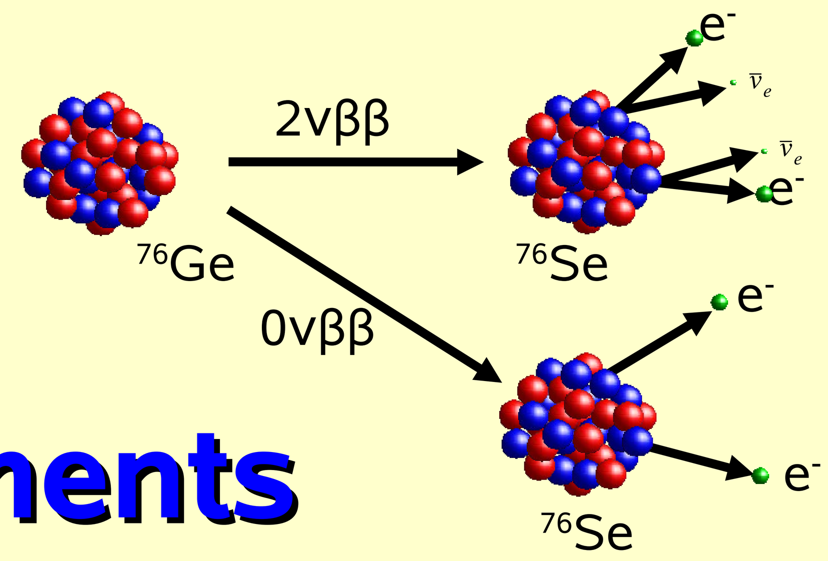
Neutron reactions on ^{76}Ge - Background in neutrinoless double beta decay experiments



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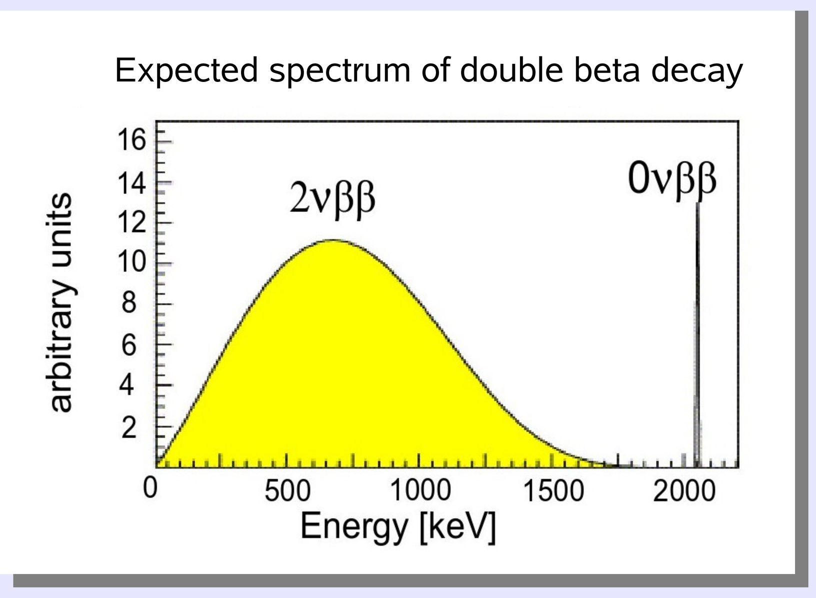
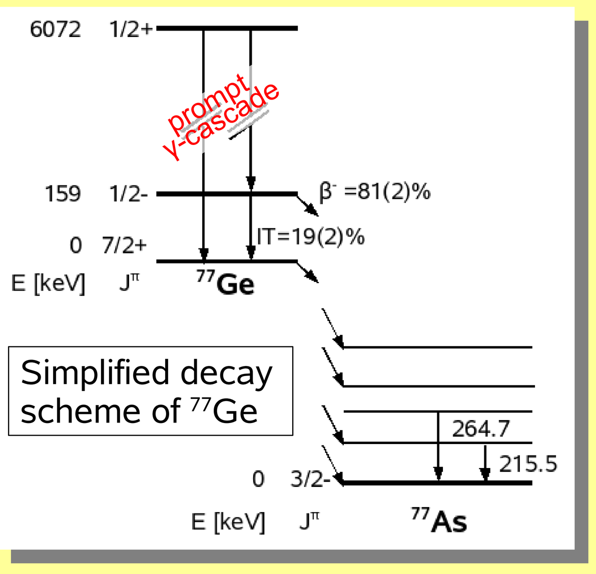
The search for the neutrinoless double beta decay (0νββ) has been a very active field for the last decades. While the double beta decay (2νββ) has been observed, 0νββ still waits for its experimental proof. The observation of 0νββ would be evidence for the Majorana nature of the neutrino. From the measured half-life the effective neutrino mass can be derived, if theory provides precise nuclear matrix elements.



