Joint Institute for Nuclear Research

SCIENCE BRINGING NATIONS TOGETHER

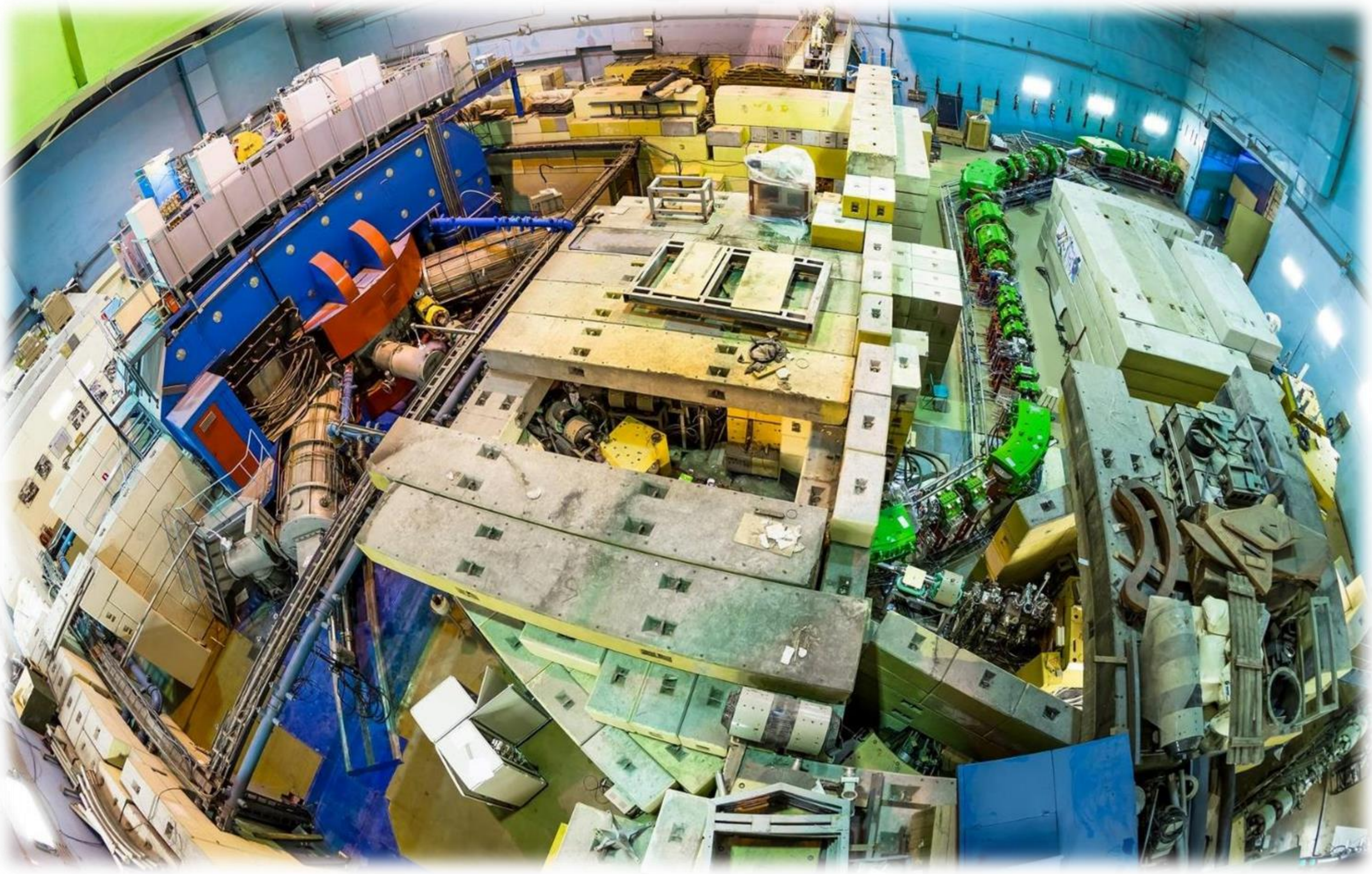
JINR 114 Flerovium FLNR Dubna

Muzalevskii Ivan

for ACCULINNA-2 collaboration

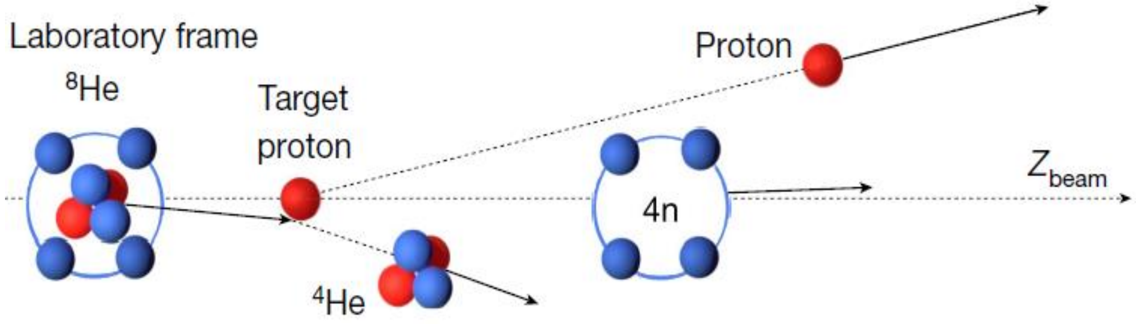
Flerov Laboratory of Nuclear Reactions JINR, Dubna

Population of tetraneutron continuum in reactions of ^{8}He on deuterium



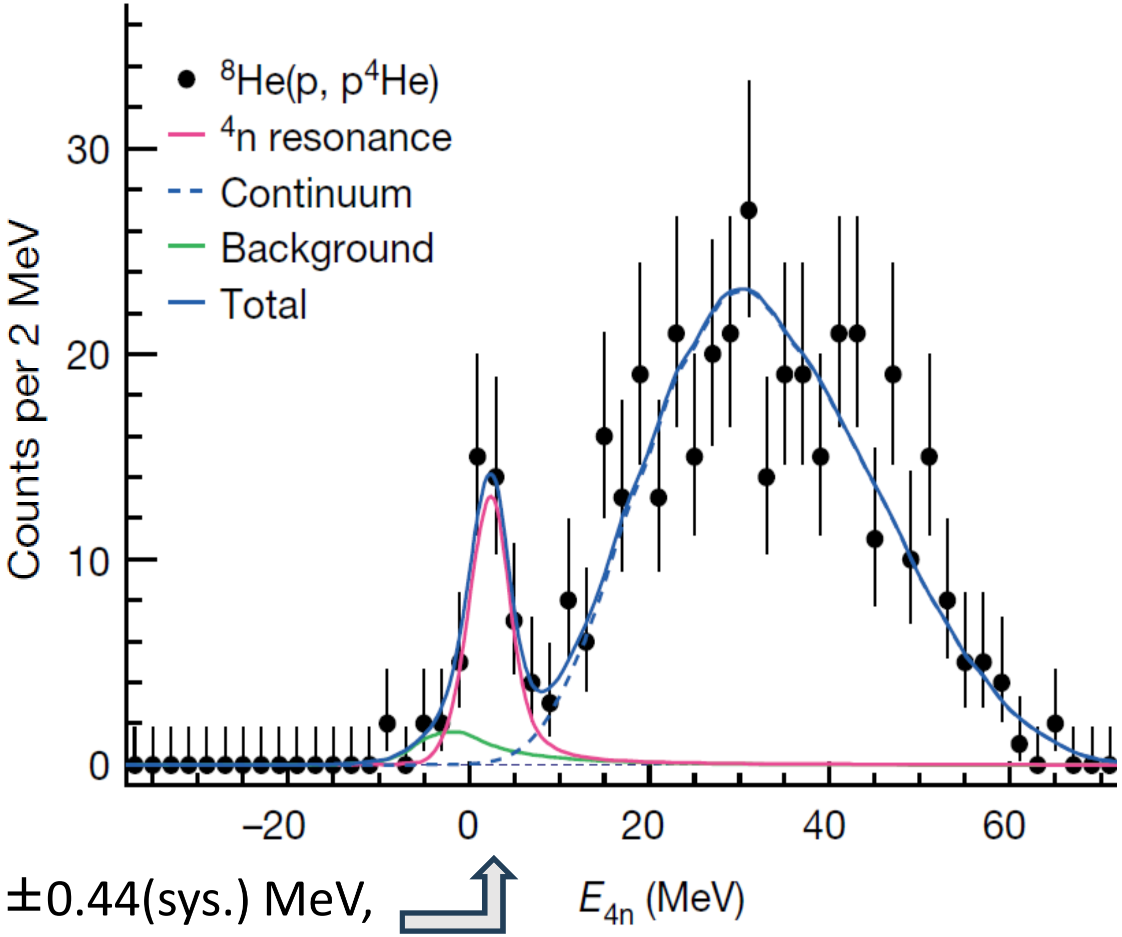
Spectrum of “tetraneutron” populated in ^{8}He(p, p^{4}He)*4n reaction*

M. Duer et al., Observation of a correlated free four-neutron system, Nature 606 (2022) 678



156 AMeV

QFS reaction of alpha-core knock-out from ^{8}He



E_r = 2.37±0.38(stat.)±0.44(sys.) MeV,

Γ = 1.75±0.22(stat.)±0.30(sys.) MeV.

ACCULINNA-2

Experiment

1. Search for 4n

   I.A. Muzalevskii, et al., Phys. Rev. C, 111:014612, Jan 2025

2. Search for ^{7}H in ^{2}H(^{8}He,^{3}He)^{7}H

   I.A. Muzalevskii et al, Phys. Rev. C 103 (2021) 044313

   A. A. Bezbakh et al, Phys. Rev. Lett., 124:022502, Jan 2020

3. Search for ^{6}H in ^{2}H(^{8}He,^{4}He)^{6}H

   E.Yu.Nikolskii et al., Phys. Rev. C 105 (2022) 064605

   I. A. Muzalevskii et al, EPJ Web of Conferences 290, 09001 (2023)

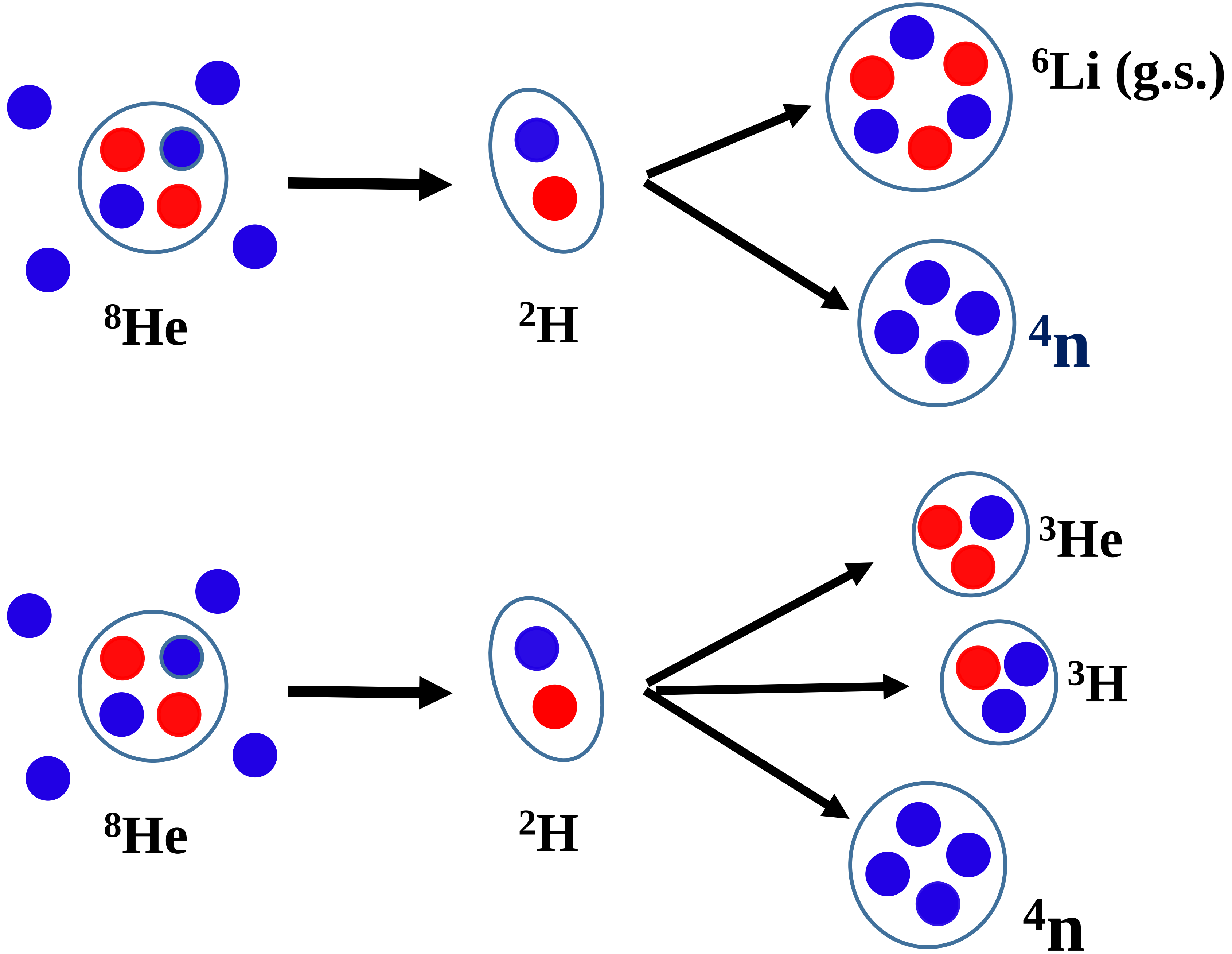
4. Reference measurement with ^{10}Be beam

   E.Yu.Nikolskii et al., Physics of Atomic Nuclei, Vol. 87 №1(2024) 1-8.

