Nuclear Inst. and Methods in Physics Research, A 867 (2017) 204–208

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Index of refraction, Rayleigh scattering length, and Sellmeier coefficients in solid and liquid argon and xenon

Emily Grace *, Alistair Butcher, Jocelyn Monroe, James A. Nikkel

Royal Holloway, University of London, Department of Physics, Egham, Surrey TW20 0EX, UK

ARTICLE INFO

Keywords:
Rayleigh scattering
Index of refraction
Liquid argon
Liquid xenon
Solid argon
Solid xenon

ABSTRACT

Large liquid argon detectors have become widely used in low rate experiments, including dark matter and neutrino research. However, the optical properties of liquid argon are not well understood at the large scales relevant for current and near-future detectors. The index of refraction of liquid argon at the scintillation wavelength has not been measured, and current Rayleigh scattering length calculations disagree with measurements. Furthermore, the Rayleigh scattering length and index of refraction of solid argon and solid xenon at their scintillation wavelengths have not been previously measured or calculated. We introduce a new calculation using existing data in liquid and solid argon and xenon to extrapolate the optical properties at the scintillation wavelengths using the Sellmeier dispersion relationship.

1. Introduction

Liquid nobles such as argon and xenon are used many particle detector experiments including neutrino detectors and low-background dark matter detectors. This family of detectors relies on the scintillation light produced by nobles when exposed to external radiation. Understanding such signal in the detectors relies on a precise optical model to simulate the path of the scintillation light between production and detection in the thermal conditions of the detector medium. Key ingredients of this optical model are the index of refraction n and the scattering length, which depends strongly on n. The index of refraction has been measured at the scintillation wavelength of 178 nm in liquid xenon, but not yet in liquid argon. These properties are not well known, and indeed calculations differ from measurements by up to 30%. The state of current knowledge about the index of refraction and scattering length in argon and xenon is reviewed in Section 1.1. This difference is more impactful in larger detectors.

Knowledge of the scattering length in liquid nobles is becoming increasingly important as detectors get larger. In the past decade most liquid argon detectors were small prototypes, where the optical path length was often much shorter than the scattering length and therefore scattering was not a significant effect. In contrast, current and planned detectors are large. Presently constructed are the DarkSide 50 (50 kg) [1], ArDM (1 ton) [2], MicrobooNE (170 tons) [3], ICARUS (760 tons) [4], DEAP3600 (3600 kg), and MiniCLEAN (360 kg). Planned are protoDUNE (770 tons) [5], DarkSide 20k (20k kg) [6], and DUNE (17,000 tons) [7]. The drift length in these detectors range from 1 to 8 m.

1.1. Survey of previous literature

The existing measurements of the index of refraction in argon and xenon are summarized in Section 1.1.1. Historically, measurements of the index of refraction at temperatures at or above the triple point have been used in calculations to predict the value below the triple point, as described in Section 1.1.2. These calculations predict the wavelength dependence, which has been used in experiment simulations [8,9] to model the propagation of photons produced at the scintillation wavelengths in liquid noble targets.

1.1.1. Measurements

- Sinnock and Smith [10] measured the index of refraction as a function of wavelength at temperatures between 90 and 20 K in argon and at temperatures between 80 and 178 K in xenon. These measurements were made in the wavelength range 350–650 nm. The typical experimental error reported is ±0.5%. (Data from [10] is shown in Figs. 1 and 3.)
- Bideu-Mehu et al. [11] measured the index of refraction of room temperature argon and xenon gas between the wavelengths of 140 and 174 nm and used these values to find the Sellmeier

* Corresponding author.
E-mail address: Emily.Williams.2012@live.rhul.ac.uk (E. Grace).

http://dx.doi.org/10.1016/j.nima.2017.06.031
Received 8 June 2017; Accepted 20 June 2017
Available online 27 June 2017
0168-9002/

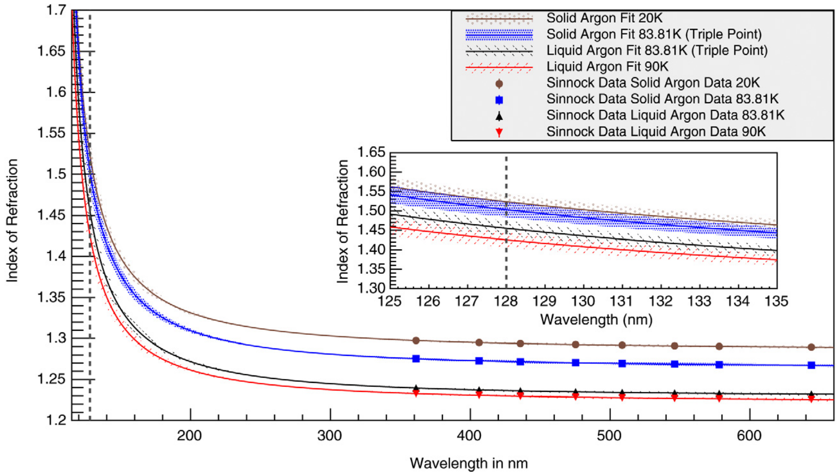

Fig. 1. Calculated index of refraction vs. wavelength (nm) for solid and liquid argon.
Source: The points show the data from Ref. [10].

