Muon-Induced Neutrons Do Not Explain the DAMA Data

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We present an accurate model of the muon-induced background in the DAMA/LIBRA experiment. Our work challenges proposed mechanisms which seek to explain the observed DAMA signal modulation with muon-induced backgrounds. Muon generation and transport are performed using the MUSIC/MUSUN code, and subsequent interactions in the vicinity of the DAMA detector cavern are simulated with GEANT4. We estimate the total muon-induced neutron flux in the detector cavern to be $\Phi_n^\nu = 1.0 \times 10^{-9}$ cm^{-2} s^{-1}. We predict 3.49×10^{-5} counts/day/kg/keV, which accounts for less than 0.3% of the DAMA signal modulation amplitude.

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Introduction.—The DAMA/LIBRA experiment [1] is a highly radiopure NaI(Tl) scintillation detector located at the Gran Sasso National Laboratory (LNGS) that aims to measure the annual modulation signature of dark matter particles [2,3]. Both the DAMA/LIBRA experiment and the first generation DAMA/NaI experiment reported the observation of an approximately annual variation in the number of events observed in the 2–6 keV energy range with a combined significance of approximately 9.3σ [4]. If the observed signal modulation is to be explained by the elastic scattering of dark matter particles, it would require that the interaction cross section of dark matter with nucleons, and the mass of dark matter particles, to be within values that are already excluded by other experiments [5–11].

One mechanism that has been proposed in order to explain the DAMA signal modulation is the production of neutrons due to the scattering of cosmogenic muons in the material surrounding the detector [12–14]. The cosmogenic muon-induced-neutron flux Φ_n^μ is expected to have an annual variation related to the mean air temperature above the surface of Earth that affects the muon flux Φ^μ at the surface, and hence underground. This proposal has been disputed for a number of reasons [3], notably as the annual variation of cosmogenic muons is approximately 30 days out of phase with the DAMA signal [15–18].

An extension to this mechanism has also been proposed, which introduces the possibility of a contribution to the total neutron flux from the interactions of solar neutrinos [19]. The solar neutrino-induced neutron flux Φ_n^ν is also expected to have an annual modulation, due to the eccentricity of Earth's orbit about the Sun. It is shown that the phase of Φ_n^ν can shift the phase of the total neutron flux relative to Φ_n^μ.

One should note that most explanations focus on the phase, rather than the amplitude, of the modulation. A rough estimate of the modulated rate of muon-induced neutrons R_n^μ in the DAMA/LIBRA experiment can be calculated as

$$R_n^\mu = S^\mu \frac{\Phi_n^\mu A t}{m} \approx 4.6 \times 10^{-5} \text{ events/day/kg}, \tag{1}$$

where Φ_n^μ is taken from previous estimates at LNGS [20,21], S^μ is the amplitude of the muon flux modulation [22,23] (relative to Φ^μ), A is the active surface area perpendicular to Φ^μ of one DAMA/LIBRA detector module, t is the number of seconds in a day, and m is the active mass of one detector module. This rate is 3 orders of magnitude less than the modulated DAMA signal, even before the acceptance for muon-induced events in the DAMA analysis is considered.

Despite the latter calculation, and previous work [3,17,18], the recent paper [19] claims that the DAMA signal can partly be explained by muons. The estimate presented by Davis in Ref. [19], includes only a very approximate calculation of the amplitude of muon- and neutrino-induced signals. The calculation of Φ_n^μ contradicts the estimates from Refs. [3,17,18]. The calculation neglects that most neutrons will be accompanied by a showering muon, and would therefore not be accepted by DAMA/LIBRA. Also, the value of the mean free path for neutrons in rock that is used (taken from Ref. [24]), is actually for liquid argon, which has approximately half of the density of LNGS rock. Reference [25] has additionally shown that the required Φ_n^ν is at least 6 orders of magnitude too large.

It is evident from such contradictions that a full Monte Carlo simulation of the muon-induced background in the DAMA/LIBRA experiment is required. This would be able to model Φ_n^μ, the detector response, and the DAMA event acceptance, and also any enhancement of Φ_n^μ due to the high-Z shielding used by DAMA/LIBRA.

