Measurement of the S-wave *nn* Scattering Length

Status of Experiment Preparation

SFB 1245 Workshop 2022

1) Motivation and Experimental Approach

- What do we know about a_{nn} to this day?
- Why is it interesting to measure a_{nn} again?
- Beam production and experimental setup
- Neutron detector HIME

2) Simulation

- Reconstructed spectra
- 2*n* reconstruction efficiency

3) Test Measurements with HIME Modules

What is known about a_{nn} to this day?

- Determined from $\pi^- d \rightarrow nn\gamma$ reactions:

  $a_{nn} = (-18.7 \pm 0.27\ (\text{expt.}) \pm 0.30\ (\text{th.}))\ \text{fm}$
- Including corrections for the magnetic *nn* interaction:

  $a_{nn}^{N} = (-18.9 \pm 0.4)\ \text{fm}$

  (Q. Chen *et al.*, 2008)

- $|a_{nn}| \gg$ typical range of interaction (~1 fm)
- Negative sign ⇒ attractive interaction at low energy

  ⇒ Di-neutron is very close to be bound

Why is it interesting to measure a_{nn} again?

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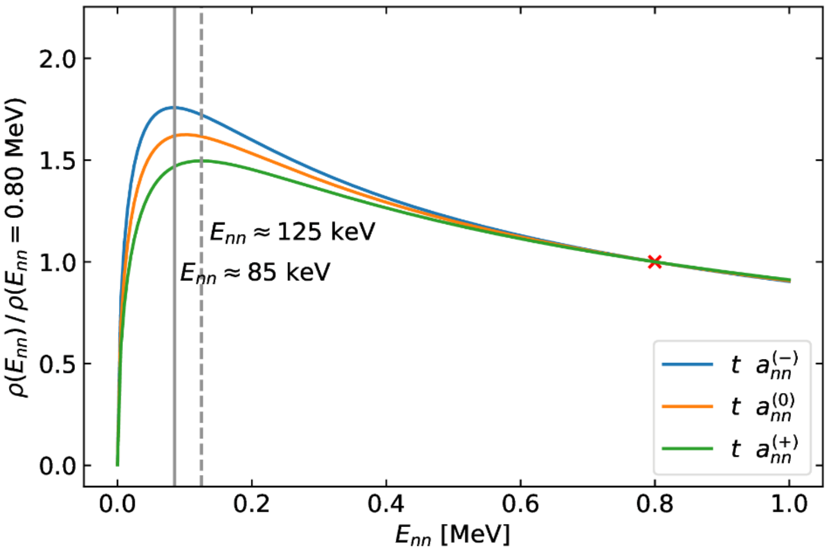
- Most widely used value from $\pi^- d \rightarrow nn\gamma$ reactions (Q. Chen *et al.*, 2008):
  (–18.7 ± 0.27 (expt.) ± 0.30 (th.)) fm
- $nd \rightarrow nnp$ (V. Huhn *et al.*, 2000) (Bonn):
  (–16.27 ± 0.40) fm
- $nd \rightarrow nnp$ (Witsch *et al.*, 2006) (Bonn):
  (–16.5 ± 0.9) fm
- $nd \rightarrow nnp$ (D. E. Gonzales Trotter *et al.*, 2006) (TUNL):
  (–18.72 ± 0.13 (stat.) ± 0.65 (sys)) fm
- New experiment proposal (T. Aumann *et al.*, 2020):
  ^{6}He(p,$p\alpha$)2n, t(p,2p)2n, d(^{7}Li,^{7}Be)2n in inverse kinematics

