Использование радиоактивных пучков для изучения экзотических ядер вблизи границ ядерной стабильности: эксперимент

А.С. Фомичев от коллаборации ACCULINNA-2

[1]Flerov Laboratory of Nuclear Reactions, JINR, 141980 Dubna, Russia
[2]Institute of Physics, Silesian University in Opava, 74601 Opava, Czech Republic
[3]SSC RF ITEP of NRC "Kurchatov Institute", 117218 Moscow, Russia
[4]National Research Nuclear University "MEPhI", 115409 Moscow, Russia
[5]Dubna State University, 141982 Dubna, Russia
[6]National Research Centre "Kurchatov Institute", Kurchatov sq. 1, 123182 Moscow, Russia
[7]Heavy Ion Laboratory, University of Warsaw, 02-093 Warsaw, Poland
[8]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[9]II. Physikalisches Institut, Justus-Liebig-Universität, 35392 Giessen, Germany
[10]Laboratory of Information Technologies, JINR, 141980 Dubna, Russia
[11]Nuclear Research Institute, 670000 Dalat, Vietnam
[12]AGH University of Science & Technology, Faculty of Physics & Applied Computer Science, 30-059 Kraków, Poland
[13]Institute of Nuclear Physics PAN, Radzikowskiego 152, 31342 Kraków, Poland
[14]Department of Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden
[15]Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119991 Moscow, Russia

http://flerovlab.jinr.ru/acculina-ii/

Зачем (more details → LVG) и как изучать ??

Карта нуклидов
- 254 стабильных ядра,
- 339 имеются в природе
- Около 3100 изотопов найдено
- Оценка: 2500 еще не найдено

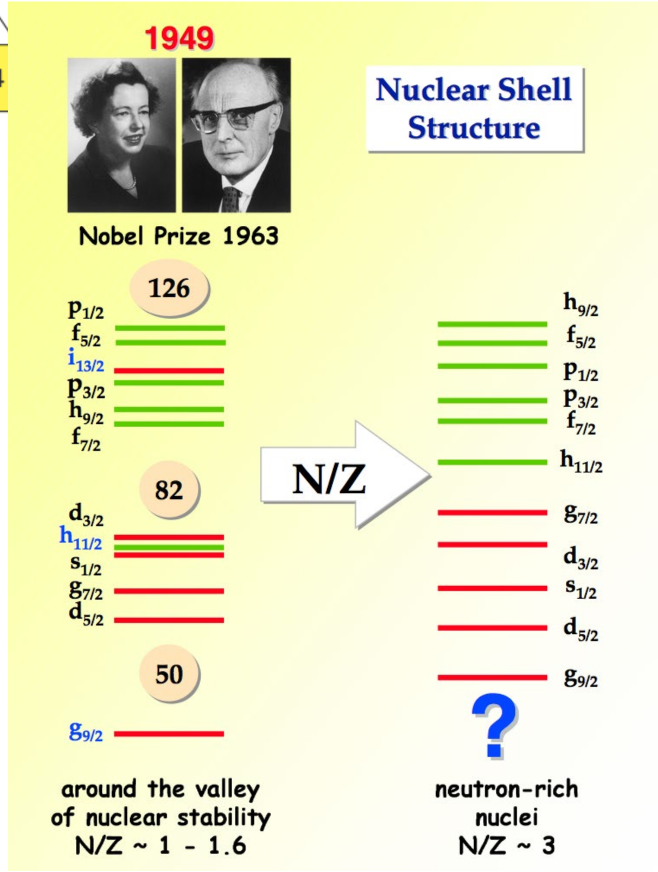
"Остров стабильности" сверхтяжелых элементов: слегка коснулись "берега"

Протонная граница стабильности: Достигнута и изучена для Z < 32

Экзотическая структура ядер:
- нейтронные/протонные гало
- протонные гало
- "Мягкие" моды возбуждения
- Новые магические числа
- Разрушение оболочечной структуры

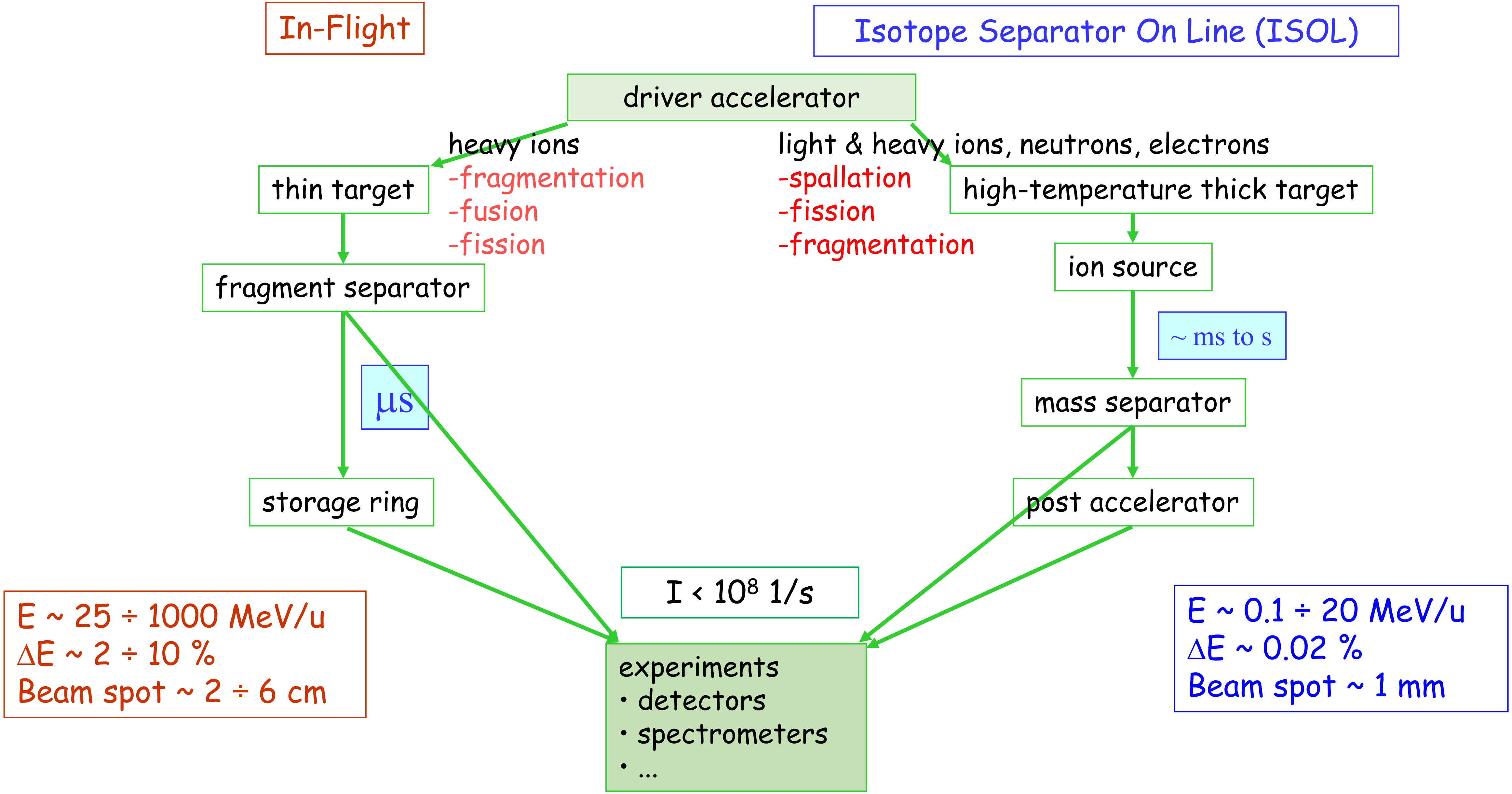
Нейтронная граница стабильности: Достигнута/изучена для N < 20

Пределы существования ядерной структуры: известны для нескольких легчайших ядер

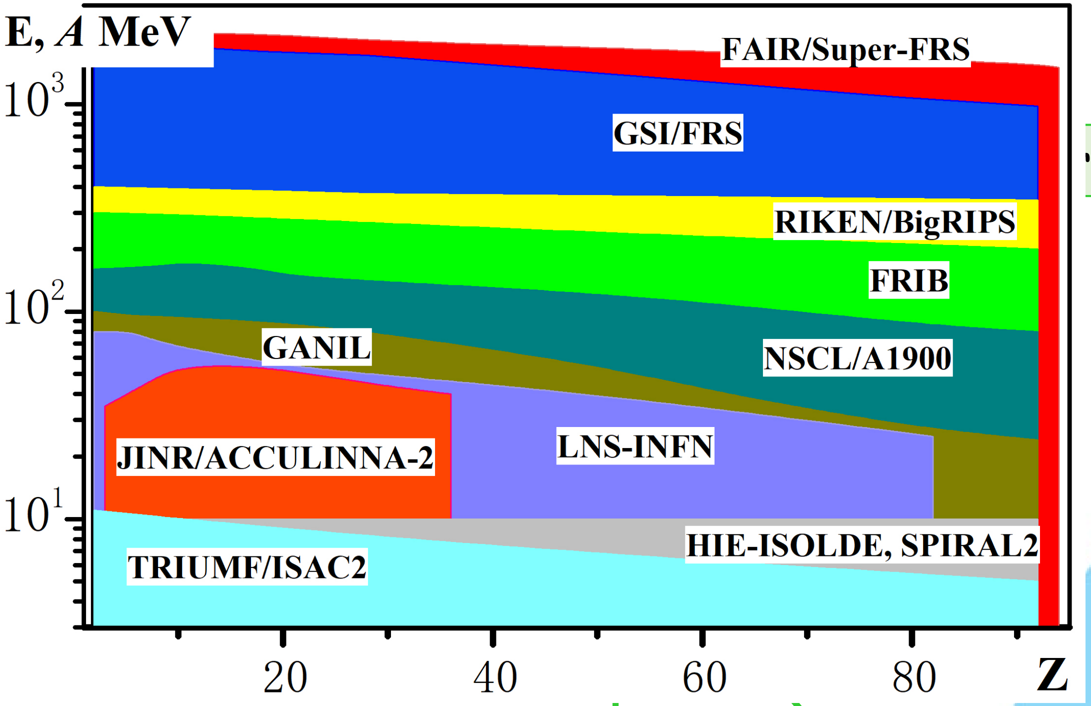


Ca: возможны 5(!) магических чисел N = 20, 28, 32, 34, 40

Production of Radioactive Ion Beams: In-Flight versus ISOL



Production of Radioactive Ion Beams: In-Flight versus ISOL



storage ring

E ~ 25 ÷ 1000 MeV/u
ΔE ~ 2 ÷ 10 %
Beam spot ~ 2 ÷ 6 cm

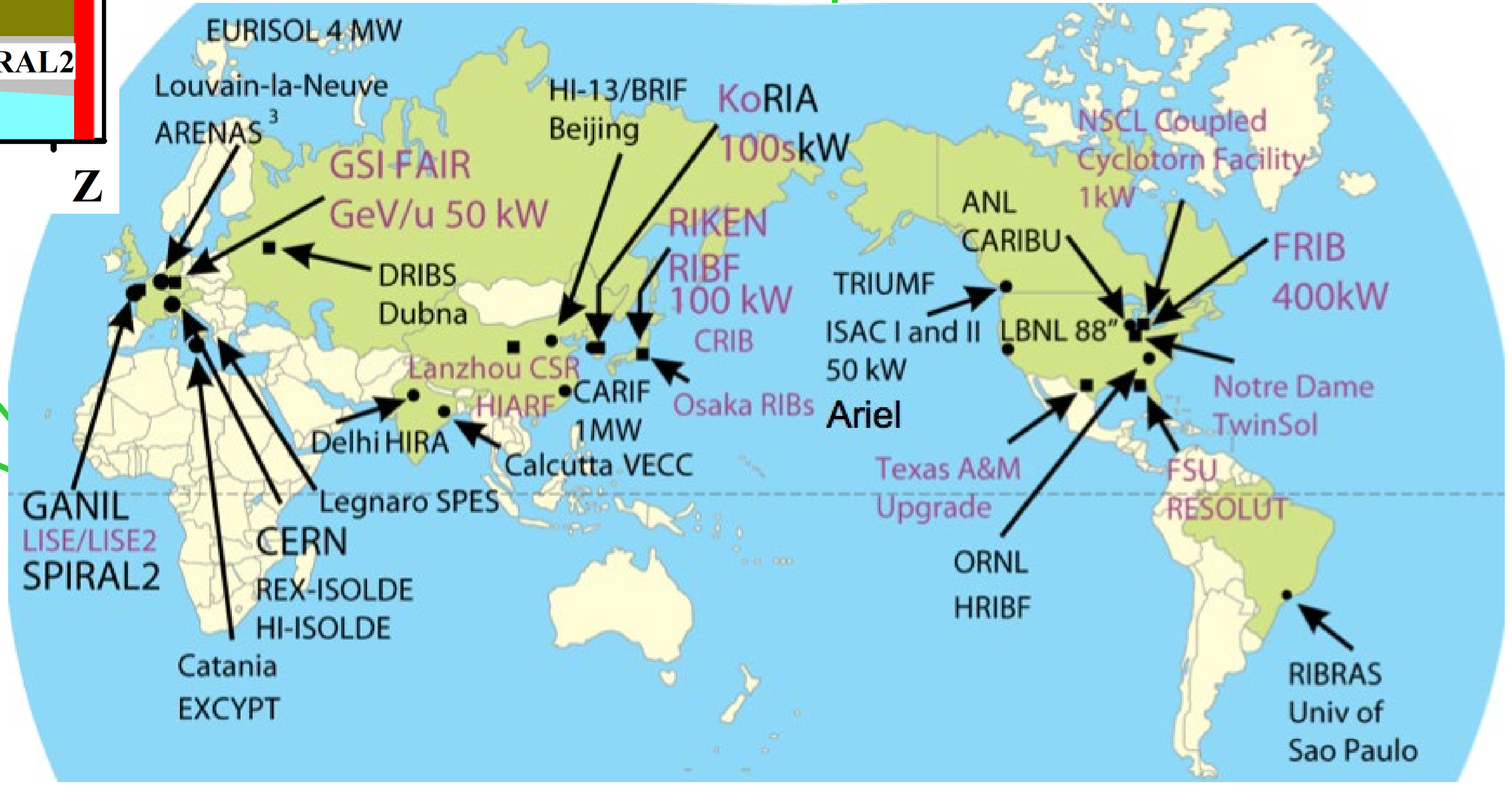
Isotope Separator On Line (ISOL)

driver accelerator

light & heavy ions, neutrons, electrons
- spallation
- fission
- fragmentation

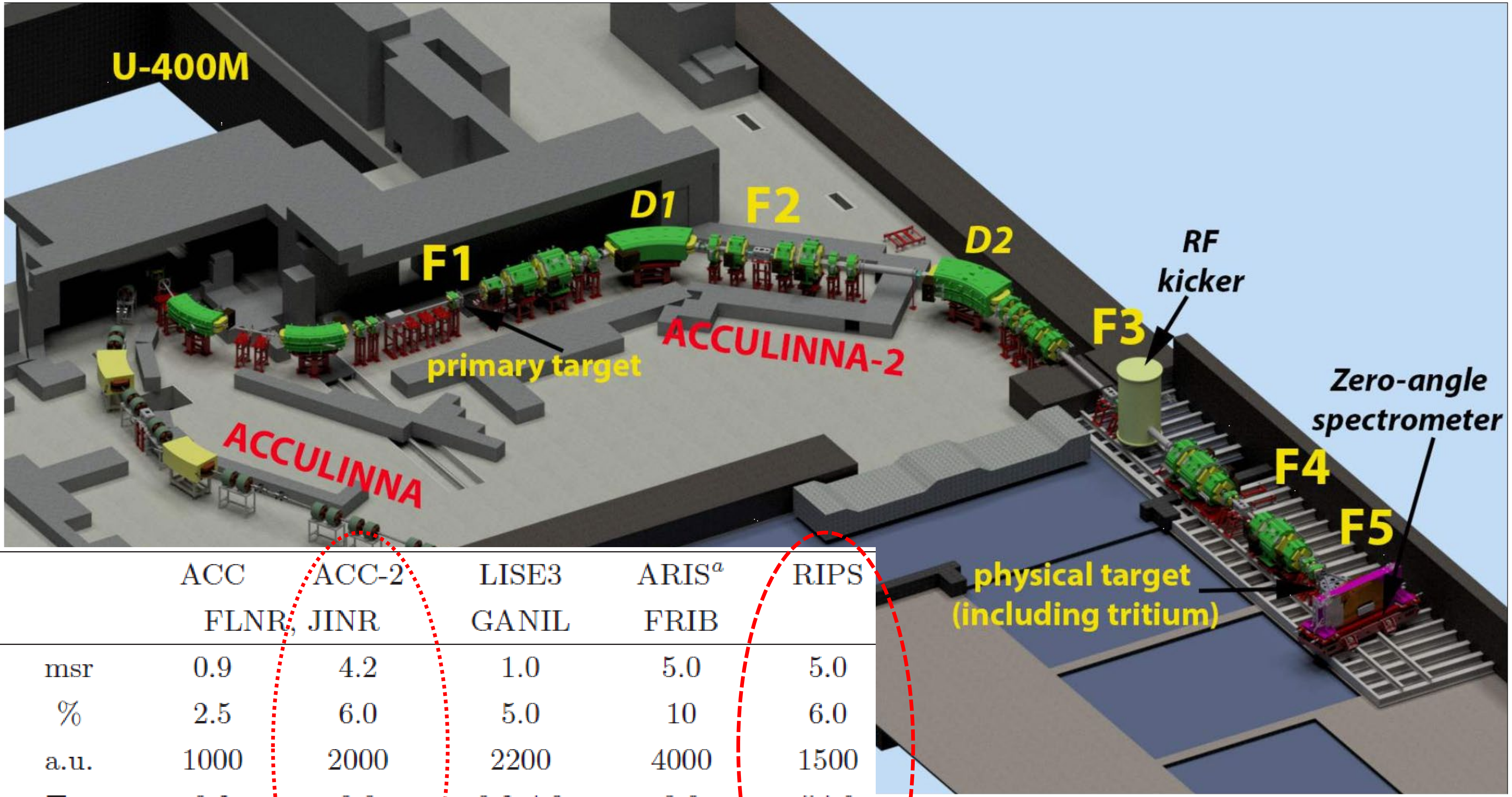
high-temperature thick target

ion source



ACCULINNA-2 fragment-separator at U-400M cyclotron

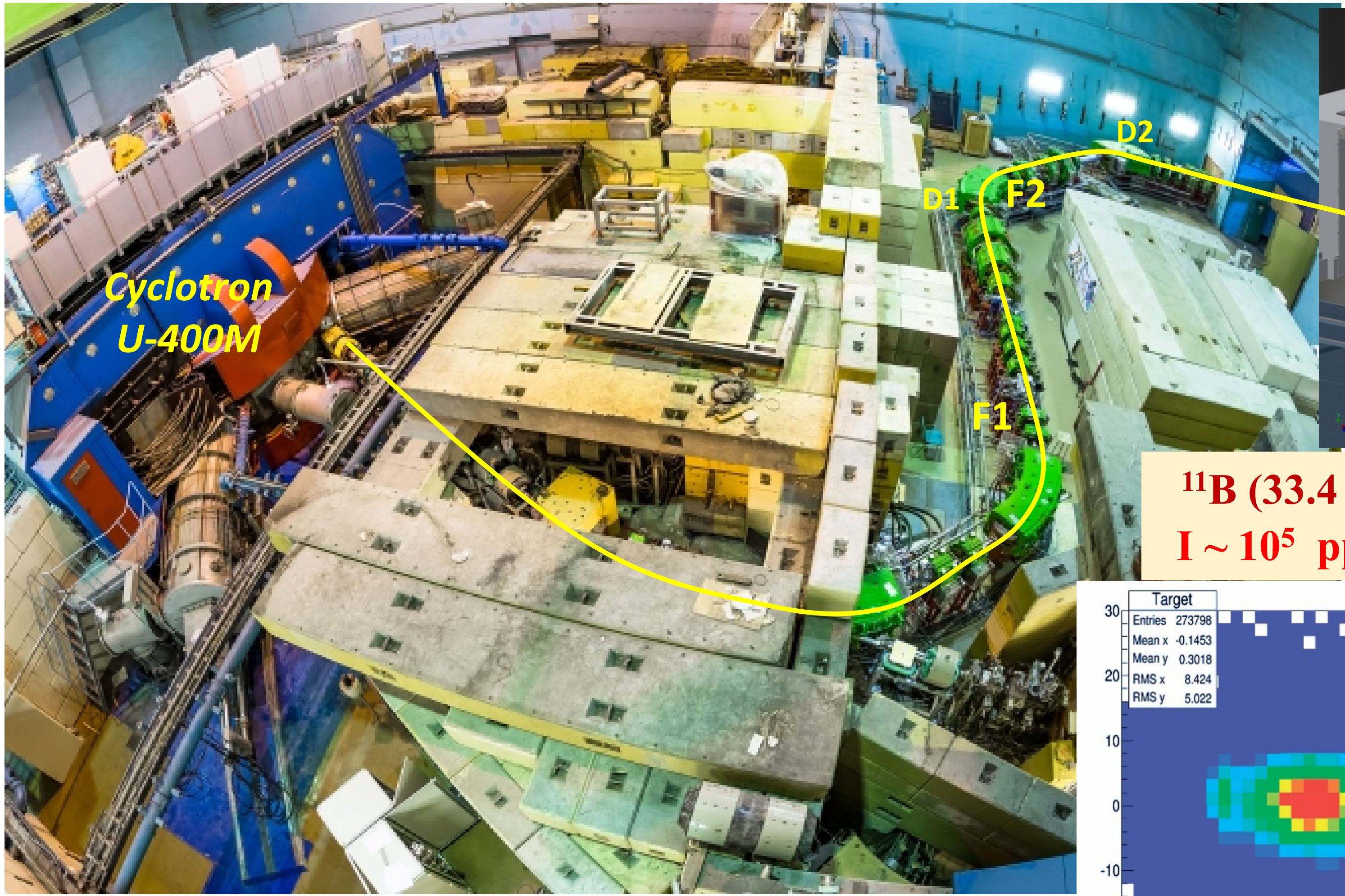
1. A.S. Fomichev et al., *The ACCULINNA-2 project: The physics case and technical challenges*, Eur. Phys. J. A 54, 97 (2018)
2. G. Kaminski et al., *Status of the new fragment separator ACCULINNA-2 and first experiments"*, NIM B 463 (2020) 504