The GERDA (GERmanium Detector Array) experiment at the LNGS (Italy) searches for the neutrinoless double beta decay in ^{76}Ge. The isotope ^{76}Ge is an ideal candidate as it can be used as source and detector at the same time. The material used for the detectors is isotopically enriched in ^{76}Ge to a level of about 86%. Since half-lives of 0νββ are very long ($t_{1/2} > 1.6 \times 10^{25}$ y for ^{76}Ge) background reduction and rejection are the major task in neutrinoless double beta experiments. A background index of 10^{-3} cts/(keV kg y) is required to meet the physics goals of GERDA (phase II).

^{76}Ge(n,γ)^{77}Ge

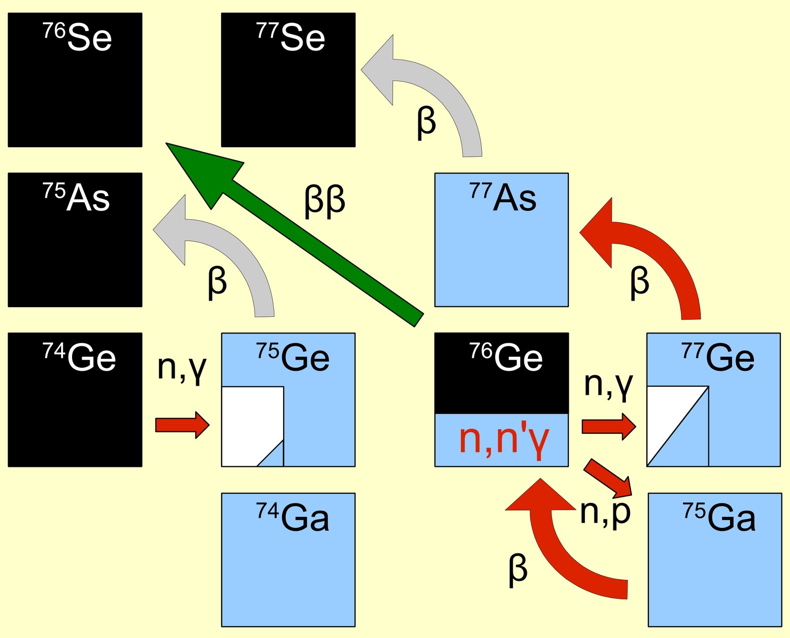


Simplified decay scheme of ^{77}Ge

Neutrons produced by cosmic muons in the underground laboratory may be captured in the germanium detectors. The excitation energy of the ^{77}Ge (6071 keV) nucleus after neutron capture on ^{76}Ge is released by a cascade of prompt γ-rays. The following β-decay of ^{77}Ge ($t_{1/2}$ = 11.3 h) and ^{77m}Ge ($t_{1/2}$ = 52.9 s) emits photons and electrons with energies above the Q-value for double beta decay ($Q_{\beta\beta}$ = 2039 keV). While photons can be rejected efficiently by pulse shape analysis, electrons have the same signature as 0νββ and can not be suppressed by this method.
Monte-Carlo simulations result in a capture rate of ~1 n-capture/(kg y), a value comparable to the number of 0νββ decays expected in GERDA. The remaining contribution to the background index by β-decay of ^{77m}Ge is 1.8×10^{-4} cts/(keV kg y).