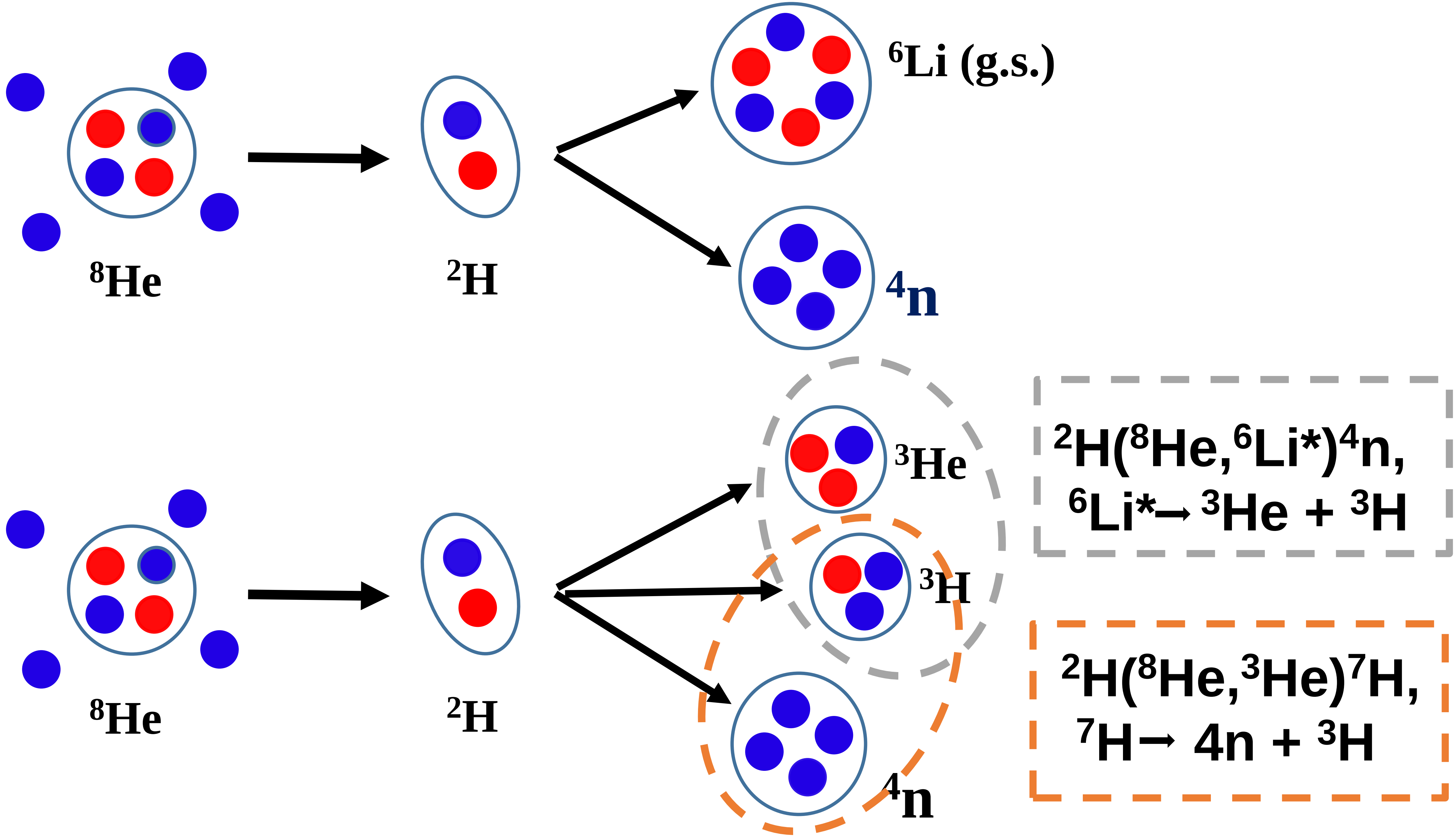
26 *A*MeV ^{8}He RIB from ^{15}N(50 *A*MeV)+Be:

I ~ 5*10^{5} pps, P ~ 95%, beam spot ~ 15 mm

Cryogenic deuterium target



^{6}Li (g.s.)
^{8}He
^{2}H
^{4}n
^{3}He
^{3}H
^{8}He
^{2}H
^{4}n

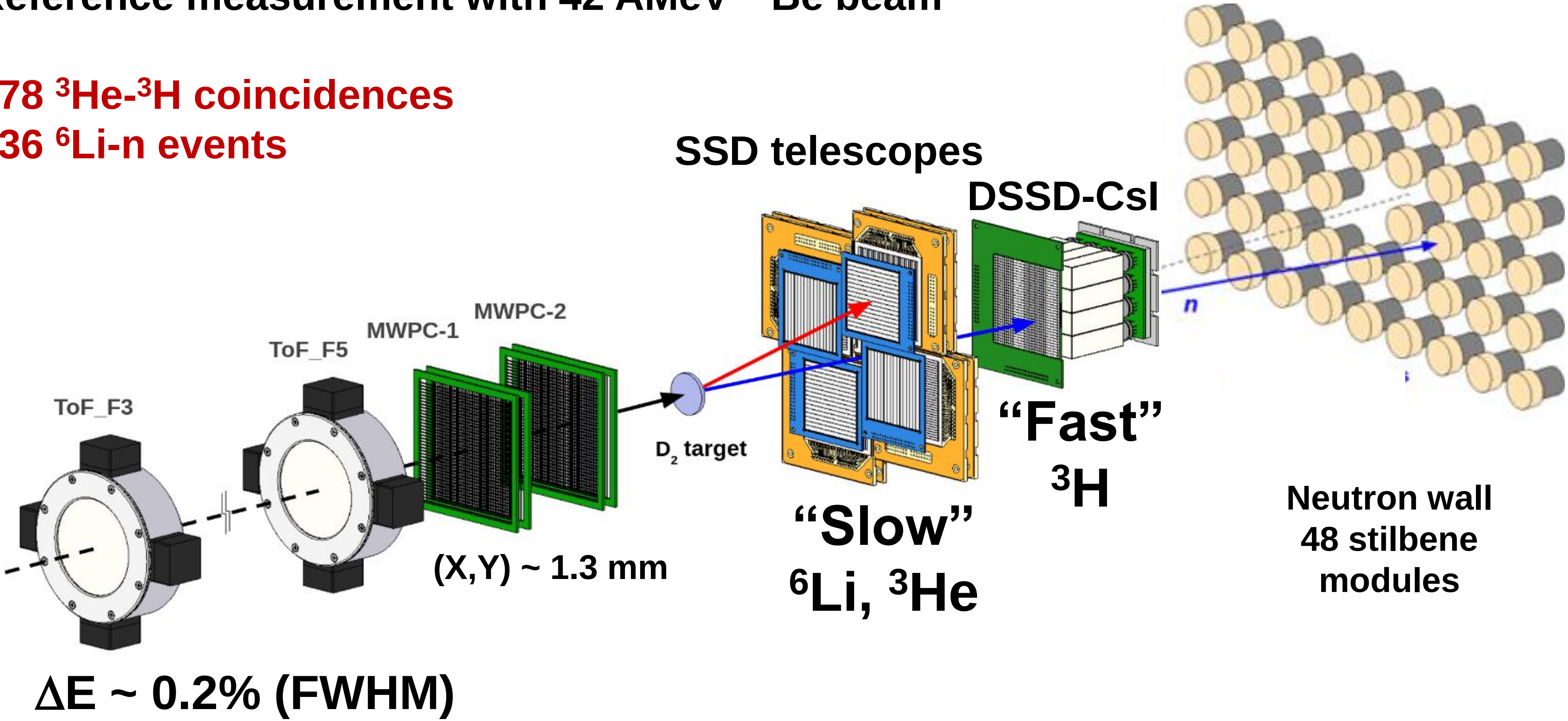


^{8}He
^{2}H
^{6}Li (g.s.)
^{4}n
^{8}He
^{2}H
^{3}He
^{3}H
^{4}n
^{2}H(^{8}He,^{6}Li*)^{4}n,
^{6}Li*→ ^{3}He + ^{3}H
^{2}H(^{8}He,^{3}He)^{7}H,
^{7}H→ 4n + ^{3}H

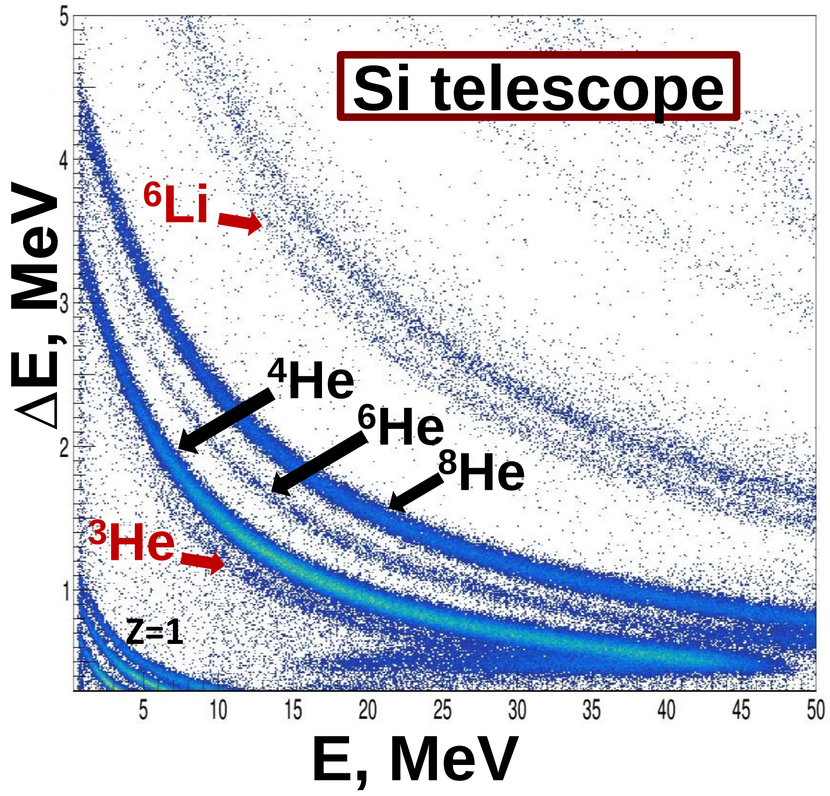
Detector setup

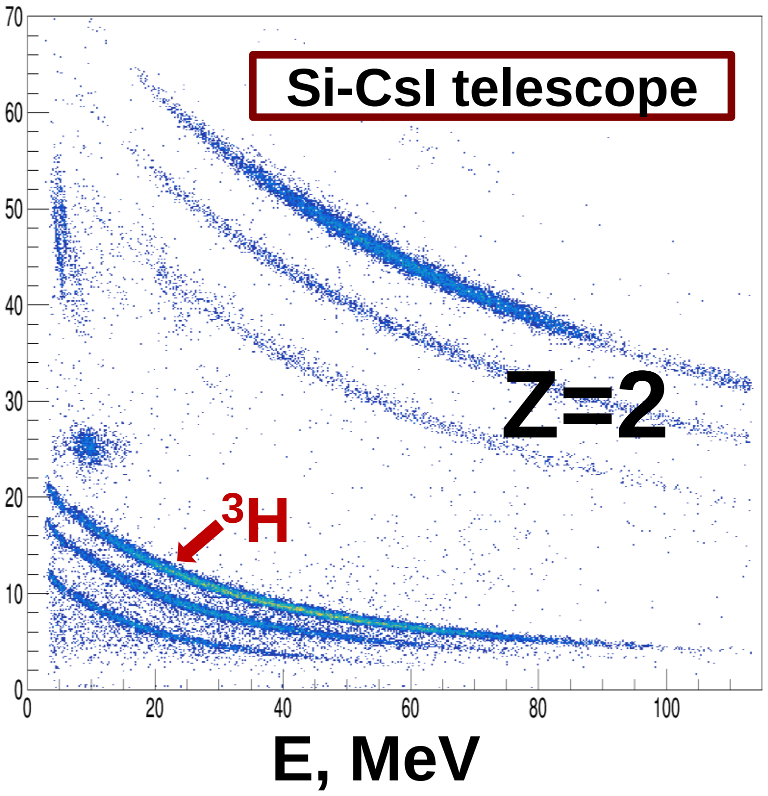
3 weeks beamtime + empty target background measurement
Reference measurement with 42 AMeV ^{10}Be beam

