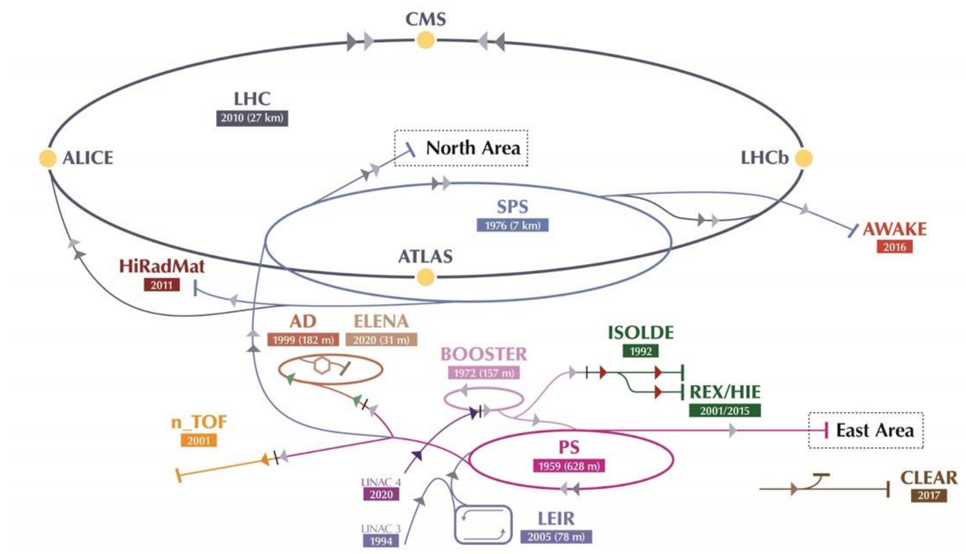
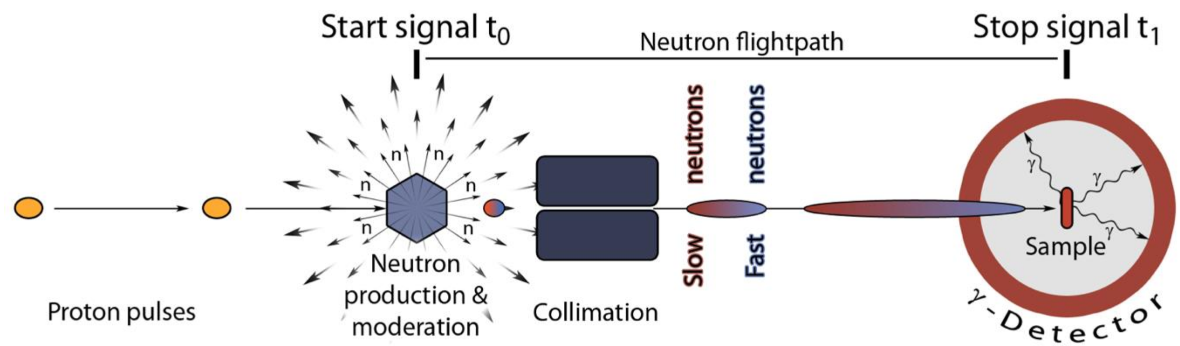
Results on Prompt Fission Gamma Rays with the STEFF detector at the n_TOF facility

Dr Toby Wright
Research Fellow
The University of Manchester

What is n_TOF





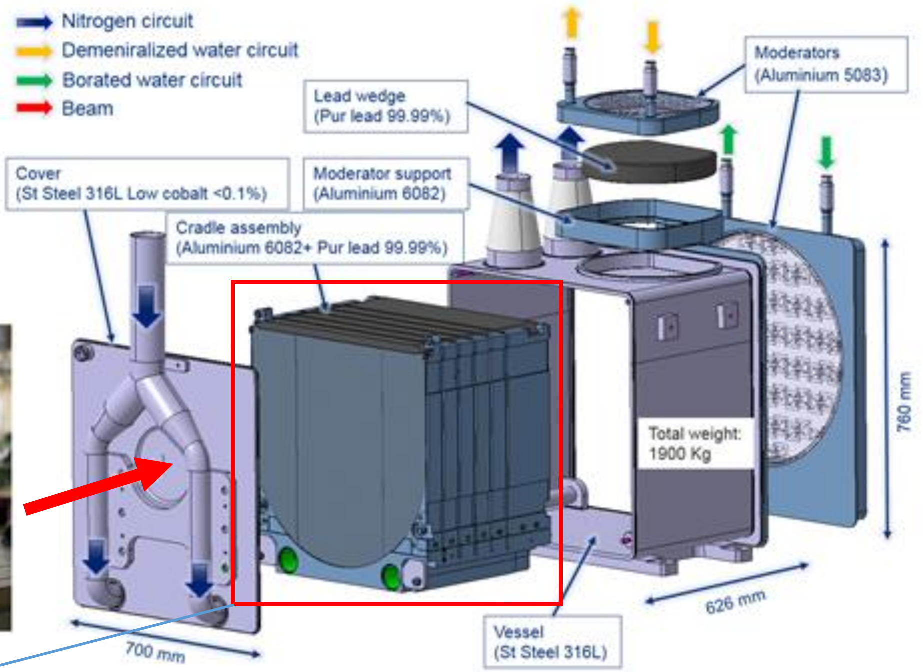
150 researchers
40 research institutions/teams
20 PhD students/year

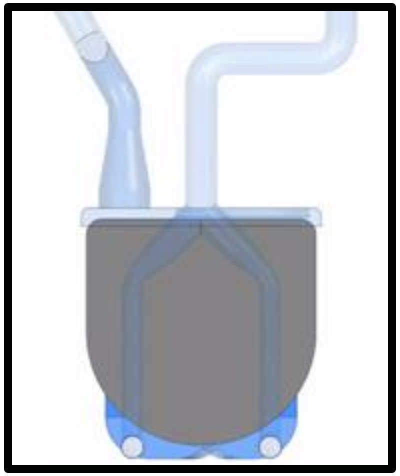
n_TOF Youtube

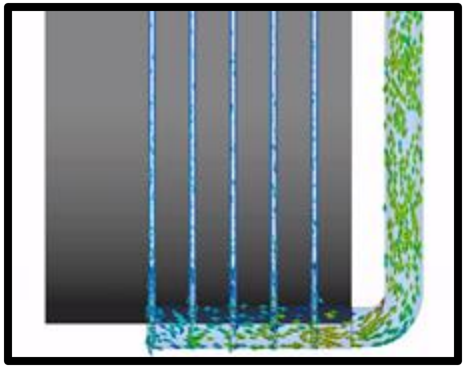
The n_TOF facility – 3rd generation target

- 20 GeV/c protons
- 8.5 x 10^{12} protons/pulse
- Max repetition rate ~ 0.8 Hz

- 7 ns rms pulse width
- 2 cm FWHM
- ~ 2 cm FWHM (capture mode)







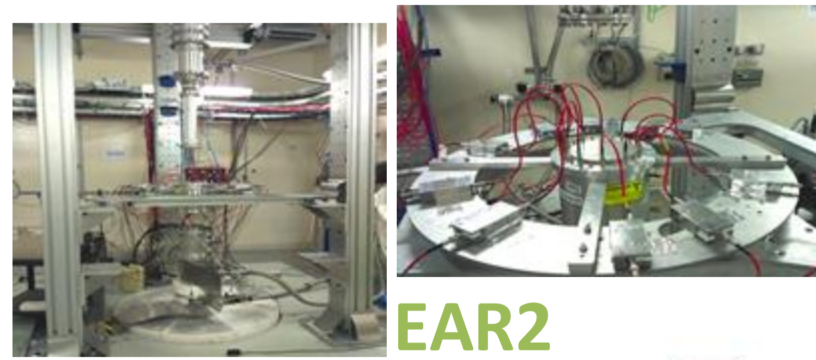
N_2 gas cooling to avoid Pb corrosion and contamination of the cooling circuit

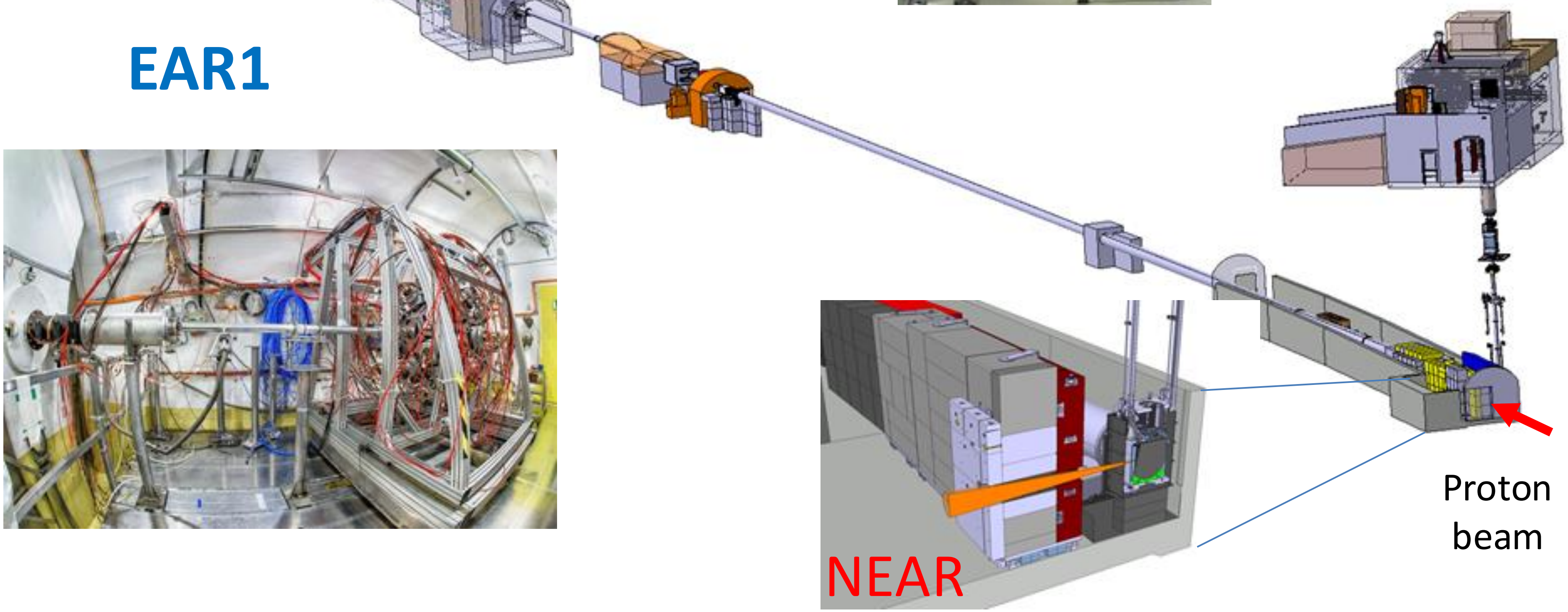
R Esposito et al. *Phys. Rev. Accel. Beams* **24**, 093001 (2021)

The n_TOF facility: EAR1 + EAR2 + NEAR

Three experimental areas (EAR)

- Horizontal flight path: **EAR1** at 200 m
- Vertical flight-path: **EAR2** at 20 m
- **NEAR** at 3m distance: activation measurements

