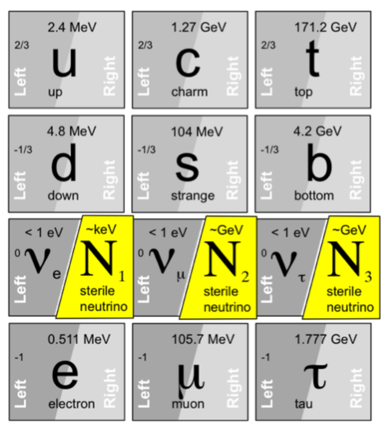
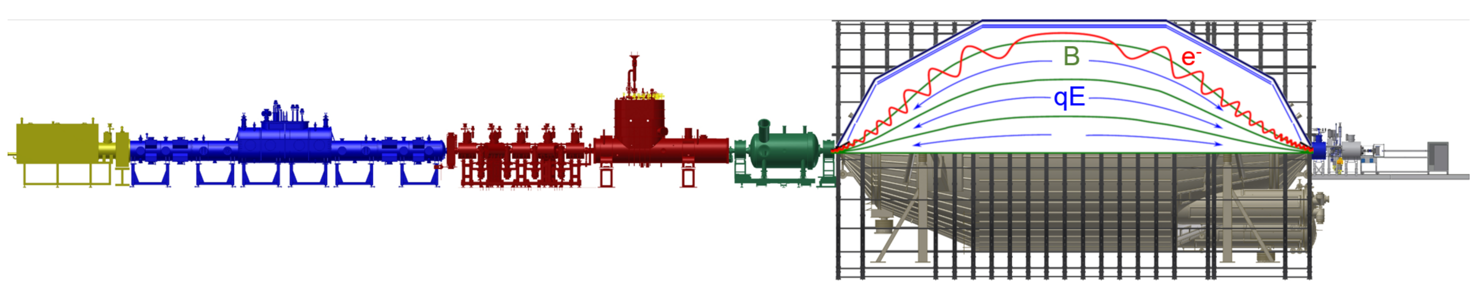
SDD prototypes with the IDef-X readout for the keV-scale sterile neutrino search with TRISTAN and analysis of first tritium data

Konrad Altenmüller[1,2], Tobias Bode[3], Tim Brunst[3], Anton Huber[4], Marc Korzeczek[4], Thierry Lasserre[1,2], Olivier Limousin[2], Daniel Maier[2], Susanne Mertens[3], Aleksander Nozik[5,6], Vladislav Pantuev[5], Aino Skasyrskaya[5], Martin Slezák[3]
[1]Technische Universität München, [2]CEA Saclay, [3]Max-Planck-Institut für Physik, München, [4]IEKP, Karlsruher Institut für Technologie, [5]Institute for Nuclear Research RAS, [6]Moscow Institute of Physics and Technology

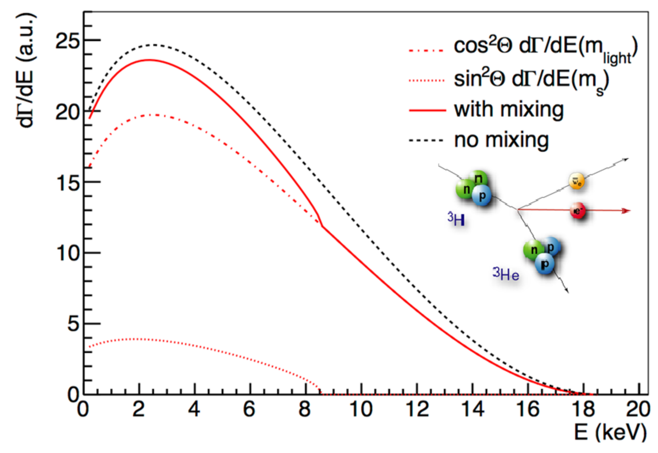
Sterile neutrinos are hypothetical leptons that are not included in the Standard Model of particle physics (SM). Several theories introduce sterile neutrinos as right-handed fermions within a minimal extension of the SM. These neutrinos would not take part in the weak interaction but would mix with active neutrinos. Despite overwhelming cosmological and observational evidence for the existence of dark matter its nature is still unknown. A sterile neutrino with a mass $\gtrsim$ 1 keV is a candidate particle (arXiv:1602.04816). Such a neutrino could be discovered in a laboratory by observing the signature of the heavy mass-eigenstate mixing in beta spectra with the TRISTAN project. TRISTAN is an expansion of the KATRIN experiment. KATRIN examines the end point of the tritium spectrum to measure the neutrino mass by counting electrons that pass a threshold, which is applied by an electromagnetic filter (MAC-E filter), thus measuring an integral spectrum. For the TRISTAN project (phase 1) KATRIN will be equipped with a novel 3000-pixel silicon drift detector (SDD) array that can handle high rates such that the entire tritium spectrum can be scanned.



