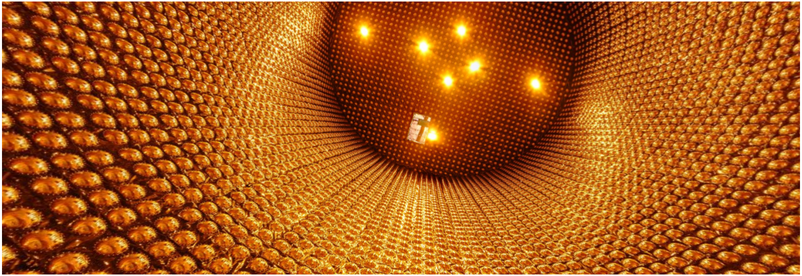
Spallation background in the Super-Kamiokande experiment

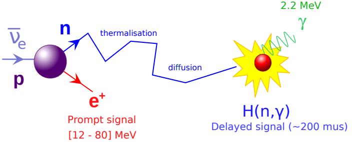
Laura Bernard, on behalf of the Super-Kamiokande Collaboration
ICHEP conference, neutrino session
July 29, 2020



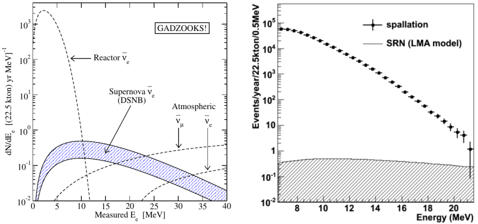
Low energy searches in the SK experiment

The Super-Kamiokande experiment has played a **major role in astrophysics** by investigating **low energy** O(10) MeV neutrinos, notably :
→ characterization of 8B solar neutrino spectrum
→ currently exhibits the **best sensitivity to relic neutrinos from distant supernovae** → See talk by S. El Hedri 30/07

Solar neutrinos : elastic scattering of ν_e
Supernova relic $\bar{\nu}_e$: Inverse β-decay
5-20 events / year are expected
→ Time & space correlated signal



Signal & backgrounds for supernovae relic $\bar{\nu}_e$:



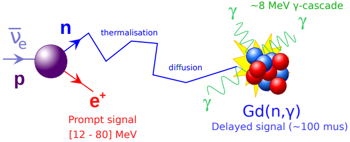
Left : Neutrino-induced background PhysRevLett.93.171101
Right : Muon spallation background ZHANG Yang PhD thesis 2015

A dominant background for SRN and solar searches is caused by muon spallation in water
→ Well caracterized in liquid scintillators but not yet in water detectors
→ Need simulations

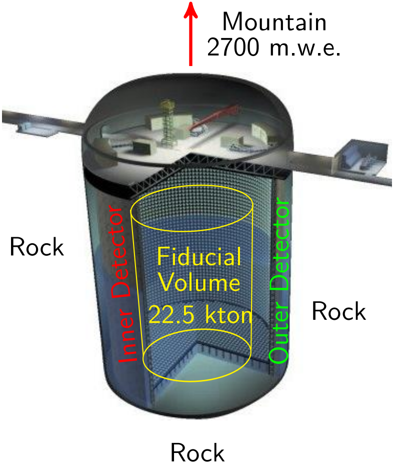
The SK detector

- Located in the Kamioka Mine, Japon
- 1000 m underground ($\sim$ 2 Hz muon rate)
- 50 kton Water Cerenkov detector
- 11129 ID PMTs (3 ns resolution, 50 cm)
- Energy coverage : 4 MeV to $\sim$ TeV

- Operational since 1996, now in phase VI
- **Gd loading just started !**



$\rightarrow$ **improved n-tagging**
$\rightarrow$ **reduce spallation background**



