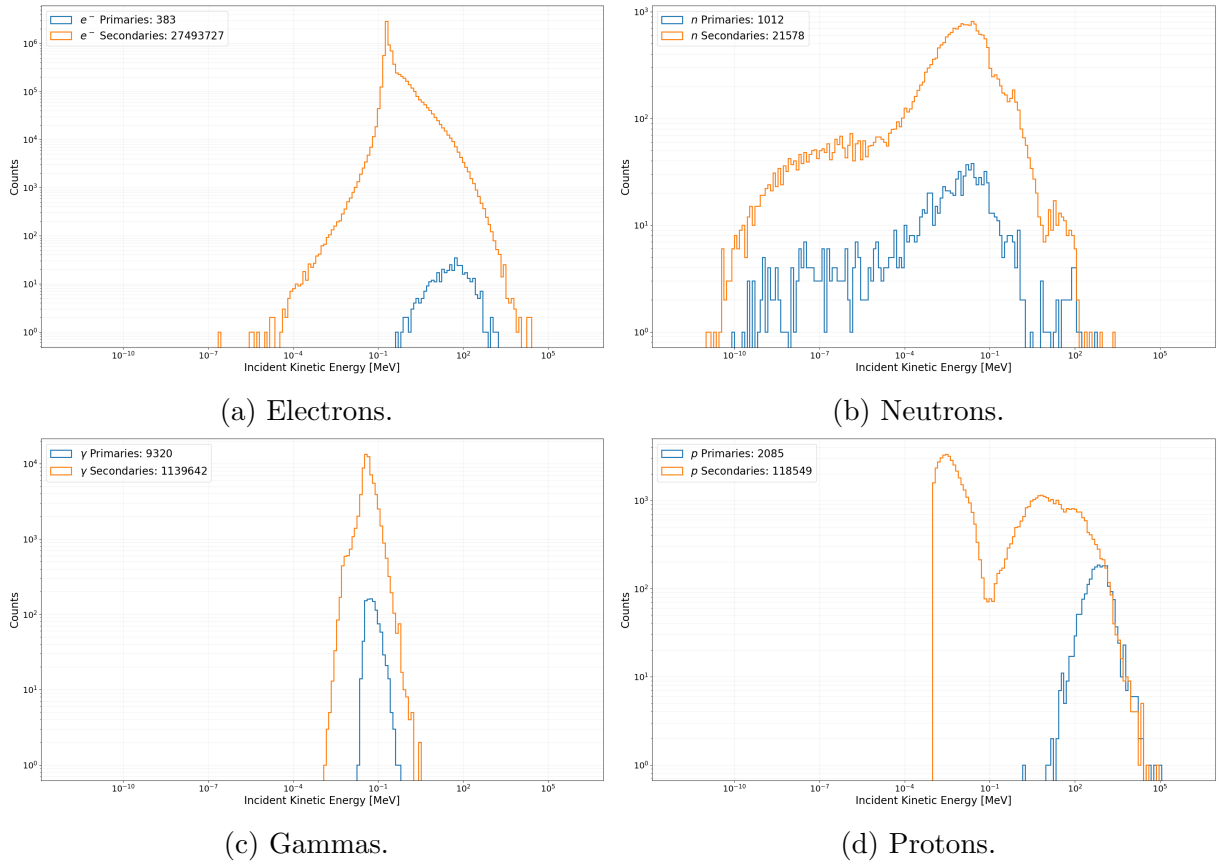


Figure 5.20: Comparison of primary and secondary particles.

Finally, muons and pions exhibit tagging efficiencies consistent with 100%. This is expected, as both particle species interact strongly with the scintillator and deposit substantial amounts of energy while traversing the detector volume, producing highly distinguishable signals.

As discussed in the previous section, the tagging efficiency characterizes the ability of the veto system to detect incoming particles. However, the more relevant quantity for evaluating the overall shielding performance is the veto efficiency, which combines both the active and passive shielding capabilities of the system. This efficiency was again determined relative to the detector volume located below the veto system and is shown in Tab 5.2.

Table 5.2: Veto efficiencies at 2-photon threshold.

	n	p	$e^\pm$	γ	$\mu^\pm$	$\pi^\pm$	Global
Veto Efficiency [%]	99.9879	100.00	100.00	99.9979	100.00	100.00	99.9991

For the two-photon threshold, the veto efficiencies are highly promising, yielding a global efficiency of 99.9991%. This result demonstrates that even in cases where the active component of the veto fails to tag an incoming particle, the passive shielding provided by the detector geometry and surrounding material is sufficient to prevent most remaining background particles from reaching the lower detector volume.

Although the selected threshold is expected to suppress the majority of PMT dark counts, it still represents a relatively optimistic operating scenario. To investigate the robustness of the system against stricter trigger conditions, the efficiency calculation was repeated for five different threshold settings ranging from 1 to 5 detected photons per PMT.

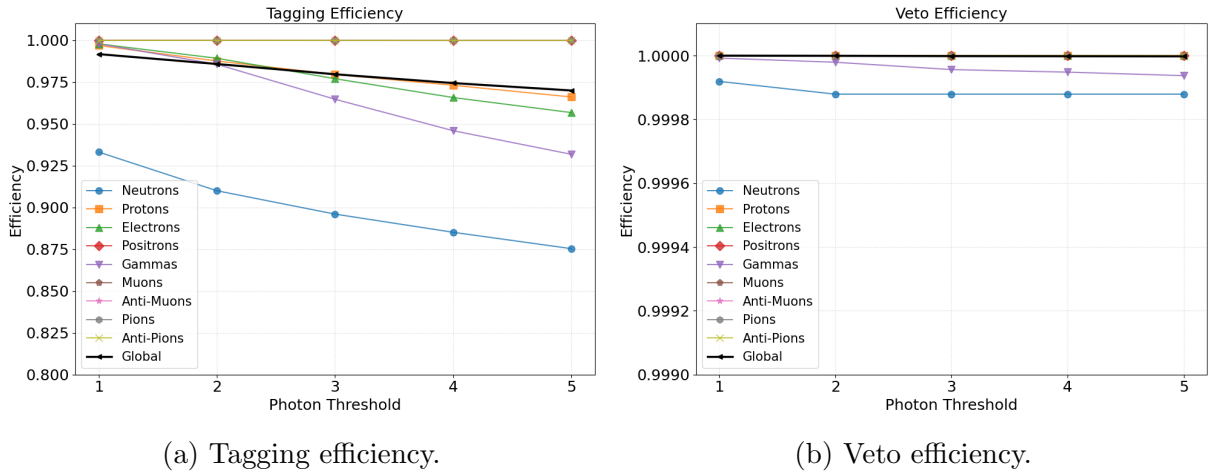


Figure 5.21: Veto and tagging efficiencies for different photon-threshold values.

The resulting distributions shown in Fig. 5.21 exhibit only modest variations in tagging efficiency for protons, gamma rays, and electrons, all of which remain above 92% across the investigated threshold range. The largest variation is observed for neutrons, whose tagging efficiency decreases to approximately 87.54% at the five-photon threshold. Nevertheless, the global tagging efficiency remains comparatively stable, decreasing only slightly to about 97.0%.

A significantly different behavior is observed in the veto-efficiency distribution, where the selected threshold regime has little impact on the overall performance. Both neutrons and gamma rays are vetoed with efficiencies exceeding 99.98%, while the global veto efficiency remains effectively constant across all threshold settings, consistently staying above 99.999%.

The simulation studies demonstrate that the proposed Gd-loaded LAB veto system provides excellent performance for the suppression of neutron- and cosmic-ray-induced backgrounds. Neutron simulations showed efficient detection and capture on gadolinium, resulting in tagging efficiencies above 93% below 1 MeV and veto efficiencies exceeding 99.5% over a wide energy range. Simulations with realistic cosmic-ray showers using the CRY library of Geant4 further confirmed high detection efficiencies for all relevant particle types and a global veto efficiency above 99.999%, largely independent of the applied

trigger threshold. These results validate the chosen detector geometry and scintillator concept and provide strong motivation for the construction of a prototype. Experimental characterization using neutron sources and cosmic rays will be required to validate the simulation predictions and to assess the detector performance under realistic operating conditions. Furthermore, these studies will assess the suitability of this technology for the DarkMESA experiment and identify possible improvements for future implementation in the NuDoubt⁺⁺ detector. Due to technical difficulties that delayed the commissioning of the experimental setup, these validation measurements could not be completed within the timeframe of this thesis and are therefore left for future work.

Chapter 6

Veto system prototype construction

6.1 Design and construction

The veto system prototype was designed based on the simulation studies presented in Ch. 5. The mechanical designs were created using the Autodesk Fusion software. Detailed technical drawings of the prototype are provided in App. B.

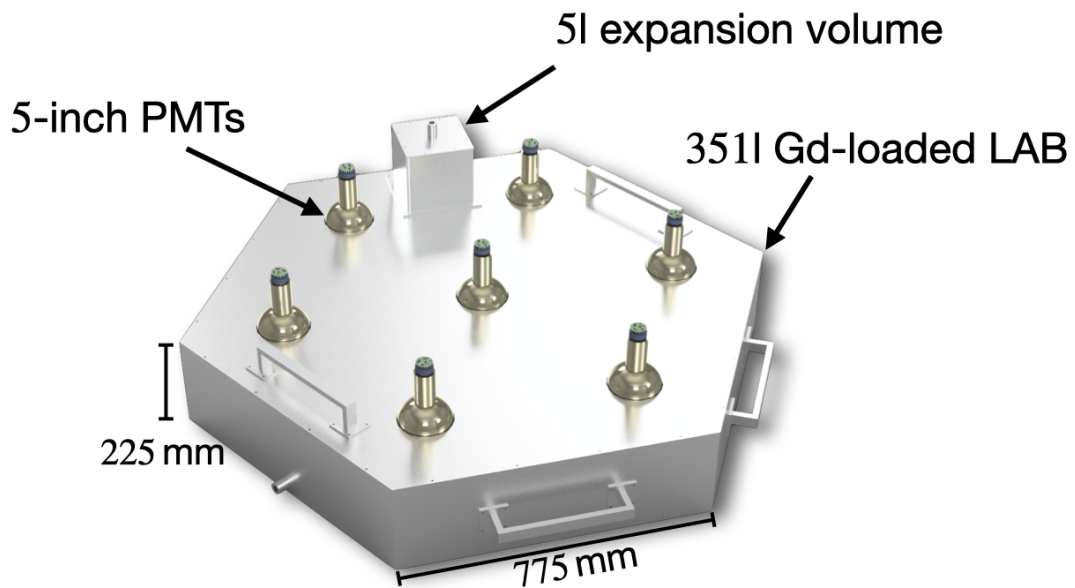


Figure 6.1: Render of the veto system prototype designed using Autodesk Fusion. The prototype consists of a hexagonal prism with polished aluminum walls of 15 mm thickness, enclosing an active volume of approximately 351l Gd-loaded LAB. The detector is instrumented with seven 5-inch (130 mm) PMTs and includes an expansion volume of approximately 5l.

The prototype shown in Fig. 6.1 consists of a hexagonal prism with polished aluminum walls of 15 mm thickness to enhance internal light reflection and provides an active volume of approximately 351l of Gd-loaded LAB scintillator. The detector is composed of two main sections: the scintillator vessel (veto bottom Fig. B.2) and the lid assembly (veto top assembly Fig. B.10), which is mounted and sealed to the top of the vessel using screws as shown in Fig. 6.2.

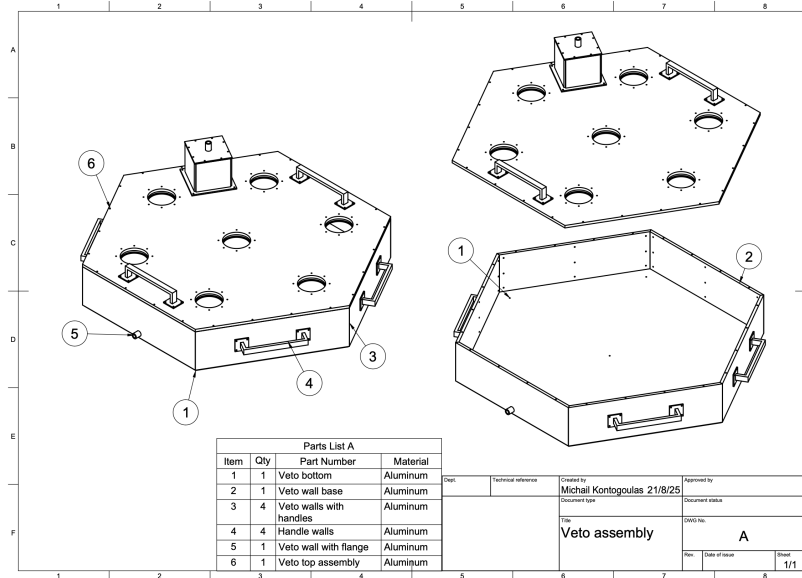


Figure 6.2: Drawing of the assembled veto system prototype.

The components and walls of the vessel were welded along the outer edges of the joints to avoid damaging the interior surfaces, as any degradation would negatively affect the reflective properties of the material. This approach was not applied to the expansion volume, which was instead screwed onto the top of the lid to prevent deformation of the lid during welding.

An expansion volume of approximately 5l is required for two reasons: first, to allow overfilling of the detector with scintillator, and second, to accommodate the thermal expansion of the liquid scintillator, which is approximately $7 \cdot 10^{-4} \text{ K}^{-1}$ [27].

The scintillator is read out by seven 5-inch PMTs, positioned as in the simulation studies (see Sec. 5.1). Each PMT is mounted above a plexiglass window without a UV-blocking filter, which is secured using a mounting ring screwed into the bottom of the lid. The absence of such a filter is important as a big part of the scintillator emission spectrum is in the UV range, as shown in Fig. 5.1.

In addition, a 1/2-inch connector was welded to one of the vessel walls to allow filling and draining of the liquid scintillator via a pump system. Once inside the vessel, contact with oxygen must be avoided, as it can cause precipitation of the Gd-complex, rendering the scintillator unusable. To prevent this, the vessel is flushed with nitrogen gas and maintained at a slight overpressure of approximately 10 mbar. Accordingly, an additional connector was installed at the top of the expansion volume to connect with the gas supply.

To ensure leak-tight operation, gaskets were installed at all connection points between components of the prototype. Viton was selected as the gasket material due to its high chemical resistance to LAB-based scintillators. Finally, multiple handles were attached to both the vessel and the lid to facilitate the transport and positioning of the detector.

6.2 Assembly of the detector

The mechanical workshop of the Institute for Nuclear Physics carried out the construction and assembly of the detector. Most components were manufactured in-house, while the lid and bottom plate were custom-ordered from an external company, as their dimensions exceeded the machining capabilities available in the workshop. These components are shown in Fig. 6.3.

As described in the previous section (Sec. 6.1), the vessel walls and bottom plate were welded together to form a mechanically stable and leak-tight container for the scintillator. The expansion volume was assembled in a similar manner through welded joints. Finally, handles were mounted to the vessel walls and lid using screw connections as shown in Fig. 6.2.



Figure 6.3: Assembly and welding of veto system components.

The assembled detector was subsequently transported to the laboratory, where additional modifications and assembly steps were carried out in preparation for the experimental operation.

The first step involved the installation and positioning of the plexiglass windows on which the PMTs would later be mounted. The aluminum rings used to secure the windows were manufactured by the external company, while the mechanical workshop of the Institute for Physics produced seven plexiglass windows with a thickness of 8 mm. In addition, seven custom-made Viton gaskets with a thickness of 3 mm, supplied by Technirub, were used to ensure a leak-tight seal around the windows.

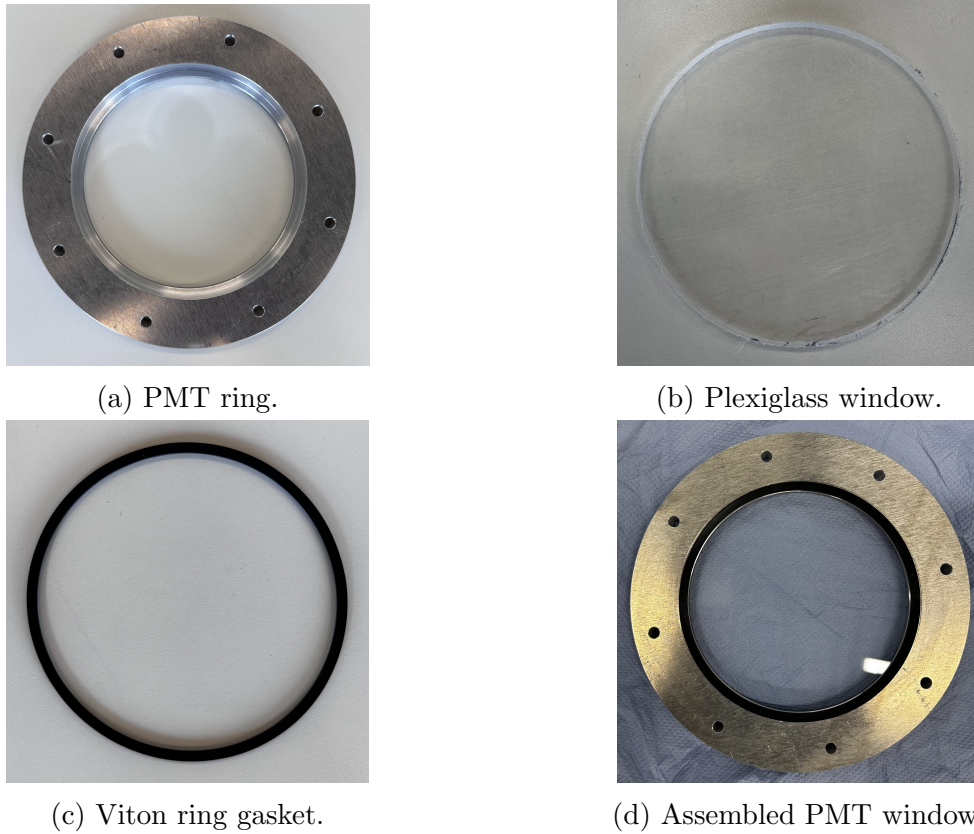


Figure 6.4: Components and assembly of PMT window.

These components were assembled by placing each plexiglass window onto the protruding support surface of the PMT mounting ring, with the Viton gasket positioned on top (see Fig. 6.4). The gasket thickness was chosen such that it protruded by approximately 0.5 mm above the metal ring, thereby ensuring a tight seal once compressed against the lid during installation. The fully assembled lid of the prototype is shown in Fig. 6.5.

