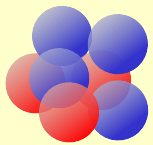
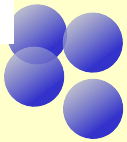
History: Searching for the Tetraneutron



^{4}n



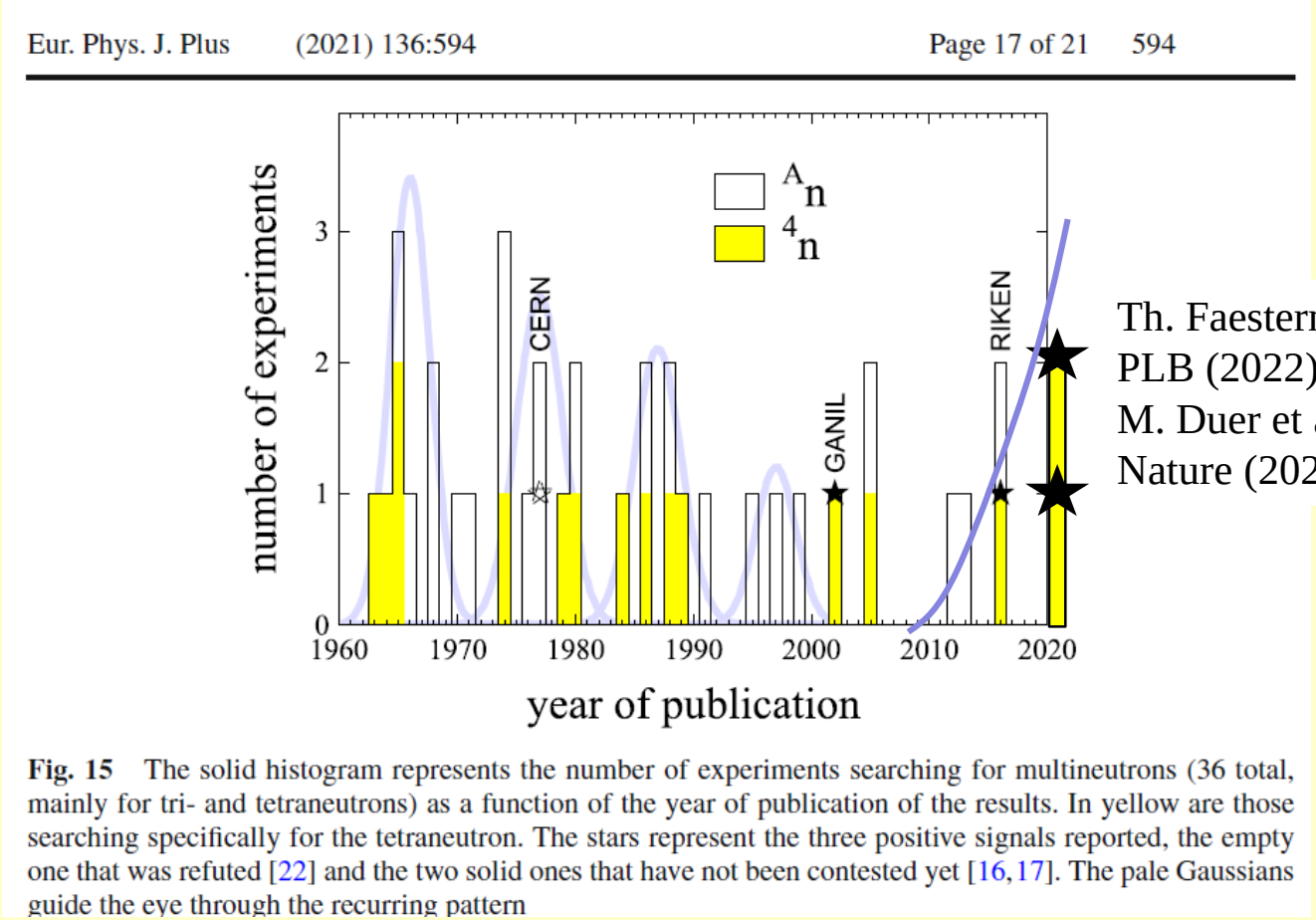


Fig. 15 The solid histogram represents the number of experiments searching for multineutrons (36 total, mainly for tri- and tetraneutrons) as a function of the year of publication of the results. In yellow are those searching specifically for the tetraneutron. The stars represent the three positive signals reported, the empty one that was refuted [22] and the two solid ones that have not been contested yet [16,17]. The pale Gaussians guide the eye through the recurring pattern

Th. Faestermann et al. PLB (2022)
M. Duer et al. Nature (2022)

F. M. Marques (2021), **The extremes of neutron richness**

Physics Letters B 824 (2022) 136799

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Indications for a bound tetraneutron

Thomas Faestermann [a,*], Andreas Bergmaier [b], Roman Gernhäuser [a], Dominik Kol
Mahmoud Mahgoub [c,d]

IOP Publishing

physicsworld

physicsworld TOP 10 BREAKTHROUGH 2022

Observing the tetraneutron

To Meytal Duer at the Institute for Nuclear Physics at Germany's Technical University of Darmstadt and the rest of the SAMURAI Collaboration for observing the tetraneutron and showing that uncharged nuclear matter exists, if only for a very short time.

MLL Maier-Leibnitz-Laboratorium für Kern-, Teilchen- & Beschleunigerphysik

RIKEN NiSHiNA CENTER

Roman Gernhäuser

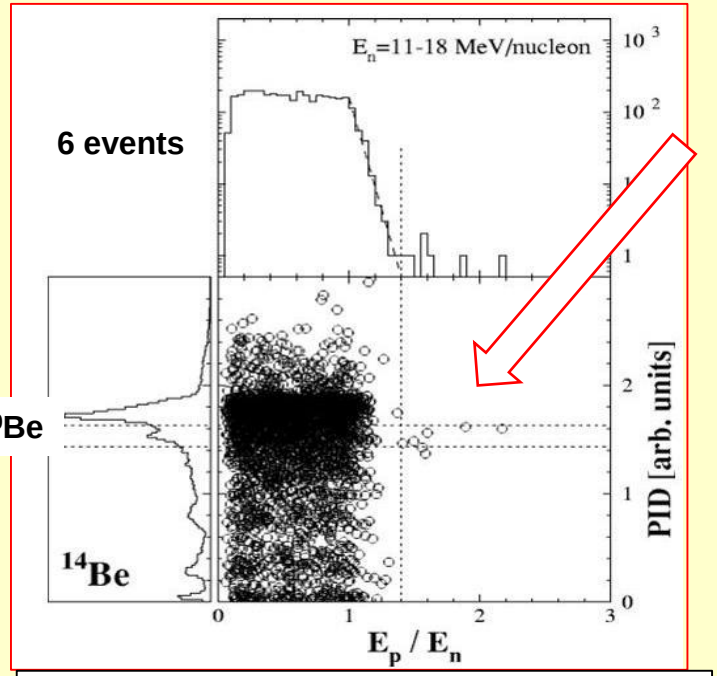
Physik Department, Technische Universität München

- Concept
- Experiment 1
- Experiment 2
- Discussion

There are many calculations, "all of them agreeing that a bound tetraneutron is not supported by theory. "(Shirokov 2016)

Motivation by Recent Experiments

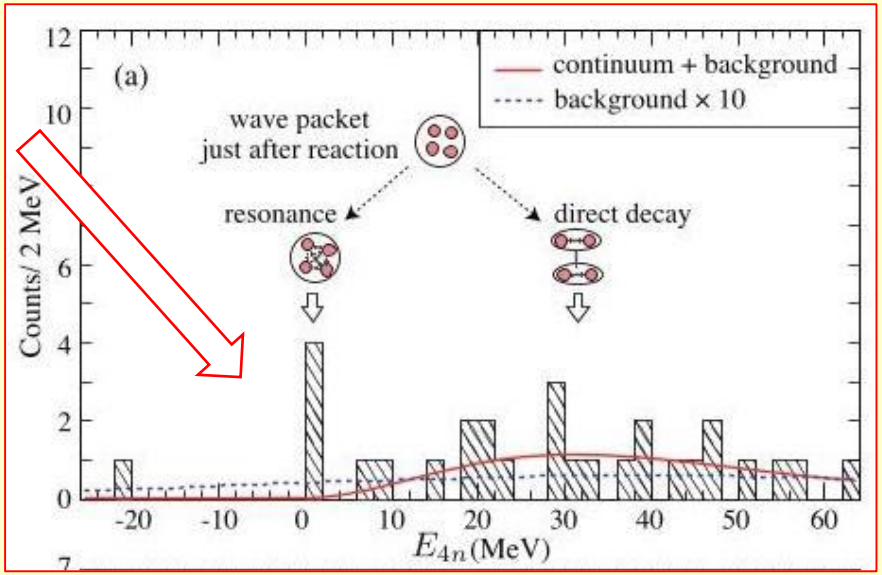
$^{14}Be \rightarrow {}^{10}Be + 4n$
Breakup on Carbon target
Direct detection of both products
Neutron signal @ 4-6 m distance
4n bound ??



F.M. Marqués, et al., Detection of neutron clusters, Phys. Rev. C 65 (2002) 044006 and arXiv:nucl -ex /0504009v1.

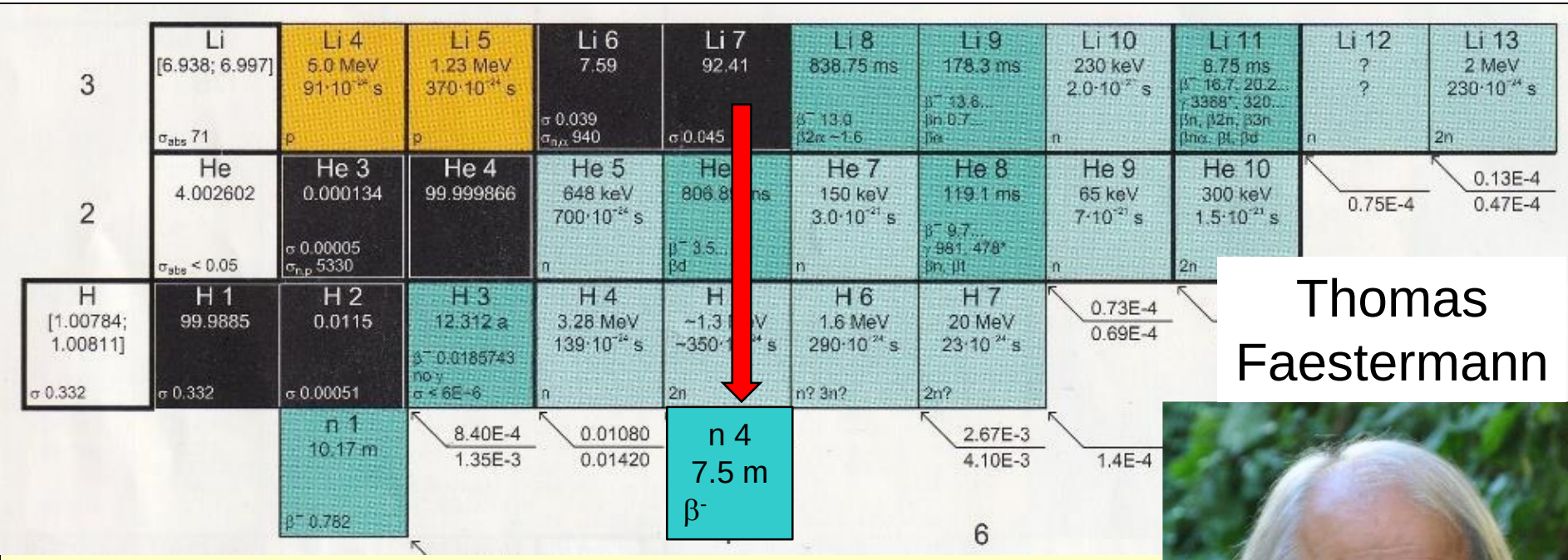
^{4}He (^{8}He, ^{8}Be) 4n

Double charge exchange
E*=0.83±1.41MeV Γ< 2.6MeV
4 events

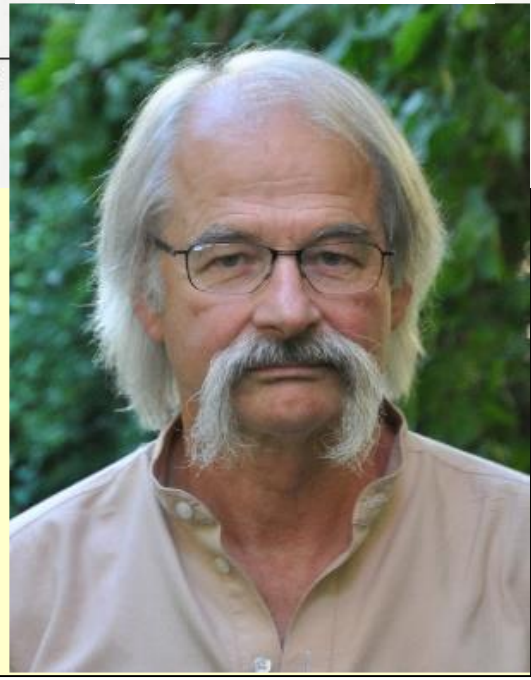


K. Kisamori, et al., Candidate resonant tetraneutron state populated by the 4He(8He,8Be)reaction, Phys. Rev. Lett. 116 (2016) 052501 .

Munich Approach



Thomas Faestermann



Basic principle: Don't touch the neutrons !

Just pick 3 protons from the ^{7}Li (target).

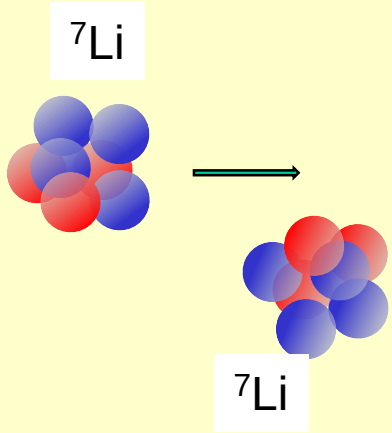
Minimize CM energy.

