Bulk NaI(Tl) scintillation low energy events selection with the ANAIS-0 module

C. Cuesta\textsuperscript{a,b,c,1}, J. Amaré\textsuperscript{a,b}, S. Cebrián\textsuperscript{a,b}, E. García\textsuperscript{a,b}, C. Ginestra\textsuperscript{a,b}, M. Martínez\textsuperscript{a,b,d}, M. A. Oliván\textsuperscript{a,b}, Y. Origoza\textsuperscript{a,b}, A. Ortíz de Solórzano\textsuperscript{a,b}, C. Pobes\textsuperscript{a,b,c,e}, J. Pumedón\textsuperscript{a,b}, M. L. Saras\textsuperscript{a,b}, J. A. Villar\textsuperscript{a,b}, P. Villar\textsuperscript{a,b}

\textsuperscript{a}Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, Calle Pedro Cerbuna 12, 50009 Zaragoza, Spain
\textsuperscript{b}Laboratorio Subterráneo de Canfranc, Paseos de los Ayerbe s/n, 22880 Canfranc Estación, Huesca, Spain
\textsuperscript{c}Present Address: Center for Experimental Nuclear Physics and Astrophysics, and Department of Physics, University of Washington, Seattle, WA, US
\textsuperscript{d}Fundación ARAID, María de Luna 11, Edificio CEEI Aragón, 50018 Zaragoza, Spain
\textsuperscript{e}Present Address: Instituto de Ciencia de Materiales de Aragón, Universidad de Zaragoza - CSIC, Calle Pedro Cerbuna 12, 50009 Zaragoza, Spain

Abstract

Dark matter particles scattering on target nuclei are expected to deposit very small energies in form of nuclear recoils (below 100 keV). Because of the low scintillation efficiency for nuclear recoils vs. electron recoils, in most of the scintillating targets considered in the search for dark matter, the region below 10 keVee (electron equivalent energy) concentrates most of the expected dark matter signal. For this reason, very low energy threshold (at or below 2 keVee) and very low background are required to be competitive in the search for dark matter with such detection technique. This is the case of ANAIS (Annual modulation with NaI Scintillators), which is an experiment to be carried out at the Canfranc Underground Laboratory. A good knowledge of the detector response function for real scintillation events in the active volume, a good characterization of other anomalous or noise event populations contributing in that energy range, and the development of convenient filtering procedures for the latter are mandatory in order to achieve the required low background at such a low energy. In this work we will present the specific protocols developed to select bulk scintillation events in NaI(Tl), and its application to data obtained with the ANAIS-0 prototype. Slight differences in time constants are expected in scintillation pulses produced by nuclear or electron recoils in NaI(Tl), so in order to analyze the effect of these filtering procedures in the case of a recoil population attributable to dark matter, data from a neutron calibration have been used.

Keywords: Dark Matter, Annual modulation, Underground Physics, Sodium iodide scintillators

1. Introduction

The annual modulation in the detection rates could evidence the presence of galactic dark matter through events even in the presence of other backgrounds [1]. The search for such an effect is of utmost interest specially in the case of using NaI(Tl) as a target because of the DAMA/LIBRA positive result: a modulation compatible with that expected for galactic halo WIMPs has been reported after 14 cycles of measurement with 9.3σ statistical significance (combining the results with the previous phase of the experiment, DAMA/NaI) [2, 3, 4]. Other experiments with gamma background rejection have obtained negative results (some of the most recent and significant negative results can be found in [5, 6, 7, 8, 9, 10, 11, 12, 13]). Recently, CoGeNT experiment has reported the presence of an annual modulation in the event rate [14, 15] that could have its origin in galactic WIMPs (although different results are contradictory conclusions [16, 17, 18]), while the dark matter hints reported by CDMS-Si [19] and CRESST [20] experiments are more likely attributable to unaccounted for backgrounds [21].

The difficulty to find dark matter candidates able to explain all the present experimental results [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13] makes important the dependence on the halo and WIMP models considered to compare different targets [28, 29, 30, 31, 32, 33], the partial understanding of the experimental backgrounds at low energy [34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44], and the uncertainties in the recoil energy calibration [45, 46, 47] which affect the interpretation of most of the available results, make highly interesting confirming the DAMA/LIBRA annual modulation observation in a model independent way. This is the goal of the ANAIS experiment. The ANAIS project is intended to search for dark matter annual modulation with 250 kg of ultrapure NaI(Tl) scintillators at the Canfranc Underground Laboratory (LSC) [48, 49, 50] in Spain. To be successful ANAIS would require a background rate at or below 2 cpd/keV/kg for a 2 keVee (electron equivalent energy) threshold, and very stable working conditions. Several prototypes have been operated in order to demonstrate the detectors performance, remaining as main challenge the achievement of radiopure enough NaI(Tl) crystals [51]. In this work, we present a thorough description of the event selection procedures applied to the ANAIS-0 module, a 9.6 kg NaI(Tl) crystal grown by Saint Gobain and similar in shape to those made for DAMA/LIBRA. In the event selection procedure based on scintillation time constants, scintillation pulses coming from a neutron calibration performed with a different NaI(Tl) crystal have been used in order to correct the calculated efficiencies obtained from gamma calibration.
tion, accounting for the slight difference in scintillation decay time [52]. Presently, two prototypes built in collaboration with Alpha Spectra Inc., Colorado, US, grown with potassium radiopure NaI powder and having 12.5 kg mass each, are taking data at LSC for a general performance and background assessment in the ANAIS-25 setup. All the developed protocols for filtering of real bulk scintillation events in the crystals detailed in this paper are being adapted and applied to the Alpha Spectra crystals data.

In section 2 the ANAIS-0 module and the experimental set-up will be described. In section 3 the energy calibration of ANAIS-0 at very low energy will be presented. The trigger efficiency will be studied in section 4. The procedure followed to select the bulk NaI scintillation events at low energy will be described in section 5. Finally, the application of such a procedure to neutron calibration data will be presented in section 6.

