A Spectrometric Approach to Characterize the Rayleigh Scattering Length for Ultrapure Liquid Scintillator Detectors

S.S. Gokhale, a R. Rosero, a R. Diaz Perez, a C. Camilo Reyes, a S. Hans, a,b and M. Yeh a,c,*

a Chemistry Division, Brookhaven National Laboratory, Upton, New York 11973
b Chemistry Department, Bronx Community College, Bronx, New York 10453
c Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973
E-mail: yeh@bnl.gov

ABSTRACT: Good optical transparency is a fundamental requirement of the liquid scintillator (LS) detectors. Characterizing the transparency of an LS to its own emitted light is the key parameter to determine the overall sensitivity of a large-volume detector. The attenuation of light in an ultrapure LS is dominated by Rayleigh scattering, which poses an intrinsic limit to the transparency of LS. This work presents a highly sensitive spectrometric approach of measuring the wavelength-dependent scattering length of ultraclean liquids by applying the Einstein-Smoluchowski-Cabannes theory to measured scattered light intensity. The scattering lengths of linear alkyl benzene (LAB) and EJ309-base (Di-isopropynaphthalene, DIN) were measured and reported in the wavelength range of 410 – 510 nm. The spectral peak maximum of scintillation light emitted by a nominal LS is around 430 nm at which the scattering length for LAB and EJ-309-base was determined to be 27.9 ± 2.3 m and 6.1 ± 0.6 m respectively.

KEYWORDS: Scintillators, Scintillation and Light Emission Processes; Neutrino Detectors; Liquid Detectors; Ionization and Excitation Processes

*Corresponding author.
1. Introduction

Large-volume liquid scintillator (LS) detectors provide the necessary stopping power and sensitivity required for neutrino detection and have played a key role in the understanding of neutrino physics over the past decades [1, 2, 3, 4]. Typically, these large detectors have target masses ranging from tens of tons to kilotons. The corresponding volumes are such that scintillation light generated in the center of the detector may have to travel several meters of the liquid medium before being collected by the photomultiplier tubes (PMTs) [5, 6]. Therefore, the transparency of the scintillation liquid to its own emitted light is imperative to determine the overall sensitivity of the detector. As the size of the detectors increases, the significance of optimizing the transmission of scintillation light through the liquid increases dramatically. The optical transparency can be optimized by ensuring high molecular purity of the solvent, however there is a limit to the transparency that can be obtained under realistic conditions because of the Rayleigh scattering of light off the molecules of liquid.

Linear alkyl benzene (LAB; CₙH₂ₙ₊₁–C₆H₅, n = 10–13) has received much attention as a detection medium for nuclear and particle physics experiments. LAB has a relatively good light yield, with a peak maximum emission at 284 nm that can be reemitted to longer wavelengths (~340nm) through multiple self-absorption and reemission processes. Its inherent properties of high flash point (130 °C), low toxicity, and long attenuation length make LAB feasible as a detection medium for large-volume scintillator detectors. The optical transmission and scintillation propagation of LAB have been studied extensively for its implications in neutrino detections [7, 8, 9]; however, there has not been a systematic measurement of scattering length over the wide range of visible region.

EJ309 (trade name under Eljen) is another scintillator material that is prepared from Diisopropylnaphthalene (DIN, C₁₆H₂₀) based solvent and has gained great interest as a scintillation material due to its unique pulse-shape characteristics of the ionization particles for short baseline neutrino detectors [10]. It is a commercially available liquid scintillator, originally developed for neutron detection [11]. EJ309-base (EJ309, exclusive of fluor or wavelength shifter) is a nonflammable solvent with very low vapor pressure. It has a high light yield with an emission spectrum dominated by a peak maximum at 360 nm after multiple self-absorption and reemission.
processes like LAB. Previous work has characterized the light collection and response of EJ309, however most of these studies have been limited to smaller volumes [12, 13]. Figure 1 shows the emission spectra for both LAB and EJ309-base under UV excitation.