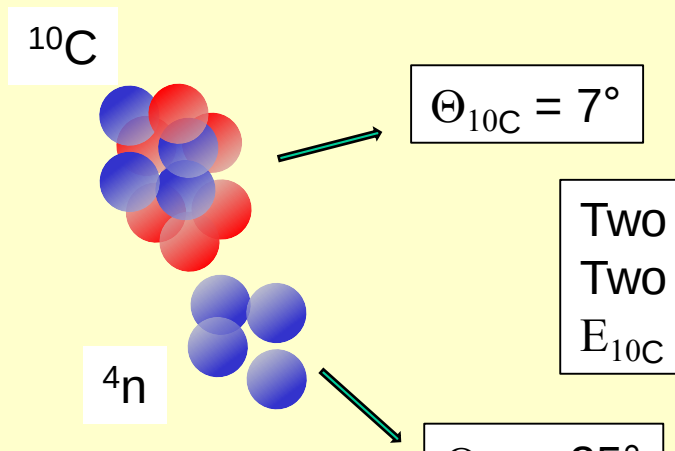
Beam: odd Z, low Coulomb barrier ^{7}Li

^{7}Li(^{7}Li,^{10}C) ^{4}n

46 MeV

Transfer Reaction $^{7}Li(^{7}Li,^{10}C)\,^{4}n$



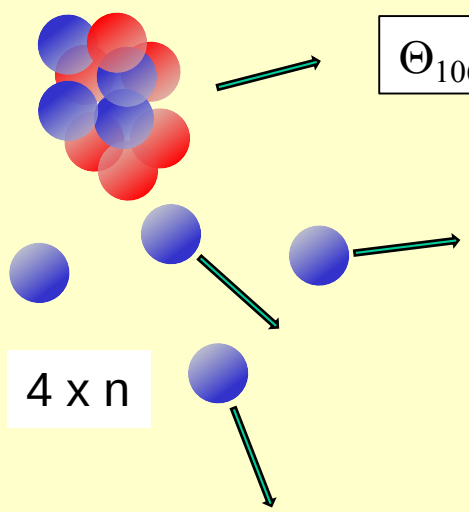


$\Theta_{10C} = 7°$

Two body kinematics
Two equations, one solution.
$E_{10C} = f(\Theta_{10C}, m_i, E^*)$

$\Theta_{4n} = 25°$

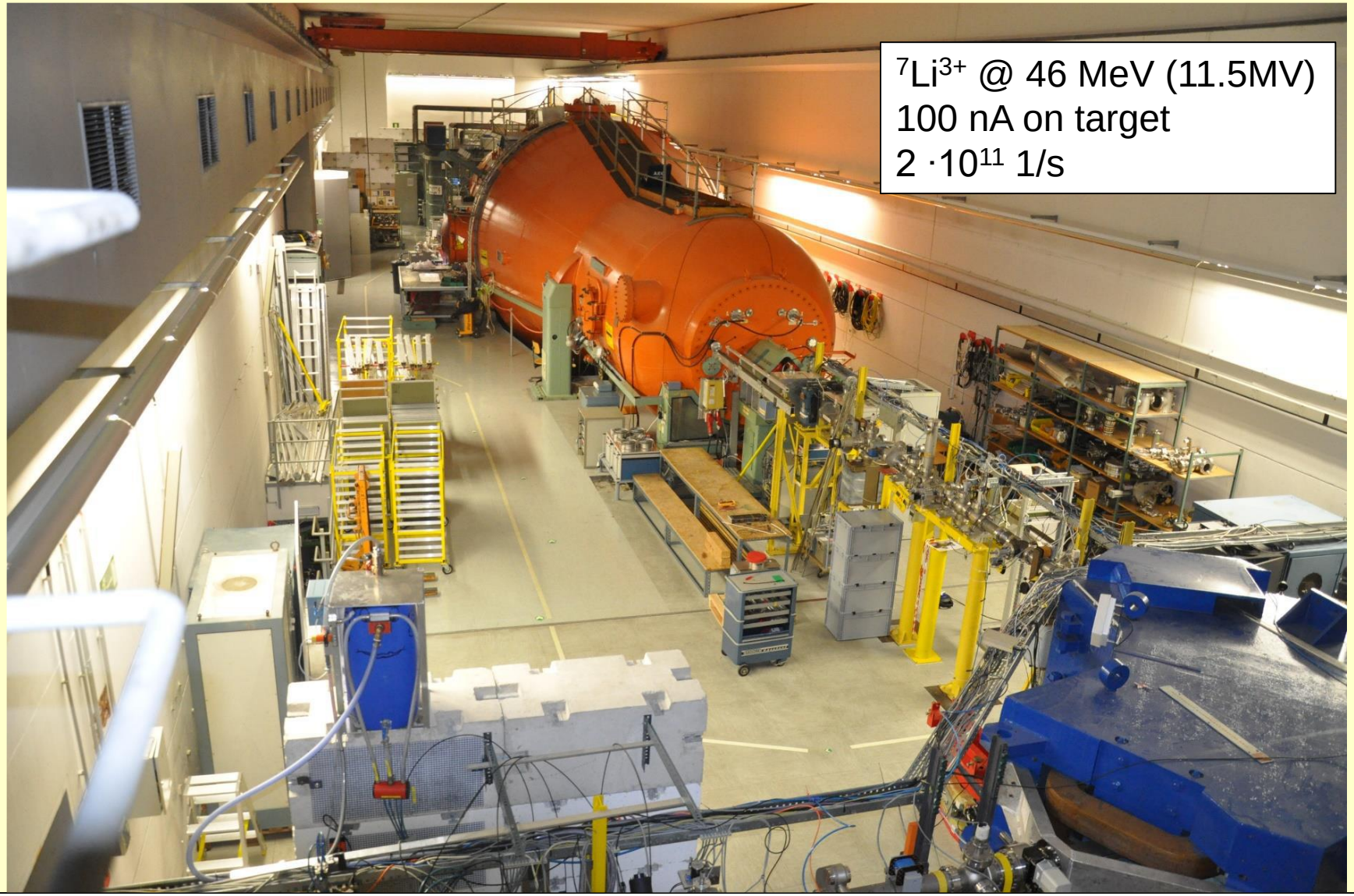
Precision Measurement:
E_{10C} and Θ_{10C}
Choose low E_{CM}



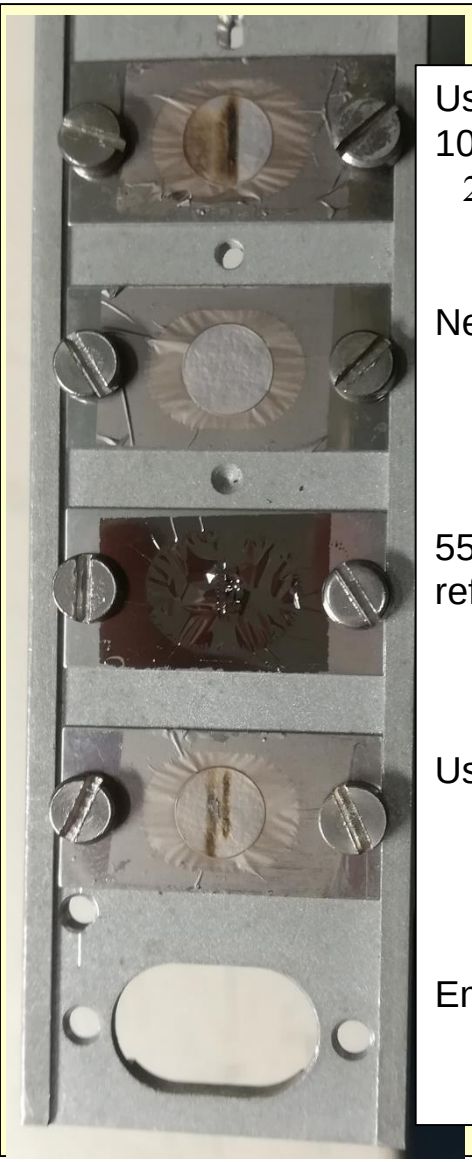
$\Theta_{10C} = 7°$

Many body kinematics
Two equations, ……

Munich Tandem Accelerator ✝Jan15th 2020



Target



Used target #4
100 μg/cm² Li_2O
20 μg/cm² C

New target # 3

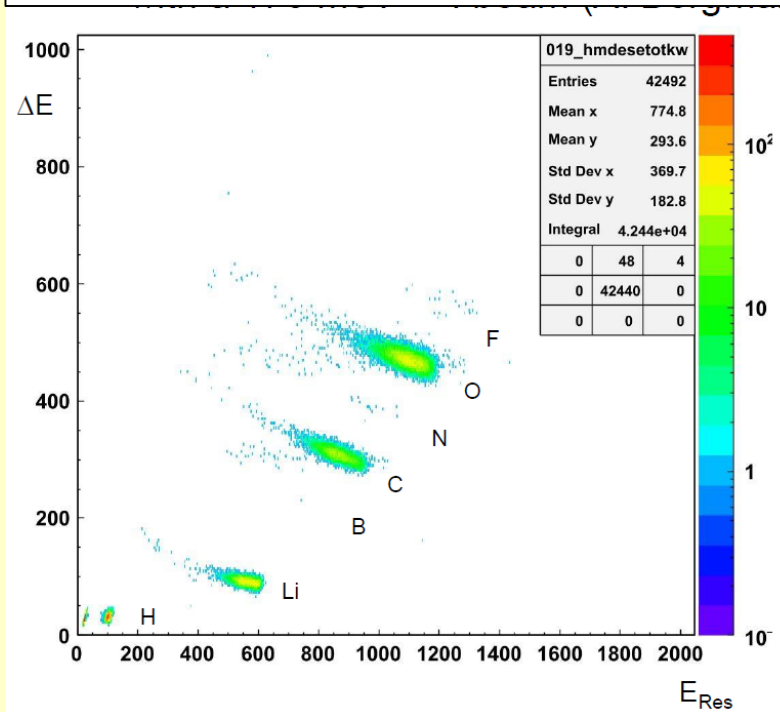
55 μg Carbon reference

Used target #2

Empty frame

Material: $^{7}Li_2O$, enriched 99%, deposited on a thin carbon foil (wobbling up and down)

Target analysis after the experiment with elastic recoil detection (ERD) 170 MeV ^{127}I beam → large water content → effective thickness increase! (A. Bergmaier)



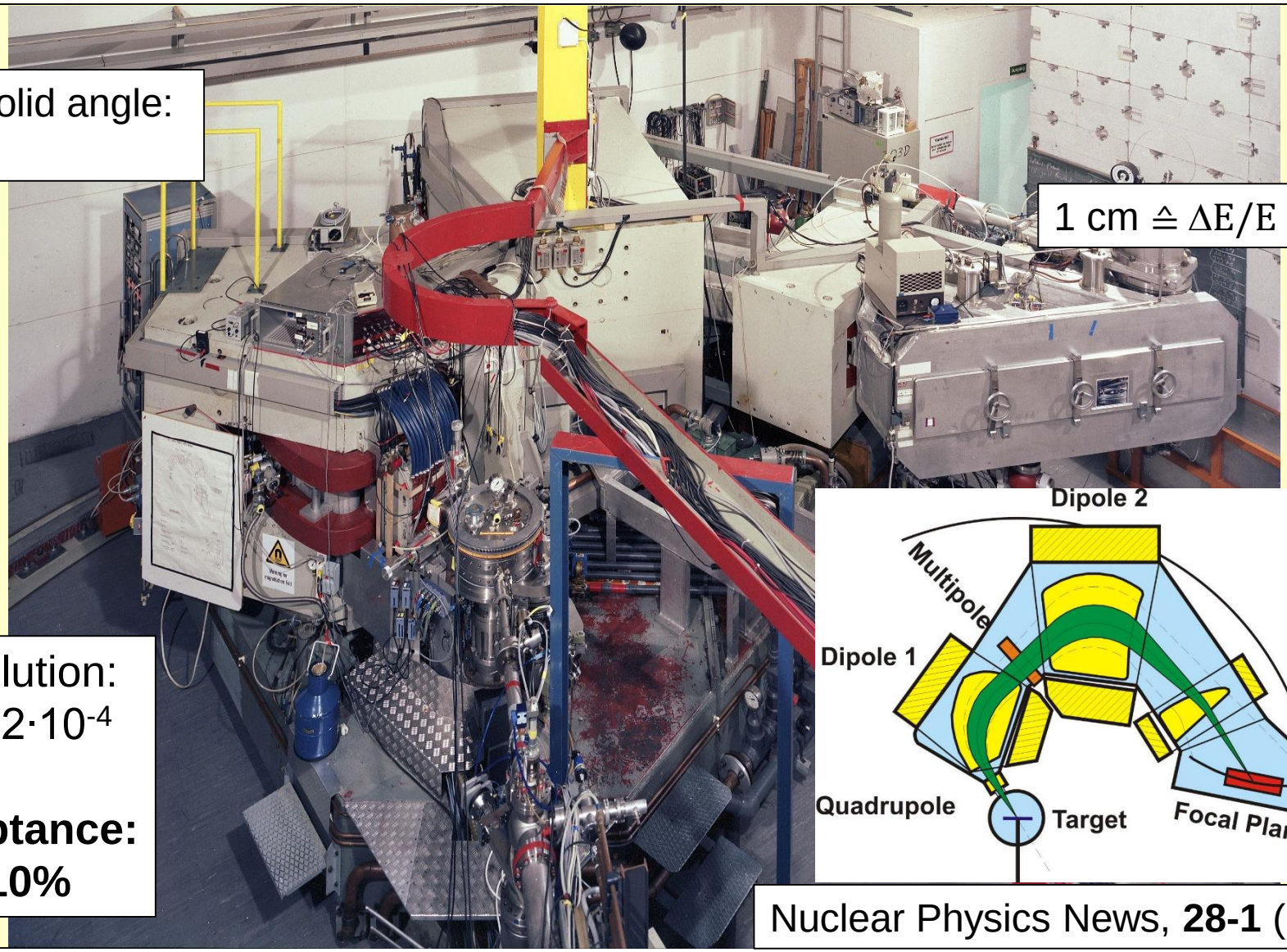
concentration

element	D	concentration
H	4751	2.5 E17 at/cm²
Li	8179	2.2 E18 at/cm²
B	1	0.2 E15 at/cm²
C	8518	1.5 E18 at/cm²
N	15	2.6 E15 at/cm²
O	18608	3.2 E18 at/cm²
F	20	3.7 E15 at/cm²

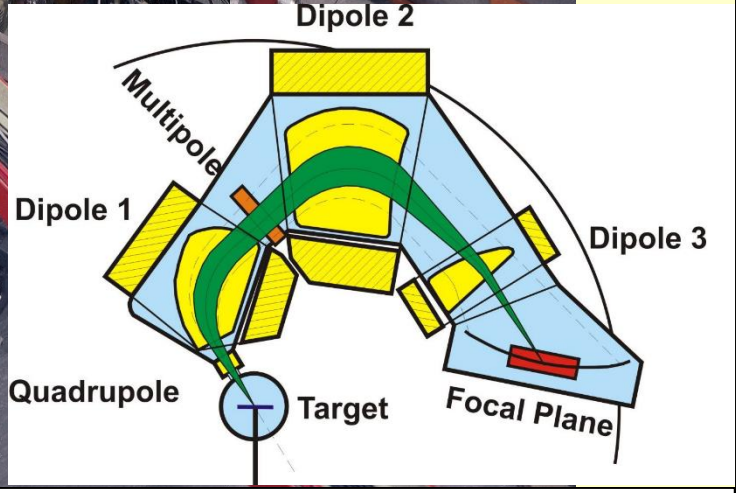
contains lots of H_2O

The Q3D Spectrograph

large solid angle:
14 msr



1 cm $\triangleq \Delta E/E \approx 10^{-3}$



Resolution:
$\sigma E/E$ $2 \cdot 10^{-4}$

Acceptance:
< 10%

Nuclear Physics News, **28-1** (2018)

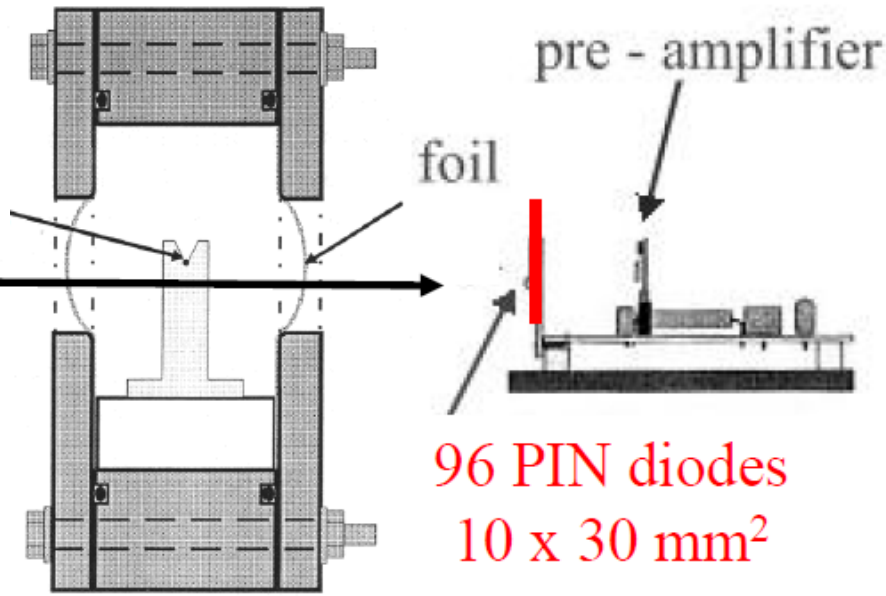
Focal Plane Detector

22mbar Isobutane

single wire proportional counter

resistive wire
10μm und
13.6 kOhm/m.

