bmb+f - Förderschwerpunkt

Astroteilchenphysik

Großgeräte der physikalischen Grundlagenforschung

CNR*09

BORDEAUX

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Neutron Activation of ^{76}Ge

Georg Meierhofer

Kepler Center for Astro and Particle Physics

University Tübingen

people involved:

P. Grabmayr
J. Jochum

Kepler Center for Astro and Particle Physics, Eberhard Karls Universität Tübingen

P. Kudejova
L. Canella

FRM II Forschungs-Neutronenquelle Heinz Maier-Leibnitz, TUM

J. Jolie

IKP, Universität zu Köln

Kepler Center for Astro and Particle Physics

Eberhard Karls Universität Tübingen

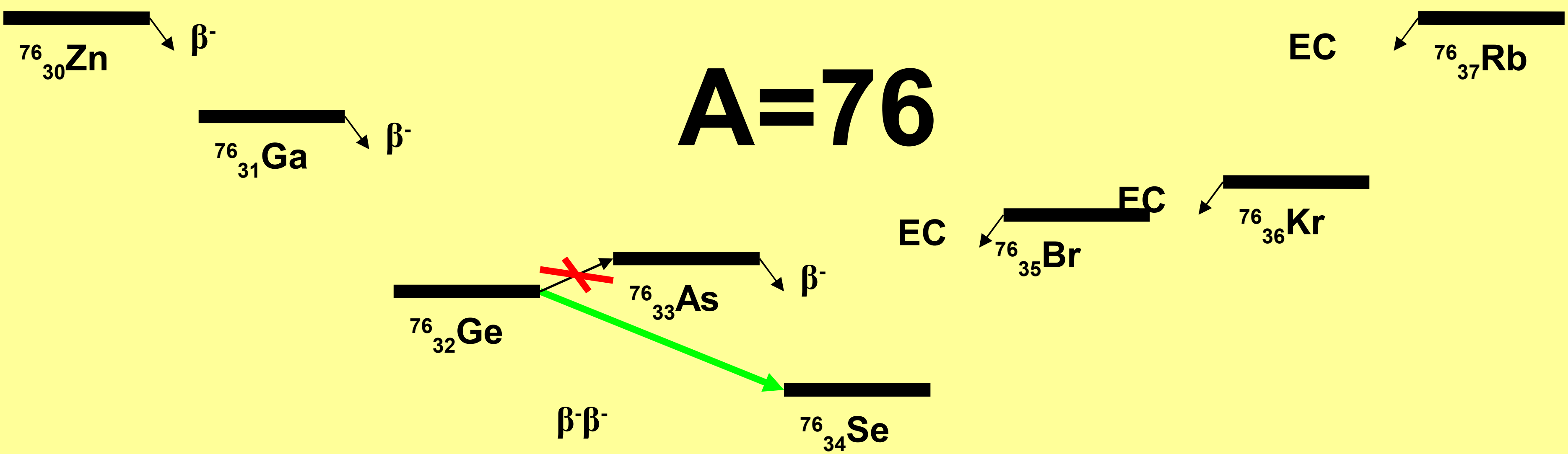
Outline

- Motivation: Neutrinoless double beta decay experiments
  - Neutrinoless double beta decay
  - GERDA experiment
- Background in GERDA
  - Neutron capture on ^{74}Ge and ^{76}Ge
  - How to reject background
- Measurements with cold neutrons
  - Prompt γ-ray spectrum in ^{75}Ge and ^{77}Ge
  - Cross section of the ^{74}Ge(n,γ) and ^{76}Ge(n,γ) reactions
- Summary

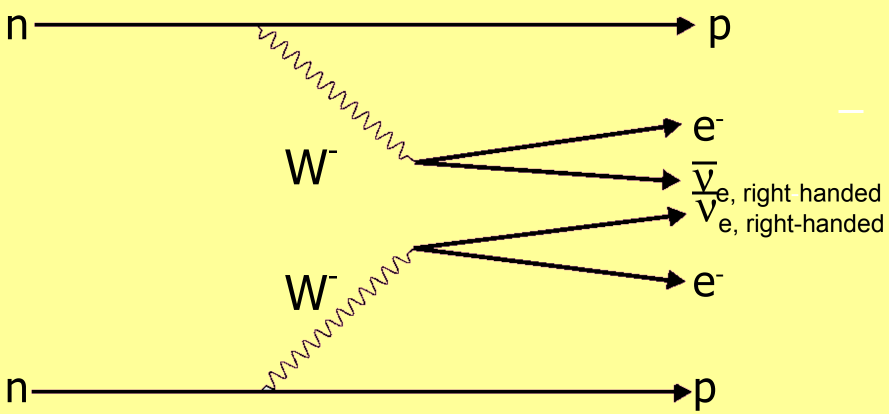
Double beta decay (2vββ)

Double beta decay (2vββ) can be observed if single beta decay is energetically forbidden, but the transition of two neutrons into two protons (or pp -> nn) is allowed. The nucleus emits two electrons (positrons) and two anti-neutrinos (neutrinos).

2vββ was observed in 11 isotopes: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U, ^{130}Ba ($\beta^+\beta^+$)

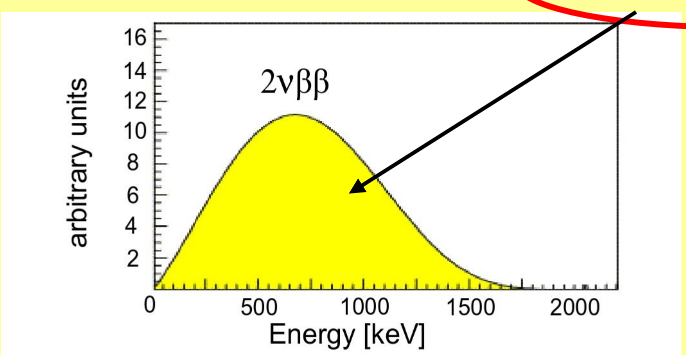


2νββ decay

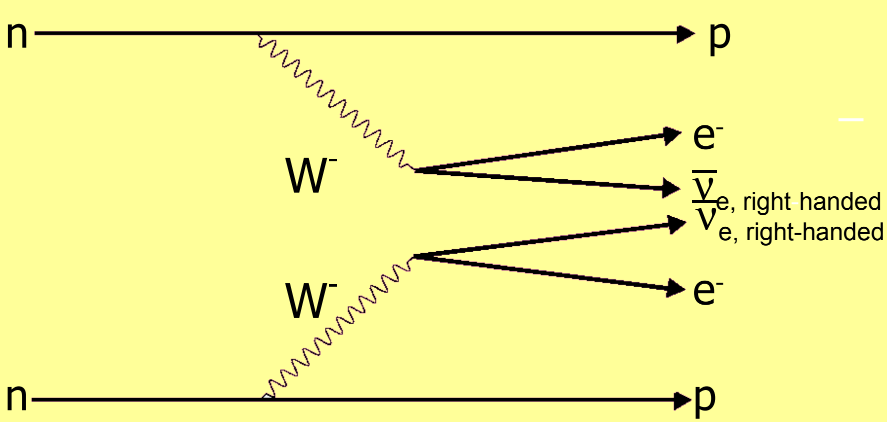


ΔL=0 no lepton number violation

$t_{1/2}$: 10^{19} - 10^{25} y



2νββ decay



$\Delta L=0$ no lepton number violation

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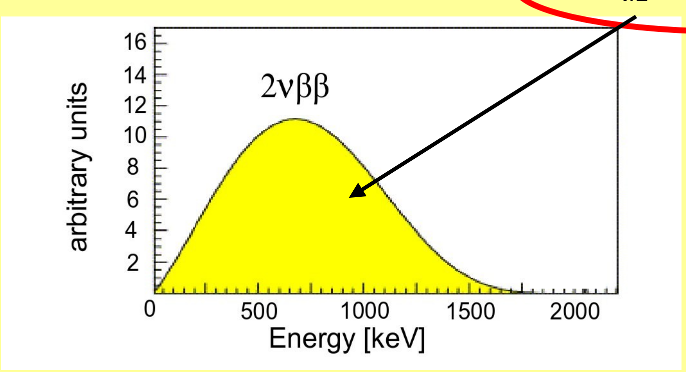
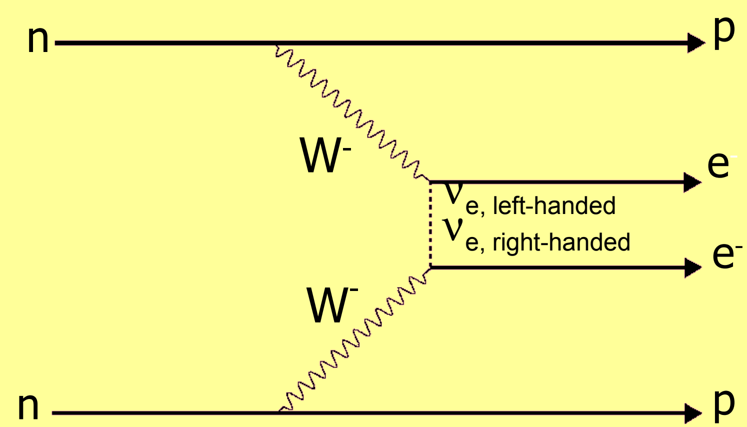


0νββ decay

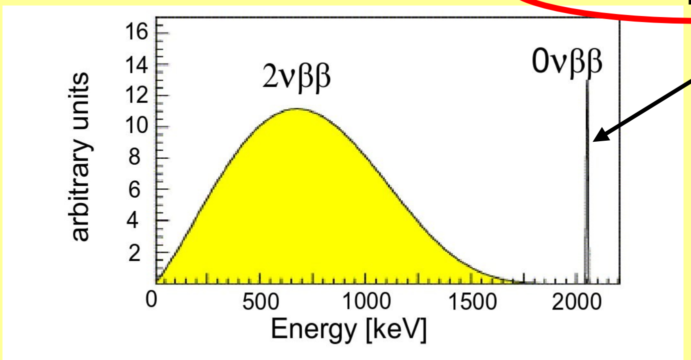


Majorana particle (helicity)

$\Delta L=2$ Lepton number violation

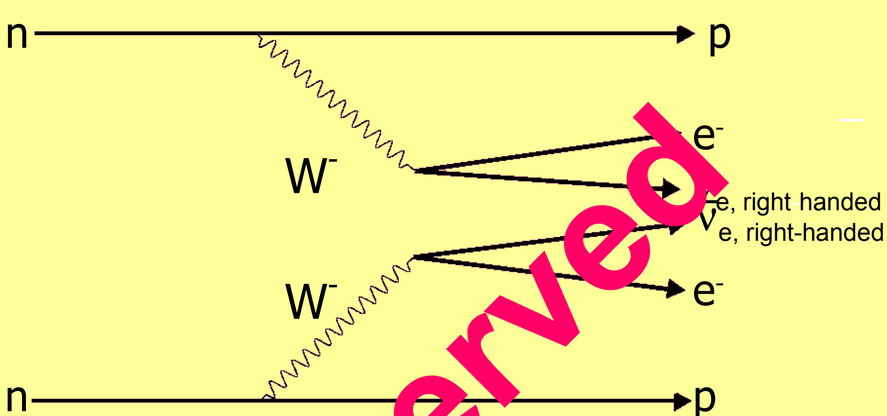
$P(\nu_{e,\ left\text{-}handed}) \sim (m/E)^2$ for $m_\nu > 0$

$t_{1/2}$: > 10^{25} y



2νββ decay

0νββ decay



observed

not observed yet

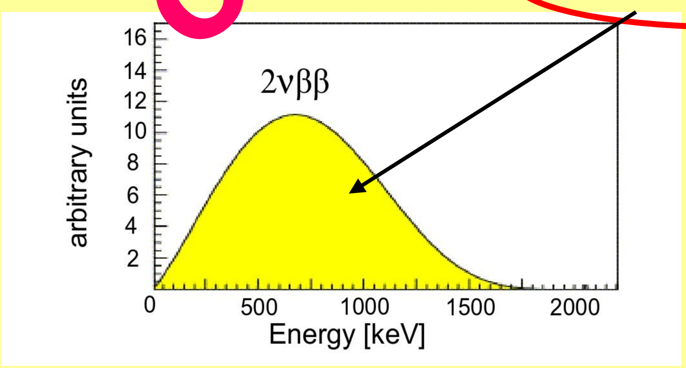
$\Delta L=0$ no lepton number violation

Majorana particle (helicity)

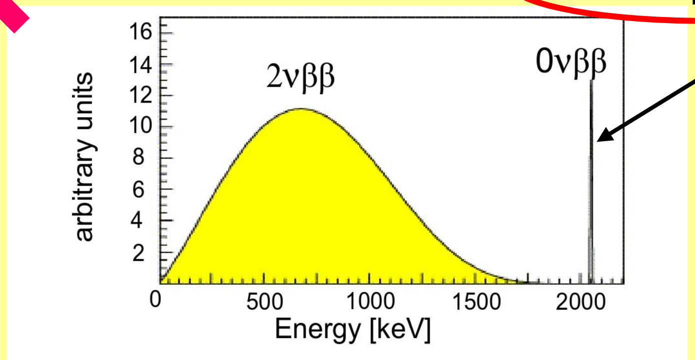
$\Delta L=2$ Lepton number violation

$P(\nu_{e,\ left\text{-}handed}) \sim (m/E)^2$ for $m_\nu > 0$

$t_{1/2}$: 10^{19} - 10^{25} y



$t_{1/2}$: > 10^{25} y



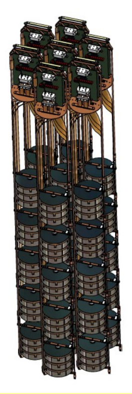
GERDA: The GERmanium Detector Array

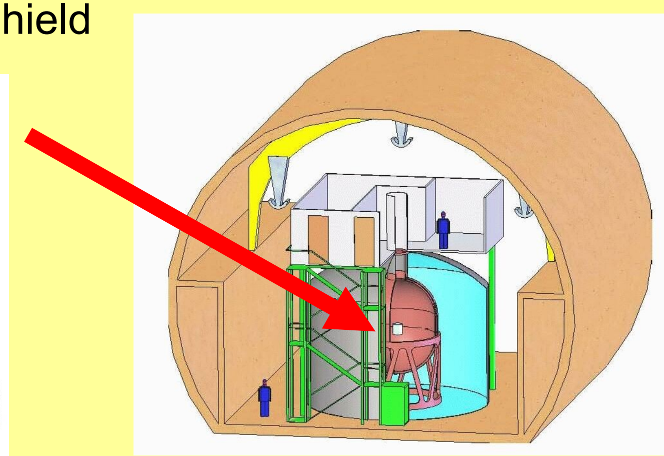
Isotope: ^{76}Ge ($Q_{\beta\beta}$ = 2039 keV)

- Phase I: ~18 kg of ^{76}Ge
- Phase II: ~40 kg of ^{76}Ge

Location: LNGS, Gran Sasso, Italy

Design: Bare HPGe detectors (~86% ^{76}Ge) submerged into LAr.
LAr acts as cooling liquid and γ-ray shield.
Cerenkov muon veto (water tank with Ø=10 m)
no high Z-materials used, 3400 m.w.e. of rock to shield cosmic radiation





Background in GERDA

Radiopurity of:
Germanium detector (cosmogenic ^{68}Ge)
Germanium detector (cosmogenic ^{60}Co)
Germanium detector (bulk)
Germanium detector (surface)
Cabling
Copper holder
Electronics
Cryogenic liquid
Infrastructure

Sources:
Natural activity of rock
Muons and neutrons

Total background level in ROI

$< 10^{-2}$ cts/(keV kg y) (Phase I)
$< 10^{-3}$ cts/(keV kg y) (Phase II)

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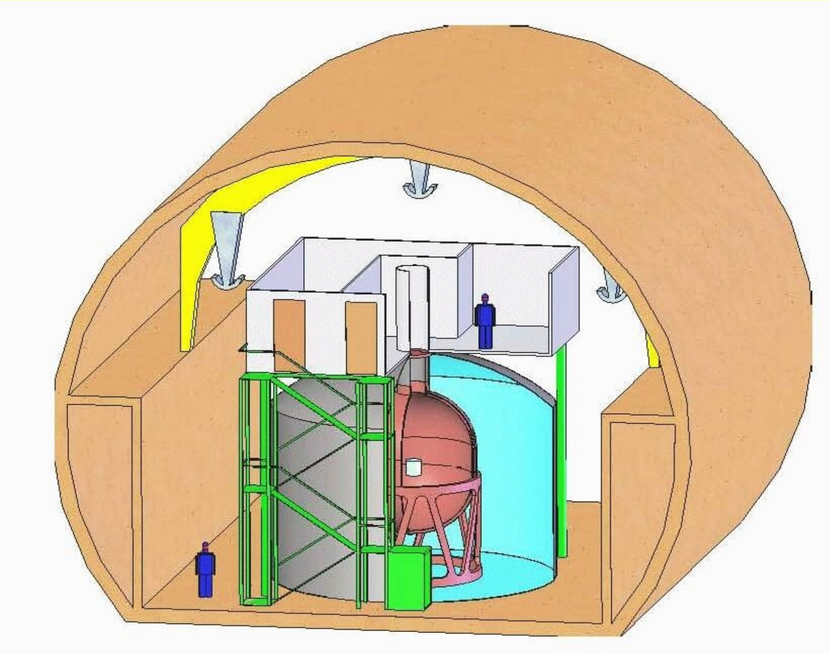

Muons produce neutrons close to the experiment, the neutrons can propagate undetected through the muon veto to the Ge-diodes and be captured by a ^{74}Ge or a ^{76}Ge nucleus.

