Writing part\_ext Wei Ji

\section{Light Collection}

\label{sec:gtest light collection}

\gtest\ studies event-based primary scintillation light and EL light. Light collection efficiency is important to understand the overall sensitivity of the detector.

\begin{align}

\text{light collection efficiency} = \frac{\text{\#\ photoelectrons seen by PMTs in an event}}{\text{\#\ photon created during an event}}

\end{align}

Light collection efficiency includes geometric collection efficiency and PMT overall quantum efficiency. Geometric collection efficiency describes the efficiency of photon propagation in gas media, photon reflection by the detector material surfaces, and photon propagation in PMT window materials to get to PMT photocathode surfaces. PMT overall quantum efficiency describes the efficiency of how many photons are absorbed by the photocathode surfaces and turn into measurable current or voltage signals.

\paragraph{Geometric collection efficiency} Geometric collection efficiency is studied by photon propagation simulation software Light Guide, as described in Ref.~\cite{Shutt2018}. In the simulation software, a simplified \gtest\ detector geometry boundary with cylindrical symmetry is drawn to represent the real detector material surfaces, which reflect and absorb photons. This simplified geometry includes the photocathode surfaces of PMTs, inner surfaces of the PTFE cones, and surfaces of the grid rings. In addition, grid wire surfaces are represents by two planes of parallel wires with the same diameter and the same pitch distance as in the real detector. The two planes are parallel to each other and close in distance to represent two distinct sets of wires interlacing each other. The empty space inside the simplified detector geometry is filled with a transparent or translucent medium. This software is capable of simulating photon propagation in the transparent or translucent medium using the physics quantity scattering and absorption of the medium.

To understand geometric collection efficiency at one specific location, \numrange{e5}{e7} simulations of single photons are generated from this specific location in a cylindrical coordinate system, (r, z). Each simulated photon is stepped either to transport through detector medium or to interact with the detector surface materials. Each simulation ends when the simulated photon is absorbed by either detector media or detector surface materials. Among all detector surfaces, the counts of photons reaching PMT photocathode surfaces are used to estimate geometric collection efficiency,

\begin{align}

\text{Geometric collection efficiency} = \frac{\text{\#\ photons reaching PMT photocathode surfaces}}{\text{\#\ photons simulated}}

\end{align}

\paragraph{PMT overall quantum efficiency}

The overall quantum efficiency of a PMT includes (1) the PMT photocathode quantum efficiency (QE), (2) the PMT electron collection efficiency, and (3) the PMT electron gain.

The PMT photocathode QE is the probability per incident photon to produce a photoelectron. For 175 nm xenon scintillation light, there is a \SI{\sim 20}{\percent} probability for 2 photoelectrons to be produced rather one, so called the double photoelectron effect. We use the term photons detected (PHD) to refer to the number of photons that produced larger than zero photoelectron. The term PHE refers to the number of photoelectrons produced at the photocathode. The quantum efficiency for the top and bottom PMTs, as quoted by Hamamatsu, are \SI{36.3}{\percent} and \SI{36.0}{\percent}, respectively, for \SI{175}{\nm} light, see Table~\ref{tab:PMTparameterHamamatsu}. The Hamamatsu QE does not account for the double photoelectron effect; that is, it is the average number of photoelectrons produced per incident photon, different from the average number of photons that produce a measurable signal per incident photon.

%PMT response includes (1) PMT quantum efficiency (Q.E.)., (2) PMT electron collection efficiency ,and (3) PMT electron gain.

%PMT Q.E. is the ratio of output photoelectrons to incident photons. It is the efficiency of photoelectric effect including the probability of photoelectric effect creating multiple photoelectrons from a single photon (double photoelectrons effect).

We use counts of photoelectrons detected (PHD) to describe the counts of photons detected without the influence of double photoelectrons effect, and counts PHE to describe the counts of photons detected with the influence of double photoelectrons effect.

Statistical average one PHD is approximately \num{1.2} PHE. PHE is the unit that is used in this analysis.

In this simulation, values of PMT Q.E. at \SI{175}{\nm} are used. They are \SI{36.3}{\percent} for the top PMT and \SI{36.0}{\percent} for the bottom PMT, see Table.~\ref{tab:PMTparameterHamamatsu}.