ejectiles



Y focus on the wire
σy << 10mm
Opening 30mm

ΔE and position
C. Albrecht

E_{Rest} and position
A. Bergmaier

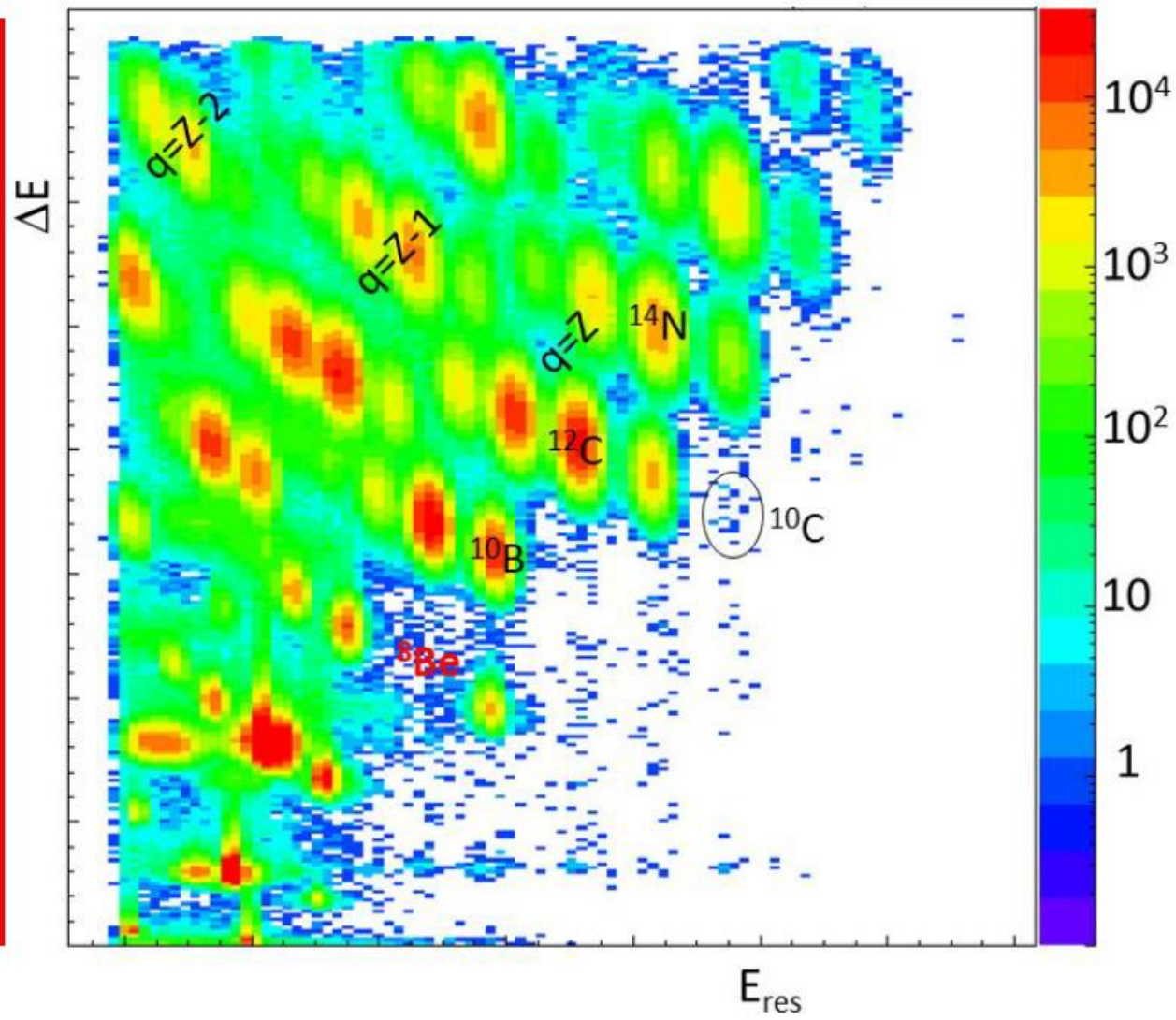
Particle Identification

magn. rigidity
$\Delta B\rho/B\rho \approx 5\%$
$\Delta E/E \approx 10\%$

$B\rho = p/q$

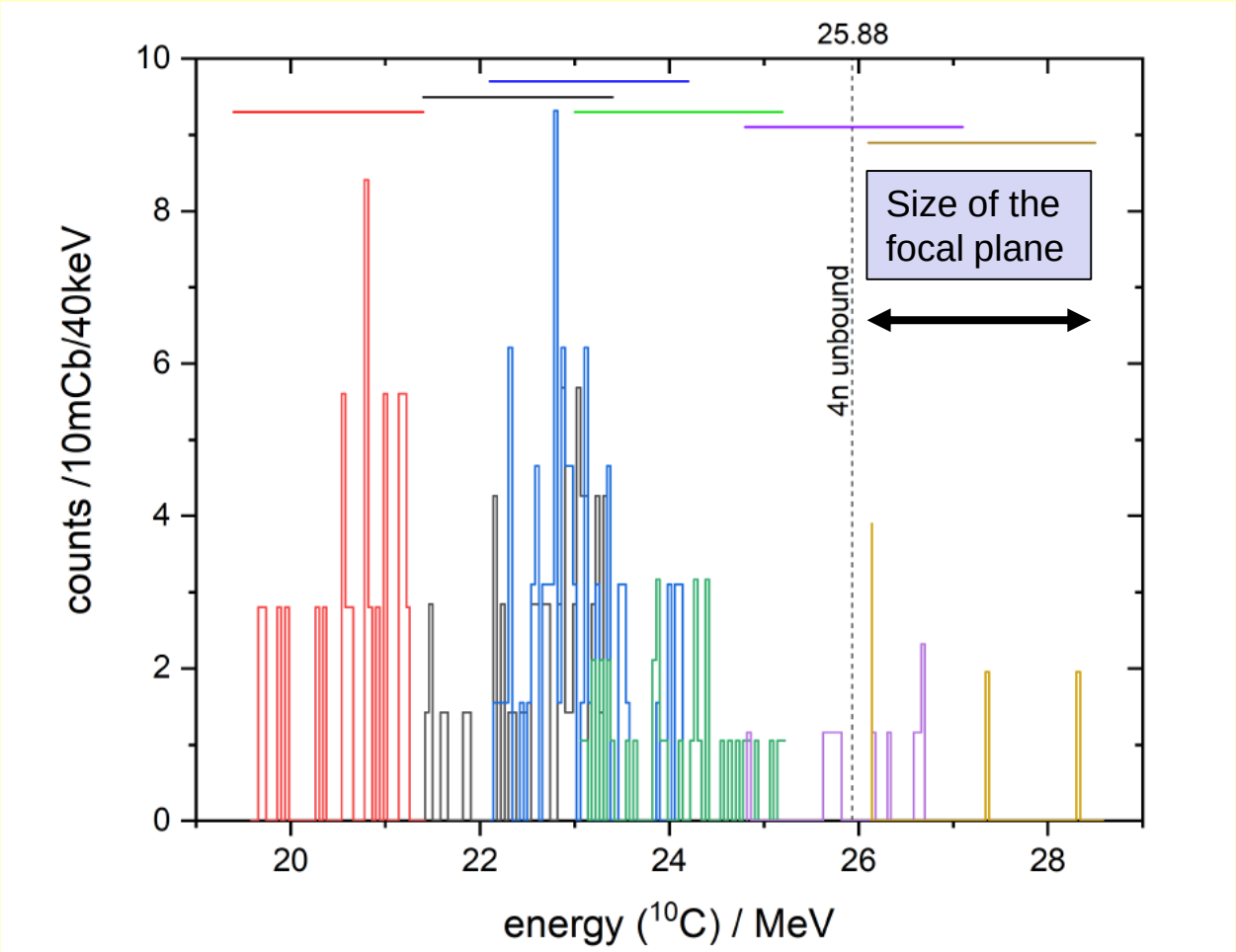
$E \sim p^2/2A$
$\sim (B\rho \cdot q)^2/2A$

$\Delta E \sim Z^2/(Av^2)$
$\sim Z^2 A/p^2$
$\sim Z^2 A/(B\rho \cdot q)^2$



All Data (7Li,10C) @ 7°

Raw data from 6 magnet settings about 16 hours each

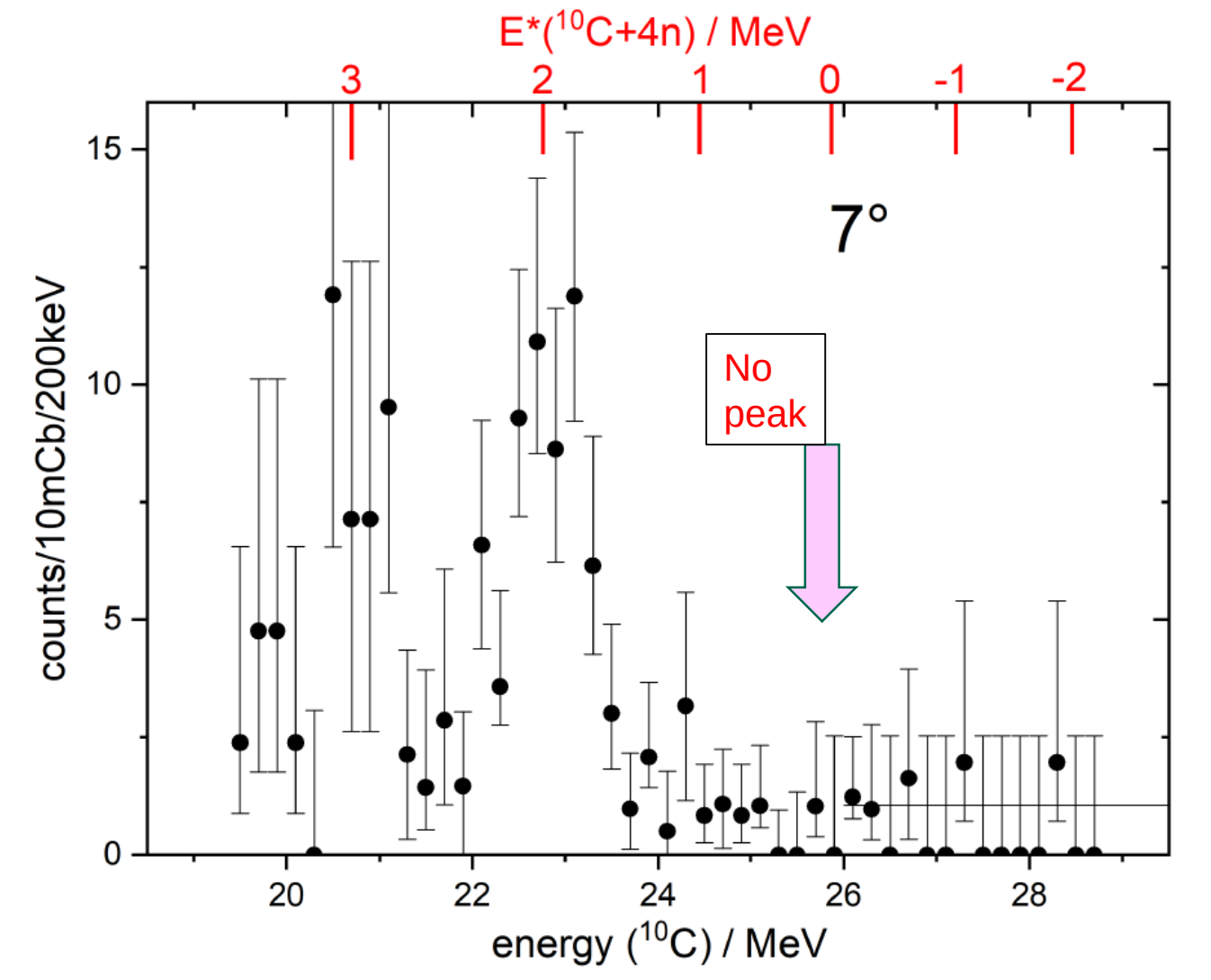


Gates:

PID: ^{10}C

$$\frac{x_{diode}}{x_{wire}} = f(x)$$

Accumulated Data



BG level measured with good statistics!

Background Interpretations

$^{12}C(^{7}Li,^{10}C)^{9}Li$ @17.3 MeV

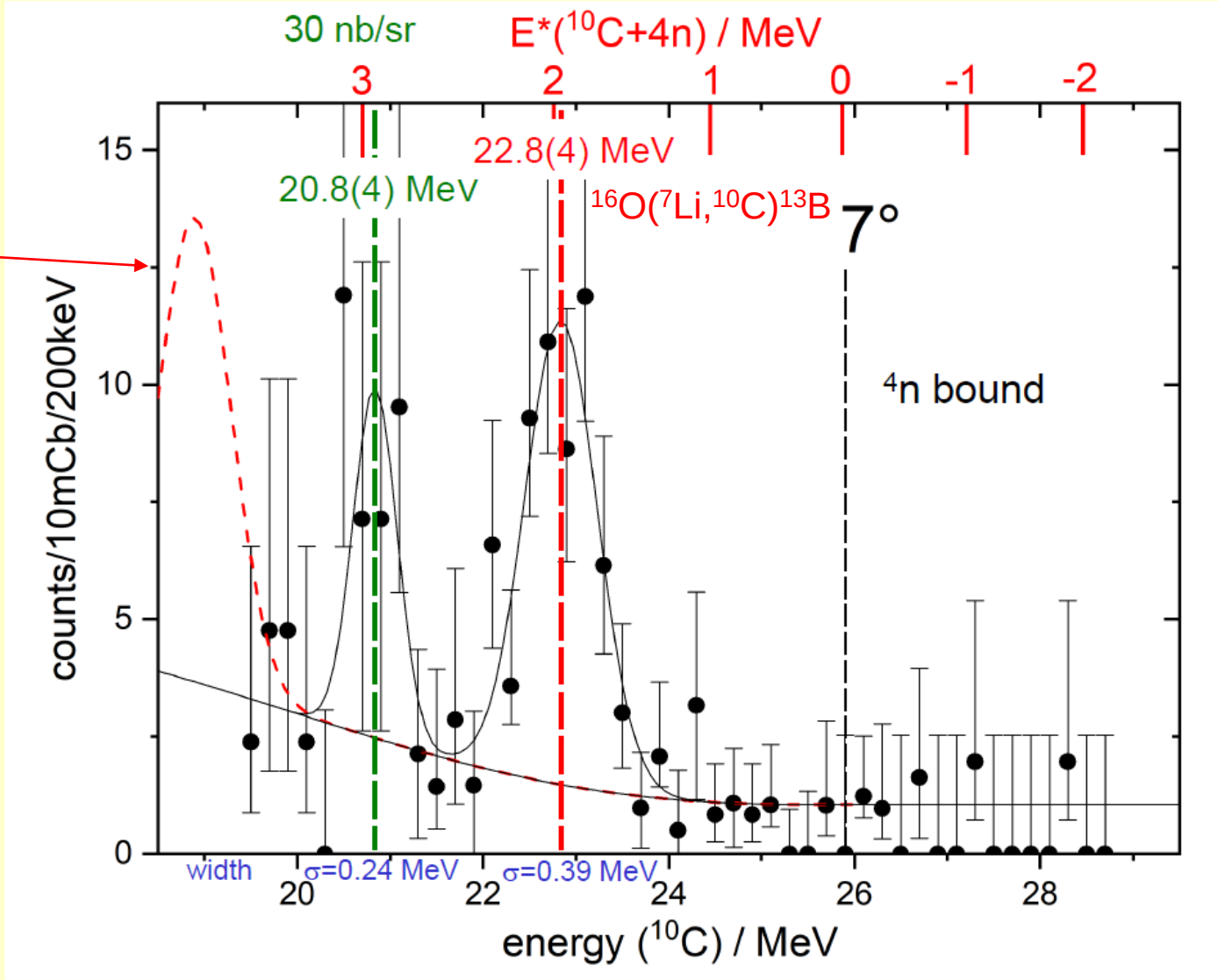
$^{16}O(^{7}Li,^{10}C^{*})^{13}B$ @ 18.9MeV

