NEUTRON BACKGROUND STUDIES FOR THE EDELWEISS WIMP SEARCH

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Protection against the neutron background will be one of the key issues for the next generation of Dark Matter Direct Detection experiments. We review and discuss critically the main contributions for the neutron background – neutrons from rock fission and alpha-n reactions, muon-induced neutron background, deep-inelastic interactions, internal U/Th contamination. We discuss the impact of these backgrounds for the EDELWEISS-II experiment, designed to reach a sensitivity of the order of 10^{-2} event/kg/day, and for an experiment at the one-ton scale.

1. Introduction

Until recently, WIMP direct detection experiments were mainly limited by the radioactive gamma-ray background, with an emphasis on the purification of materials from radioactive impurities [1,2]. With the advent of cryogenic detectors with strong event-by-event discrimination capabilities [3-5], the sensitivity of direct detection experiments has improved rapidly over the last few years, providing the most sensitive and reliable constraints on WIMP interaction rates.

Although neutrons are obviously strongly interacting neutral particles, their interaction cross-sections are sufficiently small to represent a significant threat to WIMP direct detection experiments having a few sparsely distributed detectors. Giving rise to low-energy nuclear recoils, with an energy spectrum hardly distinguishable from that of WIMP interactions (for relatively high A nuclei such as Germanium), neutrons will represent one of the main backgrounds for the next generation of direct detection WIMP experiments.

For example, the CDMS experiment [3,4], set in the shallow Stanford Underground facility at a depth of 17 meters of water equivalent (m.w.e.), has seen its sensitivity limited to ~ 1 event/kg/day [4] by the fast neutron component associated to deep-inelastic muon interactions in the rock coverage. For this reason, direct detection WIMP experiments must now be installed in deep underground laboratories where the muon flux is reduced by factors ≈ 10^4-10^6 compared to ground level, corresponding to a few tens to a few muons/m^2/day.

In the following, we will summarize the contributions of neutrons backgrounds originating from the rock radioactivity (fission and alpha-n reactions), from muon interactions in the heavy shield materials around the detectors, in the surrounding rock, and neutrons produced by fission of U contaminant inside the lead of the shield.

2. Fission and alpha-n neutrons from rock radioactivity

In deep underground laboratories, most of the neutrons originate from fission and spallation processes in the surrounding rock, at the typical level of 10^{-6} neutrons/cm^2/s for the best sites.

A measurement of the neutron background originating from the rock in the Fréjus underground laboratory has been realized in the setup described by Chazal et al. [6]. A "Bugey" cell 0.8 meter long [7], filled with NE-320 liquid scintillator and doped with 0.15% of ^{6}Li, was used to detect neutrons. A 5 cm copper shield associated with a 12 cm lead shield was used to protect the cell from the external gamma-ray radioactivity. The prompt proton recoil signal, identified thanks to pulse shape discrimination (PSD) information, is followed, after the neutron has been slowed down through elastic collisions on protons, by a signal associated to the neutron capture on ^{6}Li, again identified by PSD. Two photomultipliers on each side of the cell are used to measure the light output, allowing a position determination of the interactions along the cell.

The counting time was 115 days without paraffin shielding, and a null measurement was realized during a further counting of 140 days with a 30 cm thick paraffin shield. The small neutron count rates, ˜ 1.15 count per day and 0.38 count per day, respectively, show the difficulty of these measurements, realized here with a signal/noise ratio of ˜ 2. When corrected for the efficiency of the cell, these rates can be translated in a neutron flux of ˜ 1.6 10^{-6} neutron/cm^2/s for neutrons with energy E > 2 MeV. Note that this value is a significant reevaluation of the published value of 4.0 10^{-6} neutron/cm^2/s [6]. The main source of systematic error originates from the determination of the cell efficiency, very sensitive to the neutron energy spectrum at the cell level. Actually, the lab spectrum is strongly distorted after crossing of the Cu and Pb shields. This transformation of the spectrum, obtained by computer simulations is shown on figure 1. More reliable recent simulations showed that this distortion was underestimated in the original paper [6].

Similar measurements have been realized in the Gran Sasso underground laboratory, leading to neutron flux masurements varying rather widely, but mostly in the same range of 0.5-2 10^{-6} neutron/cm^2/s [8-10].

Although important, this neutron background can be made negligible by a low-Z shield surrounding the experiment, such as paraffin or polyethylene. Without this protection, this neutron flux component, at Fréjus depth, already leads to a nuclear recoil signal exceeding the sensitivity reached, for example, by the EDELWEISS [5] or CDMS [4] experiments. A 50 cm polytehylene shield is sufficient to reach the level of 10^{-8} picobarn of next generation experiments such as EDELWEISS-II and CDMS-II, whereas a one-meter thick water or polyethylene shield is sufficient to reduce the fission and alpha-n components at a level below 10^{-10} picobarn. To further illustrate this point, effect of the additional 30 cm polyethylene shield of the present EDELWEISS-I experiment is shown on Fig. 1.