PMT electron collection efficiency is the probability that these output photoelectrons land on the effective area of the first dynode. This landing makes the electrons go to the next dynode, thus being multiplied by the chains of dynodes. PMT electron collection efficiency depends on the mechanical design of a PMT and the voltage difference between the PMT photocathode and the PMT first dynode. The exact value of electron collection efficiency of the PMTs used in \gtest\ at their operation voltage are not measured. We estimate PMT electron collection efficiency to be \SI{90}{\percent} based on measurement of other PMTs of the same model at a higher PMT operation voltage, as described in Ref.~\cite{Lung2012

%,Akerib2013b

}.

PMT electron gain describes the multiplication process of the output photoelectrons in dynode stages. The voltage that results from this multiplication process is the measured PMT signals. The multiplication process amplifies the useful signal and eases the signal noise selection. The mean value of the PMT signal pulse area of one photoelectron is the mean \sphe\ pulse area in PMT calibration. The coefficient of variation (CV, the ratio of the standard deviation to the mean value) for mean \sphe\ pulse area is \SI{\sim 30}{\percent}, as described in Section.~\ref{sec:pmt cal}.

So, to understand the spatial dependence of light collection efficiency in the ELD, we start with \num{500000} simulations of single photons every \SI{5}{mm} in r and z dimension in the ELD, and record the geometric collection efficiency of each location. This number is then multiplied by PMT overall QE to get the total light collection efficiency. There are two light collection efficiency estimation of two different grid wire configurations that we used for grid emission tests. Run \numrange{4}{9} use configuration 1, and Run \numrange{10}{17} use configuration 2. These two configurations are identical everywhere else in the ELD except for the top grid wire pitches and diameters. Table.~\ref{tab:LC sim parameter geo} and Table.~\ref{tab:LC sim parameter material} summarize the parameters in the simulation.

\begin{table}[!h]

\centering

\begin{tabular}[!h]{ | m{8em} m{20.5em} || m{4.5em} | m{4.5em}|}

\hline

&parameter & Config~1 & Config~2 \\

& & Run 4-9 & Run 10-17 \\\hline\hline

top grid & wire pitch [\si{\mm}] & 2.5 & 5\\

& wire diameter [\si{\um}] & 100 & 150 \\\hline

bottom grid & wire pitch [\si{\mm}] & 2.5 & same \\

& wire diameter [\si{\um}] & 75 & same \\\hline

top/bottom cone %& height total [\si{\mm}] & 110 & same \\

& cylinder 1 height [\si{\mm}] & 1.17 & same \\

(PTFE reflector) & cylinder 1 radius (frustum larger radius) [\si{\mm}] & 65 & same \\

& frustum height [\si{\mm}] & 98.8 & same \\

& cylinder 2 radius (frustum smaller radius) [\si{\mm}] & 32 & same \\

& cylinder 2 height [\si{\mm}] & 10 & same \\\hline

top/bottom PMT & photocathode radius [\si{\mm}] & 32 & same \\

\hline

\end{tabular}

\caption[Light collection simulation geometry parameters.]{Light collection simulation geometry parameters}

\label{tab:LC sim parameter geo}

\end{table}

\begin{table}[!h]

\centering

\begin{tabular}[!h]{ | m{12em} m{16em} || m{10em}|}

\hline

&parameter & value \\\hline\hline

Xe (gas)

& refraction index & 1.544 \\

& Rayleigh scatter length [m] & 500 \\

& absorption length [m] & 500 \\

\hline

Quartz (synthetic quartz)

& refraction index & 1.000702 \\

\hline

PTFE

& reflectivity & 0.4 (0-1.0) (Ref.~\ref{Feuerbacher1972}) \\

& specular reflection ratio & 0\\

& Lambret diffusion reflection ratio & 1\\

\hline

SS (SS304) & reflectivity & 0.18 (Ref.~\ref{Feuerbacher1972}) \\

& specular reflection ratio & 1\\

& Lambret diffusion reflection ratio & 0\\

\hline

\end{tabular}

\caption[Light collection simulation material parameters.]{Light collection simulation material parameters}

\label{tab:LC sim parameter material}

\end{table}

As expected, the geometric collection efficiency varies at different locations in the ELD, which causes the light collection efficiency to vary, accordingly. %(Wei used to have)Geometric collection efficiency varies at different spacial locations in the detector and cause light collection efficiency also varies.

