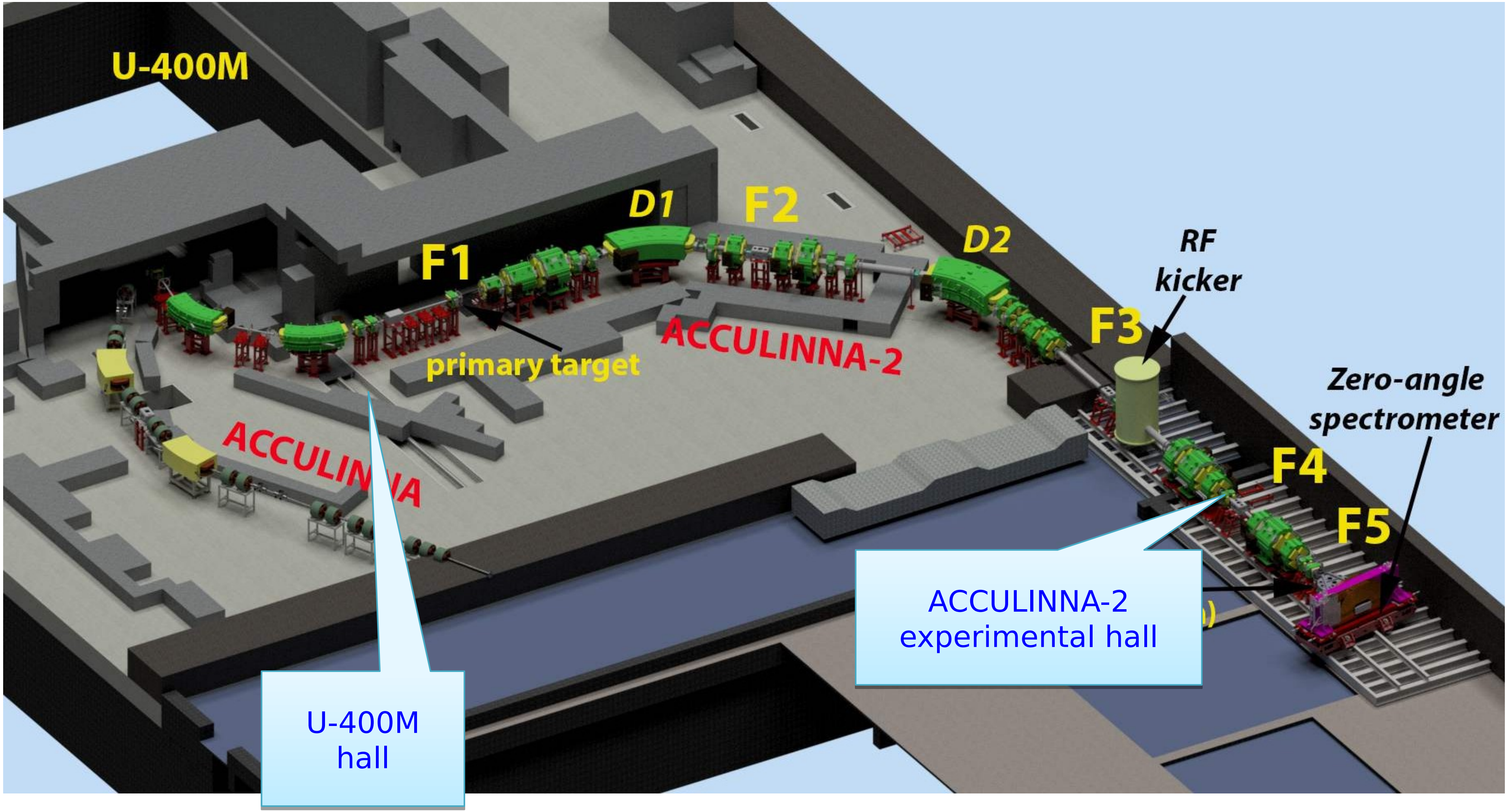
First experiments with RIBs at ACCULINNA-2 fragment-separator

Vratislav Chudoba for

ACCULINNA-2 collaboration

ACCULINNA-2


U-400M
D1
F2
D2
F1
RF
kicker
F3
primary target
ACCULINNA-2
ACCULINNA
Zero-angle
spectrometer
F4
F5
ACCULINNA-2
experimental hall
U-400M
hall

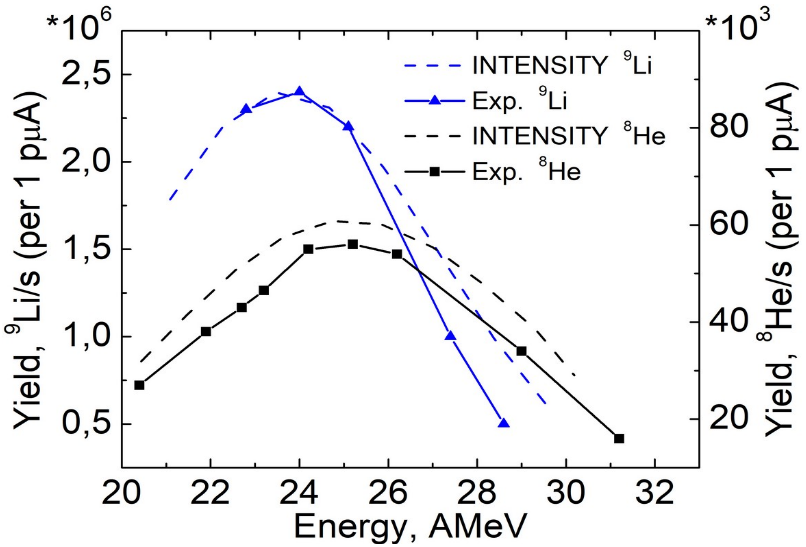
Status of works since 2018

Isotope	2018 - 2020	
	Task, reaction, method	Status
^{6}He	Elastic and inelastic scattering in ^{6}He+d interaction	B. Zalewski thesis, NIM_B
^{6}H and ^{7}H	Low energy spectra and decay modes, ^{8}He+d	PRL, PRC, Bulletin of RAS
^{8}Li and ^{9}Li	Reference reactions (d,^{4}He) and (d,^{3}He) with ^{10}Be	To be published soon
^{7}He	Low energy spectra, $^{6}He(d,p)^{7}He$, p-^{6}He-n coincidences	To be published soon
^{9}He	--”--, $^{8}He(d,p)^{9}He$, p-^{8}He-n coincidences	Under analysis
^{10}Li	--”--, $^{9}Li(d,p)^{10}Li$, p-^{9}Li-n coincidences	Bulletin of RAS (method), data under analysis
^{27}S	Rare decay modes, implantation into OTPC	Under analysis
	Detector tests (PPAC, ToF, Si, etc.)	Under analysis
^{7}H, ^{10}He, ^{16}Be, ^{17}Ne, ^{26}S	*Since 2023*	

Characteristics of obtained RIBs

Ion	E, AMeV	Reaction	I, pps	P, %	Δp, ±%
^{6}He	29	^{11}B(33.5 AMeV)+Be(1 mm)	$2.2*10^{6}$	90.2	2.0
^{8}He	28	--"--	$5.5*10^{4}$	95.4	3.25
^{9}Li	31	--"--	$5.0*10^{5}$	97.6	2.0
^{10}Be	45	^{15}N (49.3 AMeV)+Be(1 mm)	$2.3*10^{6}$	78.4	1.25
^{26}P	28	^{32}S (52.7 AMeV)+Be (0.5 mm)	15	<0.5	0.75
^{27}S	27	--"--	60	1	0.75

Real basic RIBS characteristics are in a good agreement with technical specifications and estimations.

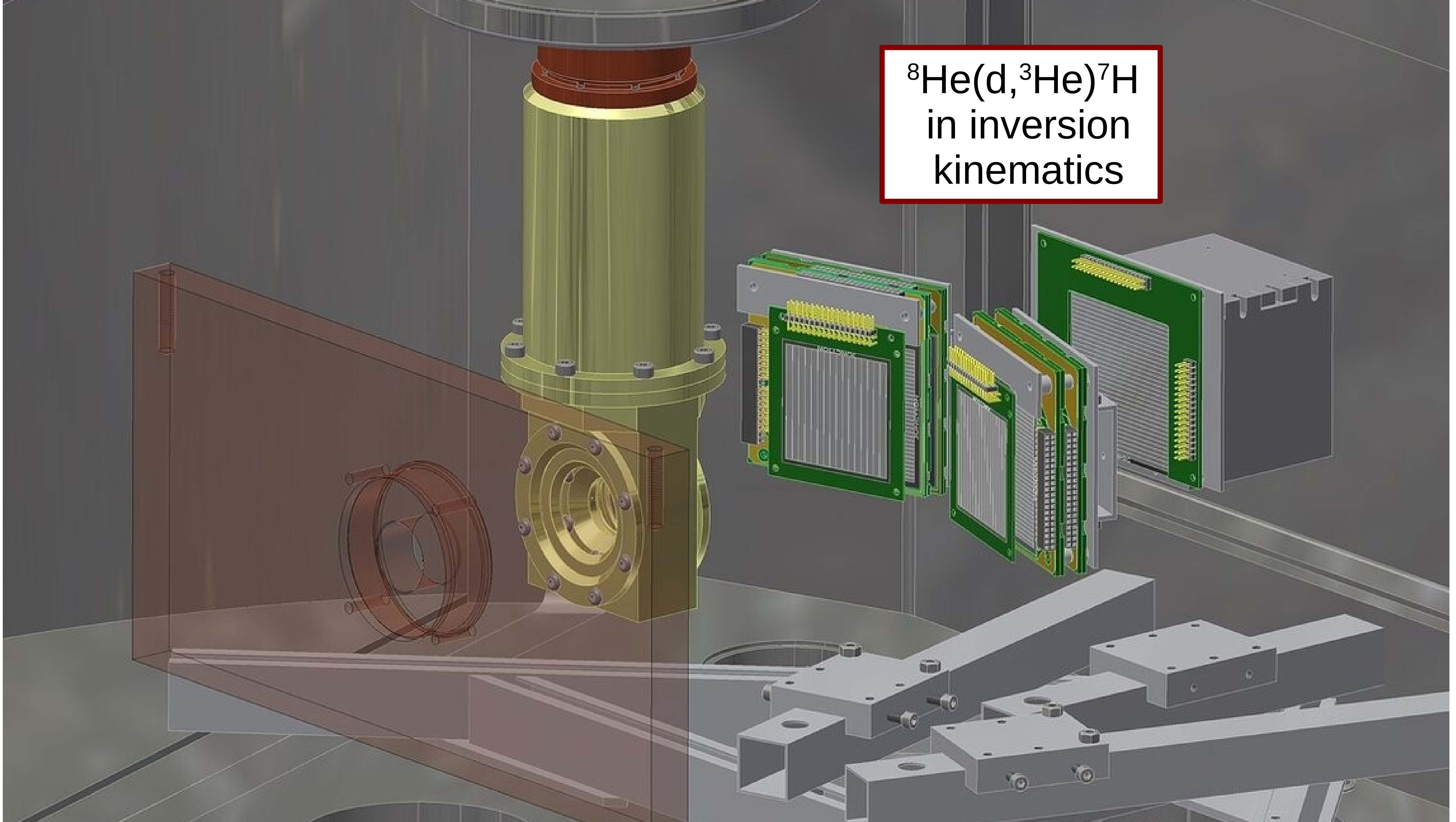


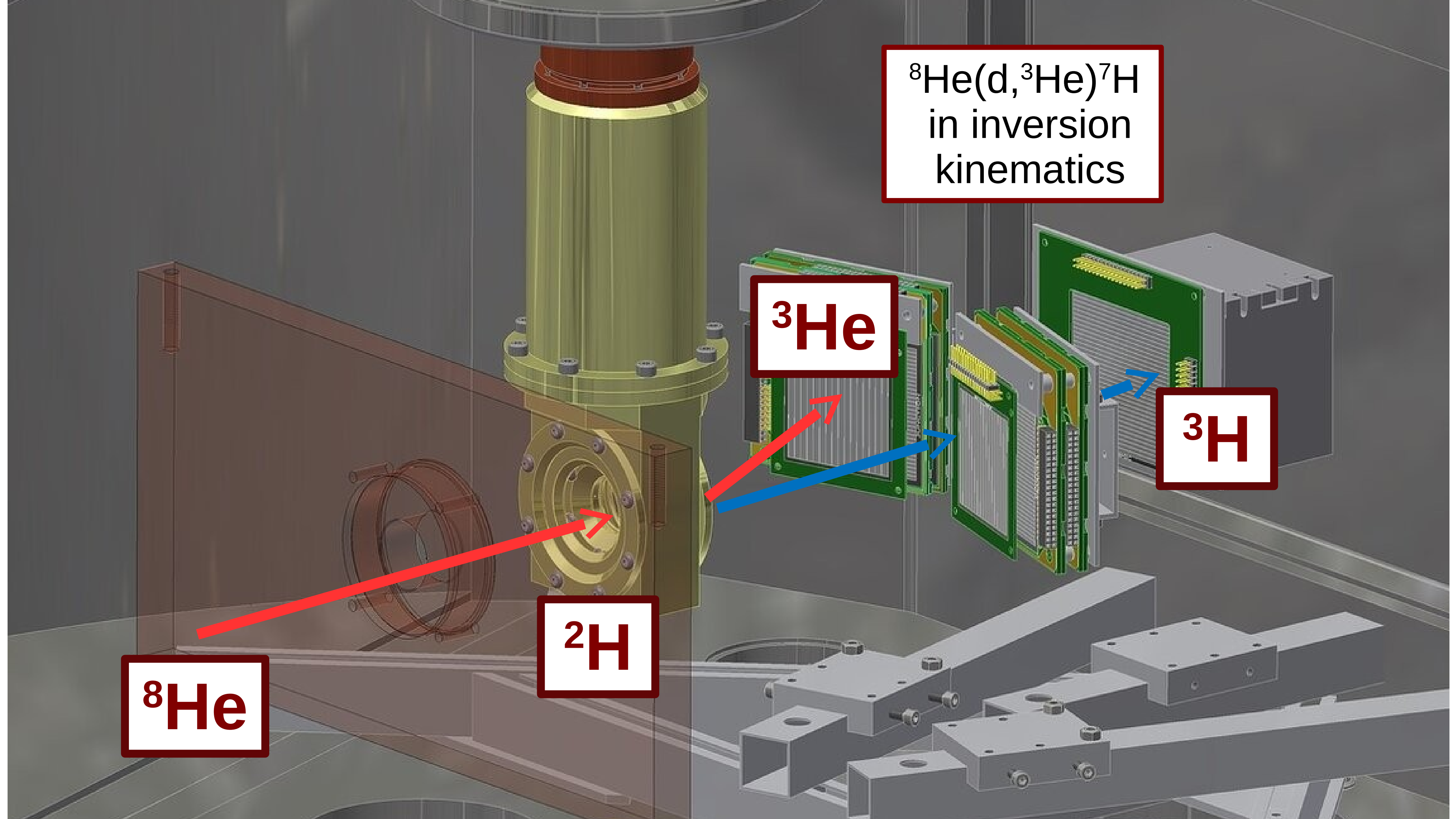
object of interest: ^{7}H

- the heaviest conceivable hydrogen isotope
- the largest A/Z = 7 ratio
- special stability of ^{7}H due to the closed $p_{3/2}$ neutron subshell
- “true” five-body core+4n decay channel of the g.s.
- extremely long-living g.s. of ^{7}H expected
  - candidate for 4n radioactivity if $E_T < 100$-300 keV
  - small width of g.s. (0.1-10 keV) expected even for $E_T = 2$ MeV
- anticipated specific correlations of fragments for core+4n decay

