

MEASUREMENT OF MUON INDUCED NEUTRON BACKGROUND AT SHALLOW SITES

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Cosmic muon induced neutrons are a major source of background for low count rate experiments like neutrino oscillation or dark matter searches. Especially at shallow sites these neutrons are the limiting factor for the ultimate sensitivity of the measurement. Measurements of the neutron rate and counter measures including active veto and passive shielding of the detector are discussed for two neutrino oscillation experiments at shallow sites: the KARMEN accelerator based experiment at RAL and the PALO VERDE reactor experiment.

1. Introduction

High energetic muons are, apart from neutrinos, the most penetrating components of secondary cosmic radiation. They can be detected even several thousand meters underground (fig. 1e). In general, direct muon hits are suppressed by active veto systems. However, high energy neutrons, produced by muon interactions with nuclei outside the experimental setup, can penetrate the veto system undetected. Experiments looking for rare low energy events, like neutrino oscillation or dark matter searches, can be dominated by this background. Two main reactions of muons with nuclei can be distinguished⁴:

- **μ^- capture:** Negative muons stopped in matter either decay ($\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$) or are captured by a nucleus ($\mu^- + p \rightarrow n + \nu_\mu$). The energy transferred to the nucleus in the process is between 15 and 20 MeV and therefore above the neutron emission threshold.
- **Deep inelastic scattering (DIS)** of muons on nuclei: Virtual photons radiated from cosmic muons interact with a nucleus and can produce one or more high energetic spallation neutrons (see also⁸).

A detailed description of simulations of the muon flux and subsequent muon induced neutron production have been described in detail by Armbruster⁴ and Wang et al⁸. Figure 1 shows the energy and zenith angle dependence of the muon flux at sea level from a simulation of the muon induced neutron background of the KARMEN neutrino experiment. It also shows the simulated distribution of DIS neutrons. The largest uncertainty of the simulation comes from the total neutron yield of muon deep inelastic scattering.

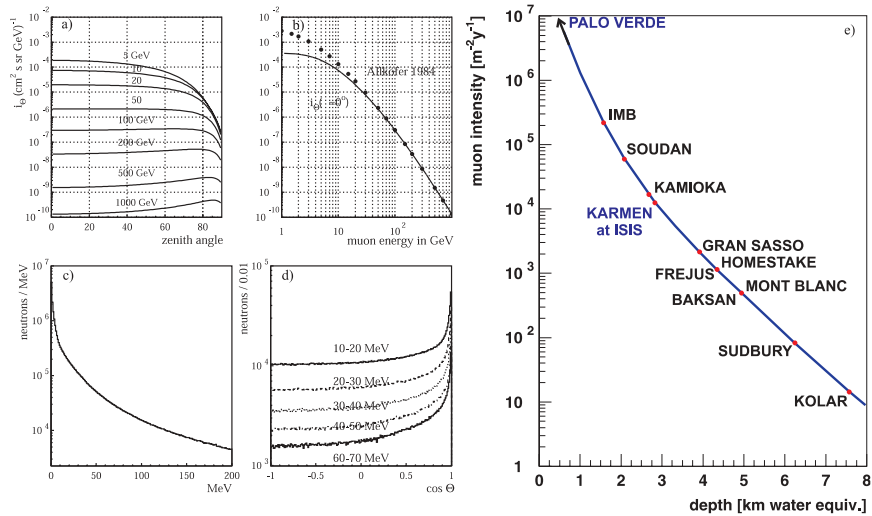


Figure 1. Cosmic ray muon flux and neutrons: a) muon flux at sea level for different zenith angles and energy (simulation); b) energy dependent muon flux at sea level (dots are from measurement¹); muon induced spallation neutrons (simulation): c) energy spectrum, d) emission angle relative to incoming muon track; e) muon flux as a function of depth (KARMEN: time structure of ISIS equivalent to depth).

The neutrino oscillation experiments KARMEN and Palo Verde both searched for space- and time-correlated inverse beta decay signatures from $\bar{\nu}_e$ events. The prompt positron from the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ is followed by a γ cascade from neutron capture after a characteristic thermalization time. Both detectors were based on organic liquid scintillator for calorimetric measurement of the energy and a fast time response. Gadolinium inside the detector was used to increase the thermal capture cross section for neutrons.

Neutrons from deep inelastic scattering can penetrate into the liquid scintillator, causing signals with visible energies up to several hundred MeV through elastic n-p scattering (see fig. 1c). After thermalization the neutrons are captured, thus providing the sequential event signatures, which are nearly identical to the inverse beta decay of a $\bar{\nu}_e$. Since both detectors had no particle identification, they could not distinguish between cosmic induced n-p recoil events and positrons from $\bar{\nu}_e$ reactions.

