Germanium spectrometry in GERDA :

The NPL intercomparison study

Dušan Budjáš, Mark Heisel, Mikael Hult, Alexander Klimenko, Matthias Laubenstein, Patric Lindahl, Anatoly Smolnikov, Hardy Simgen, Claudia Tomei, Sergey Vasiliev

Max Planck Institute for Nuclear Physics, Heidelberg
Institute for Reference Materials and Measurements, Geel
Joint Institute for Nuclear Research, Dubna
Institute for Nuclear Research, Moscow
Laboratori Nazionali Gran Sasso

Overview

1. **Introduction**
   low-level laboratories intercomparison

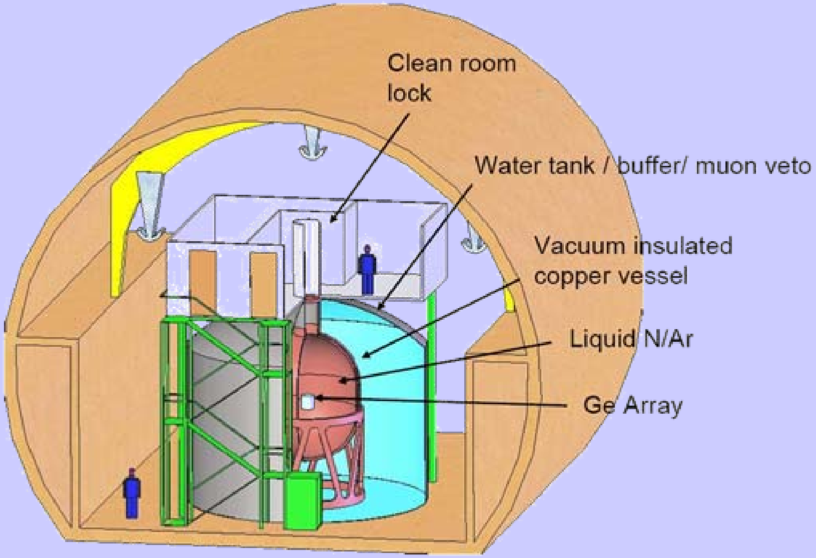
2. **Results**
   from GERDA low-level laboratories

3. **Evaluation**
   issues of Monte-Carlo simulations

4. **Summary**

Material screening challenge of GERDA

- GERDA aims to measure half-life of $0\nu\beta\beta$ decay of ^{76}Ge
- required background level : $<10^{-2}$ cts/(keV.kg.y) for phase 1
- required radiopurity of materials : ~10μBq/kg to ~mBq/kg
- many different materials
- limited time



GERDA collaboration :

- more than 4 laboratories doing material screening in 4 countries
- necessary to assure reliability and compatibility of results

Environmental Radioactivity Comparison Exercise 2005

- designed to identify analytical problems in environmental-level radioactivity measurements
- the NPL (UK) conducted twelve similar exercises since 1989

Expectations :

- to demonstrate the participant's ability to identify and quantify the activity levels of the radionuclides in the samples without prior knowledge of the content
- to complete the measurement in a timely manner
- to provide a full uncertainty budget for the measurement

Environmental Radioactivity Comparison Exercise 2005

- the NPL provided samples : liquid solutions containing α, β or γ-emitting radionuclides
- two levels : ~Bq/g or ~Bq/kg
- activities were determined by NPL with uncertainties ranging from 0,2% to 2,4%
- the 'GL' sample : low-radioactivity mixture consisting of 10 γ-emitting radionuclides with 1-20 Bq/kg each
- a candidate list of 37 possible γ-emitters was provided

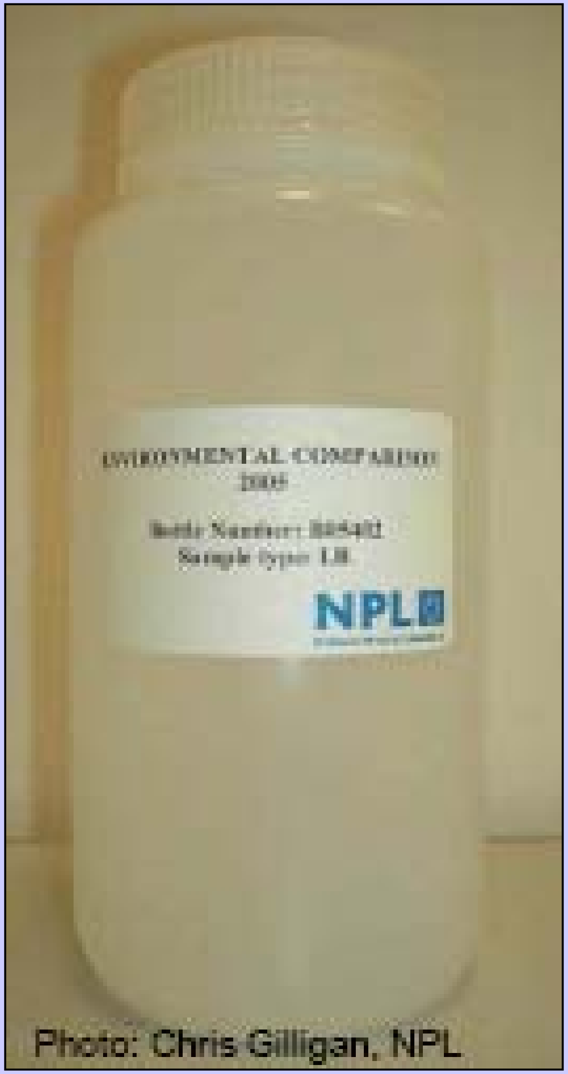


Photo: Chris Gilligan, NPL

General results

- 34 laboratories participated in the 'GL' part of the exercise
- NPL collected and analysed results, using three different statistical test to determine quality of the results.

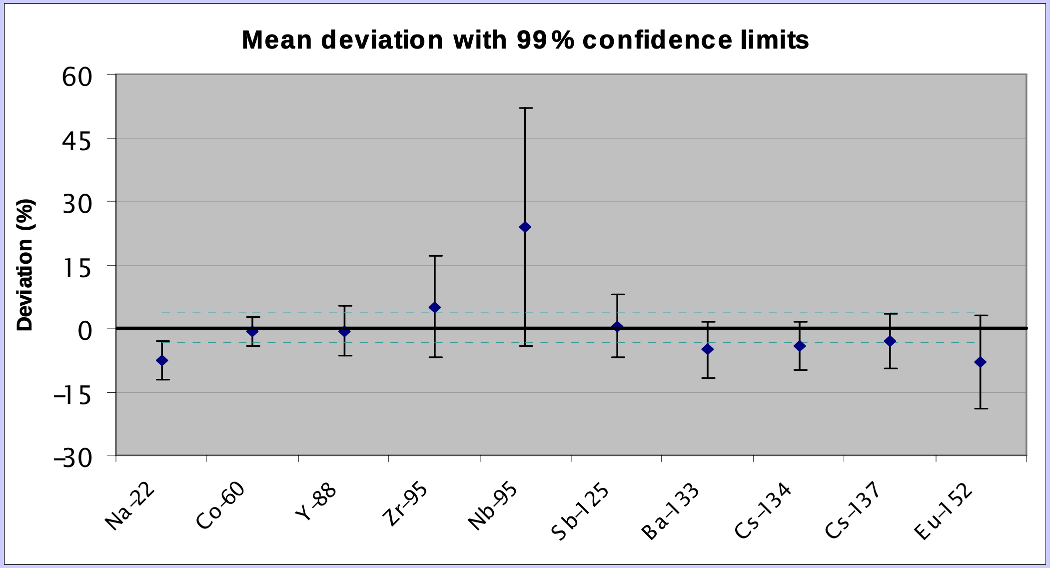
Results :

