Low-Noise JFET-CMOS Preamplifier for the GERDA Experiment

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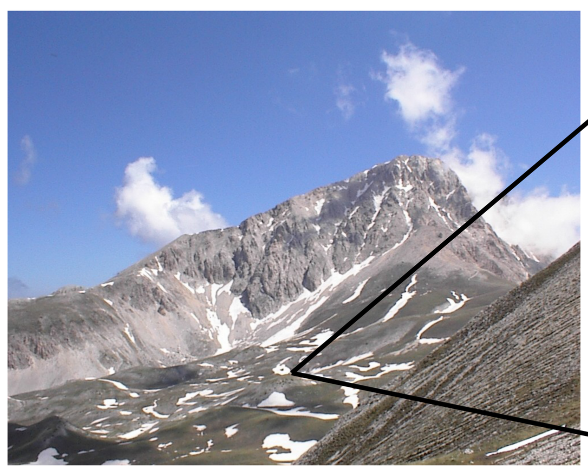
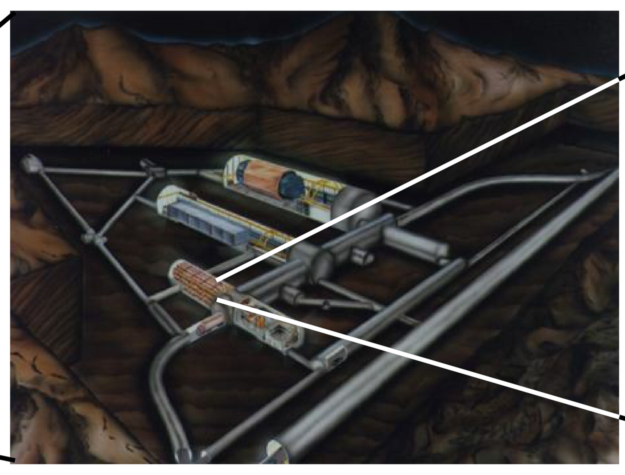
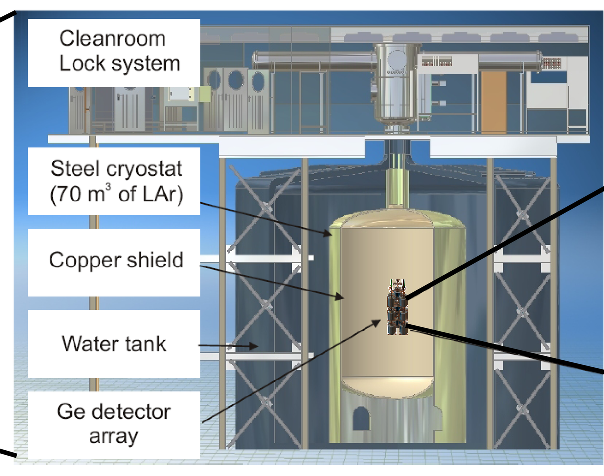
GERDA (GERmanium Detector Array) @ LNGS

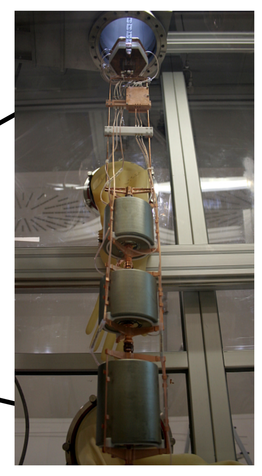
The project searches for the $0\nu\beta\beta$ decay of ^{76}Ge by using crystals made of isotopically enriched material as source and detector simultaneously. According to theory, this weakly interacting process would not only prove the neutrino to be a Majorana particle but also allow a direct measurement of the effective neutrino mass.



