First experimental campaign at the new fragment separator ACCULINNA-2: superheavy $^{6,7}H$ isotopes elucidated

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COLLABORATION:

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5 – *GSI Helmholtzzentrum fur Schwerionenforschung, Darmstadt, Germany*

6 – *Heavy Ion Laboratory, University of Warsaw, Warsaw, Poland*

7 – *Skobel'tsyn Institute of Nuclear Physics, Moscow State University, Russia*

8 – *Faculty of Physics, University of Warsaw, Warsaw, Poland*

9 – *Fundamental Physics, Chalmers University of Technology, Goteborg, Sweden*

10– *All-Russian Research Institute of Experimental Physics, Sarov, Russia*

11 – *Ioffe Physical Technical Institute, St. Petersburg, Russia*

12 – *NSCL, Michigan State University, East Lansing, Michigan, USA*

OUTLINE:

- Physics motivation. Light exotic nuclei near and beyond nucleon drip lines

  History of ^{7}H, ^{6}H research….

- New fragment separator ACCULINNA-2 at FLNR (JINR). Experimental setup

- Calibration by the $^{2}H(^{10}Be,^{3}He)^{9}Li$ and $^{2}H(^{10}Be,^{4}He)^{8}Li$ reactions with ^{10}Be beam

- Study of the ^{7}H system via $^{2}H(^{8}He,^{3}He)^{7}H \rightarrow t + 4n$. Two Runs.

  [A.A. Bezbakh et al., PRL **124**, 022502 (2020); I. A. Muzalevskii et al, PRC **103**, 044313 (2021)]

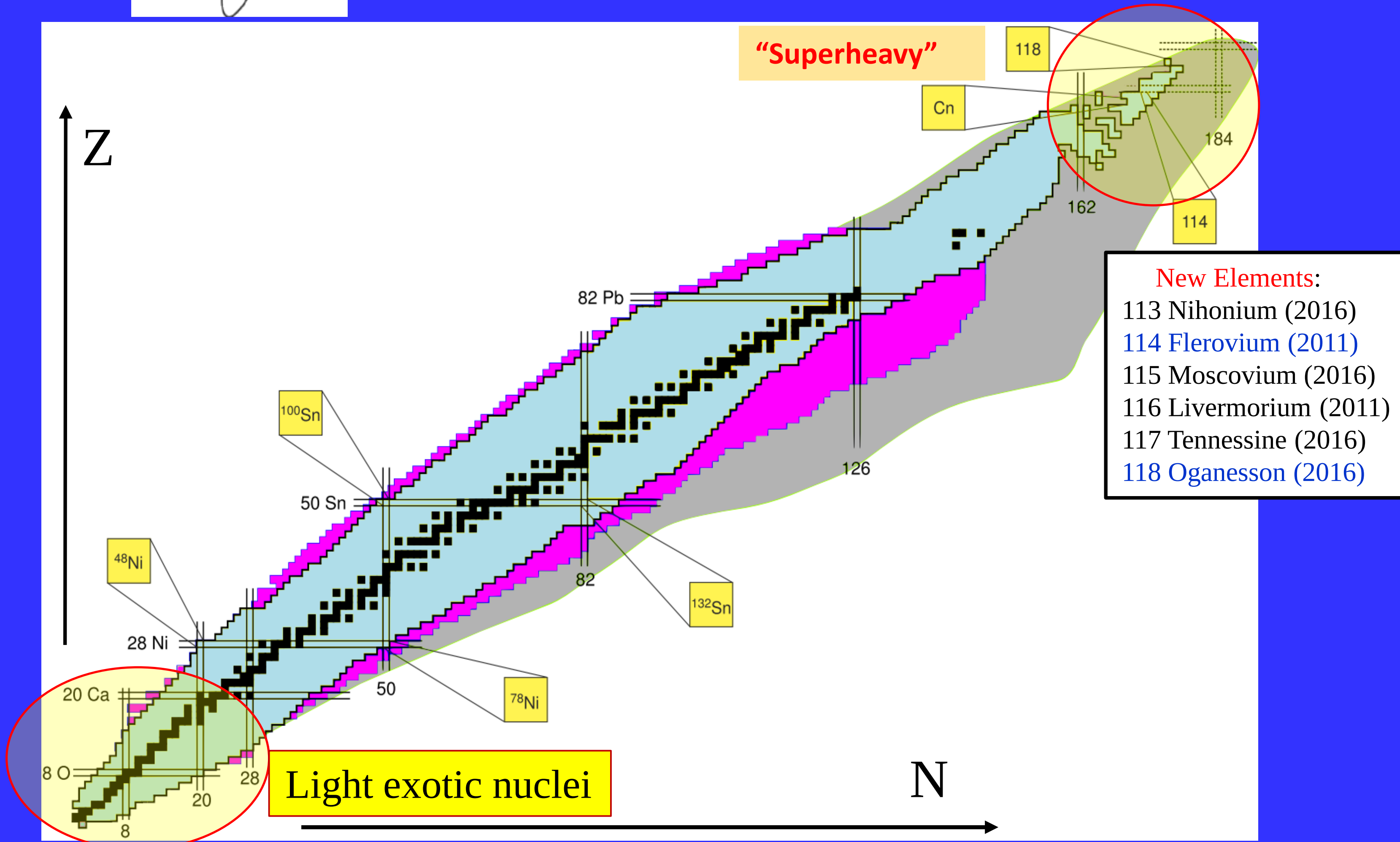
- Satellite study of the ^{6}H system via $^{2}H(^{8}He,^{4}He)^{6}H \rightarrow t + 3n$