in agreement : 69 %

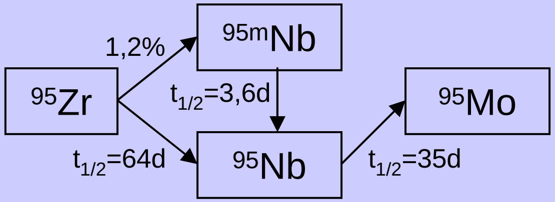
questionable : 13 %

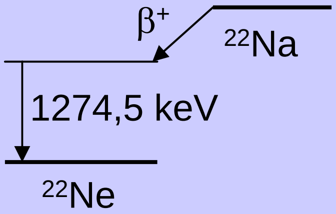
discrepant : 9 %

missing : 8 %



- 10 results were 'false positive' identifications, of them mostly for ^{57}Co and ^{154}Eu
- ^{95}Nb : less than half of the results were 'in agreement'
- other problematic nuclides : ^{22}Na, ^{133}Ba, ^{134}Cs, ^{152}Eu





GERDA associated participants

Locations of laboratories :

1. INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
2. Max-Planck-Institut für Kernphysik, Heidelberg, Germany
3. Institute for Reference Materials and Measurements, Geel, Belgium
4. Joint Institute for Nuclear Research, Dubna, Russia
5. Baksan Neutrino Observatory of INR RAS, Baksan, Russia

Results from Gran Sasso

- measured by GeMI detector located at a depth of 3800 m w.e.
- sample in acrylic container; mass : 124,4 g
- sample was measured for 92 hours

Detector used :

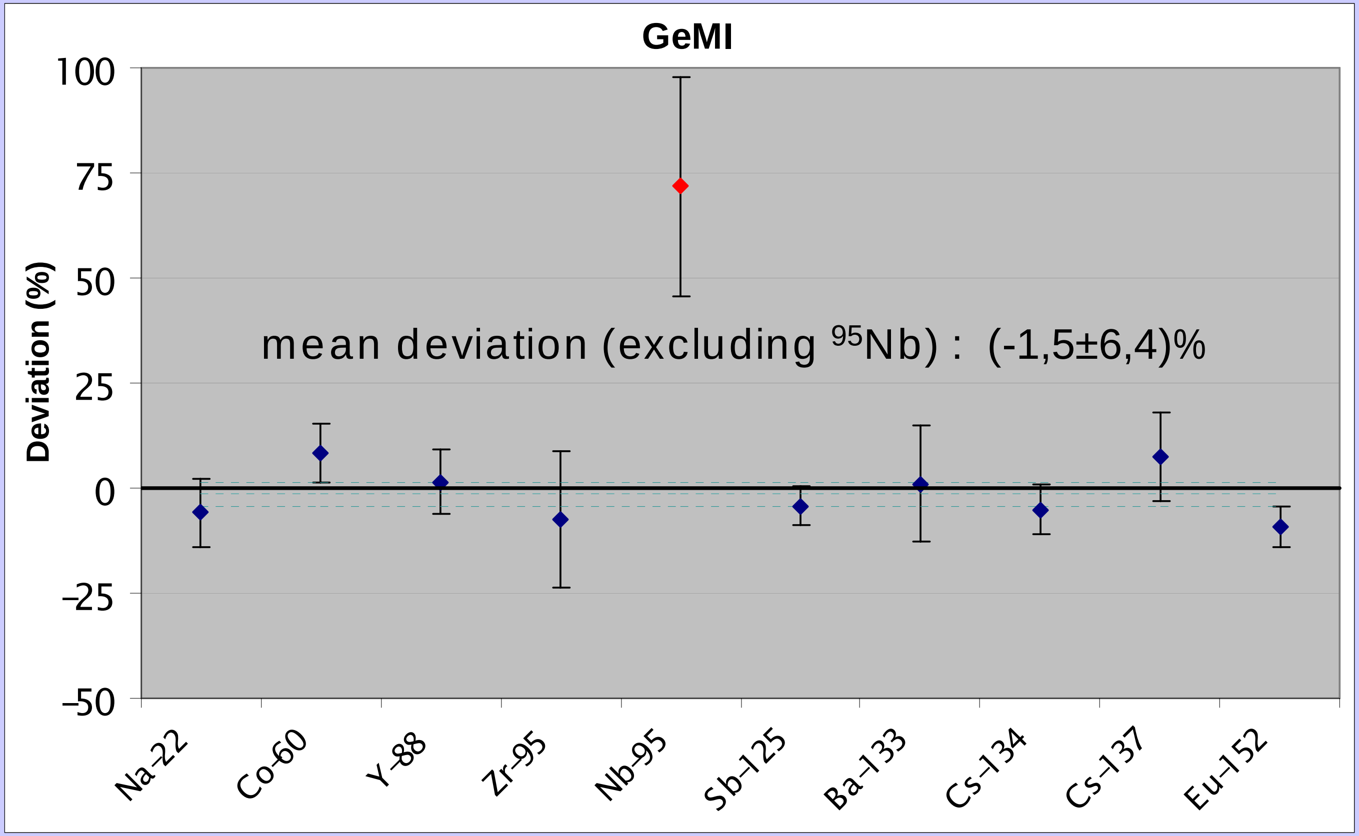
GeMI : Coaxial p-type EG&G Ortec type with N_2 flushing of the chamber and Pb/Cu shield

Active volume	413 cm^3
Active mass	2,2 kg
Relative efficiency	84 %
FWHM at 1,17 MeV	1,78 keV

Background :	[counts/h]
(40-2700) keV	56,0

- efficiency determination by using Geant 4.7.0
- ENSDF decay database

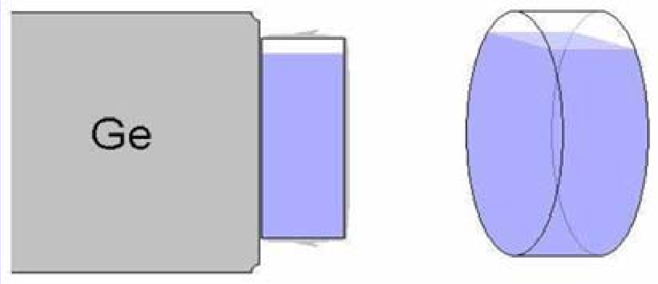
Results from Gran Sasso



- for all isotopes except ^{60}Co, ^{137}Cs, ^{22}Na and ^{88}Y the single most intense gammas were simulated and the efficiencies corrected for the branching ratios
- in this way the effect of the coincidence summing is not taken into account
- discrepancy in calculated ^{95}Nb activity needs further evaluation
- a more detailed study is ongoing

