CALCULATIONS OF BACKGROUND FROM RADIOACTIVITY IN DARK MATTER DETECTORS

Vito Tomasello

University of Sheffield & Universität Tübingen

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Outline

The simulation work here presented aim to investigate possible design solutions for EURECA dark matter experiment.

- Radioactive background sources
  - Neutron Yield and gamma Spectra
    - Lab & Detectors
      - Background Transport from lab walls
        - Background Transport from detectors components
          - Conclusions

Radioactive background sources

activity from U , Th, K traces are known to be in all materials present within and around the experimental hall

this results in production of :

gamma (electron recoils)

neutron (nuclear recoils similar to the expected WIMP signal)

To protect a detector from background radiation from rock and lab walls , shielding made of high-Z materials (against gamma-rays) and low-A materials (against neutrons) are usually installed.

The use of rejection tools (shielding and active veto system) needs to be accompanied by a sufficient control over their radioactive contamination

Materials nearby the detectors should be featured by ultra low activity

Neutron yield and spectra

neutron spectra are difficult to measure and depend on the materials

Sources4A[*] is a code for calculations of neutron yields and spectra from

(a,n) reactions, spontaneous fission

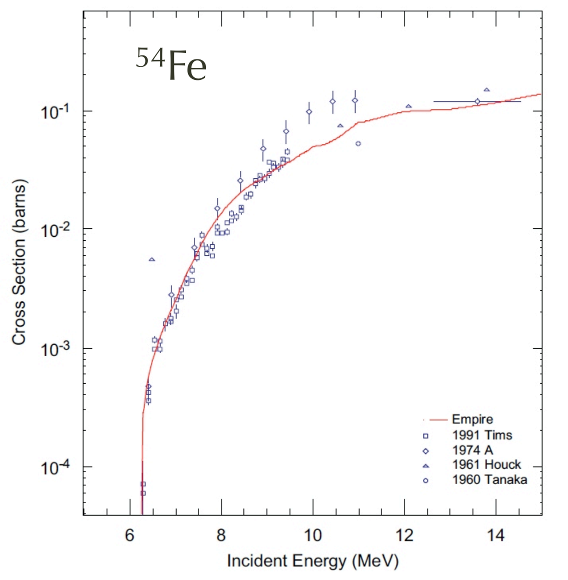
Improvement have been carried out on the original version

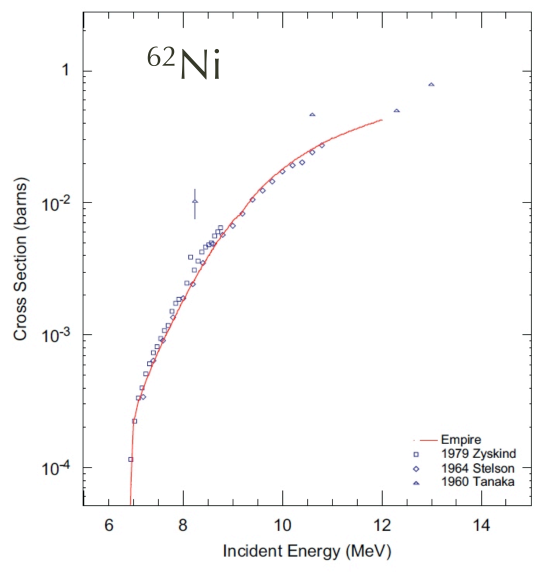
1. Limit for alpha particle moved up to 10 MeV (see Carson et al. Astropart. Phys. 21 (2004) 667; Lemrani et al., NIMA 560 (2006) 454)
2. Libraries for cross section and branching ratio, using EMPIRE 2.19[**] code, have been improved and extended. Now spectra are available for all materials relevant for dark matter searches (see Tomasello et al. NIMA, 2008, hep-ph/0807.0851)