The vessel of the veto system also required sealing with Viton gaskets to prevent leakage of the liquid scintillator. Due to the hexagonal geometry of the vessel, the use of a single continuous gasket was not feasible. Instead, three different gasket shapes were manufactured to ensure proper coverage along the surfaces and edges of the vessel walls, as shown in Fig. 6.6. Two elongated gaskets were installed along each wall segment, while separate gasket pieces were used for each corner connection of the vessel. These gaskets

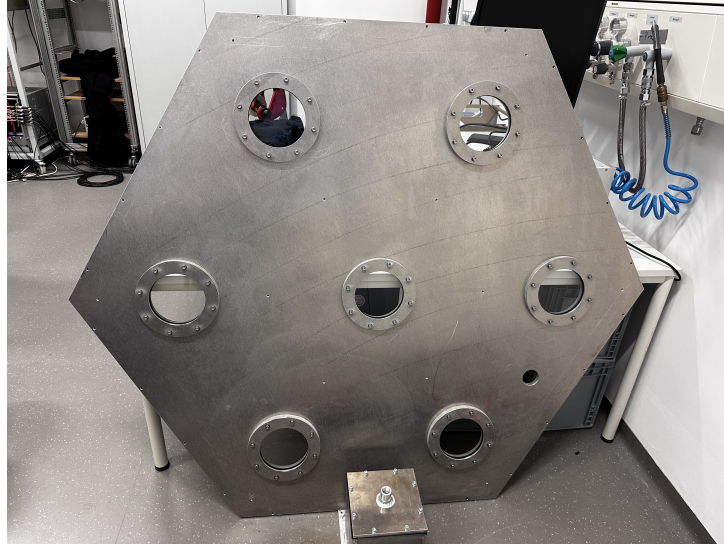
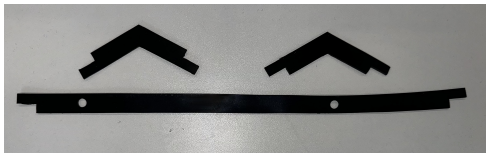


Figure 6.5: Lid with installed PMT rings.

were custom-produced by the PRISMA Detector Laboratory. Torr Seal, a two-component epoxy resin, was used to bond the gaskets to the upper surfaces of the vessel walls. This specific type of epoxy was chosen due to its chemical resistance to LAB. Additional epoxy was applied at the junctions between individual gasket segments to ensure continuous sealing. After a curing period of 24 hours, the epoxy had fully hardened, providing a mechanically stable and leak-tight seal. Finally, excess epoxy material was removed using sandpaper to ensure a uniform contact surface and proper pressure distribution across the gasket interfaces.



(a) Viton gaskets.



(b) Torr Seal epoxy resin.



(c) Gasket application.



(d) Finished vessel.

Figure 6.6: Sealing of scintillator vessel.

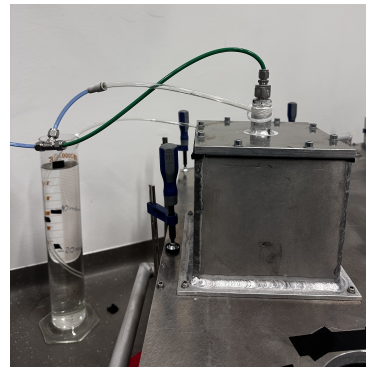
At this stage, the final step before closing and sealing the veto system consisted of cleaning the inner surfaces of both the vessel and the lid using soap, followed by isopropanol. This procedure removes industrial oils, dust, and other contaminants from the detector surfaces, preventing them from dissolving into the scintillator and preserving the reflective properties of the interior. The PMT windows were also cleaned with isopropanol.

After the lid was closed and tightly fastened to the vessel, an additional ring gasket was bonded with epoxy around the opening connected to the expansion volume. The expansion volume was then mounted on top of the vessel. In addition, its lid was sealed using a polyethylene foam gasket, which is intended only for the gas overpressure region. No Viton sealing was required at this stage, as the liquid scintillator does not reach this part of the system.

A 1/2-inch Swagelok connector was attached to the flange of the expansion volume, and a 1/2-inch ball valve was installed on the vessel flange. The expansion volume was subsequently connected to a nitrogen gas supply system as well as a makeshift hydrostatic barometer to regulate and monitor the internal pressure of the veto system. The complete setup is shown in Fig. 6.7.



(a) Vessel with closed lid.



(b) Expansion volume.

Figure 6.7: Final assembly of prototype.

6.2.1 Leak test

With the detector body fully assembled, leak tests were carried out. These tests involved applying a nitrogen overpressure of approximately 10 mbar inside the vessel and monitoring the pressure using the barometer to determine whether any gradual pressure loss occurred.

Initial measurements indicated significant leakage. To locate the leaks, a soap solution was applied to all critical sealing regions, including the gaskets between the vessel and lid, the PMT window assemblies, and the expansion volume connections. The formation of persistent bubbles at specific locations was taken as evidence of gas leakage. Since most leaks were identified at the interface between the lid and the vessel, it was concluded that the contact pressure was insufficient, despite the combined effect of the lid's weight

and the fastening screws. To address this, several F-clamps were installed to improve the mechanical compression of the seal and distribute the load more evenly, as shown in the final assembled detector in Fig. 6.8. This significantly improved the overall tightness of the system.

Additional minor leakage points were identified at the screw positions of the PMT mounting rings and were temporarily sealed using adhesive tape. During assembly, two threaded holes intended for lid fastening were stripped due to over-tightening, preventing proper screw engagement and leading to substantial leakage. To repair these locations, the holes were filled with Teflon foil, with an additional folded layer compressed and secured using a clamp. This can be seen in Fig. 6.8 as the bigger F-clamp with the red grip at the front and an additional regular-sized one at the back. This approach proved effective in restoring a reliable seal at the damaged positions.

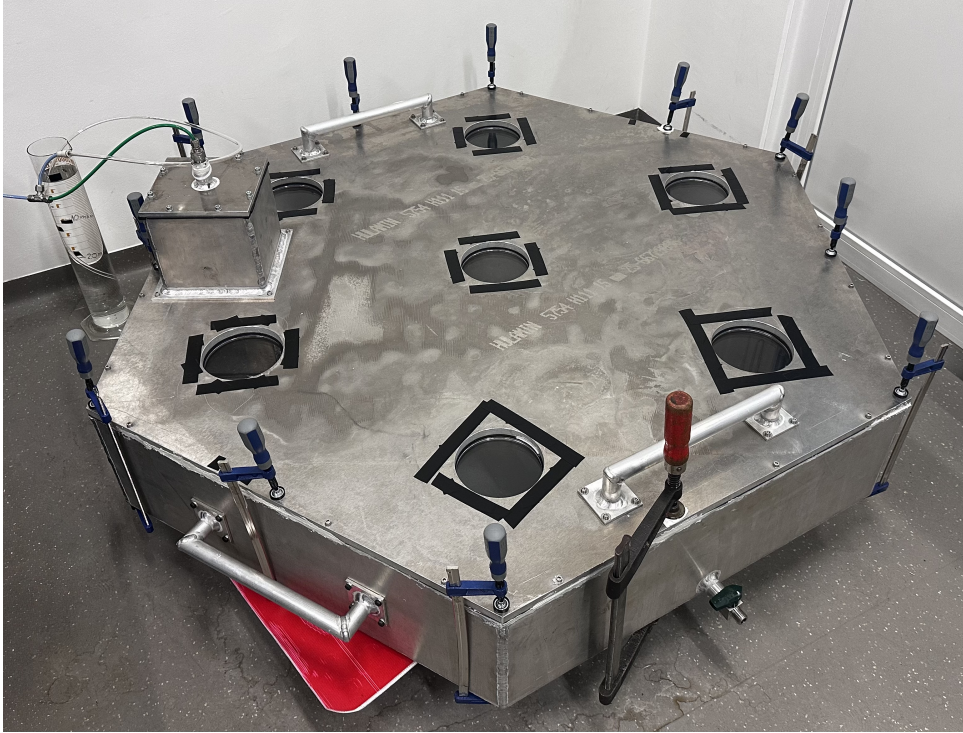


Figure 6.8: Assembled body of the veto system.

After applying these corrections, the manometer still indicated a gradual pressure decrease. The previous leak detection method using soap solution was no longer sufficient, and a more sensitive approach was adopted with support from the vacuum workshop at the Institute for Nuclear Physics. The vessel was filled with helium gas, and a helium leak detector was used to identify leakage points with high precision. Once located, these leaks were sealed using epoxy resin. After this procedure, the detector achieved full gas tightness and was able to maintain an overpressure of approximately 10 mbar.

Finally, before filling the vessel with the scintillator, a 2×2 m spill tray had to be installed beneath the veto vessel to collect any accidental liquid releases. This precaution

is necessary because, although Gd-loaded LAB is not inherently toxic, it must not enter the sewage system, as gadolinium compounds cannot be effectively removed and may pose a risk to aquatic ecosystems.

Unfortunately, due to extended delays by the manufacturer of this spill tray, the vessel couldn't be filled, and the experimental testing of the detector was postponed beyond the time frame of this thesis. Upon the installation of this tray, the detector can finally be filled via a pump system connected to the ball valve. To verify leak tightness without risking degradation of the gadolinium complex, the system will initially be filled with pure LAB under a simultaneous nitrogen overpressure. After maintaining stable conditions for at least one week and performing preliminary test measurements, the system will subsequently be filled with the Gd-loaded scintillator.

The seven 5-inch ET Enterprises 9330B PMTs will then be mounted onto the glass windows using optical grease to ensure efficient optical coupling. After installation, the PMTs will be covered with a thick black blanket to minimize external light contamination and reduce background signals.

6.2.2 Data acquisition system (DAQ)

A 16-channel CAEN V1743 digitizer module will be used for readout of the PMT signals. The module provides 12-bit resolution with a sampling rate of 3.2 GS/s and records up to 1024 samples per event. The PMTs are powered by a dedicated high-voltage supply to control and stabilize their operating gain.

The digitizer continuously acquires analog voltage signals from the PMTs, converts them into digital waveforms using high-speed analog-to-digital converters (ADCs), and processes them in real time via onboard FPGA units for storage and analysis. This approach offers several advantages. In particular, integrating the recorded pulse allows the deposited energy per event to be reconstructed from the PMT signal, enabling the extraction of particle energy spectra. In addition, the digitizer supports trigger logic, which can be used to implement coincidence conditions in the detector setup. This capability is essential for determining the tagging and veto efficiencies in the experiment, as described in Sec. 6.3.

6.3 Experimental goals

Once the prototype detector is fully operational, a series of preliminary calibration measurements will be performed to prepare it for the main experimental goals.

Initially, with the detector filled with pure LAB scintillator, cosmic-ray data will be recorded to calibrate the PMT operating voltages. This will be achieved by performing short measurements at different voltage settings and constructing gain curves to identify the optimal operating range for each PMT. Since the central PMT (see Fig. 5.4) is expected to collect more light than the peripheral channels, it will be used as a reference trigger for the remaining PMTs. After calibrating the six outer PMTs, the central PMT will be exchanged with one of the side PMTs, and the procedure will be repeated to ensure uniform calibration across all channels.

After determining the optimal operating voltages, a neutron source will be used to calibrate the scintillator energy response using the hydrogen capture gamma peak, analogous to the procedure shown in Fig. 5.7. This calibration will be performed with pure LAB, since the absence of gadolinium loading increases the relative contribution of captures on hydrogen, producing a well-defined and easily identifiable gamma peak. With this calibration completed, cosmic-ray measurements will be carried out using the LAB-filled detector.

The scintillator will then be replaced with Gd-loaded LAB. Due to the different scintillation light yields (9000 photons/MeV for LAB compared to 6000 photons/MeV for Gd-loaded LAB), the PMT voltages will need to be recalibrated using the same procedure. An equivalent set of cosmic-ray measurements will then be performed and compared to the LAB-filled case.

Subsequently, additional measurements will be conducted to determine the tagging and veto efficiencies of the prototype. This will be achieved by placing plastic scintillator plates above and below the veto system and recording cosmic-ray events in coincidence. By applying a coincidence requirement between the top plate and the veto system, the tagging efficiency can be extracted. Adding a further coincidence condition with the bottom plate allows the veto efficiency to be determined.

Finally, these measured efficiencies will be compared to the simulation results to assess the accuracy of the model. Additional studies will evaluate whether this liquid scintillator technology provides sufficient sensitivity and efficiency for integration into the DarkMESA design and serve as a proof of concept for future upscaling toward the NuDoubt⁺⁺ detector.

Chapter 7

Future upscaled veto system

As discussed in Ch. 5, the simulation results predict a highly efficient veto system capable of both tagging and vetoing a wide range of background particles, with particularly strong performance for neutrons and gamma rays. The forthcoming experimental measurements will indicate whether these predictions accurately describe the detector and its performance. Based on these results, a decision will be made whether this type of detector technology is suitable for the NuDoubt⁺⁺ experiment and whether an adapted version could serve as a viable veto system for the DarkMESA experiment. To further evaluate its long-term potential, the performance of a future upscaled detector configuration should also be investigated. Such a study would follow the conceptual design shown in Fig. 3.7 and assess the expected improvements in tagging and veto efficiency achievable with a larger detector volume.

7.1 Simulation setup

The simulation framework remains unchanged from that described in Sec. 5.1. The modified detector geometry used for the upscaled studies is shown in Fig. 7.1.

The hexagonal geometry of the veto system is retained, with the primary modification being an increase in height to 1550 mm. In addition, a second array of seven 5-inch PMTs is installed at the bottom of the veto volume, following the same hexagonal arrangement used in the prototype. The veto volume contains approximately 1373 l of Gd-loaded LAB scintillator.

Within the veto volume, an additional cylindrical detector is simulated with a radius of 550 mm and a height of 1100 mm. This volume represents a hypothetical inner detector and is filled with approximately 1045 l of opaque LAB scintillator, which is not Gd-loaded. The opacity is achieved by adding 2% of paraffin wax to the liquid scintillator. In the final detector design, this opaque scintillator would be read out by optical fibers distributed throughout the detector volume, as discussed in Sec. 3.3. However, since the focus of the present study is the performance of the veto system rather than that of the inner detector, the optical-fiber readout was not simulated. Instead, the inner detector response was modeled using a deposited energy threshold, corresponding to a minimum scintillation signal generated within the opaque medium.

The larger scintillator volumes and the higher light yield of pure LAB (9000 photons/MeV) significantly increase the computational cost of optical photon tracking. To reduce simulation time, optical photons produced within the opaque scintillator were terminated immediately after their creation using the `fStopAndKill` command. Since only the deposited energy in the inner detector was required for the veto efficiency analysis, this approximation does not affect the relevant observations.

The same two simulation scenarios investigated for the prototype were studied for the upscaled detector: first, an idealized neutron spectrum analysis, and second, simulations of cosmic rays generated with the CRY library. The resulting tagging and veto efficiencies were then compared with those of the prototype in order to evaluate how the performance of the system scales with detector size.

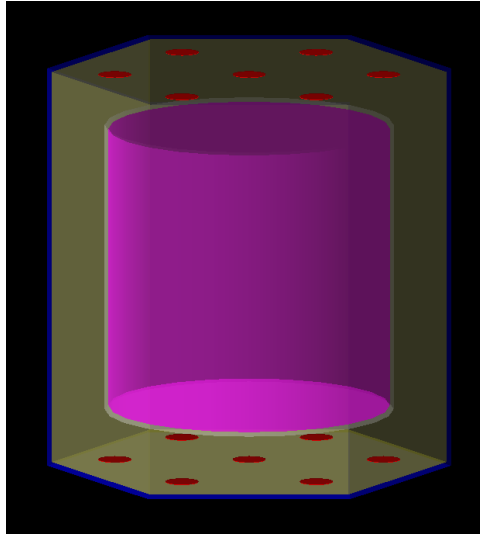


Figure 7.1: Visualization of the upscaled NuDoubt⁺⁺ detector geometry implemented in Geant4. The outer volume (orange) represents the upscaled veto system filled with 13731 of the Gd-loaded LAB scintillator with a radius of 775 mm and a height of 1550 mm. It is read out by a total of 14 5-inch PMTs (red), distributed equally between the top and bottom surfaces. The inner cylindrical volume (purple) represents the detector filled with 10451 of the opaque LAB scintillator. It has a radius of 550 mm and a height of 1100 mm. The optical-fiber readout of the inner detector is not included in the simulation.

7.2 Potential efficiency reach

7.2.1 Neutron spectrum

Once again, neutrons were simulated across a broad energy range. For each energy bin, 10^5 neutrons with fixed initial energy were generated. At energies above 10 GeV, however, a smaller number of events was simulated due to the substantially increased computational

time required. The resulting efficiencies were normalized accordingly, and the larger statistical uncertainties at these energies are reflected by the corresponding error bars.

Two neutron-generation scenarios were considered. In the first scenario, neutrons were generated at random positions in the horizontal plane near the top of the veto volume with downward-directed momentum. In the second scenario, neutrons were generated at random positions at the mid-height of the veto volume with momentum directed radially inward from the sides. These configurations were chosen to represent two limiting cases for the detector response: an optimistic scenario, in which neutrons enter from above and traverse a large fraction of the scintillator volume, and a pessimistic scenario, in which neutrons enter from the sides and therefore have a reduced path length available for moderation and capture. Studying these two extreme cases also provides insight into the impact of the current PMT arrangement. Neutrons entering from above are expected to benefit from more favorable detector geometry and light collection, whereas side-entering neutrons present a more challenging detection scenario. In the future a more realistic treatment would involve generating neutrons isotropically with random incident angles and positions should be considered.

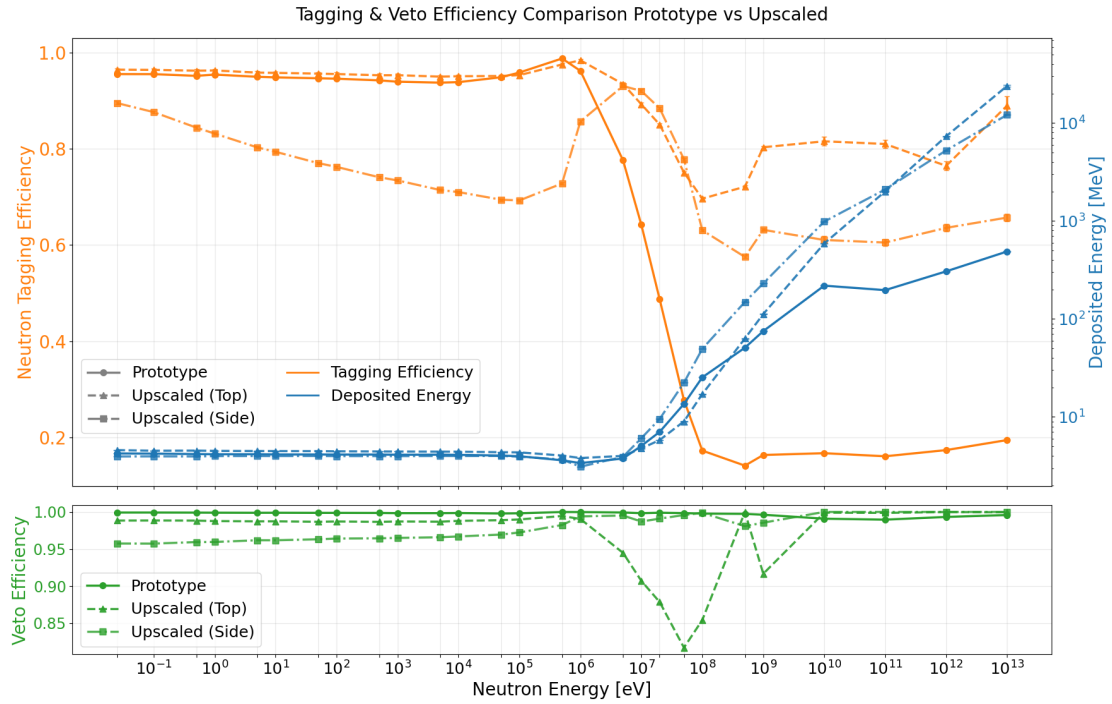


Figure 7.2: Comparison of the neutron tagging and veto efficiencies of the prototype and upscaled veto systems. For the upscaled detector, two simulation scenarios were considered: neutrons generated near the top of the veto volume with downward-directed momentum, and neutrons generated at mid-height with radially inward-directed momentum from the side.

