Low-Background Scintillation Spectroscopy for the Investigation of the Radiopurity of $CaWO_4$ Crystals

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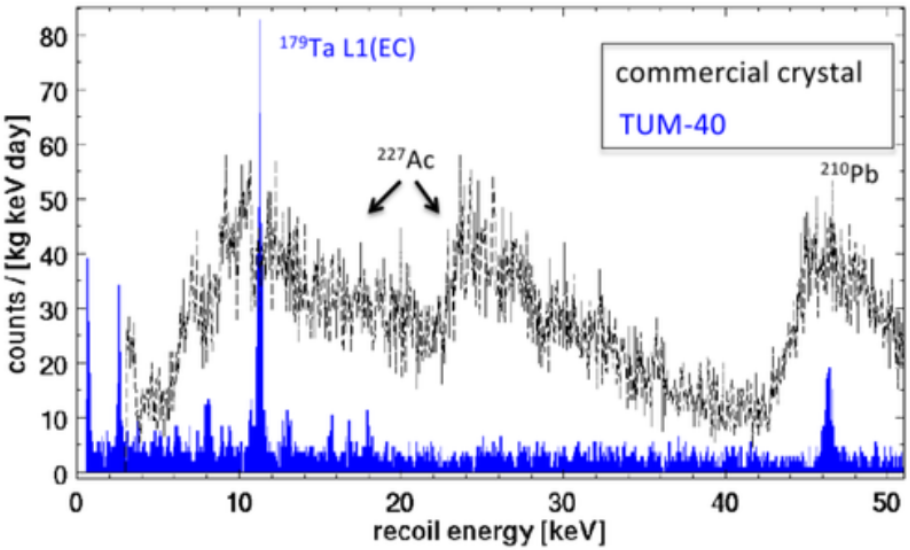
The CRESST-II Experiment

- Direct dark matter search experiment
- Search for nuclear recoils of **W**eakly **I**nteracting **M**assive **P**articles via elastic WIMP-nucleon scattering (expected WIMP signals: nuclear recoils with energies $< 40\,\mathrm{keV}$)

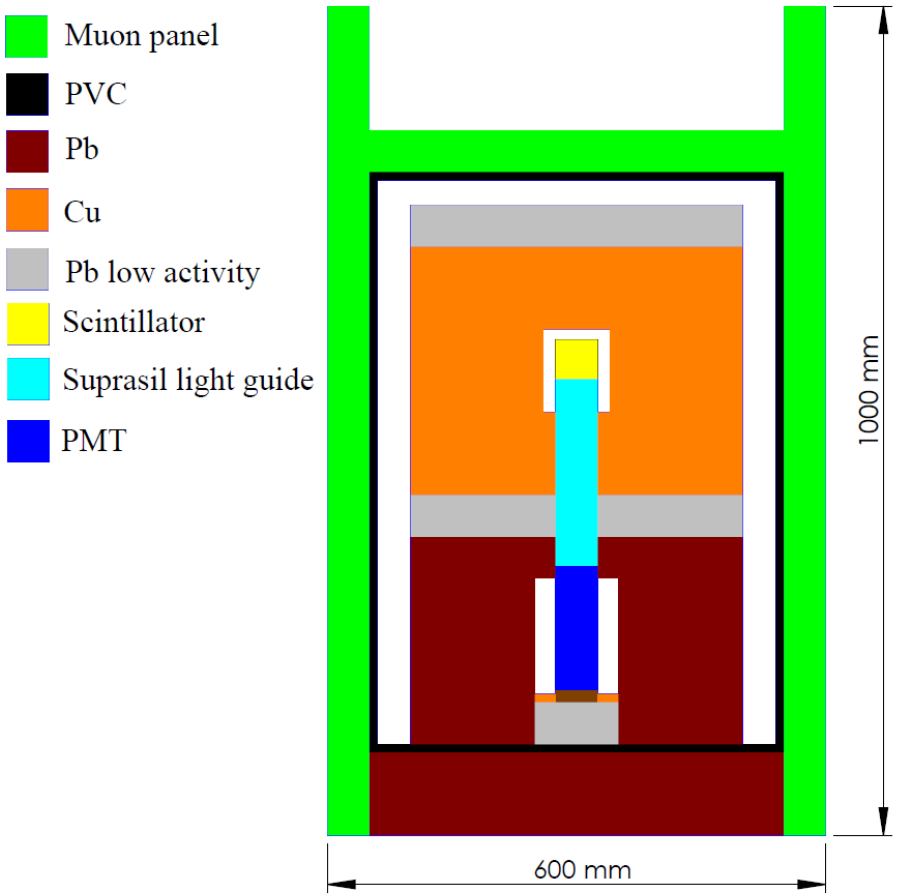
- Scintillating $CaWO_4$ single crystals as target material ($\sim 300\,\mathrm{g}$ each)
- In current run (CRESST-II phase 2) 4 TUM-grown crystals installed for the first time
- Radiopurity of $CaWO_4$ crystals limits sensitivity of CRESST-II

Radiopurity of $CaWO_4$ Crystals in Low-Energy Regime



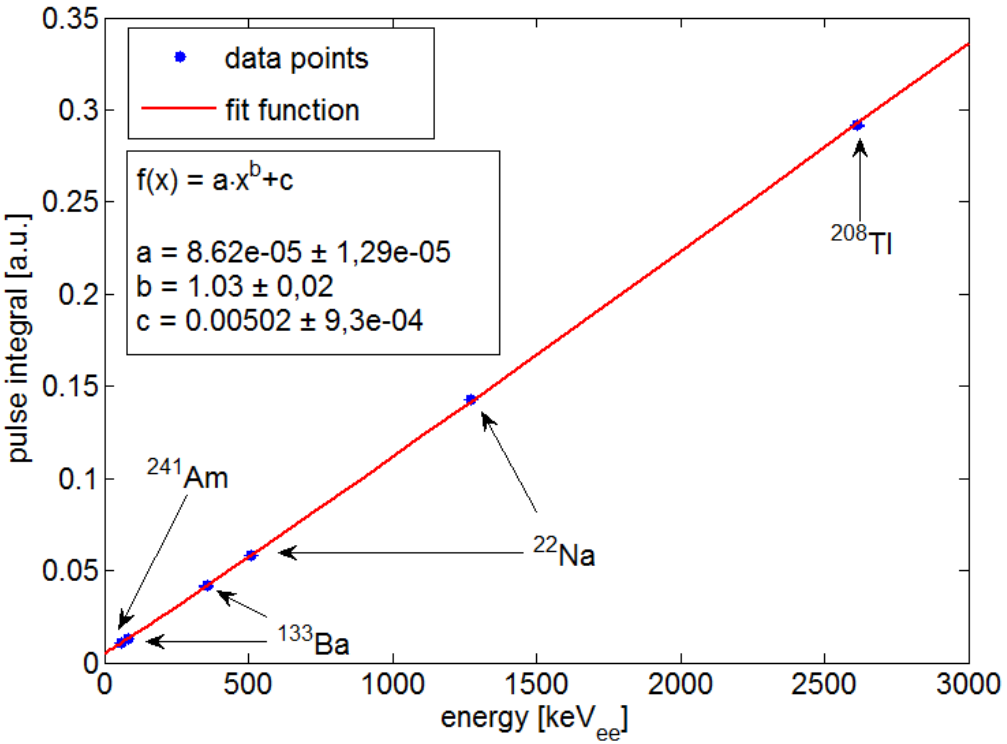
- Large fraction of background in low-energy regime originates from intrinsic contamination of the $CaWO_4$ crystals
- Relevant intrinsic decays in low-energy regime:
  ^{227}Ac ($Q_\beta = 44.8\,\text{keV}$, $T_{1/2} = 21.8\,\text{y}$)
  ^{234}Th ($Q_\beta = 273\,\text{keV}$, $T_{1/2} = 24.1\,\text{d}$)
  ^{179}Ta from cosmogenic activation
- Background level (1 - 40 keV):
  - Commercial crystals used in CRESST-II: 6 - 30/[kg keV day]
  - TUM-grown crystal TUM-40: 3.44/[kg keV day]