▲ *The NuMSM model including 3 new sterile neutrinos (L. Canetti, M. Drewes, and M. Shaposhnikov, PRL 110 061801 (2013)).*



▲*The experimental setup. From left to right: the tritium source (blue), transport section (red), pre-spectrometer (green), spectrometer with MAC-E filter (grey). The detector is located on the far right. The total length of the device is 70 m. The cut open spectrometer shows tthe electric (blue) and magnetic fields (green) and the path of an electron (red) (arxiv:1603.01014).*



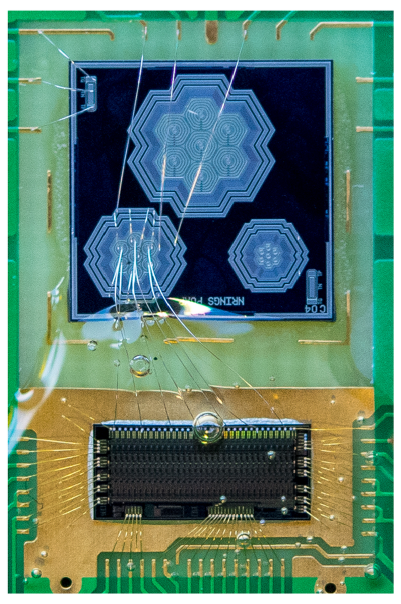
▲ *The spectrum of tritium is a superposition of different spectra for each neutrino mass eigenstate, weighted by its mixing. A keV-scale sterile neutrino would introduce a kink into the total spectrum. The kink on the plot is exaggerated.*

SDD prototypes

To test the TRISTAN detecor technology several SDD prototypes with 7 hexagonal pixels each have been produced by MPG HLL. From the expected electron flux the size of one pixel should be in the order of 1 mm. Prototypes with 0.5, 1 and 2 mm pixel diameter and 2-12 drift rings were produced. The chips are 450 µm thin. The SDDs have following features:

- no dead area due to monolithic design, efficient charge collection with multiple drift rings
- low capacitance ~ fF, energy resolution of a few hundred eV, low threshold ~ 1 keV
- ultra-thin (~ 30 nm) dead layer

Read out of the first prototypes is done with the IDefX BD ASIC by CEA/IRFU/SAp, which was originally developed for space applications.

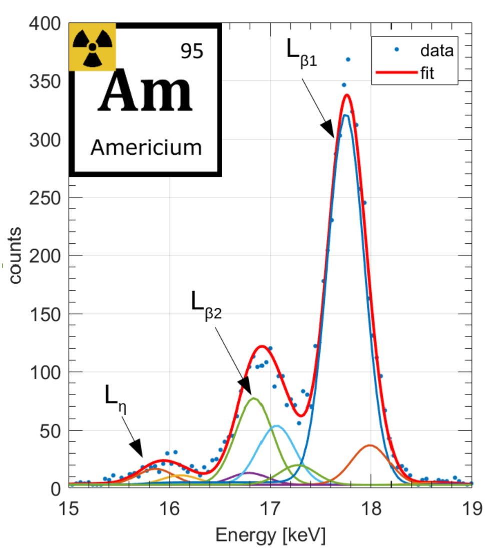


► *A prototype with 3 individual 7-pixel detectors in different sizes and the IDefX BD ASIC.*

Detector characteristics

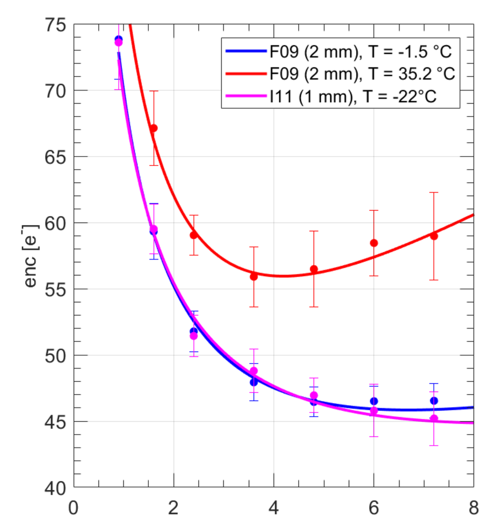
The detectors were characterized with X-rays, proving their suitability for TRISTAN.