2. Description of ANAIS-0 module and experimental set-up at LSC

The detector studied throughout this work consists of a 9.6 kg ultrapure NaI(Tl) crystal, 4” x 4” x 10”, made by Saint-Gobain (see Figure 1). The crystal was encapsulated in ETP (Electrolytic Tough Pitch) copper, closing tightly the detector, and using two synthetic quartz windows to get the light out to the photomultiplier tubes (PMTs). A Teflon sheet acts as a diffruser to increase light collection efficiency. This design allowed the testing of PMTs and light guides in different configurations, as described in [49], although in this work we will focus on results obtained without light guides and no further reference to them will be done in the following. The crystal was encapsulated at the University of Zaragoza and the coupling of the PMTs to the quartz windows was done later at the LSC. Low background Hamamatsu PMTs of two different models, R11065SEL and R6956MOD, have been used in this work, corresponding to data sets A and B respectively (see Table 1). According to the manufacturer, for both PMT models the maximum spectral response should be found at 420 nm wavelength, matching properly the emission of NaI(Tl), and being the respective spectral sensitivities at 200 to 650 nm (R11065SEL) and from 300 to 650 nm (R6956MOD). Nominal quantum efficiencies at 420 nm are 29% and 33% for the R11065SEL, and 34% and 35% for the R6956MOD PMT units used in this work (given by provider). Radioactivity screening of the PMTs was done at the HPGe test bench at the LSC. Results for the measured activities corresponding to the identified radioisotopes can be found in [53], and are significantly lower (about a factor of 3) for the R11065SEL model than for the R6956MOD model. An aluminized Mylar window, 20 µm thick and 10 mm in diameter, in the middle of one of the lateral crystal faces allows for external calibration at very low energies (see Figure 1).

ANAIS-0 module was designed to characterize and understand ANAIS background at low energy, optimize NaI scintillation events selection, fix the calibration method, and test the electronics while new more radiopure detectors are in preparation for a 250 kg detection mass experiment. ANAIS-0 was operated at the new LSC facilities, under a rock overburden of 2450 m.w.e. Underground operation at such a depth guarantees a significant cosmic ray suppression; measured muon flux at LSC is of the order of $10^{-7}$ cm$^{-2}$s$^{-1}$ [54,55]. ANAIS-0 experimental layout at LSC (see Figure 2) consisted in a passive shielding made of 10 cm archaeological lead plus 20 cm low activity lead, all enclosed in a PVC box tightly closed and continuously flushed with boil-off nitrogen, and active vetoes mounted on top of the shielding to reject coincident events in ANAIS-0 module.

Concerning the data readout, a simplified diagram of the electronic chain is shown in Figure 3. Each PMT charge output signal is separately processed: it is divided into two signals, a conveniently amplified signal going to the digitizer, and three signals differently amplified or even attenuated and fed into QDC (charge-to-digital converter) module channels to be integrated in a 1 µs window. Triggering is done by the coincidence (logical AND) of the two PMT signals at photoelectron level in a 200 ns window enabling digitization and conversion of the two signals. The building of the spectra is done by soft-
ware (off-line) by adding the signals from both PMTs. Energy spectra are obtained from the QDCs in three different gain windows chosen to match a low, a high, and a very high energy ranges: the first one covers from threshold up to 200 keV, the second up to about 6 MeV, and the latter up to about 40 MeV. In this work only the low energy range will be used. In order to obtain all the information from the shape of the pulse, each PMT signal is separately digitized.

3. Energy calibration of ANAIS-0 at very low energy

The dark matter signal in NaI is expected below 10 keVee; hence, a very good knowledge of the detector response at very low energies is mandatory, requiring powerful noise rejection protocols and reliable low energy calibration. For both purposes, reference populations of scintillation events at low energy are required. To allow that very low energy X and gamma ray emissions from external radioactive sources reach the crystal, a calibration window was included in the design of the ANAIS-0 module encapsulation (see Figure 1). The external gamma calibration sources used are: $^{55}$Fe (6.0 keV), $^{109}$Cd (22.6 keV and 88.0 keV), $^{57}$Co (6.4 keV, 14.4 keV and 122.1 keV), and $^{133}$Ba (31.7 keV and 81.0 keV). However, the less the energy of the radiation, the less representative is the event for a bulk energy deposition being eventually affected by superficial effects in the light emission and collection. Then, in order to dispose of a population of events in the bulk at very low energy, the $^{40}$K internal contamination is very useful: 3.2 keV energy depositions are obtained after K-shell EC in $^{40}$K in those cases the 1460.8 keV gamma escapes completely from the detector active volume; a fraction of such events can be effectively tagged by selecting coincidences with a 1460.8 keV energy deposition in a second detector. A dedicated set-up using the ANAIS-0 module and a second large NaI(Tl) detector (10.7 kg), named as prototype III (PIII) and described in [53], was operated at the LSC searching for such coincident events. This measurement was done right after the measurements corresponding to data set B, under similar experimental conditions: in particular, same light collection efficiency than that corresponding to data set B was checked (see section 5). This set-up allowed to determine the $^{40}$K bulk content in both crystals and to select a population of 3.2 keV events [57]. In Figure 4.a and b are shown, respectively, the high energy spectrum of PIII and the ANAIS-0 low energy events selected by the coincidence with the 1460.8 keV gamma line in PIII in a 1 σ window, shown in red in Figure 4.a. This event population will be used for energy calibration in this section, and for other purposes in next sections.