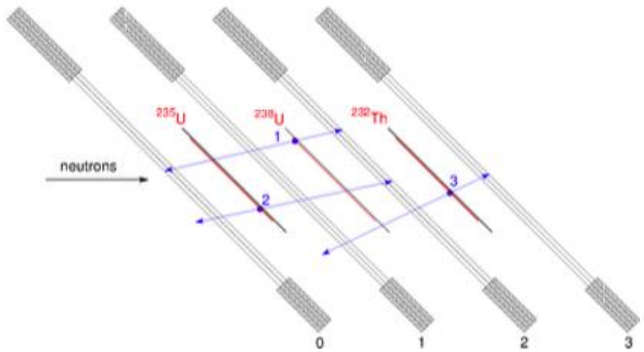




Fission at n_TOF

N. Colonna et al., “The fission experimental programme at the CERN n TOF facility: status and perspectives”, *Eur. Phys. J. A (2020) 56: 48*

PPAC



MicroMegas

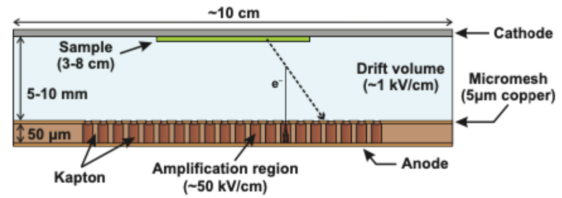


Fig. 20. An illustration of the basic principle of operation of a Micromegas detector (not to scale). An ionising particle (*e.g.* a fission fragment) ionises the gas in the drift region. The ionisation electrons drift towards the micromesh and are multiplied inside the amplification region, inducing a signal. Indicative values are given for the electrical field strengths and

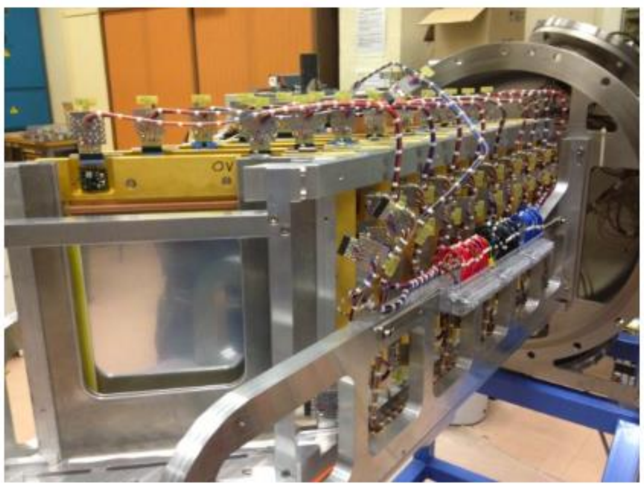
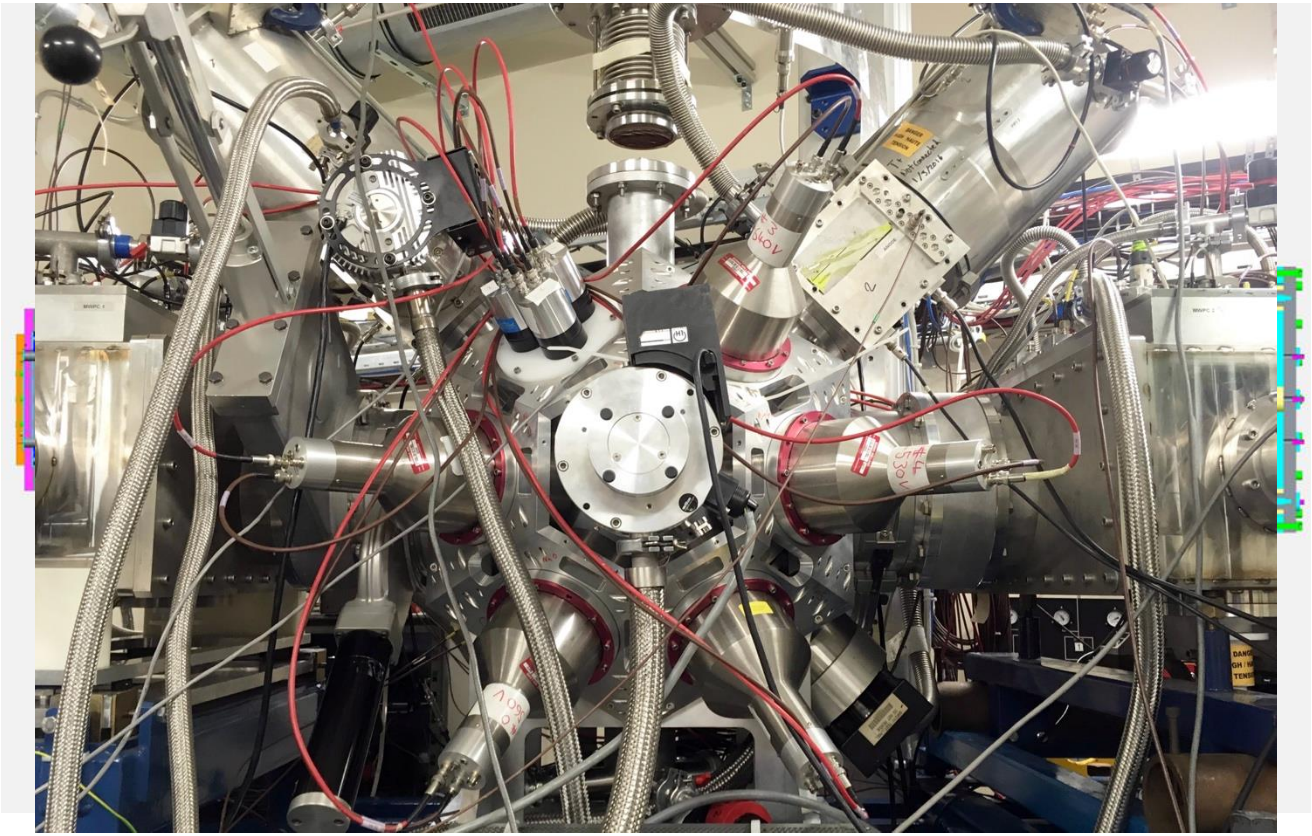


Fig. 15. PPAC and target assembly layout for Phase-II (top drawing). Ten detectors and nine samples are mounted in the scattering chamber tilted by 45° with respect to the neutron beam direction, as seen in the photograph. The sample holders are visible between the PPACs.

Fig. 23. A setup consisting of ten Micromegas detectors, coupled with six ^{241}Am samples and two ^{235}U and ^{238}U reference samples, before insertion into the chamber.

STEFF



Experimental Campaign and motivation

100 μg/cm² ^{235}U target, 81 mm diameter disc, **0.7 μm Al backing** (CEA ORSAY))

- *2E2v* measurement for fission yields
- Accurate measurement of the average energies and multiplicities of prompt fission γ-rays

Data Bank » Nuclear Data Services

NEA Nuclear Data High Priority Request List

HPRL Main	High Priority Requests (HPR)	General Requests (GR)	Special Purpose Quantities (SPQ)		New Request	EG-HPRL (SG-C)
			Standard	Dosimetry		

Results of your search in the request list

Requests are shown from the following list(s):
High Priority (H)

Explanations of each column can be found in the table heads. To view the details of a request, please click on the **link symbol** after the request ID. To send a comment on a particular entry, please view the request, and click on the **'letter'** symbol there.

ID	View	Target	Reaction	Quantity	Energy range	Sec.E/Angle	Accuracy	Cov	Field	Date
2H		8-O-16	(n,a),(n,abs)	SIG	2 MeV-20 MeV		See details	Y	Fission	12-SEP-08
3H		94-PU-239	(n,f)	prompt g	Thermal-Fast	Eg=0-10MeV	7.5	Y	Fission	12-MAY-06
4H		92-U-235	(n,f)	prompt g	Thermal-Fast	Eg=0-10MeV	7.5	Y	Fission	12-MAY-06
8H		1-H-2	(n,el)	DA/DE	0.1 MeV-1 MeV	0-180 Deg	5	Y	Fission	16-APR-07

ELSEVIER

Nuclear Data Sheets 163 (2020) 261–279

www.elsevier.com/locate/nds

Evaluation of the Prompt Fission Gamma Properties for Neutron Induced Fission of ^{235,238}U and ^{239}Pu

I. Stetcu,[1,*] M.B. Chadwick,[1] T. Kawano,[1] P. Talou,[1] R. Capote,[2] and A. Trkov[2]

[1] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

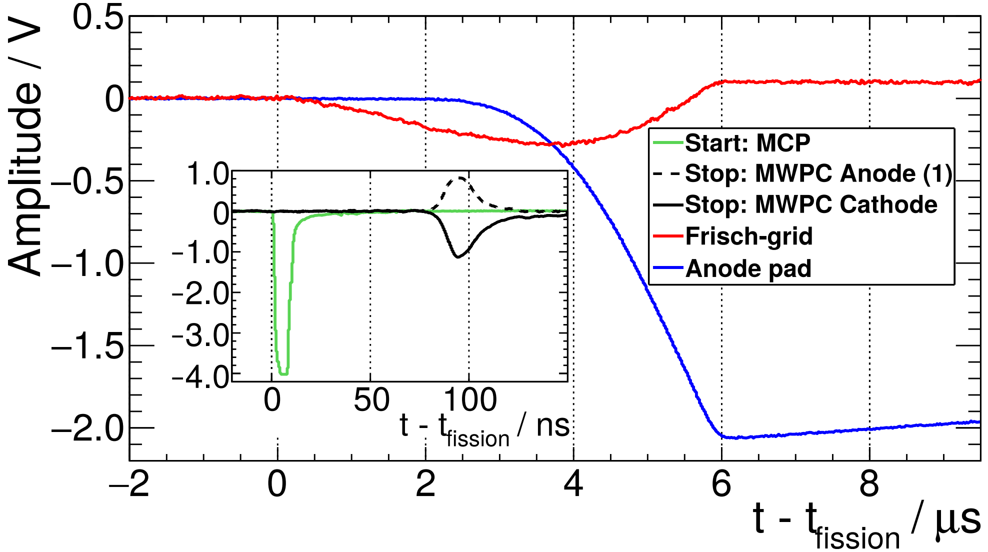
[2] *International Atomic Energy Agency, Vienna-A-1400, PO Box 100, Austria*

(Received 2 April 2019; revised received 19 July and 15 August 2019; accepted 17 August 2019)

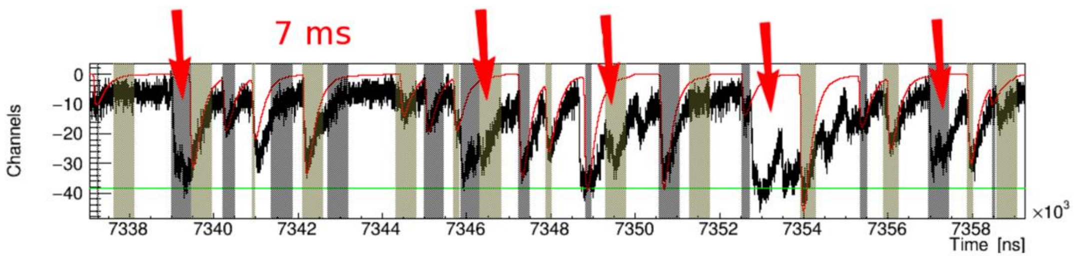
TABLE I. Evaluation of prompt fission gamma-ray properties for ^{235}U($n_{\rm th}$,f): comparison between the current evaluations, experimental data and CGMF calculations. We present the average gamma multiplicity, $\langle\nu_\gamma\rangle$, the average gamma-ray energy, $\langle\varepsilon_\gamma\rangle$, and the total prompt gamma energy released, $\langle E_\gamma^{tot}\rangle$. All energies are in MeV. Similar time coincidence windows have been employed in all experiments included in this compilation, ranging from 6 to 10 ns. The current table is an updated version of Table XXIII in Ref. [1].