Determination of a_{nn}

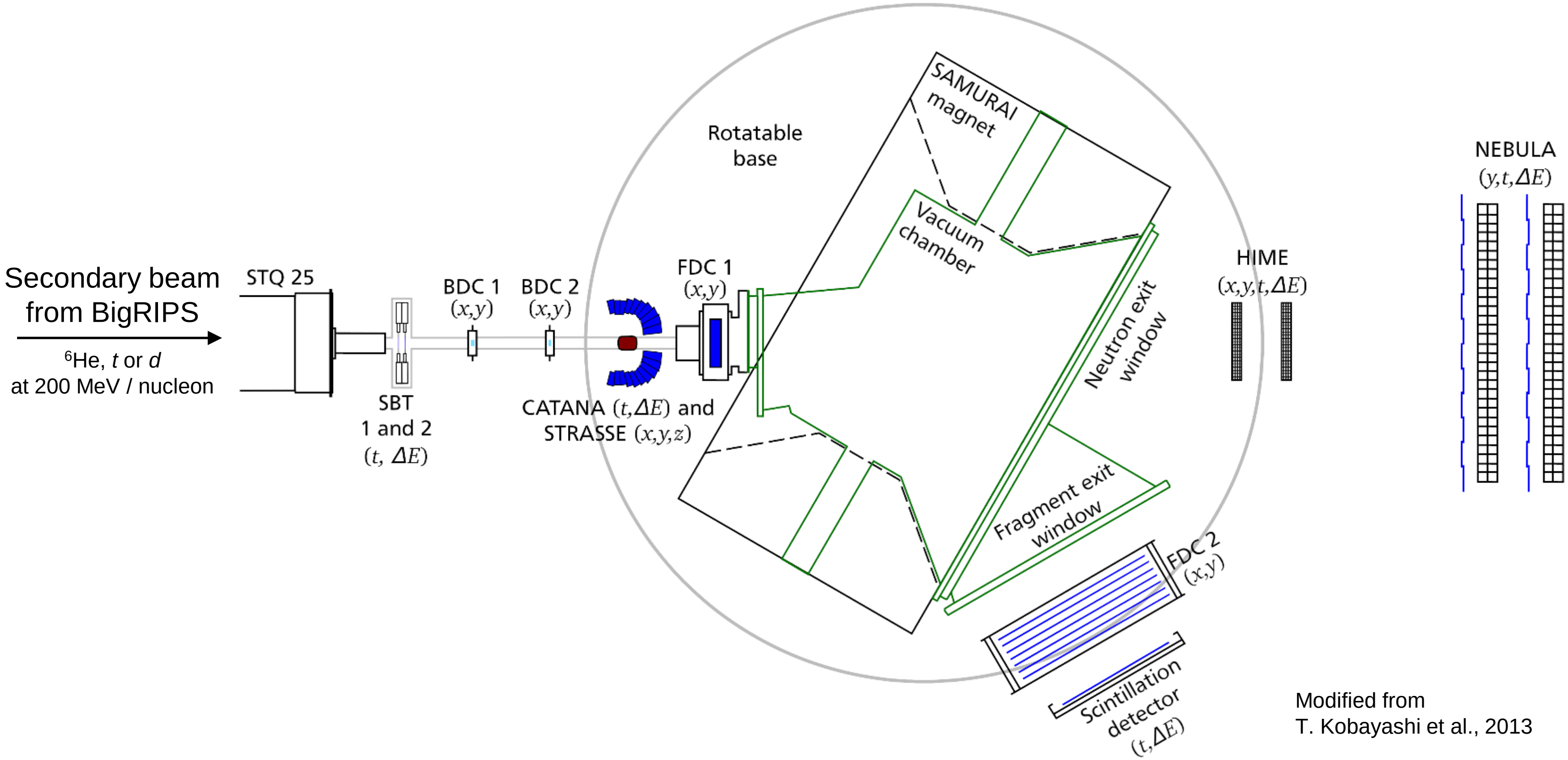


M. Göbel et al. "Neutron-neutron scattering length from the ^{6}He(p,pα)nn reaction". In: *Phys. Rev. C* 104 (2021)

$$a_{nn}^{(-)} = a_{nn}^{(0)} - 2\ \mathrm{fm}$$
$$a_{nn}^{(0)} = -18.7\ \mathrm{fm}$$
$$a_{nn}^{(+)} = a_{nn}^{(0)} + 2\ \mathrm{fm}$$

- Determine a_{nn} by comparison of the halo EFT spectrum with the experimental relative energy distribution
- Reaction channels of interest:
  - ^{6}He(*p*,*pα*)2*n* and *t*(*p*,*2p*)2*n* knockout reactions
  - *d*(^{7}Li,^{7}Be)2*n* charge exchange reaction
  - *d*(*p*,2*p*)*n* as a calibration measurement
- Anticipated accuracy: 0.2 fm

