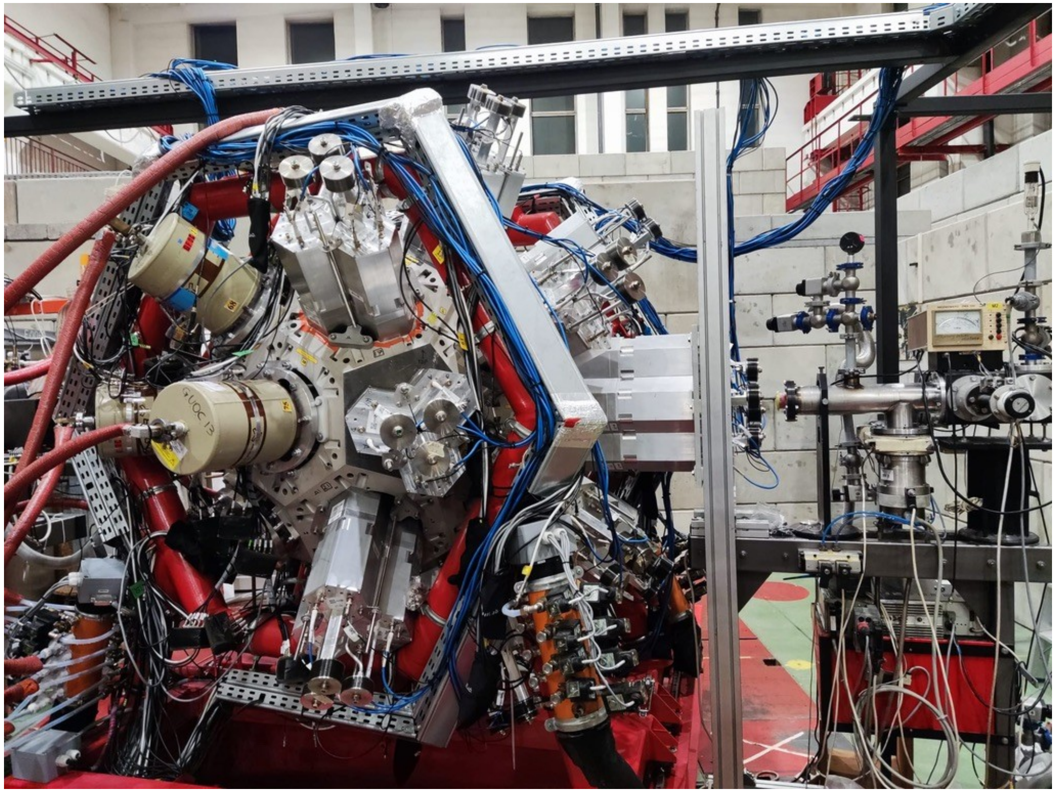
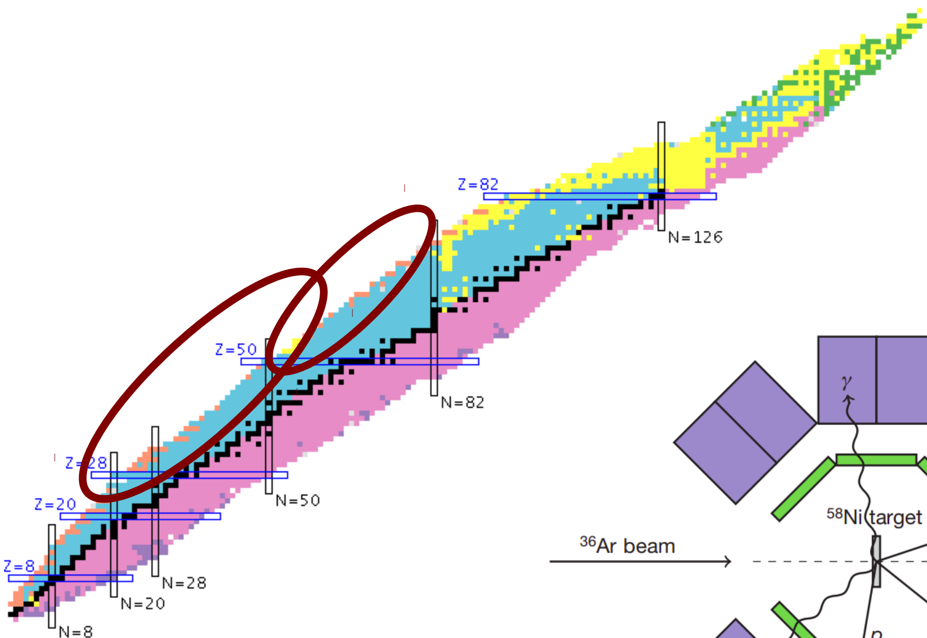
The First Year of Physics with NEEDLE



Grzegorz Jaworski
Heavy Ion Laboratory
University of Warsaw
Poland

Insight into the structure of neutron-deficient nuclei



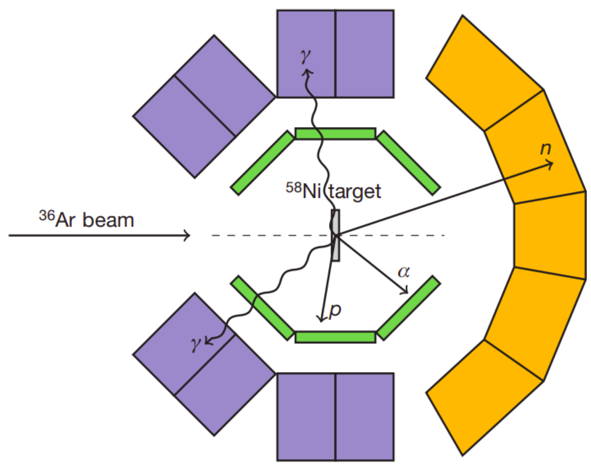


Fig: Nature 469 (2011) 09644

Neutron Wall

Various neutron detectors with:
NORDBALL, OSIRIS, GASP

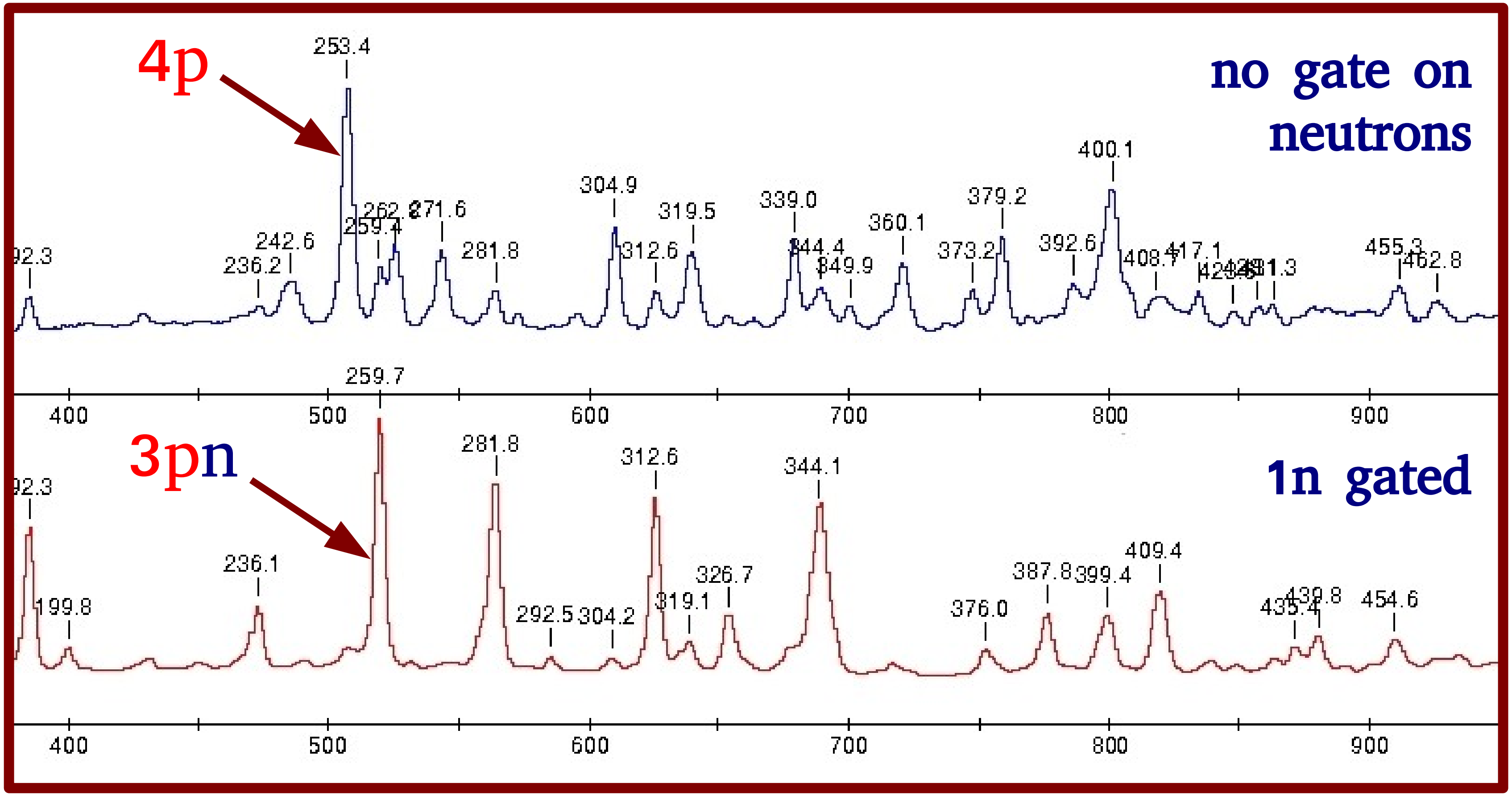
NEDA:

2018 AGATA (GANIL)
2023- EAGLE (HIL)

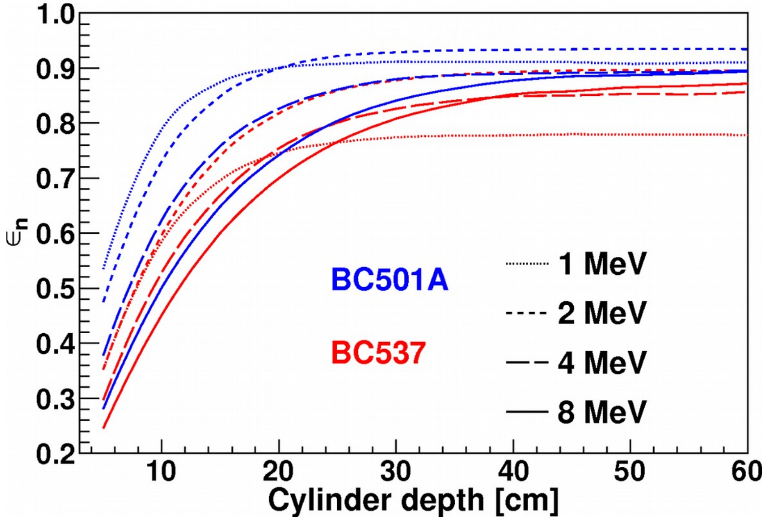
1998 EUROBALL (LNL)
2001-2003 EUROBALL (IReS)
2005-2014 EXOGAM (GANIL)
2015-2017 GALILEO (LNL)
2018 AGATA (GANIL)

n selection

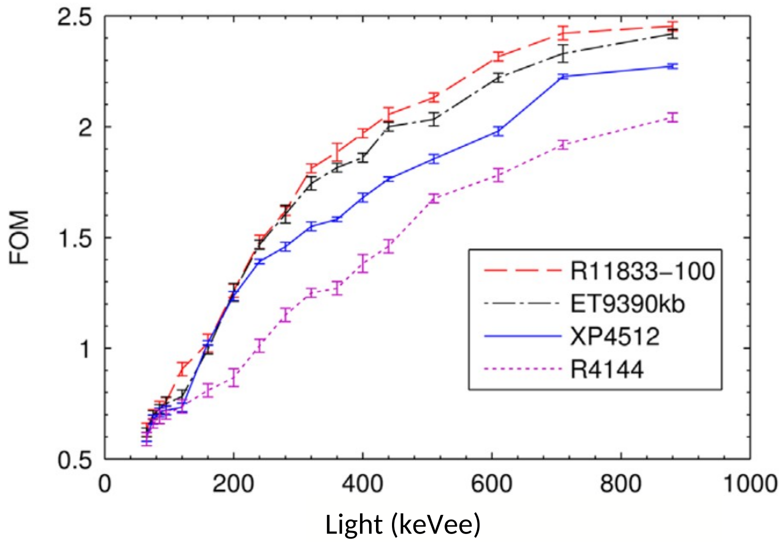
EXOGAM experiment: ^{58}Ni (240 MeV) + ^{54}Fe

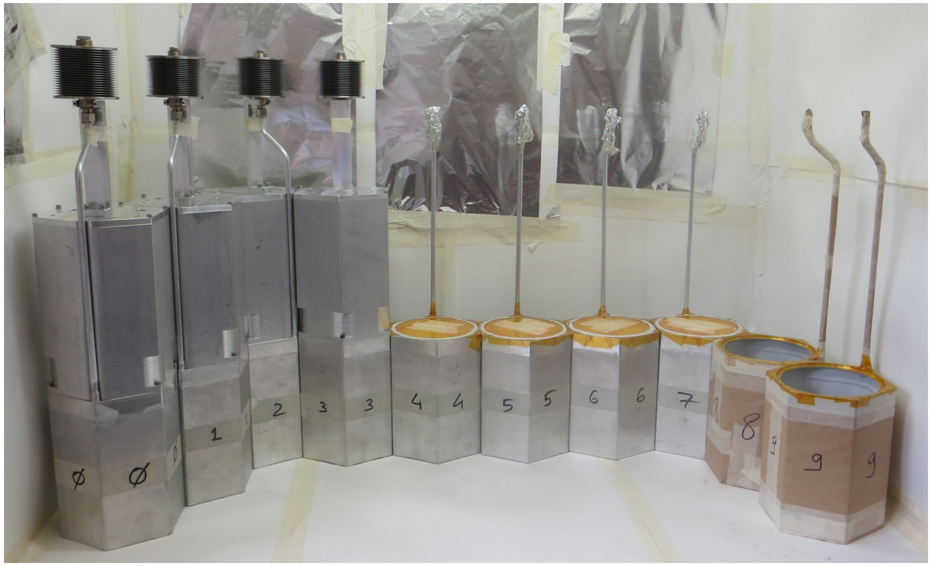


NEDA 2007-2018



Simulations:
NIM A 673 (2012) 64, EPJA 52 (2016) 55
PMTs, timing, NGD:
NIM A 767 (2014) 83, NIM A 775 (2015) 71,
NIM A 897 (2018) 59, NIM A 916 (2018) 238,
NIM A 986 (2021) 164750
Electronics:
IEE-NPSS RTC (2012) 1, IEEE-TNS 60 (2013) 3526,
IEEE-NPSS RTC (2014) 1, IEEE TNS 62 (2015) 1056,
IEEE TNS 62 (2015) 2063
General:
NIM A 927 (2019) 81, APP B 50 (2019) 573

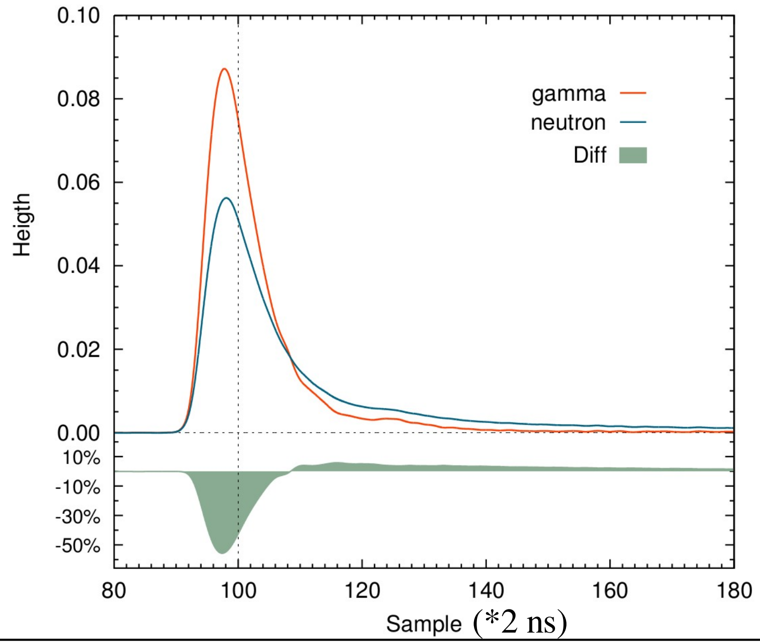


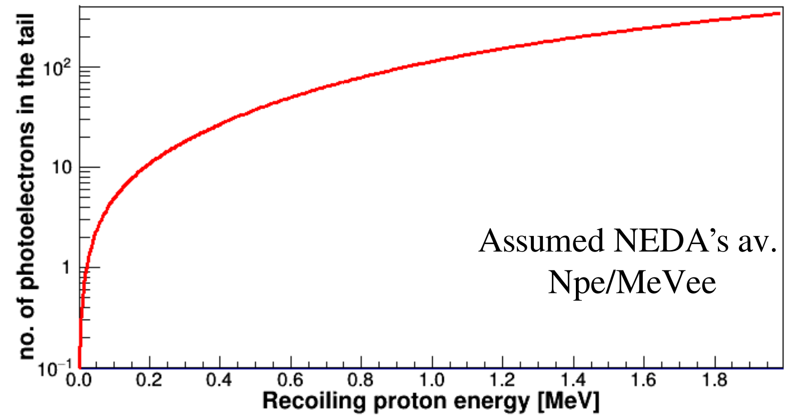


Light matters!

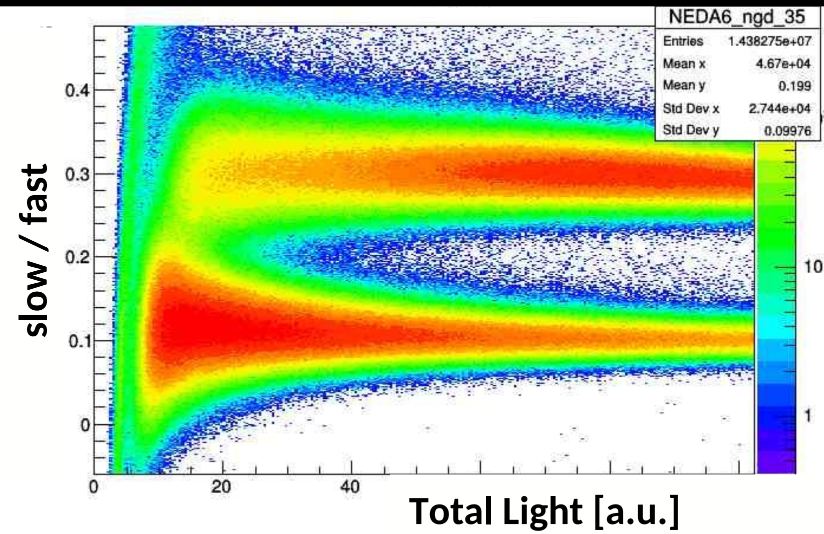
Nphe/MeVee

~1300	NW new 1998
472	NW av. 01.2018
1800	Bicron 5"x5"
2866	NEDA av.