![Emission spectra of pure LAB (solid) and EJ309-base (dash) with excitation $\lambda = 260\text{nm}$.

A nominal liquid scintillator (nLS) employed in most neutrino detectors is composed of three components: aromatic organic scintillator as the solvent, 2,5–diphenyloxazole (PPO) as the fluor, and 1,4–bis[2–methylstyrlyl] benzene (bis–MSB) as the wavelength shifter. The wavelength of the scintillation light emitted by a pure scintillator solvent is shifted to the visible region by PPO and bis-MSB. The spectral maximum of the scintillation light for an nLS is often controlled at peak $\lambda = 430\text{ nm}$, which is within the range of wavelengths in which the quantum efficiency (QE) of the detector PMTs is most sensitive. To optimize the optical clarity in the 400 – 600 nm range, the scintillator solvent is subjected to multiple purification steps to remove both inorganic and organic impurities, which may present absorption bands in the wavelength range of interest. The self-absorption of the scintillation light by LAB or EJ309-base in this wavelength region is negligible, therefore the major component of the optical attenuation process is molecular scattering.

The attenuation of light in an LS is due to a combination of absorption and scattering [14]. A photon travelling through such a liquid can either be absorbed or be deflected from its path when interacts with molecules. The absorbed photons are either reemitted to different wavelengths or converted into heat and lost. Scattering on the other hand mainly changes the direction in which the photons are propagated, and the photons can eventually be collected by the surrounding PMTs. The characteristic response of a large-volume liquid scintillator detector
consequently depends on the precise knowledge of the optical attenuation property of the detection medium.

The attenuation length of a liquid can be described by the following formula:

\[
\frac{1}{L} = \frac{1}{L_A} + \frac{1}{L_S}
\]  

(1.1)

where \(L_A\) and \(L_S\) are the absorption and scattering lengths, which are defined as the average distance that the probability of a photon travelling in a liquid medium without being absorbed or scattered is \(1/e\). It is difficult to directly measure the absorption length, but it can be determined by measuring the scattering and total attenuation lengths and substituting into equation 1.1.

Previous experiments have estimated the Rayleigh scattering length and the total attenuation length of LAB by measuring the attenuation of light at limited wavelengths of interest only [9]. The experimental data for the Rayleigh scattering lengths crossing the full region of emitted wavelengths for both LAB and EJ309-base (or DIN) have not been reported.

The present work focuses on a new approach of measuring the wavelength-dependent, optical scattering length for ultraclean liquids by applying the Einstein-Smoluchowski-Cabannes theory to its scattered light intensity measured by a fluorescence spectrometer. This approach utilizes a highly sensitive spectrometric module, as opposed to a long-arm apparatus with pathlength of several meters, to characterize the optical property of ultrapure scintillator solvents. The scattering length of LAB and EJ309-base was measured and reported in the wavelength range of 410 – 510nm respectively.

2. Theoretical Approach

The scattering of light off a volume of liquid can be expressed by the Rayleigh ratio, which is characterized as the volume scattering function \(\beta(\theta)\) for a scattering angle of 90° [15, 16]

\[
R \equiv \beta(90^\circ) = \left(\frac{I}{I_0}\right)\left(\frac{r^2}{V}\right)
\]  

(2.1)

where \(I\) is the intensity of the transversely scattered light, \(I_0\) is the intensity of the incident light, \(r\) is the distance from the scattering center to the point of observation, and \(V\) is the scattering volume. The intensity of the scattered light can be divided into two components that are parallel and perpendicular to the scattering plane. The angular distribution of these components depends on the polarization of the scattered light induced by the scattering material, which is characterized by the depolarization ratio \(\delta\) that allows for both isotropic and anisotropic contributions to the Rayleigh scattering amplitude. To account for the effect of polarization the volumetric scattering function \(\beta(\theta)\) of Rayleigh scattering can then be expressed as

\[
\beta(\theta) = R \left(1 + \frac{1 - \delta}{1 + \delta} \cos^2 \theta\right)
\]  