Neutron Capture by ^{76}Ge

Muonflux @ LNGS: 1 muon/(m^2 h)

MC-simulations:
~1 n-capture/(kg y)

↕

Limit from previous experiments:
max. 6 0νββ-counts in phase I..

Neutron Capture by ^{76}Ge

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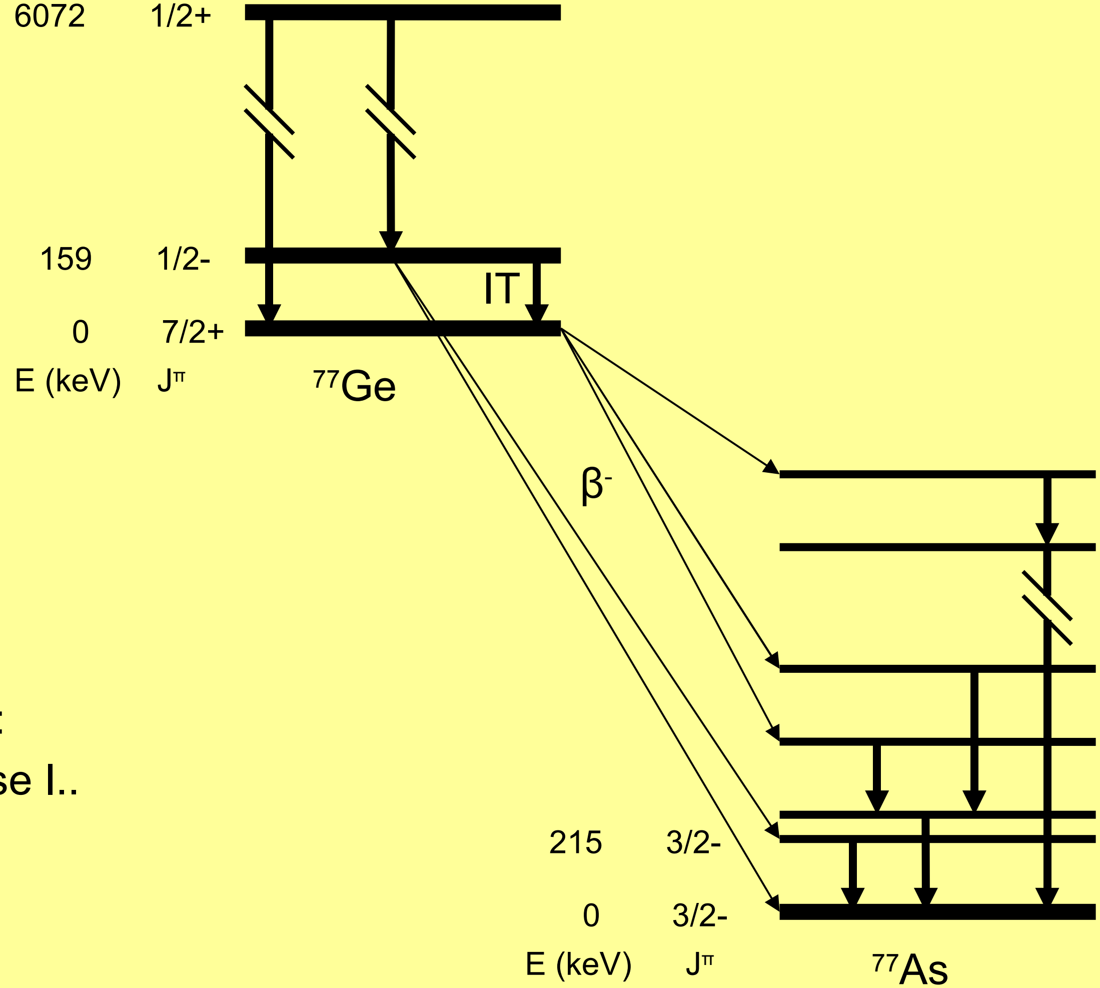
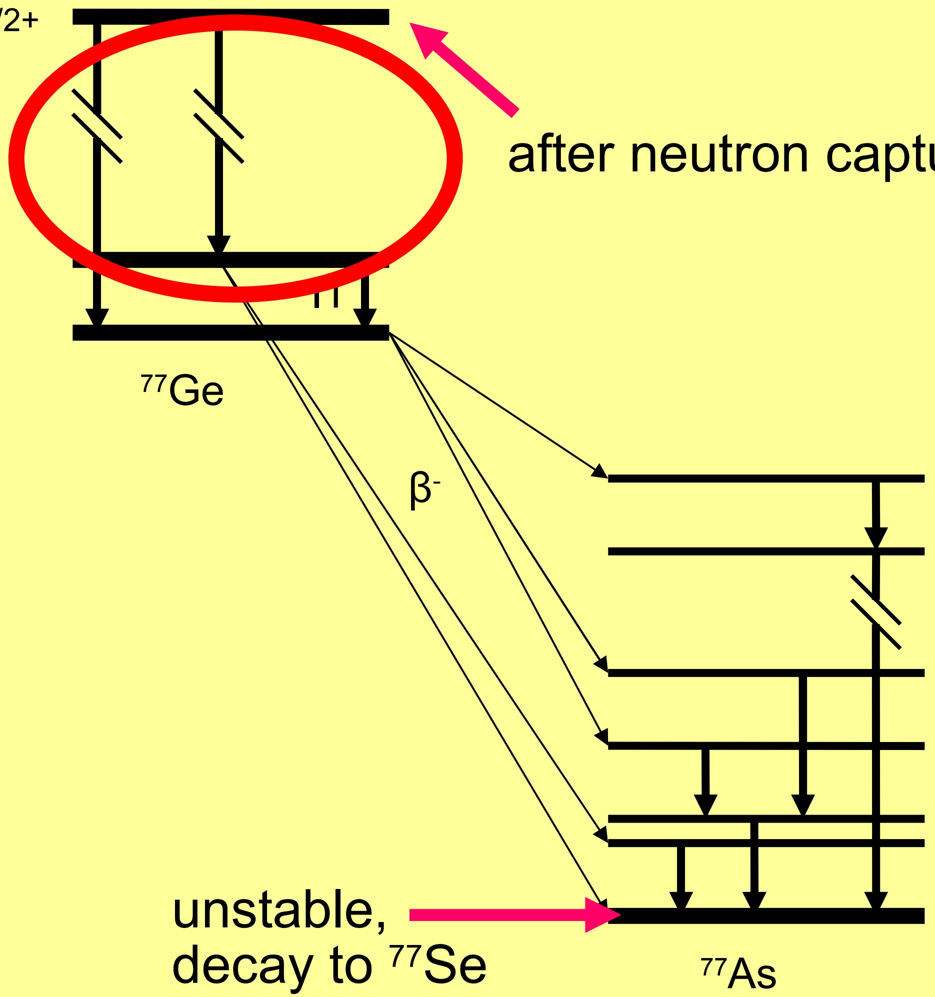


Neutron Capture by ^{76}Ge

prompt γ-cascade

E_{max} = 5911 keV

after neutron capture



unstable,
decay to ^{77}Se

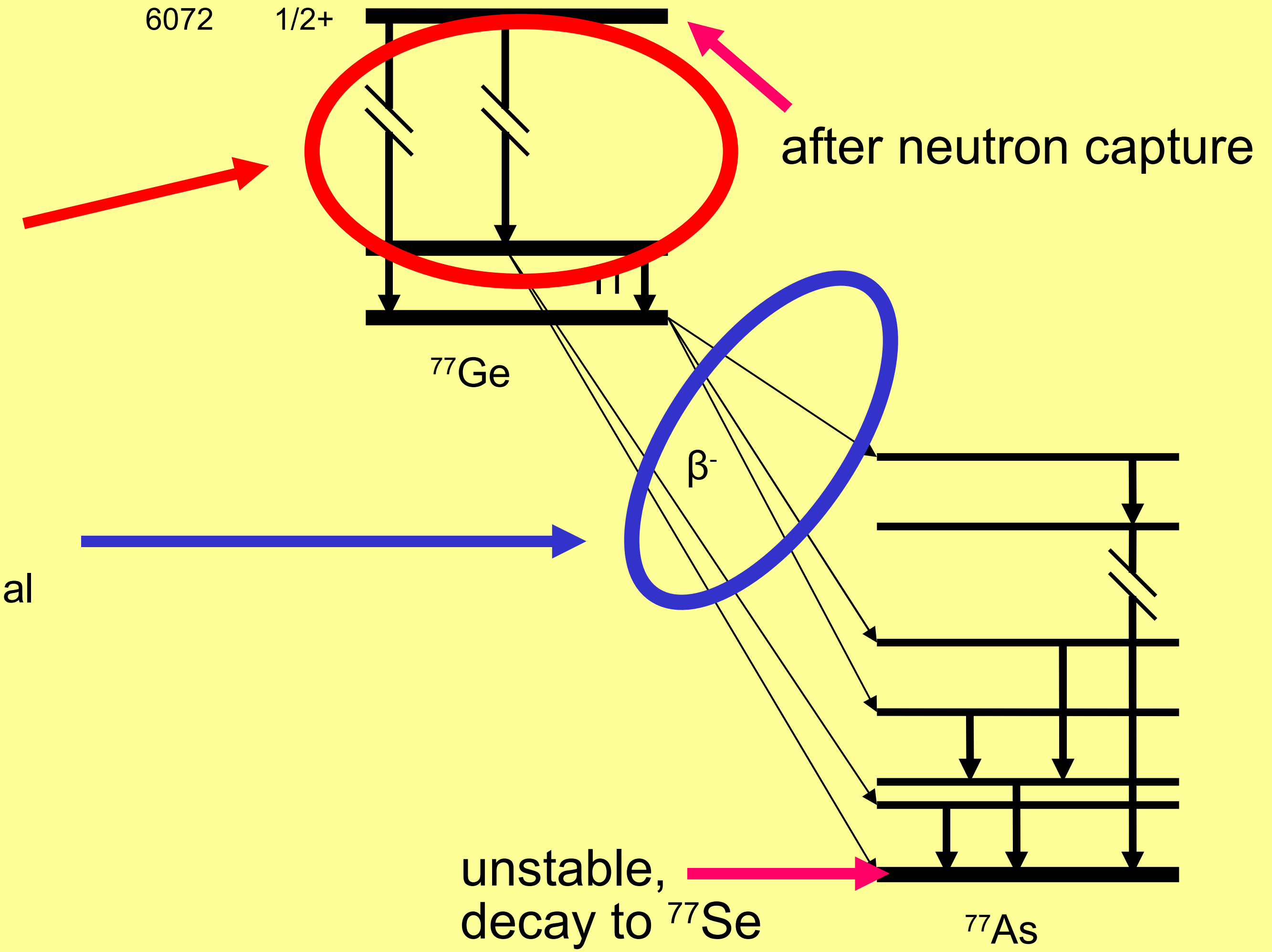
Neutron Capture by ^{76}Ge

prompt γ-cascade

E_{max} = 5911 keV

delayed β-spectrum

E_{max} = 2862 keV
continouos
mimics 0νββ signal



Neutron Capture by ^{76}Ge

prompt γ-cascade

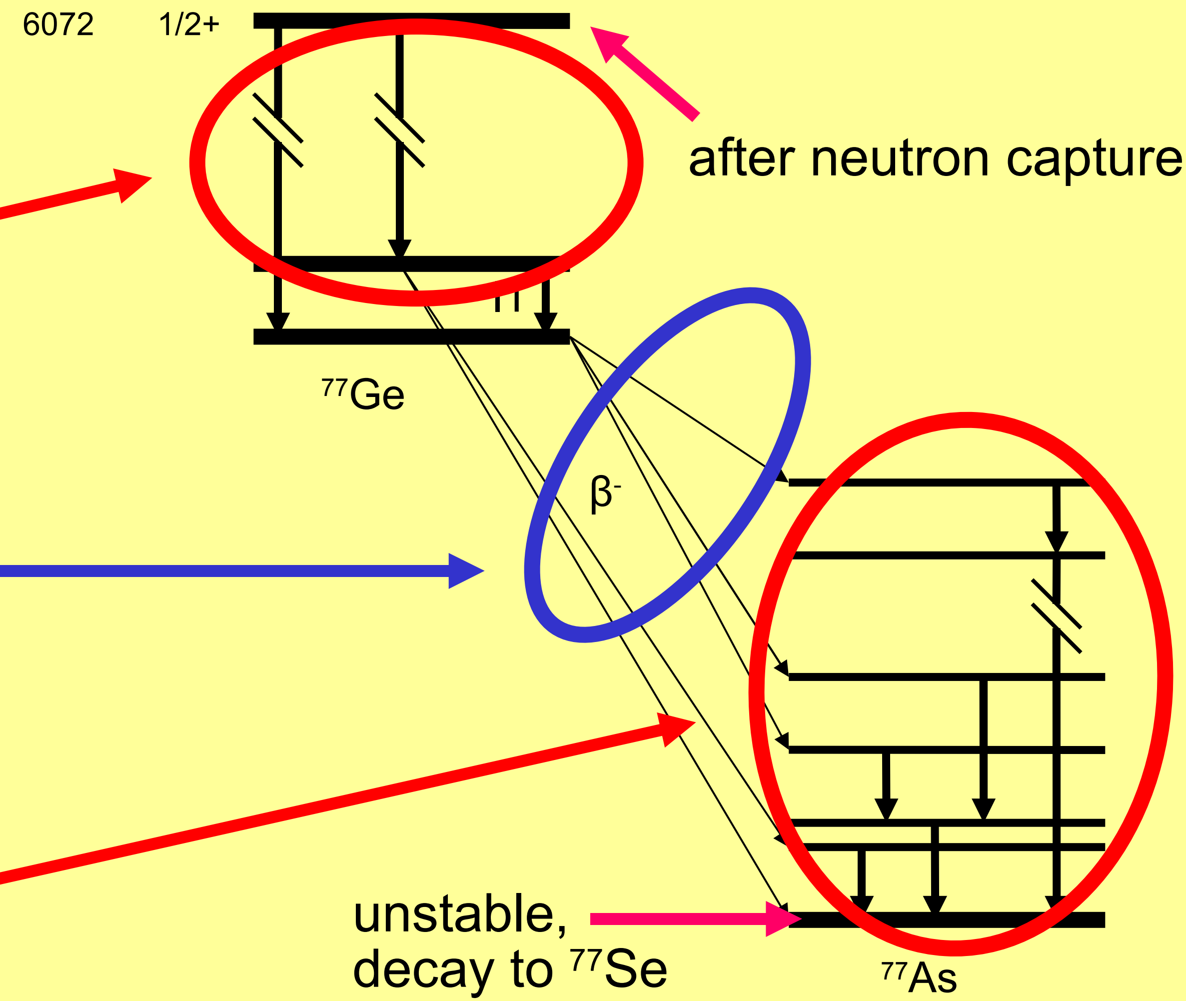
E_{max} = 5911 keV

delayed β-spectrum

E_{max} = 2862 keV
continouos
mimics 0ν β β signal

delayed γ-rays

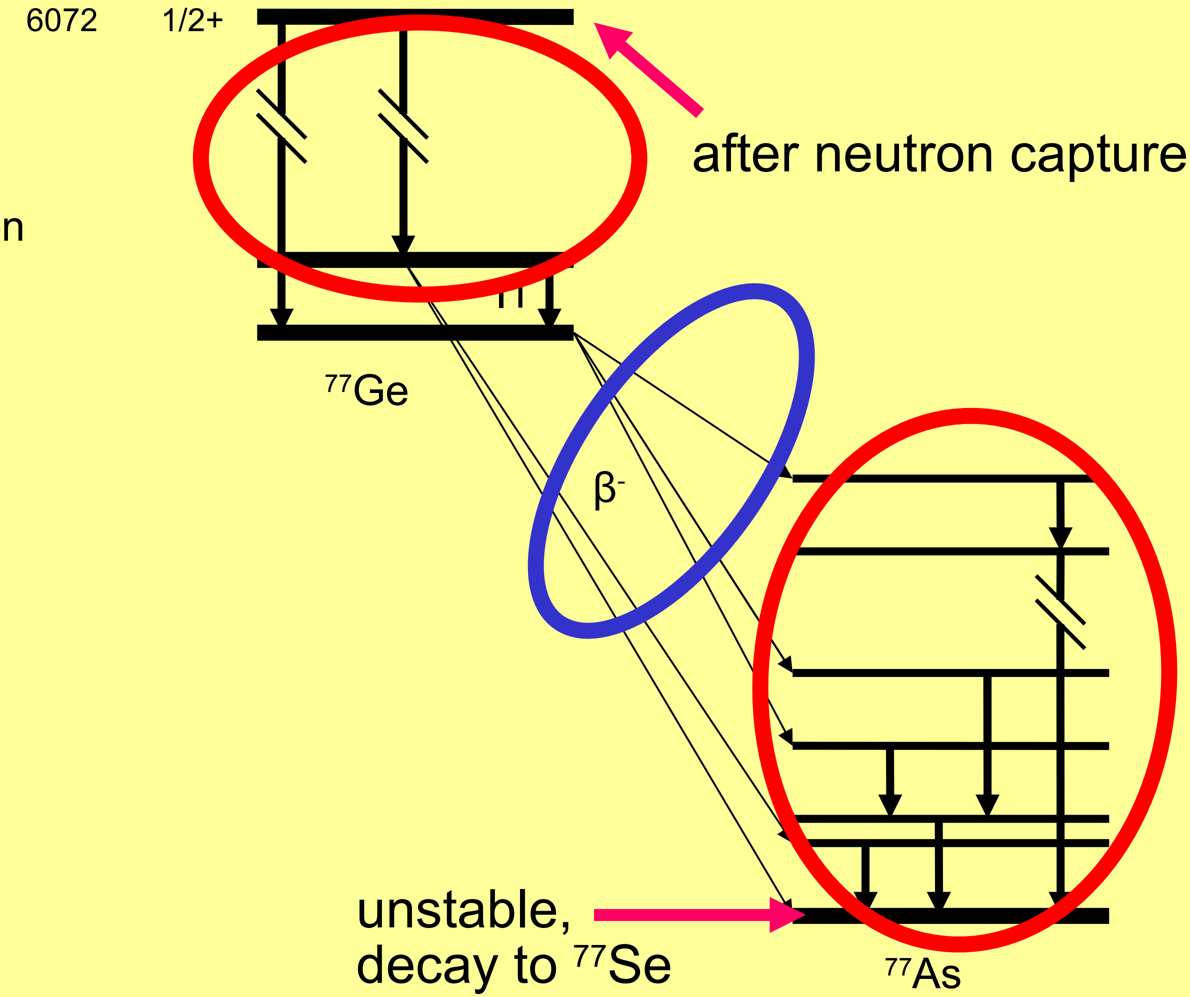
Emax = 2353 keV



Neutron Capture by ^{76}Ge

γ-rays can be rejected by pulse shape analysis and/or segmentation of detectors (multi-site events).

