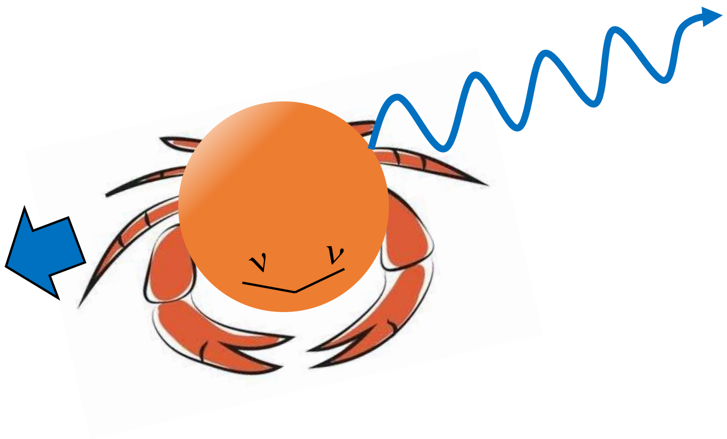
CRAB
Calibrated Recoils for Accurate Bolometry

Calibration of nuclear recoils at the 100 eV scale using neutron capture



David Lhuillier

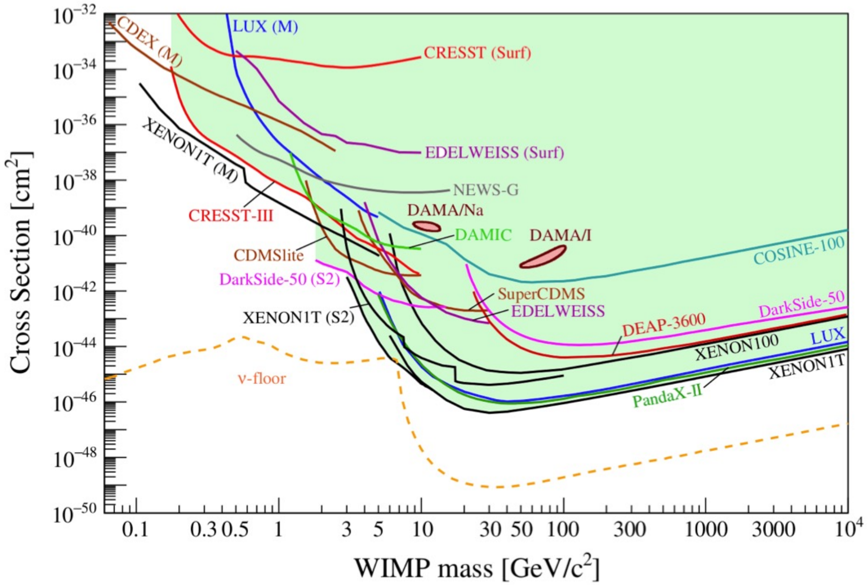
IRN Neutrino Meeting
June 10-11 2021

Sub-keV Nuclear Recoils – Scientific Case

Few 10 eV nuclear recoils can now be detected in 1-10 g scale cryogenic detectors

Light Dark Matter

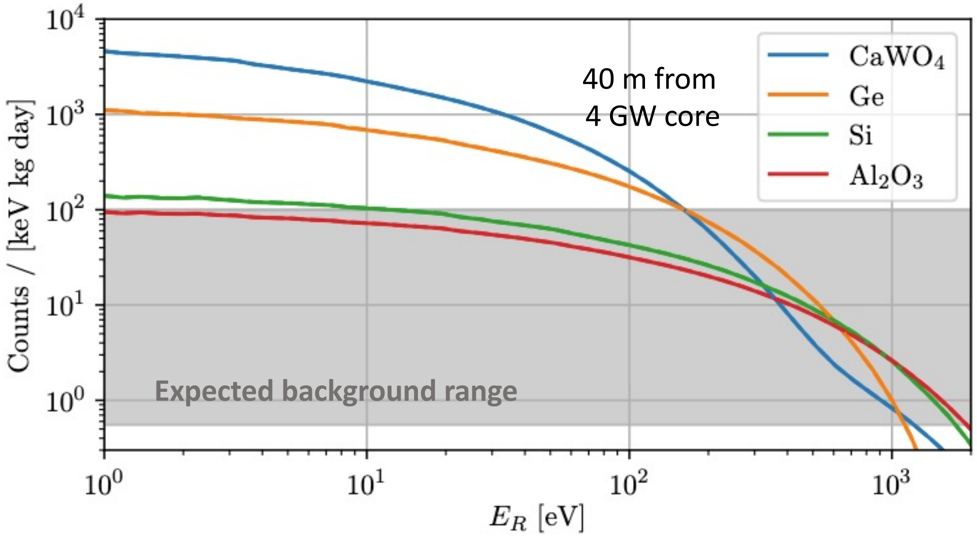
Direct Detection of Dark Matter -- APPEC Committee Report