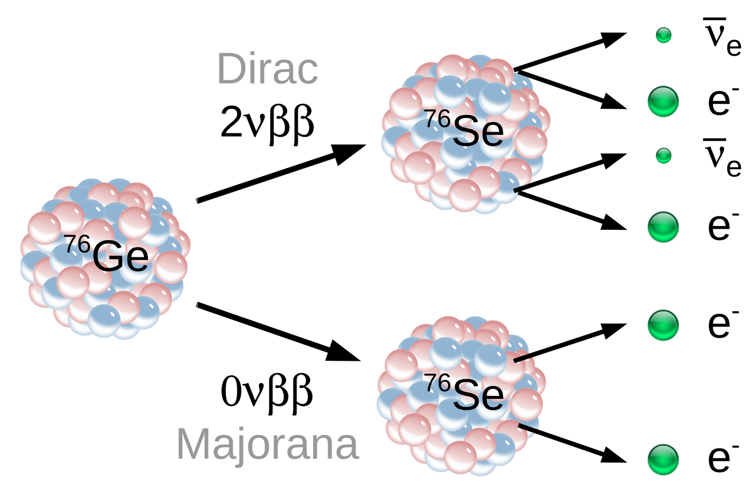


The Laboratori Nazionali del Gran Sasso is located in a mountain region about 150 km east of Rome and at the depth of 3800 meters water equivalent.





Schematic view of the experiment and a photo of three HPGe diodes.
The charge sensitive preamplifier is placed inside a copper box 30 cm above the upper detector.



MOTIVATION

- long signal cable, which connects the detector to the 1st stage amplifier — causes additional electronic noise
- transistor of the preamplifier contains radiative coating — contribution to background
- finding JFET without coating allows shortening the cable — Yeah!!!

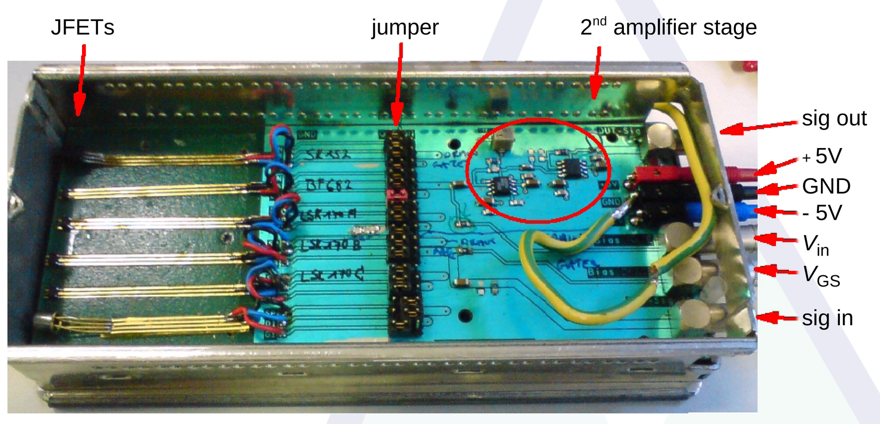
Characterization of Junction Gate Field-Effect Transistors[1]

Investigated transistors:

BF862 (Philips) LSK170A, -B, -C (Linear Systems) SK152 (Sony) MX-11rc (Moxtex)

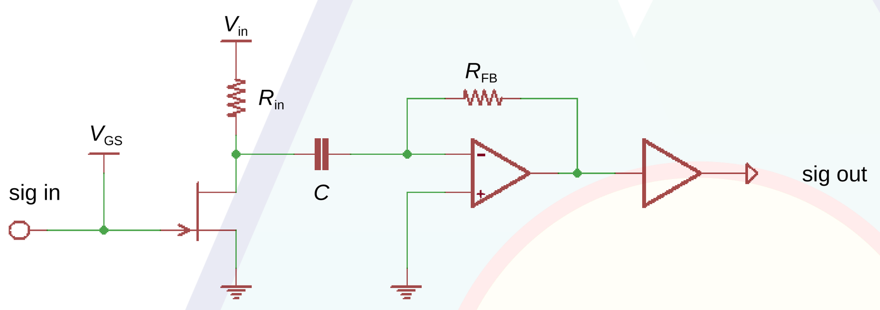
Experimental setup

- shunt jumpers to either connect the drain and gate terminal with the circuit or GND
- network analyzer HP4396B: to provide a test signal (sig in) and for read-out (sig out)
- metal box as protection against electro-magnetic radiation



Simplified circuit diagram

- 1st amplifier stage by JFET (biased via V_{in} and V_{GS})
- operating point can be adjusted by V_{in}
- 2nd amplifier stage by two op-amps (with battery driven power supply)