Muon-induced spallation processes

Illustration of muon-induced spallation in the Super-Kamiokande water tank

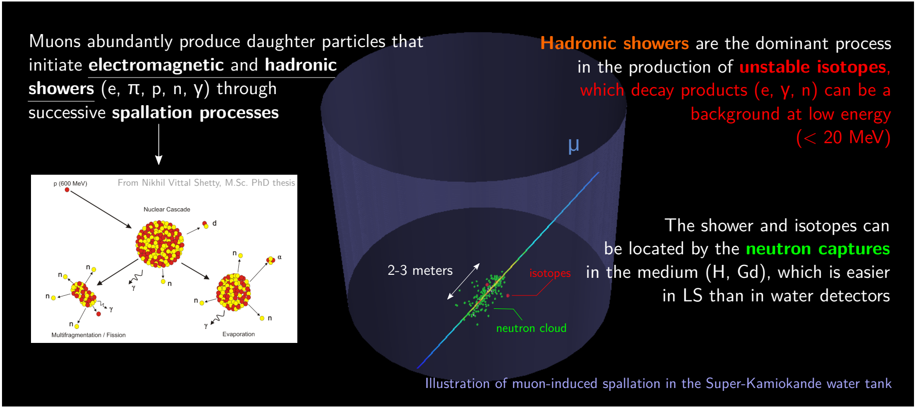
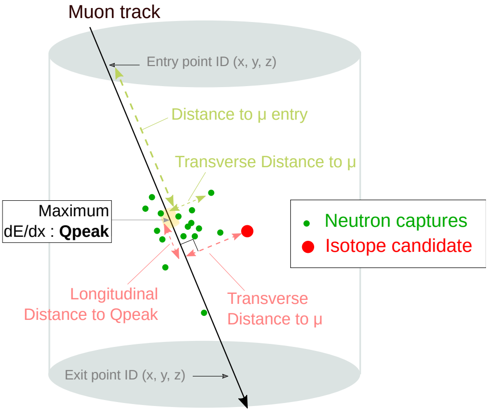


Illustration of muon-induced spallation in the Super-Kamiokande water tank

How do we deal with spallation in the data ?

K.Bays et al. Phys. Rev. D 85, 052007 (2012)
S.Locke, poster at Neutrino2020



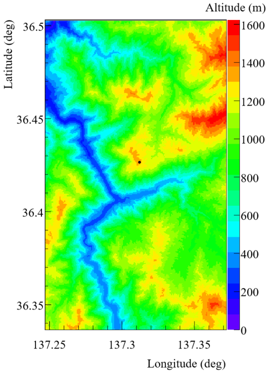
- Extract information directly from the data : Correlations between **low energy events and muon track**, **neutron cloud** to locate hadronic shower

  → Use WIT (Wideband intelligent trigger) system for a lower threshold to see 2.2 MeV γ's from n-capt

- Eliminates $\sim$ 90% of the background for [50-90]% signal acceptance
- Need to reduce even more this background

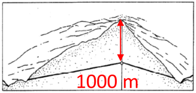
Simulation of the muon flux at SK with MUSIC

MUSIC is a 3D Monte-Carlo code for muon propagation through the rock.
Antonioli et al. Astropart.Phys.7:357-368,1997



Kenoyama topological profile
Phys.Rev.C81:025807,2010, initially from Geographical Survey Institute of Japan (1997), unpublished.

To reach the SK tank, a muon must have an energy > 1.3 TeV



Angular deviation and lateral displacement of μ's (multiple scattering, bremsstrahlung, pair production and inelastic scattering) are taken into account

- **Mean energy** of muons reaching SK tank : 258 GeV
- **Spectrum extends up to several TeV**

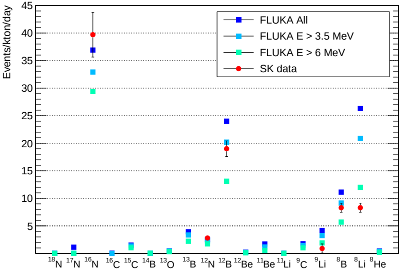
Spectra provided by A. Coffani, PhD at LLR, Polytechnique

Spallation simulation with FLUKA

FLUKA is a fully integrated particle physics MonteCarlo simulation package.
Fluka version: 2011.2x.7, flair version: 2.3-0

- A first FLUKA-based simulation of vertical μ^- in the SK tank was done in 2014 by Shirley Weishi Li and John F. Beacom. Physical Review C 89.4.
- **We reproduced this simulation and improved it by:**
  - Using the real MUSIC flux
  - Adding the μ^+ component (ratio at sea level $\frac{\mu^+}{\mu^-} = 1.26$) $\rightarrow$ reduces isotopes yields ($^{16}\mathrm{N}$)
  - Interfacing FLUKA with the official simulation of Super-K

