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The expected background spectrum in NaI dark matter detectors and the DAMA result

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ABSTRACT

Detailed Monte Carlo simulations of the expected radioactive background rates and spectra in NaI crystals are presented. The obtained spectra are then compared to those measured in the DAMA/NaI and DAMA/LIBRA experiments. The simulations can be made consistent with the measured DAMA spectrum only by assuming higher than reported concentrations of some isotopes and even so leave very little room for the dark matter signal. We conclude that any interpretation of the annual modulation of the event rate observed by DAMA as a dark matter signal, should include full consideration of the background spectrum. This would significantly restrict the range of dark matter models capable of explaining the modulation effect.

1. Introduction

The DAMA group has reported a possible signal from dark matter particles. The first evidence came from the DAMA/NaI experiment (100 kg of NaI), published in Refs. [1,2]. The most recent papers [3,4] based on DAMA/LIBRA measurements using 250 kg of NaI combined with the DAMA/NaI results presented improved statistical significance of the signal and evaluation of possible background sources and systematic uncertainties. The positive identification of the effect from dark matter particles is based on observation of the annual modulation of the event rate at low energies with period (1 year) and phase consistent with those expected from dark matter halo models [5,6].

Unlike many other experiments, DAMA/NaI and DAMA/LIBRA did not use pulse shape discrimination between electron and nuclear recoils to eliminate the background from gamma-rays for their high statistics exposure, relying only on the annual modulation of the total event rate and energy spectrum. In the presence of a non-zero signal, the event rate in any particular energy bin can be described by the equation:

$$R(E,t) = b(E) + S_0(E) + S_m(E)\cos(\omega(t - t_0)), \tag{1}$$

where $R(E,t)$ is the time-dependent event rate in a particular energy bin, $b(E)$ is the time-independent rate of background events, $S_0(E)$ is the time-independent non-modulated part of the dark matter signal (average event rate), $S_m(E)$ is the amplitude of the modulated part of the dark matter signal, ω is the frequency of modulation ($\omega = 2\pi/T$, where $T = 1$ year) and t_0 is the time in years for the maximum of the signal. A similar equation has been used in the analysis of the DAMA data [2,3] but the time-independent terms b and S_0 of the equation were combined together. Such an approach, however, neglects the correlation between the modulated and non-modulated parts of the signal. Interpretation of the DAMA signal in terms of dark matter models carried out by the DAMA group [2,3] and in many other papers (see, for instance [7–9] for recent analyses) were limited to fits to the modulated signal and, in some cases, to reconstruction of the average energy spectrum of the signal $S_0(E)$.

According to Eq. (1), the total average rate of events in each energy bin is the sum of the background rate $b(E)$ and the average rate of events from dark matter particles $S_0(E)$, the third term being cancelled out when averaged over a period of a year or several years. This means that if the background spectrum were known we would be able to check whether the sum of the reconstructed spectrum of the signal ($S_0(E)$) and background ($b(E)$) matches the measured distribution. It turns out, however, that most efforts so far were directed to calculation of the signal (mainly $S_m(E)$) in various models helping with interpretation of the measured annual modulation effect, but totally neglecting the background contribution to the event spectrum and the information about the dark matter models that can be extracted from the measured spectrum. The background event rate and spectrum can be simulated with a reasonable degree of accuracy if the abundances of radioactive isotopes in detector materials are known. The DAMA Collaboration should have included the evaluation of this spectrum in their results to support their claim of dark matter discovery.

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Limiting the data analysis to the modulated part of the spectrum only, and ignoring information from the non-modulated component of the signal and background, severely weakens the conclusions that may be derived from the experiment. Self-consistent analysis of the experimental data should include all components of the measured spectrum: background, modulated and non-modulated parts of the signal. In this way no information is missed and a proper fit of the measured spectrum to the sum of predicted distributions is possible. In practice, accurate calculation of the background spectrum in terms of the absolute event rate (events/kg/day/keV) can only be done with high accuracy if concentrations of radioactive isotopes in all materials in and around the detector are precisely known. However, any particular source of background radiation has a characteristic spectrum and a combination of spectra from different sources with certain weights should match observations with or without signal. Hence the difference between the measured and background spectra should be equal to the spectrum of dark matter events. Analysing the measured spectrum and simulated background would allow us to constrain the dark matter signal.

We have used our expertise in running NaI(Tl) dark matter experiment NAIAD [10] and in modelling radioactive background in different types of detectors [11–13] to simulate gamma-ray production, transport and detection in the DAMA/LIBRA experiment. In this paper we present detailed Monte Carlo simulations of the background spectrum in a modelled setup of the DAMA/LIBRA NaI(Tl) detector. We then discuss the implications that these results may have on interpretation of the signal claimed by the DAMA group. We demonstrate that the energy spectrum measured in the DAMA/LIBRA experiment can hardly include any dark matter signal by (i) subtracting some possible WIMP signals from the measured spectrum and comparing this to the simulated background and (ii) subtracting the simulated background spectrum from the measured one and showing that the difference spectrum has a minimum at low energies which would not be a usual feature for dark matter signals. We also show that some inconsistencies exist between low-energy and high-energy parts of the measured DAMA/LIBRA spectrum.