	$E_{\rm thresh}$	$\langle\nu_\gamma\rangle$	$\langle\varepsilon_\gamma\rangle$	$\langle E_\gamma^{tot}\rangle$
ENDF/B-VIII.0	0	8.58	0.85	7.28
ENDF/B-VII.1		7.04	0.94	6.60
JEFF-3.3		8.74	0.81	7.05
JENDL 4		7.43	0.94	6.96
CGMF		7.94	0.78	6.20
ENDF/B-VIII.0	0.10	8.19	0.89	7.25
ENDF/B-VII.1	0.10	6.87	0.96	6.59
Pleasonton [31]	0.09	6.51(30)	0.99(7)	6.43(30)
Oberstedt 2013 [32, 33]	0.10	8.19(11)	0.84(2)	6.92(9)
Oberstedt 2017 [34]	0.10	7.22	0.87	6.27
CGMF	0.10	7.01	0.87	6.15
ENDF/B-VIII.0	0.14	7.78	0.93	7.21
ENDF/B-VII.1	0.14	6.72	0.98	6.57
Verbinski [35]	0.14	6.7(3)	0.97(5)	6.51(30)
Oberstedt 2017 [33]	0.14	7.01(18)	0.89(4)	6.24(20)
CGMF	0.14	6.68	0.91	6.10
Chyzh [36]	0.15	7.35		8.35
Peelle [37]	0.15	7.45(35)	0.99(7)	7.18(26)
ENDF/B-VIII.0	0.40	5.47	1.21	6.60
ENDF/B-VII.1	0.40	5.30	1.17	6.17
Jandel [38]	0.40	4.92	1.20	5.89
CGMF	0.40	4.87	1.19	5.78
Valentine [39, 40]				6.53(3)

Analysis – signal processing

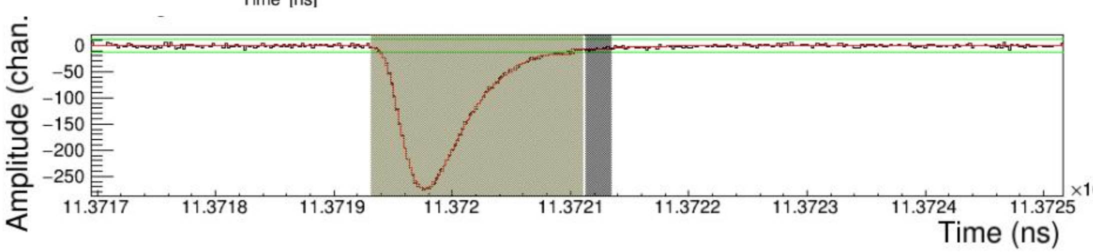


n_TOF Pulse Shape Analysis routine -> Fission Event Builder -> Waveform analysis -> MariaDB Database

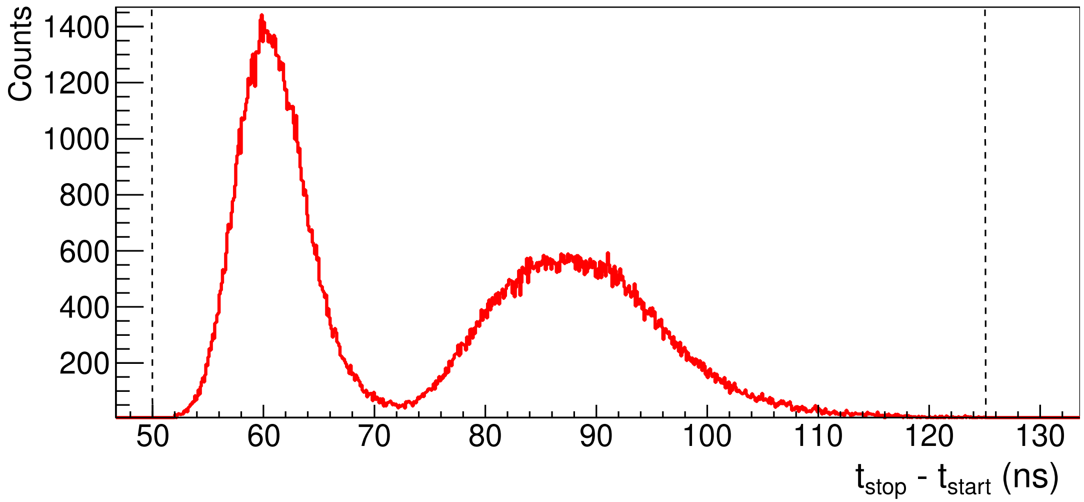


Accept events with E_n < 8 meV

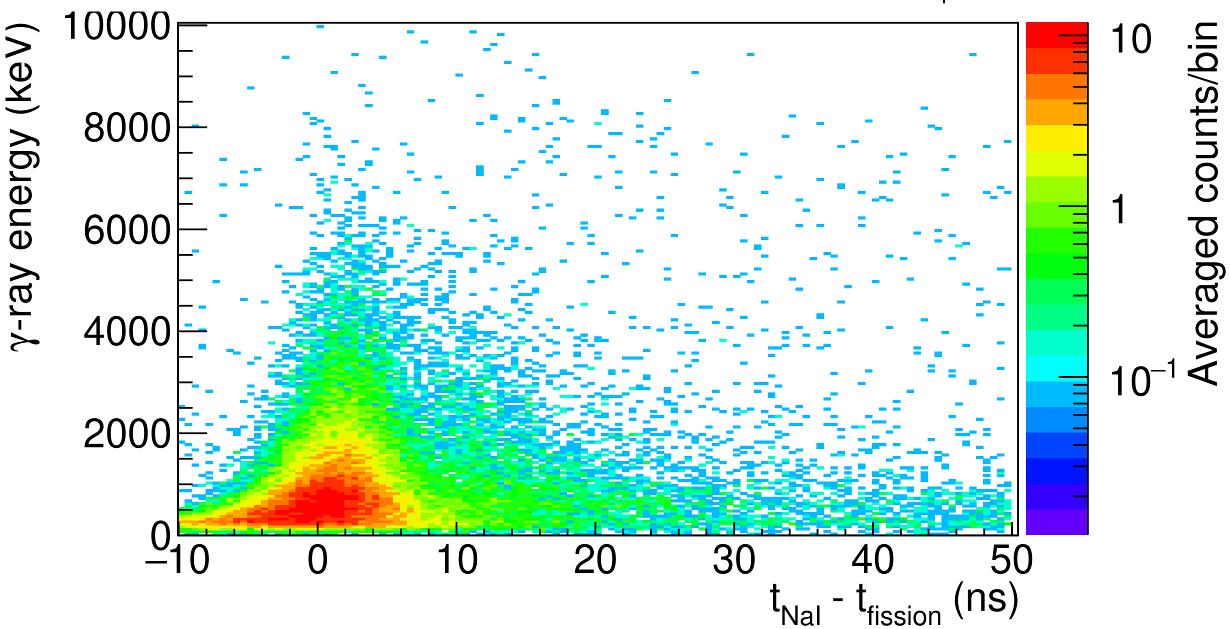
High count rate in scintillators except at very large time of flight (low neutron energy)



Analysis – Fission Fragment Time-of-Flight and γ-Ray Energy



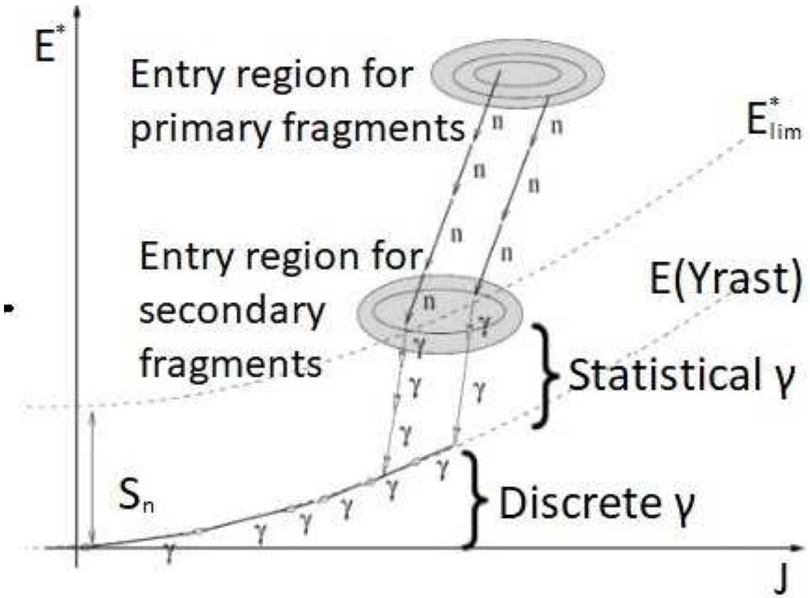
The Fission Fragment TOF spectrum. The dashed lines indicate the gate applied to identify a fission event.



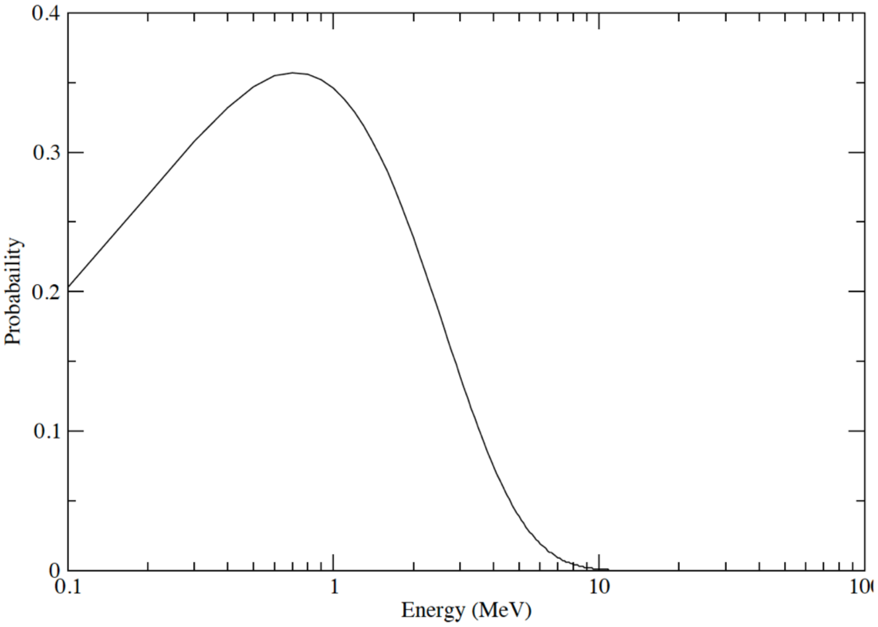
2D Histogram of γ-ray energy versus time detected with reference to the time of fission. The peak corresponding to prompt fission γ-rays is clearly visible, along with other sources of counts.