(2.2)

According to the Einstein-Smoluchowski theory, the Rayleigh scattering length can be determined by the inverse of the volumetric scattering function integrated over the solid angle [17, 18]. The following equation can therefore be derived for the Rayleigh scattering length.

\[
l_{Ray} = \left\{\frac{8\pi}{3} \frac{2 + \delta}{1 + \delta}\right\}^{-1}
\]  

(2.3)
Equation 2.3 characterizes the Rayleigh scattering length for a liquid with a nonnegligible depolarization ratio. In the case of an ideal isotropic liquid, the depolarization ratio is zero and the scattering length depends only on the Rayleigh ratio. In addition, if the liquid is perfectly uniform then the scattering will be eliminated by destructive interference except in the forward direction [19]. However, because of the thermal motions of the molecules, the local density of a liquid is constantly fluctuating. The effect of these random density fluctuations is from the dielectric constant. As the refractive index is directly related to the dielectric constant, the fluctuations can then cause an increase in the scattering amplitude. To account for this effect of nonuniformity of the liquid on scattering, according to the Einstein-Smoluchowski theory, the isotropic Rayleigh ratio can be expressed by

\[ R_{iso} = \frac{\pi^2}{2\lambda^4} \left[ \rho \left( \frac{\partial \varepsilon}{\partial \rho} \right)_T \right] kT \kappa_T \]  

(2.4)

where, \( \lambda \) is the wavelength of the scattered light, \( \rho \) is the density of liquid, \( \varepsilon \) is the average dielectric constant of the liquid, \( k \) is the Boltzmann constant, \( T \) is the temperature, and \( \kappa_T \) is the isothermal compressibility. The total Rayleigh ratio \( R \) related to the isotropic Rayleigh ratio is further given by the Cabannes formula [20]

\[ \frac{R}{R_{iso}} = \frac{6 + 6\delta}{6 - 7\delta} \]  

(2.5)

The fluctuation in the dielectric constant can be evaluated using empirical relations between density and the refractive index. Several such relations have been published in literatures [21, 22], but for organic liquids it was shown that the Eykman equation describes \( \rho(\partial \varepsilon/\partial \rho) \) well [16, 22, 23, 24]. The Eykman formula is

\[ \rho \left( \frac{\partial \varepsilon}{\partial \rho} \right)_T = \frac{(n^2 - 1)(2n^2 + 0.8n)}{n^2 + 0.8n + 1} \]  

(2.6)

where, \( n \), the refractive index of liquid, is now introduced. By combining the above equations, we obtain the Einstein-Smoluchowski-Cabannes formula for the scattering length of organic liquids,

\[ l_{Ray} = \frac{8\pi^3}{3\lambda^4} \left\{ \frac{(n^2 - 1)(2n^2 + 0.8n)}{n^2 + 0.8n + 1} \right\}^2 kT \kappa_T \frac{6 + 6\delta}{6 - 7\delta} \]  

(2.7)

3. Optical Measurements

3.1 Rayleigh Scattered Light Intensity

The light scattering measurements were performed using a PTI QuantaMaster-8000 Fluorescence Spectrometer, which uses a 75 W xenon lamp as a light source. Figure 2 shows the schematic drawing of the instrument. The pure liquids used for the scattering length measurements were high purity (18.3 MΩ-cm) water purified using a Millipore Milli-Q water system, liner alkyl benzene (Cepsa, 500-Q) cleansed by thin-film temperature-dependent vacuum distillation, and EJ309-base pretreated by Eljen using ion-extraction columns.
The incident light is scattered at a right angle by the liquid sample contained in a quartz cell. Suppression of stray light is a critical factor when accurately measuring the scattered light intensity. A combination of slits and lenses together reduce the divergence of the primary beam illuminating the liquid sample cell. The light from the xenon lamp is monochromatized by double additive, 350-mm focal length asymmetrical Czerny-Turner monochromators. The monochromators also ensure further stray light suppression with a rejection rate of $10^{-10}$. The intensity of the light emitted by the xenon lamp is not equal across the entire output spectrum. Therefore, the central part of the primary light beam from the monochromators passes an aperture and onto the sample, and the remainder is reflected towards the RCQC device, which has a reference diode detector. The reference diode detector provides a correction signal for any temporal fluctuation of the lamp intensity.

