Neutron background at Boulby mine

Vitaly A. Kudryavtsev

Department of Physics and Astronomy
University of Sheffield

On behalf of
UKDMC, ZEPLIN-II and ILIAS

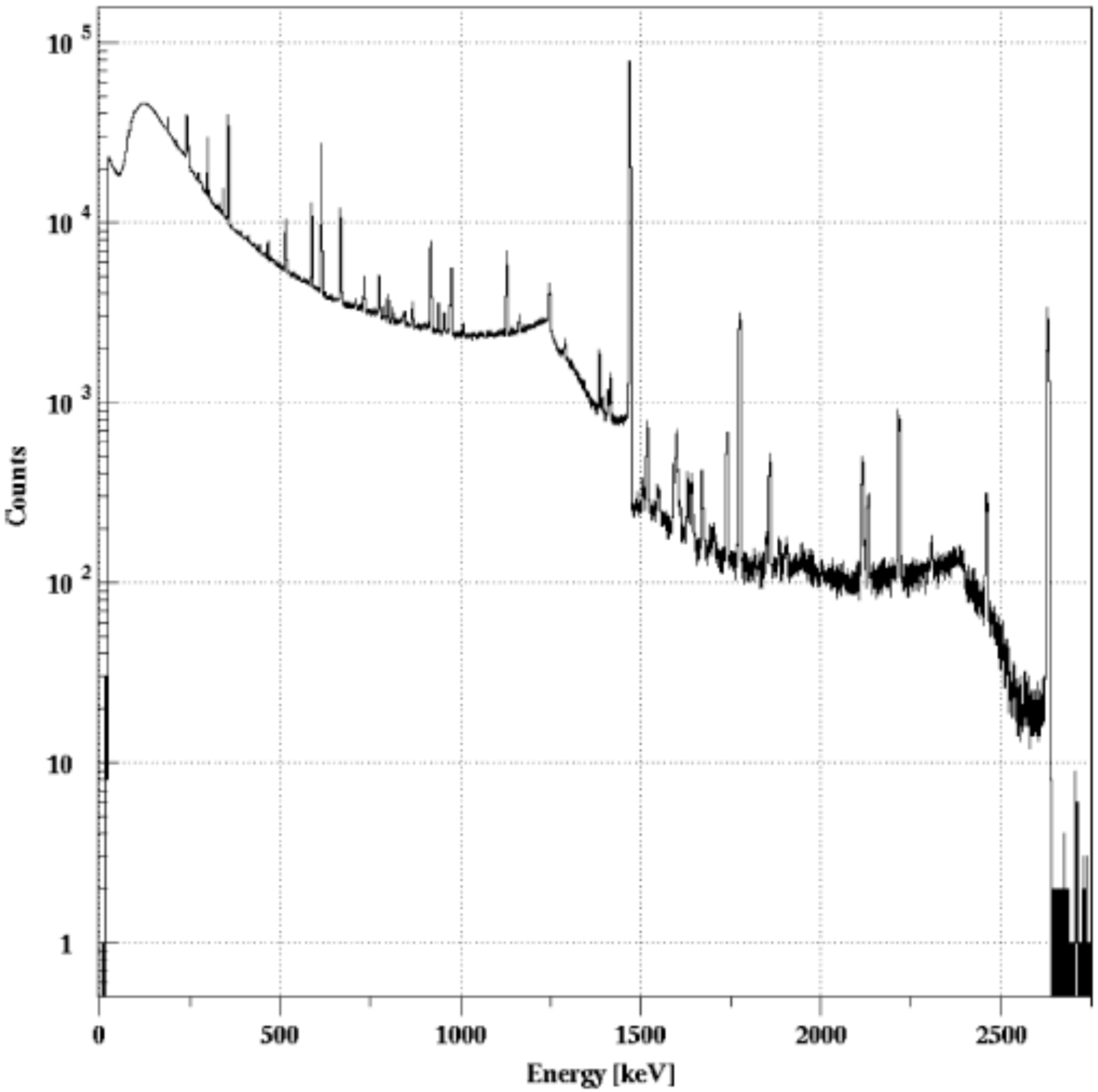
Outline

- Introduction: why do we need to know the background?
- Measurement of gamma-ray flux from rock and evaluation of uranium and thorium concentrations in rock.
- Measurement of neutron flux from rock.
- Measurement of muon flux.
- Neutrons from cosmic-ray muons (preliminary).
- Summary.

Why are we interested in background studies?

- Background is a limiting factor for sensitive experiments.
- Background from rock (gammas and neutrons) can be shielded but we need to know the required thickness of shielding.
  - Required suppression - $>10^6$ for future large-scale dark matter experiments.
- Muon-induced neutrons are difficult to suppress: we need large depth (≥ 1 km of rock) and probably an active veto system.
  - Required efficiency of an active veto system is determined by the neutron flux (depth, materials around etc.).
- Background to consider:
  - Gammas from rock (related to U/Th/K concentrations).
  - Neutrons from rock.
  - Neutrons from cosmic-ray muons.
  - Gammas and neutrons from laboratory materials (detector components, shielding etc.) - neutrons are difficult to measure; will not be considered here.

Gamma spectrum from rock



- Measurements with Ge detector.
- Detector exposed to gammas from the rock walls.
- Different lines correspond to different decaying isotopes in the U/Th/^{40}K decay chains.
- P. F. Smith et al. Astroparticle Phys. 22 (2005) 409.

U/Th concentrations

Table 1
Summary of U/Th rock concentrations derived from comparison of observed and Monte Carlo rates for the four strongest lines from each element

	Parent decays/g/s (for 1 ppb)	Line (keV)	Line strength per parent decay	Monte Carlo events/s per Ge detector (for 1 ppb)	Observed number/s for single Ge detector	Conc U/Th (ppb)	Mean of four lines (ppb)
U	1.29E−5	609	0.428	2.2E−3 ± 2E−4	0.170 ± 0.014	77 ± 12	
		352	0.342	3.1E−3 ± 3E−4	0.160 ± 0.013	52 ± 10	
		295	0.177	1.4E−3 ± 2E−4	0.084 ± 0.009	60 ± 10	
		1765	0.147	5.7E−4 ± 6E−5	0.045 ± 0.006	79 ± 10	
							67 ± 6
Th	4.06E−6	239	0.436	9.4E−4 ± 1E−4	0.101 ± 0.008	108 ± 15	
		2615	0.356	4.9E−4 ± 5E−5	0.062 ± 0.005	127 ± 15	
		583	0.304	4.5E−4 ± 5E−5	0.060 ± 0.006	133 ± 20	
		911	0.266	3.5E−4 ± 4E−5	0.049 ± 0.006	140 ± 20	
							127 ± 10

- **Also ^{40}K line requires a concentration of K of 1130±200 ppm.**
- **More information about other measurements of U/Th/K concentrations in Boulby salt and other materials can be obtained from http://hepwww.rl.ac.uk/ukdmc/Radioactivity/Index.html**

Neutron flux from rock

- **Can be calculated if U/Th concentrations in rock are known.**
- **But large uncertainties are possible because:**
  - **Cross-sections of (alpha,n) reactions are not well known;**
  - **Modelling neutron transport is complicated - it is always good to compare the simulation results with measurements;**
  - **Gamma-lines provide information about certain isotopes mainly at the end of the U/Th decay chains; extrapolation to the whole chains requires an assumption about equilibrium.**
- **Direct measurements of neutron flux can resolve ambiguities.**

Detector and detection principles

Gd-loaded liquid scintillator - 6.5 l, 2 PMTs.

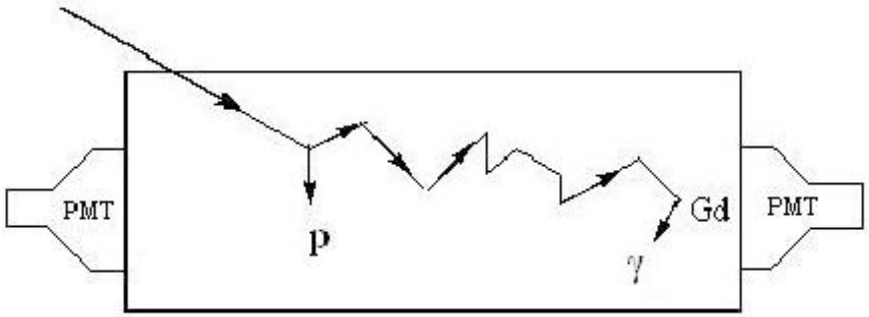
Detection principle - 2 pulses: prompt proton recoils + delayed gammas from neutron capture.