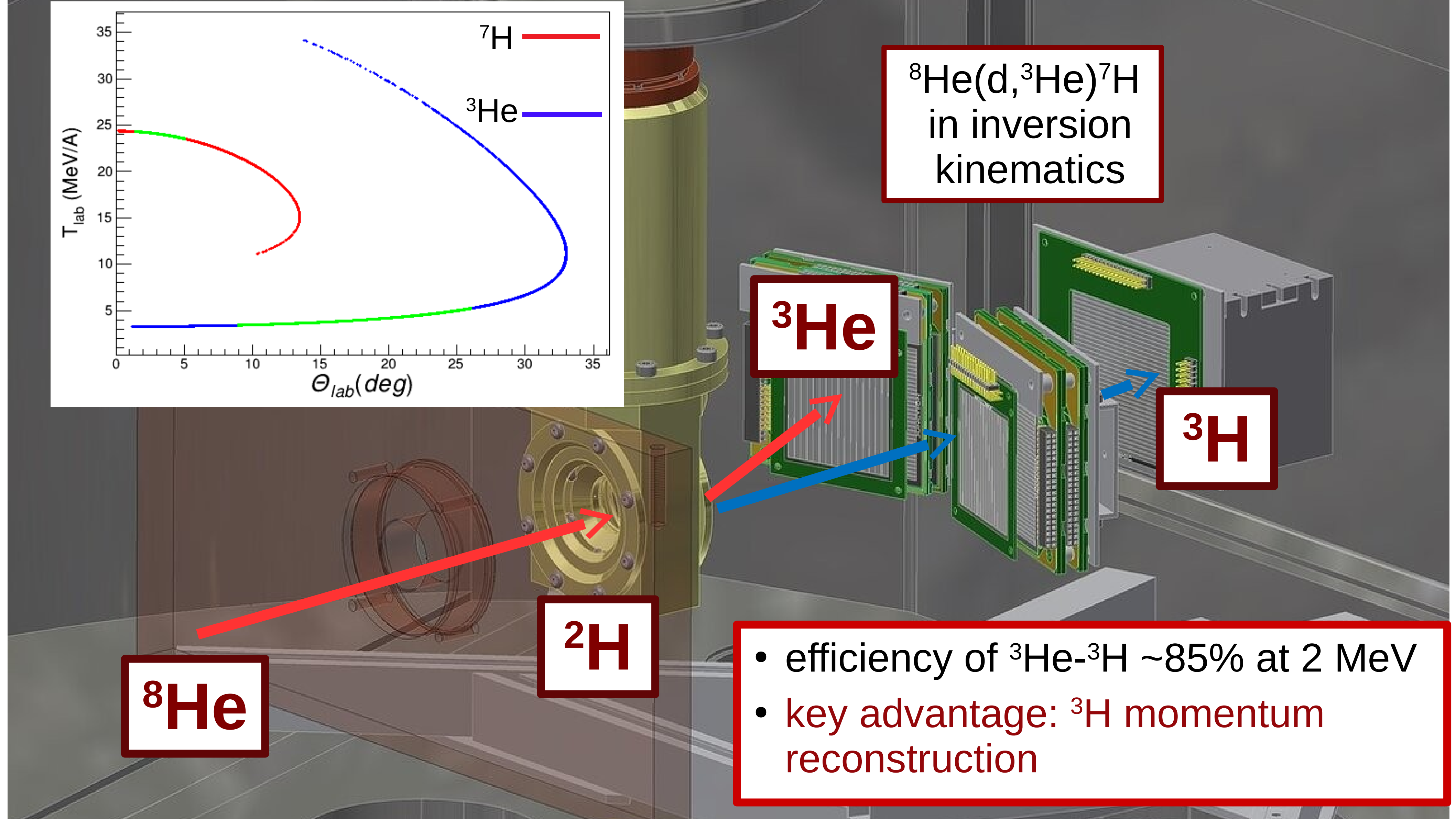
Prerequisites for successful search of ^7H

- **reliable channel identification**
- **suppression of background**
- **high energy resolution**

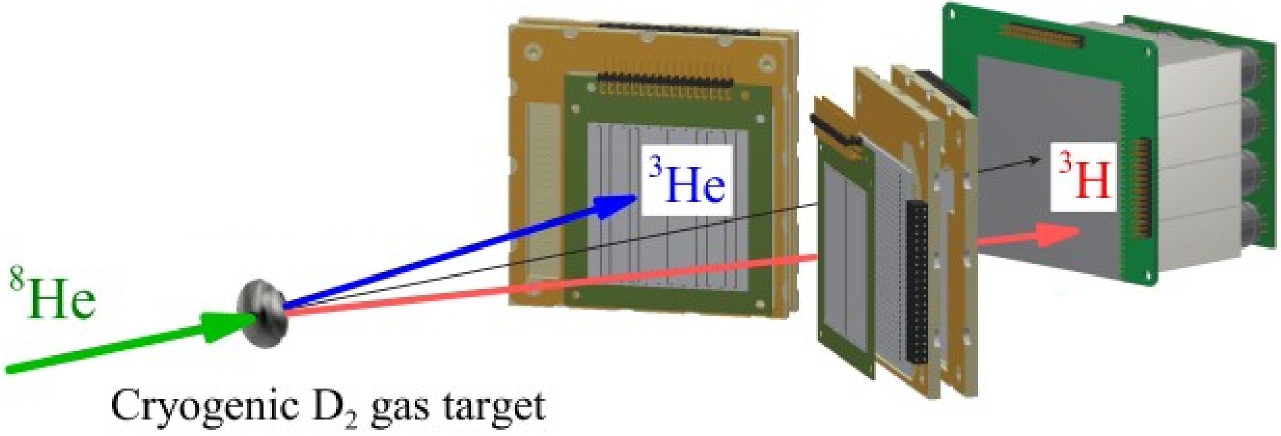

$^{8}He(d,^{3}He)^{7}H$
in inversion
kinematics



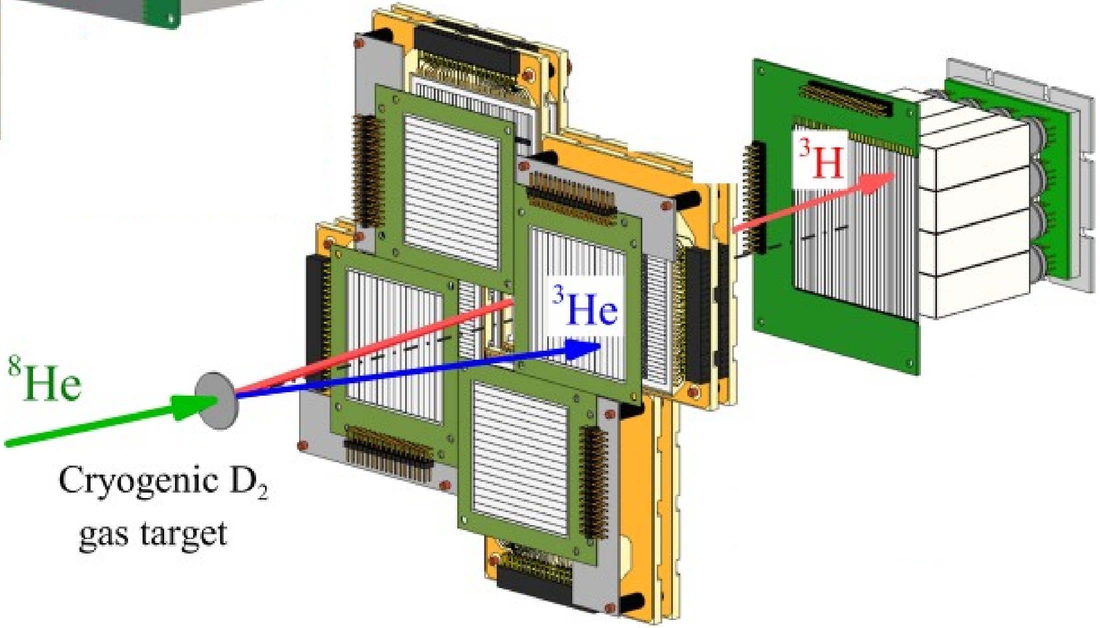
^{8}He(d,^{3}He)^{7}H
in inversion
kinematics
^{3}He
^{3}H
^{2}H
^{8}He


^{7}H
^{3}He
T_{lab} (MeV/A)
$\Theta_{lab}(deg)$
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
^{8}He(d,^{3}He)^{7}H in inversion kinematics
^{3}He
^{3}H
^{2}H
^{8}He
• efficiency of ^{3}He-^{3}H ~85% at 2 MeV
• key advantage: ^{3}H momentum reconstruction

Experiment 1, 2018
2 weeks

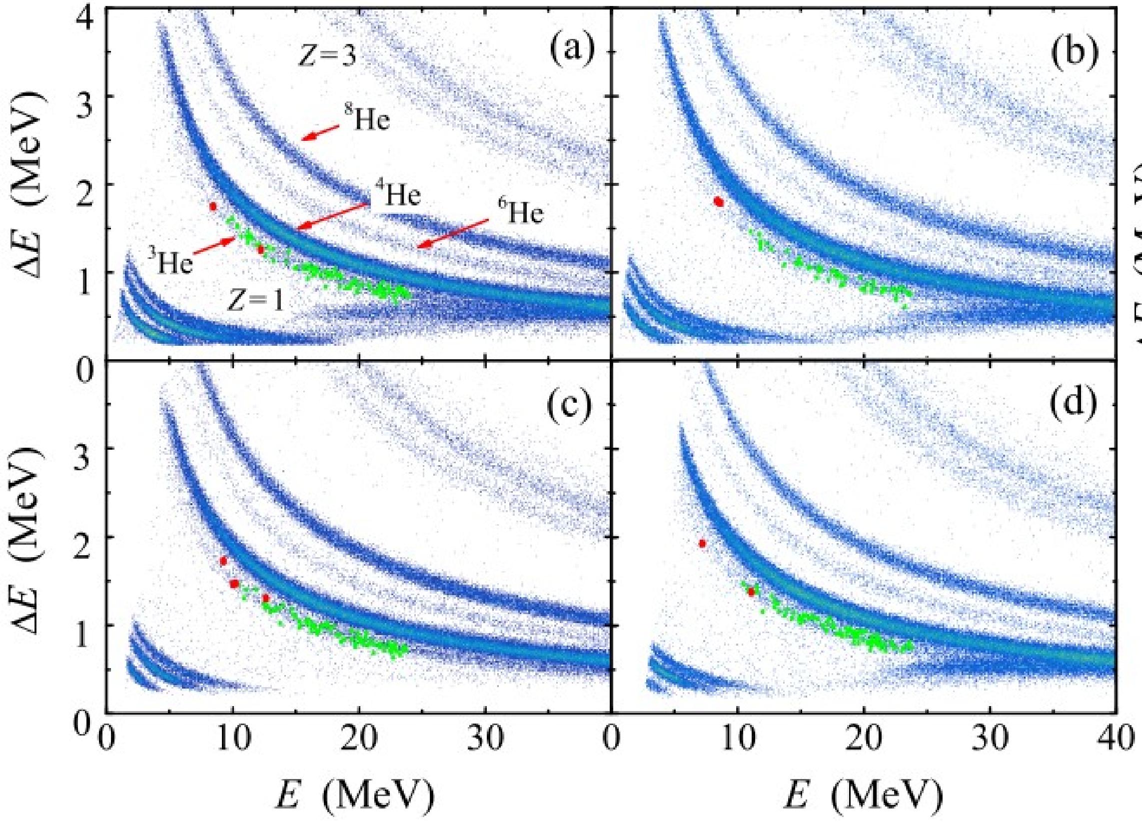


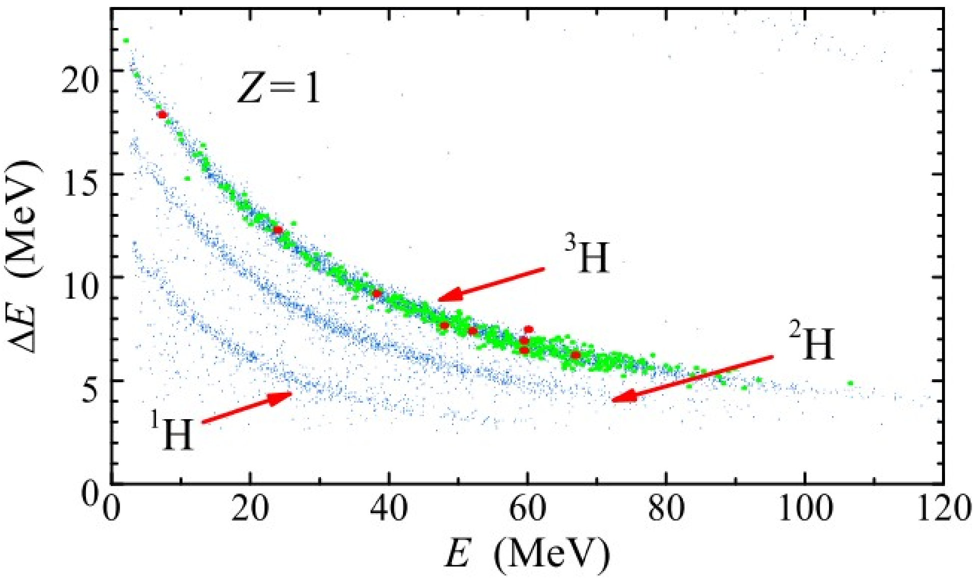
Experiment 2, 2019
3 weeks



- energy resolution for the ^{7}H missing mass ~(0.6 - 1.1) MeV
- 2018 – **119** ^{3}He-^{3}H coincidences
- 2019 – **378** ^{3}He-^{3}H coincidences
- background ~10% of events