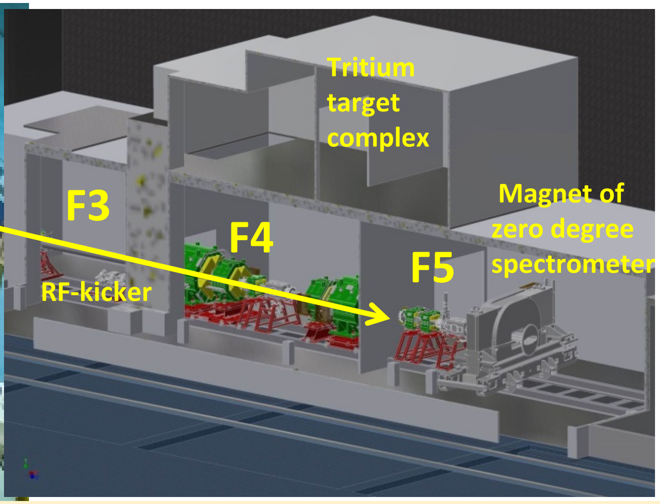


		ACC	ACC-2	LISE3	ARIS[a]	RIPS
		FLNR,	JINR	GANIL	FRIB	
$\Delta\Omega$	msr	0.9	4.2	1.0	5.0	5.0
δ_P	%	2.5	6.0	5.0	10	6.0
$P/\Delta P$	a.u.	1000	2000	2200	4000	1500
$B\rho_{max}$	Tm	3.2	3.9	3.2-4.3	8.0	5.76
Length	m	21	37	19(42)	87	21
$E_{\rm min}$	AMeV	10	5	30	30[b]	30
$E_{\rm max}$	AMeV	40	50	80	300	90

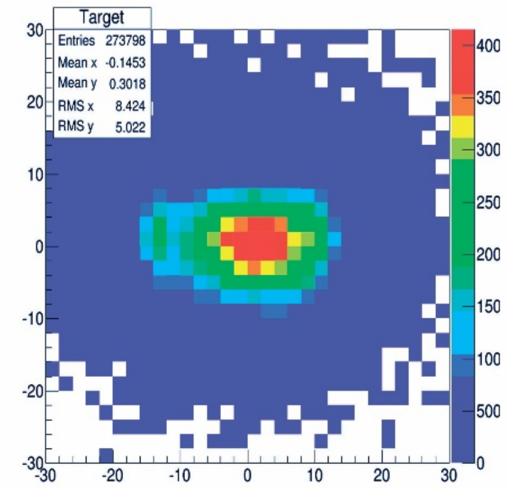
ACCULINNA-2 is comparable with RIPS, RIKEN

ACCULINNA-2 at U-400M cyclotron

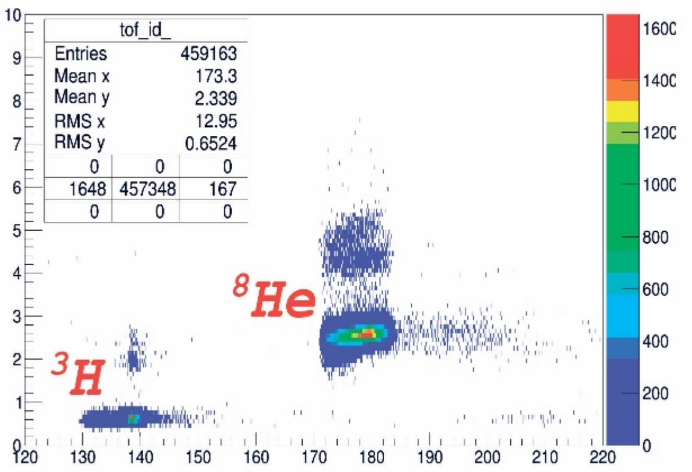




^{11}B (33.4 AMeV@1.5 pμA) + Be (1 mm)→ ^{8}He:
I ~ 10^5 pps, E ~ 26 AMeV, P ~ 90%, Ø ~ 17 mm

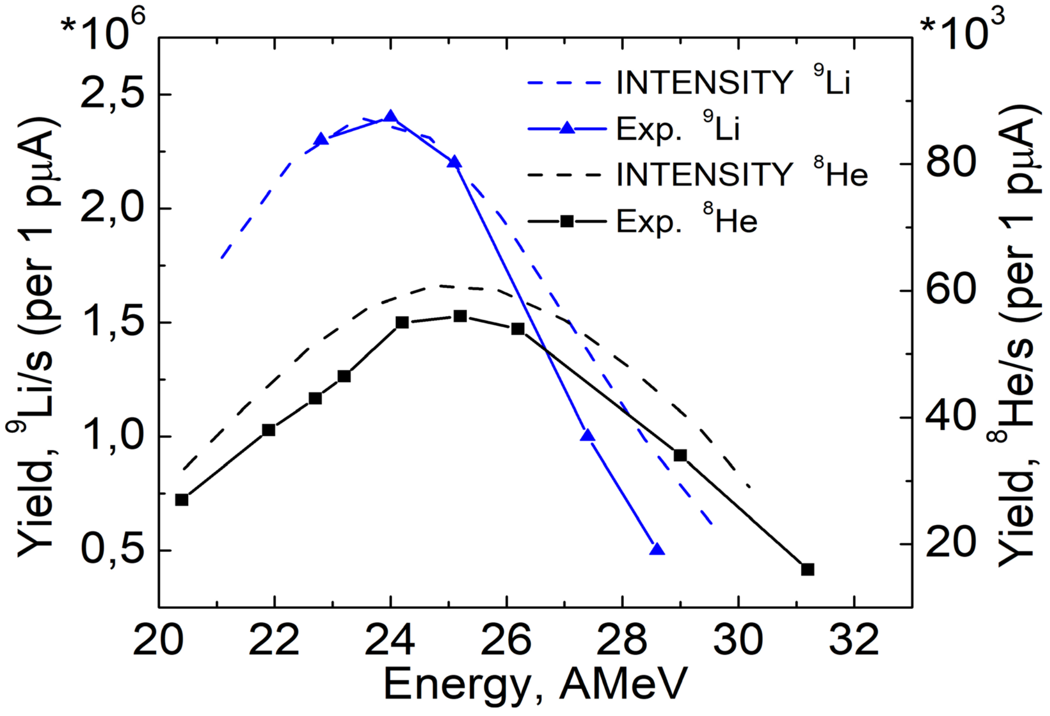


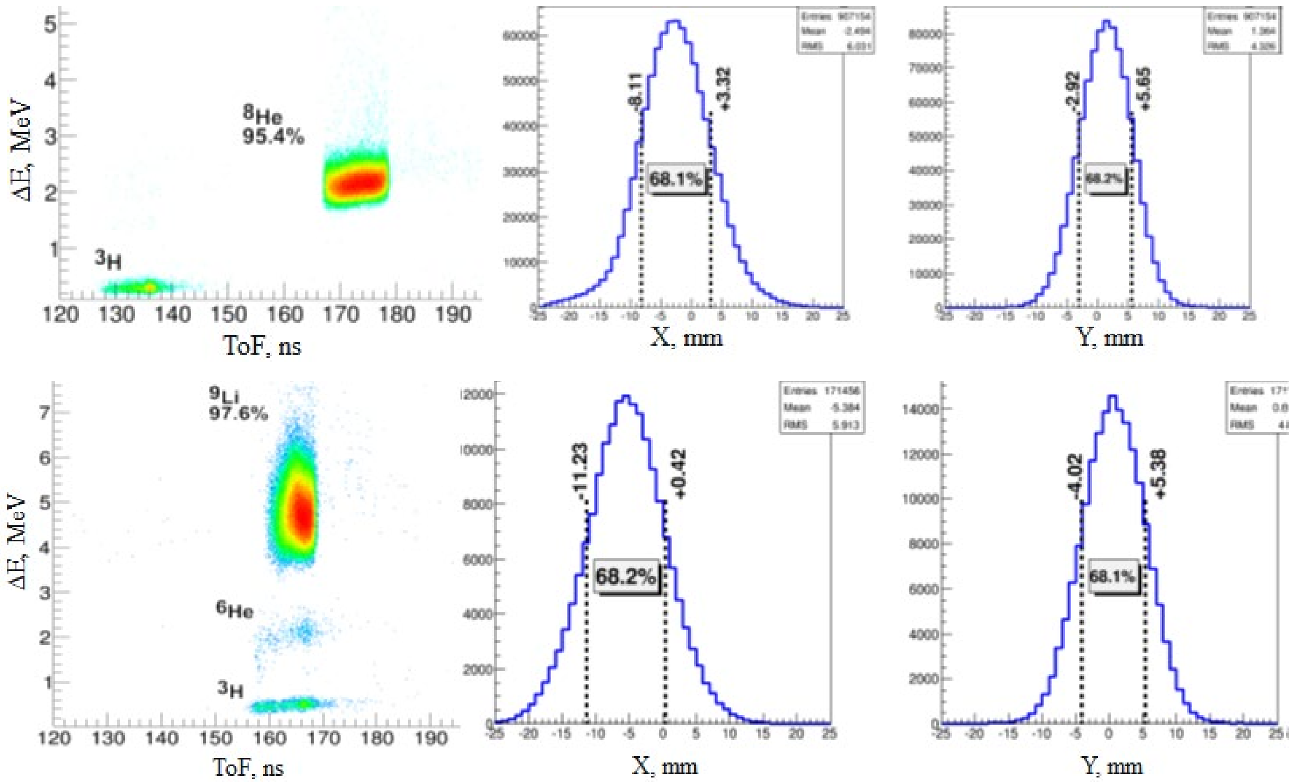
Y vs. X, mm



ΔE (MeV) vs. ToF (ns)

Characteristics of several RIBs at ACCULINNA-2 obtained in the first experiments



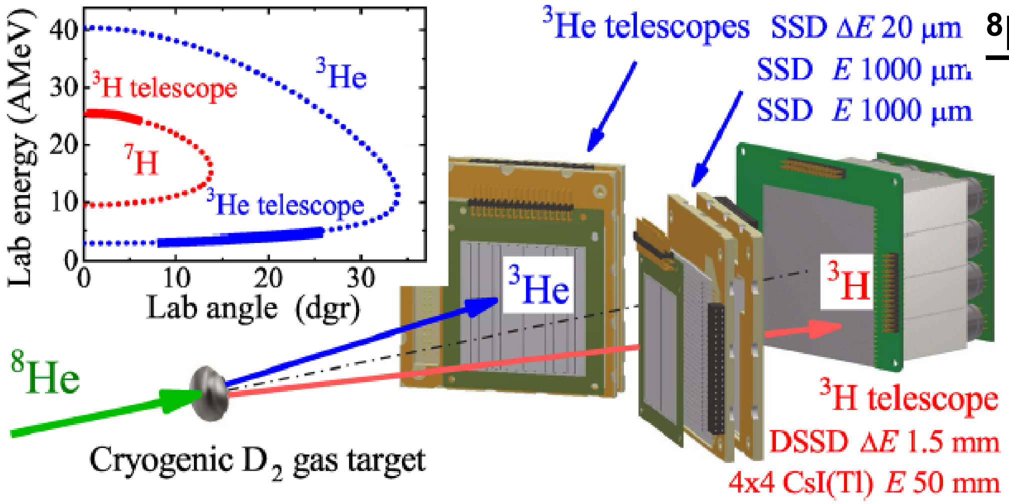


The observed basic characteristics for RIBs (intensity, purity, beam profiles in final focal plane) are in a good agreement with the technical specification and estimations.

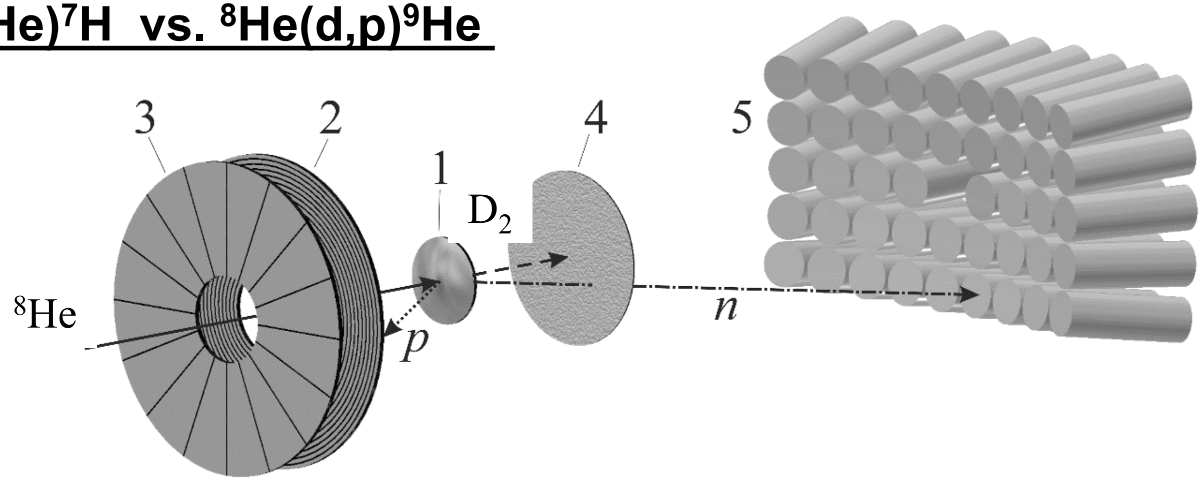
Ion	E, AMeV	Reaction	I, pps/pμA	P, %	X_Y, mm (FWHM)	Δp, ±%	Wedge Be, mm
^{6}He	29	^{11}B(33.5 AMeV)+Be(1 mm)	2.2*10^{6}	90.2	10_8	2.0	1.0
^{8}He	28	--“--	5.5*10^{4}	95.4	9_7	3.25	1.0
^{9}Li	31	--“--	5.0*10^{5}	97.6	12_9	2.0	1.0
^{10}Be	45	^{15}N (49.3 AMeV)+Be(1 mm)	2.3*10^{6}	78.4	16_11	1.25	1.0
^{26}P	28	^{32}S (52.7 AMeV)+Be (0.5 mm)	15	<0.5	18_12	0.75	0.5
^{27}S	27	--“--	60	1	18_12	0.75	0.5

Experiments at ACCULINA-2 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**
^{4}n, ^{6}H, ^{7}H	Low energy spectra and decay modes in ^{8}He+d interaction ^{8}He(d,^{6}Li)^{4}n, ^{8}He(d,^{4}He)^{6}H, ^{8}He(d,^{3}He)^{7}H	**PRL, PRC, Bulletin of RAS** A. Bezbakh, I. Muzalevskii thesisis
^{8}Li and ^{9}Li	Reference reactions (d,^{4}He) and (d,^{3}He) with ^{10}Be	**NP (ЯФ)**
^{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	**Bull. of RAS (method)**
^{27}S	Rare decay modes, implantation into OTPC	**Under analysis**
	Detector tests (PPAC, ToF, Si, etc.), setup instrumentation	**IET (ПТЭ)** S. Krupko thesis
^{7}H, ^{10}He, ^{16}Be, ^{7}B, ^{17}Ne, ^{26}S	July 2020 – March(?) 2023 **No beam, U-400M cyclotron upgrade** 2023+ ***Experimental program is under discussion***	

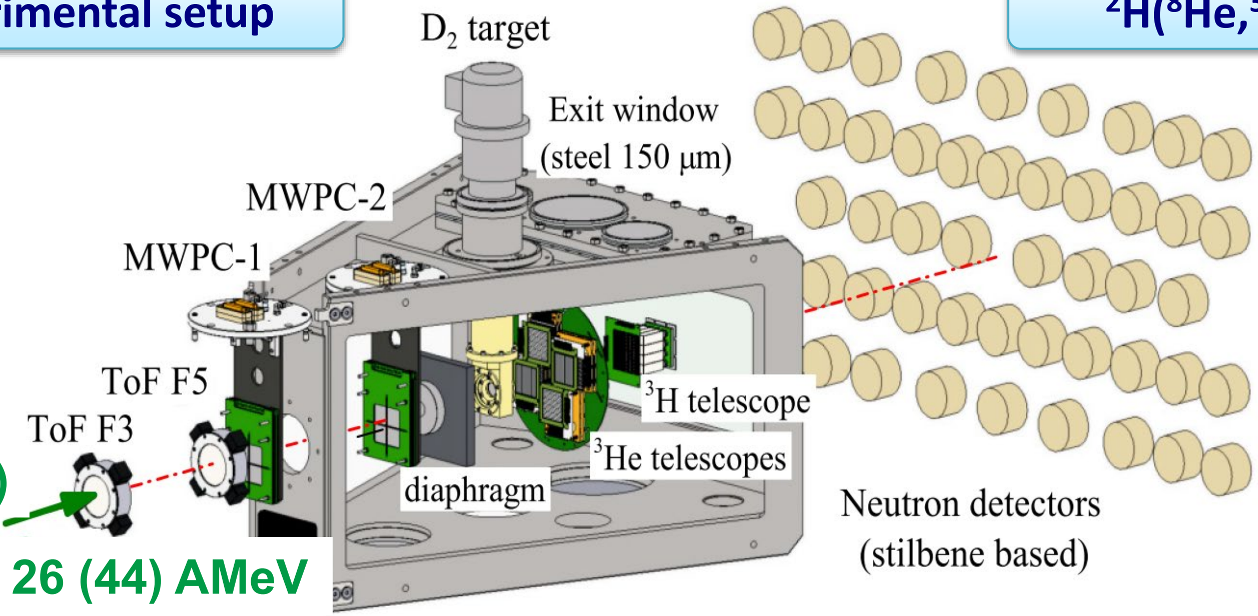


^{8}He(d,^{3}He)^{7}H vs. ^{8}He(d,p)^{9}He



Experimental setup

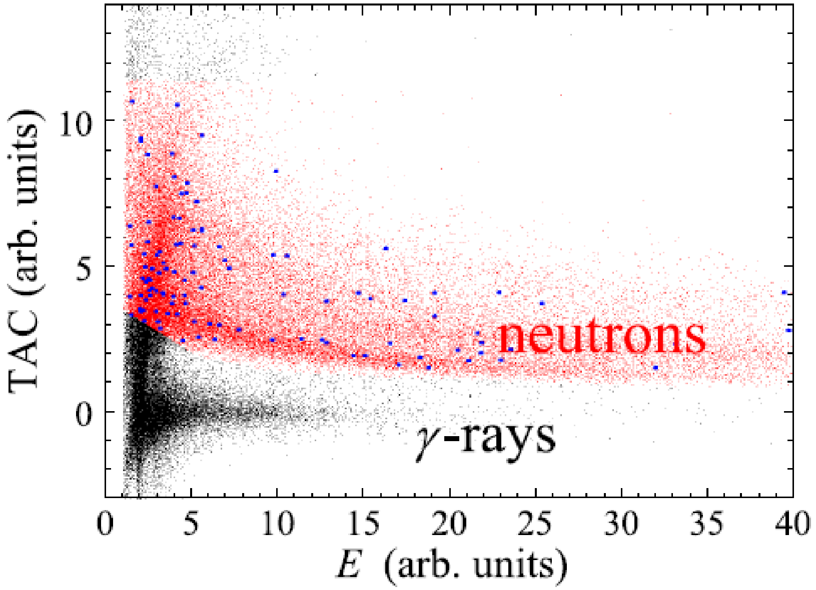
$^2H(^8He,^{3,4}He)^{7,6}H$, $^2H(^8He,^6Li)^4n$ and $^2H(^{10}Be,^{3,4}He)^{9,8}Li$