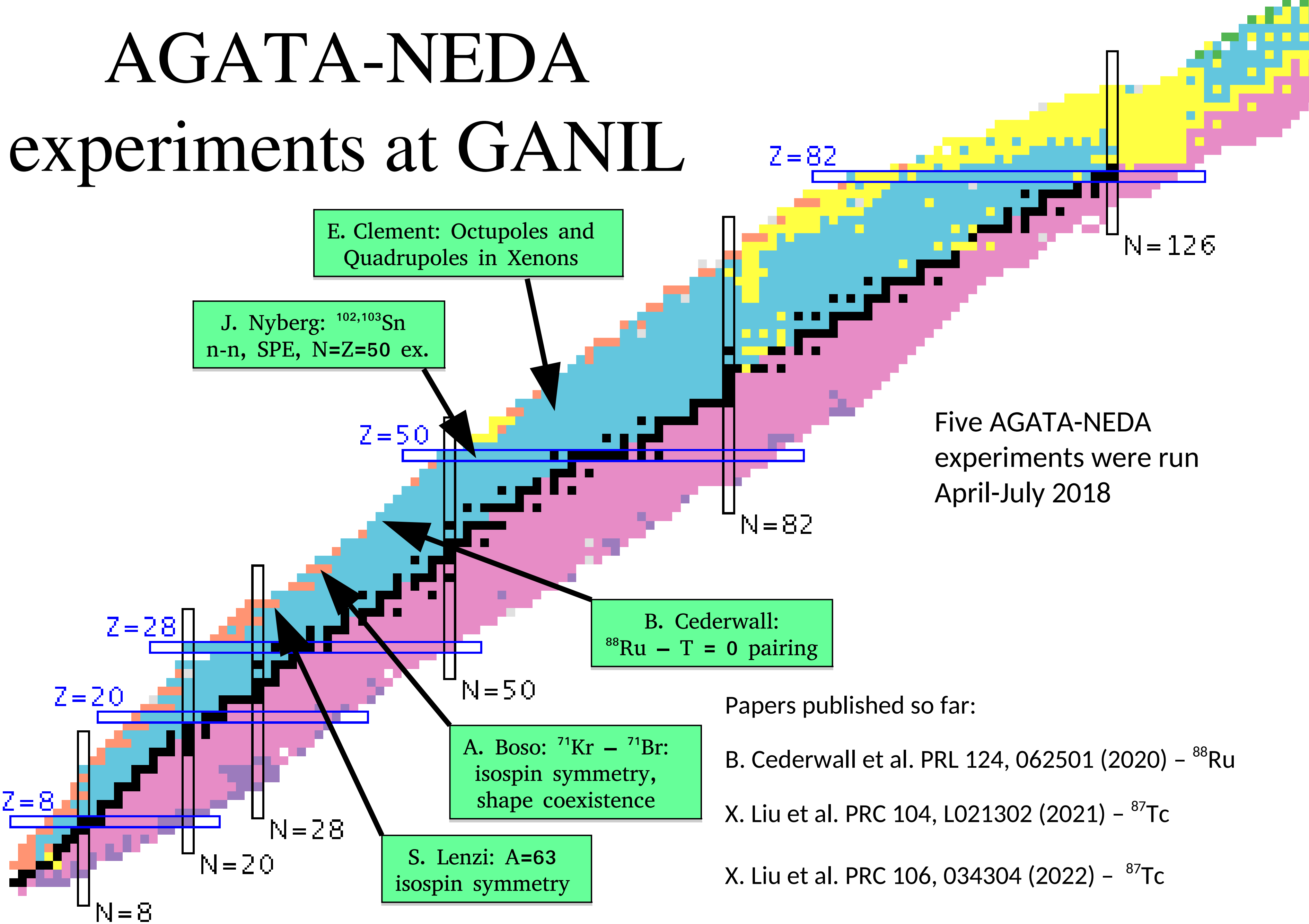




FOM = 1.88 for (50-200) keVee



AGATA-NEDA experiments at GANIL



Five AGATA-NEDA experiments were run April-July 2018

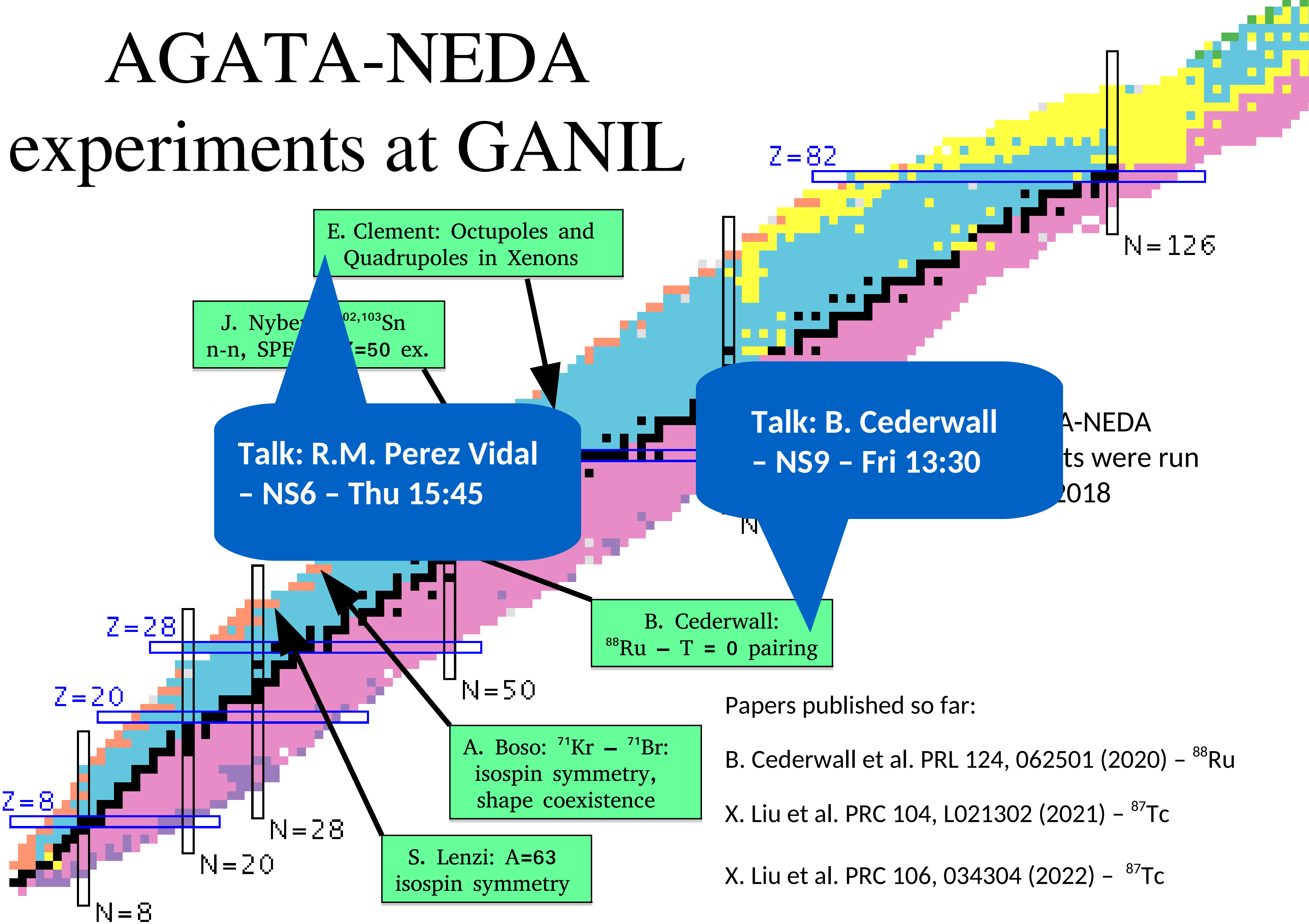
Papers published so far:

B. Cederwall et al. PRL 124, 062501 (2020) – ^{88}Ru

X. Liu et al. PRC 104, L021302 (2021) – ^{87}Tc

X. Liu et al. PRC 106, 034304 (2022) – ^{87}Tc

AGATA-NEDA experiments at GANIL



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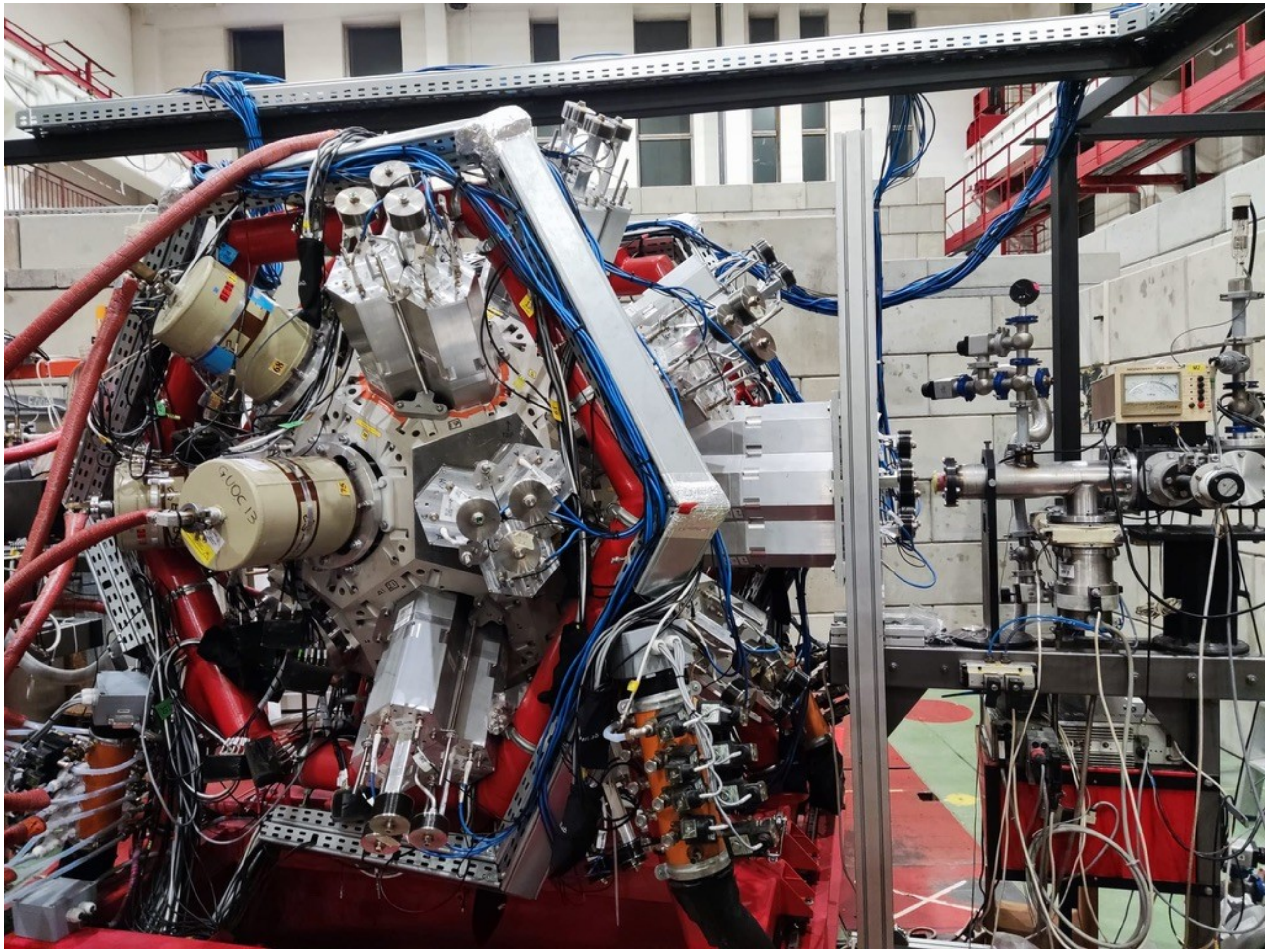
NEEDLE 2022→



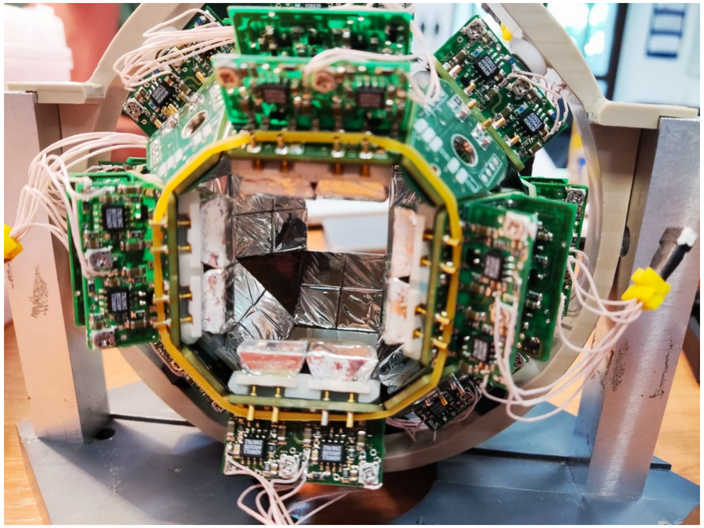
EAGLE (HPGe):
- 5 dets @ 101°
- 5 dets @ 117°
- 5 dets @ 143°

NEDA:
- 6/7 dets ~0°
- 15 dets @ 37°
- 15 dets @ 63°
- 15 dets @ 79°

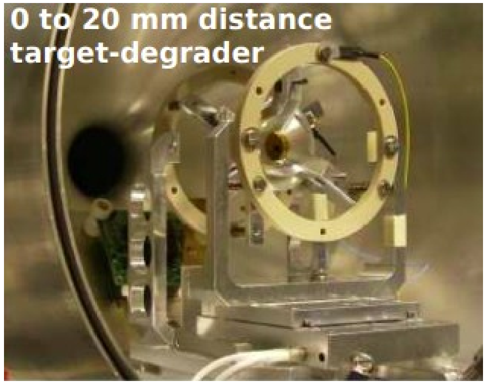
Other ancillaries

Diamant

- Full configuration:
  eff(p) = 60%
  eff(α) = 40%
- Without bw dets (plunger):
  eff(p) = 40%
  eff(α) = 35%



Plunger(s)

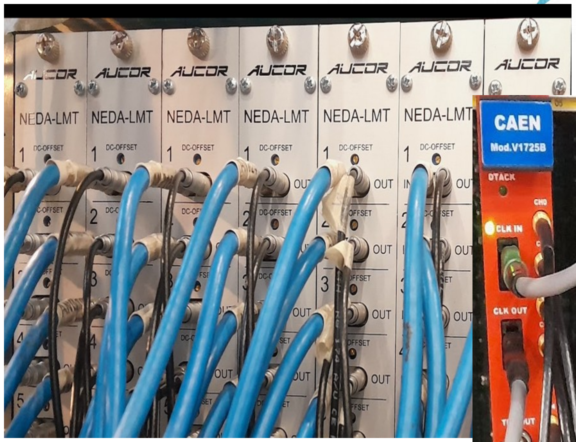


Electron spectrometer

Electronics and DAQ

Transformation from:
EAGLE: analog CAMAC based system, some digital elem.
NEDA: numexo2 (diff. input), GTS, Trigger Processor

- Custom made amplitude limiters restrict the NEDA signals to 2V (Aucor, Warsaw);
- 6 CAEN V1725(S)(B) digitizers (6x16 channels, 14-bit, 250 MHz sampling):
  - 2 units with PHA firmware for HPGe and ACS
  - 4 units with PSD firmware for NEDA („at least one PSD discriminated neutron" signal available for the trigger request)
- trigger validation logic implemented in external NIM units;
  for validated events: readout of all non-zero channels (NEDA: not only PSD discriminated neutrons – gamma-ray time ref. and multiplicity filtering possible);
- Software:
  - XDAQ (CERN) with LNL applications;
  - Spy and GreWare for on-line spectra;
  - GRAFANA for monitoring of rates;
  - ROOT selector for off-line (→ RadWare, TV, etc.).

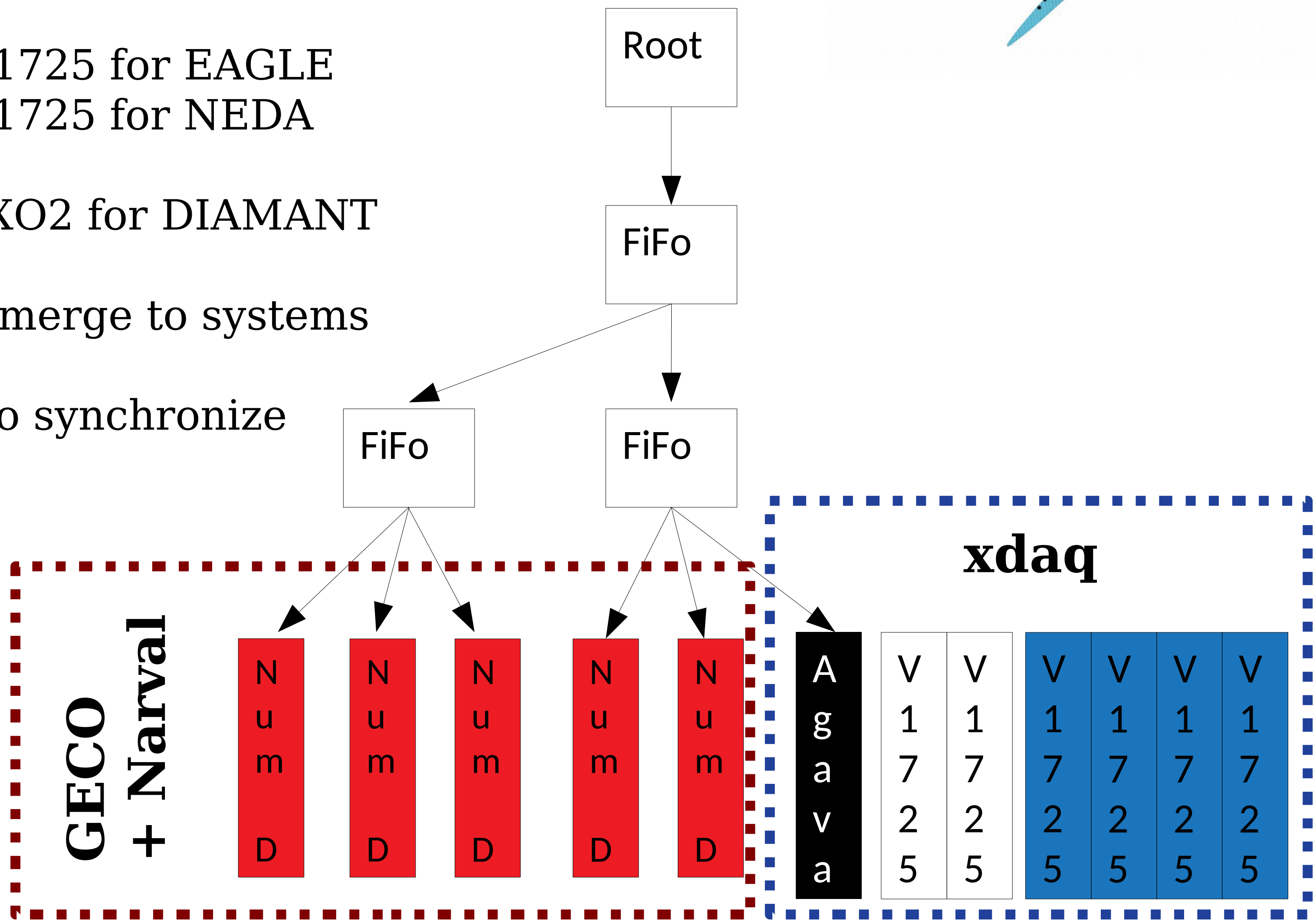


Caen digi & xdaq

- ► SiICA
- ► ULESE
- ► RFD
- ► Fast timing (?)
- ► … DIAMANT

Read-out – with DIA

- 2x Caen V1725 for EAGLE
  4x Caen V1725 for NEDA
- 5x NUMEXO2 for DIAMANT
- AGAVA to merge to systems
- GTS tree to synchronize