* Wilson et al. SOURCES4A, Technical Report LA-13639-MS, Los Alamos, 1999

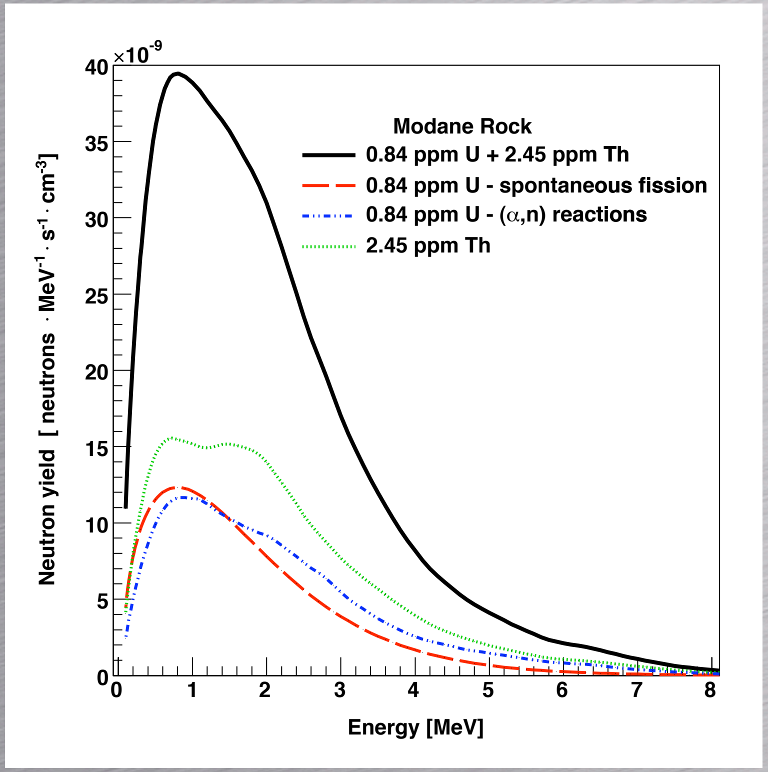
– ** http://www.nndc.bnl.gov/empire219

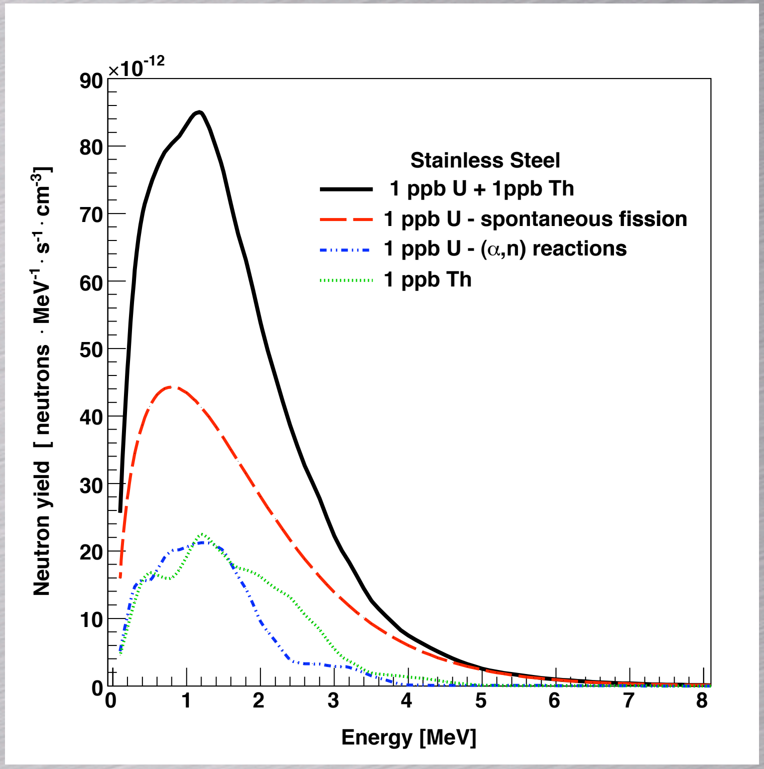
Comparison between EMPIRE 2.19 results and measured cross sections