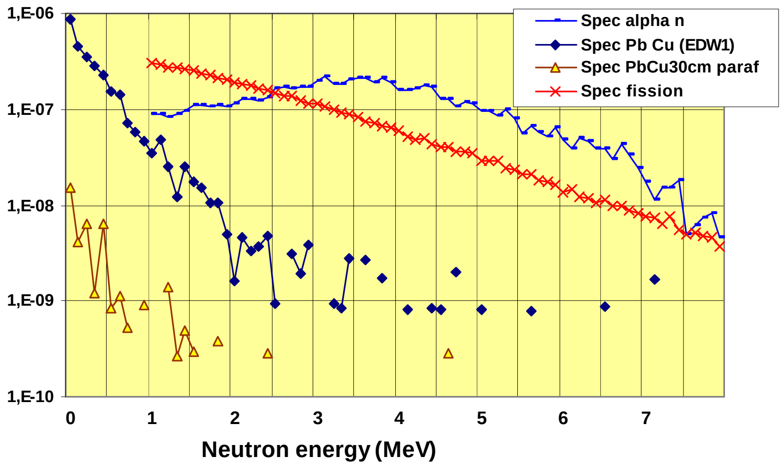

Fig. 1. Neutron energy spectra from rock radioactivity, in the lab, and after crossing of various shields

3. Neutrons produced by muon interactions

A second neutron component is associated with the neutron production by muons crossing the lead and copper shield, materials acting as neutron multipliers, or by muons interacting in the rock surrounding the experiment.

In the Gran Sasso and Fréjus underground laboratories, the muon flux is reduced by a factor 5 10^5 and 2 10^6, respectively, with respect to the muon intensity at ground level.

3.1. *Muon interactions in the Pb-Cu shield*

The high average energy of these remaining muons leads to a non negligible neutron production rate in the lead shield (see Table 1 with the relative neutron fluxes from the various sources). This is one to two orders of magnitude below the present EDELWEISS sensitivity, but must be taken into account for the EDELWEISS-II and CRESST-II experiments [11]. Fortunately, this background will be effectively reduced to a negligible level in EDELWEISS-II by identifying and vetoing with an efficiency > 95% the muons crossing the protective setup around the detectors. Such a muon veto is also required for the CDMS-II experiment in the Soudan underground laboratory, where the muon flux is $\times$50 higher than that of Fréjus.

3.2. *Deep-inelastic muon interactions in the surrounding rock*

Whereas the muon flux as a function of rock thickness is determined with relatively good precision, the production of fast neutrons associated with muon deep inelastic interactions is known with considerably larger uncertainties, particularly with respect to the neutron multiplicity. Monte-Carlo simulations of the neutron production by muons in scintillator [12,13] appear to indicate a power-law dependence of the neutron yield as a function of muon energy, increasing as:

$$N_\mu \sim 4\, E_\mu^{0.74}\, 10^{-6}\ \mathrm{n/\mu/g\ cm^{-2}}$$

For a given muon energy E_μ, the neutron energy spectrum appears rather well represented by a biexponential spectrum [12].

Monte Carlo simulations, using various generators [14-19] have been realized to simulate the propagation of fast neutrons in the polyethylene and Pb + Cu shield. The incident spectrum, predicted by the simulation proposed by Dementyev et al. [13], is represented on Fig. 2a, while the spectrum after shield crossing, at detector level, is shown on Fig. 2b (using MCNP for neutron propagation). First observation is the considerable softening of the initial spectrum. Another important information is provided by the spectrum of the incident neutrons contributing to neutrons above 1 MeV at detector level (second graph of Fig. 2a). It can be seen that most of these neutrons have energies in the 100 MeV range.

Far beyond the sensitivity of present WIMP searches, this fast neutron component is nevertheless a dangerous background for the next generation of direct WIMP experiments, corresponding to $\sim 10^{-8}$ picobarn WIMP signal. In effect, high-energy muons with energy in the TeV range may lose in a catastrophic way a large fraction of their energy in a single deep-inelastic scattering interaction on a nucleus. When this interaction occurs in the surrounding rock, a few percent of the long range hadronic component is then carried away by neutrons, at very low shower densities, making this fast and penetrating neutron component extremely difficult to detect by an external veto.