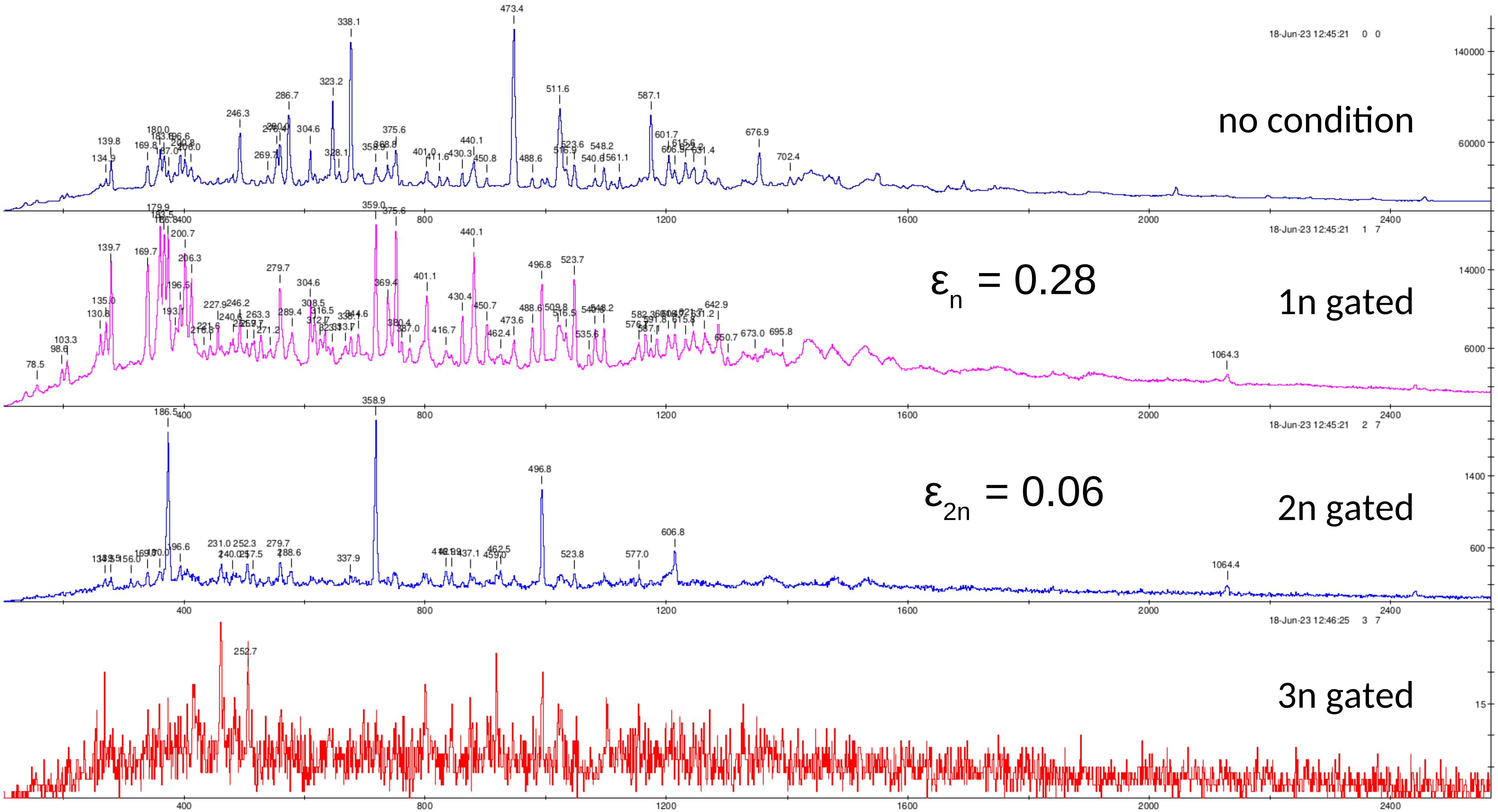
Experiments performed 2023 → today

id	dates	spokeperson	title	beam	ancillary devices
HIL 099	1/03–12/03/2023 11 days	B. Saygi, G. Jaworski	Lifetime measurement of excited states in ^{134}Sm	^{32}S, 150 MeV	NEDA, Köln plunger
HIL 097	20/03–4/04/2023 14 days	C. Petrache	Shape coexistence and octupole correlations in the light Xe, Cs and Ba nuclei	^{16}O, 86 MeV	NEDA, Köln plunger
HIL 106	13/06–29/06/2023 14 days	C. Petrache	Shape coexistence and octupole correlations in the light Xe, Cs and Ba nuclei (continuation of HIL097)	^{32}S, 150 MeV	NEDA, Köln plunger
HIL 105	13–30/11/2023 16 days	M. Palacz	Single-proton states and N=Z=28 core excitations in ^{57}Cu	^{32}S, 82 MeV	NEDA, DIAMANT
HIL 115	5-20/12/2023 15 days	M. Matejska-Minda P. Bednarczyk	Study of the anomalous behavior of the Coulomb energy difference in the A = 70, T = 1 izobaric multiplet	^{32}S, 88 MeV	NEDA, DIAMANT
HIL 114	17–31/01/2024 14 days	B. Saygi, M. Palacz	Gamma-ray spectroscopy of ^{134}Sm	^{32}S, 145 MeV	NEDA, DIAMANT
HIL 117	18–26/03/2024 7 days	K. Miernik	^{144}Dy fission studies	^{32}S, 212 MeV	NEDA, DIAMANT
HIL 126	9-24/05/2024 16 days	I. Kuti	Search for candidate wobbling bands in ^{103}Pd and in ^{101}Ru	^{12}C, 69 MeV	NEDA, DIAMANT

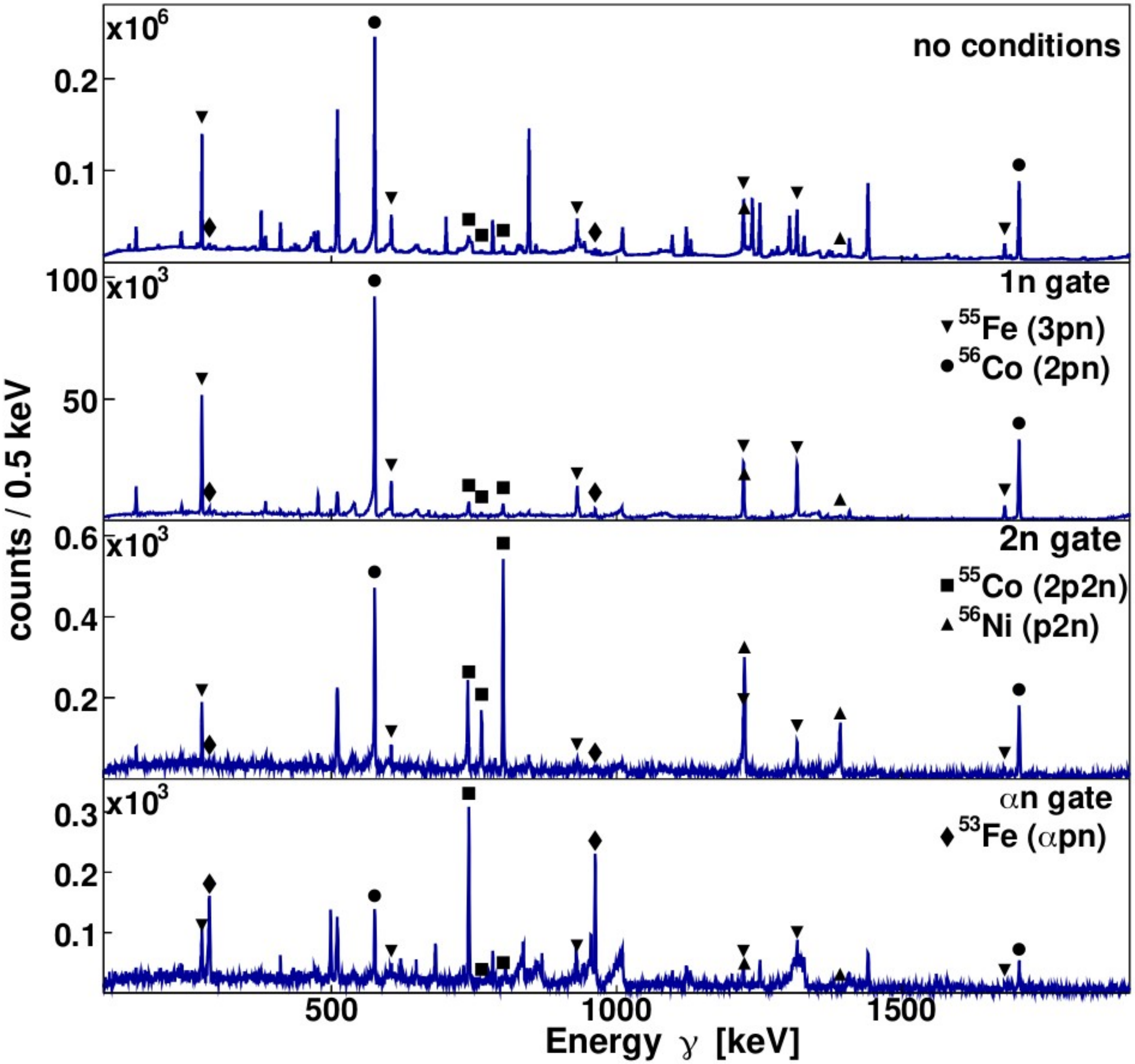
DIAMANT installation

NEEDLE Performance

$^{32}S + ^{92}Mo \rightarrow ^{124}Ce\ (CN) \rightarrow ^{120}Ba + 2p2n$ (HIL106)



NEEDLE Performance



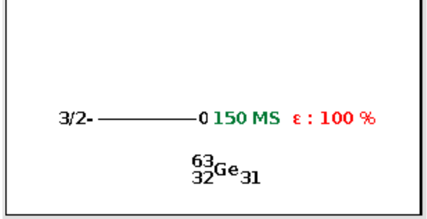
88 MeV ^{32}S + ^{27}Al

NEEDLE's Backlog

id	days	spokeperson	title	beam	anc. dev.
HIL 127	15	A. Fijałkowska, G Jaworski	The discovery of excited states in very neutron defficient europium nuclei	^{40}Ca, 180–190 MeV	NEDA DIAMANT
HIL 129	15	G. Jaworski, A. Fijałkowska	The discovery of excited states in very neutron deficient ^{63}Ge nucleus	^{40}Ca, 100–110 MeV	NEDA, DIAMANT

if only Ni beam would be available…

^{63}Ge



Observation of excited states in ^{63}Ge allowing to reckon:

→ proton and neutron spe,

→ core excitations,

→ ^{63}Ga – isospin symmetry within the states of *2p3/2, 1f5/2, 2p1/2* shells,

→ ? collective octupole effects due to *p3/2–g9/2* correlations – observed in ^{65}Ge,

→ possibly astro-physical significance.

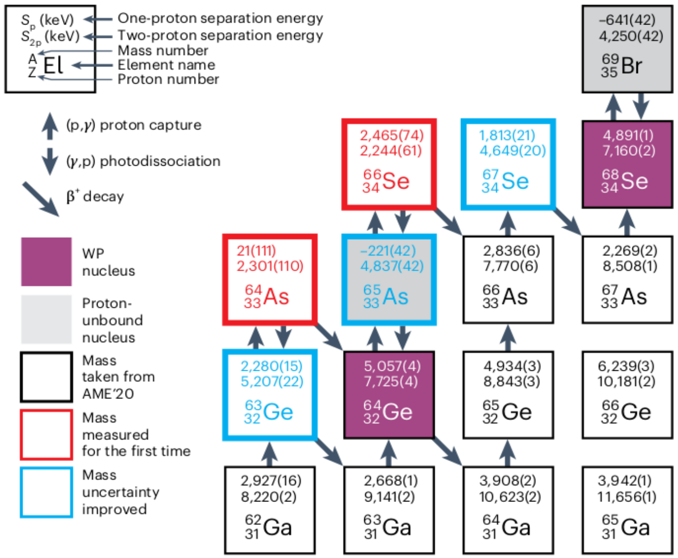
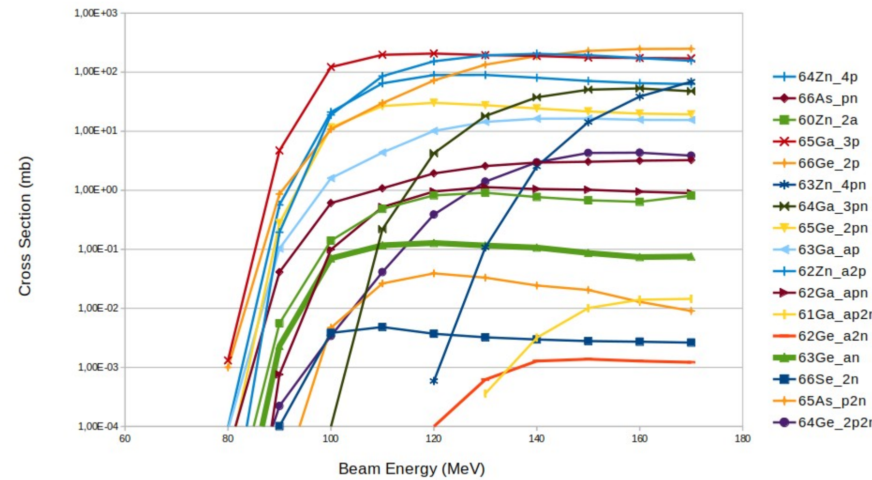
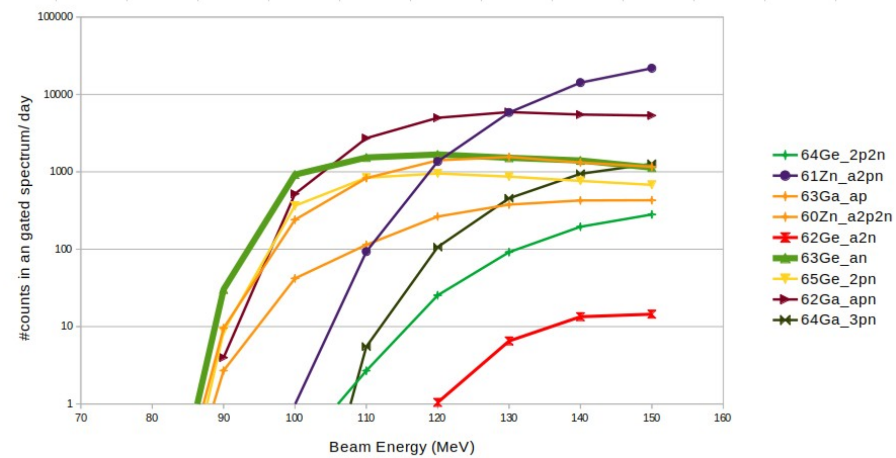


Fig. 1 | Nuclear chart around the rp process WP ^{64}Ge. The nuclides are organized according to neutron (horizontally) and proton (vertically) numbers. Nuclides whose masses were taken from the latest AME'20 database[36], whose masses were experimentally determined or whose mass uncertainties were improved in this work are indicated in black, red and blue colours, respectively. The one-proton (S_p) and two-proton (S_{2p}) separation energies (values expressed in keV) follow the same colour code. The pathway of the rp process nucleosynthesis is shown with the black arrows. The legend provides more details.

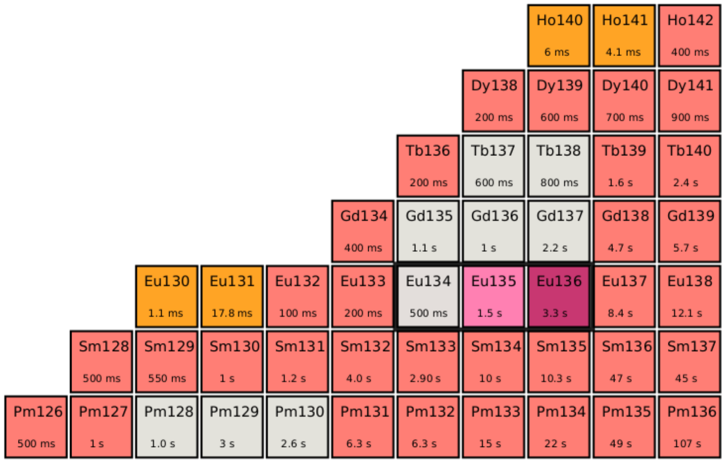
X. Zhou et al. - Nature Physics 19 (2023) 1091

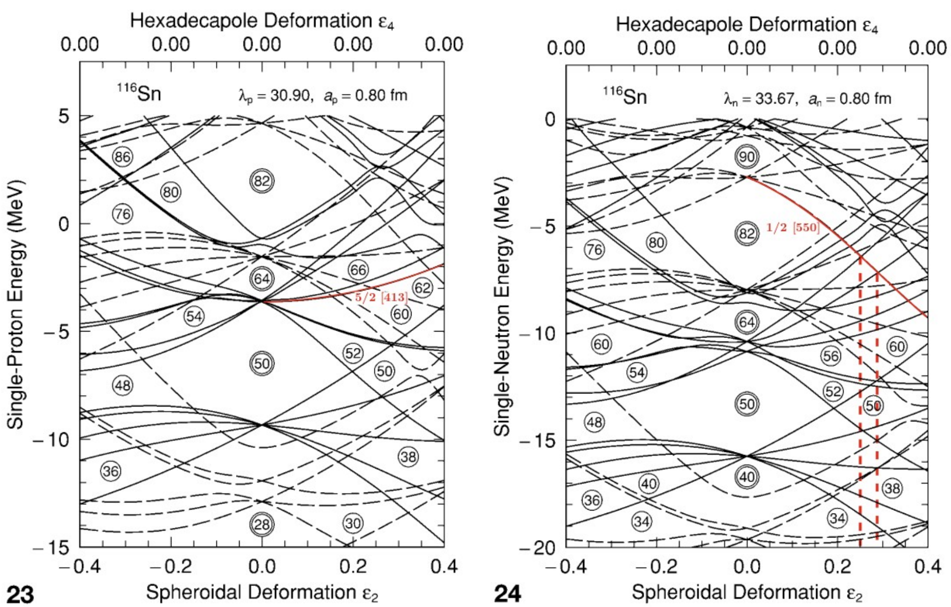




^{40}Ca beam in spe

^{135}Eu at al.





P. Möller, J. R. Nix, and K. L. Kratz. Data Nucl. Data Tables, 66:131–343, 1997

First measurement prompt gamma rays in rare-earth europium nuclei ($^{135,\,136}$Eu) produced in heavy-ion induced, fusion-evaporation reactions

Establish at least the ground state rotational sequence, to extend the knowledge of collective excitations in the isotope well beyond N=82.

Verify and possible extend knowledge about ^{137}Eu excited states

→ LoI for AGATA (+Euclides+Prisma) *Highly deformed bands in europium isotopes and identification of new isotopes* ($^{135\text{-}139}$Eu) – C. Sullivan et al.

Beginning of mapping of the region =)

NEDA will leave but can come back =D

^{40}Ca beam in spe

Beams @ HIL

Cyklotron K= 90 – 160						
Jon	Energy min [MeV]	Energy max [MeV]	Energy max [MeV/nukl]	Intensity of the extracted beam [nA]	Intensity of the extracted beam [pnA]	Intensity of the extracted beam [p/s]
$^{10}B^{+2}$	51	55	5.5	45	9.0	$5.6\ 10^{+10}$
$^{11}B^{+2}$	40	50	4.5	50	10.0	$6.3\ 10^{+10}$
$^{12}C^{+2}$	38	50	4.2	100	16.7	$1.0\ 10^{+11}$
$^{12}C^{+3}$	53	92	7.7	220	36.7	$2.3\ 10^{+11}$
$^{13}C^{+3}$		90	6.9	90	16	
$^{14}N^{+2}$	32	50	3.6	240	34.3	$2.1\ 10^{+11}$
$^{14}N^{+3}$	57	91	6.5	1500	214.3	$1.3\ 10^{+12}$
$^{15}N^{+3}$		43	2.9	50	7.1	
$^{16}O^{+3}$	46	80	5.0	400	50.0	$3.1\ 10^{+11}$
$^{16}O^{+4}$	80	120	7.5	650	81.3	$5.1\ 10^{+11}$
$^{18}O^{+4}$	100	120	6.7	2000	250.0	$1.6\ 10^{+12}$
$^{19}F^{+3}$	50	66	3.5	10	1.1	$6.9\ 10^{+9}$
$^{20}Ne^{+3}$	45	68	3.4	300	30.0	$1.9\ 10^{+11}$
$^{20}Ne^{+4}$	68	115	5.8	1300	130.0	$8.1\ 10^{+11}$
$^{20}Ne^{+5}$	130	160	8.0	120	12.0	$7.5\ 10^{+11}$
$^{22}Ne^{+3}$	44	55	2.5	260	26.0	$1.6\ 10^{+11}$
$^{24}Mg^{+4}$		77	3.2	120	10	
$^{32}S^{+5}$	79	110	3.4	50	3.1	$2.0\ 10^{+10}$
$^{32}S^{+6}$	*120*(*)	150	4.7	70	4.4	$2.7\ 10^{+10}$
$^{32}S^{+7}$	*120*(*)	142	4.4	50	3.1	$2.0\ 10^{+10}$
$^{40}Ar^{+6}$	*90*(*)	132	3.7	100	5.6	$3.6\ 10^{+10}$
$^{40}Ar^{+7}$	*130*(*)	164	4.1	35	1.9	$1.2\ 10^{+10}$
$^{40}Ar^{+8}$	*180*(*)	200	5.0	40	2.2	$1.4\ 10^{+10}$

(*) estimation, no experimental data

^{40}Ca in the autumn/winter

Take home

- Good setup to access proton-reach nuclei available in Warsaw
- Fully digital read-out, new ACQ system, all battle-tested
- NEEDLE+DIAMANT – full evaporation channel tagging available
- Join us for the experiments! Coming: ^{63}Ge, ^{135}Eu
- Get ready for the next PAC – Dec 2024!
- NEDA till mid 2026 (?)
- DIAMANT stays

tatrofil@slcj.uw.edu.pl

It's good for you!