Low mass / low recoil area to be explored

Coherent Scattering of Reactor ν's

Johannes Rothe PhD Thesis

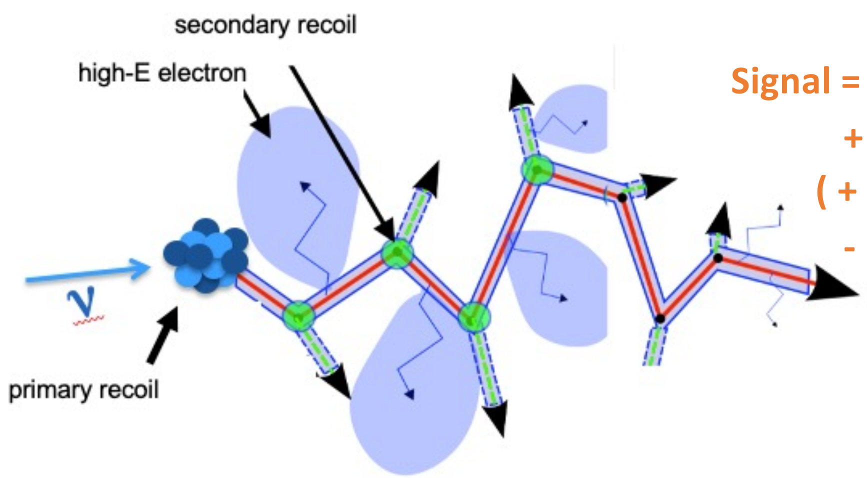


Accurate calibration ⟺ sensitivity to new physics

Region Of Interest = 10-100 eV scale

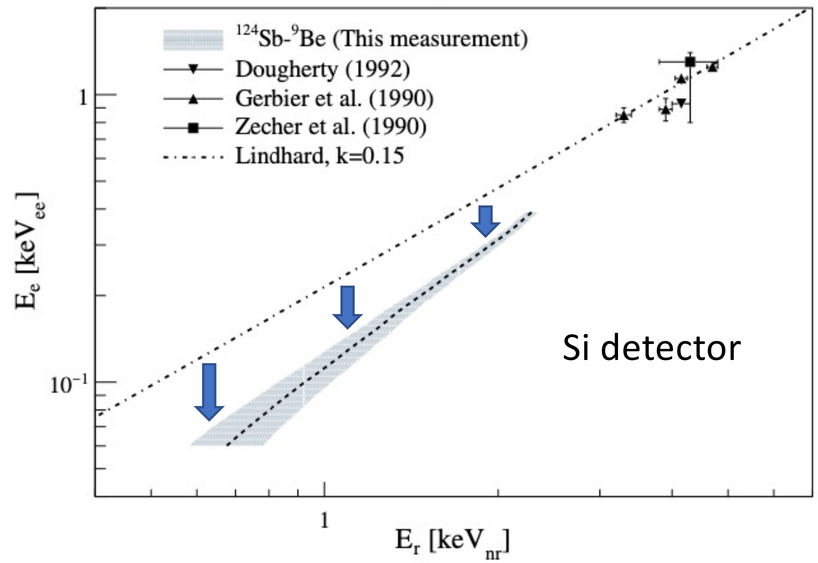
Understanding Energy Losses

keV scale initial nuclear recoil



Signal = phonons
+ ionization
(+ light)
- lattice damage

[PRD 94, 082007 (2016)](#)



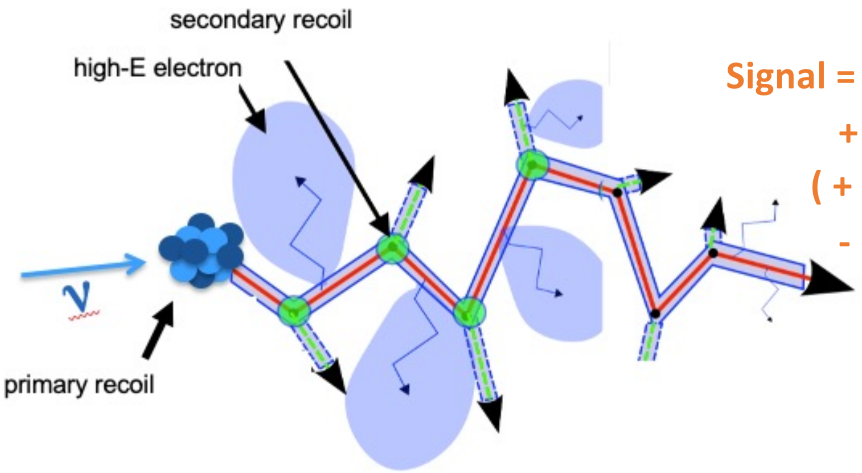
Complex model of detector response depends on:

- Detector crystal
- Recoiling particle: quenched nuclear recoils w.r.t. e-recoils
- Energy range

- Strong evolution of quenching factors
- Approximations of reference work by Lindhard not valid anymore
- Efforts of all experiments to measure their own quenching factors at low energy

Understanding Energy Losses

keV scale initial nuclear recoil



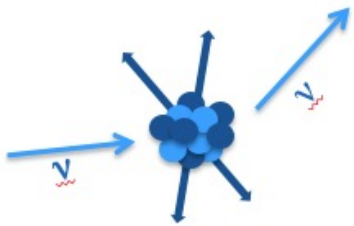
Signal = phonons
+ ionization
(+ light)
- lattice defects

Complex model of detector response depends on:

- Detector crystal
- Recoiling particle: quenched nuclear recoils w.r.t. e-recoils
- Energy range

100 eV scale and below

Phonons only limit at very low E_{recoil}

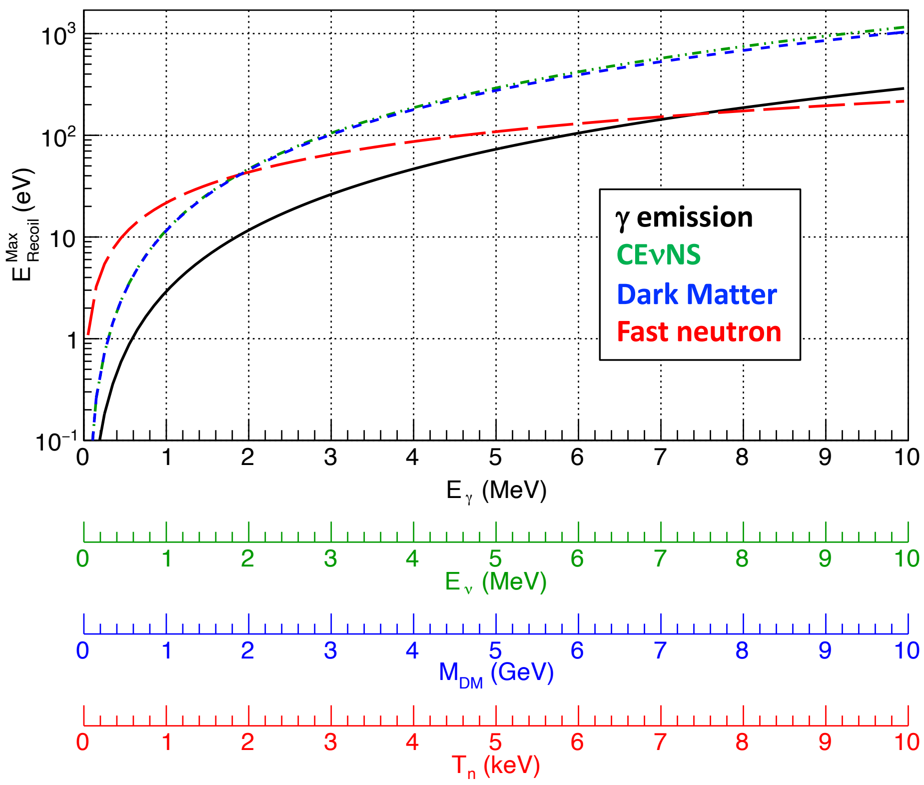


- Residual impact of energy stored in lattice defects?
- Sensitivity to recoiling particle?