One of the most important issues for ANAIS is to guarantee a good energy calibration at the lowest energies, down to the threshold. A linear fit energy vs QDC channel using all the available lines below 150 keV during the $^{40}$K dedicated set-up is shown in Figure 5.a together with the corresponding residuals. It has to be reminded that residuals at 6.4 and 6.0 keV are much larger (and both positive) considering them in percent than those corresponding to other lines. Non-proportionality in the scintillation yield with respect to the deposited energy has been observed in inorganic scintillators [59, 60]. In particular, in NaI(Tl) scintillators some non-linear effects are expected at the K-shell Iodine binding energy (33.2 keV). This fact has been observed experimentally [60, 61, 62, 63, 64], but at a level of only 5% in the amplitude response. Similarly, at around 5 keV

---

1 X-ray energies averages have been calculated according to the relative intensities given in [58], as NaI(Tl) resolution prevents from distinguishing them individually.
Figure 4: (a) High energy spectrum of the 10.7 kg detector showing in red the 1σ window around the 1460.8 keV line used for the coincidence. (b) Energy distribution of the ANAIS-0 events selected by the coincidence with the high energy window in the 10.7 kg crystal, shown in (a).

(L-shell Iodine binding energy) the same effect is expected, as it has been observed in Refs. [64, 65]. Nevertheless, the reported non-linearity cannot explain such a large effect as that seen in Figure 5b: 6.0 keV line appears with an effective energy of 4.2 keV and 6.4 keV line with 4.8 keV. However, this effect could be due to the very low penetration depth of that radiation in the crystal that could reduce the light collected with respect to the same energy deposition for bulk events, as those from 40K. It is worth mentioning that the mean free path of a 6 keV photon in NaI(Tl) is 5.1 µm, whereas for a 15 keV photon is 0.06 mm. This hypothesis is supported by similar results obtained by several groups working with large size NaI(Tl) detectors and aiming at the detection of dark matter, that have observed good linearity at low energies, but reductions in the response to 6.0 keV energy X-rays from an external source that were attributed to superficial effects [66, 67]. In Ref. [67] a Compton scattering experiment was designed in order to obtain a volume-distributed low-energy population whose results supported such assumption.

Hence, we removed both lines from the calibration procedure, obtaining the fit shown in Figure 5b. Finally, as the dark matter region of interest in NaI(Tl) scintillators is below 10 keVee, it was decided to calibrate the low energy range using only 3.2 keV, 14.4 keV and 22.6 keV lines trying to minimize possible non-linear effects in the detector response. In Figure 5c are shown the linear fit and residuals corresponding to the low energy calibration for data set A (similar calibration has been applied to data set B). Then, 0.5 keV can be taken as a reasonable estimate of the systematic error of our low energy calibration in the dark matter region of interest.

4. Trigger efficiency estimate

Lowering the threshold as much as possible is mandatory in any experiment devoted to the direct search for dark matter. The lowest achievable threshold in a scintillation experiment implies, as first step, to trigger at single photoelectron (phe) level in each PMT signal. We have studied the trigger level in ANAIS-0 by two different methods: first, the distribution of amplitude of the Single Electron Response (SER) is compared to the amplitude of a single peak (at the trigger position), and second, the 3.2 keV events population selected by the coincidence has been profitied to study how many of them trigger effectively our acquisition.

Profiting from the high sampling rate of the digitized data, the discrete arrival of the scintillation photons to the PMT photocathode can be distinguished at low energies. An algorithm...
that determines the number of peaks in the pulse has been developed. It is based on the TSpectrum ROOT class and the Search method [67]. Peaks are considered Gaussian with a minimum height and width, which are selected specifically for every data set, as the SER depends on the PMT model. By choosing these parameters according to the SER of the PMT, peaks are found, counted, and their positions saved. In Figure 6, a low energy pulse is shown and the peaks identified by the algorithm are marked. It is worth noting that this algorithm can only be applied to events with a low number of phe, otherwise the number of peaks would underestimate the number of phe, since the probability of two phe overlapped is not negligible.

Figure 6: Low energy pulse (from the population of 3.2 keV events after ⁴⁰K decay, selected by coincidence) showing peaks identified by the peak search algorithm. They are counted independently for each PMT signal and their positions saved. The pulse shown corresponds to data set B (data taken with the MATACQ).

The SER parameters (amplitude, area, etc.) are determined from a population of single photoelectron peaks built by selecting the last identified peak by this algorithm in pulses having a low number of peaks. As far as only peaks found in the last part of the pulse are used to build the SER, bias related to effective trigger efficiency is avoided. Figure 7 compares the amplitude distribution of the SER and that corresponding to a single peak (responsible of the trigger) for pulses having only one peak per PMT. The SER amplitude spectra have been Gaussian fitted: mean values and standard deviations are shown in Table 2. Full trigger at photoelectron level has been achieved in data set A, as it can be observed in Figure 7: single peak amplitude distribution follows quite well the SER distribution plus a baseline noise component also triggering the acquisition; on the other hand, an effective trigger threshold at 12 mV is observed in data set B. In this case, by comparing such effective trigger threshold with the mean value and standard deviation of the SER amplitude distribution Gaussian fit, the percent of the SER distribution effectively triggering is calculated (see Table 2). As a conclusion, full trigger at phe level was achieved in data set A, whereas trigger at or above 50% phe level can be reported for data set B.

In the case of data set A, for which a lower light collection was obtained (~2.7 phe/keV/PMT [53]), the influence of the coincidence window width on the trigger efficiency cannot be neglected. Monte Carlo simulation of the phe arrival at every PMT for a given energy deposition, supposing for bulk NaI scintillation events phe are distributed following an exponential decay with τ = 230 ns and the reported light collection efficiencies. The results for a 200 ns coincidence window indicate an efficiency of 97% in the 2-3 keV energy bin and 100% above 3 keV. In the case of data set B, with a light collection of ~3.7 phe/keV/PMT [53], the coincidence window width effect on the trigger efficiency is negligible above 2 keV.