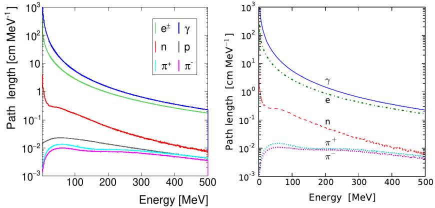
  PhD work of A. Coffani, LLR, Polytechnique



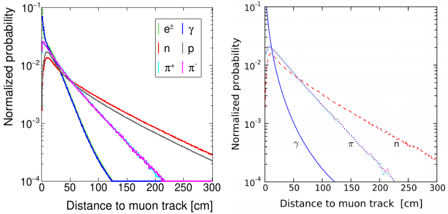
$\longrightarrow$ **Comparison of the isotope production**

- In the data, the yields have been extracted using a fit of the decay times of each isotope from μ track ZHANG Yang PhD thesis 2015
- ✓ **The comparison is within an factor of a few, consistent with uncertainties from nuclear physics models**

- Developped a Geant4-based muon-induced spallation in water simulation and compared to FLUKA
  $\rightarrow$ 4 lists tested : QGSP_BERT_HP, QGSP_BIC_HP, FTFP_BIC_HP, FTFP_BERT_HP
  Master 1 thesis from G.De La Valle, Polytechnique



Path lengths : **Left** : Geant 4 – **Right** : FLUKA



Distance of particles to muon track : **Left** : Geant 4 – **Right** : FLUKA

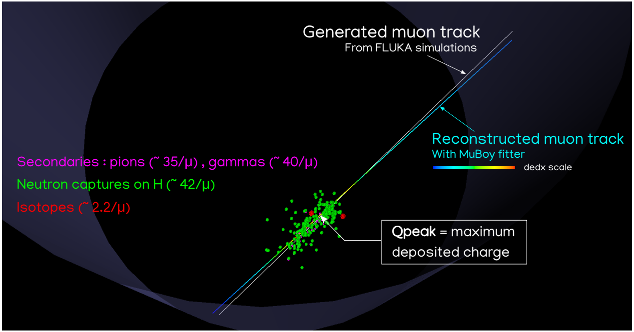
- ✓ **Overwall observables are very well reproduced** (nature of isotopes' parents as a function of the energy, path lengths, muon deposited energy, ...)
- ✓ **Yield of dominant isotopes (^{16}N, ^{12}B) within a factor 4**, consistent with uncertainties from nuclear physics, stronger discrepency for ^{8}Li (3d most important)

$\rightarrow$ Simulations are about to be implemented in a Geant-4 Super-K simulation (WCsim) to better understand impact of reconstruction, and will be of great interest for Hyper-K studies

Interfacing FLUKA with Super-K detector simulation (SKDetSim)

SKdetSim is Geant3 based $\rightarrow$ Need to evaluate how to propagate the FLUKA events to SKDetSim.

- Unstable isotopes are mainly produced in hadronic showers $\rightarrow$ Need to save **hadronic showers from FLUKA** : $\pi^{+/-/0}$, neutrons , γ ... isotope decays
    - Turn off the creation of secondaries in hadronic processes in SKDetSim
    - Turn off muon nuclear interactions in SKDetSim
- **Let SKDetSim take care of the electromagnetic part**



- Event 1

  ($t = 0$) **MIP muon**

  ($t = \frac{c}{d}$) **Particles from shower**

- Event 2 :

  ($t = t_{n-capt}$) **2.2 MeV** γ **from n-H capture**

- Event 3 :

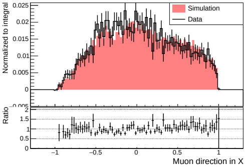
  ($t = t_{decay}$) γ/β **from isotopes decay**

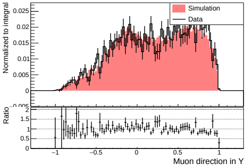
The tricky part is the muon + shower energy deposition and reconstruction

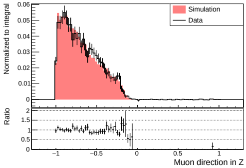
First Data/MC comparison of spallation background in water

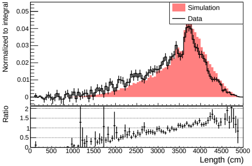
Spallation data used : may 2020, supernovae relic (SRN) analysis. Contain pairs of muons and relic candidates allowing for stat. random subtraction. Comparison done for through-going muons only.