The difference between top PMT collection efficiency and bottom PMT light collection efficiency also varies across the ELD. This difference helps discriminate the location where events happened. We use top bottom asymmetry (TBA) to describe this difference.

\begin{align}

\text{TBA} = \frac{\text{Top PMT light collection}-\text{Bottom PMT light collection}}{\text{Top PMT light collection}+\text{Bottom PMT light collection}}

\end{align}

%Fig.~\ref{fig: light collection cross section 040} shows results of the simulations.

Results in Fig.~\ref{fig: light collection cross section 040} show the light collection efficiency and the TBA in the ELD. Locations that are in the top cone region get a larger than zero TBA, and locations that are in the bottom cone get a smaller than zero TBA. TBA is close to zero in the EL region.

Among all different classes of events, our primary pulse of interest is \eep , which happens in the EL region. We estimate the light collection in this region with the same method mentioned before and finer binning. We start with \num{500000} simulations of single photons every \SI{2}{\mm} in r dimension in the middle of the EL region. Results of the simulations are shown in Fig.~\ref{fig: light collection r 040}. Light collection efficiency in the EL region falls away at r > \SI{65}{\mm}, which is the inner radius of the PTFE reflector cones. %The TBA also changes at r > \SI{65}{\mm}.

The average top and bottom PMT light collection efficiency in the EL region are \num{\sim 0.0085}. The average TBA in the EL region is \num{\sim 0}. The average total PMT light collection efficiency in the EL region is \num{\sim 0.017}. This light collection efficiency allow sus to detect \eee s.

The change of PTFE reflectivity has a big influence on the total light collection. The reported measured values of PTFE reflectivity of xenon scintillation photons in room temperature are in the range of \numrange{0.4}{0.75}. This difference in reflectivity may be a result of different synthetic processes or different material density, as discussed in Ref.~\cite{Silva2009}. The influence on the total PMT light collection is shown in Fig.~\ref{fig: light collection vs PTFE ref}. Higher PTFE reflectivity results in a higher total light collection efficiency. The actual value of reflectivity of the PTFE reflector cones has not been measured directly. We estimate the actual PTFE reflectivity of xenon scintillation photons to be \num{0.4}, according to the material density .

\begin{figure}[!p]

\centering

\begin{subfigure}[b]{\halfwidth}

\centering

\includegraphics[width=\textwidth,clip,trim={0 0 0 0}]{Figures/GasTest/LGresult/PDEvsCrossSectionTotPTFE040.jpg}

\caption{}

\label{fig:}

\end{subfigure}

\begin{subfigure}[b]{\halfwidth}

\centering

\includegraphics[width=\textwidth,clip,trim={0 0 0 0}]{Figures/GasTest/LGresult/PDEvsCrossSectionTBAPTFE040.jpg}

\caption{}

\label{fig:}

\end{subfigure}

\begin{subfigure}[b]{\halfwidth}

\centering

\includegraphics[width=\textwidth,clip,trim={0 0 0 0}]{Figures/GasTest/LGresult/PDEvsCrossSectionzTotPTFE040.jpg}

\caption{}

\label{fig:}

\end{subfigure}

\begin{subfigure}[b]{\halfwidth}

\centering

\includegraphics[width=\textwidth,clip,trim={0 0 0 0}]{Figures/GasTest/LGresult/PDEvsCrossSectionzTBAPTFE040.jpg}

\caption{}

\label{fig:}

\end{subfigure}

% \caption[]{(a) (b) (c)}

\caption[Light collection efficiency of rz cross section in the ELD.]{Light collection efficiency of rz cross section in the EL region. (a) total light collection efficiency (b) TBA. (c) total light collection efficiency at r=0. (d) TBA at r=0. The red solid curve is the edge of the ELD. The blue solid curve is the edges of the EL region. This result uses configuration 1, PTFE reflectivity \num{0.40}. z=0 is at the bottom PMT photocathode surface.}

\label{fig: light collection cross section 040} % code is in `"/media/wei/ACA8-1ECD3/CleanAmendedLightGuide/CleanAmendedLightGuide/LightGuide/UserRoutines/Plotting/Phase1/PlotRealLight20180110GasTestGeo.m

\end{figure}

\begin{figure}[!p]