A possible problem with the background spectrum in the DAMA/NaI experiment in the presence of dark matter signal was pointed out also in Ref. [14]. Several recent analyses (see, for instance [7,9]) used the measured spectrum to constrain theoretical models but did not take into account the spectrum of background events that should contribute to the observed rate.

2. Modelling of the background radiation

To model the DAMA/LIBRA background we have considered three locations of radioactive sources: (i) external sources producing gamma-rays and other particles outside the NaI crystals; (ii) internal sources of radiation evenly distributed within the volume of the crystal; and (iii) surface sources with radioactive isotopes concentrated within the thin surface layer of the crystal (assumed here to be 50 μm thick).

2.1. External background sources

The setup of the DAMA/LIBRA experiment comprising 25 NaI(Tl) crystals, ~ 10 kg each, was modelled using the published geometry [3,4]. For case (i) the source of background radiation was assumed to be in the 100 g envelopes of the photomultiplier tubes (PMTs) attached to the light guides connected to the two flat surfaces of the crystals. The exact position of the radiation source (PMTs, light guides or similar) is not important since only the high-energy gamma-rays can reach the crystal and the spectrum of events at low energies (below 30 keV) is fully determined by Compton electrons. The PMT envelopes were populated with radioactive isotopes of ^{238}U, ^{232}Th and ^{40}K. The isotopes were allowed to decay in our Monte Carlo code, based on the GEANT4 toolkit (version 9.2) [15] . All particles were generated according to GEANT4 library. All isotopes in the decay chains of ^{238}U and ^{232}Th decayed in our simulations in secular equilibrium (the spectra of gamma-rays from uranium and thorium decay chains in secular equilibrium have also been obtained in Ref. [16]). Obviously, only high-energy gamma-rays can reach NaI from large distances, with X-rays, electrons and alphas being absorbed in the surrounding materials.

We have also considered ^{60}Co in copper around the detectors and in a shield, as a possible source of background events. Simulations of ^{60}Co induced events have been carried out in the same way as for other isotopes.

Fig. 1 shows the spectra of energy depositions from electron recoils in the crystal with PMTs contaminated with ^{238}U, ^{232}Th and ^{40}K. For normalisation we have used typical concentrations of radioactive isotopes in ultra-low background PMTs produced by ETL and used by DAMA: 30 ppb of uranium and thorium, 60 ppm of potassium. Events produced by ^{60}Co decays in copper are also shown in Fig. 1 assuming a decay rate of ^{60}Co of 10 mBq/kg. This rate is significantly higher than typically measured in low-background copper. Only events in which an energy deposition above 0.5 keV is detected in a single crystal (close to the energy threshold of the DAMA experiment), were included. Multiple scattering events in two or more crystals with energy depositions exceeding 0.5 keV were excluded. If a photon scattered two or more times in one crystal, all energy depositions were summed together. The energy deposition spectra were convolved with Gaussian distributions describing the energy resolution of the DAMA/LIBRA detectors [4].

As can be seen from Fig. 1 the energy deposition spectra from all decay chains at low energies from external sources are essentially flat, due to Compton scattering of high-energy gamma-rays in the crystal. Spectra from any other decay outside the crystal have very similar shape at low energies dominated by Compton scattered electrons. The assumption of secular equilibrium does not affect the shape of the spectrum at low energies: the spectrum from any particular decay has the same flat shape below 30 keV. The broad peaks at about 150 keV are the well-known back-scatter peaks due to the scattering of photons in materials around the crystal prior to entering the sensitive volume.

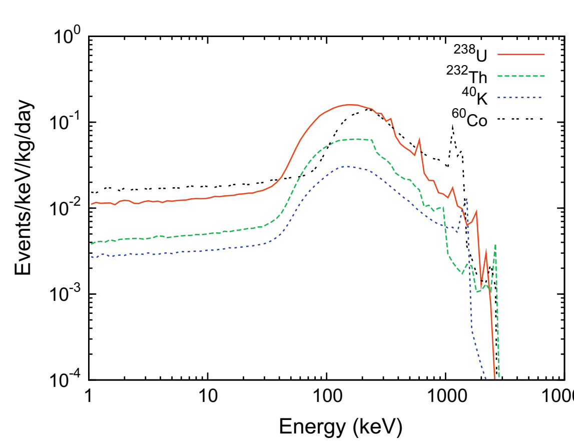

Fig. 1. Spectra of energy depositions from electron recoils in the NaI crystals from ^{238}U, ^{232}Th and ^{40}K decay chains in secular equilibrium. The source of radiation was the PMT envelopes (100 g each) attached to the light guides connected to the crystals. Also shown is the spectrum of ^{60}Co events from Cu. Only events in which a single crystal was hit, are included. See text for details.