β-particles deposit their energiy in single-site events like 0νββ-decay. **If** β-particles occure together with γ-rays -> multi-site event -> rejection.



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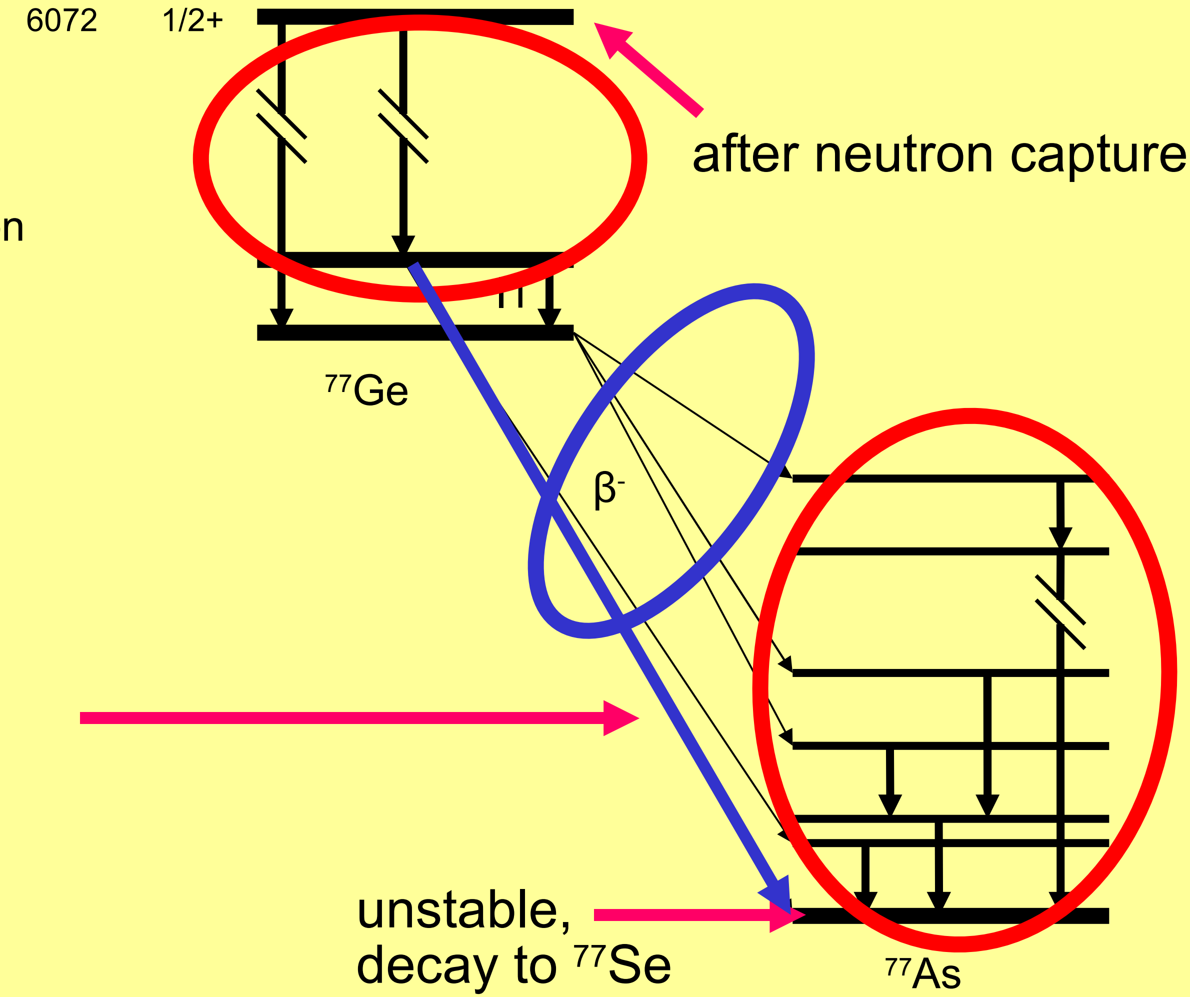
This does not work for decays directly to the ground state.
50% of all nuclei undergo this decay!
Only „coincidences“ with prompt transitions can be used.



Neutron Capture by ^{74}Ge

γ-rays can be rejected by pulse shape analysis and/or segmentation of detectors (multi-site events).

β-particles deposit their energiy in single-site events like 0νββ-decay. **If** β-particles occure together with γ-rays -> multi-site event -> rejection.

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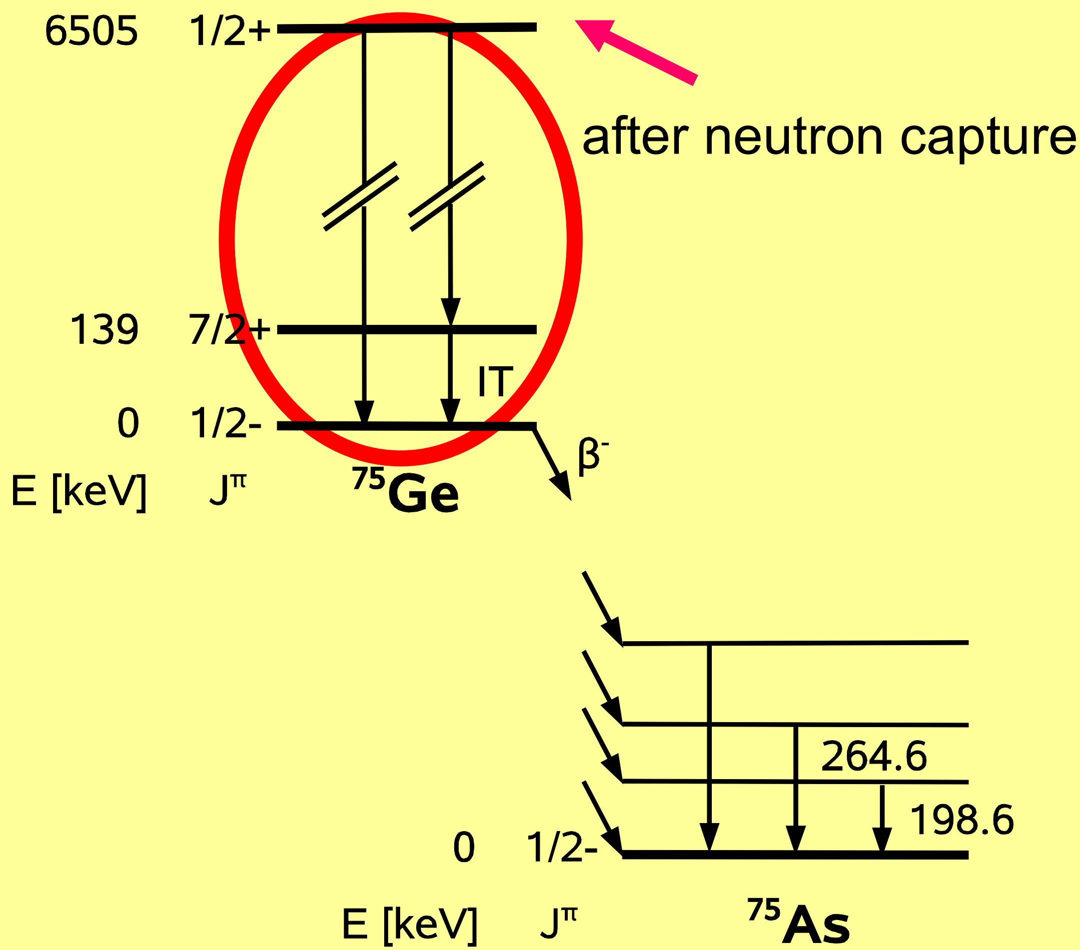
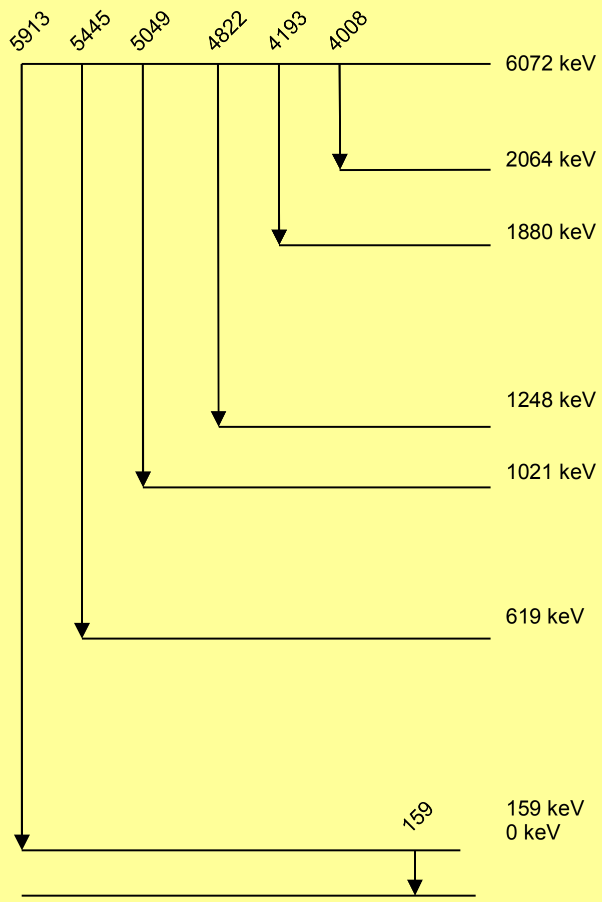


Prompt transitions in ^{77}Ge



Nuclear Data Sheets 81

not in decay scheme	**IAEA Nuclear Data Services**
E [keV]	**E [keV]**
196	862
431	1251
808	1903
851	
3895	
4514	
5420	