Muons directions and track length in tank:







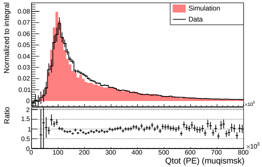


✓ **Validation of MUSIC simulation**

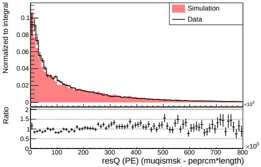
- Slight discrepencies for track length

First Data/MC comparison of spallation background in water

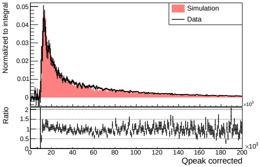
Energy deposition of muon with shower :



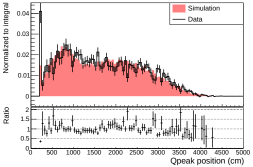
Total deposited charge (Qtot)



Residual charge (Qtot - MIP)



Charge in higher segment (Qpeak)

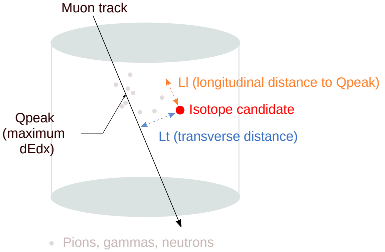


Location of Qpeak

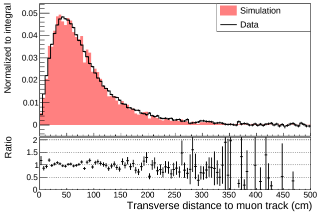
- Total charge : $\sim$ 120000 PE $\sim$ 20 GeV deposited in the tank (using 6 PE/MeV conversion)

  ✓ Validation of FLUKA shower model and interfacing with SKDetSim

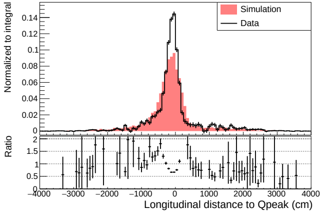
First Data/MC comparison of spallation background in water



Transverse distance from isotope muon track :



Longitudinal distance from isotope to Qpeak :



✓ **Very nice agreement for transverse distance**

- However longitudinal distance from simulation is **wider** than in the data
  → Need to investigate potential misreconstruction of Qpeak

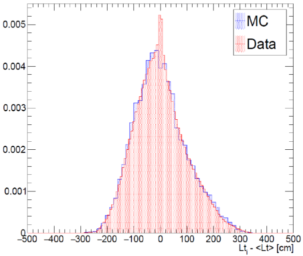
First Data/MC comparison of spallation background in water

Neutrons are very abundant in showers leading to unstable isotopes and can be **used to locate the shower and reject spallation background**

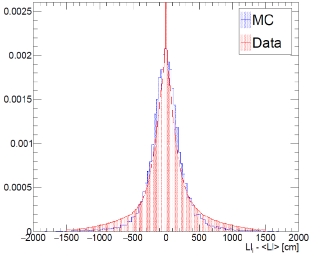
A dedicated trigger system (WIT) allows to search for very low energy events (2.2 MeV γ from n-H captures)

Simulation from PhD work of A. Coffani, LLR, Polytechnique

Data extracted by S.M. Locke, PhD, University of California, Irvine



Transverse distance of neutrons to muon track



Longitudinal distance to muon entry point

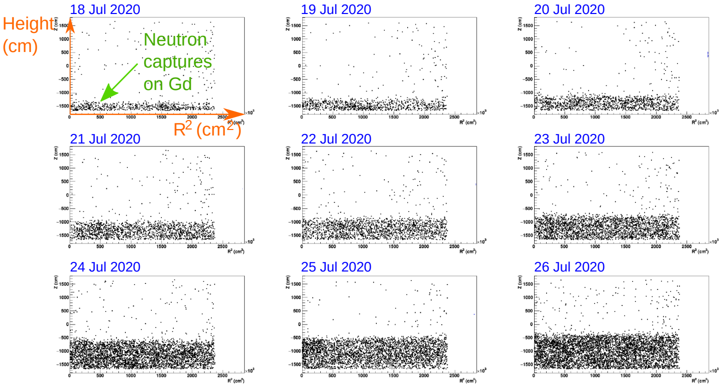
- Studies under progress
- **Very promising with the recent loading of Gd and therefore better tagging of neutron captures !**