Results from Heidelberg

- sample in acrylic 'standard cylindrical box'
- mass of the sample : 108,8g
- laboratory location : 15m w.e. under ground



Detectors used :

Dario : Coaxial p-type crystal with μ-veto, chamber evacuating and N_2 flushing, 20 cm Pb/Fe/Cu shield

Active volume	158 cm^3
Active mass	0,83 kg
Relative efficiency	31 %
FWHM at 1,33 MeV	2,3 keV

Background :	[counts/h]
(40-2700) keV	170
^{60}Co (1333 keV line)	< 0,02
^{137}Cs (662 keV line)	0,13

Bruno : Coaxial p-type crystal with μ-veto, continuous N_2 chamber flushing and 20 cm Pb/Fe/Cu shield

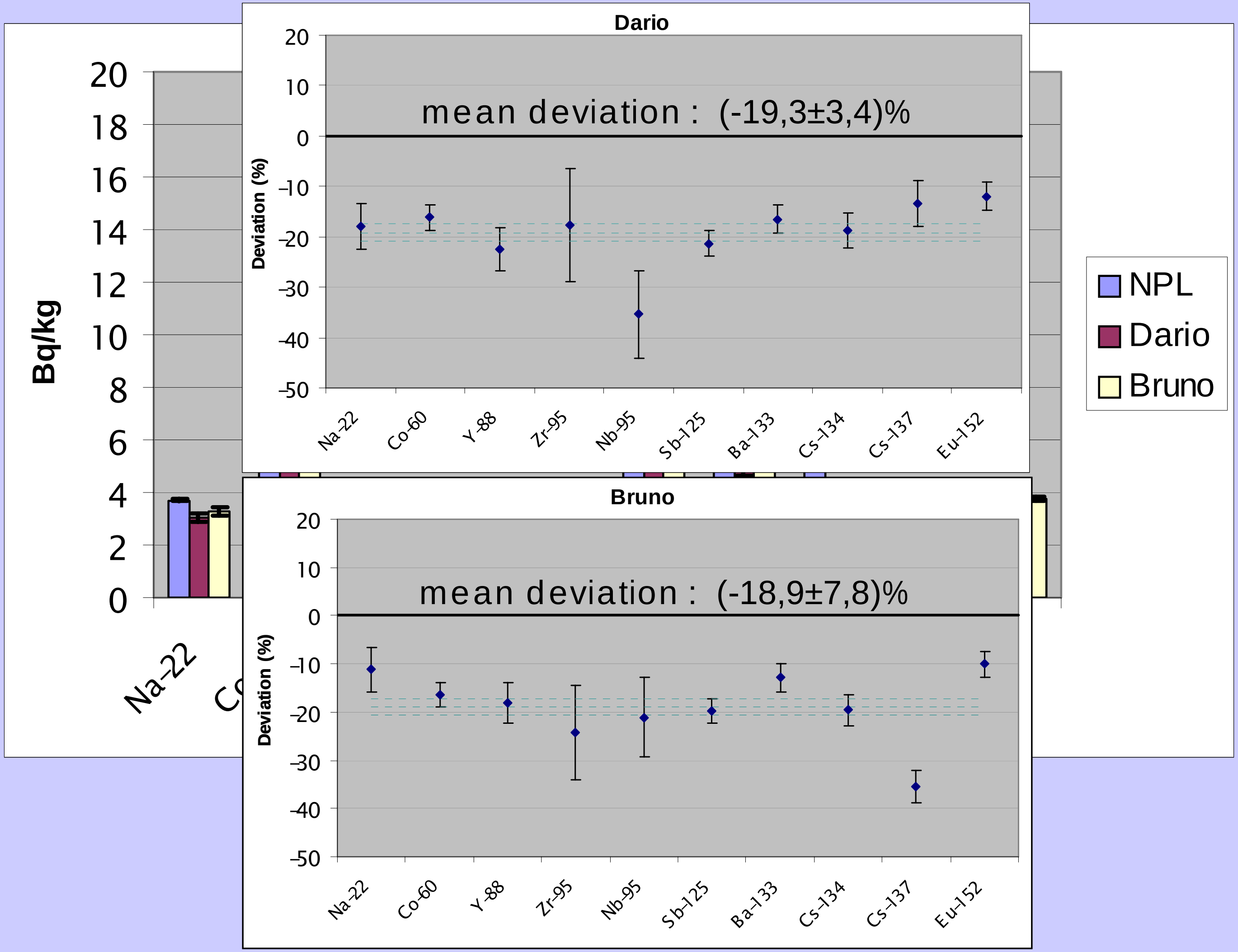
Active volume	120 cm^3
Active mass	0,63 kg
Relative efficiency	22 %
FWHM at 1,33 MeV	2,4 keV

Background :	[counts/h]
(40-2700) keV	150
^{60}Co (1333 keV line)	< 0,04
^{137}Cs (662 keV line)	0,09

- efficiency determination by using Geant4-based Monte-Carlo tool MaGe (Geant version 4.6.02)
- ENSDF decay database (Geant4 default)

Results from Heidelberg

- sample measured in 'Bruno' and 'Dario' for 6,0d and 3,9d respectively



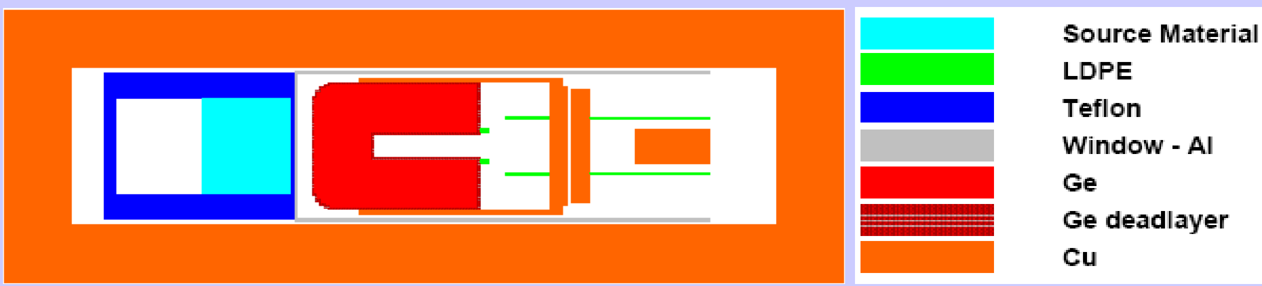
- systematic error towards lower activities

Results from Geel

- IRMM took part also in the 'GH' part of the exercise (~Bq/g sample)
- laboratory location : above ground (in Geel, Belgium)

Detector used :