Drain Source Characteristic Curve

here: exemplary for transistor BF862

- linear region:

$$I_{DS} = \frac{2I_{DSS}}{V_p^2}\left([V_{GS}-V_p]V_{DS}-\frac{V_{DS}^2}{2}\right)$$

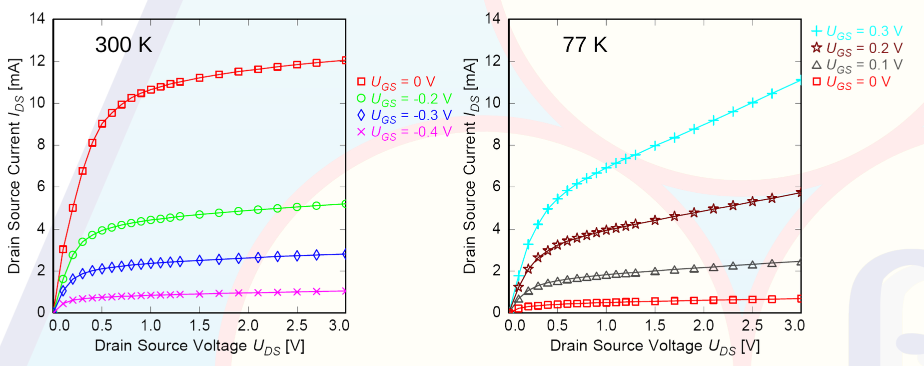
- saturation region:

$$I_{DS} = I_{DSS}\left(1-V_{GS}/V_p\right)^2\ \left(1+V_{DS}/R_{DS}\right)$$

I_{DSS}: saturation drain source current

- resistance of drain source channel:

$$R_{DS} = \left(dV_{DS}/dI_{DS}\right)$$



Transfer Characteristic Curve

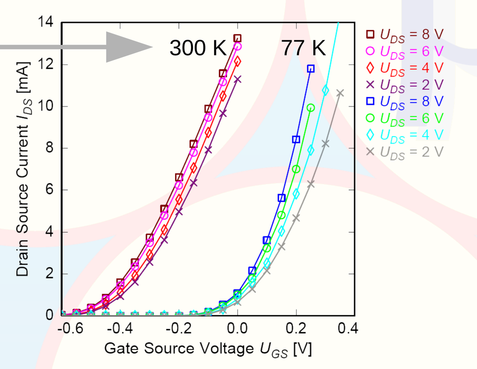
- transconductance or amplification of the transistor:

$$g_m = \left(dI_{DS}/dV_{GS}\right) = \frac{2I_{DSS}}{V_p^2}\left(V_{GS}-V_p\right)$$

- intersection with x-axis gives the pinch-off voltage V_P

temperature change results in a shift of the transfer characteristic curve in U_{GS}-direction

superimposed to the white noise: $1/f$ noise contribution for high T and low I_{DS}



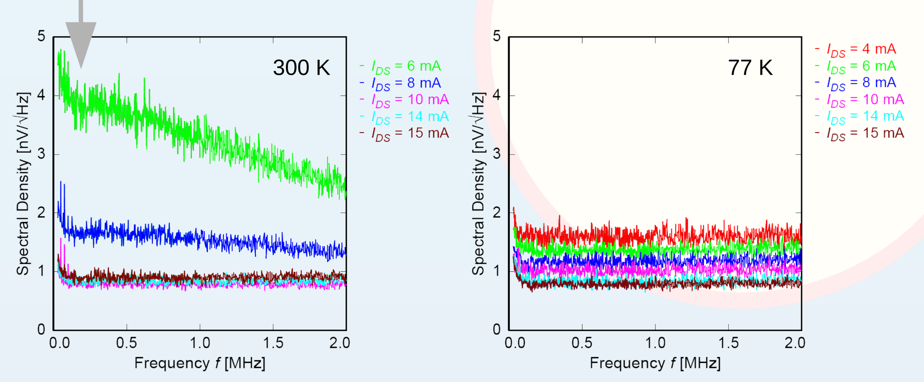
Noise Measurement

- measured data for spectral density:

$$\nu_{FET,data}(f) = \sqrt{\frac{\nu_{total}^2-\nu_{without\ FET}^2}{(R_{FB}\cdot g_m)^2}}$$