SAMURAI setup at RIKEN



Modified from
T. Kobayashi et al., 2013

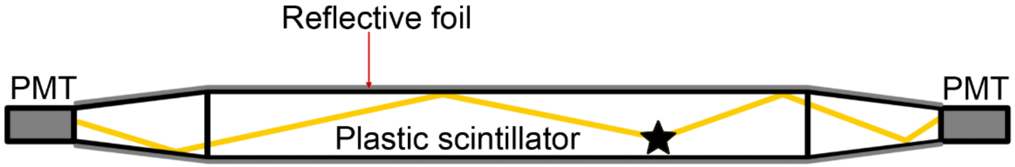
HIME Detector Design

Detector design

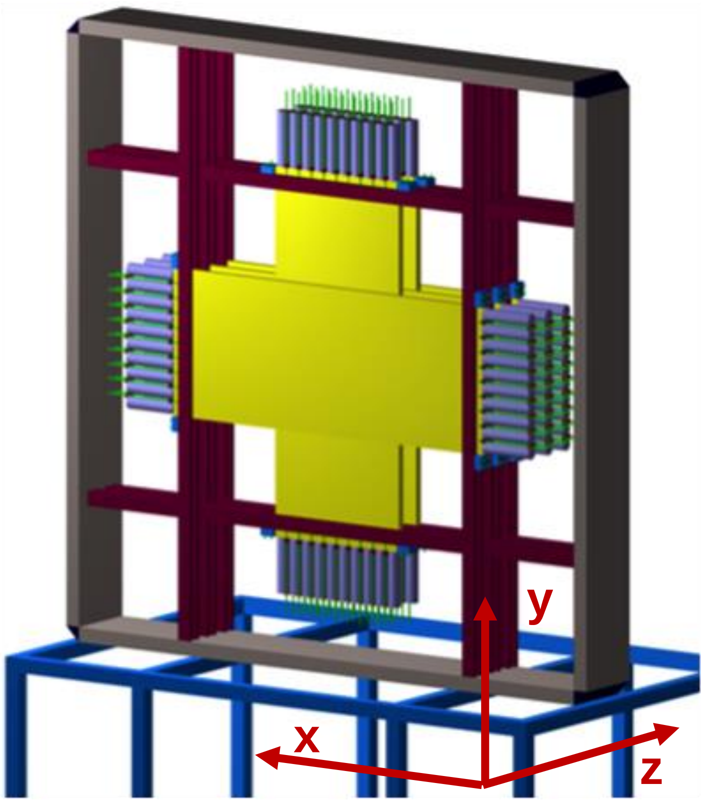
- Modular plastic scintillator based neutron detector
- Plastic scintillator bars:
  100 cm (length) x 4 cm (width) x 2 cm (depth)
- Active area of ~100 x 100 cm^2
- 24 modules per layer, 6 layers per detector wall

Resolution

- Time resolution: 100 ps (rms)
- Better than 25 keV energy resolution at the rising edge of the relative energy spectrum



HIME prototype



Invariant-Mass Measurement

Available information for each hit:

- Four-vector giving position and ToF
- Deposited energy
- Identification number of the corresponding scintillator bar

→ Use this to reconstruct the first interaction points of primary neutrons in the detector

$$M_{\mathrm{inv}}c^2 = 2m_nc^2 + E_{\mathrm{rel}} = \sqrt{\left(\sum_{i=1}^{2} P_{n_i}\right)_\mu \left(\sum_{i=1}^{2} P_{n_i}\right)^\mu}$$

$$\Rightarrow \frac{E_{\mathrm{rel}}}{m_nc^2} = \sqrt{2\left(1+\gamma_{n_1}\gamma_{n_2}\left(1-\beta_{n_1}\beta_{n_2}\cos\vartheta_{n_1n_2}\right)\right)} - 2$$

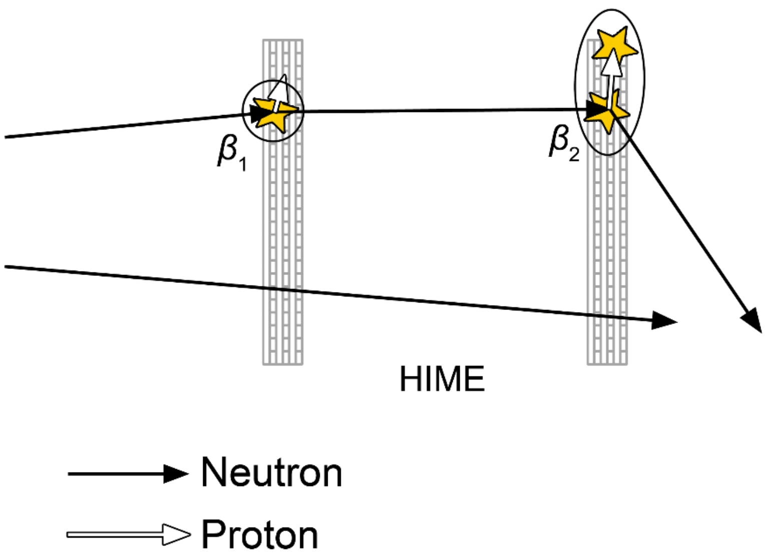
Reconstruction of Primary Neutron Hits

Reject potentially unreal two-neutron events: Request...

