Results of the first experiments at the ACCULINNA-2 separator and the scientific programme for 2024

Vratislav Chudoba for
ACCULINNA-2 collaboration

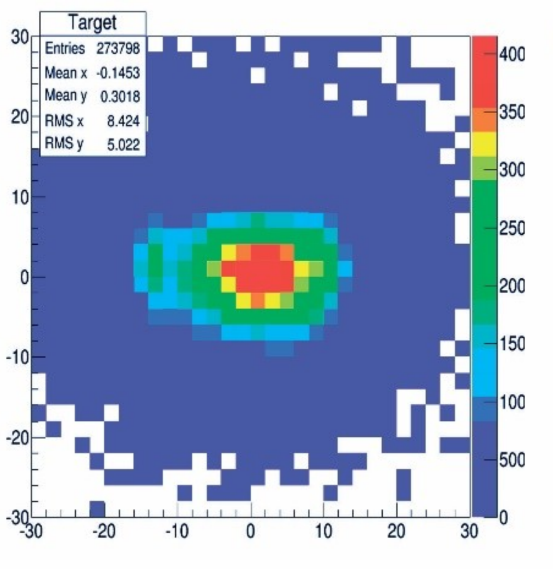
FLNR JINR, Dubna

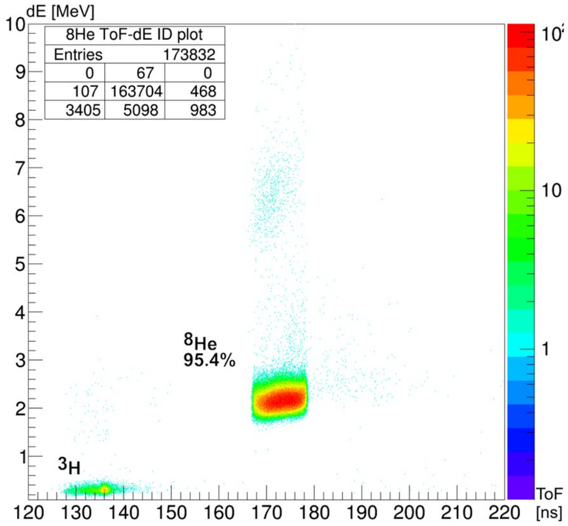
Results on previous experiments

- **Experimental session in 2018 – 2020**
- **Beams ^{8}He, ^{9}Li, and ^{6}He**
- **^{5-7}H, $^{7,9}He$, and ^{8-10}Li isotopes investigated**

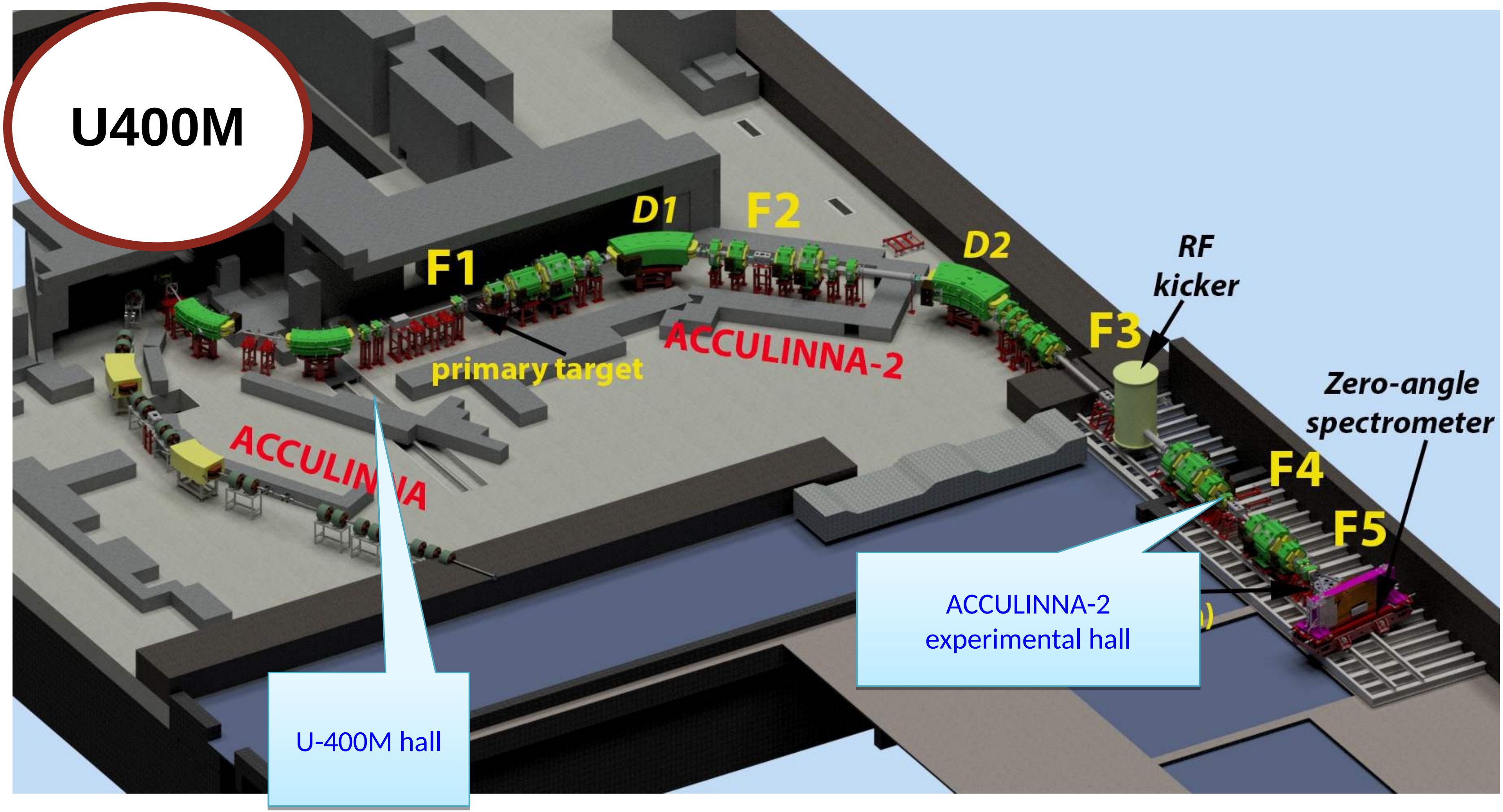
Characteristics of obtained RIBs

Ion	E, AMeV	Reaction	I, pps/pμA	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





ACCULINNA-2


U400M
D1
F2
D2
F1
RF kicker
F3
primary target
ACCULINNA-2
Zero-angle spectrometer
F4
F5
ACCULINNA
ACCULINNA-2 experimental hall
U-400M hall

Results since 2018

- elastic scattering ^{6}He+d
  - PhD. thesis of B. Zalewski, NIM B
- low energy spectra and decay modes, $^{8}He+d \rightarrow {}^{3,4}He+{}^{7,6}H$
  - PRL, PRC, Bulletin of RAS
- reference reactions (d,^{4}He) and (d,^{3}He) with ^{10}Be
  - NIM B, Phys.Atomic Nucl.
- low energy spectra, $^{6}He(d,p)^{7}He$, p-^{6}He-n coincidences
  - IJMP E, PRC
- low energy spectra, $^{9}Li(d,p)^{10}Li$, p-^{9}Li-n coincidences
  - Bulletin of RAS

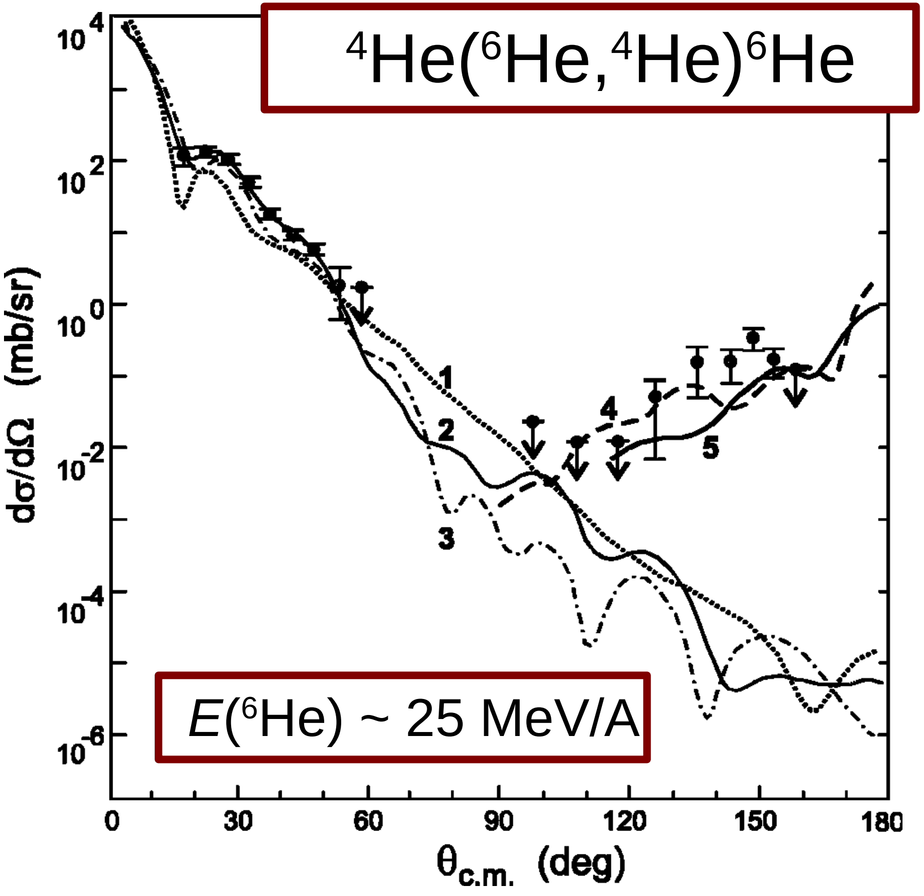
Prospects

Experiments for 2024 year

- production of ^{3}H, $^{6,8}He$, and other beams in wide energy range 10-44 MeV/A
  - methodical experiments on $^{2}H(^{6}He,^{6}Li)2n$ and $^{1}H(^{3}H,n)^{3}He$
- transfer of 2n/4n clusters
  - $^{4}He(^{8}He,^{4}He)^{8}He$
  - $^{4}He(^{8}He,^{6}He)^{6}He$
  - $^{4}He(^{6}He,^{4}He)^{6}He$

2n transfer – available data

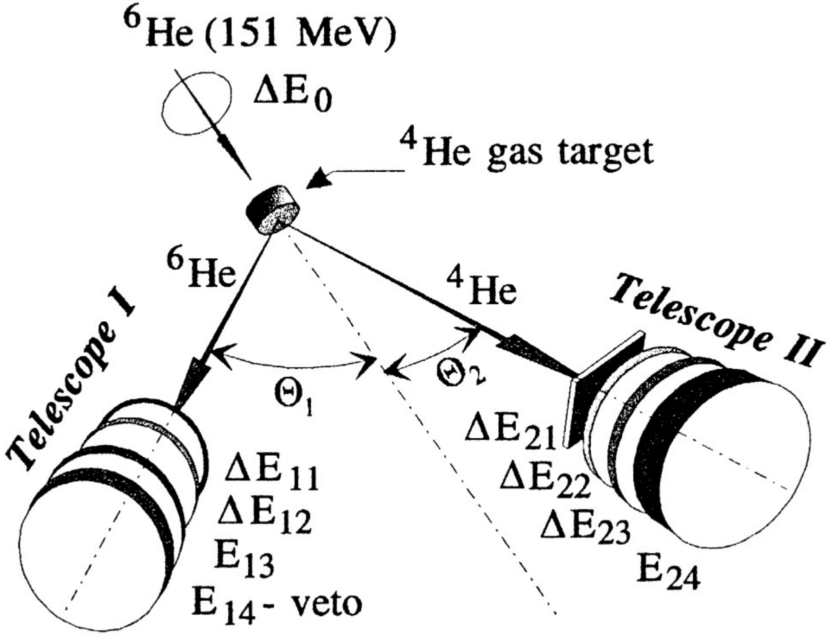
Yu. Ts. Oganessian et al., Phys. Rev. C. 60 (1999) 044605.