- theoretical expected thermal noise of the drain source channel:

$$\nu_{FET,theo}(f) = 4kT\cdot\left(\frac{2}{3g_m}\right)\cdot\Delta f$$



Experimental Results

- table for gate source voltage U_{GS} = 0 V and optimal noise values:

in good agreement with datasheets

JFET	I_{DS} [mA]	300 K: I_{DSS} [mA]	V_p [V]	R_{DS} [kΩ]	g_m [mS]	$\nu_{FET,data}$ [nV/√Hz]	$\nu_{FET,theo}$ nV/√Hz	U_{DS} [V]	77 K: R_{DS} [kΩ]	g_m [mS]	$\nu_{FET,data}$ [nV/√Hz]	$\nu_{FET,theo}$ [nV/√Hz]	U_{DS} [V]
BF862	≈ 14	12.1	−0.63	≥ 2.5	33.6	0.8	0.58	13.6	≥ 13.3	16.2	0.9	0.42	15.5
LSK170A	≈ 4	-	−0.34	-	20.0	1.2	0.72	9.8	-	-	-	-	-
LSK170B	≈ 10	9.2	−0.64	≥ 2.5	26.8	1.3	0.61	5.7	≥ 6.7	19.6	-	-	-
LSK170C	≈ 8	12.4	−0.60	≥ 1.5	31.6	1.5	0.74	0.5	≥ 2.2	24.8	1.1	0.42	20.0
SK152	≈ 23	-	−1.59	-	25.0	1.1	0.64	5.6	-	42.8	2.9	0.52	5.1
MX-11rc	≈ 15	15.3	−3.49	≥ 1.1	7.8	2.0	1.2	3.3	≥ 0,74	15.5	8.5	1.5	1.0

- characteristic properties and noise performances in good agreement with datasheet
- power dissipation $P = I_{DS}\cdot U_{DS}$ of the transistor causes heat input in LN_2 → microphonic effects
- measured noise (in nV/√Hz) is about 1.4 to 2.1 times higher than the calculated thermal noise of the FET → additional noise from transistor, experimental setup
- for common-source amplifier: amplification depends on R_{DS} (in parallel to R_D of the GERDA preamplifier) → $R_{DS} \approx R_D$ = 4.7 kΩ

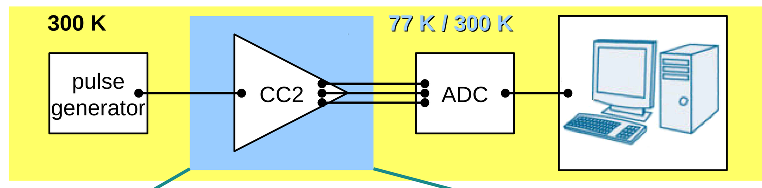
Most suitable transistors for the GERDA experiment: BF862 and LSK170B, -C!!

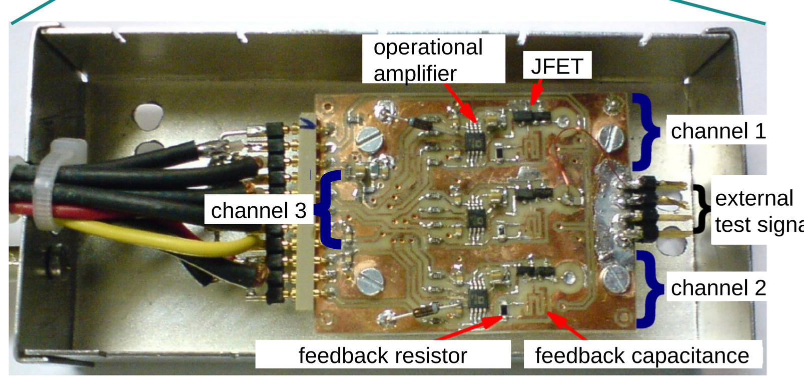
[1] J. Geist, *Bachelor Thesis*, Max-Planck-Institut für Kernphysik, 2011

Noise Measurements of the GERDA Preamplifier[2]