Acnowledgment:
the installation and the use of NEDA at HIL is supported by NCN (SONATA) grant no. 2020/39/D/ST2/00466

The Needlers

Institutes

- HIL-UW,
- LNL Legnaro
- ATOMKI
- IFJ Kraków
- FUW
- IKP Köln
- NCNR Świerk

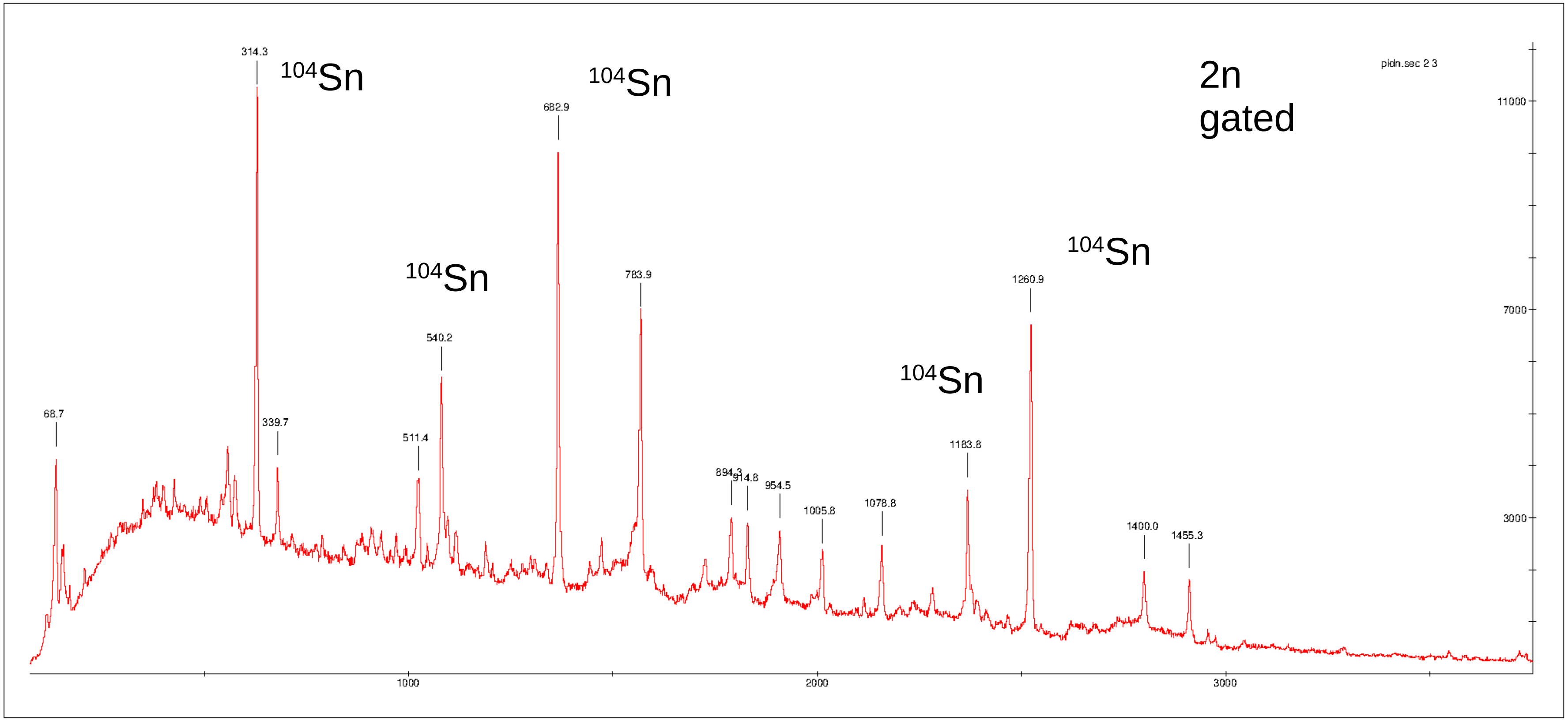
- M. Palacz (near-line, analysis, …)
- A. Goasduff, N.Toniollo (daq)
- I. Kuti, J. Molnar (DIAMANT, daq)
- M. Kowalczyk, P. Kulessa, M. Ciemała (daq, near-line)
- J. Grębosz (spy, GreWare – on-line spectra)
- M. Komorowska, M. Kisieliński, A. Špaček, T. Abraham, W. Okliński (HPGe, EAGLE front-end)
- C. Fransen, C. Lakenbrink, M. Beckers, F. v. Spee, C. Müller-Gatermann, A. Nałęcz-Jawecki (plunger)
- G. Colucci, A. Fijałkowska, K. Hadyńska-Klęk, A. Korgul, P.J. Napiorkowski, S. Panasenko, I. Piętka, J. Samorajczyk-Pyśk, P. Sekrecka, A. Tucholski, K. Wrzosek-Lipska (various support)
- B. Radomyski, M. Matuszewski (mechanics – projects, 3D print)
- R. Kopik, P. Jasiński, M. Antczak (mechanical workshop)
- A. Stolarz, J. Kowalska (targets)
- students: A. Malinowski, A. Otręba, W. Poklepa, M. Regulska, K. Solak, K. Szlęzak, K. Zdunek
- spokepersons and experiments' participants
- All HIL-UW stuff, including the cyclotrone operators: https://www.slcj.uw.edu.pl/en/staff/

NESDA

Performance at GANIL (E703 experiment)

^{50}Cr (175 MeV) + $^{58}Ni \rightarrow ^{108}Te$ (CN)

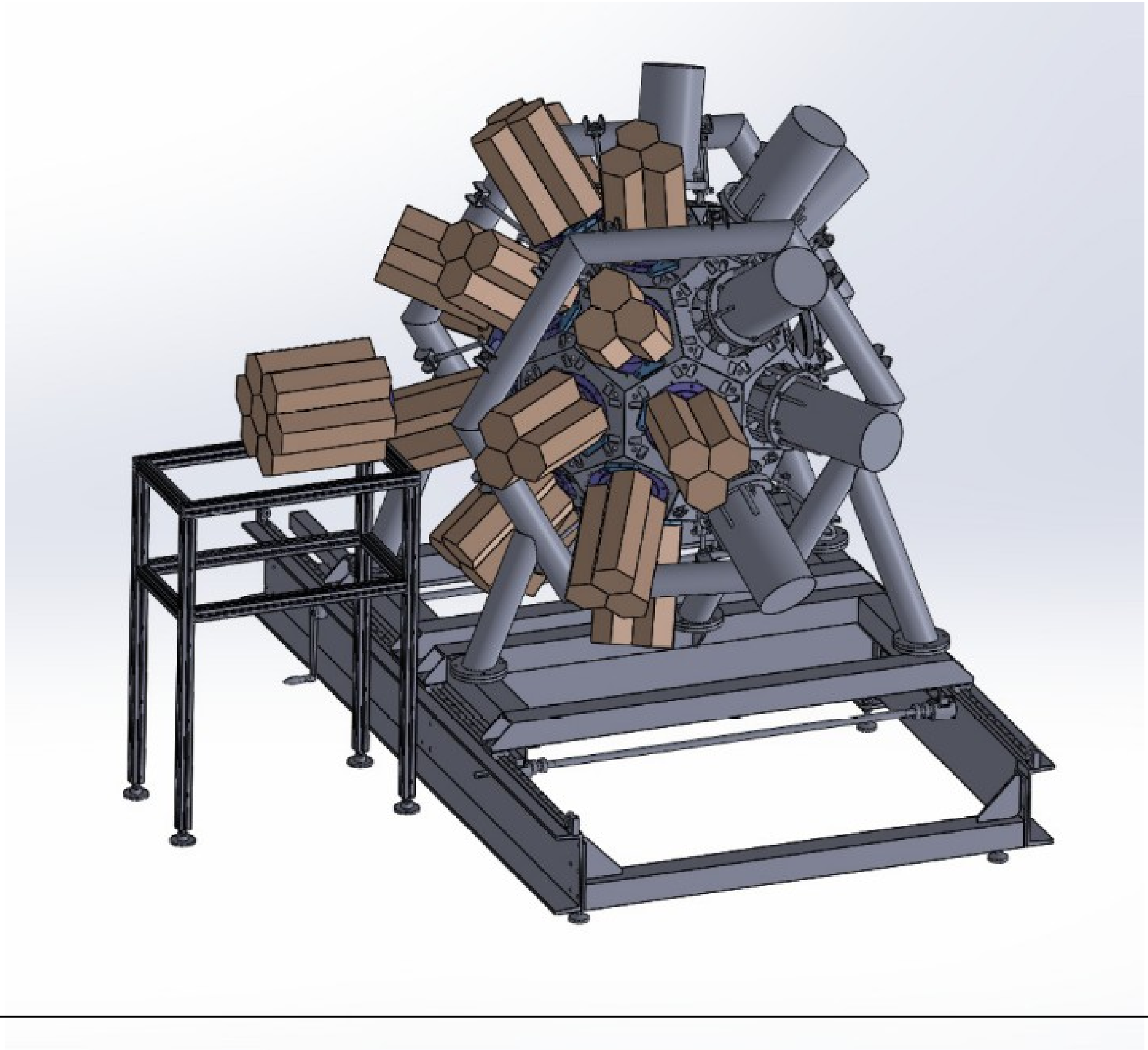
$\varepsilon_n = 0.30$ $\varepsilon_{2n} \approx 0.06$ $P(\gamma \rightarrow n) \approx 0.001$ $P(1n \rightarrow 2n) \approx 5*10^{-4}$



Total fusion x-section ≈ **300** mb

^{104}Sn produced with the emission of **2**p**2**n $\sigma(^{104}Sn) \approx$ **0.5** mb

NEEDLE 2022→



EAGLE (HPGe):
- 5 dets @ 101°
- 5 dets @ 117°
- 5 dets @ 143°

NEDA:
- 6/7 dets ~0°
- 15 dets @ 37°
- 15 dets @ 63°
- 15 dets @ 79°

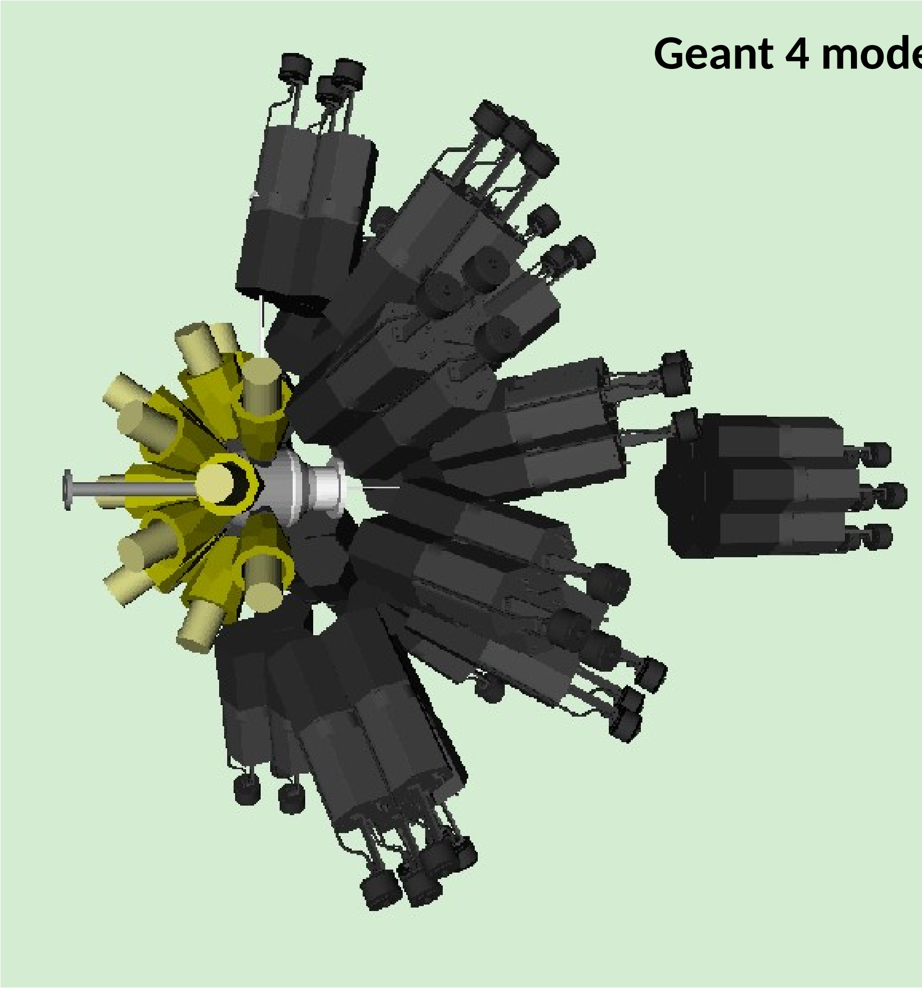
Efficiencies

Basic parameters:

- EAGLE: 15 det. ACS HPGe
  eff(γ) = 1.5% @1.3 MeV

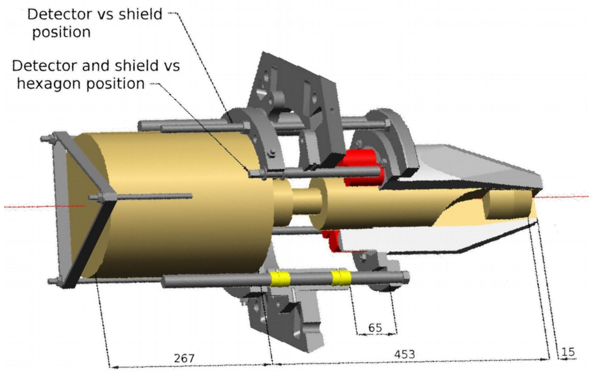
- NEDA: 51/52 det.
  eff(1n) = ~28%, eff(2n) = 6%

- NEEDLE: eff(γγ2n) = 1.26e-5



EAGLE

A flexible gamma-ray spectroscopy array able to accommodate up to 30 HPGe detectors with ACS shields and ancillary devices.



central **E**uropean **A**rray for **G**amma **L**evels **E**valuations

Truncated icosahedron:

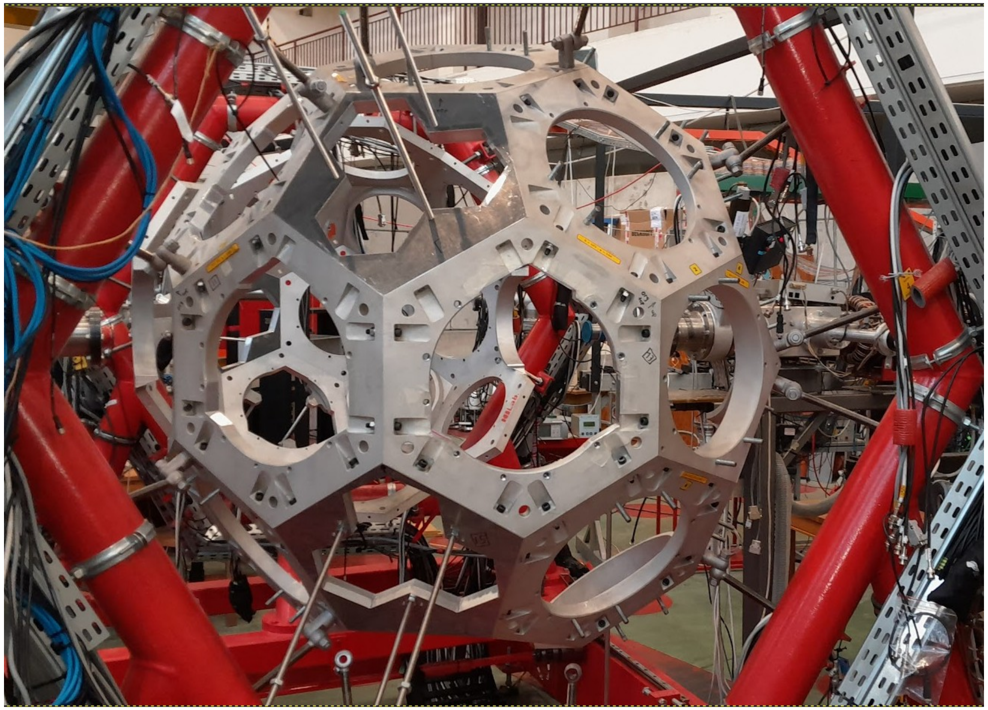
- 20 hexagonal faces, 4x5 theta angle rings: 37°, 79°, 101°, 143°
- 10 pentagonal faces 2x5 rings: 63°, 117°
- 2 pentagonal faces (beam in/out)

Minimum distance target-detector (collimator):

- hexagon: ~ 11cm eff=0.001 at 1.3 MeV
- pentagon: ~ 15 cm eff=0.0008

Loan from GAMMAPOOL
of 16 HPGe detectors (~60%) and 15 ACS.
HIL owns 19 smaller HPGe's (20 to 40%) with ACS's.
Typically ~15 detectors used in experiments, including ~14(+/- 1) GAMMAPOOL

total eff. ≈ 1.3 % at 1.3 MeV



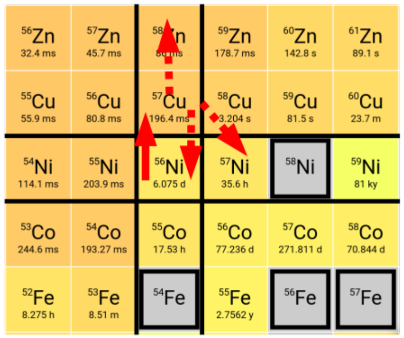
J. Mierzejewski et al. NIM A659 (2011) 84

Single proton states at N=Z=28 and core excitations in ^{57}Cu

^{57}Cu, ^{56}Ni and the astrophyscal rp-process

$T_{1/2}$ (^{56}Ni) = 6.08 d
S_p(^{57}Cu)=690 keV → proton capture followed by proton emission from excited states in ^{57}Cu

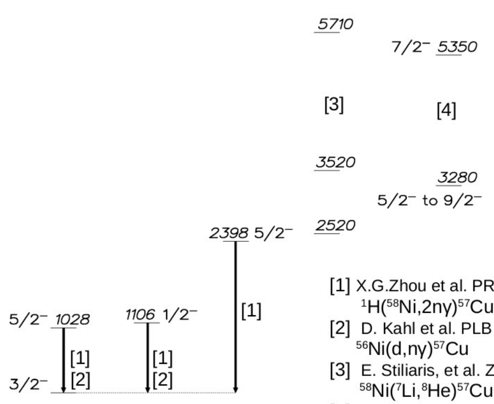
→ waiting point at ^{56}Ni



structure of excited states in ^{57}Cu essential for the rate of flow of material along the proton drip-line above ^{56}Ni.