… Speaking about Gadolinium !

First runs have been analyzed and **we officially see the neutron captures on Gd following showering μ**, as Gd is being dissolved in water from the bottom !
$\rightarrow$ See talk by Lluis Marti-Magro, "Status of the SK-Gd project", 30 Jul 2020, 10:15

Data from S.M. Locke, PhD, University of California, Irvine

Distributions of the nGd captures in the cylinder



Already see more showers, and bigger showers… promising upcoming results !

Conclusion

Muon-induced spallation is a dominant background for solar and supernovae relic neutrinos

→ **The simulation of this background in water is needed to improve rejection**

✓ **Spallation simulation is in place :**

FLUKA simulations cross-checked with existing results
GEANT4 simulations in agreement with FLUKA
Interfacing of FLUKA with SK-simulation

→ Deeper studies ongoing to understand better neutron cloud observable
→ Possible training with ML to identify spallation events from neutron cloud
→ Li9 finally decoupled from other isotopes to evaluate efficiency

✓ **First comparisons to data were presented :**

- Nice first agreement MC/data for muon + shower reconstruction
- Need more studies of the extension of shower (Ll and Lt)

Waiting for new analysis thanks to Gd in water !

Thank you for your attention

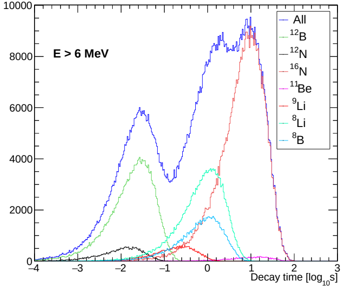
Back-up slides

Spallation simulation with FLUKA

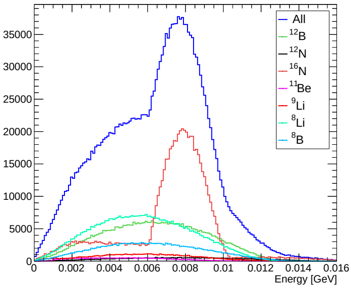
Most problematic backgrounds are the ones that decay with **longest times** (mainly $^{16}\mathrm{N}$ (7.13 s)). The spallation background goes **up to about 20 MeV** and also comes from $^{16}\mathrm{N}$.

PhD work of A. Coffani, LLR, Polytechnique

Decay times of isotopes

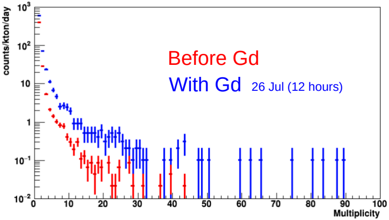


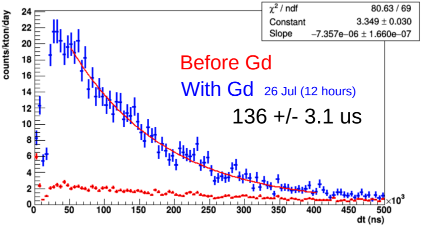
Energy spectrum of decays ($\beta + \gamma$)



Data from S.M. Locke, PhD, University of California, Irvine

Left : Neutron multiplicity – **Right :** Time capture

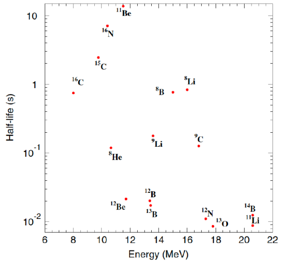




Already see more showers, and bigger showers... promising upcoming results !