Understanding detected γ-ray energy: Prompt Fission Neutron Contribution

$$P(E) = a\sinh(\sqrt{2.29E})e^{-(bE)}MeV^{-1}$$



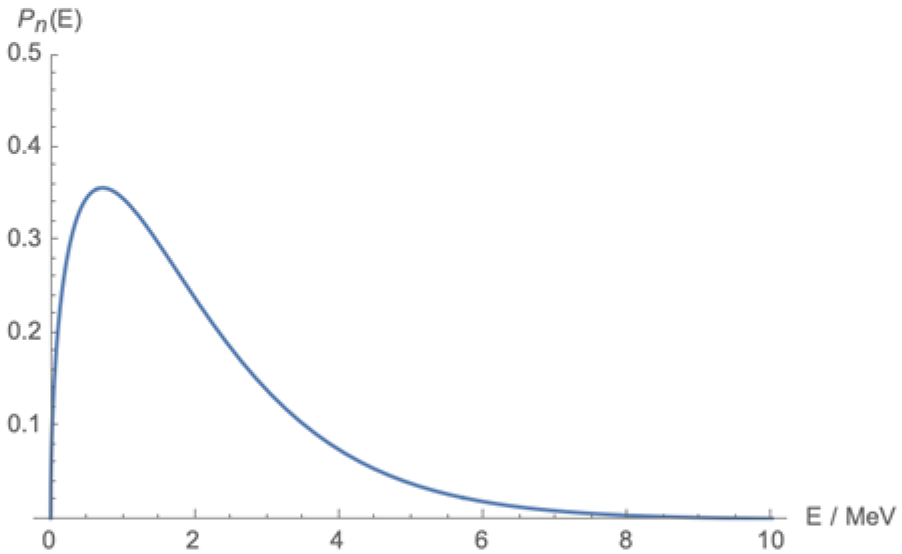
Complex situation with multiple γ-rays and neutrons emitted per fission

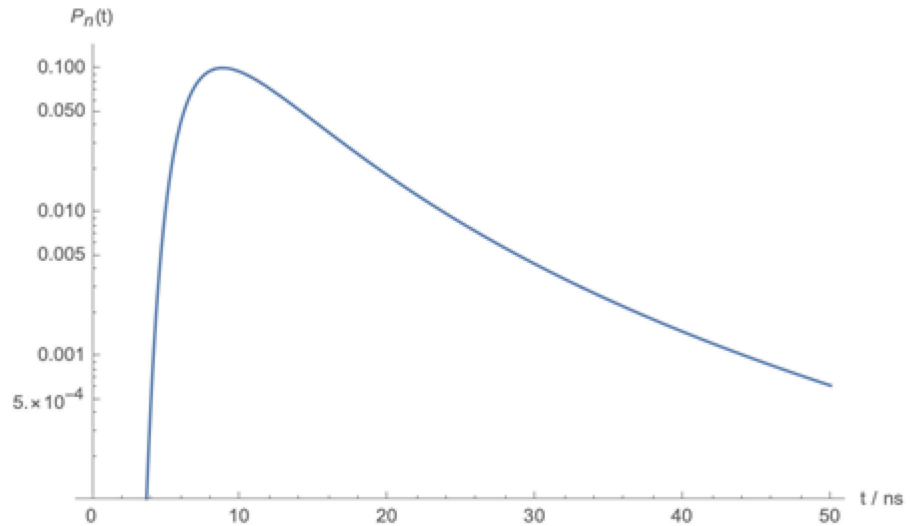


Theoretical *Watt distribution* for prompt fission neutron's energy distribution (boosted Maxwellian)

Understanding detected γ-ray energy: Prompt Fission Neutron Contribution

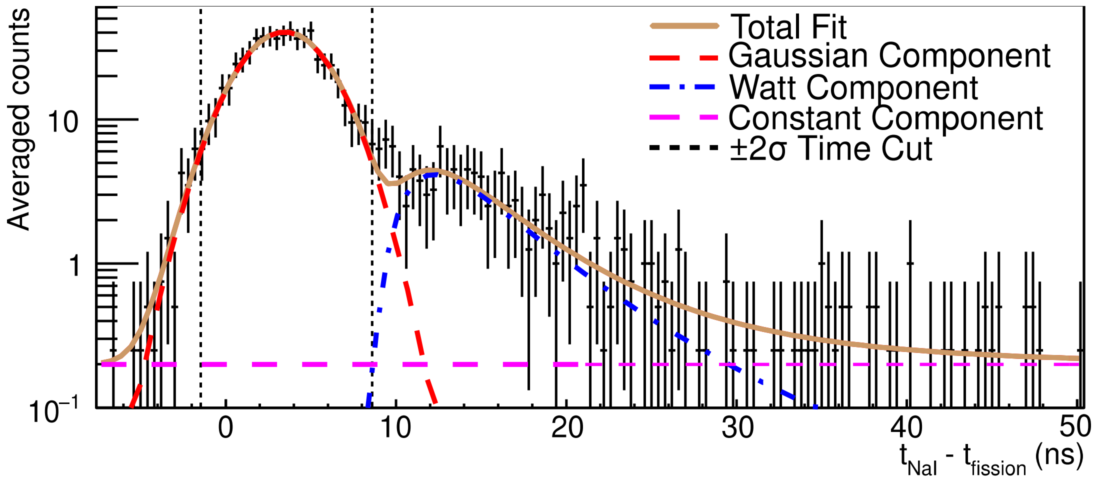
P(E) → P(t)





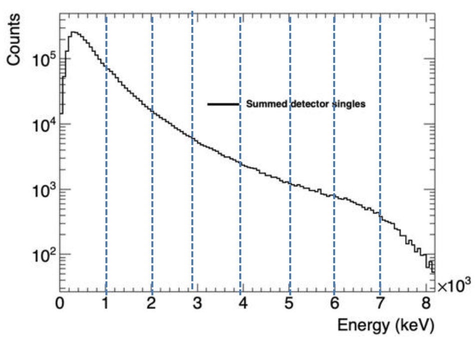
$$F(t) = \frac{a_n \sigma_n^2 e^{-\frac{208.489\sigma_n^2}{(t-\mu_n)^2}} \sinh\left(\frac{20.42\sigma_n}{t-\mu_n}\right)}{(t-\mu_n)^3}$$

Understanding detected γ-ray energy: Prompt Fission Neutron Contribution

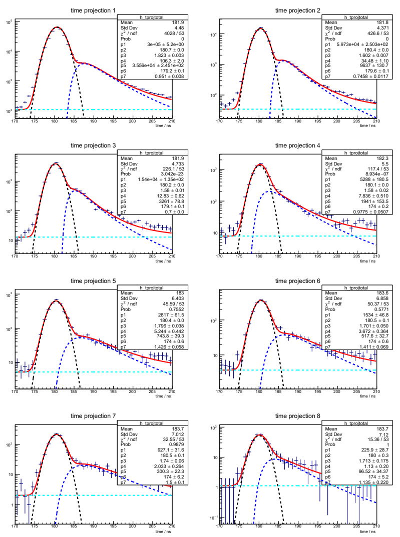


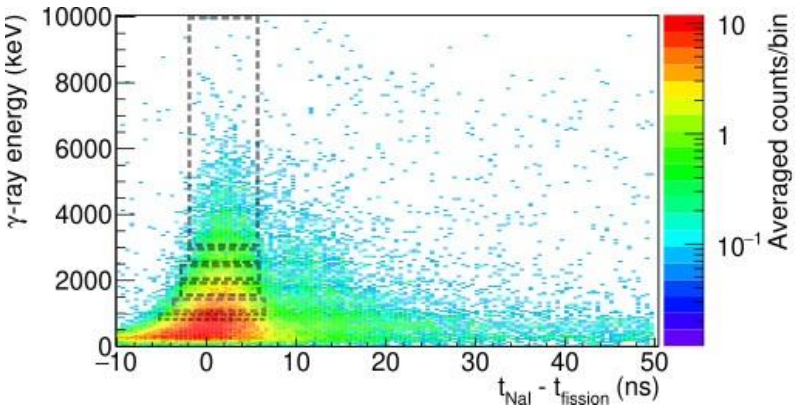
Our timing spectra contains counts around a centroid from fission γ-rays following a gaussian distribution and neutrons following a Watt distribution and a constant background.

- How do the various contributions change with γ-ray energy?



Perform fit for different γ-ray energy regions.





Need to average detectors to achieve statistics

Understanding detected γ-ray energy: Prompt Fission Neutron Contribution

Can estimate contribution in timing spectrum from neutrons.

- Use narrow (2 sigma) cut in time to reduce background to negligible levels
- Use wide cut in time to include all counts

Two methods agree within 1/2% for the mean energy and multiplicity respectively

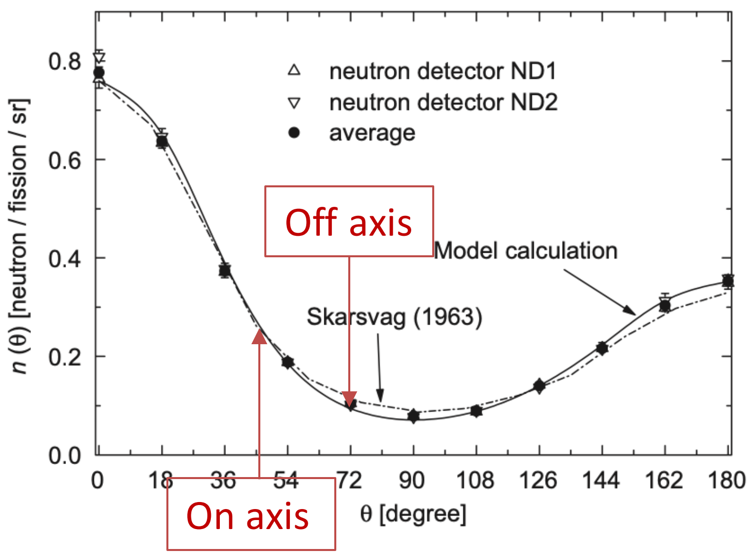
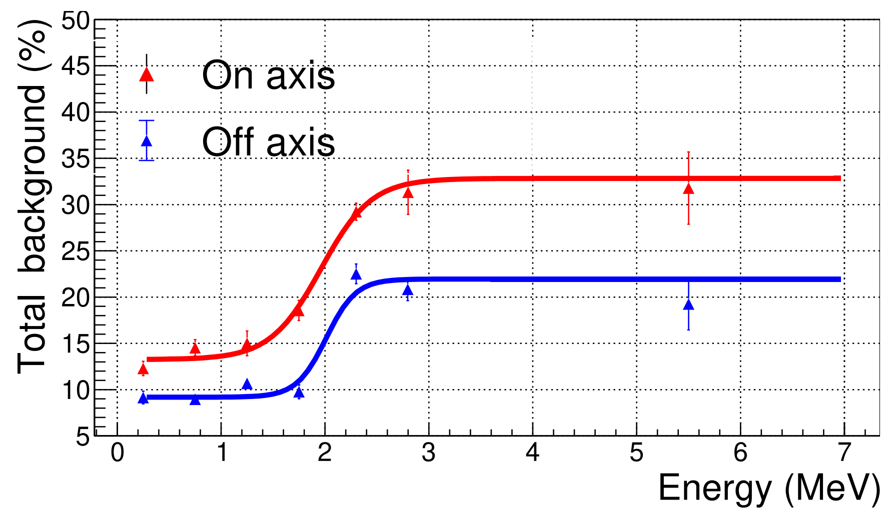


Fig. 7. Fission neutron yield as a function of the angle between neutron exit direction and the direction of motion of the light fragments.