$^{18}O(^{7}Li,^{10}C)^{15}B$ @ 12.1MeV

$^{14}N(^{7}Li,^{10}C)^{11}Be$ @ 27.3MeV

$^{14}N(^{7}Li,^{10}C^{*})^{11}Be$ @ 23.5MeV

$^{13}C(^{7}Li,^{10}C)^{10}Li$ @ Na

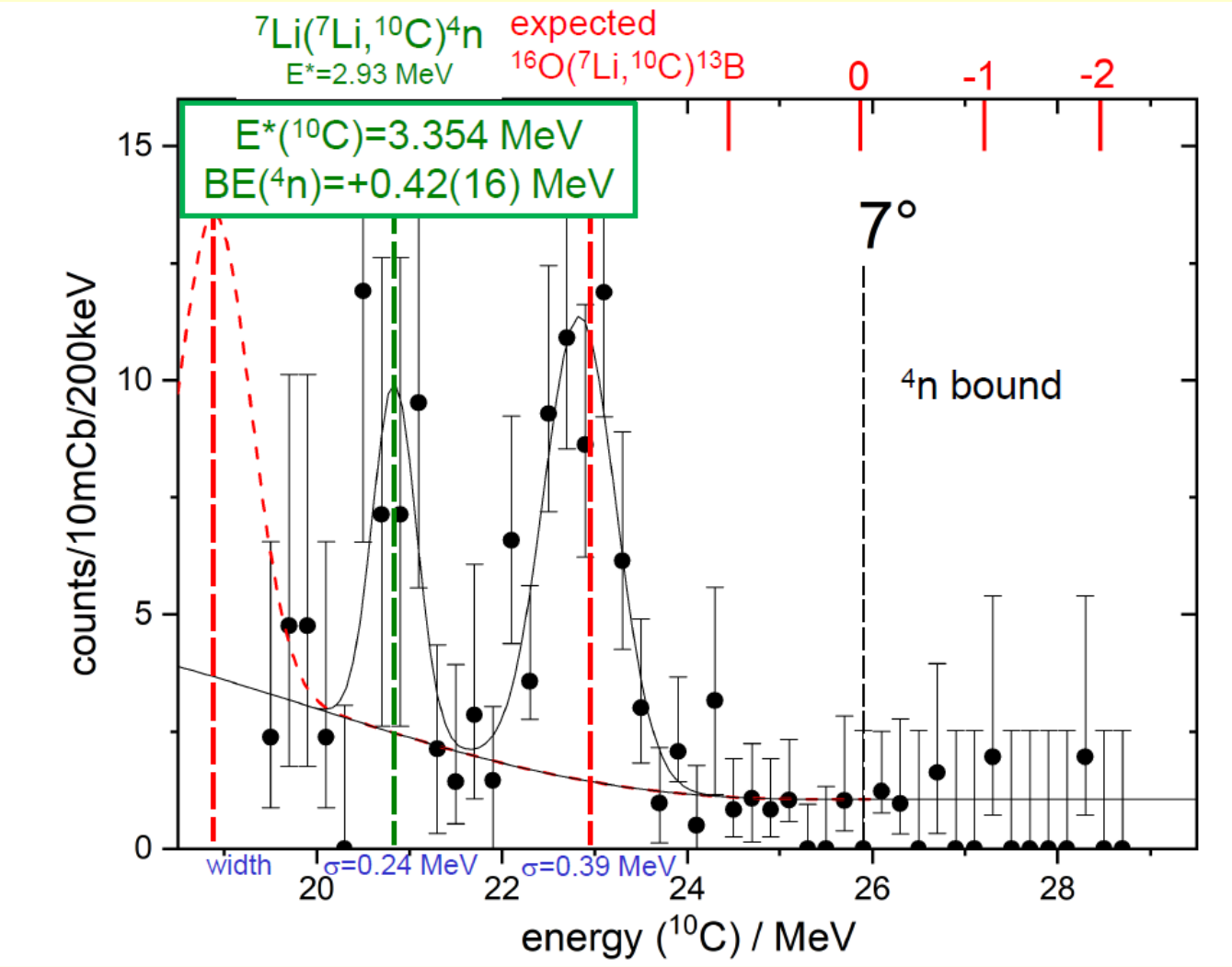


The Arguments

- 20.8 MeV line must be from $^{7}Li(^{7}Li,^{10}C)\ ^{4}n$ reaction
- ^{10}C energy corresponds to $E^*(^{10}C + 4\ n)=2.93$ MeV
- width of 20.8 MeV line is $\sigma=0.24$ MeV,

  fully explainable by energy loss differences
- this corresponds to an upper limit for the ^{4}n: $\Gamma < 0.24$ MeV
- ^{4}n with BE= -2.9 MeV and $\Gamma < 0.24$ MeV is unrealistic
- e.g. $^{6}H \Rightarrow ^{3}H + 3\ n$ with Q=2.7 MeV and $\Gamma=2.4$ MeV

=> ^{10}C is excited $E^*=3.354$ MeV and $BE(^{4}n)=+0.42(16)$ MeV



Broadening from Target

ΔE_{max} = ±0.4 MeV (^{10}C)
σE < 0.23MeV
(square distribution)

Change in angle
for the ^{10}C
$\sigma\Theta$ < 4 mrad

from γ-emission

ΔE_{max} = ±0.22MeV (^{10}C)
σE < 0.13MeV
(square distribution)

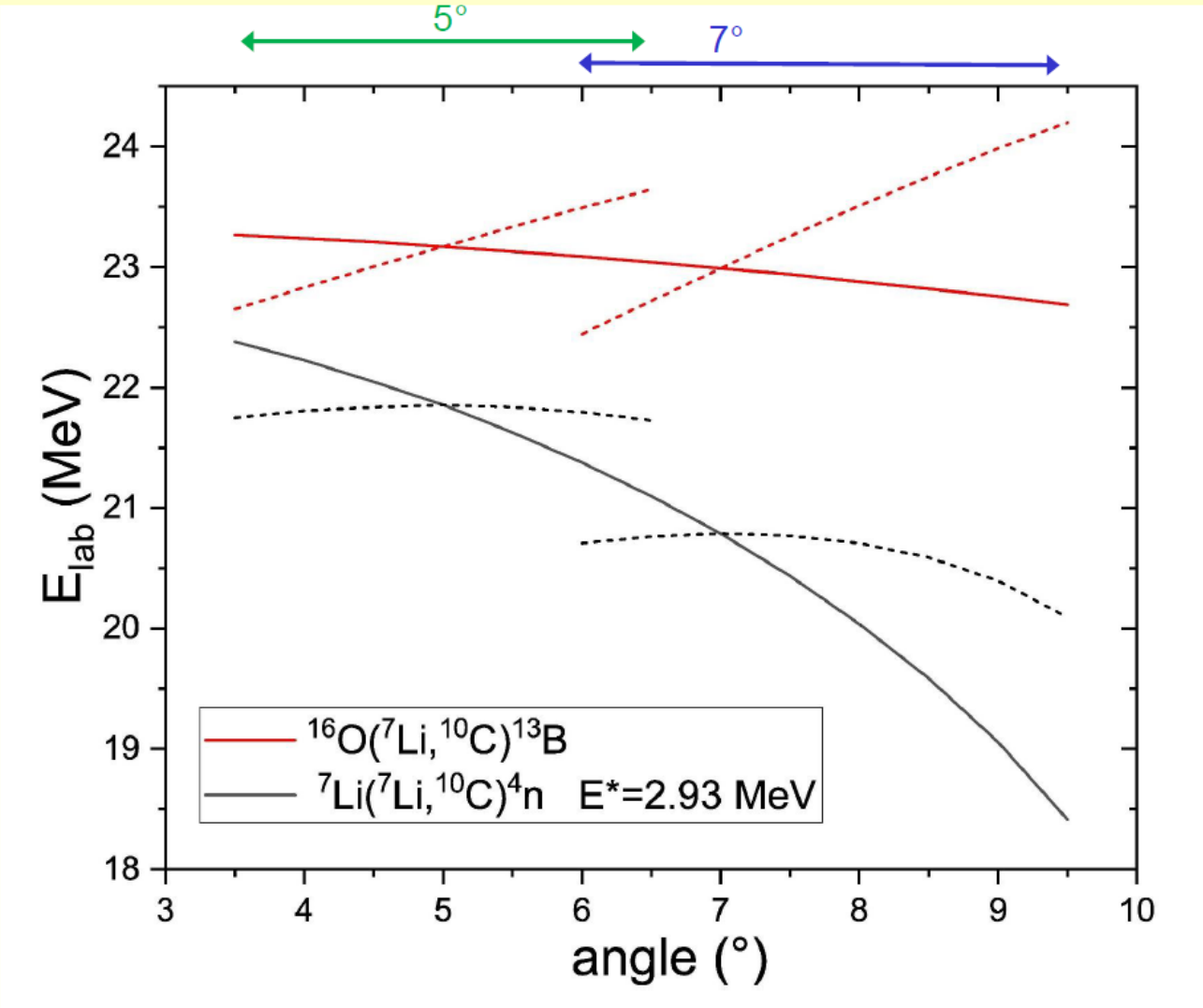
$\sigma\Theta$ < 2 mrad

Confirmation Experiment

Last nuclear physics experiment
@ the Munich Tandem
(November 2019)

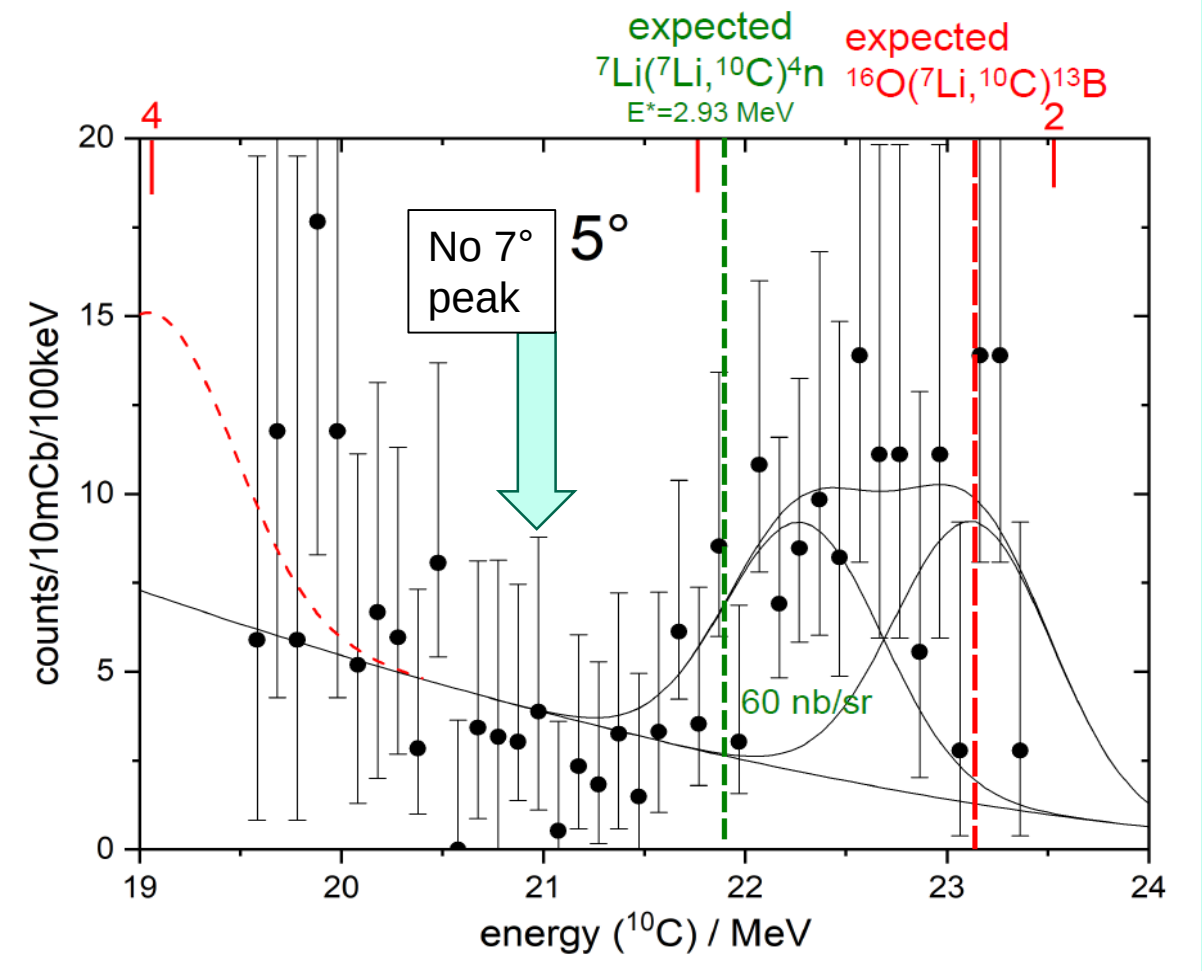
Can we combine
- Check BG
- Collect more statistics

Change to 5°
- Check kinematic shift
- Larger cross section?
- Larger angles would mean more background



Change to 5°

- Check kinematic shift ✓
- Larger cross section ✓
- Background as expected ✓



Fit with just the width constraint to resolution

Results and Consequences

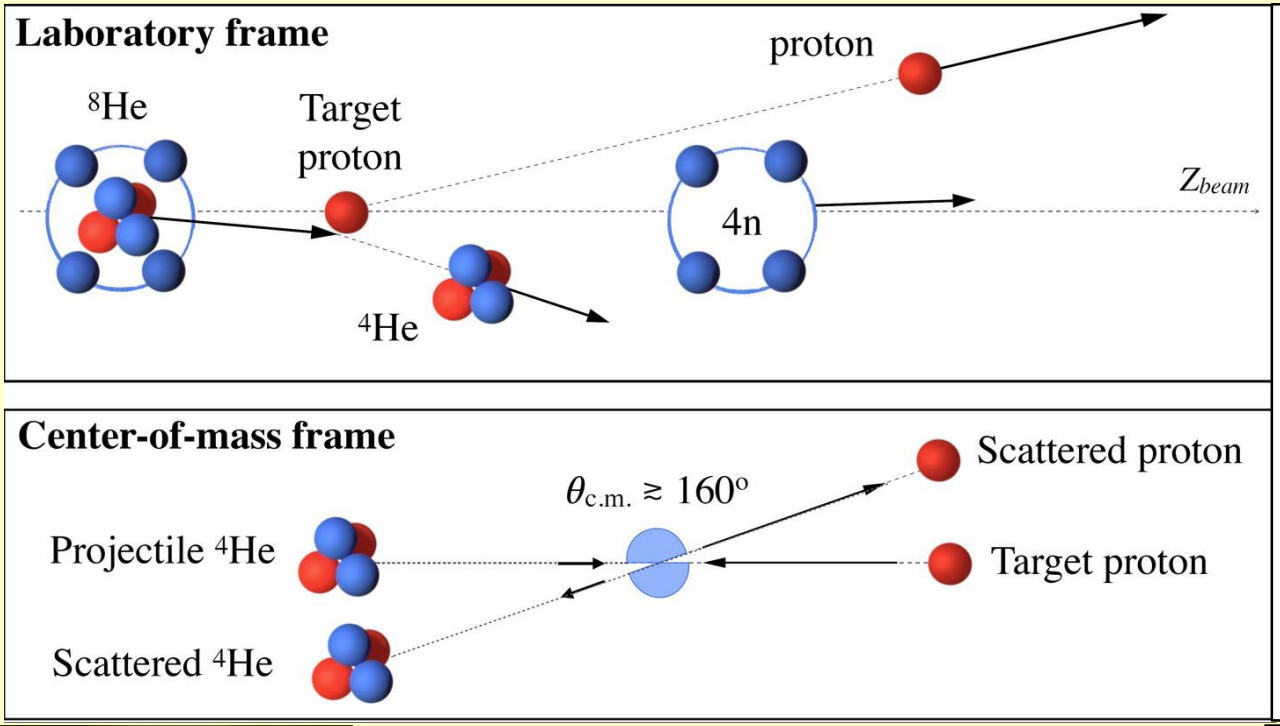
2 different experiments show a line
significance 3σ and 2σ
Corresponding to a tetraneutron with a binding energy of
BE = + 0.42(16) MeV

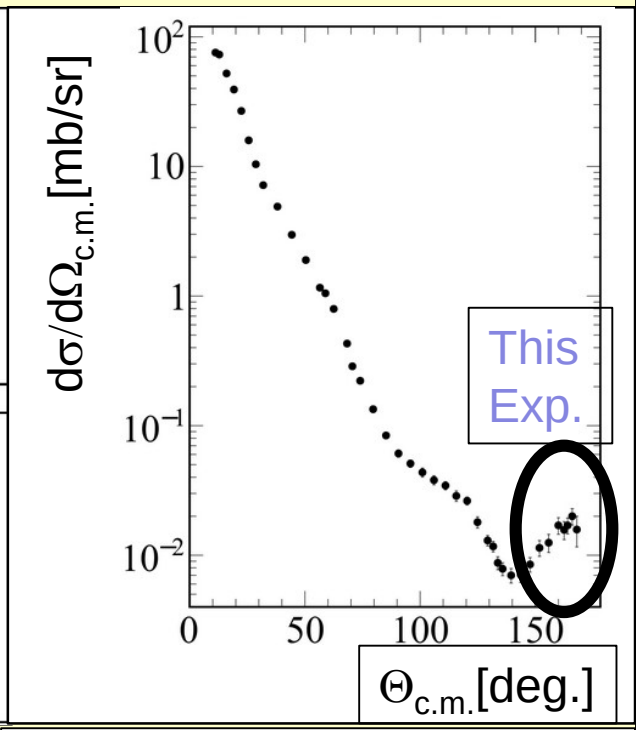
If BE(4n) > 0
There is no neutron emission just β^- -decay.