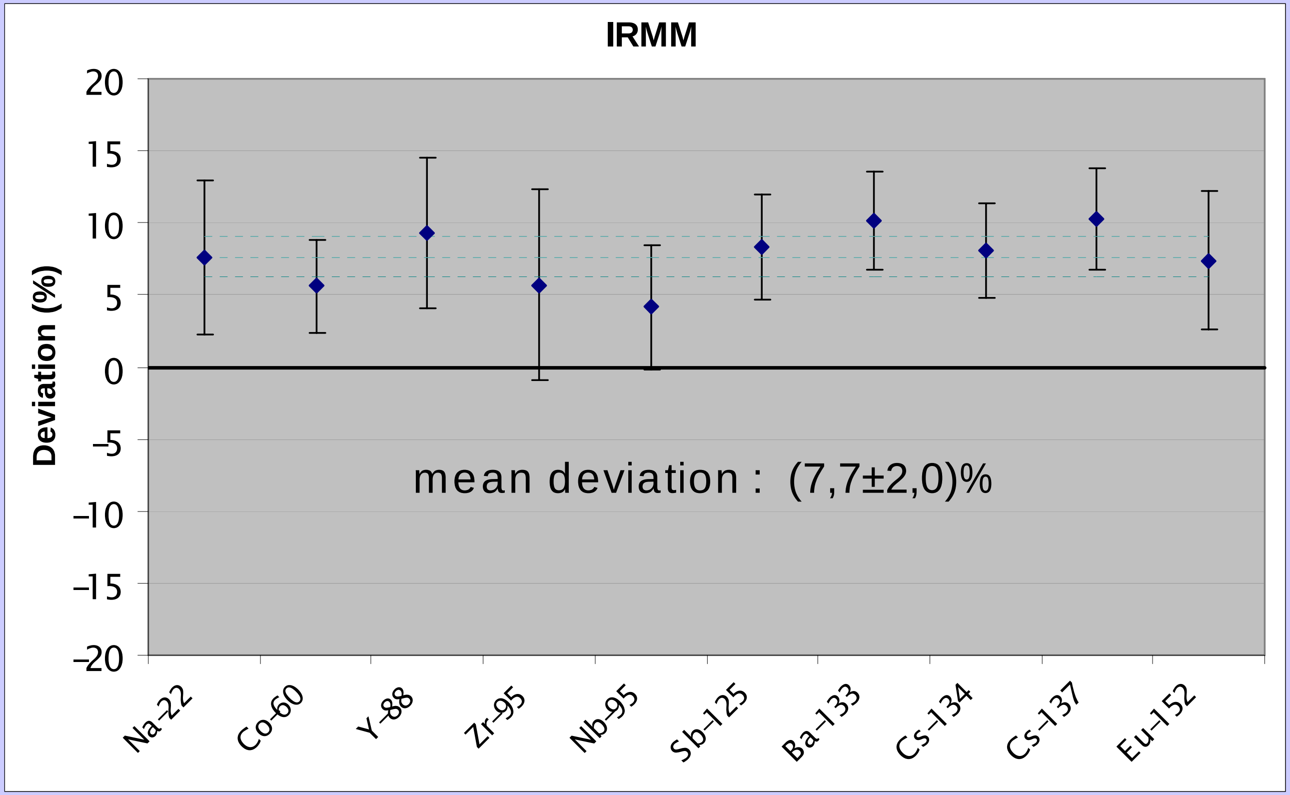
Coaxial low-background p-type crystal	
Relative efficiency	20 %



- efficiency determination by using Monte-Carlo tool EGS4
- decay database 'Nucléide' by DDEP collaboration

Results from Geel

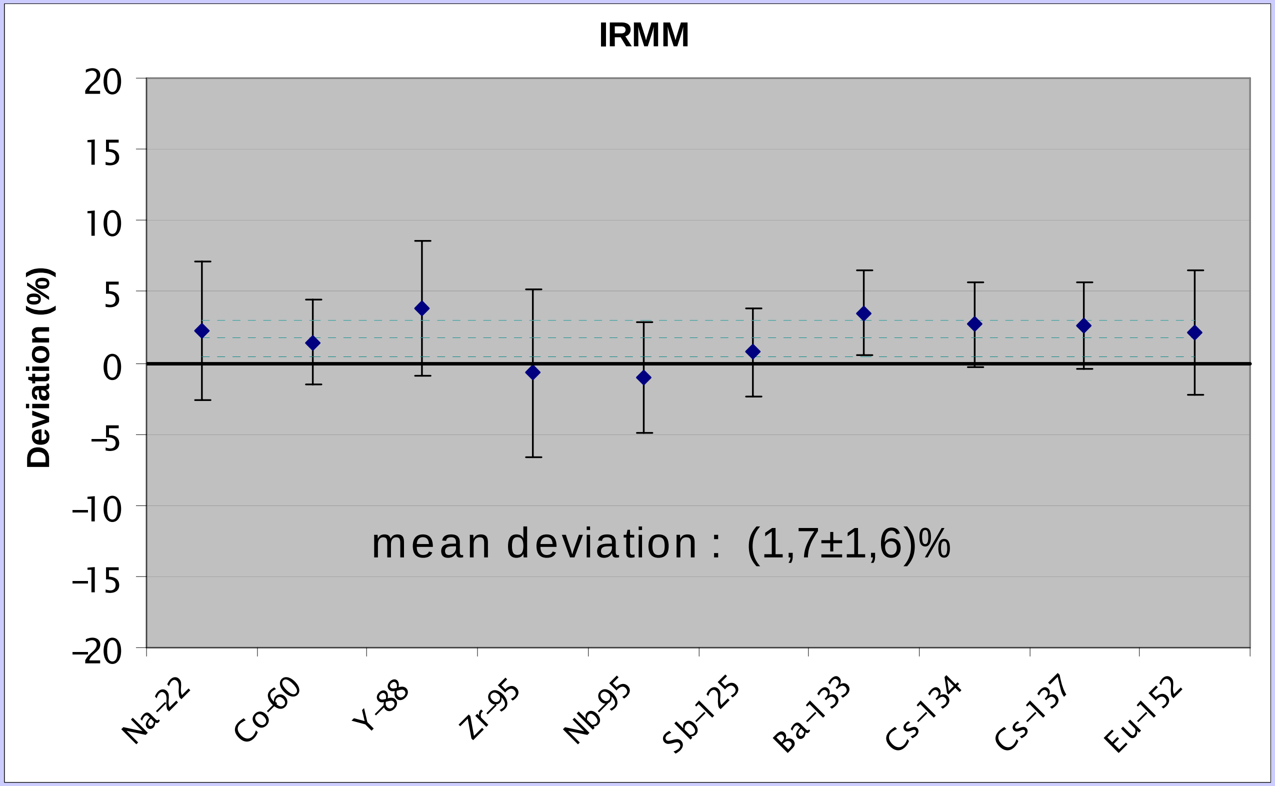
- Initial results :



- error of the representation of the bottom of the sample container in original computer model gave too low efficiency

Results from Geel

- Corrected results :



- results for the high-activity part of the exercise (~Bq/g level) had a mean deviation of (1,3±1,1)%
- 'GH' sample was measured in a standard container used for screening

Results from Dubna

- sample measured in JINR Dubna (above ground)
- sample volume : 500 ml

Detector used :

Coaxial n-type crystal with 30 cm Pb/Cu/B loaded PE shield

Active volume	256 cm^3
Active mass	1,36 kg
Relative efficiency	70 %
FWHM at 1,33 MeV	2 keV

Background :	[counts/h]
(40-2700) keV	10635
^{60}Co (1333 keV line)	8,13
^{137}Cs (662 keV line)	16,7

- efficiency determination by using Geant 4.7.0
- ENSDF decay database (Geant4 default)

