In situ measurement of relative attenuation length of gadolinium-loaded liquid scintillator using source data at RENO experiment

The RENO collaboration

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ABSTRACT: We present in situ measurements of the relative attenuation length of the gadolinium-loaded liquid scintillator in the RENO (Reactor Experiment Neutrino Oscillation) detectors using radioactive source calibration data. We observed a steady decrease in the attenuation length of the Gd-LS in the RENO detectors by ~50% in about four years since the commissioning of the detectors.

KEYWORDS: Liquid detectors; Neutrino detectors

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1 Introduction

Organic solvent-based liquid scintillators (LS) have been commonly employed for low-energy neutrino experiments due to their effectiveness. However, these experiments typically last from several months to years, the long-term stability of the LS is of utmost importance. Any changes in the light yield or attenuation length of LS requires extensive monitoring and corrections, making the experiment significantly more challenging. Unfortunately, there have been reports of the degradation of the attenuation length of the gadolinium-loaded LS (Gd-LS) in a relatively short time [1–4]. The RENO experiment also has experienced degradation of the attenuation length of its Gd-LS [5].

The attenuation length of LS in a detector can be measured by extracting LS samples from the detector and analyzing them with spectrophotometers or purposefully-built instruments. Commercially available spectrophotometers typically use light sources with various wavelengths and measure the attenuation length of the liquid samples in small cuvettes. However, due to the limited sample size, typically a few centimeters, the uncertainty of the attenuation length measurement can be significant if the attenuation length exceeds several meters [6]. As a result, spectrophotometers may not be suitable for measuring the attenuation length accurately in some cases. On the other hand, specifically built instruments to measure the attenuation length, such as the one used in [7], have achieved a sub-meter uncertainty measurements for LS with an order of a 10 m attenuation length. However, these instruments require several liters of LS to make a measurement, limiting the frequency of the measurements on fresh LS samples extracted from the detector. Moreover, once the LS sample is extracted from the detector, the environmental conditions, such as temperature, humidity, or oxygen level, may differ from those in the detector. As a result, the attenuation length measured for the LS sample kept outside the detector for an extended period could differ from that of the LS in the detector unless the environmental conditions are closely matched.

Alternatively, the attenuation length of LS can be measured in situ using radioactive sources placed in the detector [2]. In this case, the measured quantity is an effective attenuation length as the optical photons with different wavelengths are summed over. The measured attenuation length is for the same optical photon spectrum as the scintillation signal in the experiment. In principle,
this method requires a detailed photomultiplier tube (PMT) performance model for each PMT used for the measurement. Using the model can be avoided by taking ratios of PMT hits spatially and temporally. In this paper, we report on the method of measurements of the relative effective attenuation length of Gd-LS in the RENO detectors using an in situ method, and the results of the measurements using calibration radioactive source data samples spanning about 1 400 days.

2 RENO detector and calibration system

The RENO is an neutrino oscillation experiment located at Hanbit nuclear power plant in Korea. The RENO detector is described in details in [8] and only the relevant part will be briefly described here. The experiment consists of two identical detectors, near and far detectors. Figure 1 shows a schematic view of RENO detector. Each detector consists of inner and outer detectors, with the outer detector serving as a cosmic muon veto system. The inner detector is contained in a cylindrical stainless steel vessel with two nested concentric transparent acrylic vessels. The innermost vessel holds 16 tons of linear alkylbenzene (LAB) based Gd-LS [6] as a target, with a Gd concentration 0.1%. A 60 cm-thick layer of unloaded LS, called the $\gamma$-catcher, is placed between the target vessel and the outer vessel to recover energy leakage from the target. The thicknesses of the target and $\gamma$-catcher vessel walls are 2.5 cm and 3.0 cm, respectively. A 70 cm-thick buffer region filled with 65 tons of mineral oil (MO) surrounds the $\gamma$-catcher. The light signals from the inner detector are detected by 354 Hamamatsu R7081 10-inch PMTs mounted perpendicularly on the inner wall of the stainless steel vessel and immersed in the buffer. The gain of each PMT is measured before the installation and continually corrected for the gain drift. The refractive indices for Gd-LS, LS, MO, and acrylic vessels at 405 nm are measured to be 1.50, 1.50, 1.47, and 1.50, respectively [9, 10]. Therefore, no significant reflection or refraction is expected at the medium interfaces. Table 1 shows the dimensions of the detector.