Low-Background Scintillation Spectroscopy Setup



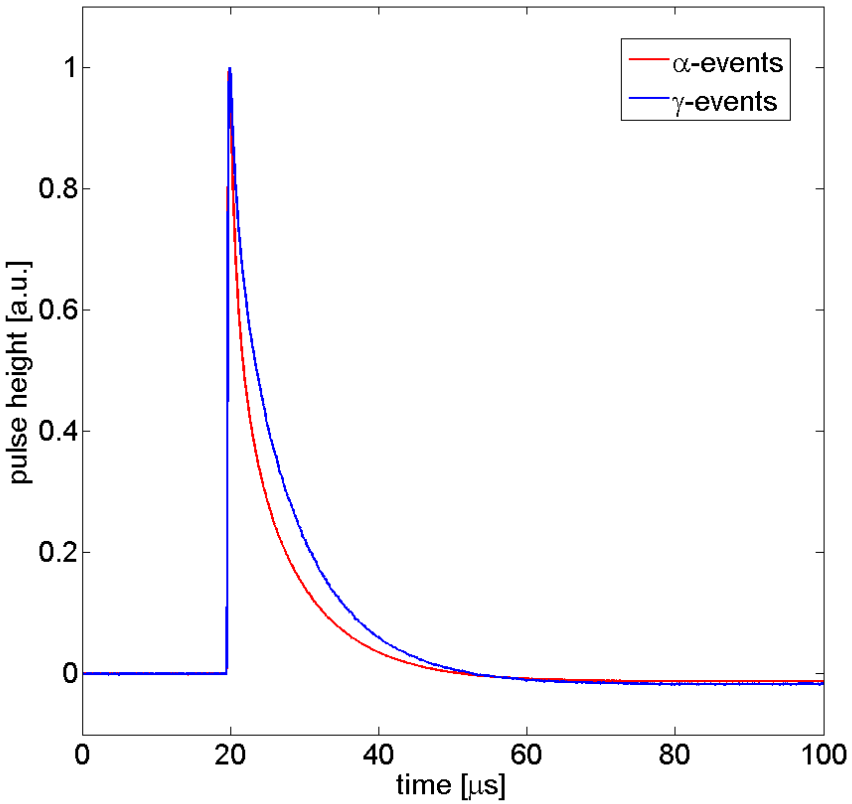
- Determination of intrinsic radioactive contaminations of $CaWO_4$ crystals
  - Feedback for crystal production to improve radiopurity
  - Preselection of radio-purest crystals for future CRESST runs
- Crystal is source and scintillator at the same time
  $\longrightarrow \sim 100\,\%$ detection efficiency for intrinsic alpha and beta decays

Energy Calibration



- Energy calibration before and after each measurement with various gamma sources (energies of gamma lines between $\sim 60\,\mathrm{keV}$ and $\sim 2600\,\mathrm{keV}$)
- Data points well fitted by power function
- Energy resolution (FWHM) at $511\,\mathrm{keV}$: $\sim 14\,\%$

Pulse Shapes of Alpha and Gamma Particles

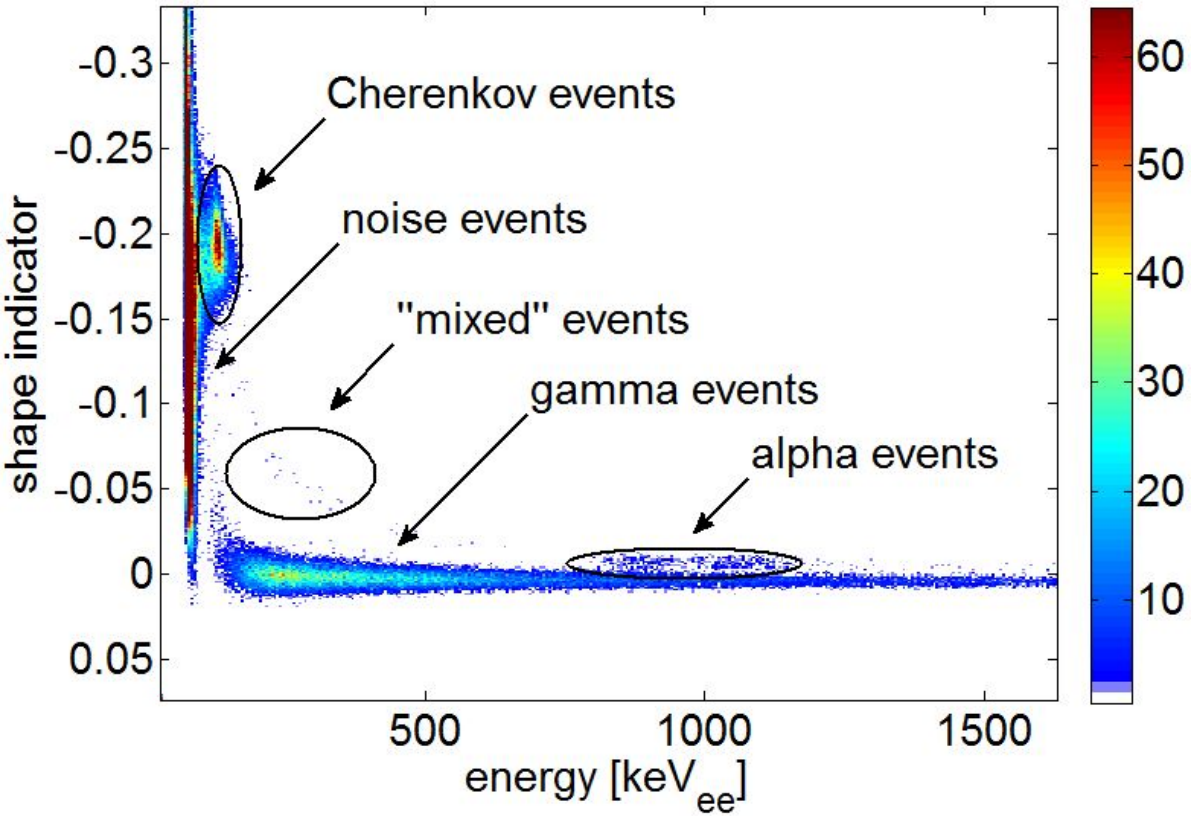


- Pulse shapes of averaged and normalized alpha and gamma pulses
- Irradiation with sources:
  - ^{241}Am alpha particles with $\lesssim 5.6\,\mathrm{MeV}$
  - ^{22}Na gamma rays with $1275\,\mathrm{keV}$
- Different decay times of alpha and gamma events

  $\longrightarrow$ pulse shape discrimination possible

  $\longrightarrow$ discrimination between alphas (internal) and gammas (internal and external)

Histogram of Energy vs. Shape Indicator



- Shape indicator:
  $SI = \frac{\sum_k f(t_k) \cdot P(t_k)}{\sum_k f(t_k)}$
  $f(t_k)$: pulse amplitude at time t_k
- Weight function:
  $P(t) = \frac{f_\alpha(t) - f_\gamma(t)}{f_\alpha(t) + f_\gamma(t)}$
- Various populations in histogram due to different event types