Only 15% of the energy weighted intensity

PGAA @ FRM II

Beam

~3 x 10^9 $n_{th}/(cm^2 s^1)$

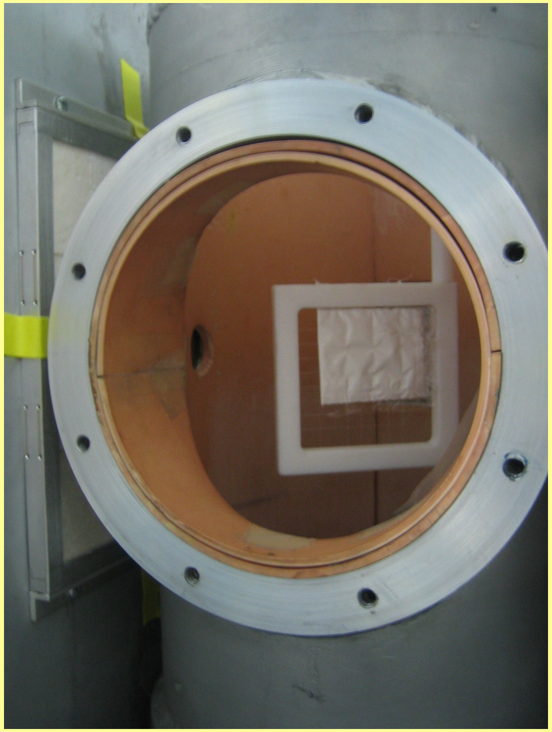
$<\lambda_n> = 6.7$ Å

$<E_n> = 1.83$ meV

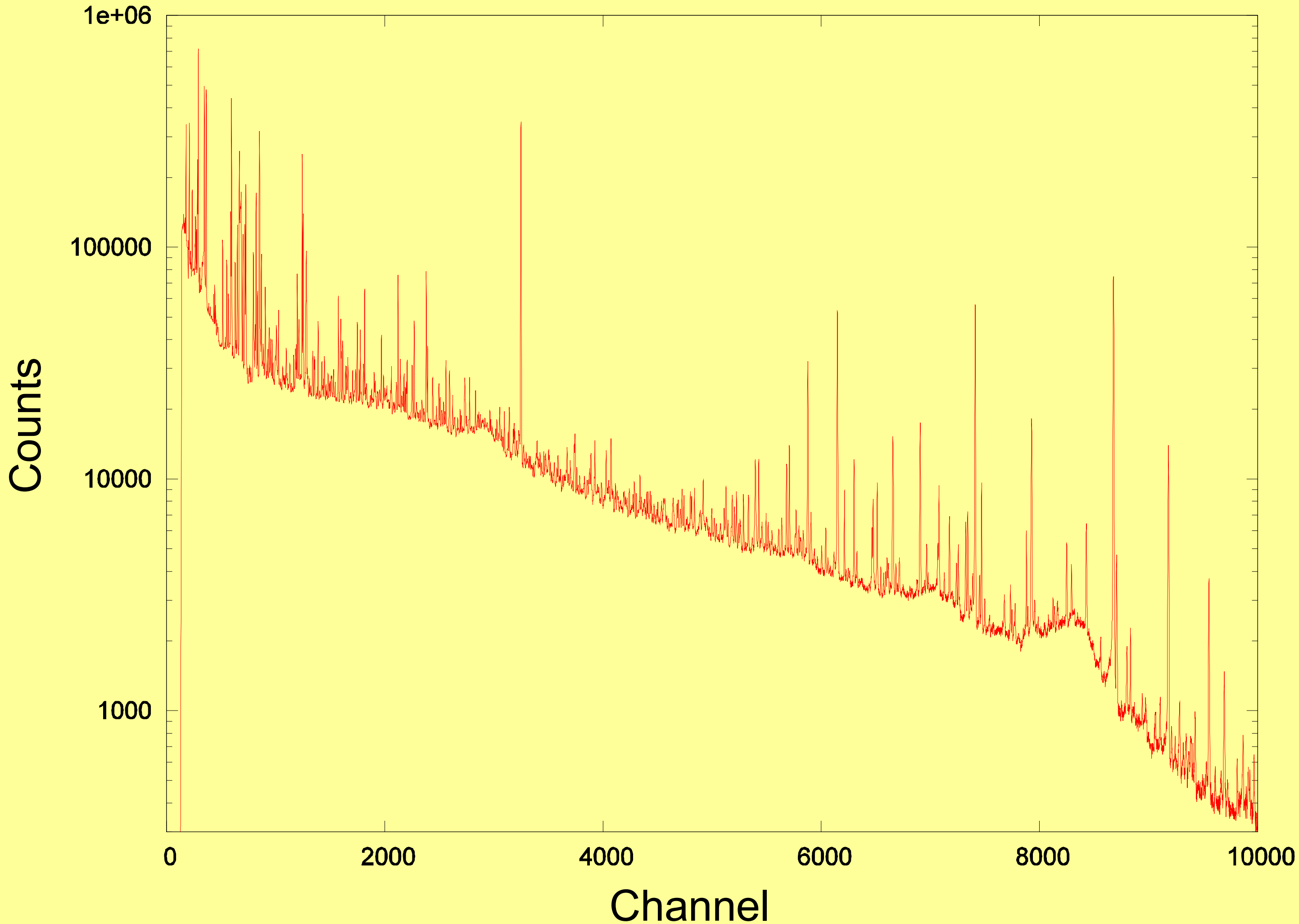
Detectors

2 HPGe
    with Compton
    suppresion

Li/Cd/Pb shielding

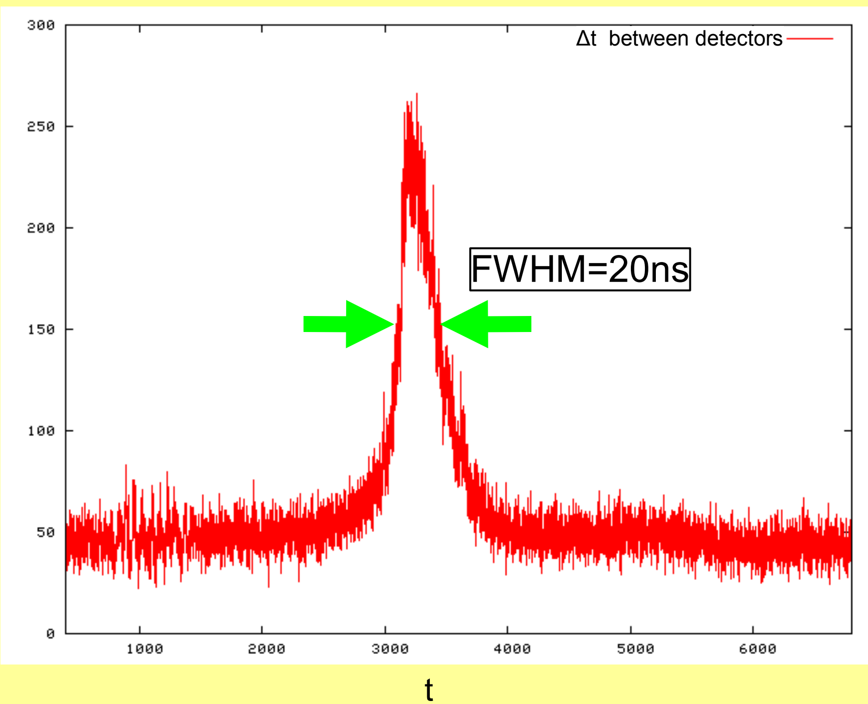


Prompt γ-spectrum in ^{77}Ge

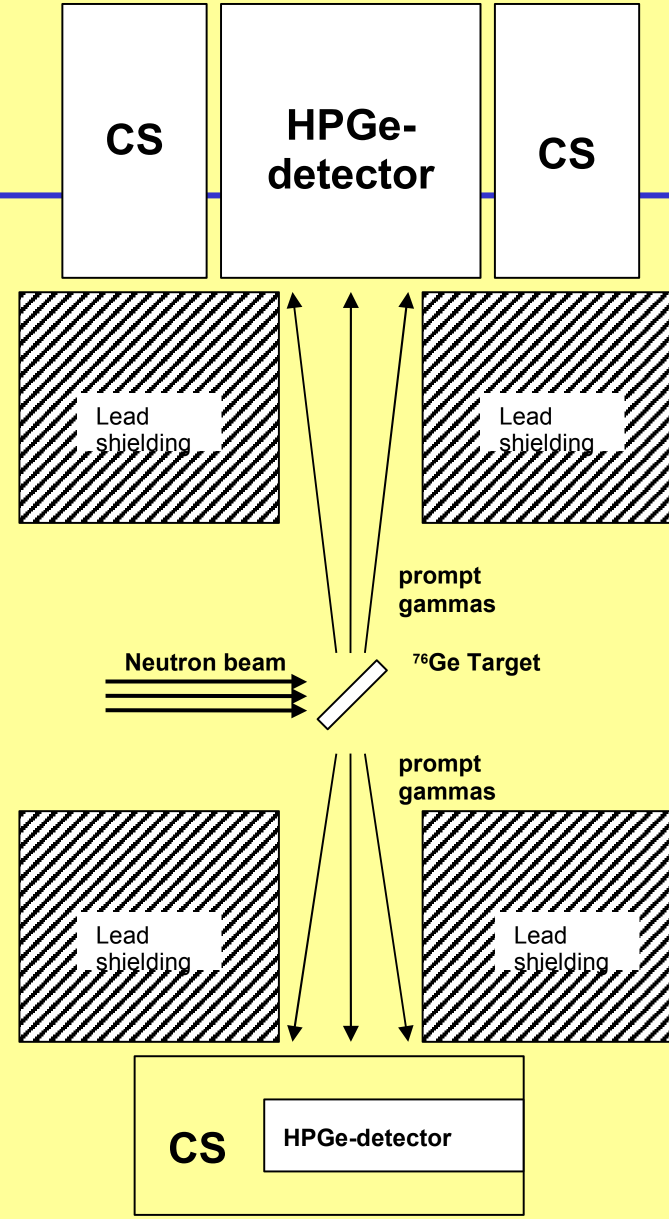


Coincidence

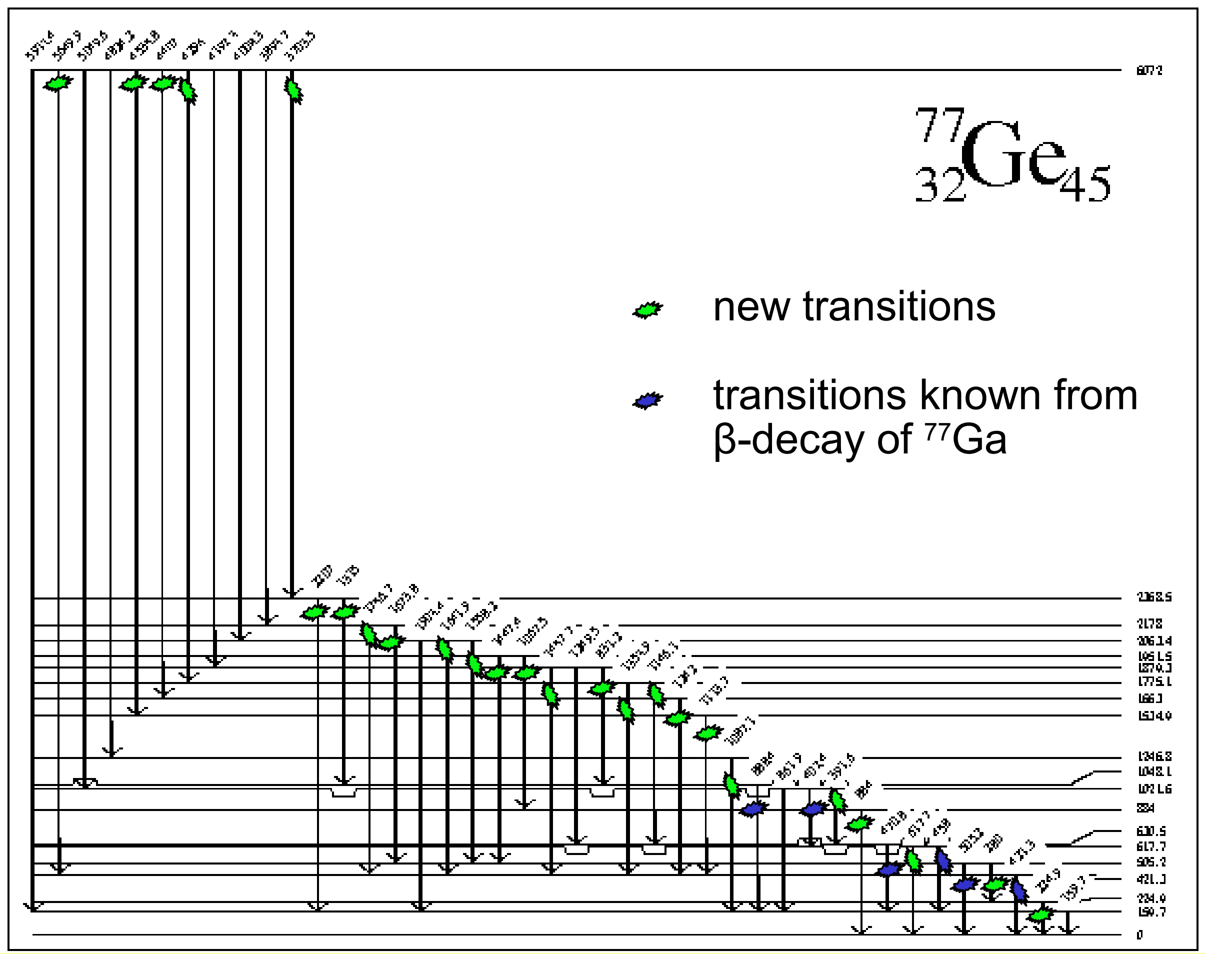
m ~ 300 mg of enriched $^{76}GeO_2$
Irradiation time 8 d



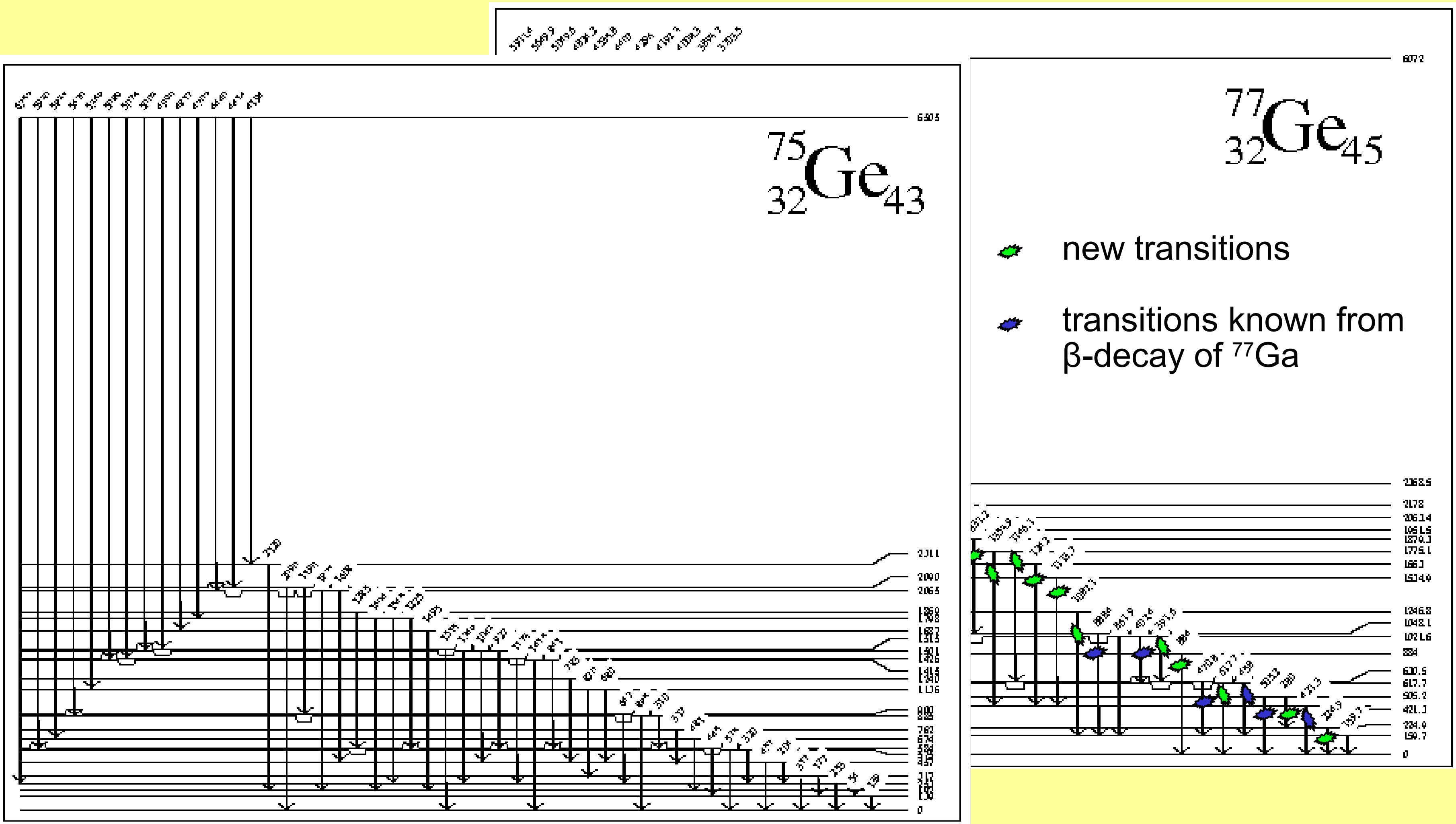
Time difference is used to distinguish between random and true coincidences.



Decay scheme in ^{77}Ge (preliminary)

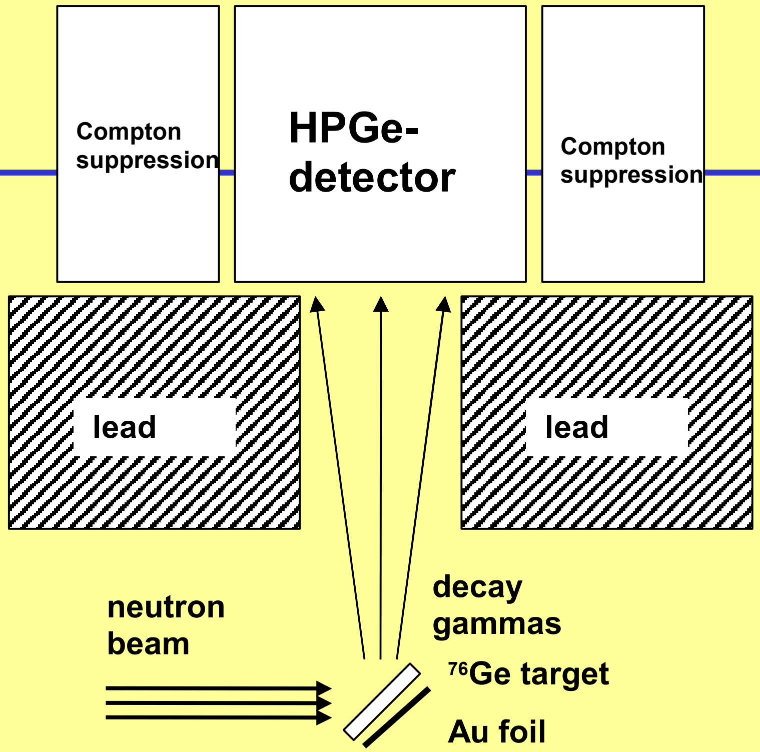


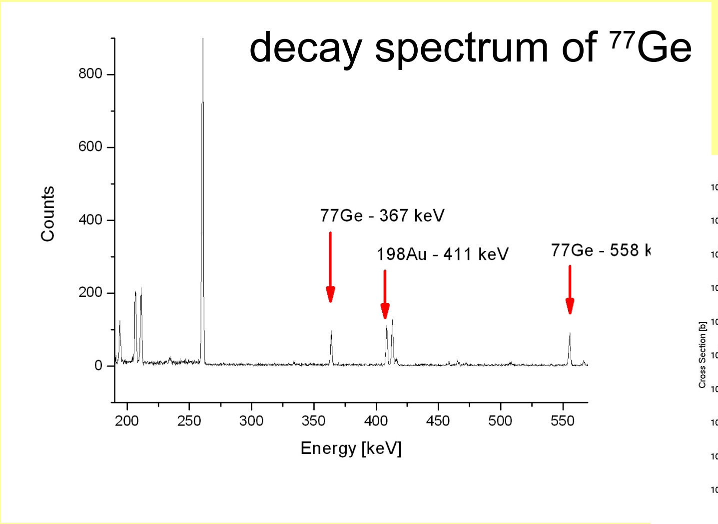
Decay scheme in ^{75}Ge (preliminary)

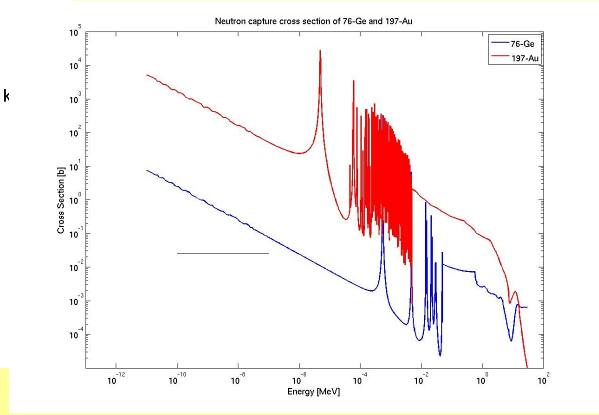


Cross-section

^{76}Ge target was activated together with a gold foil and after irradiation the γ-rays after β-decay were measured by HPGe detectors. The cross-section was calculated relative to ^{198}Au using the emission probabilities.