Results from Dubna

- Results

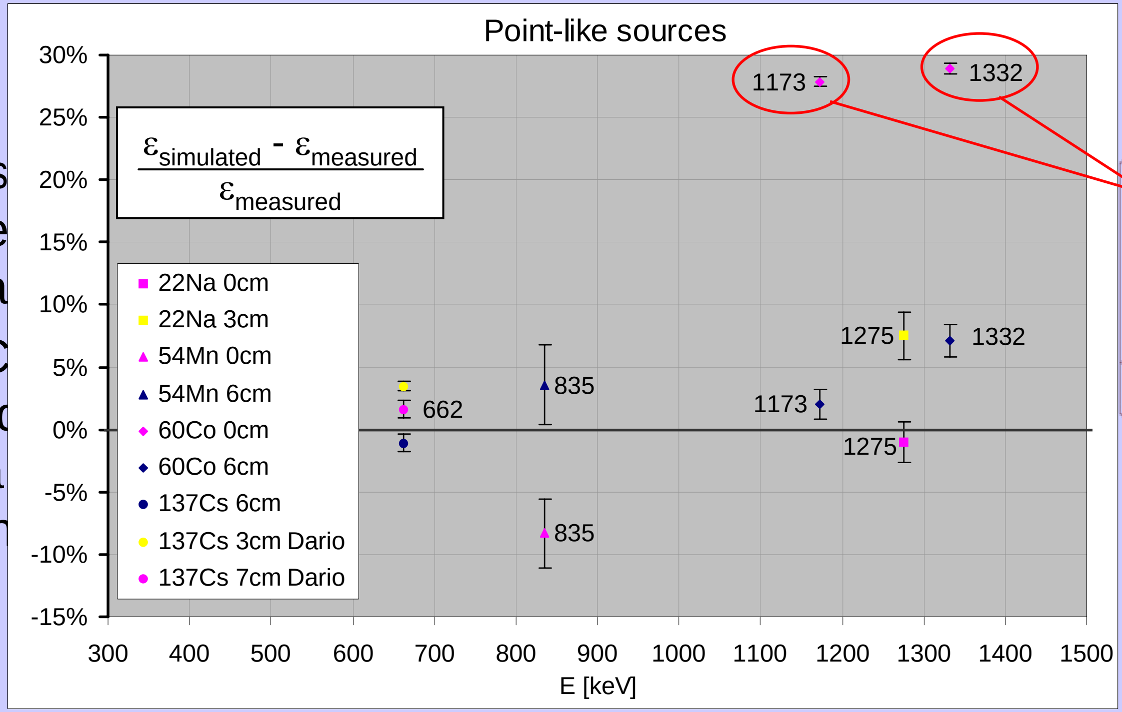
the Baksan HPGe Set Up with 3 crystals (660 m w.e.)

- measured activity of NPL sample systematically less than expected
- similar results obtained with the Baksan HPGe Set Up (660 m w.e.)

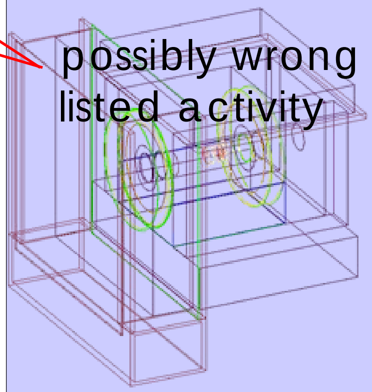
Evaluation at Heidelberg

MaGe :

- code bas
  develope
  Majorana
- a single C
  different c
  and data
  simulation



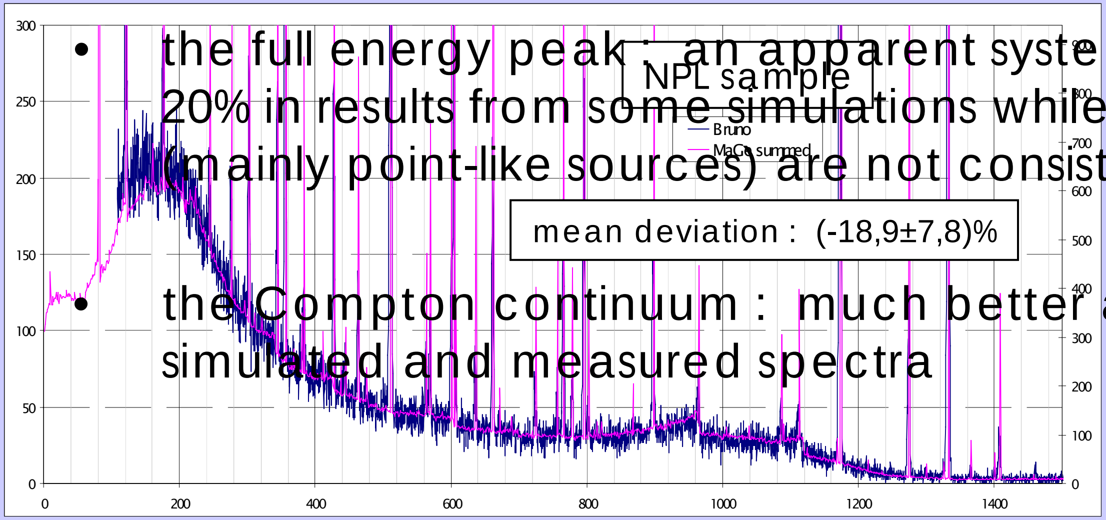
Bruno



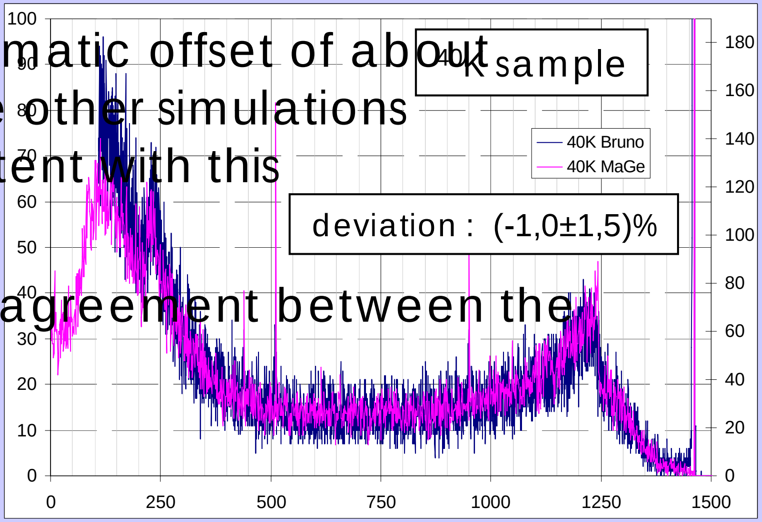
possibly wrong listed activity

Issues :

- the full energy peak : an apparent systematic offset of about 20% in results from some simulations while other simulations (mainly point-like sources) are not consistent with this



- the Compton continuum : much better agreement between the simulated and measured spectra