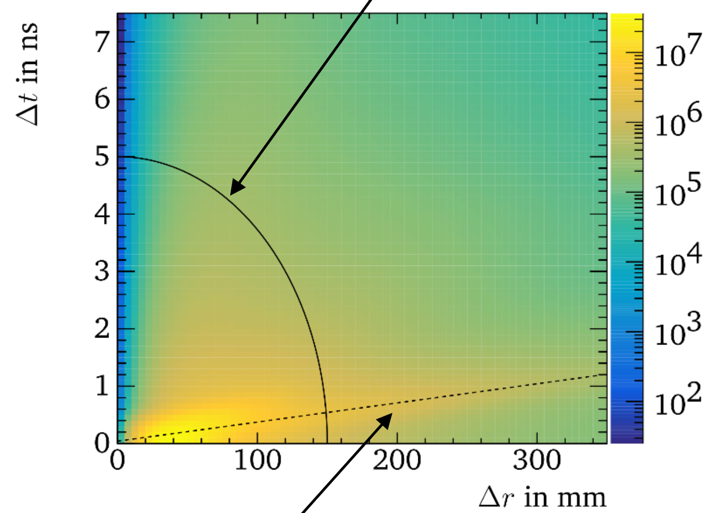
- ... at least 1 cluster in each HIME wall
- ... $\beta_1 < \beta_2$
- ... a threshold on the deposited energy

Otherwise: Cross talk possible

→ Creates an artificial peak at low E_{rel}



$$\sqrt{\left(\frac{\Delta r}{150\,\mathrm{mm}}\right)^2 + \left(\frac{\Delta t}{5\,\mathrm{ns}}\right)^2} < 1$$



$$\frac{\Delta r}{\Delta t} = 300\ \mathrm{mm\ ns^{-1}}$$

→ Photon scattering in HIME

Outline

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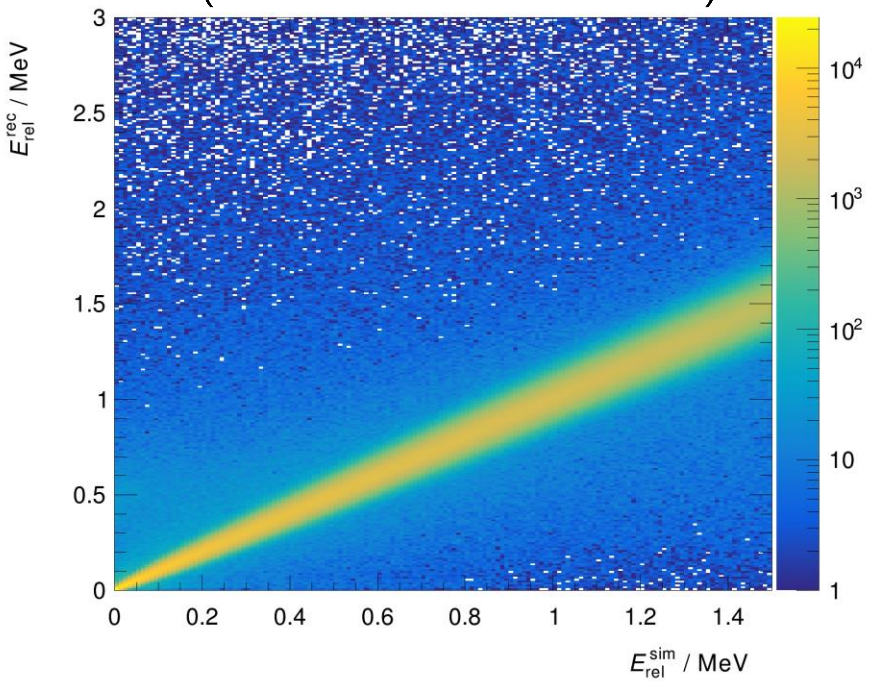
Simulation

- ANAROOT software toolkit developed at RIBF
- Single- or two-neutron events with customizable relative-energy distribution

Response matrix
(Uniform distribution simulated)



- Acceptance:
  Neutron detector sizes, geometry of the SAMURAI magnet, beam spread
- Resolution:
  Uncertainties in time and position measurements
- Two-neutron reconstruction efficiency:
  Interaction probability, efficiency of the reconstruction algorithm