A.S. Vorobyev et al. / Nuclear Instruments and Methods in Physics Research A 598 (2009) 795–801

Understanding detected γ-ray energy: Anisotropy correction

PHYSICAL REVIEW VOLUME 133, NUMBER 3B 10 FEBRUARY 1964

Directional Correlation of Fission Fragments and Prompt Gamma Rays Associated With Thermal Neutron Fission*†

Marvin M. Hoffman
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

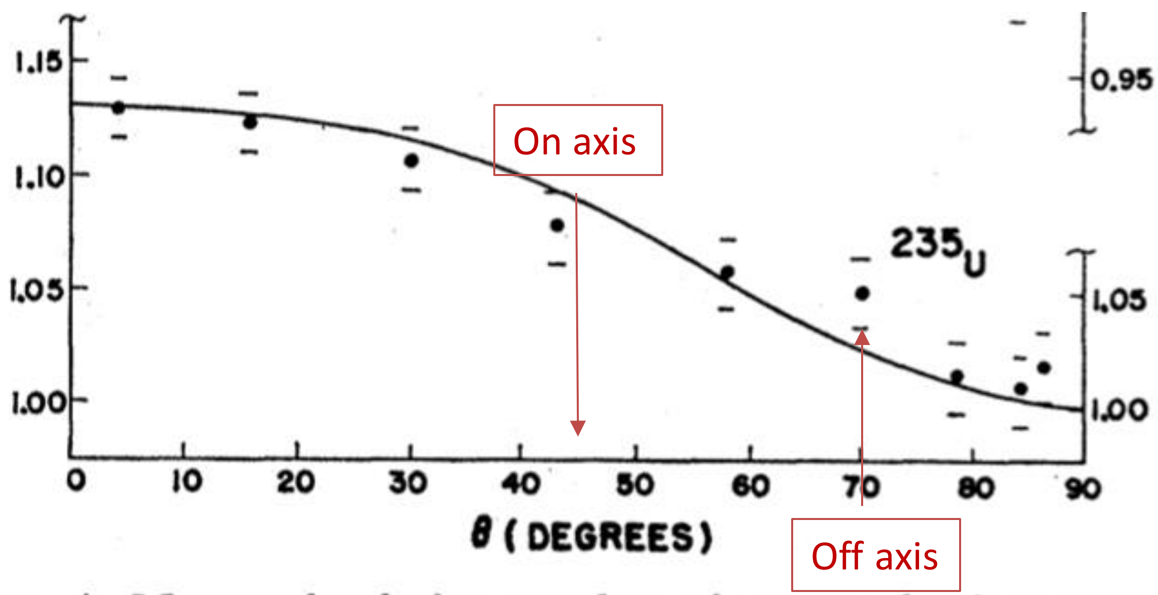
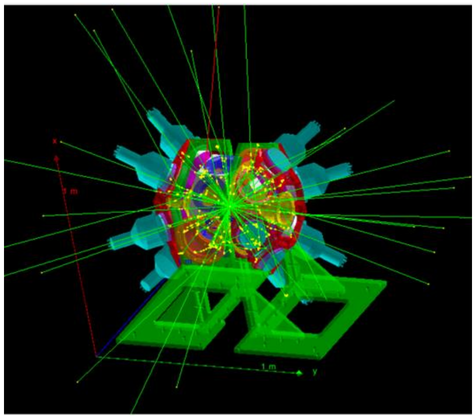


Fig. 4. Measured relative number of γ rays having energy greater than 250 keV as a function of the angle to the fragment direction. The solid curves are the results of a least-squares fit of

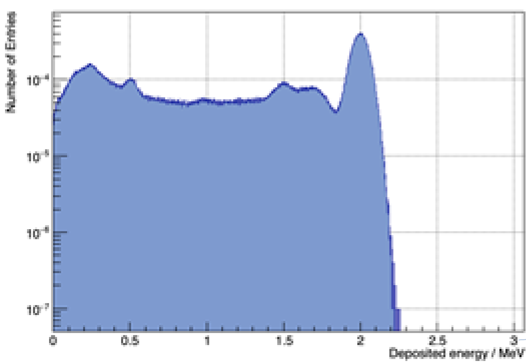
On axis measure ~1.5% higher than the mean, off axis measure ~4.5% lower

Final correction before averaging all detectors

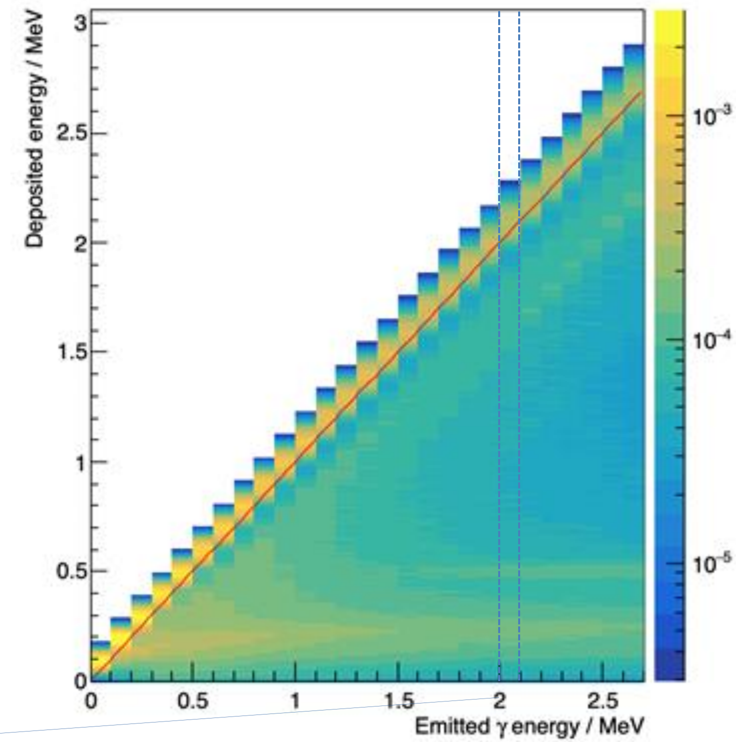
Measured -> Emitted γ-ray energy: Deconvolution



Geant4 simulation of the STEFF array

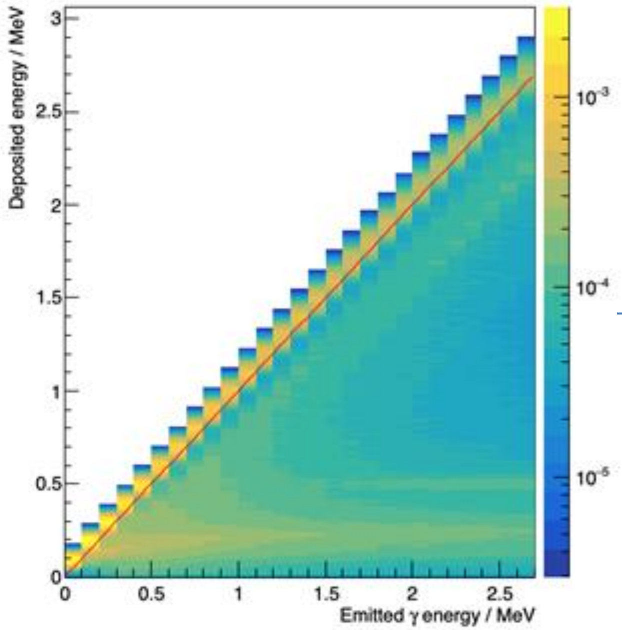


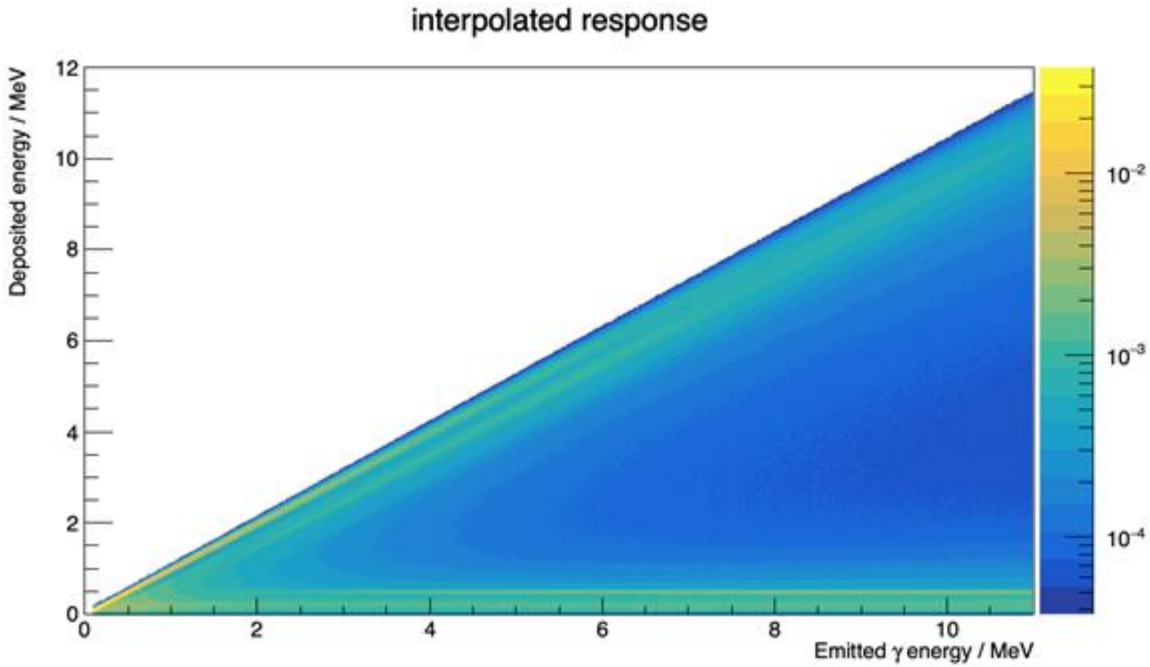
Simulated response to 2 MeV γ-ray



Response matrix

Measured -> Emitted γ-ray energy: Deconvolution





100 keV coarse response matrix

1 keV smooth response matrix

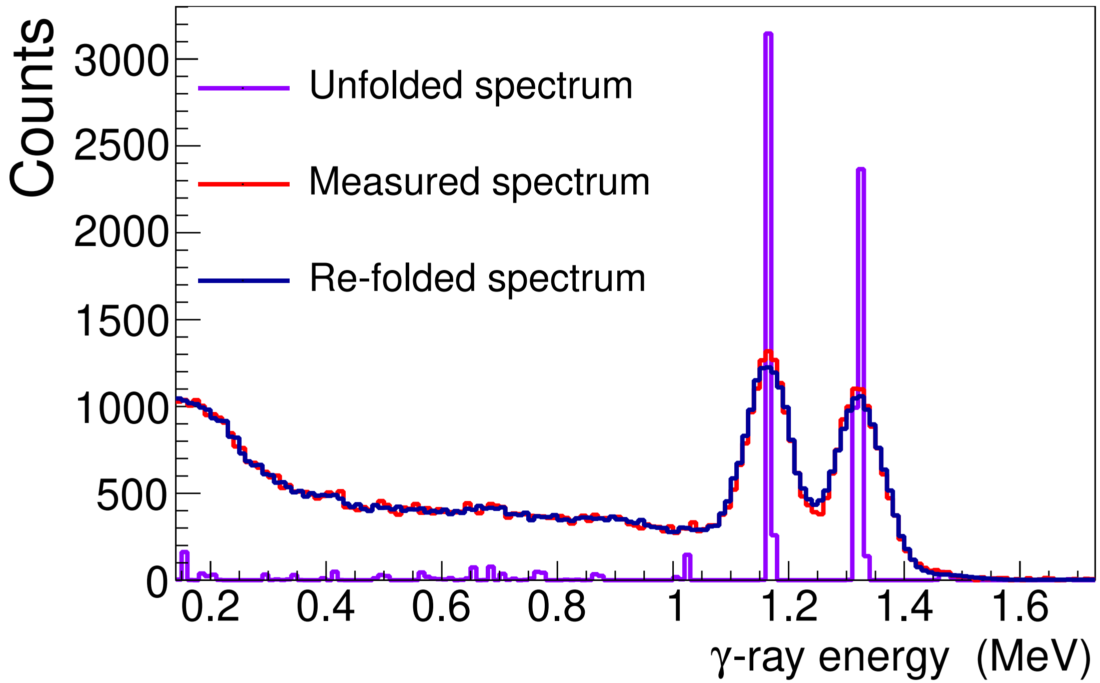
Measured -> Emitted γ-ray energy: Deconvolution - Gold method