The tagging efficiency was determined using the same analysis procedure described in Sec. 5.2, requiring a two-fold coincidence together with a minimum threshold of two PMT

hits per channel. For the veto efficiency calculation, an additional detection criterion was applied to the inner detector in the form of a deposited energy threshold. Rather than tracking the optical fiber response, this was implemented through the number of scintillation photons produced in the opaque medium. An arbitrary threshold of 1000 emitted photons was chosen, corresponding to approximately 100 keV of deposited energy. The resulting tagging and veto efficiencies can be compared directly with those obtained for the prototype detector, as shown in Fig. 7.2.

Firstly, in the scenario where neutrons are generated at the top of the veto system, the tagging efficiency below 1 MeV remains similar to that of the prototype. This is expected, as low-energy neutrons have short mean free paths and are typically moderated and captured within a small region of the scintillator. This was demonstrated in Fig. 5.9. In this regime, the increased detector volume does not significantly alter the capture or light production processes.

In contrast, when neutrons are generated at the side of the veto volume, the resulting tagging efficiency is substantially lower than in both the top-generation scenario and the prototype case. This reduction is primarily attributed to the non-optimized PMT arrangement. In this configuration, many neutrons are captured near the entry region, where the resulting scintillation light is insufficiently collected by the PMTs to satisfy the detection threshold.

In the energy range between 5-100 MeV, both upscaled scenarios exhibit comparable tagging efficiencies, which are also significantly higher than those of the prototype. At higher energies, the tagging efficiency in the upscaled detector is approximately a factor of four larger than in the prototype. The underlying mechanisms responsible for these differences can be further clarified by examining the relative contributions of different neutron interaction processes.

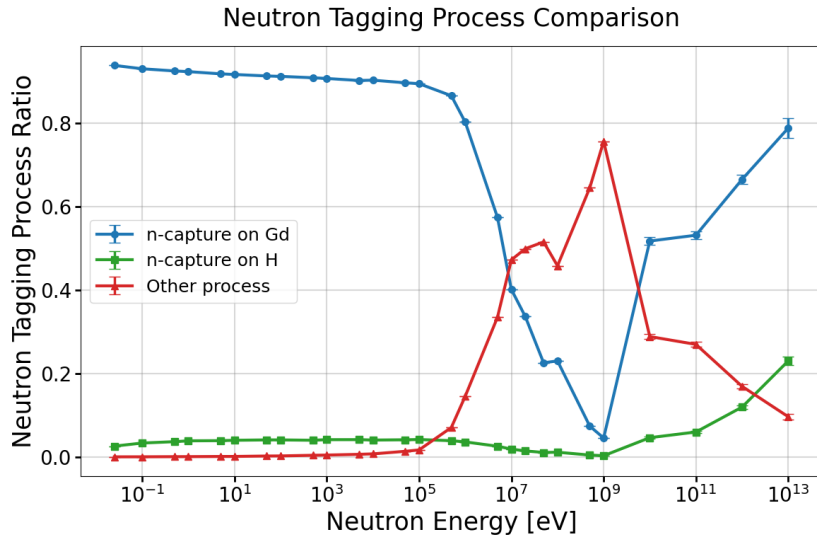


Figure 7.3: Comparison of the relative contributions of different neutron interaction channels in the scintillator of the upscaled veto system.

Comparing the tagging ratios in Fig. 7.3 with those of the prototype shown in Fig. 5.8, no significant differences are observed up to 1 MeV. After this energy, however, the distribution changes significantly. Neutron captures on Gd become significantly less dominant, reaching a minimum around 1 GeV, while tagging via other interaction processes peaks in the same energy region. This deviation from the prototype behavior is likely caused by the presence of the inner detector volume. Incident neutrons entering this region can deposit a substantial fraction of their energy through elastic scattering and inelastic interactions with nuclei, producing secondary protons and neutrons. These secondary particles may subsequently propagate back into the veto volume and interact there, effectively leading to indirect tagging of the original neutron.

At the same time, the probability that a neutron deposits sufficient energy in the inner detector and subsequently exits the volume to be captured by Gd in the surrounding veto is reduced. Consequently, most Gd captures occur in cases where neutrons are generated near the outer regions of the veto and traverse it without significantly interacting with the inner detector first.

At higher energies, neutrons become sufficiently energetic that, even after partial thermalization in the inner detector, a non-negligible fraction can still escape and be captured in the veto volume. In this regime, captures occur predominantly on Gd with a probability of approximately 80%, on H with about 22%, while tagging via other processes decreases to roughly 10%.

Returning to Fig. 7.2, the veto efficiency of the upscaled detector shows noticeable differences compared to the prototype. First, considering neutrons generated at the top of the veto system, the veto efficiency below 1 MeV is slightly lower than that of the prototype, with an average of approximately 98%. Around 100 MeV, the efficiency decreases to about 80%, consistent with the corresponding dip observed in the tagging efficiency. This behavior is likely caused by neutrons entering the inner detector and depositing sufficient energy that neither they nor their secondary products manage to escape into the veto volume, producing a strong enough signal to satisfy the detection criteria. A second reduction in efficiency is observed around 1 GeV, coinciding with the energy region where neutron captures on Gd become least dominant and other interaction channels prevail. Beyond this second dip, the veto efficiency increases again, reaching approximately 99.9% at the highest energies, which exceeds the corresponding performance of the prototype.

In the case of neutrons generated at the side of the detector, a different trend is observed. The veto efficiency starts at approximately 95% and gradually increases, reaching values above 99.999% at high energies. The absence of pronounced dips in this scenario can be attributed to the initial neutron direction and the resulting spatial distribution of secondary particles. Side-entering neutrons tend to produce secondaries with a broader angular distribution, increasing the likelihood that scintillation light is collected by both the top and bottom PMT arrays. In contrast, for neutrons injected from the top, secondary particles predominantly retain a downward momentum component and are therefore more likely to produce signals primarily in the bottom PMT array, reducing the probability of satisfying the coincidence-based detection criteria.

Overall, the lowest-efficiency region appears to coincide with the transition between dominance of Gd capture and alternative interaction processes, primarily in the energy range between 500 keV and 1 GeV. However, these interpretations remain preliminary, and more detailed studies are required to fully understand the underlying mechanisms responsible for these effects.

7.2.2 Cosmic rays with CRY

For the cosmic-ray study, a similar procedure was followed as described in Sec. 5.3. A 20 cm thick concrete ceiling was placed 2 m above the upscaled veto system, and cosmic rays were generated over a 3×3 m surface above the ceiling with downward-directed momentum.

The first step is again the calculation of the differential detection rate using Eq. 5.4. In this case, the effective detector area must include not only the top surface of the veto system but also its lateral surfaces, since particles can also enter from the sides. The inclusion of the side surfaces increases the total effective area by approximately a factor of six compared to the top surface alone, resulting in $A_{\text{det}} = 8.79 \text{ m}^2$. This leads to the differential detection rates for each particle species shown in Fig. 7.4.

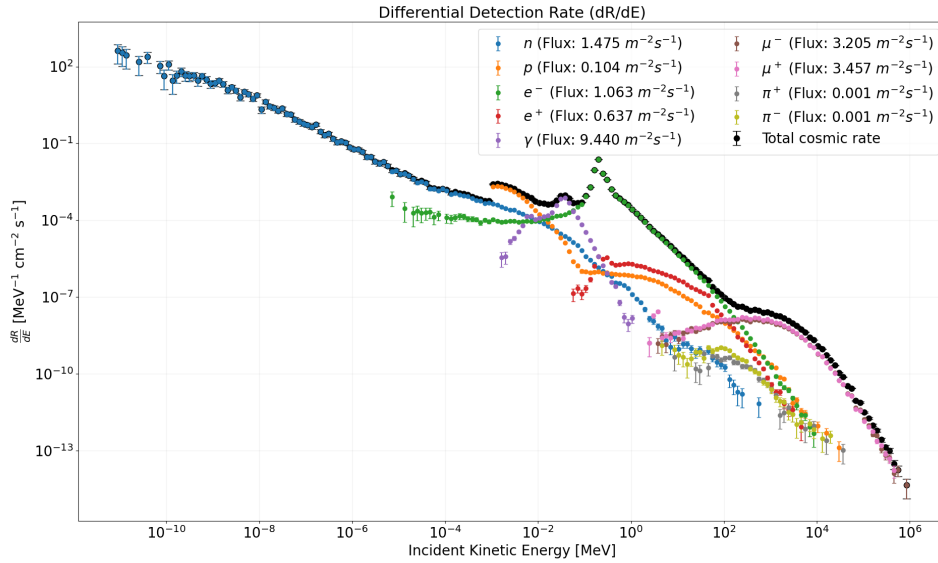
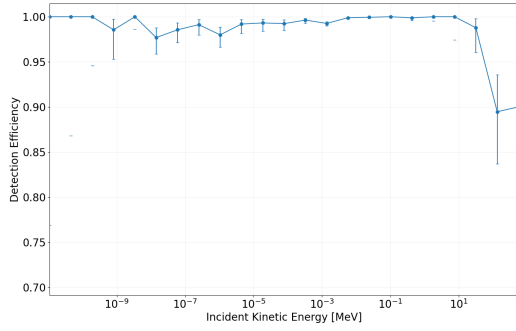
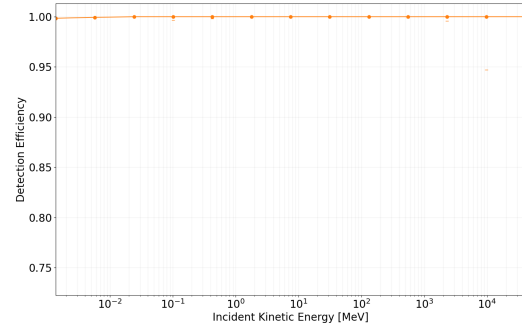


Figure 7.4: Differential detection rate for different particle species for the upscaled veto system.

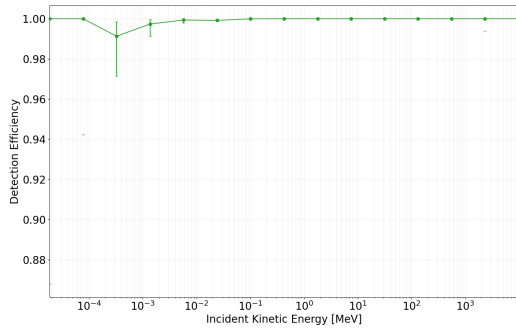
The differential detection rates shown in Fig. 7.4 are at least one order of magnitude higher than those obtained for the prototype in Fig 5.16. This increase is primarily attributed to the larger effective detector area, as well as the increased scintillator volume, which together enhance the probability that incoming particles interact within the detector and are subsequently registered. Using these rates to compute the detection efficiency according to Eq. 5.7, the efficiencies for the different particle species, as well as the global efficiency, can be derived. The resulting values are shown in Fig. 7.5 and Fig. 7.6.



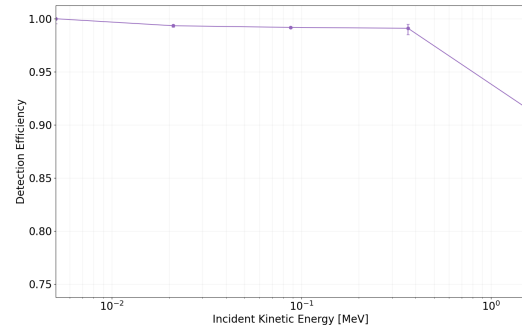
(a) Neutrons.



(b) Protons.



(c) Electrons.



(d) Gammas.

Figure 7.5: Detection efficiency of different particle types.

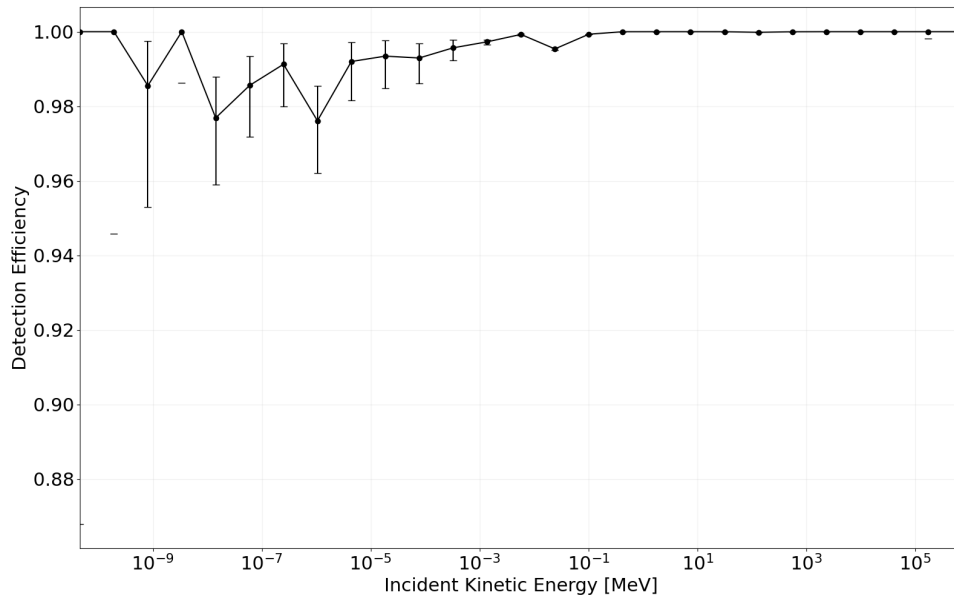


Figure 7.6: Global detection efficiency of cosmic rays.

Once again, only the particle species exhibiting significant energy-dependent variations are discussed here. The remaining results are provided in App. A.5. This study shows that the upscaled veto system achieves higher detection efficiencies across the cosmic-ray spectrum compared to the prototype (see Fig. 5.17). In particular, neutrons exhibit efficiencies above 97%, with a noticeable decrease only near 100 MeV, consistent with the behavior observed in Fig. 7.2. Protons and electrons reach efficiencies close to 100% across nearly the entire energy range, while gamma rays start at approximately 99% and decrease to about 92% above 1 MeV. The global detection efficiency shown in Fig. 7.6 drops to a minimum of approximately 97.8% between 0.01-1 eV and then steadily increases up to 100% above 100 keV. This represents a significant improvement over the prototype, where efficiencies were lower by up to roughly 20% below about 1 keV.

Departing from the differential detection rate and the derived efficiencies, the particle interaction spectrum inside the upscaled veto system can again be examined. This allows a direct comparison of the tagging and veto efficiencies for different particle species at varying detection thresholds with the corresponding results obtained for the prototype simulation.

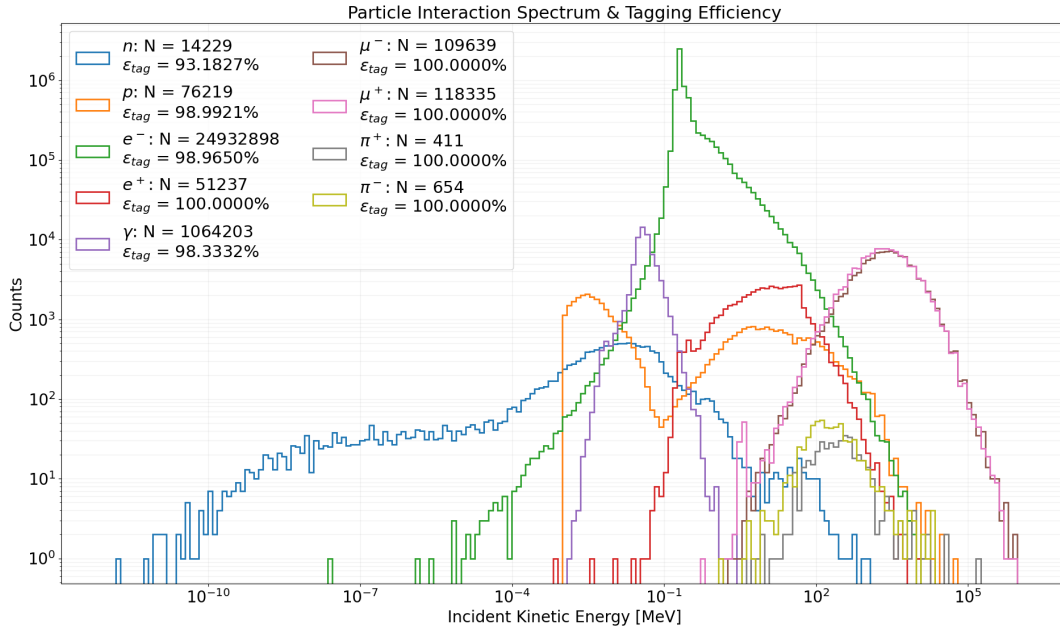


Figure 7.7: Spectrum of interacting cosmic particles inside the upscaled veto system using a two-photon threshold per PMT under a two-fold coincidence condition. The tagging efficiency for the different particle species is shown in the legend.

To maintain consistency with the prototype analysis, the case of a two-photon threshold under a two-fold PMT coincidence will be considered first. The spectra are shown in Fig. 7.7 and are fully consistent with those obtained for the prototype in Fig. 5.19. A similar trend is observed for the tagging efficiencies of the various particle species, with slightly improved overall values.

For neutrons, a tagging efficiency of 93.18% is achieved, compared to approximately 91% in the prototype case. For protons, electrons, positrons, and gamma rays, the tagging efficiencies increase only marginally by a few tenths of a percent, while muons and pions remain at 100%, as in the prototype. This modest improvement is primarily attributed to the increased scintillator volume and could be further enhanced through a more optimized PMT arrangement at the top and bottom of the veto system.

The resulting veto efficiencies, demonstrating the active and passive shielding components of the veto system, are shown in Tab 7.1.