Reconstructed Spectra

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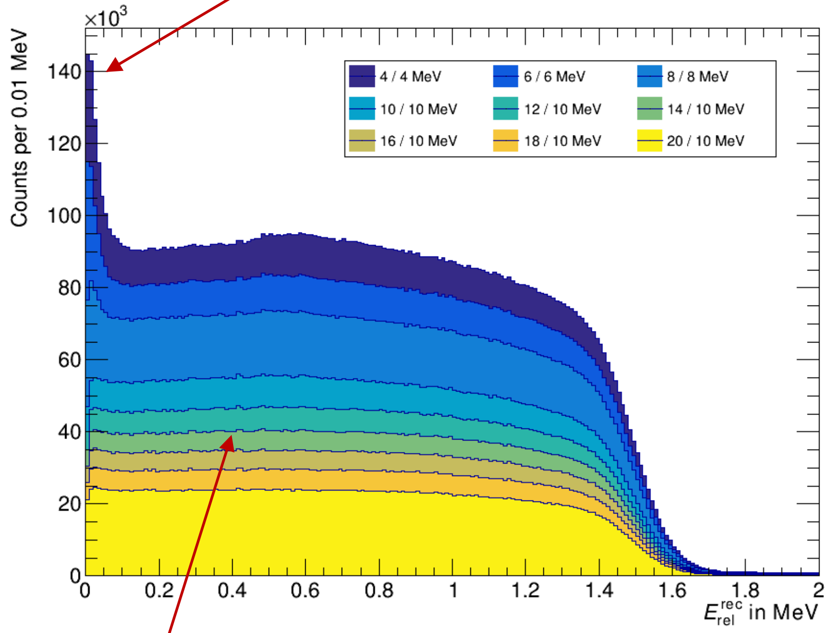
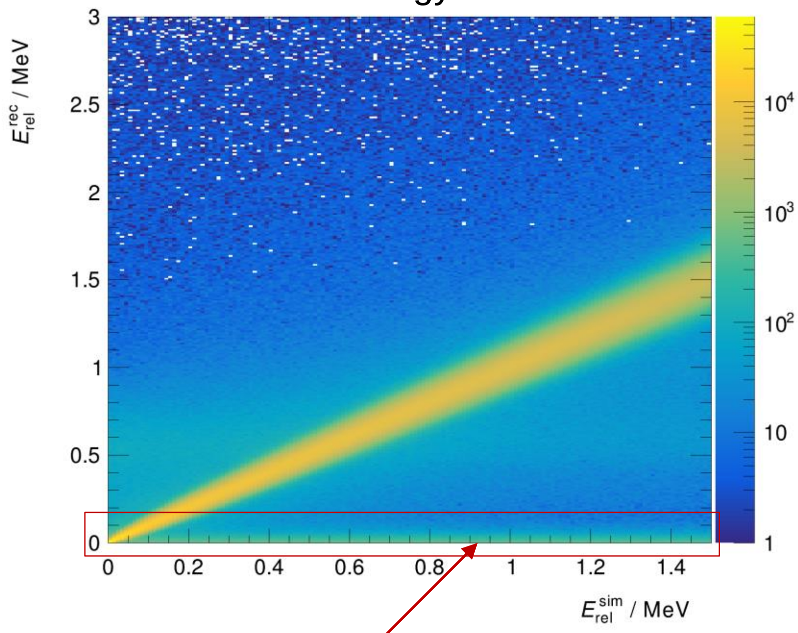
Cross talk in HIME