Neutron yield and spectra from SOURCES4A

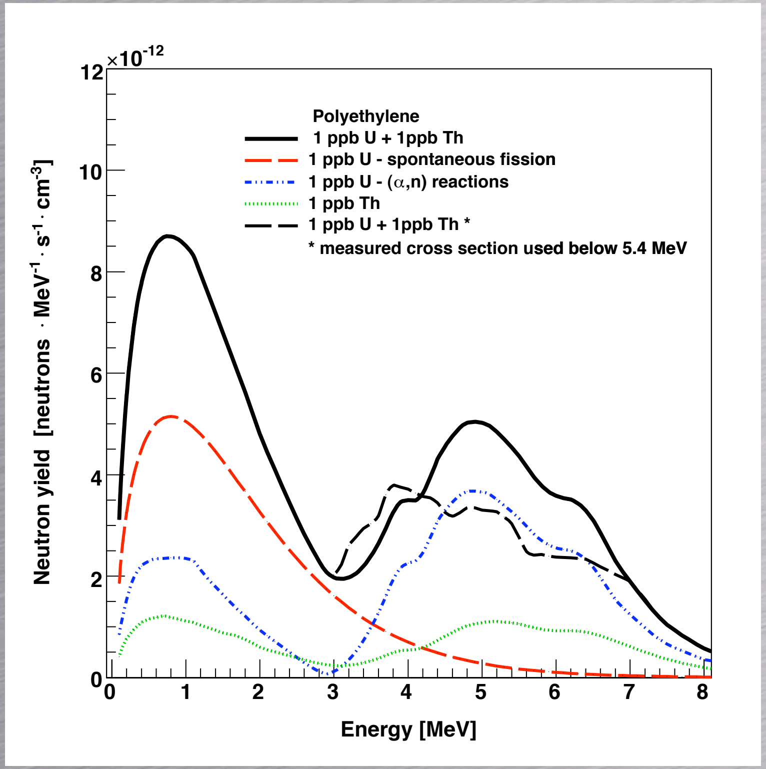


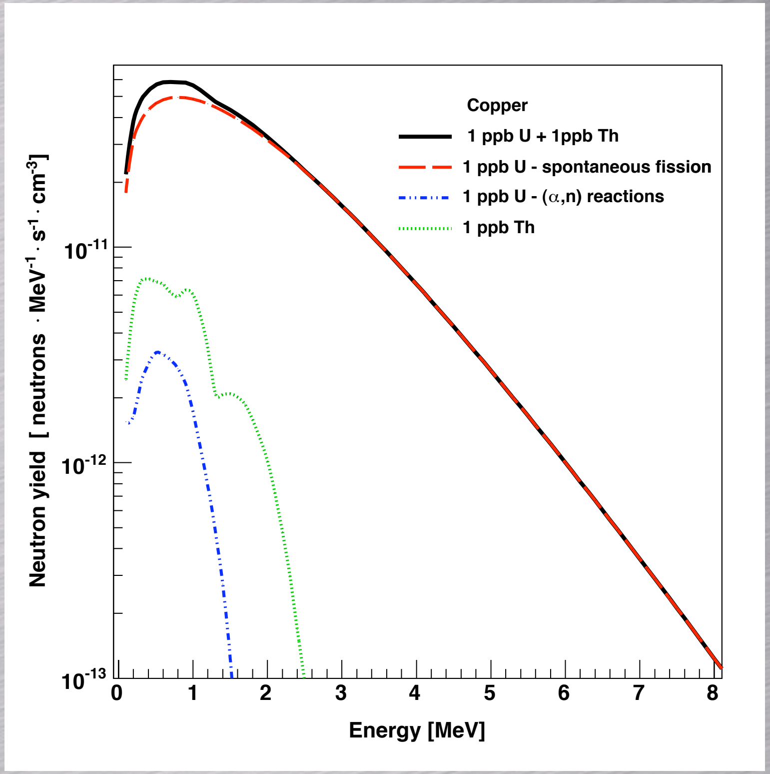


Concentration of 1ppb for U and Th in most of calculations was assumed, which can be easily scaled to the actual concentrations

In all calculations the U and Th decay chains were assumed to be in secular equilibrium

Neutron yield and spectra from SOURCES4A





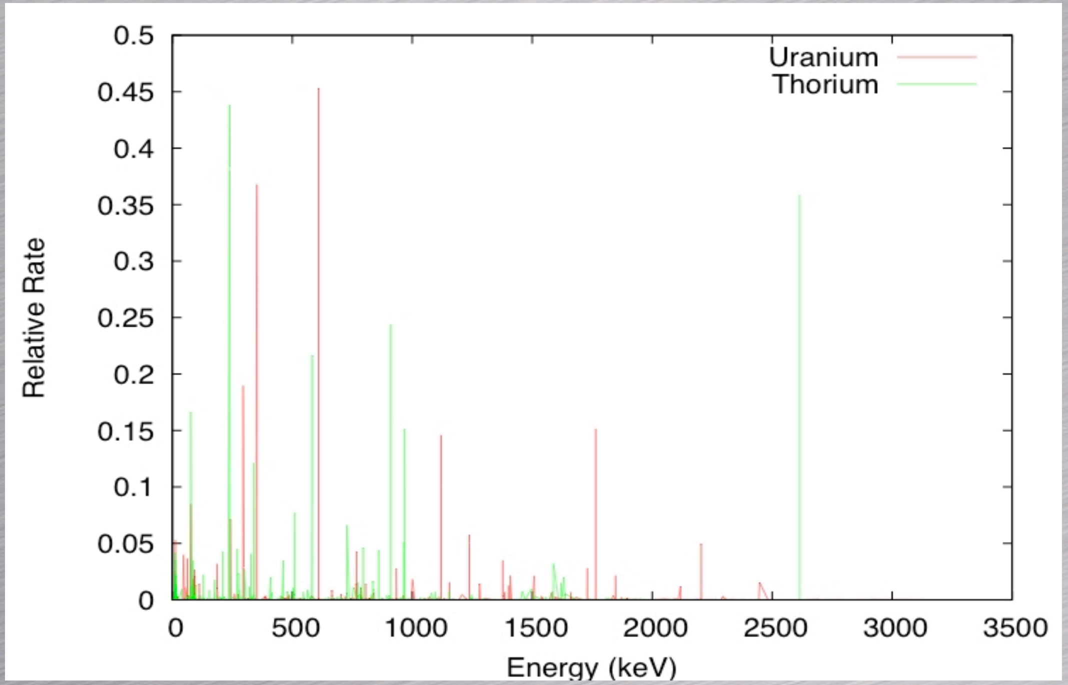
——— neutron yield =3.281e-11 $n\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$

Average Neutron Energy from U: 3.003 MeV
Average Neutron Energy from Th: 3.902 MeV

— — — neutron yield =3.006e-11 $n\,\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$

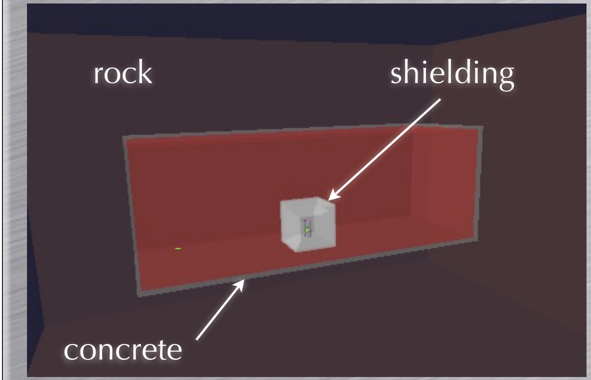
Average Neutron Energy from U: 2.762 MeV
Average Neutron Energy from Th: 3.700 MeV

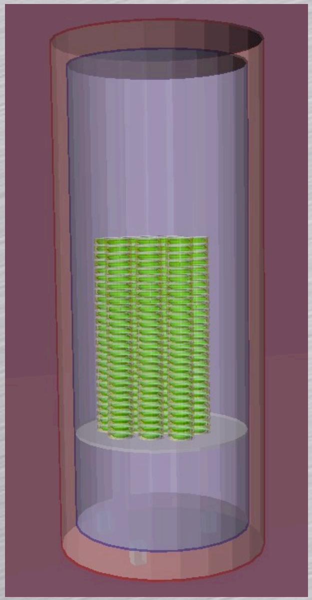
Gamma-rays production in U/Th decay chains



GEANT4 - D. Budjas and L. Pandola. Gerda Report GSTR-07-010 (2007).