In this Letter, we present an accurate calculation of Φ_n^μ and the total muon-induced background in order to show that the DAMA signal modulation cannot be explained by any muon-induced mechanism. We perform a full simulation of the DAMA/LIBRA apparatus and detector shielding in GEANT4.9.6 [26], with muons transported to the DAMA cavern in LNGS using the MUSIC/MUSUN code [27,28]. In total, we simulate 20 y of muon-induced data.

Simulation framework.—We perform the simulation of particle propagation in two stages. In the first stage, only muon transportation from the surface of Earth down to an underground site is considered and secondary particles [29] are neglected. In the second stage, the transport and interactions of all particles (including secondary particles) are fully simulated through the material surrounding the DAMA/LIBRA apparatus.

Muon transport simulation.—The first stage of the simulation is performed using the MUSIC muon transport code [27,28]. The MUSIC code propagates muons from the surface of Earth through a uniform rock of density $\rho = 2.71\ \mathrm{g\,cm^{-3}}$ and records energy distributions of muons at different depths. The MUSUN code [27] calculates muon spectra from the modified Gaisser's parametrization that takes into account the curvature of Earth and the muon lifetime, convoluted with the slant depth distribution at LNGS. This parametrization has been previously shown to have a good fit to LVD data [27]. The MUSUN code subsequently samples muons on the surface of a cuboid with a height of 35 m and perpendicular dimensions of $20\ \mathrm{m} \times 40\ \mathrm{m}$. This cuboid includes most of the corridor where the DAMA/LIBRA experiment is located and a few meters of rock around it.

DAMA/LIBRA detector simulation.—The second stage of the simulation is performed using GEANT4.9.6 [26]. The GEANT4.9.6 shielding physics list has been used, and we include the muon-nuclear interaction process. The interactions of low-energy neutrons (< 20 MeV) are described by high-precision data-driven models [30]. Previous studies [21,31–34] have validated the simulation of neutron production, transport, and detection against data. The level of agreement is better than a factor of 2.

In this phase of the simulation, all primary and secondary particles are transported from the surface of the cuboid until all surviving particles have propagated outside of the cuboid volume. The cuboid is modeled as LNGS rock with a density $\rho = 2.71\ \mathrm{g\,cm^{-3}}$ and a chemical composition as described in Ref. [35]. A corridor ("cavern") is positioned within the cuboid, such that there is 10 m of LNGS rock overburden, and otherwise 5 m of LNGS rock surrounding the cavern walls and floor.

The DAMA/LIBRA detector housing is placed halfway along the length of the cavern, adjacent to a cavern wall. The housing is composed of LNGS concrete with density $\rho = 2.50\ \mathrm{g\,cm^{-3}}$ and a chemical composition as described in Ref. [35]. The DAMA/LIBRA apparatus and detector housing are described in Ref. [1]. There are a number of concentric layers of shielding surrounding the DAMA/LIBRA detector. Extending outwards from the detector, we model 10 cm of copper, 15 cm of lead, 1.5 mm of cadmium, 50 cm of polyethylene, and 1 m of LNGS concrete.

We model each of the 25 DAMA/LIBRA detector modules, containing a central cuboidal crystal composed of NaI, in addition to light guides and photomultiplier tubes [1]. The dimensions of each module, including a further 2 mm of copper shielding, are $10.6 \times 10.6 \times 66.2\ \mathrm{cm}^3$. The 25 modules are placed in a 5×5 arrangement in the vertical and width dimensions of the cavern.

The muon-induced neutron flux.—In the stage of simulation described in 'DAMA/LIBRA detector simulation', muons and secondary particles are transported through 10 m of LNGS rock above the DAMA cavern, and also through 5 m on the sides and underside of the cavern. Integrating over the surface area of the cavern, our simulation predicts $\Phi_n^\mu = 1.0 \times 10^{-9}\ \mathrm{cm^{-2}\,s^{-1}}$, excluding backscattering [36].

In Table I, we compare our result to the simulation of Wulandari *et al.* [20], which is performed using FLUKA [37], and of Persiani [21], which is performed using GEANT4.9.3 and MUSIC/MUSUN. Integrating over all neutron energies, our results are consistent within about 30% of the previous estimates.