Captures on Gd, H, stainless steel …

$$n_{thermal} + A \rightarrow (A+1)^* \rightarrow (A+1) + \gamma' s$$

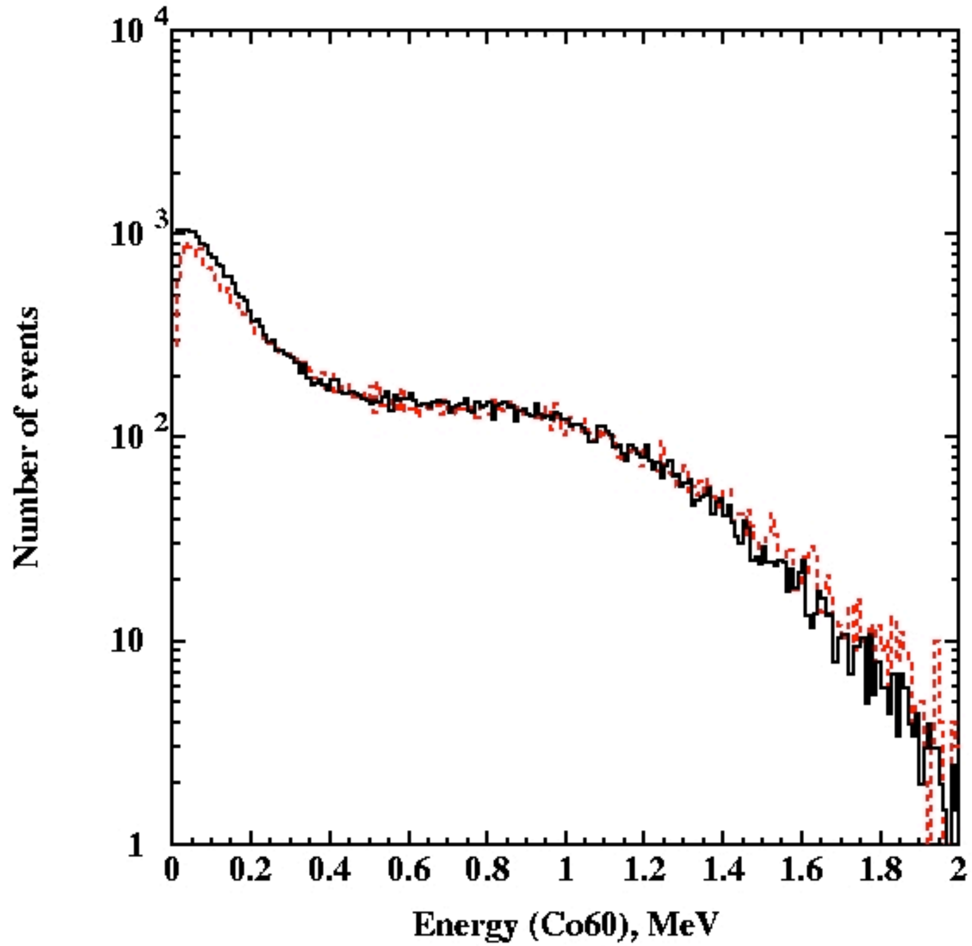
Lead and copper shielding to suppress gammas from rock

E. Tziaferi et al. Astroparticle Phys. 27 (2007) 326.



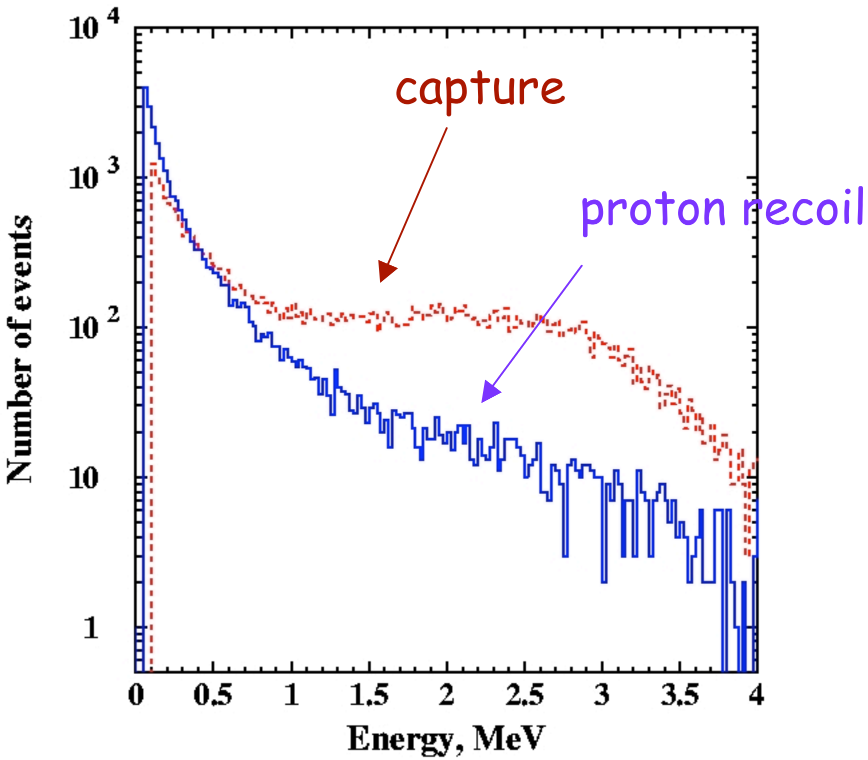
Signature: exponential distribution of time delay between the two pulses in an event.

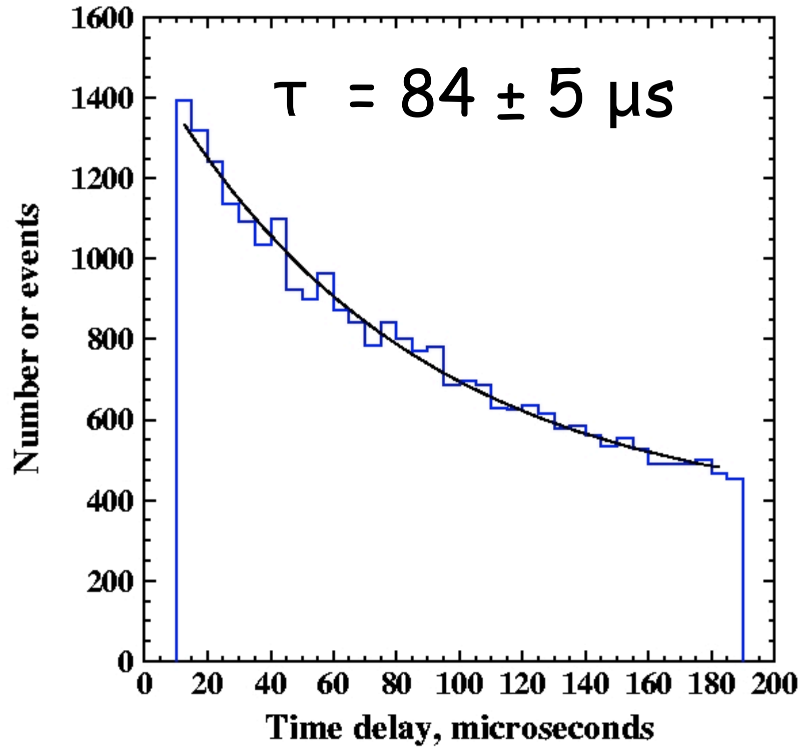
Energy calibration



- Co-57, Cs-137 and Co-60 sources.
- MC simulations to determine the energy scale.
- Red - data.
- Black - simulations.