$^4He(^6He,^4He)^6He$

$E(^6He)$ ~ 25 MeV/A

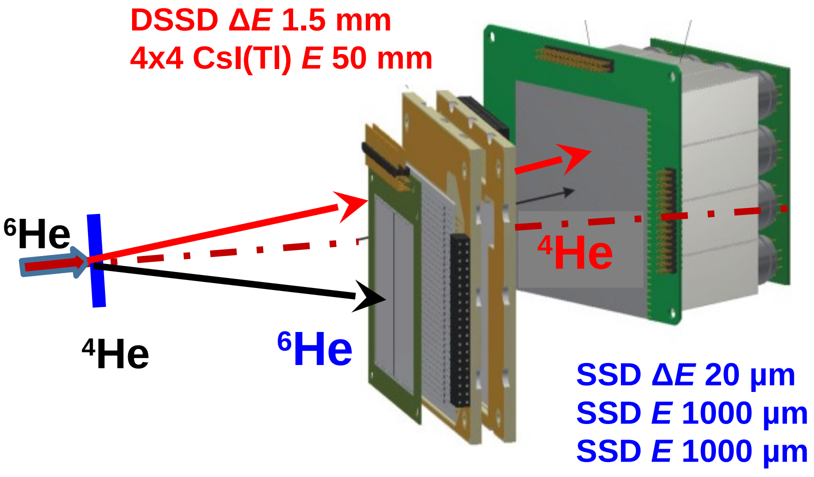
G.M. Ter-Akopian et al., Phys. Lett. B 426 (1998) 251.



$^{4}He(^{6}He,^{6}He)^{4}He$ experiment at 25-35 AMeV

Experiment in 2002

- $E(^{6}He)$ ~ 25 AMeV
- I ~ 10^{5} pps
- Target ~ 5.6×10^{20} cm^{-2}
- detection efficiency: 1



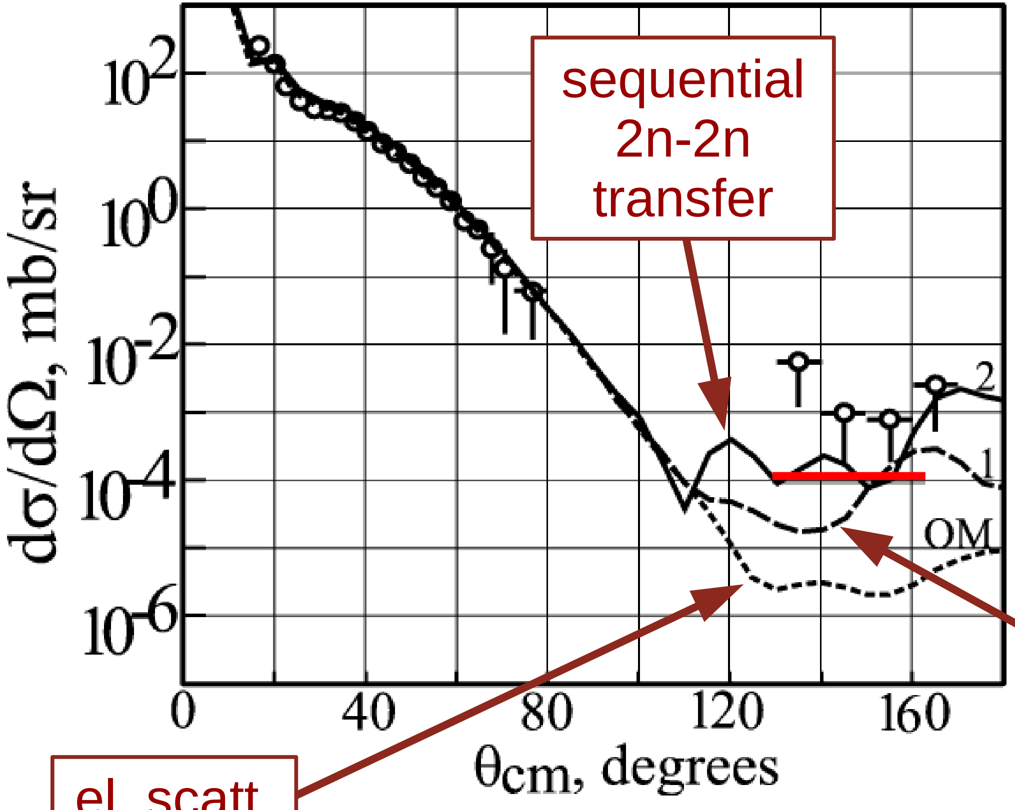
- Factor: 10 (beam) × 1 (target) × 10 (detectors)

≈ 100

Experiment in 2024

- $E(^{8}He)$ ~ 25 - 35 AMeV
- I ~ 10^{6} pps
- Target ~ 6×10^{20} cm^{-2}
- detection efficiency: 10

4n transfer – available data



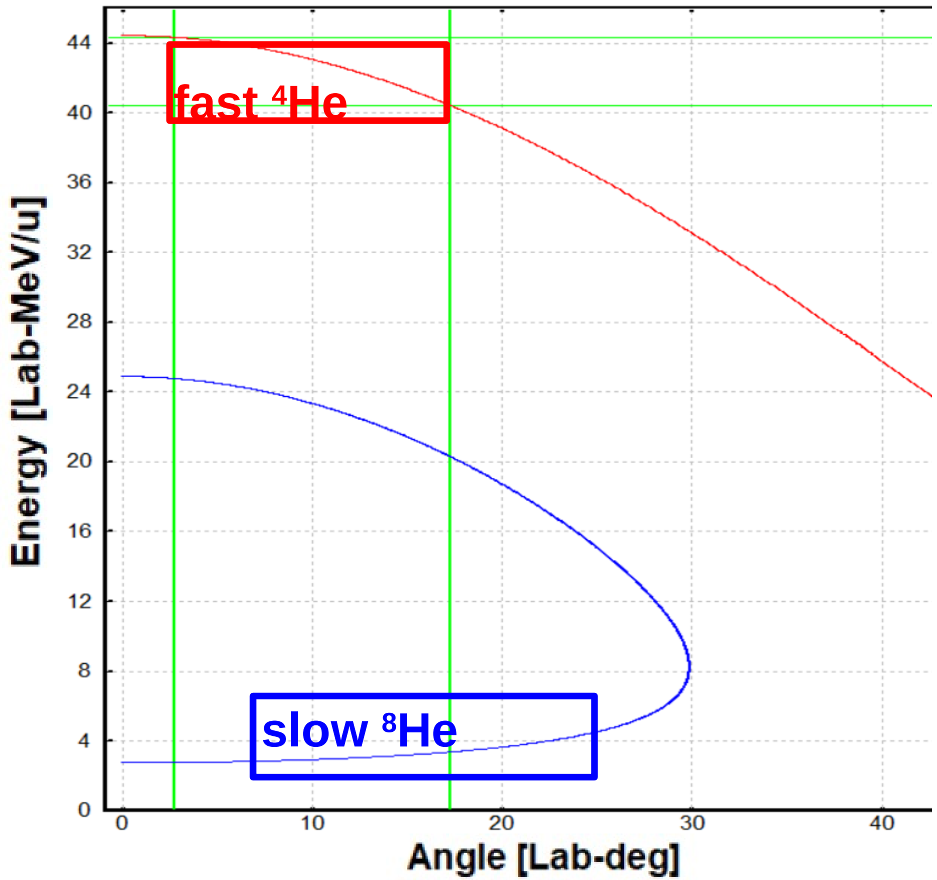
Obtained in

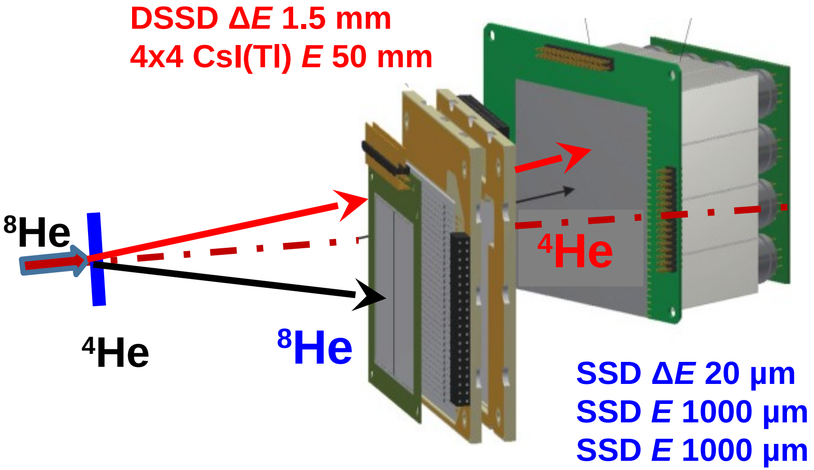
Yu. Ts. Oganessian et al., Phys. Rev. C. 60 (1999) 044605.