We additionally demonstrate a dependance of Φ_n^μ on the dimensions of the cavern by scaling Φ_n^μ to the cavern proportions used by Wulandari *et al.* [20] (compare the first two rows in Table I). We attribute this to the different fluxes and energy spectra of vertical and inclined muons.

High-Z materials in the detector shielding (lead and copper) will lead to an enhancement of Φ_n^μ which could, potentially, contribute to the modulated signal. Figure 1 shows Φ_n^μ as a function of neutron energy, as predicted in the LNGS cavern and after all particles are propagated through the various layers of the DAMA/LIBRA shielding. It is shown that Φ_n^μ increases by a factor of > 5 due to the shielding. As we will discuss in 'Analysis', this enhancement of Φ_n^μ is still insufficient to explain the DAMA data.

Analysis.—In our simulation, each detector module is treated independently and all information due to an energy deposition from any particle in the NaI crystal volumes is recorded. DAMA categorizes events as being *single hit* or *multiple hit* if the event has an energy deposit in only a single crystal or in multiple crystals, respectively. The DAMA signal region, in which the modulated signal is

TABLE I. A comparison of Φ_n^μ (in units of $10^{-10}\ \mathrm{cm^{-2}\,s^{-1}}$) predicted by this study, Wulandari *et al.* [20] and Persiani [21]. The column titled Cavern indicates the three distinct cavern geometries used: (1) in this study; (2) by Wulandari *et al.*, and (3) by Persiani. The range of considered neutron energies is shown, and (*) indicates that backscattered neutrons are included.

	Cavern	> 0 MeV	> 1 MeV	> 1 MeV (*)
This study	(1)	10	4.0	5.0
This study	(2)	7.6	5.8	10
Wulandari *et al.*	(2)	No data	4.3	8.5
Persiani	(3)	7.2	2.7	No data

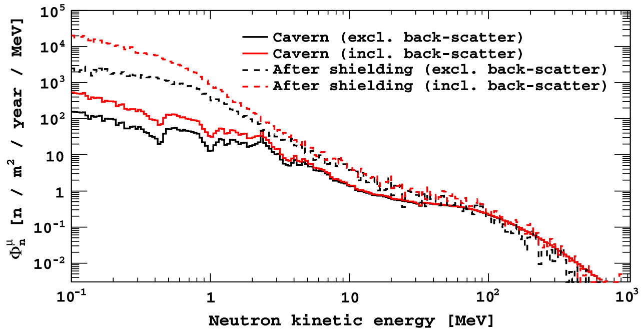

FIG. 1 (color online). The distribution of Φ_n^μ as a function of neutron energy for neutrons entering the cavern in which DAMA/LIBRA is situated (solid lines) and entering the DAMA/LIBRA detector modules after all shielding is traversed (dashed line). The distributions excluding and including back-scattered neutrons are shown in black and red, respectively.

observed, is then defined only for *single hit* events with a total energy deposit (E_{Dep}) in the range 2–6 keV.

In the following sections, we will show that the number of muon-induced events entering the DAMA/LIBRA signal region is too low to explain the signal modulation.

Resolution and quenching factors.—We model the DAMA/LIBRA experimental resolution by applying a Gaussian smearing to the sum of all energy deposited in each crystal, using resolution parameters provided by Ref. [1]. As GEANT4 does not account for the quenching of energy depositions in nuclear recoils, we apply correction factors obtained from previous studies [38–42]. Figure 2 shows the energy spectrum of all crystals with energy depositions, after corrections factors are applied.