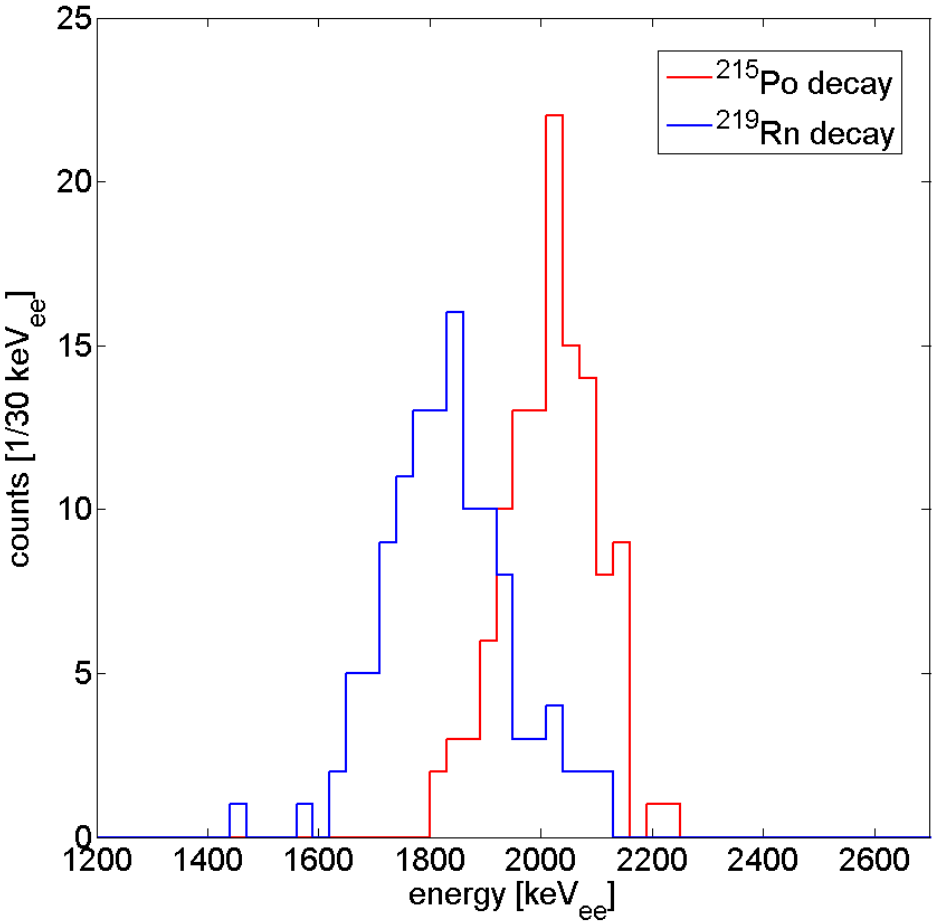
Coincidence Search

Search for coincidence between decay of a mother isotope and a following short-lived daughter isotope

- ^{238}U chain: $^{214}\mathrm{Bi} \xrightarrow[Q_\beta = 3.3\,\mathrm{MeV}]{T_{1/2} = 19.9\,\mathrm{min}} {}^{214}\mathrm{Po} \xrightarrow[Q_\alpha = 7.8\,\mathrm{MeV}]{T_{1/2} = 164\,\mu\mathrm{s}} {}^{210}\mathrm{Pb}$
- ^{235}U chain: $^{219}\mathrm{Rn} \xrightarrow[Q_\alpha = 6.9\,\mathrm{MeV}]{T_{1/2} = 3.96\,\mathrm{s}} {}^{215}\mathrm{Po} \xrightarrow[Q_\alpha = 7.5\,\mathrm{MeV}]{T_{1/2} = 1.78\,\mathrm{ms}} {}^{211}\mathrm{Pb}$
- ^{232}Th chain: $^{220}\mathrm{Rn} \xrightarrow[Q_\alpha = 6.4\,\mathrm{MeV}]{T_{1/2} = 55.6\,\mathrm{s}} {}^{216}\mathrm{Po} \xrightarrow[Q_\alpha = 6.9\,\mathrm{MeV}]{T_{1/2} = 145\,\mathrm{ms}} {}^{212}\mathrm{Pb}$

$\longrightarrow$ determination of ^{226}Ra, ^{227}Ac, and ^{228}Th activities possible

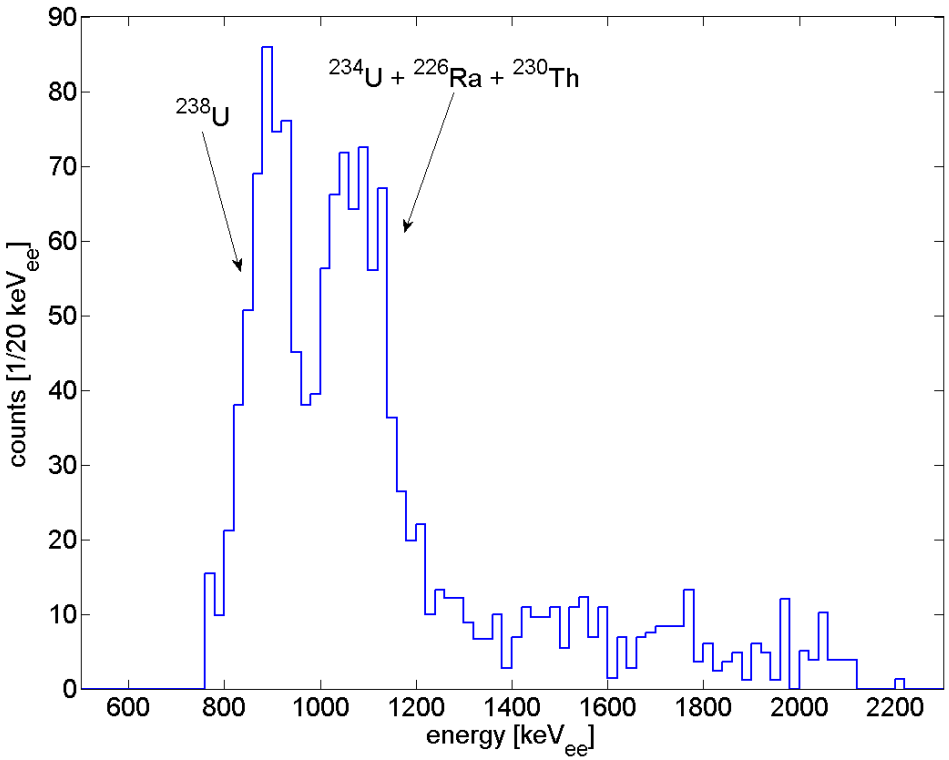
$^{219}Rn \longrightarrow {}^{215}Po \longrightarrow {}^{211}Pb$ Coincidence



- Energy spectrum of ^{219}Rn and ^{215}Po decay
- Total measurement time: $\sim 42\,d$
- Number of found coincidences (accidental coincidences):

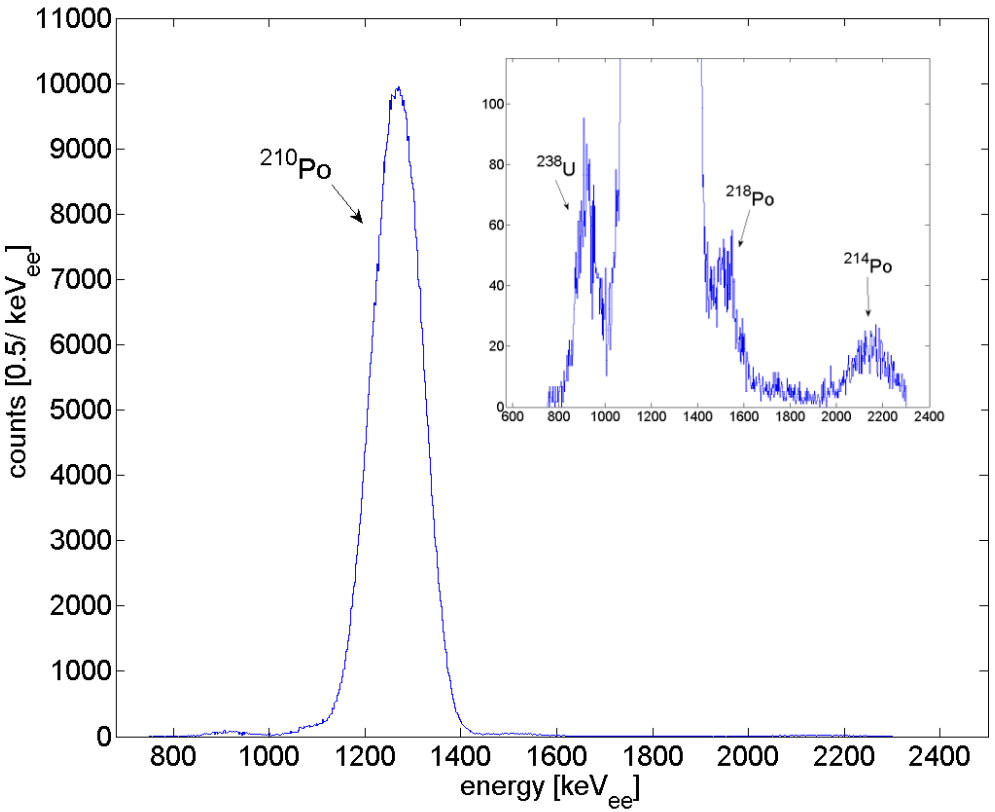
  $^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Pb$: 65 (0)
  $^{219}Rn \rightarrow {}^{215}Po \rightarrow {}^{211}Pb$: 120 (1)
  $^{220}Rn \rightarrow {}^{216}Po \rightarrow {}^{212}Pb$: 48 (10)

