Data handling, evaluation and unfolding methods for radionuclide spectrometry based on low-temperature calorimetric detectors

M. Paulsen[1,2], J. Beyer[1], L. Bockhorn[3,4], K. Kossert[3], O. J. Nähle[3], P. C.-O. Ranitzsch[3]

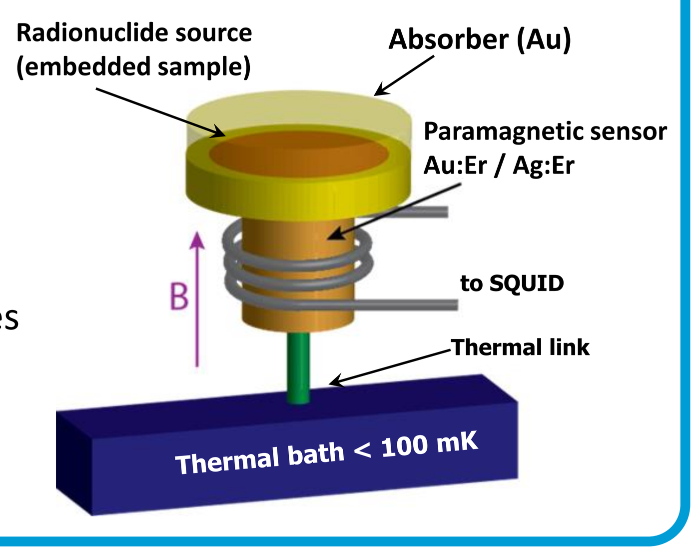
[1]PTB Berlin, Germany, [2]Kirchhoff-Institute for Physics, Universität Heidelberg, Germany, [3]PTB Braunschweig, Germany, [4]Institut für Festkörperphysik, Leibniz Universität Hannover, Germany

Metallic Magnetic Calorimeters (MMCs) are energy-dispersive low-temperature detectors that are particularly suitable for radionuclide spectrometry over wide energy ranges and with high energy resolution. To obtain a high-resolution beta spectrum with enough statistics to allow a shape analysis, a large number of decays, in the order of 10^6, needs to be recorded. A continuous digital data stream for pulse signal detection at high sampling rates may then generate data sets of up to one terabyte in size. This contribution presents a database approach that enables sensible pulse data handling and sorting as well as spectrum evaluation. For higher energy spectra (~ $E_{max} \geq 300$ keV) an unfolding algorithm may be applied. The procedures were implemented in Python and EGSnrc, respectively.

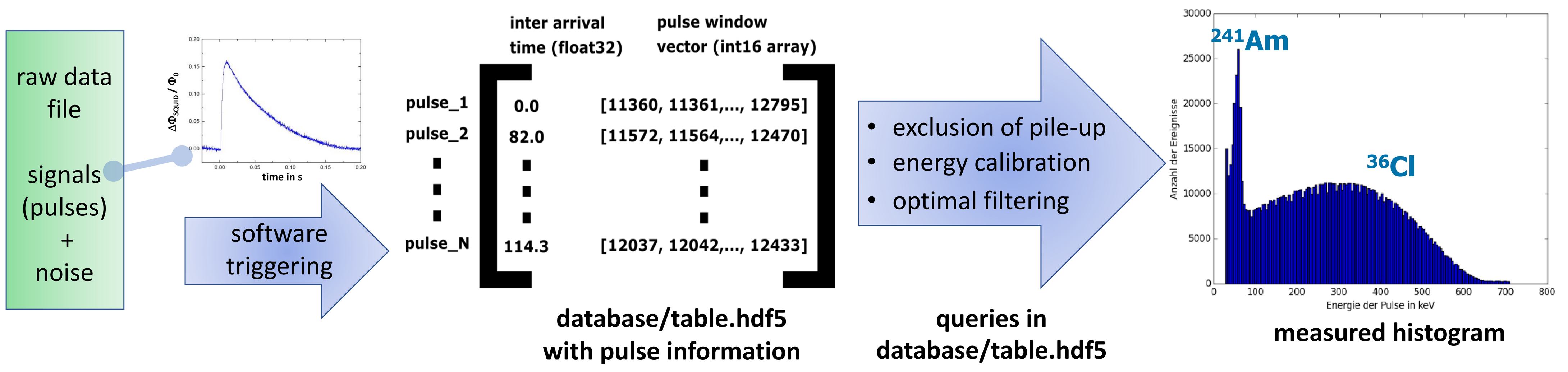
Beta spectrometry with MMCs

Source embedded into the detector absorber [1-4]:

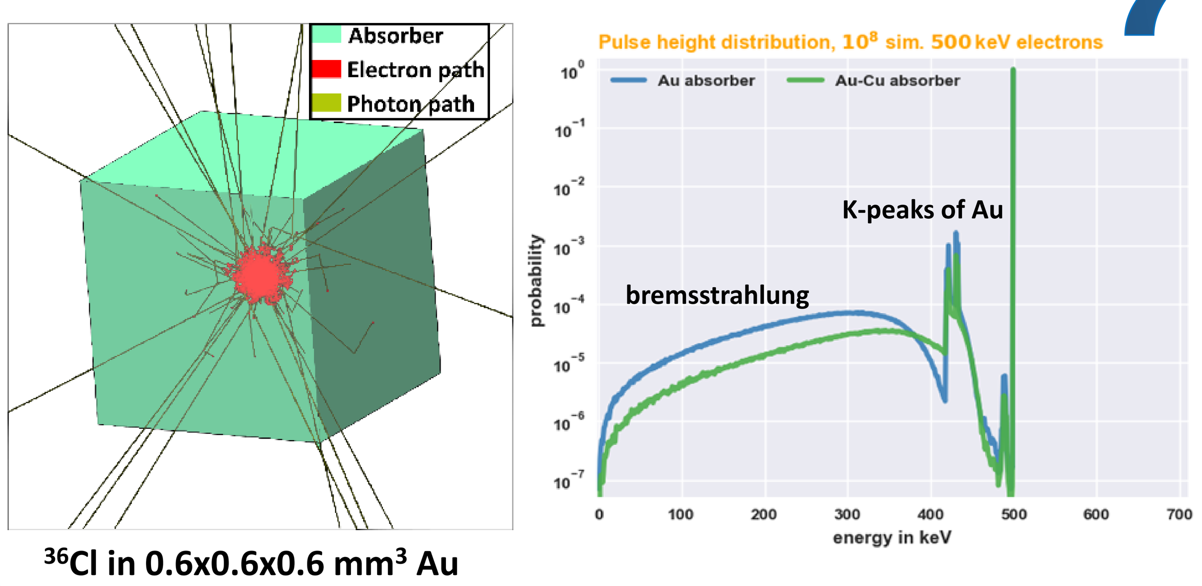
- 4π solid angle
- no back-scattering
- energy loss of beta particles in the source: full thermalization of β energy must be ensured