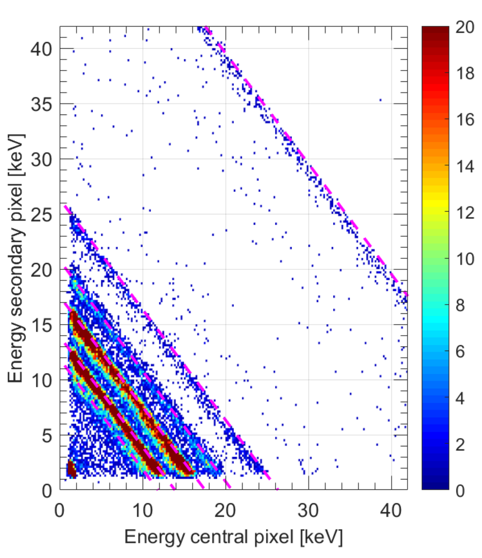
- The IDefX ASIC noise-floor of enc 44 was reached with every SDD design.
- resolution: fwhm = 400 eV @ 10 keV
- symmetric peaks show that the charge collection is efficient



◄ *The detectors were characterized with a ^{241}Am-source and the noise floor of enc 44 was reached.*

► *Detector parameters can be obtained by measuring the noise for different peaking times. The 2-mm detector has a higher enc at long peaking times than the 1-mm detector, because more heat and thus more leakage current is produced.*





The fraction of events, where the charge is shared between neighboring pixels, is between 3 % (2 mm) and 20 % (0.5 mm). Following observation were made:

- no curvature of correlated lines (see plot on the left) → no charge lost between the pixels
- integral cross talk shifts energies of reconstructed shared events
- charge sharing shows an energy dependence, most likely due to the initial charge cloud size (to be studied with simulations)

▲ *When plotting simultaneous events from neighboring pixels a correlation caused by charge sharing is visible. The magenta dashed lines mark the peaks of the ^{241}Am-spectrum.*

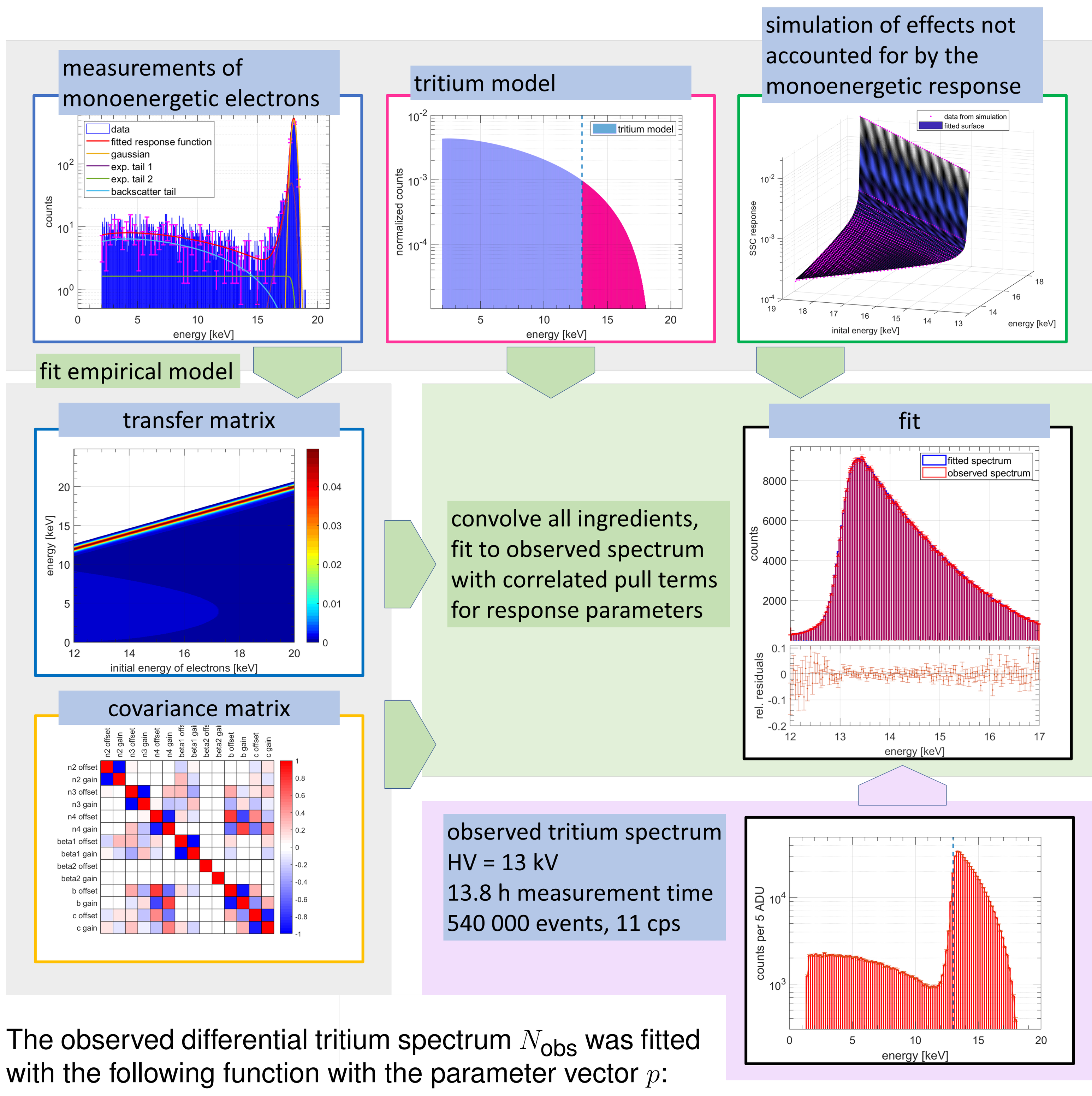
First tritium data with the Troitsk nu-mass spectrometer