  [E.Yu. Nikolskii et al., PRC **105**, 064605 (2022)]

- Summary

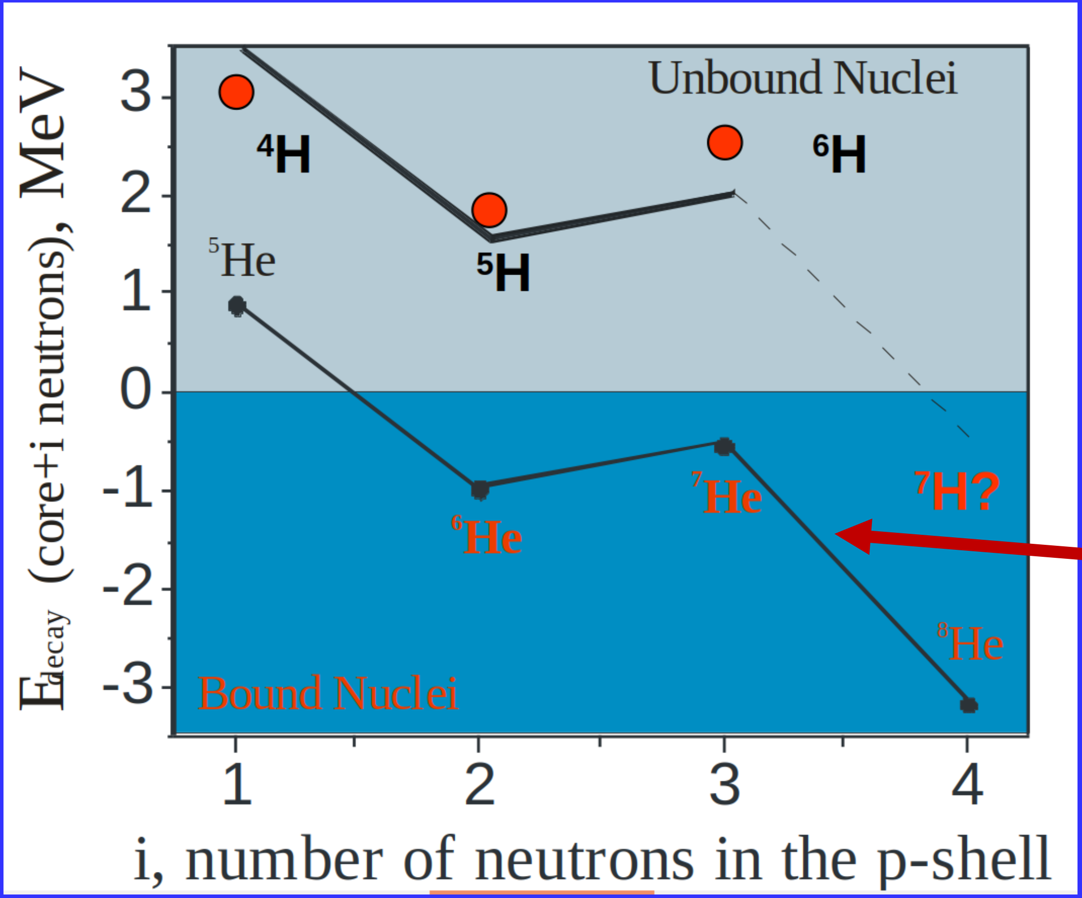
- Looking ahead

Main areas of interest at FLNR, JINR



^{4,5}H, ^{6}H, ^{7}H, ^{7}He, ^{8,9,10}He, ^{10}Li, [^{6}He+d], ^{6}Be, ^{17}Ne, ^{27}S

EXOTIC NUCLEI: Superheavy hydrogen isotopes $^{6,7}H$



The largest A/Z ratio !!

Unique many-body neutron decay channels !!

"Helium anomaly"