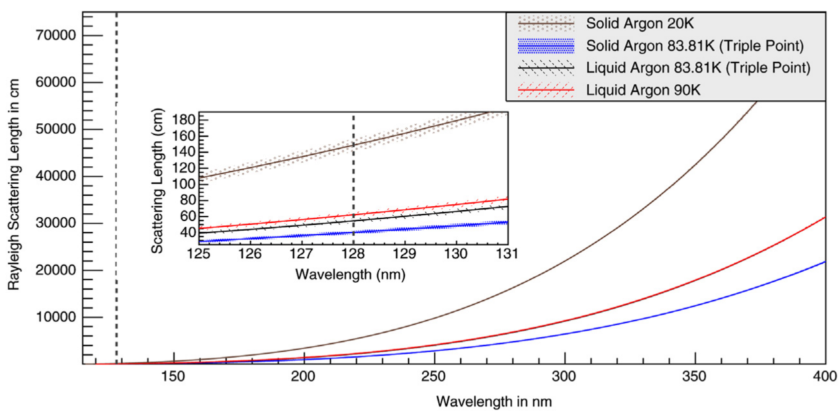

Fig. 2. Calculated Rayleigh scattering length (cm) vs. wavelength (nm) for solid and liquid argon.

coefficients for the gas based Sellmeier [12] equation. The typical experimental error reported is ±0.1%

- Ishida et al. [13] measured the attenuation length of liquid xenon and argon at the wavelengths of 178 nm and 128 nm respectively. They found values of 66 ± 3 cm for argon at 87 K and 29 ± 2 cm for xenon at 196 K.
- Solovov et al. [14] measured the index of refraction and attenuation length of liquid xenon at the triplet point and obtained a value of 1.69 ± 0.02 for the index of refraction and 36 ± 2 cm for the attenuation length.
- The ArDM collaboration published an in situ measurement of the attenuation length of liquid argon in the detector. This yield a measurement of 52 ± 7 cm [15].

1.1.2. Calculation

Seidel et al. calculated the Rayleigh scattering length for liquid argon and xenon. Seidel's calculated values were 90 cm for argon and 30 cm for xenon (the authors did not include the error on their calculation). The calculated Rayleigh scattering length agrees within errors with the measured values for xenon from Ishida et al. The calculation is robust in the sense that the xenon value was calculated using the measured value of the index of refraction in liquid xenon, with no extrapolation in temperature or pressure. In the case of argon, Seidel et al. [16] used STP gas data from Bideu-Mehu et al. [11] to extrapolate the index of refraction at the scintillation wavelength. This was value was adjusted according to the density change from liquid to solid, but any temperature dependence was neglected, a decision made based on the gas measurements by Achtermann et al. [17].

2. Rayleigh scattering length calculation dependence on index of refraction

In the following calculation, the temperature dependence is allowed. Similarly to Seidel et al., we then fit the temperature and density-controlled data from Sinnock and Smith [10] to find the Sellmeier coefficients, which enter the calculation of the index of refraction and thereby the Rayleigh scattering length.

Rayleigh scattering is the process of light elastically scattering off of particles smaller than the wavelength of light. The length of travel for a photon through a medium before Rayleigh scattering is strongly dependent on the wavelength of the light as well as the optical properties of the material. The Rayleigh scattering equation for liquids and solids is

$$l^{-1} = \frac{16\pi^3}{6\lambda^4}\left[kT\rho\kappa_T\left(\frac{(n^2-1)(n^2+2)}{3}\right)^2\right], \tag{1}$$

where l is the scattering length, λ is the wavelength of light, n is the index of refraction corresponding the wavelength of light, T is temperature, ρ is density, and κ_T the isothermal compressibility. For this equation to be valid the index of refraction should be evaluated at the temperature, density and wavelength [18]. There are also material dependent correction factors than can be added to Eq. (1) that do not apply in the case of nobles [19]. This expression for Rayleigh scattering length will be used in the extrapolations in Section 3.