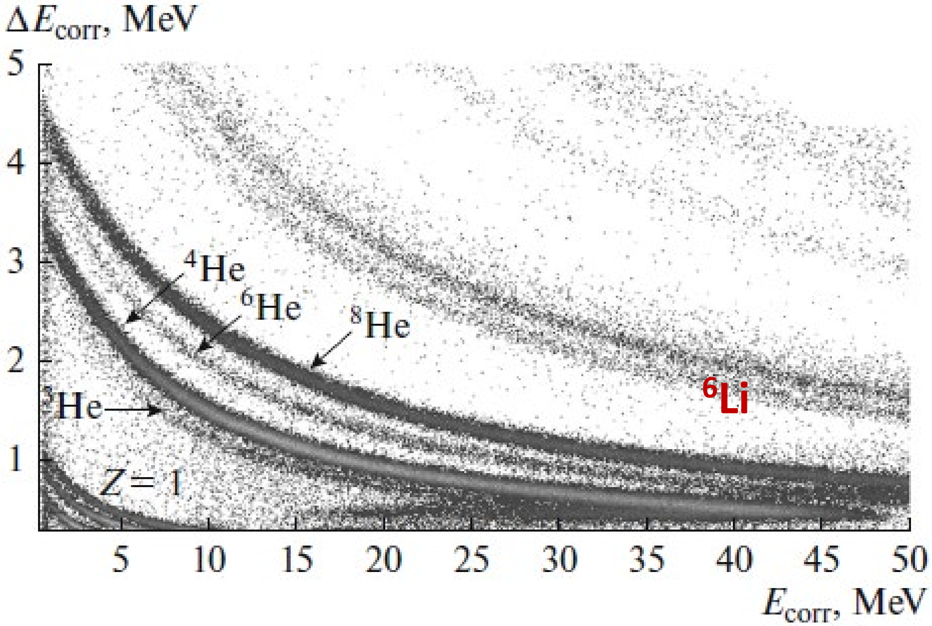
^8He (^{10}Be)

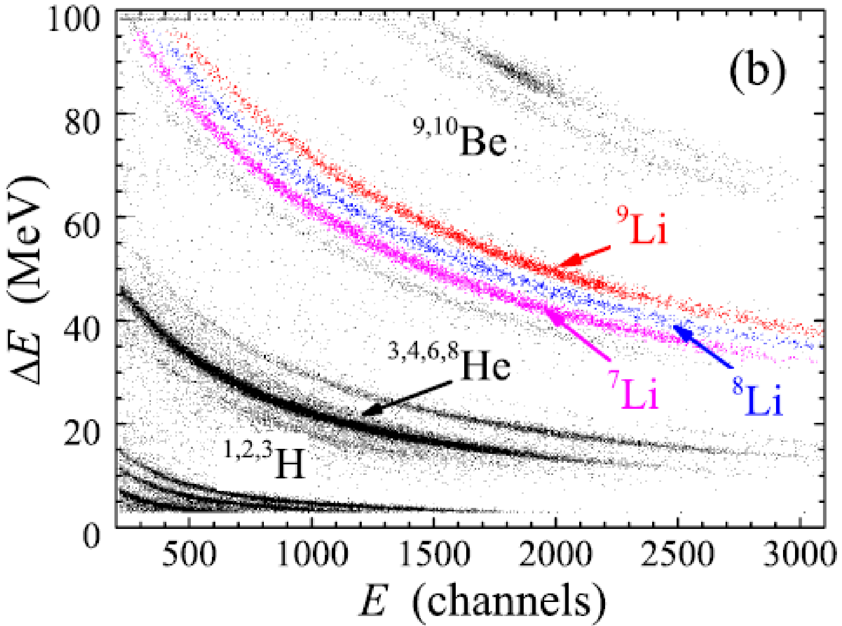
10^5 1/s @ 26 (44) AMeV

The ID plot for neutron spectrometer

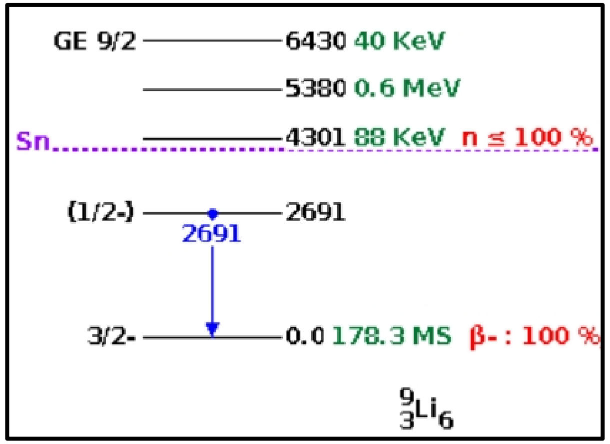


Particle ID for side telescopes
after thickness correction of 20-μm SSD



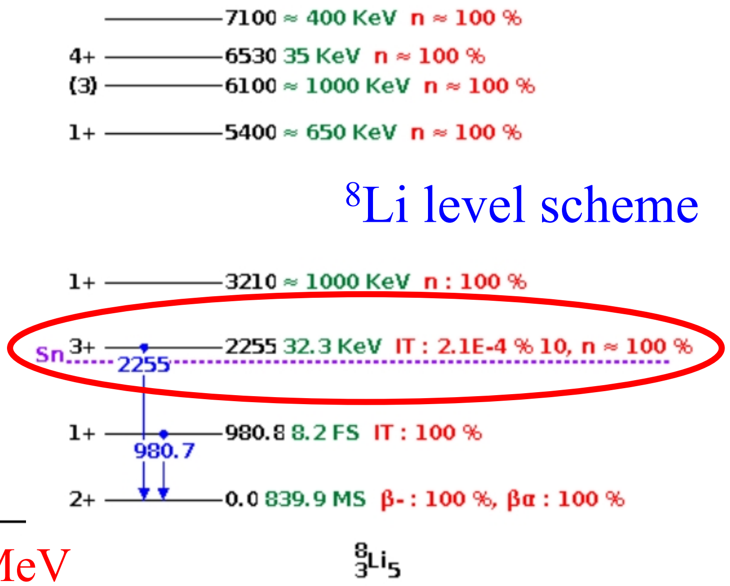


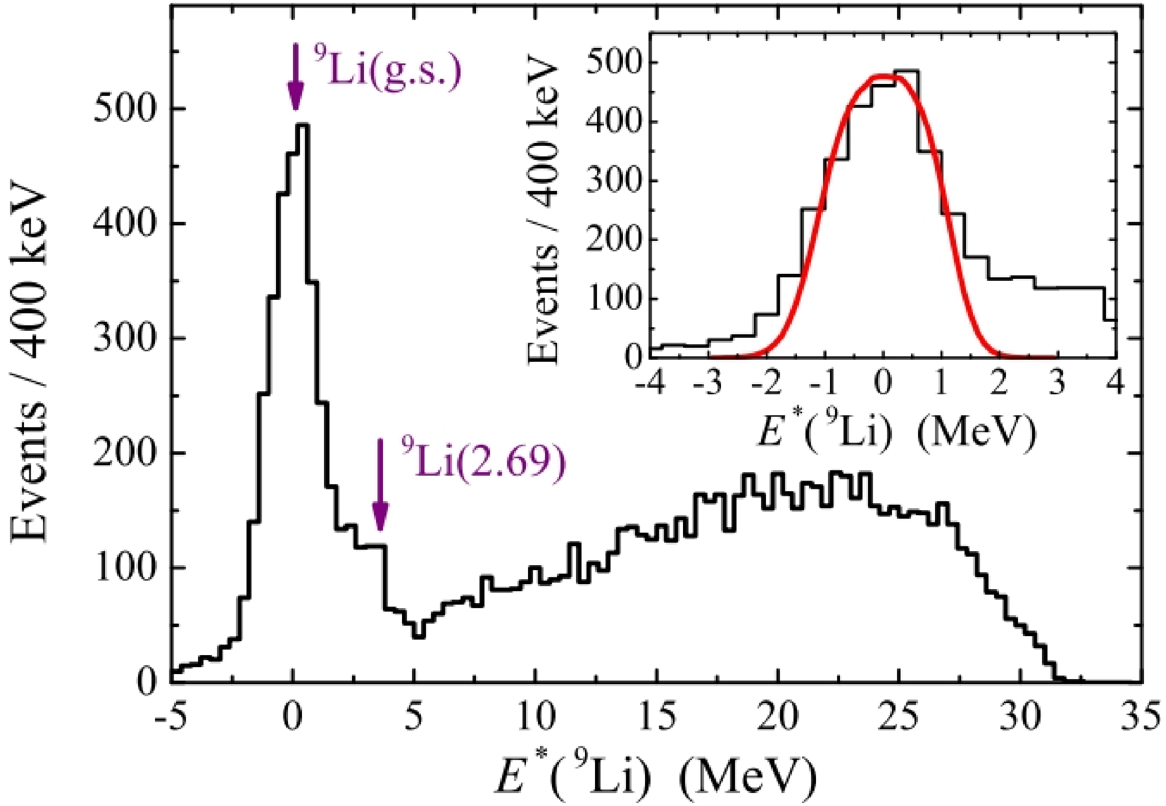
Particle ID in central telescope consisted of in DSSD (1500-μm) and CsI(Tl)/PMT (50 mm, 4x4)

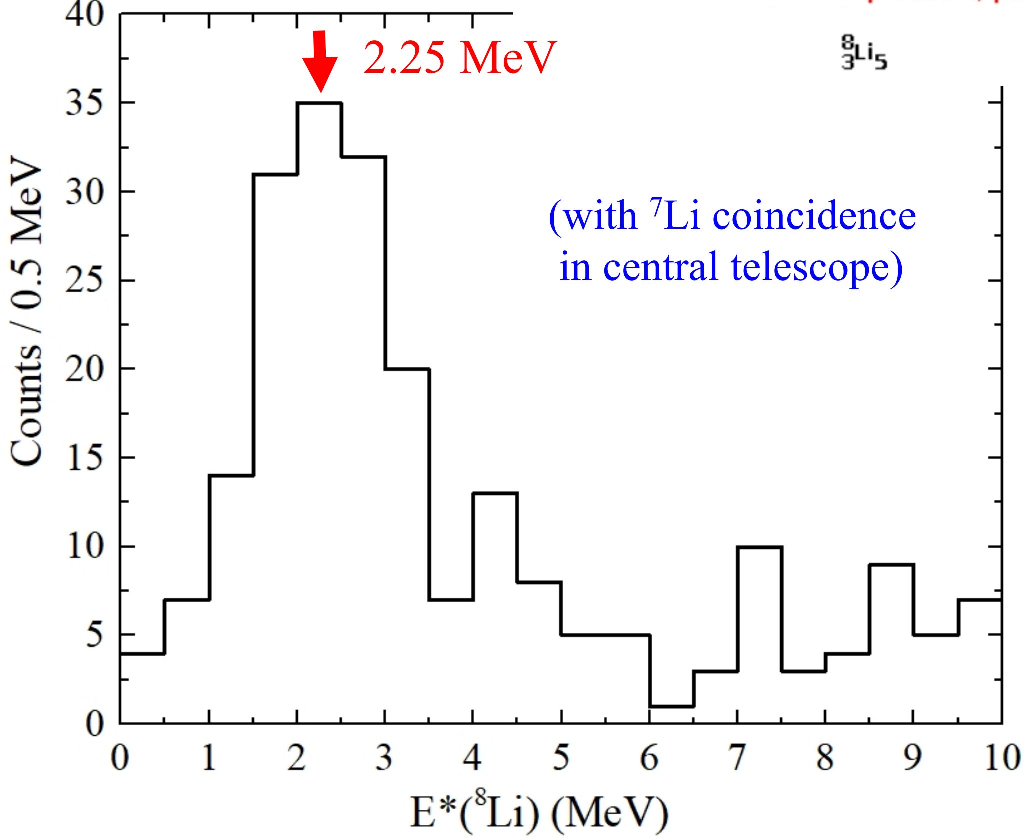


Data for the reference reactions $^{2}H(^{10}Be,^{3}He)^{9}Li$ and $^{2}H(^{10}Be,^{4}He)^{8}Li$:

** energy calibration and resolution for the missing mass spectra;*
*** detector efficiency;*







Main results for ^7H and ^6H

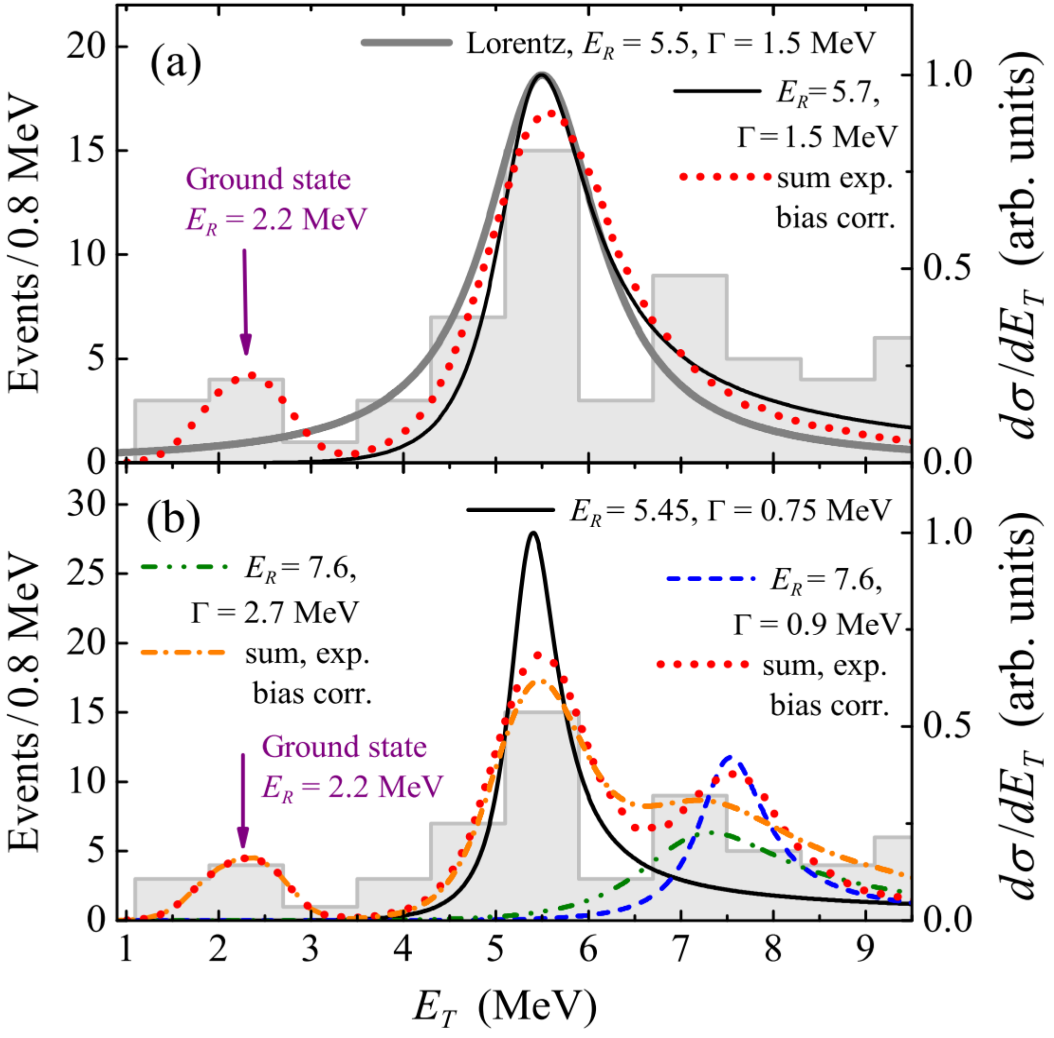
^7H Ground state: 2.2 MeV
Excited states: 5.5, 7.5 MeV

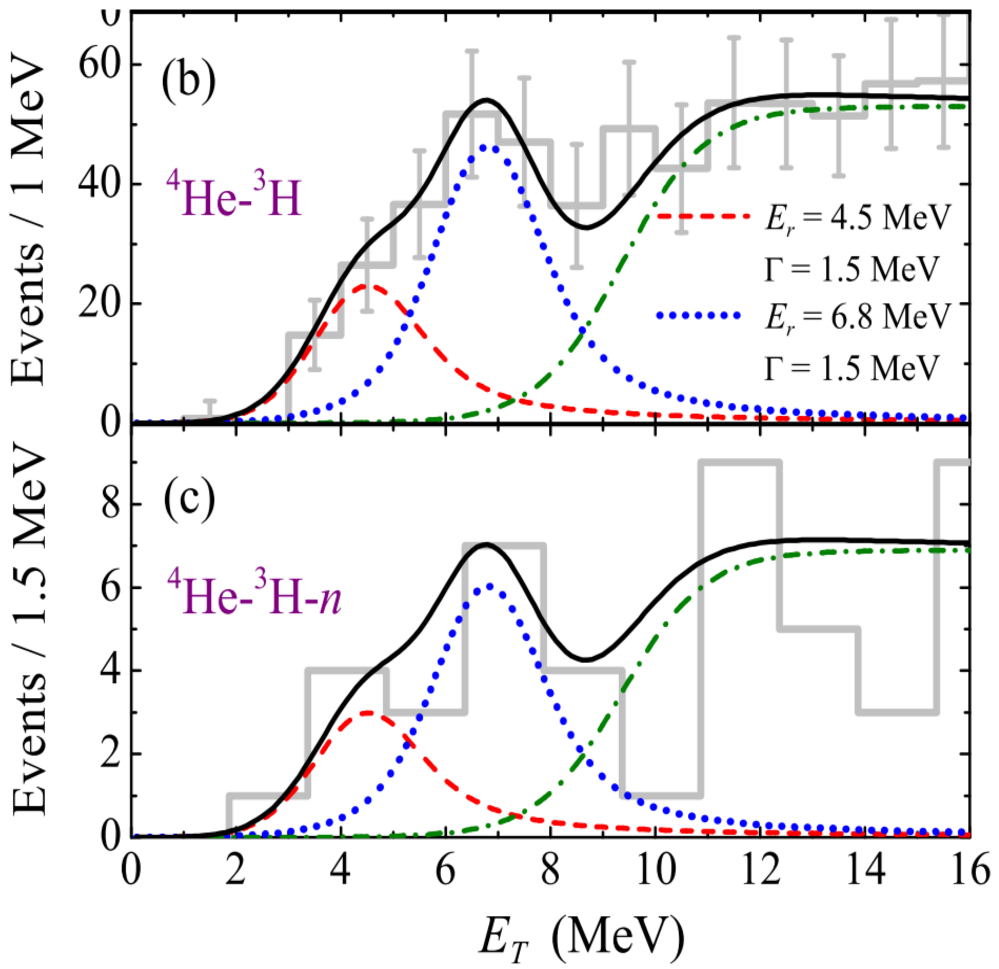
^6H Ground state: 4.5 MeV
Excited state: 6.8 MeV

$d\sigma/d\Omega_{c.m.} \approx 24$ μb/sr for $\theta_{c.m.} \approx 5°–9°$ and ≈ 7 μb/sr for $\theta_{c.m.} \approx 15°–19°$

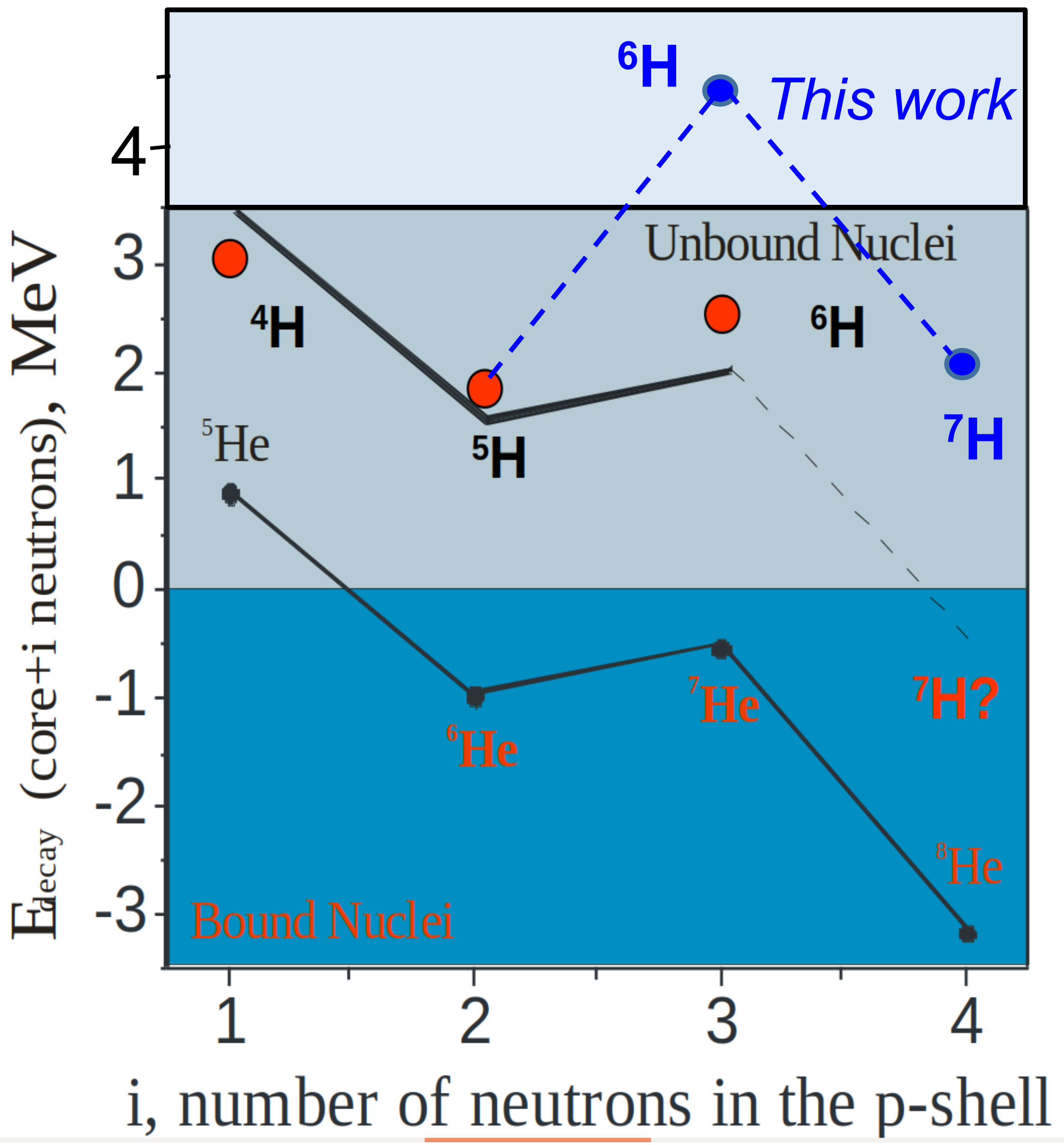
$d\sigma/d\Omega_{c.m.} \simeq 190^{+40}_{-80}$ μb/sr in the $5° < \theta_{c.m.} < 16°$