Isotope	Half-life (s)	Decay mode	Yield (total) ($\times10^{-7}\mu^{-1}\mathrm{g}^{-1}\mathrm{cm}^2$)	Yield (E > 3.5 MeV) ($\times10^{-7}\mu^{-1}\mathrm{g}^{-1}\mathrm{cm}^2$)	Primary process
n			2030		
^{18}N	0.624	β^-	0.02	0.01	^{18}O(n,p)
^{17}N	4.173	$\beta^- n$	0.59	0.02	^{18}O(n,n+p)
^{16}N	7.13	$\beta^-\gamma$ (66%), β^- (28%)	18	18	(n,p)
^{16}C	0.747	$\beta^- n$	0.02	0.003	(π^-,n+p)
^{15}C	2.449	$\beta^-\gamma$ (63%), β^- (37%)	0.82	0.28	(n,2p)
^{14}B	0.0138	$\beta^-\gamma$	0.02	0.02	(n,3p)
^{13}O	0.0086	β^+	0.26	0.24	(μ^-,p+2n+μ^-+π^-)
^{13}B	0.0174	β^-	1.9	1.6	(π^-,2p+n)
^{12}N	0.0110	β^+	1.3	1.1	(π^+,2p+2n)
^{12}B	0.0202	β^-	12	9.8	(n,α+p)
^{12}Be	0.0236	β^-	0.10	0.08	(π^-,α+p+n)
^{11}Be	13.8	β^- (55%), $\beta^-\gamma$ (31%)	0.81	0.54	(n,α+2p)
^{11}Li	0.0085	$\beta^- n$	0.01	0.01	(π^+,5p+π^++π^0)
^{9}C	0.127	β^+	0.89	0.69	(n,α+4n)
^{9}Li	0.178	$\beta^- n$ (51%), β^- (49%)	1.9	1.5	(π^-,α+2p+n)
^{8}B	0.77	β^+	5.8	5.0	(π^+,α+2p+2n)
^{8}Li	0.838	β^-	13	11	(π^-,α+^{2}H+p+n)
^{8}He	0.119	$\beta^-\gamma$ (84%), $\beta^- n$ (16%)	0.23	0.16	(π^-,^{3}H+4p+n)
^{15}O			351		(γ,n)
^{15}N			773		(γ,p)
^{14}O			13		(n,3n)
^{14}N			295		(γ,n+p)
^{14}C			64		(n,n+2p)
^{13}N			19		(γ,^{3}H)
^{13}C			225		(n,^{2}H+p+n)
^{12}C			792		(γ,α)
^{11}C			105		(n,α+2n)
^{11}B			174		(n,α+p+n)
^{10}C			7.6		(n,α+3n)
^{10}B			77		(n,α+p+2n)
^{10}Be			24		(n,α+2p+n)
^{9}Be			38		(n,2α)
sum			3015	50	

S.Li and J.Beacom, Phys. Rev. C 89, 045801 (2014)

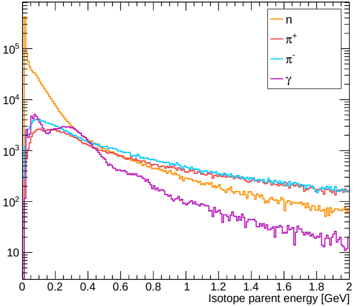


Interfacing FLUKA with Super-K detector simulation (SKDetSim)

The actual simulation of the Super-Kamiokande detector is Geant3 based, so an in-depth study was needed to evaluate how to propagate the FLUKA spallation to SKDetSim.

From FLUKA, we know that :

- Unstable isotopes are mainly produced by **neutrons** (53.4%), **pions** (30.7%), **secondary muons** (8.1%), and **gammas** (7.1%)
  $\rightarrow$ Need to save **hadronic showers from FLUKA**
- Particles contributing to cerenkov radiation are e and gammas from EM shower
  $\rightarrow$ **Let SKDetSim take care of the electromagnetic part**



From FLUKA, we save:

- $\pi^{+/-/0}$, n-captures, isotope decays : positions, momenta
- Muon information : energy, entrance and direction (Muons undergo small deflections)

... and input it to SKDetSim:

- Turned off the creation of secondaries in hadronic processes
- Turned off muon nuclear interactions