Veto for ^{77m}Ge decay

A possible veto strategy is the introduction of a sufficient dead time (e.g. t_{dead} = 4 min) after neutron capture. This veto can be triggered by the observation of the prompt γ-cascade. The trigger efficiency depends mainly on the knowledge of the prompt transitions in ^{77}Ge. Only two experiments measuring the prompt radiation in the ^{76}Ge(n,γ)^{77}Ge reaction were performed in the past. Only 14 transitions were reported.



Reaction	Energy (keV)	I_γ (%)*
^{76}Ge(n,γ)^{77}Ge		
	2029	0.38
	2035	0.27
^{77}Ge (β-decay)		
	2000.10	0.561
	2037.76	0.061
	2077.17	0.233
	2089.60	0.347
^{76}Ga (β-decay)		
	2040.70	0.33
	2073.75	4.24
	2091.9	0.18

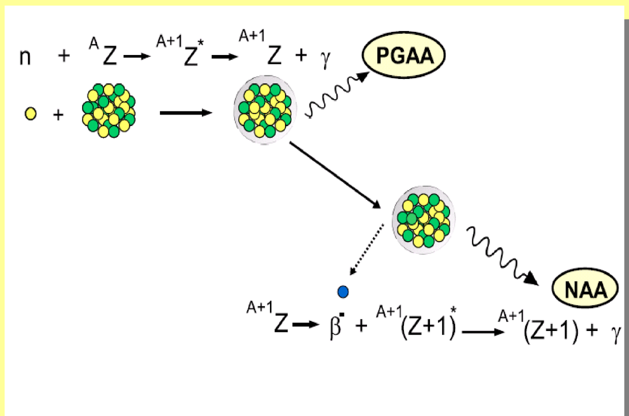
* per 100 interactions

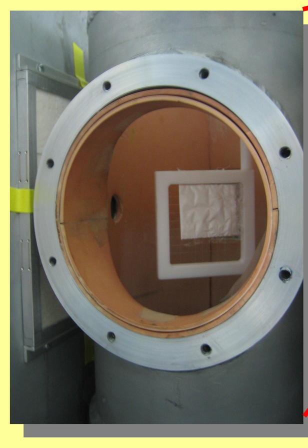
Reactions by fast neutrons on ^{76}Ge

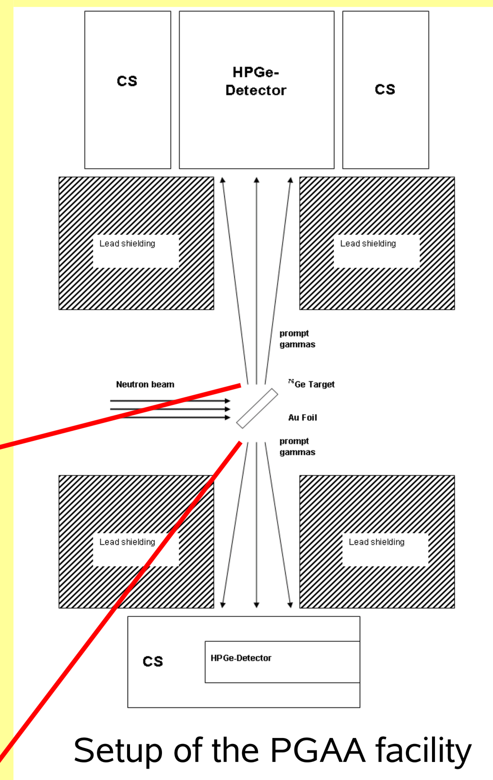
Fast neutrons induced by cosmic muons undergo additional reactions contributing to the background.
^{76}Ga nuclei can be produced from ^{76}Ge by fast neutrons with energies above the reaction threshold of 6.3 MeV. The cross section equals 2.5 mb at 14 MeV. ^{76}Ga decays after a short half-life time of 32.6 s back to ^{76}Ge. Photons and electrons of high energy (4.2 and 6.5 MeV resp.) are emitted.
Neutrons with energies exceeding 4 MeV are able to excite states in ^{76}Ge above 2039 keV by inelastic scattering.