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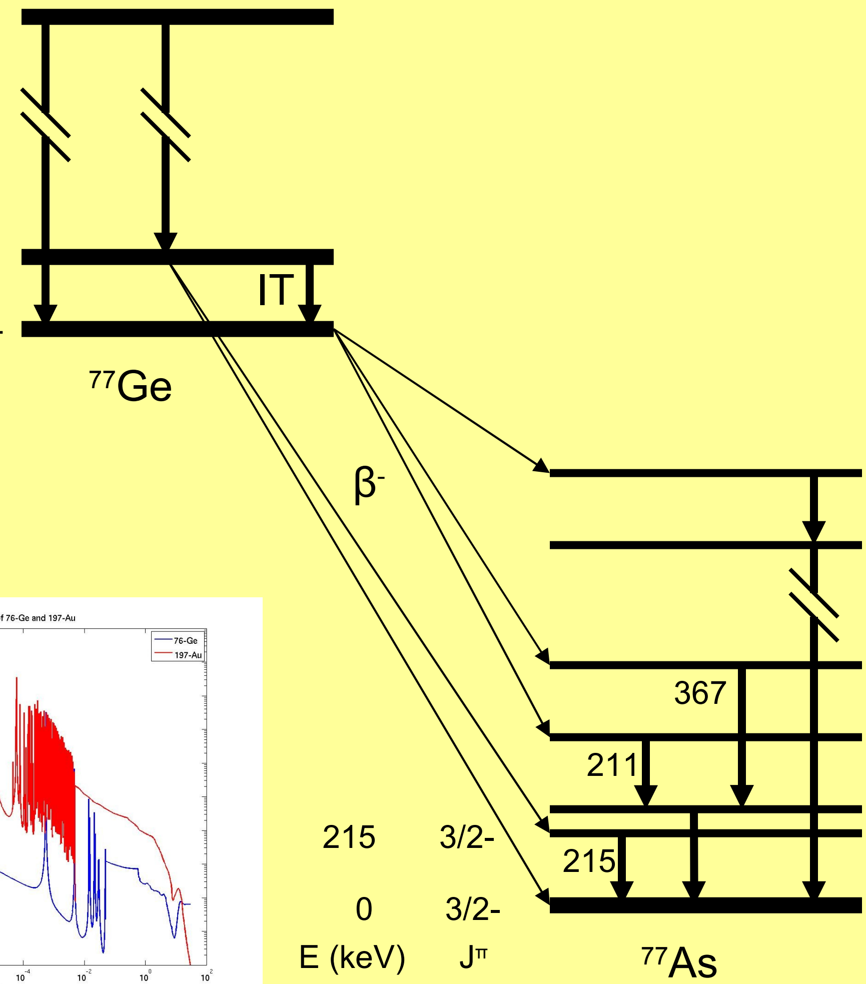

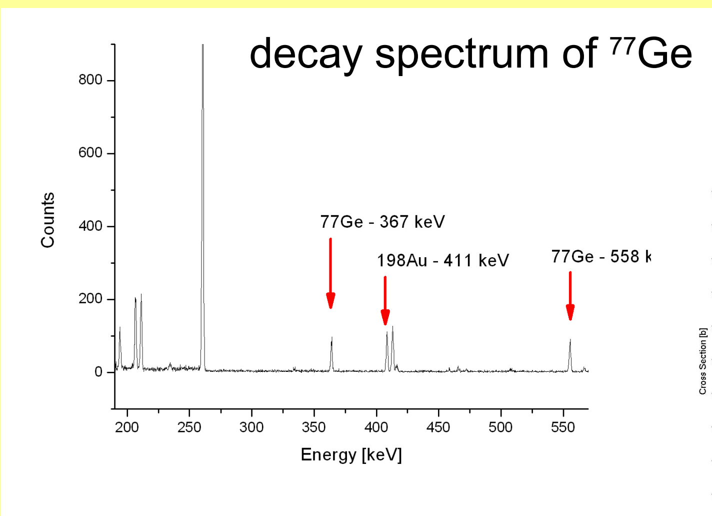

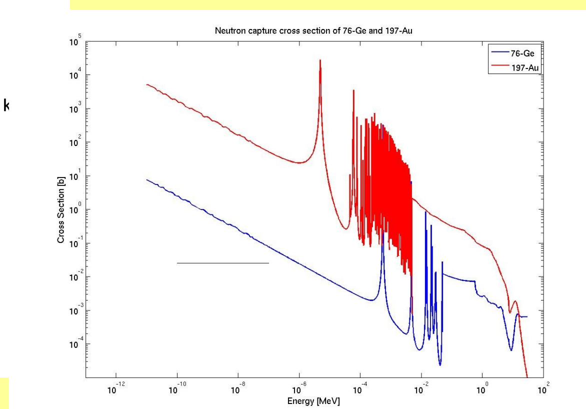

Cross-section results

Evaluating the data one could see that the emission probabilities given in literature are not consistent. Some transitions lead to lower cross-sections than those used here. Check needed.

^{76}Ge

$\sigma(^{77}Ge)$ direct	46.9 ± 4.7 mb
$\sigma(^{77}Ge)$	68.8 ± 3.4 mb
$\sigma(^{77m}Ge)$	115 ± 16 mb

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^{74}Ge (preliminary)

σ(^{75}Ge) direct	368 ± 52 mb
σ(^{75}Ge)	499 ± 53 mb
σ(^{75m}Ge)	131.4 ± 6.8 mb

Summary

- The knowledge of the prompt spectrum after neutron capture by ^{76}Ge is important for background analysis in GERDA.
- The observation of a prompt cascade in GERDA would allow to veto the delayed electrons from β-decay of ^{77}Ge

Measurement of the prompt spectrum using PGAA

- To predict the background contribution by neutron capture in GERDA the capture cross section has to be known well.

Measurement using the PGAA facility

Pulse shape analysis

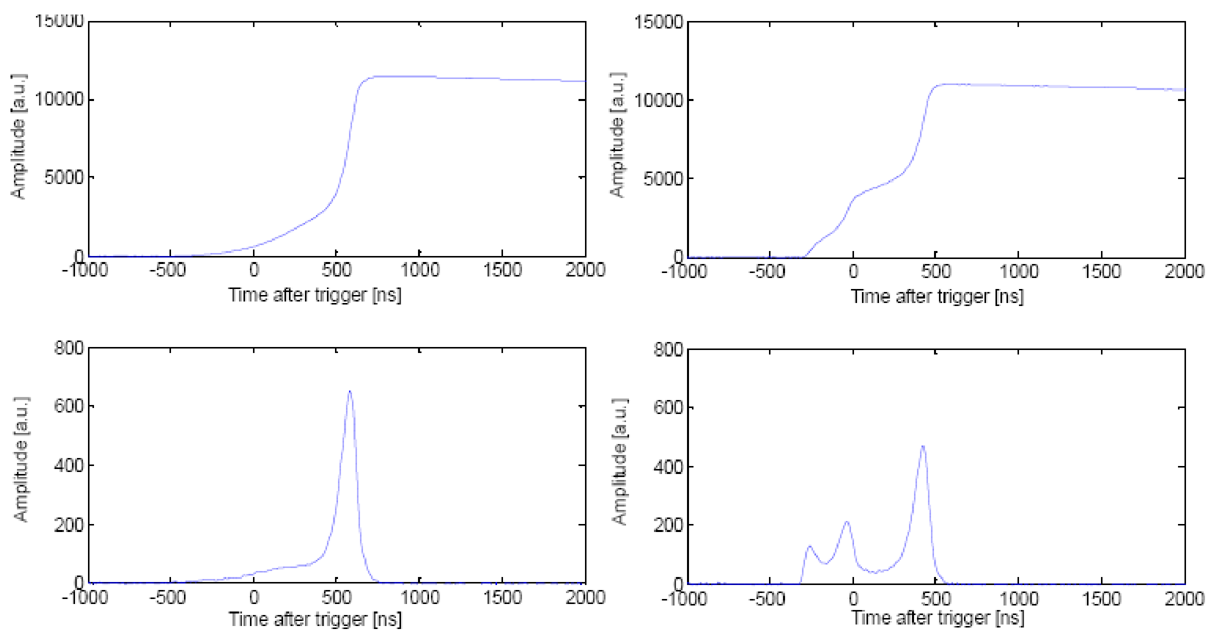
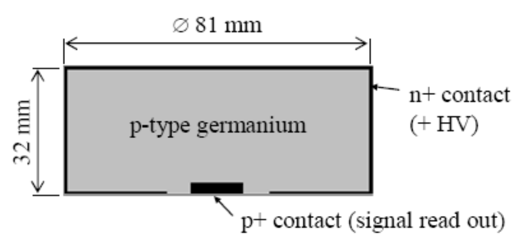


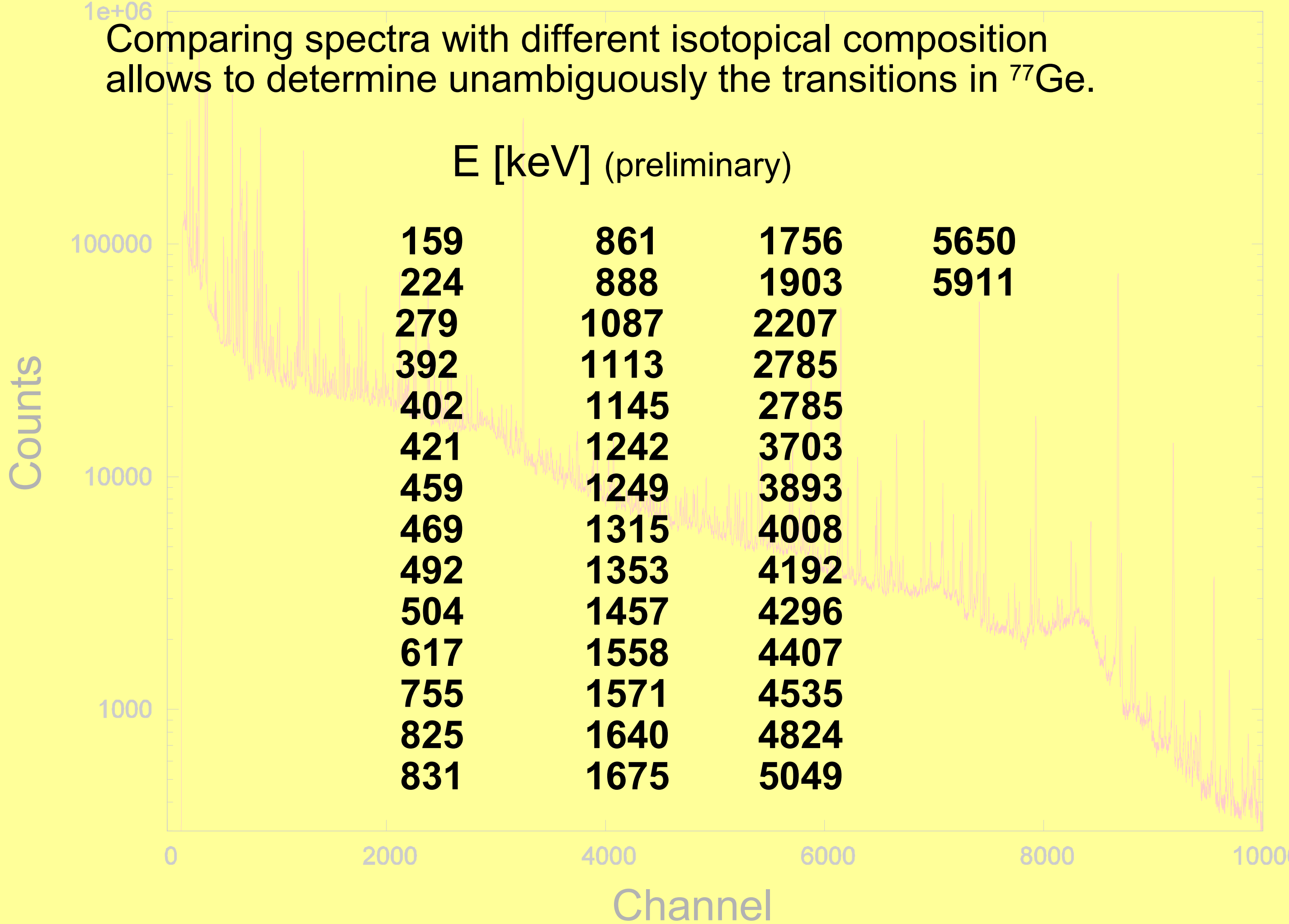
Figure II-16 Signal traces recorded by FADC (10 ns per point). **Top row:** Voltage pulses from the preamplifier (corresponding to detector charge pulses). **Bottom row:** The same pulses after 50 ns smoothing and 10 ns differentiation (analogous to detector current pulses). **Left column:** A typical candidate for a SSE. **Right column:** A candidate for a multiple-scattered photon induced MSE. Both events had approximately equal energy. The events were recorded from a ^{228}Th radioactive source.



PhD thesis D. Budjas, Heidelberg 2009

Prompt γ-spectrum in ^{77}Ge

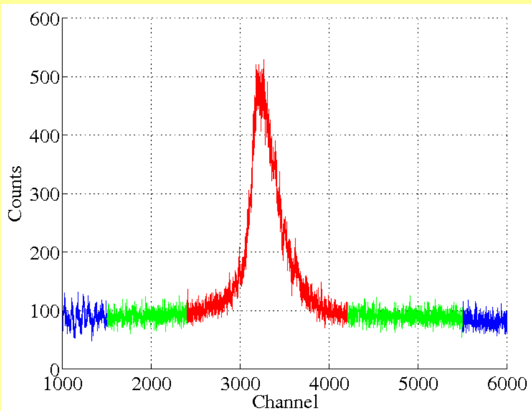
Comparing spectra with different isotopical composition allows to determine unambiguously the transitions in ^{77}Ge.

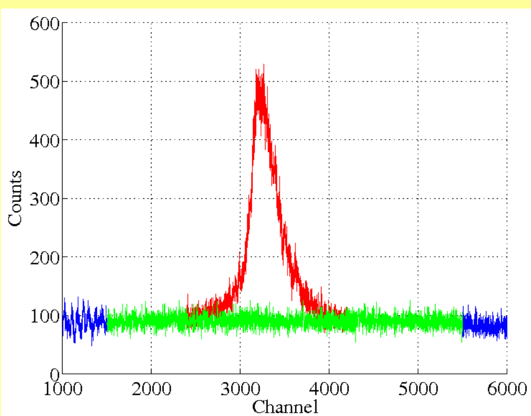


E [keV] (preliminary)

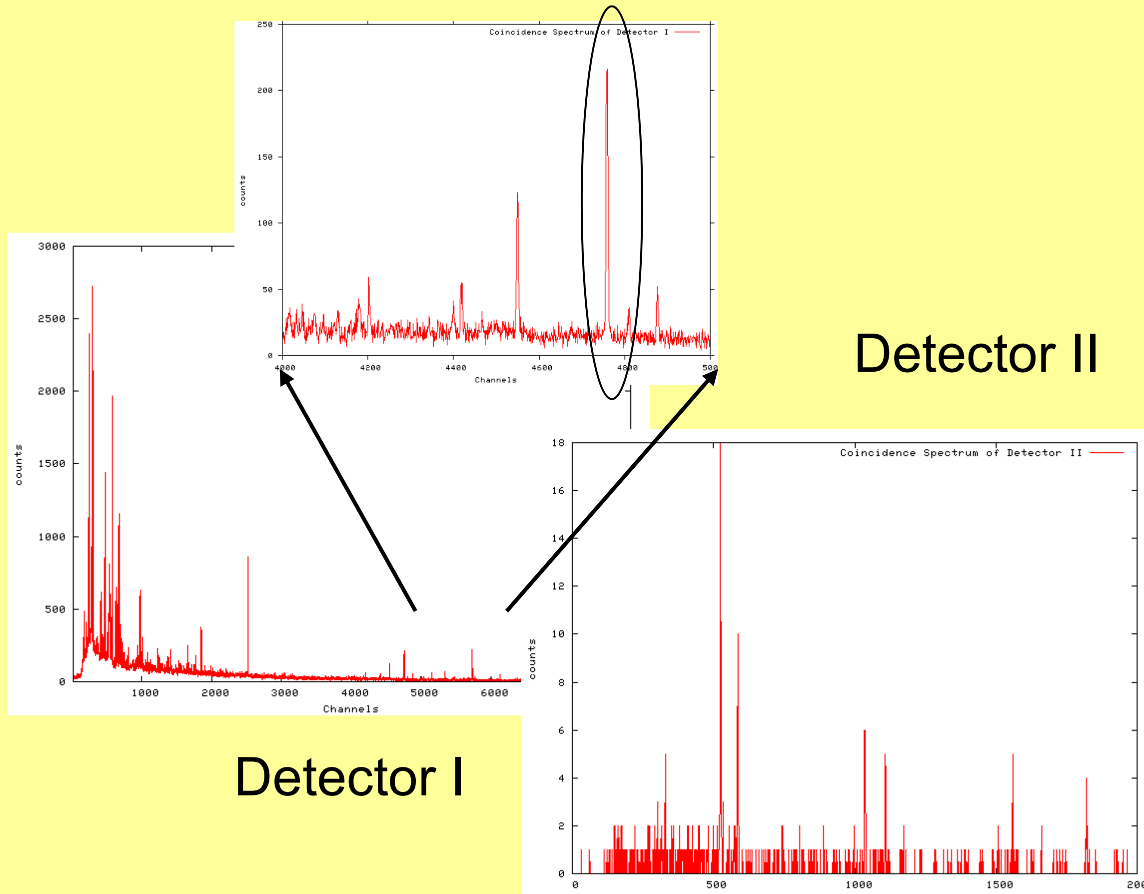
159	**861**	**1756**	**5650**
224	**888**	**1903**	**5911**
279	**1087**	**2207**	
392	**1113**	**2785**	
402	**1145**	**2785**	
421	**1242**	**3703**	
459	**1249**	**3893**	
469	**1315**	**4008**	
492	**1353**	**4192**	
504	**1457**	**4296**	
617	**1558**	**4407**	
755	**1571**	**4535**	
825	**1640**	**4824**	
831	**1675**	**5049**	