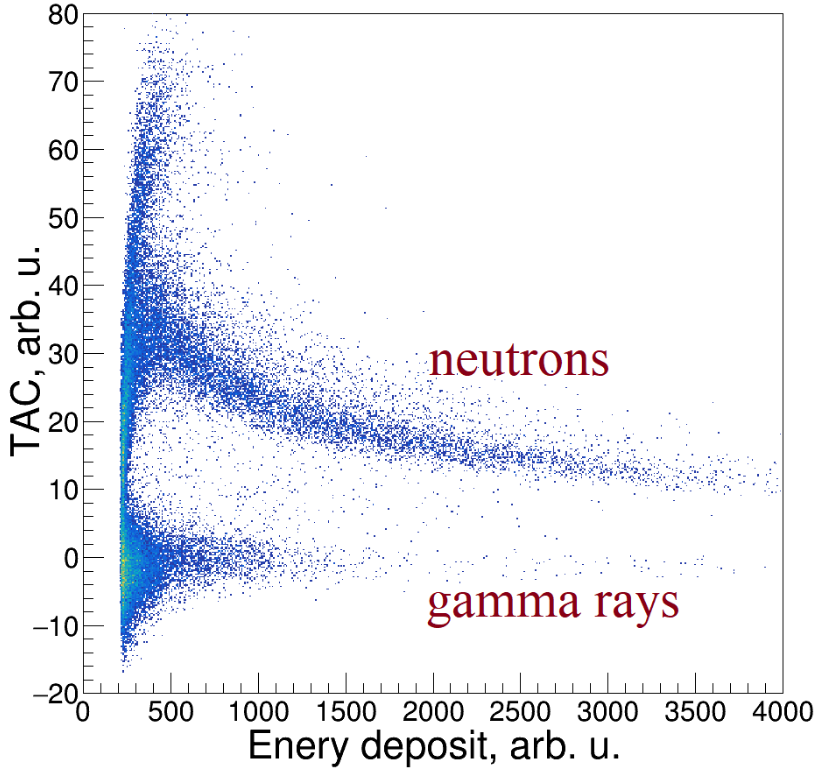
378 ^{3}He-^{3}H coincidences
136 ^{6}Li-n events



Particle identification



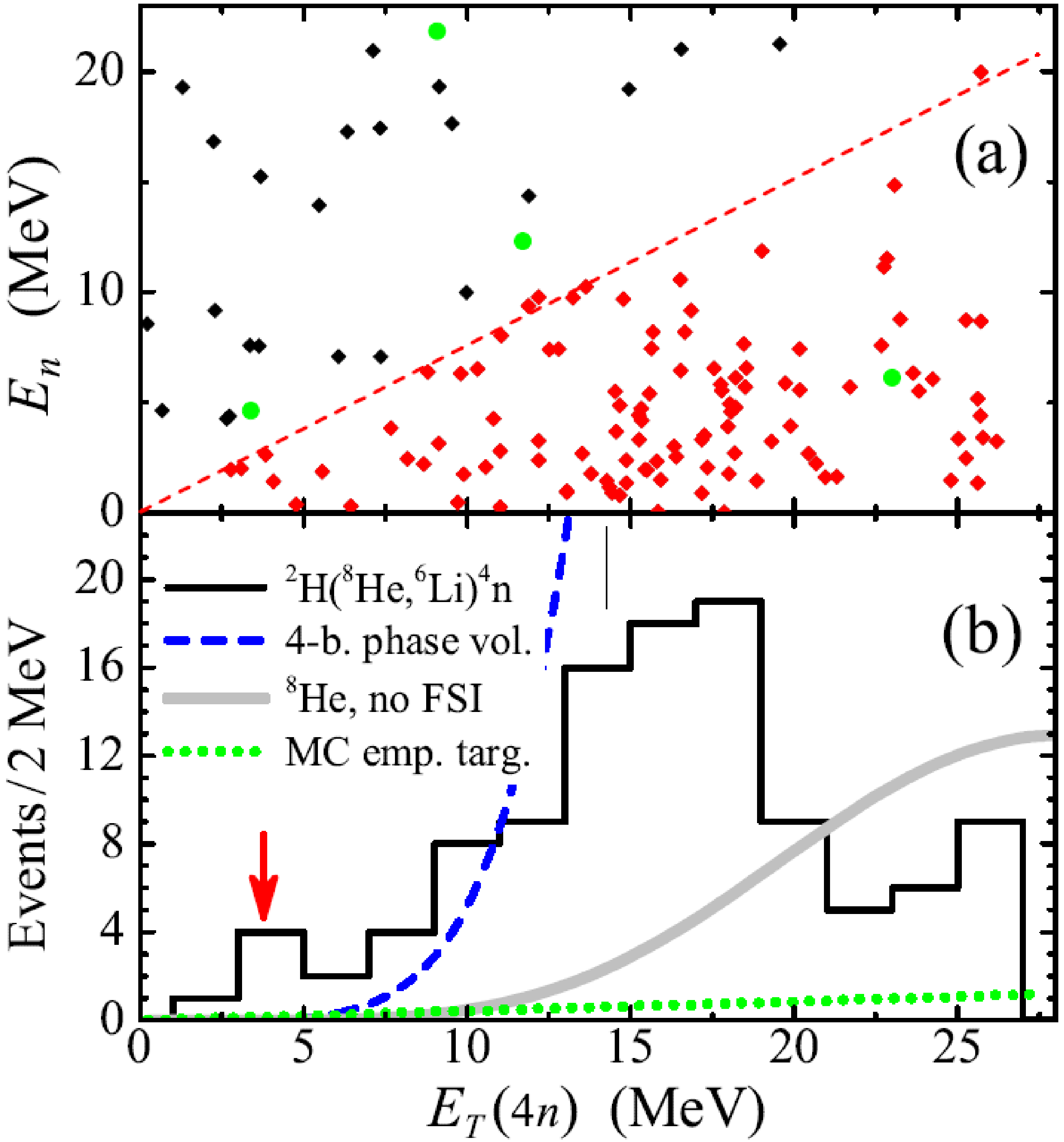




- Detection of “low energy” ^{6}Li, ^{3}He only in Si telescope with 20μm in the front
- Detection “high energy” ^{3}H in central telescope
- Neutron identification & detection by dE-TAC & ToF

$^{2}H(^{8}He,^{6}Li)^{4}n$ results

- 136 ^{6}Li-n events
- Good reaction identification
- background free
- **^{4}n peak at 3.2 MeV**
- Not described by 4-body phase vol. or Fourier transform of ^{8}He source