\centering

\begin{subfigure}[b]{\halfwidth}

\centering

\includegraphics[width=\textwidth,clip,trim={0 0 0 200}]{Figures/GasTest/LGresult/PDEvsRadiusPTFE040MiddleTopBottomconfig1.jpg}

\caption{}

\label{fig:}

\end{subfigure}

\begin{subfigure}[b]{\halfwidth}

\centering

\includegraphics[width=\textwidth,clip,trim={0 0 0 180}]{Figures/GasTest/LGresult/PDEvsRadiusPTFE040MiddleTopBottomTBAconfig1.jpg}

\caption{}

\label{fig:}

\end{subfigure}

\begin{subfigure}[b]{\halfwidth}

\centering

\includegraphics[width=\textwidth,clip,trim={0 0 0 200}]{Figures/GasTest/LGresult/PDEvsRadiusPTFE040MiddleTopBottomconfig2.jpg}

\caption{}

\label{fig:}

\end{subfigure}

\begin{subfigure}[b]{\halfwidth}

\centering

\includegraphics[width=\textwidth,clip,trim={0 0 0 180}]{Figures/GasTest/LGresult/PDEvsRadiusPTFE040MiddleTopBottomTBAconfig2.jpg}

\caption{}

\label{fig:}

\end{subfigure}

% \caption[]{(a) (b) (c)}

\caption[Light collection efficiency in the EL region with different configurations.]{Light collection efficiency in the EL region with different configuration. (a) total light collection efficiency in configuration 1. (b) total light collection efficiency in configuration 2. (c) TBA in configuration 1. (d) TBA in configuration 2. The blue solid curve is \SI{0.13}{\mm} below the top grid. The yellow solid curve is \SI{0.13}{\mm} above the bottom grid. The red solid curve is in the middle between the top and bottom grids. This result uses PTFE reflectivity \num{0.40}.}

\label{fig: light collection r 040} % code in "/media/wei/ACA8-1ECD3/CleanAmendedLightGuide/CleanAmendedLightGuide/LightGuide/UserRoutines/Plotting/Phase1/CPlotRealLight20180110GasTestGeo.m

\end{figure}

% \begin{figure}[!ht]

% \centering

% \includegraphics[width=0.6\textwidth,clip,trim={0 0 0 170}]

% {Figures/Ch10/PDEvsRadiusPTFE075.jpg}

% \includegraphics[width=0.6\textwidth]

% {Figures/Ch10/PDEvsRadiusPTFE075MiddleCircle.jpg}

% \caption{Light collection efficiency(PDE) inside the detector region between anode grid and gate grid(simulated with PTFE reflectivity of $0.75$). Top: light collection efficiency vs radius from the center of the grid ring at different location. Blue: 2 mm above the gate grid. Red: in the middle between the anode grid and the gate grid. Yellow: 2 mm below the anode grid. Bottom: light collection efficiency in the middle between the anode grid and the gate grid. Red solid curve is the region of the grid wires. }

% \label{fig: light collection r 075}

% \end{figure}

\begin{figure}[!p]

\centering

\includegraphics[width=\figurewidth]

{Figures/Gastest/LGresult/PTFESweep.jpg}

\caption[Light collection efficiency in the EL region with different PTFE reflectivity/]{Light collection efficiency in the EL region with different PTFE reflectivity. This result uses configuration 1. }

\label{fig: light collection vs PTFE ref} % code in ""/media/wei/ACA8-1ECD3/CleanAmendedLightGuide/CleanAmendedLightGuide/LightGuide/UserRoutines/Plotting/Phase1/PTFEsweep.m

\end{figure}

\section{Light production}

The ELD measures primary scintillation photons and electroluminescence photons. So, first I will introduce these two light production processes. Then, I will discuss about the light production in noble gas, e.g. xenon, which is the medium that the ELD normally operates in.

\paragraph{Primary scintillation} Primary scintillation is the process in which photons are created directly by energy deposition of external particle events. These photons have two sources: direct excitation, and excitation from recombination after ionization. An external particle travels through the media in the ELD, transferring its energy to atoms in the medium, e.g. xenon, through exciting and ionizing these atoms. The excited atoms will return to their ground states by emitting photons of series energies corresponding to the energy level of the atoms, which is called relaxation of the excited atom. These photons from direct excitation from external particles are the first source of primary scintillation photons. The ionized atoms are not able to produce photons by themselves. However, they can recombine with the electrons around them and form excited atoms, which deexcite in a similar process as direct excited atoms, and emit photons simultaneously. These photons are the second source of primary scintillation photons. The quantity of second source of primary scintillation photons is dependent on the recombination process, which depends on properties of the atoms, and is influenced by the detector environment, especially the electric field (or reduced electric field) on the recombination site. A strong electric field forces electrons to quickly drift away from the ionization site and reduce the probability of recombination, thus reduce the quantity of primary scintillation light production.