In order to quantify the trigger efficiency at threshold in a direct way, we profit from the availability of the selected population of 3.2 keV presented in the previous section. The trigger configuration of every event is described with the T variable: T = 1, if only ANAIS-0 triggered; T = 2, if only PIII triggered; and T = 3 if both detectors triggered. In Figure 8 spectra of the ANAIS-0 module in coincidence with the 1460.8 keV line in the PIII are shown. No events with T = 1 are found in this population because the imposition of the coincidence implies that PIII always triggers. Events in the peak at 3.2 keV (those above 1.5 keV in Figure 8) triggered with almost full efficiency (98%), supporting a very high trigger efficiency at or even below 2 keVee. In conclusion, very high trigger efficiency above 2 keVee has been achieved with ANAIS-0 prototype and full trigger at photoelectron level has shown to be achievable, fulfilling the goal of ANAIS experiment.

![Figure 7](image7.png)

Figure 7: SER (black) and single peak amplitude (blue) distribution for data sets A (a) and B (b). Different PMT models have been used in each data set.

| Data set | Signal | µ_{SER} | σ_{SER} | Eff. |
|----------|--------|---------|---------|------|
| A        | PMT 0  | 20 ± 1  | 7.3 ± 0.1 | 100  |
|          | PMT 1  | 23 ± 1  | 8.0 ± 0.1 | 100  |
| B        | PMT 0  | 12 ± 1  | 5.9 ± 0.1 | 50   |
|          | PMT 1  | 16 ± 1  | 11 ± 1   | 65   |

Table 2: Mean photoelectron amplitude (µ_{SER}), standard deviation (σ_{SER}), together with the percent of the photoelectron distribution effectively triggering every PMT signal channel (see text for details). Data are shown for data sets A and B. If the existence of an unphysical region of negative amplitudes is taken into account, recalculated triggering efficiencies are 60% (data set A) and 70% (data set B).
5. Bulk NaI scintillation low energy events selection

Below 10 keVee, raw data from NaI scintillator detectors are dominated by other than bulk scintillation events, having mainly their origin in the PMTs. Strong rejection of such kind of events is required, see Figure 8 in order to reduce the effective energy threshold down to 2 keVee. Dark matter particles are expected to interact in our detector by elastic scattering off Na and I nuclei. Hence, the energy is deposited through the interaction of the corresponding recoiling nucleus in the crystal. Dark matter events are expected to be very similar to those produced by neutrons, and to share some features with those having beta/gamma origin; the last two can be produced using calibration sources in order to have reference populations that allow a good NaI(Tl) bulk scintillation event characterization. However, dark matter events neither should be correlated with muon interactions in the vetoes, nor appear in coincidence between two or more modules, nor accumulate in short time periods, nor show anomalous scintillation time constants in the pulse shape, for instance. All these events populations, non attributable to dark matter interactions, should be conveniently filtered.

The goal is to find a compromise between a high acceptance of bulk NaI scintillation events and low contribution of other spurious events, not rejected by the filtering. This filtering procedure implies in some cases an effective reduction in the acquisition live time, while in others the efficiency of the selection filter to preserve the bulk scintillation events in NaI(Tl) active volume has to be estimated by studying reference populations, specially at very low energies. $^{57}$Co, $^{109}$Cd, and $^{133}$Ba calibration data and the 3.2 keV events following $^{40}$K decay in the bulk have been used for that purpose, whereas $^{252}$Cf calibration data will be analyzed in section 6.

We describe below in detail the filtering procedure followed with ANAIS-0 data. Table 3 shows the efficiency factor considered, as well as the available live time, before and after the application of each filtering procedure to the two data sets considered in this work. All the filters have been applied consecutively and in the order presented in the text to every data set.

1. Muon related events. Active plastic scintillator vetoes were installed on top of the ANAIS-0 shielding to reject the residual cosmic muon flux contribution to the background of ANAIS, and also to monitor the muon rate in the laboratory at the shielding position in order to evaluate any possible seasonal variation. A good comprehension of the muon related events in the ANAIS experiment is required because the annual modulation in the muon rate is well known [69, 70, 71], and it should be discarded as responsible of any modulation observed in the very low energy events rate. This issue has been discussed in the frame of the DAMA/LIBRA experiment [56, 57, 42, 43], and is even more important for the ANAIS experiment because residual muon flux at LSC is about one order of magnitude larger than at Gran Sasso Laboratory, given the smaller rock overburden. Muon coincident events in ANAIS-0 have been identified using the time after the last muon event in the plastic scintillators: a counter is reset by any event triggering one (or more) of the active vetoes; the value of this counter is read and associated to every event in the NaI(Tl) detector. Events coincident in a 20 μs window with a signal in the muon vetoes are rejected off-line. As the ANAIS-0 acquisition rate was $\sim$1 Hz, and muon coincident events rate during data set A was 43.43 ± 0.05 cpd, neither live time nor efficiency corrections are required.

However, muons can produce other kind of events, non-coincident with the veto signals, as delayed neutrons. Furthermore, when a very high energetic particle interacts in the ANAIS-0 module, photons emitted in the tail of the...
pulse, up to hundreds of ms after the pulse onset, are able
to trigger again the acquisition because of the very slow
NaI(Tl) scintillation evidenced in [72] and the setting of
the trigger at photoelectron level. We observed a clear in-
crease in the total acquisition rate after every very high en-
ergy deposition event (see Figure 10), many (but not all) of
them could be identified by the coincidence with a signal
in the muon veto scintillator because of the partial cover-
age. For that reason, in data set A all the events trigger-
during 0.5 s after a high energy event (over 9 MeVee
to guarantee to be well above the usual alpha and gamma
backgrounds) are rejected and the corresponding live time
deducted. Nevertheless, in data set B, because PMT sig-
als saturated at energies much below 9 MeVee, it was de-
cided to reject 0.5 s after the arrival of a muon at the plas-
tic vetoes (conservative approach). The same criterion was
also applied to data set A to verify its compatibility. Spe-
tra of events rejected in both data sets are shown in Fig-
ure 11. Rates of events rejected by this filter in the 2-20
keV region are 4.39 cpd/kg and 8.65 cpd/kg for data sets A
and B, respectively. Main difference between both spec-
tra is found in the 2-6 keV region, and can be explained
by considering the different characteristics of PMT mod-
els used in each data set: quantum efficiencies are different
and PMT body consists of Kovar metal in data set A and
glass in data set B, allowing in the latter for the production
of Cerenkov radiation in the PMT itself after a direct muon
interaction.