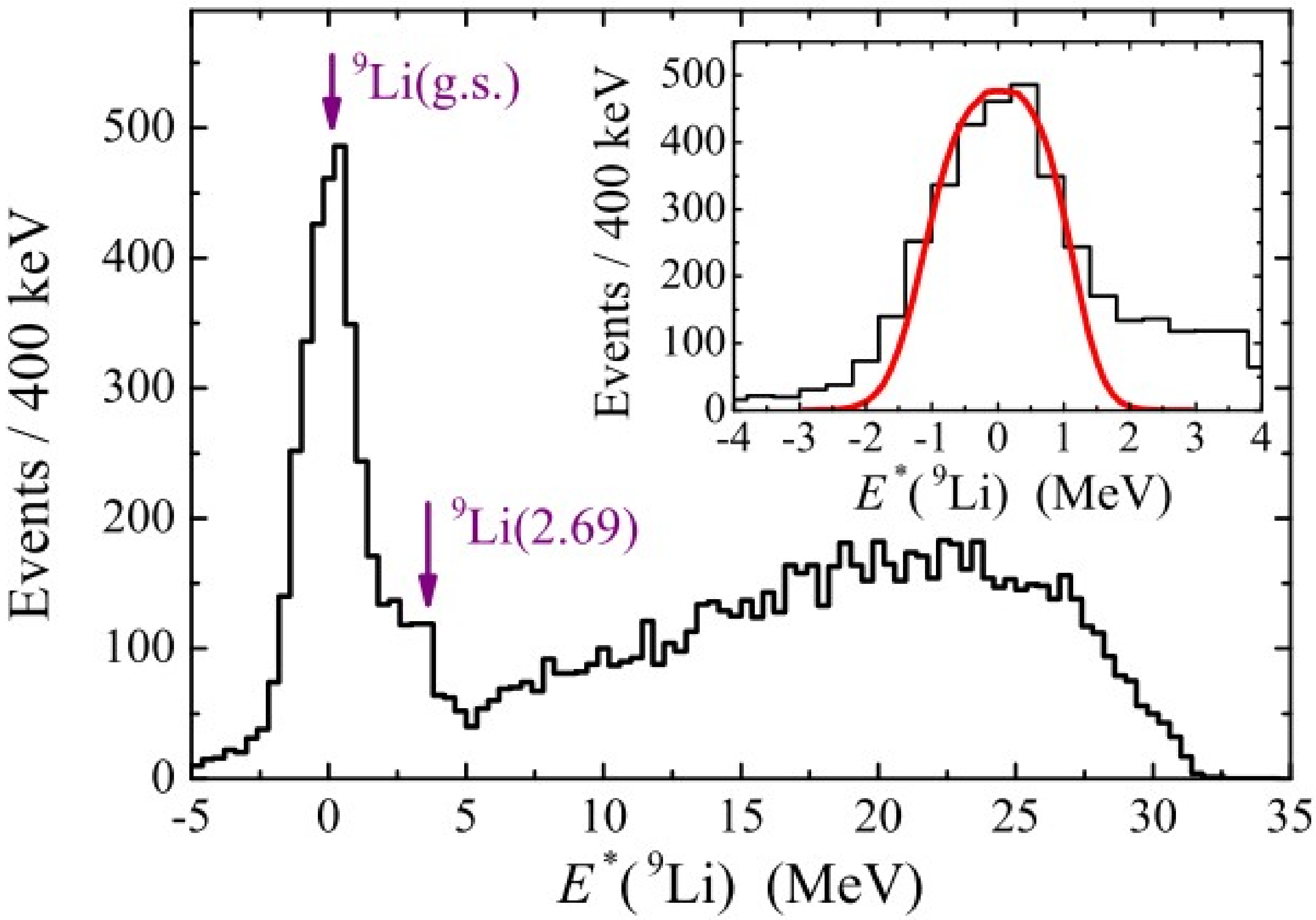
Channel identification





- reliable identification of both ^{3}He and ^{3}H
- special treatment of 20 µm Si detectors

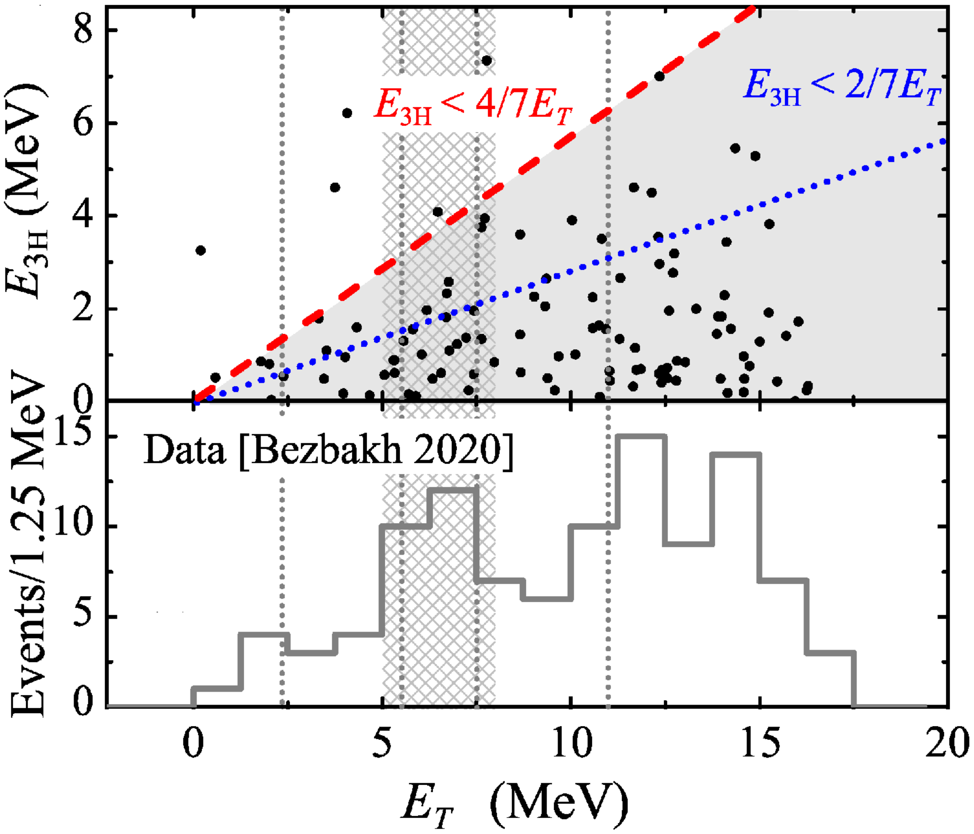
Calibration reaction



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

- ^{10}Be at 42 AMeV
- Independent MM calibration with ^{10}Be beam
- MC simulations validated by the comparison ^{9}Li data

MM spectrum: Exp1

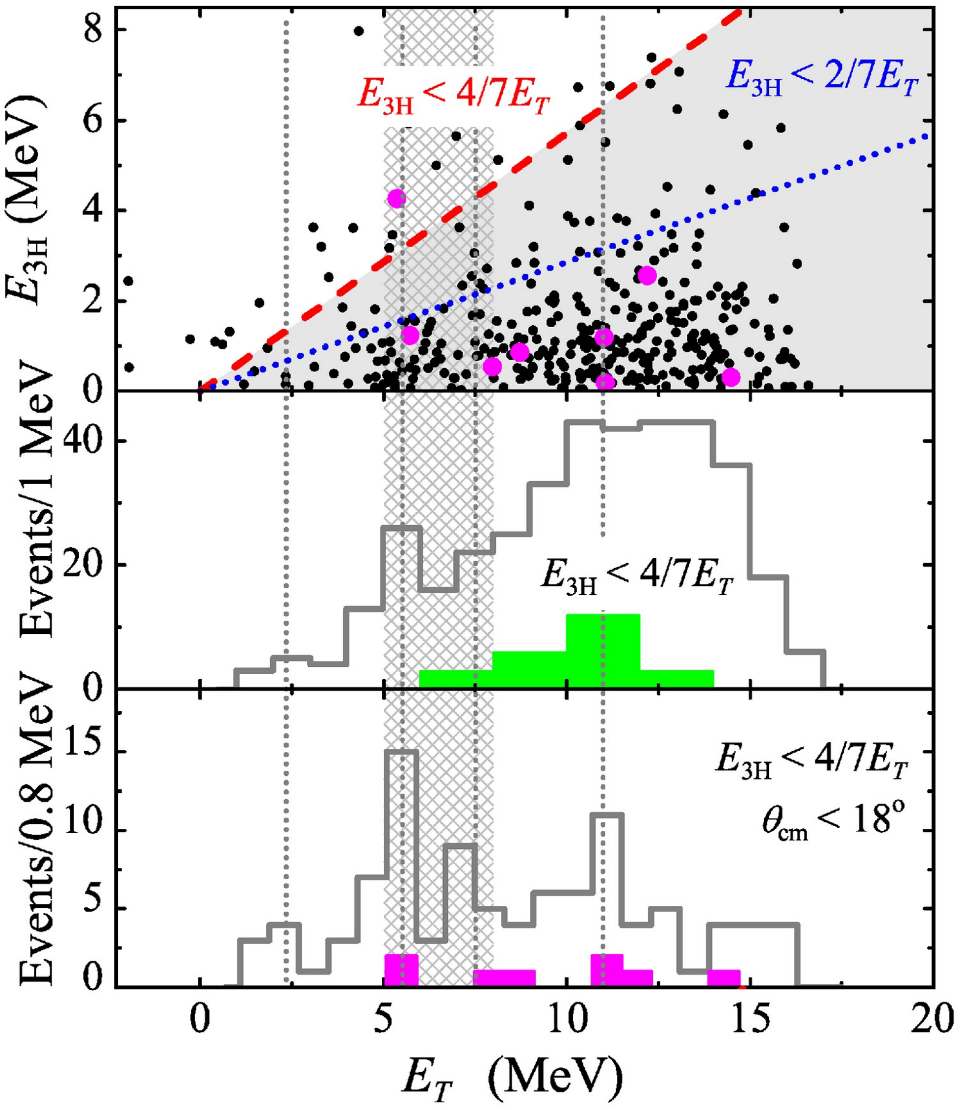


- kinematical “triangle” cuts reduce the backgrounds
- ground state at 1.8(5) MeV
- excited state at 6.5(5) MeV
  - possibly 5.5-7.5 MeV doublet
- some evidence for ^{7}H excited state at 11 MeV

Bezbakh et al., **Phys.Rev.Lett.** 124, 022502 (2020)

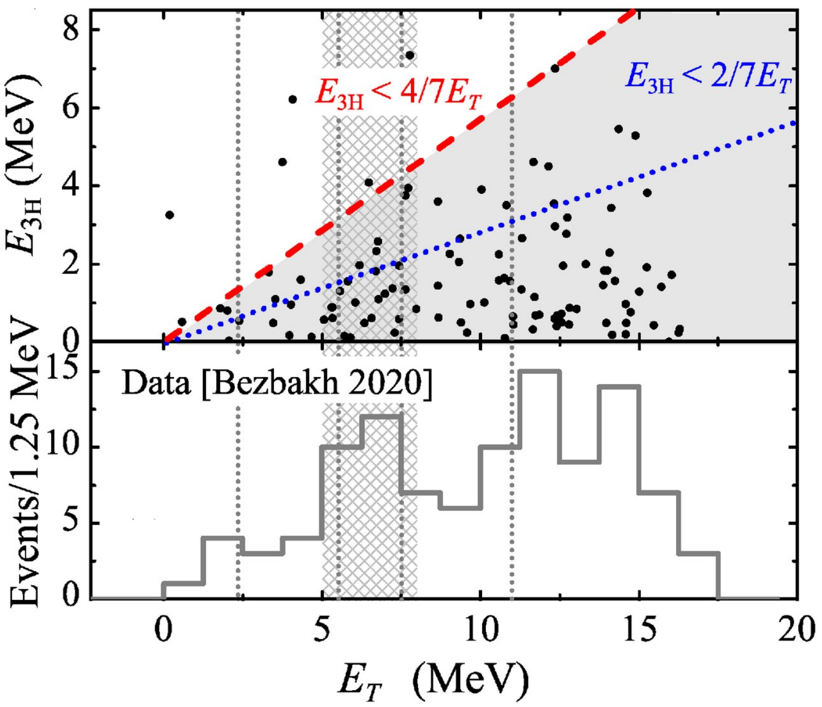
MM spectrum: Exp2

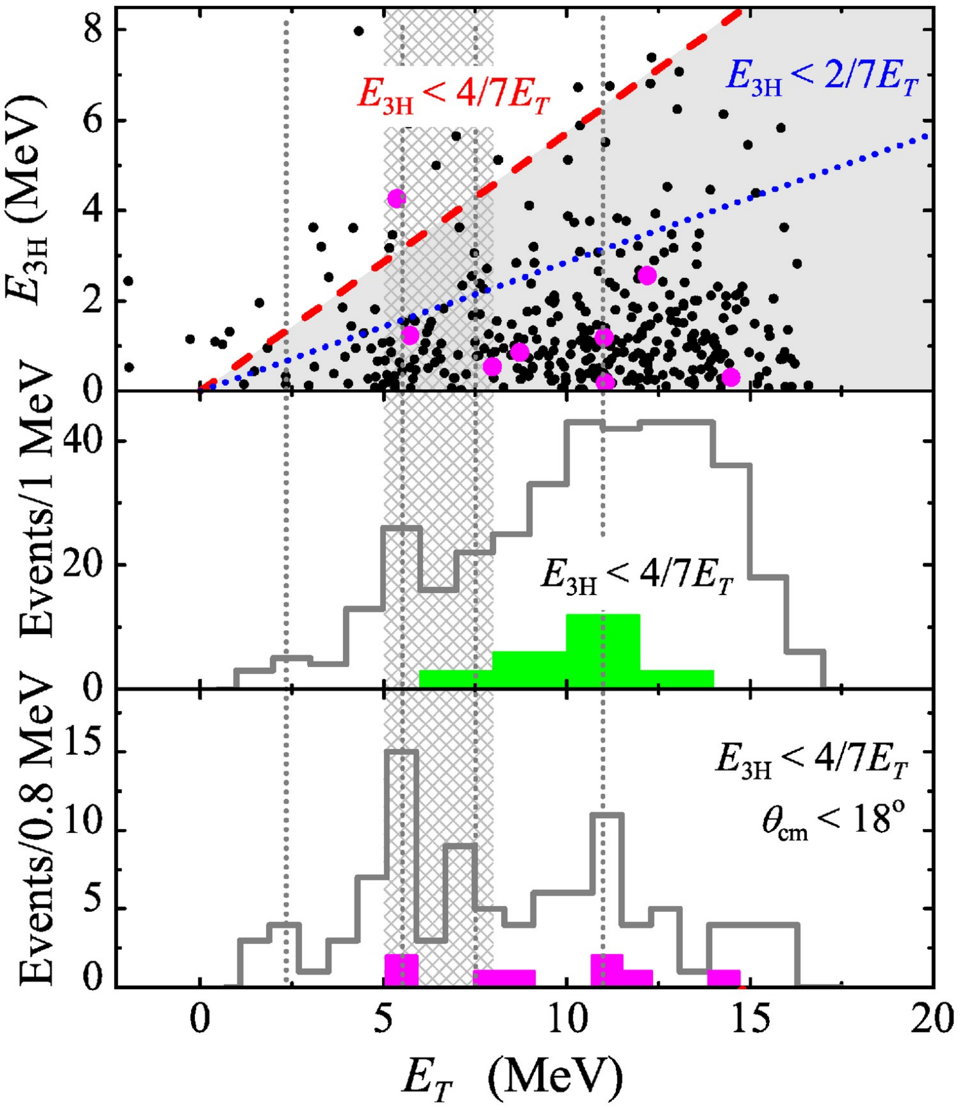
- ^{7}H ground state at 2.2(5) MeV
- ^{7}H excited state at 5.5(3) MeV (possibly doublet at 5.5-7.5 MeV)
- peak at 11(3) MeV
- reaction c.m. angle cutoff θ_{cm}<18° provides especially safe result for the ^{7}H g.s.