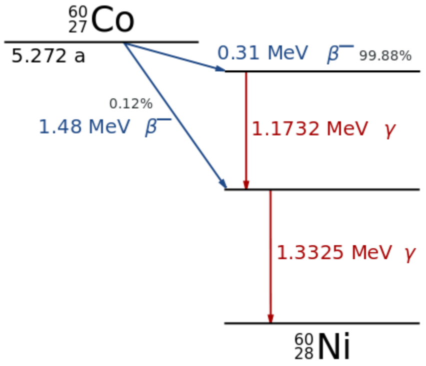
'Gold' deconvolution algorithm

$$x^{(n+1)}(i) = \frac{y'(i)}{\sum_{m=0}^{M-1} A_{im} x^{(n)}(m)} x^{(n)}(i) \qquad x^{(0)} = [1,1,\dots,1]^T$$

Jandel, M., Morháč, M., Kliman, J., Krupa, L., Matoušek, V., Hamilton, J.H., Ramayya, A.V.: Decomposition of continuum γ-ray spectra using synthesized response matrix. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **516**(1), 172–183 (2004). https://doi.org/10.1016/j.nima.2003.07.047

Validate the response matrix





Results

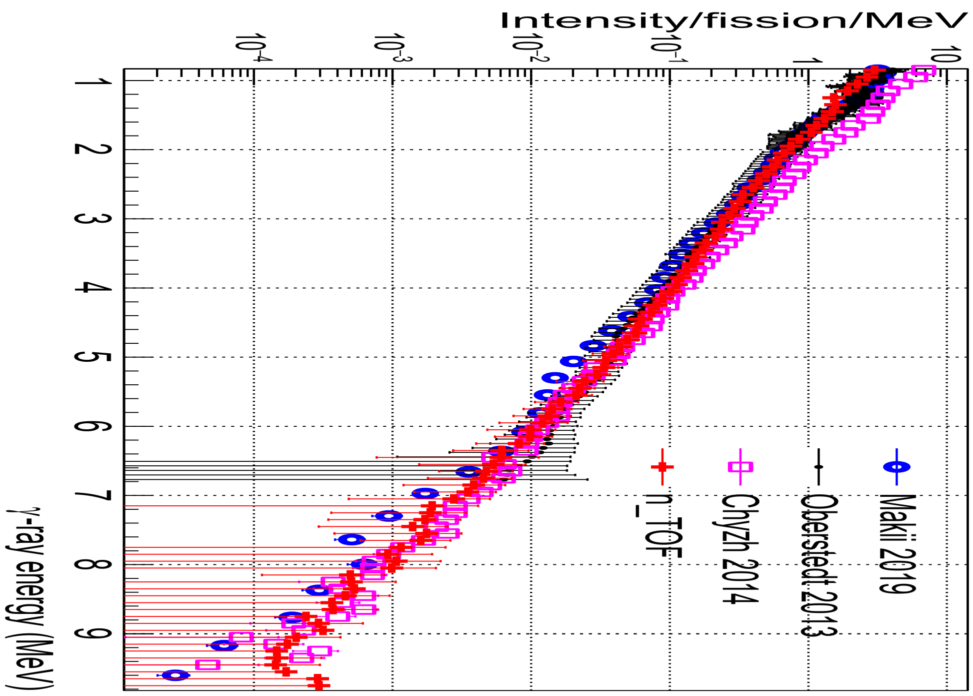


Table 1 The resulting values of $\bar{E}_\gamma$, $\bar{\nu}_\gamma$ and $\bar{E}_\gamma \times \bar{\nu}_\gamma$ in this work compared to other recent measurements over a common energy region of 0.8 to 6.8 MeV. The uncertainties on the n_TOF results include both statistical and systematic contributions; for the other data sets, the fractional uncertainties from their published results have been used to estimate the uncertainty in this energy range. No correlation has been included in the calculation of the $\bar{E}_\gamma \times \bar{\nu}_\gamma$ uncertainty.

Reference	$\bar{E}_\gamma$ (MeV)	$\bar{\nu}_\gamma$	$\bar{E}_\gamma \times \bar{\nu}_\gamma$ (MeV)
Oberstedt *et al.*[1]	1.64(4)	2.99(4)	4.9(1)
Chyzh *et al.*[2]	1.56(4)	3.24(15)	5.1(3)
Makii *et al.*[3]	1.56(4)	3.04(7)	4.7(2)
n_TOF	1.71(5)	2.66(18)	4.54(3)

Recent measurements in agreement within uncertainties (up to 7%) therefore HPRL entry satisfied

[1] Oberstedt, A., Belgya, T., Billnert, R., Borcea, R., Bryś, T., Geerts, W., Göök, A., Hambsch, F.-J., Kis, Z., Martinez, T., Oberstedt, S., Szentmiklosi, L., Takàcs, K., Vidali, M.: Improved values for the characteristics of prompt-fission γ-ray spectra from the reaction ^{235}U(n_{th},f). Phys. Rev. C **87**, 051602 (2013). https://doi.org/10.1103/PhysRevC.87.051602

[2] Chyzh, A., Wu, C.Y., Kwan, E., Henderson, R.A., Bredeweg, T.A., Haight, R.C., Hayes-Sterbenz, A.C., Lee, H.Y., O'Donnell, J.M., Ullmann, J.L.: Total prompt γ-ray emission in fission of ^{235}U, ^{239,241}Pu, and ^{252}Cf. Phys. Rev. C **90**, 014602 (2014). https://doi.org/10.1103/PhysRevC.90.014602

[3] Makii, H., Nishio, K., Hirose, K., Orlandi, R., Léguillon, R., Ogawa, T., Soldner, T., Köster, U., Pollitt, A., Hambsch, F.-J., Tsekhanovich, I., Aïche, M., Czajkowski, S., Mathieu, L., Petrache, C.M., Astier, A., Guo, S., Ohtsuki, T., Sekimoto, S., Takamiya, K., Frost, R.J.W., Kawano, T.: Effects of the nuclear structure of fission fragments on the high-energy prompt fission γ-ray spectrum in ^{235}U(n_{th}, f). Phys. Rev. C **100**, 044610 (2019). https://doi.org/10.1103/PhysRevC.100.044610

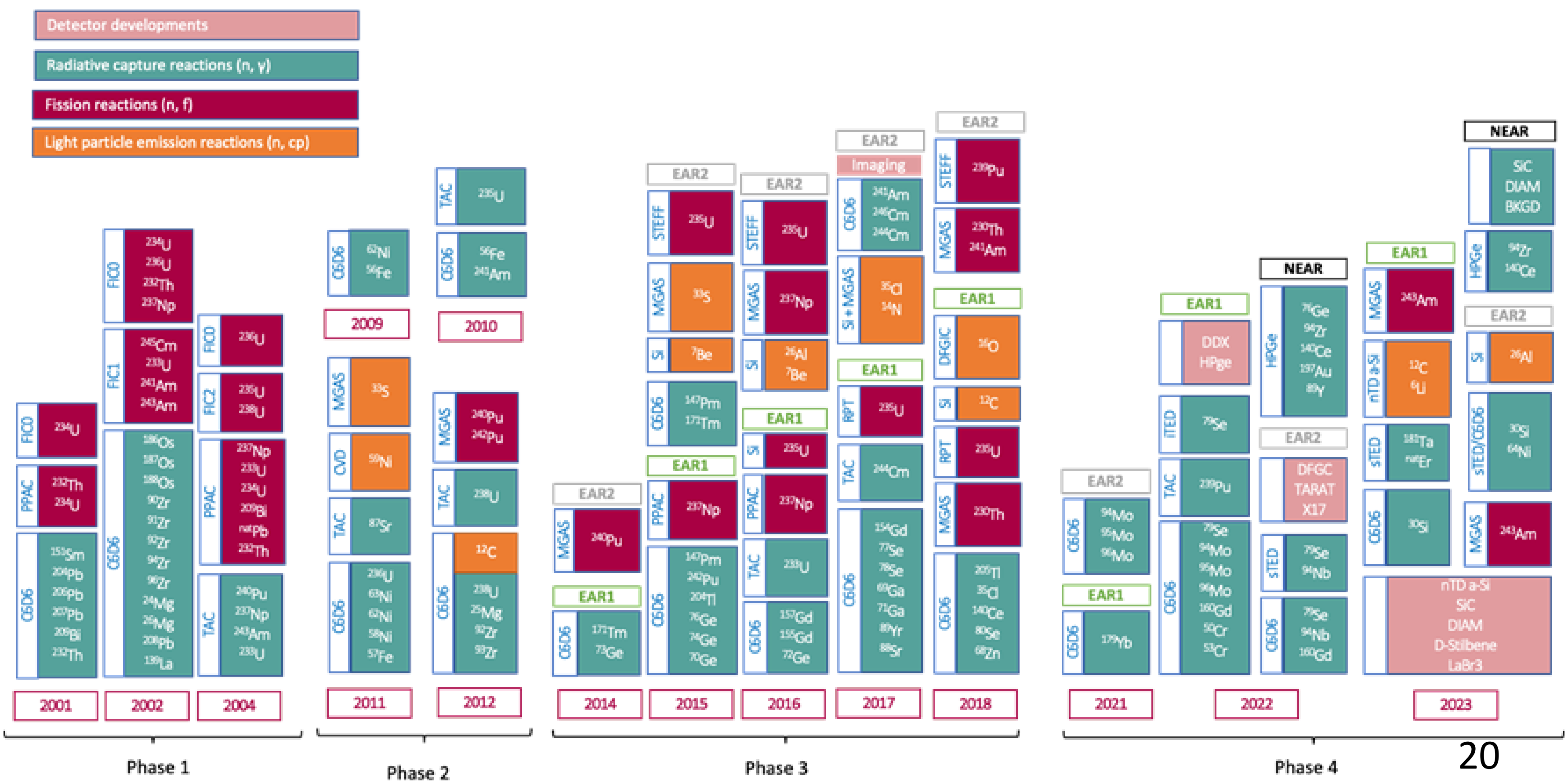
Acknowledgements

- University of Manchester team:
  - Prof. Gavin Smith
  - Dr Nikolay Sosnin
  - Dr Sam Bennett
  - Dr Paul Davies (now University of York)
  - Dr Adhitya Sekhar
  - Vlad Popescu