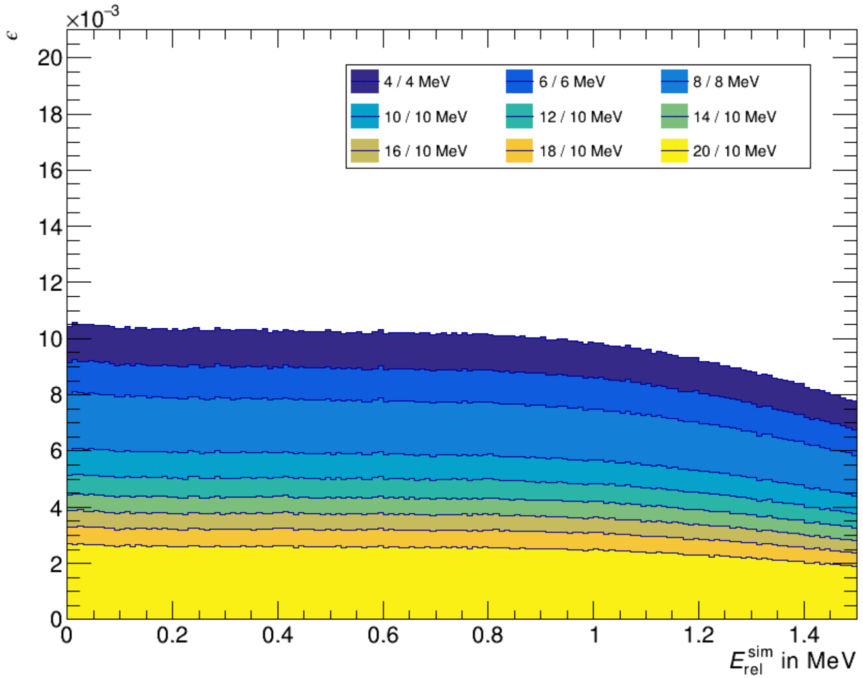
4 MeV energy threshold



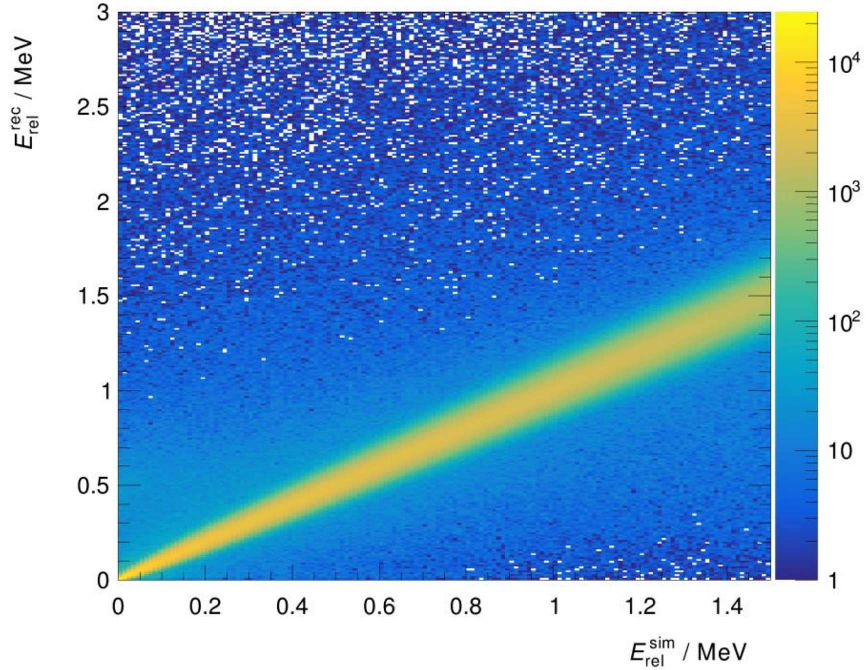
Shape stops changing above ~14 MeV
→ Lowest energy cut without having to accept cross talk

No correlation of reconstructed and simulated relative energies!

2n-Reconstruction Efficiency



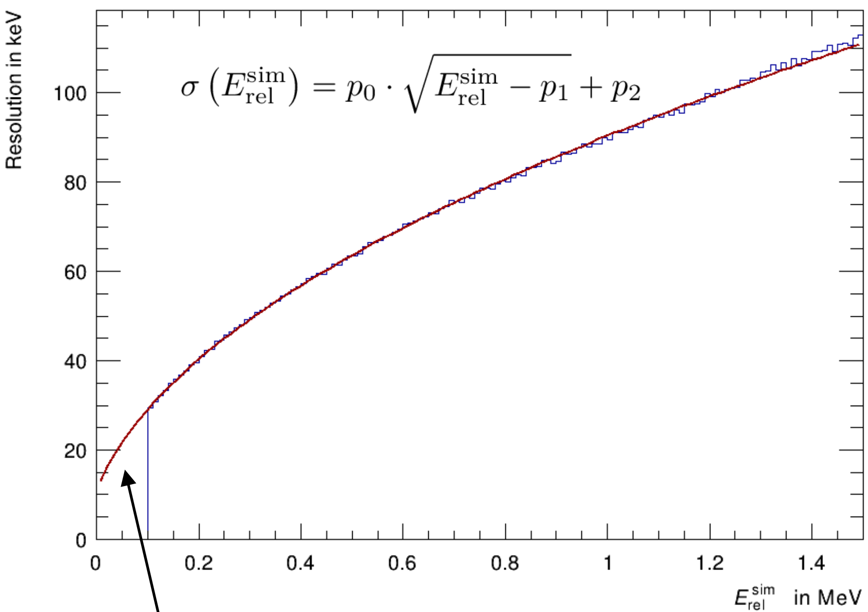
15 MeV energy threshold



Close to constant efficiency
in the relative-energy range of interest!

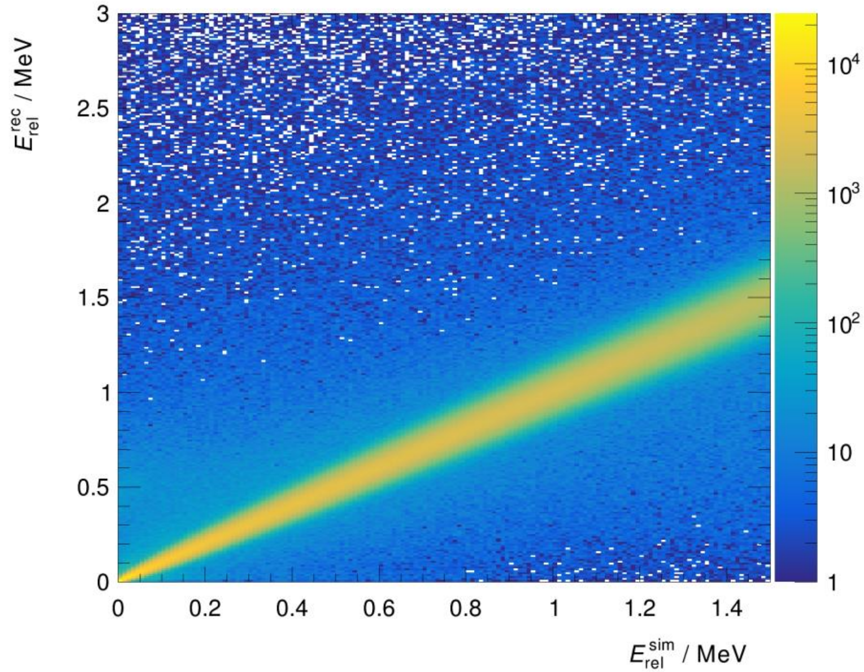
$$\epsilon_i = \frac{1}{N_i^{\mathrm{sim}}} \sum_{j=1}^{\infty} R_{ij}$$