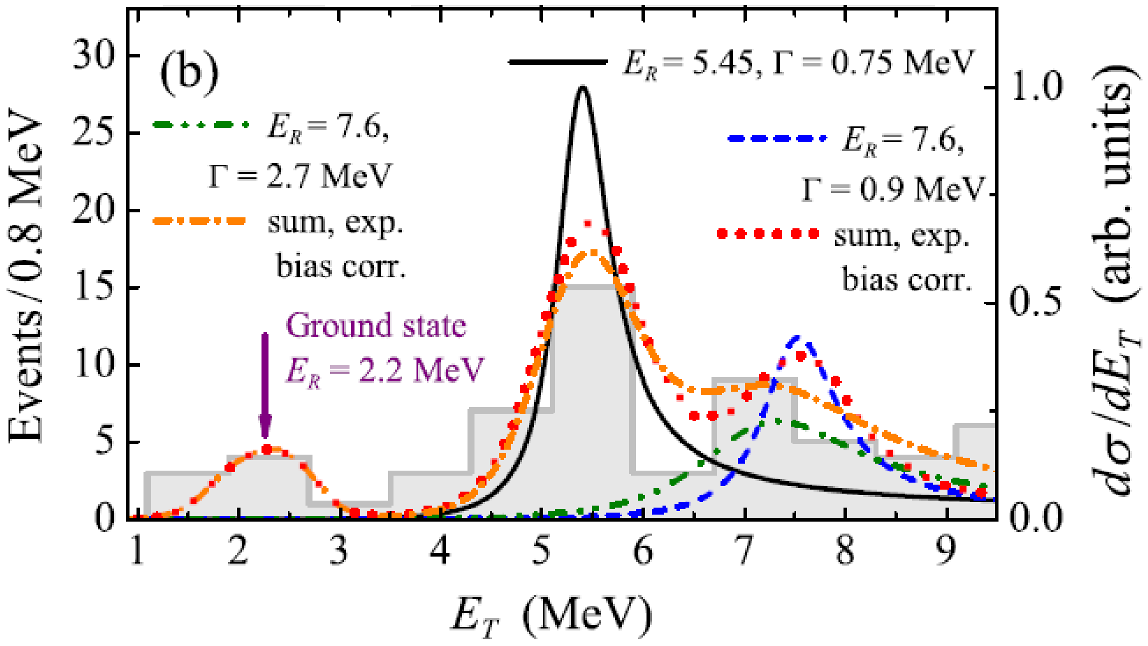


$^2H(^8He,^3He^3H)^4n$ results

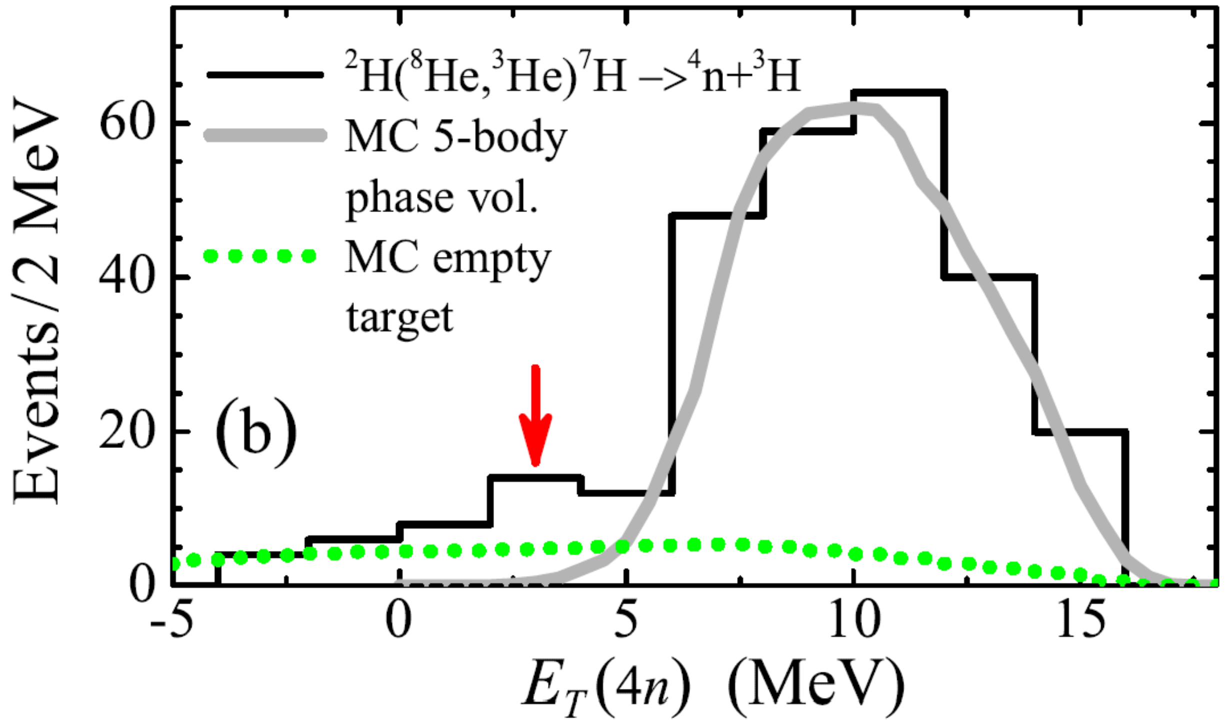
^4n MM from ^3He + ^3H

^7H states

MM(^7H)>8 MeV



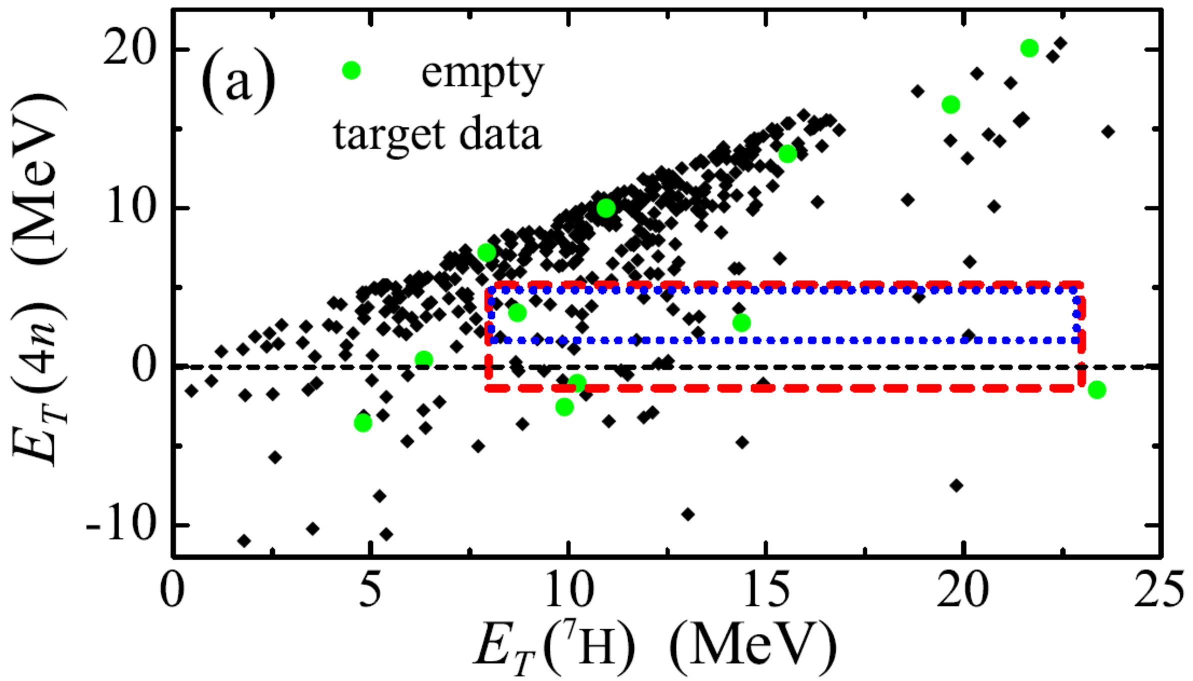
Phys. Rev. C 103 (2021) 044313



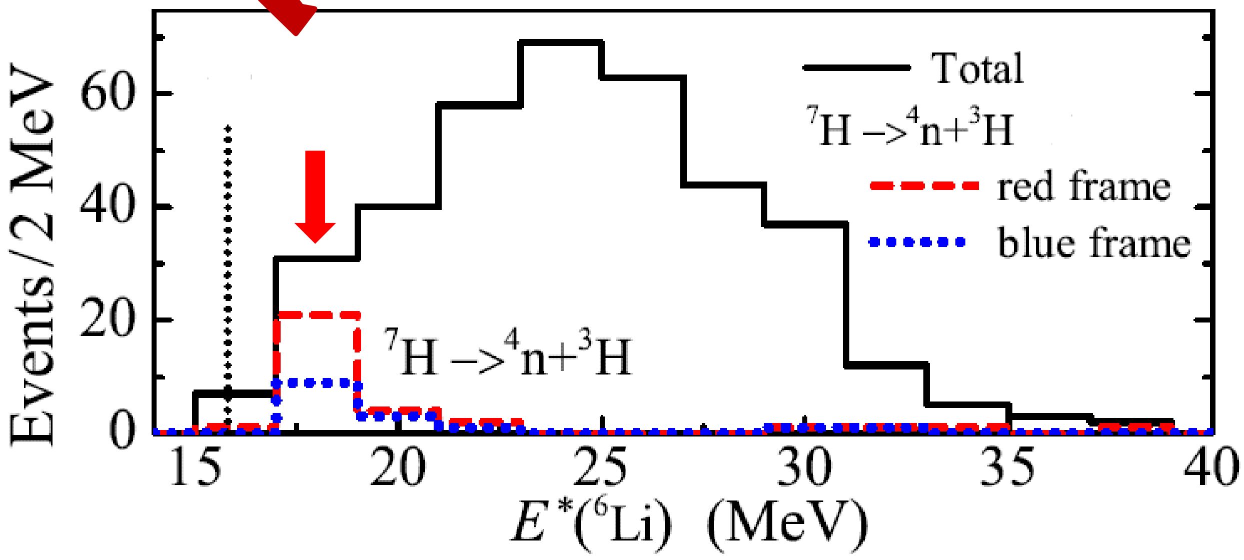
^4n peak at 3.2 MeV

$^{2}H(^{8}He,^{3}He^{3}H)^{4}n$ results

^{7}H-^{4}n correlation



$^{6}Li^{*}$-^{4}n correlation

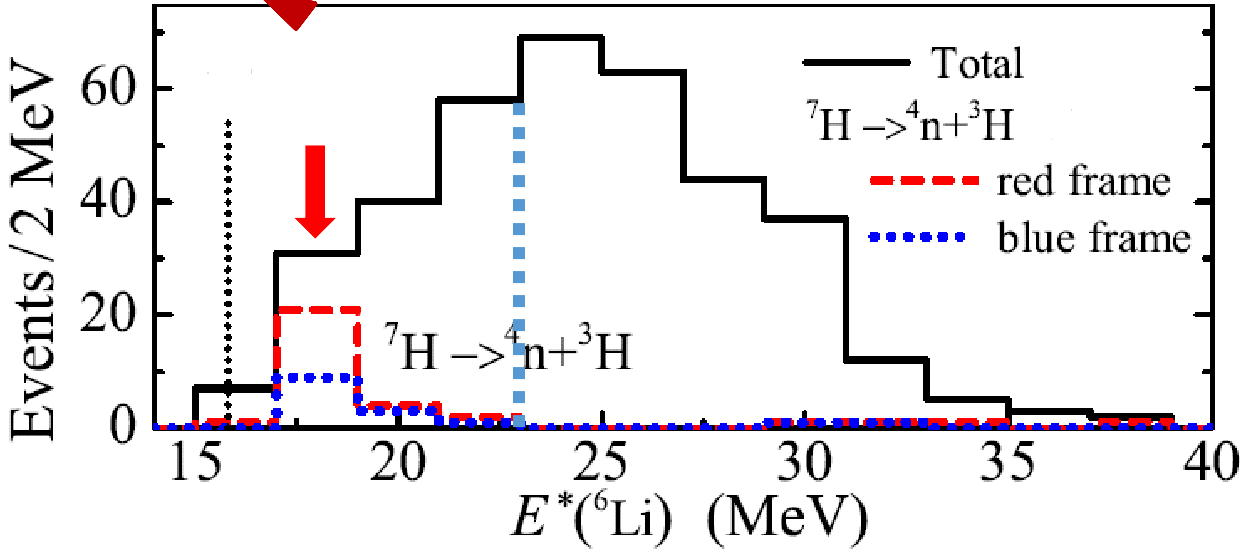


Resonance behavior ^{3}He-^{3}H

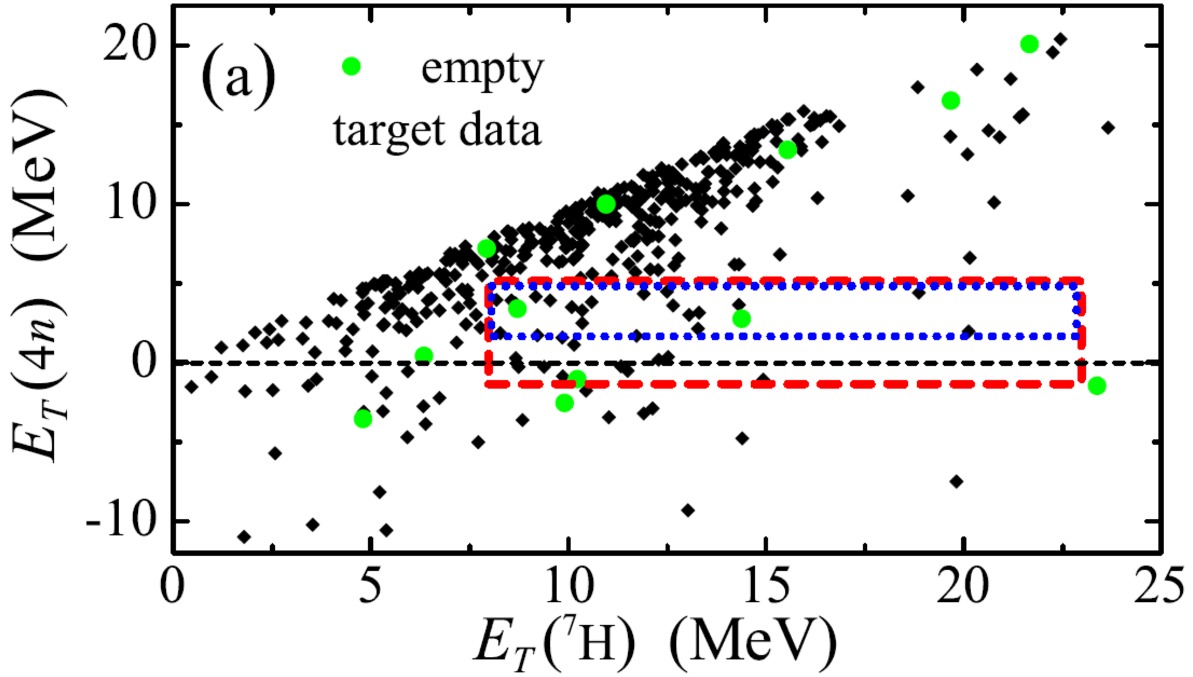
Strong correlation with 2- ^{6}Li (2—) 18 MeV state

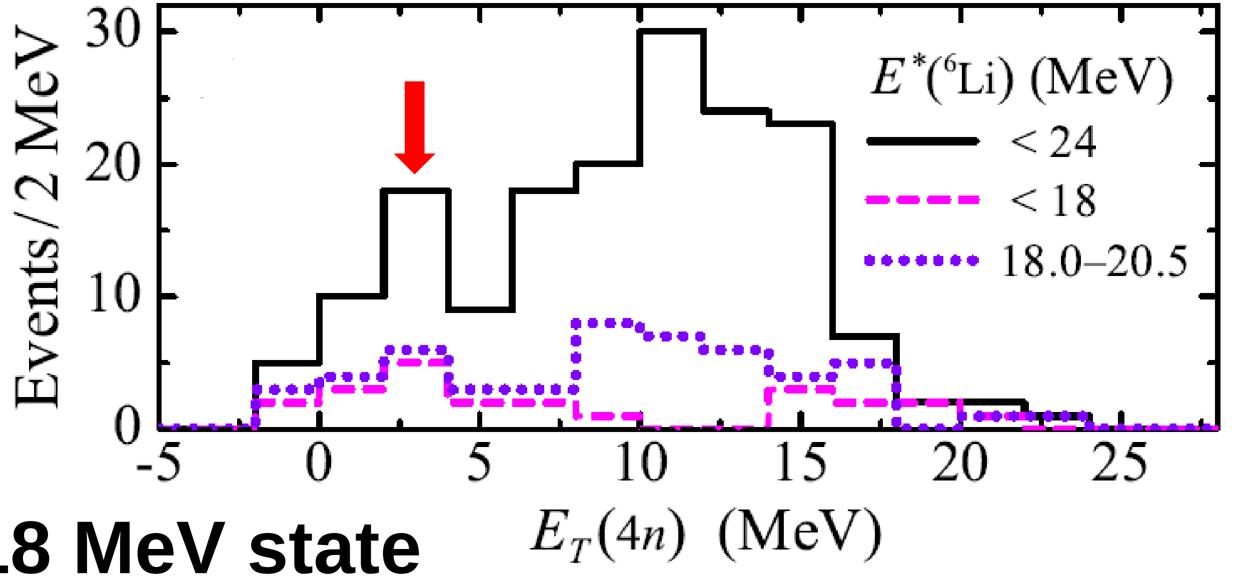
$^{2}H(^{8}He,^{3}He^{3}H)^{4}n$ results

$^{6}Li^{*}$-^{4}n correlation



^{7}H-^{4}n correlation





Resonance behavior ^{3}He-^{3}H

Strong correlation with 2- ^{6}Li (2—) 18 MeV state

Summary comparison of experimental data and theory

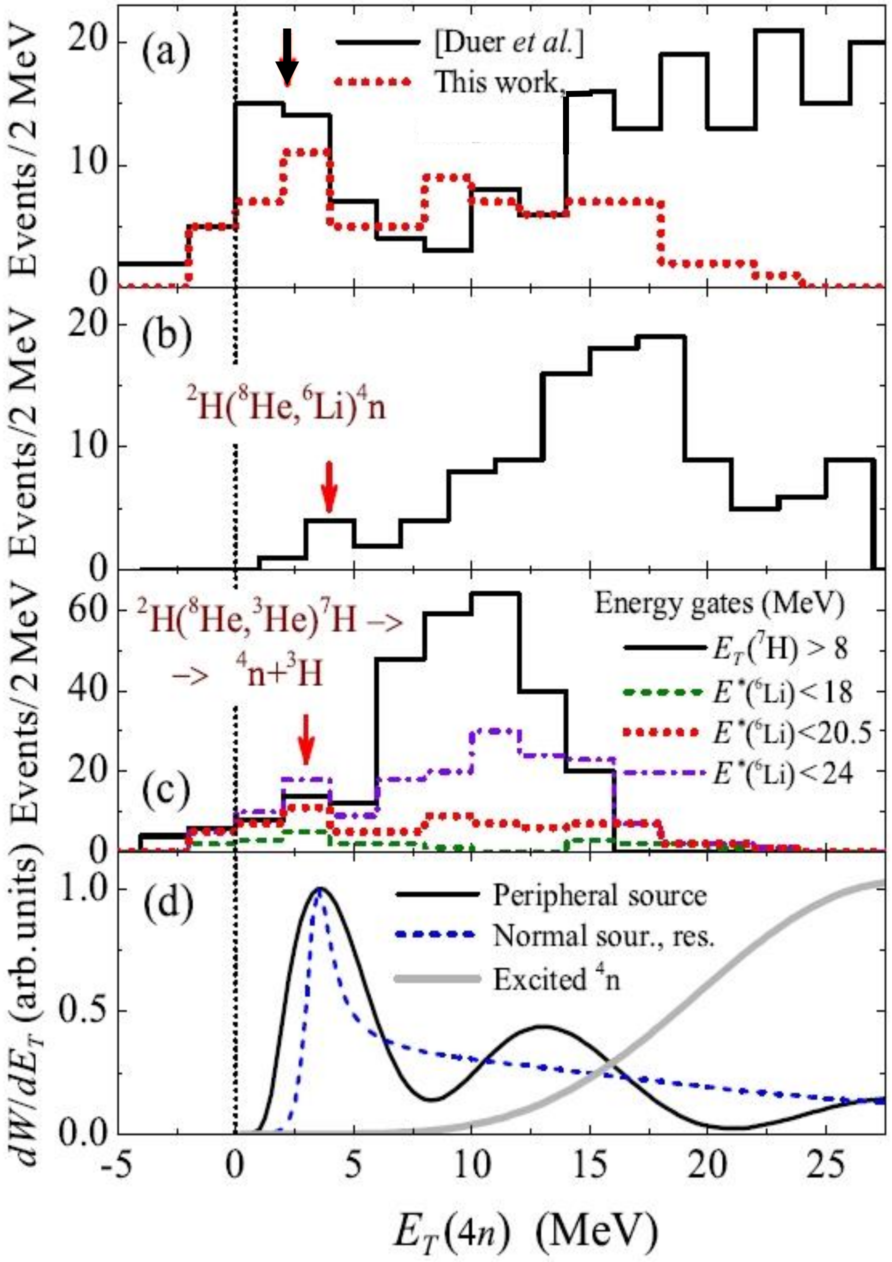
I.A. Muzalevskii, et al.,
Phys. Rev. C, 111:014612, Jan 2025