MC-simulation precision

- Geant4 cross-sections for particle interactions were validated, precision of few percent [1,2,3]
- branching ratios for radioactive decays from Geant4 (ENSDF) database were found to differ from ToI (^{235}U, ^{228}Ac)
- unstable daughters decay instantly in Geant4 simulations
- uncertainties in detector parameters and incomplete charge collection have significant impact [3]
- validation studies of MaGe have been previously performed in MPIK (LArGe project) and LNGS :

  good agreement for ^{137}Cs, ^{226}Ra, reasonable agreement for ^{60}Co (no angular correlation of gammas)

1. E. Poon, F. Verhaegen, Med. Phys. 32 (2005) 1696
2. K. Amako et al., IEEE Trans. Nucl. Scie. 52 (2005) 910
3. S. Hurtado et al., Nucl. Instr. Meth. A 518 (2004) 764

Possible reasons for discrepancy

1. inaccurate detection set-up geometry representation
   - very probable effect
   - doesn't explain well the observed deviations of all simulations
   - suspicious similarities between 2 labs/ 4 different detectors

2. incomplete charge collection inside the crystal
   - creates peak's tail to lower energies
   - more difficult evaluation - background subtraction from peak
   - cannot account for more than 10%

3. inaccuracy of simulated physics in Geant4
   - angular correlation of gammas not simulated
   - decay description shown to be wrong only for few isotopes
   - cross-sections of Geant4 repeatedly shown to be accurate within few %
   - not supported by successful evaluation at LNGS and other studies

4. inaccuracy or nonuniformity of the sample
   - some point-like sources used for simulation validation found to be inaccurate
   - highly improbable for the NPL sample

Conclusions

Intercomparison between GERDA associated low-level laboratories has been conducted.

All isotopes have been identified correctly,
no false identifications occurred.

Results :

- IRMM Geel : 1,7% mean deviation
- JINR Dubna : -19,9% mean deviation
- LNGS Gran Sasso : -1,5% mean deviation
- MPIK Heidelberg : -19,1% mean deviation

Detection accuracy is very good for the needs of GERDA collaboration : ultra-low background material selection.

Present discrepancies are however not understood yet and need further investigation. Validation studies of the Geant4 and the MaGe are continuously ongoing.

Thank you for your attention

The GERDA Collaboration :

1. INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
2. Joint Institute for Nuclear Research, Dubna, Russia
3. Max-Planck-Institut für Kernphysik, Heidelberg, Germany
4. Jagiellonian University, Krakow, Poland
5. Università di Milano Bicocca e INFN Milano, Milano, Italy
6. Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
7. Institute for Theoretical and Experimental Physics, Moscow, Russia
8. Russian Research Center Kurchatov Institute, Moscow, Russia
9. Max-Planck-Institut für Physik, München, Germany
10. Dipartimento di Fisica dell'Università di Padova e INFN Padova, Padova, Italy
11. Physikalisches Institut, Universität Tübingen, Germany
12. Institute for Reference Materials and Measurements, Geel, Belgium

Appendix : Comparison

Institute	Crystal	Background	MC	Discrepancy
LNGS	2,2 kg p-type	56 cts/h	Geant4.7.0	-2,8%
MPIK	0,8 (0,6) kg * p-type	170 cts/h (150 cts/h)	MaGe Geant4.6.02	-19,3% (-18,9%)
IRMM	p-type	-	EGS4	1,6%
JINR	1,36 kg n-type	10635 cts/h	Geant4.7.0	-19,9%

* Dario detector (Bruno detector)

Treatment of results by NPL

For each isotope and participant:

- deviation from assigned NPL value:

$$D = \frac{L - N}{N} \qquad u_D = \frac{L}{N}\sqrt{\left(\frac{u_L}{L}\right)^2 + \left(\frac{u_N}{N}\right)^2}$$

- three tests on the quality of results:

$$\zeta = \frac{L - N}{\sqrt{u_L^2 + u_N^2}} \qquad R_L = \frac{u_L}{L} \qquad z = \frac{L - N}{R_{med} N}$$

zeta-score | rel. uncertainty | z-score

→ classify results as ´in agreement´, ´questionable´ or ´discrepant´

L .. laboratory value
N .. assigned value by NPL
u .. corresponding uncertainties

Appendix : NPL 'GL' sample results

Nuclide	[Bq/kg]*	In agreement	Questionable	Discrepant	Missing
Na-22	3,72(1)	24	5	1	3
Co-60	18,84(6)	26	4	3	0
Y-88	3,84(1)	26	2	3	2
Zr-95	1,84(2)	22	4	1	6
Nb-95	3,84(4)	14	4	10	5
Sb-125	6,48(4)	25	3	3	2
Ba-133	5,74(4)	24	6	2	1
Cs-134	5,30(4)	27	3	3	0
Cs-137	2,89(2)	25	5	2	1
Eu-152	4,19(3)	16	6	3	8
Total		229	42	31	28
Total (%)		**69**	**13**	**9**	**8**

*reference time: 1 October 2005 12:00 GMT

Appendix: Results

Isotope	NPL		Dario		Bruno	
Na-22	3,718	(14)	3,05	(17)	3,30	(17)
Co-60	18,84	(6)	15,80	(48)	15,75	(47)
Y-88	3,843	(14)	2,98	(17)	3,15	(16)
Zr-95	1,836	(19)	1,51	(21)	1,39	(18)
Nb-95	3,84	(4)	2,48	(33)	3,03	(31)
Sb-125	6,48	(4)	5,10	(15)	5,20	(17)
Ba-133	5,74	(4)	4,79	(16)	5,00	(16)
Cs-134	5,30	(4)	4,31	(18)	4,26	(17)
Cs-137	2,884	(20)	2,50	(13)	1,86	(10)
Eu-152	4,19	(3)	3,69	(11)	3,77	(11)

Appendix : results from Dubna

$T_{1/2}$, y	Nuclide	Activity (Bq / kg) 01.10.2005	Activity (Bq / kg) 30.01.2006	Measured Activity 30.01.2006	R=Expect/ Measured
2.602	^{22}Na	3.718(14)	3.402	2.786(46)	1.221
5.271	^{60}Co	18.84(6)	18.033	14.768(80)	1.221
106.65 d	^{88}Y	3.843(14)	1.762	1.444(38)	1.220
64.02 d	^{95}Zr	1.836(19)	0.490	0.353(60)	1.388
34.975 d	^{95}Nb	3.84(4)	1.127	0.908(32)	1.241
2.758	^{125}Sb	6.48(4)	5.960	4.596(8)	1.297
10.52	^{133}Ba	5.74(4)	5.615	4.480(6)	1.253
2.062	^{134}Cs	5.30(4)	4.739	3.740(6)	1.267
30.07	^{137}Cs	2.884(20)	2.862	2.368(4)	1.209
13.542	^{152}Eu	4.19(3)	4.119	3.472(10)	1.186