$^4n \rightarrow {}^4H$ (Q_β = 7.27 MeV)
$0^+ \rightarrow 2^-$ first unique forbidden log ft ≈ 9
$0^+ \rightarrow 1^-$ first forbidden log ft ≈ 7 (E*=310 keV)

→ $T_{1/2}$ ≈ 450 s But hard to detect (neutron capture)

Method: ^{8}He(p,p^{4}He) quasi-elastic knockout





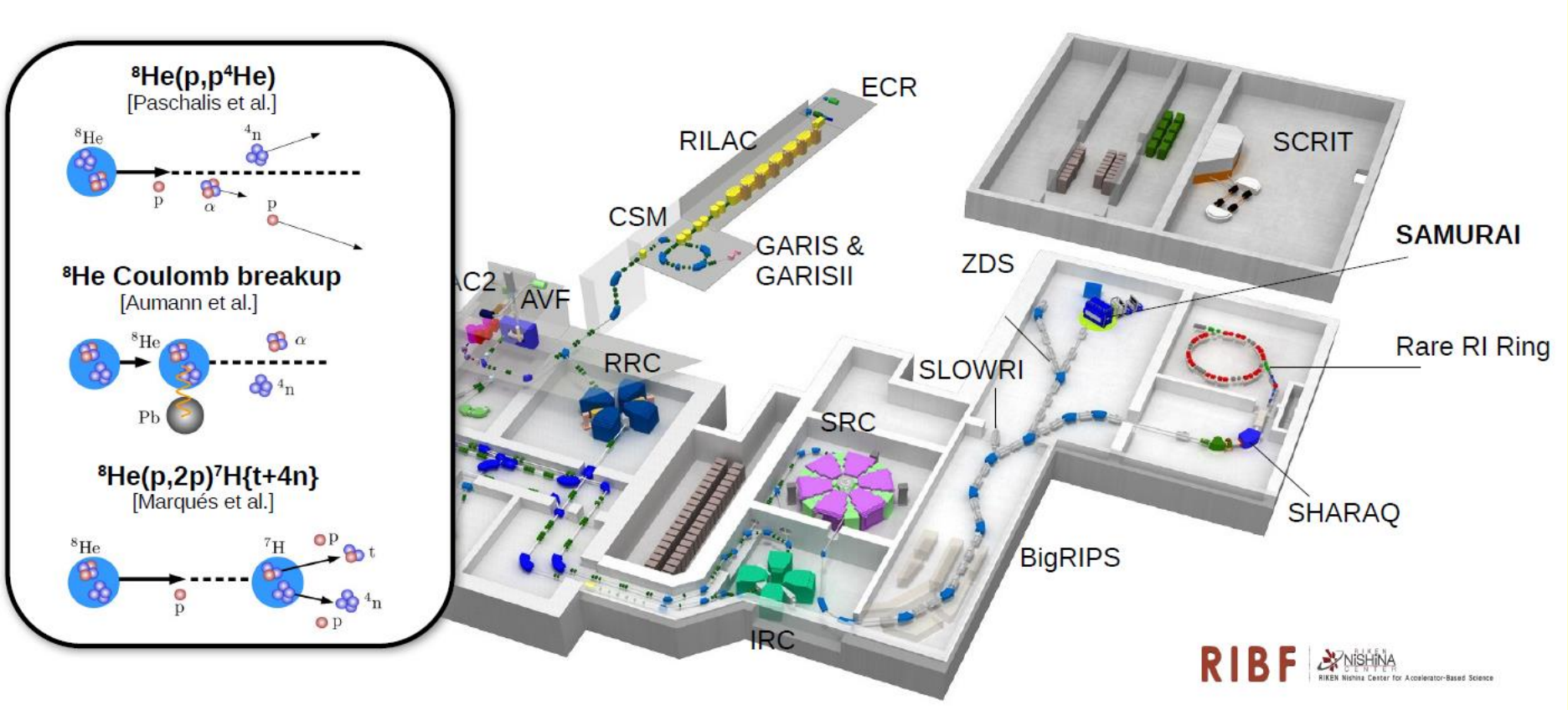
p-α @ 156 MeV
V. Comparat et al., PRC (1975)

High-energy 156 MeV/nucleon

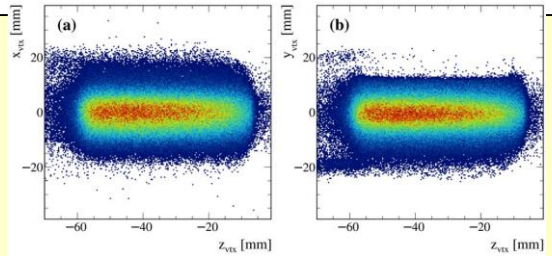
- Large momentum transfer ➢ "**recoil-less**" production
- 4n energy spectrum ➢ missing mass of **charged particles**
- ^{8}He is a good starting point:➢ pronounced α-core structure

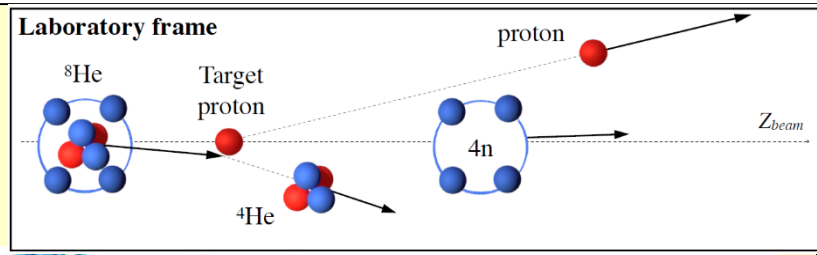
➔ **large overlap <^{8}He|α⊗4n>**

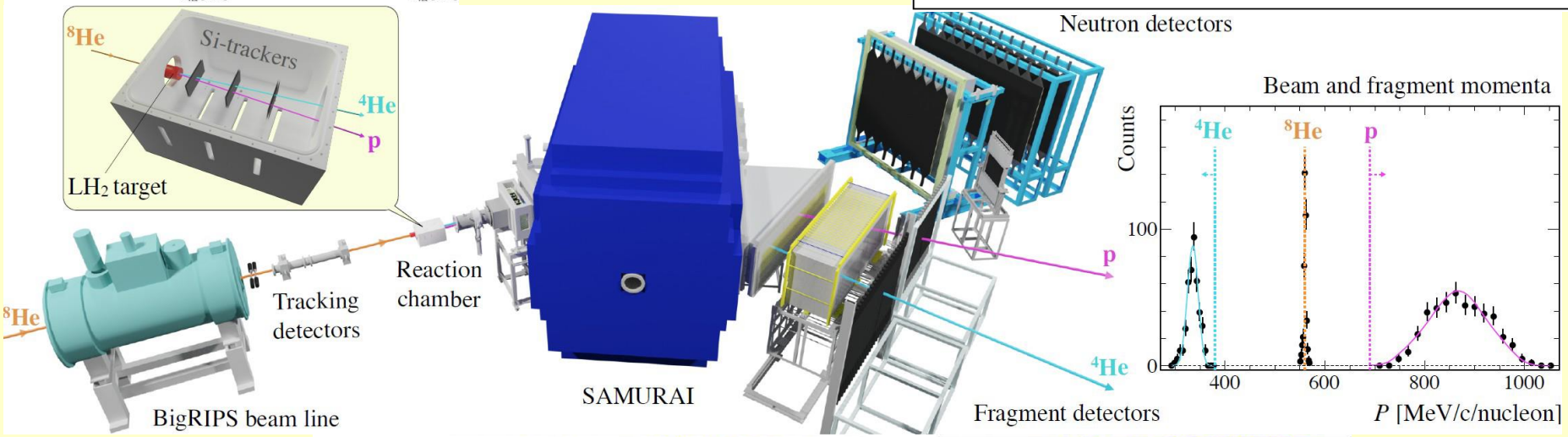
^{18}O campaign at SAMURAI

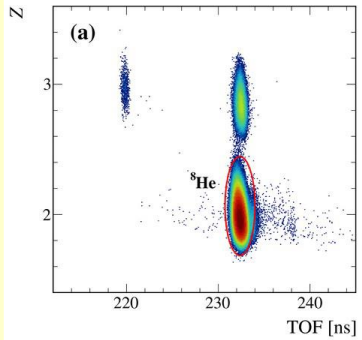


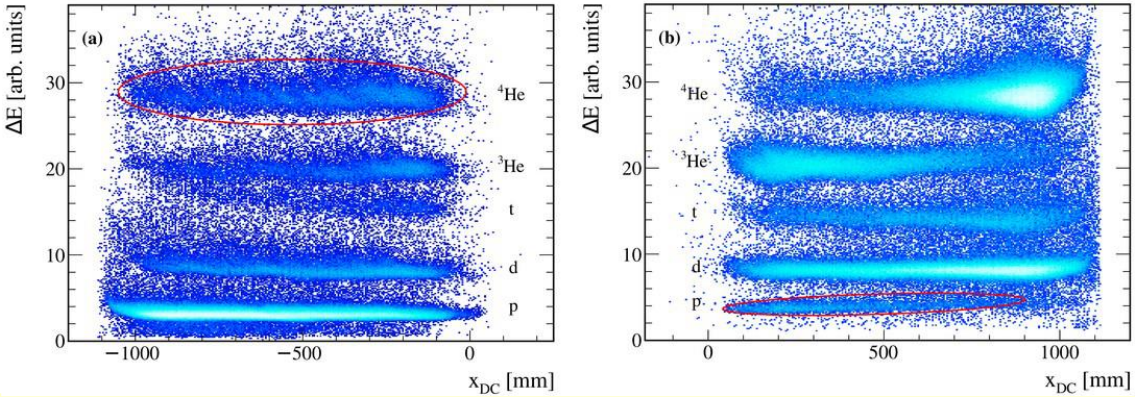
Setup @ SAMURAI



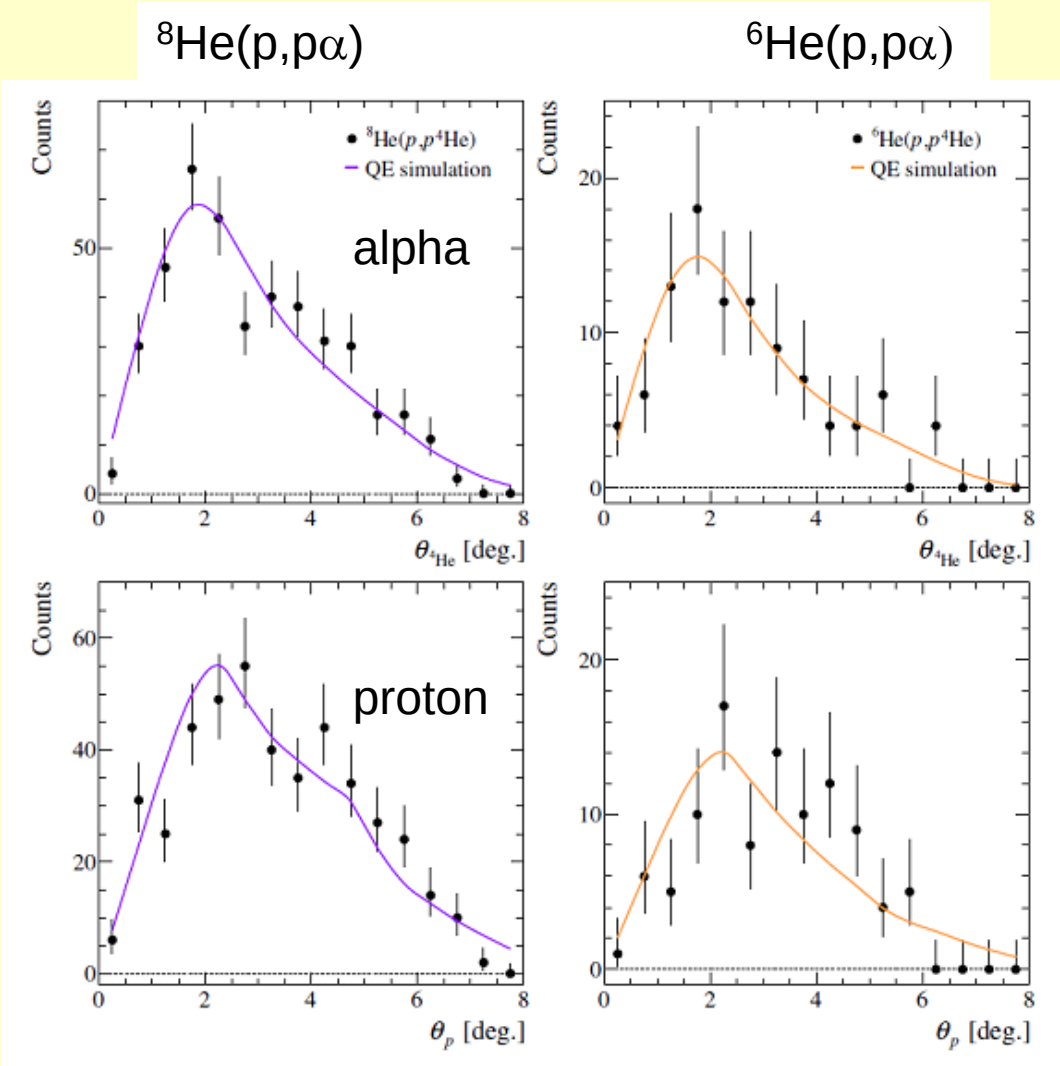


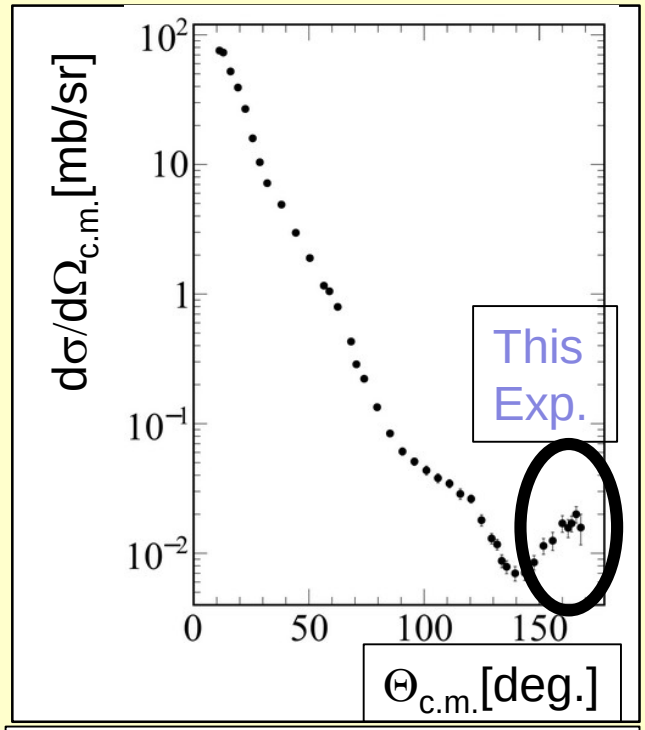






Recoil Angles

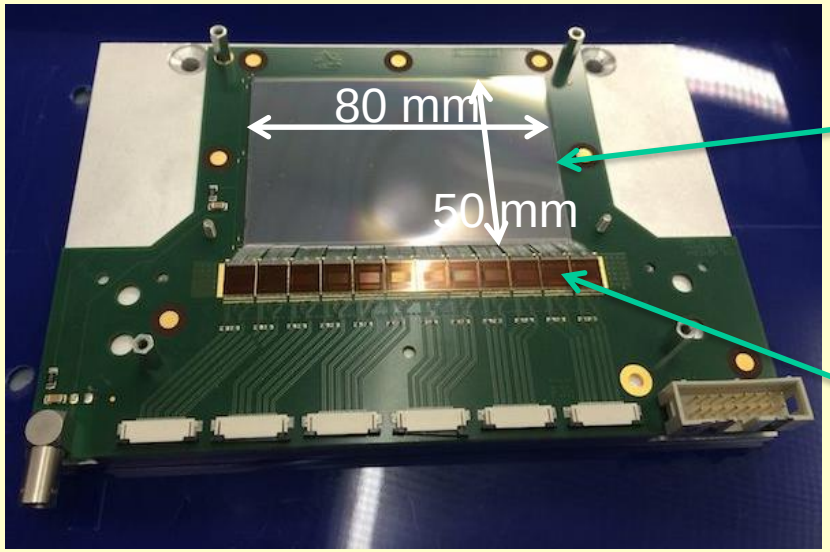




p-α @ 156 MeV
V. Comparat et al., PRC (1975)