Neutron calibration

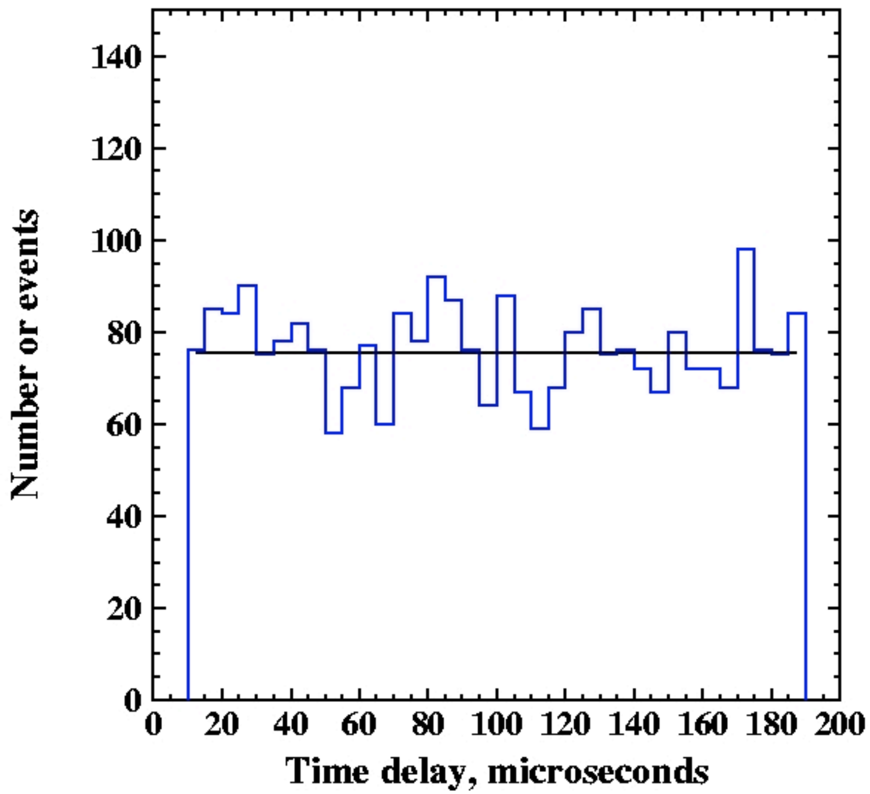




- **Cf-252 neutron source.**
- **Energy spectra of two pulses and time delay distribution.**
- **Proves that the detector is sensitive to neutrons and provides efficiency for neutron detection.**

Gamma calibration

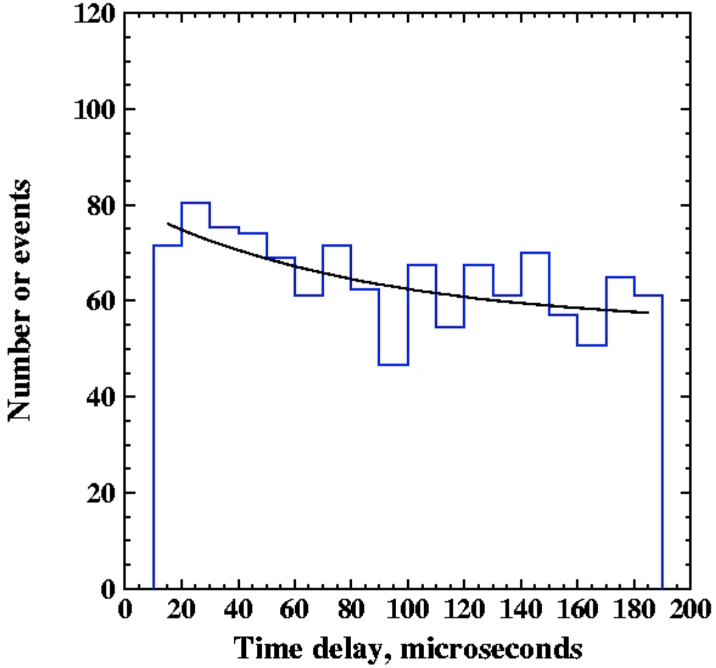
^{60}Co with coincidences



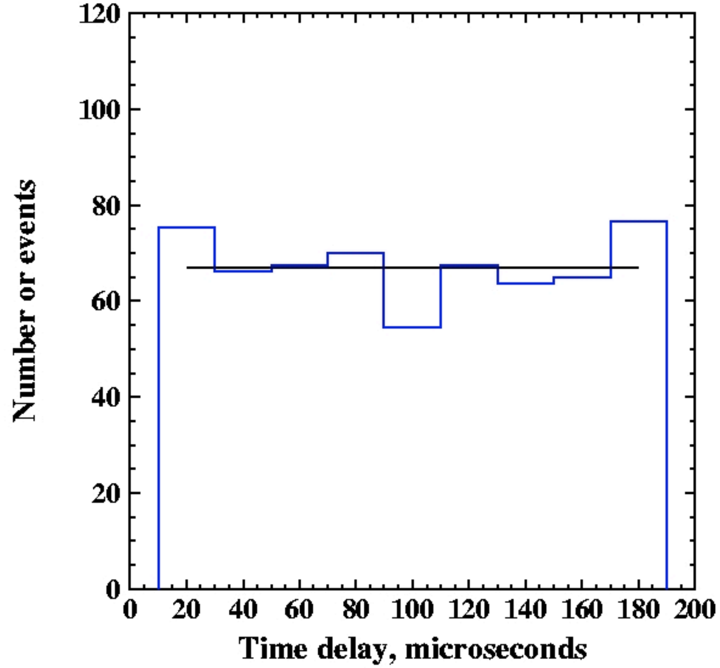
- Time delay distribution does not have an exponential shape - only random coincidences between two background pulses.

