

<sup>4</sup>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

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

1







- Experiment 1Experiment 2
- Discussion

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





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



<sup>4</sup>He (<sup>8</sup>He, <sup>8</sup>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**





Just pick 3 protons from the <sup>7</sup>Li (target). Minimize CM energy. Beam: odd Z, low Coulomb barrier <sup>7</sup>Li









#### 







#### **Target**







#### The Q3D Spectrograph













#### **Particle Identification**











11

















- 20.8 MeV line must be from <sup>7</sup>Li(<sup>7</sup>Li,<sup>10</sup>C) <sup>4</sup>n reaction
- <sup>10</sup>C energy corresponds to E\*(<sup>10</sup>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 <sup>4</sup>n:  $\Gamma$  < 0.24 MeV
- 4n with BE= -2.9 MeV and  $\Gamma$ < 0.24 MeV is unrealistic
- e.g.  $^{6}H = >^{3}H + 3 \text{ n with } Q = 2.7 \text{ MeV and } \Gamma = 2.4 \text{ MeV}$

=> 10C is excited E\*=3.354 MeV and BE(4n)=+0.42(16) MeV









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

 Collect more statistics

Change to 5°

- Check kinematic shift
- Larger cross section?
- Larger angles would mean more background



![](_page_16_Picture_1.jpeg)

![](_page_16_Figure_2.jpeg)

![](_page_17_Figure_0.jpeg)

![](_page_17_Picture_2.jpeg)

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

If BE(4n) > 0  
There is no neutron emission just 
$$\beta^{-}$$
 -decay.

## Method: <sup>8</sup>He(p,p<sup>4</sup>He) quasi-elastic knockout

![](_page_18_Picture_1.jpeg)

![](_page_18_Figure_2.jpeg)

![](_page_19_Picture_0.jpeg)

![](_page_19_Figure_2.jpeg)

![](_page_19_Figure_3.jpeg)

![](_page_20_Picture_0.jpeg)

#### Setup @ SAMURAI

![](_page_20_Picture_2.jpeg)

![](_page_20_Figure_3.jpeg)

![](_page_21_Picture_0.jpeg)

#### **Recoil Angles**

![](_page_21_Picture_2.jpeg)

![](_page_21_Figure_3.jpeg)

![](_page_22_Picture_0.jpeg)

### **Silicon Detectors for SAMURAI @ Riken**

![](_page_22_Picture_2.jpeg)

![](_page_22_Picture_3.jpeg)

Si detector Hamamatsu 100 µm SSD 100 µm strips

12 x APV25 2 x 762 ch per layer

![](_page_22_Picture_6.jpeg)

#### Design by M. Böhmer, S. Reichert

![](_page_22_Picture_8.jpeg)

![](_page_22_Picture_9.jpeg)

![](_page_22_Picture_10.jpeg)

)23

![](_page_23_Picture_0.jpeg)

#### **Vertex Reconstruction**

![](_page_23_Picture_2.jpeg)

![](_page_23_Figure_3.jpeg)

![](_page_24_Picture_0.jpeg)

![](_page_24_Picture_2.jpeg)

#### <sup>6</sup>He(p,pα) quasi-elastic knockout

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

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%

![](_page_24_Figure_11.jpeg)

![](_page_25_Picture_0.jpeg)

![](_page_25_Figure_2.jpeg)

![](_page_25_Figure_3.jpeg)

![](_page_26_Picture_0.jpeg)

![](_page_26_Picture_2.jpeg)

![](_page_26_Figure_3.jpeg)

International Workshop XLIX on Gross Properties of Nuclei and Nuclear

![](_page_27_Figure_0.jpeg)

![](_page_27_Figure_2.jpeg)

![](_page_27_Figure_3.jpeg)

![](_page_28_Figure_0.jpeg)

![](_page_28_Picture_2.jpeg)

![](_page_28_Figure_3.jpeg)

![](_page_29_Figure_0.jpeg)

![](_page_29_Picture_2.jpeg)

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

![](_page_29_Figure_4.jpeg)

![](_page_30_Picture_0.jpeg)

#### **Direct Detection of the Neutrons**

![](_page_30_Picture_2.jpeg)

![](_page_30_Picture_3.jpeg)

![](_page_30_Figure_4.jpeg)

# 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

![](_page_31_Picture_0.jpeg)

![](_page_31_Picture_2.jpeg)

![](_page_31_Figure_3.jpeg)

![](_page_32_Picture_0.jpeg)

![](_page_32_Picture_1.jpeg)

![](_page_32_Picture_2.jpeg)

![](_page_32_Picture_3.jpeg)