2. KARMEN

The KARMEN^a experiment was operated from 1990 to 2001 at the ISIS spallation neutron source at the Rutherford Appleton Laboratory in England. ISIS produces equal fluxes of ν_μ , $\bar{\nu}_\mu$ and ν_e from π^+ decay and subsequent μ^+ decay at rest. The unique time structure of the ISIS neutrino pulses (10 μ s, 20 Hz repetition rate) provided a suppression of the continuous cosmic muon flux for KARMEN, equivalent to a shielding of almost 3000 *mwe* (meter water equivalent). KARMEN investigated neutrino-nucleus interactions and searched for $\bar{\nu}_\mu - \bar{\nu}_e$ appearance oscillations².

The KARMEN detector³ was a segmented high resolution liquid scintillation calorimeter (see Fig. 2a). Its volume (65 m³) was optically separated into 512 independent modules. The walls of each cell contained Gadolinium coated paper for an efficient detection of thermal neutrons. Two layers of veto counters surrounded the scintillator tank. A blockhouse of 7000 t of steel slabs provided a passive shielding against the hadronic and electro-magnetic component of cosmic showers. The modular structure of the blockhouse allowed the integration of an additional outer veto system half way through the steel shielding. This veto system was installed in 1996, marking the beginning of the KARMEN-2 experiment. The upgrade of the experimental configuration reduced the cosmic induced background for the $\bar{\nu}_\mu - \bar{\nu}_e$ search^{2,4} to a level where beam correlated neutrino-nucleus reactions dominated the background rate.

Figure 2b shows the time correlation of muons tagged by the outer veto system and the n-p recoil event in the central detector. A subsequent neutron capture signal identified the event as a muon induced neutron. The time distribution shows three distinct contributions: i) DIS neutrons, ii) muon capture on iron and iii) stopped muons in the detector. The solid histogram represents the expected time distribution from a GEANT3.21 simulation, which is in good agreement with the experimental data. Figure 2c

^aKARlsruhe Rutherford Medium Energy Neutrino experiment

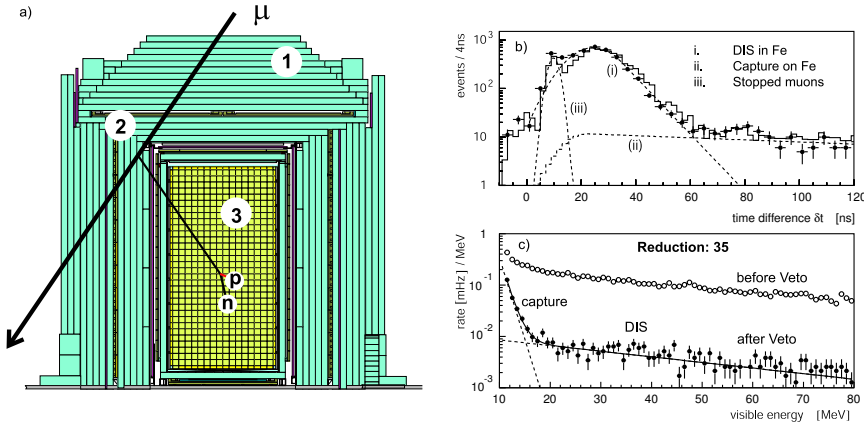


Figure 2. a) KARMEN detector (3) in a 7000 ton steel bunker (1) and active veto system (2); muon induced neutrons: b) time of flight spectrum, c) *visible* energy spectrum.

shows the *visible* energy distribution in the central detector of prompt events with a correlated neutron capture signal (open circles). After removing all events with an outer veto tag (full circles), the background rate could be reduced by a factor of 35. The remaining spectrum consists of two components. The soft component is caused by neutrons from muon capture reactions and can be described as an exponential distribution e^{-E/E_0} with $E_0 \approx 1.4$ MeV. The much harder component attributed to DIS neutrons has an exponential parameter of $E_0 \approx 42$ MeV.

3. Palo Verde

The Palo Verde neutrino oscillation experiment⁵ was operated from 1998 to 2000 at the Palo Verde Nuclear Generating Station (11.6 GW) near Phoenix, Arizona. The main goal was the search for $\bar{\nu}_e - \bar{\nu}_x$ oscillations in the disappearance mode. The detector was located in a shallow underground site (32 *mwe* overburden), thus eliminating the hadronic and electro-magnetic component of cosmic radiation and reducing the muon flux by a factor of ~ 5 . The segmented detector contained 11.3 tons of 0.1% Gd-loaded liquid scintillator in an array of 66 acrylic cells, as shown in Fig. 3a. The central detector was surrounded by a 1 m water shield to moderate and capture background neutrons produced by muons outside the detector and to absorb γ 's from the laboratory walls. Surrounding the water tanks was a 4π veto system made of 40 large liquid scintillator counters.