2. Events having an anomalous baseline estimate. The
baseline or DC-level is calculated for every event pulse by
averaging the first points of the pretrigger region, clearly
before the pulse onset. If a photon arrives in the pretrig-
ger region, neither the baseline will be properly calculated,
nor other related pulse parameters. These events are eas-
ily identified by their anomalous low baseline level and
they will not be considered for the analysis, see Figure 12.
They can be attributed to tails of pulses which arrived dur-
ding the DAQ rearm time after a previous event, or PMT
dark current photoelectrons. During data set A, the base-
line was calculated with 100 points (80 ns) whereas dur-
ding data set B, after the electronic chain upgrade, with
500 points (250 ns); hence, more events are rejected by
this filter in data set B. In addition, R6956MOD PMTs
(used in data set B) present a higher dark current rate than
R11065SEL PMTs (used in data set A) leading also to re-
ject more events by this filter. A 99.8% of the events above
2 keV pass the filter in data set B, and a 100% in data set A,
indicating that our filtering is not removing significantly
events above our threshold (see later). These numbers can
be considered as the efficiency of the cut in a conservative
way. Although they represent a small percentage of the to-
cal number of events, work is in progress to recalculate the
baseline for these events, and this filter could be avoided
in the future.

3. Events having a very low number of peaks. We re-
ject events having ≤3 peaks in any of the PMTs, apply-
ing the algorithm that determines the number of peaks in
the pulse described in section 4. According to the light
yield measurements, 5.34± 0.05 phe/kEv in data set A and
7.38 ± 0.07 phe/kEv in data set B [53], this implies an ef-
fective analysis threshold below 2 keVee. This filter allows
to reject events triggering due to a chance coincidence be-
tween uncorrelated photoelectrons in both PMTs (directly
related to their respective dark currents), or events having
their origin in the PMTs due to its own radioactivity (pos-
sible Cerenkov light emission in the PMT glass, for in-
stance) that are expected to produce a signal very similar
to SER, except in amplitude/area. The effect of this fil-
ter in data of a 57Co calibration is shown in Figure 13 for
data sets A and B. This filter is mostly removing events

Figure 10: ANAIS-0 module total trigger rate (in blue) along a week (a), and
10 s zoom (b). In red, very high energy events (above 9 MeVee) are marked. It
can be observed the clear correlation between these events (mostly attributable
to muon interactions in the NaI(Tl) crystal) and the increase in the trigger rate.

Figure 11: Low energy spectra of the muon related events rejected for data set
A (black) and B (blue). Muon related events that would be rejected for data set
A using the criterion applied in data set B are shown in red. See text for details.
Figure 12: Distribution of baseline parameter for PMT 0 and PMT 1 data corresponding to data sets A (a) and B (b). Cut value applied to reject events having anomalously estimated baseline is shown in red. Data set A pulses were digitized with the scope, and data set B with the MATACQ, showing different typical baseline values.

below 2 keVee, and 6.4 and 14.4 keV lines are not affected by this filter at all. Same conclusion can be drawn from the $^{40}$K selected population at 3.2 keVee, as it can be seen in Figure 13. We have estimated the efficiency of this cut assuming Poisson distribution of the number of peaks according to the light collection measurements. In data set A, a 78% efficiency in the 2-3 keVee energy region is derived, a 96% in the 3-4 keVee region, and a 100% above 4 keVee. In data set B, a 95% efficiency in the 2-3 keVee energy region is derived, and a 100% acceptance above 3 keVee for bulk scintillation events. This cut efficiency has been also estimated with the 3.2 keV population coming from $^{40}$K decay (described in section 3), resulting a slightly higher value than the previously reported. In the following we apply the efficiencies derived by assuming Poisson distribution of the number of peaks in the pulse, being the most conservative choice.

The low energy background spectra before and after the application of filter 3 are shown in Figure 14 for data sets A and B. Also, the spectra of the events rejected by this filter are shown. Cerenkov light in the PMT glass produces very fast pulses with energies up to 20 keVee that are rejected by this filter. The spectra corresponding to the events rejected by this filter for data sets A and B, although sharing some features, are different, supporting the hypothesis of their PMT origin. In particular, data set B PMTs present larger dark current, higher radioactive contamination, and Cerenkov light emission in the PMT glass is expected to be produced while PMTs used in data set A are not made with glass. This could explain the much higher events rate rejected by filter 3 in that data set.

4. Events faster than NaI(Tl) bulk scintillation. With the purpose of rejecting events clearly faster than typical NaI(Tl) bulk scintillation pulses, different parameters have been studied. Among them, so called P1s has shown to perform well in the discrimination of anomalous fast events. P1s is defined by the ratio between the addition of the pulse areas from 100 to 600 ns for the two PMT signals, and the addition of the areas from pulse onset:

$$P1s = \frac{\text{Area}_1(100 - 600\,\text{ns}) + \text{Area}_2(100 - 600\,\text{ns})}{\text{Area}_1(0 - 600\,\text{ns}) + \text{Area}_2(0 - 600\,\text{ns})}$$

(1)

This parameter is expected to be around 0.7 for the NaI(Tl) scintillation events even though it shows a slight dependence on the energy (see Figure 15 where this parameter is shown for $^{57}$Co calibration data up to 100 keV).
In order to calculate the efficiency of a filter based on this parameter for the acceptance of bulk scintillation events, data from $^{57}$Co and $^{109}$Cd calibrations have been studied for data set A: mean values and standard deviation of $P_1$s in different energy windows (1 keV width) have been calculated by fitting to a gaussian function the $P_1$s parameter distribution. During data set B no $^{109}$Cd calibration was available, but data from $^{57}$Co and $^{133}$Ba were used instead. In principle, the values of this parameter should be characteristic of the NaI(Tl) scintillation and do not depend on the special data set features. However, small differences have been observed in the $P_1$s values corresponding to data from data sets A and B that could be attributed, for instance, to the better resolution of the MATAQ. An analysis energy threshold of 2 keVee is imposed hereafter because there are not enough good calibration events below such an energy to allow the definition of an useful acceptance region.