Experimental hall & detectors





Ge crystals: 324 x 320 g = 103.68 kg

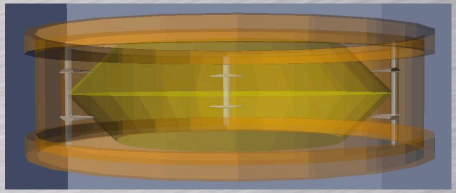
27 floors (12 crystal each)

Inner copper vessel: 0.5 cm thick, mass 128 kg

Outer copper vessel: 0.5 cm thick, mass 181 kg

Plate: 1.0 cm thick, mass 22.1 kg (Cu)

or 19.7 kg (stainless steel)



Lab design similar to the one of the Modane Underground Laboratory (Fr)

Lab size : 30 m X 10 m X 10 m

Concrete : 30 cm thick

All nuclear recoil event rate have been estimated by means of the following assumptions:

1. All depositions due to the same background sources, within the same crystal have been considered as single deposition → no position sensitivity have been assumed within a single crystal
2. Afterward depositions below 10 < keV have been neglected → Energy threshold set to 10 keV
3. All nuclear recoils accompanied by depositions from gamma have been ignored → perfect discrimination assumed for gamma-rays induced events
4. Events featured by nuclear recoils in different crystal have been rejected → only single nuclear recoils have been selected

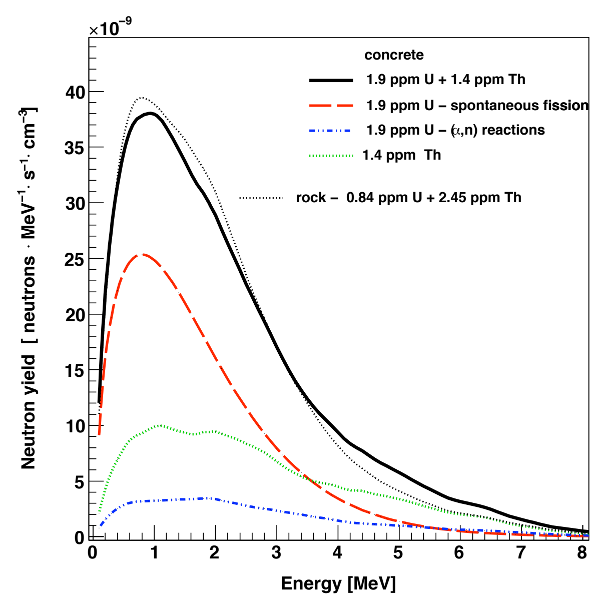
Background Transport

experimental hall walls: rock & concrete

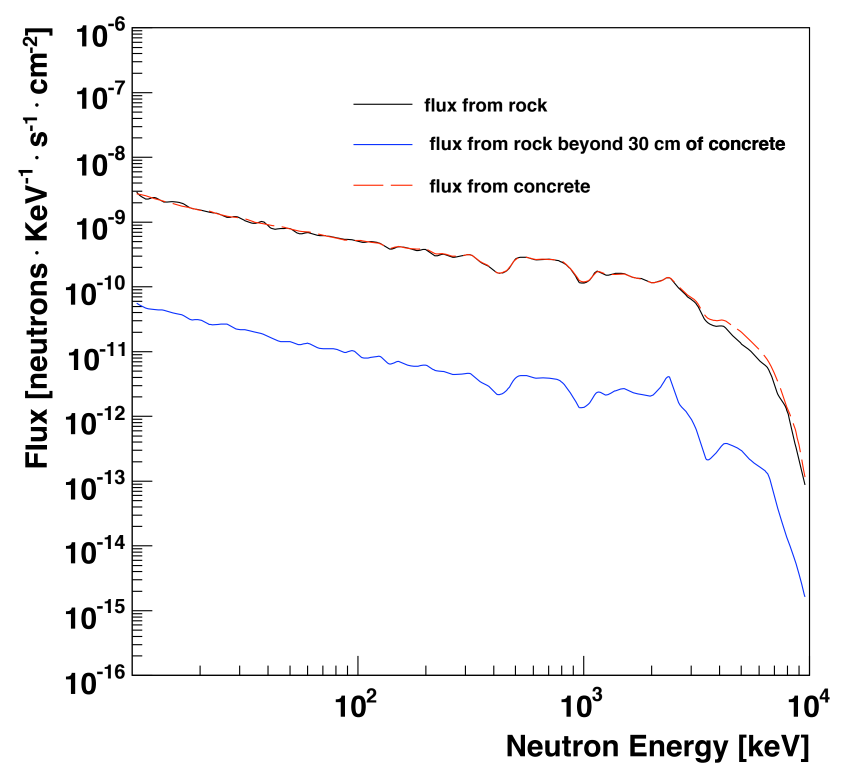
% mass	H	C	O	Na	Mg	Al	Si	P	K	Ca	Ti	Mn	Fe
Rock	1	6	50	0.44	0.84	2.6	7	0.06	0.21	31	0.07	0.03	1.9
Concrete	1.1	7.8	49.7	0.01	0.78	0,5	2,7	0.07	0.02	36.8	0.10	0.01	0.52

10% H_2O in w.l.i.