→ Need **direct** measurement

Sub-keV Nuclear Recoils

Curves of maximum recoils for a W nucleus



Equivalent kinematics for several neutral particles:

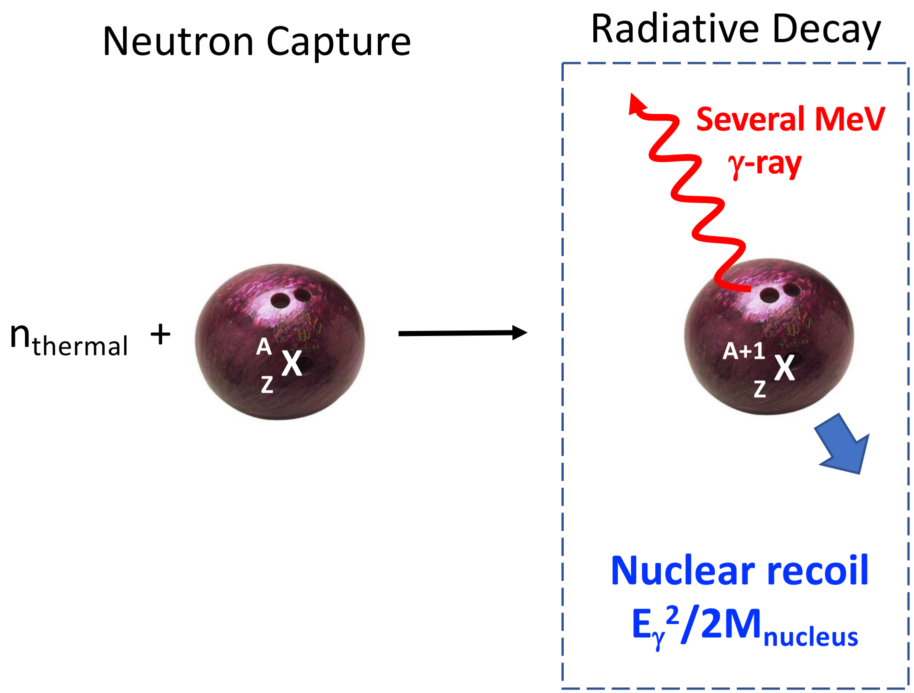
- MeV neutrinos
- GeV DM

Signal for new physics

- MeV γ's
- keV neutrons

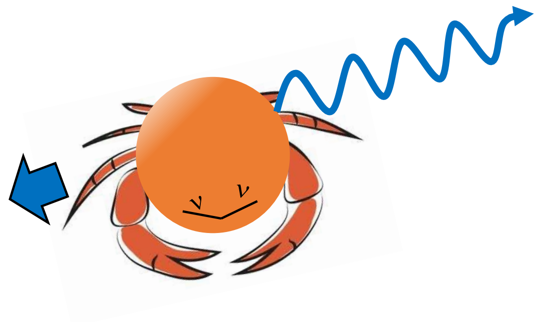
Background or … Calibration tools

Principle of the CRAB Method



1. Capture of a thermal (~25 meV) neutron
2. Emission of a single, several MeV, γ-ray by the compound nucleus. Escapes the detector with no energy deposit.
3. Pure signal of a calibrated nuclear recoil from the 2-body kinematics, in the 100 eV region.

CRAB Meets all Specifications

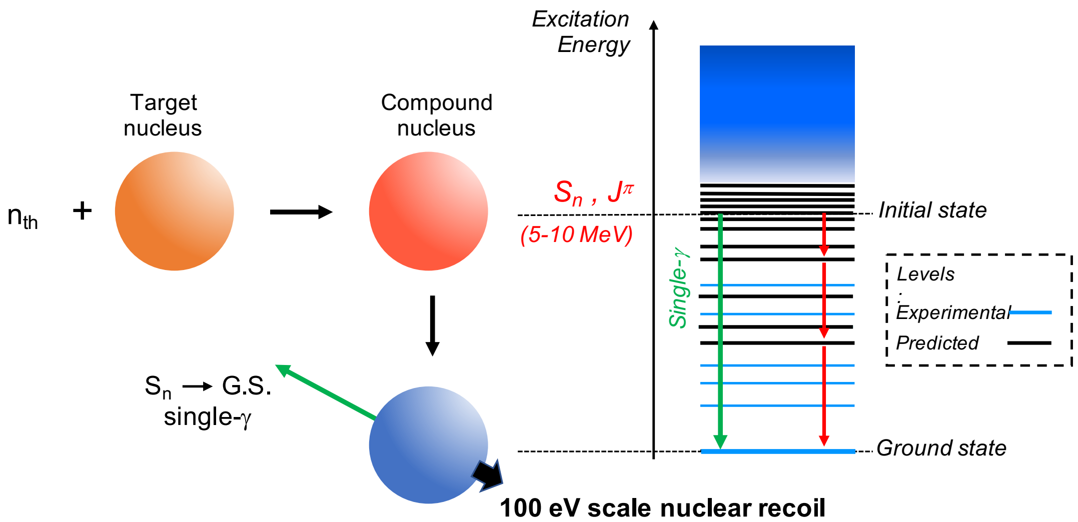


- With 1 barn-scale capture cross-sections, the **volume** of cm-size detectors is **uniformly probed.**
- The signal is induced by **nuclear recoils.**
- In the **100 eV energy range of interest** for physics.
- The process can be tagged by the detection in coincidence of the emitted high-E γ. In principle each isotope of the detector can provide a different calibration line.

→ Potential for low background and accurate calibration + linearity study.

A simple idea but implementation for heavy nuclei implies complex nuclear physics…

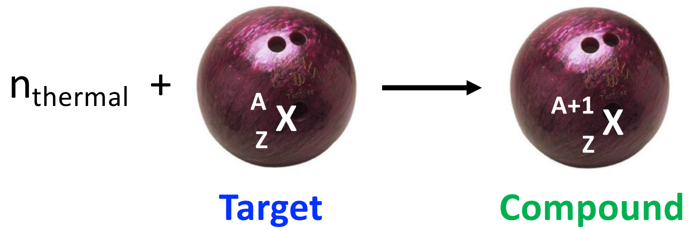
FIFRELIN Simulation Software



- FIFRELIN code designed to describe the de-excitation of all fission fragments O. Litaize et al., Eur. Phys. J. A 51, 1 (2015)
- After a n-capture, the compound nucleus has an excitation energy of S_n (neutron separation energy). γ-cascades are generated by sampling transitions in level schemes:
  - Including all measured transitions
  - Completed by level density models
- Predictions validated with the independent code DICEBOX + improved n-Gd detection in the STEREO detector H. Almazán et al., Eur. Phys. J. A 55, 183 (2019).

Calibration signal: peak of mono-energetic recoils from the single-γ transitions.