| Layer            | Outer Diameter (cm) | Outer Height (cm) | Material          |
|------------------|---------------------|-------------------|-------------------|
| Target           | 275.0               | 315.0             | Gd-LS             |
| Target Vessel    | 280.0               | 320.0             | Acrylic Plastic   |
| $\gamma$-Catcher | 394.0               | 434.0             | LS                |
| $\gamma$-Catcher Vessel | 400.0 | 440.0             | Acrylic Plastic   |
| Buffer           | 538.8               | 578.8             | MO                |
| Buffer Vessel    | 540.0               | 580.0             | Stainless Steel   |
| Veto             | 840.0               | 889.8             | Water             |

There are two 1-dimensional source calibration systems available on each detector, one for the target and the other for the $\gamma$-catcher. These systems allow for deploying a radioactive source in the liquids in the vertical direction ($z$-direction). Only the target calibration system is used for this measurement, where the source moves along the axial centerline of the target. The system consists of a Teflon-PFA container housing a radioactive source, which is attached at the end of a wire made of aromatic polyamide that is driven by a stepper motor. A weight is attached to the source container.
Figure 1. Schematic view of the RENO detector. There are two 1-dimensional calibration systems each for target and γ-catcher, that deploy radioactive sources vertically (z-direction).

to counteract the buoyancy when the source is submerged in the liquid. The relative z-position accuracy of the source is measured to be within a few millimeters and the systematic uncertainty of a few centimeters is expected due to possible shifts in the z-position.

3 Data and event selection

In this study, the data taken between Nov. 2011 and April 2015 with a $^{60}\text{Co}$ radioactive source are used. The source is positioned between $(x, y, z) = (0, 0, -120)$ and $(0, 0, 120)$ cm in the target. Here, $(0, 0, 0)$ represents the center of the target. Table 2 shows the dates of the data samples taken for this measurement.

The event vertex was reconstructed for each event using the weighting method described in [11]. Figure 2 shows the reconstructed event vertex distributions of a calibration data sample for the far detector. The event vertex distributions in x-y, y-z, and z-x are fit with 2-dimensional Gaussian functions simultaneously. The event selection criterion used is based on the reconstructed vertex position of each event, denoted by $(x, y, z)$. Only events that satisfy the following condition are used for the analysis:

$$\frac{(x - \bar{x})^2}{\sigma_x^2} + \frac{(y - \bar{y})^2}{\sigma_y^2} + \frac{(z - \bar{z})^2}{\sigma_z^2} < 1,$$

where $(\bar{x}, \bar{y}, \bar{z})$ and $(\sigma_x, \sigma_y, \sigma_z)$ are the means and widths, respectively, of the fits. This event vertex criterion ensures that the event occurred at the desired vertex position and removes most of background events. No other event selection requirement is used.
Table 2. List of $^{60}$Co source calibration data used in the measurement. The source is positioned between $z = \pm 120$ cm. The numbers within the parentheses are the elapsed time in days since 2011-08-01, corresponding to the commissioning of the RENO detectors.

| Detector | Date       | Source z-position | Intervals (cm) |
|----------|------------|-------------------|----------------|
| Far      | 2011-11-08 |                   | 40             |
|          | 2012-07-13 |                   | 40             |
|          | 2012-10-27 |                   | 40             |
|          | 2013-12-09 |                   | 40             |
|          | 2014-01-17 |                   | 10             |
|          | 2015-04-14 |                   | 10             |
| Near     | 2011-11-10 |                   | 40             |
|          | 2012-04-19 |                   | 40             |
|          | 2012-07-12 |                   | 40             |
|          | 2012-10-27 |                   | 40             |
|          | 2013-12-09 |                   | 40             |
|          | 2014-01-18 |                   | 10             |
|          | 2015-04-13 |                   | 10             |