Alpha Spectrum - TUM-Grown Crystal



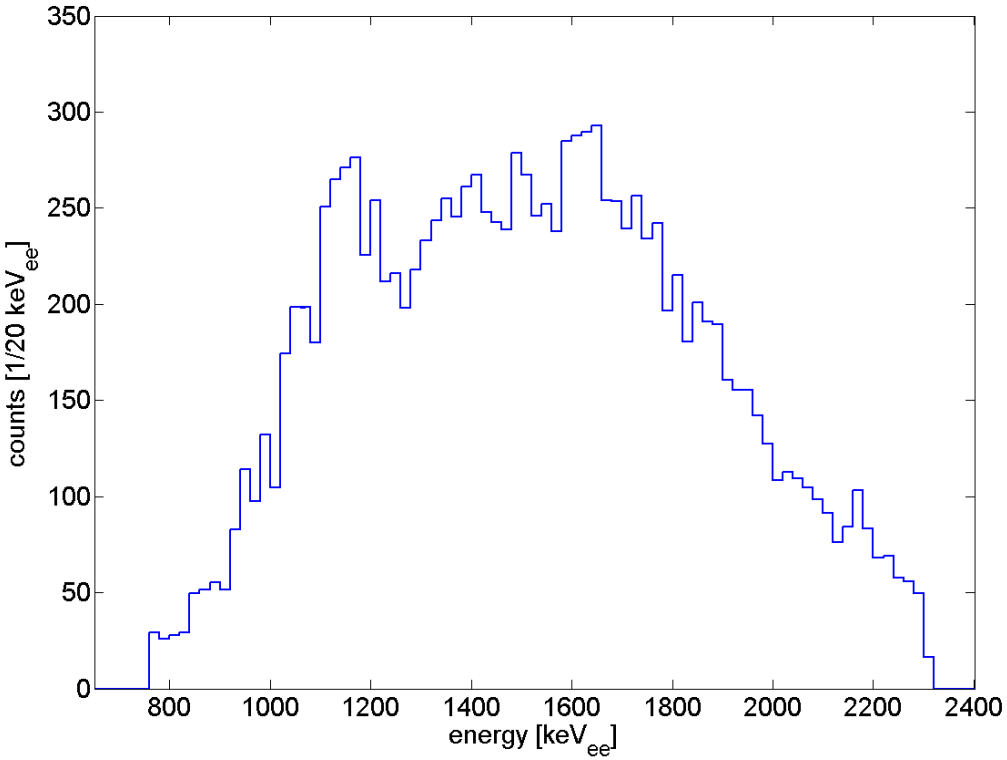
- TUM-grown crystal "Karl II"
- Energy range from 750 keV_{ee} to 2300 keV_{ee}
- Determination of ^{238}U and ^{230}Th activities from peaks of the spectrum
- Total alpha activity from integral over spectrum
- Alpha spectra similar for all investigated TUM-grown crystals

Alpha Spectrum - Commercial Crystal from Ukraine



- Commercial crystal "Boris"
- Energy range from 750 keV_{ee} to 2300 keV_{ee}
- Determination of ^{238}U and ^{210}Pb activities from peaks of the spectrum
- Total alpha activity from integral over spectrum

Alpha Spectrum - Commercial Crystal from Russia



- Commercial crystal "Sabine"
- Energy range from 750 keV_{ee} to 2300 keV_{ee}
- No activity determination of specific isotopes from spectrum possible
- Total alpha activity from integral over spectrum

Activities of TUM-Grown Crystals

TUM-grown crystals

	Jakob II	**LGS**	**Ernst**	**Karl II**
	activity [mBq/kg]			
total alpha activity (750-2300 keV_{ee})	3.75 ± 0.92	5.77 ± 0.77	5.45 ± 0.38	6.14 ± 0.93
^{238}U	0.53 ± 0.10	1.42 ± 0.24	1.41 ± 0.18	1.98 ± 0.29
^{230}Th	1.03 ± 0.20	0.95 ± 0.40	0.70 ± 0.31	0.94 ± 0.48
^{226}Ra	$0.055^{+0.019}_{-0.016}$	$0.196^{+0.021}_{-0.019}$	$0.053^{+0.019}_{-0.016}$	$0.088^{+0.018}_{-0.016}$
^{227}Ac	$0.143^{+0.017}_{-0.015}$	$0.117^{+0.011}_{-0.010}$	$0.111^{+0.015}_{-0.013}$	$0.143^{+0.014}_{-0.013}$
^{228}Th	< 0.015	$0.028^{+0.008}_{-0.007}$	< 0.020	$0.038^{+0.012}_{-0.010}$
raw material supplier	AA[1]	AA[1]	MV[2]	MV[2]
growth number	1	6	1	2

[1] Alfa Aesar; [2] MV Laboratories

Feedback for Crystal Production Process

- Radiopurity of crystals depends on raw materials
  $\longrightarrow$ importance of raw material preselection
- Radiopurity improves with decreasing growth number
  $\longrightarrow$ crystal growth is purification process (strongly depending on element)
  $\longrightarrow$ regularly remove residual melt or try recrystallisation

Activities of Commercial Crystals

Commercial crystals

	Boris	**Sabine**
	activity [mBq/kg]	
total alpha activity (750-2300 keV_{ee})	1293 ± 6	14.85 ± 0.76
^{238}U	8.22 ± 0.47	—
^{226}Ra	$4.830\,^{+0.149}_{-0.145}$	$0.722\,^{+0.052}_{-0.049}$
^{227}Ac	$0.360\,^{+0.033}_{-0.030}$	$1.181\,^{+0.042}_{-0.040}$
^{228}Th	$0.099\,^{+0.027}_{-0.023}$	$0.351\,^{+0.029}_{-0.027}$
^{210}Pb	1269 ± 4	—

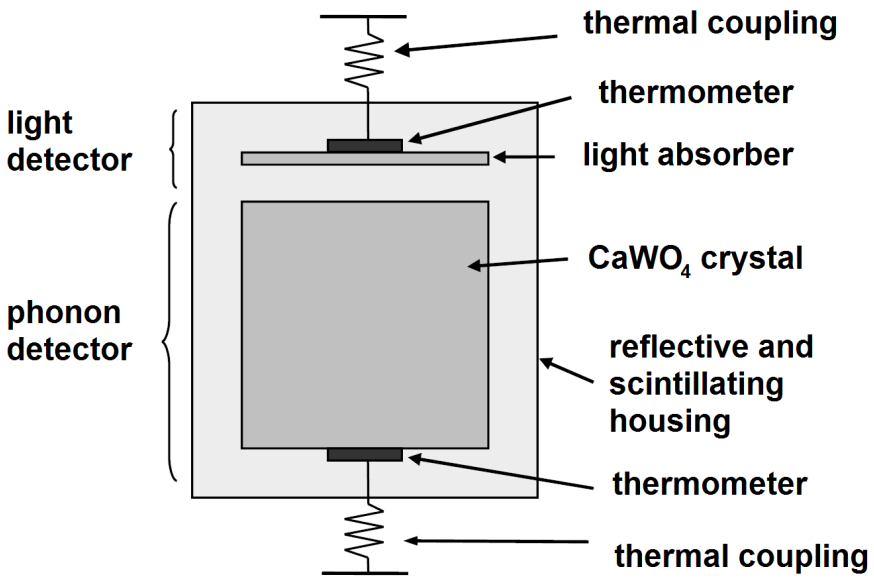
Conclusion and Outlook

- Conclusion
  - Activities determined down to the μBq/kg level
  - Important feedback for crystal production process
  - Preselection of $CaWO_4$ crystals (regarding radiopurity) for future CRESST runs possible
  - Radiopurity of investigated TUM-grown crystals better than radiopurity of investigated commercial crystals (at least a factor 2 lower activities)
- Outlook
  - Setup ready for further measurements
    (e.g. crystal grown out of recrystallized material only)
  - Improvement of setup possible
    (e.g. additional lead shielding)