Extremely precise vertex reconstruction

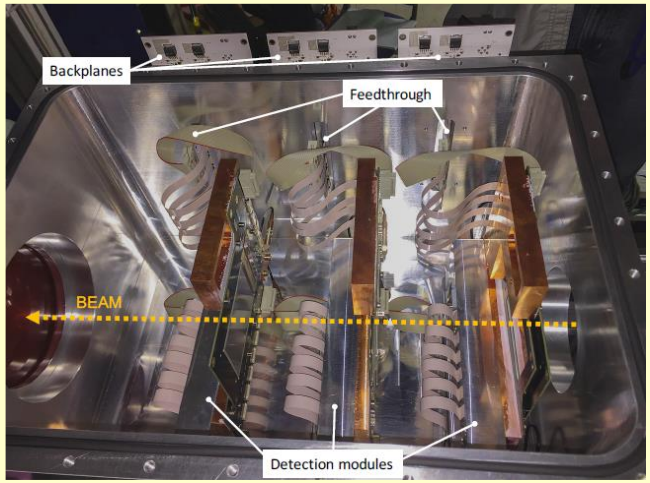
Silicon Detectors for SAMURAI @ Riken

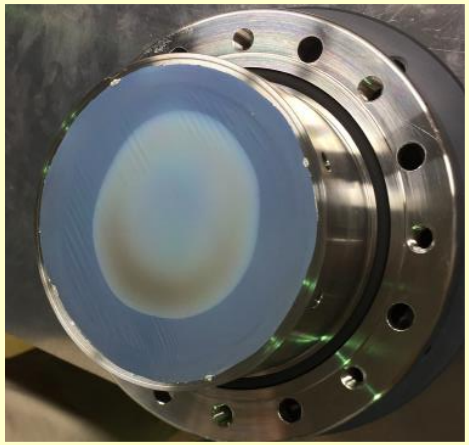


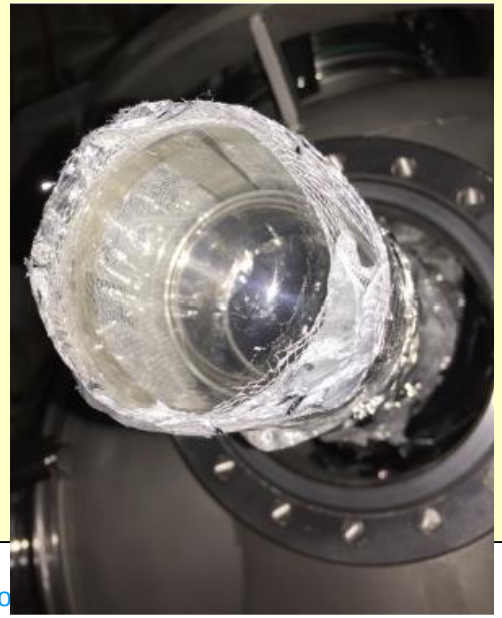
Si detector
Hamamatsu
100 μm SSD
100 μm strips

12 x APV25
2 x 762 ch
per layer

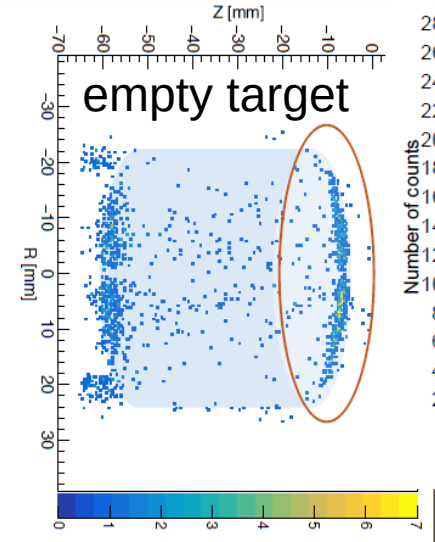
Design by
M. Böhmer, S. Reichert

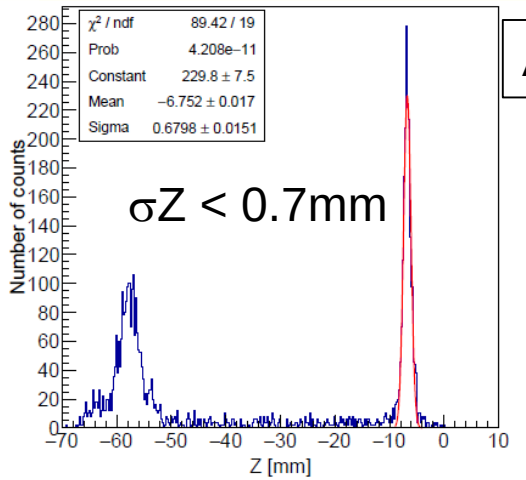




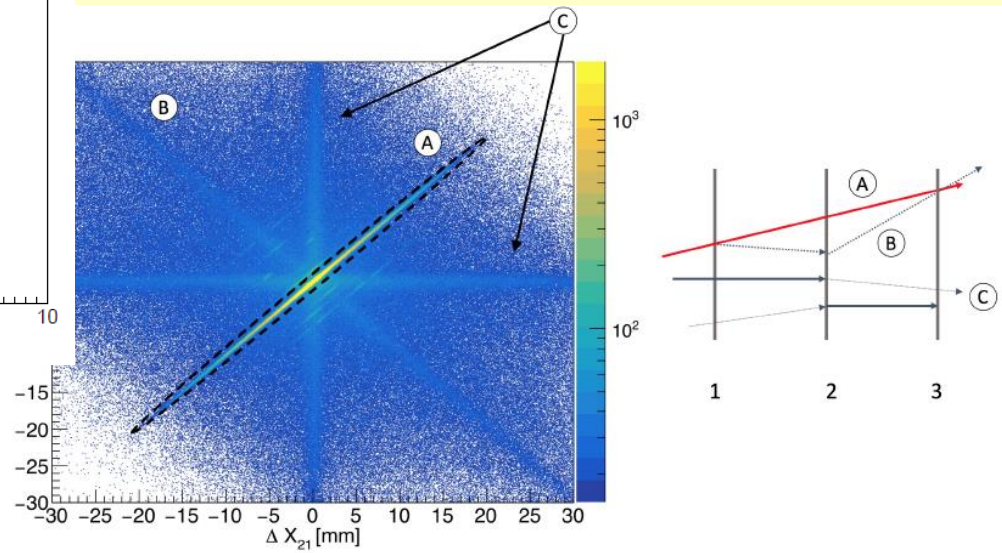


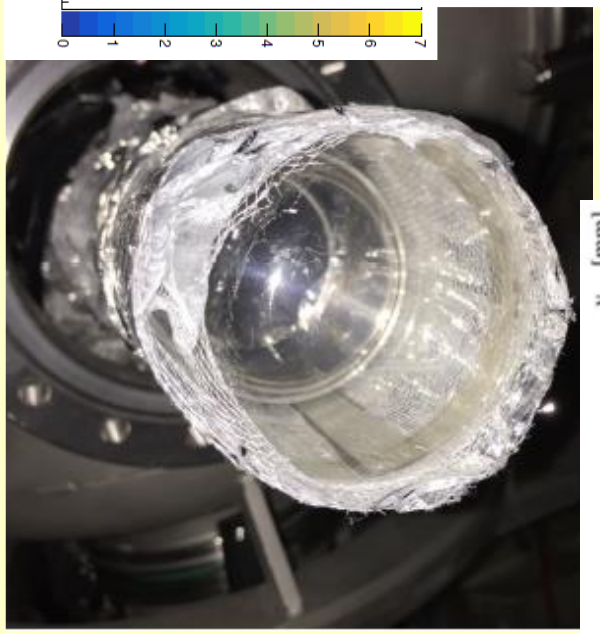
Vertex Reconstruction



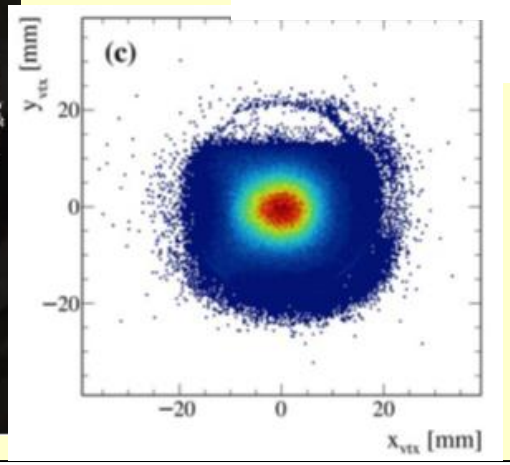


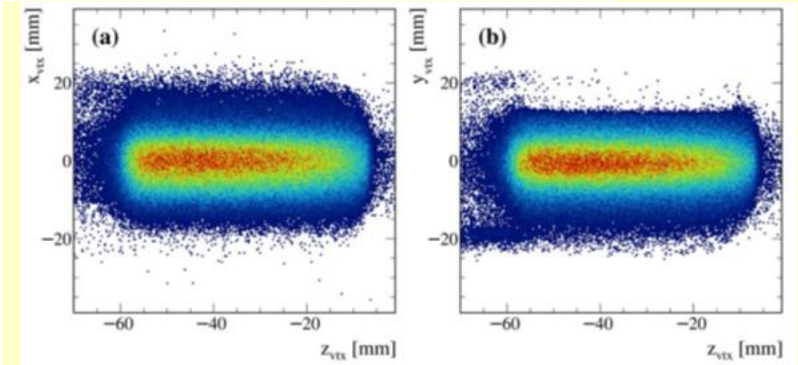
Any fragmentation reaction with two CP





target not completely filled

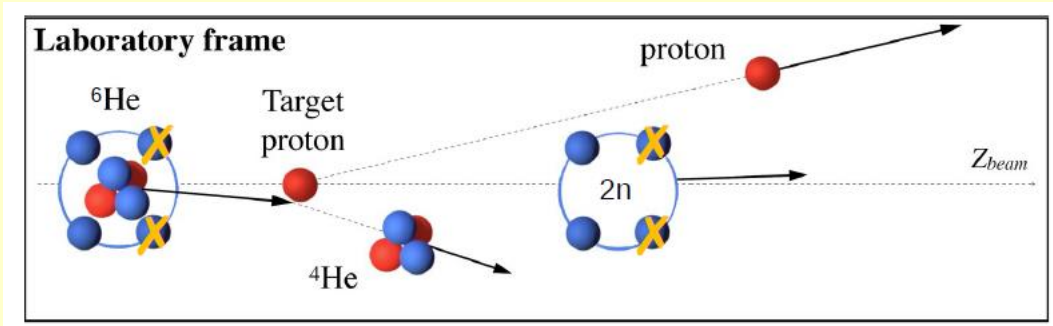




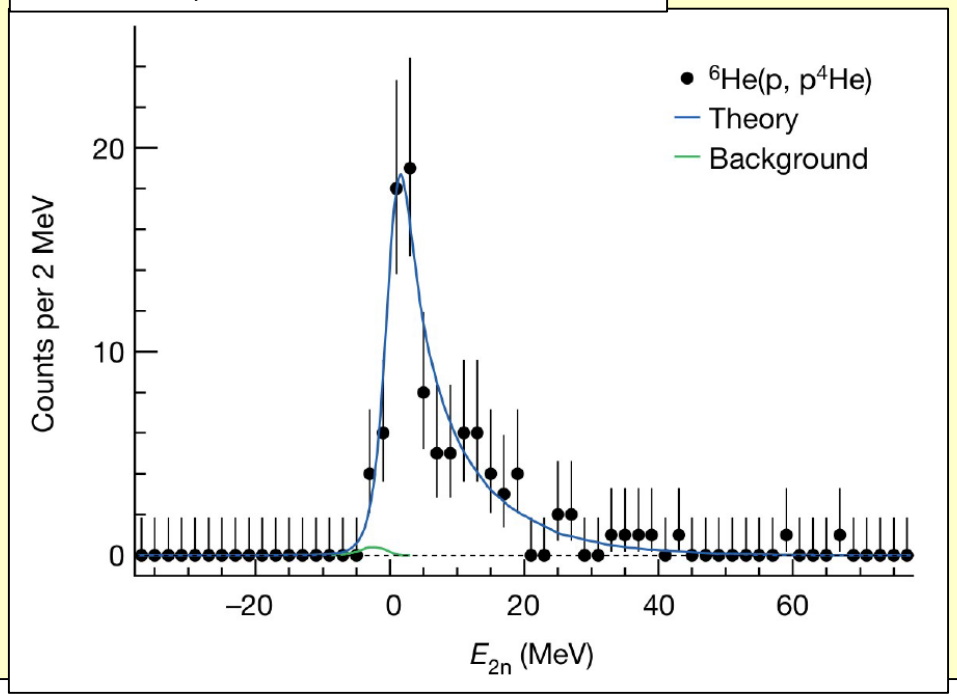
Benchmark Measurement

^{6}He(p,pα) quasi-elastic knockout

- Similar mechanism, similar kinematics
- Two-neutron relative-energy spectrum is expected to be well described by theory



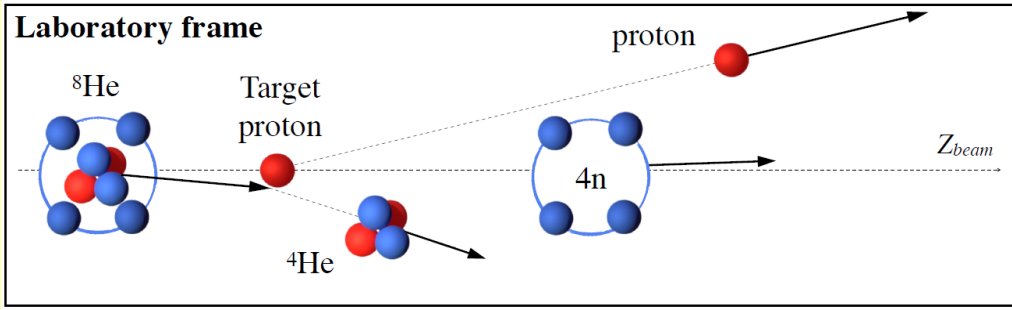
$$E_{2n} = \sqrt{E_{miss}^2 - \boldsymbol{p}_{miss}^2} - 2m_n$$



