Demand for new instrumentation for well logging

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Detecting materials and readout devices

- **Neutron sensitive**
  - $^3$He gas based tubes – *low supply*
  - $^6$Li glass scintillators
  - Diamond detectors
  - SiC detectors

- **Gamma sensitive**
  - Inorganic crystals
  - Glass ceramics – *future*

- **Charge particles sensitive** – *very limited use!*
  - Plastics scintillators
  - Diamond detector – *future*

- **Light readout**
  - PMT
  - SiPM
γ sensitive tools: measure formation elements

Very often:
Crystal diameter is limited even for wireline tools.
For open holes < 7.5 cm
For cased holes < 5 cm, often < 2 cm.
For Logging While Drilling (LWD) < 2 cm.
That means – only high density \( \rho > 6 \text{ g/cc} \) crystals are subject of interest.

pulse neutron generator (PNG) produce 14 MeV neutrons \( \approx 10^8 \text{ n/s} \)

Crystals in tools with PNG must be fast!
Decay time < 100 ns. BGO – 300 ns.
Energy resolution better than BGO required as well.

Faster crystals and higher PNG rates require new, fast data acquisition systems

CsI(Na) for Natural Gamma (U, Th, K)

BGO crystal must be thermostabilized – flASKed. Temperature inside flask should be < 60 °C – limited measurement time

All T measurements done with high temperature PMT

Crystals for Natural Gamma can be slow < 1 – 1.5 μs, but heavy and with good energy resolution!
Replacing traditional scintillators in logging tools

NaI crystal still very often used in downhole logging.

LYSO – energy resolution and temperature dependence between NaI and BGO. Nearly as heavy as BGO. Fast ~ 40 ns. In some measurements can be a good replacement for both scintillators.

NaI – good energy resolution and temperature performance, but light – counting statistics are low!
When internal radioactivity is not a big deal!

LYSO energy resolution measured with Cs-137 source at room temperature. Before and after background subtraction.

For high energy range (> 1 MeV) measurements LYSO internal radioactivity will not effect measured data.

LYSO (P420) crystal has 3 times higher counting statistics than NaI and 1.8 times higher than B380.

Inelastic $\gamma$ spectra from formation irradiated by 14 MeV neutrons.

For some (especially windows based) downhole measurements, due to higher counting statistics and reasonable energy resolution, LYSO is much better than not only NaI, but also B380!
Core Measurements at Research Vessel JR

Drilling vessel “JOIDES Resolution”

- Under the seafloor NGR is at least 10 times lower than for continental crust. Composed by U-238, Th-232 families and K-40
- Available acquisition time ~ 10 minutes/1.5m long core section
- Main background sources – Cosmic Rays and NGR from surroundings and detecting systems internal radioactivity

Data from M. Vasilyev et. al., Journal of Applied Geophysics 75(2011) pp. 455-463
New Generation – new level of precision!

Active shielding – plastic scintillator

Passive shielding – clean lead

With New Generation NGR system stratigraphic correlations are possible!

Nal energy resolution: 7.4 – 8.5%

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Multi Gamma-ray Tool (MGT) with 4 NaI detectors measured in hole drilled 80 m from the main cored hole

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New Generation NGR system on board of JR

U-238 radioactivity anticorrelations with core bulk density vs. depth on long and short range. Anticorrelations are very obvious even for very low sediment radioactivity on the level of few counts/sec

Data acquisition running at any weather - even at high sea!

Energy spectra statistics and resolution good enough for U, Th, K determination with experimental and Monte Carlo standards

Data from M. Vasilyev et. al., Journal of Applied Geophysics 75(2011) pp. 455-463
Cosmic muons for oil reservoir monitoring

- Reservoir side view
  - Water injection
  - Oil Extraction
  - Pipe with muon detectors

- Reservoir top-down view
  - Flow rate: 60 m/year
  - Water injected
  - Oil Extracted
  - Muon Detectors

- Plastic scintillator strips
  - 2 cm
  - 6 cm
  - 2 cm
  - 10 cm
  - 200 cm

Detector in a Pipeline
Reservoir depth muon monitoring estimation

- Results based on numerical model developed using muon energy loss parametrization in ground and integration of Gaisser parametrization for cosmic muon flux at sea level.
- 25 detectors ~ correspond to the 55-60 meters long string
- Reasonable reservoirs depth range limited by ~ 700 m
- Not practical for oil fields monitoring, but proposed to be used for monitoring a CO$_2$ subsurface storage facilities.
We need glass ceramics: LWD

- Imaginary directionary drilling system to navigate shale gas and oil plays

Crossection of non-cylindrical probe

Crossection of cylindrical probe

- The predicted accuracy of NG measurements will allow to distinguish Formation A and Formation B with NG signal contrast > 15 API

- Accuracy to distinguish Formation A and Formation B only when the NG signal contrast is > 50 API

Amorphous glass ceramics can have any shape even at high temperature. Sometime it is a big advantage!
Nanostructured Glass Ceramics

• Nanostructured scintillation glass ceramics
  – KGS3-3 Li6 scintillation glass ceramics for neutron detection
    • performs ~ 1.5 -2 times better than commercial GS20 scintillator used for neutron detection in current downhole applications

• Nanostructured gamma sensitive scintillation glass ceramics
  • Allows to separate gamma ray energy deposition process (matrix) and scintillation process (nanocrystal)
  • Good high temperature dependence
  • Ability to manipulate with glass matrix (density, light absorption etc.) to tune properties
  • Can be used to manufacture scintillation element of any shape and size using molding techniques
  • GYGAG:Ce has excellent Light Yield, but too small so far for practical downhole logging
  • DSB type glass ceramics can be made big enough, but Light Yield is just 50% from BGO
6Li based nanostructured glass ceramics

Nanostructured glass ceramics produce more light than commercial GS20 6Li glass.

Inner light guide can be done from different materials, such as: undoped Li glass – KGS, gamma sensitive DSB or single crystal scintillator or just optical glass (TK glass). Outer 6Li KGS glass is produced (baked) from rectangular fibers.

Final modules

Neutron sensitive nanostructured glass ceramics – technology ready to be used in real tools.
High temperature Diamond Detector

Diamond Detector with housing and preamp

DiamondHT PNG 14MeV neutron spectra as a function of temperature

Room temperature spectra

PNG 14 MeV energy spectrum

Counts

0 50 100 150 200 250

QDC channel

Counts

0 50 100 150 200 250 300 350 400 450 500

QDC channel

Room temperature spectra

$^{12}\text{C}(n,\alpha)$

$^{9}\text{Be}$

$^{12}\text{C}(n,n')$

$R = 1.8\%$

$^{12}\text{C}(n,3\alpha)$
Summary

- Good temperature tolerance (up to 175 C) usually required, but sometime exceptions are possible.
- High density, high $Z_{\text{eff}}$ for $\gamma$ sensitive crystals and glass ceramics.
- High LY for $n$ and $\gamma$ sensitive materials.
- Even scintillators with strong internal radioactivity can be used for some measurements.
- Nanostructured glass ceramics to form non-cylindrical detectors.
- Diamond detectors for $n$ and in future $\alpha$ detection.
- Some plastic detectors for on-surface projects and static muon underground detection.
- Some large NaI detectors for on-surface projects.