Analysis





Time information



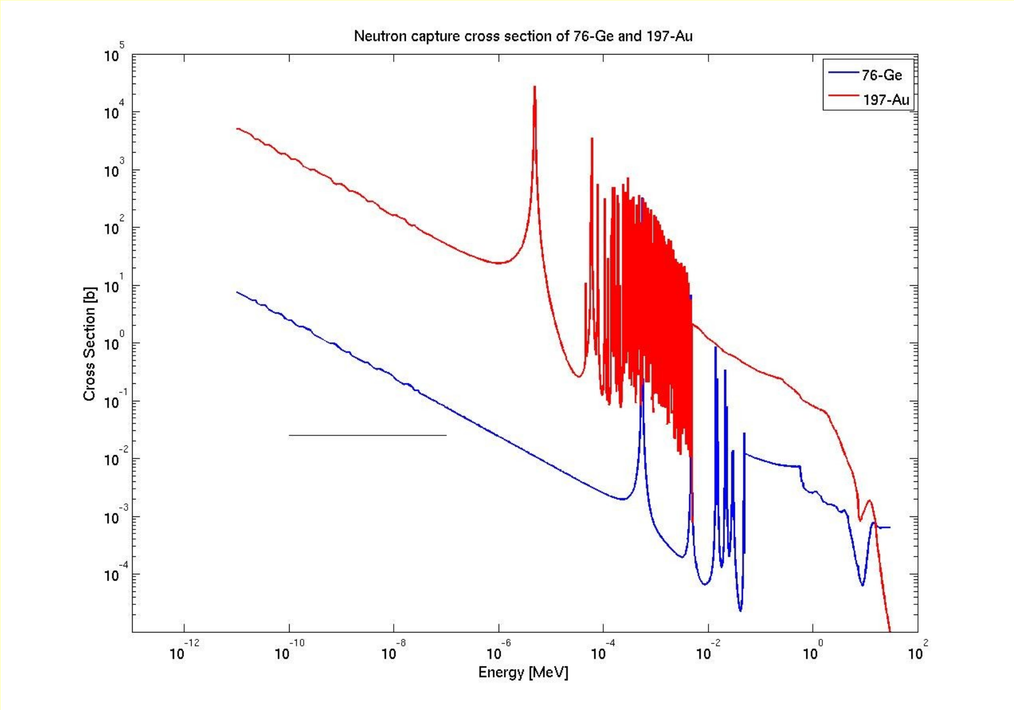
Detector II

Detector I

Cross Section

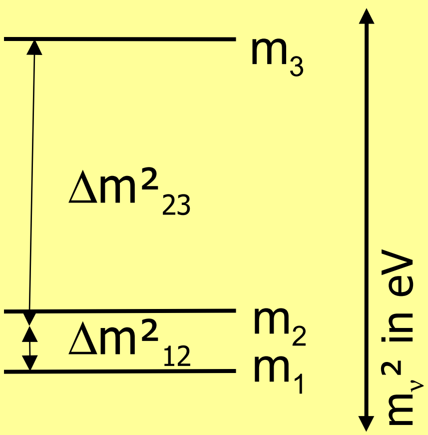
$$\sigma_{Ge}(\lambda) = \frac{A_{Ge} * \left(I_{(Au,\gamma)} * n_{Au}(r) * \Phi(r)\right)}{A_{Au} * \left(I_{(Ge,\gamma)} * n_{Ge}(r) * \Phi(r)\right)} \sigma_{Au}(\lambda)$$

$$\sigma_{0,Ge} = \frac{\left(A_{Ge} * I_{(Au,\gamma)} * n_{Au}\right)}{\left(A_{Au} * I_{(Ge,\gamma)} * n_{Ge}\right)} \sigma_{0,Au}$$



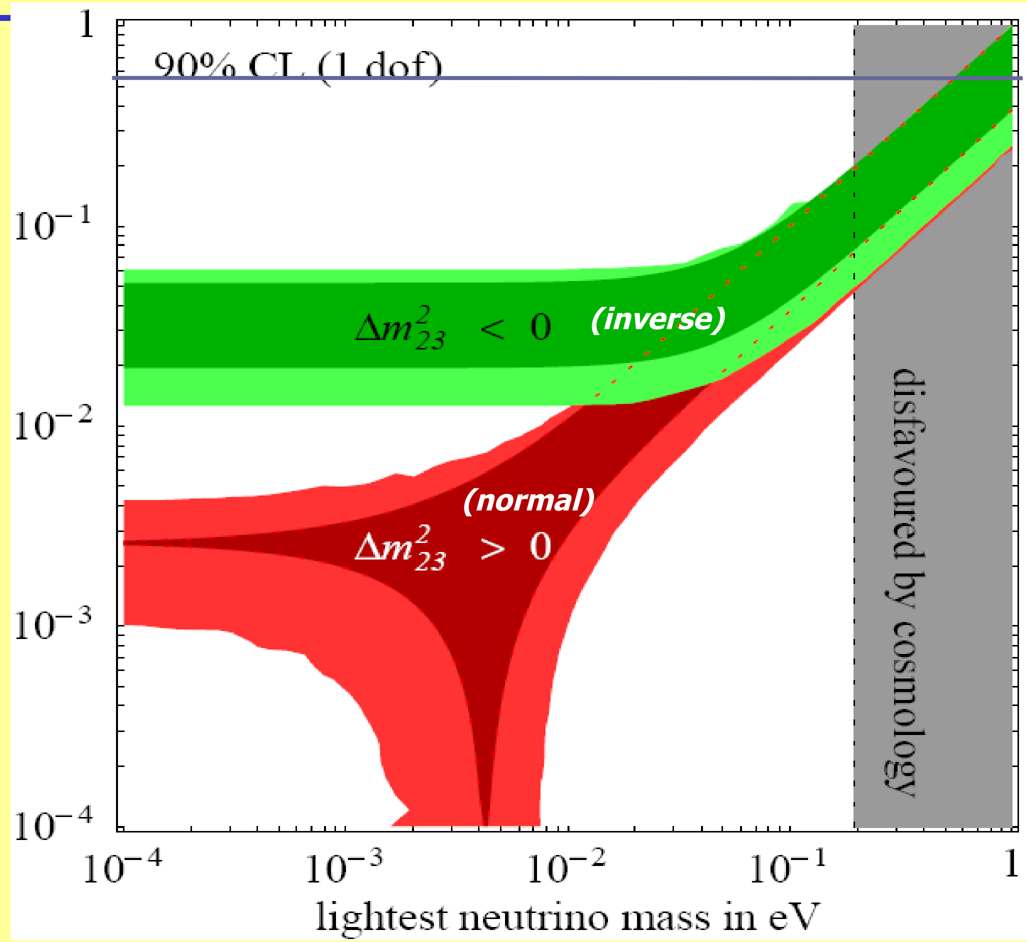
What can we lern from 0νββ?

If 0νββ is observed:



Δm^2_{12} = (7.92±0.07)·10-5 eV² (solar ν)
Δm^2_{23} = (2.6±0.4)·10-3 eV² (atm. ν)

- ✓ Mass hierachy (degenerate, inverted or normal)



F.Feruglio, A. Strumia, F. Vissani, NPB 637

Sensitivity

Background

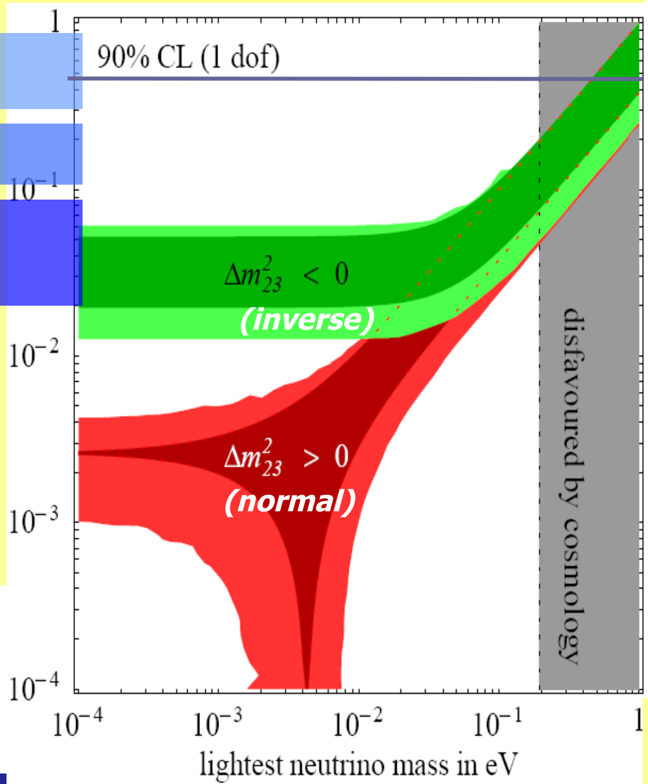
Phase I: 10^{-2} cts/(keV kg y)

Phase II: 10^{-3} cts/(keV kg y)

Phase I

Phase II

Phase III



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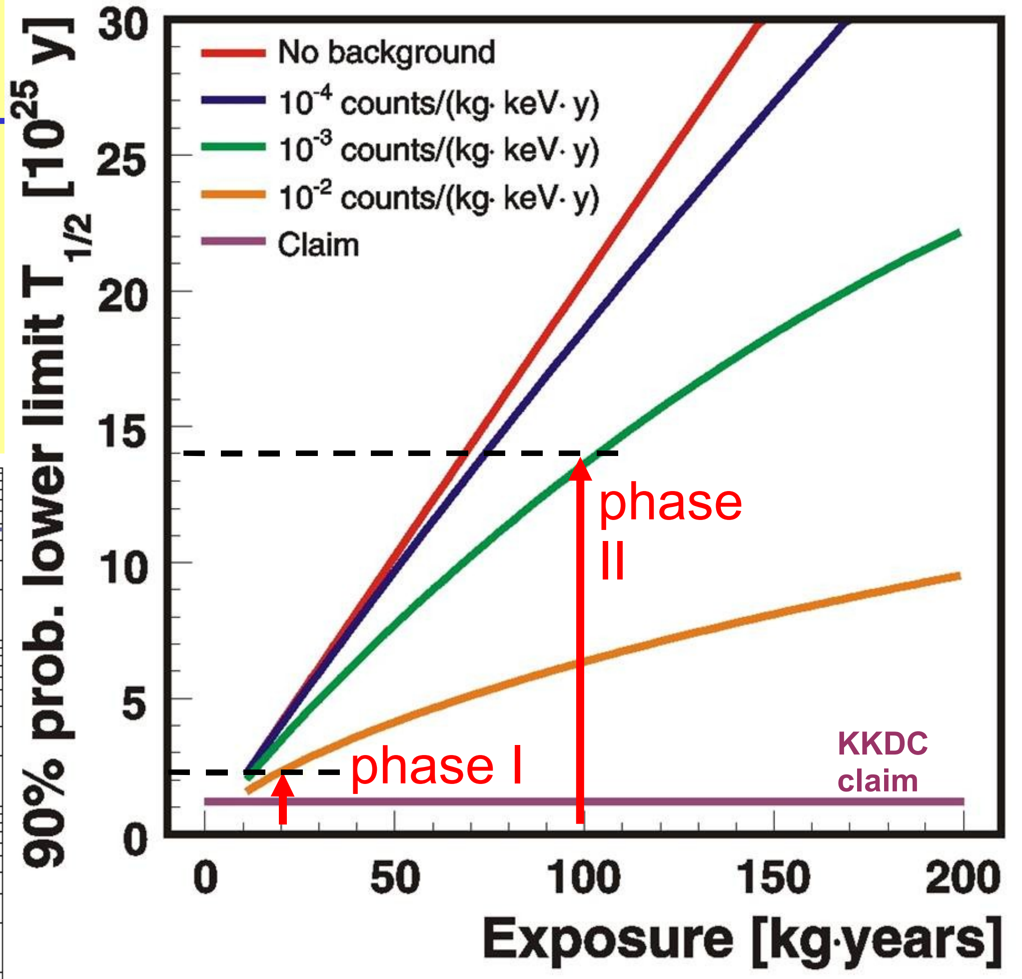
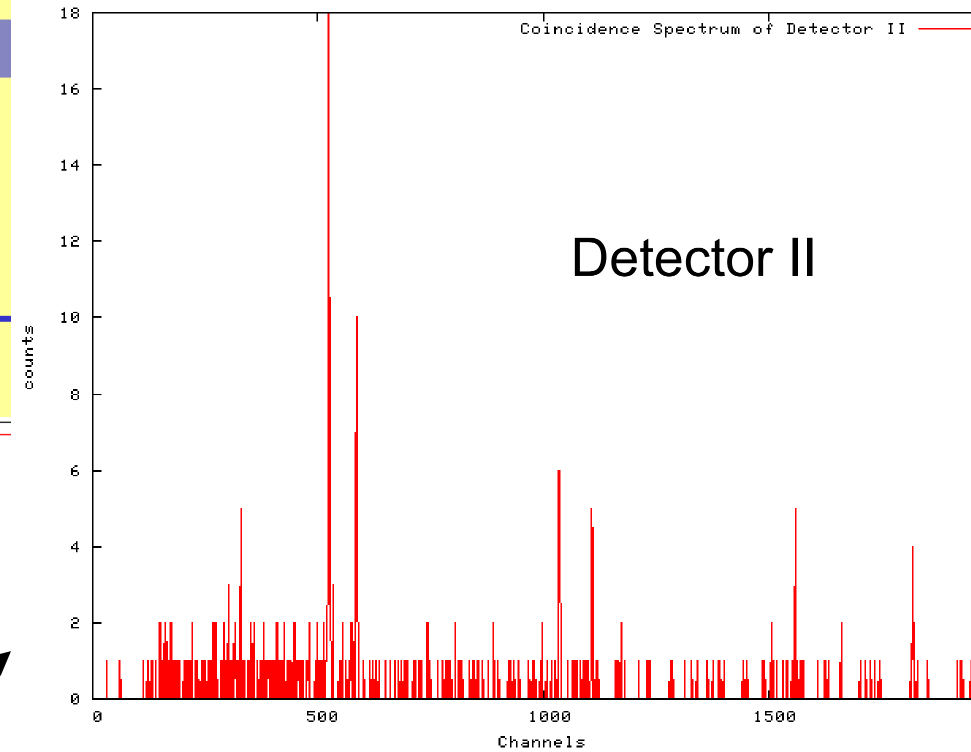
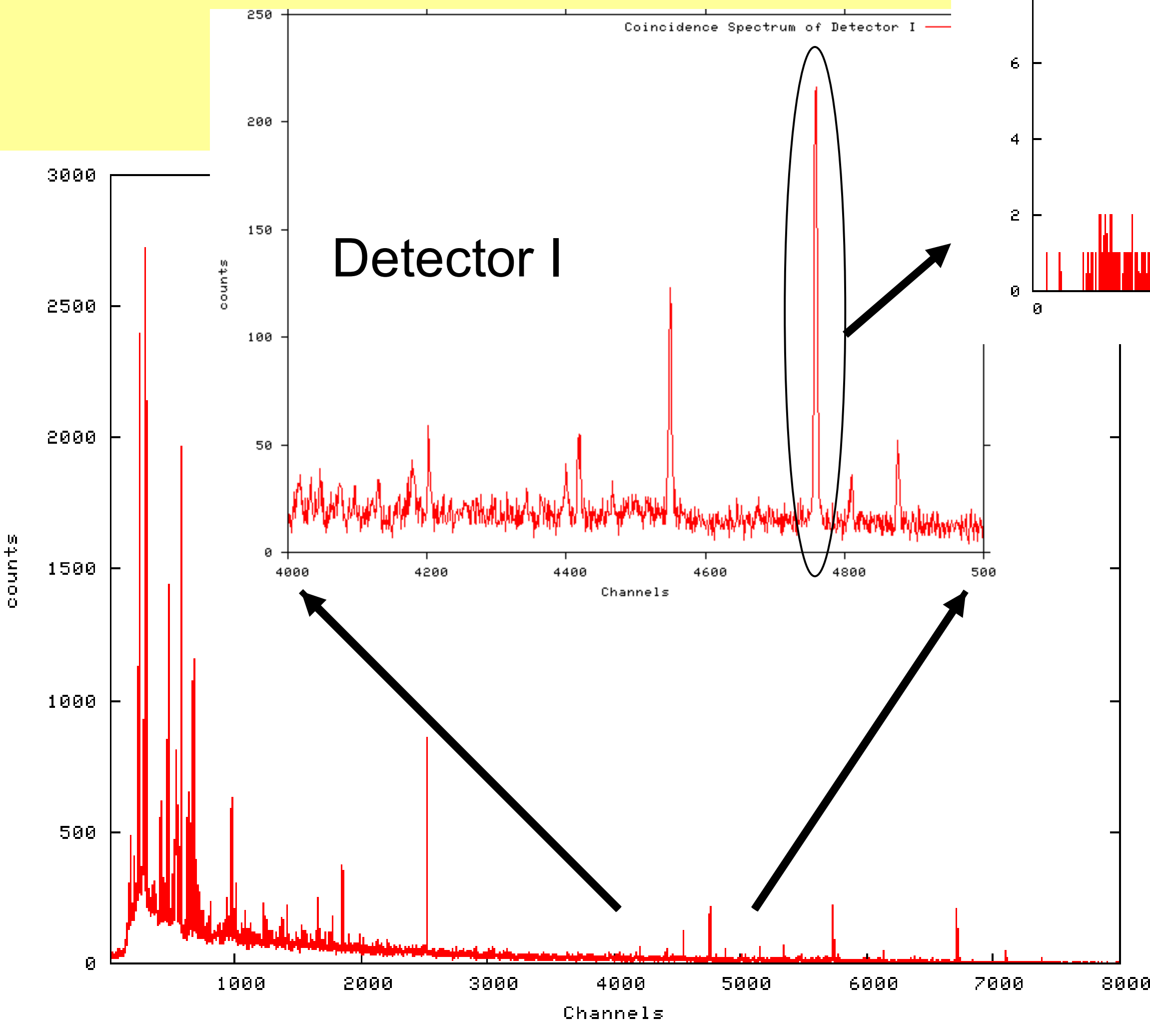