One TRISTAN prototype detector (1 mm pixel diameter) was installed in May/June 2017 at the Troizk ν-mass experiment (INR RAS) and first tritium spectra were taken, as well as data from monoenergetic wall- and electron-gun electrons. This not only allows us to further characterize the detector, but also to test the complete TRISTAN analysis.

▲ *The Troitsk ν-mass experiment is a technological predecessor of KATRIN. A TRISTAN 1-mm prototype detector was installed into the spectrometer to measure electrons from different sources.*

Analysis of tritium spectra

The observed tritium spectrum can be described as convolution of the theoretical spectrum with the system response. The system response was studied by oberserving the spectra of monoenergetic electrons. For this analysis electrons emitted from the spectrometer electrodes were used that were magnetically focused onto the detector.



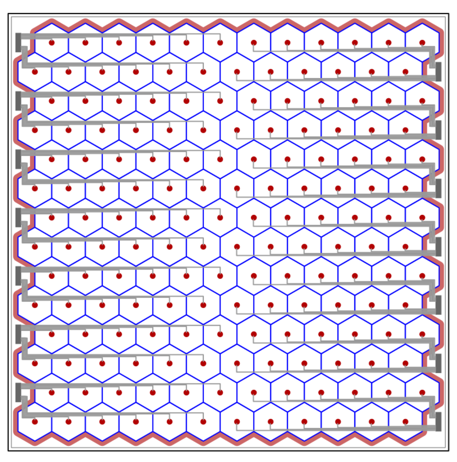
The observed differential tritium spectrum N_{obs} was fitted with the following function with the parameter vector p:

$$f_{\text{spec.}}(p,E) = n \cdot \sum_{j}^{N} f_{\text{resp.}}(p, E_{\text{in},j}, E) \times \left[\sum_{n}^{N} f_{\text{sim.}}(E_{\text{in},n}, E_j) \cdot f_{\text{model}}(\Delta m_{\text{s}}, \sin^2\theta_{\text{s}}, E_{\text{in},n}) \right]$$

During the chi-squared minimization the pull terms $(p-\hat{p})^T \cdot Cov^{-1} \cdot (p-\hat{p})$ prevent the parameters p to venture into unphysical regions while respecting their covariance. The covariance matrix Cov and the expectation values $\hat{p}$ of the parameters p were obtained during the parametrized fit of the monoenergetic electron data.

Even though the first data has low statistics we learned many things:

- we measured electrons from different sources and evaluated their suitability for obtaining the system response
- no monoenergetic electron source reproduces exactly the response of tritium electrons → simulations were performed to estimate these systematic effects that again are validated by measurements
- we discovered unexpected systematics that will be important for TRISTAN, e.g. beam size effects of e-gun data, electron discharges etc.



▲ *The next prototype with 14 x 12 SDDs (~4x4 cm) is in development.*

More measurements and the final SDD array

The measurements at Troitsk are an excellent tool to prepare the TRISTAN project. After successful testing of the 7-pixel arrays, the next stage of prototyping is in development: a SDD array with ~160 3-mm-SDDs. We will resume measurements at Troitsk ν-mass with this detector and perform a sterile neutrino search. The final detector will consist of 21 160-pixel-modules.

TRISTAN phase 1 will start data taking in 5 years after the neutrino mass program of KATRIN is finished.