R. Wolski et al., Nucl. Phys. A 701 (2002) 29.

- $^4He(^8He,^8He)^4He$ at FLNR
  - $E(^8He)$ ~ 26 AMeV
  - I ~ 4×10^3 pps
  - Target ~ 2.4×10^{21} cm^{-2}

4n transfer





^{8}He: I ~ 10^5 s^{-1}, E ~ 25, 30, 35 AMeV

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

^{4}He(^{8}He,^{6}He)^{6}He

4n and 2n transfer

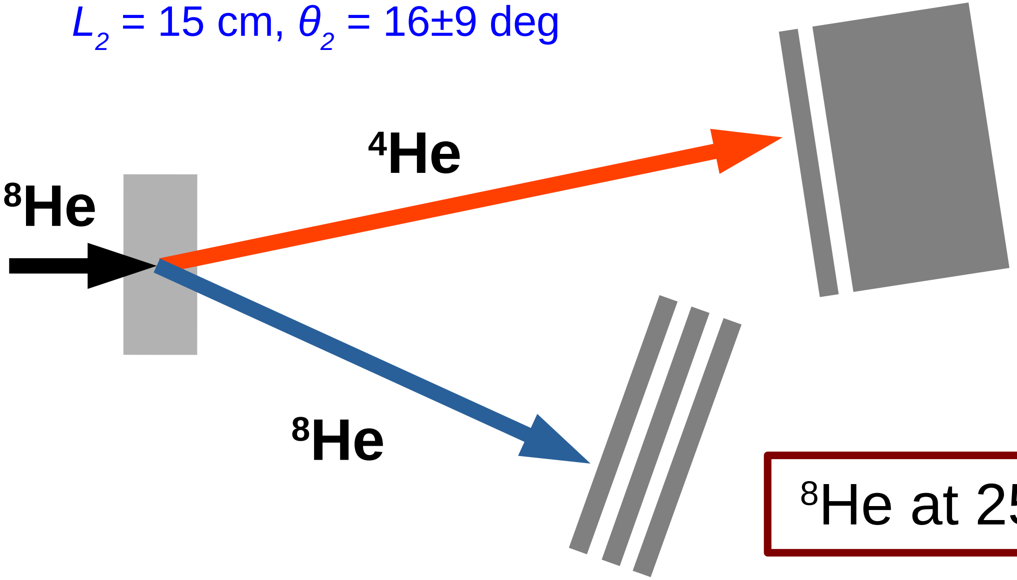
$^{4}He(^{8}He,^{4}He)^{8}He$

"symmetrical" geometry

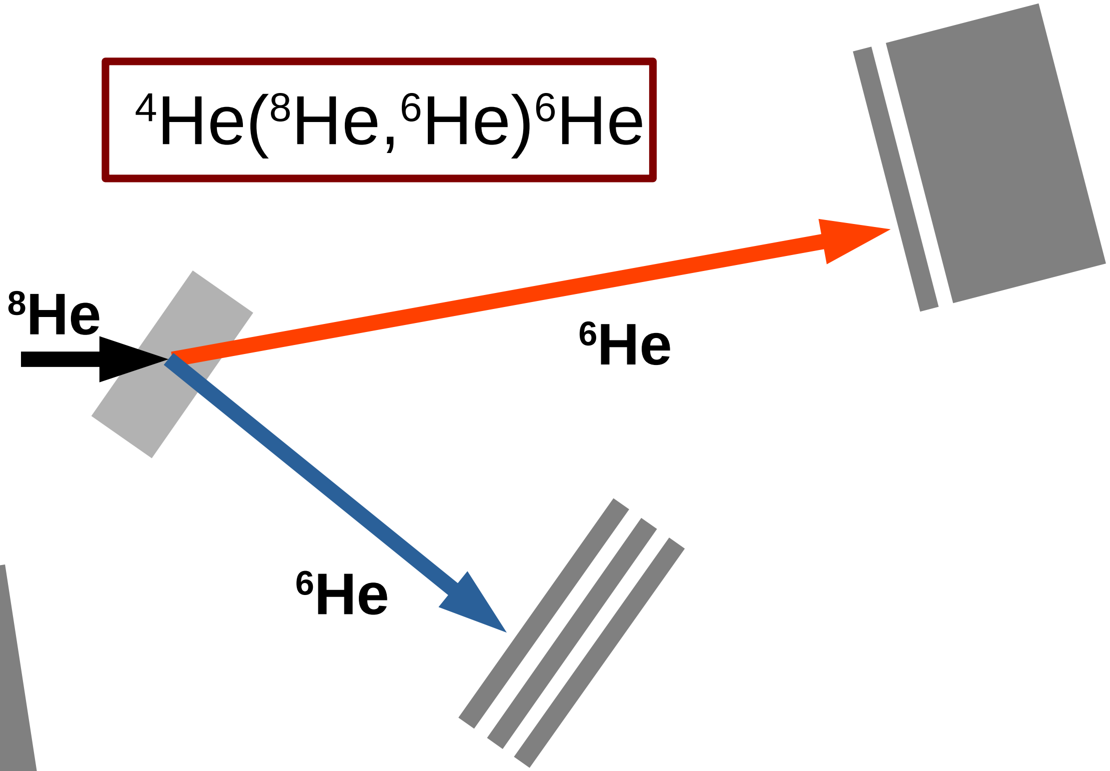
Θ_{CM} ~ 146 – 172 deg.

L_1 = 25 cm, θ_1 = 10±7 deg

L_2 = 15 cm, θ_2 = 16±9 deg



$^{4}He(^{8}He,^{6}He)^{6}He$



"asymmetrical" geometry

Θ_{CM} ~ 145 – 155 deg.

L_1 = 35 cm, θ_1 = 12±5 deg

L_2 = 12 cm, θ_2 = 31±12 deg

^{8}He at 25 MeV/A

4n and 2n transfer

Experiment in 2002

- $E(^8He)$ ~ 26 AMeV
- I ~ 4×10^3 pps
- Target ~ 2.4×10^{21} cm^{-2}
- detection efficiency: 1

Experiment in 2024

- $E(^8He)$ ~ 26 AMeV
- I ~ 10^5 pps
- Target ~ 2.1×10^{21} cm^{-2}
- detection efficiency: 4

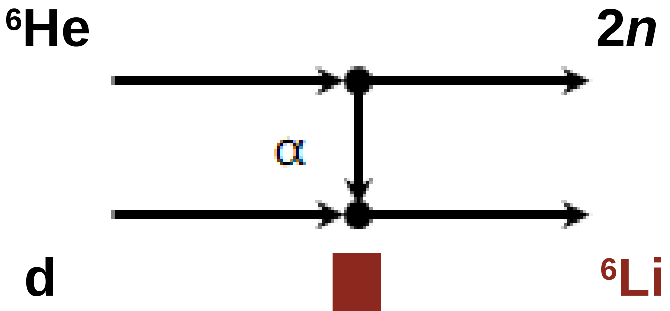
- Factor: 25 (beam) × 0.9 (target) × 4 (detectors) **≈ 90**

2n and 4n transfer

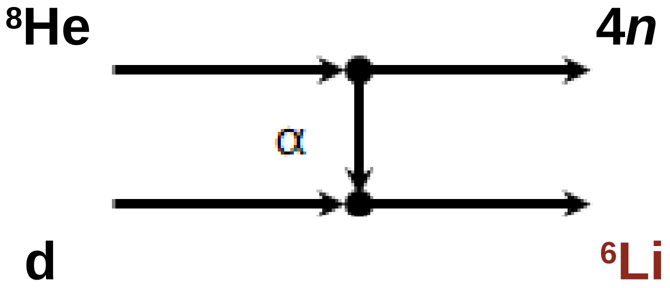
- $^{4}He(^{8}He,^{4}He)^{8}He$, 100 nb/sr assumed
  - ~80 coincidences ^{4}He-^{8}He per week
- $^{4}He(^{8}He,^{4}He)^{8}He$, 100 nb/sr assumed
  - ~20 coincidences ^{6}He-^{6}He per week
- $^{4}He(^{6}He,^{4}He)^{6}He$, 100 μb/sr assumed
  - ~10^{4} coincidences ^{4}He-^{6}He per week

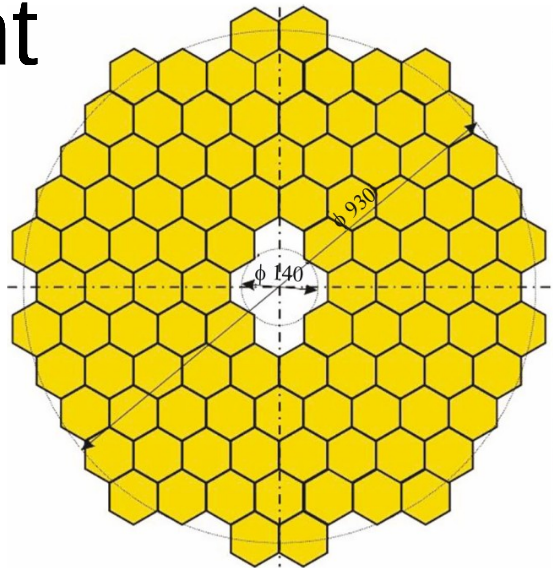
First test measurement

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



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





- 100 units of BC-404 scintillators
- 75 mm thick, 100 mm diameter
- E_n = 20 – 35 MeV
- ε_n ~ 0.2 for single neutron

Conclusions

- Production of ^{3}H, $^{6,8}He$, and $^{10,12}Be$ beams in wide energy range 10-44 MeV/A
  - test of modules for neutron wall
- Transfer of 2n/4n clusters
  - ~80 coincidences of ^{8}He-^{4}He per week expected
  - ~20 coincidences of ^{6}He-^{6}He per week expected
  - ~10^{4} coincidences of ^{6}He-^{4}He per week expected

End

Characteristics of obtained RIBs

Ion	E, AMeV	Reaction	I, pps/pμA	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
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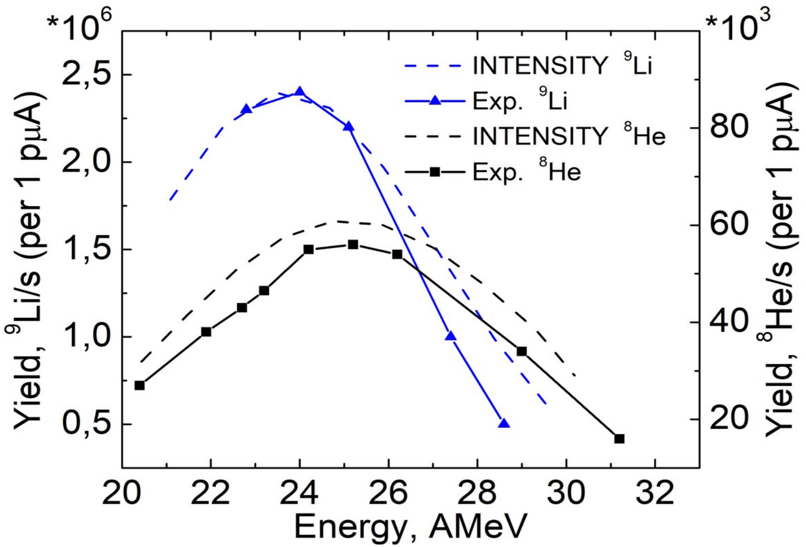
^{26}P	28	^{32}S (52.7 AMeV)+Be (0.5 mm)	15	<0.5	0.75
^{27}S	27	--“--	60	1	0.75