no evidence of the ≈2.6–2.9 MeV $d\sigma/d\Omega_{c.m.} \lesssim 5$ μb/sr



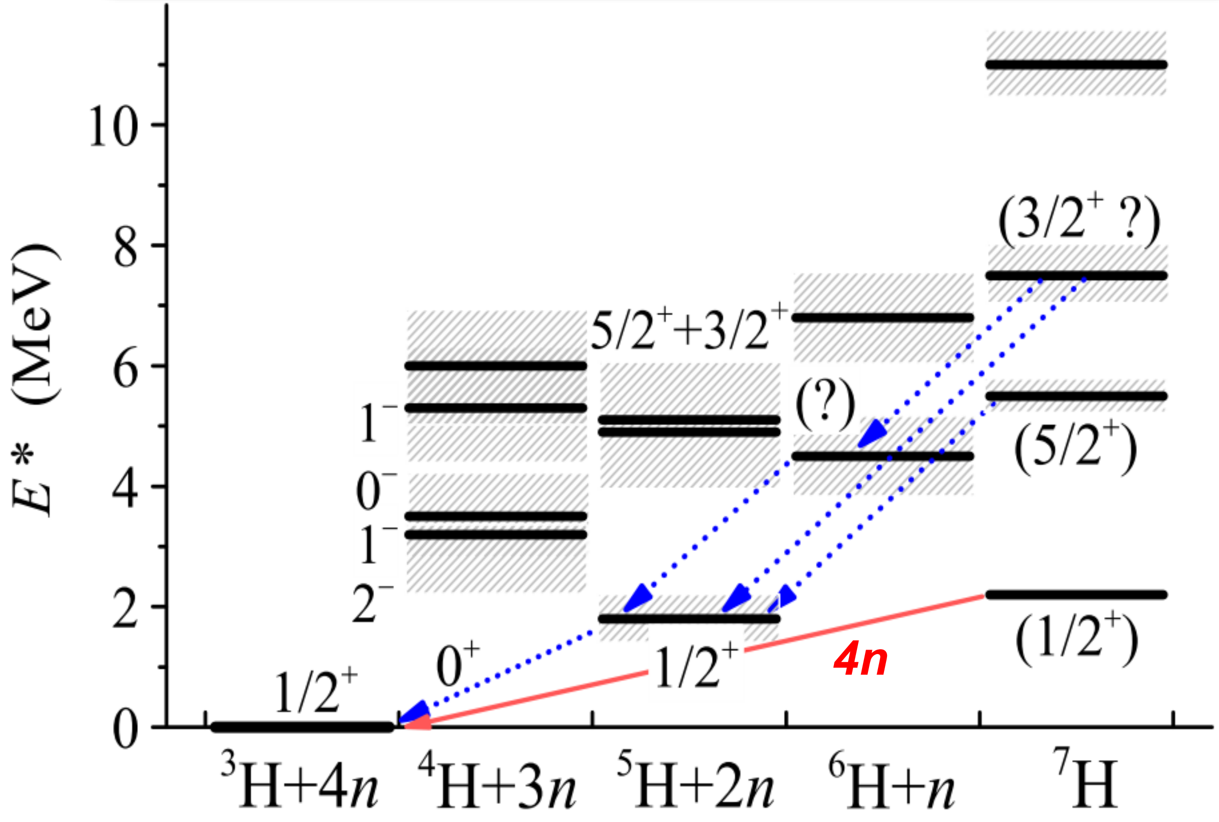


Hydrogen and helium chains: today status

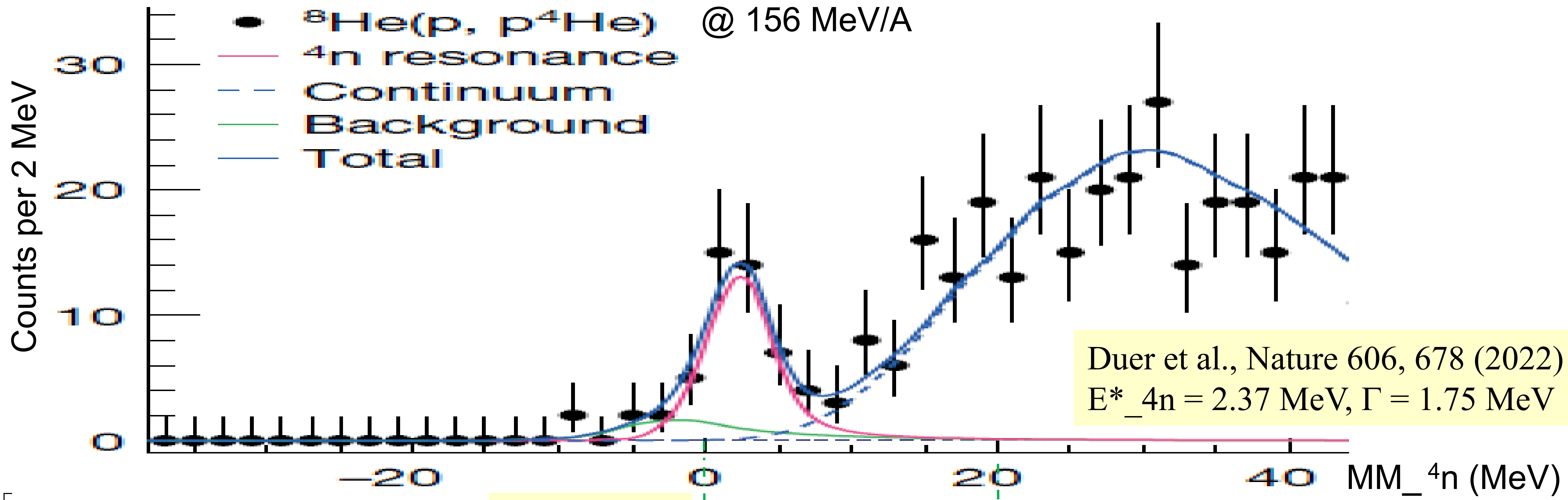


* New level schemes for all isotopes $^3H \div {}^7H$

** The unique true *4n*-decay mechanism is proved to be realized for ^7H. *This is the first such case found in the nuclide map.*

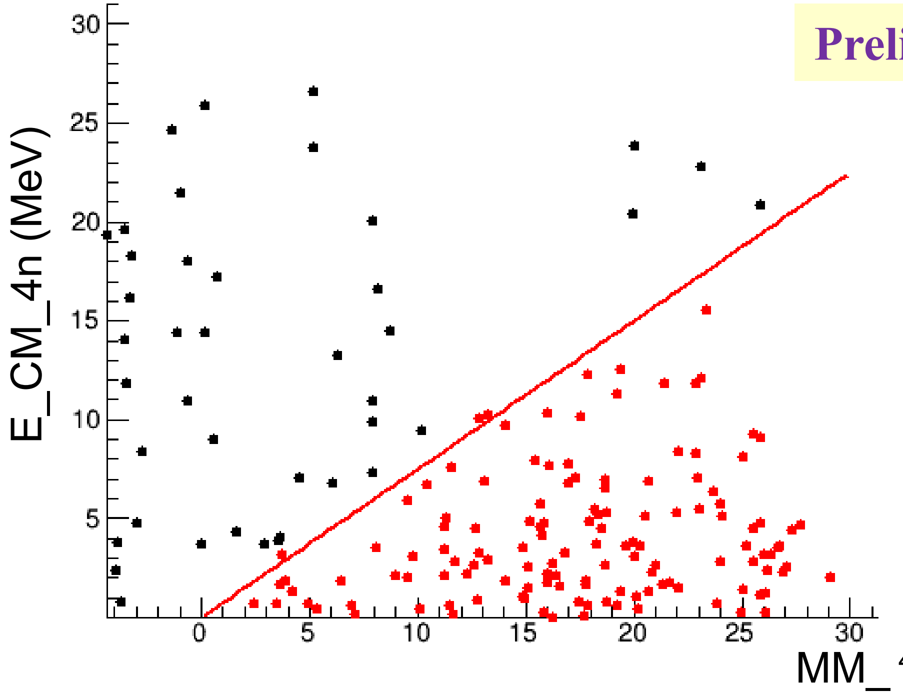


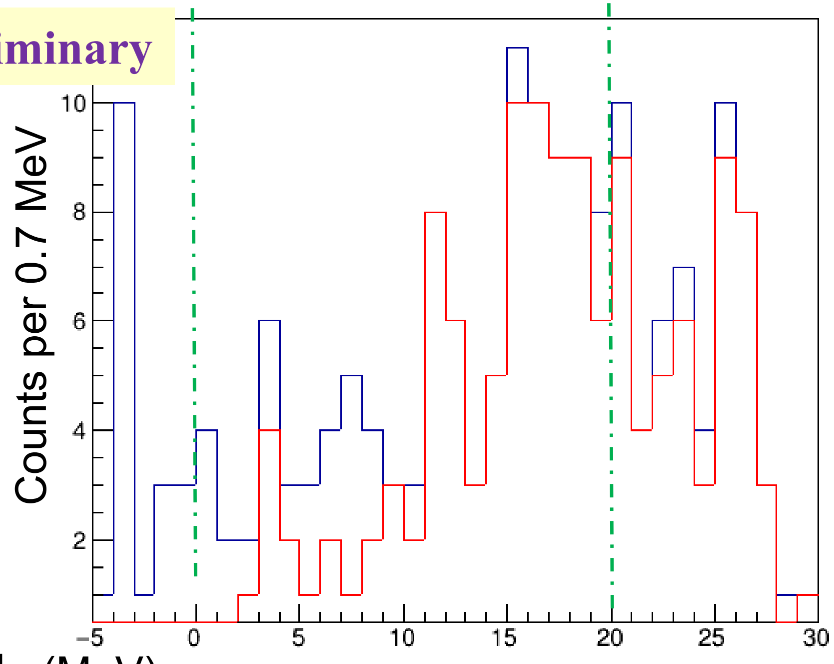
^4n



Duer et al., Nature 606, 678 (2022)
E*_4n = 2.37 MeV, Γ = 1.75 MeV

Preliminary



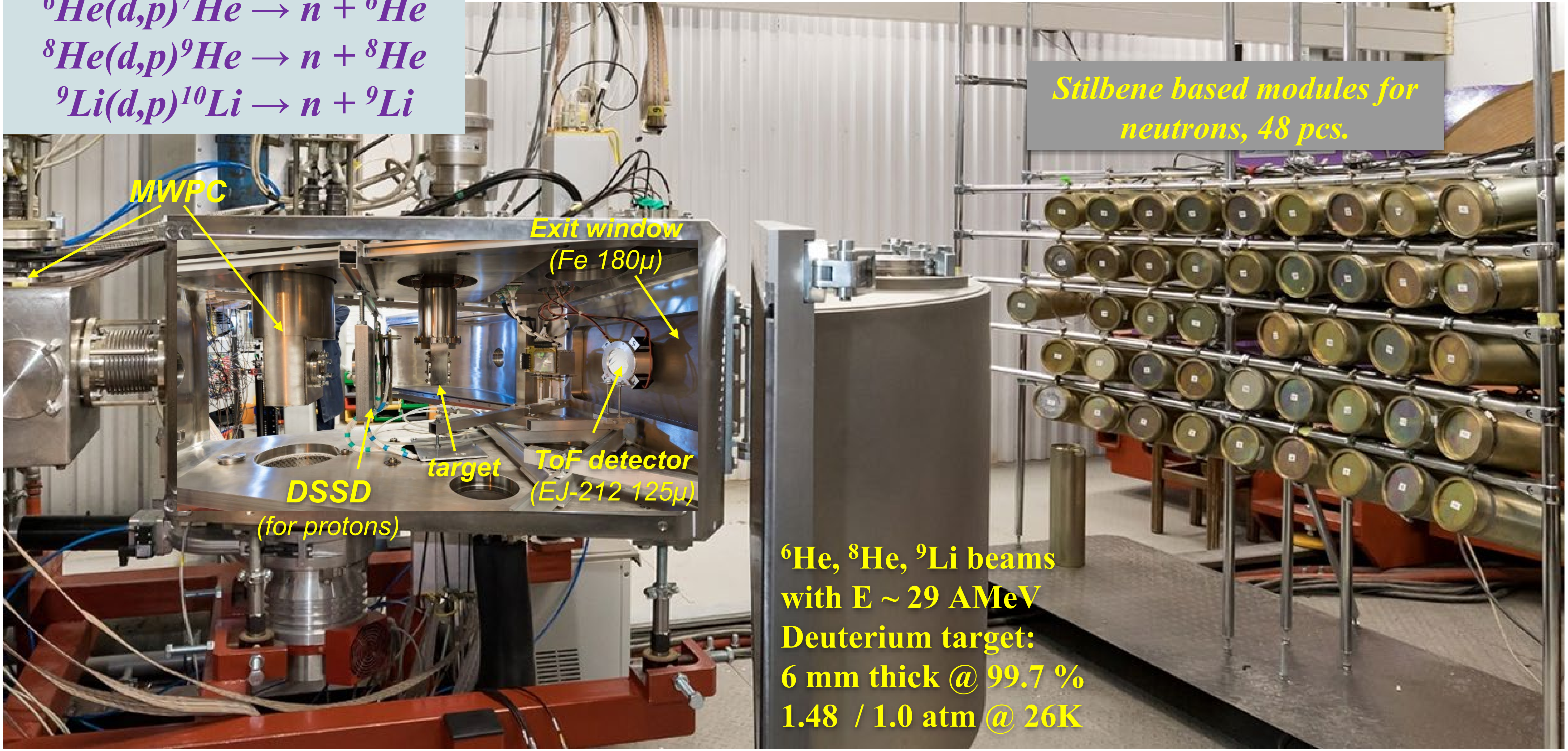


$^8He(d,^6Li)^4n$ @ 26 MeV/A
^6Li-n coincidences:
blue – all events;
red – inside triangle ¾
E*_4n ~ 3.5 MeV

(more details → LVG)

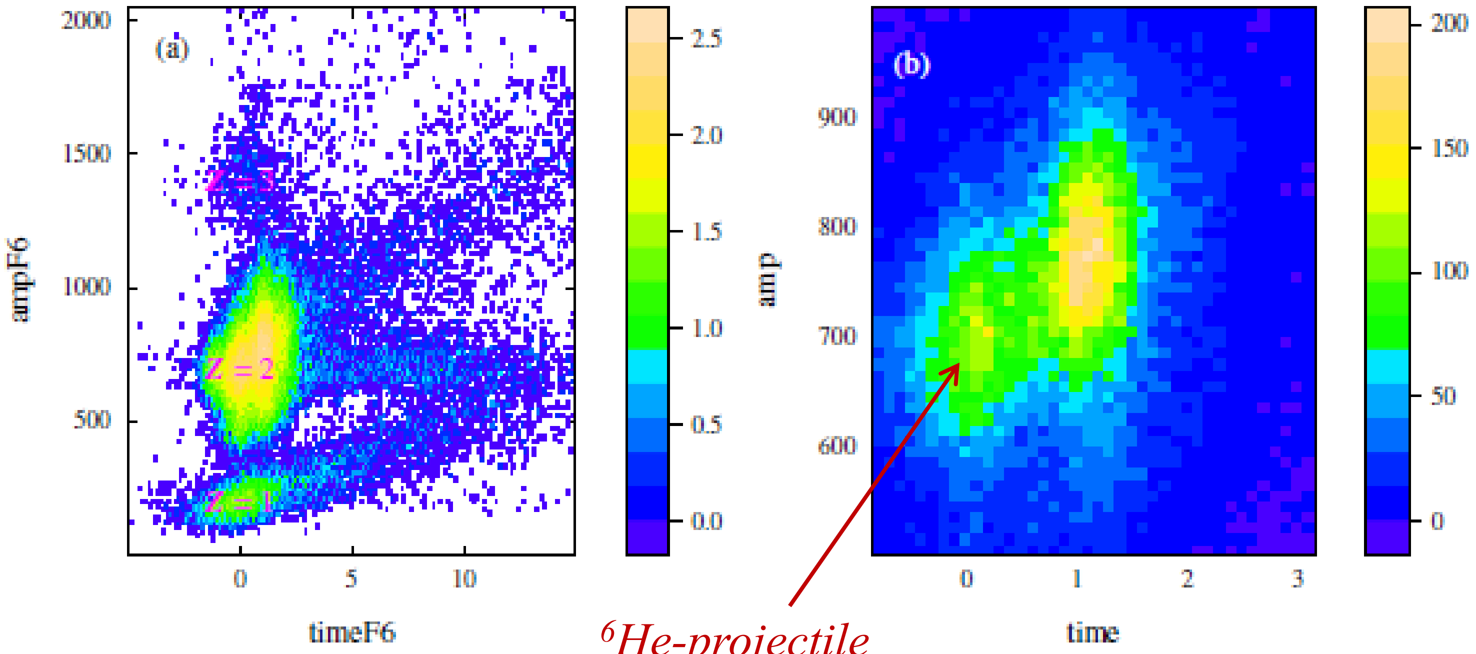
Setup for the study ^{7}He, ^{9}He and ^{10}Li isotopes in the reaction *(d,p)*

$$^6He(d,p)^7He \rightarrow n + {}^6He$$
$$^8He(d,p)^9He \rightarrow n + {}^8He$$
$$^9Li(d,p)^{10}Li \rightarrow n + {}^9Li$$



Stilbene based modules for neutrons, 48 pcs.

^{6}He, ^{8}He, ^{9}Li beams with E ~ 29 AMeV
Deuterium target:
6 mm thick @ 99.7 %
1.48 / 1.0 atm @ 26K

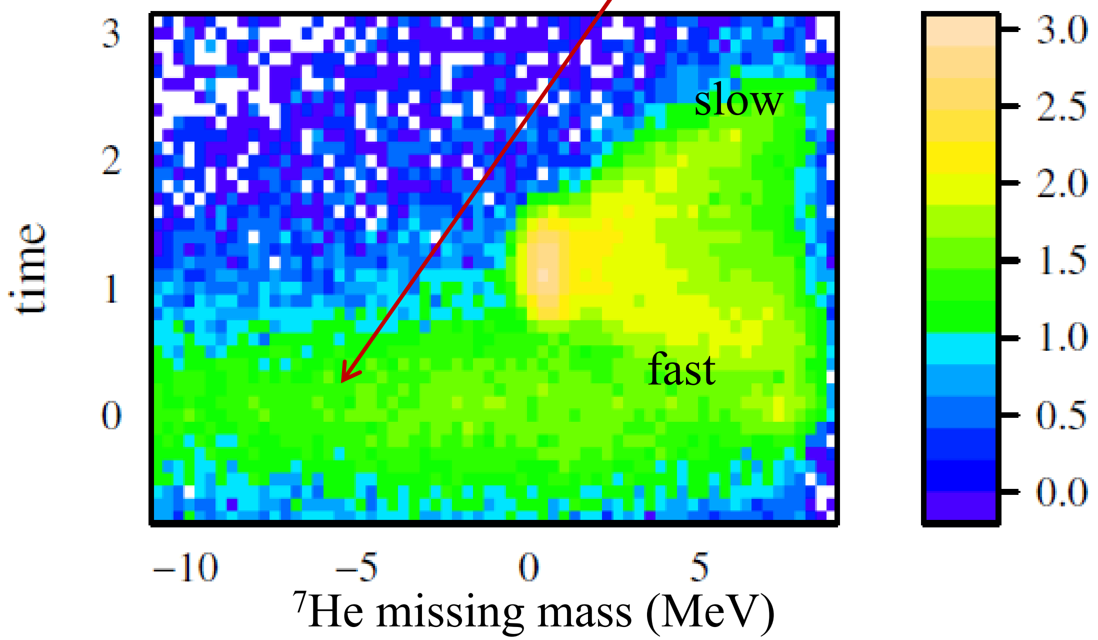


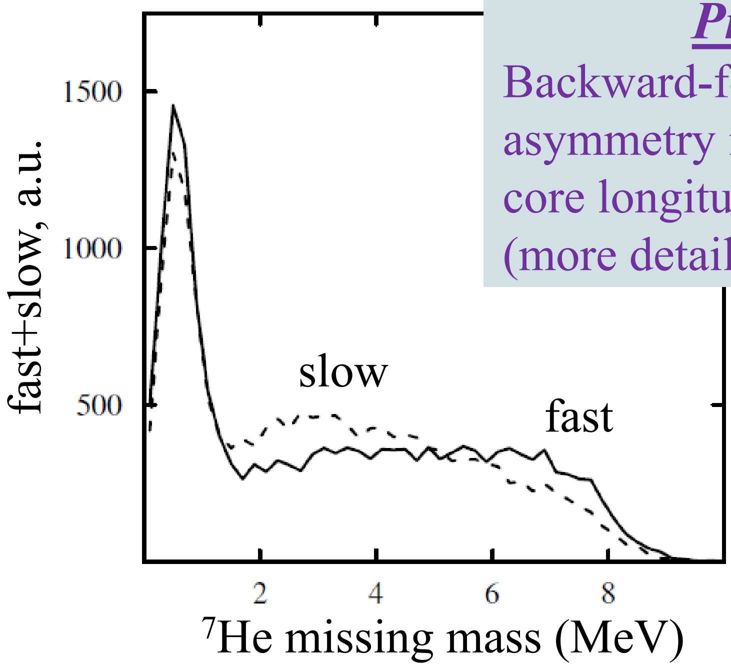
^6He-projectile

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

ID plot of the events obtained by ToF measurements on the base 79 cm "target – thin plastic EJ-212" in logarithmic scale (left panel)

