On the attenuation of light in water.

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Abstract

The measurements of the absorption of light and the theory of light scattering are reviewed. The probability density function of the arrival time of light has been evaluated for different hypotheses. Based on the present results, the hypothesis that the attenuation of light is dominated by scattering and not by absorption cannot be excluded.

1 Introduction

In general, the propagation of light through water is affected by absorption and scattering. The absorption of light corresponds to the disappearance of the photon and scattering to a change of direction of the photon. The absorption length of pure water has been measured by various authors. A commonly used result is the so-called Smith&Baker measurement [1]. The absorption length due to Smith&Baker is shown in figure 1. It is used in the Antares simulation of the detector response to muons and neutrinos.

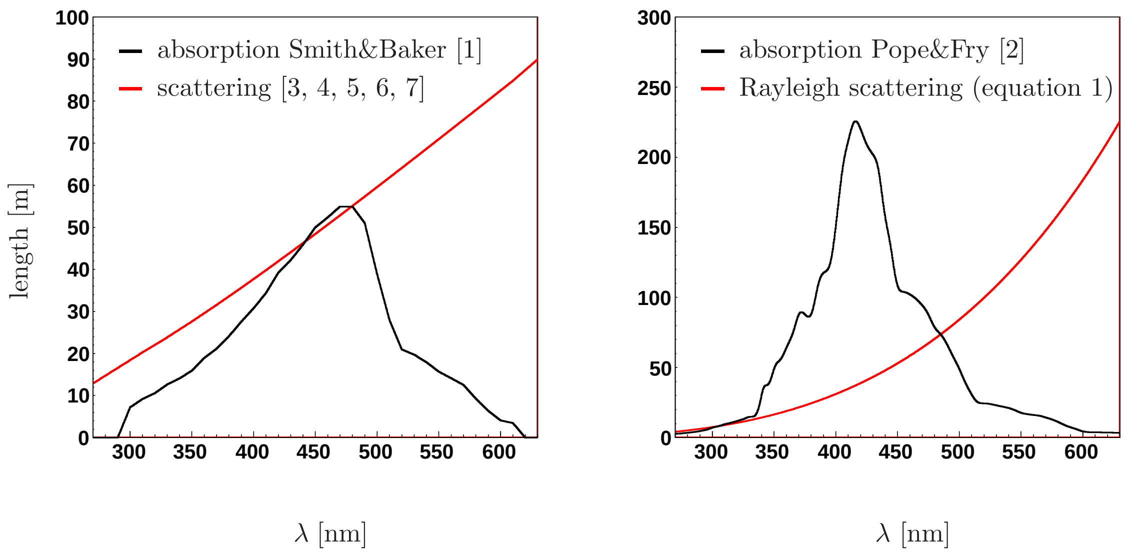

Figure 1: Absorption length (black) and scattering length (red) as a function of the wavelength of the light. Left Antares and right pure water.

Two main contributions to the scattering of light can de identified. Particles with sizes much larger than the wavelength of the light contribute primarily to the small angle scattering. This is usually referred to as Mie scattering. Particles with sizes much smaller than the wavelength of the light contribute primarily to the large angle scattering. This is usually referred to as Rayleigh scattering. The cross section of Rayleigh scattering can be formulated as:

$$\sigma(\lambda) \quad = \quad \frac{2\pi^5}{3} \times \left(\frac{n^2 - 1}{n^2 + 1}\right)^2 \times \frac{D^6}{\lambda^4} \tag{1}$$

where λ refers to the wavelength of the light, n to the index of refraction and D the diameter of the particle. Although other molecules may contribute, the main contribution to the Rayleigh cross section arises from water molecules. The angular distribution of the scattered light can be formulated as:

$$\frac{dP}{d\Omega} \quad = \quad \frac{1}{4\pi} \times \frac{1}{1 + \frac{a}{3}} \times (1 + a\, \cos^2 \theta_s) \tag{2}$$

where θ_s refers to the scattering angle. For spherical particles, $a = 1$. For water molecules, a is usually set to $a = 0.853$.

Assuming the absorption length due to Smith&Baker, the scattering length and the angular distribution have been determined using *in situ* measurements [3, 4, 5, 6, 7]. The scattering length that is now used widely in Antares is shown in figure 1, left. The dependence of the scattering length on the wavelength varies somewhat between λ^1 and λ^2. The angular distribution is that of the `p.0075` model. In this, a 17% fraction of Rayleigh scattering is ussumed that is independent of the wavelength of the light. This contradicts sharply the dependence of the Rayleigh cross section on the wavelength (see equation 1).

More recently, the absorption length of pure water has been measured by Pope&Fry [2]. The result is shown in figure 1, right. As can be seen from figure 1, the results disagree with those obtained by Smith and Baker in the region between 330 nm and 520 nm. According to the authors: "This disagreement is most likely due to a combination of (1) our more effective water purification and maintenance, (2) the absence of scattering effects in the ICAM, and (3) the greater sensitivity of the ICAM." [2].