Muzalevskii et al., Physical Review C 103, 044313 (2021)

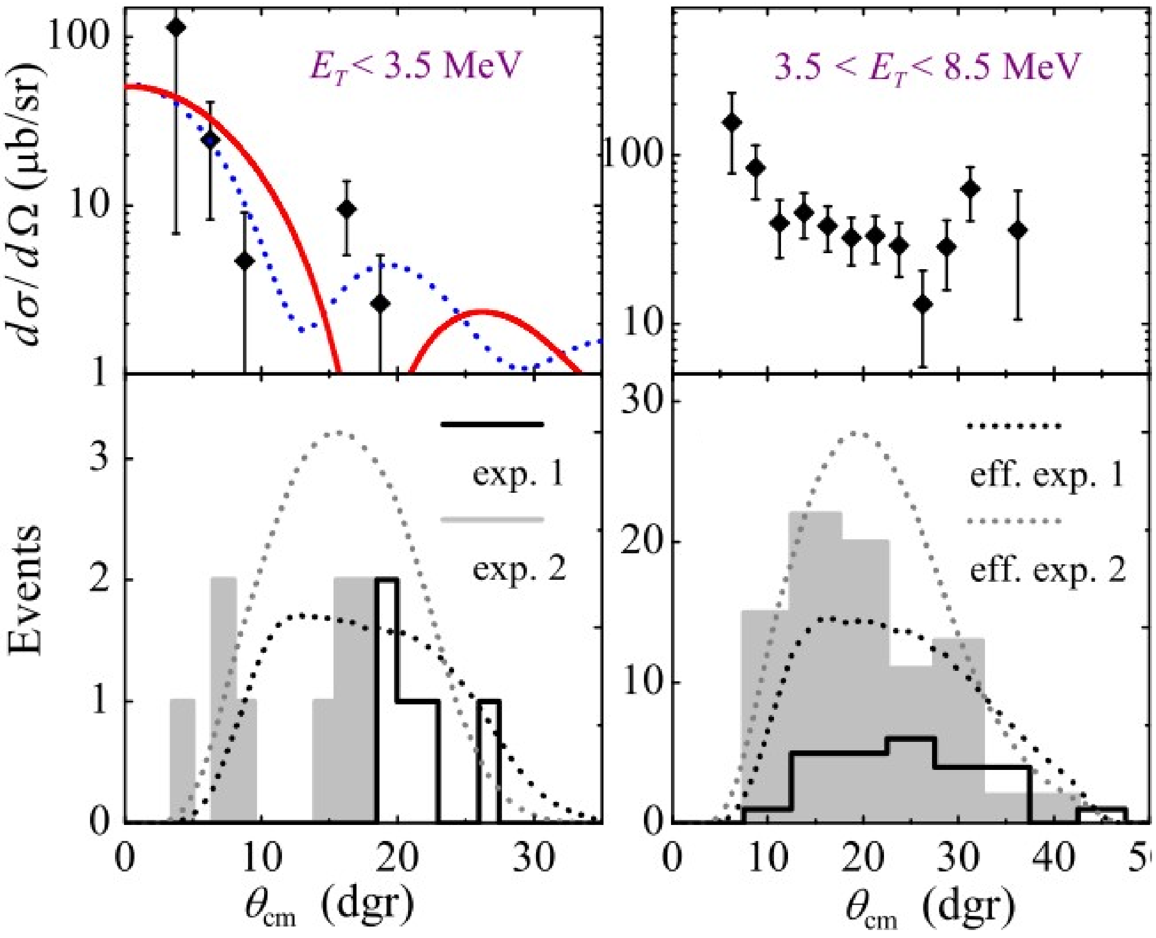
MM spectra





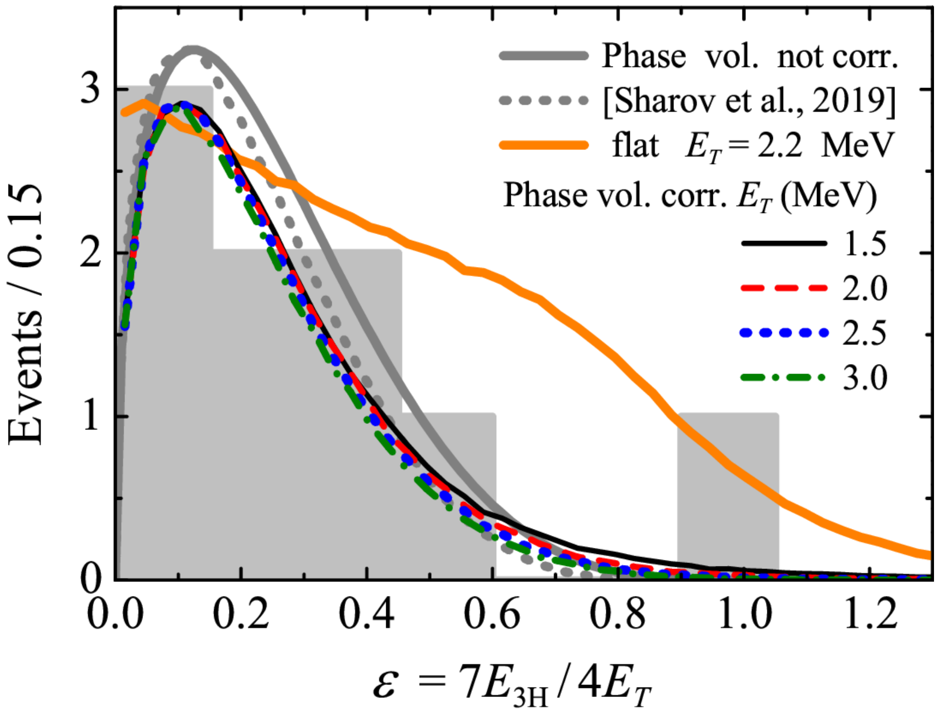
- consistent results in 2 independent JINR experiments
- consistent with data of Nikolskii et al.
- level- and decay-scheme for the ^{7}H

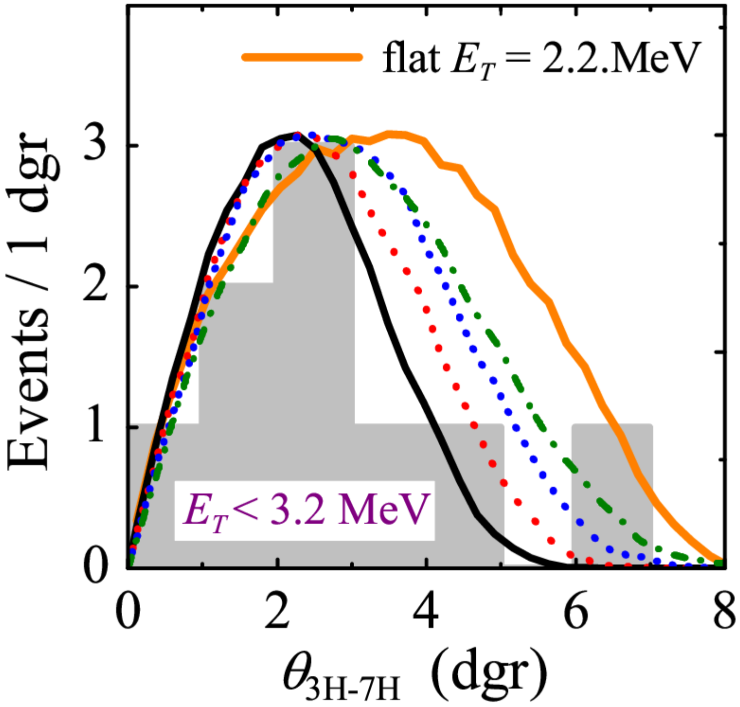
Reaction angle distributions



- Exp1 — second diffraction maximum is populated for the ^{7}H g.s.
- Exp2 planned to populate the forward peak for the ^{7}H g.s.
- gap in the data from 9 to 14 degrees observed in the second data

Energy and angular distributions of tritons





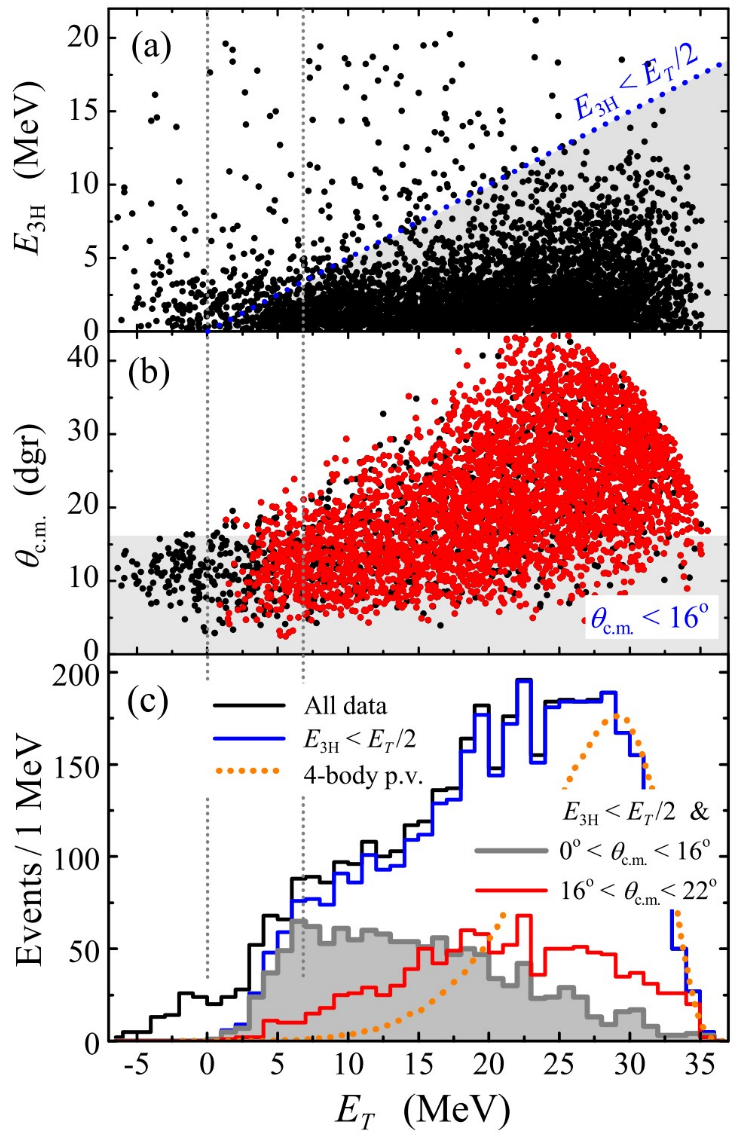
- reflection of the specific dynamics of true five-body decay
- obtained in independent way

Both patterns consistent with correlated emission of tritons expected for **true five-body** decay

“Satellite” data on ^{6}H from ^{2}H(^{8}He,^{4}He)^{6}H

- setup not suitable for this reaction channel
- higher cross section
- higher statistics
- large background
- neutron coincidences data