Rock = 2.65 g/cm3 , Concrete = 2.4 g/cm3



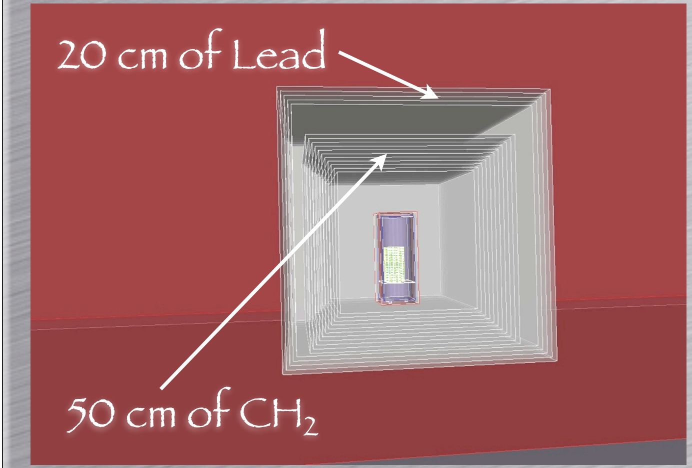
Since their similar composition, rock and concrete show a similar neutron yield



consequently with 30 cm of concrete with radioactivity levels as measured in the existing Modane laboratory, the gamma-ray flux from concrete will largely dominate over the flux from rock.

Background Transport

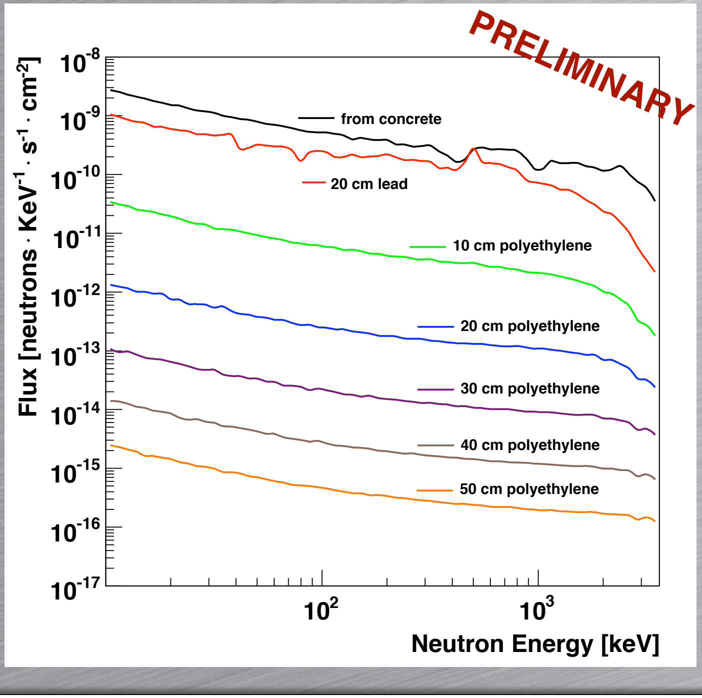
experimental hall walls: rock & concrete

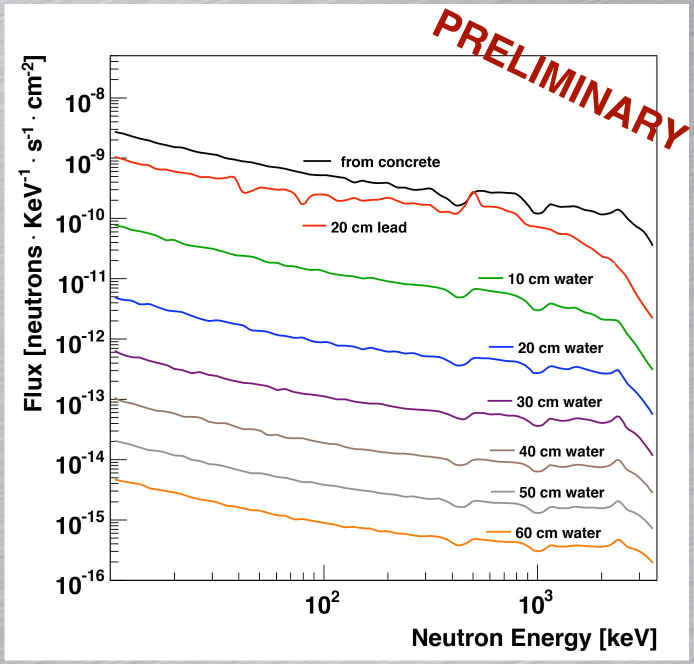


neutron event rate from concrete

shielding composition	events
20 cm Pb +50 cm CH_2	0.064
20 cm Pb +60 cm H_2O	0.125

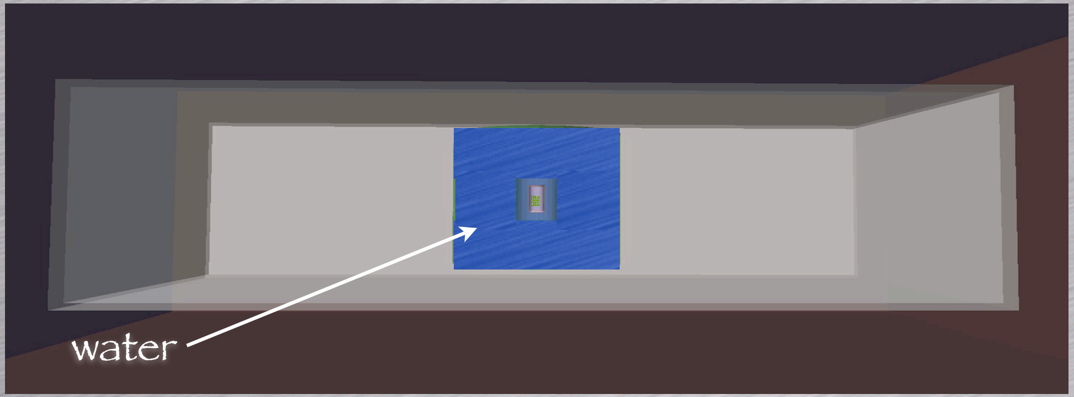
All rates are given as number of single electron recoils in 10-50 keV energy range per year in 103.68 kg of Ge.