Good Candidates from Nuclear Data



- **Target nucleus:**
  - High natural isotopic abundance $\mathbf{Y_{ab}}$
  - High capture cross-section $\boldsymbol{\sigma_{n\text{-}\gamma}}$
- **Compound nucleus:**
  - High branching ratio for single-γ transition $\mathbf{I_\gamma^{Prim}}$
  - Long-lived final state
- Figure of Merit = $Y_{ab} \times \sigma_{n\text{-}\gamma} \times I_\gamma^{Prim}$ is favorable for several tungsten and germanium isotopes.

Target Isotope	Y_{ab} (%)	$\sigma_{n-\gamma}$ (barn)	S_n (keV)	I_γ^{Prim} (%)	Recoil (eV)	FoM
^{182}W	26.50	20.32	6191	13.94	112.5	7506
^{183}W	14.31	9.87	7411	5.83	160.3	823
^{184}W	30.64	1.63	5754	1.48	96.1	74
^{186}W	28.43	37.89	5467	0.26	85.8	281
^{70}Ge	20.52	3.05	7416	1.95	416.2	122
^{72}Ge	27.45	0.89	6783	0.0	338.7	-
^{73}Ge	7.76	14.70	10196	0.0	754.9	-
^{74}Ge	36.52	0.52	6506	2.83	303.2	54
^{76}Ge	7.75	0.15	6073	0.0	257.3	-

Feasibility Study

2011.13803 [physics.ins-det] - accepted in JINST

Two practical cases:

- **$CaWO_4$ – CRESST → NUCLEUS**
  Phys. Rev. D96, 022009 (2017)

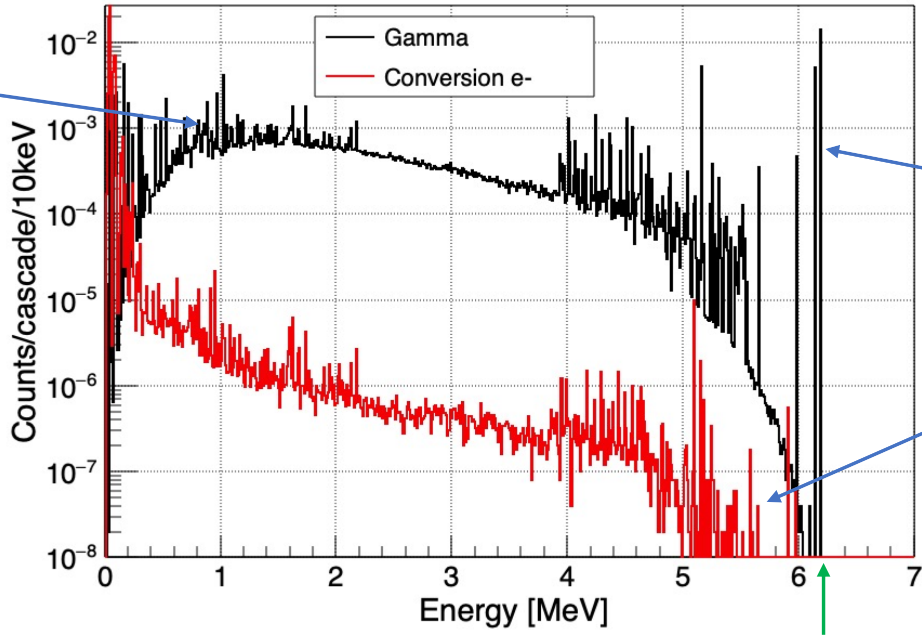
- **Ge – EDELWEISS → RICOCHET**
  Phys. Rev. D99, 082003 (2019)

Emitted γ and e^- Spectra from ^{183}W atoms

Continuous recoil spectrum

γ-rays of intermediate energy corresponding to multi-γ cascades and leading to a continuous spectrum of nuclear recoils.

n + ^{182}W → ^{183}W*



S_n energy

Line of calibrated recoils

Sizeable probability of single-γ transition (very favorable case of ^{183}W)

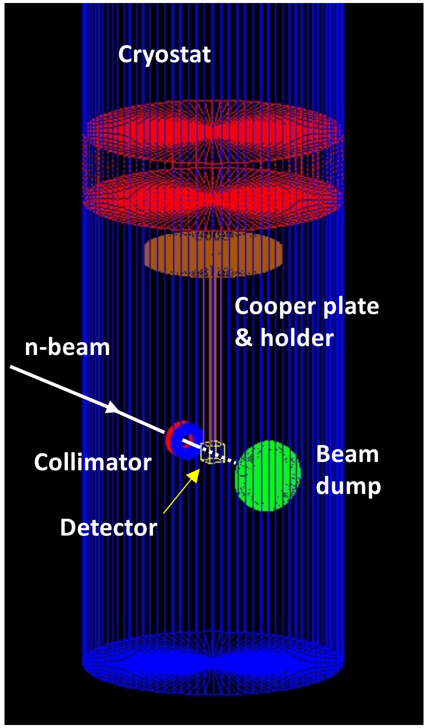
No conversion e^- for high-E γ's, protecting the nuclear recoils associated to single-γ transitions

GEANT4 Simulation of E_{dep} in the Detector

Specific physics lists & libraries

- EMZ: low E electromagnetic processes
- Neutron_HP: low E neutron physics
- NCRYSTAL: neutron interactions in crystals.

Detailed geometry



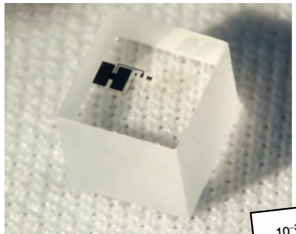
1st step:

- Send n_{th} beam.
- Record n-capture vertices in the crystal.
- Track scattered neutrons.

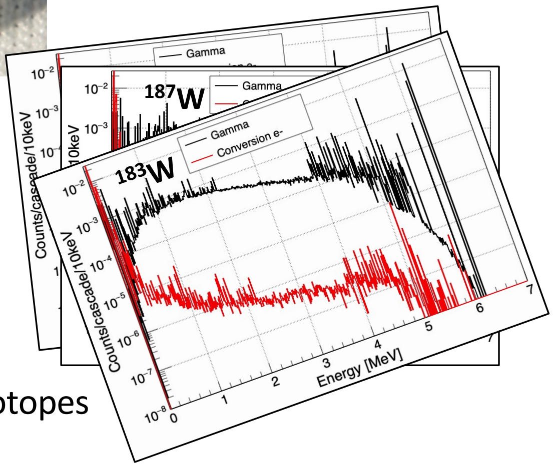
2nd step:

- From each n-capture vertex in the crystal, send a cascade of particles as predicted by FIFRELIN for the compound nucleus.
- Record the energy deposited in the detector.
- Compute the nuclear recoil from conservation of total momentum.
- Smear the total deposited energy by the expected resolution.