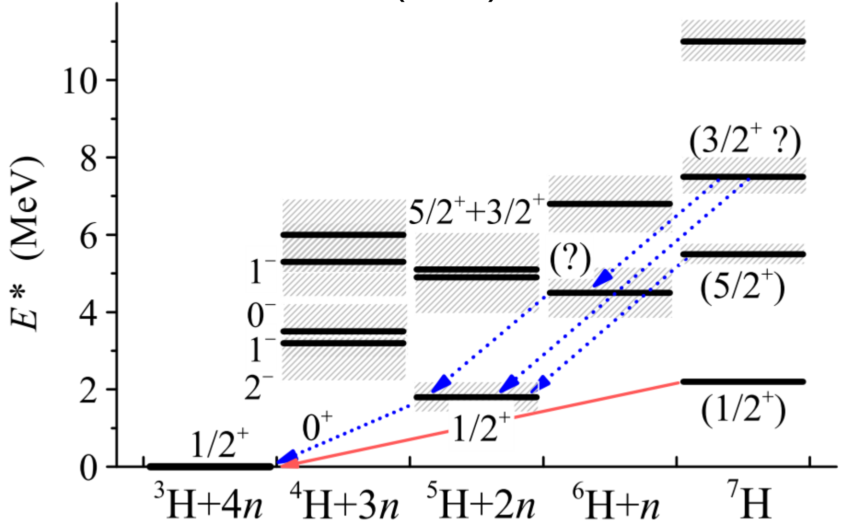
Real basic RIBS characteristics are in a good agreement with technical specifications and estimations.



Conclusions on recent experiments

- **^{7}H** *A. A. Bezbakh et al.*, Phys. Rev. Lett. 124 (2020) 022502 *I. A. Muzalevskii et al.*, Phys. Rev. C 103 (2021) 044313
  - g.s. at 2.2 MeV; resonant states at 5.5 MeV, probably 7.5 MeV, and 11 MeV observed
- **^{6}H** *E. Y. Nikolskii et al.*, Phys. Rev. C 105 (2022) 064605.
  - Resonant state at 2.7 MeV not observed
  - eminent peak at 6.5 MeV observed
  - lower possible energy limit for g.s. 4.5 M

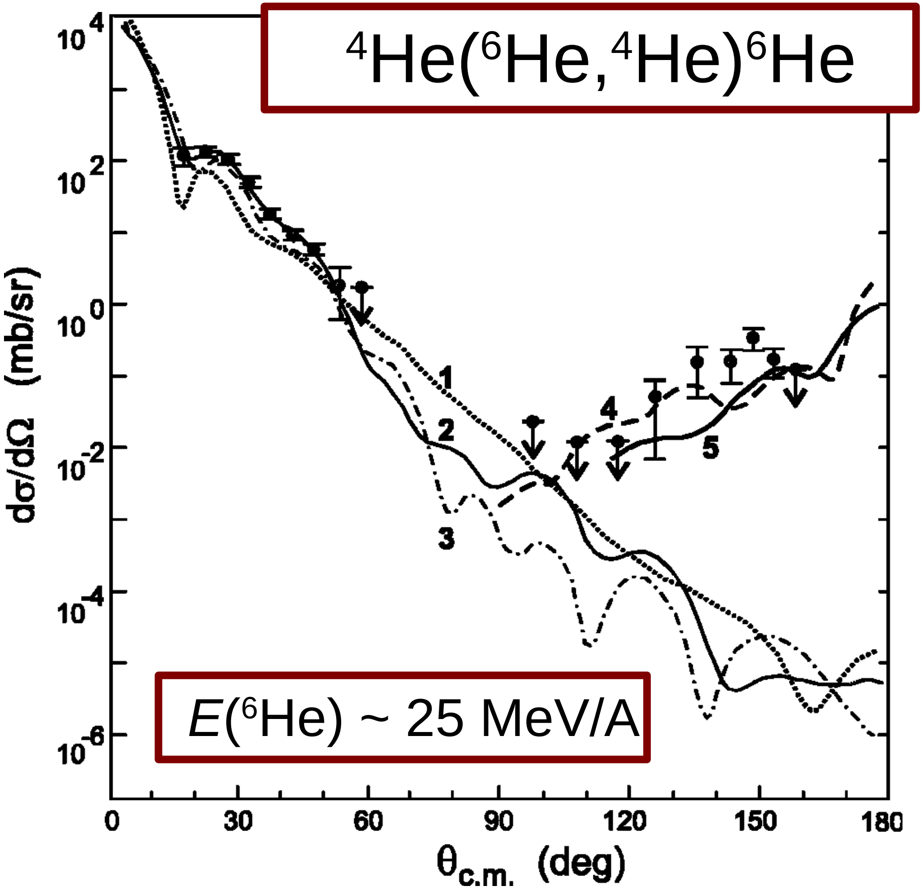
A. A. Bezbakh et al., Phys. Rev. Lett. 124 (2020) 022502
I. A. Muzalevskii et al., Phys. Rev. C 103 (2021) 044313
E. Y. Nikolskii et al., Phys. Rev. C 105 (2022) 064605.



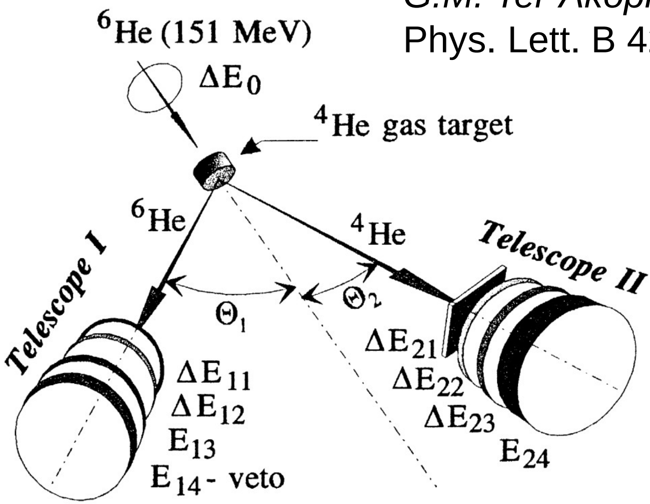
- calibrations confirmed by ^{10}Be(^{2}H,^{3}He)^{9}Li and ^{10}Be(^{2}H,^{4}He)^{8}Li reaction
- evidence for novel mode of nuclear decay (true 4n decay) obtained for the first time

Backup: 2n transfer – available data

Yu. Ts. Oganessian et al., Phys. Rev. C. 60 (1999) 044605.



G.M. Ter-Akopian et al., Phys. Lett. B 426 (1998) 251.



(1) optical-model with the parameters as for $^6Li+^4He$

(2) OM fit with the parameters for $^6He+^4He$

(3) OM with the real double-folding potential of the $^6He+^4He$

(4) 2n-cluster exchange

(5) four-body model of the 2n transfer

4n transfer

$^4He(^8He,^4He)^8He$, 100 nb/sr assumed

θ_{CM}, deg. ($\Delta\theta_{CM} = 4^0$)	θ_{LAB}, deg. **^{8}He slow**	E, *A*MeV **^{8}He slow**	θ_{LAB}, deg. **^{4}He fast**	E, *A*MeV **^{4}He fast**	Counting rate, events/day
140	27,4	5,35	19,7	39,3	0,1
144	26,2	4,93	17,8	40,2	0,4
148	24,7	4,47	15,9	41,1	0,9
152	22,8	4,08	13,9	41,8	1,4
156	20,5	3,73	11,9	42,5	1,7
160	17,8	3,44	9,9	43,1	2,0
164	14,8	3,20	7,9	43,6	2,3
168	11,5	3,02	5,9	44,0	1,9
172	7,8	2,88	3,9	44,2	0,4

- ~80 coincidences ^4He-^8He per week in total

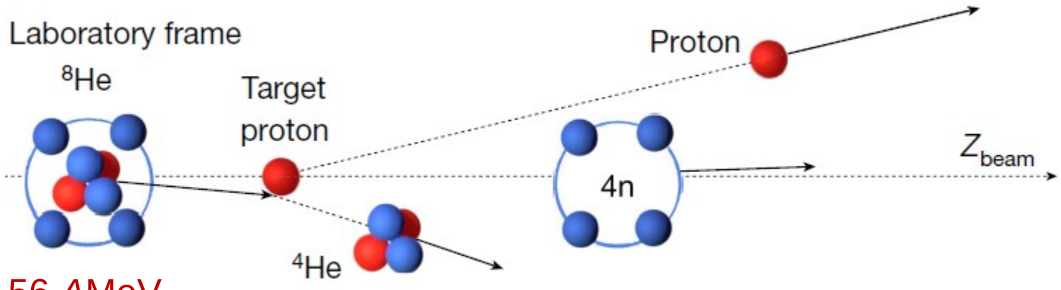
2n transfer

$^4He(^8He,^6He)^6He$, 100 nb/sr assumed

θ_{CM}, deg. ($\Delta\theta_{CM}=4^0$)	θ_{LAB}, deg. **^{6}He slow**	E, *A*MeV **^{6}He slow**	θ_{LAB}, deg. **^{6}He fast**	E, *A*MeV **^{6}He fast**	Counting rate, events/day
148	42,5	4,03	13,0	35,8	0,2
152	40,8	3,36	11,3	36,5	0,4
156	38,5	2,80	9,8	37,0	0,8
160	35,2	2,31	8,2	37,5	0,7
164	30,7	1,91	6,5	37,9	0,4
168	24,9	1,59	4,9	38,2	0,1