Background Transport experimental hall walls: rock & concrete

Here water is used as alternative to Pb/CH_2 shielding
Since 2-3 meter of water are enough to suppress neutron background, only background rate from gammas needs to be investigated



Electron recoils from:	Rock	Concrete	Concrete
	3 m of water	3 m of water	2 m of water
U	5.1	486	47800
Th	41	765	43800
K	1.4	49	11300
Sum	48	1300	103000

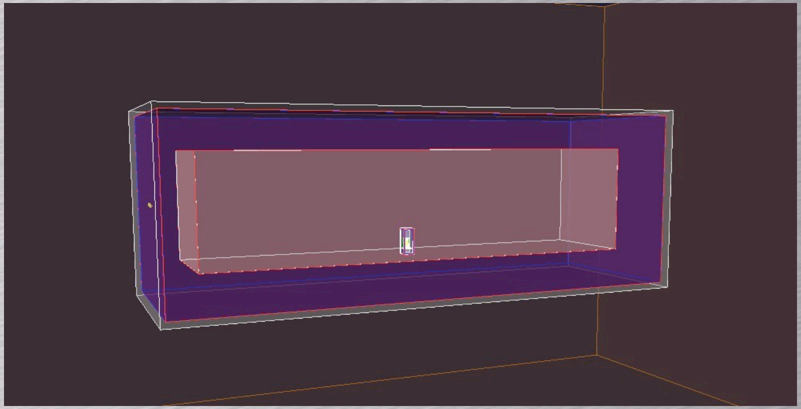
- For 2 meter of water discrimination factor of $>10^5$ is needed even for 100 kg target or additional shielding (4.5 cm of lead -> a factor of 10 attenuation).

Background Transport

experimental hall walls: rock & concrete

Here water is located along the walls within a stainless steel shield.

The detector is assumed to be exposed to the background fluxes from the inner vessel of the water shield



Single recoils from:	Ge recoils (vessel - 0.5 cm thick)	Ge recoils (vessel - 2 cm thick)	Electron recoils (vessel - 0.5 cm	Electron recoils (vessel - 2 cm
1 ppb U	3.2	12.8	170000	541000
1 ppb Th	1.1	4.4	73500	187000
1 ppm K			26900	71700
Sum	4.3	17.2	270000	800000

- Discrimination factor of about 10^6 is needed for 100 kg target (if the thickness of the vessel is 2 cm) or additional shielding (4.5 cm of lead -> a factor of 10 attenuation).
- The exact size of the lab is not very important: if the lab is bigger than the mass of steel is higher but it is further away from the detector.
- 1 mBq/kg of ^{60}Co from 2 cm thick water tank gives about 43000 ev/year.