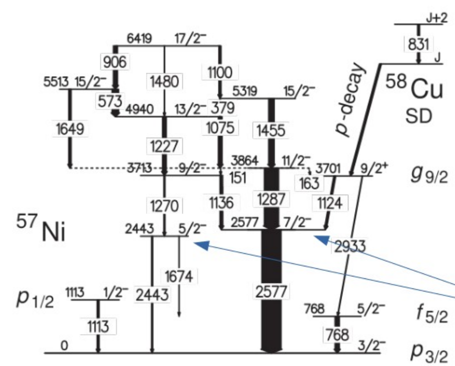
M. Regulska – BSc thesis
A. Malinowski – MSc thesis

Known excited states in ^{57}Cu



[1] X.G.Zhou et al. PRC 53 (1986) 982
^{1}H(^{58}Ni,2nγ)^{57}Cu
[2] D. Kahl et al. PLB 797 (2019) 134803
^{56}Ni(d,nγ)^{57}Cu
[3] E. Stiliaris, et al. Z.Phys. A 326 (1987) 139
^{58}Ni(^{7}Li,^{8}He)^{57}Cu, ^{58}Ni(^{14}N,^{15}C)^{57}Cu
[4] D.J. Vieria et al. PLB B60 (1976) 261
proton emission after ^{57}Zn β+ decay

^{57}Ni – the A=57 mirror of ^{57}Cu



In ^{57}Cu comparing to ^{57}Ni:

- $p_{3/2}$ and $p_{1/2}$ states should have similar relative Coulomb shifts
  → similar exc. energies of $1/2^-$, $5/2_2^-$, $7/2^-$
- $f_{5/2}$ expected at higher energy, close to $p_{1/2}$
  → $5/2^-$ close to $1/2^-$, i.e. $E_x \approx 1$ MeV

coupling of a $p_{3/2}$ nucleon to 2^+ in ^{56}Ni

^{28}Si(^{32}S,2pnγ)^{57}Ni

S_p(^{57}Ni)=7559 keV

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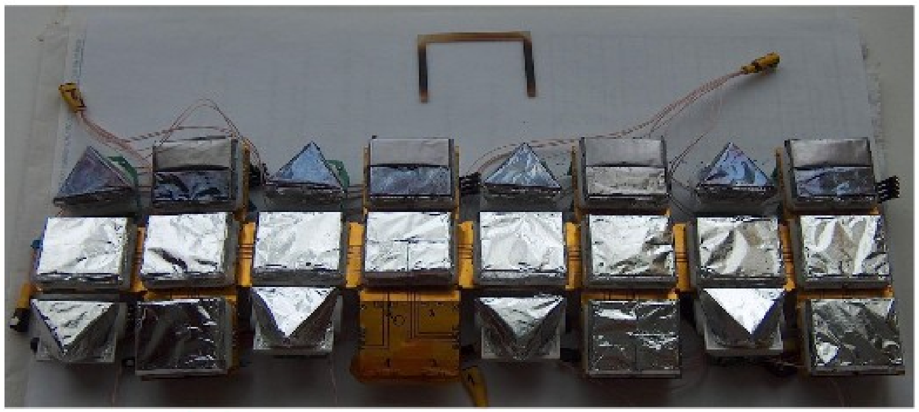
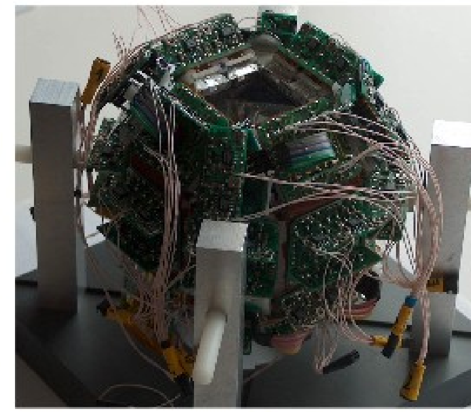
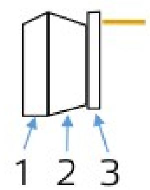
DIAMANT





CsI(Tl) scintillators (1), optically coupled with light guides (2) to PIN photodiodes (3), with in-vacuum preamps



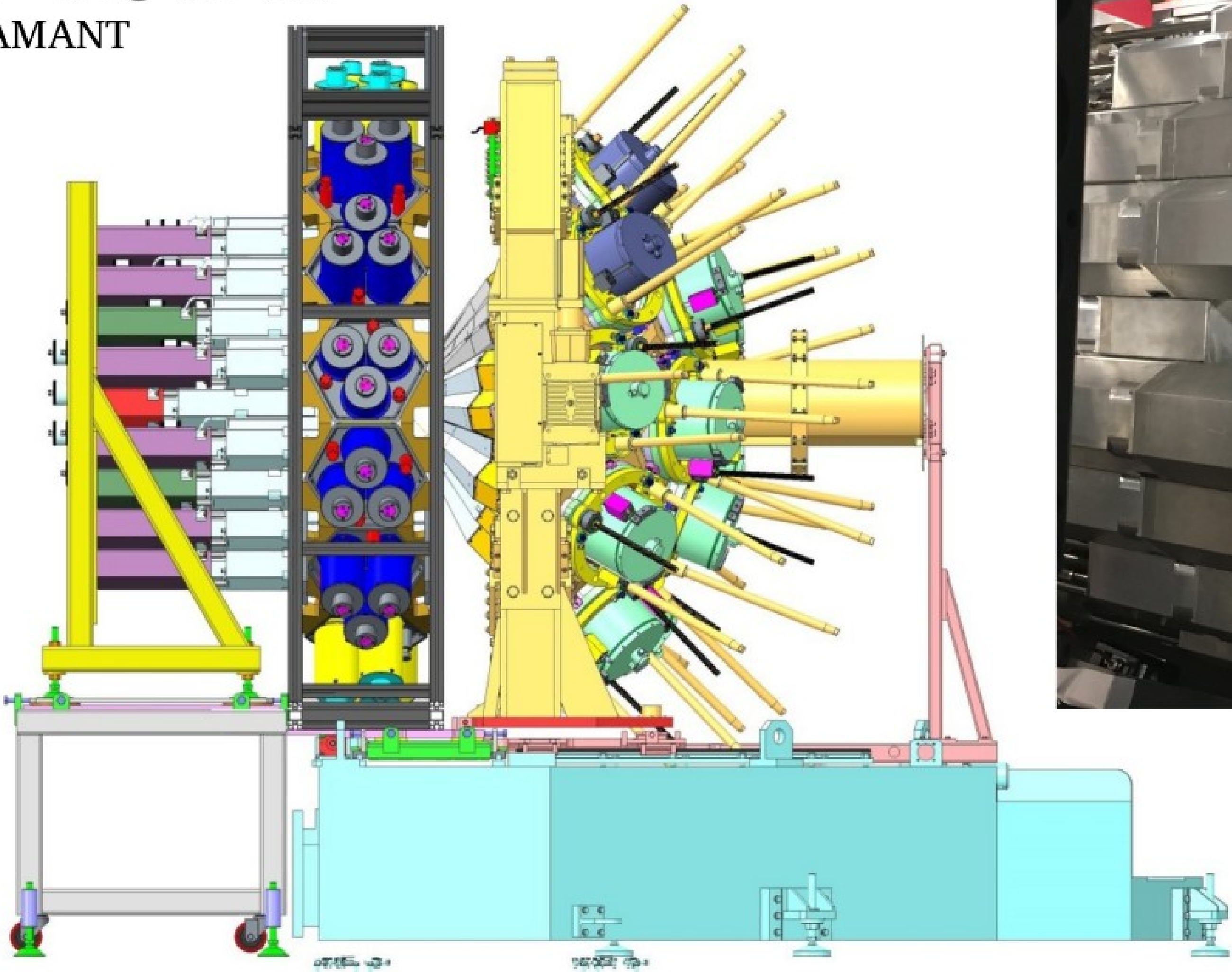
80 CsI(Tl) scintillators, mounted on a flexible PCB, the FlexiBoard

Being very compact, DIAMANT can be easily placed around the target, inside the reaction chamber.

Courtesy of I. Kuti

NEDA at GANIL (2018)

AGATA @ 145 mm
NEDA(54)@ 510 mm
NW (42)@ 650 mm
DIAMANT



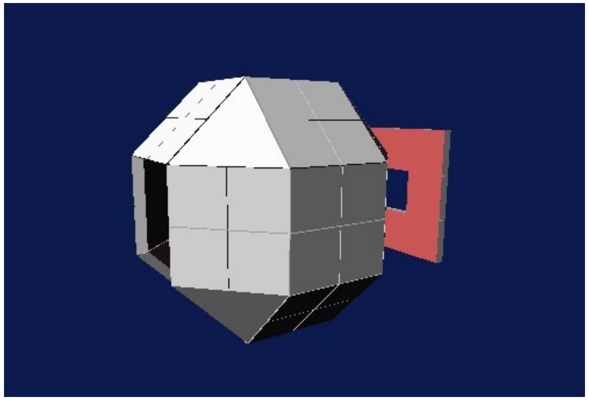
DIAMANT

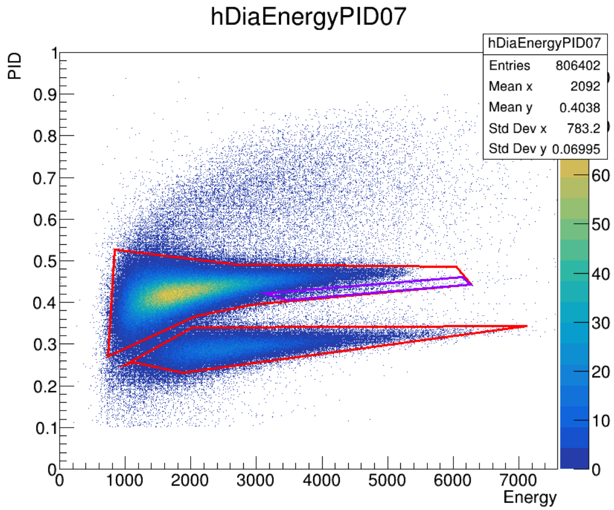
80 CsI detectors, rhombicuboctahedron, plus f.w.
able to register and distinguish
protons and alpha particles
emitted in a fusion-evaporation reaction

$\epsilon_p \approx 0.6$ $\epsilon_\alpha \approx 0.4$

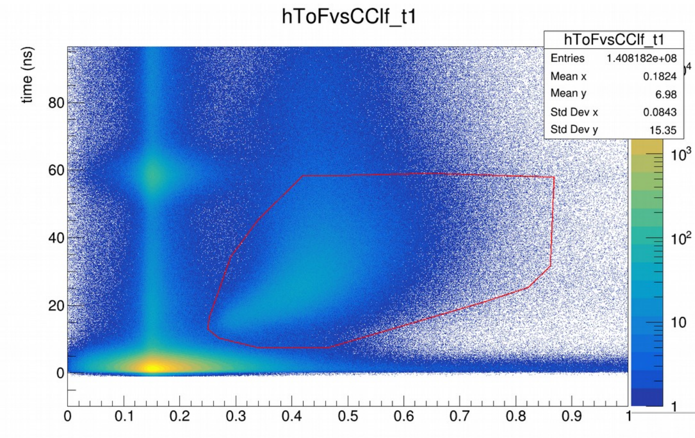
DAQ:

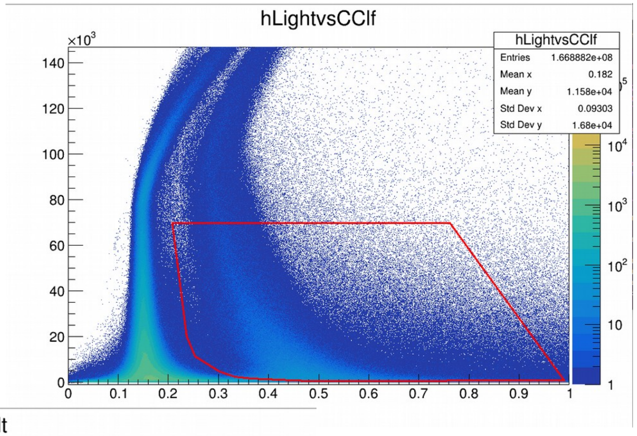
- present: NUMEXO2 digitizers
  and GANIL software, AGAVA;
- in progress: new CAEN R5560 digitizer
  purchased by ATOMKI to replace NUMEXO2
  128 channels/125 MHz/14 bit
  (double trapezoid firmware
  development in progress)

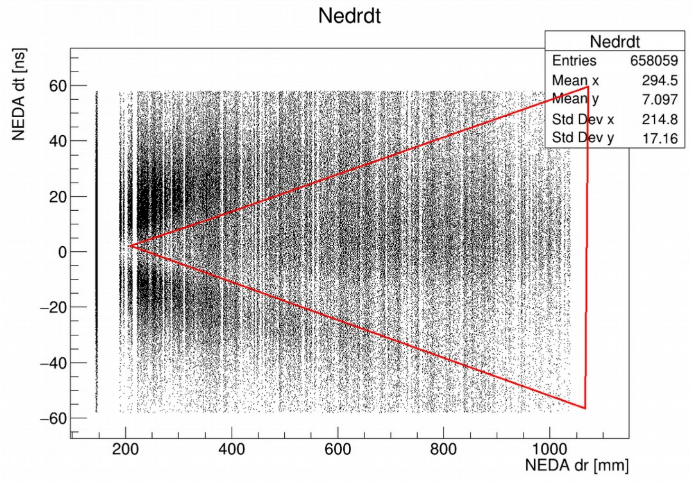




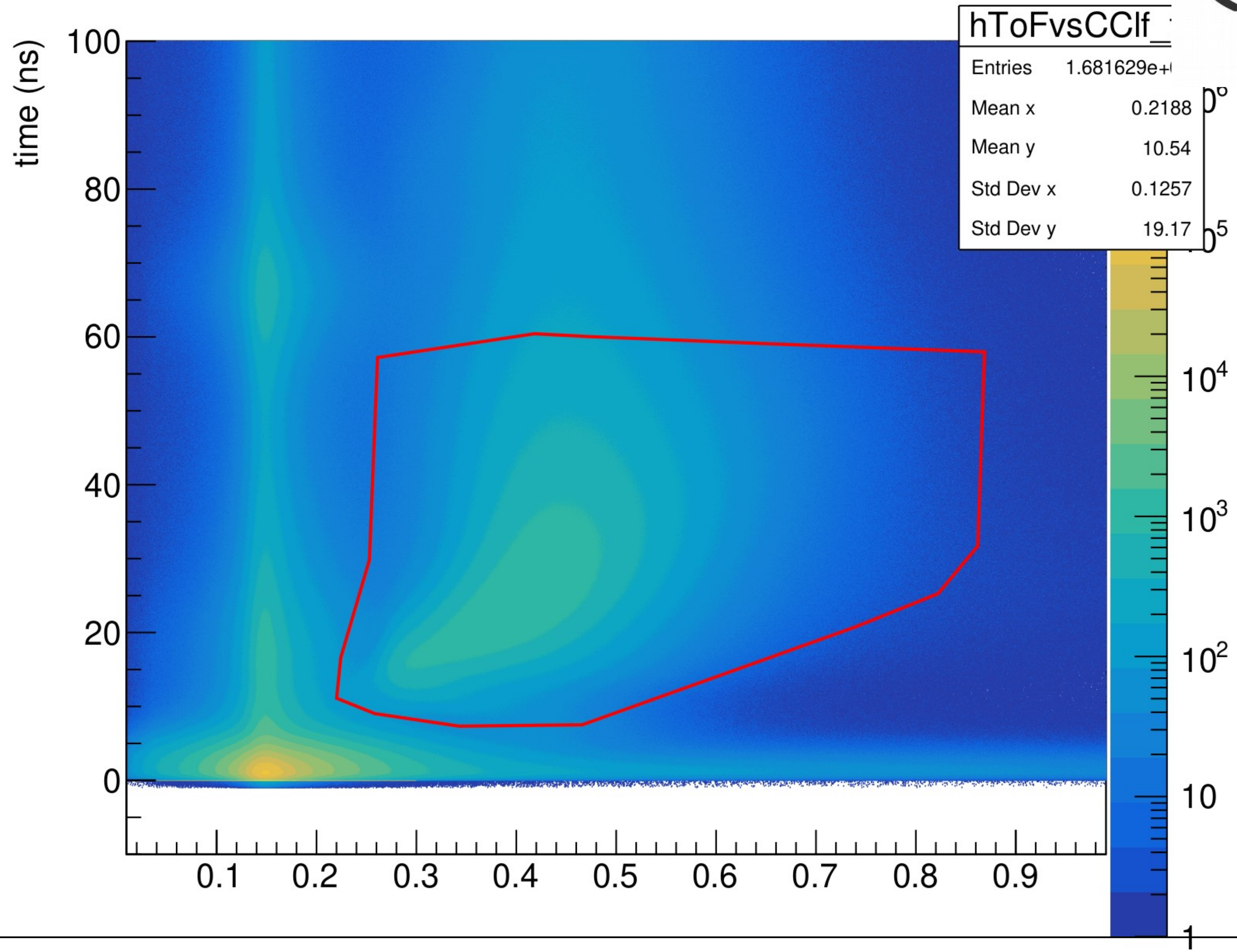
Rozróżnienie neutron/γ oraz 2n/1n





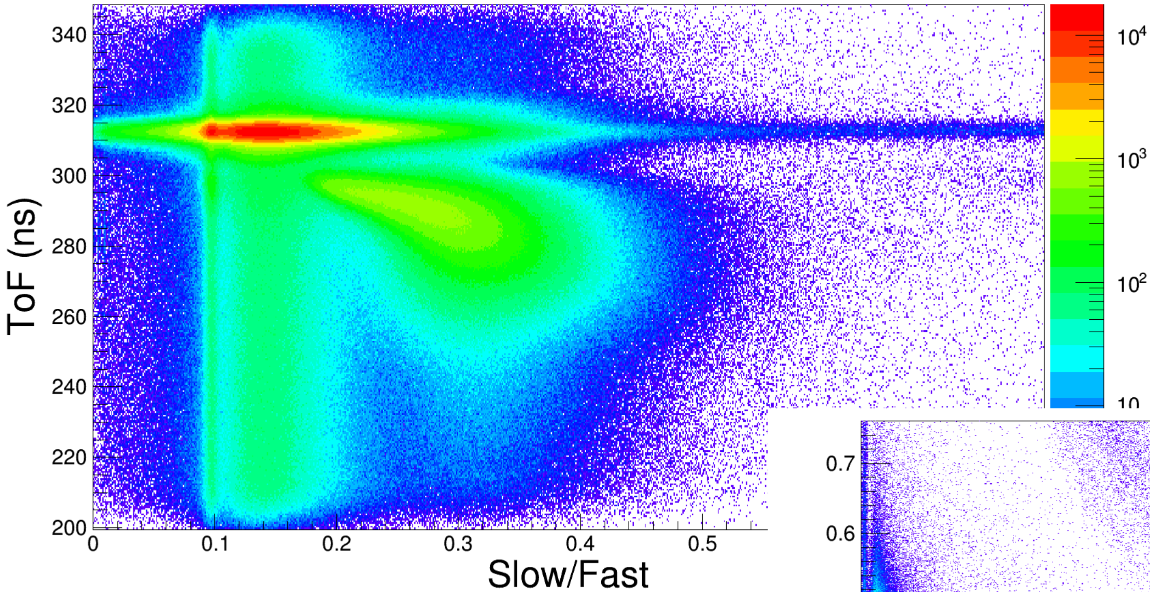


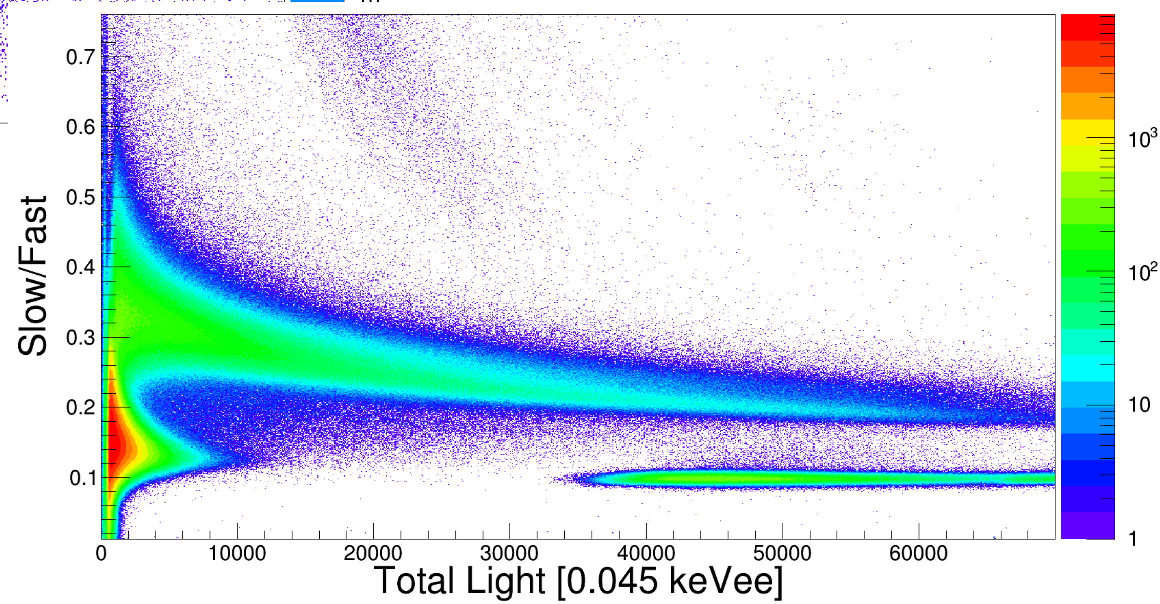
NGD ToF vs CC



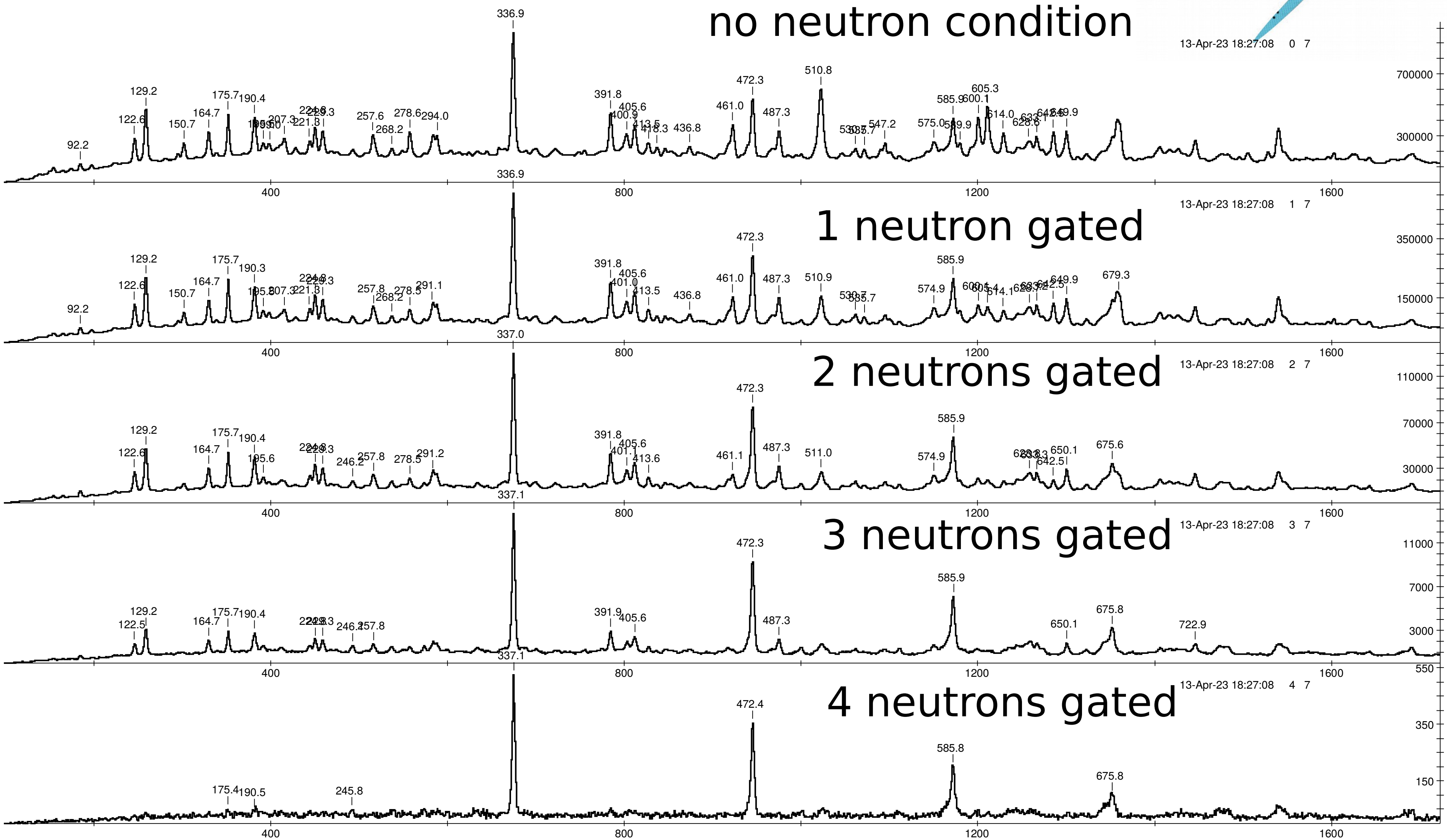
hToFvsCClf_
Entries 1.681629e+
Mean x 0.2188
Mean y 10.54
Std Dev x 0.1257
Std Dev y 19.17
time (ns)
100
80
60
40
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
10^4
10^3
10^2
10
1