Two filtering criteria have been applied. In the first one, an acceptance region of good scintillation events at 97.7% is defined by selecting events having $P_1$s value larger than the mean minus 2σ at every energy window. In the second one, a constant cut of $P_1$s > 0.4 is selected, and the corresponding efficiency factor calculated in every energy window, and shown in Figure 16. Figure 15 shows the distribution of the $P_1$s parameter as a function of the energy for background data together with the mean $P_1$s value derived from calibration data and the 2 cut values applied for the filtering, as a function of the energy. A population of events with faster scintillation constant than the typical of NaI(Tl) is clearly observed in both data sets.

The goodness of the so calculated efficiencies for this filter is checked by using the 3.2 keV events coming from the internal $^{40}$K disintegration, which have been selected by the coincidence method. It can be observed in Figure 17c that these events are not rejected by this filter, as expected for bulk NaI scintillation events. In the energy region from 2 to 10 keV, there are 553 events. After applying the filter with the 97.7% acceptance criterion, 537 events remain that correspond to 550 events after applying...
the efficiency correction. When applying the filter with a constant cut at $P_{1s}>0.4$, 505 events remain that correspond to 576 events after applying the efficiency correction, confirming that both filtering criteria are not losing good scintillation events down to 2 keVee, and even pointing at an underestimate of the efficiency for the second criterion. Figure 18 shows the spectra obtained after applying this filter with the two different criteria to the background data, and Figure 19 a zoom into the low energy region. It can be also observed in Figure 18 the spectra of the events rejected by this filter.

From 2 to 3 keVee the first criterion is so conservative that it almost does not reject events at all. However, when applying a more effective rejecting criterion, it can be observed that above 3 keVee both criteria result in the same filtered spectrum. Spectra corrected by the corresponding efficiencies are shown in more detail in Figure 19. By looking at the $P_{1s}$ distribution of the low energy events in the background, we can conclude that rejection of the anomalous events is larger than 99% above 8 keV for both criteria, but it differs near the threshold: in the 2-3 keV region we estimate rejection of 23% for the $2\sigma$ cut, whereas of 89% for the $P_{1s}>0.4$ cut.

The origin of these rejected events could be related to surface energy depositions in the NaI(Tl) crystal from isotopes implanted, for instance, after $^{222}$Rn deposition and decay. In fact, in the case of CsI(Tl) crystals it has been recently evidenced that $^{222}$Rn surface deposition originates an anomalously fast event population down to very low energies [73] and it has also been proposed as solution to similar fast anomalous events populations identified in old NaI(Tl) dark matter search experiments [67, 74, 75].

Another possibility could be related with scintillation in quartz windows, for instance, clearly evidenced in the case of natural quartz [76]. However, it cannot be completely excluded this effect could also be present with much lower intensity when using synthetic quartz windows.

Figure 20 shows the spectra of data sets A and B after having applied the previously described filters and correcting as explained before live time and efficiency of every selection procedure. For filter 4, the most conservative approach has been selected, trying to minimize rejection, and the $2\sigma$ cut has been
applied. The 3.2 keV line coming from the $^{40}$K disintegration is dominating the low energy spectrum (from 2 to 6 keV) in both data sets. From 6 keV up to 30 keV a rate of 2-3 cpd/keV/kg is measured with both PMT models, which is on the limit of the ANAIS experiment requirements. Although the PMTs used in both data sets have very different radiopurity levels [53], differences in the backgrounds observed up to 45 keV are minimal. This hints at a very low contribution from PMT contamination in the low energy range, as our simulations suggested [49]. New ultrapure NaI crystals from Alpha Spectra taking data in the LSC (ANAIS-25 set up) will contribute also to conclude that radiopurity levels of R6956MOD PMTs could be enough to reach ANAIS goals in terms of background at very low energy even without using light guides.

6. Neutron calibration

Neutron interactions are relevant for a dark matter experiment because they produce nuclear recoils of the target constituent nuclei as the WIMPs do. Nuclear recoil events in NaI are faster than $\beta/\gamma$ ones [67, 77, 78, 29], however at low energies there is only a slight difference in pulse shape and particle discrimination cannot be done on an event by event basis.

Unfortunately, neutron sources are not easily brought to an underground facility and ANAIS experiment had only the chance to do a neutron calibration in 2007 using a $^{252}$Cf source. The neutron emission rate of the $^{252}$Cf source was $4 \times 10^4$ n/s. At that moment, only the PIII was taking data. Because of that, we have reanalyzed those data in order to obtain information about nuclear recoils pulse shape and then, the effect of the previously explained filters on such a population. Figure 21 shows the low energy spectrum obtained with the $^{252}$Cf source. Threshold effects are observed at energies lower than 10 keVee. According to specific Geant4 simulations, up to 30 keVee most of the events in the spectrum can be attributed to Na nuclear recoils.

Figure 21: $^{252}$Cf neutron source calibration spectrum taken with PIII. Only low energy (below 150 keVee) is shown.
Figure 22: (a) P1s parameter versus energy for $^{252}$Cf calibration data taken with PIII. The upper red line represents the P1s mean value obtained in 1 keV width windows and the lower red line the cut value chosen to define the acceptance region (the mean minus 2 $\sigma$). (b) $^{252}$Cf calibration (black), $^{109}$Cd + $^{57}$Co calibrations (blue), P1s mean value and the cut value chosen to define the acceptance region (the mean minus 2 $\sigma$) for the $^{252}$Cf (red) and $^{109}$Cd + $^{57}$Co (green) calibrations.

The filtering described in this article can be applied with only slight modifications to ANAIS experiment.

