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High-accuracy measurement of the emission spectrum of liquid xenon in the vacuum ultraviolet region

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ABSTRACT

The emission spectrum of cryogenic liquid xenon in the vacuum ultraviolet region was measured by irradiating liquid xenon with gamma-rays from a radioactive source. To achieve a high signal-to-noise ratio, we employed coincident photon counting. Additionally, the charge of the photo-sensor signals was measured to estimate the number of detected photons accurately. In addition, proper corrections were incorporated for the wavelength; response functions of the apparatus obtained using a low-pressure mercury lamp, and photon detection efficiencies of the optical system were considered. The obtained emission spectrum is found to be in the shape of a Gaussian function, with the center at $57{,}199 \pm 34$ (stat.) ± 33 (syst.) cm^{-1} (174.8 ± 0.1 (stat.) ± 0.1 (syst.) nm) and the full width at half maximum of 3328 ± 72 (stat.) ± 65 (syst.) cm^{-1} (10.2 ± 0.2 (stat.) ± 0.2 (sys.) nm). These results are the most accurate values obtained in terms of the data acquisition method and the calibration for the experimental system and provide valuable information regarding the high-precision instruments that employ a liquid-xenon scintillator.

1. Introduction

Liquid xenon is an excellent scintillation material because of a number of advantages such as its large photon yield and fast response. This material is used primarily in astrophysics and particle physics studies. A currently on-going underground experiment [1] employs a ton-scale detector containing ultrapure liquid xenon as the scintillator with the aim of directly detecting the weakly interacting massive particle (WIMP), which is supposed to constitute dark matter. An accelerator-based experiment [2] searches for rare muon decays using a ton-scale liquid-xenon scintillator as an efficient gamma-ray detector to observe new signs of physics beyond the Standard Model. Time-projection chambers using liquid xenon as a drift medium are now under development [3] with the aim of furthering the use of positron emission tomography for medical applications.

The principal part of the emission spectrum of liquid xenon is in the vacuum ultraviolet (VUV) region, as is also the case for gaseous xenon. The emission mechanism [4] is considered to be a common radiative de-excitation process of the excimer Xe_2^*. This excimer is produced from the primary ionized or excited xenon atoms through interactions with ambient ground-state xenon.

However, different values for the emission wavelength have been reported and used in previous studies. Jortner et al. reported [5] that the emission spectrum of liquid xenon is centered at 56,180 cm^{-1} with the full width at half maximum (FWHM) of 4500 cm^{-1}. These values can be readily converted into wavelengths of 178.0 nm and 14.3 nm, respectively, with the central value being used widely. However, a textbook [6] listed slightly shorter values, such as 174 nm for the central wavelength. This small difference is not negligible when planning or performing accurate experiments. Contrary to the case in the visible region, the same amount of difference in the wavelength affects various optical parameters significantly in the VUV region. The Rayleigh scattering length is a representative example. We can calculate the scattering length following the discussion by Seidel et al. [7] using recent values of the refractive index of liquid xenon [8]. The results show that a difference of only 4 nm in the wavelengths can cause a change of 20% or more in the Rayleigh scattering length of approximately 40–50 cm for the VUV scintillation light of liquid xenon.

Furthermore, for other practical applications of liquid-xenon scintillators, knowledge of the correct emission spectrum is indispensable, notably in determining the accurate response of a detector. The correct wavelength dependence of photon transmittance of any devices must be considered. Optical processes occurring inside or at the boundary of the liquid xenon, such as

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scattering, reflection, and refraction, are usually wavelength dependent.

The purpose of this study was to determine the emission spectrum of liquid xenon accurately. We developed a sophisticated optical system suitable for use with cryogenic liquid xenon and performed spectroscopic intensity measurements for the observed scintillation phenomenon with high sensitivity. The optical system was calibrated using a standard light source, and the data were corrected carefully using proper spectroscopic procedures.

2. Experimental setup

2.1. Optical system

We constructed an optical system on the basis of the coincident-photon-counting technique [9] to measure the monochromated weak emission of liquid xenon. Fig. 1 shows the side view of the optical system. The optical components were placed under vacuum condition to allow for VUV light conduction and to thermally insulate the liquid-xenon container effectively.

Liquid xenon was cooled cryogenically in a small cylindrical container placed within a vacuum chamber and excited by gamma-rays (1.17 and 1.33 MeV) from a standard checking ^{60}Co source (1.8 MBq), which was placed outside the surface of the vacuum chamber. The container was made of stainless steel and was equipped with MgF_2 viewports at both ends. The inner dimensions of the container were the following: diameter of 16 mm and length of 56.6 mm.