Measurements of the neutron flux

4 months without polypropylene shielding

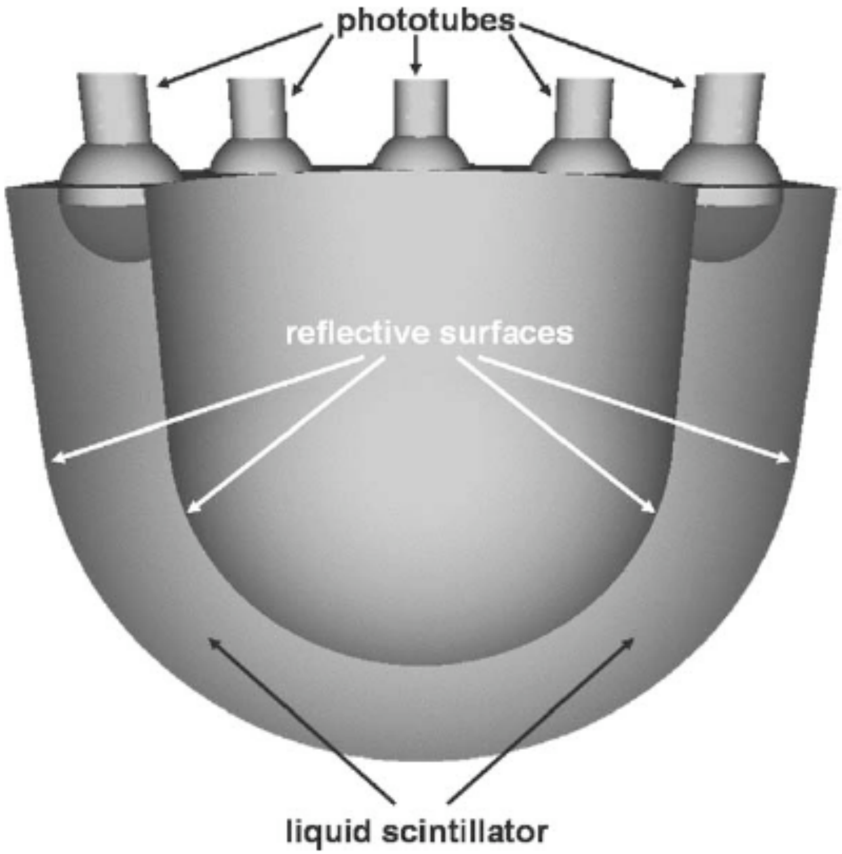


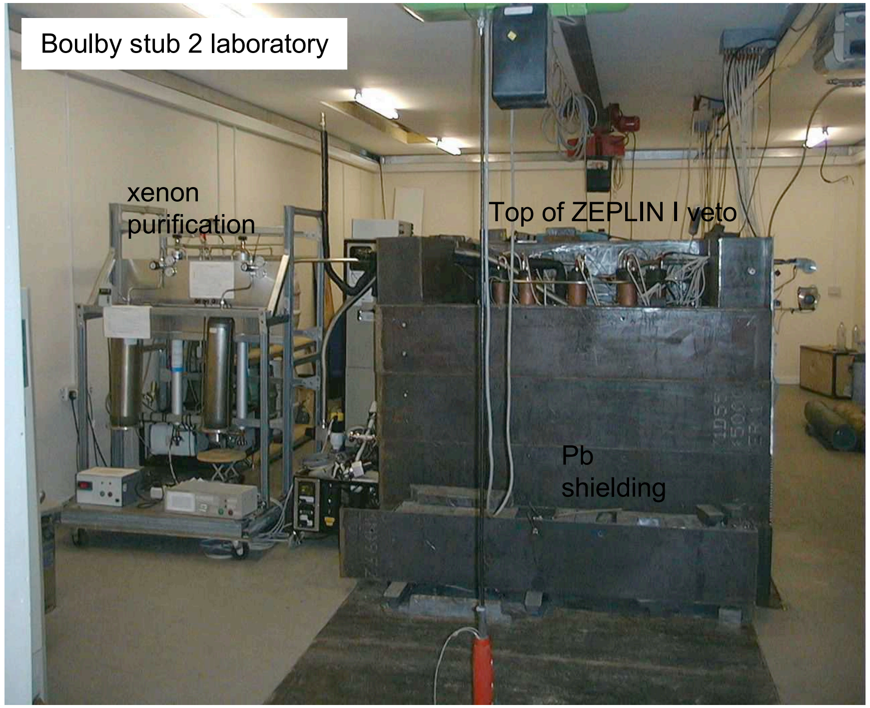
2.5 months with polypropylene shielding



- **Neutron flux at Boulby (E>0.5 MeV on lead shielding taking into account the backscattering of neutrons from rock):** **(1.72 ± 0.61 (stat.) ± 0.38 (syst.)) × 10^{-6} n/cm^2/s - in agreement with MC assuming measured concentrations of U/Th (1.20×10^{-6} n/cm^2/s).**

Atmospheric muons





- **No dedicated experiment at Boulby (unlike Gran Sasso, Modane and other labs).**
- **Fortunately there is a large scintillator detector - ZEPLIN I/II veto - 0.93 tonne of liquid scintillator.**

Muon rate and spectrum

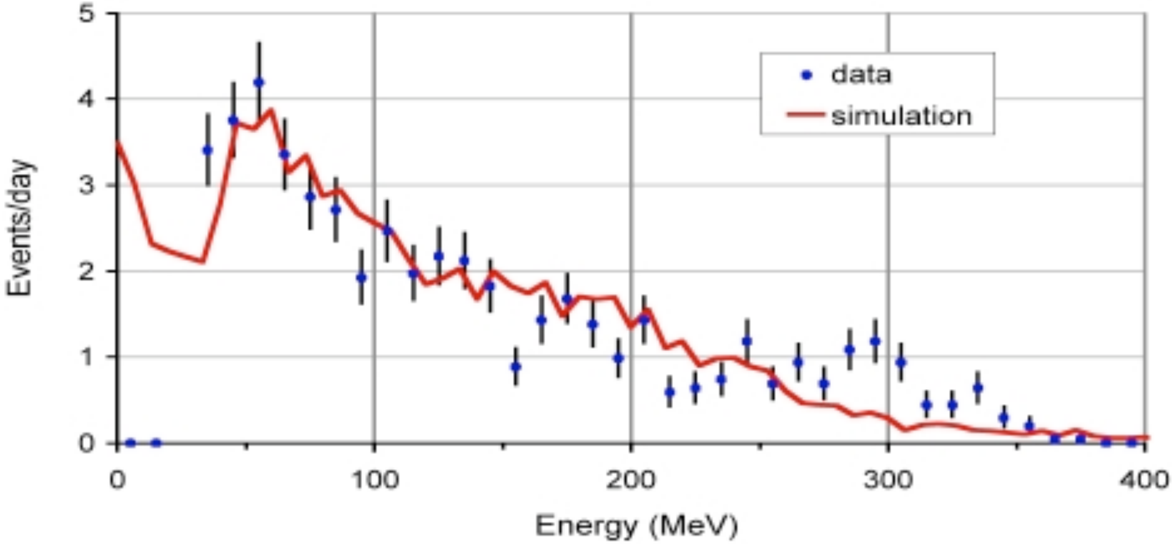


Table 2
Muon rates in data collection runs

Run start	N_{muons}(E > 30 MeV)	duration (days)	rate (day^{-1})
26-7-02	1028	19.830	51.8 ± 1.6(stat)
28-8-02	712	12.886	55.3 ± 2.1(stat)
11-9-02	1097	20.249	54.2 ± 1.6(stat)
Total	2837	52.965	53.6 ± 1.0(stat)

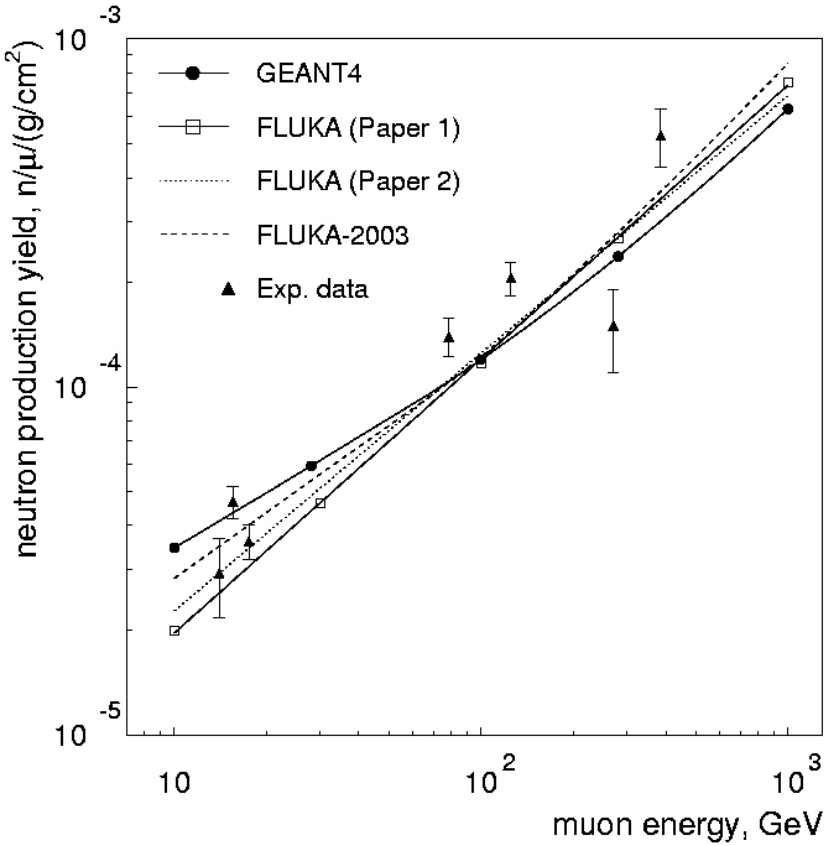
- **Simulations (to evaluate muon detection efficiency).**
- **Muon transport through rock - MUSIC - Antonioli et al., Astrop. Phys. 7 (1997) 357, Kudryavtsev et al. Phys. Lett. B 471 (1999) 251.**
- **Muon sampling underground - MUSUN - Kudryavtsev et al. NIMA, 505 (2003) 688).**
- **Detector response - in-house code.**