- ~20 coincidences ^6He-^6He per week in total

Study of 4n system at RIKEN

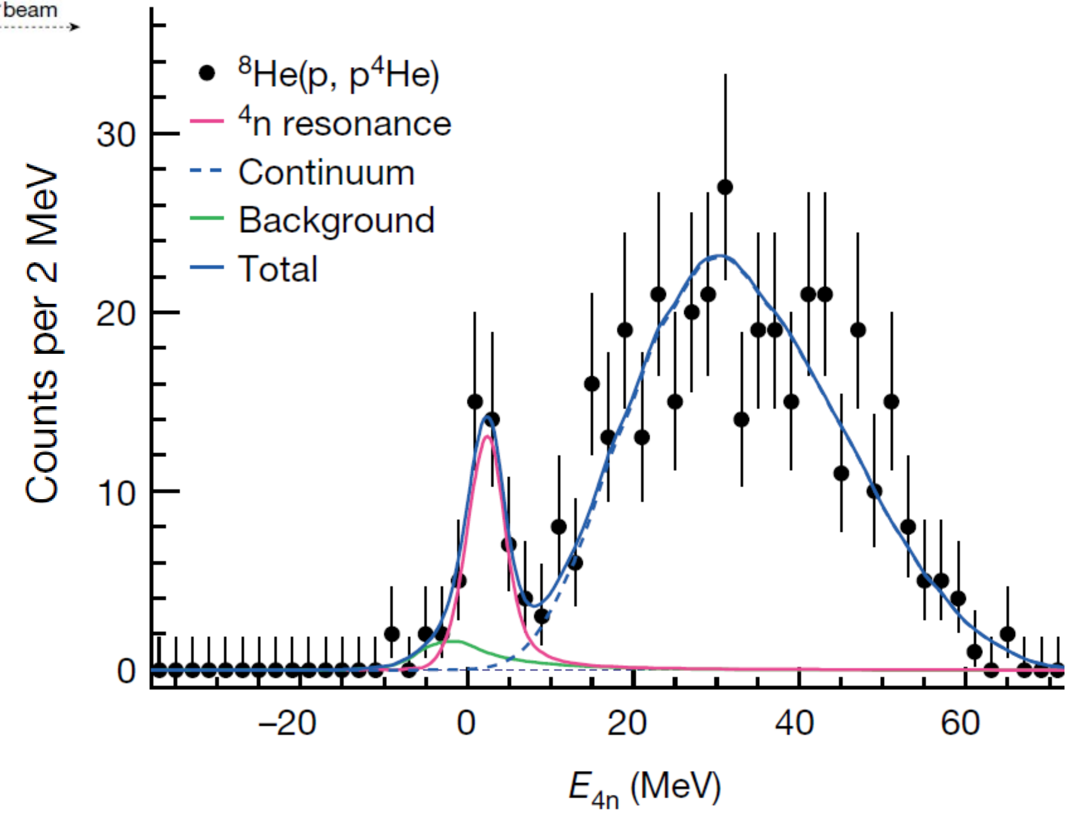


156 *A*MeV

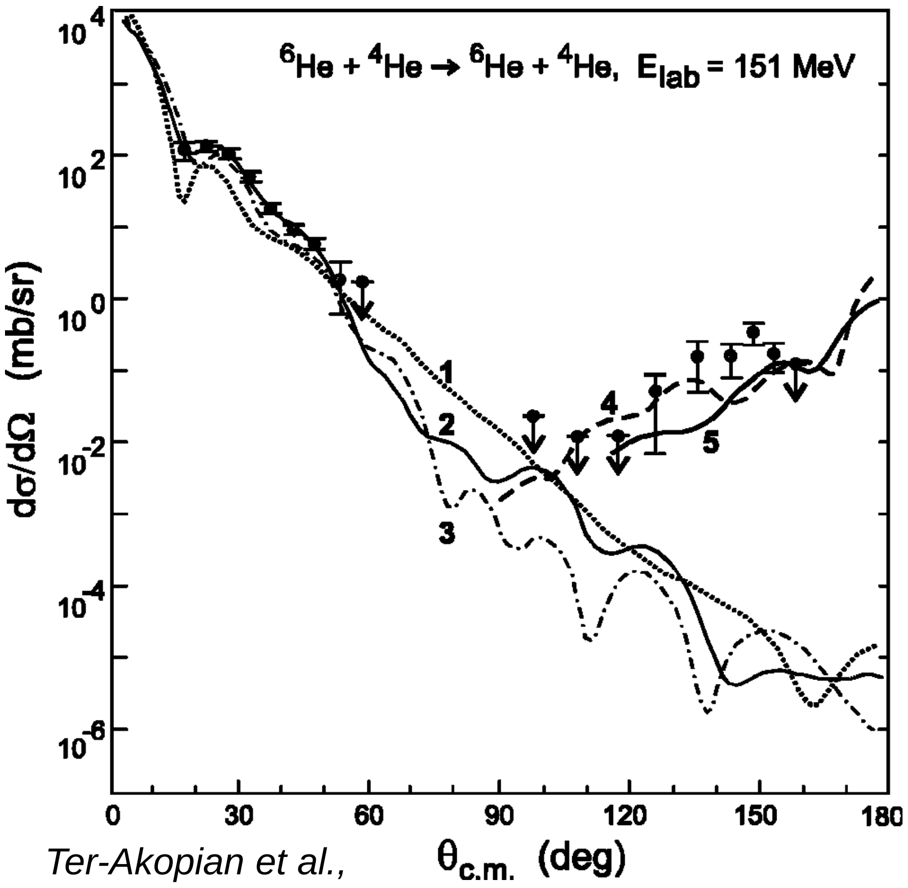
- **QFS ^{1}H(^{8}He, p^{4}He)*4n***
- ***E*(^{8}He) ~ 156 *A*MeV**

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

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



2n transfer



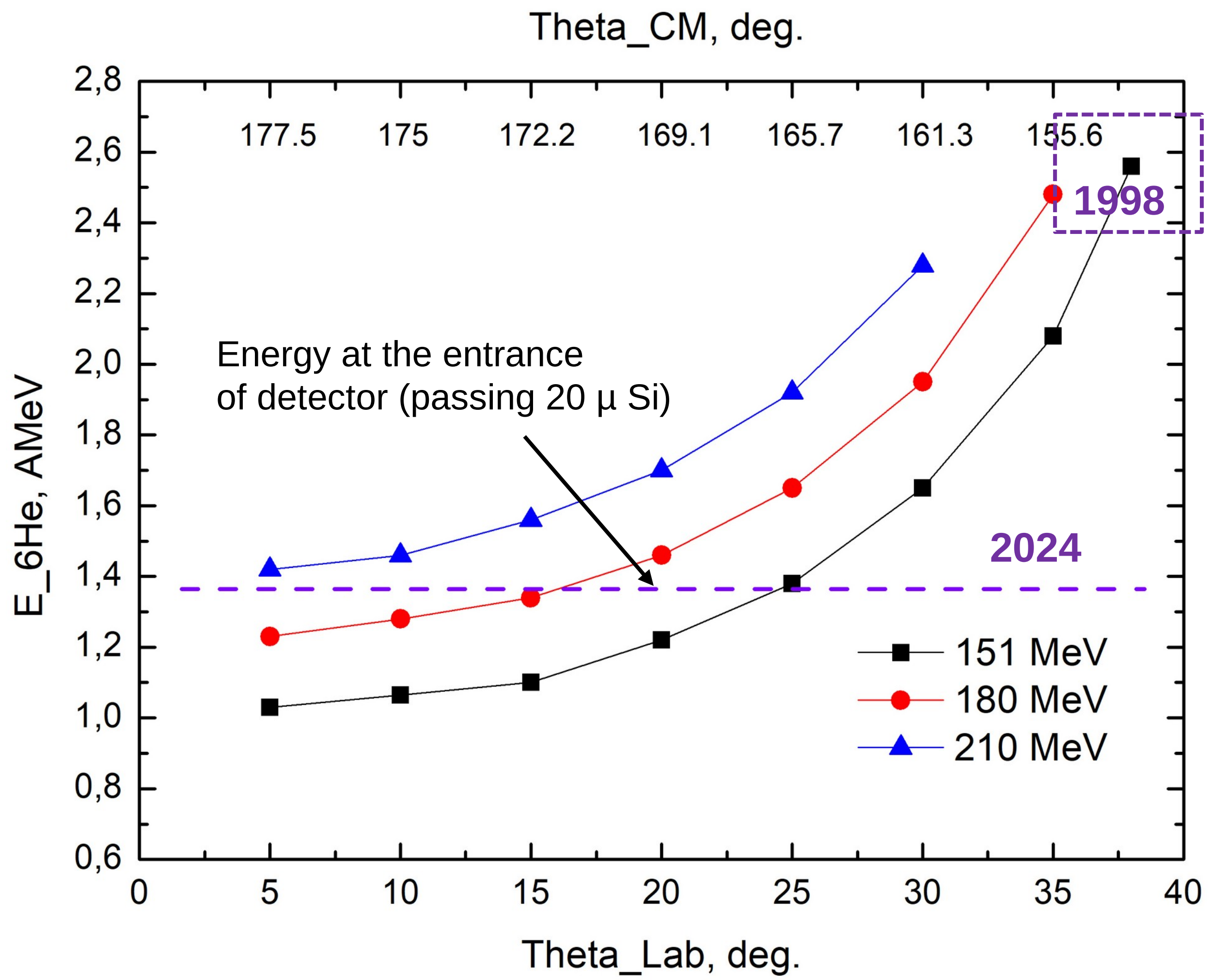
Ter-Akopian et al., Phys. Lett. B 426 (1998) 251, *Oganessian et al.*, Phys. Rev. C. 60 (1999) 044605.

^{4}He-^{6}He coincidences: ~ 16÷50 / day

(10 μb/sr, 10^6 pps, $3*10^{20}$ Atoms/cm^2)

Ion	θ_{lab}, deg.	θ_{cm}, deg.	E, AMeV	Counting, per day
^{4}He fast	4	8.1	50.3	51
	8	16.2	49.5	47
	12	24.3	48.3	50
	16	32.4	46.5	51
^{6}He slow	15.4	171.9	1.41	16
	27.35	163.8	1.93	37
	34.9	155.7	2.77	58
	39.2	147.6	3.92	50