Experimental setup

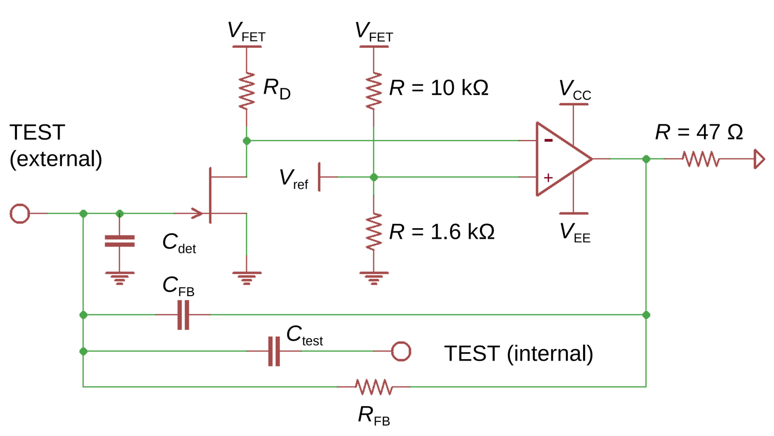
- pulse generator to simulate the current pulses from the detector
- CC2: charge sensitive preamplifier used in GERDA (developed by Stefano Riboldi, Universita degli Studi di Milano)
- circuit board contains 3 channels
- ADC (Analog to Digital Converter) to digitize the analogue signals
- digital filter for signal processing
- again an outer metal covering serves as shielding against electro-magnetic radiation





Simplified circuit diagram

- the TEST (external) entrance allows calibration of the capacitance C_{FB}
- C_{det} to simulate the capacitance of the germanium detector
- op-amps: OPA211 and AD8652, both functional @ 77 K
- operating point is determined by V_{FET}
- U_{GS} adjusted by neg. feedback → R_{FB}



Calculation of Equivalent Noise Charge

- filter with time-varying parameters:

$$\omega(t') = h(t-t')$$

time reflected copy of the pulse response h(t) shifted by the time t' of observation

- weighting function for CR-(RC)^n-filter:

$$= e^n\left(\frac{R\cdot C-t'}{R\cdot C}\right)^n \exp\left(\frac{n(R\cdot C-t')}{R\cdot C}\right)$$

- pulse shaper approximated by 1 differential & 8 following integral circuits → $R\cdot C = 8\cdot\tau$
- $1/f$ noise from CMOS op-amp

$$ENC_{1/f}^{\ 2} = const.$$

- parallel noise: dominated by feedback resistance R_{FB}

shot noise originated from the leakage current of the detector

$$ENC_p^{\ 2}(t_0) = \frac{1}{2}\left(2eI_l+\frac{4kT}{R_p}\right)\cdot\int_{t_0}^{\infty}\omega^2(t')dt' \approx \frac{1}{2}\left(\frac{4kT}{R_p}\right)5.04\cdot\tau$$

- serial noise: due to the noise of the transistor: g_m, ...

$$ENC_s^{\ 2}(t_0) = \frac{1}{2}C_{input}^2\left(4kT\cdot R_s\right)\cdot\int_{t_0}^{\infty}\dot{\omega}^2(t')dt' \approx \frac{1}{2}C_{input}^2\left(4kT\cdot R_s\right)\frac{0.34}{\tau}$$

- energy resolution in ^{76}Ge spectroscopy:

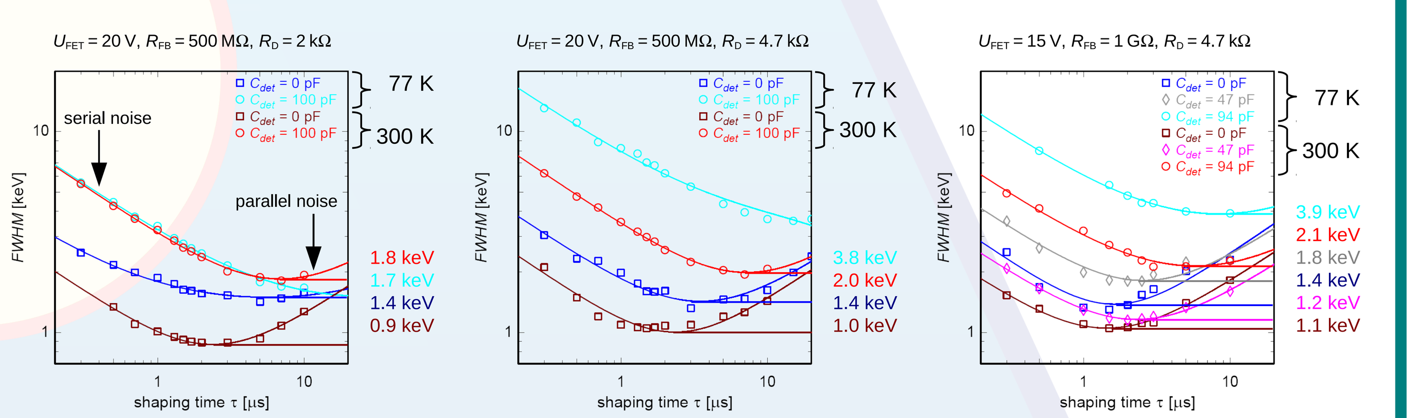
$$FWHM = 2.35\,\frac{3eV}{e}\sqrt{ENC_{1/f}^2+ENC_p^2+ENC_s^2}$$

$C_{input}=C_{det}+C_{FB}+C_{test}+C_{gate}$

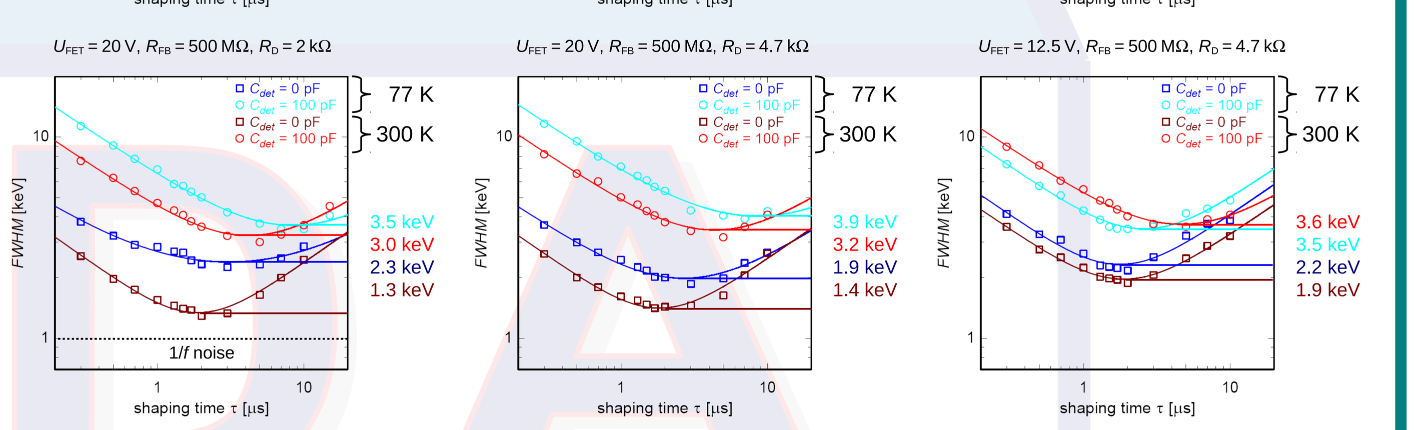
best resolution is obtained if the detector is capacitively matched to the transistor (gate)

Preliminary Experimental Results

BF862



LSK170C



- serial noise increases with higher input capacitance, but not with ∝ C_{input}
- resolution deteriorates with decreasing temperature!
- measured data do not agree with our expectations for $g_m = 2/(3R_s)$ from the previous experiment (see left)
  - → higher serial noise: differences between a factor of 2 @ 300 K and 3 orders of magnitude @ 77 K
  - → amplification of the transistor not high enough to neglect the noise of the op-amp?
- $\Delta E_{total}^2 = \Delta E_{stat}^2 + \Delta E_{electronics}^2$ with $\Delta E_{stat} \approx$ 1.4 keV @ E = 1.4 MeV → ΔE_{total} is still dominated by electronic noise
- further improvements of the experimental setup, e.g.:
  - → voltage divider
  - → smaller R_D
  - → op-amp

[2] L. Gamer, *Bachelor Thesis*, Max-Planck-Institut für Kernphysik, 2011

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