Nikolskii et al., arXiv:2105.04435



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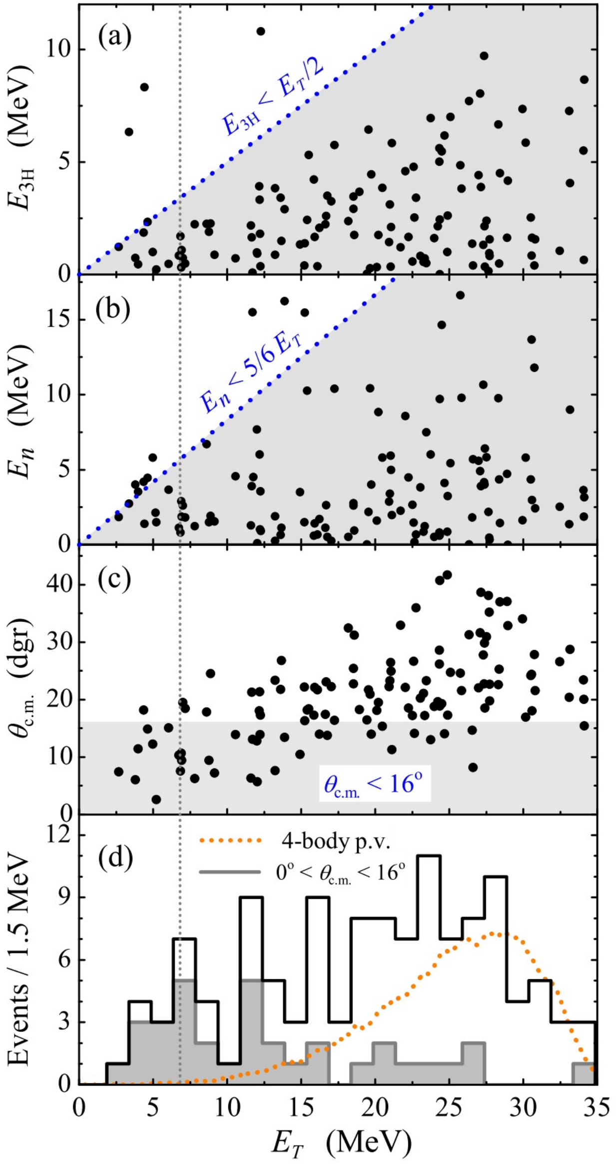
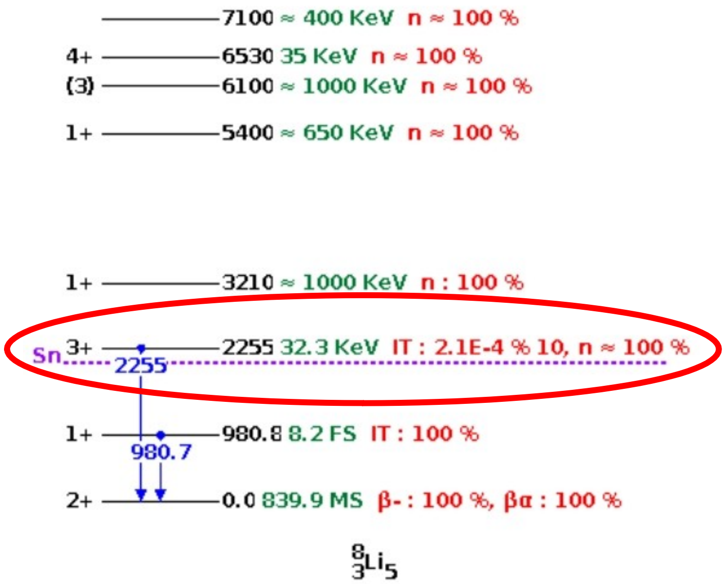
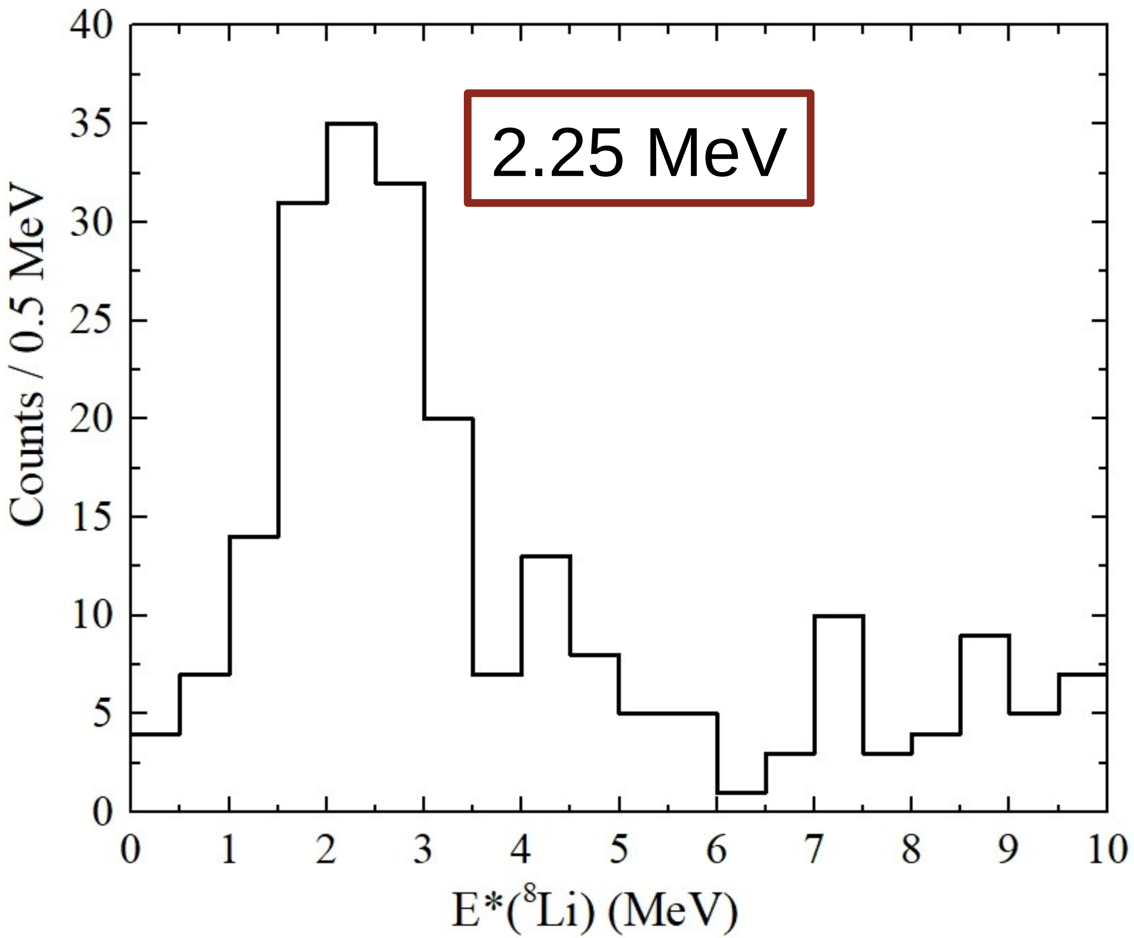


Calibration reaction

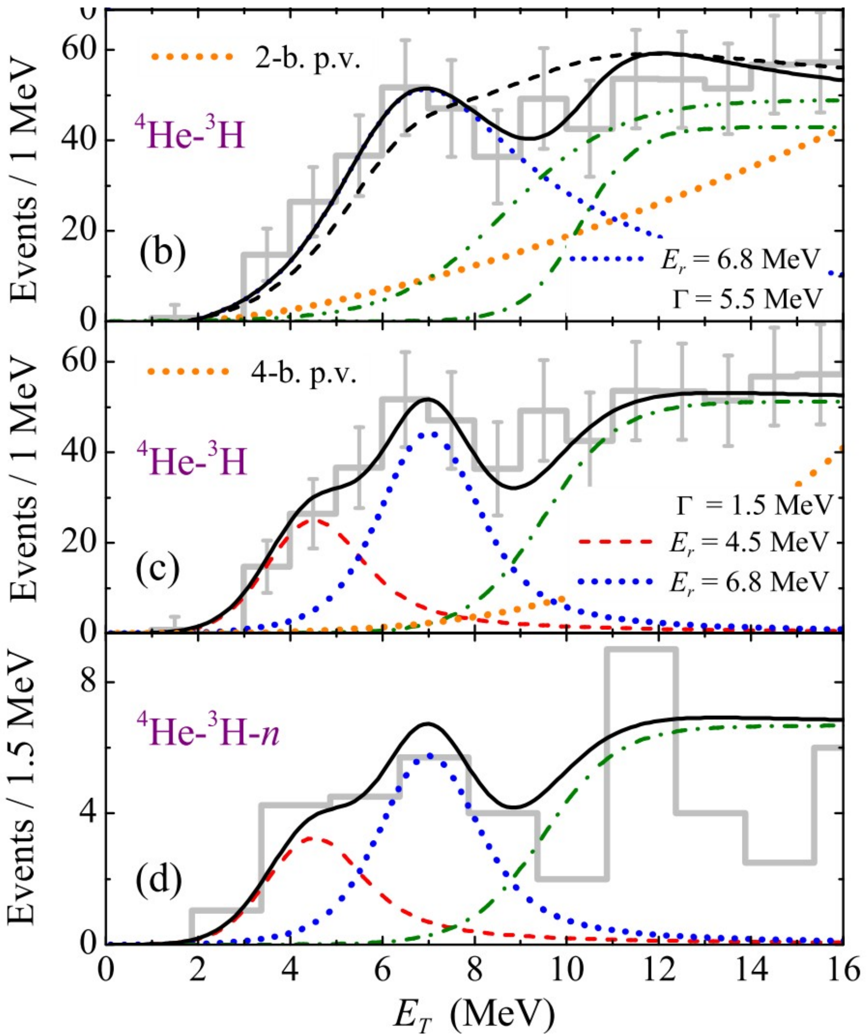
$^{10}Be(d,{}^{4}He){}^{8}Li$

- 3^{+} state found at expected energy
- check of detection eff.

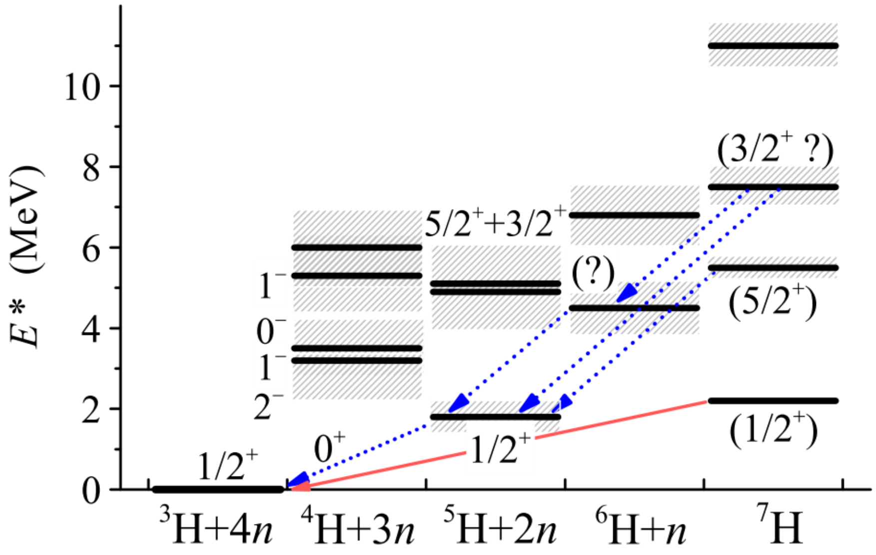




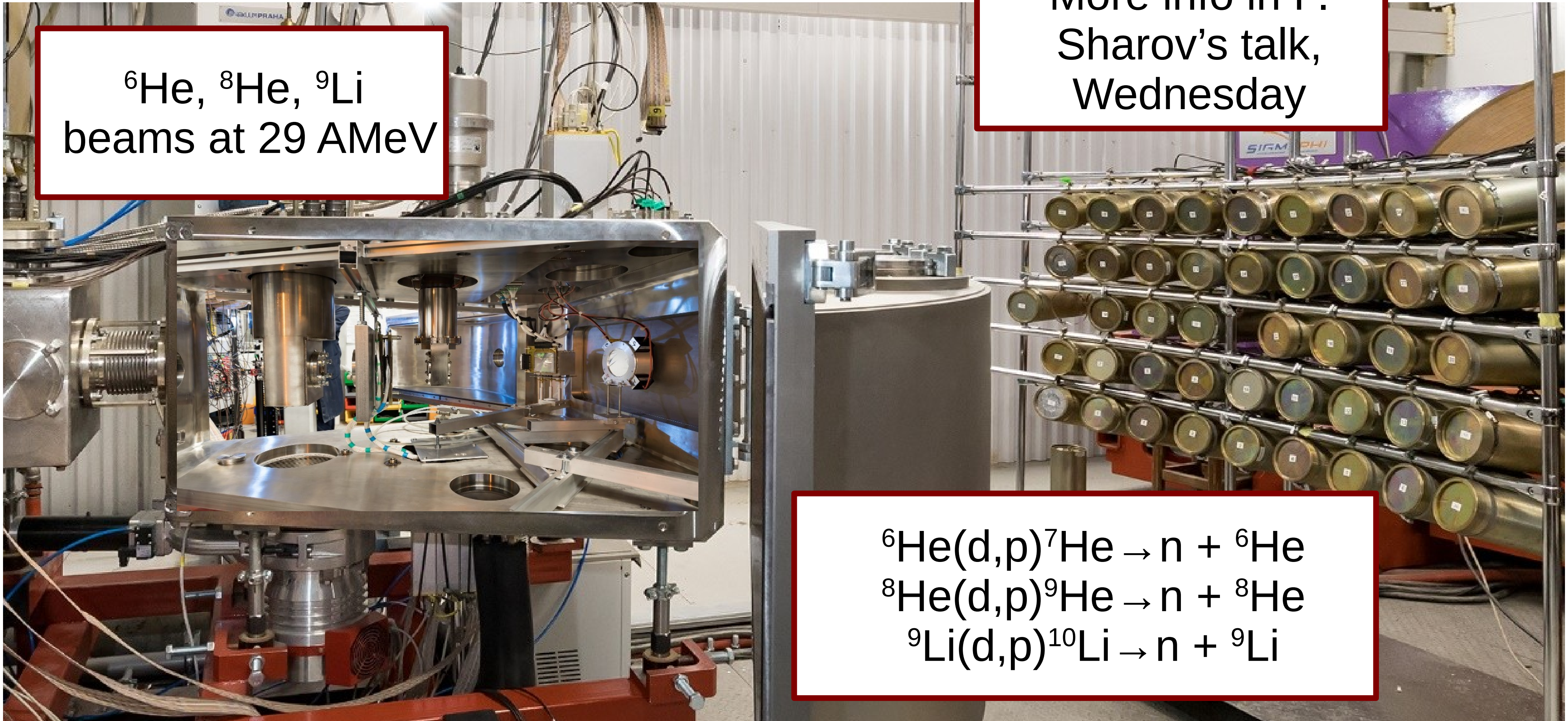
Preliminary results on ^6H



- State at ~2.6 MeV not observed
- Resonance at 6.5 MeV
- Possible resonance at 4.5 MeV



Setup for the study ^{7}He, ^{9}He and ^{10}Li isotopes in the reaction (d,p)