Thank you for your attention.

backup slides

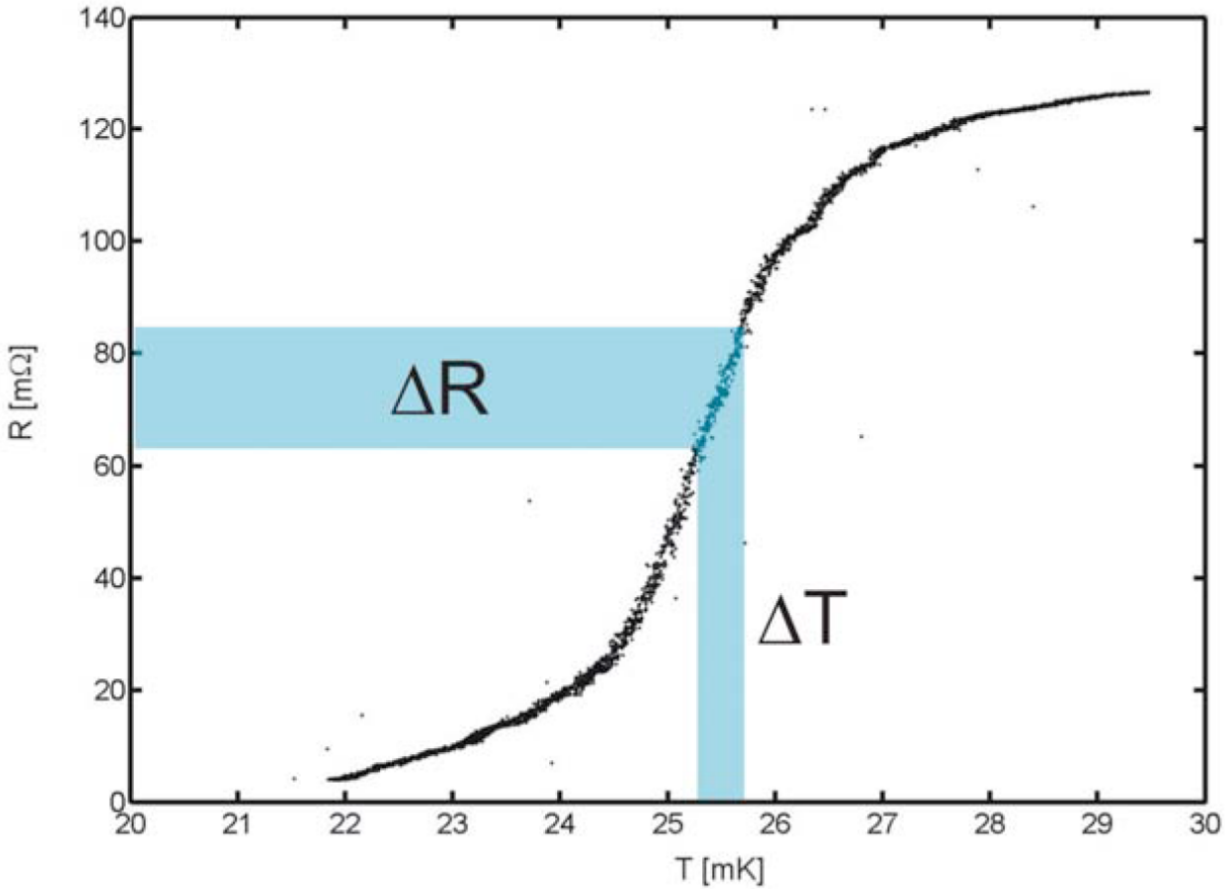
Schematic of CRESST-II Detector Module



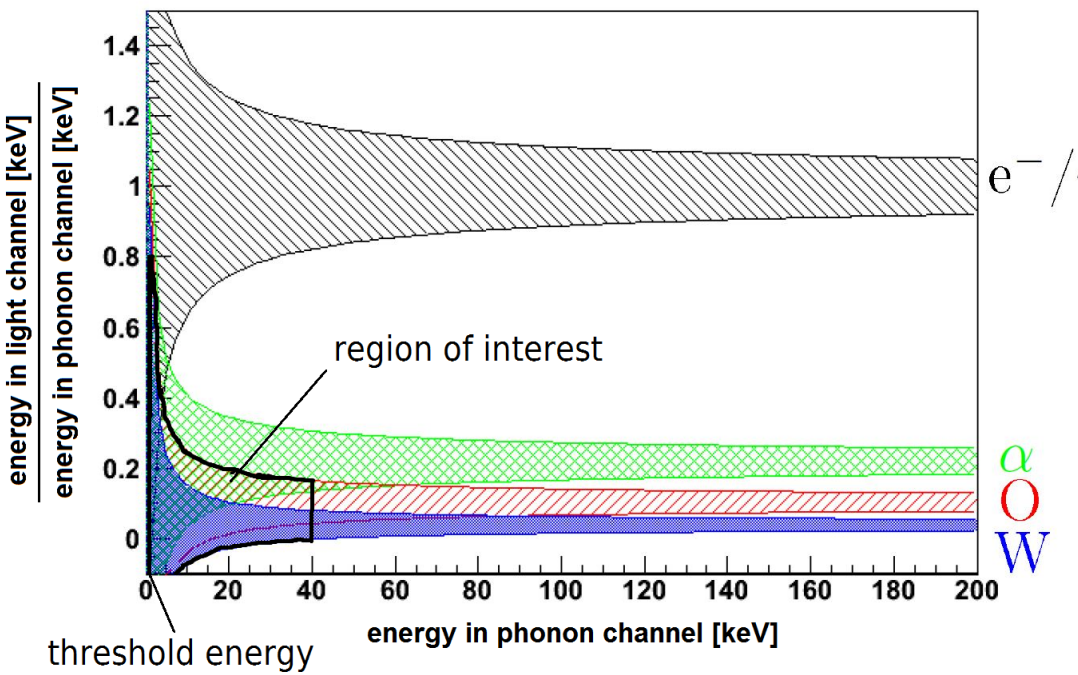
- Energy deposition in the $CaWO_4$ crystal produces phonons (heat) and photons (light)
- Simultaneous read-out of light and phonon channel

  $\longrightarrow$ active background discrimination on an event-by-event basis possible