Muon flux: results

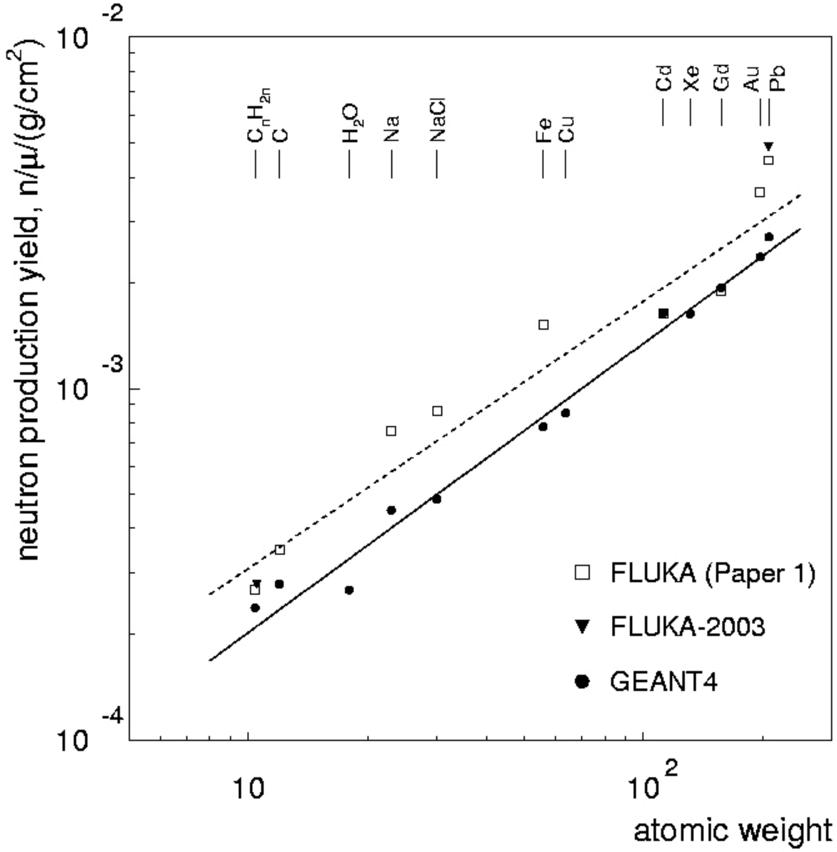
- **Vertical depth: 1070 m or 2805 ± 45 m w.e.**
- **Integrated (over solid angle and energy) muon flux (through a sphere with unit cross-sectional area):**
  $(4.09 \pm 0.08\ (\text{stat.}) \pm 0.13\ (\text{syst.}))\times10^{-8}$ cm^{-2} s^{-1}.
- **Vertical muon intensity: 3.32×10^{-8} cm^{-2} s^{-1} sr^{-1}.**
- **Published in: M. Robinson et al., NIMA 511 (2003) 347.**

Muon-induced neutrons

FLUKA: Kudryavtsev et al. NIMA, 505 (2003) 688.

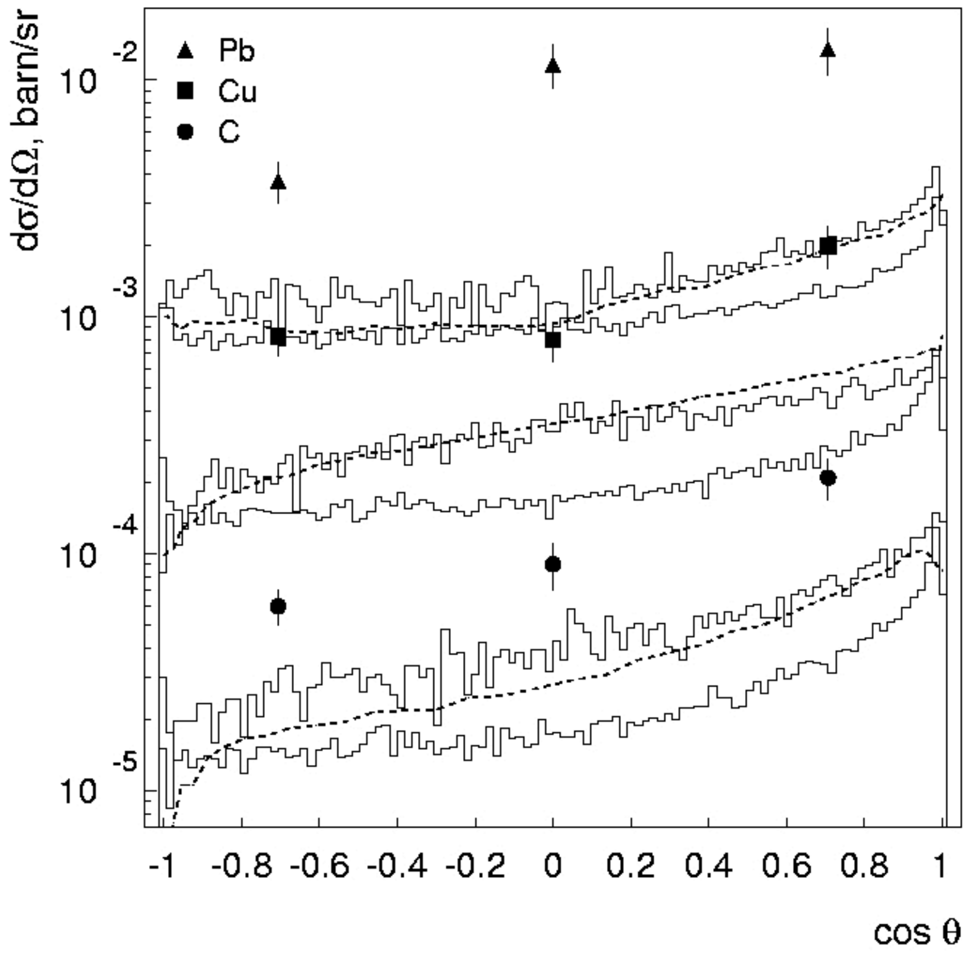


GEANT4: Araujo et al. NIMA 545 (2005), 398.



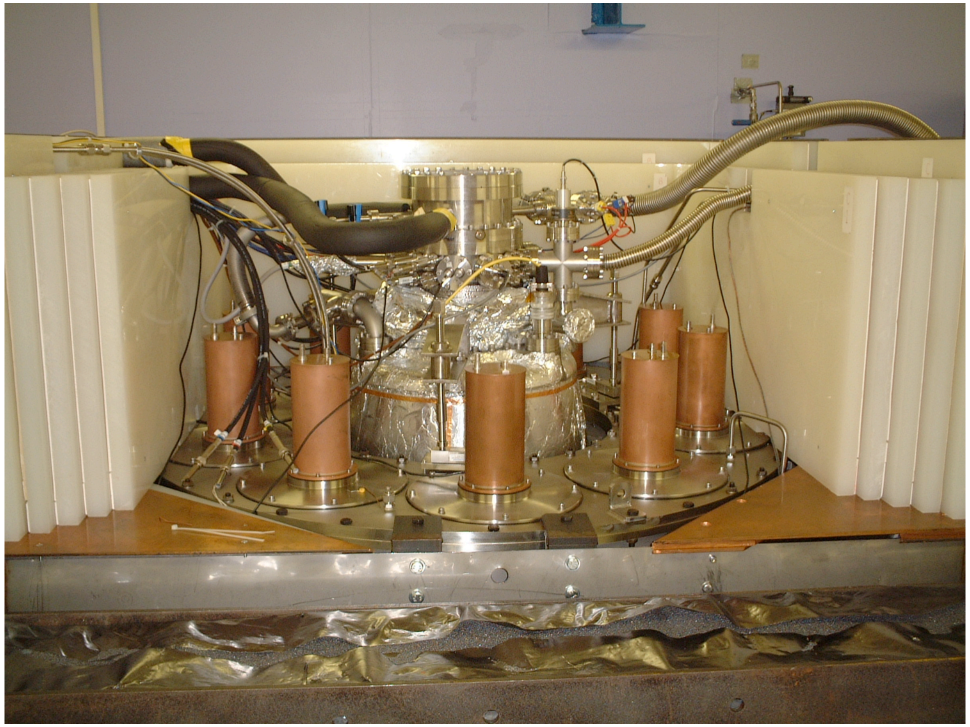
- Most data are for light targets.
- Data are controversial.
- Models may not be very accurate - tests are needed.