The spectrometer measures the intensity of the scattered light by means of a cooled photomultiplier tube (PMT). The scattered light is admitted to the PMT through an optical system consisting of lens, slit, and monochromator, which ensures a good delimitation of scattering volume and the solid angle of the cone of scattered light. The spectrometer applies a correction
factor to compensate the variation in the detection efficiency of the optics, gratings, PMT, etc. for all the different light wavelengths. The scattered light intensity spectra were measured for each wavelength of incident monochromatic light. The gaussian peak area corresponds to the total number photons collected by the PMT over the acquisition period, while the peak height corresponds to the maximum intensity of the scattered light. In order to measure this wavelength-dependent scattering response, the samples were illuminated with monochromatic light sequentially over the range of wavelengths, and the absolute intensity of the scattered light was measured. Figure 3 shows the wavelength-dependent Rayleigh scattering responses for LAB.

![Scattered light intensity spectra for LAB](image)

**Figure 3.** Scattered light intensity spectra for an LAB sample illuminated with different wavelengths of monochromatic light. The scattering intensity decreases as a function of wavelength by a theoretical factor of $\lambda^{-4}$.

The intensity of the Rayleigh scattered lights given by the peak heights decreases with an increase in the wavelength and is roughly proportional to $\lambda^{-4}$. The Gaussian peaks correspond to the intensity of scattered light for different wavelengths, however for wavelengths shorter than 410 nm the scattered light peaks appear to be convolved with the emitted light from the excitation-reabsorption-remission process. Figure 4 shows that the influence of emitted light on the scattered light intensity in the region of 400–440 nm can be seen from the elevated baseline of longer wavelength tail of the Gaussian, whereas the output spectra for incident light wavelengths >440 nm consists of only the Gaussian distribution of the scattered light. Therefore, only wavelengths longer than 450 nm were used for the scattered intensity fitting to eliminate the interference of emitted light with the scattered length analysis for both LAB and EJ309-base.

The scattered light spectrum at each wavelength consist of pairs of peaks, the primary elastic Rayleigh scattering peak and a secondary inelastic Raman peak. The intensity of the Raman peak
is an order of magnitude smaller than that of the Rayleigh scattering peak positioned at longer wavelengths.

3.2 Depolarization Ratio

In the case of fluids composed of isotropic particles, the light scattered in the plane transverse to the plane containing the incident, and scattered beams is completely polarized. However, for anisotropic particles the effect of varying polarizability along all the different axes results in an overall increase in the magnitude of scattering. The value of the depolarization ratio for LAB and water have been previously published at certain wavelengths only [25, 26, 27]. The depolarization ratio for EJ309-base has not been previously measured or reported.

As a fundamental physical property, the depolarization ratio is defined as the ratio of horizontally to vertically polarized light scattered at 90°. For this study, the depolarization ratio for liquids was estimated over a range of wavelengths by measuring the intensities of the polarized light scattering off the sample liquids. The QuantaMaster spectrofluorometer was reconfigured for polarized light measurements. In this configuration, the spectrofluorometer employed Glan–Thompson polarizers in both the excitation and emission optical paths. The excitation polarizer was set to illuminate the sample liquid with vertically polarized light, and the angle of the emission polarizer was then alternately set to measure the intensity of the horizontal (i.e.

