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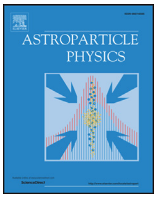

Light yield determination in large sodium iodide detectors applied in the search for dark matter

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ABSTRACT

Application of NaI(Tl) detectors in the search for galactic dark matter particles through their elastic scattering off the target nuclei is well motivated because of the long standing DAMA/LIBRA highly significant positive result on annual modulation, still requiring confirmation. For such a goal, it is mandatory to reach very low threshold in energy (at or below the keV level), very low radioactive background (at a few counts/keV/kg/day), and high detection mass (at or above the 100 kg scale). One of the most relevant technical issues is the optimization of the crystal intrinsic scintillation light yield and the efficiency of the light collecting system for large mass crystals. In the frame of the ANAIS (Annual modulation with NaI Scintillators) dark matter search project large NaI(Tl) crystals from different providers coupled to two photomultiplier tubes (PMTs) have been tested at the Canfranc Underground Laboratory. In this paper we present the estimates of the NaI(Tl) scintillation light collected using full-absorption peaks at very low energy from external and internal sources emitting gammas/electrons, and single-photoelectron events populations selected by using very low energy pulses tails. Outstanding scintillation light collection at the level of 15 photoelectrons/keV can be reported for the final design and provider chosen for ANAIS detectors. Taking into account the quantum efficiency of the PMT units used, the intrinsic scintillation light yield in these NaI(Tl) crystals is above 40 photons/keV for energy depositions in the range from 3 up to 25 keV. This very high light output of ANAIS crystals allows triggering below 1 keV, which is very important in order to increase the sensitivity in the direct detection of dark matter.

1. Introduction

Thallium Activated Sodium Iodide (NaI(Tl)) scintillators have been widely used for radiation detection [1,2] since they were proposed by R. Hofstadter in 1948 [3]. Among other remarkable features, the very high intrinsic scintillation light yield has probably been a key factor leading to their widespread use. Sodium iodide scintillators have been applied very satisfactorily in fields as different as: nuclear medicine, environmental monitoring, nuclear physics, aerial survey, well logging, homeland security, etc. Energy ranges from 10 keV to several MeV can be covered with state-of-the-art technology, but applications requiring high sensitivity at lower energies have moved to other detection techniques having better energy resolution and/or lacking the hygroscopic property of NaI, which makes it difficult for low energy radiation to access the sensitive volume. However, these detectors have been successfully applied since the nineties in the direct search for dark matter in the form of WIMPs (Weakly Interacting Massive Particles), that should pervade the galactic halo and because of their very low interaction probability with matter, they could reach that sensitive volume independently of the encapsulation or even the placement of the detector in an underground location, as is usually done in order to reduce the cosmic-ray-induced background. Several experimental efforts using NaI(Tl) detectors applied in the search for dark matter can be found in the literature [4–9], as well as several proposals for the near future [10–14].

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The ANAIS project aims at the installation of a 112.5 kg NaI(Tl) experiment at the Canfranc Underground Laboratory (LSC), in Spain, to study the annual modulation effect expected in the interaction rate of dark matter particles as result of the Earth's motion around the Sun [15]. In the frame of ANAIS a long effort has been carried out in understanding radioactive backgrounds in NaI(Tl) detectors [16–19] and in the assessment of NaI(Tl) detectors performance [20–22]. For such a purpose, crystals from different providers (BICRON, Saint-Gobain, and Alpha Spectra) have been studied. In this work, we will present our estimates of total light collected by the PMTs for low energy depositions produced using external sources, but also internal contamination homogeneously distributed in the crystal bulk. Total light seen by the light detection system in scintillating detectors is one of the most relevant figures of merit, contributing strongly to the achievable energy threshold, succesful implementation of PMT noise rejection procedures, and energy resolution. It depends on intrinsic scintillation light yield of the scintillating material and light collection efficiency of the detection system, including self-absorption, trapped light by total internal reflection, light losses by the multiple reflections and scattering in the non-sensitive detector surfaces, and Quantum Efficiency (QE) of the PMTs used as light sensors. It can be determined by comparing the signal produced by the full-absorption of a given energy in the scintillating material and the signal corresponding to a single p.e.; then, it can be converted into scintillation photons reaching the PMT by correcting by the QE provided by the manufacturers of the PMT units used. However, intrinsic scintillation light yield for NaI(Tl) is not easy to deconvolve from the total light collected measurement, as light collection efficiency should be known. Knoll and others [23] suggested the intrinsic scintillation efficiency in NaI(Tl) to be 40,000 photons/MeV, implying a W_s value of 25 eV for the average energy required to produce a scintillation photon. More recent estimates of W_s as low as 15 eV can be found in the literature [24]. However, there are theoretical estimates of lower W_s value in NaI(Tl), resulting in a maximum scintillation efficiency of about 100,000 photons/MeV [25]. The high light collection values reported in this work for very large NaI(Tl) crystals using gamma/electron radiation at very low energy could be an interesting input for such calculations, as far as most of the previous reports and analysis do not reach such low energy range [23–29] and have been obtained with smaller crystals, for which light propagation and collection is not expected to be such a relevant issue; moreover, some aspects of the scintillation mechanism in NaI(Tl) crystals are not yet fully understood [30,31].