I.A. Muzalevskii et al, Phys. Rev. C 103 (2021) 044313

E.Yu.Nikolskii et al., Physics of Atomic Nuclei, Vol. 87 №1(2024) 1-8

E.Yu.Nikolskii et al., Phys. Rev. C 105 (2022) 064605

I. A. Muzalevskii et al, EPJ Web of Conferences 290, 09001 (2023)



Duer *et al.*
E(4n) ≈ 2.4 ± 0.6 MeV

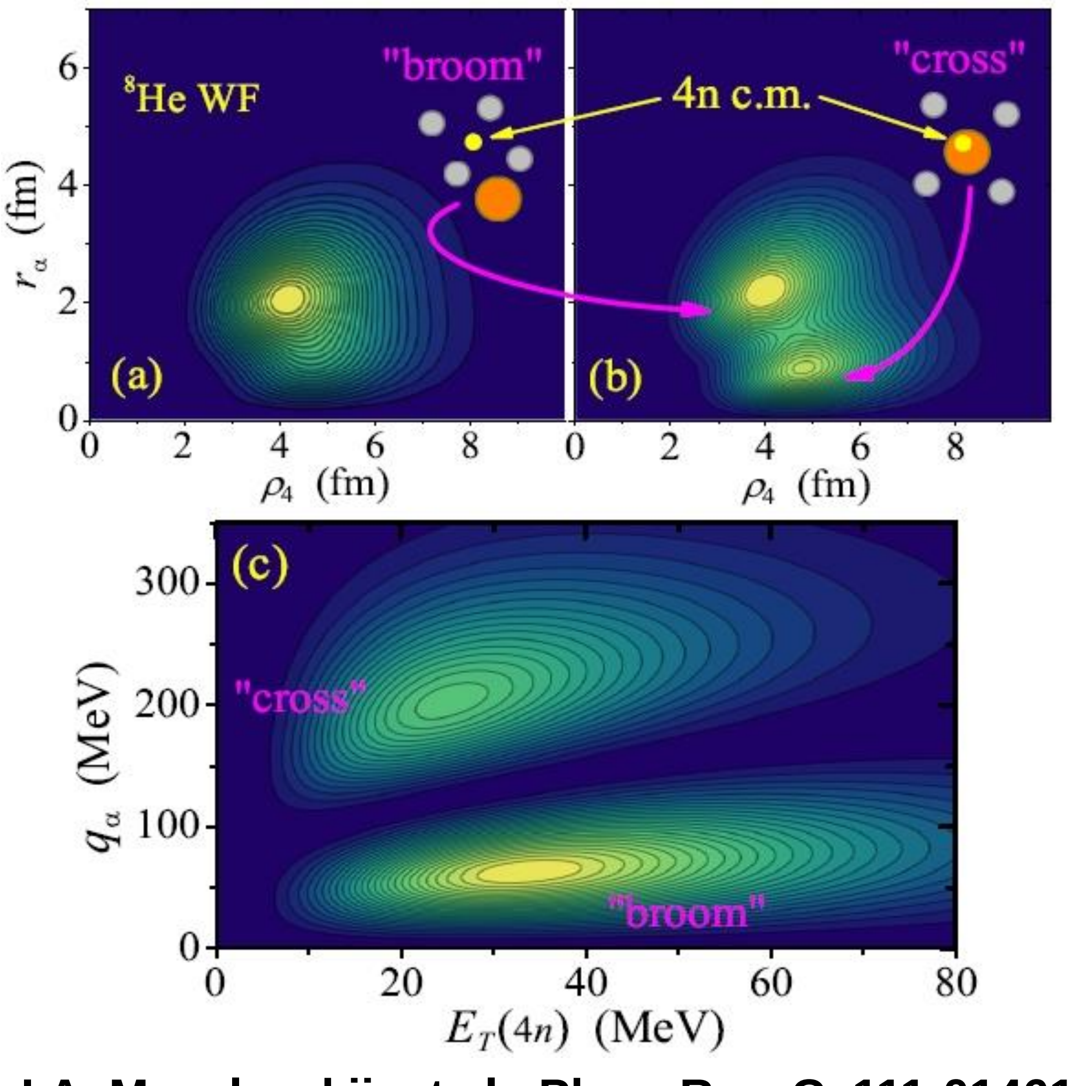
This work
E(4n) ≈ 3.5 ± 0.7 MeV

This work
E(4n) ≈ 3.2 ± 0.8 MeV

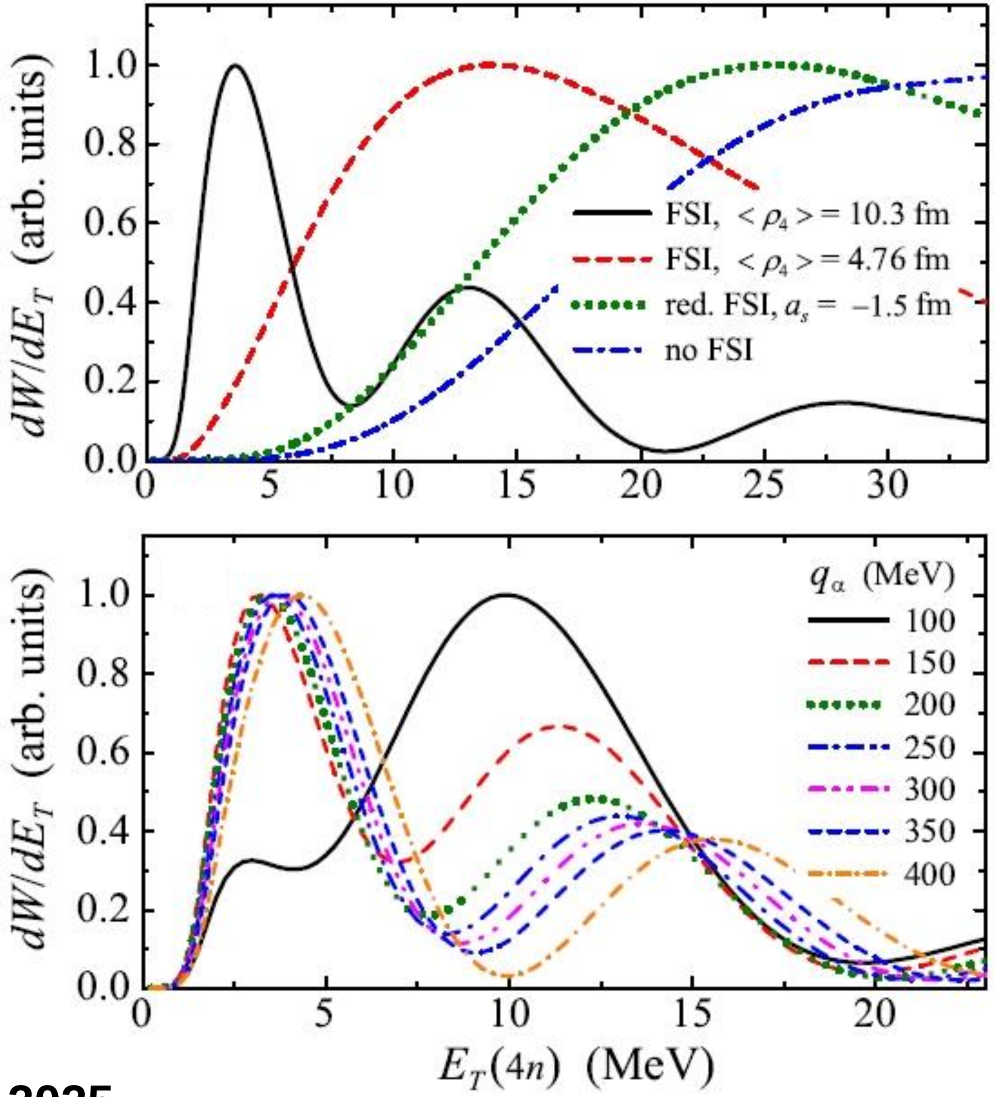
Extreme peripheral source
or
Real resonant behavior

Low-energy 4n events may arise from extreme peripheral reaction mechanism with ^{8}He source

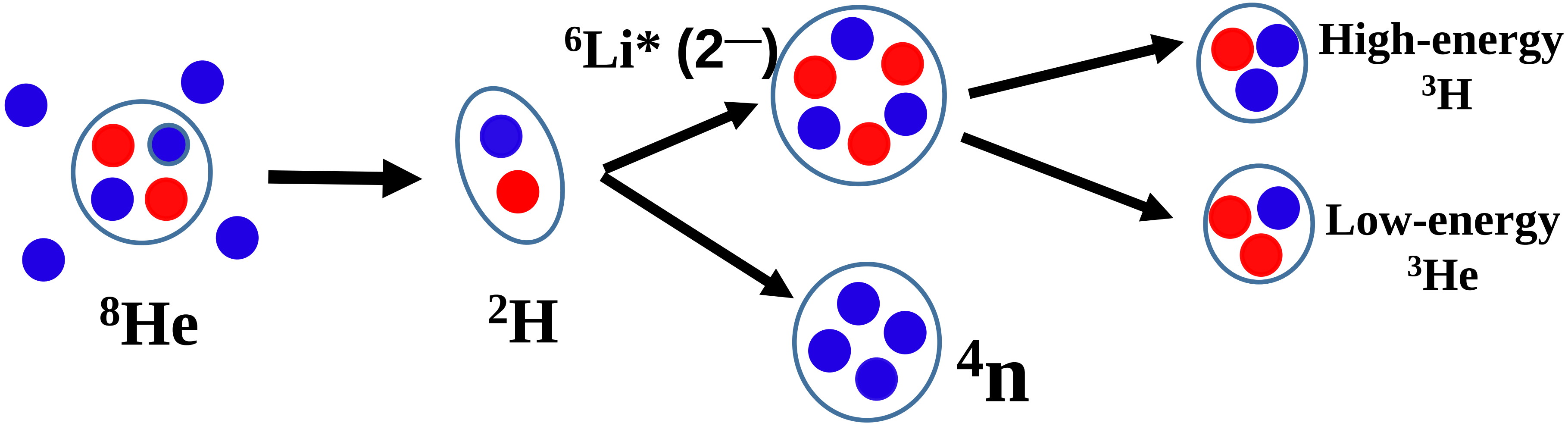
^{8}He Wave Function (WF) correlation density



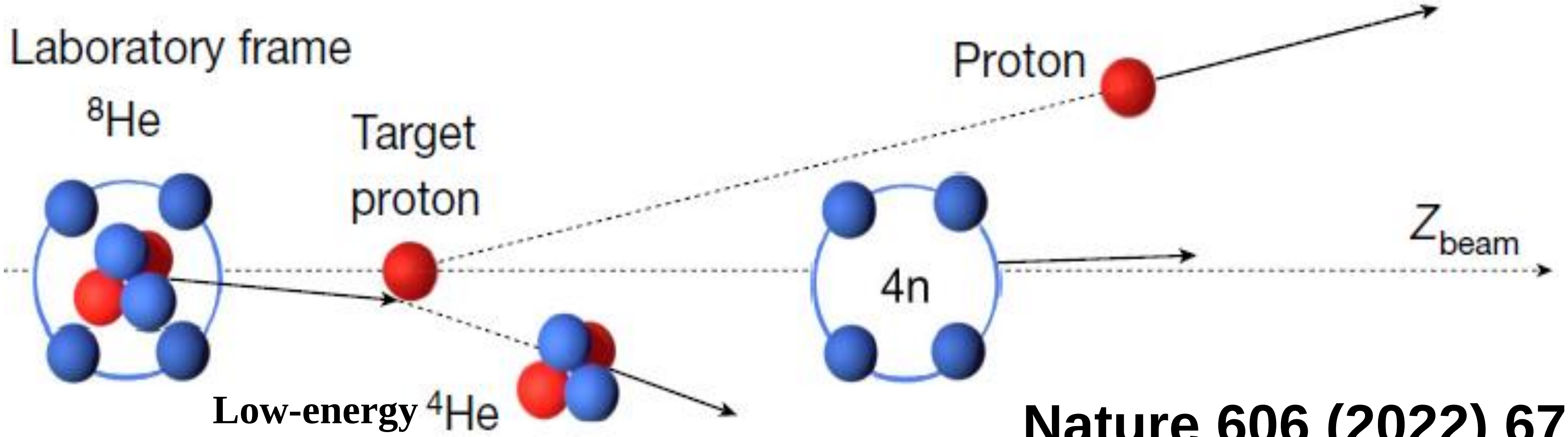
^{8}He WF as a source for ^{4}n population



I.A. Muzalevskii, et al., Phys. Rev. C, 111:014612, Jan 2025



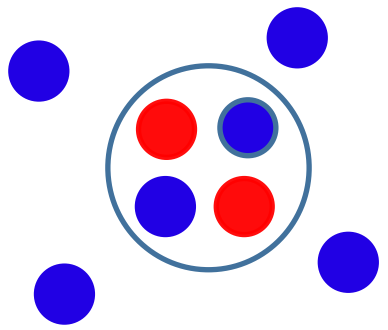
Very specific kinematics selection in ^{8}He interaction for both experiments!