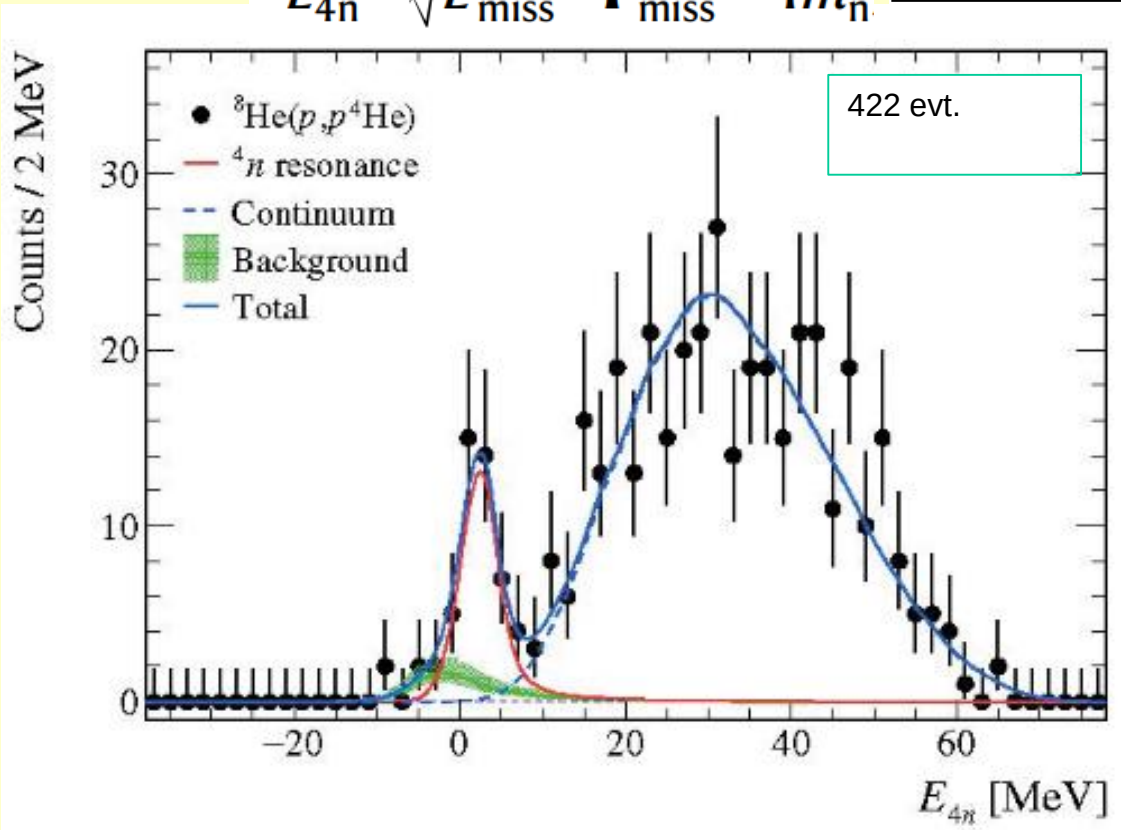
Very good agreement:

- confirms the expected di-neutron low-energy peak ~100 keV
- systematic uncertainty – 0.4 MeV (energy) 0.3 MeV (width)
- No events in unphysical region
- Low background contribution ~1%

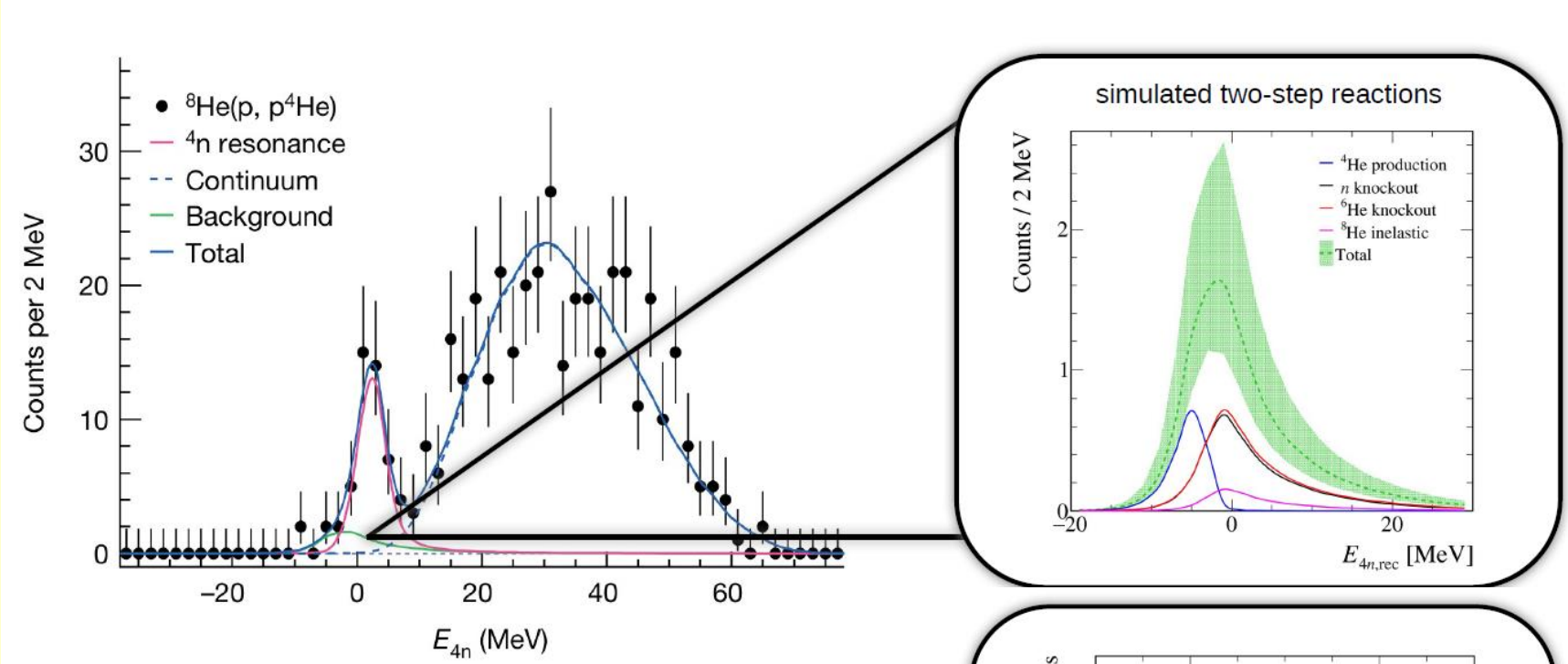
^{8}He(p,p^{4}He) quasi-elastic knockout

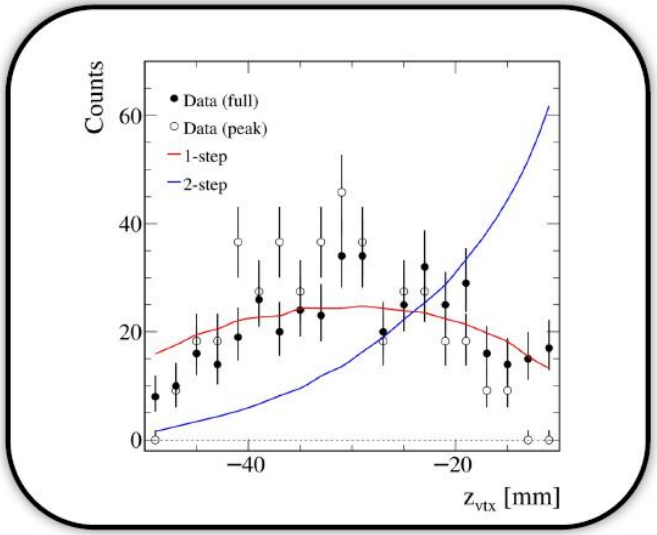


$$E_{4n} = \sqrt{E_{miss}^2 - \mathbf{P}_{miss}^2} - 4m_n$$



Background Considerations

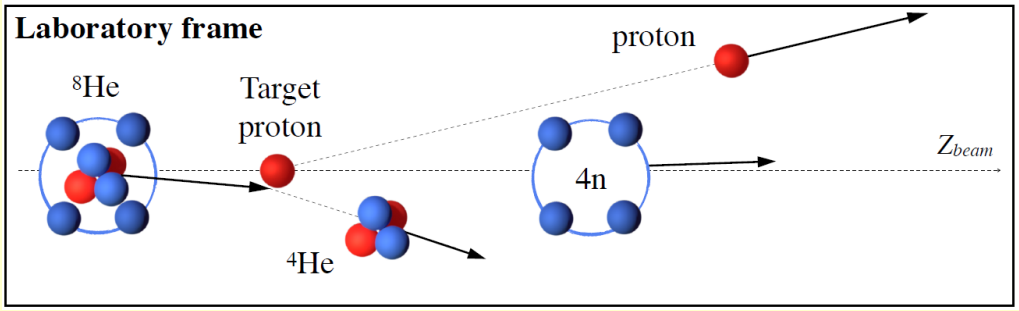


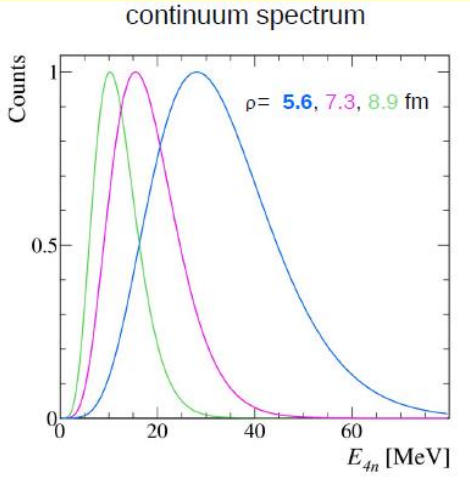


- Total contribution of two step reactions is **2.6%** only.
- One-step reactions have a different kinematics than two-step reactions

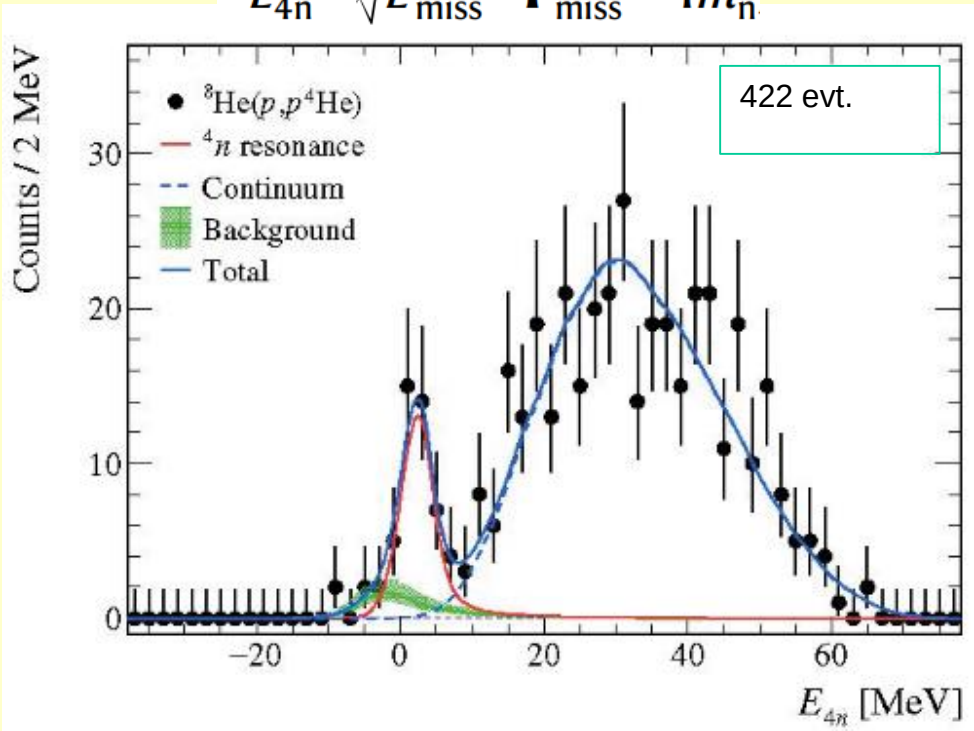
Components and Interpretation

Five-body (^{4}He+4n) COSMA model
- ➢ initial structure (^{8}He)
- ➢ reaction mechanism
- ➢ sensitive to the hyperradius ρ
- ➢ **5.6 fm reproduces ^{8}He radius**





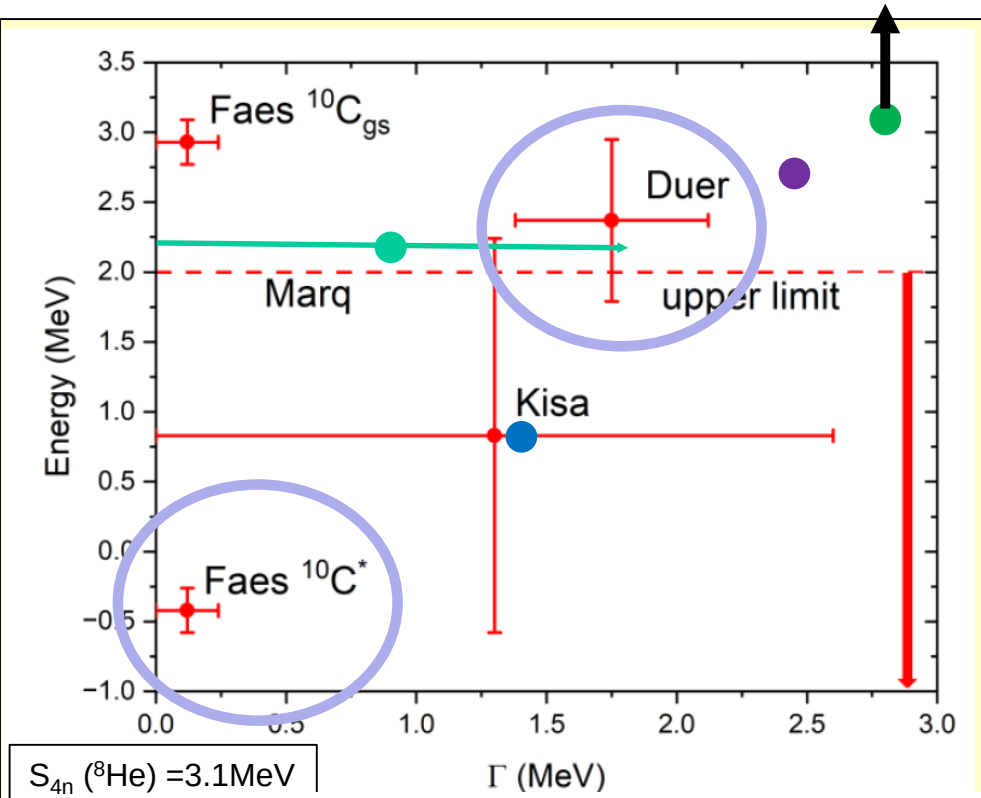
$$E_{4n} = \sqrt{E_{miss}^2 - \mathbf{P}_{miss}^2} - 4m_n$$



5Body Cluster Orbital Shell Model Approximation COSMA
Zhukov et al., PRC (1994);
Grigorenko et al., EPJA (2004)

E_r=2.37 ±0.38(stat.) ±0.44(sys.)MeV,
Γ= 1.75 ±0.22(stat.) ±0.30(sys.)MeV.