Figure 4. Example of scattered light spectra at four different incident light wavelengths for LAB. The spectra for wavelengths shorter than 450 nm show emitted light at the long wavelength tail of the Gaussian peaks. Raman scattered photons for $\lambda_s = 410, 430$ nm are also shown.
perpendicular) component of the light scattering off the sample. The ratio of perpendicular to the parallel component of the polarized scattered light at a specific wavelength then gives the depolarization ratio at the wavelength. Figure 5. shows the measured values of the depolarization ratio for the three pure liquids.

![Graph showing depolarization ratios for three pure liquids](image)

**Figure 5.** Depolarization ratios at a range of wavelengths for the three pure liquid samples.

### 3.3 Refractive Index

To accurately model the propagation and scattering of light in a liquid with the *Einstein-Smoluchowski-Cabannes* formula, it is also imperative to know the refractive index of the liquid, in addition to the depolarization ratio. The index of refraction for a material is dependent on the wavelength of light and the material property of the medium. This variance in the index of refraction is known as dispersion and it is described by the *Sellmeier* formula

\[
n^2(\lambda) = 1 + \sum_{i=1}^{N} \frac{B_i}{1 - (C_i/\lambda)^2}
\]  

(3.3.1)
where B and C are \emph{Sellmeier} coefficients from data fitting. For the wavelength range between 410–510 nm, the refractive index decreases monotonically with wavelength \( \lambda \). The refractive index for both pure water and LAB has been previously determined for a number of different wavelengths [28, 29]. It has been shown that for pure organic liquids, the contribution of the temperature fluctuations in the refractive index is negligible [30].

Refractive index at seven different wavelengths was measured for the three pure liquids using a refractometer (ATR – L refractometer manufactured by Schmidt + Haensch GmbH). The \emph{Sellmeier} formula was then fitted to these measured refractive index data from 390 to 720 nm. Figure 6. shows the measured refractive index values (with \emph{Sellmeier} fit) to published reference values for water.

![Figure 6. Refractive index of omega water. Plot compares the measured data (triangles) and the \emph{Sellmeier} fit (solid line) to the reference data (circles).](image)

The \emph{Sellmeier} coefficients were determined using an iterative model such that a best fit (\( R^2 = 1 \)) was obtained from the measured refractive index data and then be applied to Equation 3.3.1 to describe the refractive index in the wavelength range of 410 – 520 nm. The values of the refractive index for LAB and EJ309-base as a function of wavelength along with the fitted \emph{Sellmeier} equation, are shown in Figure 7.
Figure 7. Refractive index data for LAB and EJ309-base iteratively fitted with the Sellmeier equation.
4. Results and Analysis

The scattering length of pure liquids can be determined for a range of wavelengths if the Rayleigh ratios have been determined. In the case of organic liquid scintillators, the Rayleigh ratios are either intrinsic to the material or dependent on the experimental configuration. Some of these parameters are constants, and the rest must be obtained experimentally.

By combining and rearranging equations 2.1, 2.3, and 2.7, we formulated an expression for the intensity of the scattered light, \( I \), in equation 4.1. The term \( \text{Fitting Constant} \) is a product of two characteristic parameters: material constant \( (C_{\text{Mater}}) \) and geometry constant \( (C_{\text{Geom}}) \).

\[
I = \text{Fitting Constant} \cdot \left( \frac{n^2 (n^2 - 1) (2n^2 + 0.8n)}{\lambda^4 (n^2 + 0.8n + 1)} \right)^2 \left( \frac{(6 + 6\delta)}{(6 - 7\delta)} \right)
\]

(4.1)

The term \( C_{\text{Mater}} \) accounts for the effect that the material properties have on the intensity of the Rayleigh scattered light. The scattered length can then be computed from \( C_{\text{Mater}} \), depolarization ratio \( (\delta) \), and refractive index \( (n) \) as

\[
l_{\text{Ray}} = \frac{6}{8\pi} \cdot \frac{1}{C_{\text{Mater}}} \cdot \frac{(1 + \delta)}{(2 + \delta)} \cdot \left( \frac{n^2 (n^2 - 1) (2n^2 + 0.8n)}{\lambda^4 (n^2 + 0.8n + 1)} \right)^2 \left( \frac{(6 + 6\delta)}{(6 - 7\delta)} \right)^{-1}
\]