Acknowledgements

This work has been supported by the Spanish Ministerio de Economía y Competitividad and the European Regional Development Fund (MINECO-FEDER) (FPA2011-23749), the Consolider-Ingenio 2010 Programme under grants MULTIDARK CSD2009-00064 and CPAN CSD2007-00042, and the Gobierno de Aragón (Group in Nuclear and Astroparticle Physics, ARAID Foundation and C. Cuesta predoctoral grant). C. Ginestra and P. Villar have been supported by the MINECO Subprograma de Formación de Personal Investigador. We also acknowledge LSC and GIFNA staff for their support.

References

[1] K. F. et al., Annual Modulation of Dark Matter: A Review, Rev. Mod. Phys. 85 (2013) 1561.
[2] R. B. et al., Final model independent result of DAMA/LIBRA phase 1, Euro. Phys. J. C 73 (2013) 2648.
[3] R. B. et al., The DAMA/LIBRA apparatus, Nucl. Ins. Meth. A 592 (2008) 297.
[4] R. B. et al., New results from DAMA/LIBRA, Euro. Phys. J. C 67 (2010) 39-49.
[5] D. A. et al., First results from the LUX dark matter experiment at the Sanford Underground Research Facility, Phys. Rev. Lett. 112 (2014) 091304.
[6] E. A. et al., Dark Matter Results from 225 Live Days of XENON100 Data, Phys. Rev. Lett. 109 (2012) 181301.
[7] Z. A. et al., Dark Matter Search Results from the CDMS II Experiment, Science 327 (2010) 1619.
[8] R. A. et al., Silicon Detector Results from the First Five-Tower Run of CDMS II, Phys. Rev. D 88 (2013) 031104.
[9] R. A. et al., Search for Low-Mass WIMPs with SuperCDMS, arXiv 1402.7173.
[10] Z. A. et al., Combined limits on WIMPs from the CDMS and EDELWEISS experiments, Phys. Rev. D 84 (2011) 011102.
[11] G. G. et al., A Dark Matter Search with MALBEK, arXiv.org arXiv (2014) 1407.2238.

Summary

Low energy events are of utmost interest for the ANAIS experiment because dark matter particles are expected to produce very small energy depositions in the detector. For this reason, a very good knowledge of the detector response function for real scintillation events in the active volume of the detector and a good understanding and characterization of other anomalous or noise event populations in that energy region are required. Efficiently filtering all the low energy events populations non attributable to dark matter interactions is one of the main issues for ANAIS. Among them, events having scintillation time constants other than NaI(Tl) one or events in coincidence with a signal in the plastic scintillator veto should be rejected. Specific protocols to reject such events have been developed and applied to data from ANAIS-0 module. We have demonstrated the ability to reject anomalous or spurious event populations and to estimate the corresponding efficiencies or live time corrections down to 2 keVee. We have shown how to adapt our filtering procedures to a nuclear recoil population as the expected for galactic halo WIMPs interacting in our detector. We have followed a very conservative approach, not maximizing rejection but acceptance. A 2 keVee energy threshold can be confirmed after applying such protocols to ANAIS-0 data, and further improvement is expected in next prototypes, by improving light collection efficiency and increasing the number of reference events in every energy bin. The background below 6 keVee is clearly dominated by the 3.2 keV line from $^{40}$K and in the region from 6 to 30 keVee a rate of 2-3 cpd/keV/kg has been obtained without light guides for the two PMT models considered.

Table 4: Efficiency correction factor (Eff.) for the selection of events using filter 4 that should be considered in order to conveniently correct for the fraction of nuclear recoils in the acceptance window.

| Energy region | Eff. |
|---------------|------|
| 5 - 10 keV    | 0.862|
| 10 - 15 keV   | 0.942|
| 15 - 20 keV   | 0.949|
| 20 - 25 keV   | 0.959|

Table 4: Efficiency correction factor (Eff.) for the selection of events using filter 4 that should be considered in order to conveniently correct for the fraction of nuclear recoils in the acceptance window.

Acknowledgements

This work has been supported by the Spanish Ministerio de Economía y Competitividad and the European Regional Development Fund (MINECO-FEDER) (FPA2011-23749), the Consolider-Ingenio 2010 Programme under grants MULTIDARK CSD2009-00064 and CPAN CSD2007-00042, and the Gobierno de Aragón (Group in Nuclear and Astroparticle Physics, ARAID Foundation and C. Cuesta predoctoral grant). C. Ginestra and P. Villar have been supported by the MINECO Subprograma de Formación de Personal Investigador. We also acknowledge LSC and GIFNA staff for their support.

References

[1] K. F. et al., Annual Modulation of Dark Matter: A Review, Rev. Mod. Phys. 85 (2013) 1561.
[2] R. B. et al., Final model independent result of DAMA/LIBRA phase 1, Euro. Phys. J. C 73 (2013) 2648.
[3] R. B. et al., The DAMA/LIBRA apparatus, Nucl. Ins. Meth. A 592 (2008) 297.
[4] R. B. et al., New results from DAMA/LIBRA, Euro. Phys. J. C 67 (2010) 39-49.
[5] D. A. et al., First results from the LUX dark matter experiment at the Sanford Underground Research Facility, Phys. Rev. Lett. 112 (2014) 091304.
[6] E. A. et al., Dark Matter Results from 225 Live Days of XENON100 Data, Phys. Rev. Lett. 109 (2012) 181301.
[7] Z. A. et al., Dark Matter Search Results from the CDMS II Experiment, Science 327 (2010) 1619.
[8] R. A. et al., Silicon Detector Results from the First Five-Tower Run of CDMS II, Phys. Rev. D 88 (2013) 031104.
[9] R. A. et al., Search for Low-Mass WIMPs with SuperCDMS, arXiv 1402.7173.
[10] Z. A. et al., Combined limits on WIMPs from the CDMS and EDELWEISS experiments, Phys. Rev. D 84 (2011) 011102.
[11] G. G. et al., A Dark Matter Search with MALBEK, arXiv.org arXiv (2014) 1407.2238.
[12] E. B. et al., First dark matter search results from a 4-kg CF$_2$/ bubble
chamber operated in a deep underground site, Phys. Rev. D 86 (2012)
052001.