Appendix : Baksan detector

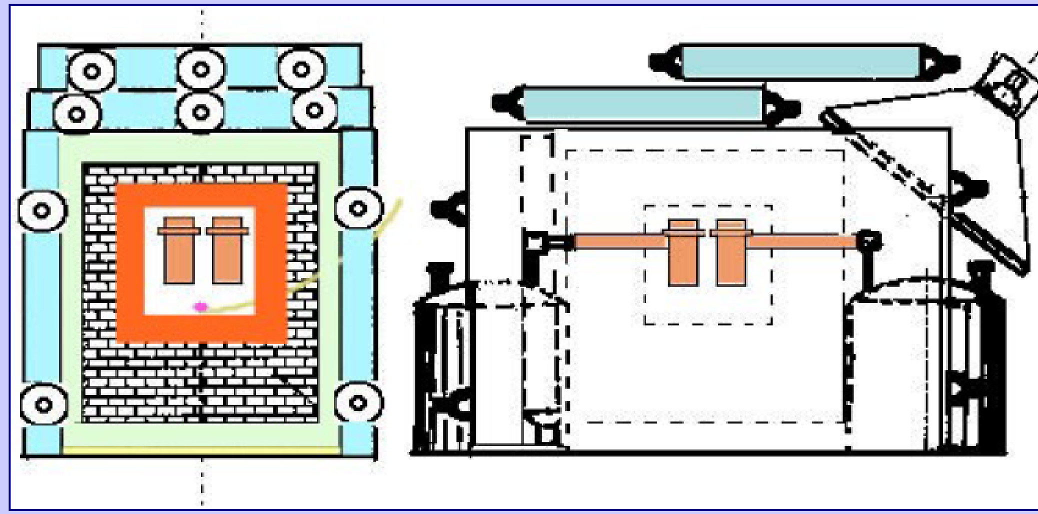
- Baksan Neutrino Observatory of INR RAS (660 m w.e.)

Detector :

IGEX/Baksan HPGe Set Up with three coaxial n-type crystals with nitrogen flushing located in 1 m concrete/dunite/steel shield and additional 40 cm Cu/Pb/PE shield and liquid scintillator muon veto

Active mass	4 x 1 kg

Background :	[counts/h]
(60-2700) keV	10,1
^{60}Co (1333 keV line)	0,009
^{137}Cs (662 keV line)	0,03



Appendix : HADES

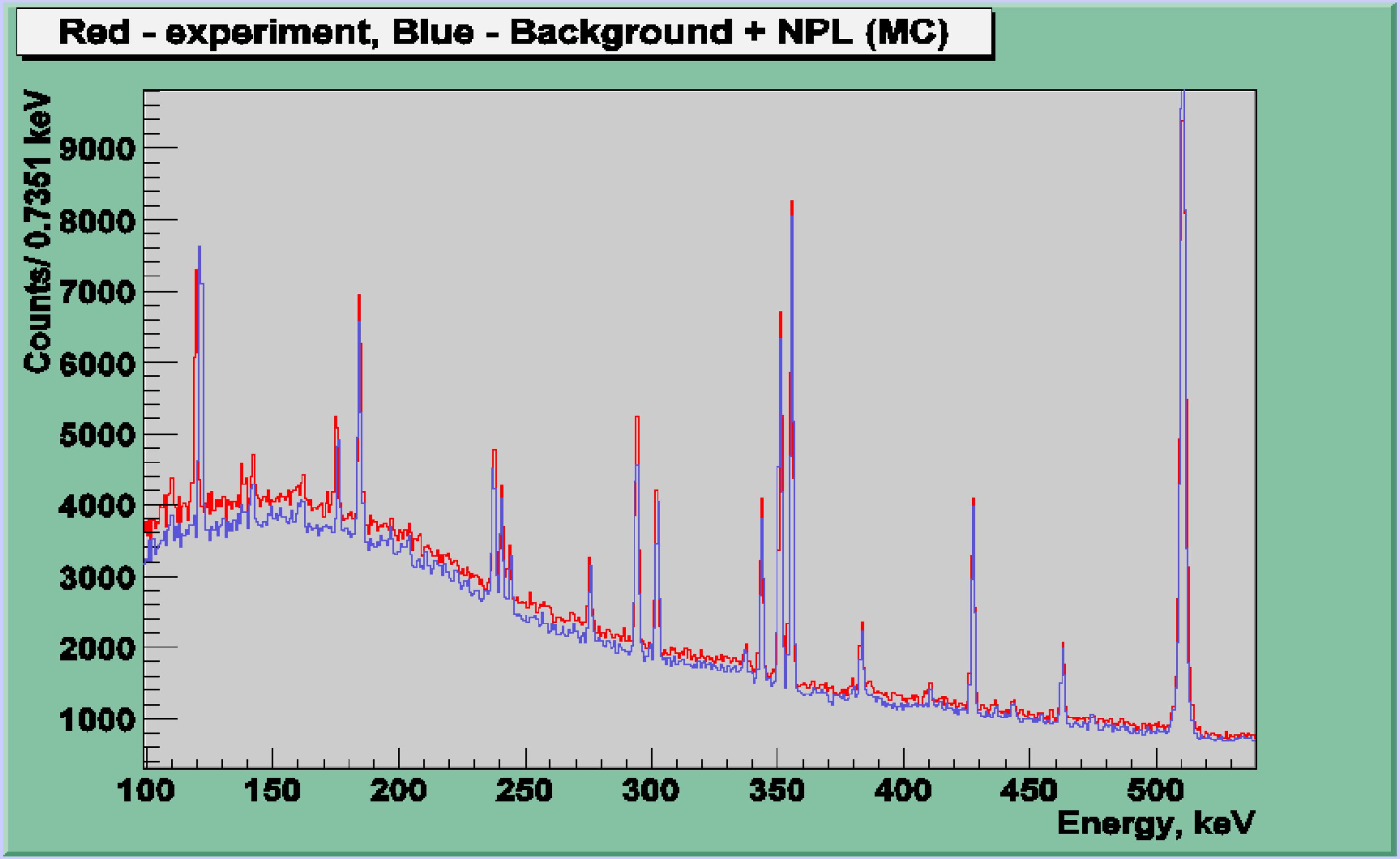
HADES underground facility (500 m w.e.)