n/γ discrimination



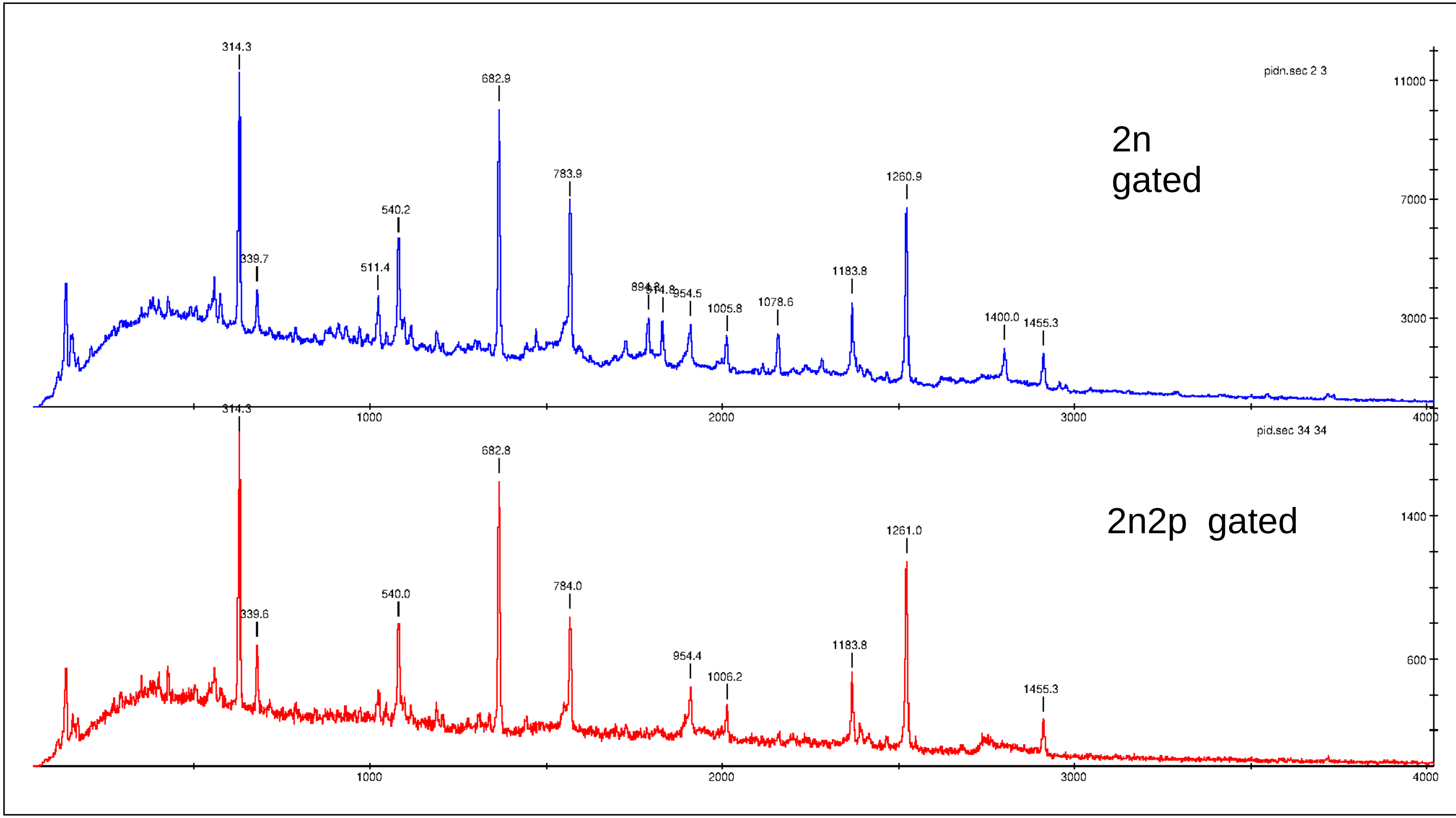


NEEDLE Performance



$^{16}O + ^{106}Pd \rightarrow ^{122}Xe\ (CN) \rightarrow ^{118}Xe + 4n$ (HIL097)

NEDA and DIAMANT



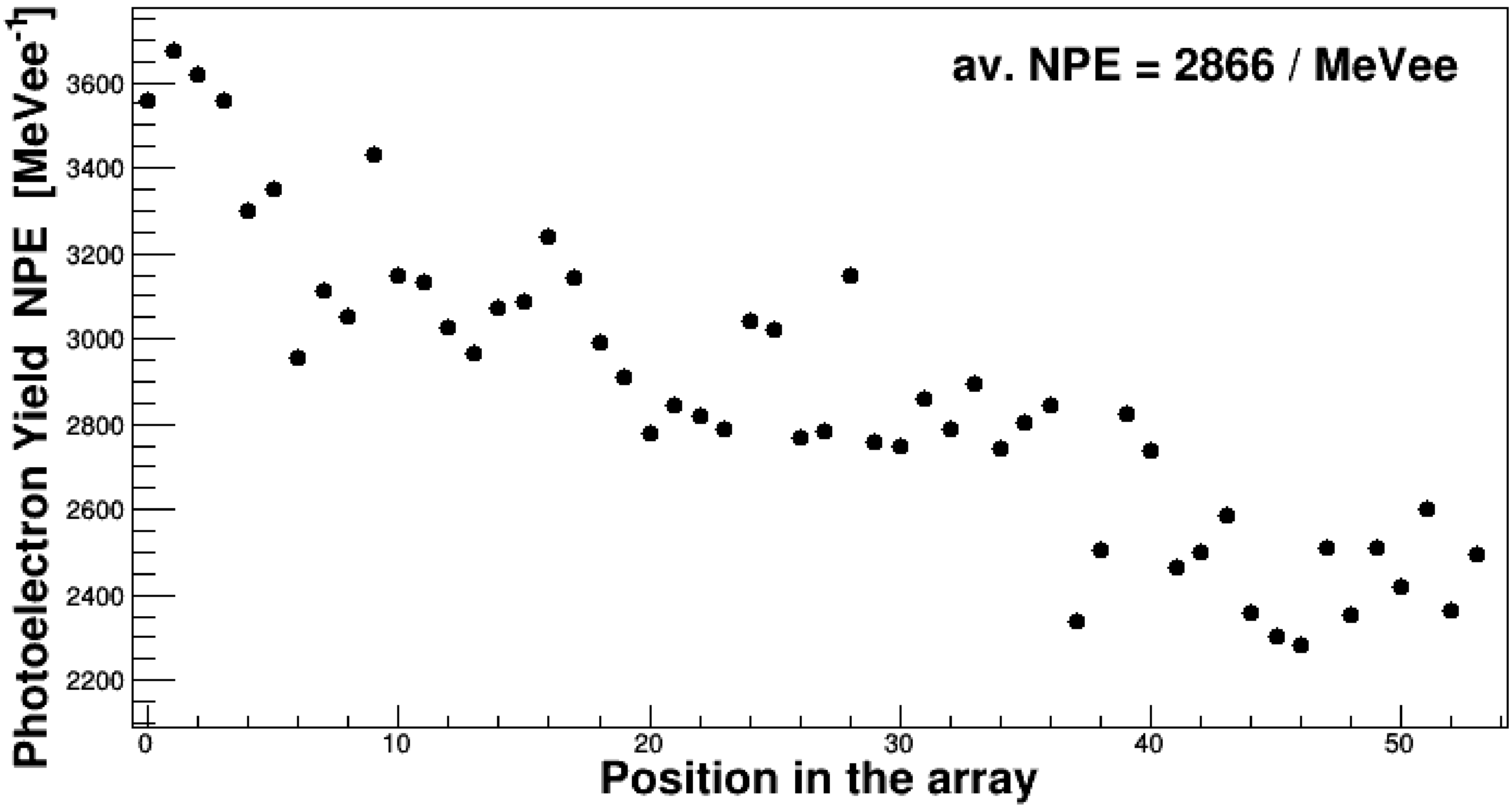
Read-out – NEEDLE

NEDA: Caen V1725 x4 with DPP-PSD
EAGLE: V1725 x2 with DPP-PHA

- 250 MHz, 14 bit
- 16-ch VME modules:
  - MCX connectors
- Dynamic range 0.5 and 2 Vpp
  + setable DC offset
- DPP algorithms implemented in FPGA: PHA, PSD
- Read-out – optical link (and VME64)
- 16 programmable LVDS I/Os
- Daisy chain possibility
- COMPASS, C & LabVIEW libraries

NEDA: Amplitude limiters needed

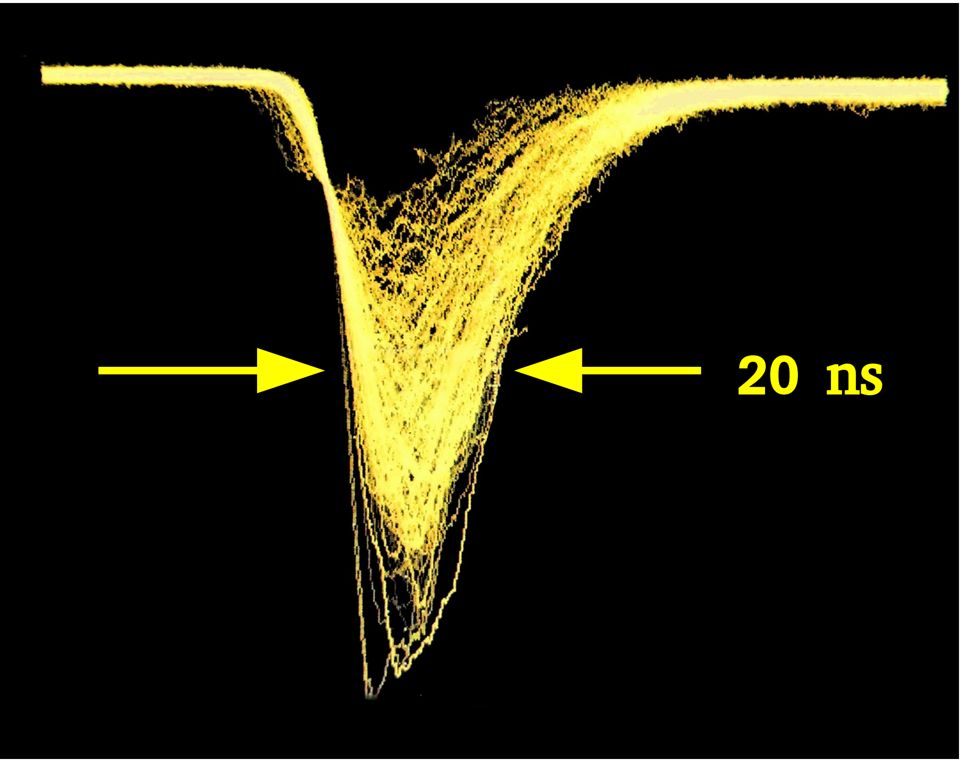
xdaq based DAQ

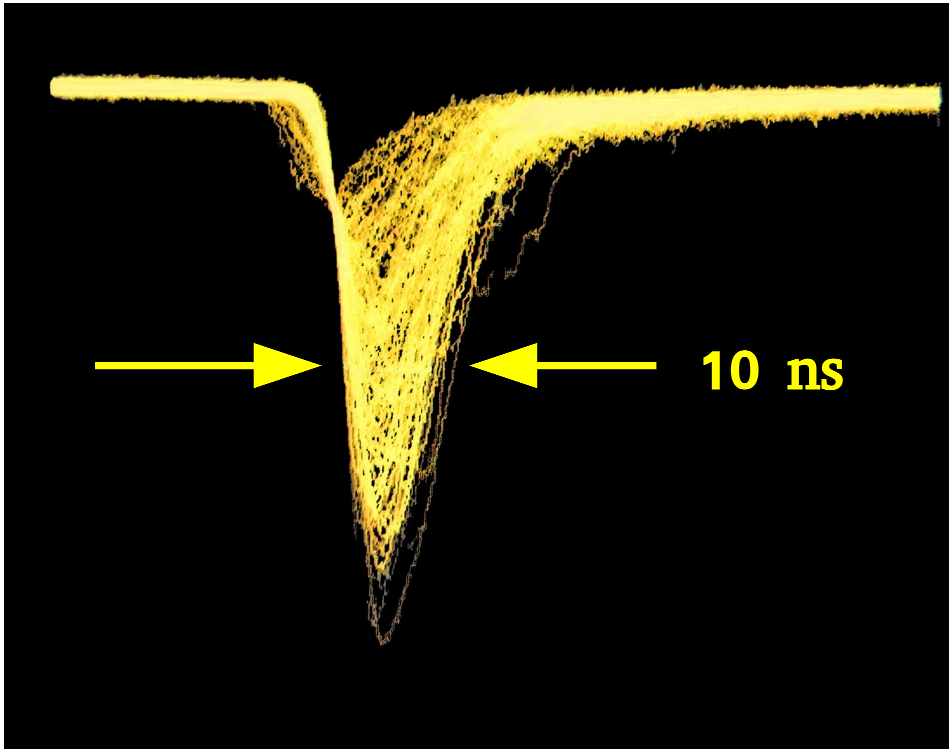

av. NPE = 2866 / MeVee
Photoelectron Yield NPE [MeVee^{-1}]
3600
3400
3200
3000
2800
2600
2400
2200
0
10
20
30
40
50
Position in the array

Construction

NEDA

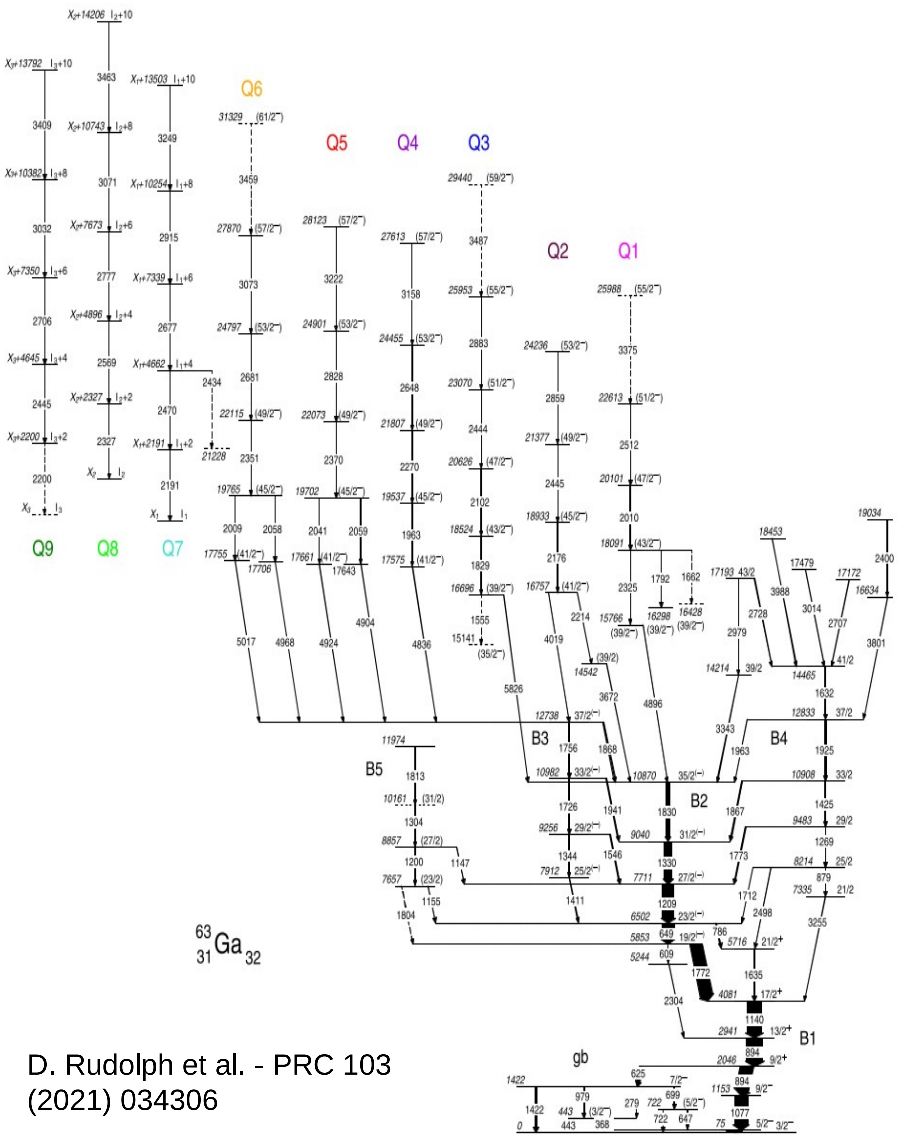
NWall





Quality starts from the initial signal.