Open Questions 2



S_{4n} (^{8}He) =3.1MeV
S_{4n} (^{19}B) =1.5MeV

ab-initio no-core shell model

- Shirokov et al (2016): E_R = 0.8 MeV Γ = 1.4 MeV
- Fossez et al (2017): $E_R \approx$ 7.3 MeV Γ > 2.6 MeV
- Li et al (2019): E_R = 2.6 MeV Γ = 2.4 MeV

chiral effective field theory

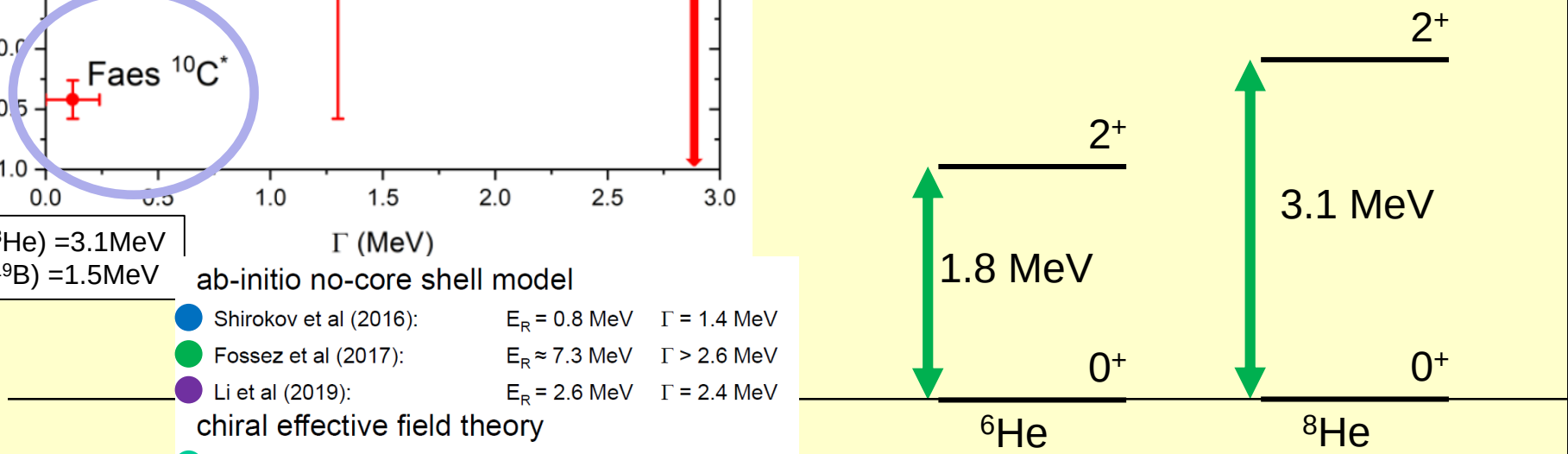
- Gandolfi et al (2017): E_R=2.1 MeV Γ = ?

continuum calculations

- Deltuva et al (2018+2019): no resonance
- Higgins et al (2020): no resonance

Same argument:
How can 4 neutrons in $p_{3/2}$ go to the ground-state?
Transfer angular momentum to spin 2^+

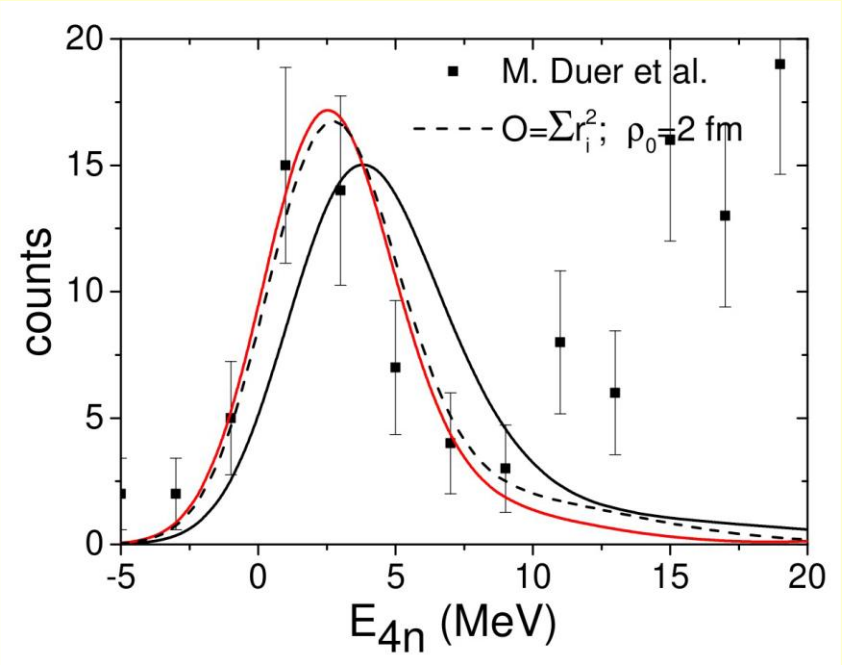
typical energies



Recent Calculations

Trigger for new calculations / explanations
Laszauskas, Hiyama & Carbonell, arXiv:2207.07575 (2022)

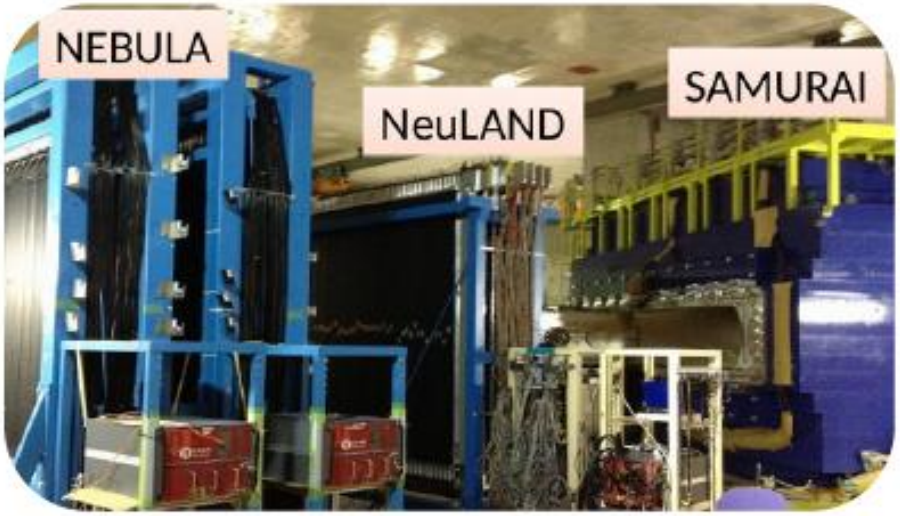
Reaction model: fast removal of 4He core from ^{8}He
➢ (^{4}He+4n) initial state
➢ 4 interacting neutrons in the final state
Solving the 4-body
Faddeev-Yokubovsky equations

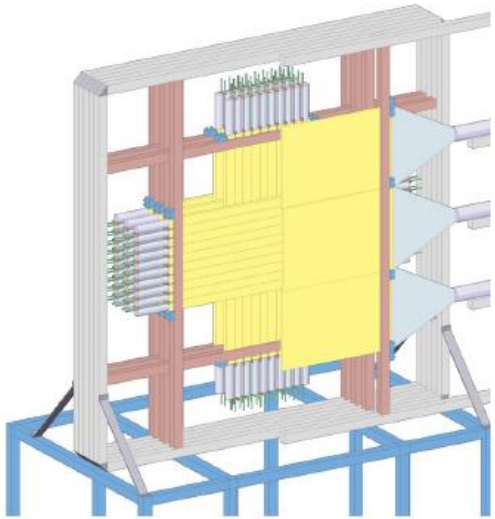


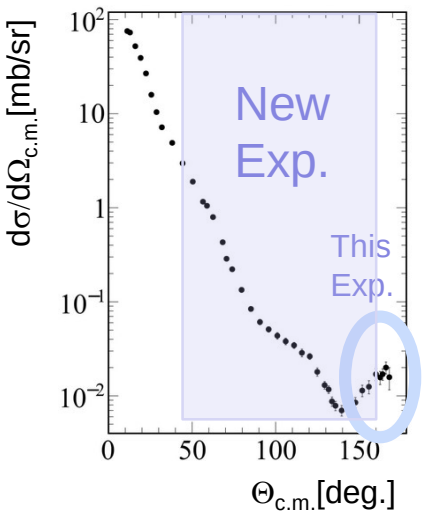
Low energy structure: consequence of 2n+2n FSI and presence of 2n+2n in the periphery of ^{8}He?

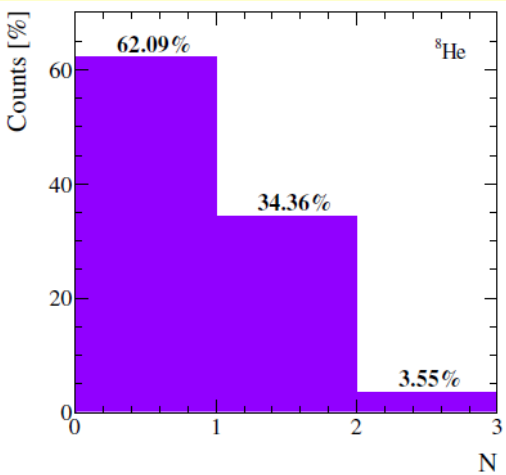
No real ^{8}He initial state,
No continuum

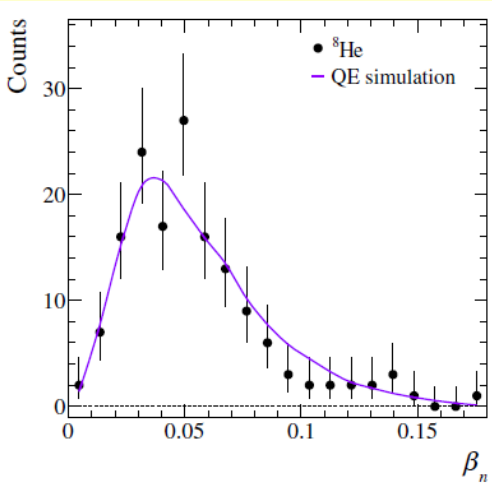
Direct Detection of the Neutrons







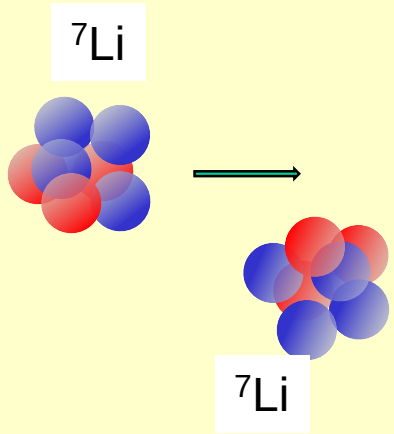




HIME: HIgh-resolution detector for Multi-neutron Events

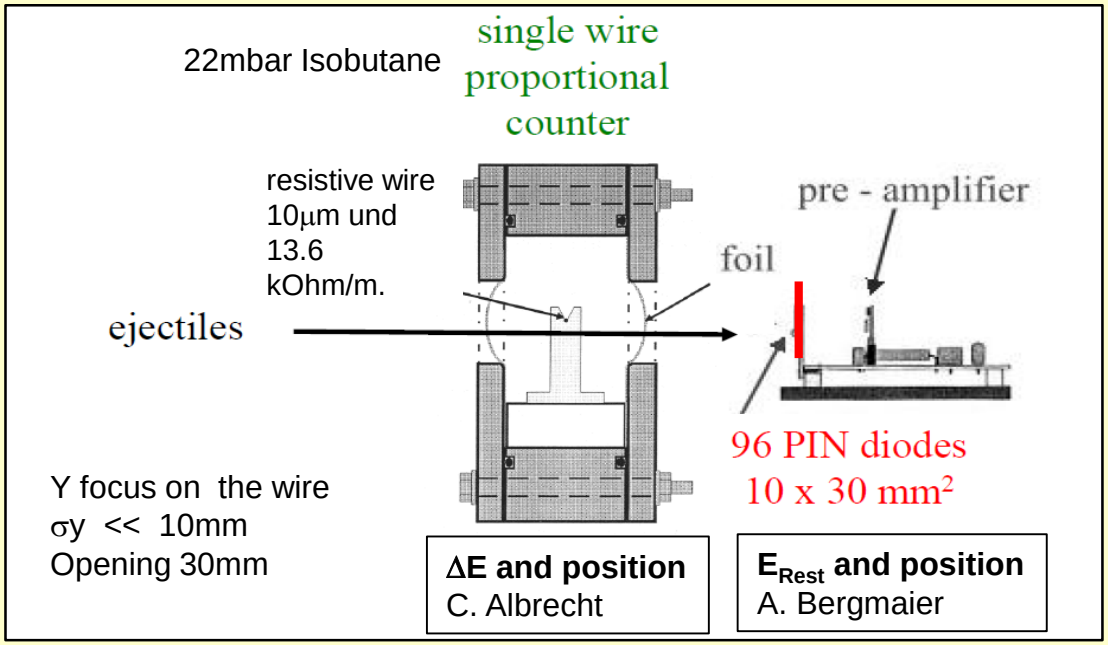
- 100 cm X 4 cm X 2 cm bars
- Full detector 100X100 cm2 (being built at TUDa)
- 100 x more statistics
- higher multi neutron efficiency
- Resolution: timing: 100 ps (rms)
  energy: **25 keV**

Transfer Reaction $^{7}Li(^{7}Li,^{10}C)\,^{4}n$

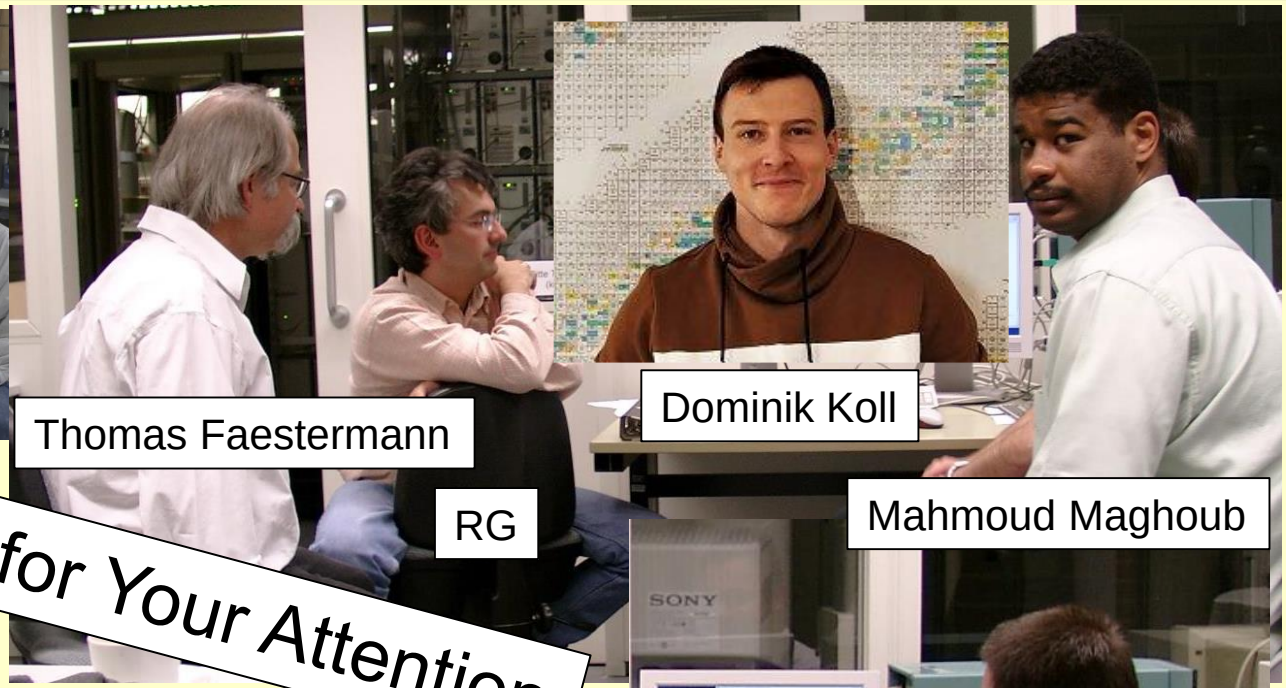


Repeat the experiment with more statistics
$^{7}Li(^{7}Li,^{10}C)\,^{4}n$
Do a background measurement with $^{6}Li_2O$ target
$^{6}Li(^{7}Li,^{10}C)$ **no peak** at al.

Shipping the Detector to:
Bing Guo
HI-13 tandem accelerator,
China Institute of Atomic Energy

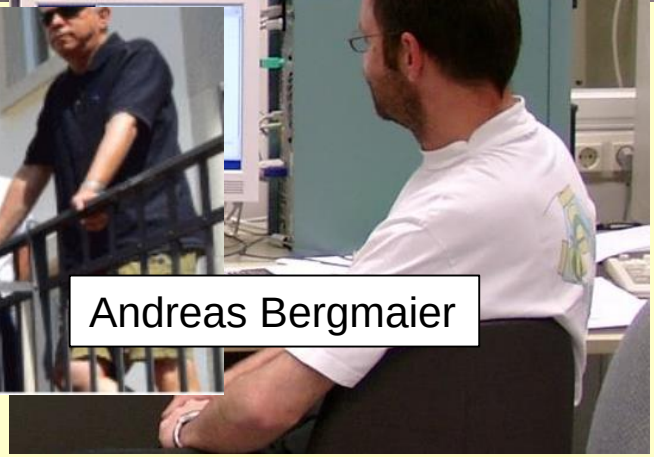


The Teams



Thank You for Your Attention

and many more



Theory Predictions

ab-initio no-core shell model

Shirokov et al (2016):	E_R = 0.8 MeV	Γ = 1.4 MeV
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Gandolfi et al (2017):	E_R=2.1 MeV	Γ = ?

continuum calculations

Deltuva et al (2018+2019):	no resonance
Higgins et al (2020):	no resonance

all of them agreeing that a bound tetraneutron is not supported by theory. (Shirokov)