Table 7.1: Veto efficiencies of upscaled veto system at 2-photon threshold.

	n	p	e^-	e^+	γ	$\mu^\pm$	$\pi^\pm$	Global
Veto Efficiency [%]	99.6429	99.9515	99.7981	100.00	99.6076	100.00	100.00	99.7929

Contrary to the tagging efficiency, which is largely independent of the inner detector, the veto efficiency shows a reduction compared to the prototype results. The primary cause of this deviation is the detection threshold imposed on the inner detector. Assuming an idealized inner detector with perfect sensitivity, in which any deposited energy is sufficient to register an event, the global veto efficiency decreases to 99.6545%. If instead a more realistic threshold of 1 MeV is applied, the efficiency increases slightly to 99.8611%. This demonstrates that the assumed inner detector response has a non-negligible impact on the overall veto performance. In addition to a more educated selection of inner detector threshold, further improvements in veto efficiency could be achieved through optimization of the PMT configuration within the veto system itself.

Another relevant aspect is the angular dependence of the detection efficiency. As already indicated by the neutron studies in Fig. 7.2, the veto system exhibits a higher efficiency for particles incident from the top compared to those entering from the sides.

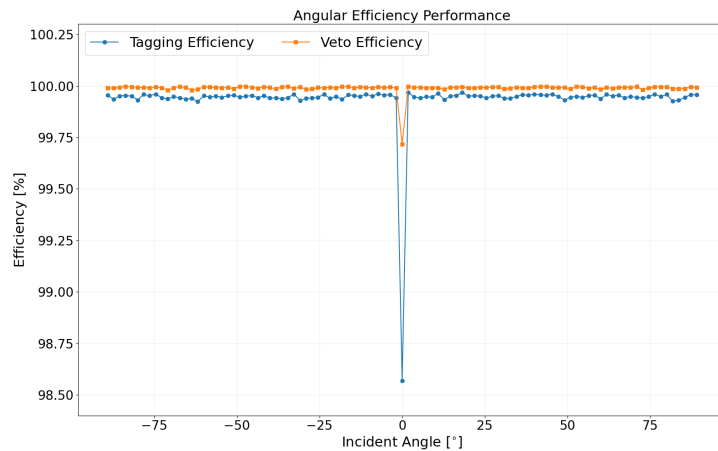


Figure 7.8: Angular performance of the upscaled veto system.

The tagging and veto efficiencies are shown in Fig. 7.8 as a function of the incident angle. A slight reduction in efficiency can be observed for particles entering vertically from the top compared to those entering at angles. This is expected, as vertically incident particles traverse a shorter path length in the scintillator and therefore produce less total light. However, this effect remains small due to the overall symmetry of the scintillator volume within the veto system. In addition, the unoptimized PMT placement has a reduced impact compared to the neutron-only studies, since the cosmic-ray spectrum is dominated by charged particles that deposit substantial energy and generate large amounts of scintillation light, which is more easily detected. Overall, the tagging efficiency remains above 99.9% across the full angular range, while the veto efficiency is approximately 100%.

The last step is to study the dependence of the efficiencies on the PMT photon threshold, which is considered to reflect more realistic experimental conditions. The corresponding results are shown in Fig. 7.9.

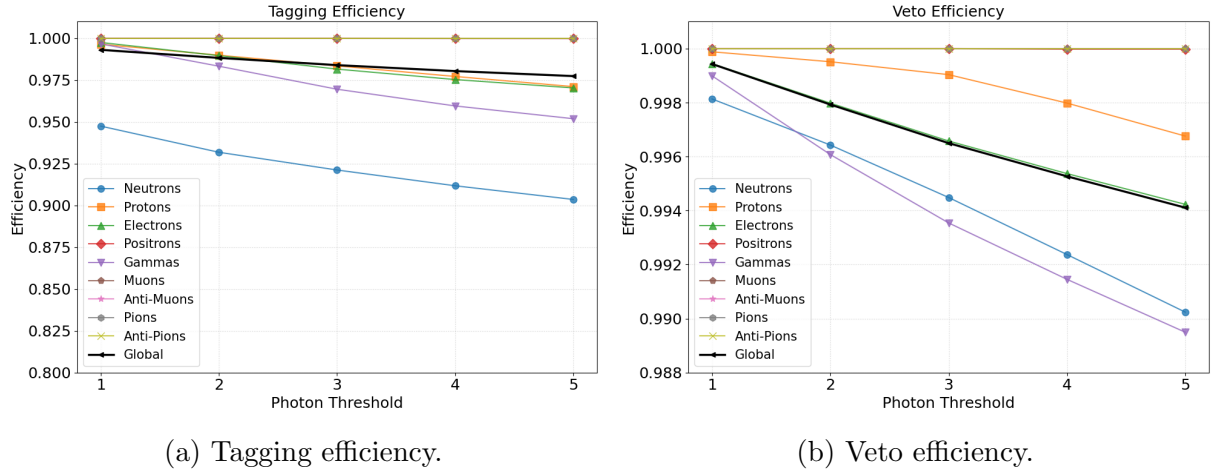


Figure 7.9: Veto and tagging efficiencies of the upscaled veto system for different photon-threshold values.

In the case of the tagging efficiency, values remain above 95% for all particle species across the different threshold settings, with the exception of neutrons, which decrease to 90.36% at the highest 5-photon threshold. Despite this reduction, the global tagging efficiency remains above 97.74%. Moving on to the veto efficiency, a much more pronounced decrease is observed across all particle types as the threshold increases. Neutrons and gamma rays exhibit the strongest reduction, reaching 99.02% and 98.95% at the highest threshold value, respectively. In contrast, the remaining particle species show only minor variations and maintain consistently high veto efficiencies. Overall, the global veto efficiency decreases to approximately 99.41%.

Finally, Fig. 7.10 compares the global efficiencies of the prototype and the upscaled detector. It becomes evident that the prototype achieves a slightly higher veto efficiency, while the upscaled version performs better in terms of tagging efficiency.

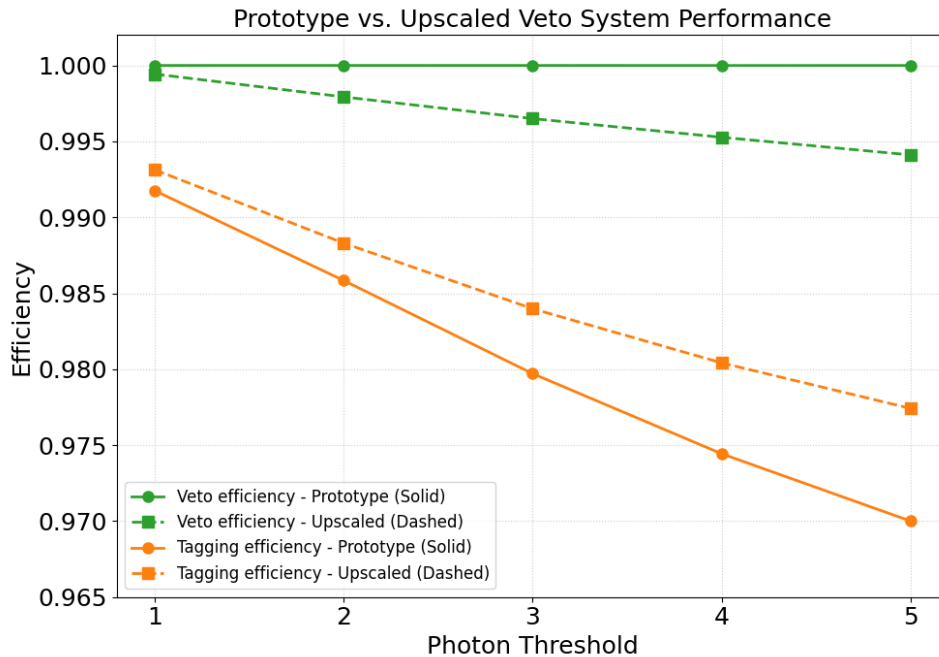


Figure 7.10: Performance comparison between the veto system prototype and the up-scaled version. The efficiencies of the prototype are shown as solid lines, while those of the upscaled detector are shown as dashed lines.

Of course, several aspects must be considered to fairly interpret this comparison. The most important point is the suboptimal positioning of the PMTs in the upscaled veto system (see Fig. 7.1). The current arrangement leaves regions near the detector edges, particularly around the inner detector boundaries, less efficiently covered, which reduces the overall light collection efficiency. An improved design should include a more optimized PMT layout and potentially an increased number of PMTs, with additional detectors placed at intermediate heights within the veto volume to improve spatial coverage.

Beyond the PMT configuration, the reduced veto efficiency of the upscaled detector is also partly related to the treatment of the inner detector. No optical-fiber readout was simulated for the opaque scintillator volume; instead, a deposited energy threshold was used as a simplified proxy for event detection. Since no dedicated studies of the opaque scintillator response were performed in this thesis, the threshold was chosen at approximately 100 keV as an approximate value. Different threshold choices would directly affect the resulting veto efficiency. In future work, implementing an explicit optical fiber readout in the simulation would provide a more realistic and reliable description of the inner detector response.

Overall, the upscaled veto system demonstrates an improved tagging efficiency across particle species and a generally higher overall detection efficiency, as also reflected in Fig. 7.5 and Fig. 7.6. Together with the neutron spectrum results shown in Fig. 7.2, this suggests that the increased scintillator volume is the main driver behind the improved tagging performance. This is particularly relevant for the upscaled configuration,

where tagging efficiency is independent of the inner detector response. The veto efficiency obtained in these simulations is promising, especially considering the simplified and unoptimized detector design used in this study. However, it should be regarded as a preliminary result and is expected to improve with more refined simulations and an optimized detector layout in future work.

Chapter 8

Summary & Outlook

In the ongoing search for dark matter, the DarkMESA experiment aims to set new limits using the low-energy, high-intensity electron beam at MESA. Its crystal calorimeter design has shown promising results in simulation studies, combined with a highly efficient plastic scintillator veto system reaching efficiencies of up to 99.93%. However, as new detector technologies emerge, opportunities arise to further improve performance and sensitivity. One such development is the opaque liquid scintillator and fiber readout technology currently under investigation by the NuDoubt⁺⁺ collaboration. This concept also includes a surrounding gadolinium-loaded transparent liquid scintillator veto system. Due to its potential for improved sensitivity and particle identification, it has attracted increasing interest within the DarkMESA collaboration. Based on these shared goals, a new collaboration between the two groups has been initiated.

The goal of this thesis was the development and construction of a prototype veto system implementing a Gd-loaded liquid LAB scintillator. Simulation studies were performed using Geant4 to determine an optimized geometry as well as the expected sensitivity and efficiency of the detector. Two main scenarios were investigated: first, a detailed study of the neutron energy spectrum, given the importance of neutrons as background sources in dark matter experiments; and second, a study of cosmic-ray backgrounds using the CRY library in Geant4. These studies demonstrated the energy dependence of both tagging and veto efficiencies for neutrons and other background particles. A veto efficiency above 99% was found for neutrons across the full energy spectrum (see Fig. 5.13). In the cosmic-ray study, neutron veto efficiencies above 99.98% were achieved across different detection thresholds, with a global efficiency exceeding 99.999% over the full particle spectrum (see Fig. 5.21).

Based on these simulation results, detailed technical drawings of the prototype and its components were produced and provided to the mechanical workshop of the Institute for Nuclear Physics for construction. The prototype consists of a hexagonal vessel containing approximately 371 l of Gd-loaded LAB and is read out by seven 5-inch PMTs. Plexiglass windows were integrated into the lid to support PMT mounting. An additional 5 l expansion volume was included to accommodate overfilling and thermal expansion of the scintillator. Viton gaskets were used at all sealing interfaces to ensure leak-tight operation. Although the experimental setup was not fully completed by the end of this thesis, the detector was assembled and prepared for initial measurements once filled with scintil-

lator. The first steps will include PMT voltage calibration, followed by energy calibration using a neutron source and identification of the hydrogen capture peak. Subsequently, cosmic-ray measurements will be performed to determine the tagging and veto efficiencies using additional plastic scintillator plates placed above and below the prototype. These results will then be compared to the simulation predictions to assess their accuracy.

Finally, preliminary simulation studies of the future upscaled veto system were conducted. The same simulation scenarios as for the prototype were considered, and both tagging and veto efficiencies were evaluated. In the neutron study, two configurations were analyzed: neutrons incident from the top and from the side of the detector. The results in Fig. 7.2 show a substantial increase in tagging efficiency by roughly a factor of four compared to the prototype, while the veto efficiency remains largely comparable, though slightly reduced in certain energy regions. In the cosmic-ray study, the upscaled veto system exhibits improved detection efficiency due to its larger scintillator volume (see Fig. 7.6), which also leads to higher tagging efficiency overall. In contrast, the veto efficiency decreases slightly to about 99.41% (see Fig. 7.9), primarily due to the non-optimal PMT arrangement and the simplified treatment of the inner detector threshold. More detailed simulations with an improved detector design will be required in future work to obtain more realistic estimates.

The development and evaluation of this veto system will continue beyond this thesis. Further measurements will be conducted to validate the simulation results and assess the detector's experimental performance. Planned tests include combined operation with both the NuDoubt⁺⁺ opaque liquid scintillator prototype and the DarkMESA Phase A prototype calorimeter. Additional simulations will also explore the upscaled veto system integrated with a crystal calorimeter as the inner detector. Based on the combined experimental and simulation results, a decision will be made regarding the future development of this technology for the NuDoubt⁺⁺ experiment and its potential integration into the DarkMESA design, either as a primary detector component or as a complementary veto system alongside the planned crystal calorimeter.

Appendix A

Simulation studies

A.1 Scintillator properties data table

Table A.1: Data table of Gd-loaded LAB scintillator properties.

Wavelength [nm]	Attenuation length [m]	Refractive index	Normalized emission spectrum
390	0.9	1.483	0.10
400	1.1	1.480	0.37
410	1.2	1.479	0.63
420	1.4	1.478	1.00
430	2.3	1.476	0.92
440	3.0	1.474	0.60
450	3.9	1.472	0.55
460	5.0	1.470	0.45
470	6.1	1.468	0.26
480	7.5	1.466	0.19
490	9.2	1.465	0.13
500	10.7	1.464	0.08
510	12.4	1.463	0.05
520	14.1	1.462	0.03
530	15.8	1.461	0.02
540	17.5	1.460	0.01
550	19.2	1.459	0.005

A.2 ET Enterprises 9330B Series PMT

130 mm (5") photomultiplier 9330B series data sheet



1 description

The 9330B is a 130mm (5") diameter, end window photomultiplier with blue-green sensitive bialkali photocathode on a plano-concave window. It has 11 high gain, high stability SbCs dynodes of linear focused design for good linearity and timing.

2 applications

- radiation monitoring
- scintillation spectroscopy

3 features

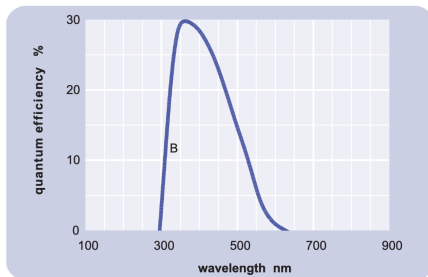
- high gain
- low operating voltage
- good SER
- good pulse height resolution
- large active area

4 window characteristics

9330B borosilicate	
spectral range (nm)*	300 - 630
refractive index (n_d)	1.49
K (ppm)	300
Th (ppb)	250
U (ppb)	100

* wavelength range over which quantum efficiency exceeds 1 % of peak

5 typical spectral response curves



6 characteristics

	unit	min	typ	max
photocathode: bialkali				
active diameter	mm		115	
quantum efficiency at peak	%		30	
luminous sensitivity	$\mu\text{A/lm}$		75	
with CB filter		8	12	
with CR filter			2	
dynodes: 11LFSbCs				
anode sensitivity in divider B:				
nominal anode sensitivity	A/lm		200	
max. rated anode sensitivity	A/lm		2000	
overall V for nominal A/lm	V		1200	1700
overall V for max. rated A/lm	V		1400	
gain at nominal A/lm	$\times 10^6$		3	
dark current at 20 °C:				
dc at nominal A/lm	nA		4	100
dc at max. rated A/lm	nA		40	
dark count	s ⁻¹		1500	
pulsed linearity (-5% deviation):				
divider A	mA		30	
divider B	mA		100	
pulse height resolution:				
single electron peak to valley	ratio		2	
rate effect (I_a for $\Delta g=1\%$):	μA		20	
magnetic field sensitivity:				
the field for which the output decreases by 50 %				
most sensitive direction	$T \times 10^{-4}$			
temperature coefficient:	% °C ⁻¹		± 0.5	
timing:				
multi electron rise time	ns		13	
multi electron fwhm	ns		25	
single electron rise time	ns		5	
single electron fwhm	ns		8	
transit time	ns		65	
weight:	g		350	
maximum ratings:				
anode current	μA			100
cathode current	nA			500
gain	$\times 10$			27
sensitivity	A/lm			2000
temperature	°C	-30		60
V (k-a) ⁽¹⁾	V			2500
V (k-d1)	V			650
V (d-d) ⁽²⁾	V ⁶			300
ambient pressure (absolute)	kPa			202

⁽¹⁾ subject to not exceeding max. rated sensitivity ⁽²⁾ subject to not exceeding max rated V(k-a)

7 typical voltage gain characteristics

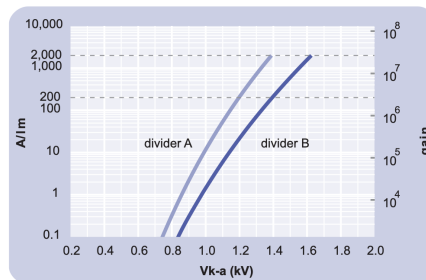


Figure A.1: ET Enterprises 9330B Series PMT (page 1) [28].

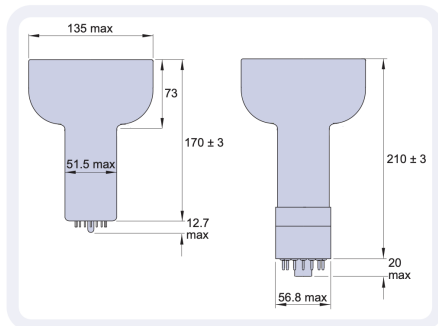
8 voltage divider distribution

	k	d ₁	d ₇	d ₈	d ₉	d ₁₀	d ₁₁	a
A	450V	R		R	R	R	2R	R
B	450V	R		R	2R	3R	4R	3R

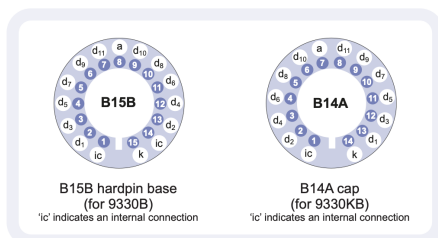
Characteristics contained in this data sheet refer to divider A unless stated otherwise.