^{6}He, ^{8}He, ^{9}Li beams at 29 AMeV

More info in P. Sharov's talk, Wednesday

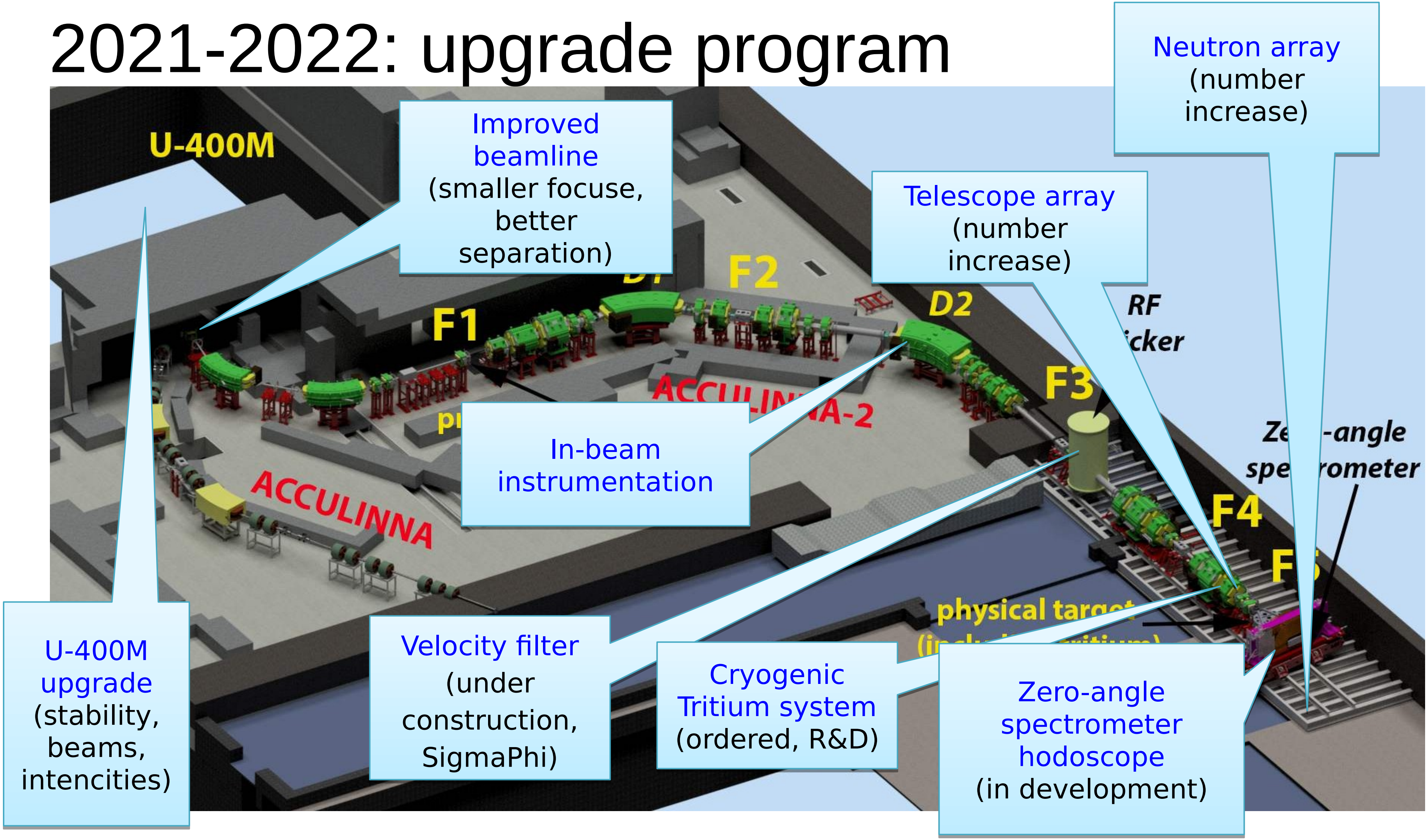
$^{6}He(d,p)^{7}He \rightarrow n + {}^{6}He$

$^{8}He(d,p)^{9}He \rightarrow n + {}^{8}He$

$^{9}Li(d,p)^{10}Li \rightarrow n + {}^{9}Li$

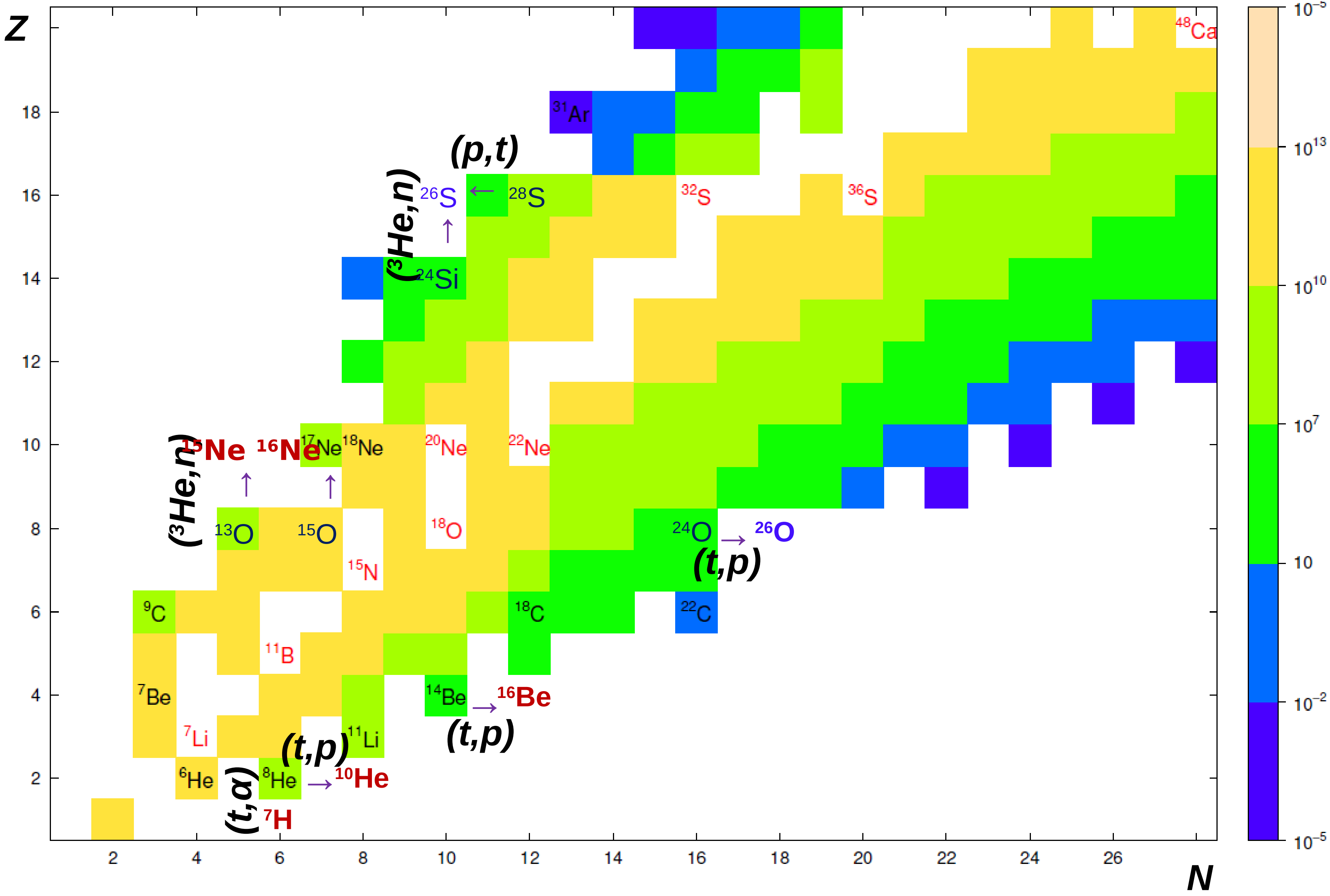
Prospects

2021-2022: upgrade program



Experiment with new targets (since 2023)

- Transfer reactions on ^{3}He target
  - $^{13}O(^{3}He,n)^{15}Ne$
  - $^{24}Si(^{3}He,n)^{26}S$
- Transfer reactions on ^{3}H target
  - $^{8}He(t,p)^{10}He$
  - $^{14}Be(t,p)^{16}Be$
  - $^{8}He(t,\alpha)^{7}H$
- Charge-exchange reactions
  - (p,n), (^{3}He,^{3}H), (^{3}H,^{3}He)


Z
N
(p,t)
(³He,n)
(³He,n)
(t,p)
(t,p)
(t,p)
(t,α)
²⁶S
²⁸S
³²S
³⁶S
³¹Ar
⁴⁸Ca
²⁴Si
¹⁵Ne
¹⁶Ne
¹⁷Ne
¹⁸Ne
²⁰Ne
²²Ne
¹³O
¹⁵O
¹⁸O
²⁴O
²⁶O
¹⁵N
⁹C
¹⁸C
²²C
¹¹B
⁷Be
¹⁴Be
¹⁶Be
⁷Li
¹¹Li
⁶He
⁸He
¹⁰He
⁷H
10⁻⁵
10¹³
10¹⁰
10⁷
10
10⁻²
10⁻⁵

Our team

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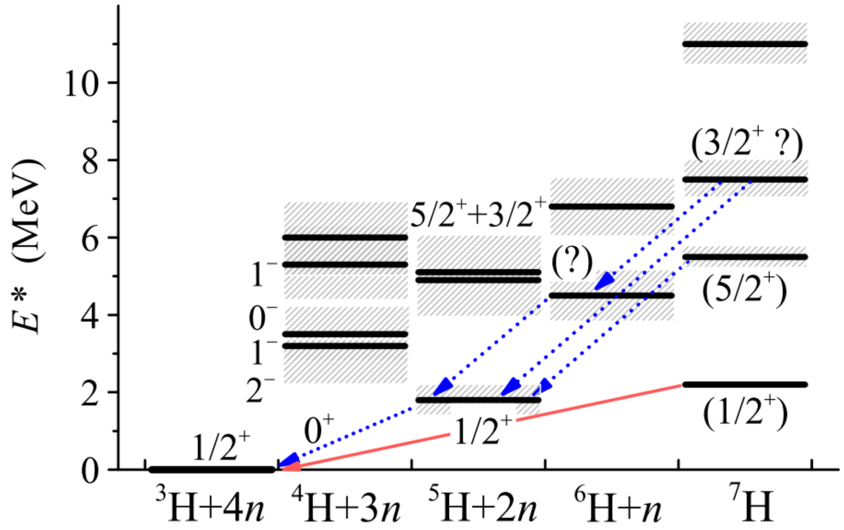
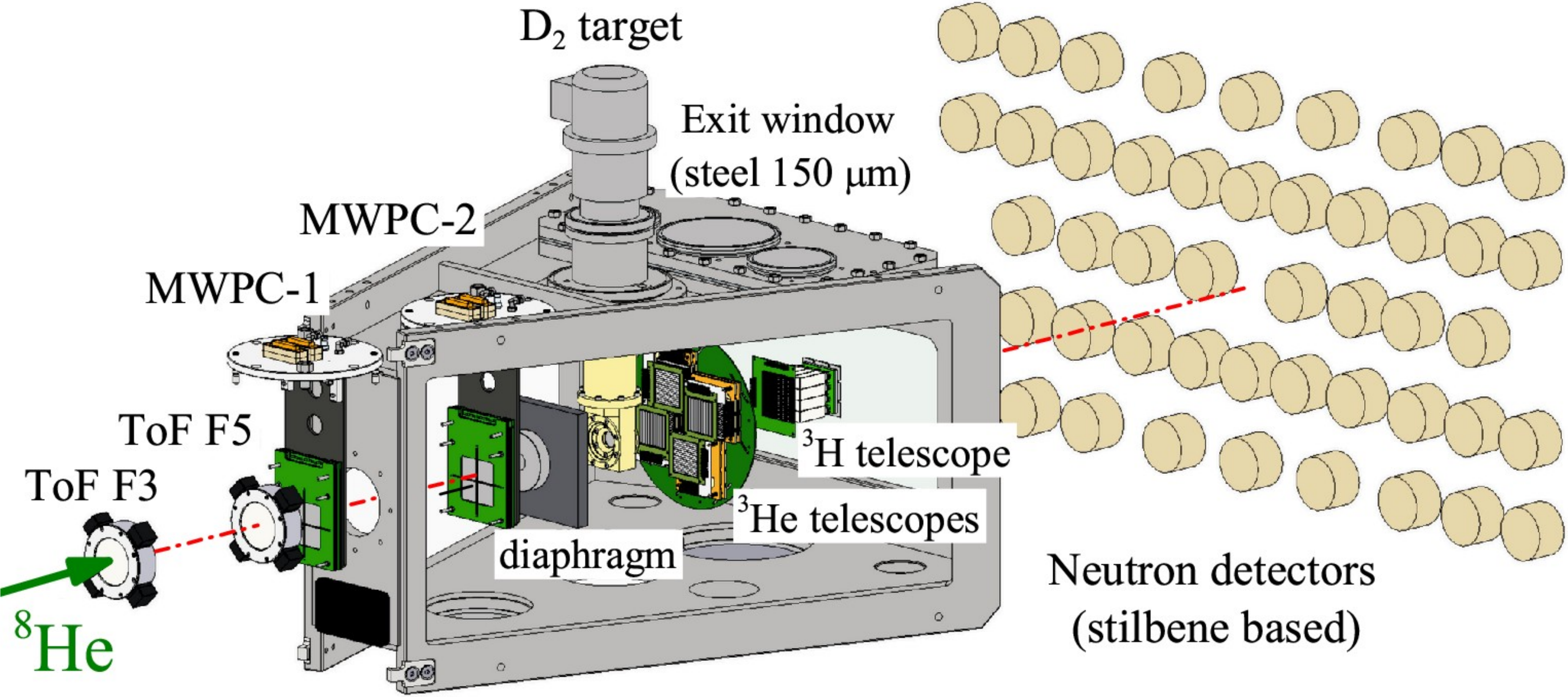
Conclusions

- 9 isotopes investigated during a first period (2018-2020)
- a long-term problem of quest for ^{7}H g.s. investigated
- complicated experiment, extremely low cross section and low statistics
- preliminary results on ^{6}H g.s. in contradiction with previous works
- neutron registration strongly increase quality of the ^{6}H data
- calibrations confirmed by $^{10}Be(^{2}H,^{3}He)^{9}Li$ and $^{10}Be(^{2}H,^{4}He)^{8}Li$ reaction
- true 4n decay reliably observed for the first time
- material for 3 PhD theses acquired for the moment