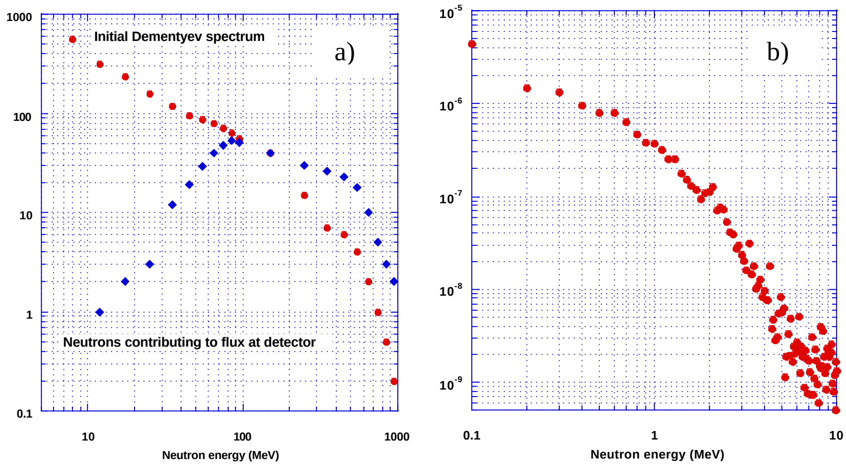

Figure 2. Neutron energy spectra from muon interactions in rock. a) spectrum in lab and for neutrons contributing at detector location b) spectrum at detector location

A large passive shield of light material, or preferably a large active scintillator shield, as considered, respectively, for the GENIUS [20] and the Borexino experiments [21] can strongly reduce this small but dangerous background. Experiments aiming at the 10^{-10} picobarn sensitivity range will require such active shields. Additionally, the correlation between the neutron angular distribution and the muon direction [12] makes it probable that a significant fraction of these large showers can be rejected by the muon veto information.

4. Neutrons from U fission inside the shield

Whereas this background can probably be kept at interaction rates below that of WIMPs with 10^{-8} picobarn cross-sections, a veto is here obviously inefficient, and these internal neutrons will have to be identified by their strong interaction cross-section. Extremely challenging, this small internal background must be kept below a few neutron interactions per year for setups of total mass ˜ 100 ton range since a WIMP cross-section of 10^{-10} pbarn corresponds to ˜ 10 events/ton/year…

When slowing down, neutrons trajectories are typically a few meters long before their energy is degraded below ˜ 0.5-1 MeV threshold required to trigger a detector. A compact array of detectors, realized for example in the CUORICINO experiment [22], can then fight this neutron background by rejecting events with multiple interactions, at the expense of a 50% fiducial cut on the detector total mass, assuming ˜ 1000 detectors in a cubic structure. An alternative strategy is followed by CDMS by using two sets of Si and Ge detectors.

5. Comparison of neutron energy spectra from the various sources at detector level

On Fig. 3 are compared the various spectra at detector level, after propagation from their initial production location (rock, or lead shields) through the various shields. It turns out that all these spectra have rather similar shapes in the 0.5-5 MeV energy range, the most dangerous energy region for WIMP search.

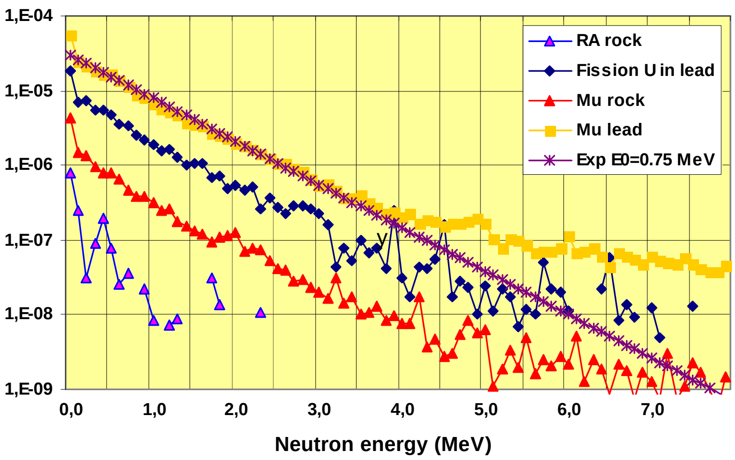

Figure 3. Neutron energy spectra from the various sources, at the EDELWEISS II detector location

6. Conclusions

We have estimated the various neutron background contributions at Fréjus depth for the EDELWEISS-I and -II setups. Table 1 summarizes the flux levels in germanium detectors for the EDELWEISS-II setup, designed to reach a sensitivity of 10^{-8} picobarn in terms of WIMP cross-section. Experiments aiming at the 10^{-10}

picobarn grail will require a more ambitious active veto and a detector structure allowing to identify the internal neutron background.

Neutron origin	*Rock radioact*	*U in lead*	*m in lead*	*m in rock*
Predicted flux at det. after shields	$0.4\ 10^{-10}$ n/cm^2/sec	$<1.2\ 10^{-10}$ n/cm^2/sec	$10\ 10^{-10}$ n/cm^2/sec	$0.4\ 10^{-10}$ n/cm^2/sec
Relative rates after veto 95%	1	<1.5	1	2

Table 1. Summary of neutron energy fluxes at EDELWEISS II detector level.

Acknowledgments

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