9 external dimensions mm

The drawings below show the 9330B in hardpin format and the 9330KB with the B14A cap fitted.



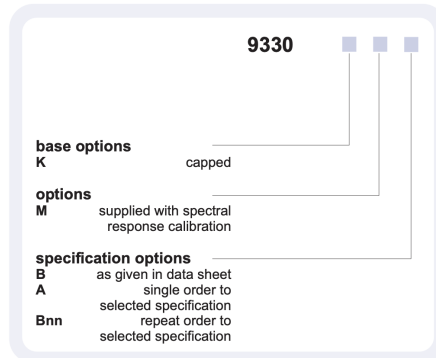
10 base configurations (viewed from below)



Our range of B15B sockets is available to suit the hardpin base. Our range of B14A sockets is available to suit the B14A cap. Both socket ranges include versions with or without a mounting flange, and versions with contacts for mounting directly onto printed circuit boards.

11 ordering information

The 9330B meets the specification given in this data sheet. You may order **variants** by adding a suffix to the type number. You may also order **options** by adding a suffix to the type number. You may order product with **specification options** by discussing your requirements with us. If your selection option is for one-off order, then the product will be referred to as 9330A. For a repeat order, ET Enterprises will give the product a two digit suffix after the letter B, for example B21. This identifies your specific requirement.



12 voltage dividers

The standard voltage dividers available for this pmt are tabulated below:

9330B	9330KB	k	d ₁	d ₇	d ₈	d ₉	d ₁₀	d ₁₁	a
C623C	C632C	450V	R		R	R	R	2R	R
C623D	C632D	450V	R		R	2R	3R	4R	3R

R = 330k Ω

*mumetal is a registered trademark of Magnetic Shield Corporation

ET Enterprises Limited
45 Riverside Way
Uxbridge UB8 2YF
United Kingdom
tel: +44 (0) 1895 200880
fax: +44 (0) 1895 270873
e-mail: sales@et-enterprises.com
web site: www.et-enterprises.com

ADIT Electron Tubes
300 Crane Street
Sweetwater TX 79556 USA
tel: (325) 235 1418
toll free: (800) 399 4557
fax: (325) 235 2872
e-mail: sales@electron tubes.com
web site: www.electrontubes.com

choose accessories for this pmt on our website

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ET Enterprises
electron tubes

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DS_9330B Issue 7 (26/01/12)

Figure A.2: ET Enterprises 9330B Series PMT (page 2) [28].

A.3 Neutron spectra

Some additional spectra of the deposited energy are shown in Fig. A.3. Only one neutron energy is shown per order of magnitude for comparison, as the intermediate spectra are analogous.

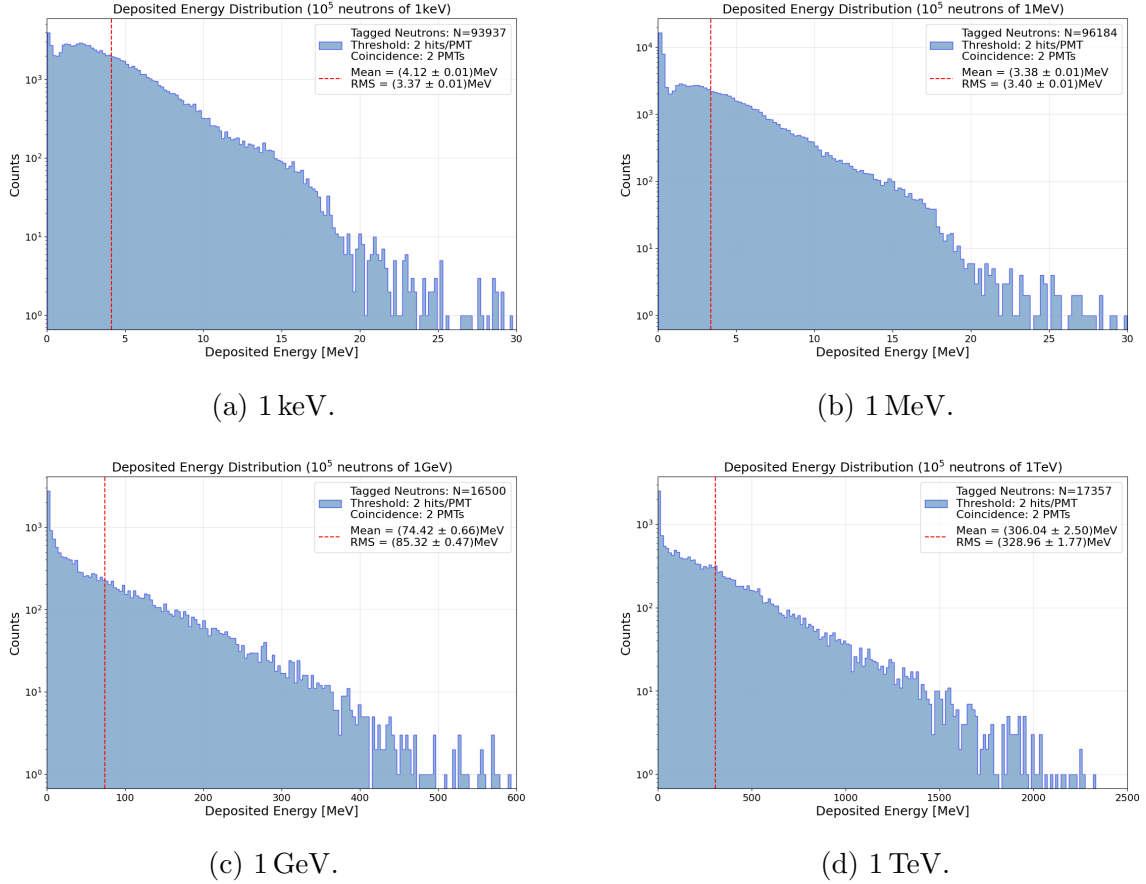


Figure A.3: Deposited energy spectra for 10^5 neutrons at various energies.

Below, in Fig. A.4, are also shown the spectra of the relative contributions from different interaction processes that led to neutron detection. These contributions include neutron capture on gadolinium (blue), capture on hydrogen (green), and other interaction processes (red) such as elastic and inelastic scattering on nuclei. For the energy calibration of the neutron signals described in Sec. 5.2, only the spectra up to 1 MeV were used due to their easily distinguishable and consistent neutron capture peak on H. At higher energies, the neutrons need to thermalize by first depositing a significant part of their energy before they may be captured. This overwhelming energy deposition drowns the capture signal, making the investigation of its peak more complicated.

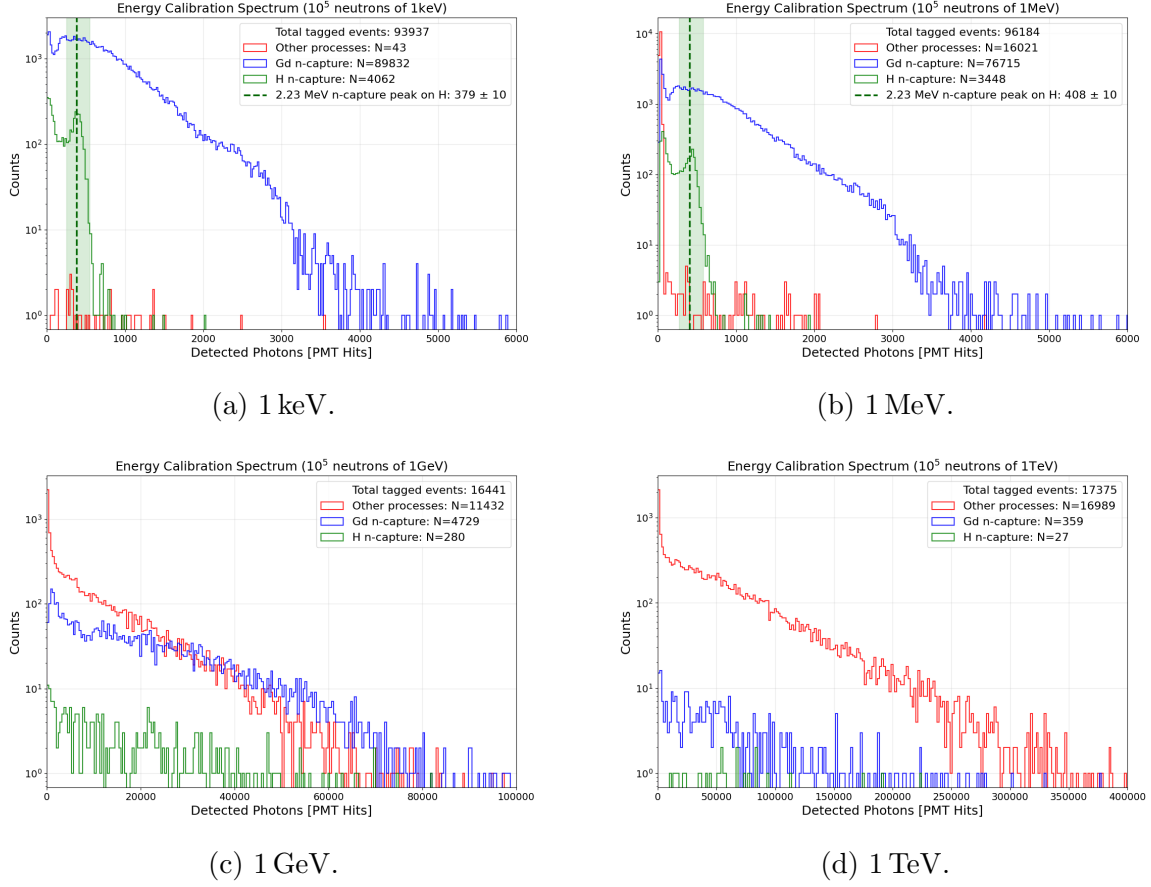
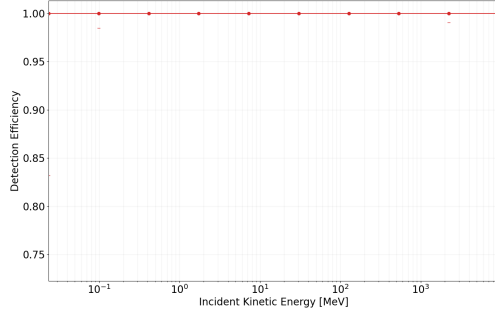


Figure A.4: Spectra of the relative contributions of different interaction processes at various energies. Neutron capture on Gd is shown in blue, capture on H in green, and other processes in red. Only the energy scenarios up to 1 MeV were used for the energy of the neutron signals.

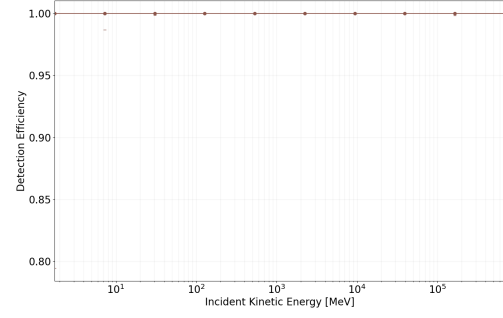
A.4 Detection efficiencies of prototype

The plots of the detection efficiencies of the remaining particle species are shown in Fig. A.5. The efficiency of these particles remains constant at 100% across their entire energy spectrum.

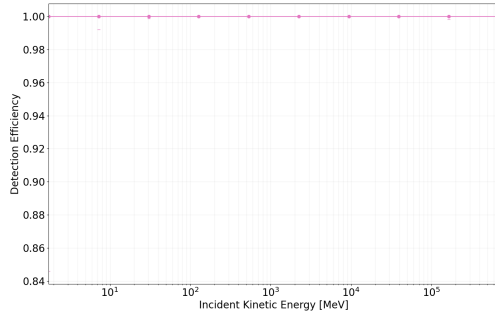
Positrons are very efficiently detected just like electrons, via scintillation and Cherenkov emissions as they fly through the scintillator volume above approximately 100 keV. Below this energy, they may be detected via e^-e^+ annihilation, which further increases their detection efficiency to 100% in this region. In the case of muons and anti-muons, due to their low interaction cross section, they tend to penetrate the entire detector volume with minimal interactions; however, they still may generate strong Cherenkov light signals, which significantly increase their detection probability. Their detectability is further improved by secondary particles and showers generated either when muons pass through the concrete ceiling or the veto aluminum walls. Pions and anti-pions are mostly detected via their decay channels into muons (see Sec. 4.3.2), making their detection very efficient.



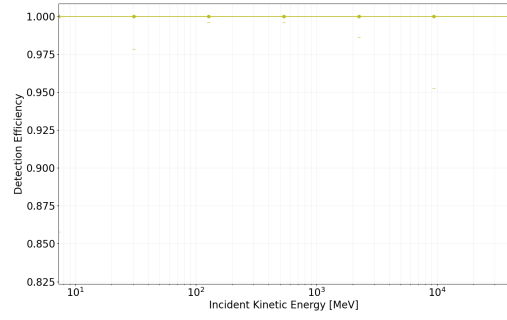
(a) Positrons.



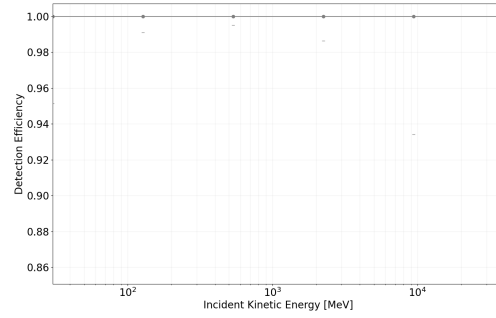
(b) Muons.



(c) Anti-muons.



(d) Pions.

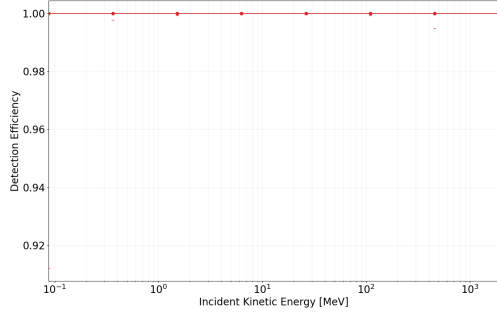


(e) Anti-pions.

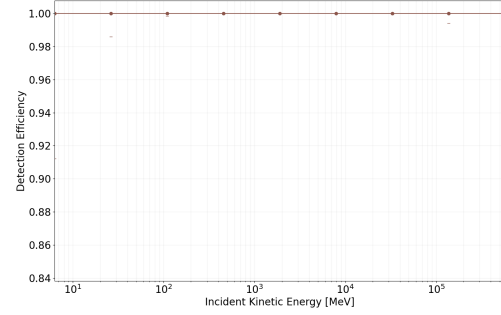
Figure A.5: Detection efficiency of different particle types.

A.5 Detection efficiencies of upscaled detector

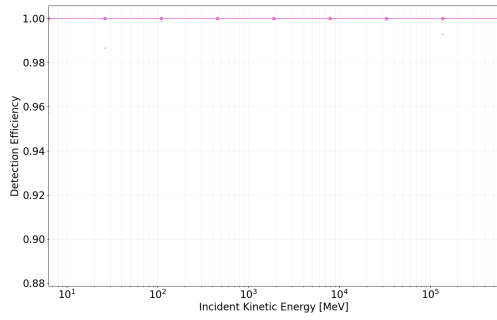
Analogous detection efficiencies are observed in the upscaled veto system across the following particle species shown in Fig. A.6, as in the case of the prototype.



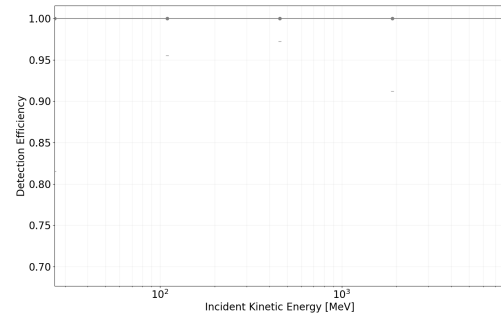
(a) Positrons.



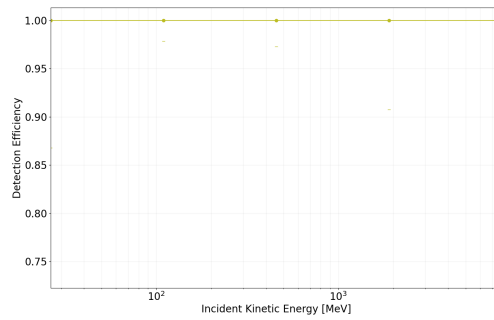
(b) Muons.



(c) Anti-muons.



(d) Pions.



(e) Anti-pions.

Figure A.6: Detection efficiency of different particle types in the upscaled veto system.

Appendix B

Veto system drawings

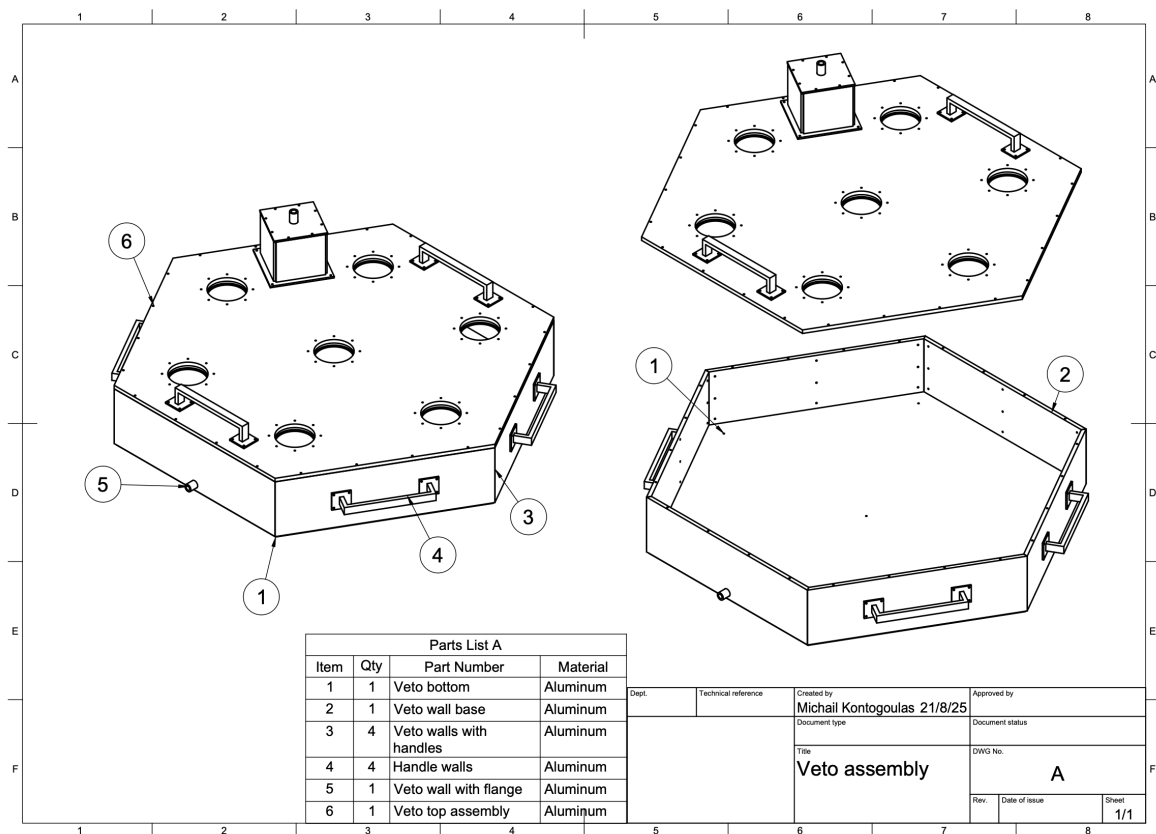


Figure B.1: Drawing of the assembled veto system prototype.