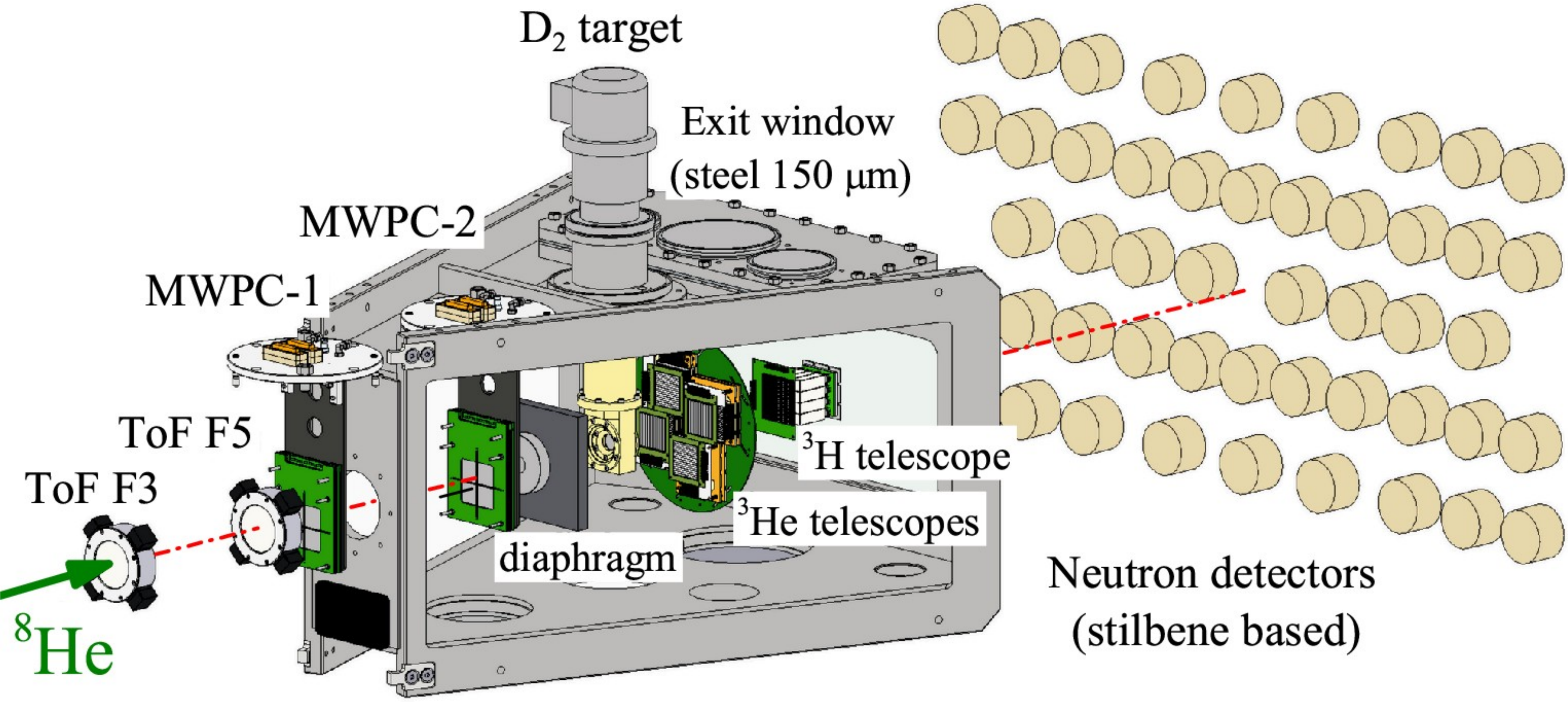
$^{4}He(^{6}He,^{6}He)^{4}He$ experiment at 25-35 AMeV



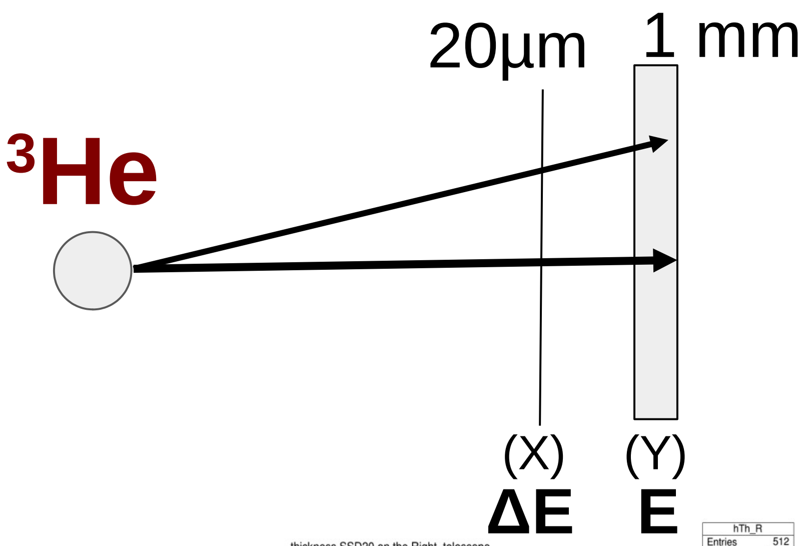
50-year-long quest

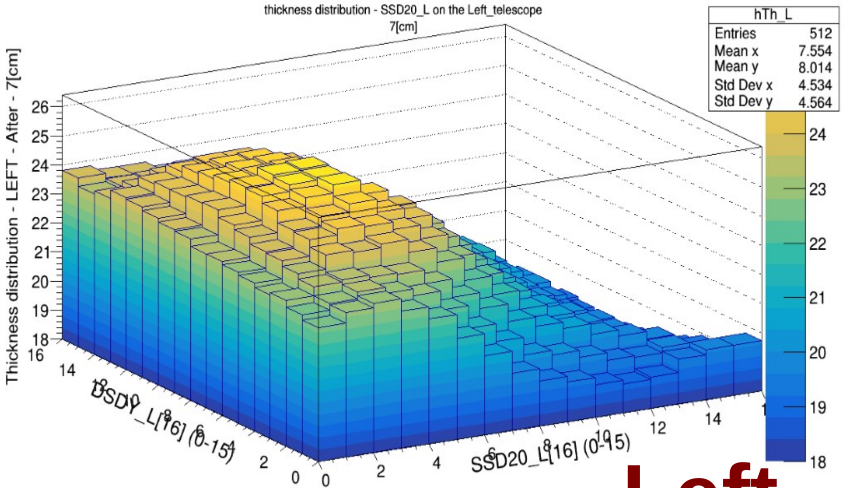
- predicted in 1972
  - A. I. Baz' et al., "Light and intermediate nuclei near the border of nuclear stability" (Nauka, Moscow, Moscow, **1972**).
- $^{7}Li(\pi^{-},\pi^{+})$
  - K. Seth, "Pionic probes for exotic nuclei," **(1981)**;
  - V. Evseev et al., Nuclear Physics A 352, 379 **(1981)**;
- ^{252}Cf ternary fission
  - D. Aleksandrov et al., Yad. Fiz. 36, 1351 **(1982)**;
- $d(^{8}He,^{7}H)$
  - M. S. Golovkov et al., Phys. Lett. B 588, 163 **(2004)**;
- $^{11}B(\pi^{-},p\ ^{3}He)$
  - Y. Gurov et al., The EPJ A 32, 261 **(2007)**;
  - Y. Gurov et al., PPN 40, 558 **(2009)**;