Nature 606 (2022) 678

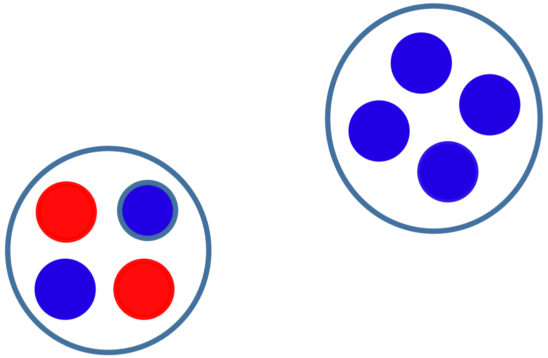
Interpretation

1. **Two hypothesis for 4n peak interpretation:**
   1. **“real” resonance**
   2. **^{8}He structure effect in the presence of 4n FSI within “peripheral” reaction behaviour**



^{8}He “cross”

2. Sudden removal of ^{4}He core from ^{8}He
   - Transferred momenta **q(^{4}He) = q(4n)**
3. Hypespherical model for
   5 body **^{8}He** (alpha + 4n) & 4 body **4n**
   [L. V. Grigorenko et al., Eur. Phys. J. A 19, 187 (2004)]



^{8}He “broom”

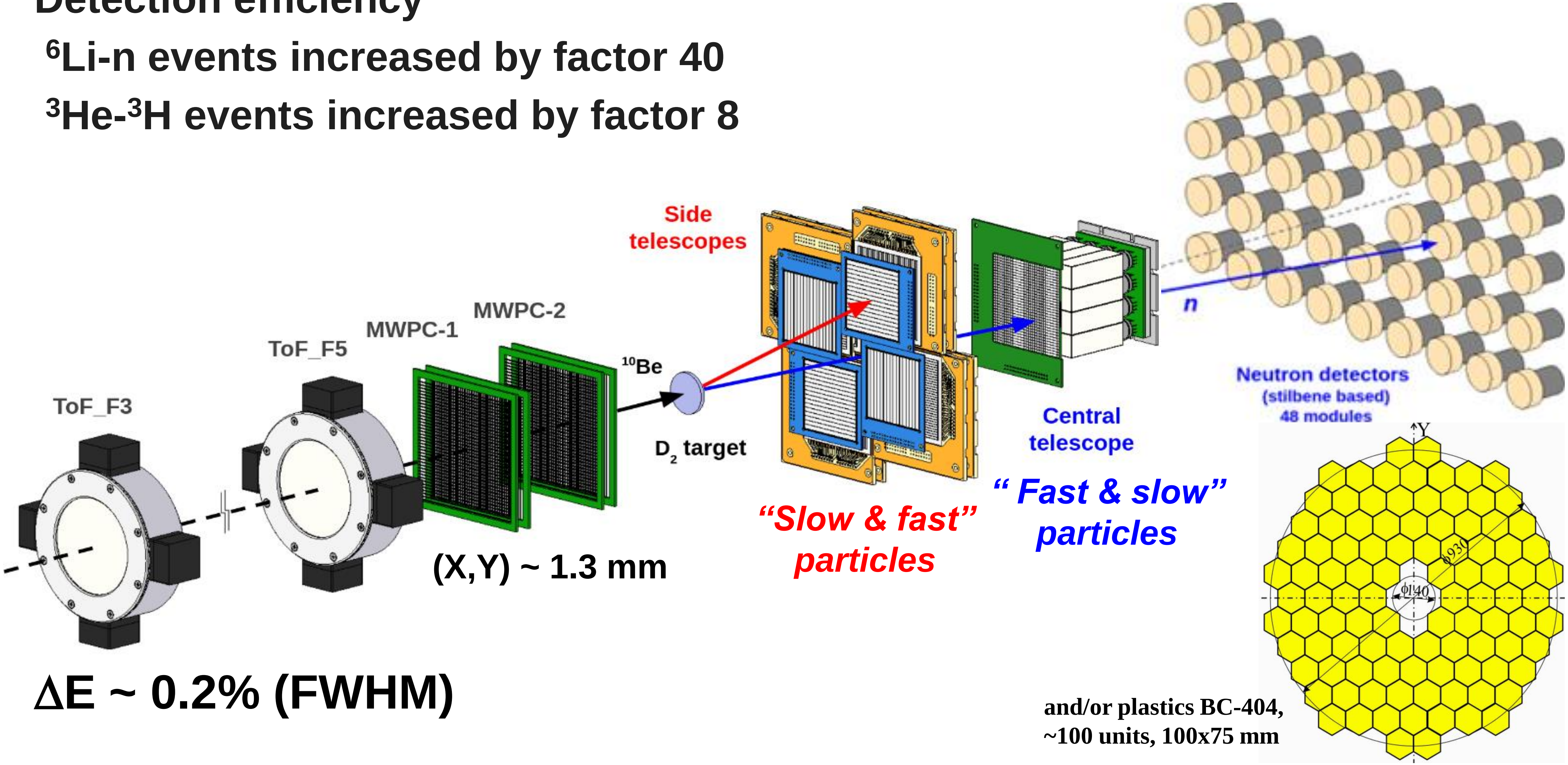
4. Two configurations of ^{8}He (4n-halo “broom” and “cross”)

New detector setup for 4n, ^{7}H studies

Detection efficiency

^{6}Li-n events increased by factor 40

^{3}He-^{3}H events increased by factor 8



ΔE ~ 0.2% (FWHM)

Thanks for attention

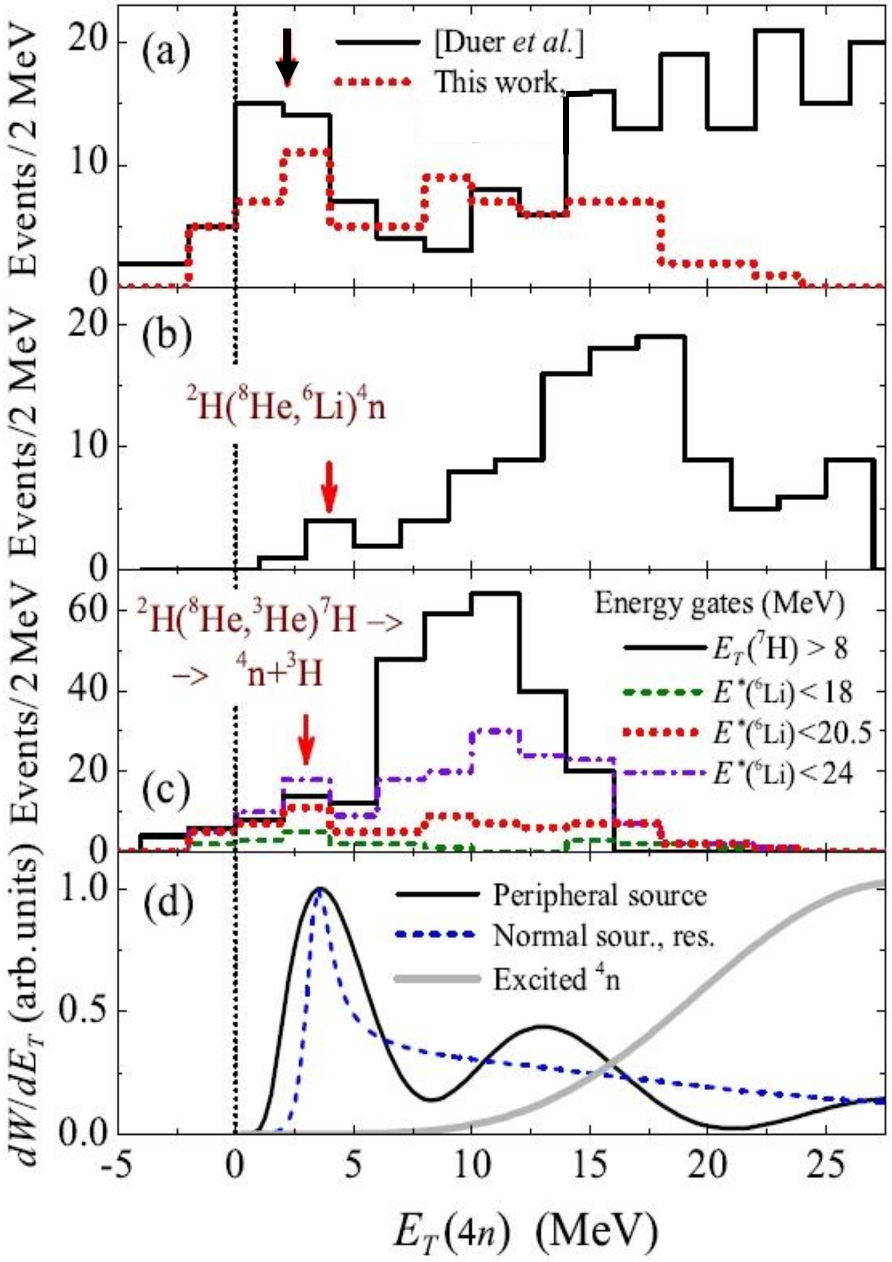
I.A. Muzalevskii, et al., Phys. Rev. C, 111:014612, Jan 2025

I.A. Muzalevskii et al, Phys. Rev. C 103 (2021) 044313

E.Yu.Nikolskii et al., Physics of Atomic Nuclei, Vol. 87 №1(2024) 1-8

E.Yu.Nikolskii et al., Phys. Rev. C 105 (2022) 064605

I. A. Muzalevskii et al, EPJ Web of Conferences 290, 09001 (2023)



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Extreme peripheral source
or
Real resonant behavior

Acknowledgements
Prof. L.V. Grigorenko and
Dr. N.B. Shulgina
for developing the theoretical model

Low-energy 4n events may arise from extreme peripheral reaction mechanism with ^{8}He source

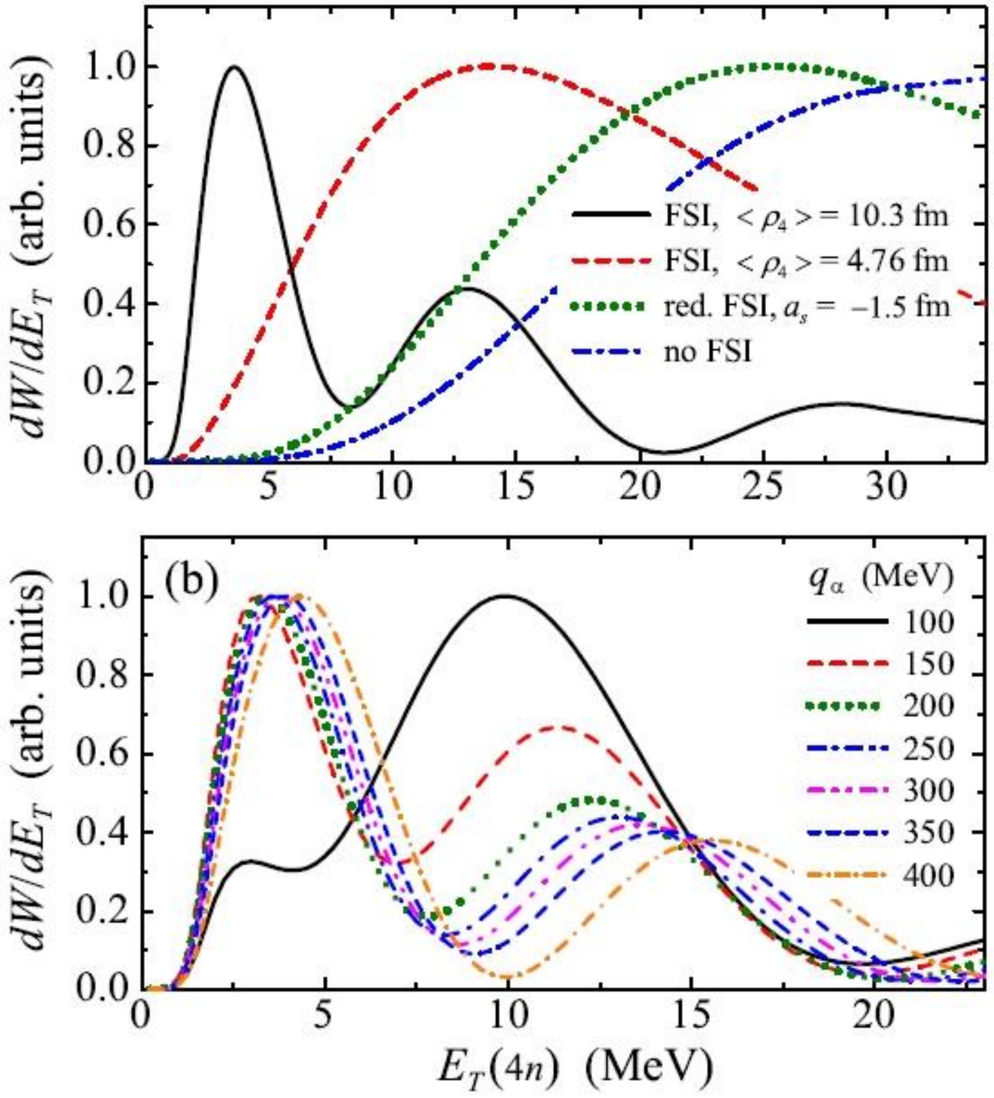
Low-energy peak in ^{4}n is possible if:

- ^{4}n FSI
- **peripheral character of reaction**

[L. V. Grigorenko *et al.*, Eur. Phys. J. A 19, 187 (2004)]
[I.A. Muzalevskii *et al.*,Phys Rev C 111, 014612 2025]

- Low-energy (~3 MeV) related to high q-value and “cross” structure **explains low cross-section**
- High-energy (~13 MeV) related to low q-value and “broom” structure

^{8}He WF as a source for ^{4}n population

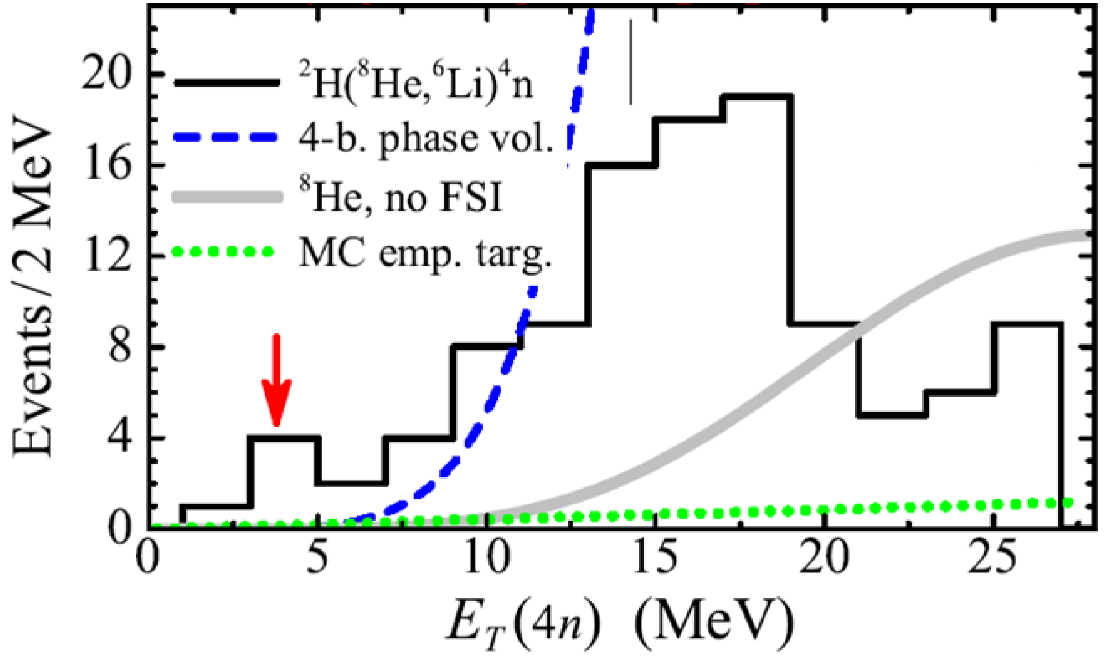


$^2H(^8He,^6Li^*(3.56))^4n$, $^6Li^* \longrightarrow {}^6Li$ (g.s) + γ

Channel is suppressed!

1. **Only single-step direct mechanisms are expected at 26 AMeV beam energies**
    - $^4He(d, \gamma)^6Li$ – single-step parity violating process studied in Phys. Rev. C 29, 755 (1984)
    - Thus, only complicated mechanisms can populate such ^6Li

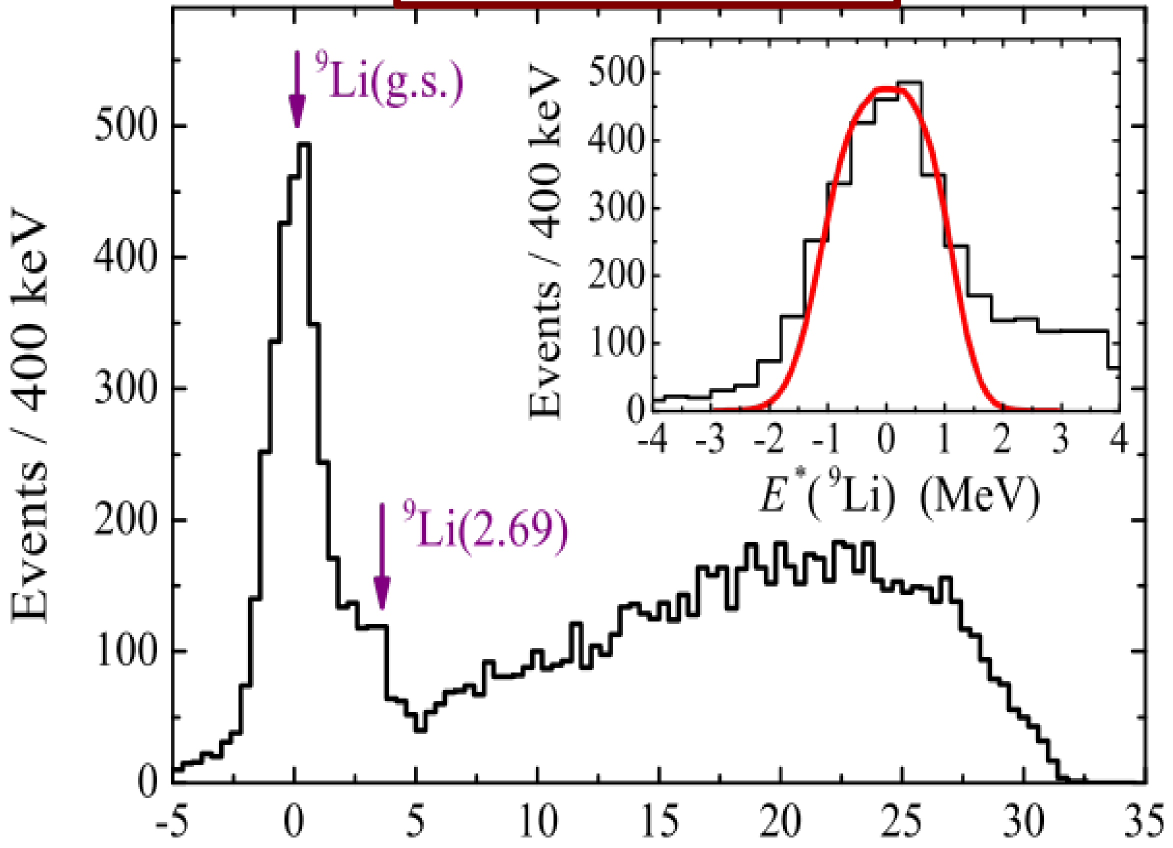
2. **4n state at decay threshold is non-realistic hypothesis**



Reference run

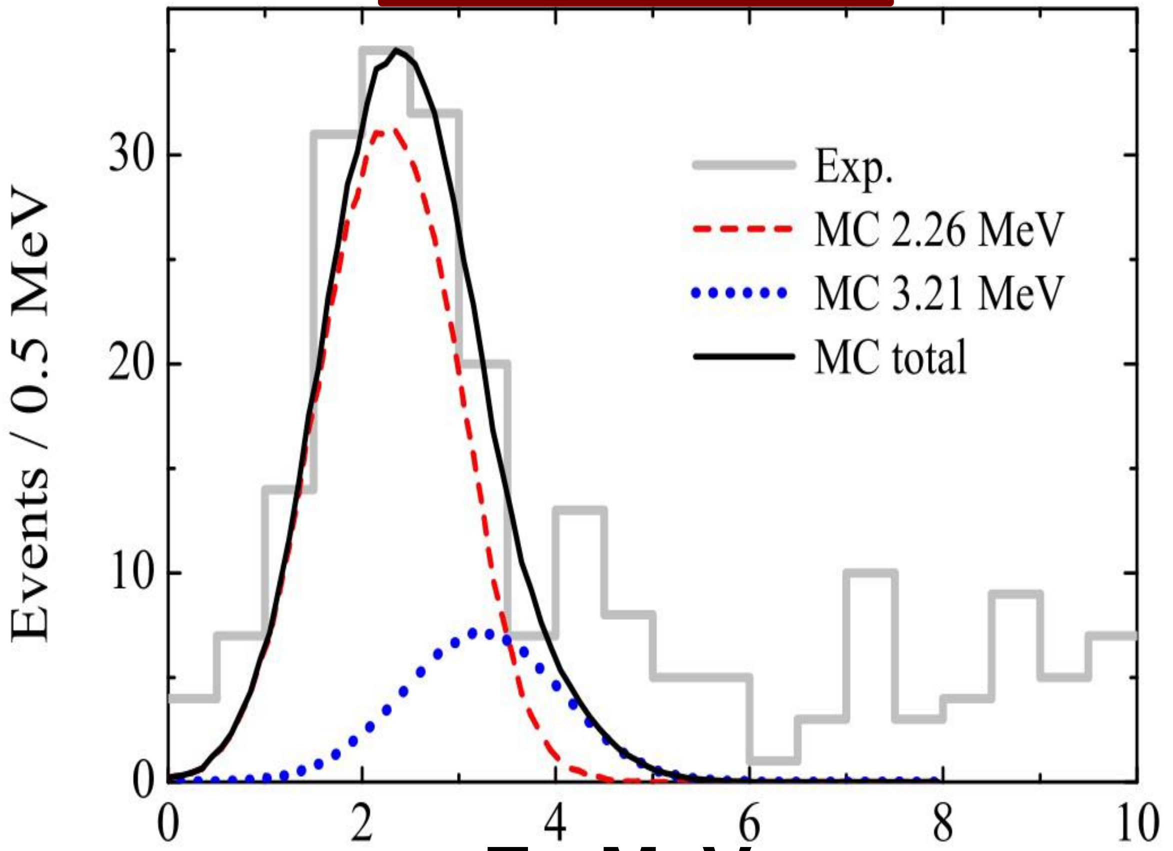
Independent **MM reconstruction test** with 42 AMeV ^{10}Be beam

^{2}H(^{10}Be,^{3}He)^{9}Li



E$_T$, MeV

^{2}H(^{10}Be,^{4}He)^{8}Li

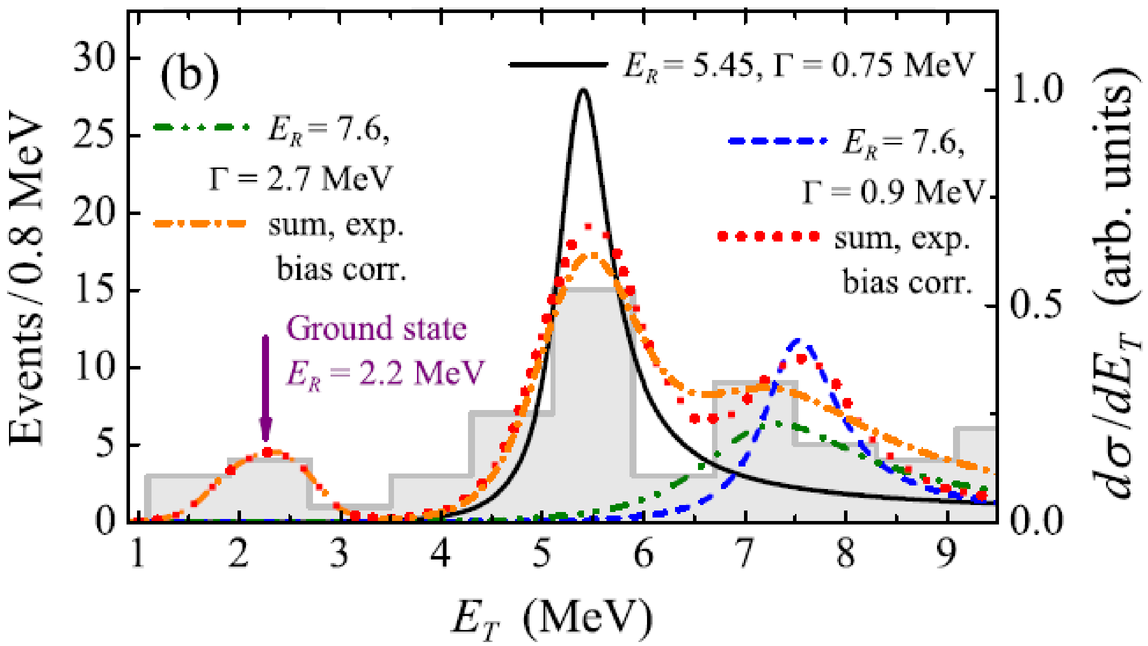


E$_T$, MeV

- **Particle && reaction identification test**
- **Full agreement of MC simulations with experimental data**