APPENDIX B. VETO SYSTEM DRAWINGS

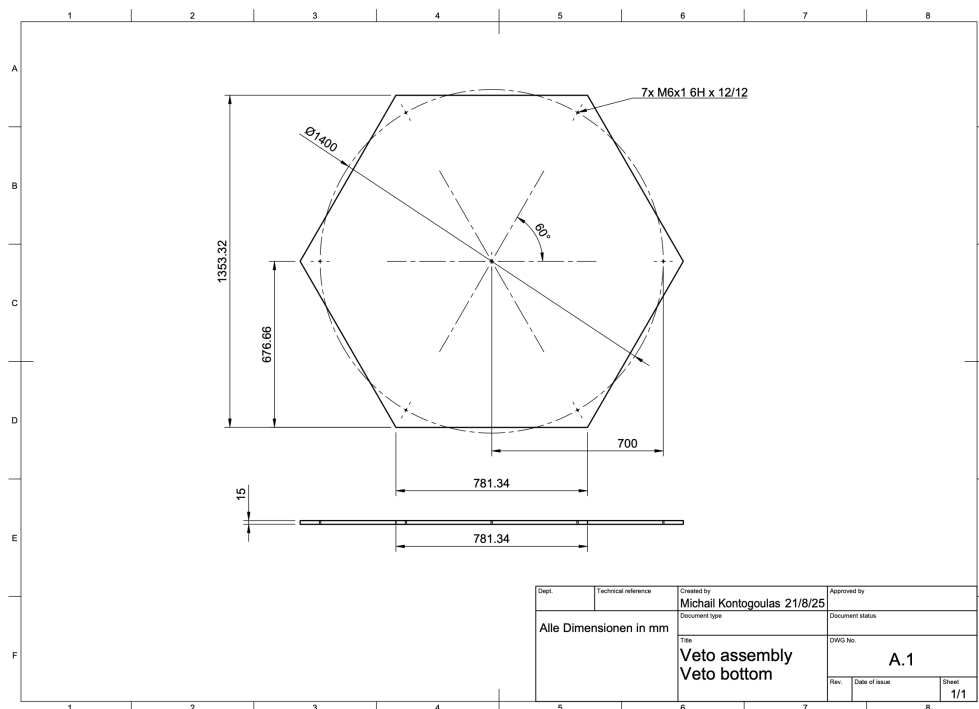


Figure B.2: Drawing of the bottom layer of the veto system vessel.

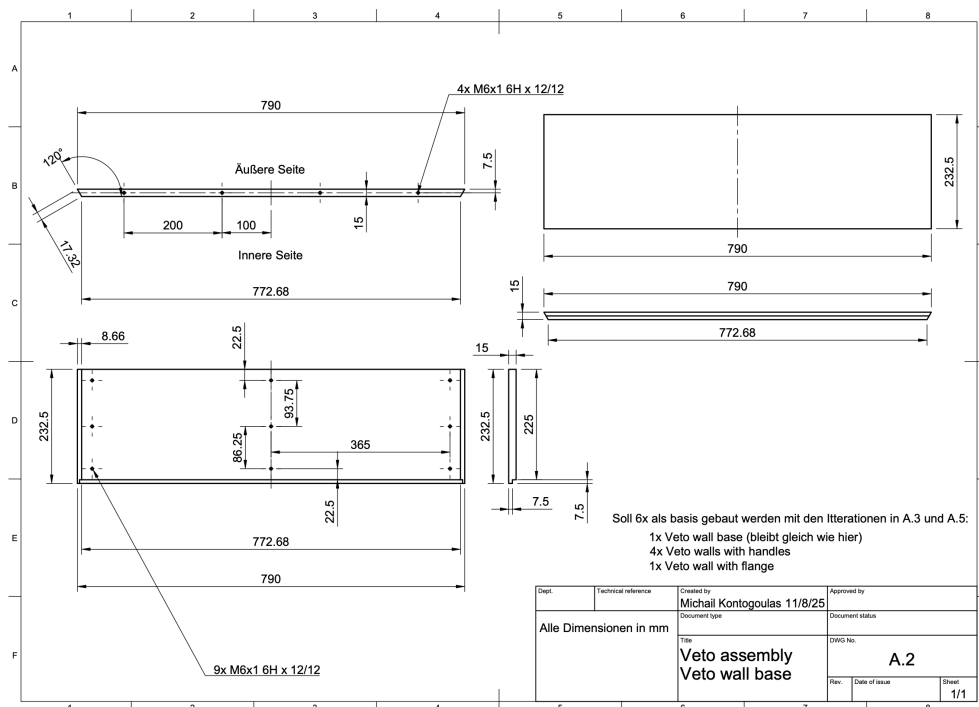


Figure B.3: Drawing of the vessel's walls.

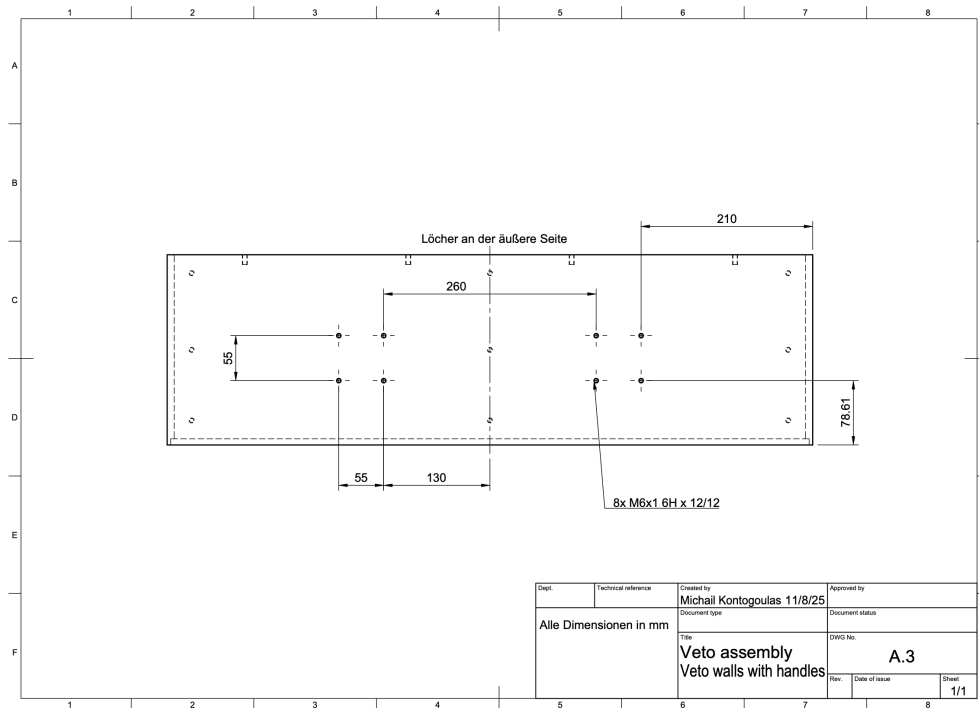


Figure B.4: Drawing of threaded holes on the walls for mounting the handles.

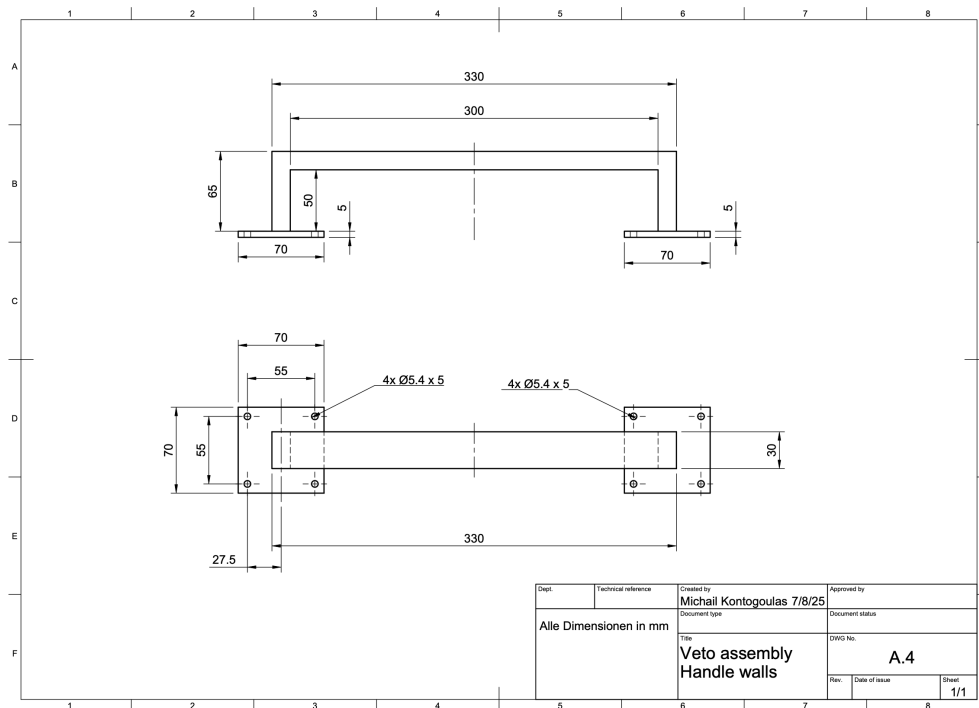


Figure B.5: Drawing of handles for the vessel's walls.

APPENDIX B. VETO SYSTEM DRAWINGS

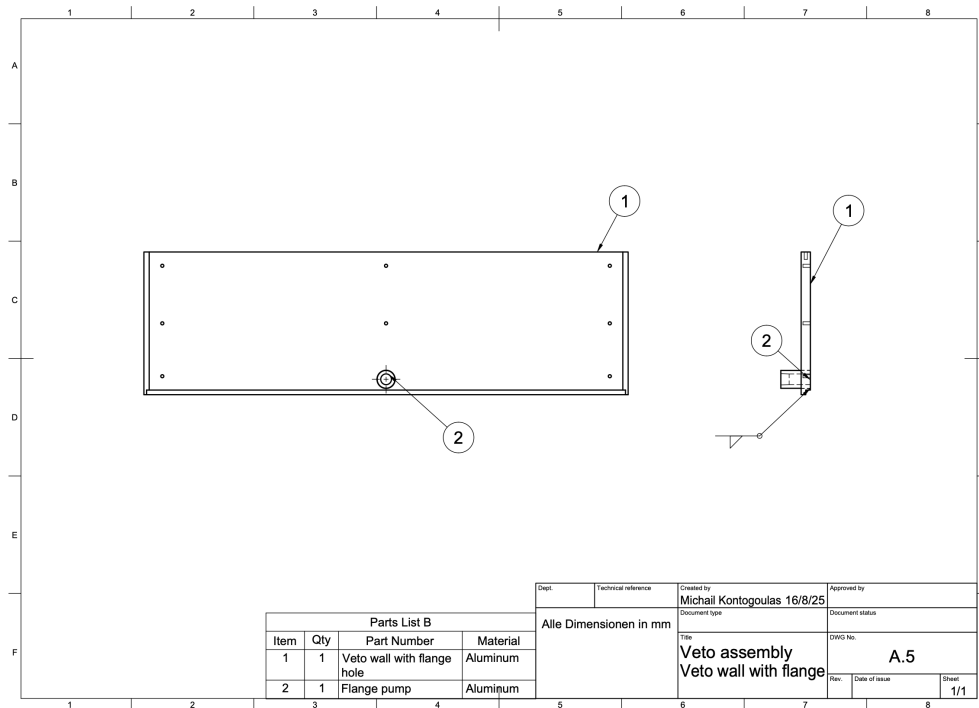


Figure B.6: Drawing of welding of 1/2-inch connector flange to one of the walls.

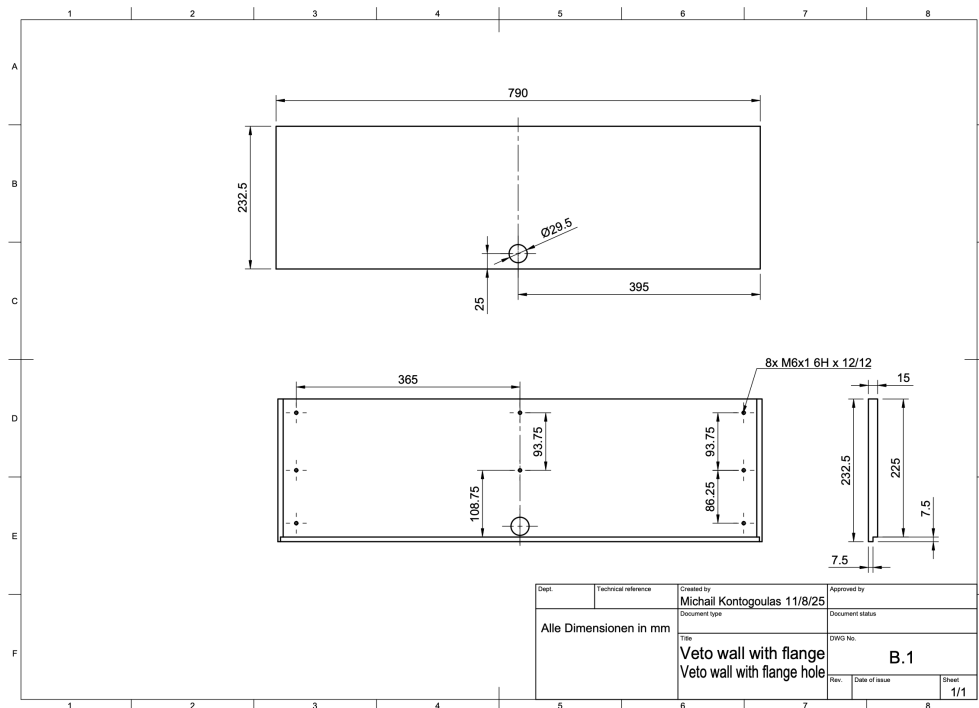


Figure B.7: Drawing of wall with insertion hole for the connector flange.

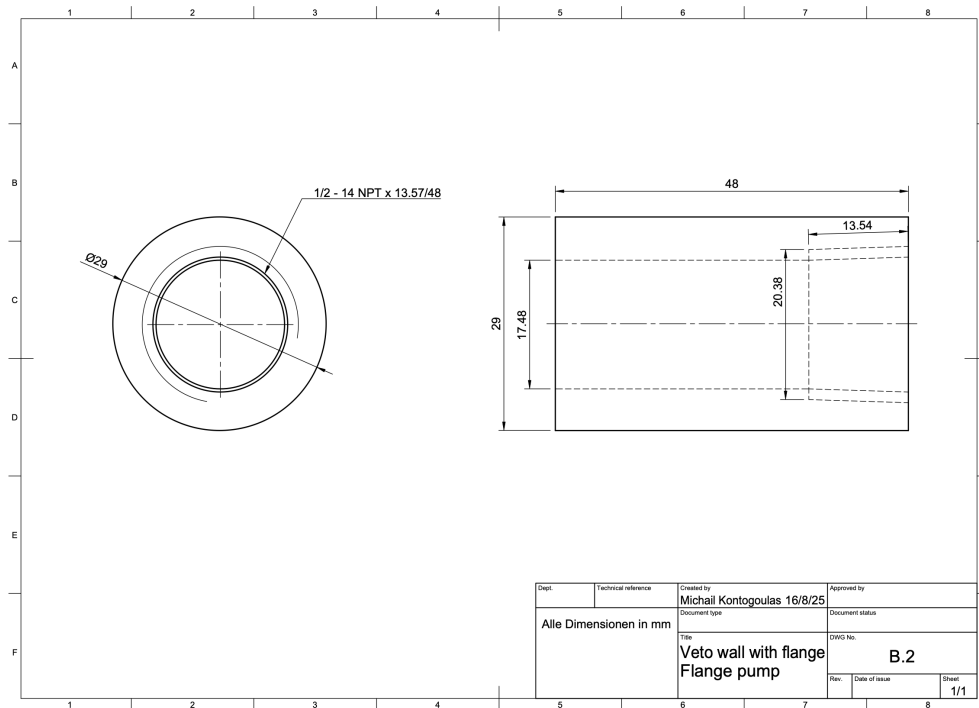


Figure B.8: Drawing of the 1/2-inch connector flange for the pump connection.

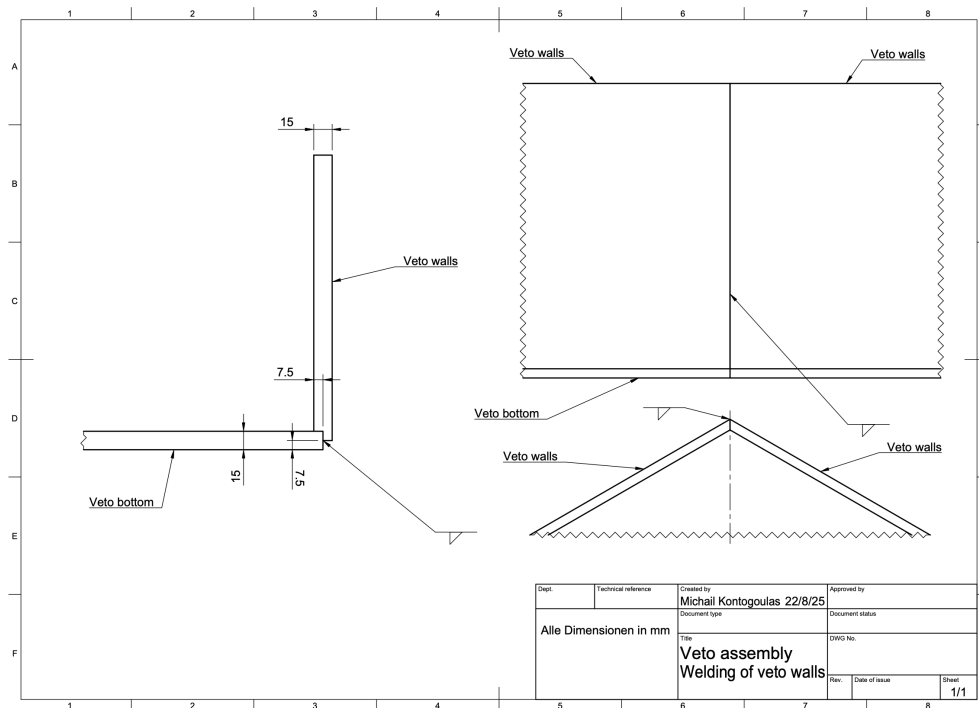


Figure B.9: Drawing of the vessel's welding process.