[13] M. F. et al., Final analysis and results of the Phase II SIMPLE dark matter
search, Phys. Rev. Lett. 108 (2012) 251301.

[14] C. E. A. et al., Search for an Annual Modulation in a $p$-Type Point Con-
tact Germanium Detector, Phys. Rev. Lett. 107 (2011) 141301.

[15] C. A. et al., Search for An Annual Modulation in Three Years of CoGeNT
Dark Matter Detector Data, arXiv.org arXiv (2014) 1401.3925.

[16] C. E. A. et al., Maximum Likelihood Signal Extraction Method Applied
3.4 years of CoGeNT Data, arXiv 1401.6234.

[17] J. D. et al., Quantifying the evidence for Dark Matter in CoGeNT data,
arXiv.org arXiv (2014) 1405.0495.

[18] C. Kelso, in: Talk at the 2014 TeVPA/IDM Conference: A max-
imum likelihood analysis of the CoGeNT public dataset, http://
http://indico.cern.ch/event/278032/session/12/contribution/
253/material/slides/1.jpg

[19] R. A. et al., Silicon detector dark matter results from the final exposure of
CDMS II, Phys. Rev. Lett. 111 (2013) 251301.

[20] G. A. et al., Results from 730 kg days of the CRESST-II Dark Matter
search, Euro. Phys. J. C 72 (2012) 1971.

[21] R. Strauss, in: Talk at the 2014 TeVPA/IDM Conference: New Results
from the CRESST Experiment, http://indico.cern.ch/event/
http://indico.cern.ch/event/278032/session/12/contribution/109/material/slides/0.
df

[22] D. H. et al., Interpretation for CoGeNT and DAMA/LIBRA, Phys. Rev.
D 82 (2010) 123509.

[23] M. F. et al., On the DAMA and CoGeNT Modulations, Phys. Rev. D 84
(2011) 041301.

[24] T. S. et al., Dark Matter attempts for CoGeNT and DAMA, JCAP 08
(2011) 008.

[25] P. B. et al., Observations of annual modulation in direct detection of relic
particles and light neutrinos, Phys. Rev. D 84 (2011) 055014.

[26] C. K. et al., Toward a consistent picture for CRESST, CoGeNT and
DAMA, Phys. Rev. D 85 (2012) 043515.

[27] M. F. et al., Resolving astrophysical uncertainties in dark matter direct
detection, JCAP 01 (2012) 024.

[28] D. C. et al., Complementarity of dark matter direct detection: the role of
bolometric targets, J. Cosm. Astrop. Phys. 07 (2013) 028.

[29] D. C. et al., Scintillating bolometers: a key for determining WIMP pa-
rameters, Int. J. Mod. Phys. A 29 (2014) 1443009.

[30] A. Green, Dependence of direct detection signals on the WIMP velocity
distribution, JCAP 10 (2010) 034.

[31] A. Green, Astrophysical uncertainties on direct detection experiments,
Mod. Phys. Lett. A 27 (2012) 1230004.

[32] A. Friedland, I. Sheoemaker, Integrating In Dark Matter Astrophysics at
Direct Detection Experiments, Phys. Lett. B 724 (2013) 183.

[33] E. del Nobile et al., Generalized Halo Independence Comparison of Direct
Dark Matter Detection Data, arXiv.org arXiv (2014) 1306.5273.

[34] V. K. et al., The expected background spectrum in NaI dark matter detec-
tors, Phys. Rev. D 85 (2012) 012026.

[35] A. Mousa, PhD Thesis at oujda University, Morocco, arXiv.org arXiv
(2014) 1405.0495.

[36] G. G. et al., Pulse shape discrimination and dark matter search with
a 250kg NaI(Tl) dark matter search experiment at the Canfranc Underground Laboratory, Ph.D. thesis, Universidad de Zaragoza (2013).

[37] A. Green, Dependence of direct detection signals on the WIMP velocity
distribution, JCAP 10 (2010) 034.

[38] A. Green, Astrophysical uncertainties on direct detection experiments, Mod.
Phys. Lett. A 27 (2012) 1230004.

[39] A. Friedland, I. Sheoemaker, Integrating In Dark Matter Astrophysics at
Direct Detection Experiments, Phys. Lett. B 724 (2013) 183.

[40] E. del Nobile et al., Generalized Halo Independence Comparison of Direct
Dark Matter Detection Data, arXiv.org arXiv (2014) 1306.5273.

[41] V. K. et al., The expected background spectrum in NaI dark matter detec-
tors, Phys. Rev. D 85 (2012) 012026.

[42] A. Mousa, PhD Thesis at oujda University, Morocco, arXiv.org arXiv
(2014) 1405.0495.

[43] G. G. et al., Pulse shape discrimination and dark matter search with
a 250kg NaI(Tl) dark matter search experiment at the Canfranc Underground Laboratory, Ph.D. thesis, Universidad de Zaragoza (2013).

[44] A. Green, Dependence of direct detection signals on the WIMP velocity
distribution, JCAP 10 (2010) 034.

[45] A. Green, Astrophysical uncertainties on direct detection experiments, Mod.
Phys. Lett. A 27 (2012) 1230004.
detector with a $^{252}\text{Cf}$ neutron source, Nucl. Ins. Meth. B 194 (2002) 337–342.

[78] R. B. et al., New limits on WIMP search with large-mass low-radioactivity NaI(Tl) set-up at Gran Sasso, Phys. Lett. B 389 (1996) 757.

[79] V. K. et al., Characteristics of alpha, gamma and nuclear recoil pulses from NaI(Tl) at 10-100 keV relevant to dark matter searches, Phys. Lett. B 452 (1999) 167.