Theoretical calculations of ^{7}H(t+4n) energy:

E **= 0.87 MeV** (7-body hyperspherical functions)
N.K. Timofeyuk, PRC 65 064306 (2002)

E = **3 MeV** (7-body hyperspherical functions, p.s.e.)
A.A. Korsheninnikov et al., PRL 90 082501 (2003)

E = **7 MeV** (AMD)
S. Aoyama and N. Itogaki, NP A738 362 (2004)

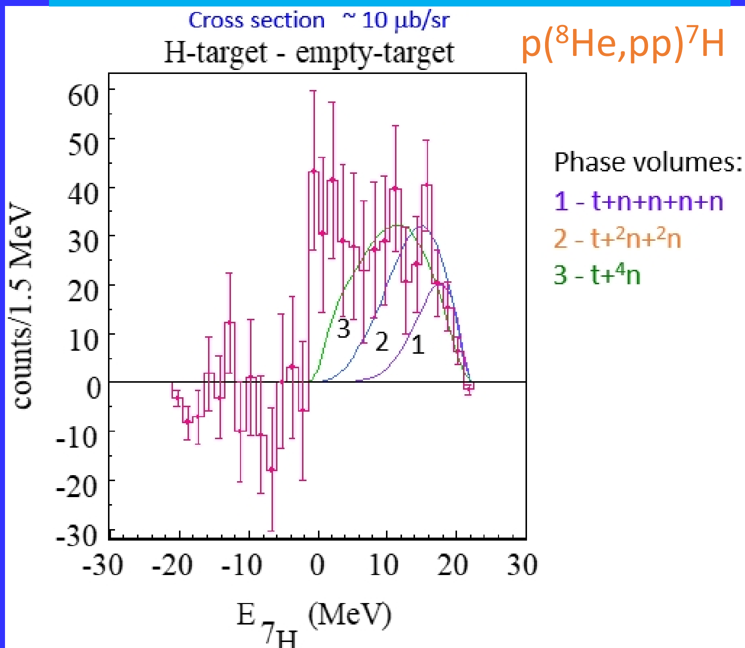
Estimation of width of ^{7}H: **E ≤ 3 MeV ⇔ Γ ≤ 1 MeV**
M.S. Golovkov et al., PL B588 163 (2004)