Normal Conducting to Superconducting State Transition

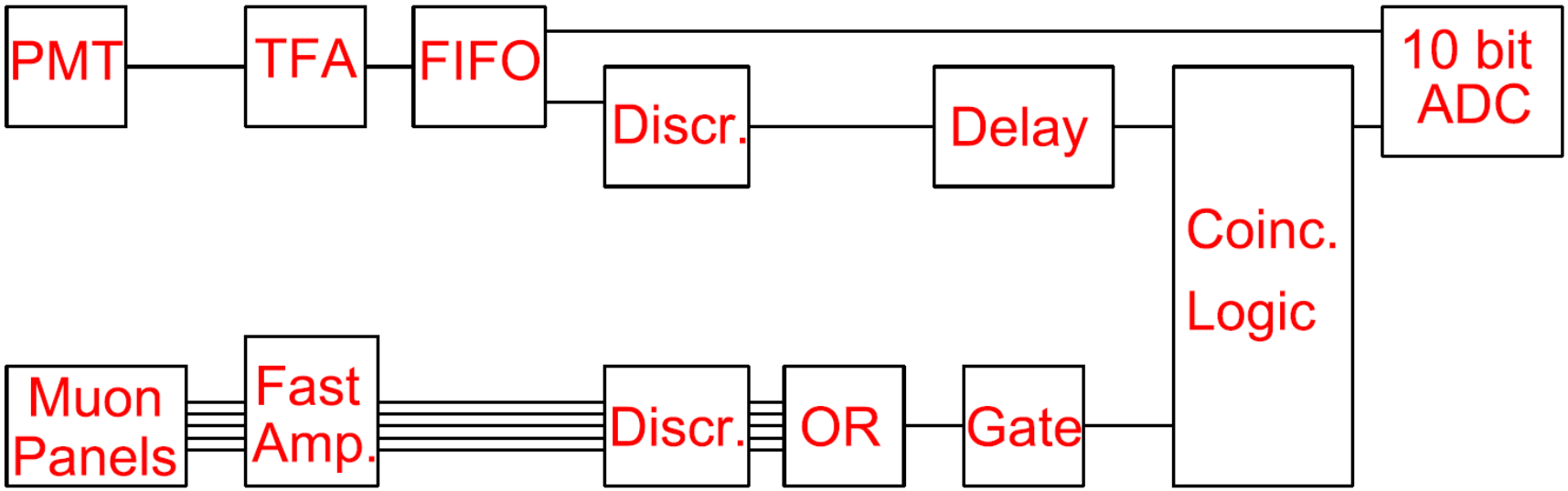


Active Background Discrimination

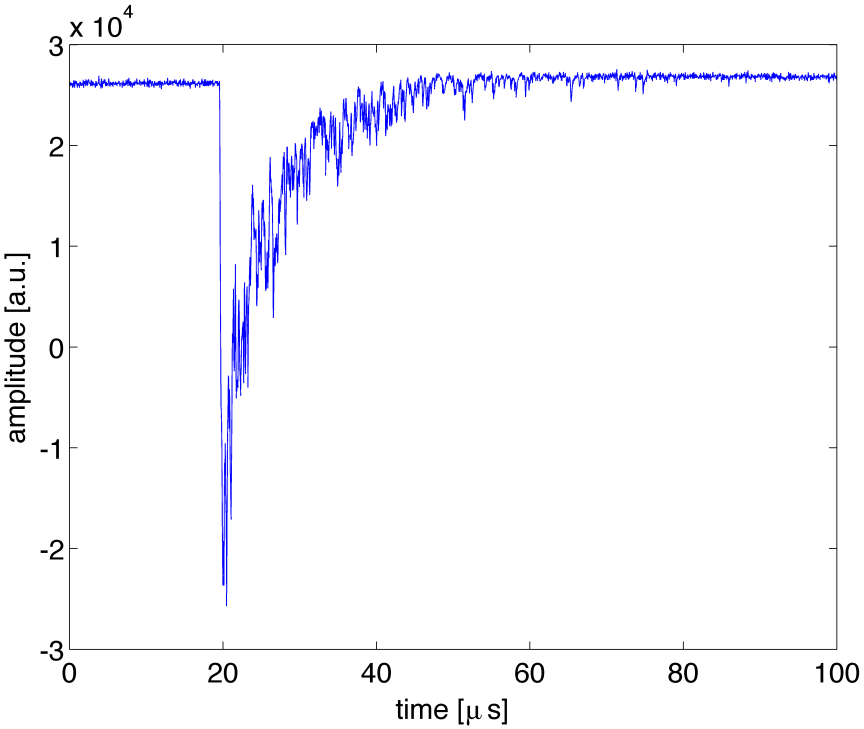


- Search for nuclear recoils of WIMPs
- Region of interest (ROI): nuclear recoil bands $< 40\,\text{keV}$ and $> \text{E}_{\text{threshold}}$
- Radiopurity of $CaWO_4$ crystals important because of leakage from e^-/γ-band into ROI