Favorable Nuclear & Electromagnetic Physics



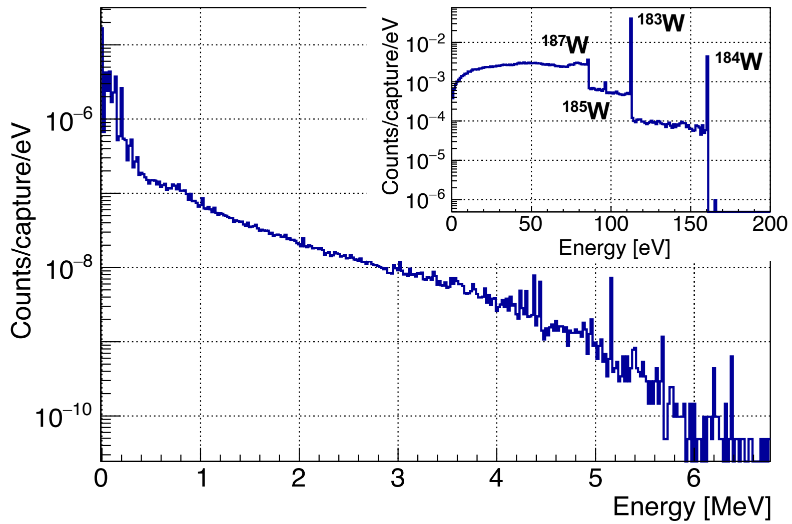
NUCLEUS
$CaWO_4$ crystal
5x5x5 mm^3



FIFRELIN
predictions
for all W isotopes

GEANT4

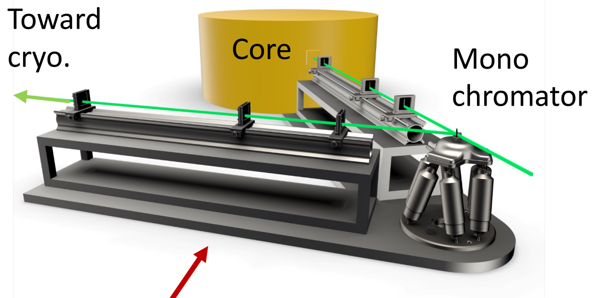
E_{dep} by nuclear recoils + γ-rays + conversion e^-
(no resolution effect)



- **Clear single-γ calibration lines above the continuous distribution from multi-γ cascades!**
- The 0-200 eV Region Of Interest (ROI) is dominated by pure nuclear recoils. Electromagnetic E deposits are either 0 or way above the ROI.

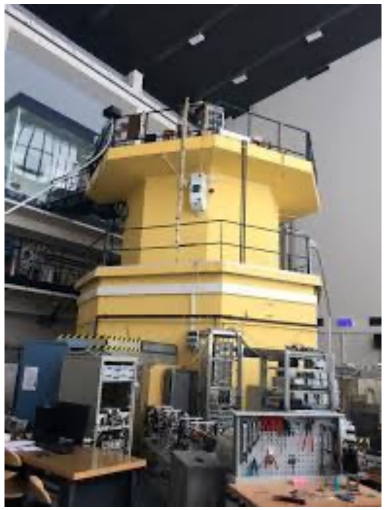
Experimental Setup

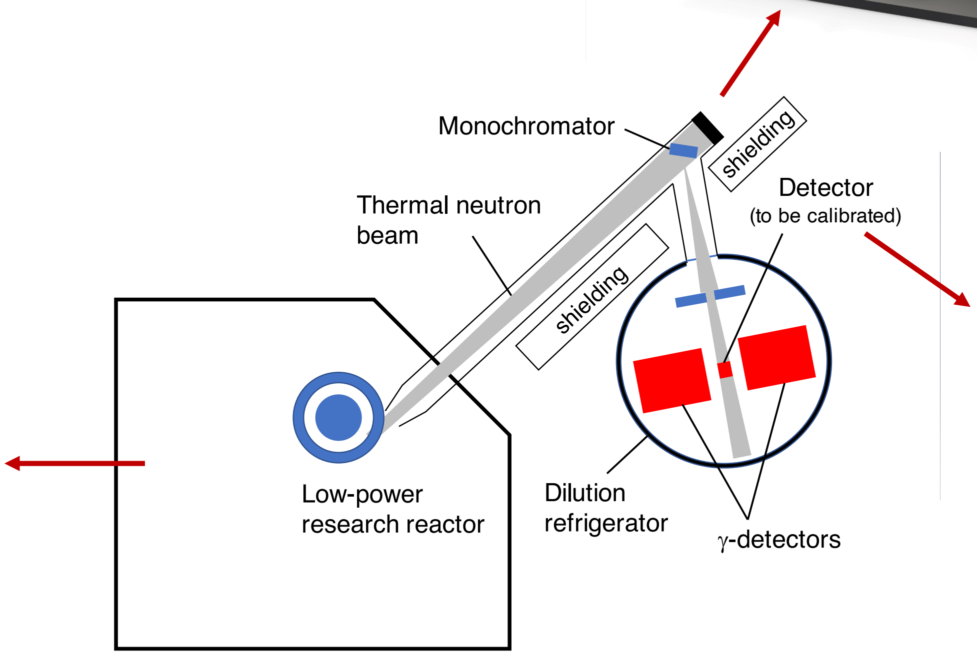
- High E deposits from the γ-cascades drives the maximum acceptable capture rate and incident neutron flux: **270 n/cm²/s** for a NUCLEUS crystal.

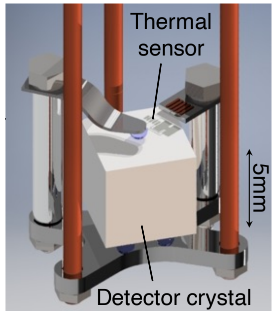


Standard beam-line equipment would provide a neutron beam within specs.