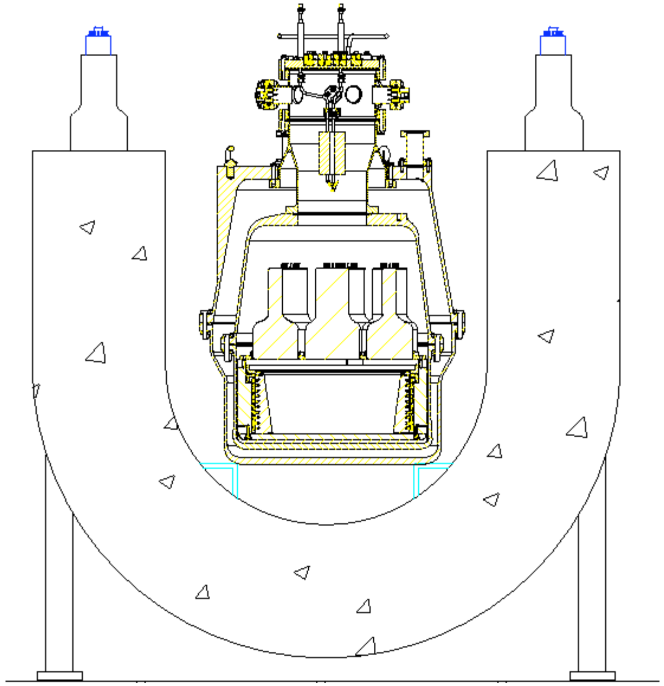
Muon-induced neutrons



- **Differential cross-section of neutron production in thin targets for 190 GeV muons (E_n>10 MeV). Upper (thick) histograms - GEANT4; dashed line - FLUKA (Araujo et al.); data - NA55 (Chazal et al. NIMA, 490 (2002) 334).**
- **Other data for lead (Bergamasco et al. Nuovo Cim. A, 13 (1973) 403; Gorshkov et al. Sov. J. Nucl. Phys., 18 (1974) 57) are old and controversial but also show significantly higher neutron production compared with simulations.**
- **Lead is important since it is used as a shield in underground experiments.**

Measurements with ZEPLIN II veto



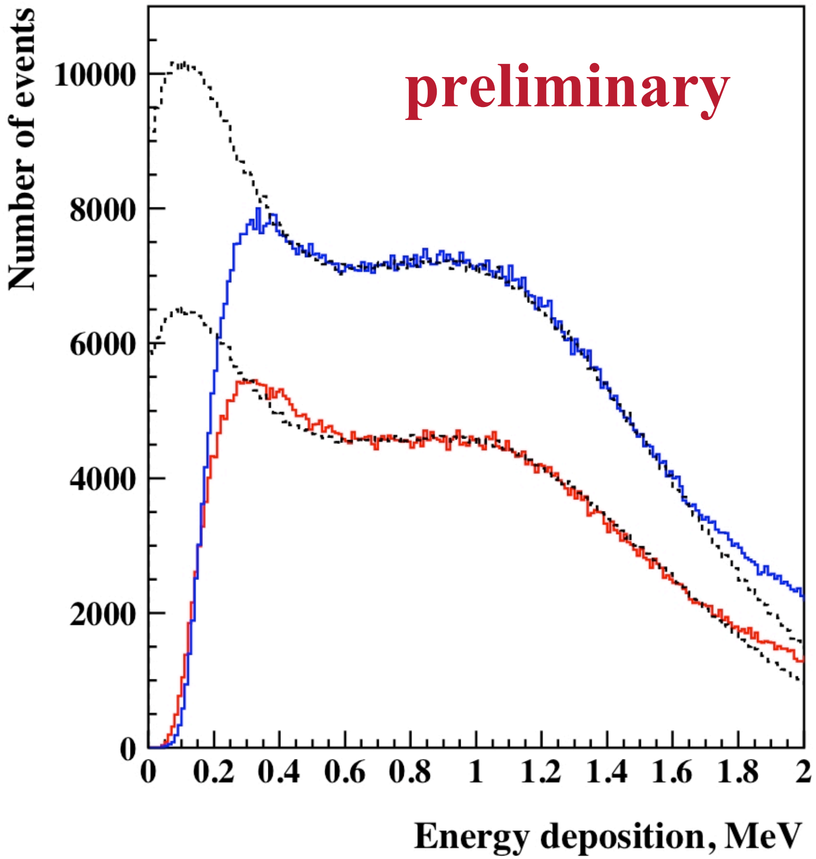


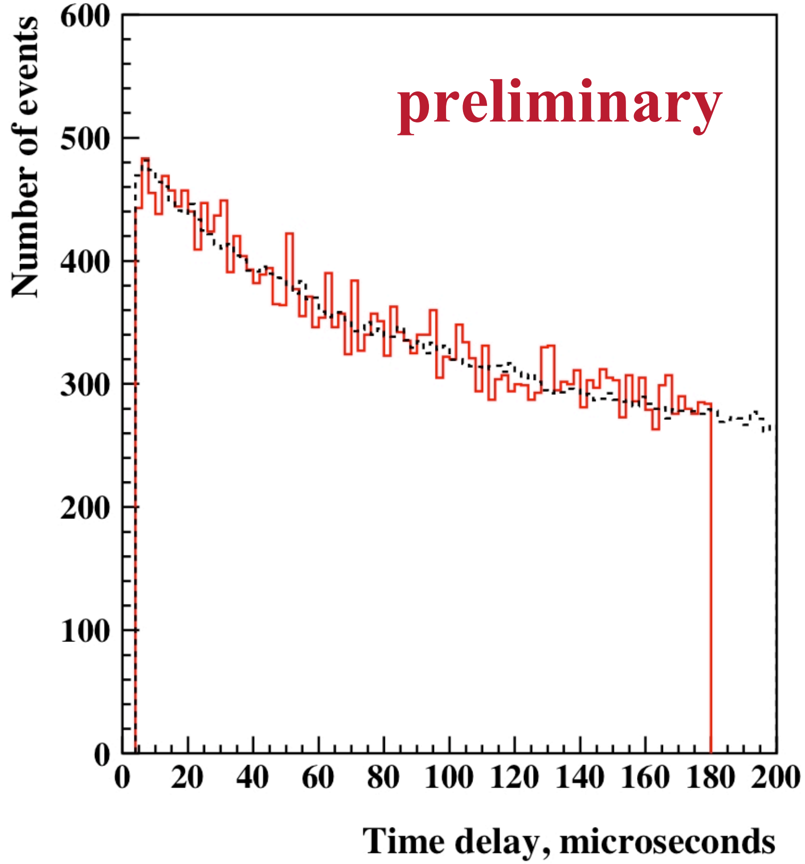
- 0.93 tonne of liquid scintillator + paraffin shielding interleaved with Gd impregnated resin + Gd painted on the inner surface of the veto vessel.
- Lead castle - about 52 tonnes - one of the targets for neutron production.
- Detailed MC is required to take into account geometry and physics - in progress.

Detection principle

- **Neutron detection principle: delay coincidences between muon signal and neutron capture:**
  - **Muon (or cascade) signal - large energy deposition (PMTs and DAQ are saturated);**
  - **Neutron capture signal - delayed by a few tens of microseconds, capture mainly on H.**
- **The detector is triggered by high-energy pulses: either high-energy gammas depositing energy close to PMTs (non-uniform light collection shifts the measured energy to higher values), or muons (cascades).**
- **Energy threshold: hardware - about 10 MeV, software - about 30 MeV. Average energy deposition of muons - more than 50 MeV.**
- **Energy threshold for secondary (neutron) pulse analysis: about 0.2 MeV; increased to 0.7 MeV at the 2nd stage of analysis to avoid background etc.**
- **3-fold coincidences between PMTs are required for trigger and secondary pulses.**
- **Total live time: 204.8 days (August 2006 - April 2007).**