(4.2)

The value of the material constant for water \( C_{\text{Mater}}^{\text{Water}} \) was obtained based on previously published scattering length data and the presently measured values of \( \delta \) and \( n \). There have been several studies, which have reported data sets for the attenuation lengths of pure water. Most of the works report the data measured on laboratory-scale experimental geometries. The wavelength dependent Rayleigh scattering length data of pure water employed in the Super-Kamiokande experiment on the other hand were measured in an actual detector geometry, and as such it is interpreted as the most accurate measurement of the scattering length for pure water. Therefore, the Super-Kamiokande data set was used as the reference values for this work [31, 32, 33].

Figure 8 shows the measured and fitted Rayleigh scatter intensity data for pure water. Each data point represents the value of the peak height taken from the scattered light spectrum at each wavelength of incident light. The iterative best fit \( (R^2 = 0.9955) \) performed on this data using equation 4.1, yields a value for the Fitting Constant, which can then be used to decouple the constants related to the system parameters, \( C_{\text{Geom}} \).

To account for any variation in the measured data related to the instrumentation system, the scattered light intensity measurement was repeated several times for each sample liquid. An averaged scattered light intensity value at each wavelength was then obtained by combining the data sets from the repeated measurement runs. It was observed that the variation in the measured values of the scattered light intensity due to fluctuations in the system were less than 3%.
Figure 8. Plot showing the peak height intensities of scattered light measured for pure water for different incident light wavelengths and the best fit line obtained using equation 4.1 for the data in the wavelength range of 370 – 510 nm. The goodness of fit was verified by calculating the $R^2$ parameter ($R^2 = 0.9955$).
The best fit ($R^2=0.9889$) of the measured Rayleigh scattered intensity data for LAB was obtained by iteratively determining the value for $C_{Mater}^{LAB}$, while the system parameter ($C_{Geom}$) decoupled previously was held as the constant. The derived $C_{Mater}^{LAB}$ and the measured values of $\delta_{LAB}$ and $n_{LAB}$ were then used to determine the wavelength dependent Rayleigh scattering length for LAB using equation 4.2. Figure 9 shows the measured scattered light intensity and the corresponding fitted Rayleigh scattering equation for LAB. For incident light up to 430 nm wavelength, the scattered light intensity spectra show the influence of light emission from the excitation of the LAB molecules (see Figure 4), which appears as a divergence of the measured intensity from the $\lambda^{-4}$ dependence. The data fitting was therefore performed for wavelengths $>$430 nm and then extrapolated back to the range of 410–430 nm.

![Figure 9](image.png)

**Figure 9.** Measured scattered light intensity for LAB and the best fit using equation 4.1 for the Rayleigh scattered intensity in the wavelength range of 440 – 520 nm. The goodness of fit was verified by calculating the $R^2$ parameter ($R^2 = 0.9889$). The 95% confidence interval was computed using the standard error of the fit and is depicted as the band along the fitted curve.
EJ309-base showed greater light scattering compared to LAB, which is confirmed by the greater anisotropy depolarization ratio than that of LAB (see Figure 5), and therefore its scattering length will presumably be shorter. Unlike the LAB, the EJ309-base had not been subjected to additional purification or filtering steps for this present work. Figure 10 shows the measured scattered light intensities for EJ309-base and the corresponding fitted ($R^2=0.9875$) Rayleigh scattering equation. As in the case of LAB shown in Figure 4, the Rayleigh scattering intensity formula was fitted to only the measured data above the wavelength of 430 nm to avoid the influence of emitted scintillation light on the scattered light intensity. The Rayleigh scattering lengths of LAB and EJ309-base in the wavelength region of 410 – 520 nm computed using Equation 4.2 are reported in Table 1.