Background Transport

detectors components

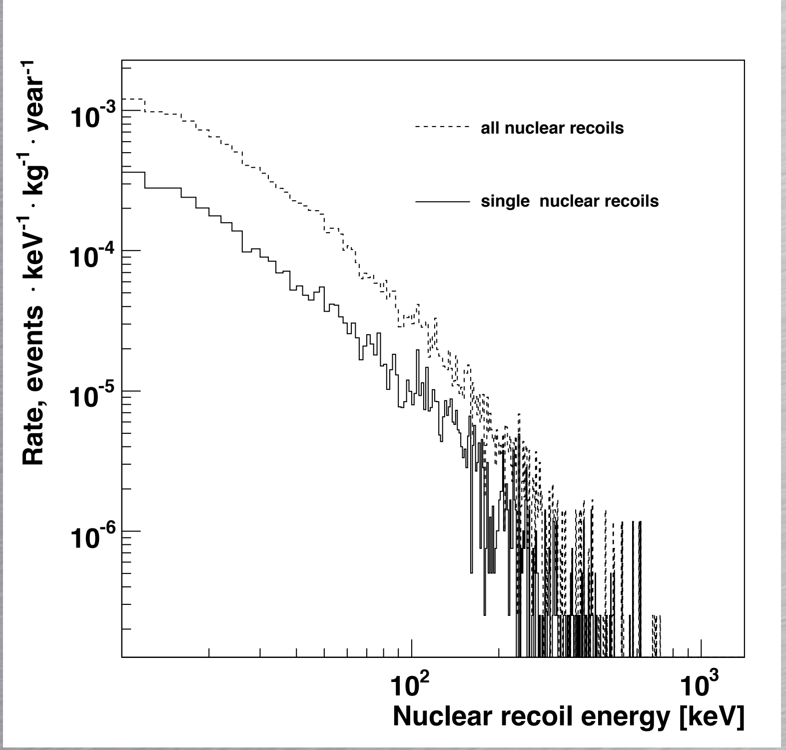
electron recoil rate from gammas in Cu

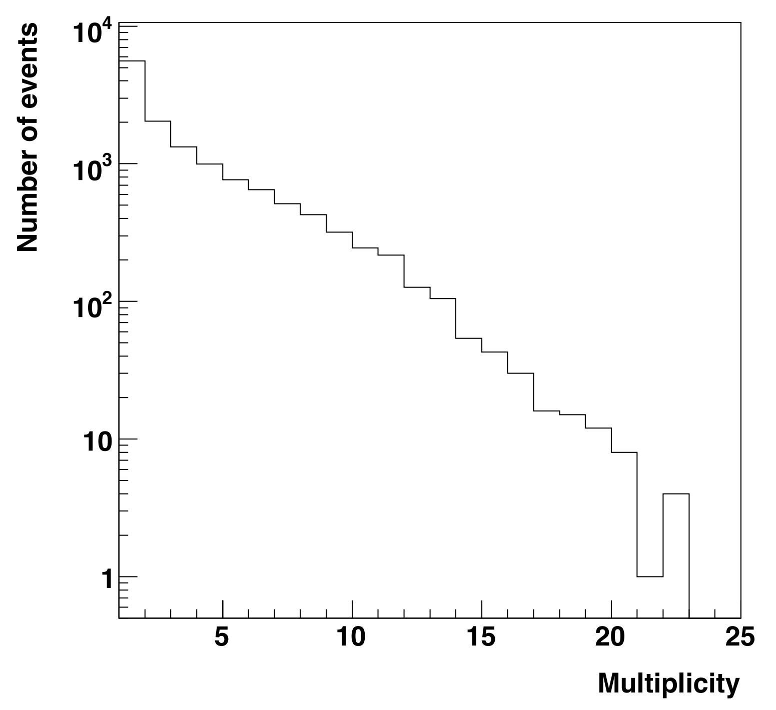
Electron recoils from:	Inner vessel (139 kg)	Outer vessel (181 kg)	Sum (320 kg)
0.01 ppb U	2680	1960	4640
0.01 ppb Th	1160	829	1989
10 ppb K	26	22	48
Sum	3866	2811	6677

- Discrimination factor of 10^4 is needed for 100 kg target.
- If 10 kg of stainless steel with 1 ppb of U/Th is added, then the rate may go up by a factor of 3 or more if SS is close to the detectors.

Background Transport detectors components

nuclear recoil from neutrons





Energy spectrum of nuclear recoils in 103.68 kg from 1ppb of U and Th in the CH_2 shielding (50 cm thick) surrounding the cryostat

Dashed curve accounts also for events with depositions from both nuclear and electron recoils

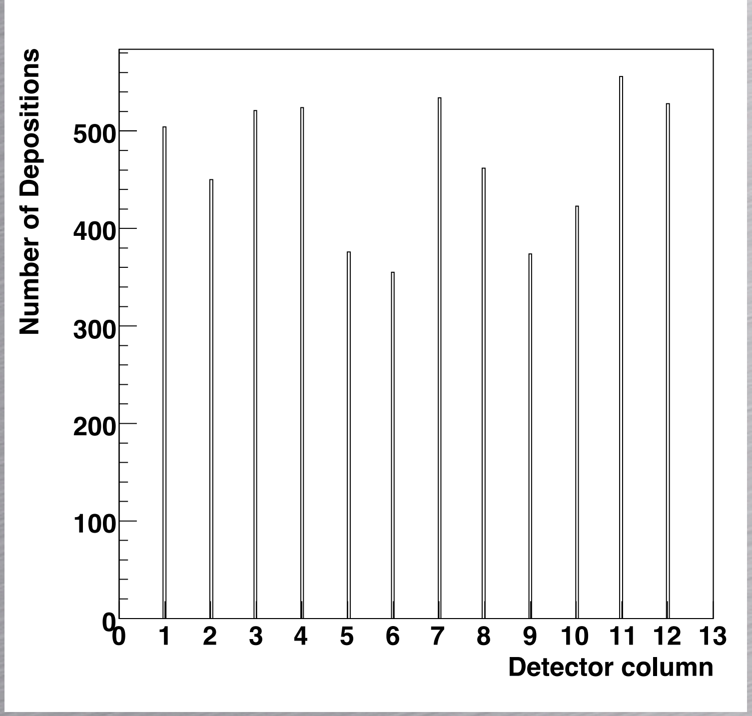
Multiplicity distribution of energy depositions due to nuclear recoils i from 1ppb of U and Th in the CH_2 shielding (50 cm thick) surrounding the cryostat.

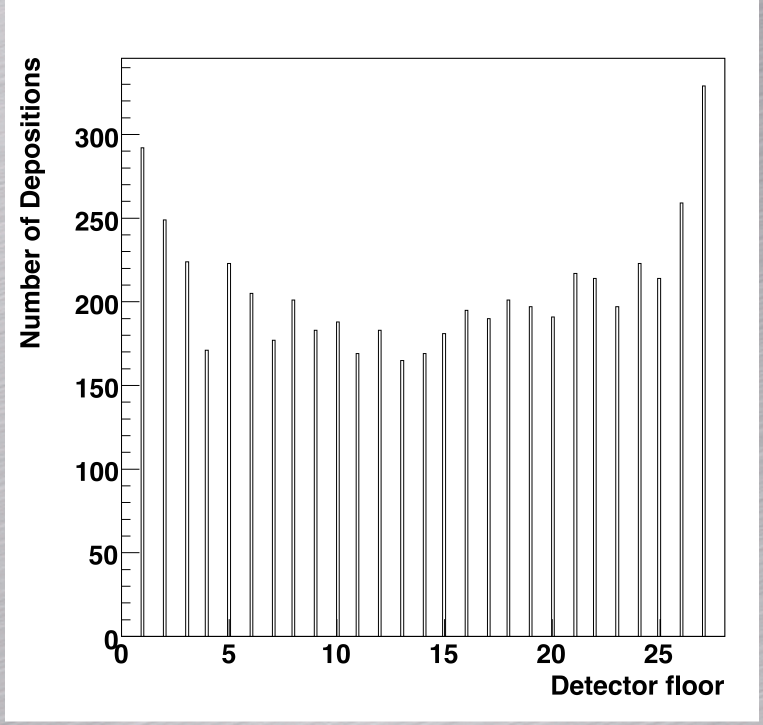
Events included are the ones showing at least one depositions from nuclear recoils above 10 keV

Background Transport

detectors components

Distribution of single nuclear recoils among the detectors from 1ppb of U and Th in the CH_2 shielding (50 cm thick) surrounding the cryostat.