The scintillation light emitted through one end of the container was detected directly by a VUV-sensitive photomultiplier (PMT) with a quartz window (Hamamatsu Photonics, a custom product based on R7600, referred to as PMT1). The voltage applied to PMT1 was +800 V. The scintillation light exiting the other end of the container was first monochromated by a Seya-Namioka-type vacuum monochromator (Acton, VM-502-S). The primary specifications of the monochromator were as follows: wavelength accuracy of 0.1 nm, focal length of 0.2 m. and *F*-number of 4.5. By considering the *F*-number, the container size and its position were set to minimize the amount of light reflected by the inner surface of the container; therefore, all light entered directly into the monochromator. The wavelength setting and scan rate of the monochromator were controlled using a Linux-based software program implemented in a data acquisition system. The monochromated light was then measured with another VUV-sensitive, high-gain PMT with a MgF_2 window (Hamamatsu Photonics, R6836PX, referred to as PMT2). The voltage applied to PMT2 was +1450 V.

2.2. Data acquisition system

The intensity of the monochromated scintillation light was measured using a scaler and a charge-sensitive analog-to-digital converter (ADC) (HOSHIN ELECTRONICS CO., LTD, C009) module in parallel under the control of a computer automated measurement and control (CAMAC) system. To measure the faint signal efficiently even in the intrinsic dark noise of the PMTs, the coincidences and accidental coincidences were counted to deduce the net signal counts.

A schematic diagram of the data acquisition system is shown in Fig. 2. Each analog pulse output from PMT1 was amplified 7.1 times and fed into a constant-fraction discriminator (CFD) to issue the nuclear instrumentation module (NIM) pulse for the scintillation timing. The output analog pulse of PMT2, which detected photons of monochromated light, was first duplicated by a linear fan-in/fan-out module (LeCroy, 428F). One pulse was fed into the analog input of the ADC to evaluate the signal charge in each pulse. Here, the charge integration time was selected to be 250–300 ns (depending on the run) to cover most of the scintillation. The other analog pulse was fed into the CFD to output a NIM pulse used to count the numbers of coincidences and accidental coincidences in combination with the NIM pulse of PMT1. The coincidence condition was that the PMT2 signal should appear within 240–300 ns (depending on the run) after the PMT1 signal. By contrast, the accidental coincidence condition was that a 1 μs delay was added to the PMT2 signal for the coincidence condition; this condition did not result in a correlation. In addition, these NIM pulses were counted separately as single rates of every PMT.

The NIM pulses were also used for other purposes in the electronics. The gate pulse was generated for the ADC using the NIM pulse of PMT1. Another NIM pulse, with a width of 500 μs, was used to inhibit the input of the ADC during the ADC data conversion, which lasted for 200 μs.

2.3. Xenon-handling system

A diagram of the xenon-handling system is shown in Fig. 3. After evacuating the entire gas line to a residual pressure on the order of 10^{-5} Pa, pure xenon gas was introduced into the line through a purifier containing 5000 activated getter pills (SAES Getters, St707 Pill/4-2/50). While maintaining the target pressure at approximately 110 kPa, the xenon gas was cooled and condensed in the container continuously using a pulse-tube refrigerator (Iwatani Corp., PDC08Y); additional xenon gas was supplied continuously.

The pressure of the xenon gas was measured with a digital manometer (Yokogawa Electric Corp., MT110). The refrigeration power was compensated for with a heater attached on the cold head to maintain a target temperature; a platinum resistance thermometer and a digital indicating controller (CHINO Corp., DB1000) were employed for this purpose.

The fluid level of the liquid xenon was monitored using three platinum resistance thermometers (LakeShore, PT-111) set vertically at different points in the container at an interval of approximately 8 mm from the bottom. The temperatures from the three thermometers were read with a data acquisition/switch unit

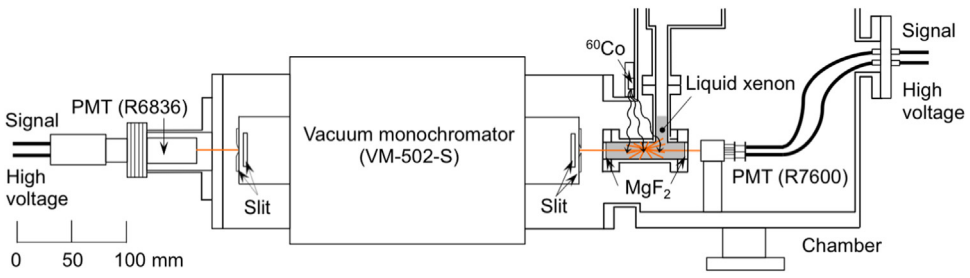

Fig. 1. The schematic side view of the optical system under vacuum. A ^{60}Co source is located on the side surface of the chamber and irradiates liquid xenon. The scintillation light was emitted through two ends of the liquid xenon container; one end was detected directly by a PMT, and the other was detected by another PMT after passing through the monochromator.