^{63}Ga – mirror nuclei of



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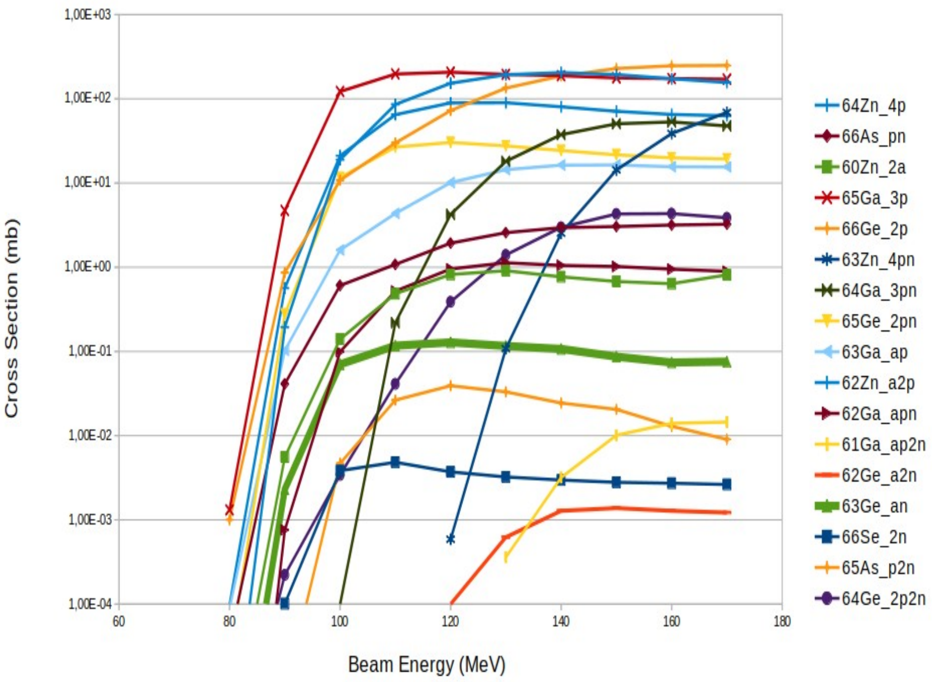
Reactions and x-secs

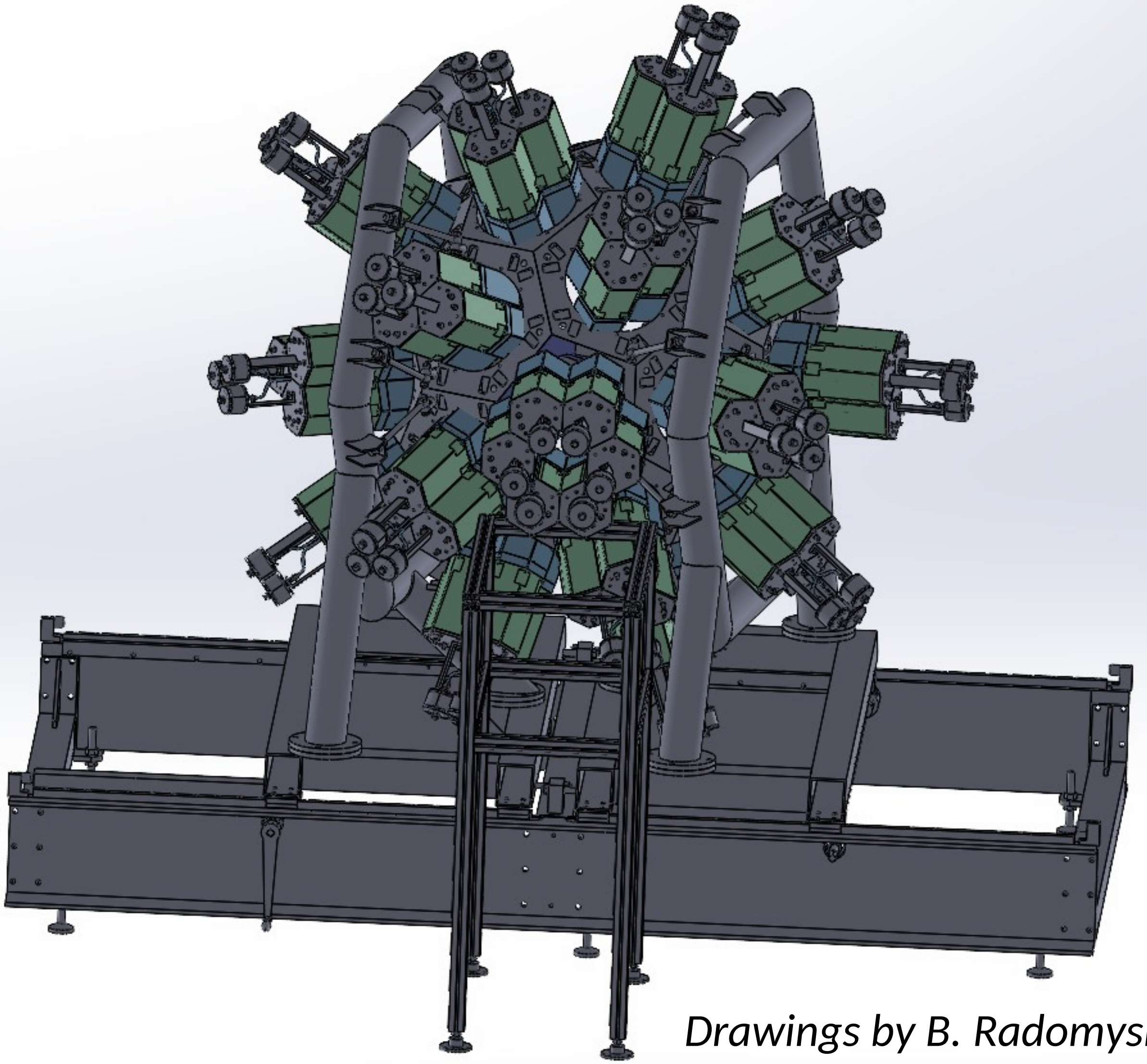
$^{40}Ca + ^{28}Si \rightarrow ^{78}Se \rightarrow ^{63}Ge + \alpha n$ (^{40}Ca @ 105 MeV)

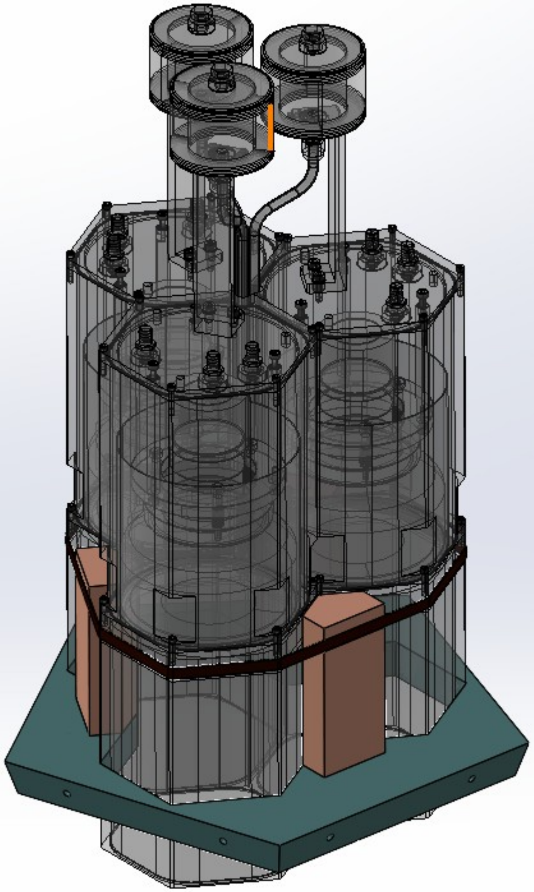
^{63}Ge x-sec: ~0.1 mb (HIVAP)

$^{36}Ar + ^{32}S \rightarrow ^{78}Se \rightarrow ^{63}Ge + \alpha n$ (issue: ~60 k€ cost for ^{36}Ar bottles)



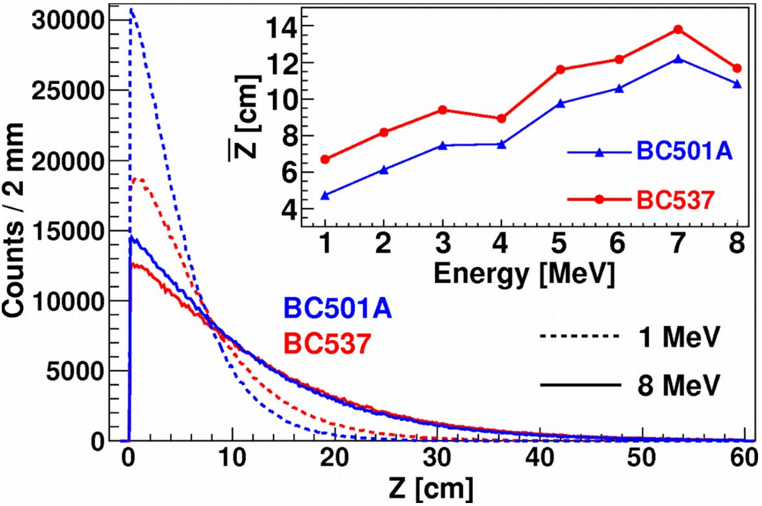
Mechanics



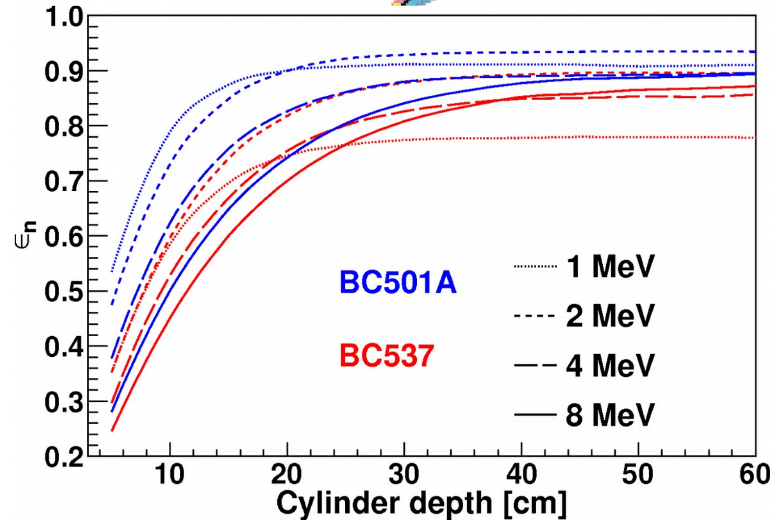


Drawings by B. Radomyski

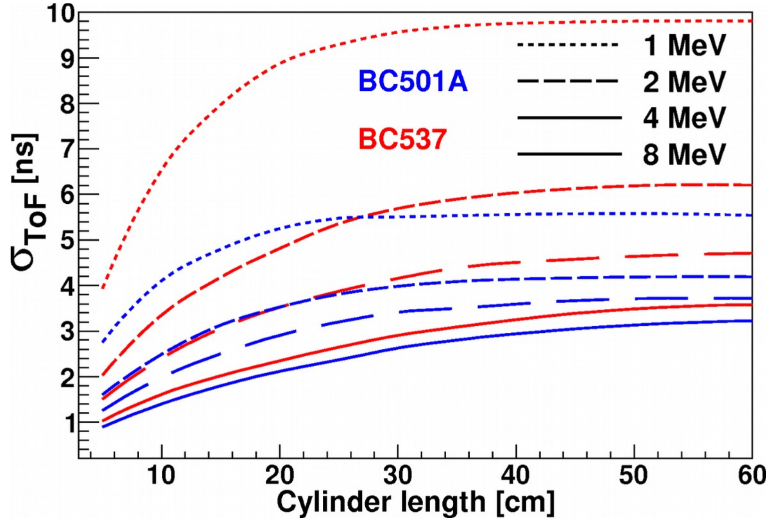
Single cell



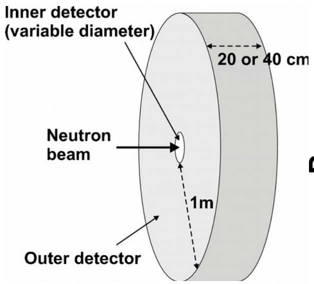
Counts / 2 mm
Z [cm]
BC501A
BC537
1 MeV
8 MeV
$\overline{Z}$ [cm]
Energy [MeV]
BC501A
BC537



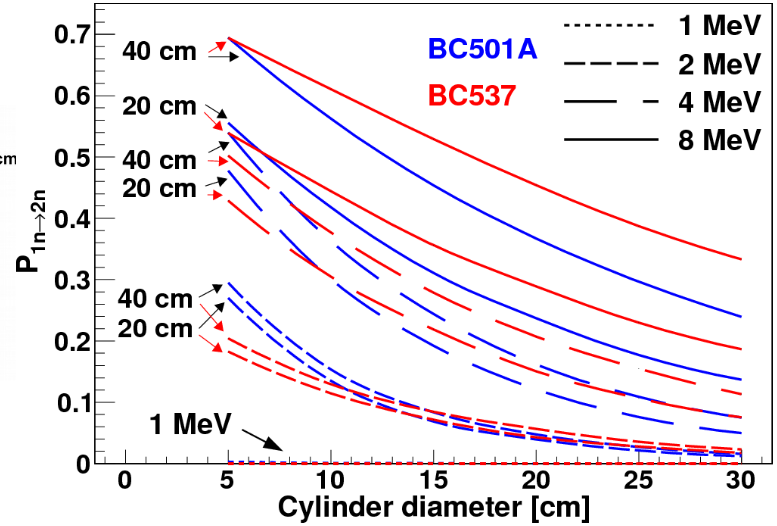
ϵ_n
Cylinder depth [cm]
BC501A
BC537
1 MeV
2 MeV
4 MeV
8 MeV



σ_{ToF} [ns]
Cylinder length [cm]
BC501A
BC537
1 MeV
2 MeV
4 MeV
8 MeV



Inner detector
(variable diameter)
20 or 40 cm
Neutron
beam
1m
Outer detector

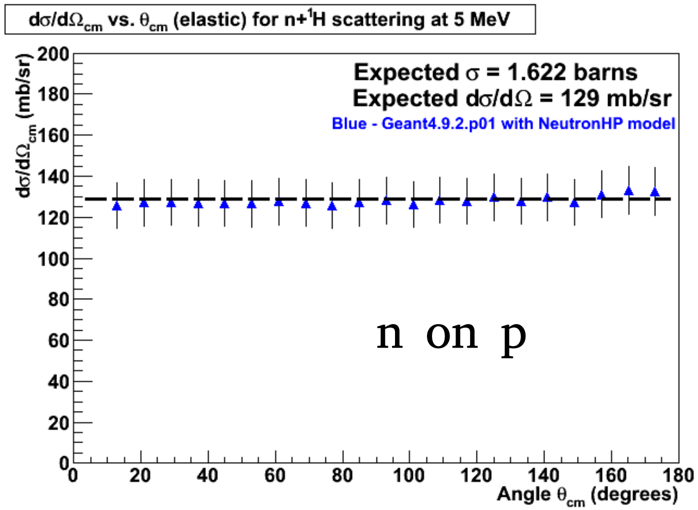


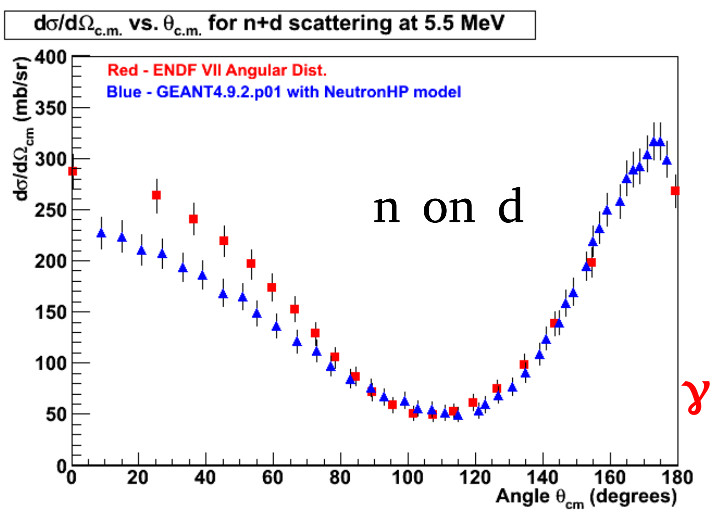
$P_{1n\rightarrow 2n}$
Cylinder diameter [cm]
BC501A
BC537
1 MeV
2 MeV
4 MeV
8 MeV
40 cm
20 cm
40 cm
20 cm
40 cm
20 cm
1 MeV

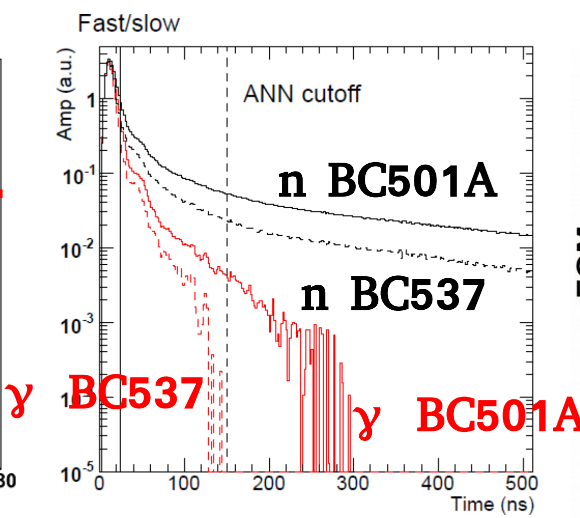
Scintillator

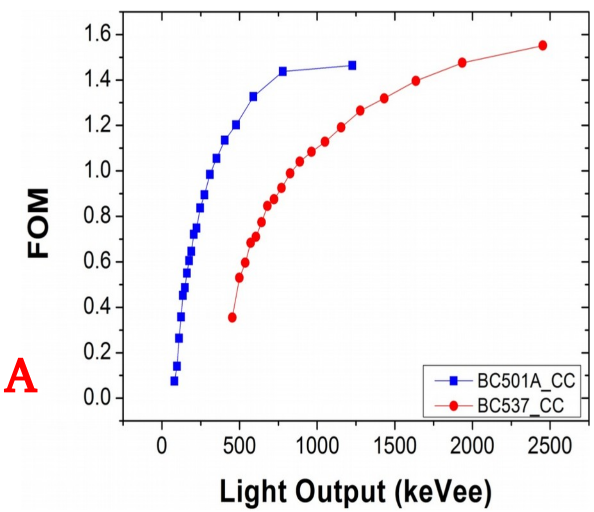
? BC501A / BC537 / EJ299 / … ?

preliminary

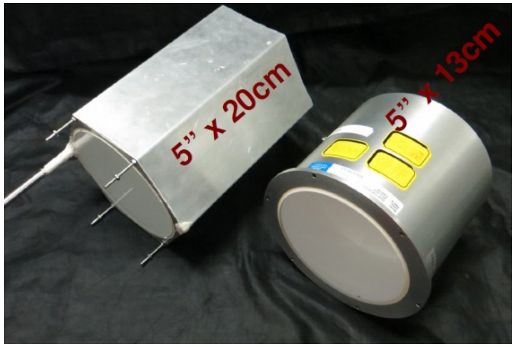




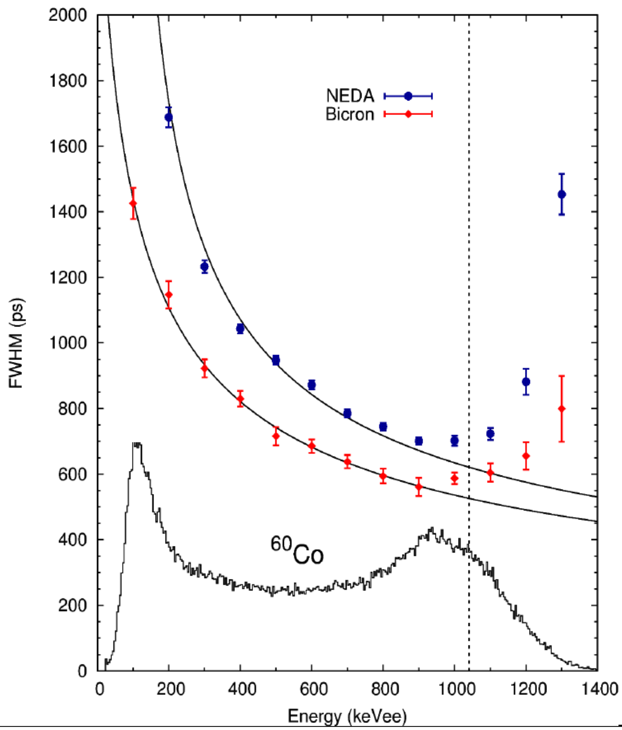




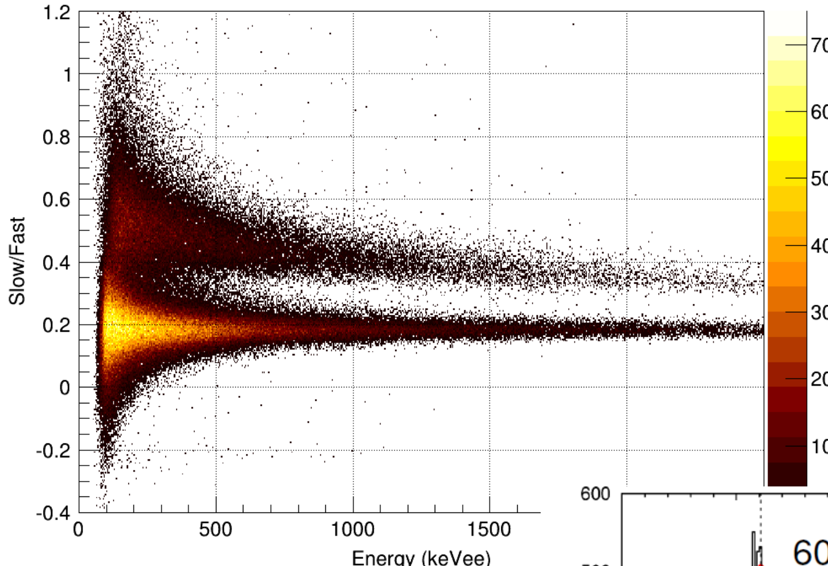
Prototype



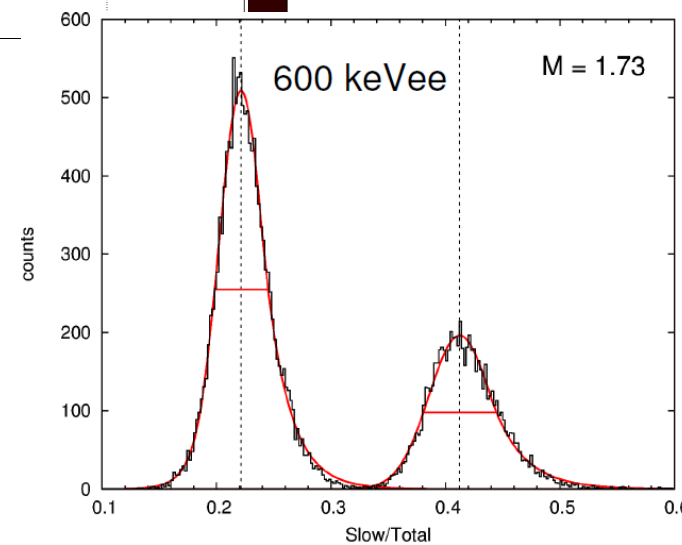
5” x 20cm
5” x 13cm



NEDA
Bicron
^{60}Co
FWHM (ps)
Energy (keVee)
0
200
400
600
800
1000
1200
1400
1600
1800
2000