![Figure 10.](image)

*Figure 10.* Measured scattered light intensity and for EJ309-base and the best fit using equation 4.1 for the Rayleigh scattered intensity in the wavelength range of 440 – 520 nm. The goodness of fit was verified by calculating the $R^2$ parameter ($R^2 = 0.9875$). The 95% confidence interval was computed using the standard error of the fit and is depicted as the band along the fitted curve.
Table 1. Rayleigh scattering length as a function of wavelength for LAB and EJ309-base.

| Wavelength (nm) | LAB (m)       | EJ309-base (m) |
|----------------|---------------|----------------|
| 410            | 22.9 ± 2.3    | 5.0 ± 0.5      |
| 420            | 25.3 ± 2.5    | 5.5 ± 0.5      |
| 430            | 27.9 ± 2.3    | 6.1 ± 0.6      |
| 440            | 30.6 ± 2.6    | 6.7 ± 0.5      |
| 450            | 33.6 ± 3.1    | 7.4 ± 0.7      |
| 460            | 36.8 ± 3.6    | 8.1 ± 0.8      |
| 470            | 40.2 ± 3.3    | 8.9 ± 0.7      |
| 480            | 43.9 ± 4.1    | 9.7 ± 1.0      |
| 490            | 47.8 ± 5.5    | 10.6 ± 1.2     |
| 500            | 51.8 ± 5.8    | 11.5 ± 1.2     |
| 510            | 56.2 ± 7.1    | 12.5 ± 1.3     |
| 520            | 60.9 ± 7.7    | 13.6 ± 1.6     |

5. Discussion and Conclusions

The Rayleigh scattering length of a pure liquid was calculated using an approach derived from the Einstein-Smoluchowski theory applied to the measured data of the Rayleigh scattered light intensities at different wavelengths of incident light. As this method relies on actual measured values to calculate the Rayleigh scattering length, it is critical to properly estimate the influence of all parameters of the experimental system. The experimental parameters were characterized by first measuring the scattered light intensity for a reference material (pure water), whose scattering length data are well understood. This enabled decoupling the experimental parameters from the Rayleigh scattered intensity measurement for the unknown sample liquids i.e. the organic liquid scintillators.

The present study illustrates a highly sensitive spectrometric approach to determine the scattering length of any ultrapure liquids. Several optical parameters, such as the depolarization ratio, the refractive index, and the Rayleigh scattered light intensities were experimentally measured over a range of incident light wavelengths for two organic liquid scintillators: LAB and EJ309-base. These measured parameters were then used to obtain the Rayleigh scattering lengths from the Einstein-Smoluchowski-Cabannes formula. Characterization of the measurement error caused by system fluctuations was performed by repeating each type of measurement several times for every sample. Error propagation using the standard deviations for the combined data sets for each of the various measured quantities, accounts for the uncorrelated uncertainties that must be added to obtain the statistical uncertainty for the values of scattering length calculated at each wavelength.

The measured scattering lengths of LAB comprehend the emitted wavelength region, 410 – 520 nm, of an nLS and are in good agreement with previously published values that are only available in few wavelengths [25, 26]. In the case of EJ309-base this work is the first publication of wavelength dependent scattering lengths for a DIN-based solvent. The $\lambda^4$ dependence of Rayleigh scattering was clearly demonstrated by the measurements even for pure water; however, some influences on the absorption-reemission process was also observed for the organic liquid scintillator samples.
Scintillation and optical transport in a large-volume liquid scintillator detector involves a complex interdependence of many parameters, and yet the optical properties such as the scattering length allow some broad conclusions to be made regarding the performance of liquid scintillators. The measured Rayleigh scattered length is an imperative input parameter for optical transport simulations. Based on the results of this study, the scattering length (e.g. $\lambda = 430$ nm) of $27.9 \pm 2.3$ m for LAB confirms its feasibility for use in large-volume detectors, while the shorter scattering length of $6.1 \pm 0.6$ m for EJ309-base makes it a good scintillator candidate for smaller scale detectors.

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