Vienna TRIGA-Mark-II reactor (250 kW)



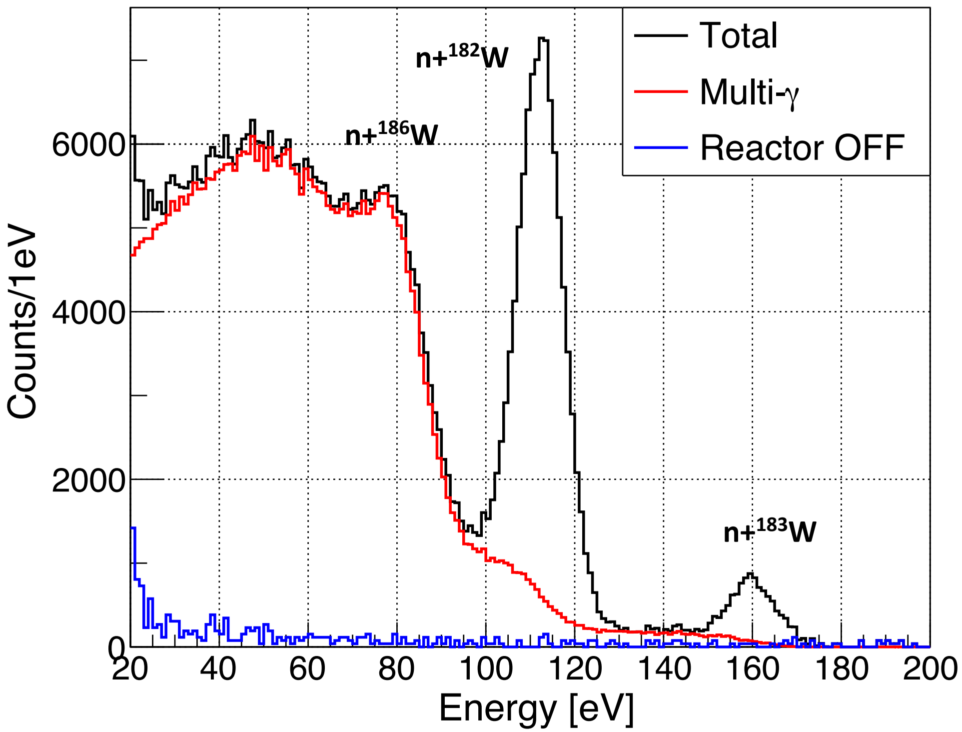




Low-mass detector holder to reduce background induced by neutron scattering.

Recoil spectrum in a CaW0$_4$ Nucleus crystal

Single rates



- Detector characteristics and background at surface taken as measured in *Phys. Rev. D96, 022009 (2017).* No significant background expected from the ambient γ and n fluxes measured on reactor site.

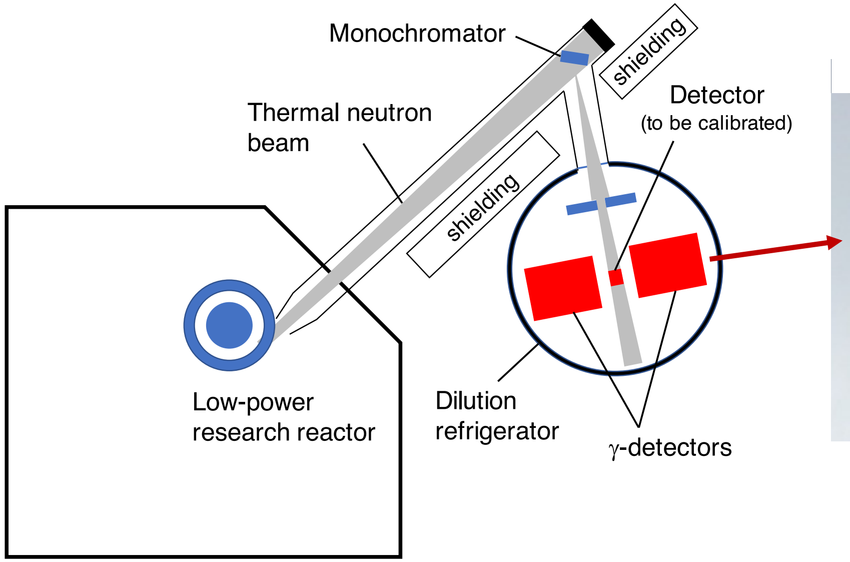
  - 0.76 g crystal, 5 eV energy resolution (1σ)
  - 3.4 day run with 270 n/cm^2/s
    → Total of 2.10^6 n-captures

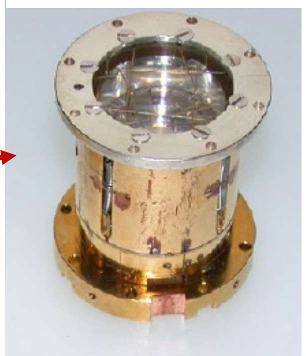
- **Clear calibration peaks at 112 and 160 eV !** 1% stat accuracy on the peak position achievable within 1h.

- Large and steep background underneath the 3rd peak at 86 eV…

γ-Tagging

Tagging the high-E γ of a primary transition cleans the continuous recoil spectrum from the other transitions/isotopes

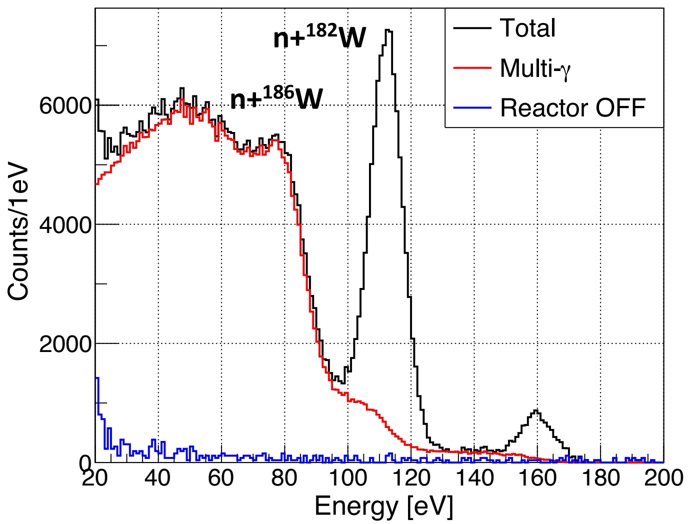




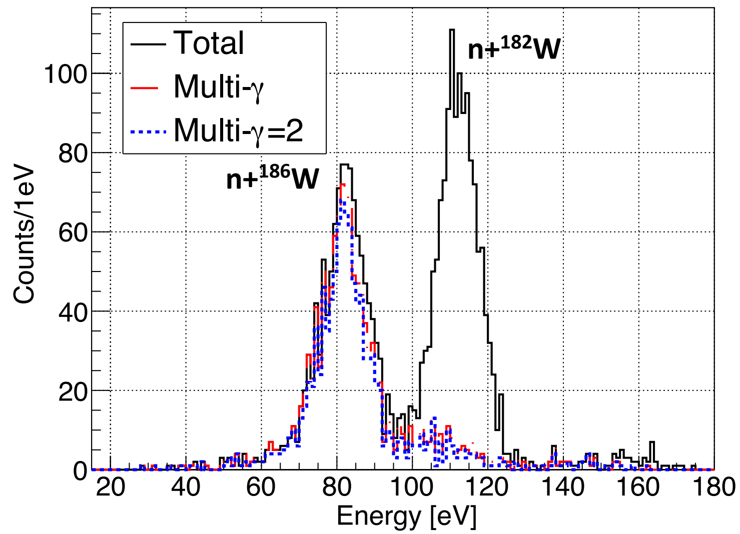
- Two Φ3” x 3” γ-detectors
- On both sides of the bolometer, 4 cm away.
- BGO considered here.
- Φ2cm x 2cm BGO crystal already tested at 20 mK. 5.2% E resol (FWHM) obtained for the ^{208}Tl line (2.615 MeV). *Nature 422, 876 (2003)*