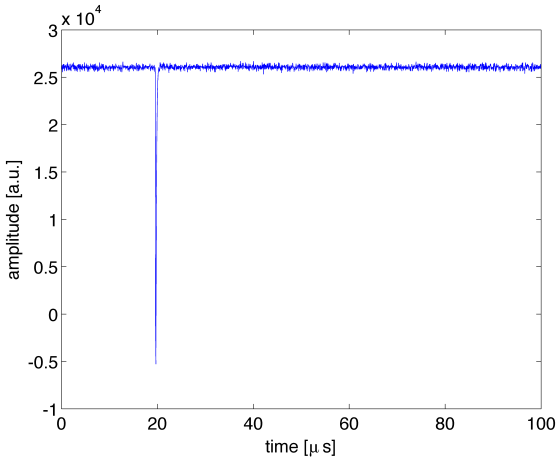
Schematic of Data Acquisition System



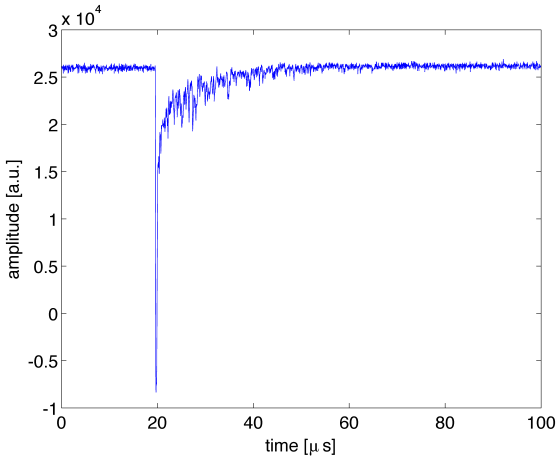
Typical Pulses



scintillation light pulse

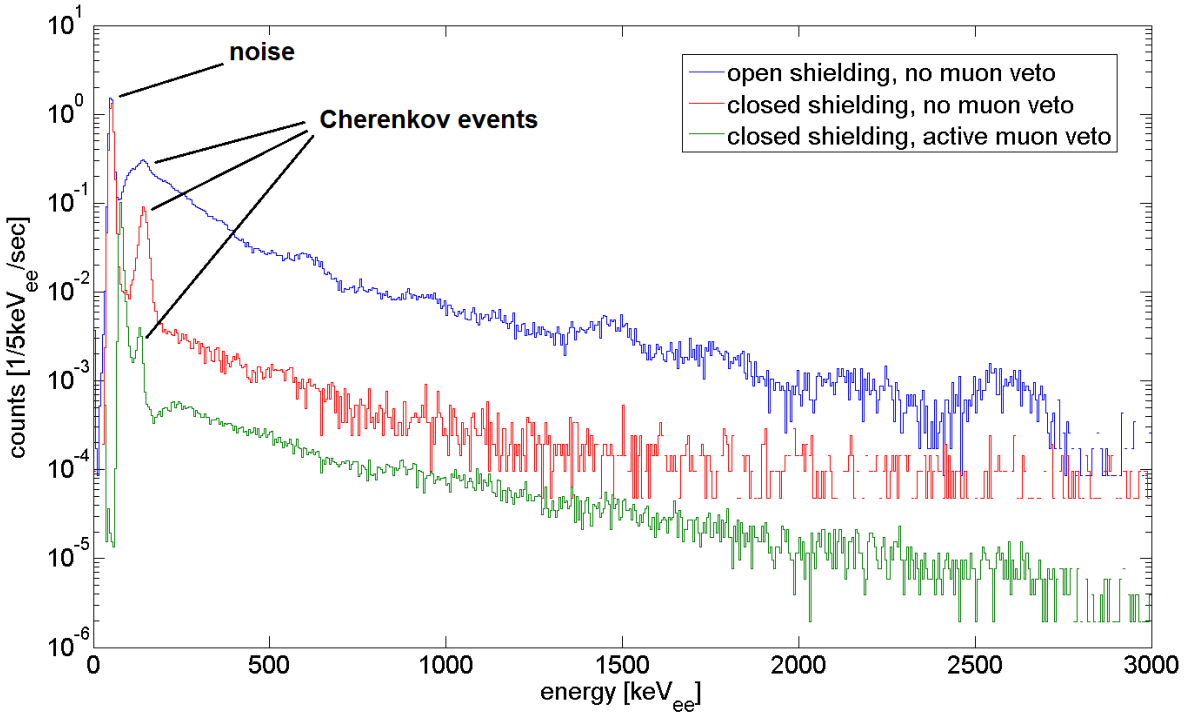


Cherenkov light pulse



"mixed" event pulse

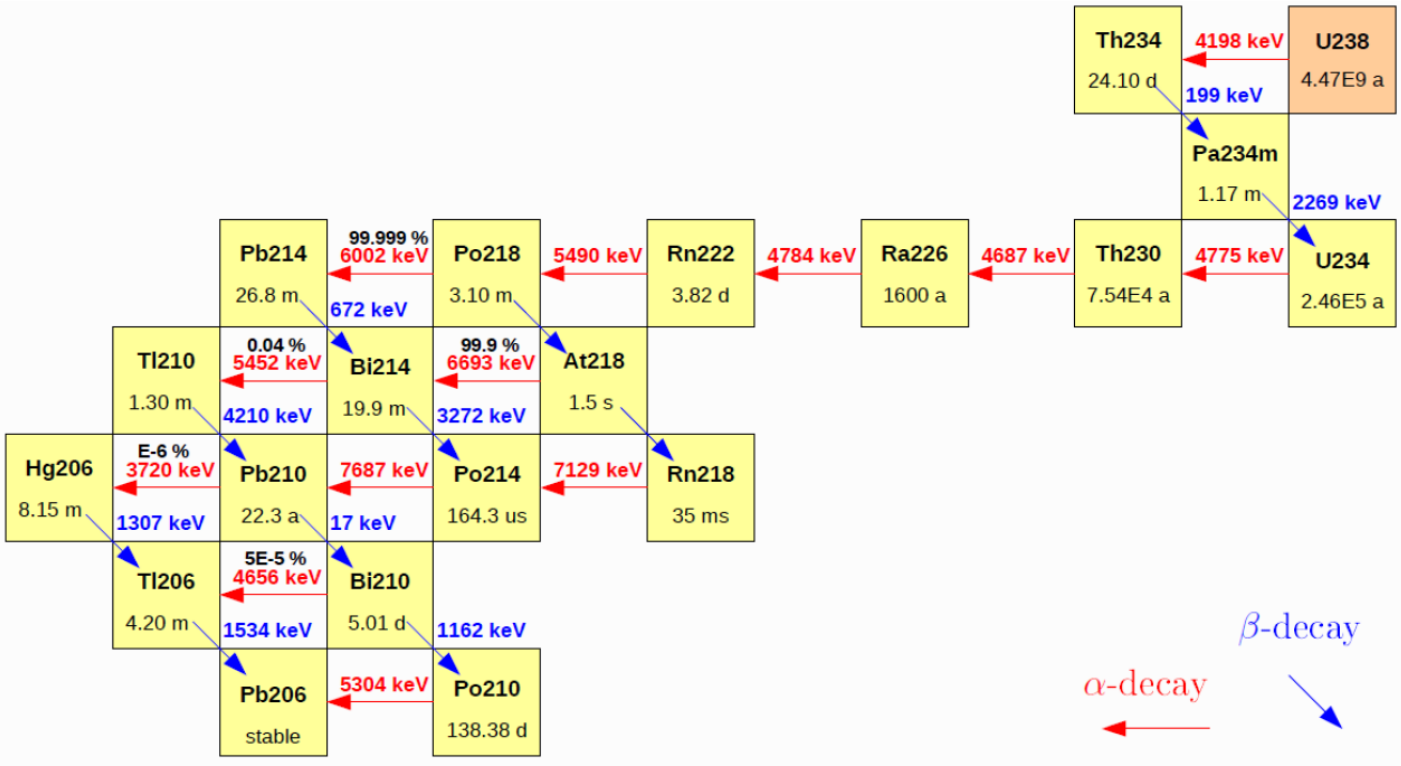
Background Spectra of $CaWO_4$ Crystal



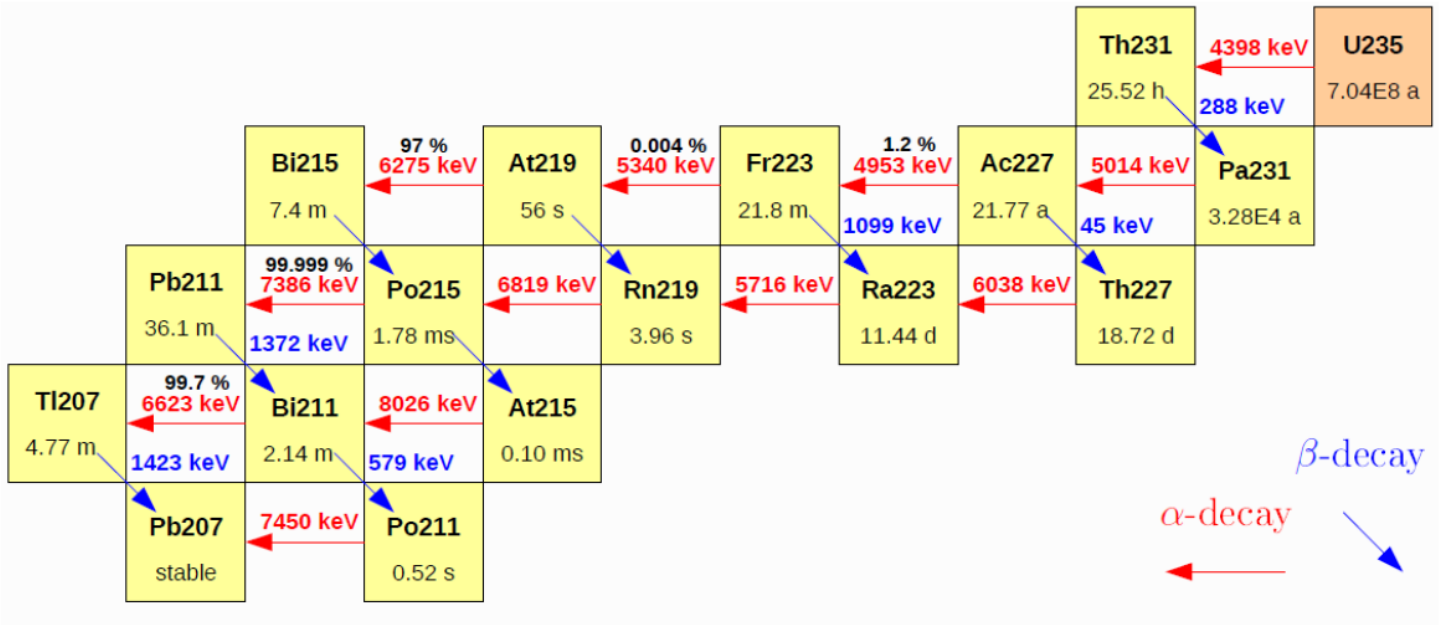
Reduction of background: integral count rate in energy range from 170 keV_{ee} to 3000 keV_{ee}

blue spectrum $\xrightarrow{\text{factor} \sim 30}$ red spectrum $\xrightarrow{\text{factor} \sim 5}$ green spectrum (0.05 Hz)