\paragraph{Electroluminescence} Electroluminescence (EL) is a phenomenon in which when an electron drifts through a strong electric field in a medium, it collides with atoms in the medium, excites them which will afterwards emit scintillation light. Since, EL process is related to electrons in the media, we measure EL photons to study the electron production in the detector. The mechanism of EL is similar to primary scintillation; the electron gains energy from drifting through the strong electric field and simultaneously loses energy though exciting and ionizing medium atoms. Moreover, the ionization process are usually associated with electron multiplication (gas gain), which creates more electrons in the strong electric field region, and produces more EL scintillation light. The quantity of EL scintillation photons and the probability of electron multiplication, are related to the strength of reduced electric field of the medium. With proper strength of reduced electric field, EL can produce more photons than primary scintillation. Because of its association with electrons and its production quantity, EL photons are the most important signals measured in the ELD.

The primary scintillation photons are called \sone , and the EL scintillation photons are called \stwo , because the primary scintillation photons are produced earlier than the other photons created by electroluminescence process of uncombined electrons. The same concepts of primary scintillation, as well as \sone, \stwo , are also used in liquid noble detectors, as described in Chapter.~\ref{chap:lz}.

\paragraph{Noble gas scintillation}

For most noble gas atoms (\ce{A}), e.g. neon, argon, krypton, and xenon, the scintillation process usually forms an intermediate excited excimer state (\ce{A\_2^\*}). The emitted photons from the intermediate excimer state are almost monoenergetic, \SI{7.1}{\electronvolt} (\SI{\sim 175}{\nm}), and transparent to the media. Because of the existence of the intermediated excited excimer states, it creates appreciable quantity of monoenergetic photons from the excitation of these states. These features allow us to efficiently collect these monoenergetic photons with designed devices, e.g. PMTs, and use these photons to study reactions between external particles and media atoms.

The chemical processes of scintillation are:

\begin{align}

\text{scintillation process: } & \ce{A + A^\* -> A\_2^\*} \\

& \ce{A\_2^\* ->A + A + \gamma }.

\end{align}

where A is the noble gas atom; \ce{A^\*} is the noble gas excited state; \ce{A\_2^\*} is the excimer state.

The chemical processes of recombination are:

\begin{align}

\text{recombination process: } & \ce{A + A^{+} -> A\_2^{+} } \\

& \ce{e^{-} + A\_2^{+} ->A\_2^\* + \gamma\prime} \\

\text{or: } & \ce{e^{-} + A^{+} -> A^{\*} + \gamma\prime}

\end{align}

where \ce{A^+} is the noble gas ionized state; \ce{A\_2^+} is the ionized dimer state.

where $\gamma$ is the monoenergetic photons from deexcitation of the excimers, and $\gamma\prime$ is photons of other energy.

Both scintillation and recombination processes end up with deexcitation of excimers. The recombination process turn ions into excited atoms and excimers, which will deexcite similar as the scintillation process. The quantity of the monoenergetic photons is related to the reaction energy between external particles and media atoms, and properties and physical environment of the media (especially media density and electric field).

These two primary scintillation processes happen fast in xenon, the duration of which is dominated by the excimers decay time. The excimers can be separated to two types, the singlet state (\ce{^1\sigma\_u^+}, \ce{0\_u^+}) and triplet state (\ce{^3\sigma\_u^+}, \ce{1\_u^+}), with separate decay times. The singlet state and the triplet state are known to be created from a three-body deconstruction of noble gas atom excited state \ce{^2P\_{1/2}} state and \ce{^2P\_{3/2}} state, which has a different initial quantity from the event. Because these creation processes are three body reactions, the creation rate of the these two states have strong dependence on the gas density of atoms. The decay time of both of these two states have a dependence on the gas density, as described in Ref.~\cite{Keto1974}. Some other materials also show that the decay time is very different between liquid noble gas and very dense noble gas. The decay time for the singlet state and the triplet state in liquid xenon are \SI[separate-uncertainty=false]{4.3 \pm 0.6}{\ns} and \SI[separate-uncertainty=false]{22.0 \pm 2.0}{\ns}, as measured in Ref.~\cite{Hitachi1983}. For dense xenon with pressure in the range of \SIrange{2.7}{32}{\atm}, the decay time for singlet states varies from \SI[separate-uncertainty=false]{15 \pm 3}{\ns} to \SI[separate-uncertainty=false]{5.5 \pm 1.0}{\ns}. The decay time for triplet state is \SI[separate-uncertainty=false]{96 \pm 5}{\ns} in the same pressure range.