γ-Tagging - $CaWO_4$ Case

Single mode



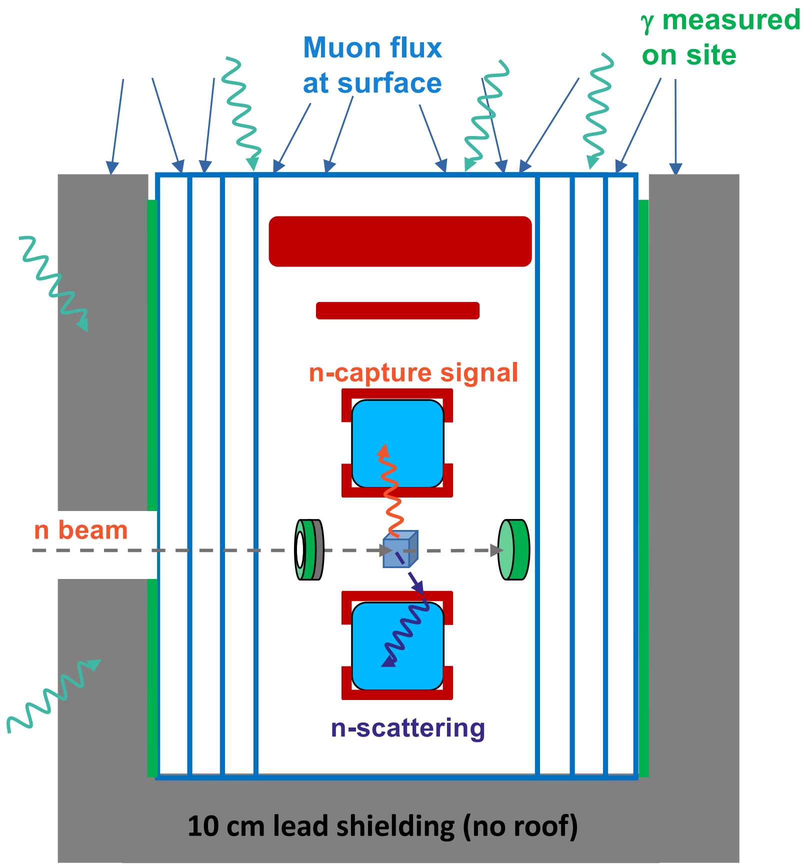
Coinc mode

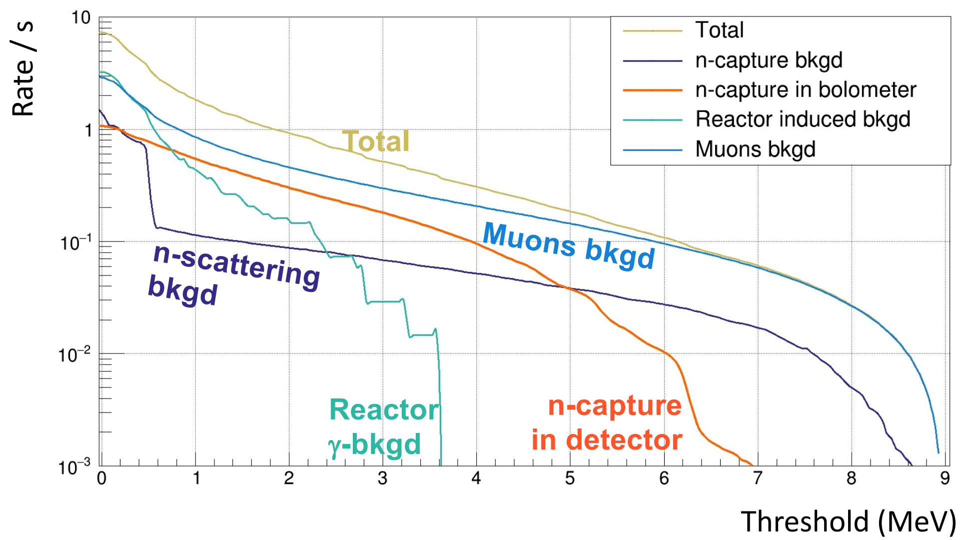


- Requesting **5.47±0.2 MeV in one of the two BGO** detectors (2σ E_{resol} cut) makes a 3rd calibration peak clearly visible around 80 eV.
- Same approach can be applied to the single-γ transitions of the other isotopes.

→ 3 peaks in the 80 – 160 eV range allowing an accurate study of the calibration coeff. and linearity