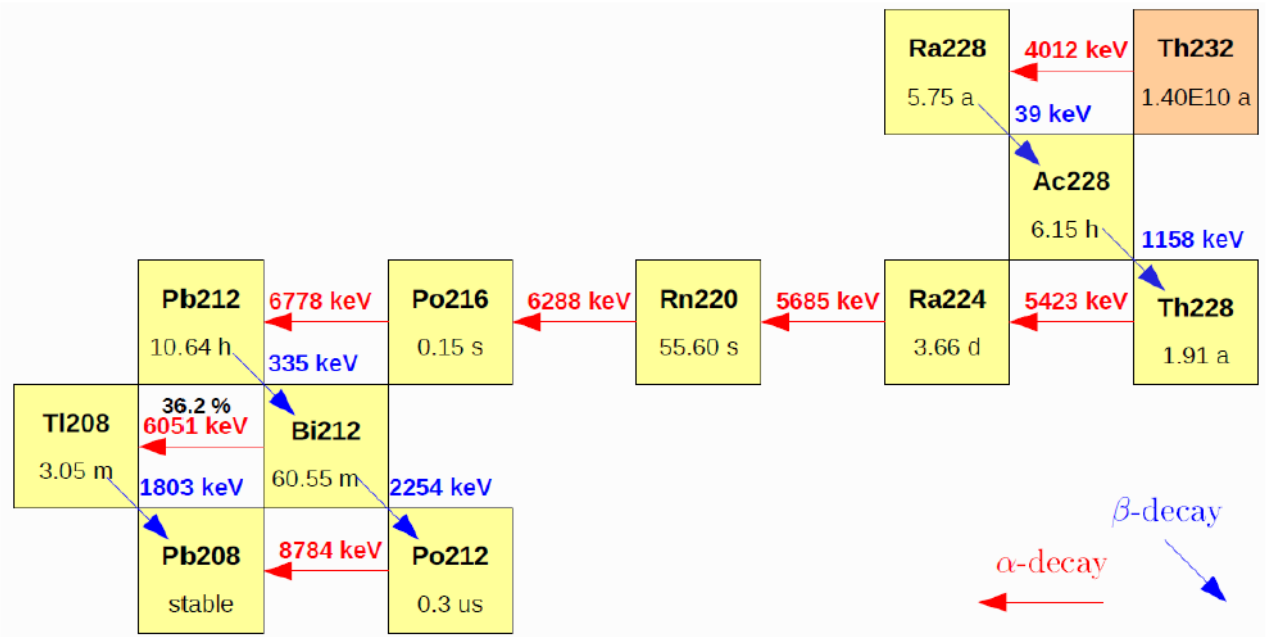
Uranium-Radium Decay Series



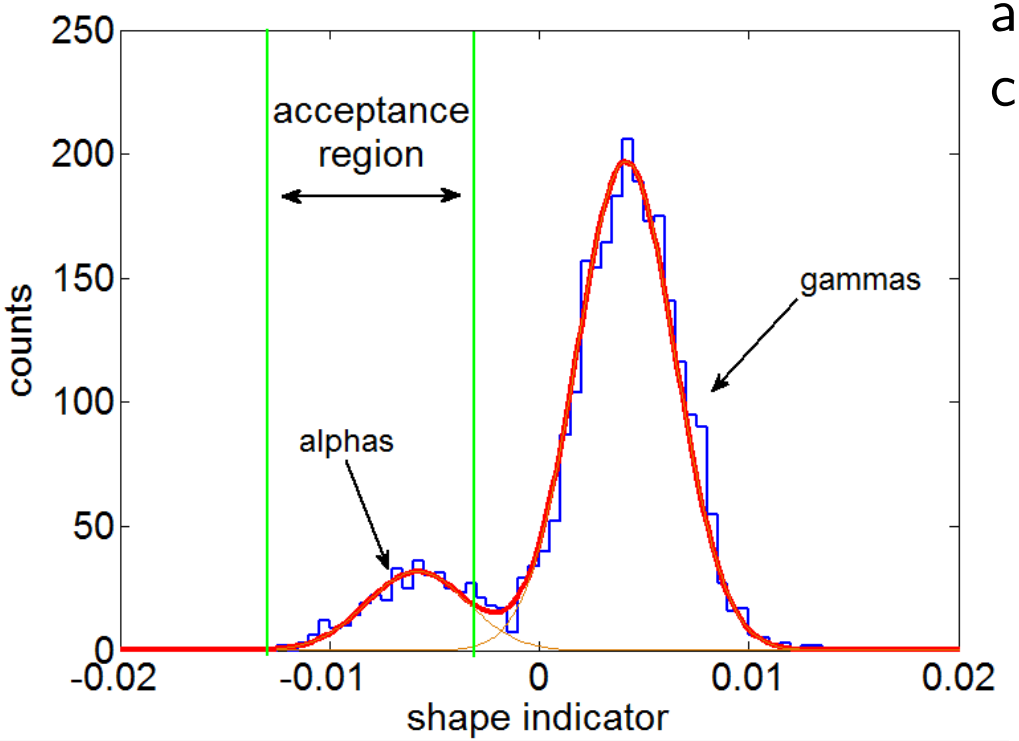
Uranium-Actinium Decay Series



Thorium Decay Series



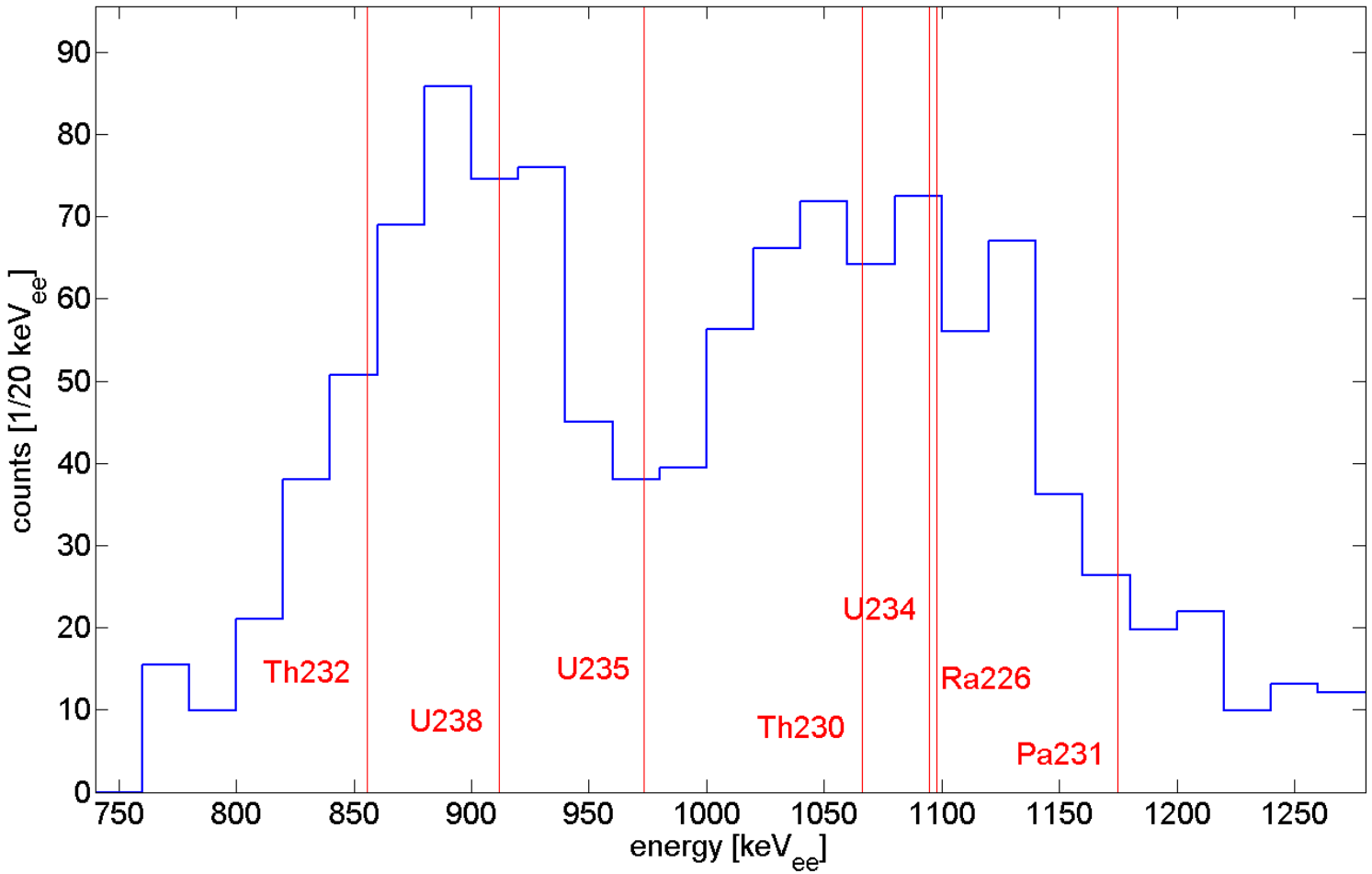
Identification of Alpha Events for the Alpha Spectra



Identification of alpha events for the alpha spectrum of each $CaWO_4$ crystal:

1. Double Gaussian fit of shape indicator histogram (for each 310 keV_{ee} step from 750 keV_{ee} to 2300 keV_{ee})
2. Acceptance region for alphas: leakage of gammas into alphas $< 0.5\,\%$
3. Efficiency correction due to acceptance region

Alpha Spectrum - TUM-Grown Crystal "Karl II"



Alpha Spectrum - Commercial Crystal "Boris"