Background Transport

nuclear recoil rate from neutrons

detectors components

	Radioactive contamination	Inner vessel 139 kg	Outer vessel 181 kg	Plate 22.1 kg (Cu) 19.7 kg (SS)	Sum
copper	0.01 ppb U (n yield =1.24e-10)	0.0149	0.0135	0.0068	0.0352
	0.01 ppb Th (n yield =8.39e-12)	0.0013	0.00114	0.000586	0.00303
stainless steel	1ppb U (n yield =1.47e-10)			0.812	
	1ppb Th (n yield =5.16e-11)			0.284	
	sum	0.0162	0.0146	0.00739 (Cu) 1.1 (SS)	0.0382(Cu)

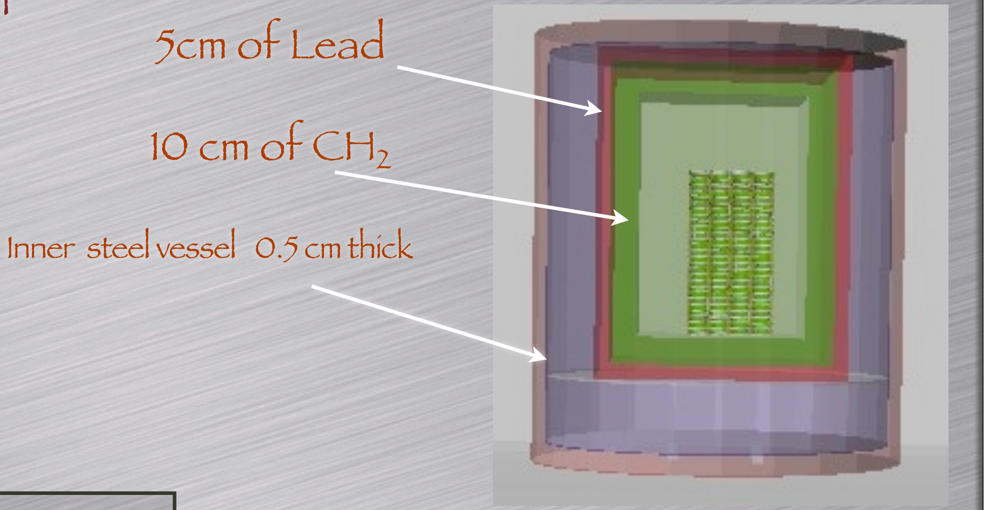
	Radioactive contamination	Polyethylene shielding mass= 21179 Kg
polyethylene	0.1ppb U (n yield = 2.70e-12)	0.342
	0.1ppb Th (n yield = 5.81e-13)	0.100

neutron yield is given in n cm^{-3} s^{-1}

- **Rate is given as number of single nuclear recoils in 10-50 keV energy range per year in 103.68 kg of Ge.**
- **For 5-50 keV the rate is 20% higher than for 10-50 keV.**
- **If 10 kg of stainless steel with 1 ppb of U/Th is added close to the detectors, then the rate may go up by a factor of 10.**

Background Transport detectors components

In the case of a inner cryostat vessel made of stainless steel, internal shielding is needed.



5cm of Lead

10 cm of CH_2

Inner steel vessel 0.5 cm thick

nuclear recoil rate from neutrons

stainless steel mass = 347 Kg

Radioactive contamination	events
1ppb U (n yield =1.47e-10)	0.031
1ppb Th (n yield =5.16e-11)	0.011

polyethylene mass = 366 Kg

Radioactive contamination	events
0.1 ppb U (n yield = 2.484e-12)	0.235
0.1 ppb Th (n yield = 5.261e-13)	0.053

CONCLUSIONS

In light of the simulations carried out so far, several important conclusions can be drawn helping the design of future large-scale dark matter detectors :

- External lead (20 cm) - internal CH_2 / H_2O (50cm /60-70cm) can be enough to suppress background from walls. However a proper selection of concrete ingredients can reduce the background rate further more .
- The thickness of water shield of around 3 meters is enough to suppress the gamma- ray background from rock and concrete to below 1 event per year at 10 -50 keV (in 100 kg of Ge target) if a discrimination factor of 10^4 is achieved.
- If the vessel of the water tank is made out of stainless steel with concentrations of U/Th of about 1 ppb and that of K of about 1 ppm, additional shielding against neutrons and gamma-rays from this source is required.
- A few hundred kg of low radioactivity copper (< 0.01 ppb U/Th) can be used in the detector construction. This will produce a neutron background rate much less than 1 event per year at 10–50 keV and not limit detector sensitivity to WIMPs. The gamma-ray induced background rate would require a discrimination factor of about 10^4. If this is not achievable, the mass of copper and other materials should be reduced to the minimum.
- No more than a few kg of stainless steel or other material with concentrations of about 1 ppb of U/Th are allowed inside the shielding
- If polyethylene is used within the cryostat, due to the gamma background, a further shield would be required (very pure copper could be a choice)
- Materials with higher concentrations of radioactive isotopes (more than 1 ppb of U/Th) should be avoided or their mass should be limited to less than a few kg.