In order to quantify a possible contribution of Rayleigh scattering to the attenuation of light, the Rayleigh scattering length has been determined using equation 1. In this, the diameter of the water molecule has been set to maximise the agreement between the Rayleigh scattering length and the Smith&Baker absorption length. The value thus obtained amounts to $D = 0.22$ nm which agrees well with many other results. The agreement between the Rayleigh scattering length and the Smith&Baker absorption length between 300 nm and 430 nm is striking (see Analysis e-log entry 461).

2 Probability density function

The probability density function (PDF) of the arrival time of light has been worked out in reference [8]. In this formalism, a single scattering approximation is applied. The result therefore includes contributions of direct light and light that scattered only once. The more times the light has scattered, the later it arrives at a PMT located at a given distance from the muon trajectory (or shower). The result may thus be interpreted as an approximation of the amount of detectable light that contributes effectively to the reconstruction of the muon trajectory. In the following, two hypotheses will be considered, namely:

H0: Attenuation of light dominated by absorption.

Quantity	Reference
Absorption length	Smith&Baker
Scattering length	figure 1, left
Scattering angle distribution	`p0.0075`

H1: Attenuation of light dominated by Rayleigh scattering.

Quantity	Reference
Absorption length	Pope&Fry
Mie scattering length	figure 1, left
Mie scattering angle distribution	`p0.0075`
Rayleigh scattering length	equation 1
Rayleigh scattering angle distribution	equation 2

The first hypothesis corresponds to the conditions that are currently used in the simulations for Antares. In the second hypothesis, the water is assumed to be pure according Pope&Fry. The attenuation is then primarily due to Rayleigh scattering. For Mie scattering, the `p.0075` model is used. In this, the contribution of Rayleigh scattering, p, has been set to $p = 0$. The results are shown in figure 2 for two different distances of closest approach of the muon track to the photo-multiplier tube (PMT).

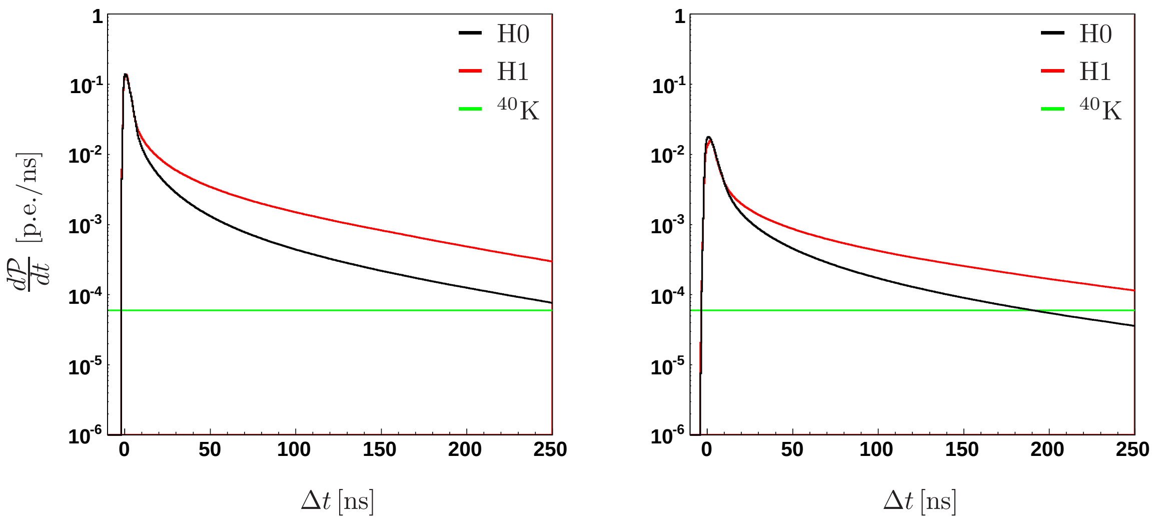

Figure 2: The probability density function of the arrival time of light for a PMT located at 25 m (left) and 50 m (right). The energy of the muon has been set to 1 TeV and the PMT is oriented towards the muon (i.e. West in reference [8]).

As can be seen from figure 2, the two hypothesis yield similar PDFs for small arrival times ($|\Delta t| \leq 20$ ns). For late arrival times ($\Delta t > 20$ ns), the second hypothesis yields more light. This can be attributed to the contribution of Rayleigh scattered light which is (much) larger in the second hypothesis. It should be noted that there is also a contribution to the PDF of random noise due to Potassium (^{40}K) decays. As an example, a singles rate of 60 kHz corresponds to a level at 6×10^{-5} ns^{-1} (see figure 2).

3 Discussion

As can be seen from figure 2, the two hypothesis do not yield significantly different PDFs in the time window that is relevant for the reconstruction of the muon trajectory. This in turn implies that the second hypothesis based on the Pope&Fry measurements of the absorption length can not be excluded. However, the estimate of the singles rate due to Potassium decays may be larger because the light may scatter more frequently in this hypothesis but arrive eventually at a PMT anyway. This could resolve a longstanding discrepancy between the observed and the calculated rates. Furthermore, the validity of the second hypothesis may constrain the uncertainty of the inputs to the simulations. For example, if the first hypothesis is considered as a working solution, one should not vary the Smith&Baker absorption length by more than the uncertainty on the Rayleigh scattering length. Finally, it would put the discussion about the water properties in the different sites in the Mediterranean sea in a new perspective.

References

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