Resolution



Better than 25 keV for low $E_{\mathrm{rel}}^{\mathrm{sim}}$

15 MeV energy threshold



Determination of resolution:
Gaussian fits in the range
$0.1\ \mathrm{MeV} \leq E_{\mathrm{rel}}^{\mathrm{sim}} \leq 1.5\ \mathrm{MeV}$

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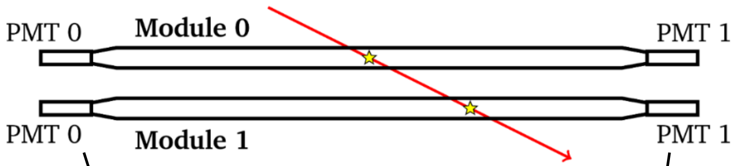
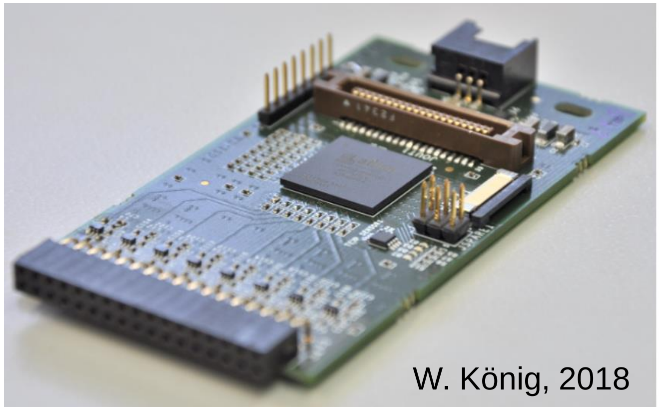
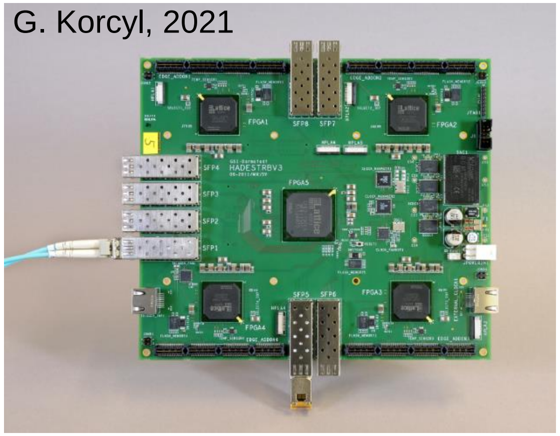
Test Setup in the Lab



Analogue signals


W. König, 2018

Logic signals


G. Korcyl, 2021

Digital data packet

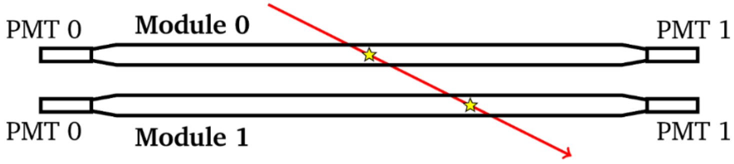
PaDiWa board
→ discriminates the analogue signal

TRB3 board, consisting of 5 **f**ield **p**rogrammable **g**ate **a**rrays (FPGAs → allow programming of logic gates)