4 Method of relative attenuation length measurement

When a radioactive source is submerged in a LS, particles from the source lose their energy in the immediate vicinity of the source and optical photons from the scintillating process are radiated isotropically. If a light source emits $N$ optical photons isotropically in a uniform medium at $\vec{r}$ from a PMT pointing in $\hat{\xi}$ direction, then the number of photons detected by the PMT, $n$, can be written as

$$n = N \frac{\Omega(\vec{r}, \hat{\xi})}{4\pi} \epsilon(\vec{r}, \hat{\xi}) \exp(-r/\lambda),$$

(4.1)

where $\Omega(\vec{r}, \hat{\xi})$ is the PMT coverage in solid angle, $\epsilon(\vec{r}, \hat{\xi})$ is the PMT efficiency, and $\lambda$ is the attenuation length of the medium. Here, $\lambda$ is the effective attenuation length for scintillating photons but not of the specific wavelength photons. It takes into account any effects experienced by optical photons in a medium, including reflection of the photons at the boundary of the medium.

The optical photons generated in the target must traverse three layers of liquids in the target (“t”), $\gamma$-catcher (“c”), and buffer (“b”) as well as two layers of acrylic vessel walls to reach any PMT in the inner detector. The ratio of numbers of photons detected by any two PMTs $i$ and $j$ is

$$\frac{n_i}{n_j} = \frac{\Omega_i \epsilon_i \prod_{\ell} \exp(-r^{(\ell)}_{i}/\lambda^{(\ell)})}{\Omega_j \epsilon_j \prod_{\ell} \exp(-r^{(\ell)}_{j}/\lambda^{(\ell)})}$$

$$= \frac{\Omega_i \epsilon_i}{\Omega_j \epsilon_j} \exp\left(-\sum_{\ell} \frac{\Delta r^{(\ell)}_{ij}}{\lambda^{(\ell)}}\right),$$

(4.2)

where $\Delta r^{(\ell)}_{ij} = r^{(\ell)}_{i} - r^{(\ell)}_{j}$ in layer $\ell$, $\Omega_i \equiv \Omega(\vec{r}_i, \hat{\xi}_i)$, and $\epsilon_i \equiv \epsilon(\vec{r}_i, \hat{\xi}_i)$. Here $\hat{\xi}_i$ is the unit vector in the direction that the $i^{th}$ PMT is pointing. If $|\Delta r^{(\ell)}_{ij}/\lambda^{(\ell)}|$ ($\ell \neq t$) can be made much smaller than
Figure 2. The reconstructed event vertex distributions in (a) x-y, (b) x-z, and (c) y-z of the data taken at 2014-01-17 at far detector. A ⁶⁰Co source is located at a nominal z-position of −50 cm. The widths of the distributions are approximately 20 cm in all directions.