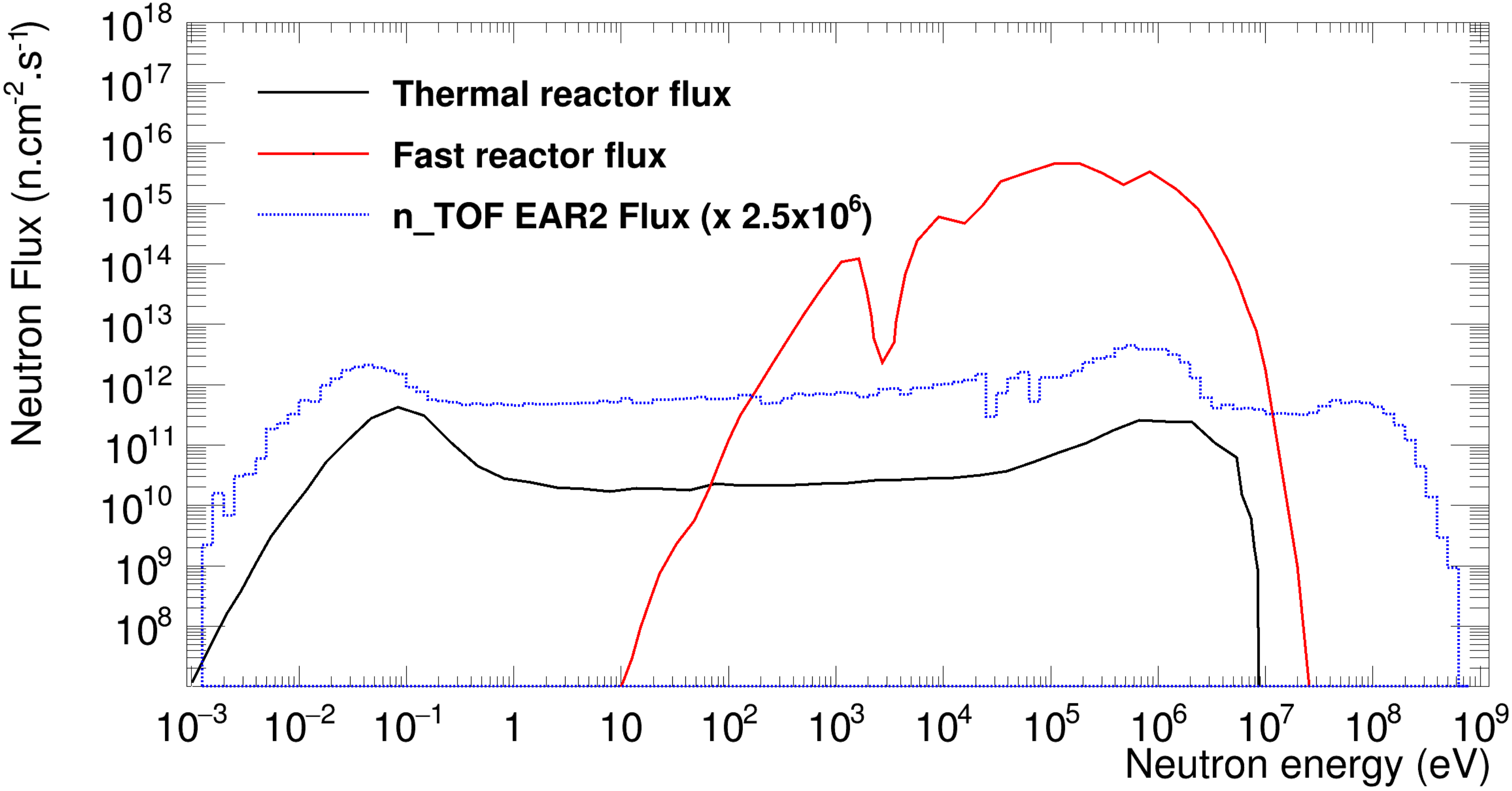
MANCHESTER 1824
The University of Manchester

- The n_TOF collaboration

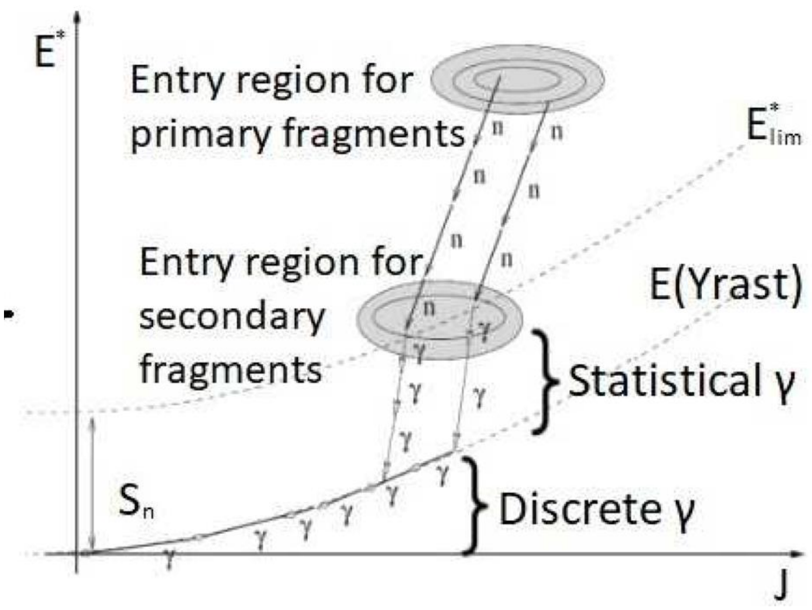
The n_TOF history in a nutshell



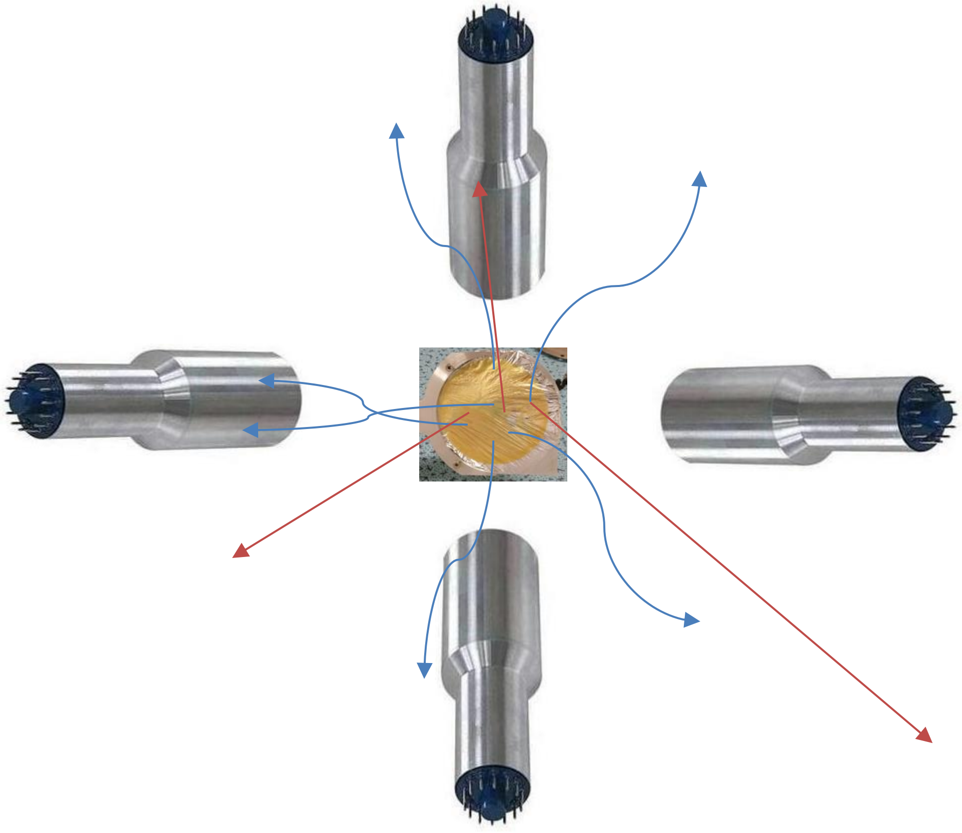
The n_TOF facility



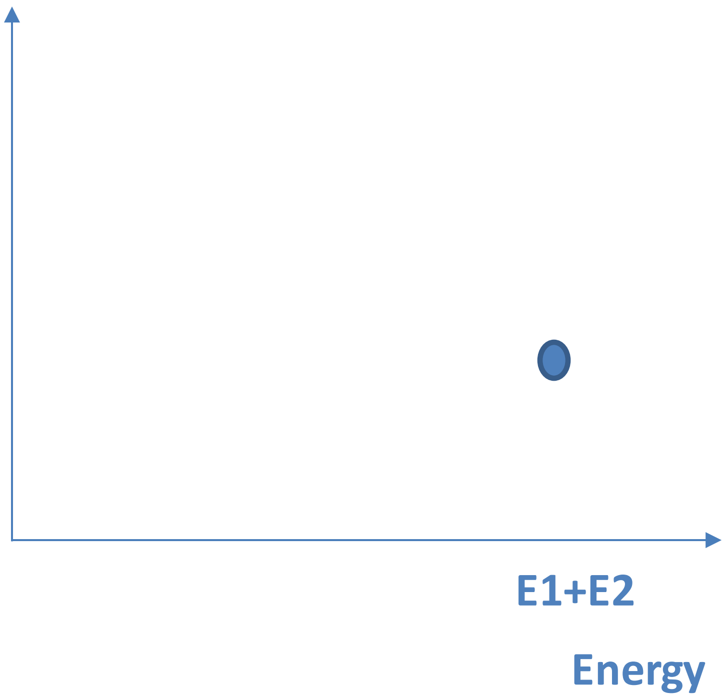
Detected γ-rays – understanding their origin

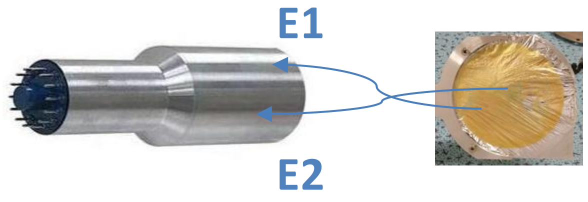


Complex situation with multiple γ-rays and neutrons emitted per fission

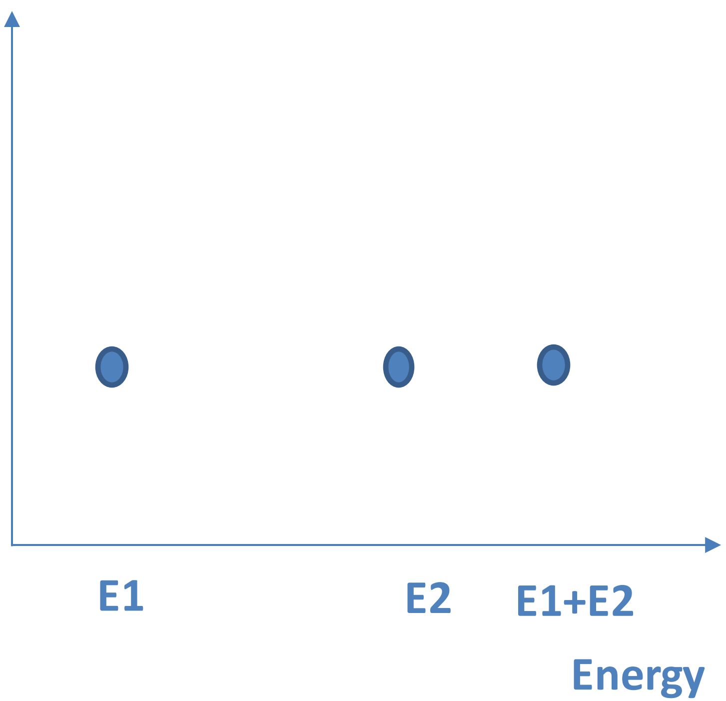


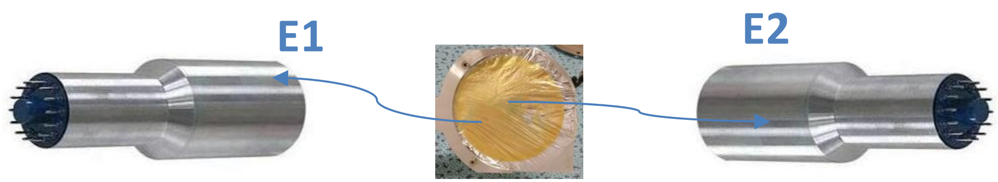
Understanding detected γ-ray energy: Multiple hits correction