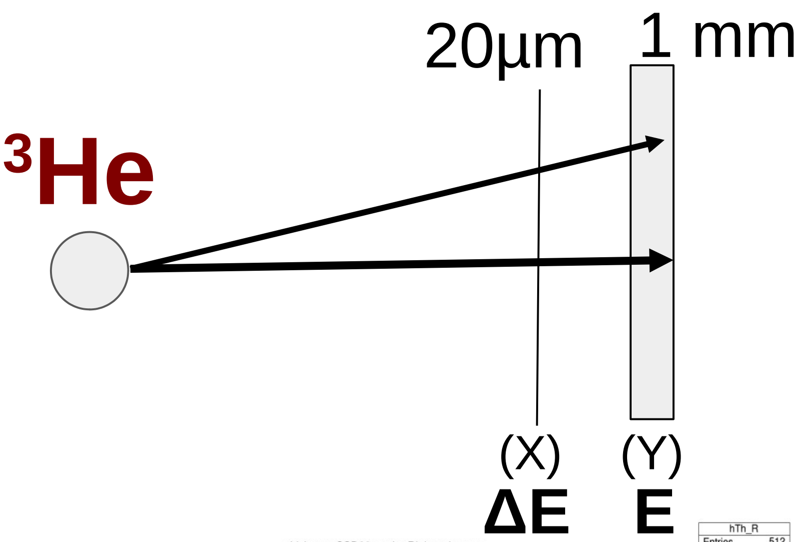


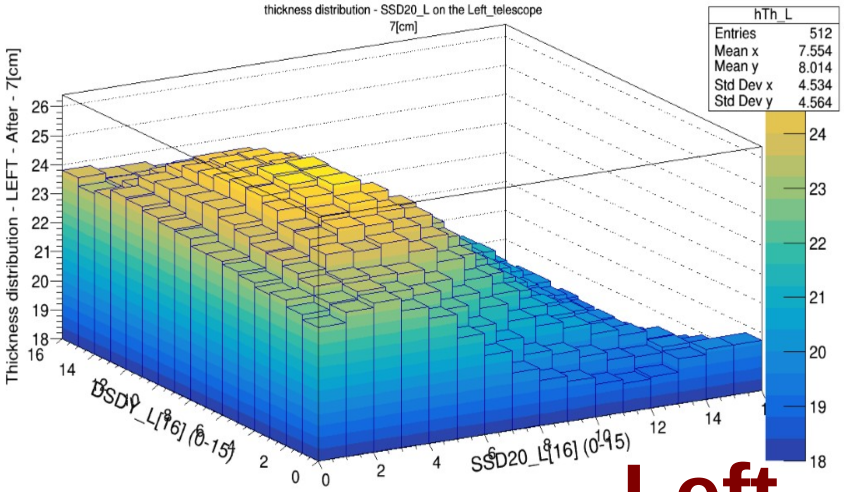
End

Appendix: Full setup

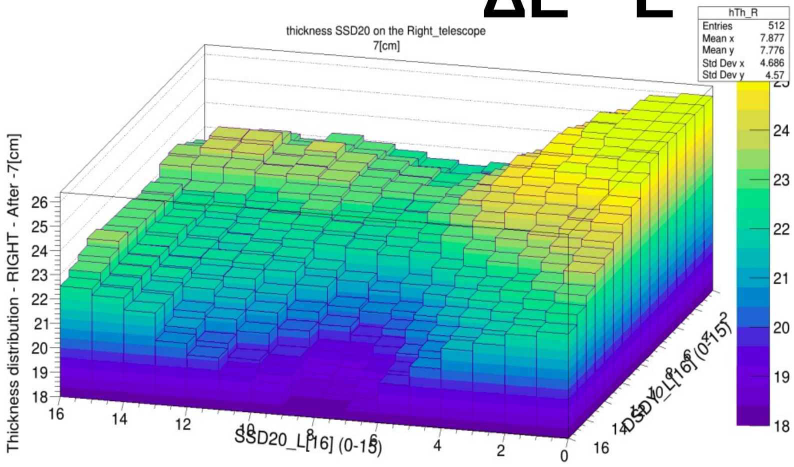


Appendix: Identification of ^{3}He





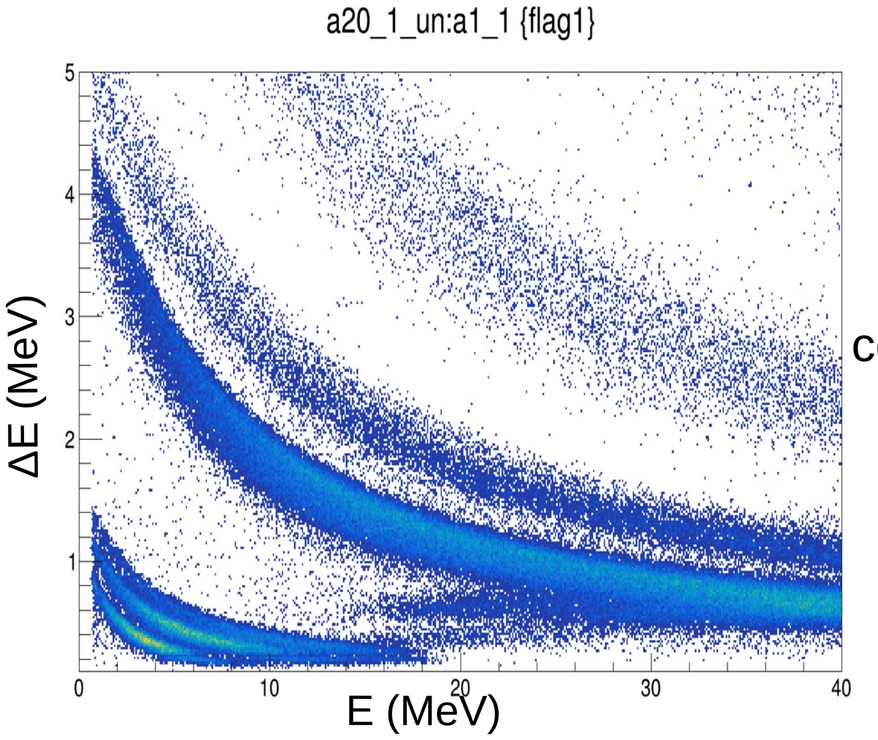
Left telescope



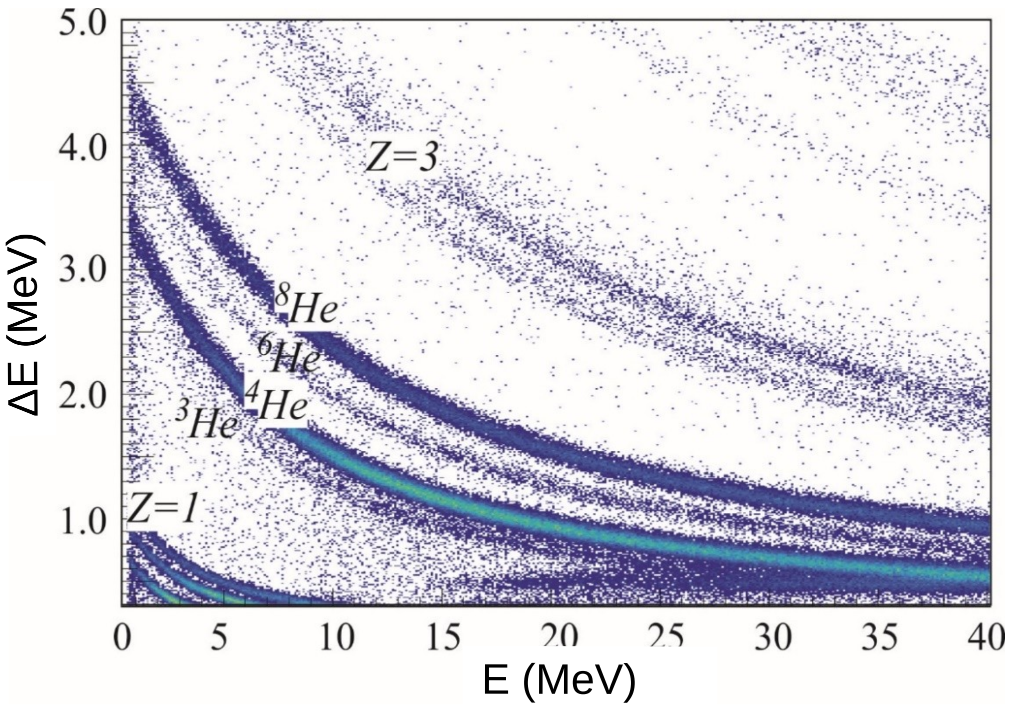
Right telescope

I. Muzalevski et al., Bull.Rus.Acad.Sci.: Phys., 84, 500 (2020)

Appendix: Identification of ^{3}He

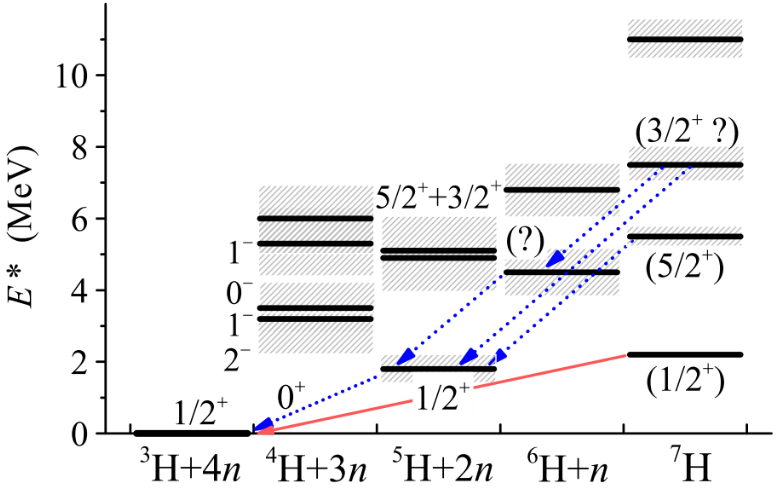


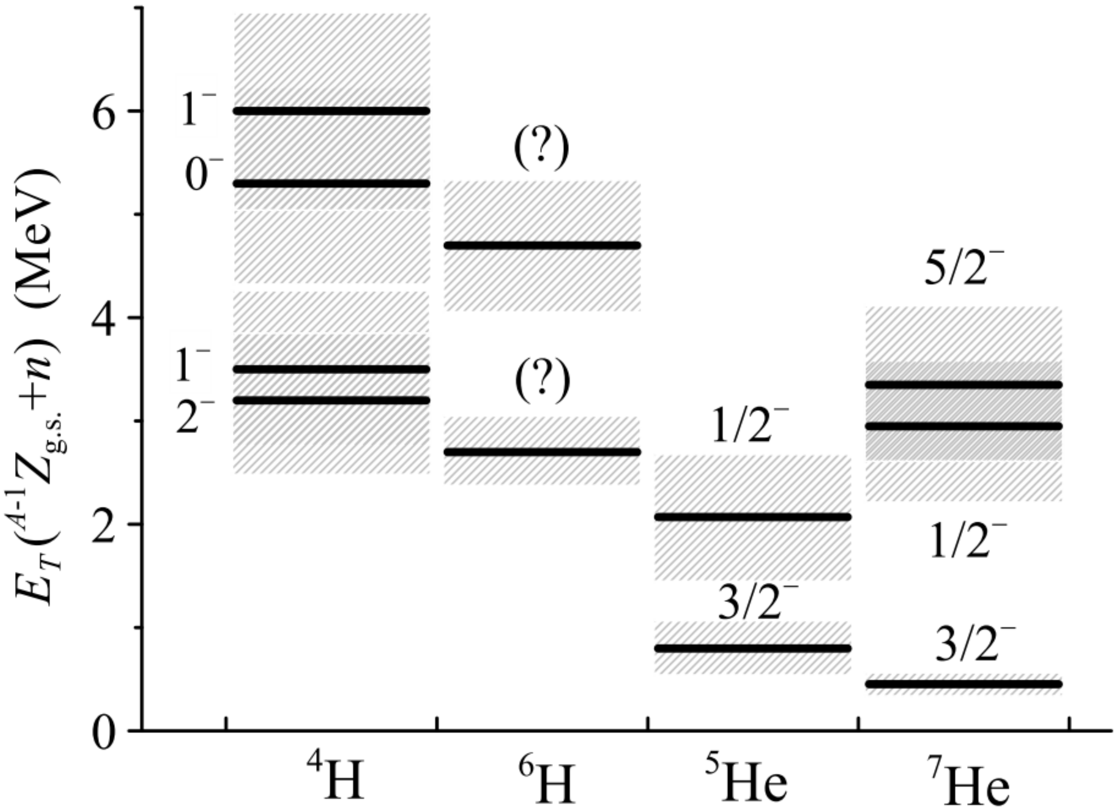
correction



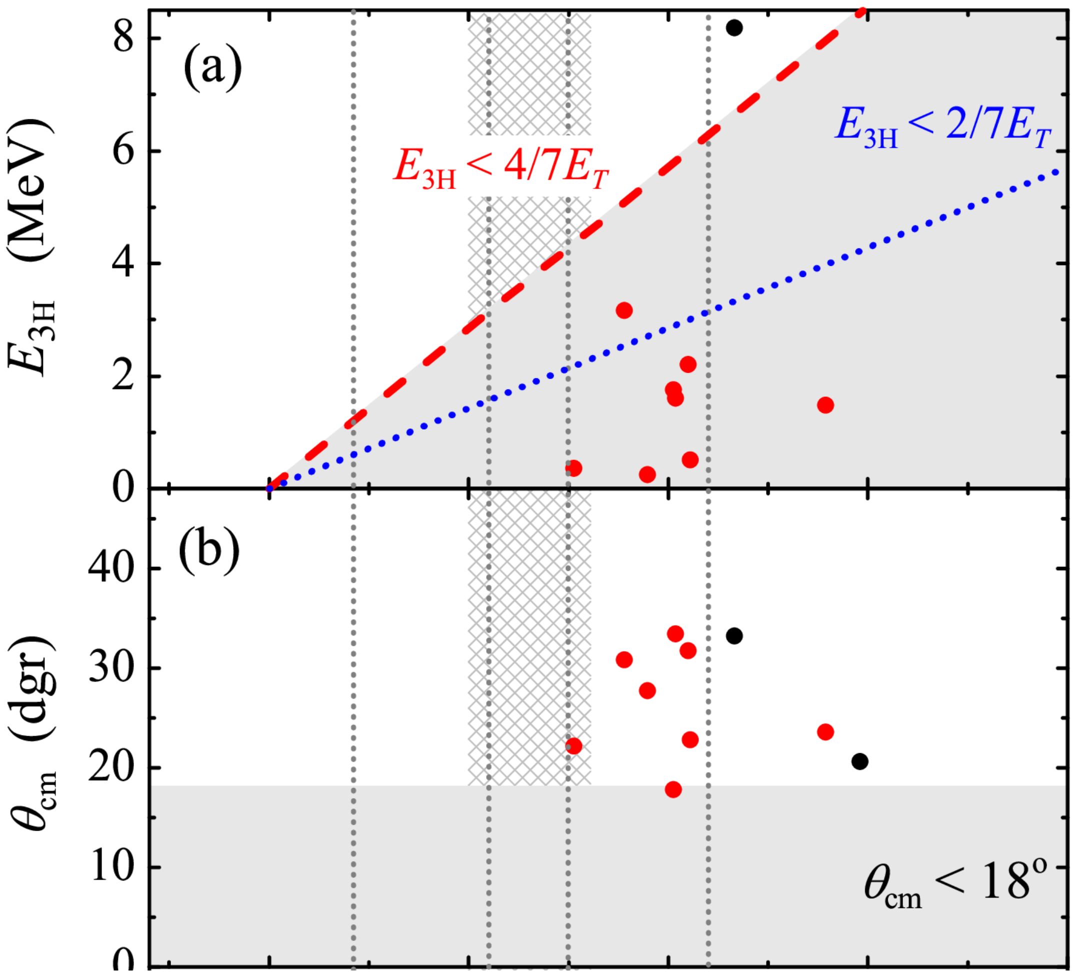
I. Muzalevski et al., Bull.Rus.Acad.Sci.: Phys., 84, 500 (2020)