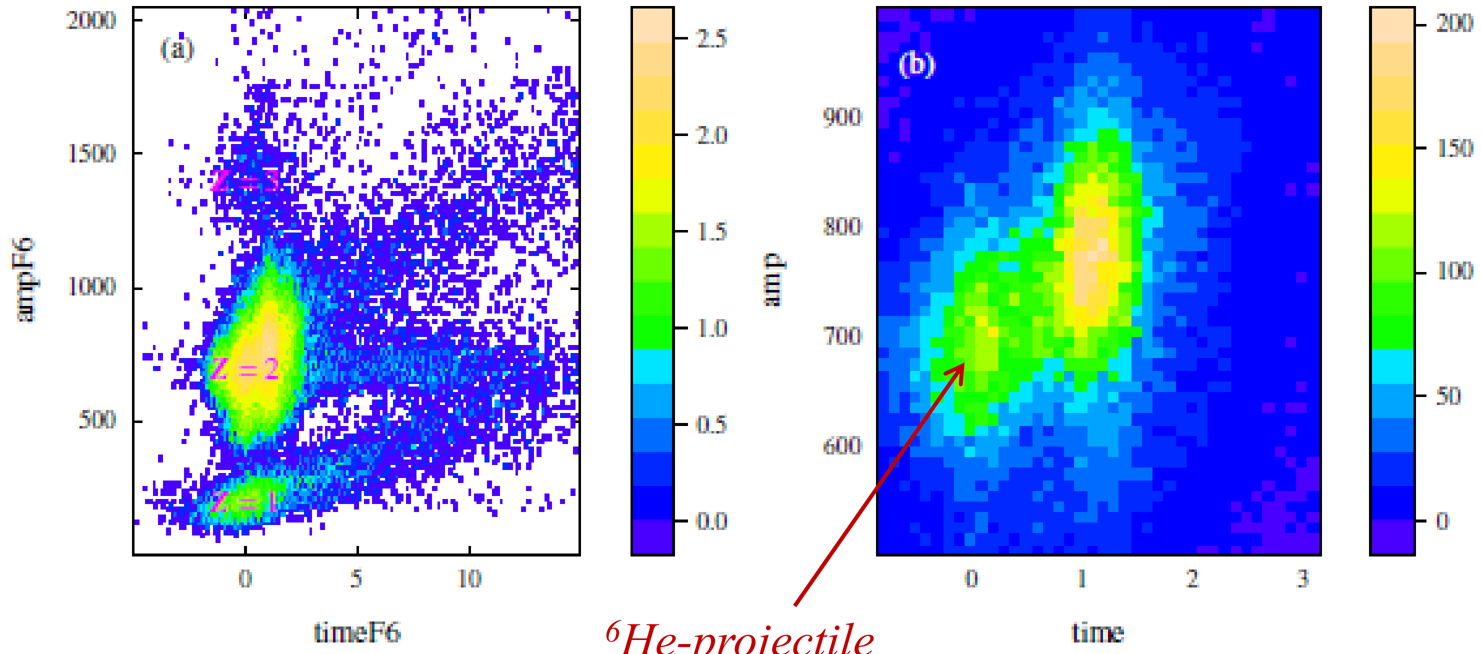
Two groups of events with Z=2 (^6He-projectile and ^6He as a result of ^7He decay) are obviously seen especially in linear scale (right panel)





Preliminary:

Backward-forward (fast-slow) asymmetry in the distribution of core longitudinal momentum (more details → LVG)



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

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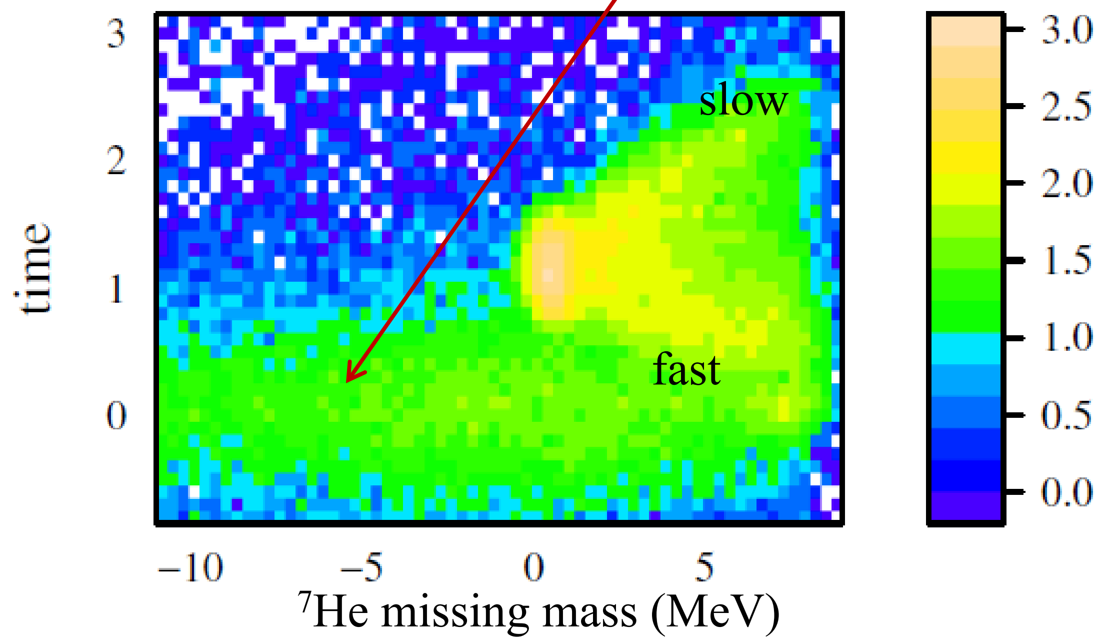
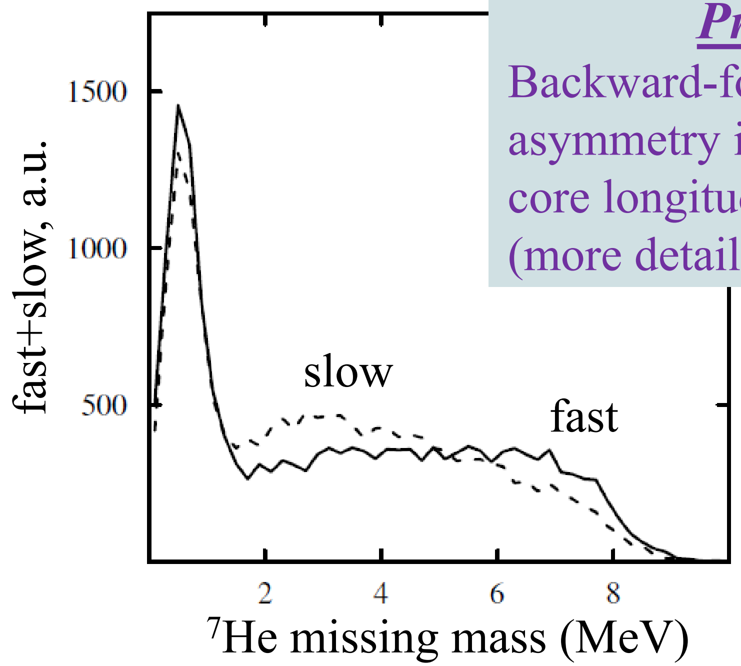




Preliminary:

Backward-forward (fast-slow) asymmetry in the distribution of core longitudinal momentum (more details → LVG)

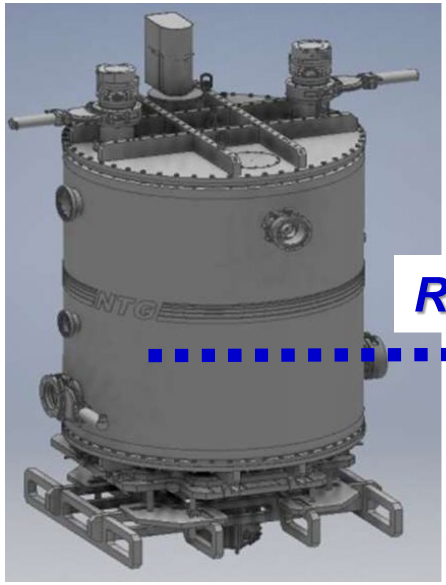
> 2023:

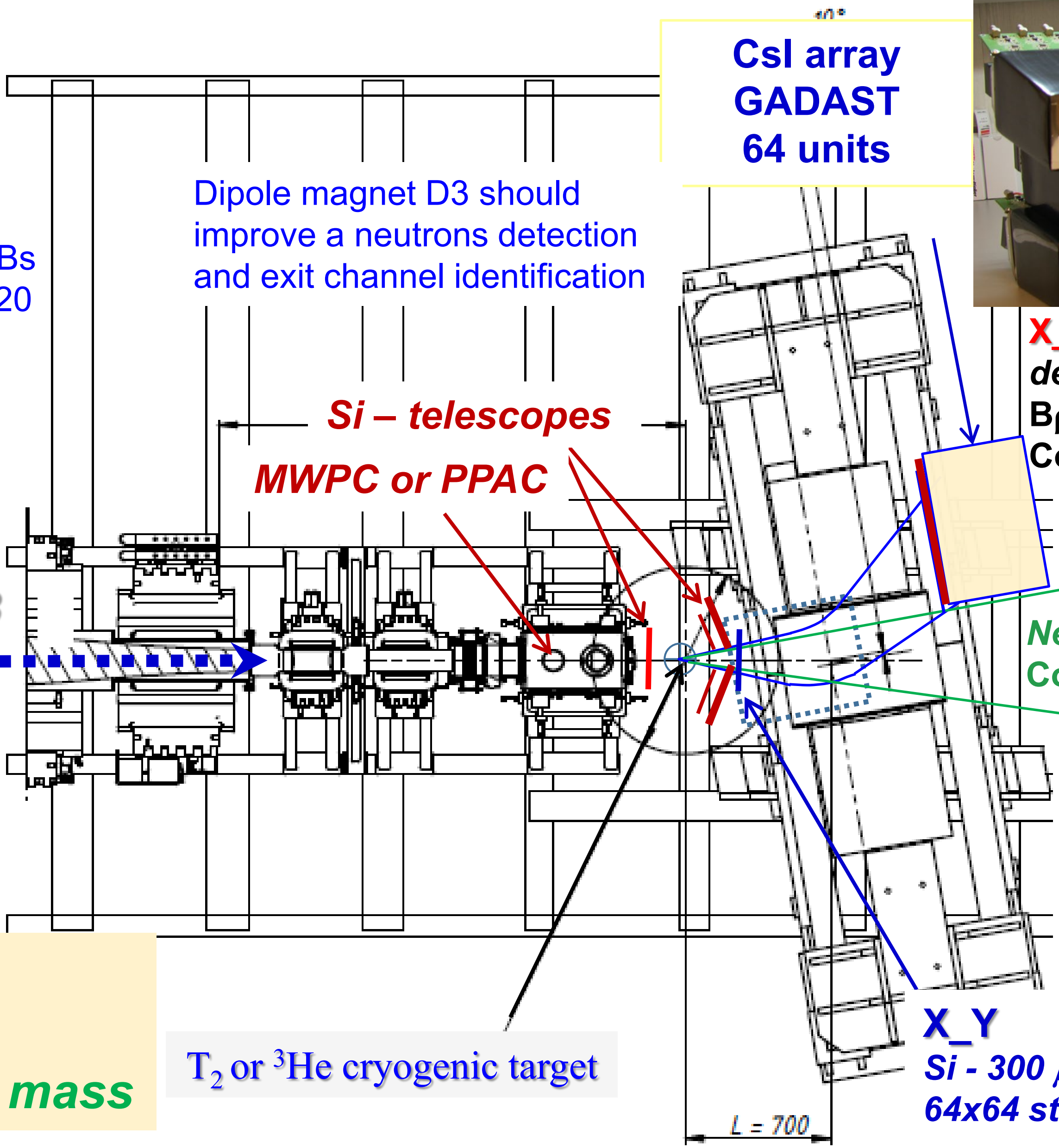
- more statistics
- ^{4,6}He ID
- low background

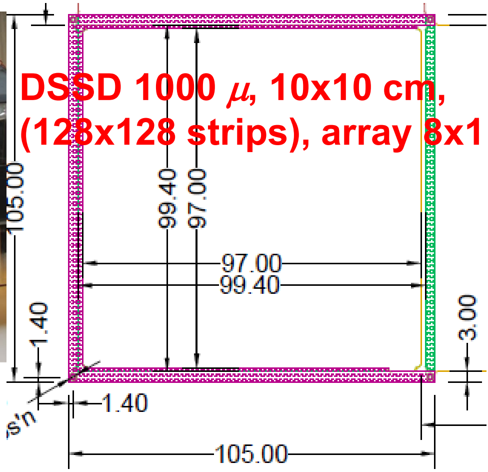
Scheme of the experiments with ^{3}He - T_2 targets and new technique (since 2023)

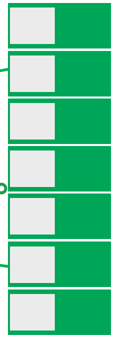
$^{13}O(^{3}He,n)^{15}Ne$
$^{24}Si(^{3}He,n)^{26}S$

RF-kicker should enhance RIBs purification by a factor of 10÷20

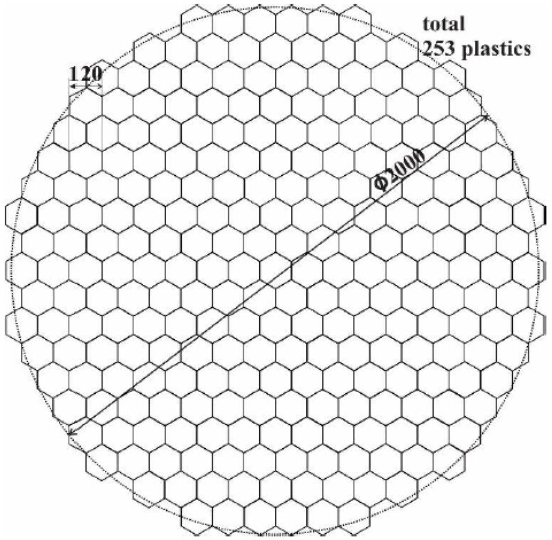








Stilbene array
64 units
(80x50mm)

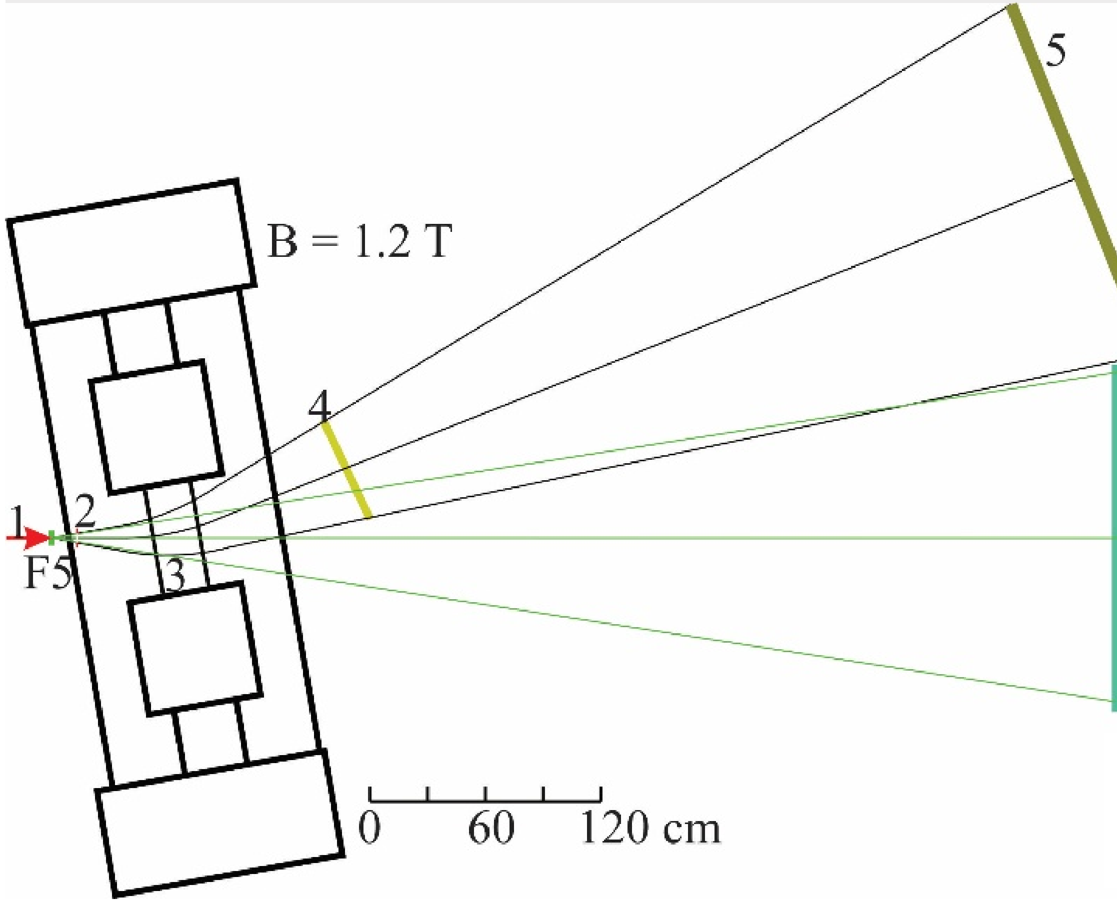


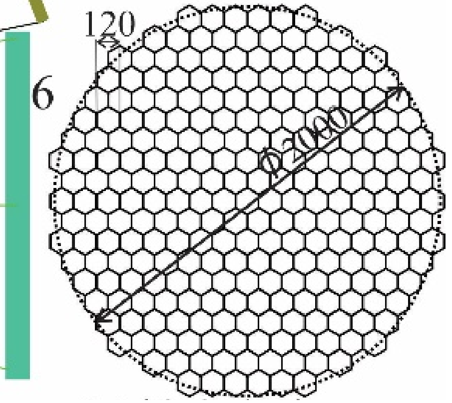
Alternative:
BC-408 array
253 units
(160x200mm)

$^{8}He(t,p)^{10}He$
$^{14}Be(t,p)^{16}Be$
$^{8}He(t,\alpha)^{7}H$ – *inv. mass*

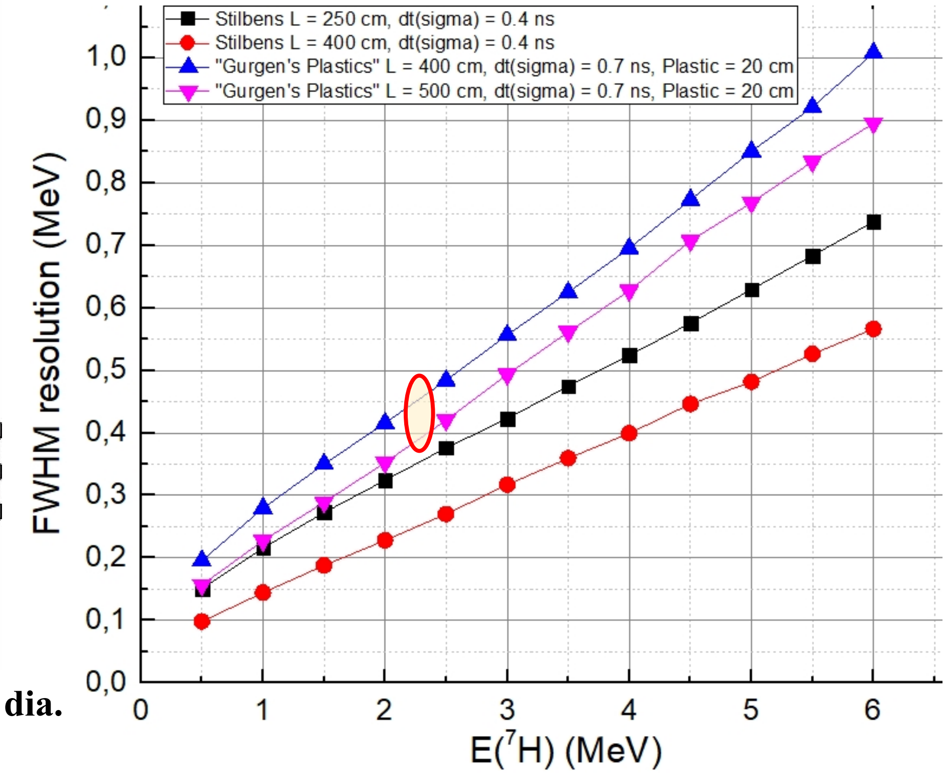
T_2 or ^{3}He cryogenic target

Example 1: first estimations for the case $^{8}He+T_2$(liquid) → ^{4}He(stopped) + ^{7}H(inv. mass)





BC-408, hexagonal design, dia. of external circle 16 cm, thickness 20 cm, 253 units

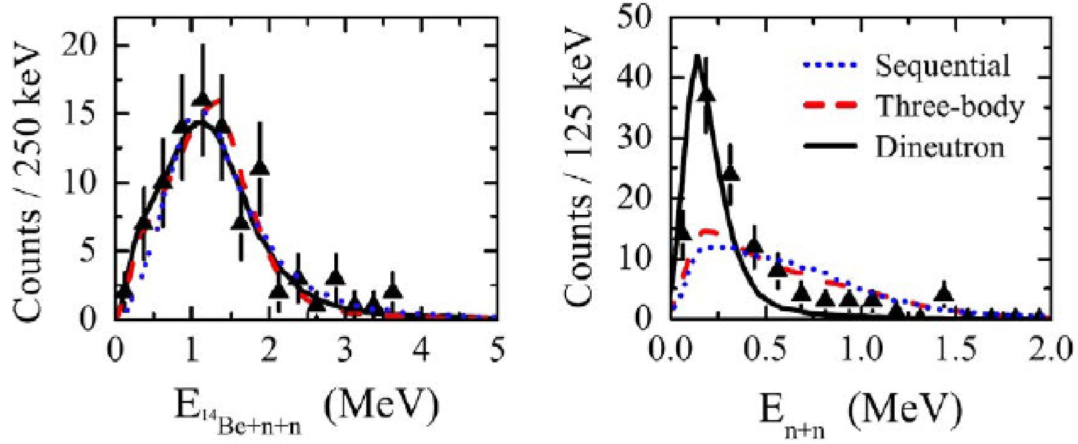


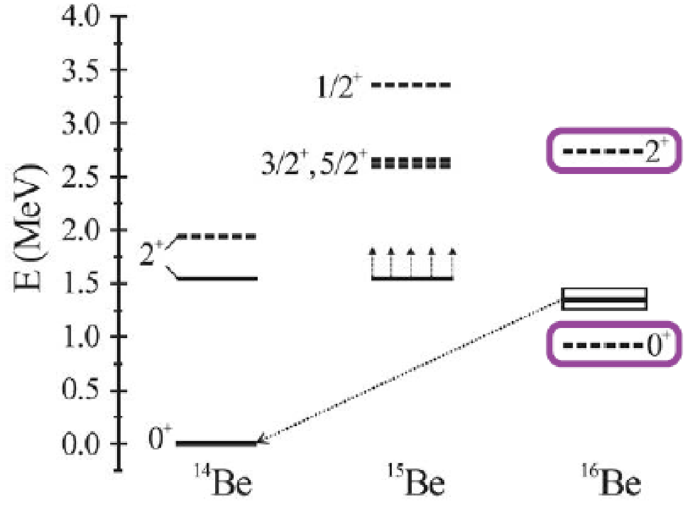
Zero-angle spectrometer with its dipole magnet installed after the physic target in F5: 1 – radioactive beam, 2 – annular Si detector giving triggering signals, 3 – the lower magnetic pole, 4 – array of position sensitive ΔE-TOF detectors, 5 – position sensitive TOF or ΔE-E detectors, 6 – the wall of tightly composed neutron detectors.