Appendix: Full setup

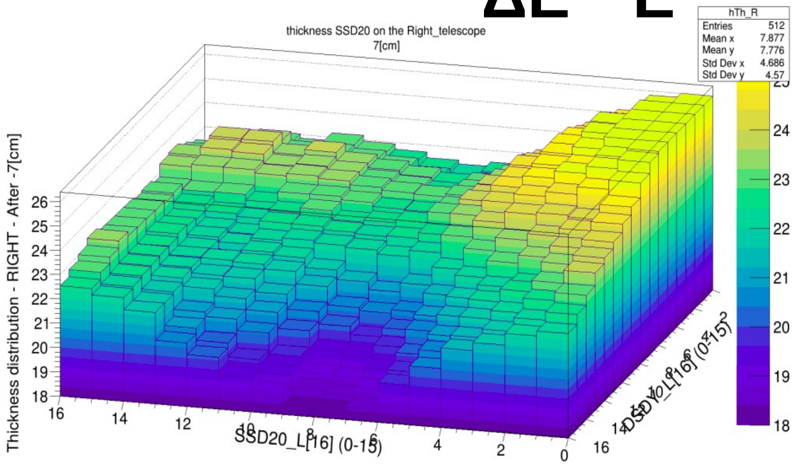


Appendix: Identification of ^{3}He





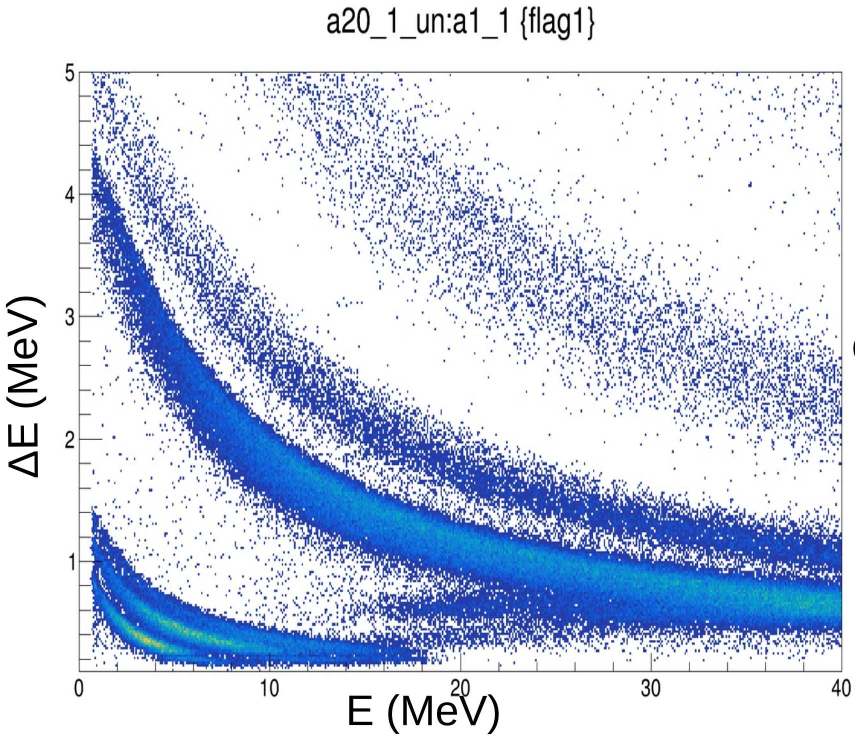
Left telescope



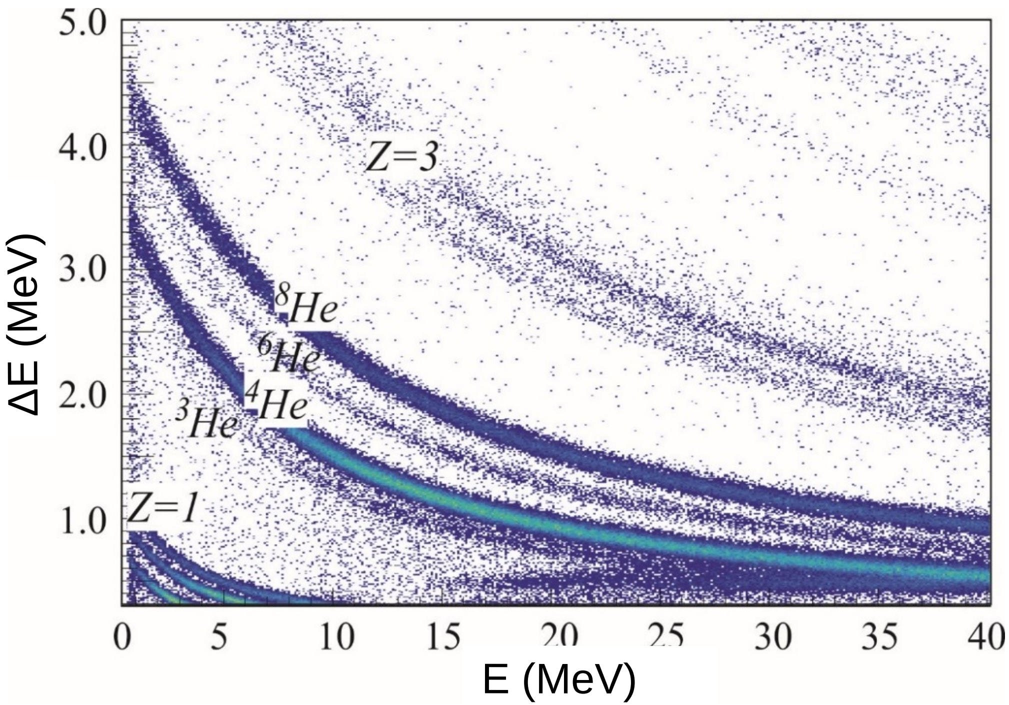
Right telescope

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

Appendix: Identification of ^{3}He

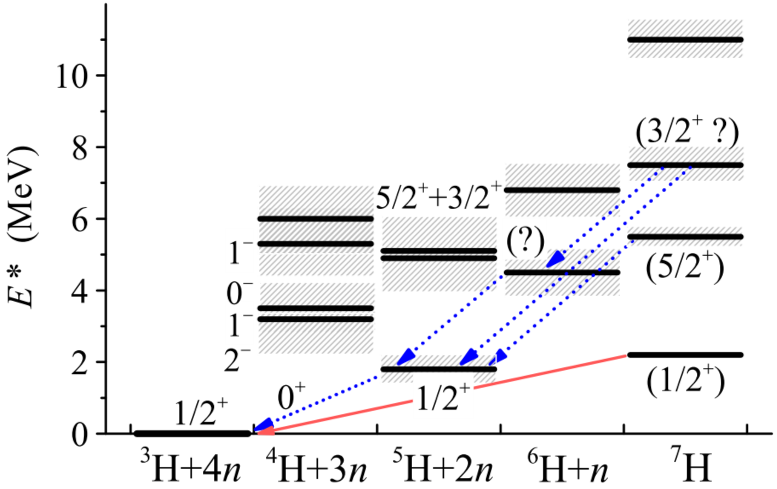


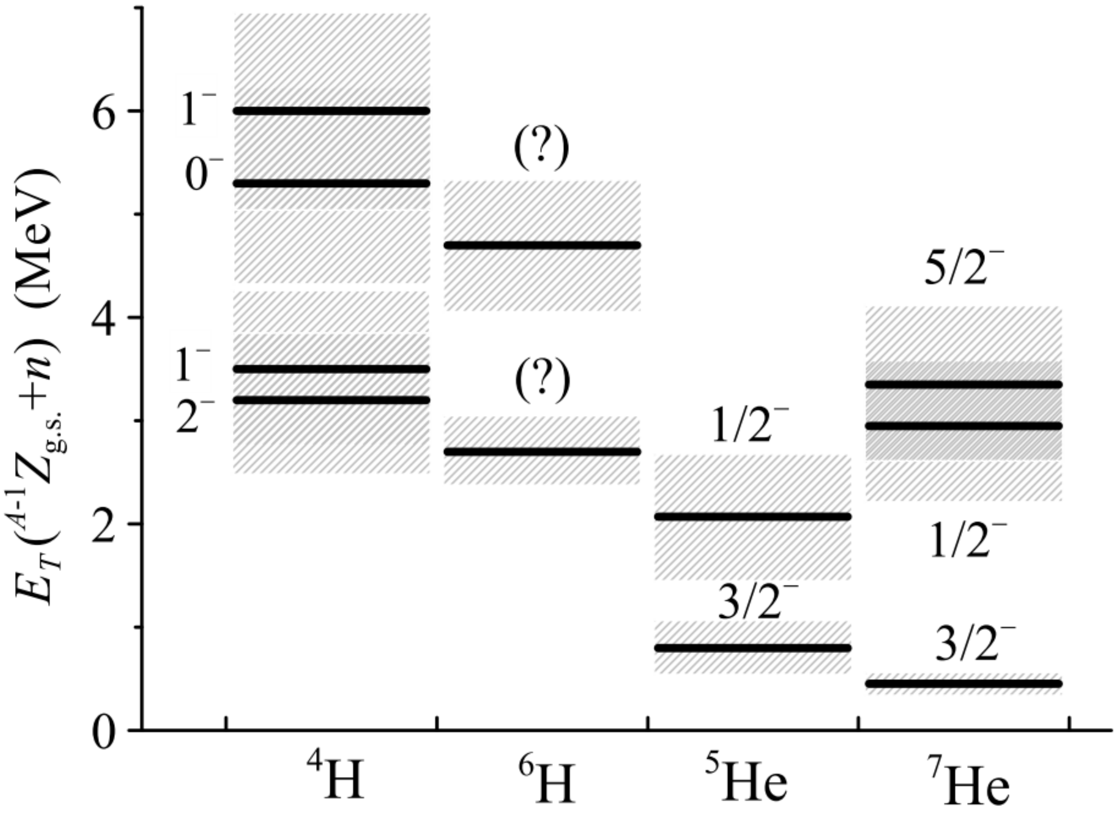
correction



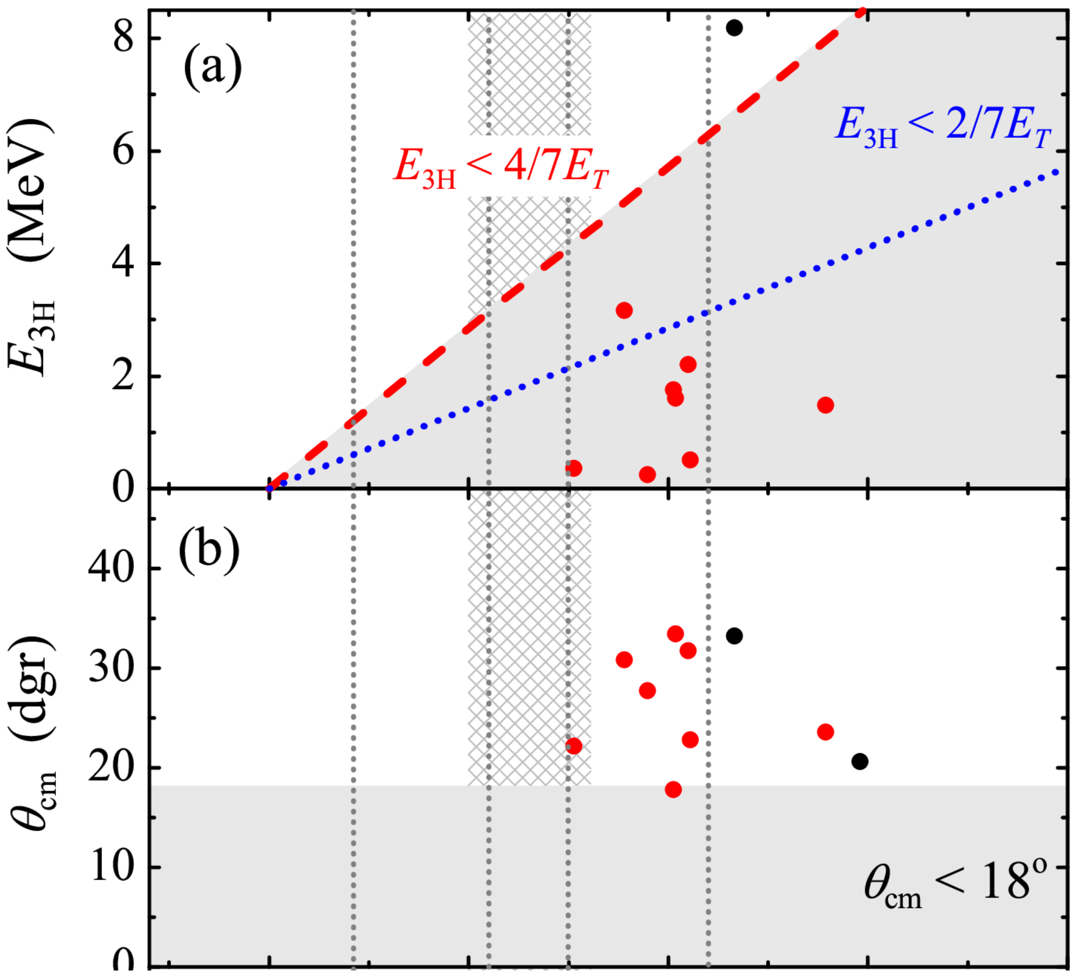
I. Muzalevski et al., Bull.Rus.Acad.Sci.: Phys., 84, 500 (2020)