Experiments

The cross sections and prompt γ-ray spectra of the (n,γ)-reaction of ^{74}Ge and ^{76}Ge were investigated at the facility for prompt gamma activation analysis (PGAA) at the research reactor FRM II near Munich, Germany. A maximum flux of 2.9×10^9 neutrons/(cm² s) with a mean energy of 1.83 meV can be provided. For γ-ray detection two HPGe detectors are available.



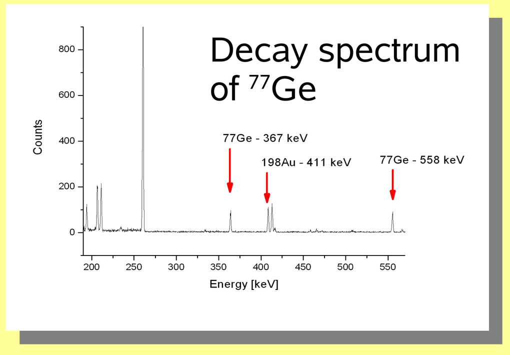




Setup of the PGAA facility

Cross section

Small targets of GeO_2, isotopically enriched in ^{76}Ge with a mass of about 500mg and known geometry were activated together with a piece of gold foil. After irradiation the decay spectra of ^{77}Ge and ^{198}Au were measured by HPGe detectors.
The thermal neutron capture cross sections of ^{76}Ge were calculated relatively to the very well known thermal cross section of Au comparing the intensity of γ-rays of ^{77}Ge with the peak area at E_γ = 411 keV of the gold reference. The uncertainties are dominated by the branching ratio of the isomeric state.
Analyzing the ^{77}Ge decay spectra it was found, that the emission probabilities given in literature are inconsistent with our measurement. The same discrepancy was observed by other groups in recent experiments.
The cross sections for ^{74}Ge(n,γ) were determined in an analogous way.



Decay spectrum of ^{77}Ge

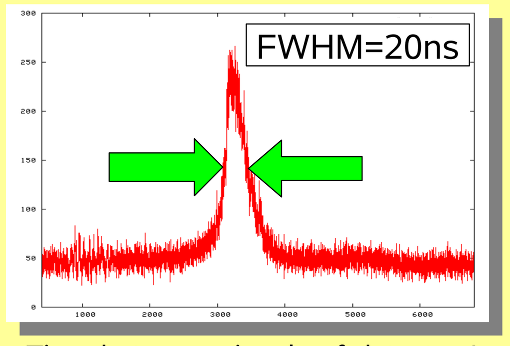
Thermal cross sections for the ^{76}Ge(n,γ) and ^{74}Ge(n,γ) reactions.

Isotope	Cross section (mb)
^{77}Ge	
σ^e exp.	68.8 ± 3.4
σ^d direct	46.9 ± 4.7
σ^m	115 ± 16
^{75}Ge	
σ^e exp.	497 ± 52
σ^d direct	365 ± 51
σ^m	130.5 ± 5.6