Ground-state energy resolution ~400 keV
Liquid T_2 ~3*10^{21} cm^{-2}
Intensity of ^{8}He ~10^{5} 1/s
Reaction cross section ~0.1 mb/sr
Triton trigger eff. ~0.7
***t+4n* detection eff. ~0.015**
$^{7}H_{g.s.}$ counting rate: ~5 per day

Example 2: ^{16}Be in the ^{14}Be(t,p)^{16}Be reaction as a new flag ship experiment at ACCULINNA-2

Spyrou, PRL 108 (2012) 102501



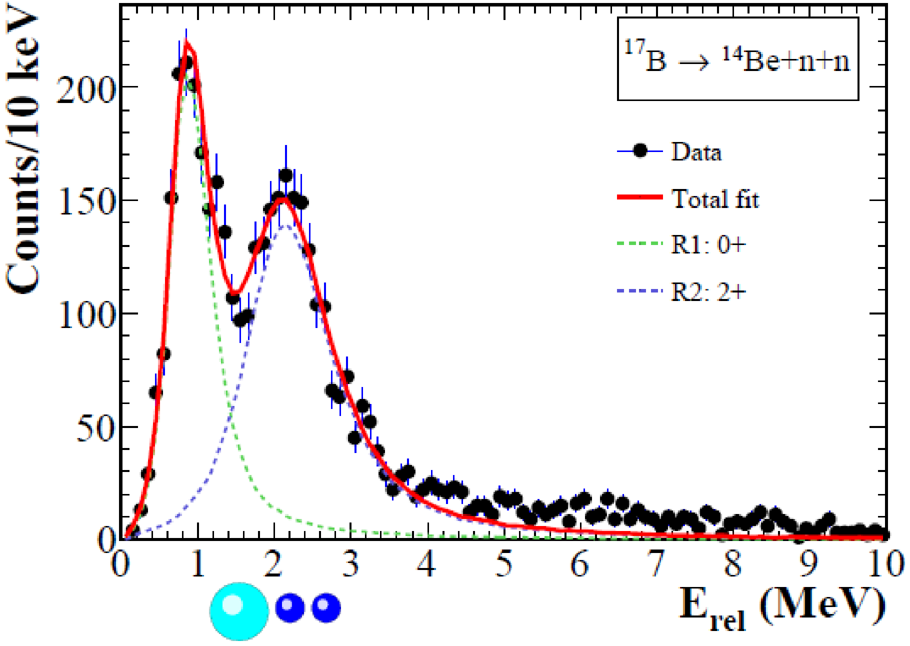


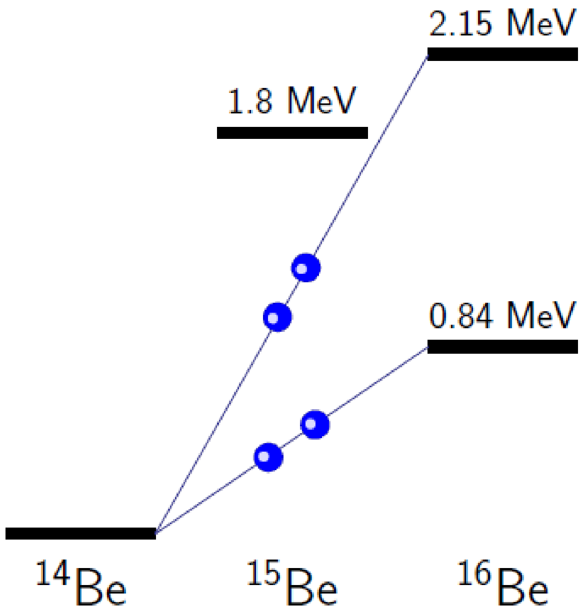
Proton knockout from ^{17}B

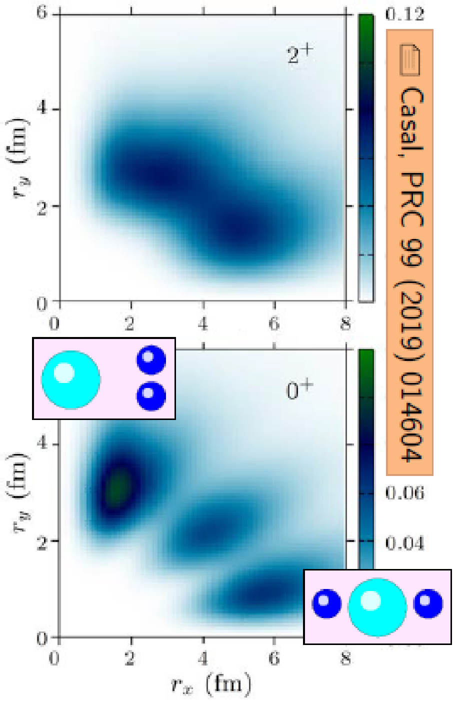
Exp. data – solid lines:
1.35 / 0.84 MeV (MSU/RIKEN)

shell model – dashed lines

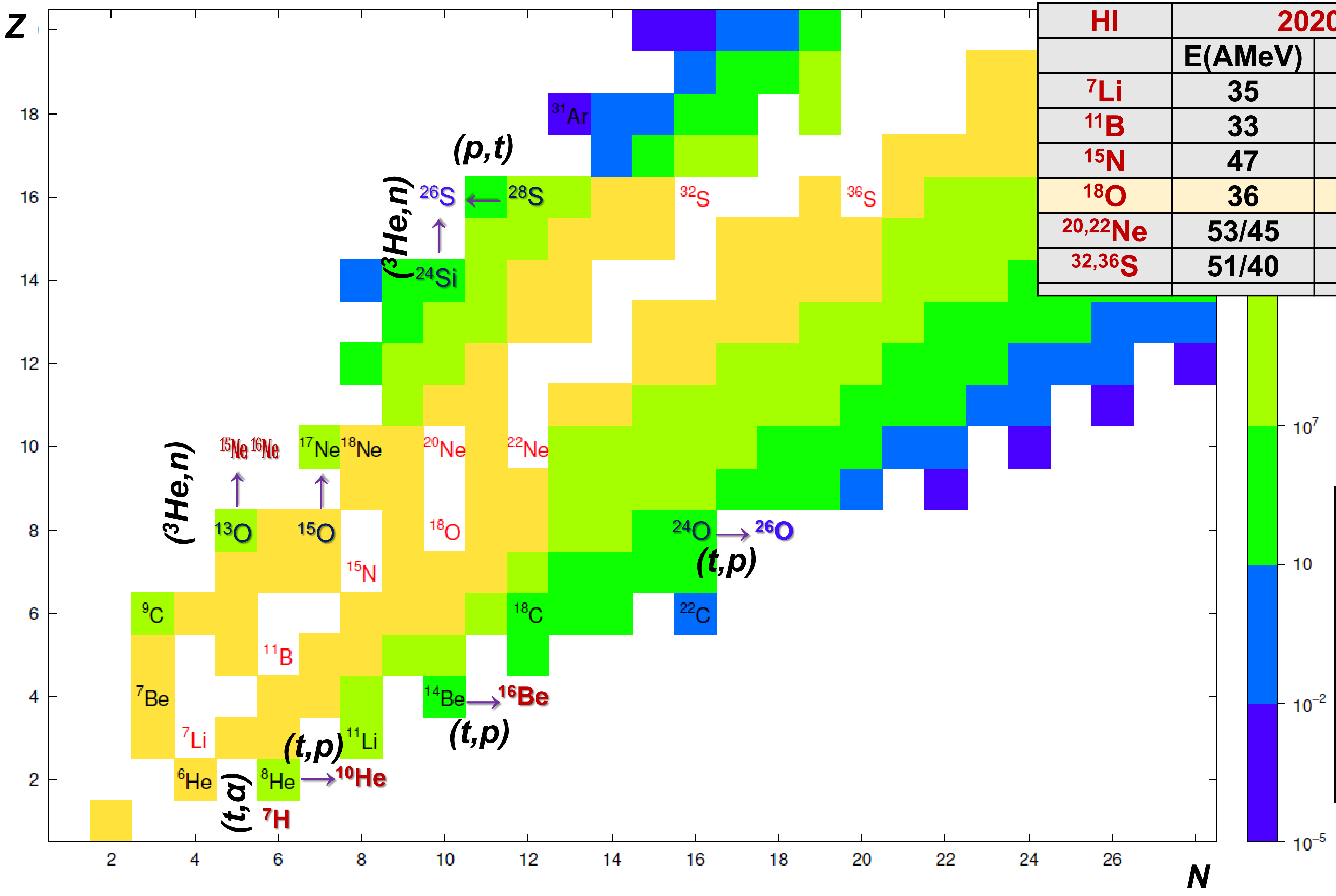
Spectrum of ^{16}Be depends on initial state of the ^{17}B (projectile with 2n halo).







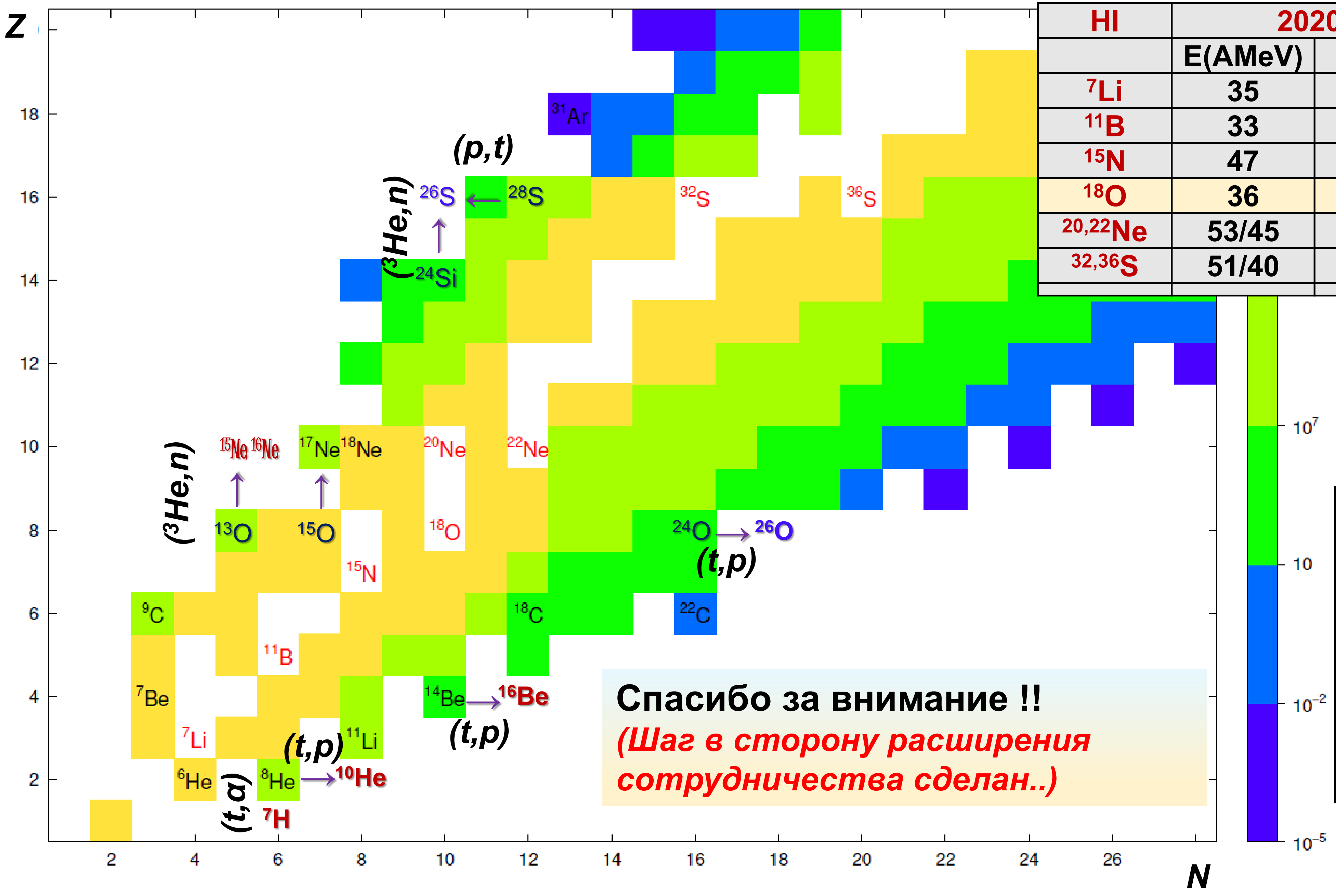
Other examples: day one ($^{15-17}$Ne, ^{7}H, ^{10}He, ^{16}Be) & day two (^{13}Li, ^{26}O, ^{26}S) experiments (since 2025)



HI	2020		2023	
	E(AMeV)	I(pμA)	E(AMeV)	I(pμA)
^{7}Li	35	5	39	10
^{11}B	33	3	34	6
^{15}N	47	0.5	51	2
^{18}O	36	0.5	40	1.5
^{20,22}Ne	53/45	0.3	54/50	1
^{32,36}S	51/40	0.2	52/44	0.2

RI	2023	
	Y, pps	P, %
^{8}He	$6*10^5$	90
^{11}Li	$3*10^4$	80
^{14}Be	$2*10^3$	85
^{13}O	$2*10^5$	55
^{24}O	$7*10^2$	50
^{17}Ne	$5*10^5$	80
^{28}S	$1.2*10^4$	70

Other examples: day one ($^{15\text{-}17}$Ne, ^{7}H, ^{10}He, ^{16}Be) & day two (^{13}Li, ^{26}O, ^{26}S) experiments (since 2025)



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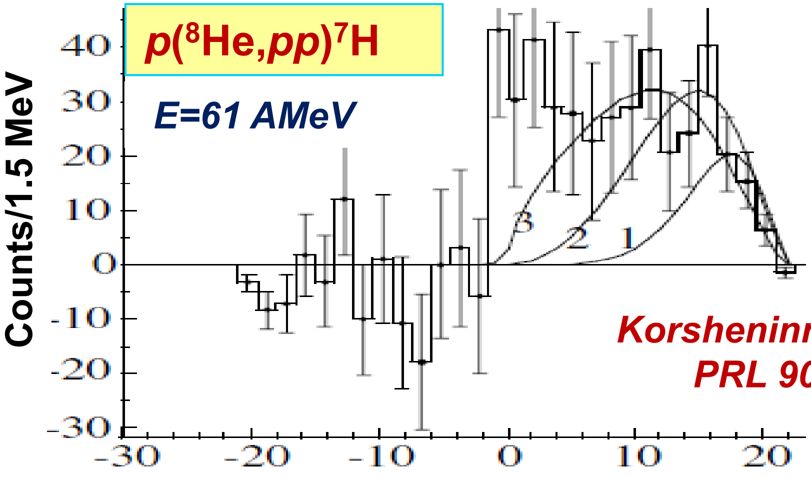
Спасибо за внимание !!

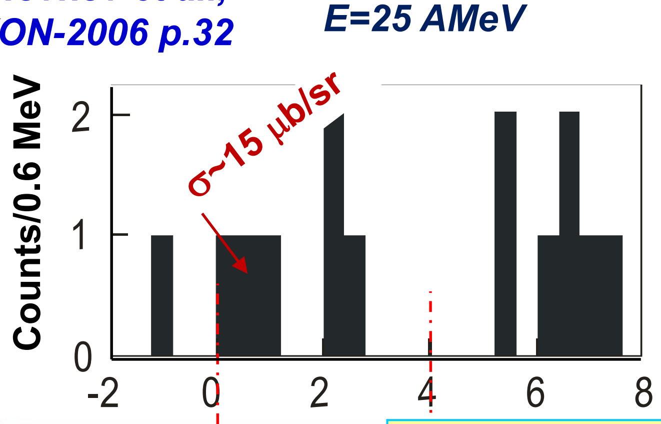
(Шаг в сторону расширения сотрудничества сделан..)