The structure of this paper is as follows: in Section 2 we describe the ANAIS prototype modules used in the reported measurements and in Section 3, the data acquisition system. In Section 4 we describe our analysis procedure to derive the Single Electron Response (SER) and the full-absorption lines considered for the determination of the light collected at each PMT. Finally, in the last sections results are presented and conclusions drawn.

2. Modules description

In this work, crystals from three different manufacturers, and having different size and shape, have been characterized in terms of the light collected by each PMT and in total in each crystal:

- A 10.7 kg hexagonal prism NaI(Tl) crystal (distance between opposite vertices in the hexagonal face 15.94 cm, and 20.32 cm high) disassembled from the original stainless steel encapsulation made by BICRON. It was polished and cleaned at the University of Zaragoza (see Fig. 1a). The hexagonal surfaces were polished to optical quality by mechanical polishing using sapphire grain sandpapers of decreasing grain size; lateral surface of the prism was left rough (only polishing using large sapphire grain sandpaper). A new 1 mm-thick Oxygen Free High Conductivity (OFHC) copper encapsulation was specifically designed for this prototype, shown in Fig. 2a. In the following, we will refer to this detector as PIII.
- A 9.6 kg parallelepiped ultrapure NaI(Tl) crystal (10.2 × 10.2 × 25.4 cm^3), made by Saint-Gobain, was encapsulated at the University of Zaragoza using 1 mm-thick Electrolytic Tough Pitch (ETP) copper, and it is shown in Fig. 1b, and Fig. 2b. Only the square surfaces were polished using isopropanol; lateral surface was left rough, as the manufacturer produced. In the following, this module is labelled A0.
- Several units of 12.5 kg crystals made by Alpha Spectra Inc. (AS) using a low-potassium content NaI powder (purified at AS) and encapsulated in Oxygen Free Electrolytic (OFE) copper at AS. They are cylindrical, with 12.1 cm in diameter and 29.8 cm in length. Surface finish was done at AS, and the corresponding surface treatment is under confidentiality agreement. We include below data from the first four units AS has built for ANAIS-112 experiment, that are labelled as D0, D1, D2, and D3. Fig. 1c shows D0 and D1 crystals at AS, and Fig. 2c shows the D0 module.

Table 1
Quantum efficiency at 420 nm for the PMT units used in the determination of the NaI crystals' total light yield presented in this work. Provided by manufacturer.

PMT model	PMT unit reference	QE (%)
Ham R11065SEL	BA0086	28.68
	BA0057	32.90
Ham R6956MOD	ZK5902	34.9
	ZK5908	34.4
Ham R12669SEL2	FA0018	33.9
	FA0060	36.4
	FA0034	35.9
	FA0090	39.0

All the modules share some common features:

- Low background Hamamatsu PMTs of different models have been used for the tests. QE nominal values from manufacturer for the different units used in the reported measurements are given in Table 1.
- An aluminized Mylar window (20 μm thick and 10 mm diameter) in the middle of one of the lateral faces allows for external calibration of all the modules at very low energies (see Fig. 2).
- Tight sealing is done at the level of the two 7.6 cm diameter quartz optical windows and two PMTs are coupled to each crystal in a second step:
  - 1.27 cm thick natural quartz optical windows were used for the PIII module;
  - 1 cm thick synthetic quartz optical windows were used for A0 and all the AS modules.

These modules have been operated at the facilities of the LSC, in Spain, under 2450 m.w.e. Detectors, in all the different set-ups considered in this work, one of which is shown in Fig. 3, were installed in a shielding consisting of 10 cm archaeological lead plus 20 cm low activity lead, all enclosed in a PVC box tightly closed and continuously flushed with nitrogen gas. For the here reported analysis we have used data from calibration runs using external sources, and from background data at very low energies, which have profited from the underground location and shielding. Next, we list some details of the different set-ups for which results will be presented in Section 4.