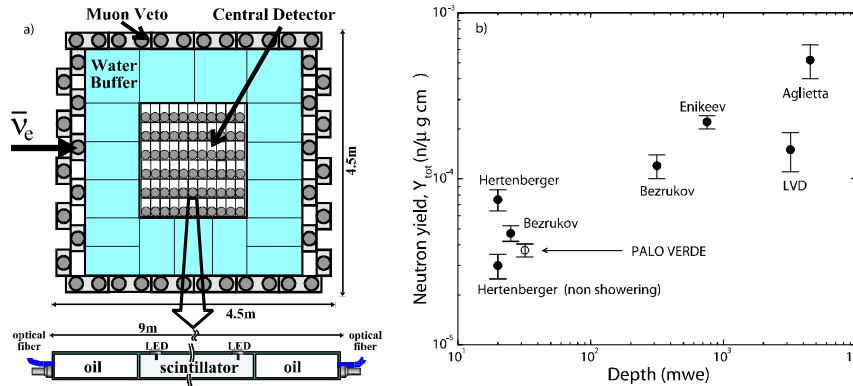


Figure 3. a) Palo Verde detector; b) neutron yield per muon as a function of depth.

The $\bar{\nu}_e$ events were identified by space- and time-correlated e^+ and n signals from an inverse β -decay reaction. The visible energy of each sub-event was in the range of 1 to 8 MeV⁶. The total sequential event rate after veto and after all cuts was ≈ 50 events/day, including ≈ 25 neutrino events per day. More than half of the remaining background events came from neutrons produced by deep inelastic muon scattering (DIS) outside the veto system in the surrounding walls of the laboratory. The sequence was produced either by n-p recoil in the scintillator followed by neutron capture or by multi-neutron capture events. Other background contributions came from unvetoes muons in the water buffer and from random coincidences (mainly radioactivity). The neutron background was identified and removed by a method described in ⁹.

A special measurement with a modified neutrino trigger was performed⁷ to determine the total neutron yield for muons scattering inside the scintillator of the central detector. Muon capture events were excluded by requiring through-going muon tracks with at least two veto hits. Detection efficiencies, event topologies and corrections for neutrons produced outside the central detector were simulated, using GEANT3.21. Hadronic interactions were simulated with FLUKA, low energetic neutron transport with GCALOR. The analysis took into account the production of up to three neutrons. Higher neutron multiplicities were neglected. The resulting total neutron yield

$$Y_{tot} = \sum_{n=1}^3 n \cdot Y_n = (3.60 \pm 0.09_{stat} \pm 0.31_{syst}) \cdot 10^{-5} \frac{\text{neutrons}}{\mu \cdot \text{g} \cdot \text{cm}^{-2}}$$

is consistent with existing results shown in figure 3b.

4. Conclusion

Muon induced neutrons were the dominant part of cosmic ray background for the neutrino oscillation searches with KARMEN and Palo Verde. A good understanding of neutron production and propagation in the vicinity of the detector has been demonstrated by both experiments, showing good agreement between simulated and measured neutron spectra in an MeV energy range. Apart from direct particle identification (e.g. pulse shape discrimination), which could not be used in this case, three counter-measures have been taken to reduce the cosmic muon induced neutron background:

- (1) **External passive shielding** of the muon flux by adding massive shielding or going underground.
- (2) **An active veto system** with high detection efficiency for muon tracks in the vicinity of the detector.
- (3) **Internal passive shielding** between veto system and detector to remove neutrons produced by muons passing outside the active veto system.

As demonstrated by the successful upgrade of the KARMEN-2 experiment, a sufficient reduction of the neutron background can only be achieved with a combination of an active veto system and internal passive shielding.

References

1. O. C. Allkofer et al., *Cosmic Rays on Earth*, Reihe Physik Daten Nr. 25-1, Karlsruhe, 1984
2. B. Armbruster et al., *Phys. Rev.* **D65**, 112001 (2002).
3. G. Drexlin et al., *Nucl. Instr. and Meth. A* **289**, 490 (1990).
4. B. Armbruster (PhD thesis), *Forschungszentrum Karlsruhe FZKA-6102* (Mai 1998).
5. F. Boehm et al., *Phys. Rev.* **D62**, 072002 (2000).
6. F. Boehm et al., *Phys. Rev.* **D64**, 112001 (2001)
7. F. Boehm et al., *Phys. Rev.* **D62**, 092005 (2000)
8. Y.F. Wang et al., *Phys. Rev.* **D64**, 013012 (2001)
9. Y.F. Wang et al., *Phys. Rev.* **D62**, 013012 (2000)