- Used for trigger logic
- Time precision < 20 ps

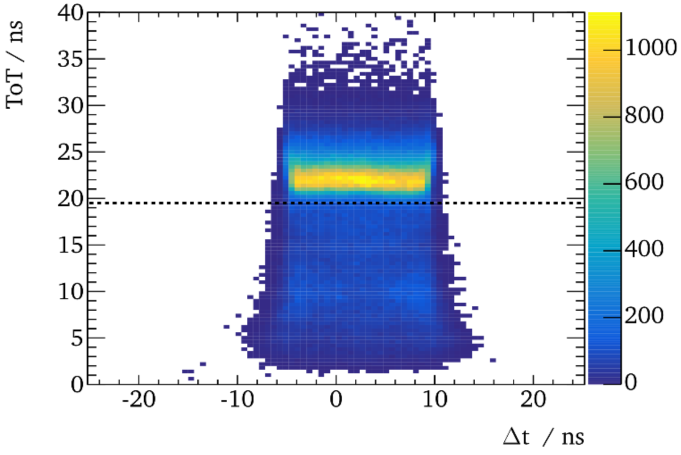
Details: http://trb.gsi.de/

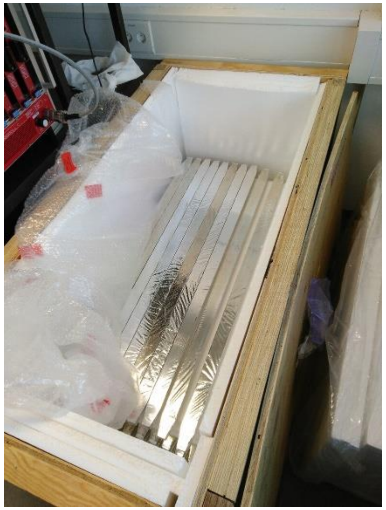
Test Setup in the Lab



Time measurements determine:

- One of the spatial coordinates $x = \frac{v}{2}(t_0 - t_1)$
- Time of flight $\mathrm{ToF} = \frac{t_0 + t_1}{2}$
- Energy deposition $E_{\mathrm{dep}} \propto \sqrt{\mathrm{ToT}_0 \cdot \mathrm{ToT}_1} + \mathrm{offset}$





Outlook

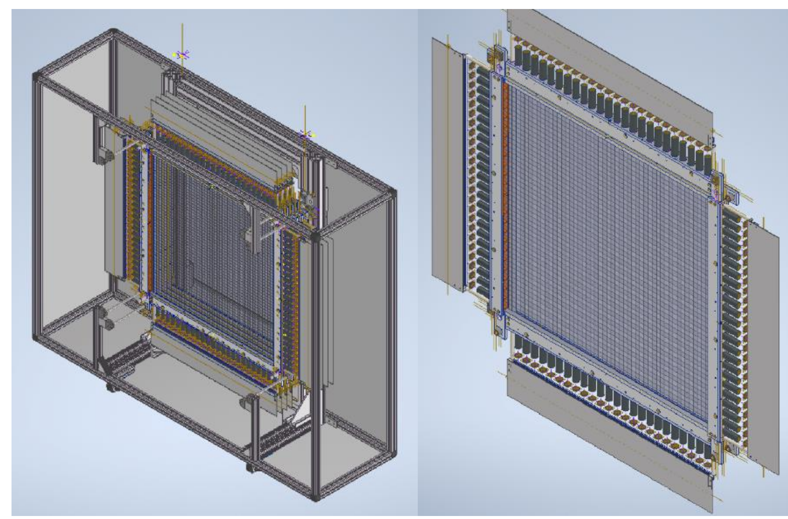
T. Aumann 2022

RIKEN

- Prototype in Japan will be tested with digital DAQ from Darmstadt (will be brought to Japan on Monday)
- Existing scintillator modules of the prototype will be rearranged

IKP

- New holding structure currently under development
- DAQ is tested and working,
  some of the scintillators and PMTs were taken in operation
  → Individual components are working, upscale the setup



D. Rossi 2022

List of Acronyms

- **BigRIPS:** RIKEN projectile fragment separator
- **BDC:** Beam drift chamber
- **CATANA:** Calorimeter for γ-ray transitions in atomic nuclei at high isospin asymmetry
- **FDC:** Forward drift chamber
- **FPGA:** Field programmable gate array
- **HIME:** High-resolution detector array for multi-neutron events
- **IRC:** Intermediate ring cyclotron
- **NEBULA:** Neutron detection system for breakup of unstable nuclei with large acceptance
- **PaDiWa:** PANDA DIRC WASA
  - **DIRC:** Detection of internally reflected cherenkov light
  - **PANDA:** Antiproton annihilation at Darmstadt
  - **WASA:** Wide angle shower apparatus
- **RIBF:** Radioactive Ion Beam Facility
- **RIKEN:** Rikagaku Kenkyūjo
- **RRC:** RIKEN ring cyclotron
- **SAMURAI:** Superconducting analyzer for multi particles from radioisotope beams
- **SBT:** Scintillators for beam time of flight
- **SRC:** Superconducting ring cyclotron
- **STQ:** Superconducting triplet quadrupole
- **STRASSE:** Silicon tracker for spectroscopy at SAMURAI experiments)
- **TRB:** Depending on the mode of operation, choose between:
  - TDC readout board
  - Triggerless readout board
  - Triggered readout board