^{7}H history

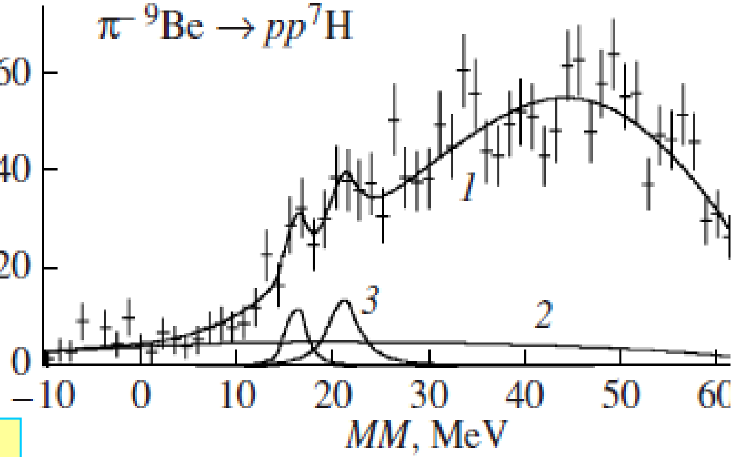
Korsheninnikov et al., PRL 90(2003)



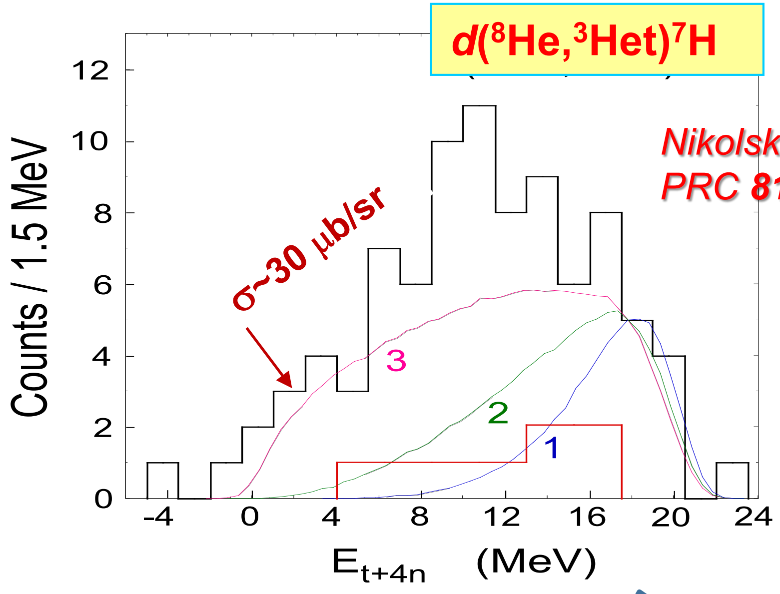
Golovkov et al., EXON-2006 p.32



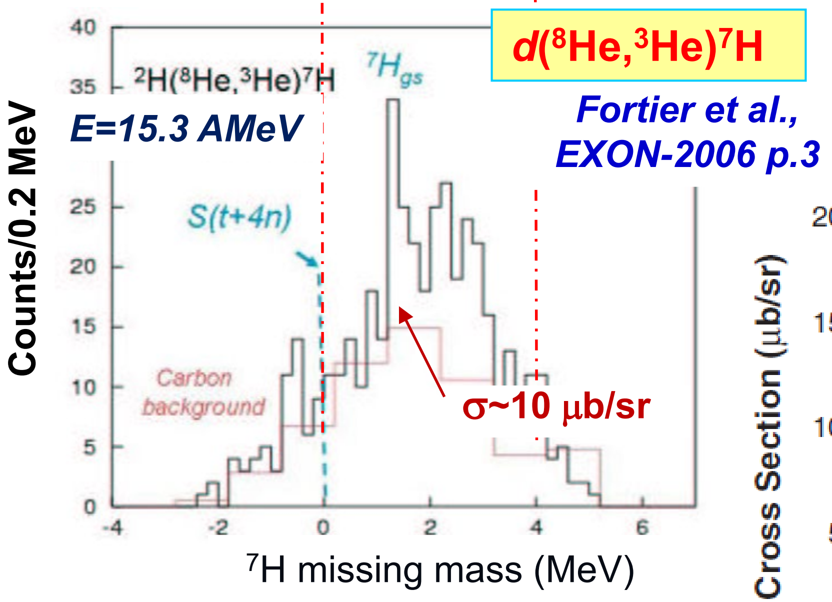
Gurov et al., Phys. Part. Nucl. 40 (1990) 558



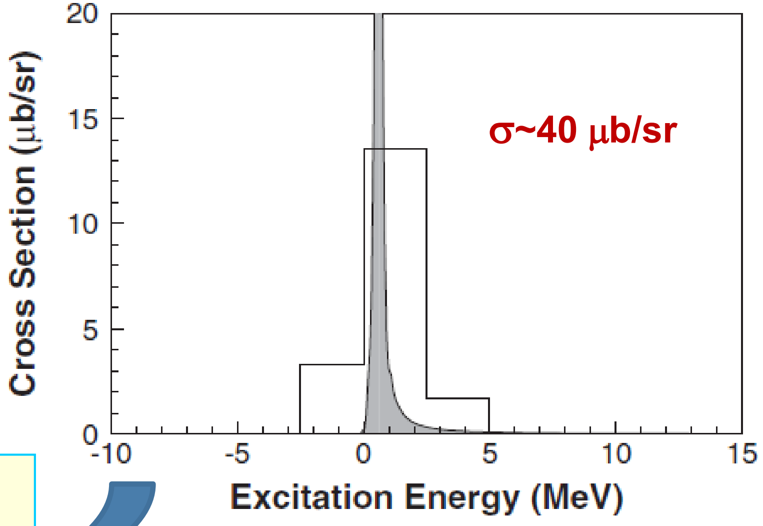
Nikolskii et al., PRC **81** (2010)



Fortier et al., EXON-2006 p.3

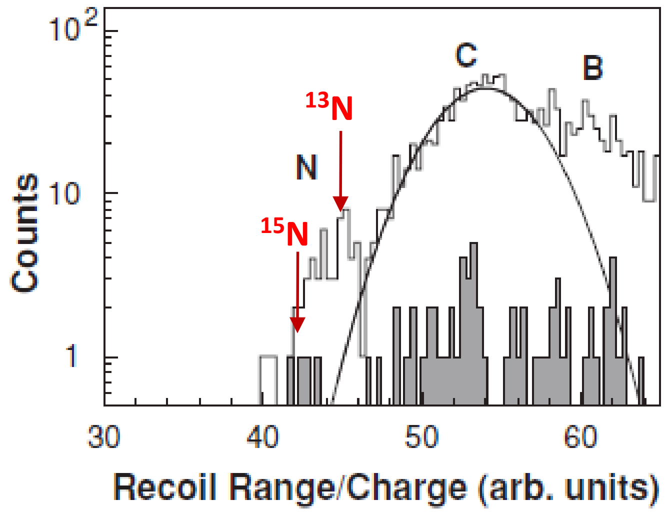


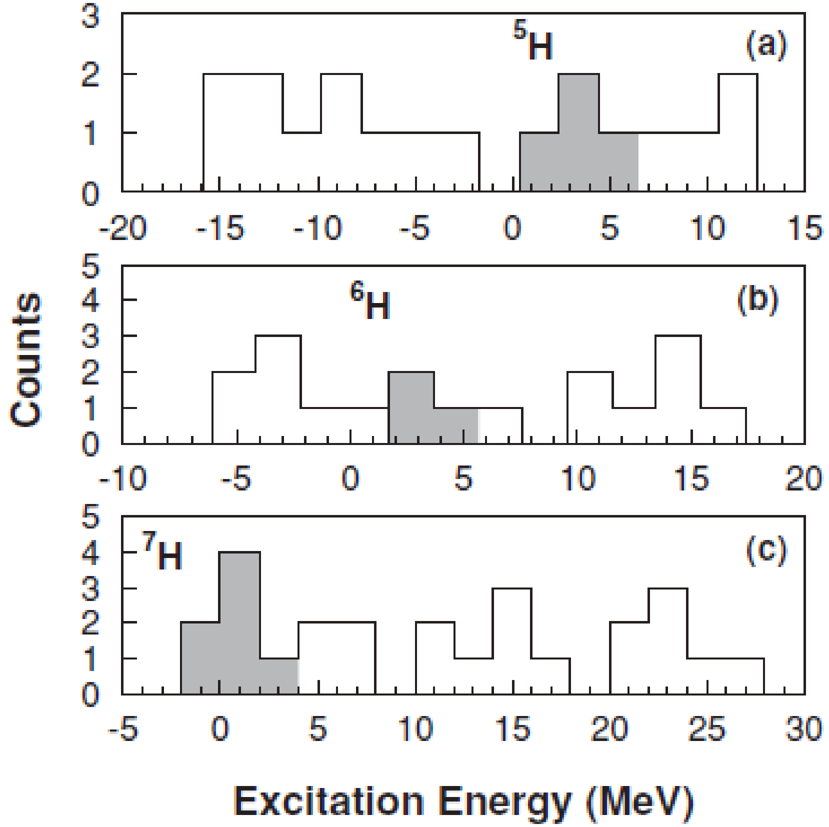
Caamaño et al. PRL 99 (2007)
^{12}C(^{8}He,^{13}N)^{7}H @ E=15.4 AMeV



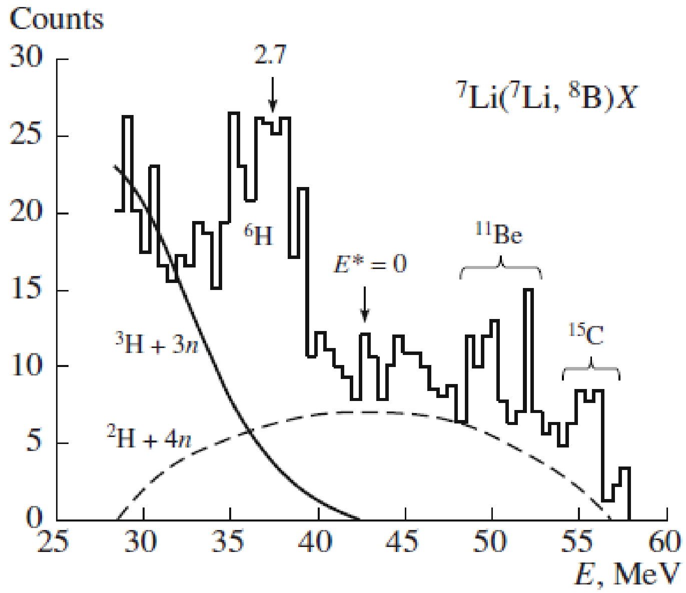
При одинаковом $SF(p+^{7}H) \sim 1$
сечения должны отличаться в 100 раз!!

$^{12}C(^{8}He, ^{15,14,13}N)^{5,6,7}H$, PRC C78 (2008) 044001

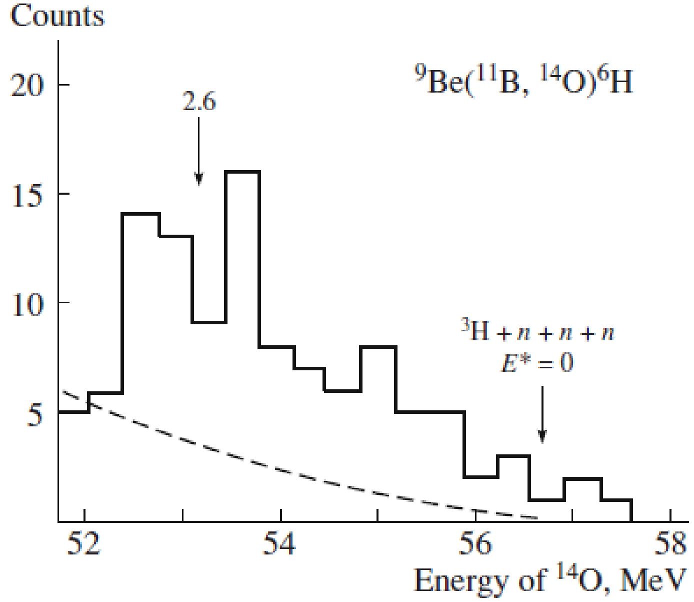




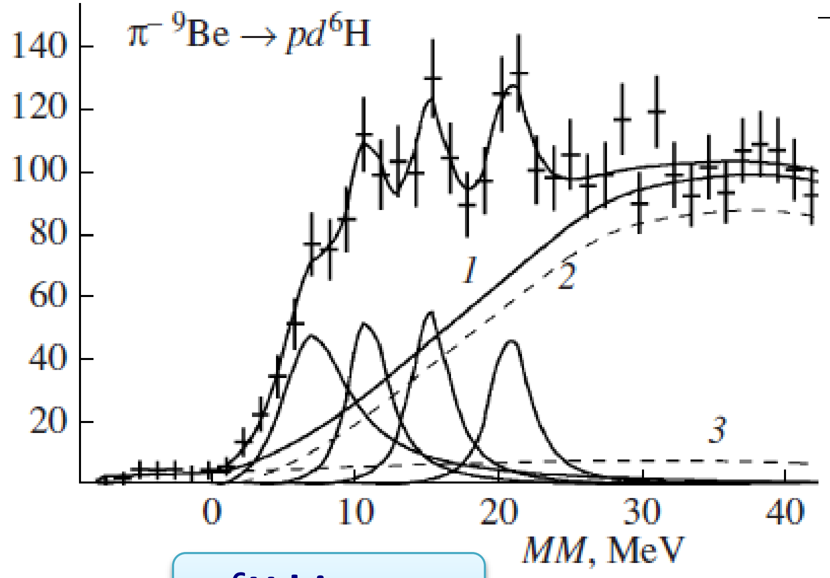
$^{7}Li(^{7}Li,^{8}B)^{6}H$, ЯФ т.39 (1984) 513



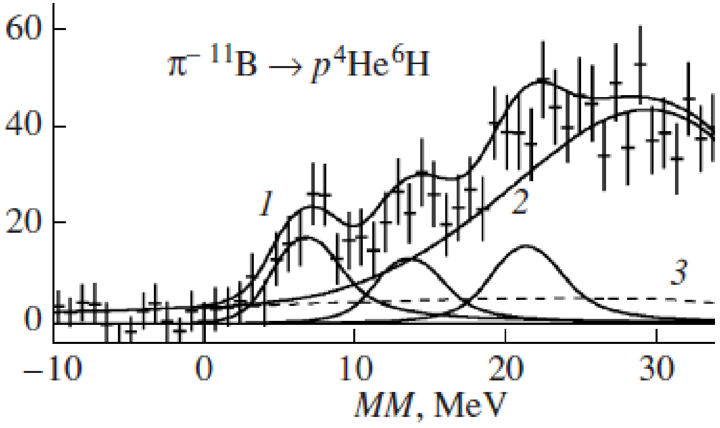
$^{9}Be(^{11}B,^{14}O)^{6}H$, Nucl.Phys. A460 (1986) 352



Phys. Part. Nucl. 40 (1990) 558

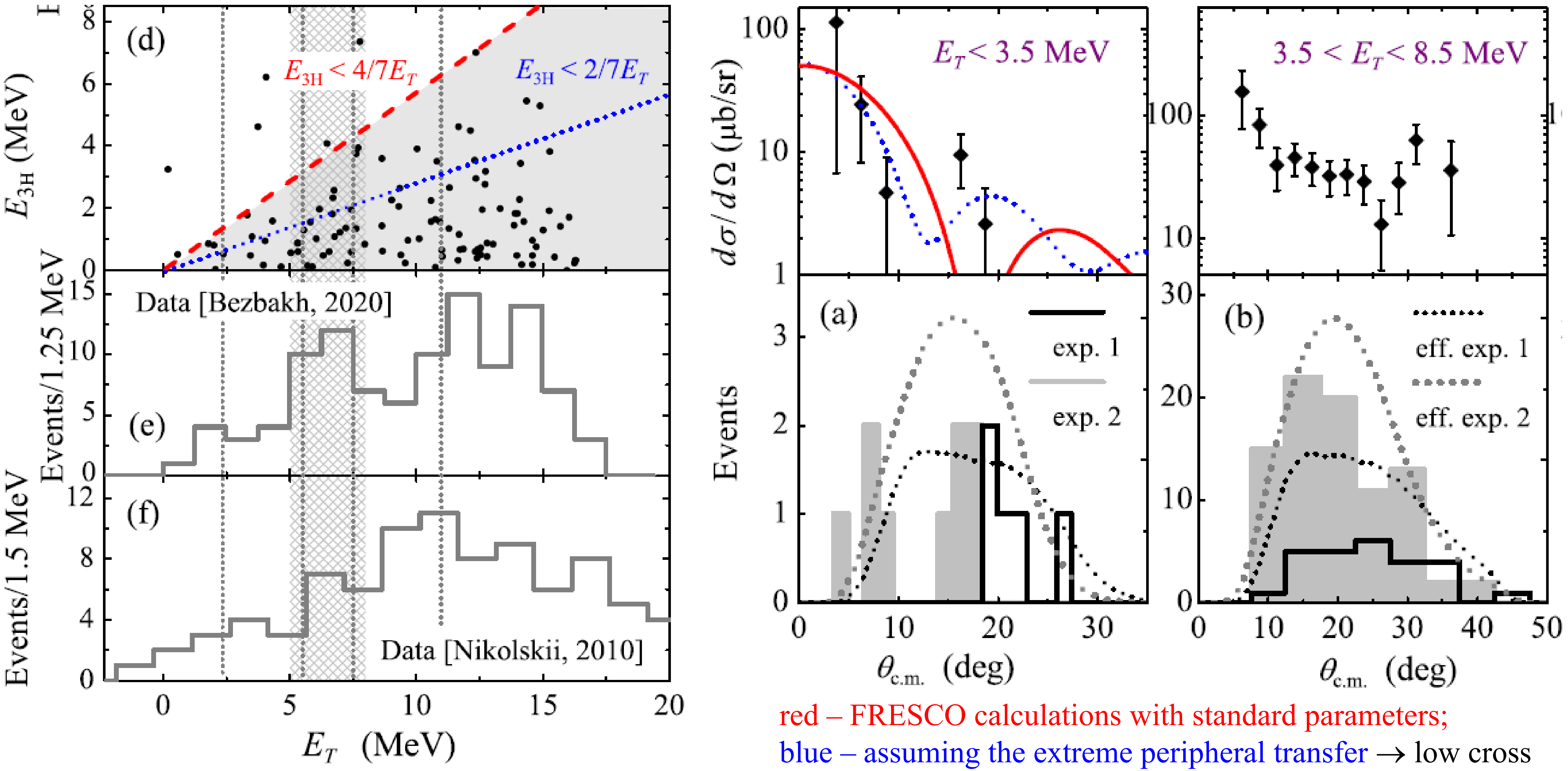


^{9}Be(π^-, pd)^{6}H		^{11}B(π^-, p^4He)^{6}H	
E_r, MeV*	Γ, MeV**	E_r, MeV	Γ, MeV
6.6 ± 0.7	5.5 ± 2.0	7.3 ± 1.0	5.8 ± 2.0
10.7 ± 0.7	4 ± 2	–	–



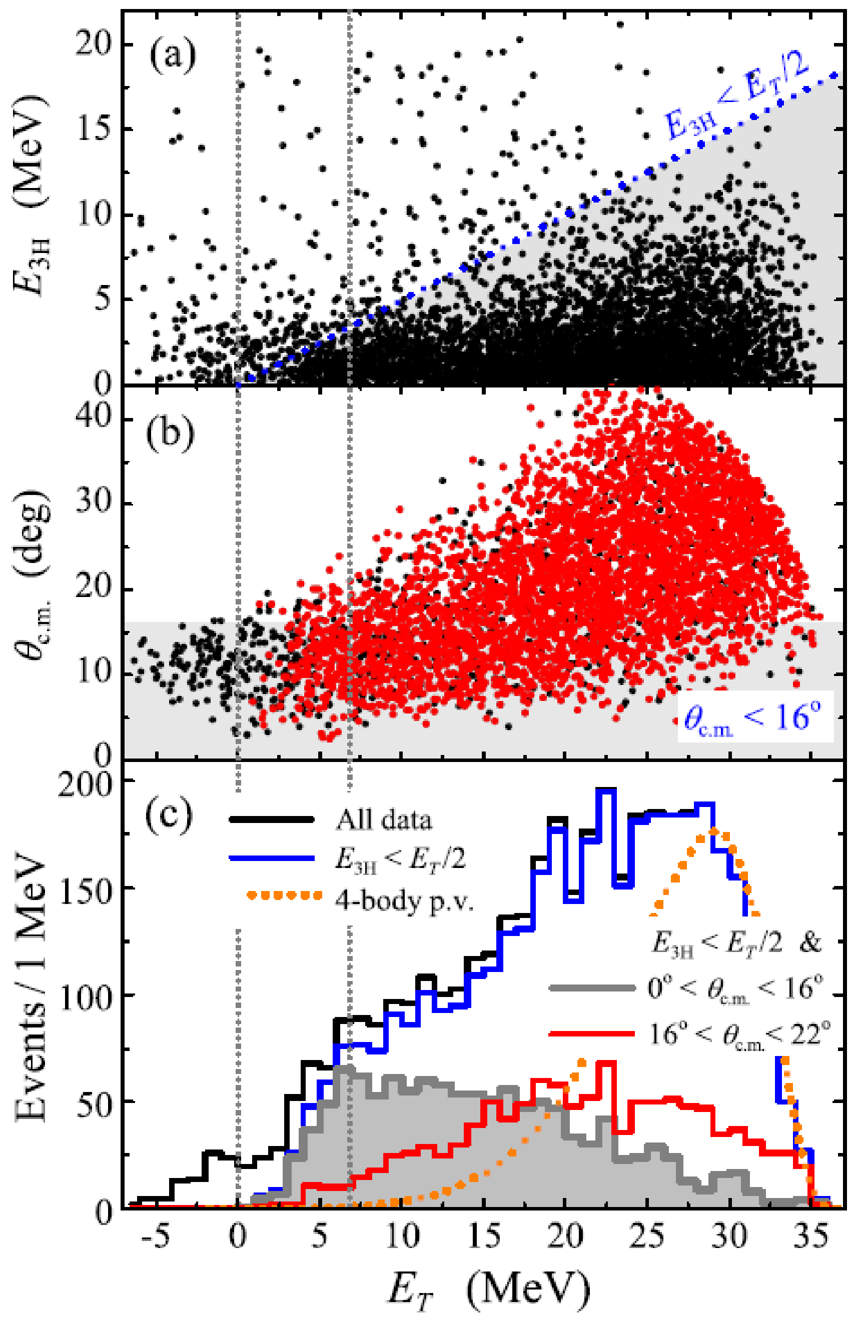
^{6}H history

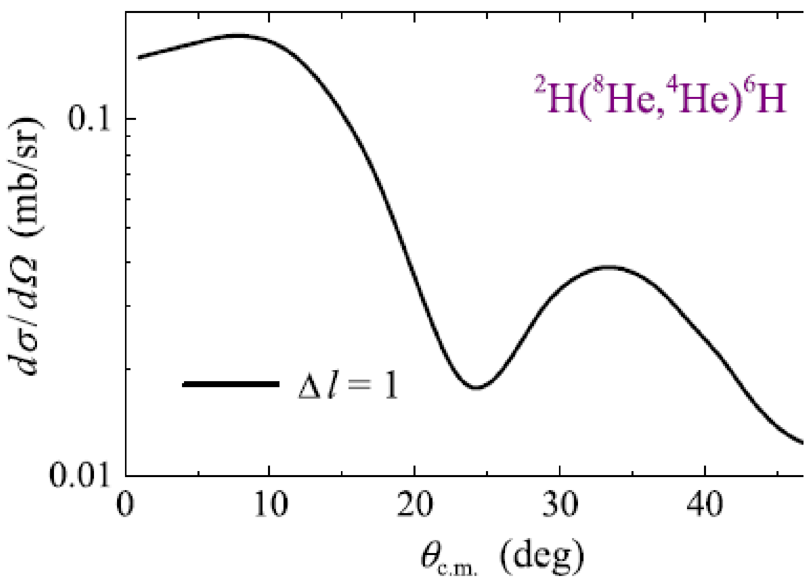
Details for ^{7}H data

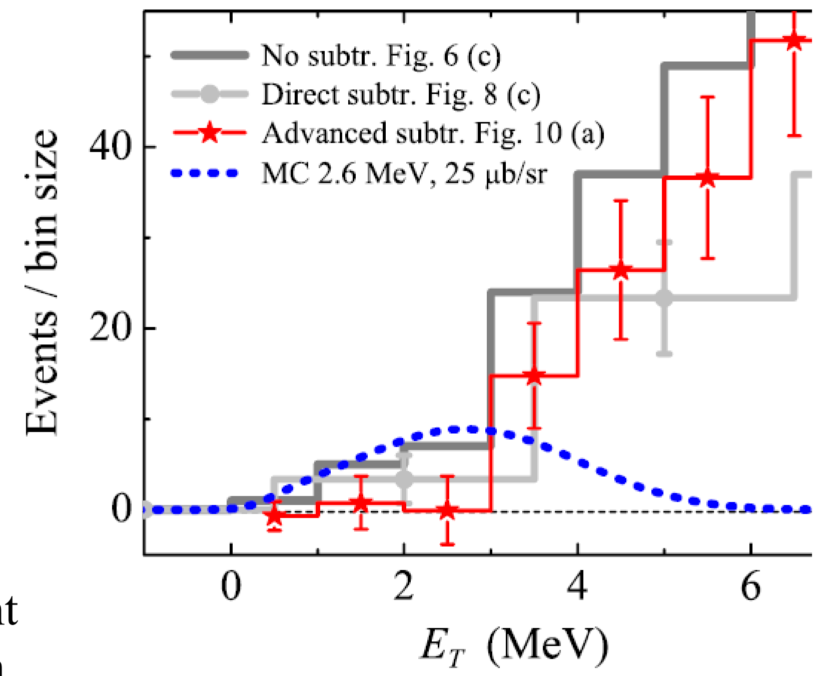


red – FRESCO calculations with standard parameters;
blue – assuming the extreme peripheral transfer → low cross section for the ^{7}H_g.s.