If \( \frac{\Omega \epsilon_i}{\Omega \epsilon_j} \) does not change with respect to \( \Delta r \), one can measure \( \lambda^{(t)} \) by measuring \( n_i, n_j, \) and \( \Delta r_{ij} \). A similar technique has been used to measure the attenuation length of Gd-LS in at CHOOZ experiment [2] where the CHOOZ detector has only the target to consider. For the RENO detectors this condition can be satisfied using two sets of six PMTs each installed at top and bottom closest to the axial centerline of the target, where the target calibration sources are deployed along. The schematic of the arrangement of these PMTs relevant to this study is shown in figure 3. For the source positions at \( z = \pm 120 \) cm, where the effects from the other layers are the greatest in the data used in this study, the deviations in \( n_i/n_j \) coming from the other layers are estimated to be less than 1%. The effects of the uniform changes in attenuation lengths in non-target layers over time to the measurement should be negligible as well. Since each of the six PMTs at either top or bottom used for the measurements has the same distance and polar angle with respect to the radioactive source, they are treated as a single PMT. Henceforth, the top six PMTs shall be labeled as “u” and the bottom ones as “d.” Although using multiple PMTs makes the measurement by eq. (4.3) less
Figure 3. The location of six PMTs (solid line circle) nearest to the centerline of the detector at the top ($u$) and bottom ($d$) ends of the inner detector from above (not drawn to scale). They are equally spaced at 55 cm from the centerline where calibration sources are deployed. The distance from any of the PMTs on either top or bottom and to the calibration source is the same. The path lengths between the radioactive source and the top (bottom) PMT in target, $\gamma$-catcher, and buffer are $r_u(t)$, $r_d(t)$, and $r_{ud}(t)$, respectively.

Sensitive to the characteristics of individual PMT by averaging them out, however, the measurement is still found to be sensitive to the $\epsilon_\cdot(\vec{r}, \cdot)$ model.

Introducing the time dependence to eq. (4.3) and defining the ratio as $R(t, \Delta r)$ give

$$R(t, \Delta r) \equiv \frac{n_u(t)}{n_d(t)} = \frac{\Omega_u \epsilon_u(t)}{\Omega_d \epsilon_d(t)} \exp \left(-\frac{\Delta r}{\lambda(t)}\right), \quad (4.4)$$

where $\epsilon_u(t) = \epsilon(\vec{r}_u(t), \cdot)$ and $\Delta r = \Delta r_{ud}$. The term $\Omega$ is a geometrical term and does not have the time dependence. Taking the ratio of $R(t, \Delta r)$'s obtained at two different times $t_1$ and $t_2$

\footnote{The superscript "(i)" signifying the parameter to be that of the target shall be omitted from henceforth for convenience.}
gives
\[
\frac{R(t_1, \Delta r)}{R(t_2, \Delta r)} = \frac{\epsilon_u(t_1)\epsilon_d(t_2)}{\epsilon_u(t_2)\epsilon_d(t_1)} \exp \left( -\frac{\Delta r}{\lambda_m(t_1, t_2)} \right),
\]
where
\[
\frac{1}{\lambda_m(t_1, t_2)} \equiv \frac{1}{\lambda(t_1)} - \frac{1}{\lambda(t_2)}.
\]

Here, \( \Omega_u(d) \) is a geometrical factor and does not change over time. Therefore, \( \Omega_u(d) \) terms cancel out in the equation. If the angular efficiency profile of a PMT remains the same over time, then \( \epsilon_u(d)(t_1)/\epsilon_u(d)(t_2) \) at any radioactive source position becomes constant for any time interval between \( t_1 \) and \( t_2 \). The coefficient of the exponential of \( -\Delta r/\lambda_m(t_1, t_2) \), which contains the PMT performance model, becomes a constant coefficient with respect to the source position, i.e., with respect to \( \Delta r \). Therefore, if either \( \lambda(t_1) \) or \( \lambda(t_2) \) is known, the other can be calculated from the measured \( \lambda_m(t_1, t_2) \).

![Graphs showing the ratio of ratios \( R(t_R, \Delta r)/R(t, \Delta r) \) for various detector configurations.](image)

**Figure 4.** The ratio of ratios \( R(t_R, \Delta r)/R(t, \Delta r) \) (see eq. (4.5)) for (a) far detector at 2012-07-13 \( (t = 347 \text{ days}) \), (b) at 2015-04-12 \( (1351 \text{ days}) \), (c) near detector at 2012-07-12 \( (346 \text{ days}) \), and (d) at 2015-04-13 \( (1351 \text{ days}) \) and \( t_R = 900 \text{ (901) days at 2014-01-17 (2014-01-18) since 2011-08-01 for far (near) detector, fit with an exponential function.}