\todo{think about should I take about ionization/scintillation ratio here?}

EL photons in xenon are the predominant signals we measure. These photons are predominantly created by direct excitation in gaseous xenon is . The chemical process is,

\begin{align}

\text{EL process (direct excitation): } &\ce{e^- + A -> e^- + A^\*} .

\end{align}

The EL reduce photon production quantity (ratio of photon production quantity to gas density) per electron trajectory length of direct excitation is found to have a linear dependence on the reduced electric field ($E\_s/N$), as described and summarized in Ref.~\cite{Santos1994, Fonseca2004, Monteiro2007, Chepel2013a}:

\begin{align}

&\frac{dL\_s}{dx}=a \frac{E\_s}{N} + b ,

\end{align}

where $L\_s$ is the reduced photon production quantity; x is the electron trajectory length; $E\_s$ is the electric field strength (at the scintillation site); N is the density of gas; a and b are constant parameters, which are measured in Ref.~\cite{ Fonseca2004, Chepel2013a} to be:

\begin{align}

a &= \SI[separate-uncertainty=false]{0.137(2)}{\photon\per\electron\per\V} , \\

b &= \SI[separate-uncertainty=false]{-4.7(1) e-18 }{\photon\cm\squared\per\electron\per\atom}.

\end{align}

An EL process is usually associated with simultaneous electron multiplication. This process describes an electric accelerated by electric field, collides with gas molecules, ionize them generating additional free electrons. The chemical process is,

\begin{align}

\text{EL process (electron multiplication): }&\ce{e^- + Xe -> e^- + e^- +Xe^{+}}

\end{align}

The probability of electron multiplication per electron per unit length is also quoted as the first Townsend ionization coefficient ($\alpha$), which depends on the strength of reduced electric field, as measured in Ref.~\cite{Kruithof1940, Derenzo1974}. Conventionally, reduced first Townsend ionization coefficient is measured with E/$p\_0$ instead of reduced electric field, where E is the electric field; $p\_0$ is pressure of the gas reduced to \SI{0}{\celsius}. The reduced first Townsend ionization coefficient $\eta \equiv \alpha / E$ is also frequently used.The measured reduced first Townsend ionization coefficient is shown in Fig.~\ref{fig:first Townsend}.

\begin{figure}[!p]

\centering

\includegraphics[width=\figurewidth,clip,trim={0 0 0 0},angle=0,origin=c]{Figures/GasTest/XenonPhysicsUseful/FirstTownsendCoefficientKruithof1960.jpg}

\caption[The reduced first Townsend ionization coefficient $\eta \equiv \alpha / E$ for neon, argon, krypton, and xenon.]{The reduced first Townsend ionization coefficient $\eta \equiv \alpha / E$ for neon, argon, krypton, and xenon, from Ref.~\cite{Kruithof1940}.}

\label{fig:first Townsend}

\end{figure}

The duration of EL process is related electron drift velocity (v), which also depends on reduced electric field (E/n), as measured in Ref.~\cite{English1953,Bowe1960,Pack1962,Brooks1982,Berghofer2004}. In the range of \SIrange{5}{25}{\townsend}\footnote{A Townsend, or Td, is defined as \SI{1}{\townsend} = \SI{e-21} {\V\m\squared} = \SI{e-17}{\V\cm\squared}.}, a naive linear fit from Ref.\cite{Brooks1982} shows in xenon,

\begin{align}

v\ [\si{\mm\per\us}] \approx 0.56 E/n\ [\si{\townsend}]

\end{align}

Therefore, xenon is a good scintillation medium for its quantity of photon production and its transparency to these photons. With its well characterized quantities, we chose it as the major operation medium for the ELD.