Energy and neutron calibrations

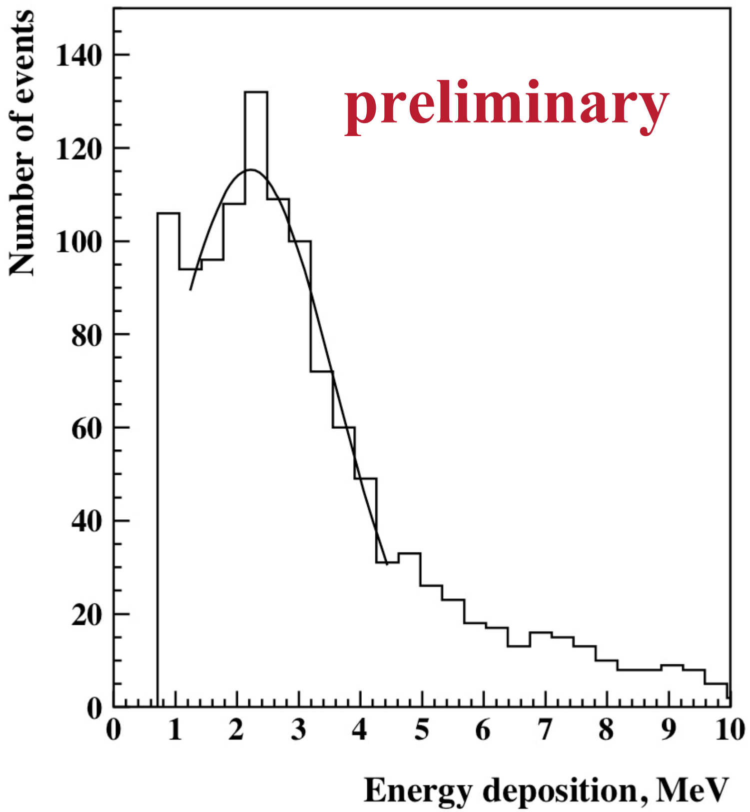


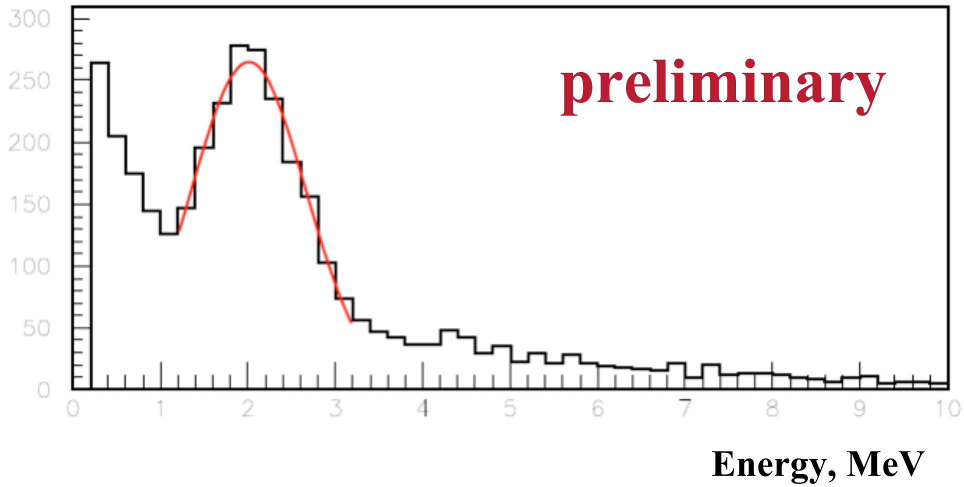


Co-60 spectra collected in August 2006 and March 2007 (before and after the data run).

Neutron calibration with Am-Be source; simulations using GEANT4.

Energy spectrum of the secondary pulses

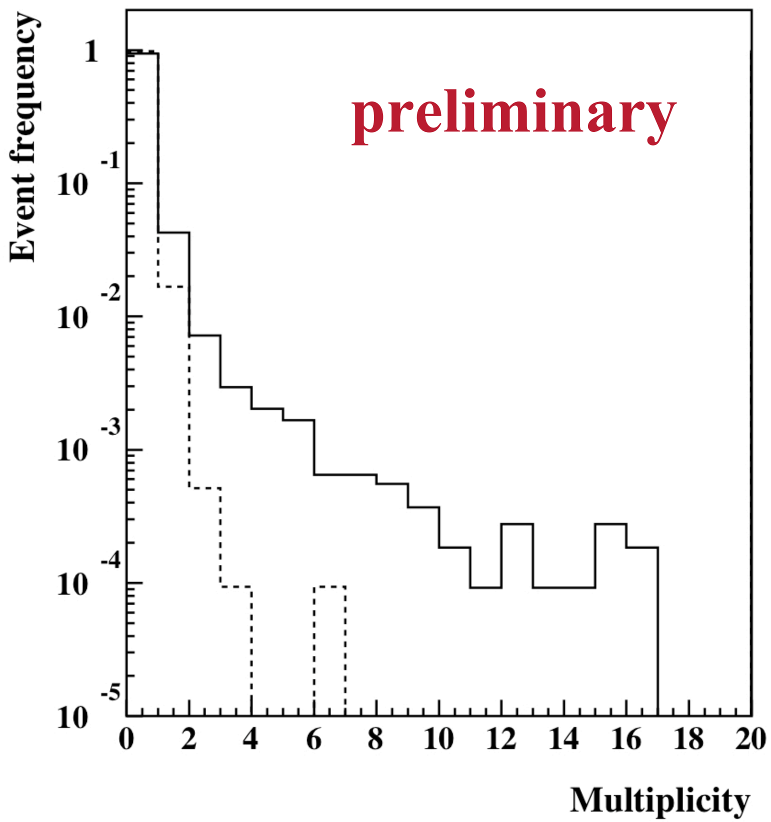


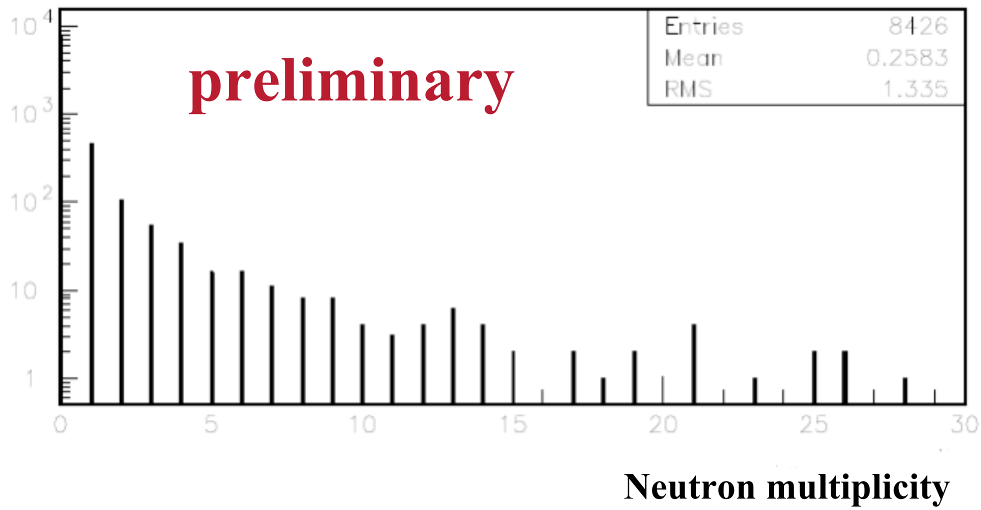


Simulated spectrum (GEANT4) - preliminary, results obtained 2 days ago.
Spectrum was folded with the energy resolution function determined from the Co-60 calibrations.

Spectrum of secondary pulses after muon trigger; an independent calibration using 2.22 MeV peak - capture on H.