Appendix: Energy levels

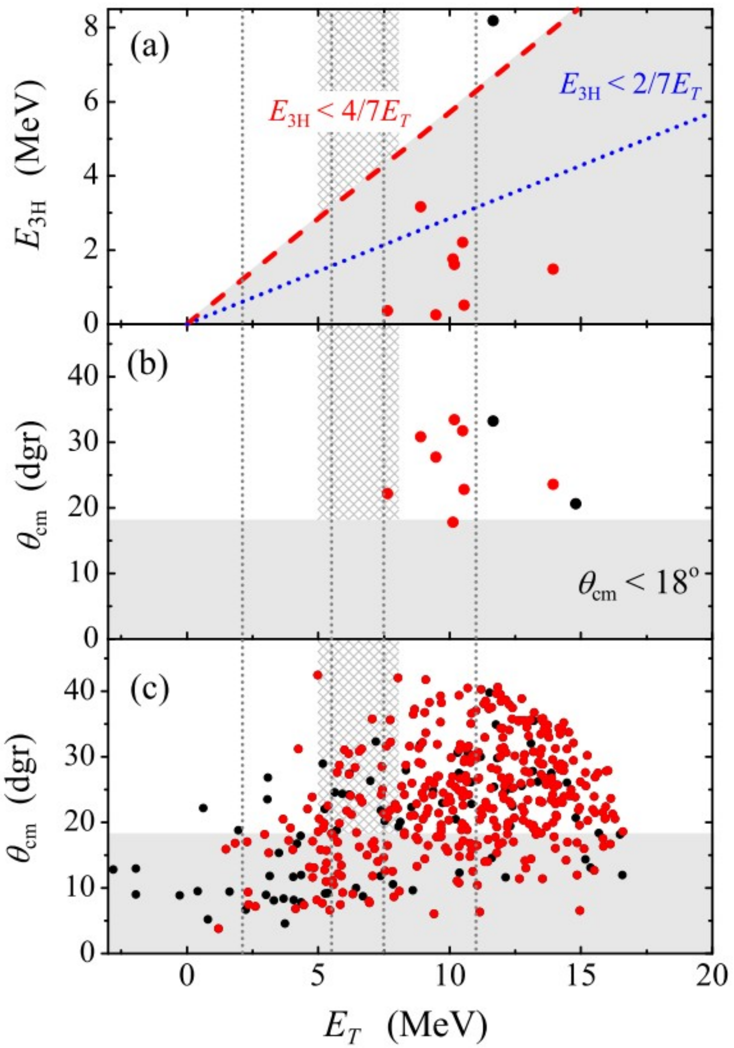




Appendix: Background measurement

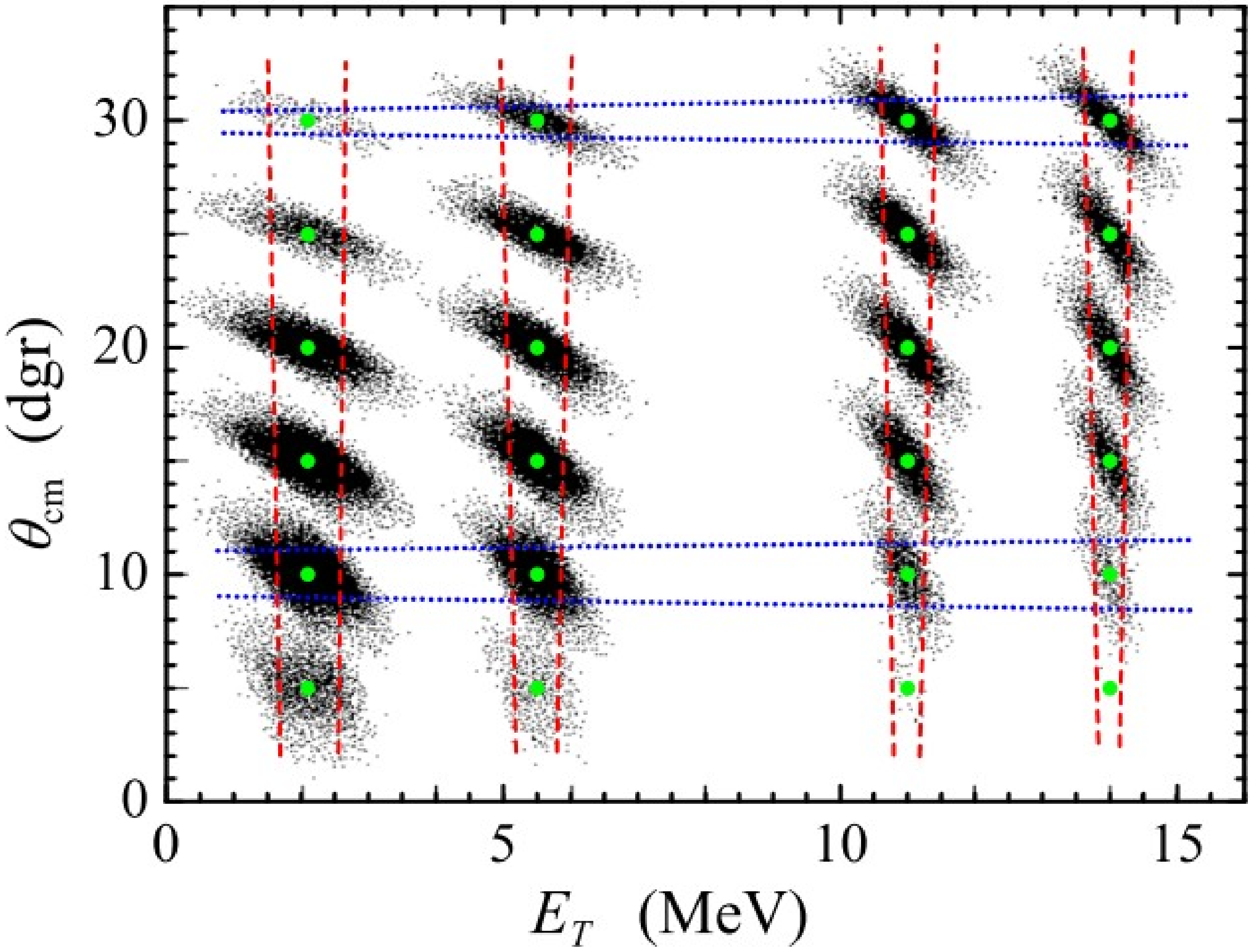


Appendix: Background measurement



- 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



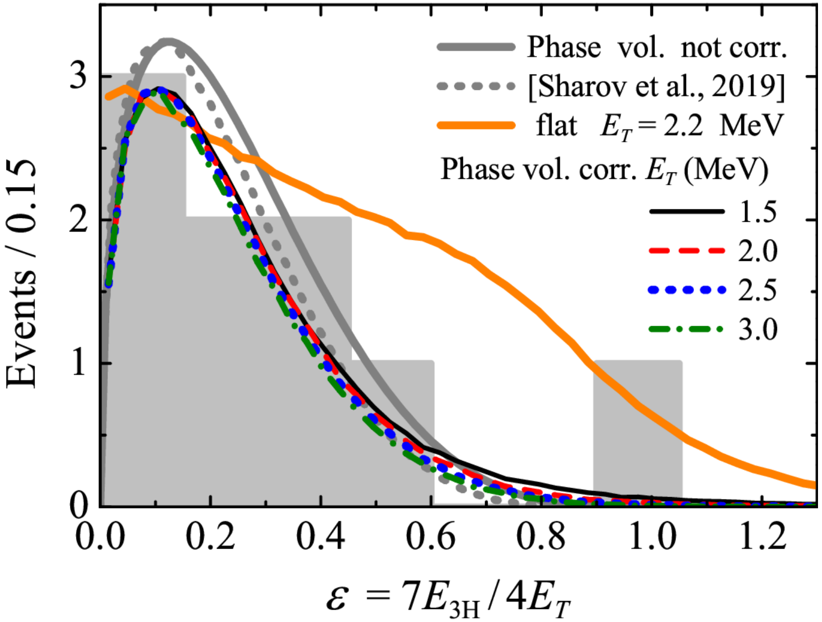
- complete MC simulations to check the detection setup
- higher energy resolution than in the previous experiments (less than 1 MeV) is obtained

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.



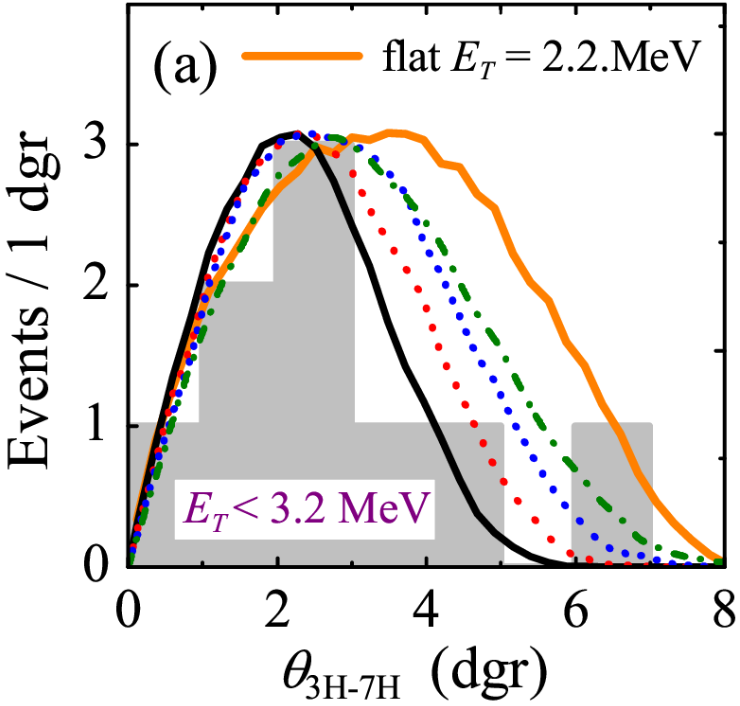
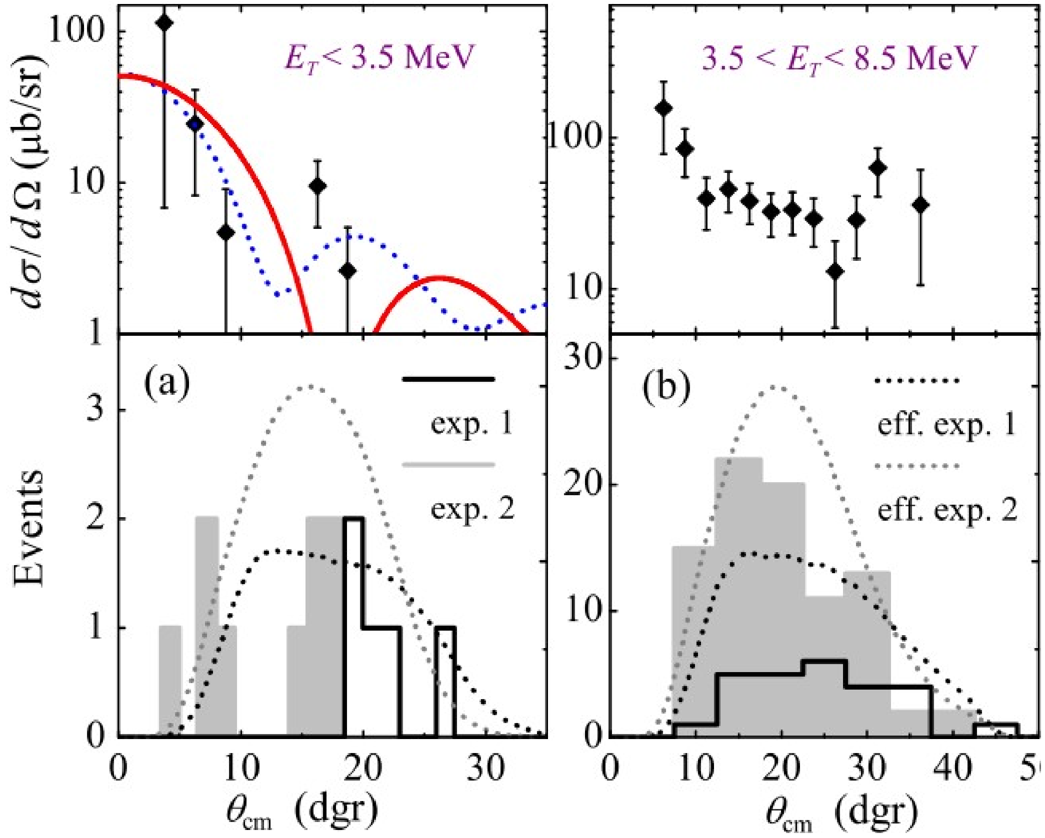


TABLE II. Mean values of the ε distributions of Figs. 13 and 14.

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.