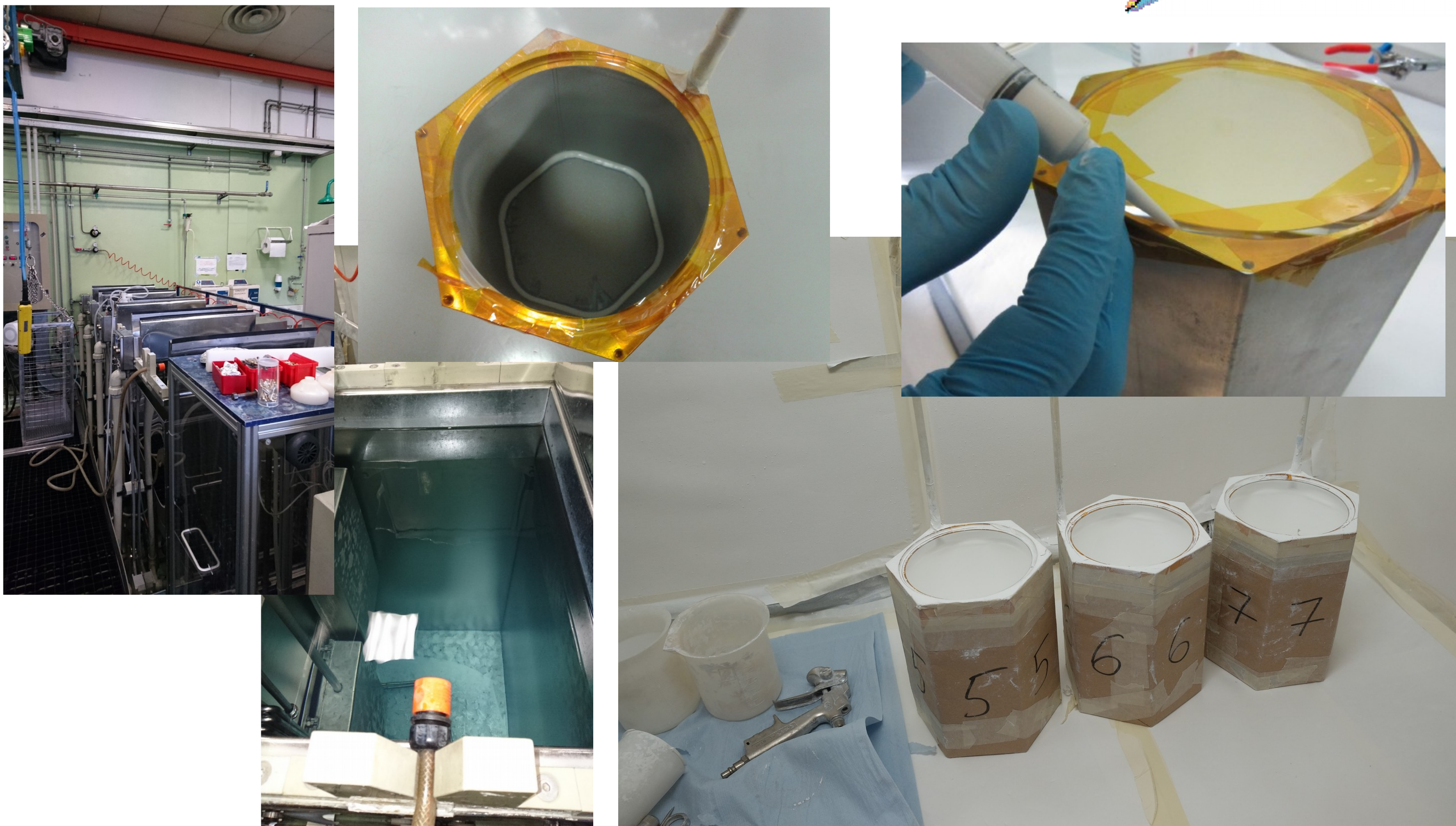


Slow/Fast
Energy (keVee)
0
500
1000
1500
-0.4
-0.2
0.2
0.4
0.6
0.8
1
1.2
10
20
30
40
50
60
70



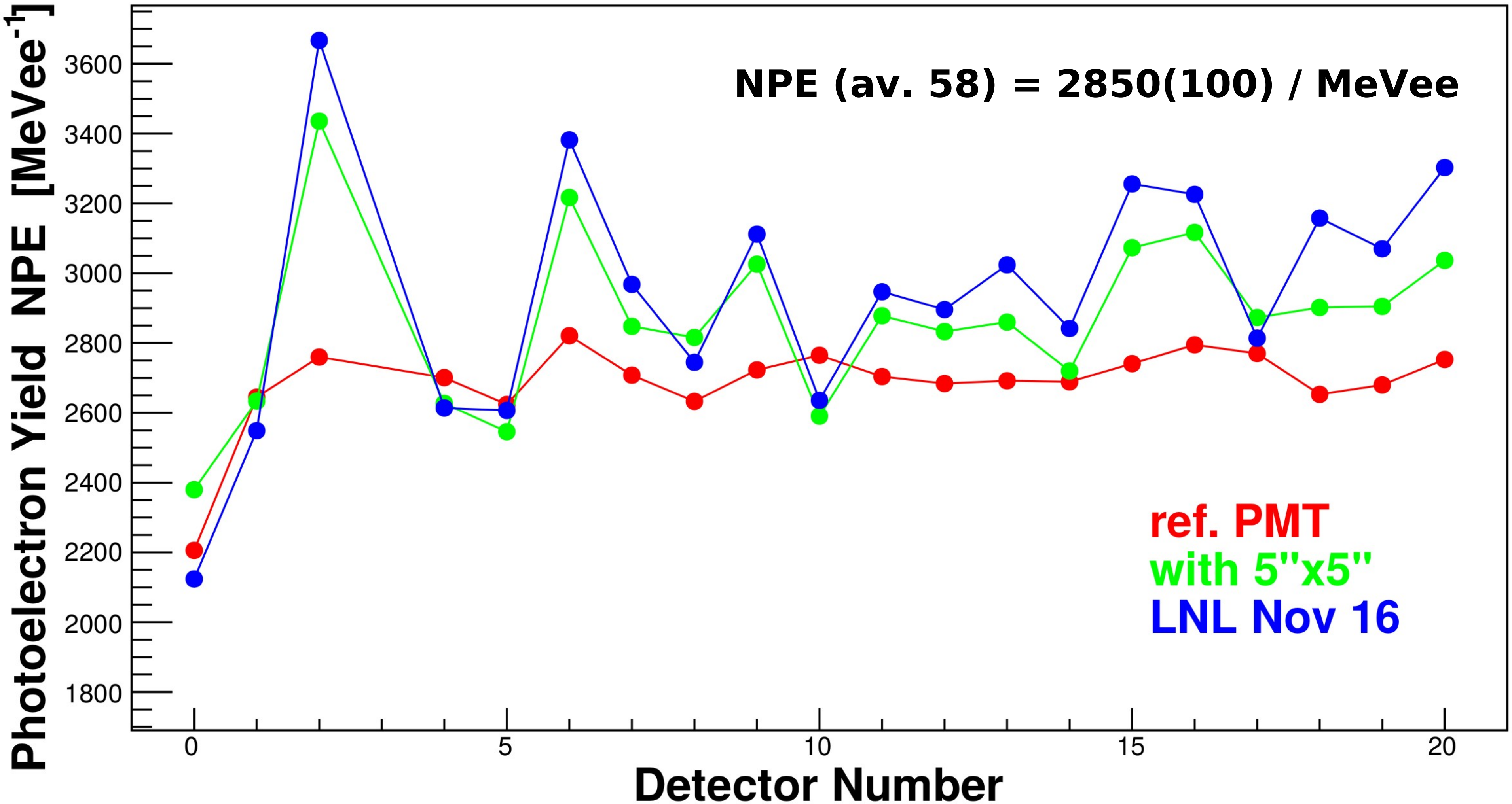
600 keVee
M = 1.73
counts
Slow/Total
0.1
0.2
0.3
0.4
0.5
0.6
0
100
200
300
400
500
600

Detector production

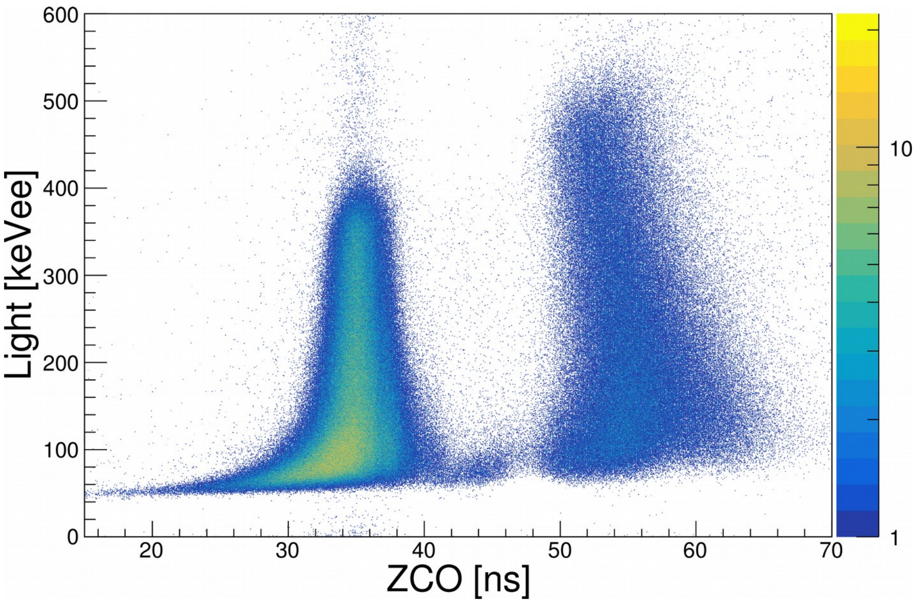


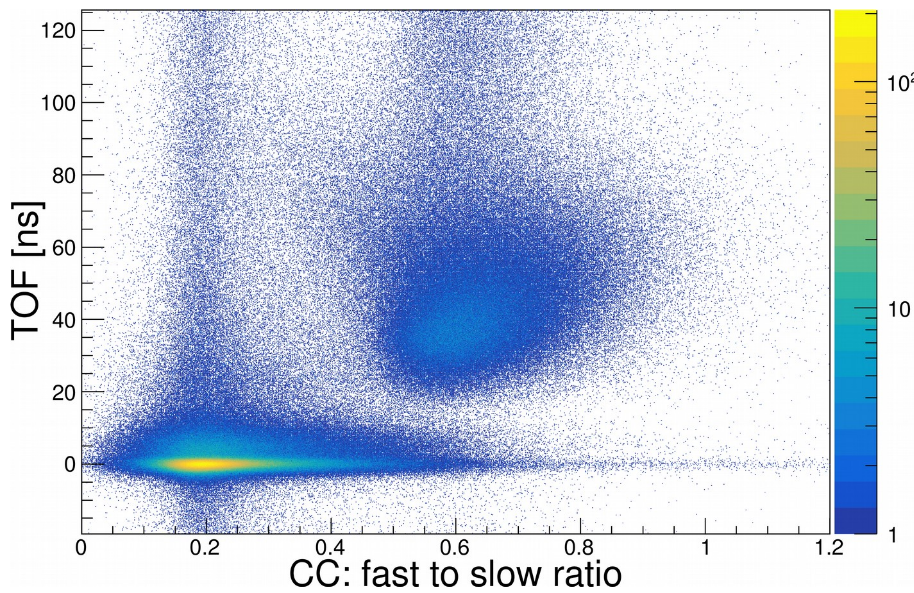
Detector production

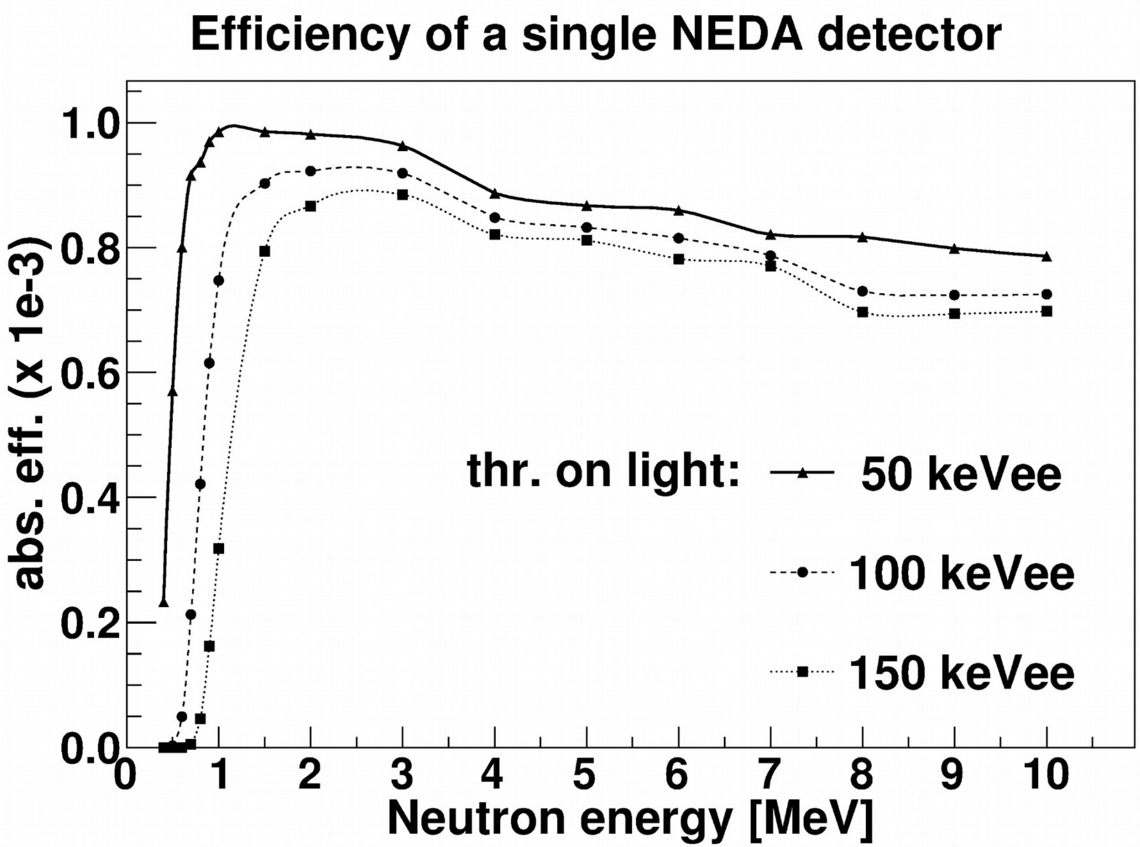
Characterisation



Characterisation







Efficiency of a single NEDA detector
abs. eff. (x 1e-3)
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
7
8
9
10
Neutron energy [MeV]
thr. on light:
50 keVee
100 keVee
150 keVee

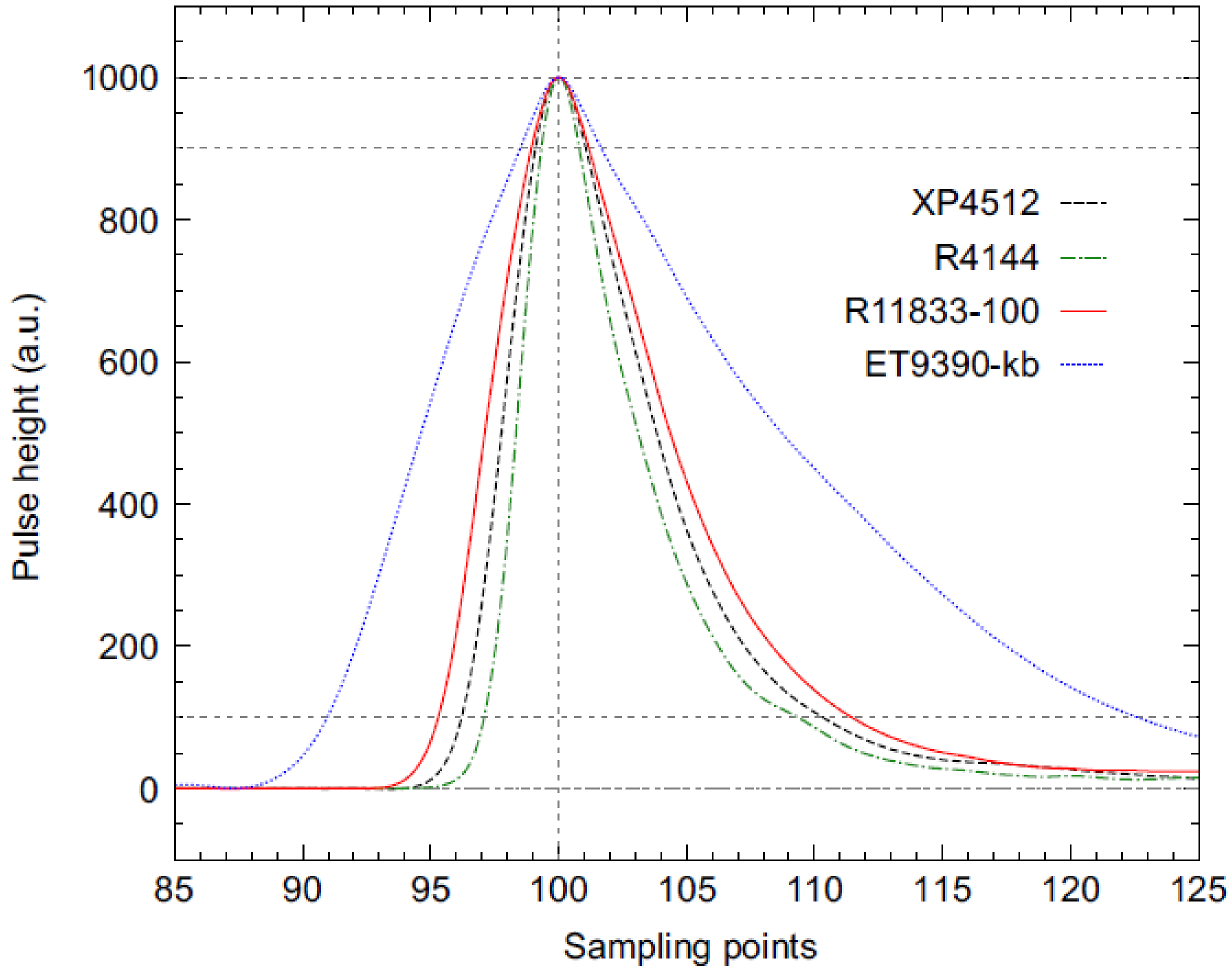


Fig. 2. Digitized waveforms averaged over 10^5 events for the four 5 in. PMTs coupled to a cylindrical 5 in. by 5 in. BC501A. The sampling frequency of the digitizer was 500 MS/s. The waveforms were normalized to a pulse height of 1000 and time aligned at the maximum of the signal. Dashed lines are drawn at 10%, 90%, at the maximum and at the baseline of the waveform to guide the eye.

Geant 4 simulations

Light to energy dependence

Light output for 2 MeV neutrons
Instrumental response function included

G.Jaworski et al. NIM A673 (2012) 64

Geant 4 simulations

Neutron detection efficiency

G.Jaworski et al. NIM A673 (2012) 64