Data handling and evaluation



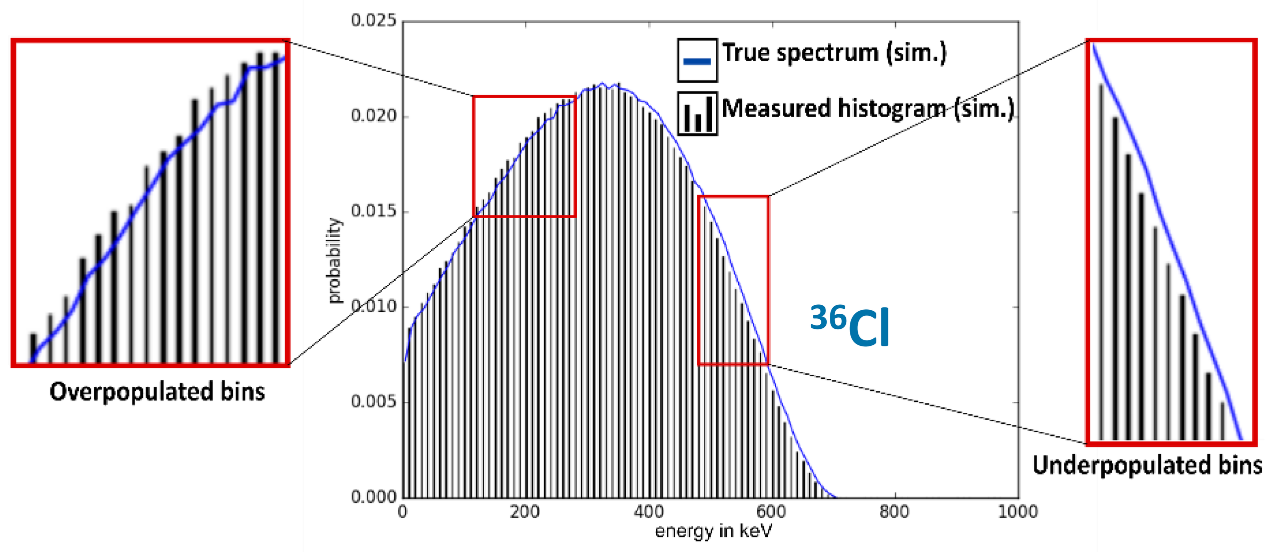
Energy escape at higher energies



^{36}Cl in 0.6x0.6x0.6 mm³ Au

Spectrum distortions at higher energies

- electrons are completely stopped but *bremsstrahlung photons escape*: some electrons with high initial energies are detected with reduced energies.
- the measured spectrum *underestimates* the probabilities for *electron emission with high energies* whereas *low-energy emissions are overestimated.*
- this leads to a *systematic skew* in the measured spectrum.



Unfolding algorithm

Unfolding problem (discrete, underdetermined, random):

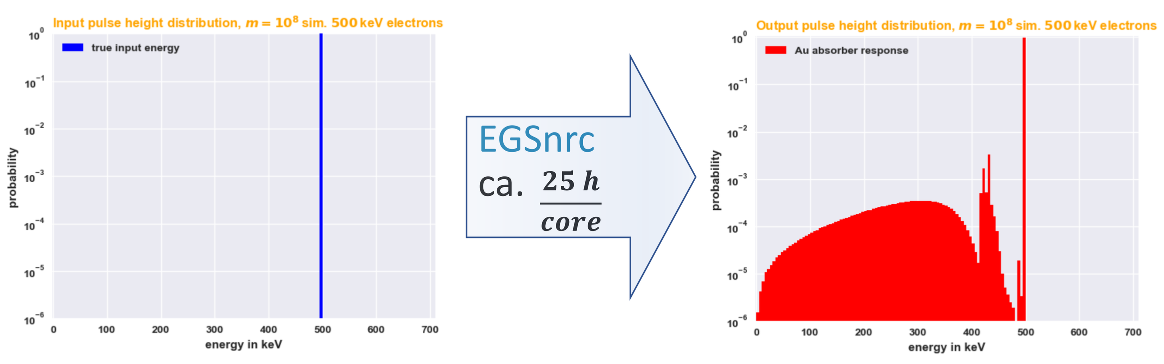
$$\boldsymbol{h}_{N,n}^{meas} = \boldsymbol{R}_N \boldsymbol{h}_{N,n}^{true}$$

N: nr. of bins
n: nr. of meas. decays

measured histogram (output) — response matrix (absorber) — true histogram (input)

„divide-and-conquer" approach [5]:

1) Monte Carlo simulation of N *single-energy bins* (inputs) in absorber geometry over the entire energy interval:



2) Use pulse height distributions i.e. N outputs from step 1) to construct a *response matrix estimate* $S_{N,m}$ columnwise, where m is the number of simulated events/bin. This results in an *NxN* non-negative triagonal matrix which is invertible with prob. 1.

3) Calculate the unfolded histogram by multiplying $S_{N,m}^{-1}$ (response matrix inverse) with the measured histogram.

→ estimate of the true histogram:

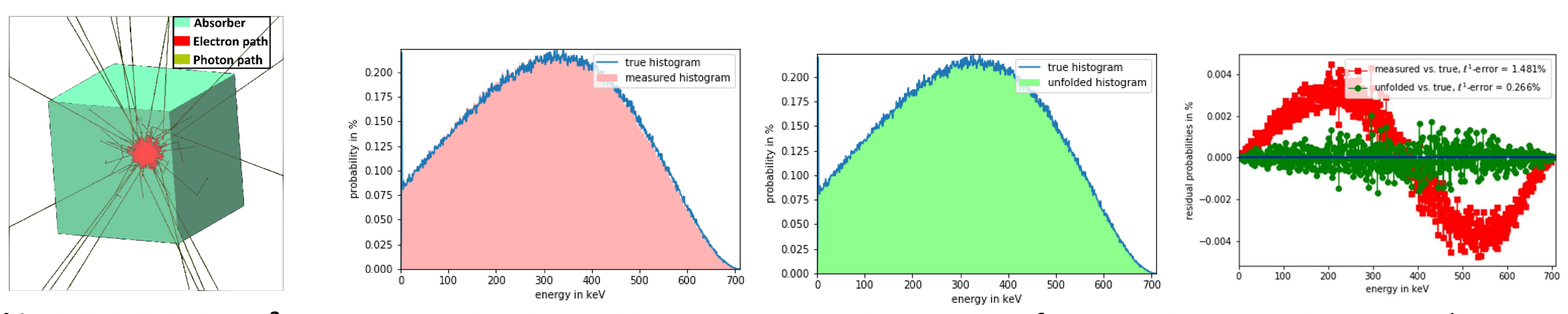
$$\boldsymbol{h}_{N,n}^{true} \cong \boldsymbol{h}_{N,m,n}^{algo} = (\boldsymbol{S}_{N,m})^{-1} \boldsymbol{h}_{N,n}^{meas}$$

Correction of spectrum distortions

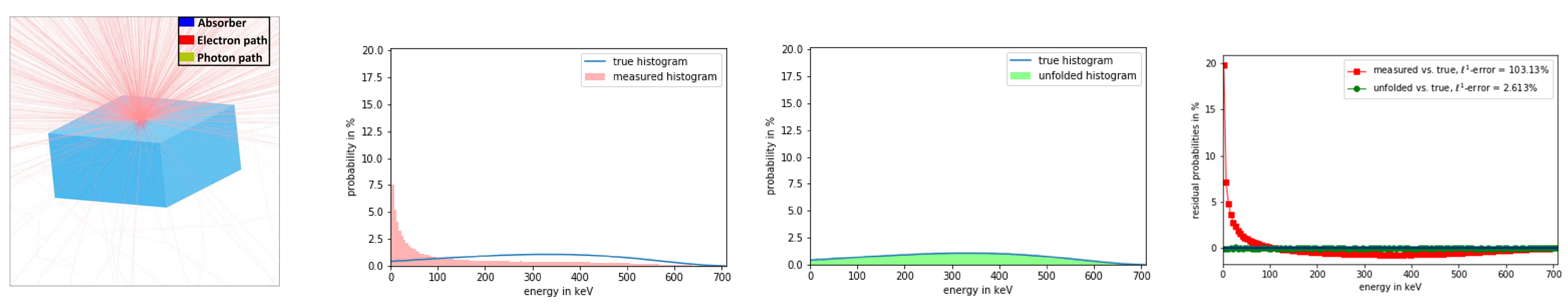
The proposed unfolding algorithm has several advantages [5]:

- the true spectrum shape is not needed as an input.
- it reduces the simulated measured ℓ^1-error (sum of absolute residuals) ≥ 82% at an energy bin width of 1 keV.
- the method is pleasingly parallel and was implemented on a multicore computer cluster.

Simulated examples for ^{36}Cl (E_{max} = 709.5 keV):



^{36}Cl in 0.6x0.6x0.6 mm³ Au — 1 keV bin width, N=710 energy bins, m=1·10⁶ sim. single-energy bin events/bin



^{36}Cl on 0.6x0.6x0.3 mm³ Au — 5 keV bin width, N=142 energy bins, m=1·10⁵ sim. single-energy bin events/bin

Simulated measured (red) and unfolded histograms (green) in a 4π/on a 2π absorber (top row/bottom row) along with the simulated true histograms. The bremsstrahlung skew is visible in the residual plots (right column) and the correction provided by the unfolding algorithm is substantial. The number of decays in the true ^{36}Cl histogram was n=2.5·10⁶.

Remark: Energy escape may be reduced by using bilayer absorbers [3,4] that can be further combined with unfolding methods.

Acknowledgements: This work was performed as part of the EMPIR Project 15SIB10 MetroBeta. This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

References:
[1] M. Loidl et al. J. Low Temp. Phys 193 (2018) 1251–1256.
[2] M. Paulsen et al. JINST, (accepted), (2019).
[3] L. Bockhorn et al., Poster ID: 208-125, LTD-18 (2019).
[4] M. Loidl et al., Poster ID: 208-125, LTD-18 (2019).
[5] M. Paulsen, K. Kossert and J. Beyer, NIMA, (submitted) (2019).