APPENDIX B. VETO SYSTEM DRAWINGS

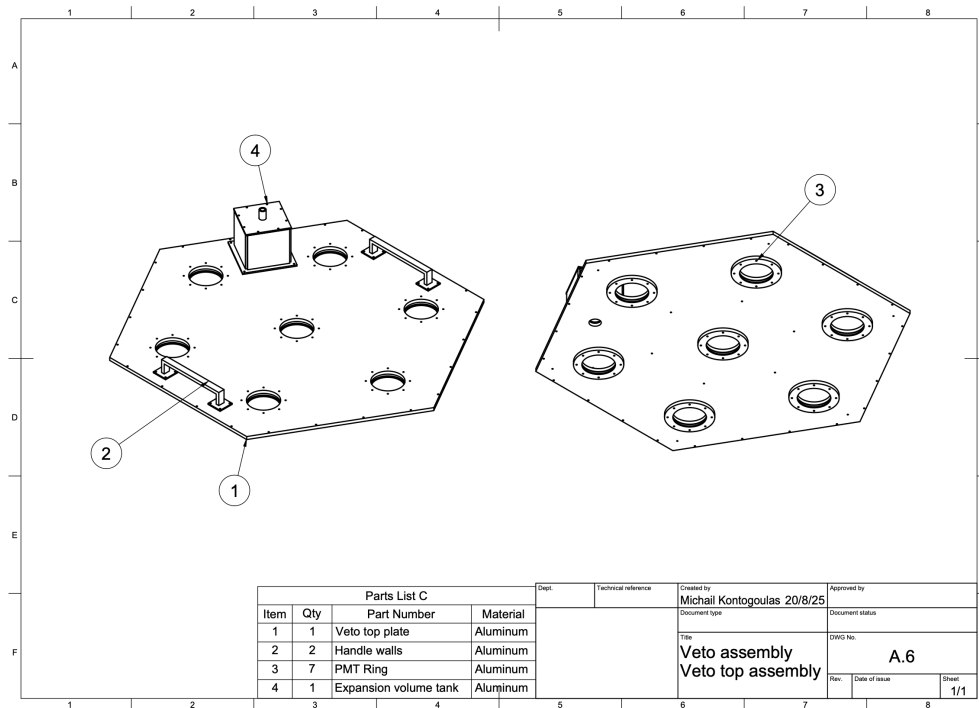


Figure B.10: Drawing of the assembled lid of the vessel.

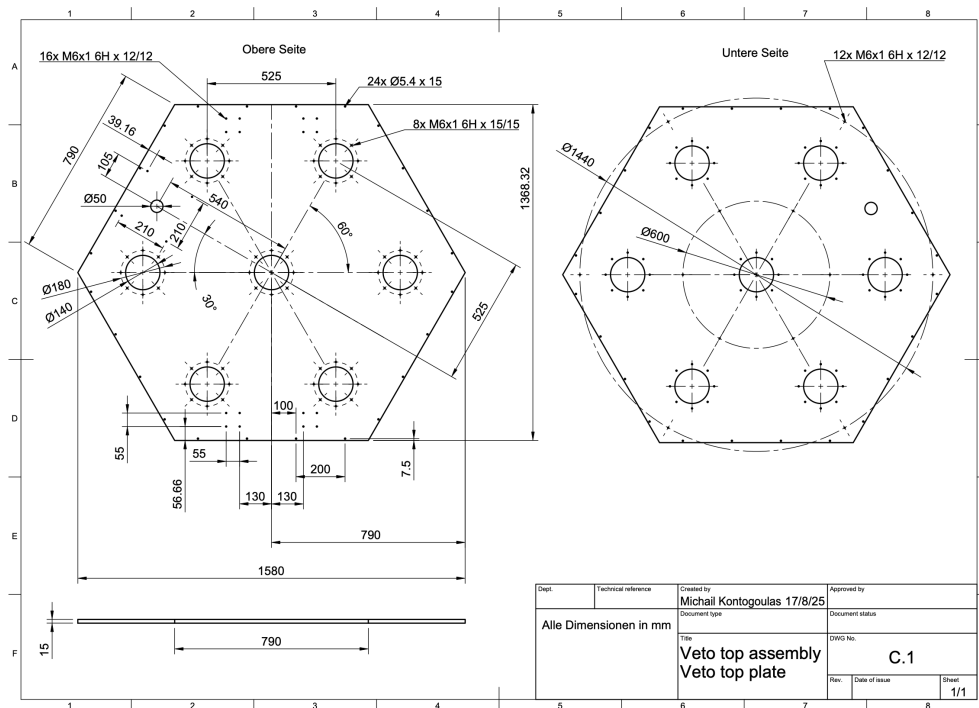


Figure B.11: Drawing of the vessel's lid.

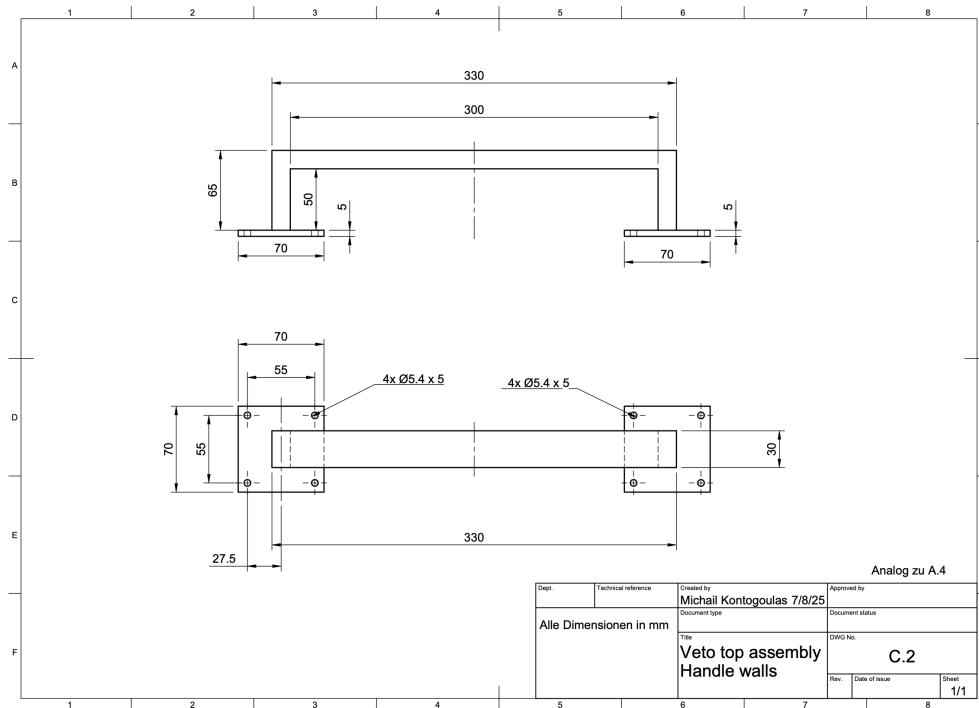


Figure B.12: Drawing of handles for the lid.

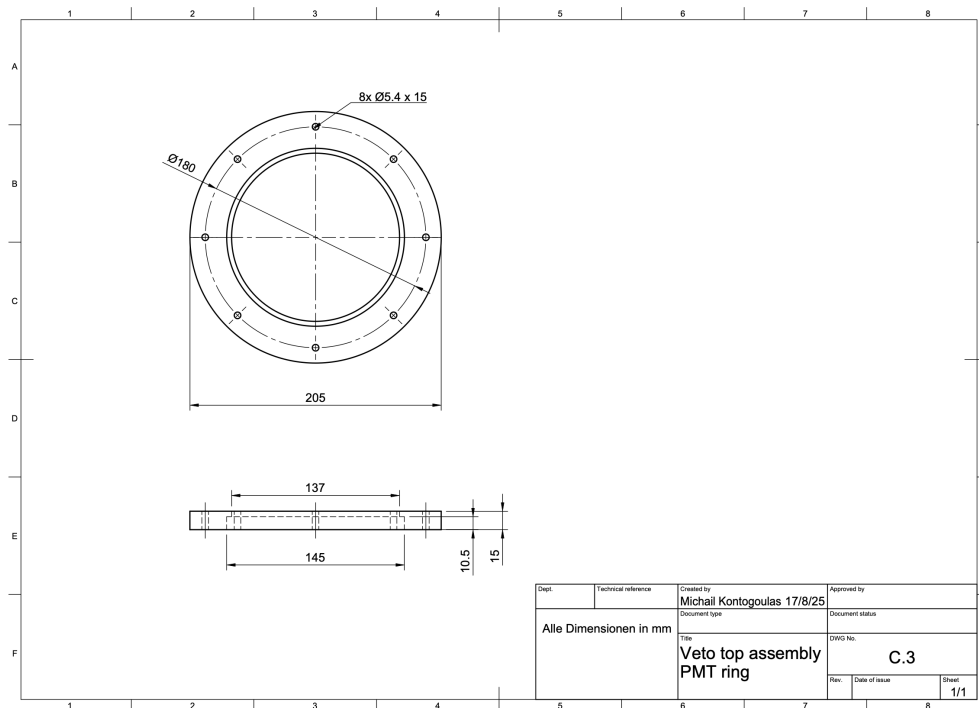


Figure B.13: Drawing of PMT mounting rings.

APPENDIX B. VETO SYSTEM DRAWINGS

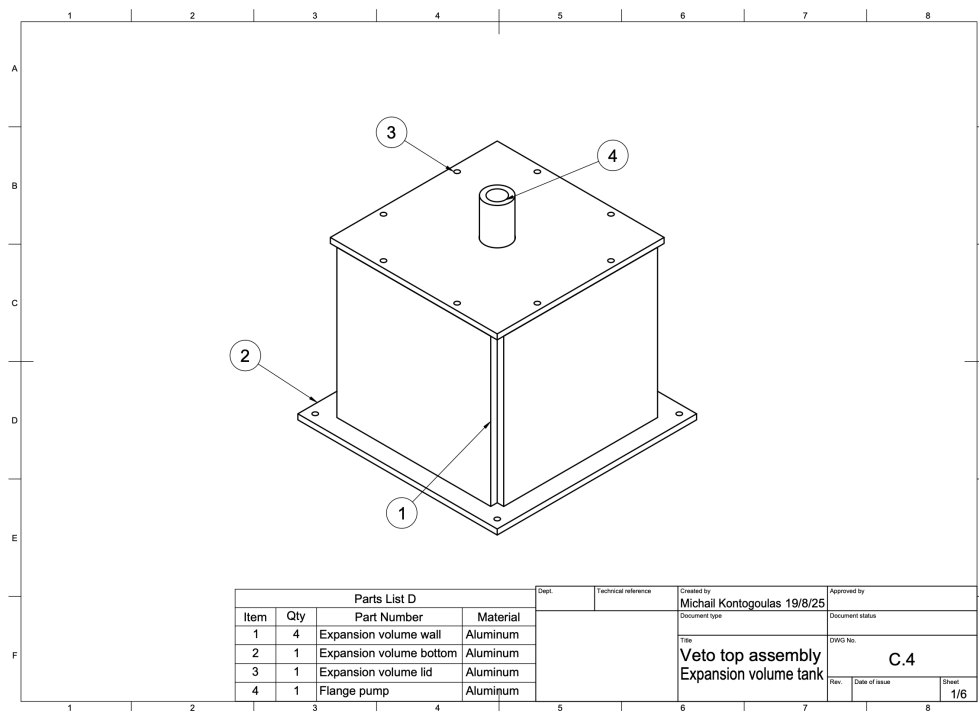


Figure B.14: Drawing of the assembled expansion volume.

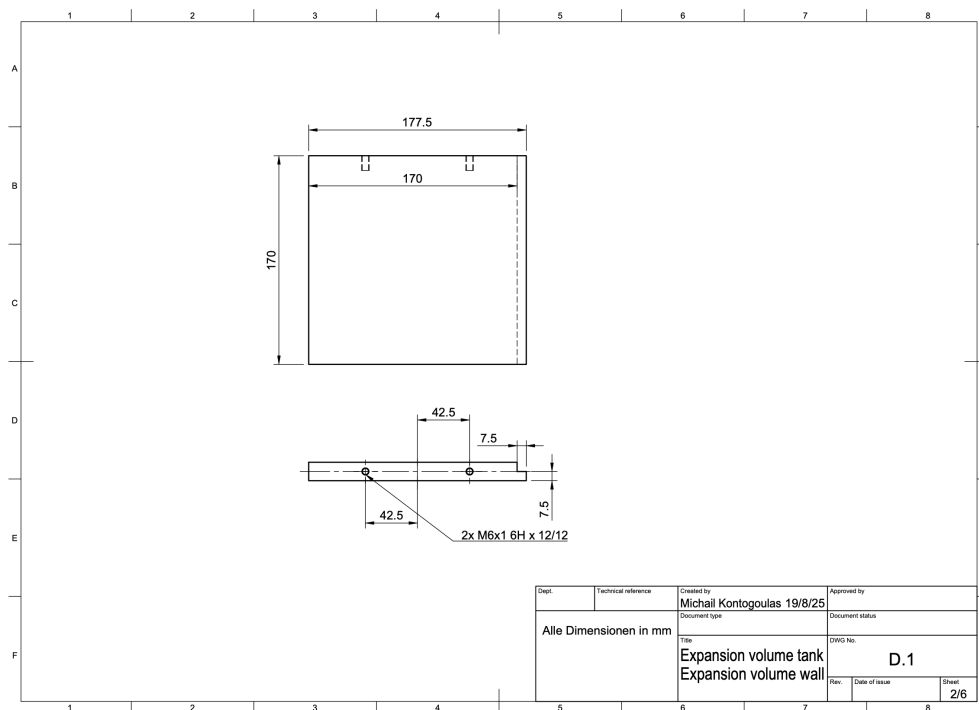


Figure B.15: Drawing of the expansion volume's walls.

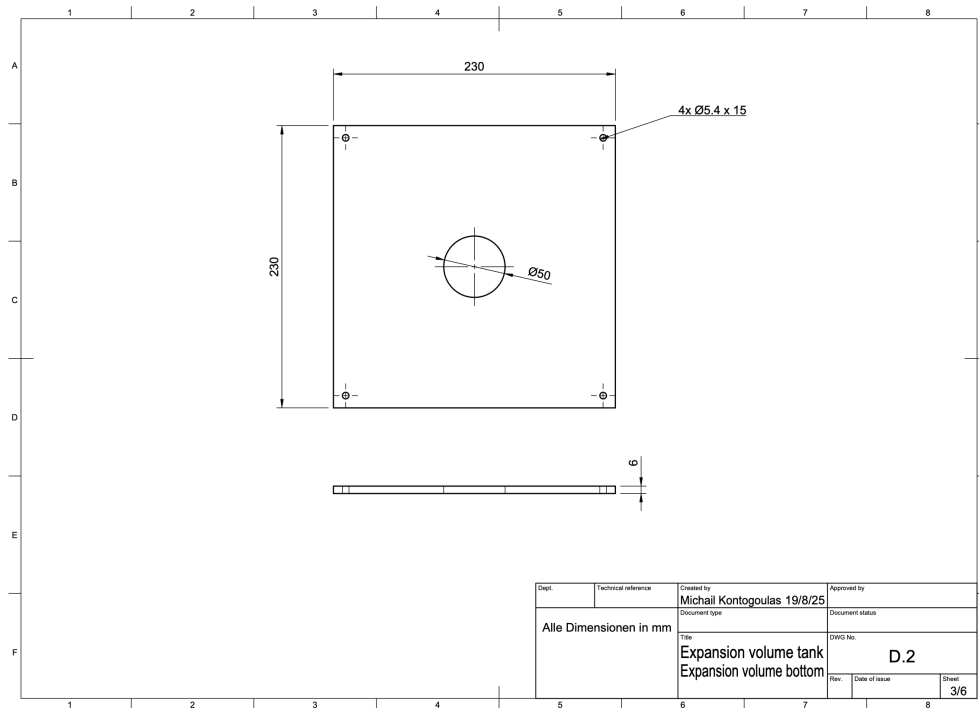


Figure B.16: Drawing of the expansion volume's bottom layer.

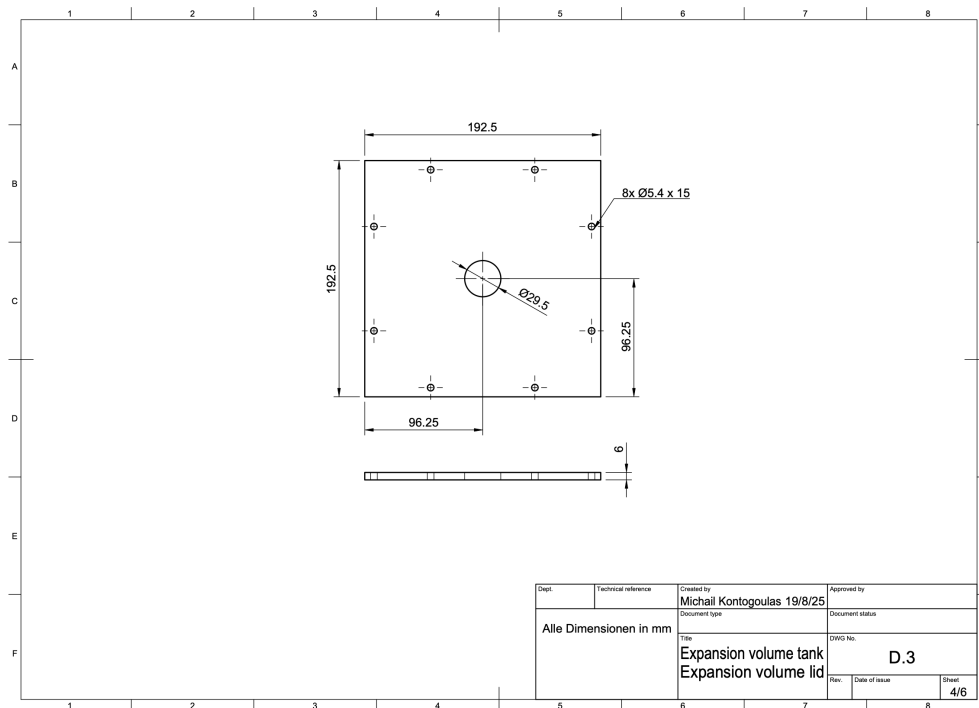


Figure B.17: Drawing of the expansion volume's lid.