Multiplicity distribution



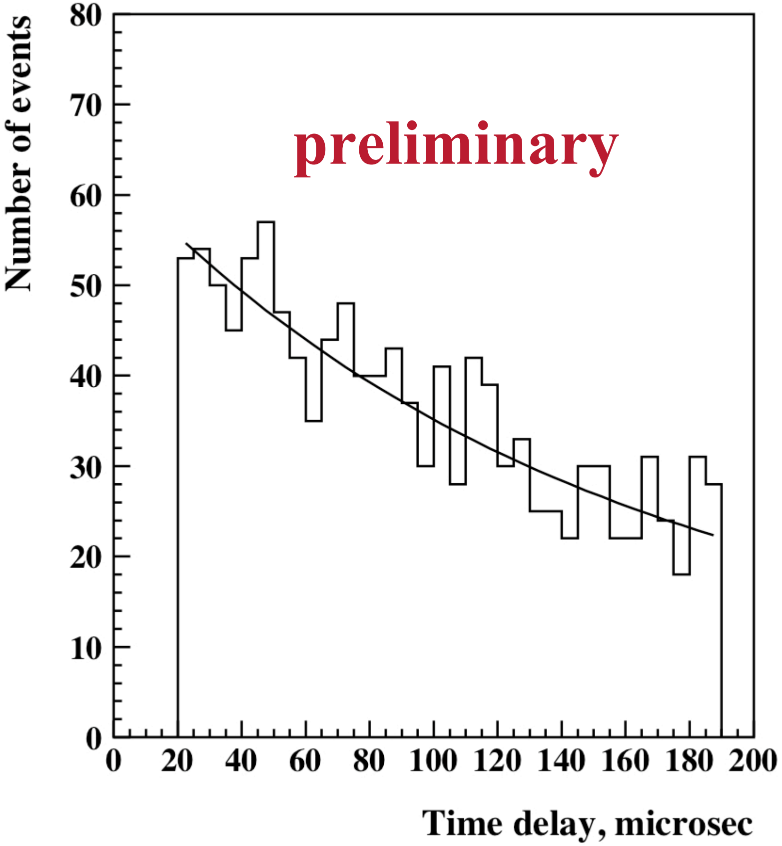


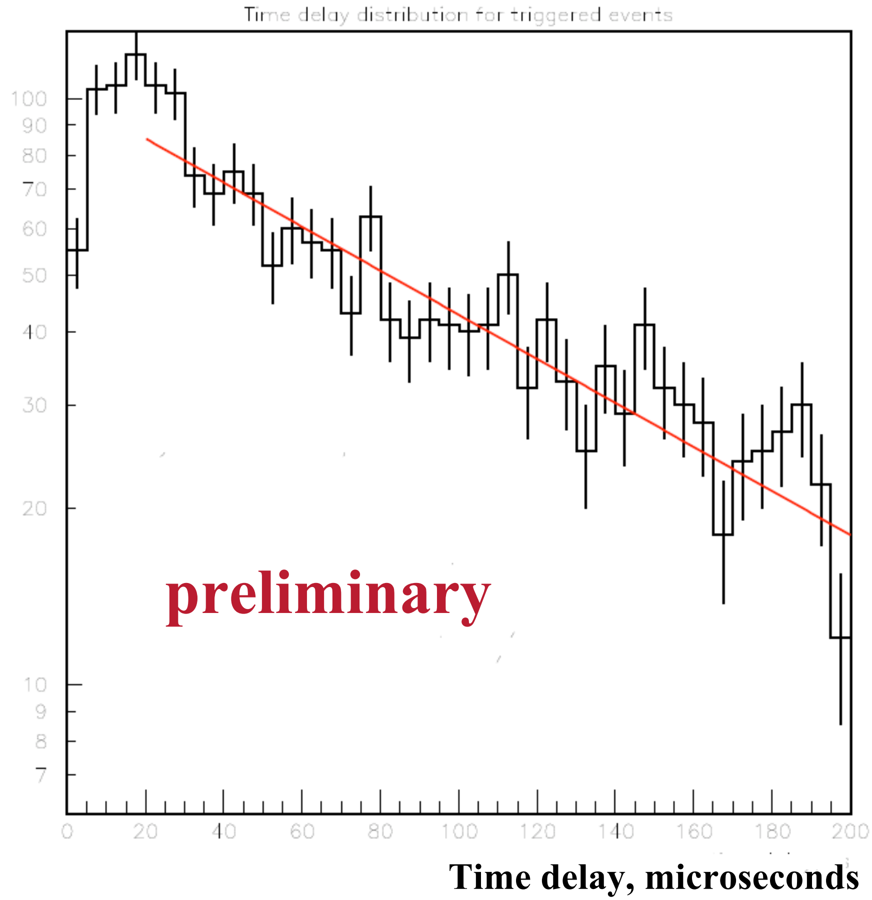
Simulated (GEANT4) multiplicity of secondary pulses (neutrons > 500 ns) - preliminary.

Solid histogram - neutrons, muon trigger (E>30 MeV);
Dashed histogram - background, gamma-ray trigger (10<E<30 MeV).

Time delay distributions

204.8 days of run time

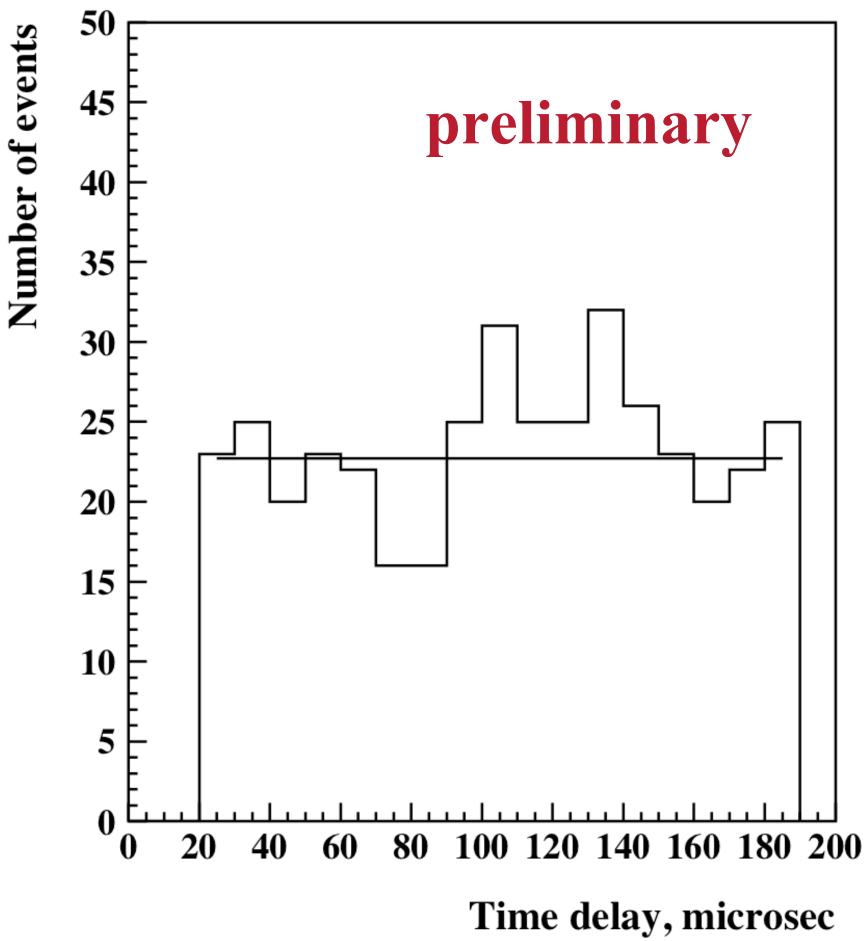




Data run, muon trigger (E>30 MeV)
Neutron rate: 0.15 ± 0.03 (stat) ± ? (syst) per muon.

Simulations (preliminary):
0.27 ± 0.04 (stat) ± 0.04 (syst) n/μ.

Time delay distribution



Data run, gamma-ray trigger (10<E<30 MeV).

Conclusions

- Gamma and neutron backgrounds from radioactivity in rock at Boulby are pretty well known.
- Gamma-line intensities have been measured with Ge detector. U/Th/K concentrations in rock have been evaluated:

  K - 1130 ± 200 ppm; U - 67 ± 6 ppb; Th: 127 ± 10 ppb.
- Neutron background has been measured using small liquid scintillator cell: $(1.72 \pm 0.61\ (\text{stat.}) \pm 0.38\ (\text{syst.})) \times 10^{-6}\ \text{n/cm}^2\text{/s}$ (E>0.5 MeV) and found to be consistent with simulations based on the evaluated U/Th concentrations - $1.20 \times 10^{-6}\ \text{n/cm}^2\text{/s}$.
- Muon flux has been measured using ZEPLIN I liquid scintillator veto:

  $(4.09 \pm 0.08\ (\text{stat.}) \pm 0.13\ (\text{syst.})) \times 10^{-8}\ \text{cm}^{-2}\ \text{s}^{-1}$.
- Same veto has been used to measure muon-induced neutrons; the rate was measured as 0.15±0.03(stat)±?(syst) neutrons/muon. Simulations are in progress to convert this result into the neutron yield per muon. Preliminary result from simulations: 0.27±0.04(stat)±0.04(syst) n/μ - not much higher than the measured rate but still some improvements to be done (larger statistics, remove any bias). Our results do not support the statement that GEANT4 models significantly underestimate muon-induced neutron yield.

Thanks to:

- Cleveland Potash Ltd.
- University of Sheffield, CCLRC/STFC-RAL, Imperial College, University of Edinburgh, LIP-Coimbra.
- PPARC/STFC.
- ILIAS.