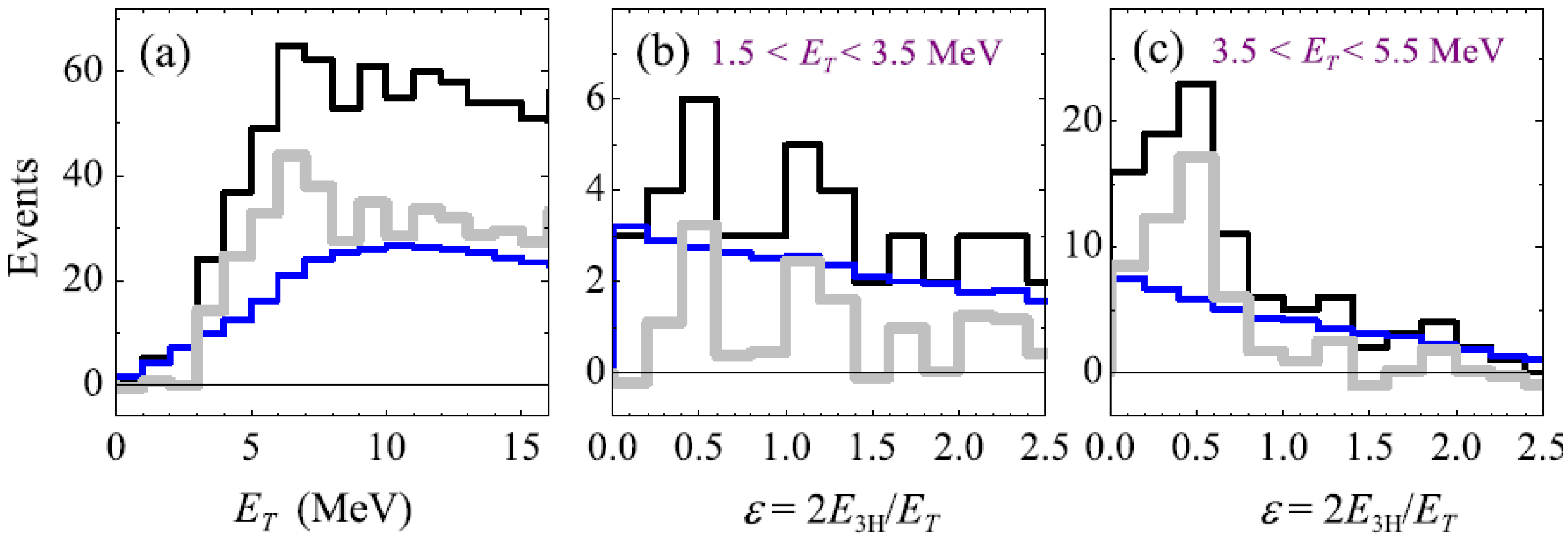
Details for ^{6}H data



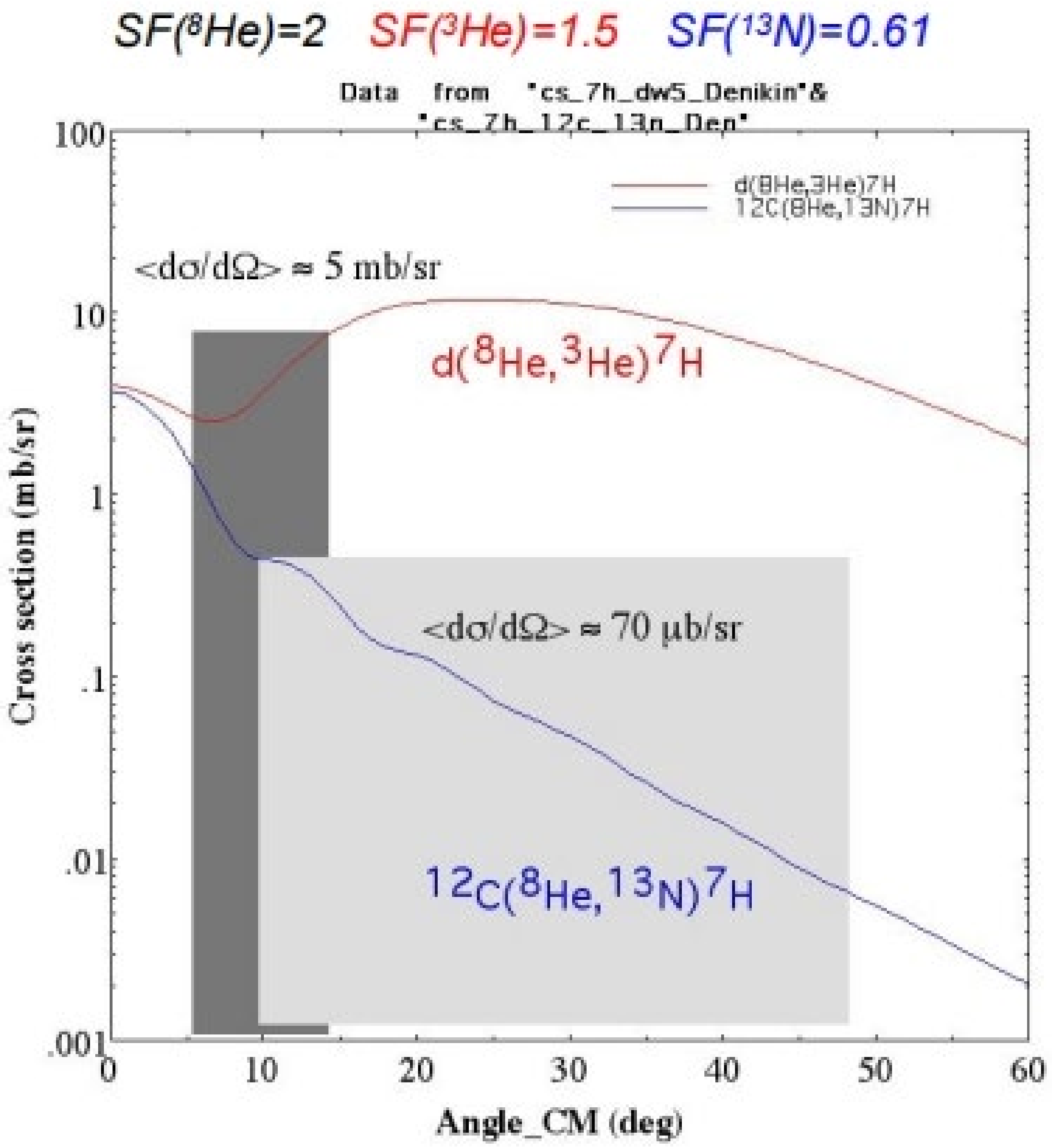




Diffraction minimum at ~24º is consistent with the absence of the 6.8 MeV bump in MM spectrum for 16º<ϑ_cm<22º → Δl=1.



DWBA cross sections for the d(^{8}He,^{3}He) and ^{12}C(^{8}He,^{13}N) reactions



*Nikolskii et al., PRC **81** (2010)*

RIKEN:

$d\sigma/d\Omega_{exp.}$ ~ 30 μb/sr

$d\sigma/d\Omega_{DWBA}$ ~ 5 mb/sr !!

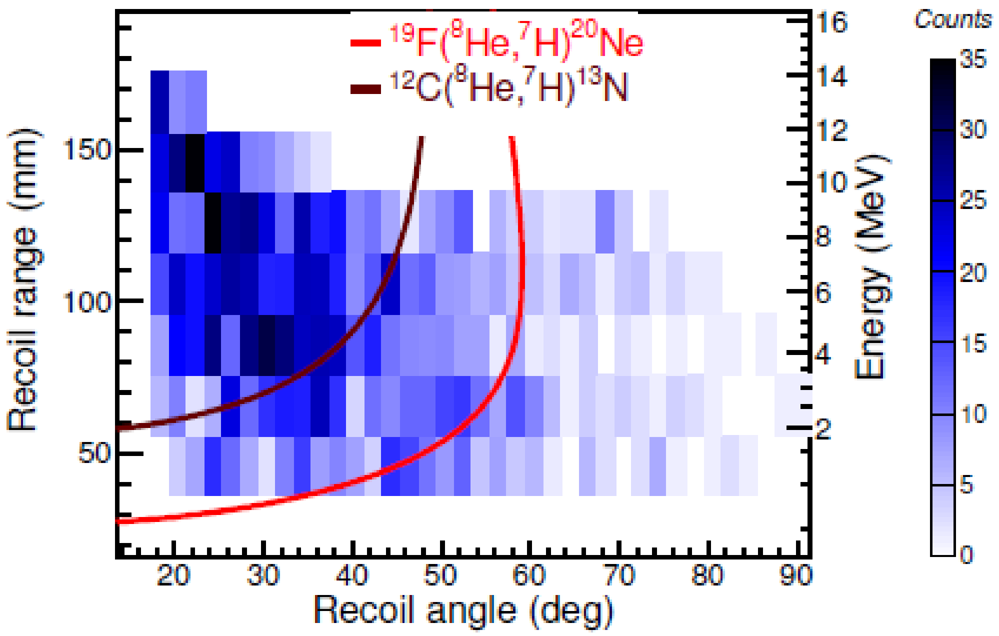
$Q_{react.}$ = – 19.32 MeV

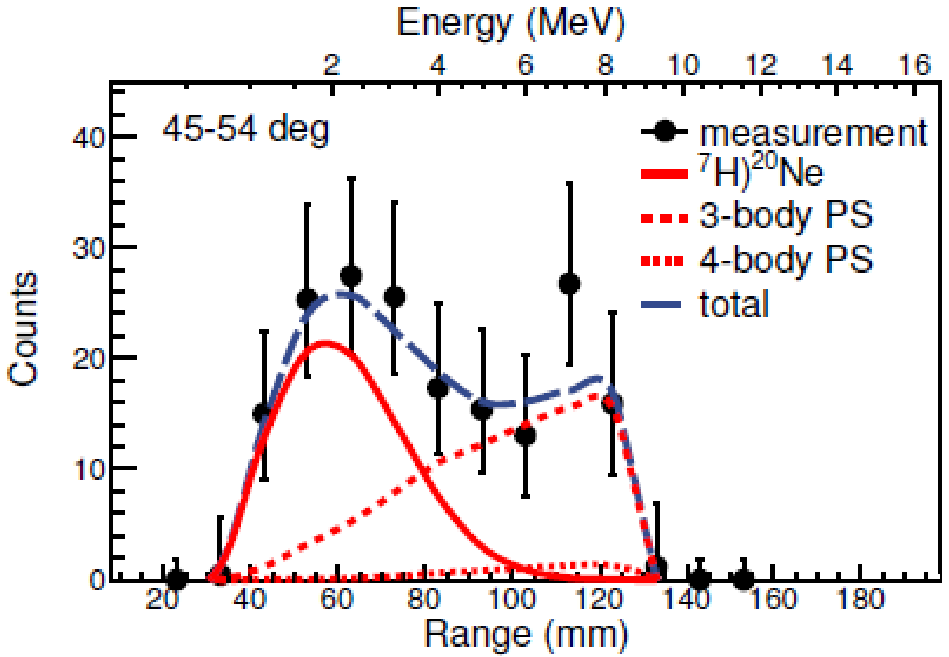
GANIL:

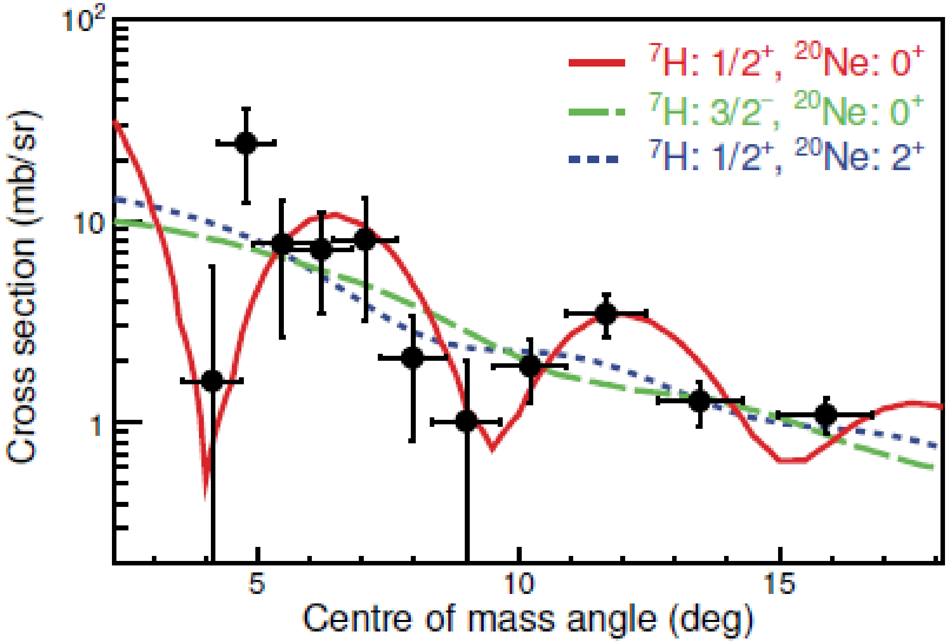
$d\sigma/d\Omega_{exp.}$ ~ 40 μb/sr

$d\sigma/d\Omega_{DWBA}$ ~ 70 μb/sr

$Q_{react.}$ = – 22.87 MeV







$Q_{react.}$ = – 11.97 MeV
$d\sigma/d\Omega$ ~ 10 mb/sr ?!
CF_4: 4×10^{19} & 10^{19} at./cm^2
(very thin target);
no background measurements;
no isotope identification;

EPJ Web of Conferences **232**, 04002 (2020)
HIAS 2019

Structure of superheavy hydrogen ^{7}H

M. Caamaño[1,*], T. Roger[2,**], A. M. Moro[3], G. F. Grinyer[4],

^{4}n, ^{6}H, ^{7}H Data & References

[Ref.] Reaction / E (AMeV)	dσ/dΩ, μb/sr ϑ_cm, deg.	Q_value	Q_opt	E_x	ϑ_rec_max	ϑ_7H_max
[1] 8He(2H,3He)7H* / 26	30 (5°-18°)	-19.32	+0.0	-19.3	34 (3He)	13.8
[13] 8He(2H,3He)7H / 15.3	100 (0°-50°)				20.7 (3He)	8.7
[2] 8He(2H,3He)7H / 42	~30 (6°-14°)				40 (3He)	16
[3] 8He(1H,2He)7H / 61.3	~10 per MeV	-28.41	+0.0	-28.4	27 (2He)	7.4
8He(3H,4He)7H** / 26	?100?	-5.00	+0.0	-5.0	51 (4He)	26
11Li(4He,8Be)7H** / 30	?200?	-10.92	-29.3	+18.3	32 (8Be)	37
[4] 8He(19F,20Ne)7H / 15.4	~2000 (4°-16°)	-11.97	-38.4	+26.4	58 (20Ne)	180
[5] 8He(12C,13N)7H / 15.4	40.1 (10°-48°)	-22.87	-30.5	+7.6	48 (13N)	180
[5] 8He(12C,14N)6H / 15.4	18.7 (9°-46°)	-13.3	-30.5	+17.4	46.4 (14N)	180 (6H)
[6] 8He(2H,4He)6H* / 26	<5 (5°-16°)	+0.44	+0.0	+0.4	38 (4He)	24 (6H)
[7] 11B(9Be,14O)6H / 8	~0.016	-29.87	-23.7	-6.2	17 (14O) 8°	42 (6H)
[8] 7Li(7Li,8B)6H / 11.7	~0.06	-34.98	-18.2	-16.8	19 (8B) 10°	26 (6H)
[15] 6Li(π-,π+)X / 220	<0.005					

[Ref.] Reaction / E (AMeV)	dσ/dΩ, nb/sr	Q_value	Q_opt	E_x	ϑ_rec_max	ϑ_4n_max
[9] 11B(7Li,14O)4n / 8	<1 per MeV	-16.72	-31.9	+15.2	18 (14O) 8°	180
[9] 9Be(7Li,12N)4n / 11.9	-"-	-23.37	-42.8	+19.5	21 (12N) 5°	180
[9] 9Be(9Be,14O)4n / 11.9	-"-	-17.6	-50.0	+32.4	26 (14O) 5°	180
[16] 7Li(7Li,10C)4n / 11.4	<30	-18.17	-36.4	+18.2	28 (10C) 7.4°	180
[10] 7Li(7Li,10C)4n / 11.7	<0.1	-18.17	-36.4	+18.2	28 (10C) 2°	180
[11] 7Li(7Li,10C)$4n^{1}$ / 6.6	1.2 (6°-9.5°)	-18.17	-20.4	+2.2	17 (10C) 5°,7°	46
[12] 8He(4He,8Be)$4n^{2}$ / 186	3.8 nb for ϑ_cm<5.4°	-3.19	-364.7	+361.5	30 (8Be)	82
[13] 8He(2H,6Li)$4n^{3}$ / 15.3	?	-1.63	-12.3	+10.7	23 (6Li)	36
[18+] 8He(2H,6Li)4n / 26	~50-70? (5°-40°)	-1.63	-20.9	+19.3	23.6 (6Li)	36.6
[14] 14Be(12C,10Be)$4n^{4}$/35	σ(4n) ~ 1mb	-4.94		0 (14Be)	(14Be,X+n)	
		0.06		5 (14Be)	0.42 (10Be)	1.04
[17] 4He(π-,π+)$4n^{5}$ / 232	?? very low				0°	
[19] 8He(p,p4He)$4n^{6}$ / 156	<1μb el.scat.	-5.07	-69.2	64.1		

1. Bezbakh et al., PRL 124, 022502 (2020); Muzalevskii et al., PRC 103, 044313 (2021).
2. Nikolskii et al., PRC 81, 064606 (2010).
3. Korsheninnikov et al., PRL 90, 082501 (2003).
4. Gaamano et al., PLB 137067 (2022).
5. Gaamano et al., PRL 99, 062502 (2007).
6. Nikolskii et al., PRC 105, 064605 (2022).
7. Belozyorov et al., Nucl.Phys. A460 (1986) 352.
8. Aleksandrov et al., Sov. Yad. Fiz. 39 (1984) 513.
9. Belozyorov et al., Nucl.Phys. A477 (1988) 131.
10. Aleksandrov et al., JETP Lett. 81 (2005) 43.
11. Faestermann et al., PLB 824 (2022) 136799.
12. Kisamori et al., PRC 116, 052501 (2016).
13. Fortier et al., AIP Conf.Proc. 912 (2007) 3.
14. Marques et al., PRC 65, 044006 (2002).
15. Parker et al., PLB 251 (1990) 483.
16. Cerny et al., Phys.Lett. 53B (1974) 247.
17. Gilly et al., Phys. Lett. 19, 335 (1965); Ungar et al., Phys. Lett. 144B, 333 (1984); Marques and Carbonell, EPJ A (2021) 57:105 and ref. therein.
18. Muzalevskii et al., Bul. of the Russian Academy of Sciences: Physics, **84** (2020) 500; 18+. К вопросу о заселении ^{3,4}n в реакции ^{8}He+d. (PRC, ЯФ или Письма ЭЧАЯ?).
19. Duer et al., Nature 606, 678 (2022).