Single hit and multiple hit events.—An important detail that is neglected in previous attempts [12–14,19] to explain the DAMA signal modulation with muon-induced backgrounds is the acceptance for *single hit* events. Figure 3 shows the number of crystals in events with $E_{\mathrm{Dep}} \geq 2$ keV per crystal, and in which at least one crystal in the event has a total energy absorption of 2–6 keV. It is shown that $< 9\%$ of these events are *single hit* events, which suppresses any

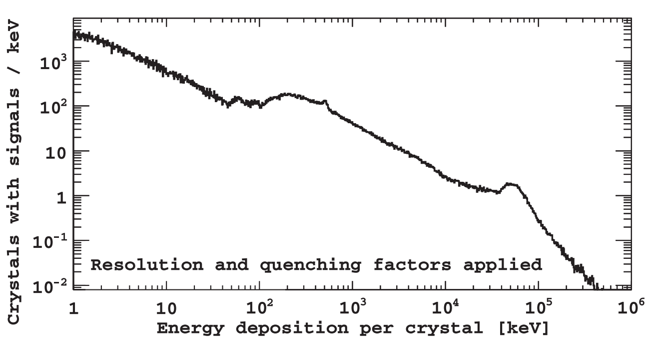

FIG. 2. The energy spectrum for all crystals with energy depositions, with resolution, and nuclear recoil quenching factors applied. The equivalent of 20 y of muon-induced data are presented.

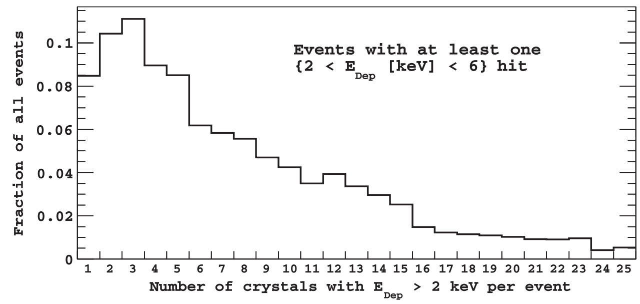

FIG. 3. The distribution of the hit multiplicity in events with $E_{\mathrm{Dep}} \geq 2$ keV per crystal. At least one crystal has a total energy absorption in the range 2–6 keV. The equivalent of 20 y of muon-induced data is presented.

enhancement of Φ_n^μ due to interactions in the detector shielding.

Events in the signal region.—In this section, we present the number of muon-induced *single hit* events predicted by our simulation. The distribution of the energy deposited in crystals in *single hit* events is shown in Fig. 4. For $E_{\mathrm{Dep}} < 20$ keV, the muon-induced background is dominated by isolated neutrons.

In the range 2–6 keV there are 245 muon-induced events predicted over a period equivalent to 20 y. The total sensitive mass of the DAMA/LIBRA detector is 242.5 kg; therefore, we predict the rate of muon-induced events in this energy range to be 3.49×10^{-5} counts/day/kg/keV with approximately 6% statistical uncertainty. We estimate the systematic uncertainty to be approximately 30% by comparing different predictions of Φ_n^μ, as presented in ‘The muon-induced neutron flux’.

We are able to compare our prediction to the conservative estimate presented in Refs. [17,18], which is in agreement with our results.

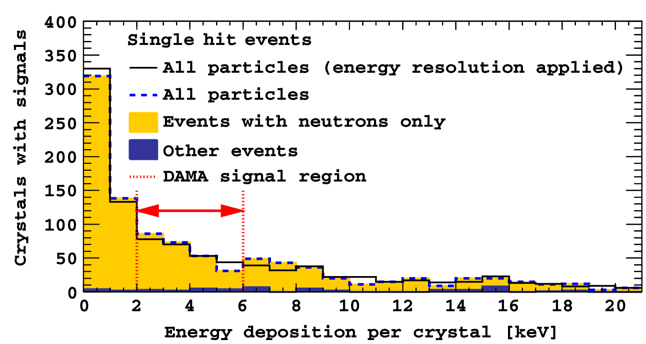

FIG. 4 (color online). The distribution of the total energy deposition in *single hit* events. The blue dashed line and the black solid line show the sum of all energy depositions before and after energy resolution is considered, respectively. The stacked colored bars indicate the relative fraction of all events (before energy resolution is considered) attributed to events in which only neutrons deposit energy (yellow) and other events (blue). The equivalent of 20 y of muon-induced data is presented.