Appendix: Energy levels

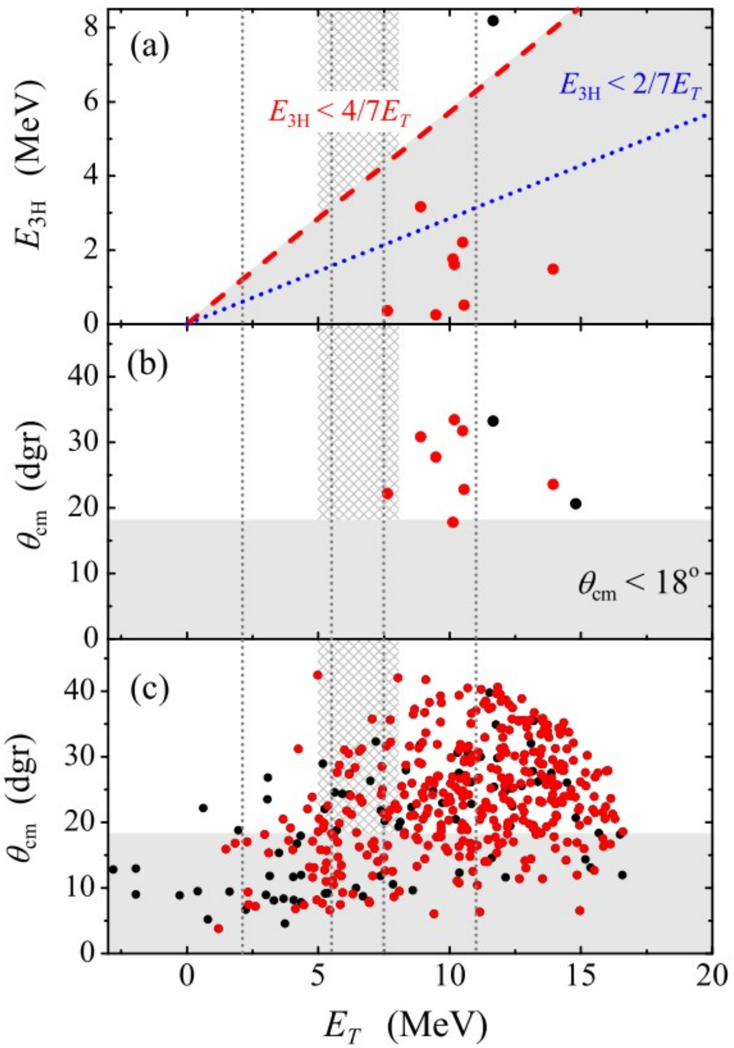




Appendix: Background measurement

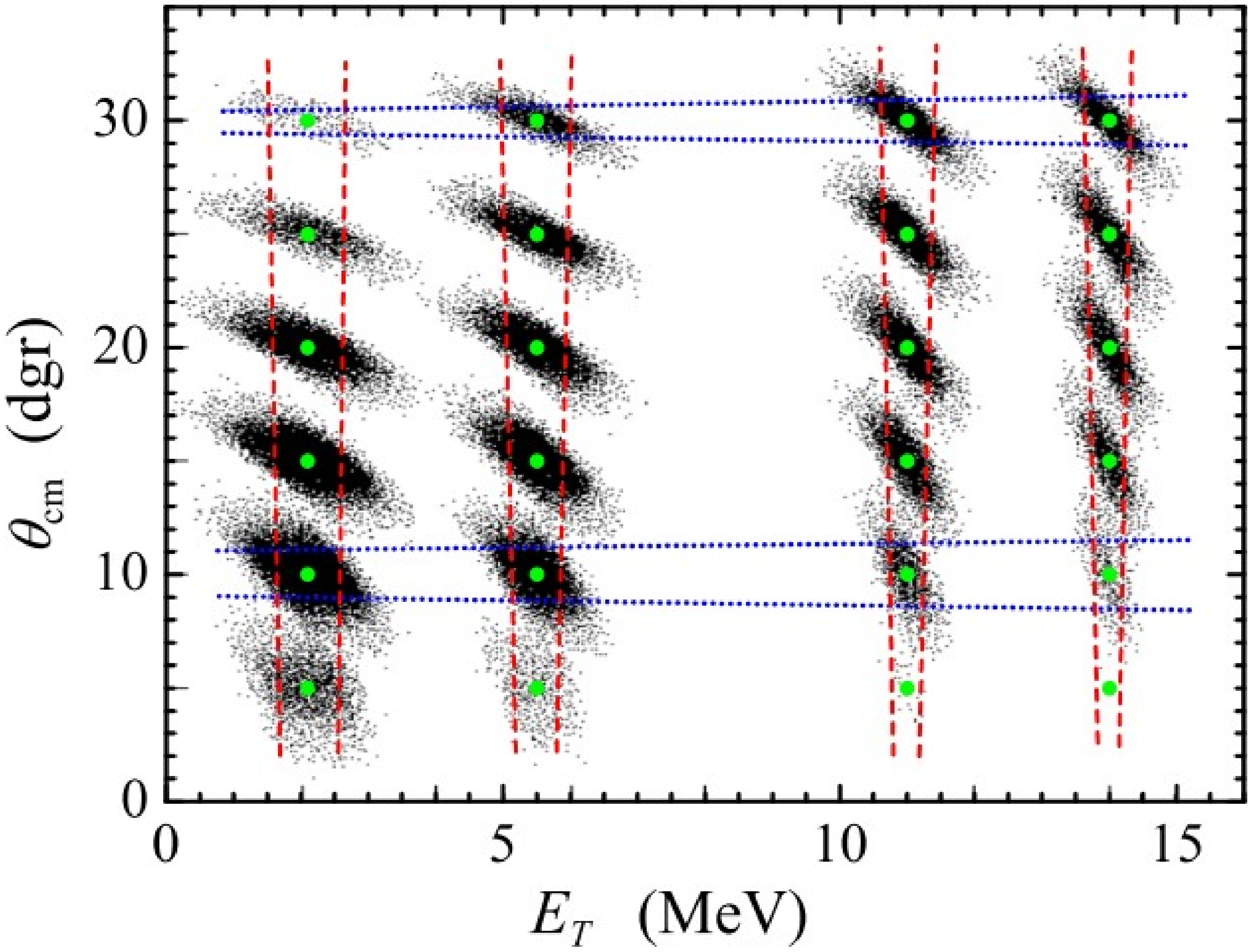


Appendix: Background measurement



- Empty target events are located mainly outside the energy ranges of interest
- Only hypothetical 11 MeV state can be contaminated
- Reaction cm angle cutoff qcm < 18 dgr is expected to provide ^{7}H spectrum free from empty target background

Appendix: Experimental resolution



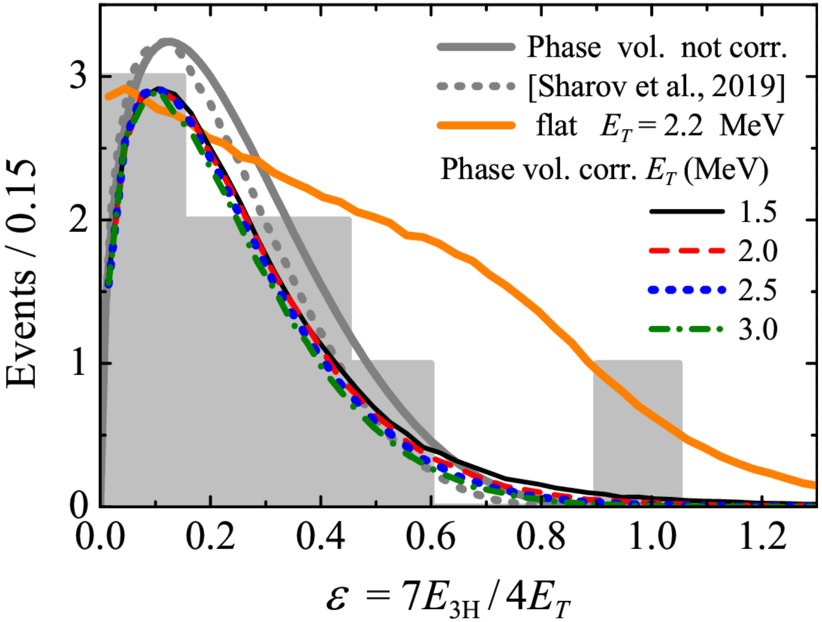
- complete MC simulations to check the detection setup
- higher energy resolution than in the previous experiments (less than 1 MeV) is obtained

Appendix: Resolution

Energy and angular resolutions

E_T	2.2 MeV		5.5 MeV		11 MeV		14 MeV	
10°	0.95	2.2	0.73	2.3	0.48	2.5	0.38	2.8
20°	1.10	1.6	0.93	1.8	0.64	2.2	0.52	2.6
30°	1.13	1.2	0.99	1.3	0.77	1.8	0.69	2.0

Appendix: additional evidence for 7H g.s.



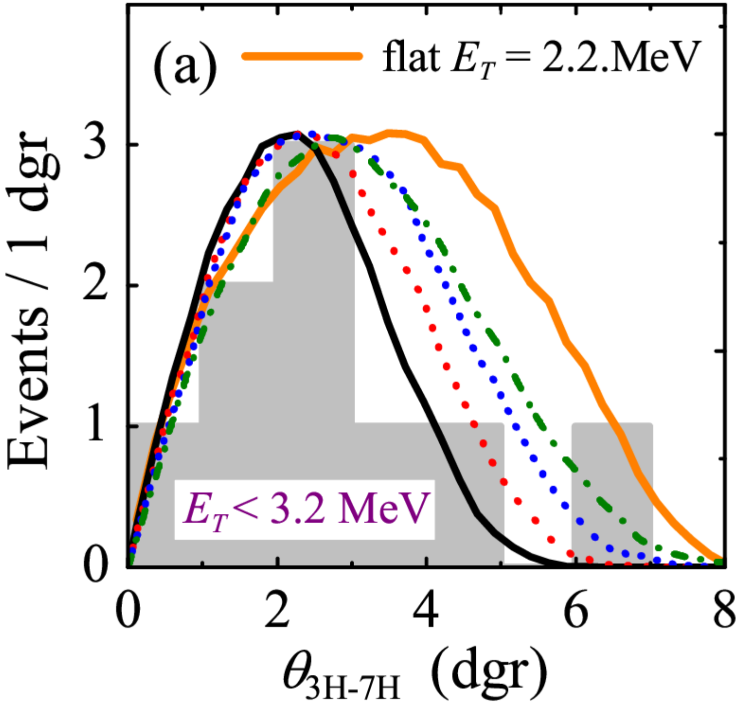
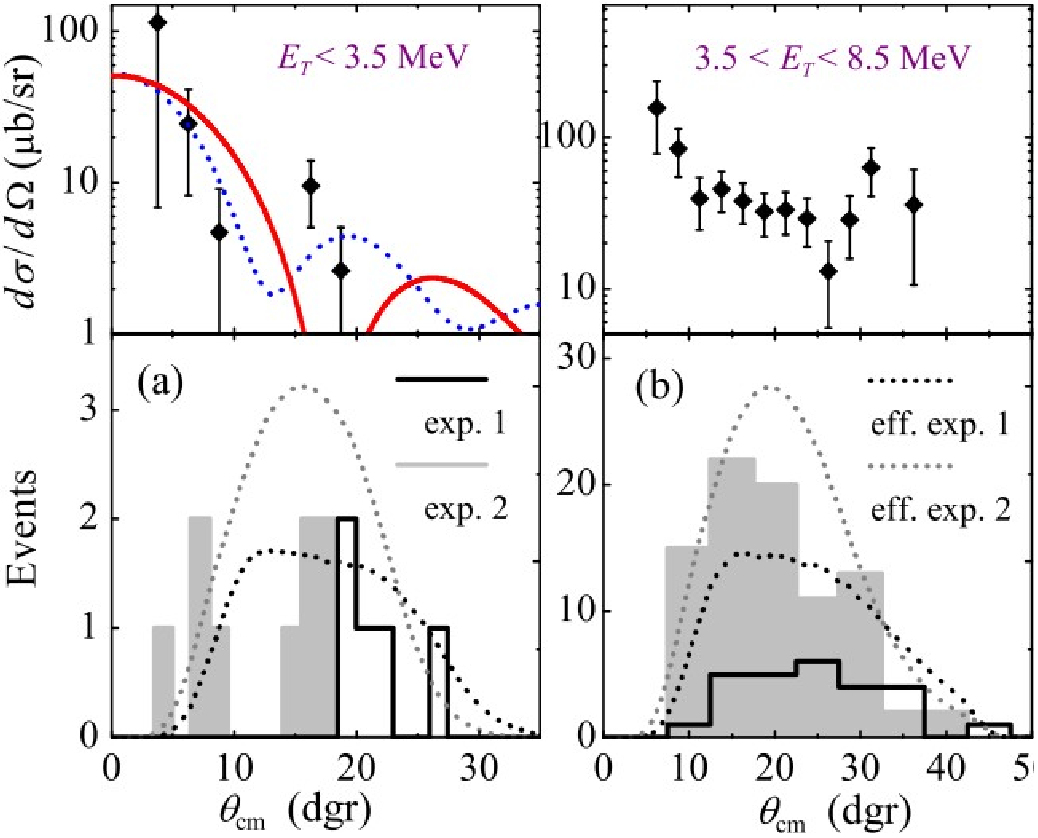


TABLE II. Mean values of the ε distributions of Figs. 13 and 14.

Value	flat	1.5	2.0	2.5	3.0	Exp.
$\langle \varepsilon \rangle$	0.45(11)	0.27(6)	0.25(6)	0.24(6)	0.23(6)	0.31
$\langle \theta_{3H\text{-}7H} \rangle$	3.6(6)	2.3(4)	2.6(4)	2.9(4)	3.1(4)	2.9

Appendix: CMS angular distributions



Theoretical FRESCO calculations

- Standard calculation – diffraction minimum is sitting on top of the maximum in the data.
- To fit the position of diffraction minimum the non-standard calculation conditions should be used:
  - extreme peripheral transfer
  - large absorption

Interpretation

consistent with expected very "fragile" character of ^{7}H g.s. and very small g.s. population cross section.