Spectra of ^{7}H and ^{6}H

^{7}H
Ground state: 2.2 MeV
Excited states: 5.5, 7.5 MeV

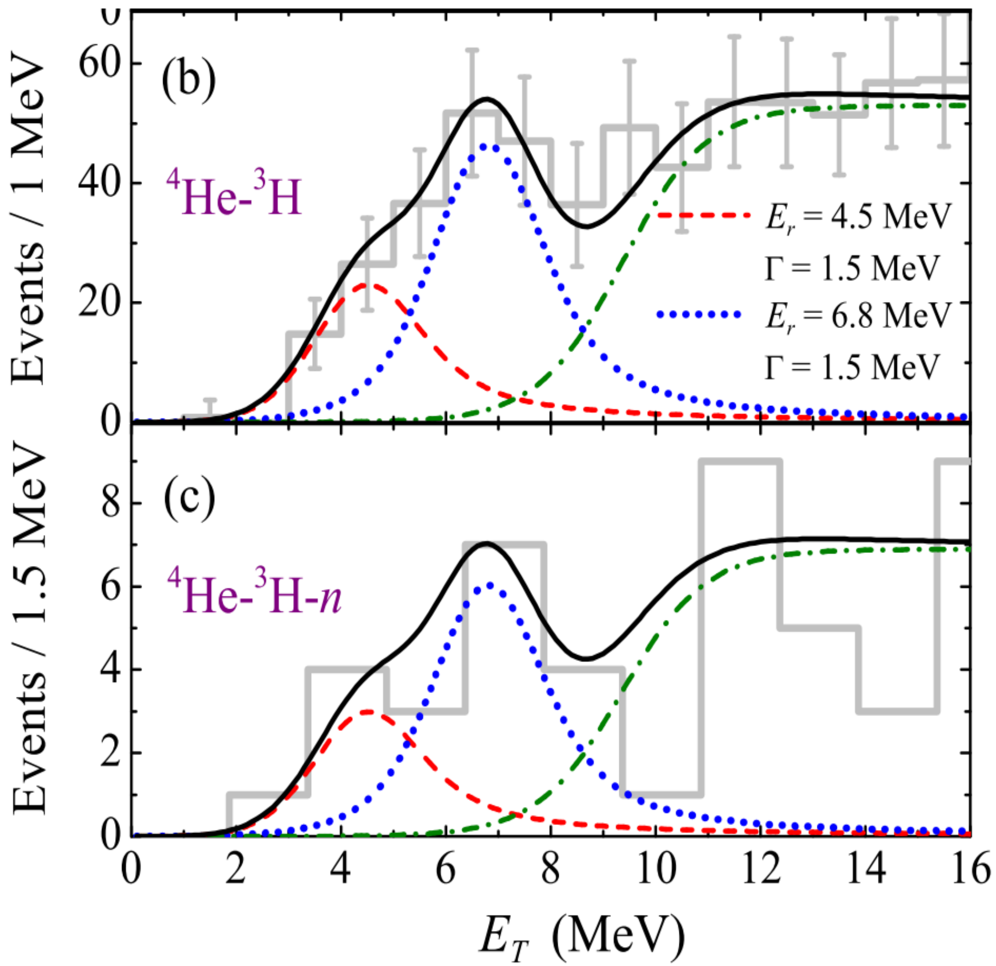


The energy profile of the ground state at 2.2(5) MeV and first excited states at 5.5(3) and 7.5(3) MeV obtained in the ^{2}H(^{8}He,^{3}He)^{7}H reaction [30]; the experimental missing mass spectrum of ^{7}H is shown by gray histogram.

A.A. Bezbakh et al., Phys. Rev. Lett. 124 (2020) 022502
I.A. Muzalevskii et al., Phys. Rev. C 103 (2021) 044313.

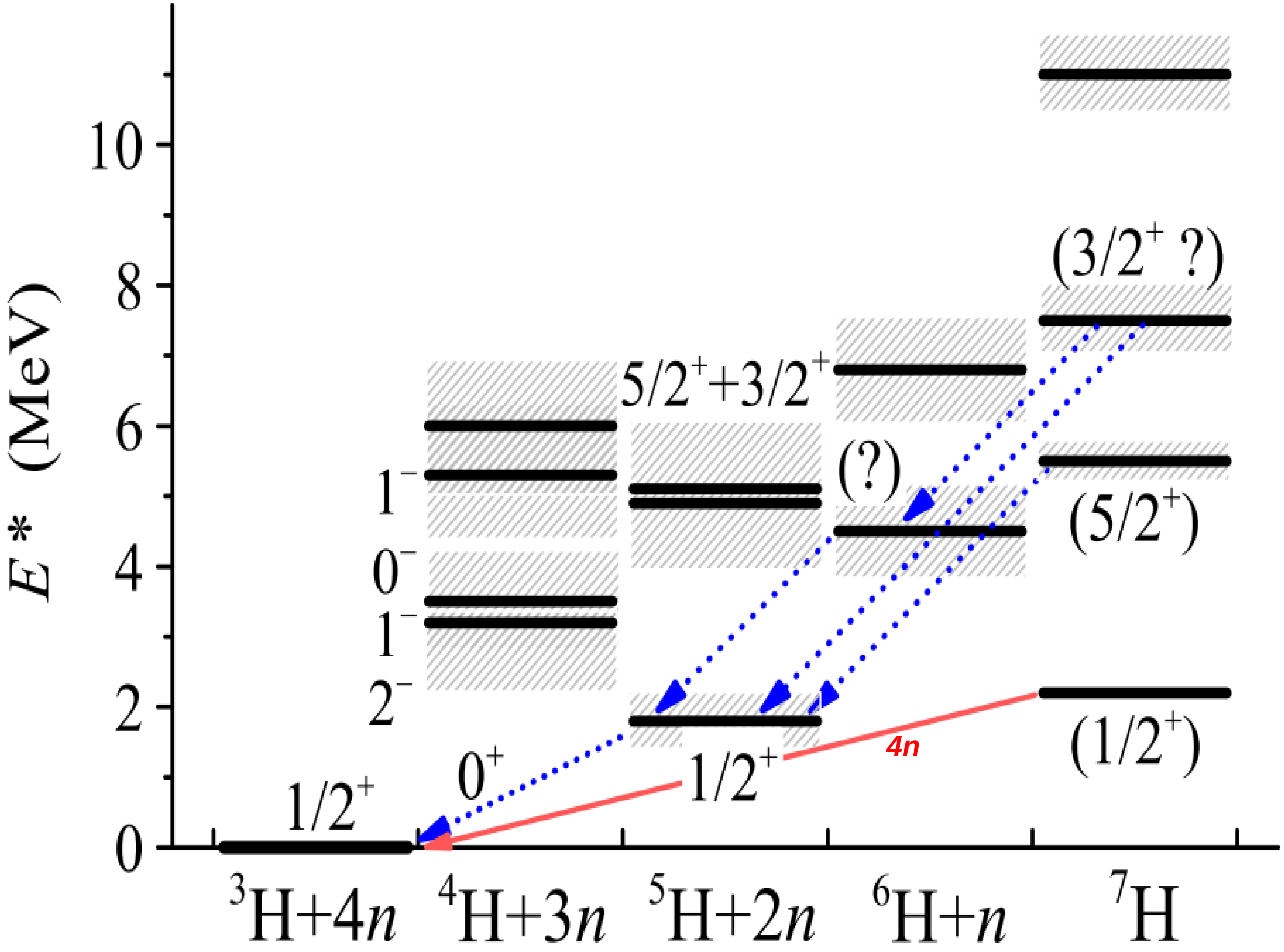
^{6}H
Ground state: 4.5 MeV
Excited state: 6.8 MeV

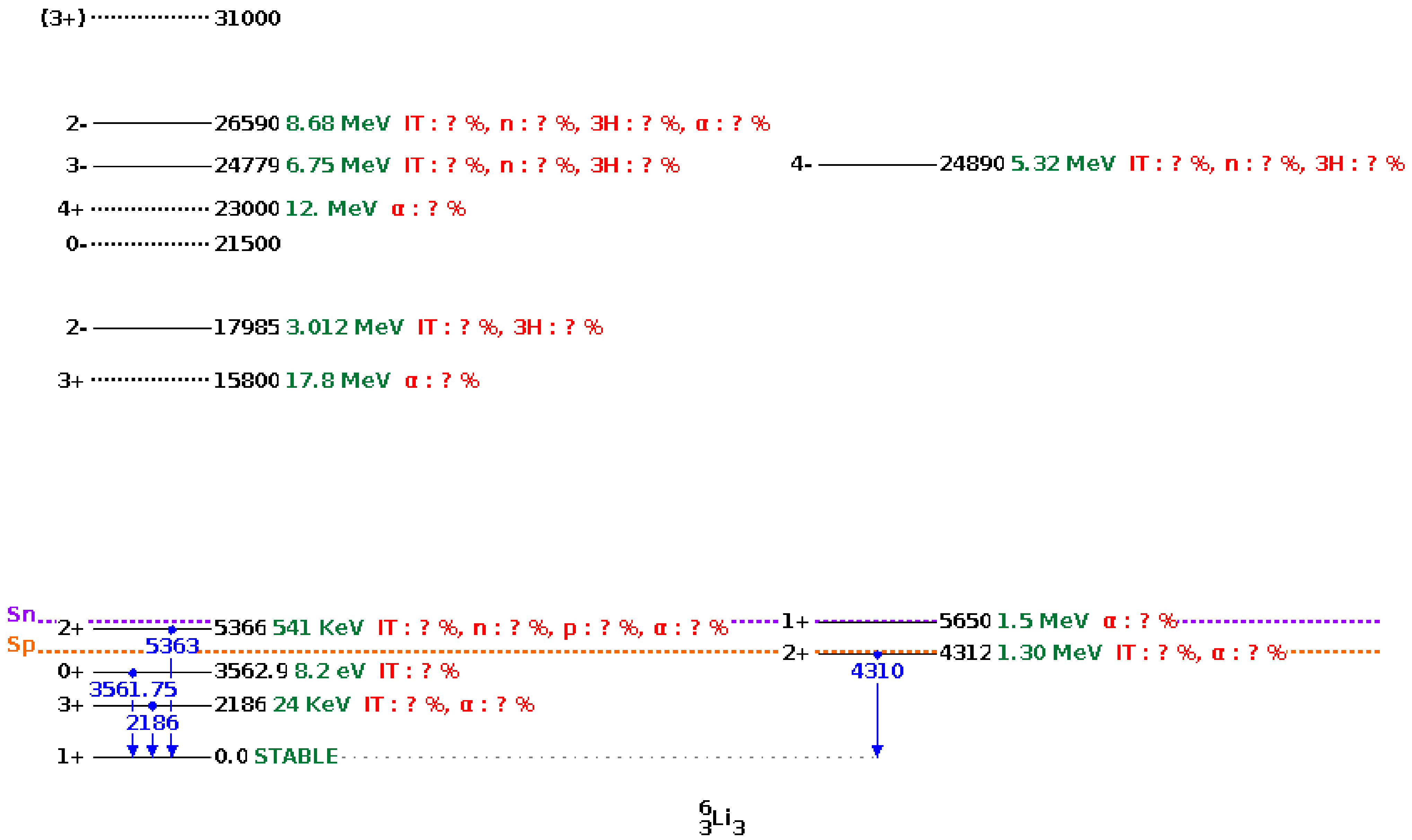
Study of ^{6}H system in the ^{2}H(^{8}He,^{4}He)^{6}H → t + 3n reaction



E. Yu. Nikolskii et al. Phys. Rev. C 105, 064605, *The ^{6}H states studied in the ^{2}He(^{8}He,^{4}He) reaction and evidence of extremely correlated character of the ^{5}H ground state*

New information on hydrogen isotopes





(3+) 31000
2- 26590 8.68 MeV IT : ? %, n : ? %, 3H : ? %, α : ? %
3- 24779 6.75 MeV IT : ? %, n : ? %, 3H : ? %
4- 24890 5.32 MeV IT : ? %, n : ? %, 3H : ? %
4+ 23000 12. MeV α : ? %
0- 21500
2- 17985 3.012 MeV IT : ? %, 3H : ? %
3+ 15800 17.8 MeV α : ? %
Sn
2+ 5366 541 KeV IT : ? %, n : ? %, p : ? %, α : ? %
1+ 5650 1.5 MeV α : ? %
Sp
2+ 4312 1.30 MeV IT : ? %, α : ? %
5363
4310
0+ 3562.9 8.2 eV IT : ? %
3561.75
3+ 2186 24 KeV IT : ? %, α : ? %
2186
1+ 0.0 STABLE
$^{6}_{3}Li_{3}$