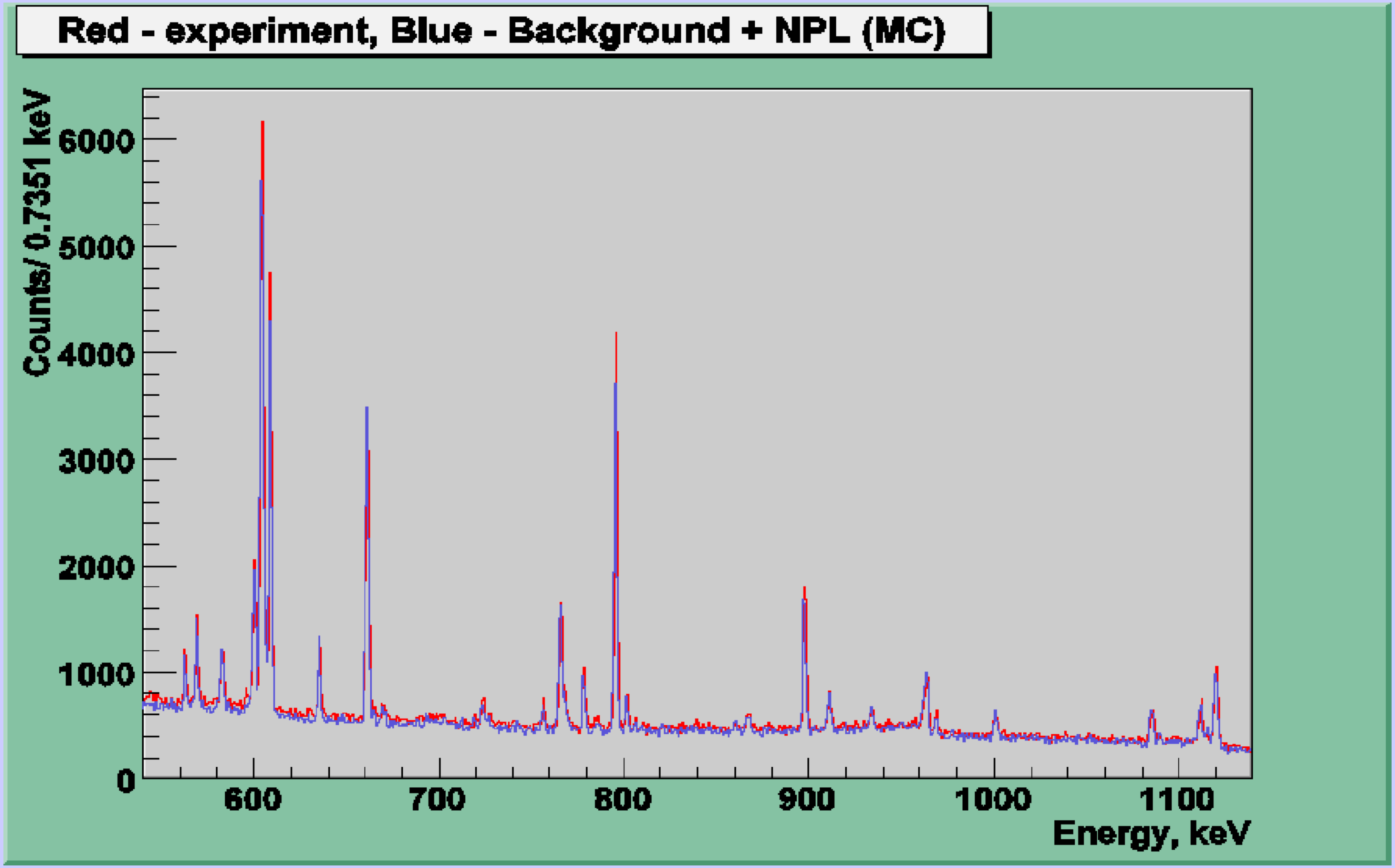
Coaxial p-type crystal with N_2 flushed chamber and 28 cm Pb/Cu shielding

Active volume	251 cm^3
Active mass	1,34 kg
Relative efficiency	60 %
FWHM at 1,33 MeV	1,9 keV

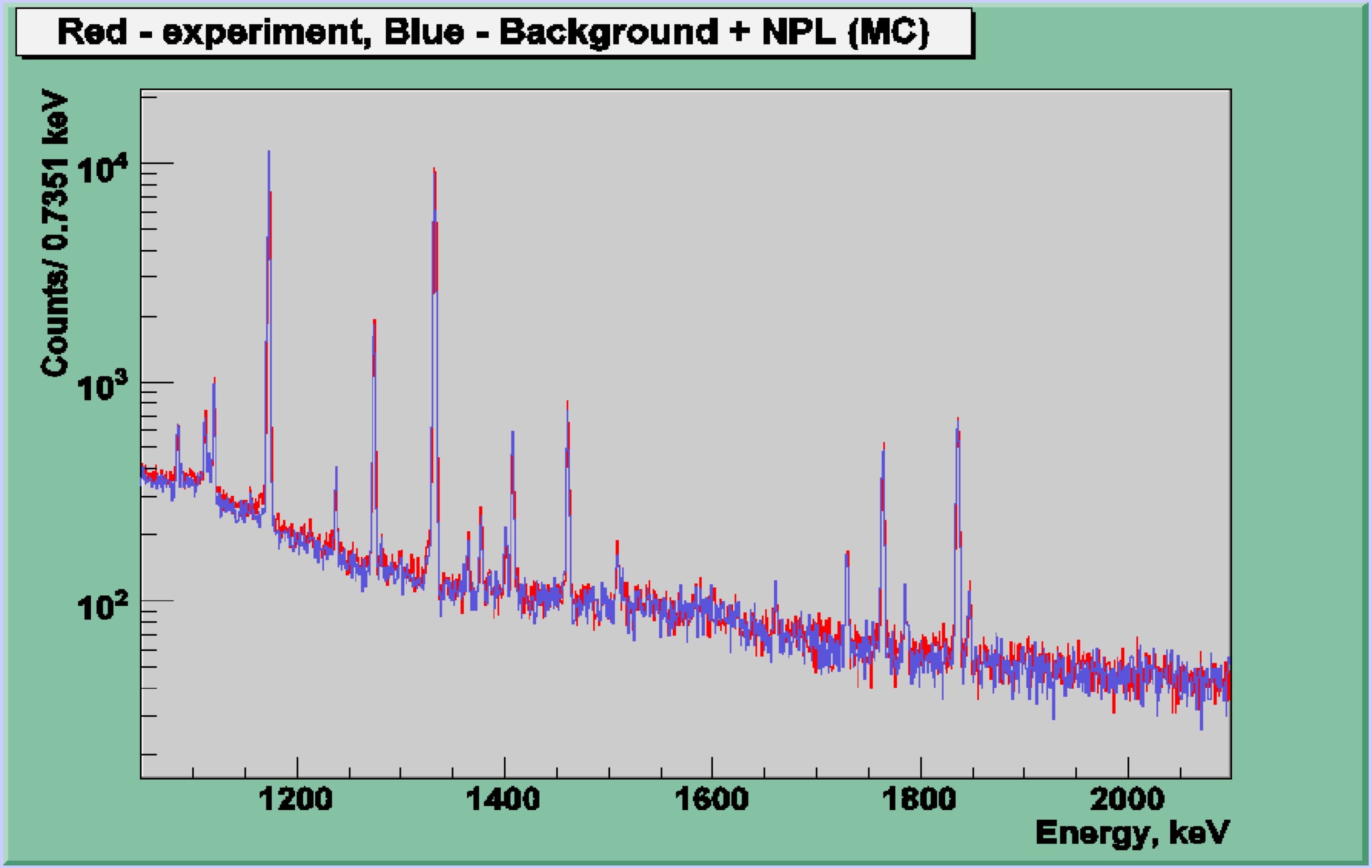
Background :	[counts/h]
(40-2700) keV	14,5
^{60}Co (1333 keV line)	0,04
^{137}Cs (662 keV line)	0,07

- the NPL sample was measured on all detectors in HADES to check the evaluation accuracy


Red - experiment, Blue - Background + NPL (MC)
Counts/ 0.7351 keV
9000
8000
7000
6000
5000
4000
3000
2000
1000
100
150
200
250
300
350
400
450
500
Energy, keV



Red - experiment, Blue - Background + NPL (MC)
Counts/ 0.7351 keV
0
1000
2000
3000
4000
5000
6000
600
700
800
900
1000
1100
Energy, keV



Red - experiment, Blue - Background + NPL (MC)
Counts/ 0.7351 keV
10^4
10^3
10^2
1200
1400
1600
1800
2000
Energy, keV