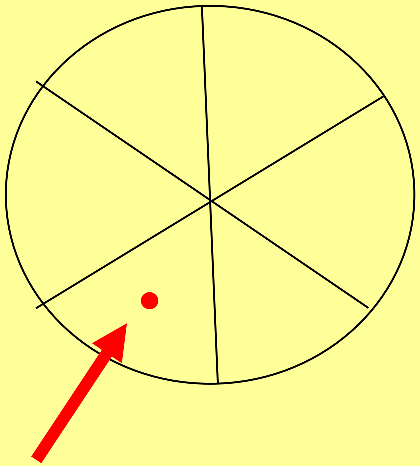
Coincidence

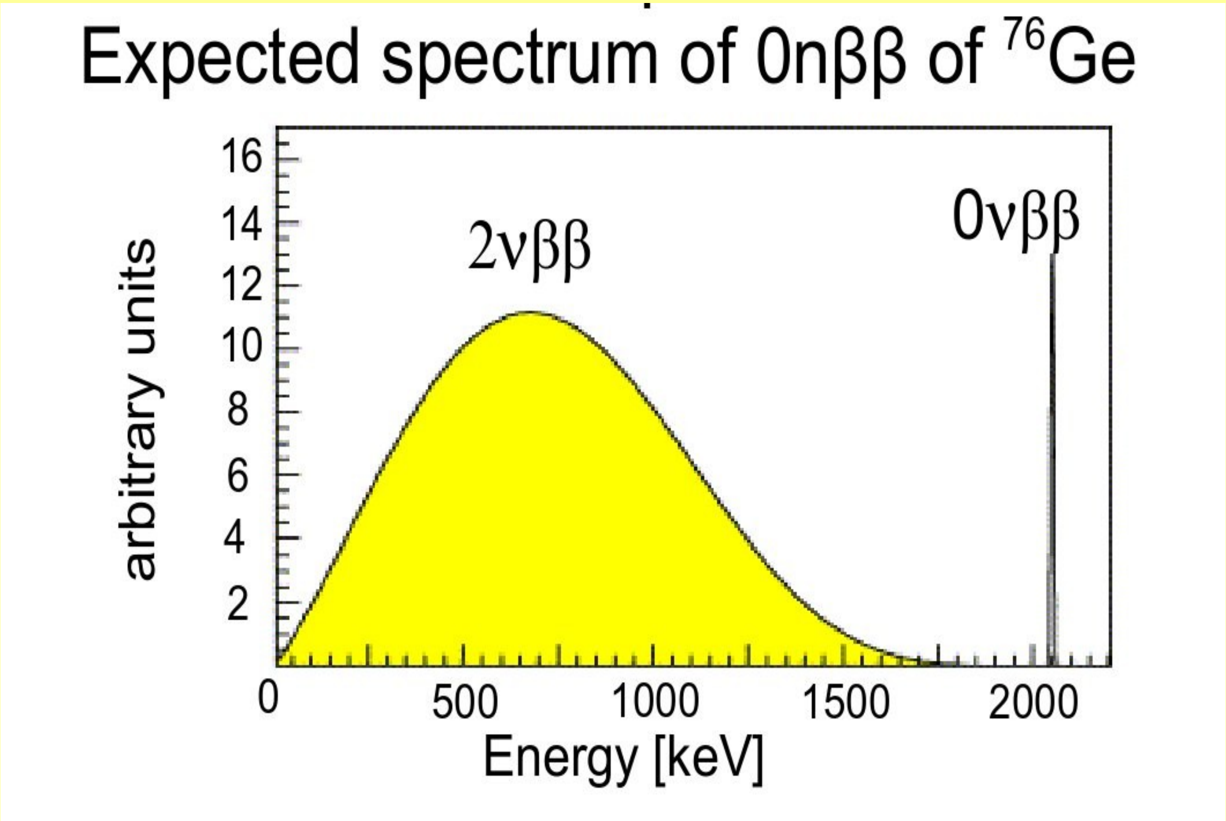




0νββ-Decay

segmented detector



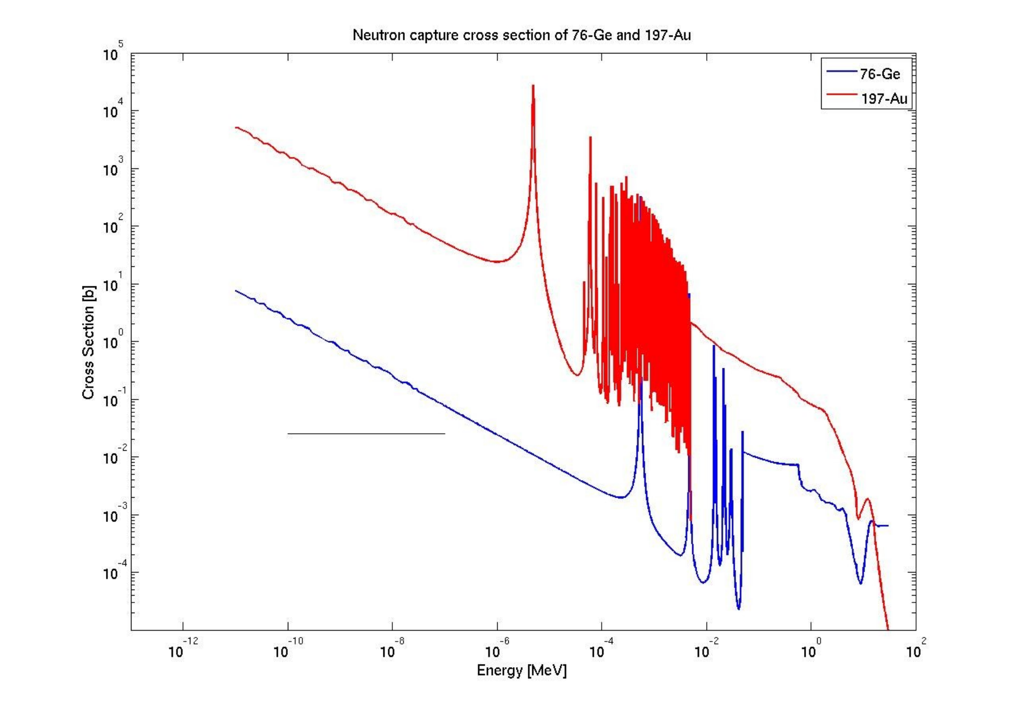


0νββ event,
energy is deposited in a very small volume due to the short range of electrons

Cross Section

$$\sigma_{Ge}(\lambda) = \frac{A_{Ge} * \left(I_{(Au,\gamma)} * n_{Au}(r) * \Phi(r)\right)}{A_{Au} * \left(I_{(Ge,\gamma)} * n_{Ge}(r) * \Phi(r)\right)} \sigma_{Au}(\lambda)$$

$$\sigma_{0,Ge} = \frac{\left(A_{Ge} * I_{(Au,\gamma)} * n_{Au}\right)}{\left(A_{Au} * I_{(Ge,\gamma)} * n_{Ge}\right)} \sigma_{0,Au}$$

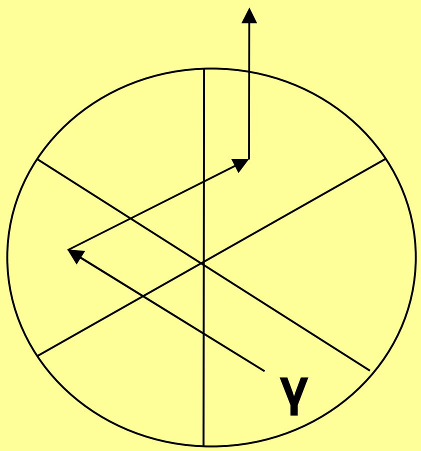


Neutron Capture in GERDA

~1 n-capture/(kg y) (MC simulation)

⇒ Possible background in the region of interest (2039 keV)

Source	γ-ray Background in ROI	Rejection method
Prompt Gamma Rays	Peak? Compton scattering	
β-Decay of ^{77}Ge	Peak (2037.76 keV) Compton scattering (E_{max}=2353.4 keV)	
β-Decay of $^{77}Ge^{m}$	X (E_{max}=1676.5 keV)	X
β-Decay of ^{77}As	X (E_{max}=682.9 keV)	X



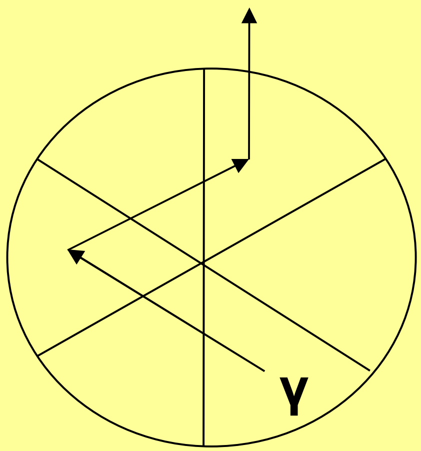
segmented detector

Neutron Capture in GERDA

~1 n-capture/(kg y) (MC simulation)

⇒ Possible background in the region of interest (2039 keV)

Source	γ-ray Background in ROI	Rejection method
Prompt Gamma Rays	Peak? Compton scattering	multisite events
β-Decay of ^{77}Ge	Peak (2037.76 keV) Compton scattering (E_{max}=2353.4 keV)	multisite events
β-Decay of $^{77}Ge^{m}$	X (E_{max}=1676.5 keV)	X
β-Decay of ^{77}As	X (E_{max}=682.9 keV)	X



segmented detector

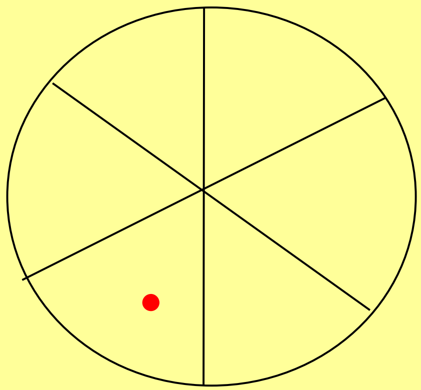
Neutron Capture in GERDA

~1 n-capture/(kg y) (MC simulation)

⇒ Possible background in the region of interest (2039 keV)

Source	**β- Background in ROI**	**Rejection method**
Prompt Gamma Rays	**X**	**X**
β-Decay of ^{77}Ge	**Continuous (E_{max}=2486.5 keV)**	
β-Decay of $^{77}Ge^{m}$	**Continuous (E_{max}=2861.7 keV)**	
β-Decay of ^{77}As	**X (E_{max}=682.9 keV)**	**X**

segmented detector



Neutron Capture in GERDA

~1 n-capture/(kg y) (MC simulation)

⇒ Possible background in the region of interest (2039 keV)

Source	γ-ray Background in ROI	Rejection method	β- Background in ROI	Rejection method
Prompt Gamma Rays	Peak? Compton scattering	multisite events	X	X
β-Decay of ^{77}Ge	Peak (2037.76 keV) Compton scattering (E_{max}=2353.4 keV)	multisite events	Continuous (E_{max}=2486.5 keV)	
β-Decay of $^{77}Ge^{m}$	X (E_{max}=1676.5 keV)	X	Continuous (E_{max}=2861.7 keV)	detection of prompt gamma rays
β-Decay of ^{77}As	X (E_{max}=682.9 keV)	X	X (E_{max}=682.9 keV)	X

Neutron Capture in GERDA

~1 n-capture/(kg y) (MC simulation)

⇒ Possible background in the region of interest (2039 keV)

Source	γ-ray Background in ROI	Rejection method	β- Background in ROI	Rejection method
Prompt Gamma Rays	Peak? Compton scattering	multisite events	X	X
β-Decay of ^{77}Ge	Peak (2037.76 keV) Compton scattering (E_{max}=2353.4 keV)	multisite events	[illegible]s [illegible]5 keV)	
β-Decay of ^{77}Ge^{m}	X (E_{max}=1676.5 keV)	X	continuous (E_{max}=2861.7 keV)	detection of prompt gamma rays
β-Decay of ^{77}As	X (E_{max}=682.9 keV)	X	X (E_{max}=682.9 keV)	X

Only 15% of the energy weighted intensity known

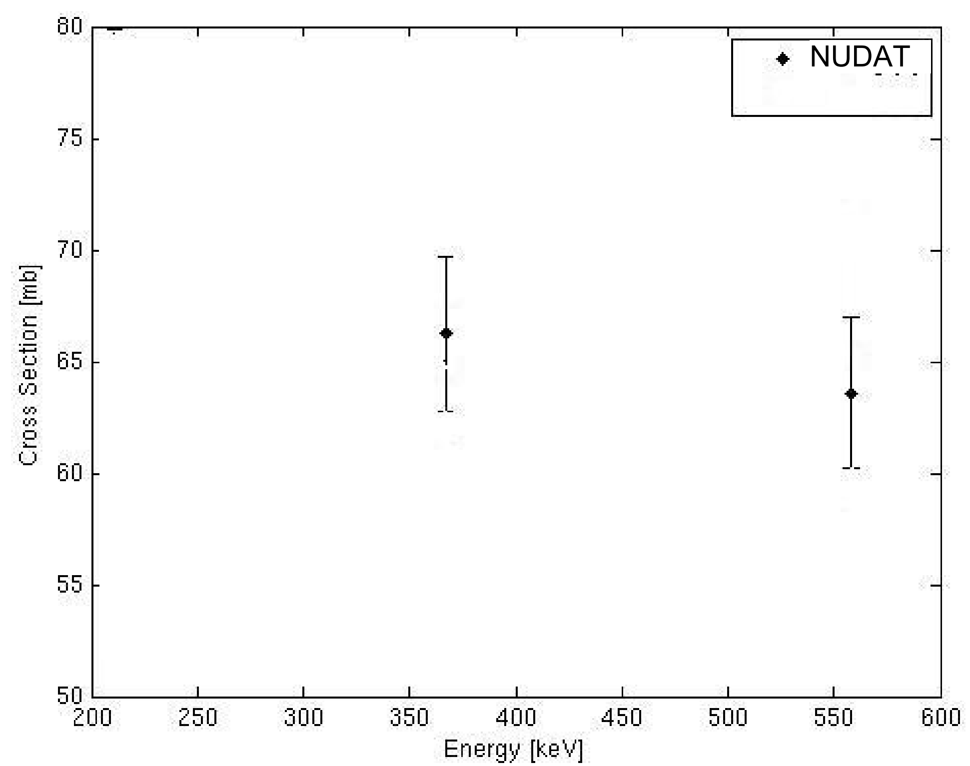
Capture Cross Section of 76(n,γ) in the Literature