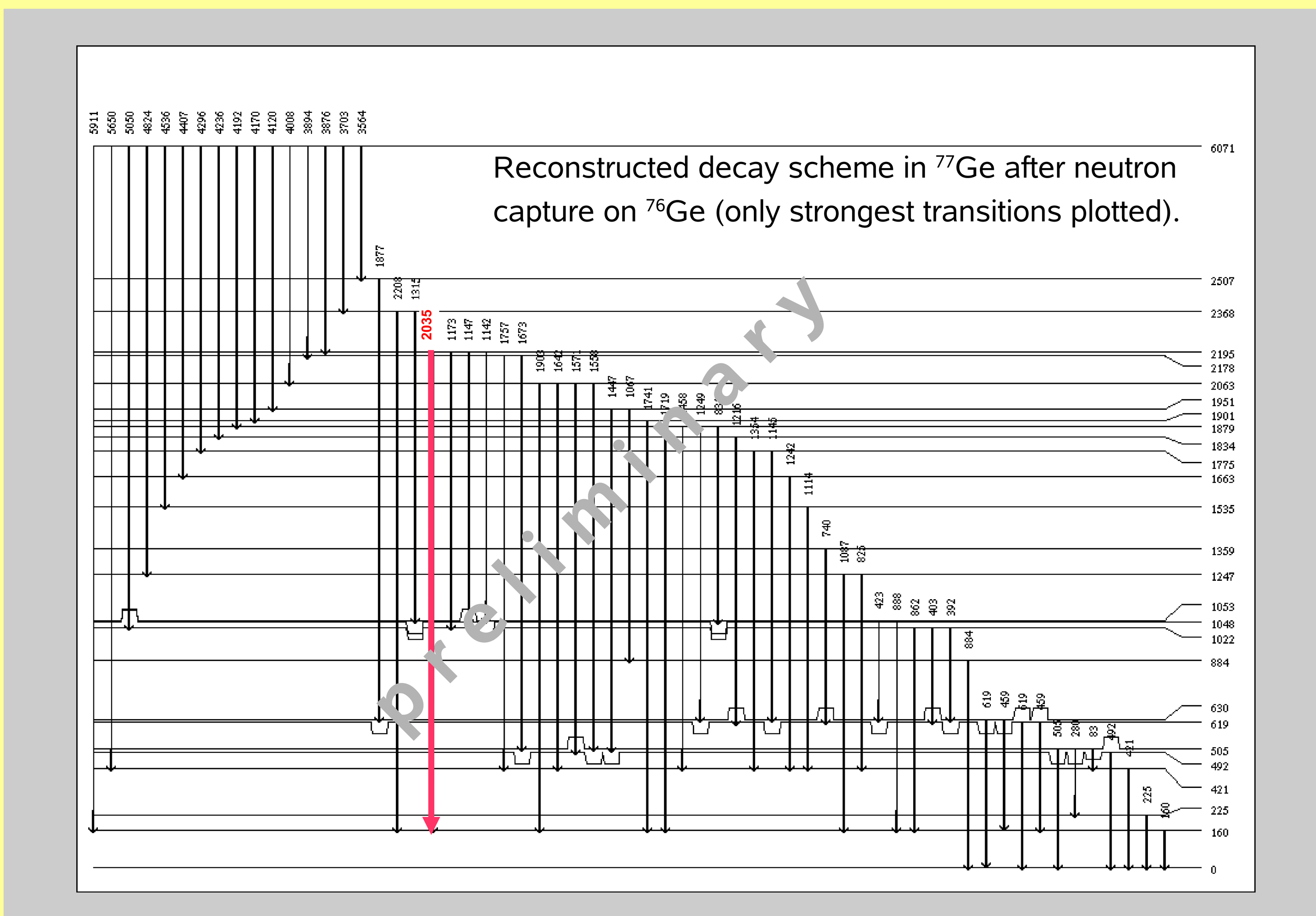
G. Meierhofer *et al.*, Eur Phys. J A 40, 61 (2009).
G. Meierhofer *et al.*, PRC 81, 027603 (2010).

Prompt γ-rays

Samples of GeO_2 powder (m ~400 mg) with different isotopical composition were irradiated with cold neutrons for more than 50000 s. Comparing these spectra γ-rays in ^{77}Ge were unambiguously identified.
The very high neutron flux enabled the use of the two HPGe detectors in coincidence. From these data the decay scheme after neutron capture could be reconstructed. In total over 120 transitions were found in ^{77}Ge after neutron capture on ^{76}Ge, including two lines at 2029 and 2035 keV.



Time between signals of detector I and detector II. The events in the peak correspond to true, events in the continuous region are due to random coincidences.



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