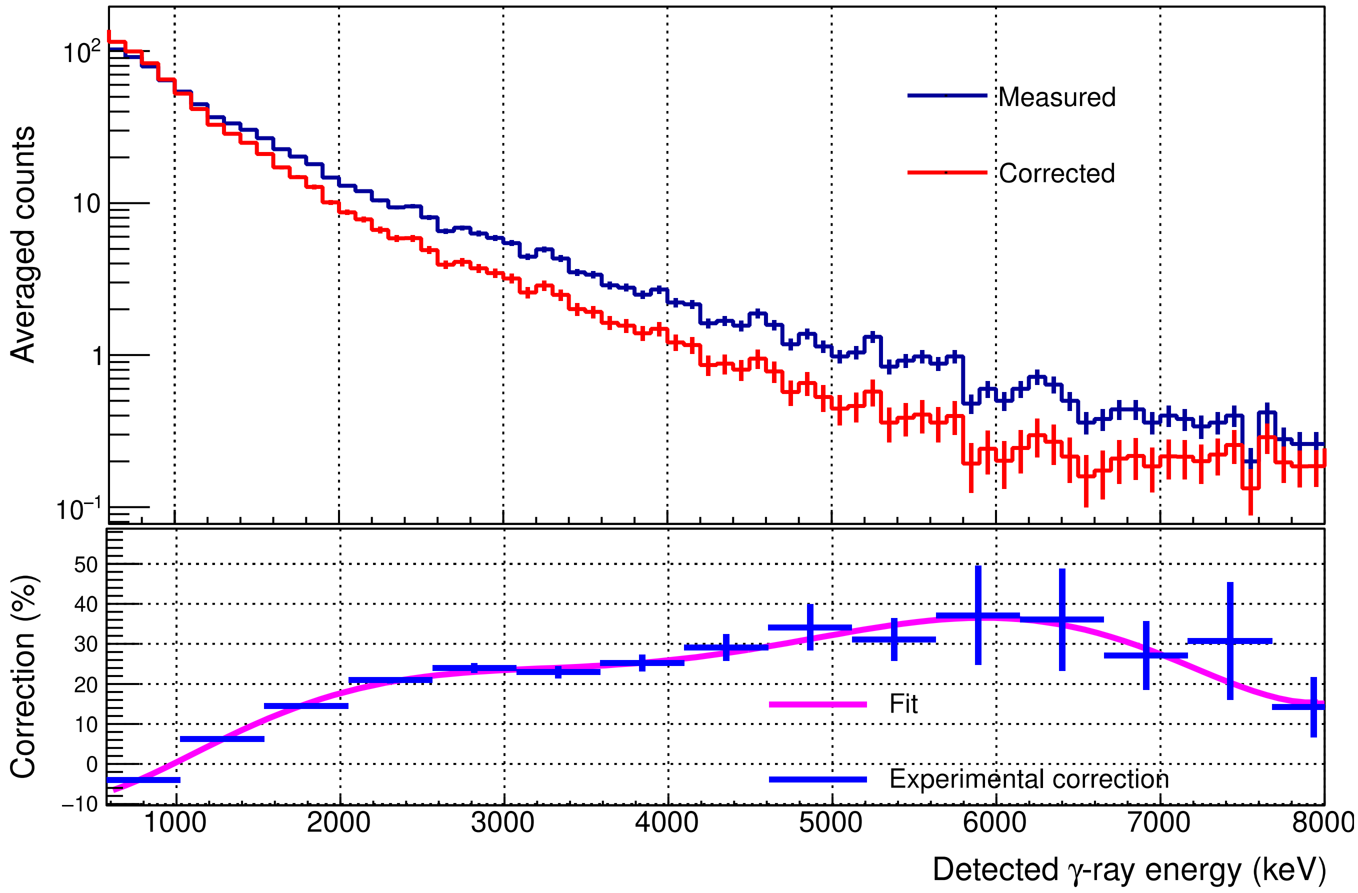


Understanding detected γ-ray energy: Multiple hits correction

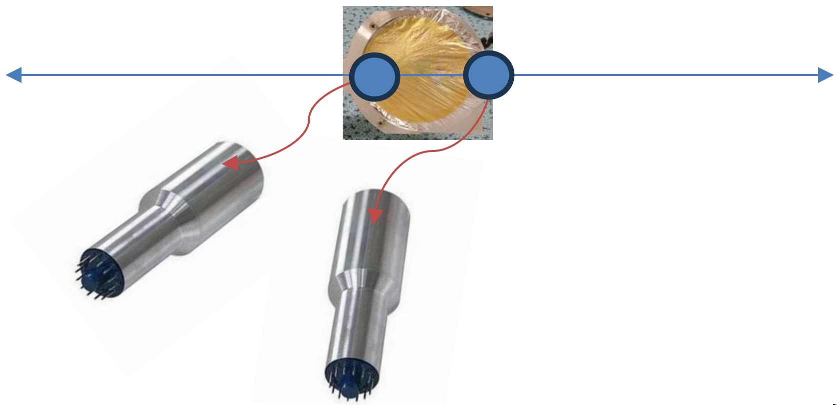




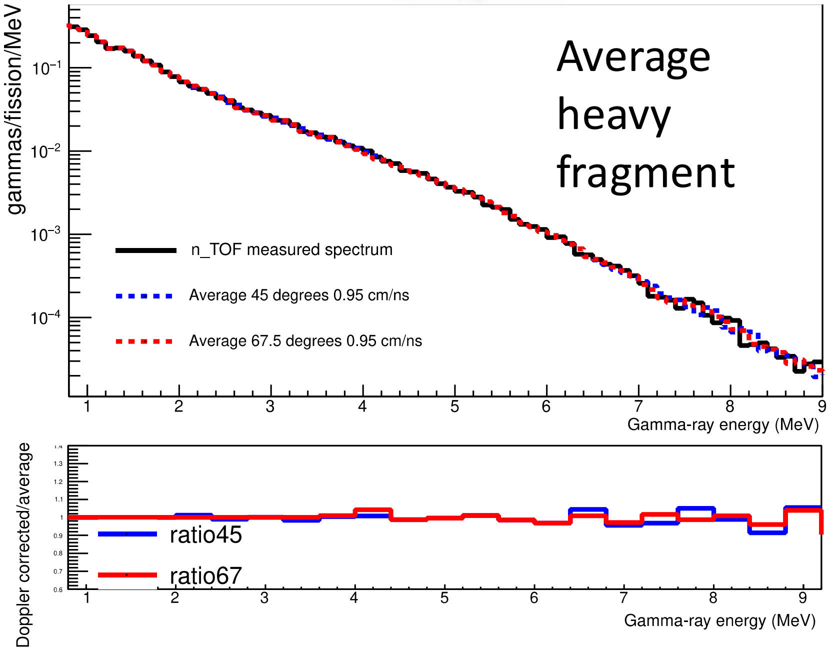
Understanding detected γ-ray energy: Multiple hits correction

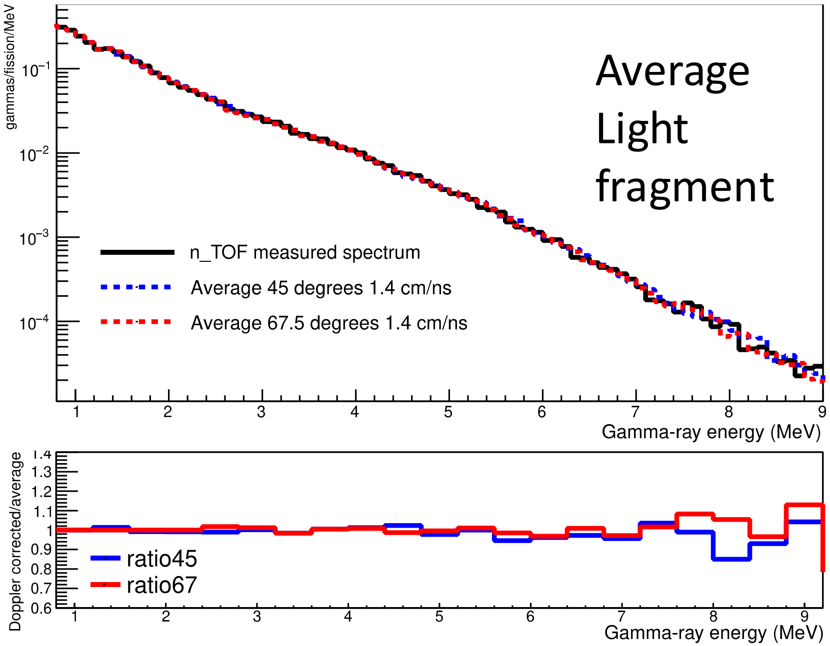


Understanding detected γ-ray energy: Doppler correction

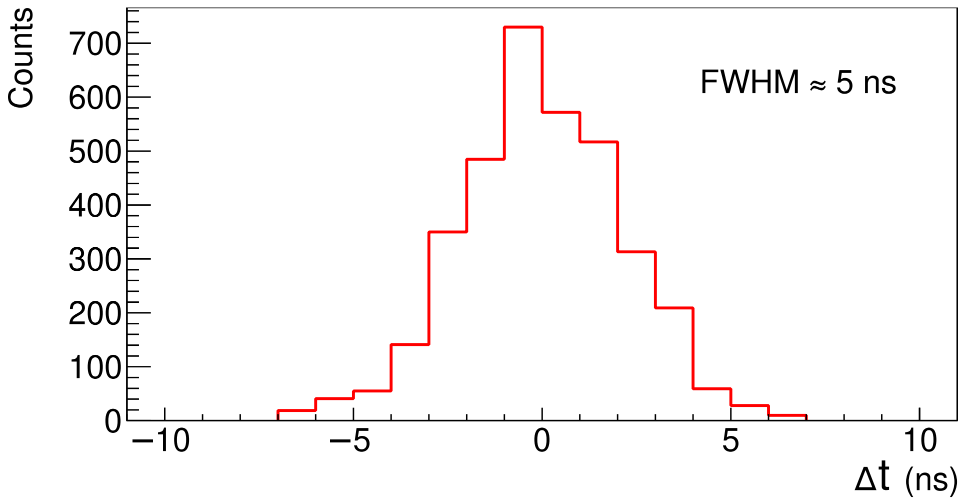


$$E'_\gamma = \frac{E_\gamma}{\gamma(1+\beta cos\theta)}$$

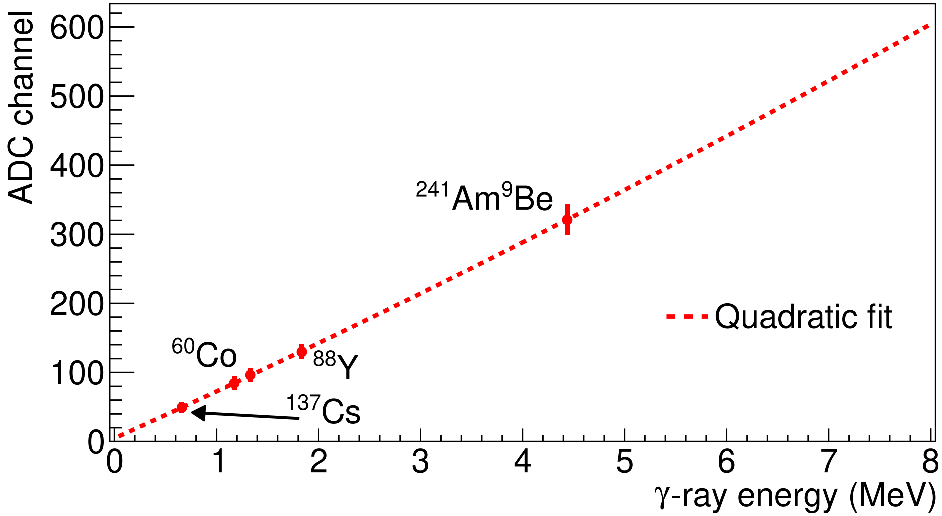




Analysis – NaI Calibration



The time Δt between signals in different detectors corresponding to detected photo-peak γ-rays from a ^{60}Co source for a single NaI detector within the array. These γ-rays are emitted simultaneously, thus the measured distribution in time shows our intrinsic timing resolution.



Energy calibration for the same NaI detector. The quadratic fit is shown with a dashed line. The error bars on the data points represent full-width half-maxima of the γ- ray peaks.

Start only ($LaBr_3$)