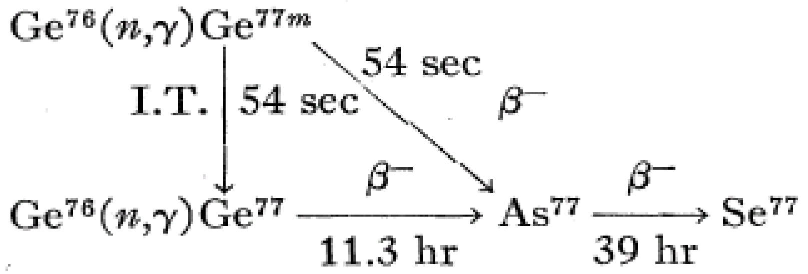
	cross section [mbarn]
$\sigma(^{77}Ge^{g})$	Seren (1947): 85 ±17
	Pomerance (1952): 350 ± 70
	Brooksbank (1955): 300 ± 60
	Metosian (1957): 76 ± 15
	Lyon (1957): 43 ± 2
$\sigma(^{77}Ge^{m})$	Metosian (1957): 87 ± 15
	Lyon (1957): 137 ± 15

Cross Section

Preliminary results:

	Our measurement
	cross section [mbarn]
σ($^{77}Ge^{g}$ direct)	46.2 ± 5.5
σ($^{77}Ge^{g}$)	64.9 ± 3.5
σ($^{77}Ge^{m}$) using IT using β-decay	 98 ± 12 112 ± 14





Cross Section

Preliminary results:

	Our measurement
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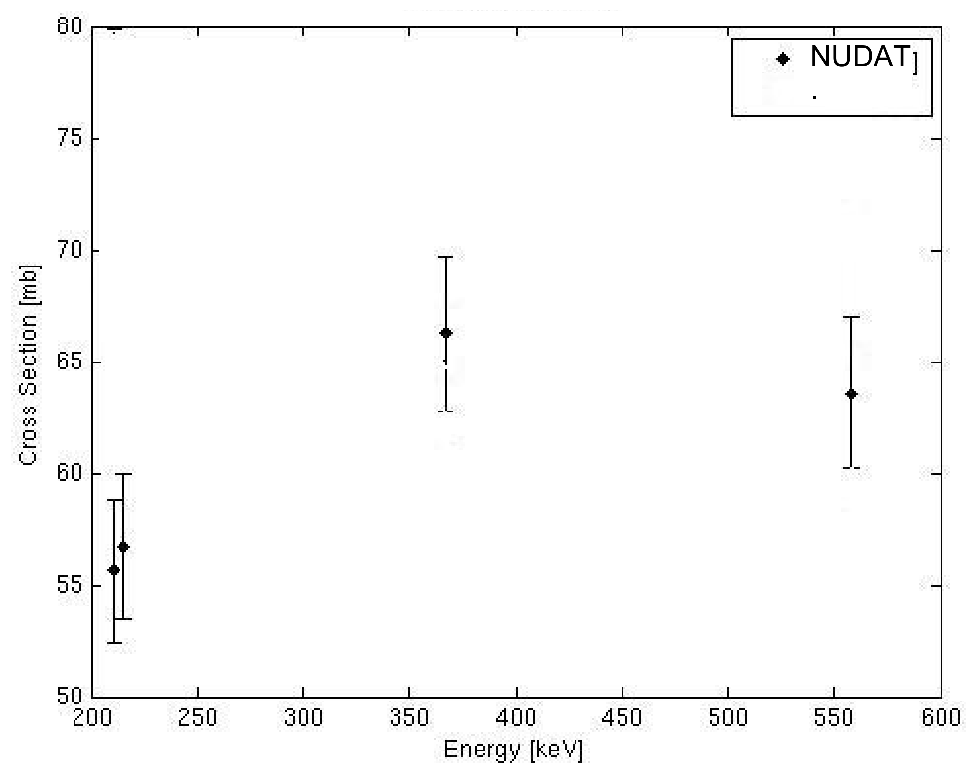
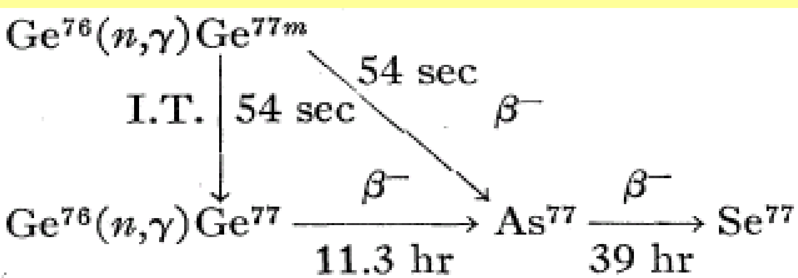
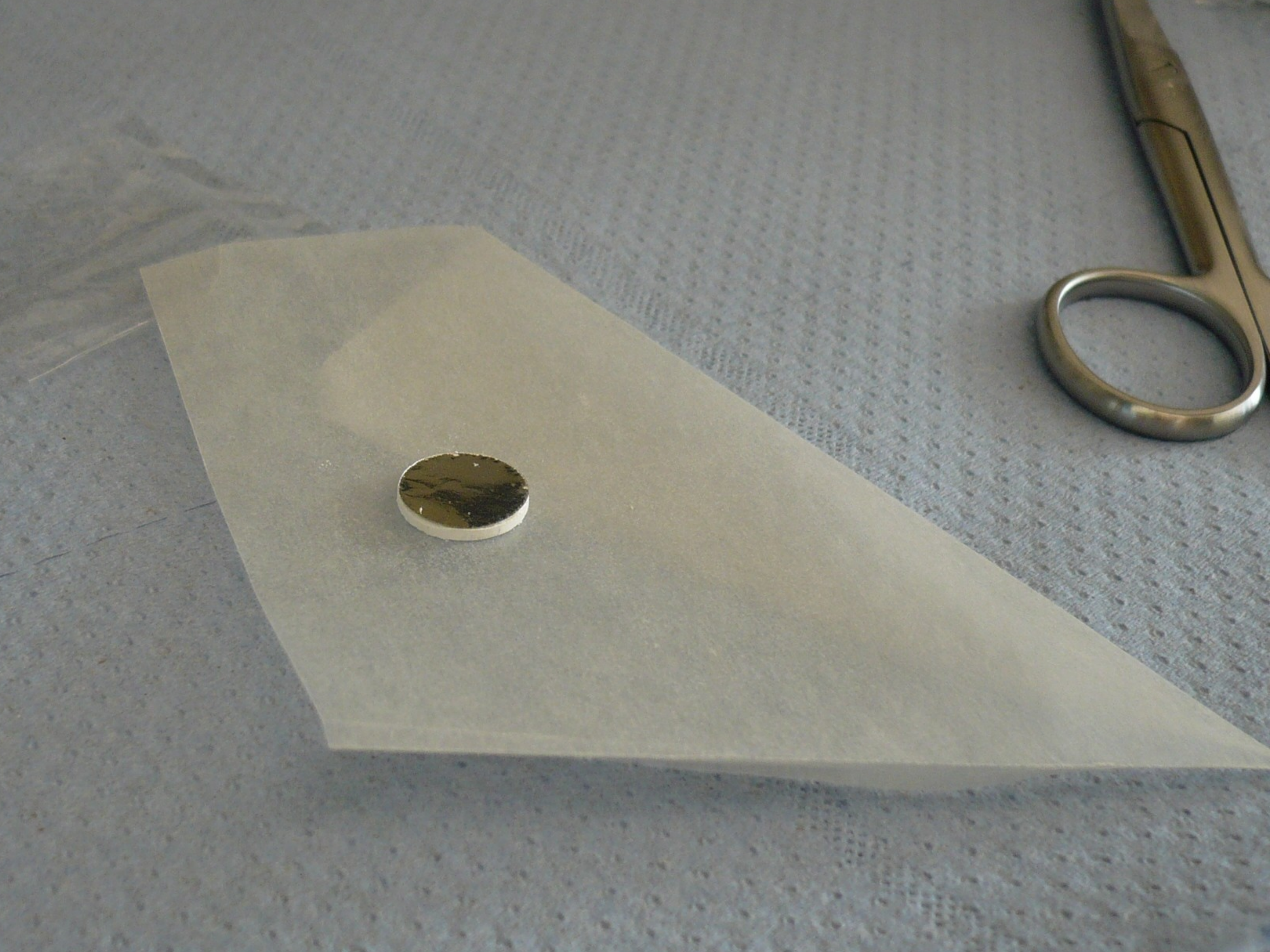


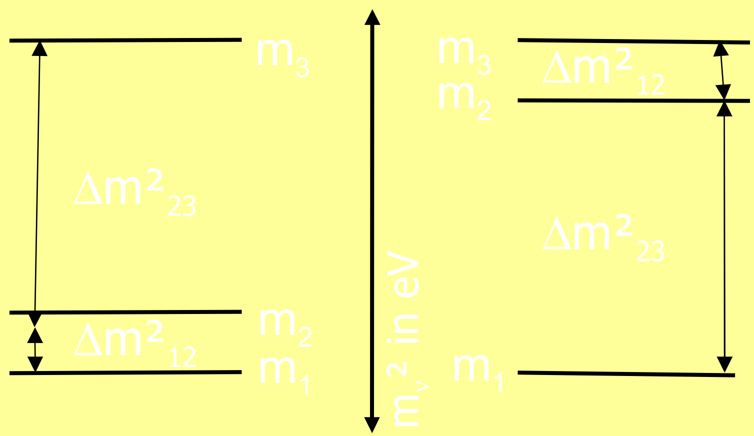




What can we lern from 0νββ?

If 0νββ is observed:

- ✓ Neutrino is a Majorana particle
- ✓ Neutrino mass
- ✓ Mass hierachy (degenerate, inverted or normal)



Δm^2_{12} = (7.92±0.07)·10-5 eV² (solar ν)
Δm^2_{23} = (2.6±0.4)·10-3 eV² (atm. ν)

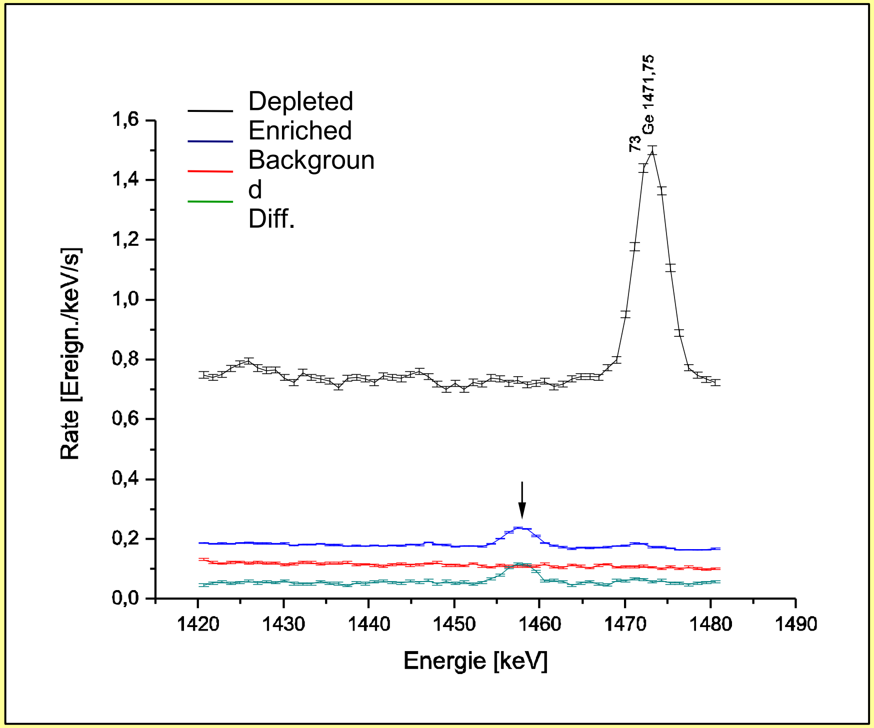
Cross Section

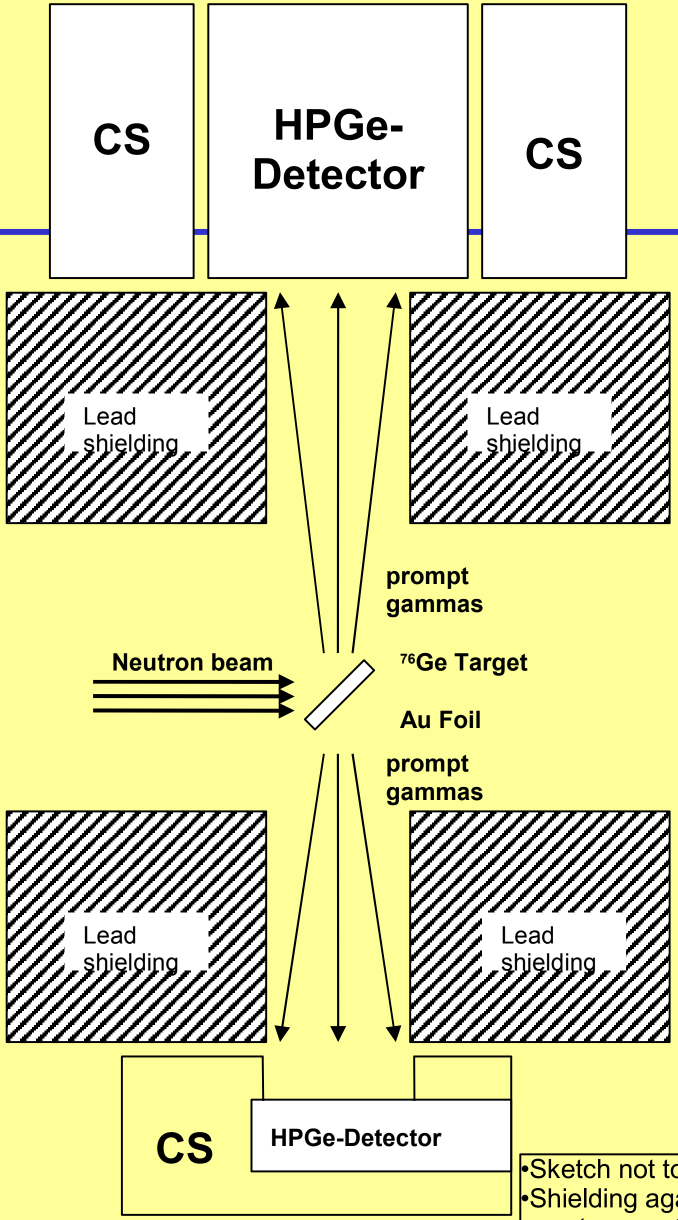
Preliminary Results:

	Our measurement	Literature
	cross section [mbarn]	cross section [mbarn]
$\sigma(^{77}Ge^{g}$ direct)	46.0 ± 5.0	Lyon (1957): 6 ± 5
$\sigma(^{77}Ge^{g})$	64.3 ± 4.4	Seren (1947): 85 ±17 Pomerance (1952): 350 ± 70 Brooksbank (1955): 300 ± 60 Metosian (1957): 76 ± 15 Lyon (1957): 43 ± 2
$\sigma(^{77}Ge^{m})$ using IT using β-decay	 98 ± 12 112 ± 14	Metosian (1957): 87 ± 15 Lyon (1957): 137 ± 15

Prompt Gamma Ray Spectrum

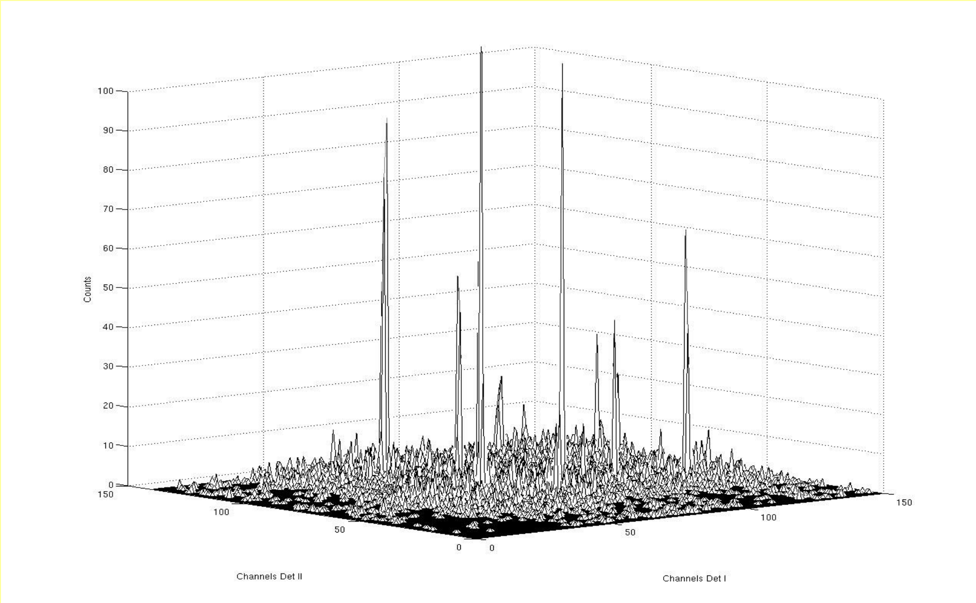
Single spectra
m ~ 300 mg
Irradiation time > 50 000 s





- Sketch not to scale
- Shielding against neutrons not shown

Prompt Gamma Ray Spectrum



Coincidence spectra
m ~ 300 mg
Irradiation time 10 d
Coincident events 100 000