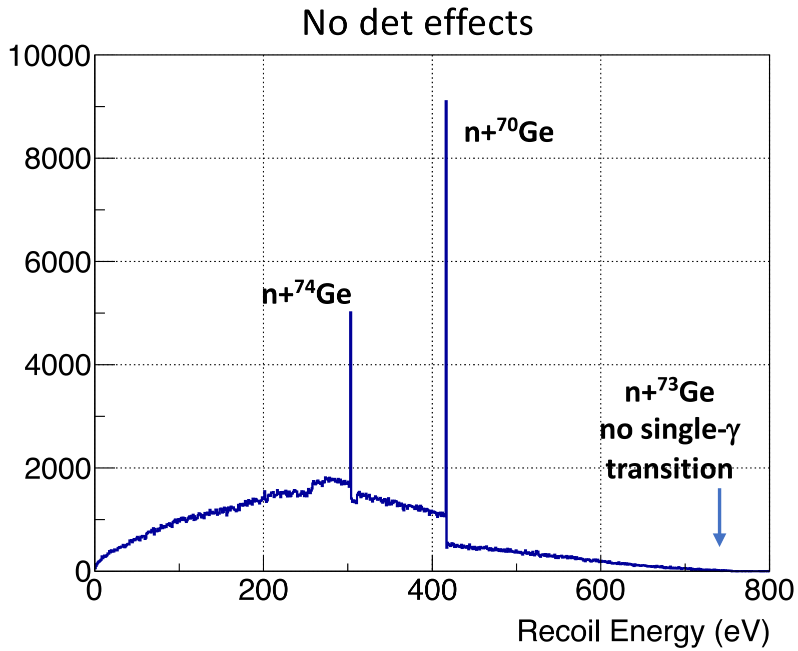
Single Rates in the BGO Detectors

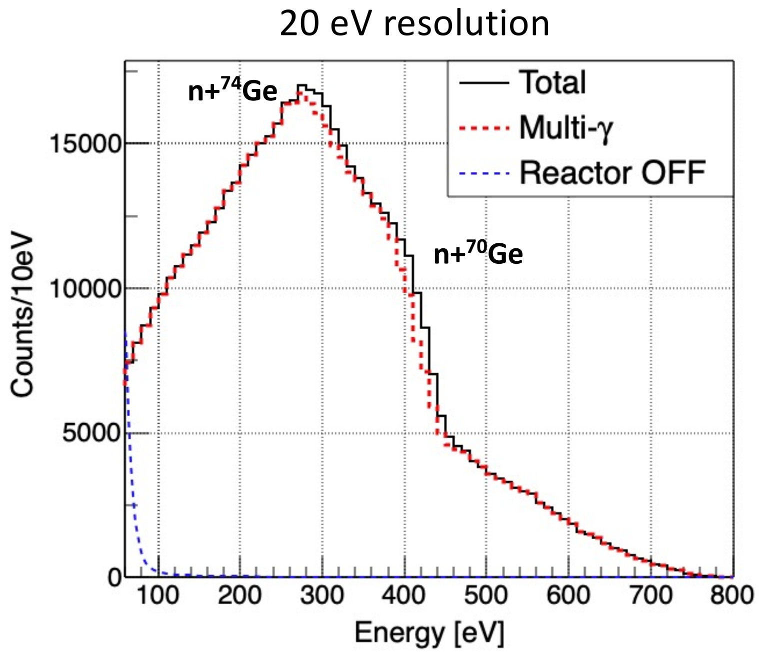




- Total rate ~10 Hz with no threshold. Dominant contribution from muons could be further reduced with a veto counter.
- No pile-up or dead-time issue, negligible accidental coincidences

Ge Case

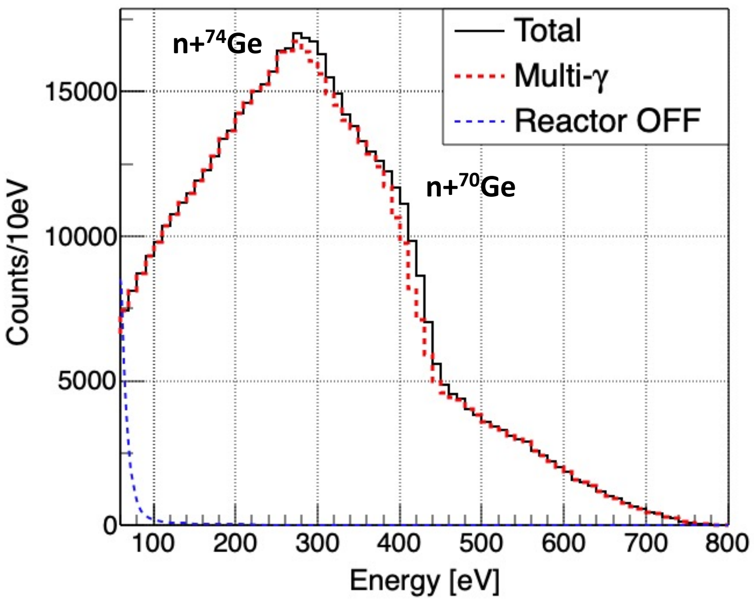




- **30 g Ge crystal** (1.8 cm size) from EDELWEISS R&D - *Phys. Rev. D99, 082003 (2019)*
- **5 n/cm²/s** → ~2 n-capture/s (slower time response in larger crystal)
- 7 day run
- Critical impact of **energy resolution** taken as 20 eV (1σ)

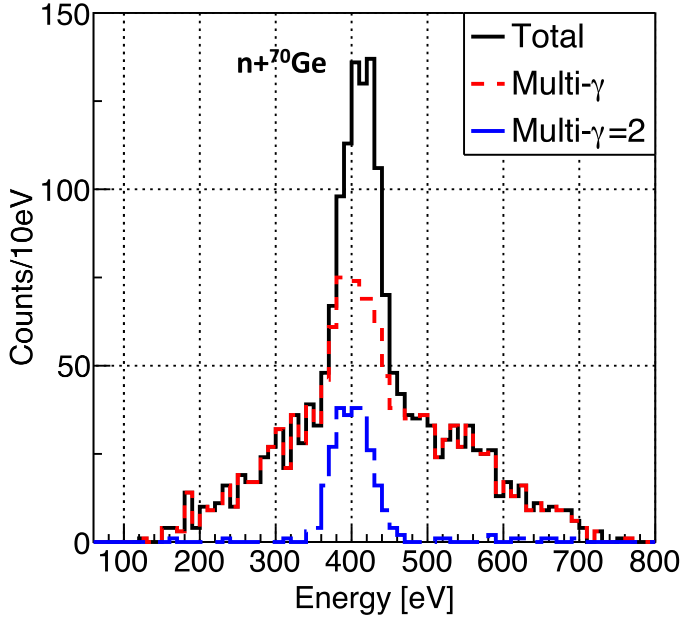
Ge Case

Single mode



- Calibration peak of n+^{70}Ge stands on top of a large and steep background.

Coinc mode: E_γ = 7.4±0.2 MeV in one of the BGO's



- Nice calibration peak at the expected 416 eV.
- Mean position retrieved with 1%-level bias from simple fit with 2 gauss functions – no detailed knowledge of the multi-γ background is needed.

Conclusion

- A detailed feasibility study shows a strong potential of the CRAB method with a unique combination of key features:
  - **Pure nuclear recoils**
  - In the (few) 100 eV range
  - Uniformly distributed in the detector volume
  - High accuracy expected from comfortable S/B and rates.

- **Transportation to other experiments** using simultaneous measurements with e-recoil techniques (X-rays sources, LED pulses)

- **Tungsten is a golden nucleus** → first validation of the method is possible with $CaWO_4$ crystals in single mode.

- **Coinc mode with γ-tagging:** allows application of the CRAB method to **Germanium** and/or lower resolution detectors!

Perspectives

- **First measurement foreseen in 2023 at the Vienna reactor**
- **Various materials** can be tested with the FIFRELIN+GEANT4 toolkit
- Measurement of **quenching factors** in the sub-keV regime
- Bolometer-γ-γ triple coincidence could probe even **lower recoils**
- The γ-tagging defines the **direction of the nuclear recoil** → sensitivity to the orientation w.r.t. the crystal lattice could be investigated…

CRAB proto-collaboration under construction

…