The calculated event rate accounts for $\sim 0.3\%$ of the modulation amplitude reported by DAMA of $(1.12 \pm 0.12) \times 10^{-2}$ counts/day/kg/keV [4]. It is clear from this comparison that, even if the systematic uncertainty is bigger than our estimates, no muon-induced background can be used to explain the observed signal modulation. Our simulations (Figs. 3 and 4) also show that, if muon-induced backgrounds could explain the DAMA data, one should expect a non-negligible modulation of the muon-induced background above 6 keV, as well as for events with multiple hits, which is not seen by DAMA.

Discussion.—In this section we will argue that muon-induced neutrons cannot explain the DAMA data, even before any estimate of Φ_n^μ is performed.

We start the discussion in a general way, by considering any possible source of modulated signal, including dark matter, as has been done in Ref. [43]. The measured rate of events at DAMA/LIBRA is clearly dominated by radioactive background above 6 keV, which imposes a strict limit on any interpretation of the modulated signal. This radioactive background is almost flat at low energies [43], with the exception of a peak from ^{40}K at about 3 keV, which agrees with the DAMA measurements. To preserve the shape ("flatness") of the radioactive background in the region 2–6 keV, the total signal should be small and hence, the modulated fraction of the signal should be large. As an example, the measured modulated signal rate of 0.0190 counts/day/kg/keV at 2–3 keV, assumed to be 5% of the total (average) signal, will give the total signal rate of 0.38 counts/day/kg/keV. This is already a significant fraction of the total measured rate at 2–3 keV (about 30%), requiring the radioactive background rate to drop by 30% at this energy while maintaining a flat background above 6 keV. No model of radioactivity predicts a dip in the background below 6 keV [43].

Let us now consider muon-induced backgrounds within this context. We assume that Φ_n^μ and Φ^μ are modulated in a similar way, linked to the mean muon energy at LNGS [44]. The LVD [22] and Borexino [23] experiments have observed a muon flux modulation in the range of 1.3%–1.5% of the total Φ^μ. If the modulated signal in DAMA is due to a muon-induced effect, then the total rate of this "effect" will be $0.0112/0.014 \approx 0.8$ counts/day/kg/keV. This is approximately equal to the total rate of ~ 1 counts/day/kg/keV observed by DAMA in the 2–6 keV energy range [4]. The effect is more dramatic in the 2–3 keV energy range, where the modulated signal is approximately 0.0190 counts/day/kg/keV [4]. This would imply a total muon-induced background of $0.0190/0.014 \approx 1.4$ counts/day/kg/keV, which is higher than the total rate of events observed by DAMA. This is excluded by radioactivity models [43].

It is clear from the latter discussion that for any explanation of the DAMA signal to be consistent with the measured spectrum of events, it must satisfy the following qualitative criteria: (i) The amplitude of the effect must be very small compared to the DAMA event rate. (ii) The modulation amplitude of the effect must not be much smaller than the average amplitude of the effect. (iii) Any effect not satisfying the latter two criteria implies that there is a new model of suppressed radioactivity in the region 2–6 keV, that does not apply above 6 keV. (iv) The modulation of the effect must only affect *single hit* events, while disregarding *multiple hit* events. (v) The explanation must simultaneously predict the phase and the period of the modulation. An explanation which incorporates muon-induced backgrounds cannot satisfy these criteria.

Conclusions.—We have presented an accurate simulation of the muon-induced background in the DAMA/LIBRA experiment, in response to proposals to explain the observed DAMA signal modulation with muon-induced neutrons. We have performed a full simulation of the DAMA/LIBRA apparatus, shielding, and detector housing using GEANT4.9.6.

We have calculated the muon-induced neutron flux in LNGS to be $\Phi_n^\mu = 1.0 \times 10^{-9}$ cm^{-2} s^{-1} (without backscattering), which is consistent with previous simulations. After selecting events which satisfy the DAMA signal region criteria, our simulation predicts a background rate of 3.49×10^{-5} counts/day/kg/keV. This accounts for approximately 0.3% of the modulation amplitude. We find that one would expect a non-negligible modulation of muon-induced background above 6 keV, as well as for events with multiple hits, which is not seen by DAMA.

We conclude from our study that muon-induced neutrons are unable explain the DAMA data. Furthermore, a large signal event rate, independently of the source of this signal, is inconsistent with radioactive background models.

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