To measure \( 1/\lambda_m(t_1, t_2) \), we plot \( R(t_1, \Delta r)/R(t_2, \Delta r) \) as a function of \( \Delta r \) using eq. (4.5) with respect to a reference time \( t_R = t_1 \) against \( t_2 \). The time \( t \) is calculated as the elapsed time in days since 2011-08-01, corresponding to the commissioning date of the detectors. Here, \( t_R \) is chosen...
to be 900 (901) days for far (near) detector, corresponding to the fifth (sixth) set of data samples is taken (see table 2). Figure 4 shows $R(t_R, \Delta r)/R(t, \Delta r)$ as a function of $\Delta r$, where $t$ is 347 and 1352 days (346 and 1351 days) for far (near) detector.\textsuperscript{2} The resulting $1/\lambda_m(t_R, t)$ vs $t$ for all data is shown in figure 5 and the fitting results with a second order polynomial is shown in table 3. The point at $t = 900$ (901) days for the far (near) detector is not shown in figure 5 and not used in fitting $\lambda_m(t_R, t)$ with a second order polynomial since $\lambda_m(t, t) = 0$ by definition.

![Figure 5](image_url)

**Figure 5.** The relative inverse of attenuation lengths $1/\lambda_m(t_R, t)$ (see eq. (4.6)) as a function of the days since 2011-08-01 for far (red circles) and near (blue squares) detectors. The slope of $R(t_R, \Delta r)/R(t, \Delta r)$ represents the difference between the inverses of the attenuation length at a given time $t$ in days and at the reference time $t_R$ at 2014-01-17 (2014-01-18) for far (near) detector. The solid lines show the second order polynomial fits. The fitting results are shown in table 3.

If the shape of $1/\lambda(t_R, t)$ curve is known, the relative attenuation length can be obtained with respect to $t_R$ at any time within the time range of calibration data are taken. For example, if the attenuation length Gd-LS of 12.0 ± 0.5 m at day 0 is assumed for both far and near detectors, the attenuation lengths are calculated to have been degraded to 5.7 ± 0.3 m and 5.0 ± 0.3 m for far and near detectors, respectively, over a period of about 1350 days.

The Gd-LS in the target had been exposed to ambient air for ∼1400 days. Since the detectors were purged with nitrogen gas and sealed, the degradation of the attenuation length appears to have stopped for both the near and far detectors. The cause of this degradation is under investigation, but it could be attributed to oxidation or humidity.

### 5 Summary

An in situ method is presented for measuring the relative attenuation length for the target Gd-LS at RENO experiment using a radioactive source without assuming a PMT efficiency model. It is found that the attenuation length of the Gd-LS in the RENO detectors has been degraded by about 50% over 1350 days since the filling of the detectors, assuming the initial attenuation length of Gd-LS at beginning of the experiment is greater than ∼10 m.

\textsuperscript{2}Note that a data point is missing near $\Delta r = −140$ cm in figure 4(b). This is due to a missing data point near $\Delta r = −140$ cm at $t_R$. 
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Table 3. Fitting results of figure 5 with a second order polynomial $\lambda_m^{-1}(t_R, t) = p_0 + p_1 t + p_2 t^2$, where $t$ is in days since 2011-08-01.

| Detector | $p_0$ ($\times 10^{-4}$ cm$^{-1}$) | $p_1$ ($\times 10^{-7}$ cm$^{-1}$day$^{-1}$) | $p_2$ ($\times 10^{-10}$ cm$^{-1}$day$^{-2}$) |
|----------|-----------------------------|-----------------------------|-----------------------------|
| Far      | 5.39 ± 0.53                | −3.71 ± 1.76                | −2.25 ± 1.08                |
| Near     | 7.42 ± 0.48                | −4.70 ± 1.70                | −2.90 ± 1.07                |

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