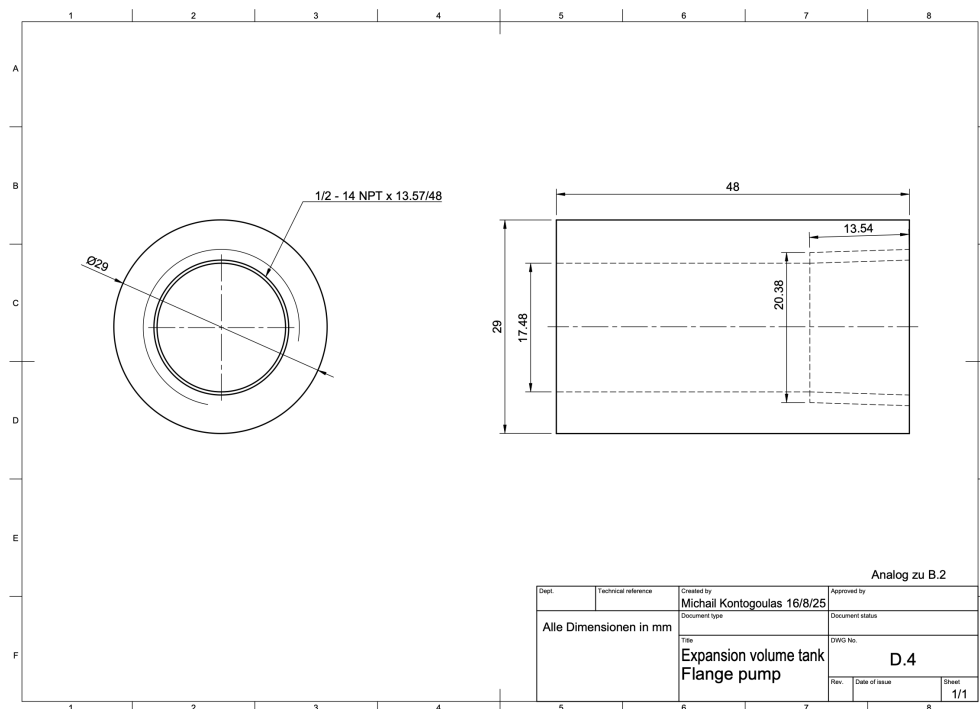


Figure B.18: Drawing of the 1/2-inch connector flange for the gas module connection.

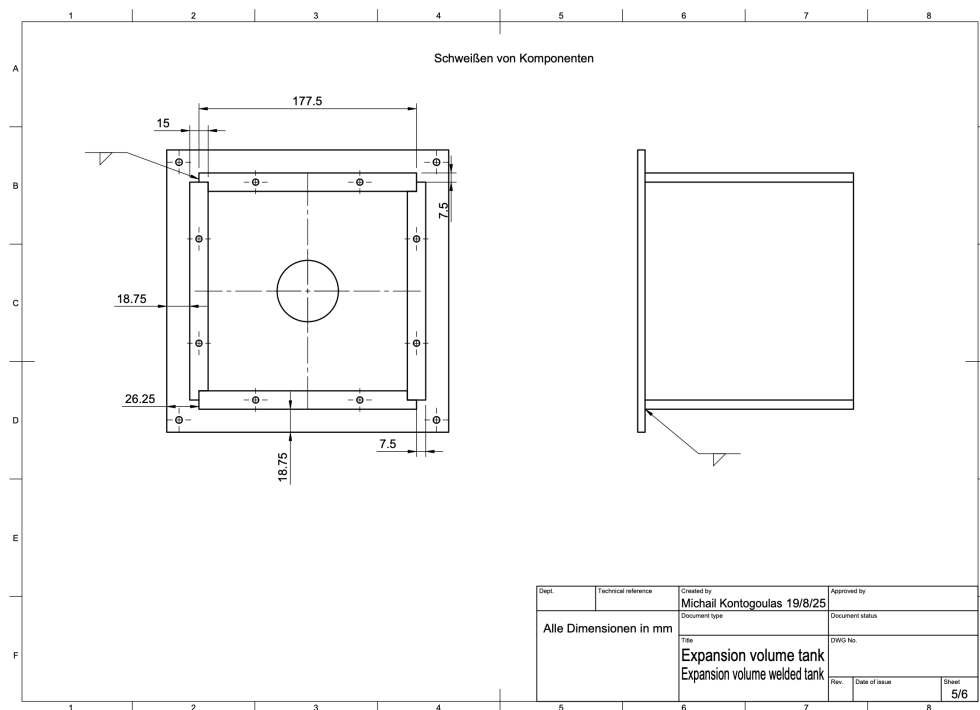


Figure B.19: Drawing of the welding process of the expansion volume vessel.

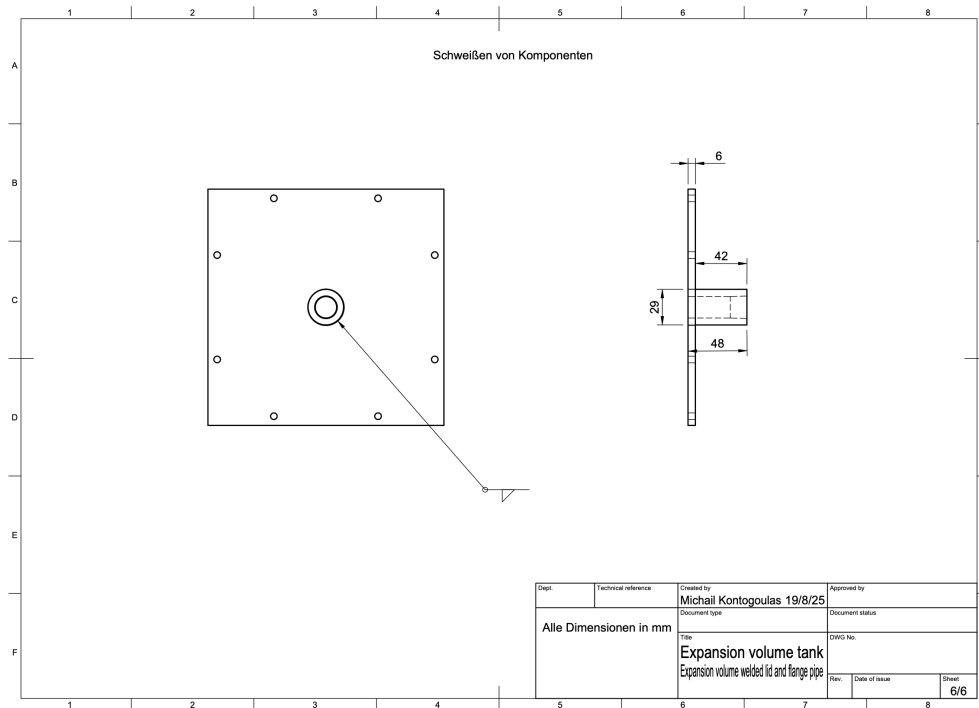


Figure B.20: Drawing of the connector flange welding to the expansion volume lid.

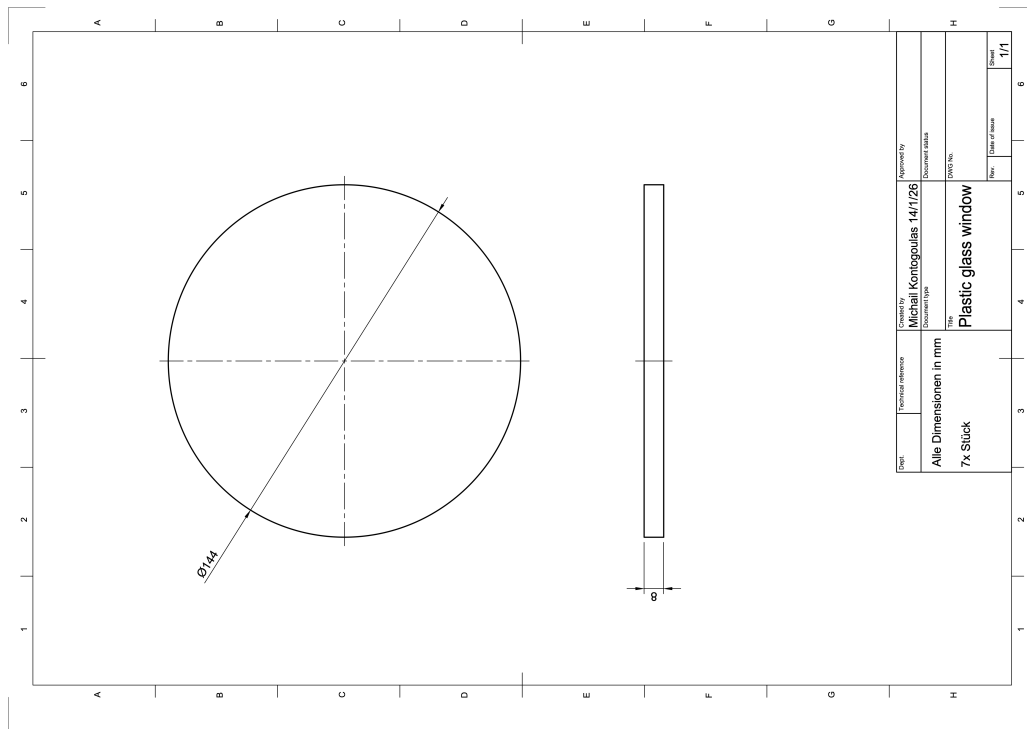


Figure B.21: Drawing of the Plexiglas windows to be mounted on the PMT rings.

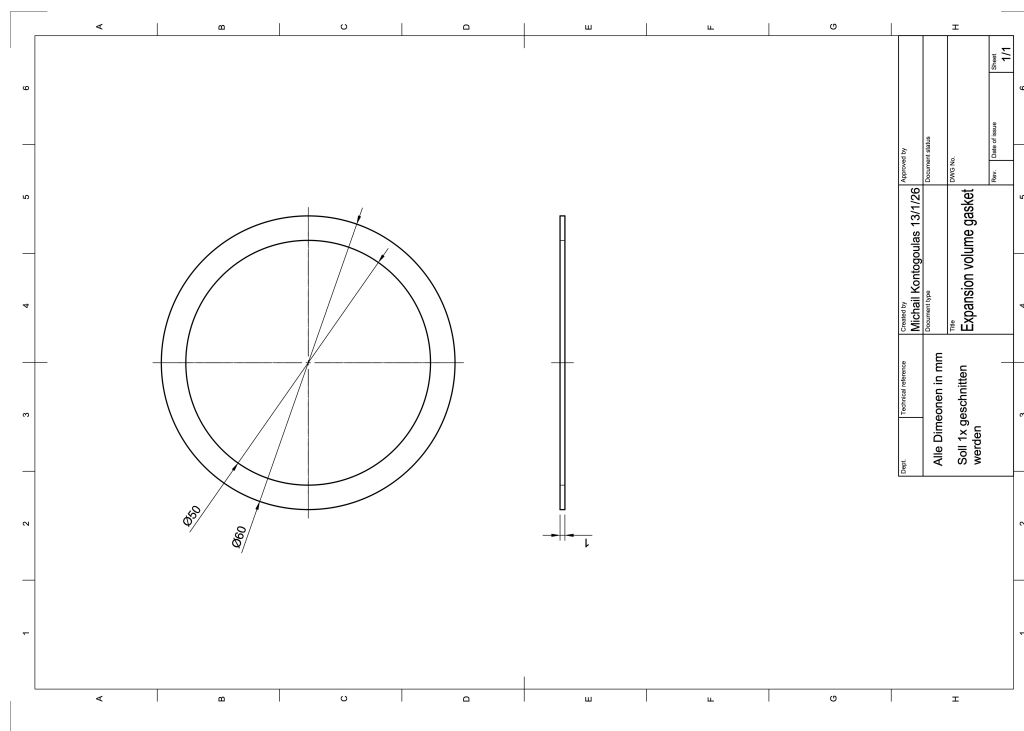


Figure B.22: Drawing of the expansion volume Viton gasket.

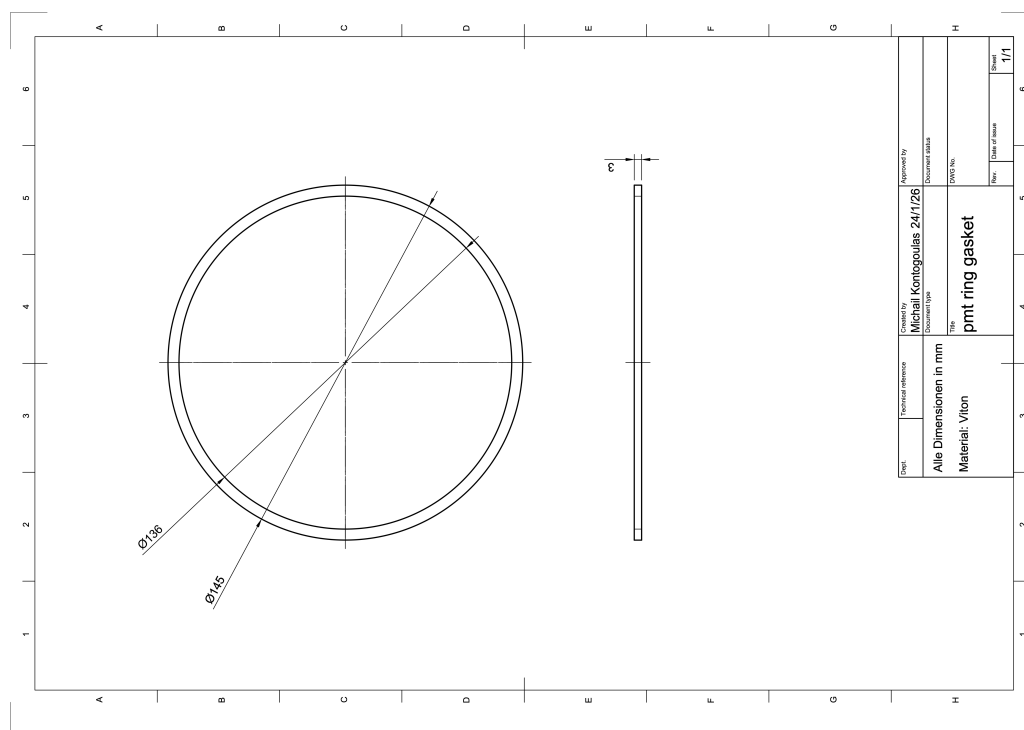


Figure B.23: Drawing of the PMT ring mount Viton gasket.

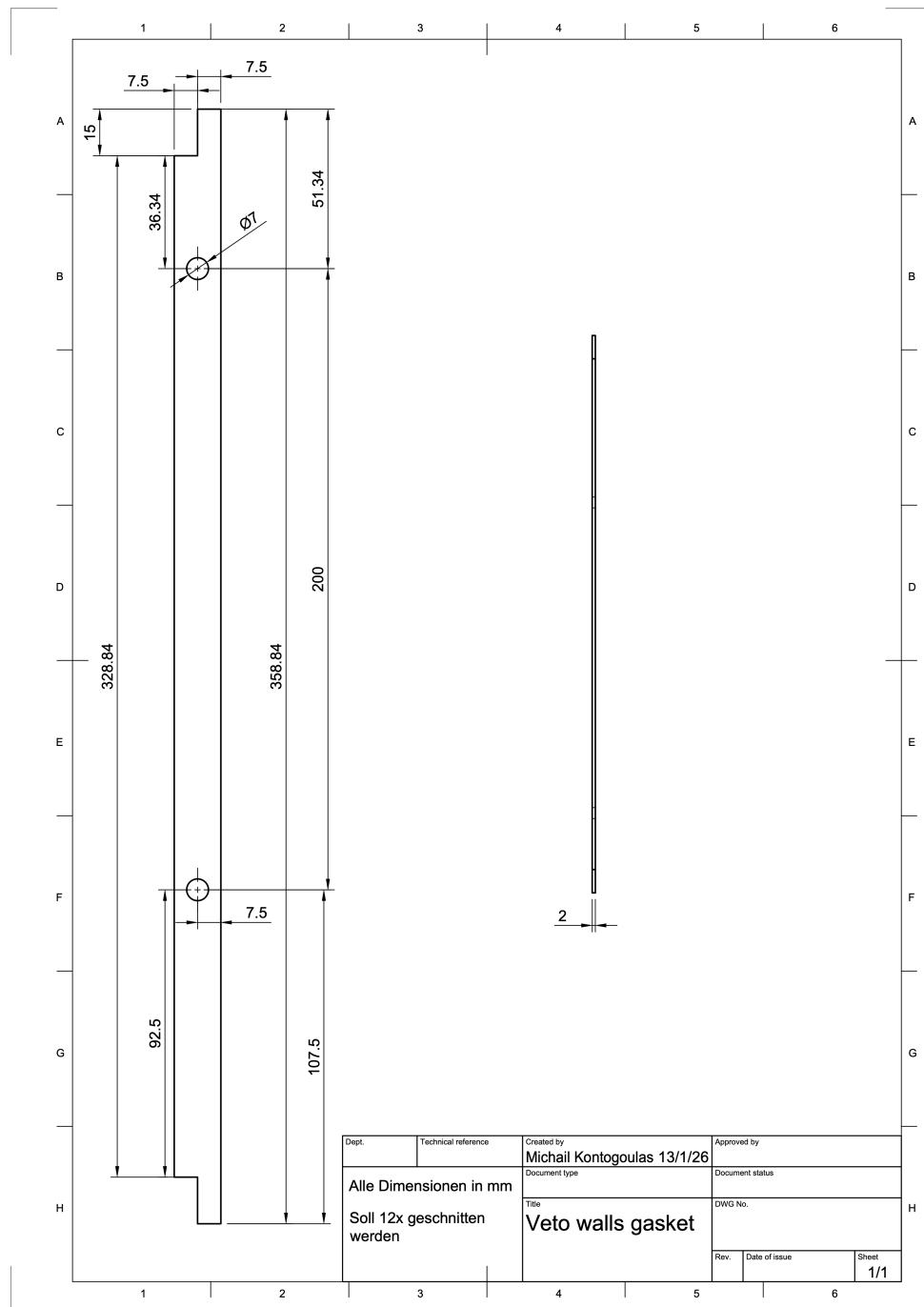


Figure B.26: Drawing of the Viton gasket for the vessel walls.

Appendix C

Use of AI tools

Table C.1: AI tools used during this thesis.

AI tool	Used for	Reason
Gemini by Google	Coding assistance for Python and C++	Primarily used for debugging and quickly propagating code modifications. This was used both for the Geant4 simulations and the analysis code.
ChatGPT by OpenAI	Formulation improvements	To improve the quality and readability of the written text.
Grammarly	Spell checking	To detect and correct typing and grammatical errors while writing.

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