New Result:

E ≈ **9.5 MeV**, Γ = **3.5 MeV** (Variational Gaussian Expansion Approach)
E. Hiyama et al., PLB **833** 137367 (2022)

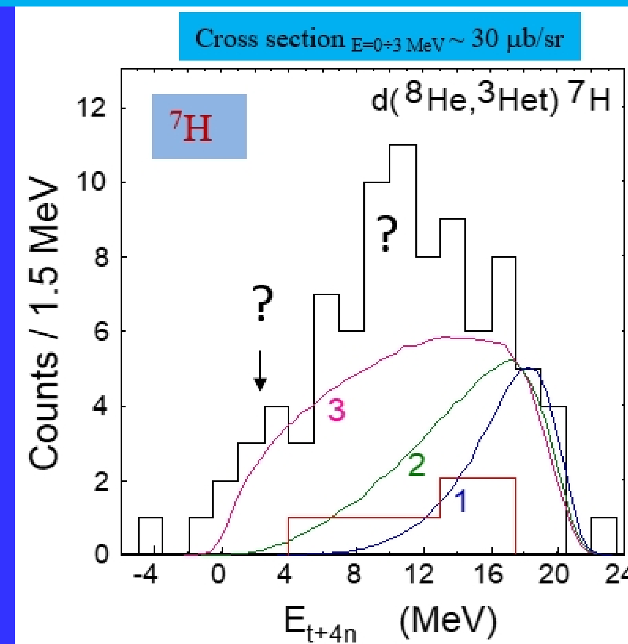
Experiments to search for ^{7}H states

1st RIKEN experiment to search for ^{7}H

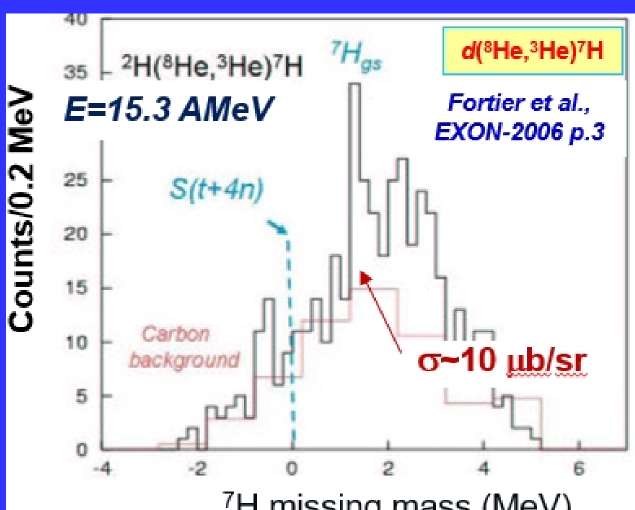


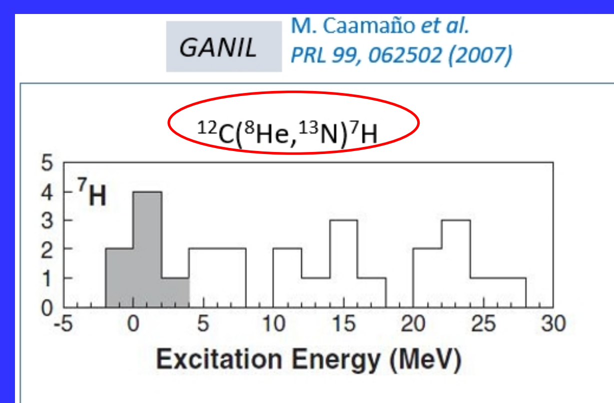
A. A. Korsheninnikov et al. PRL **90**, 082501 (2003)

2nd RIKEN experiment to search for ^{7}H



E.Yu.Nikolskii *et al.*, PRC **81,** 064606 (2010)



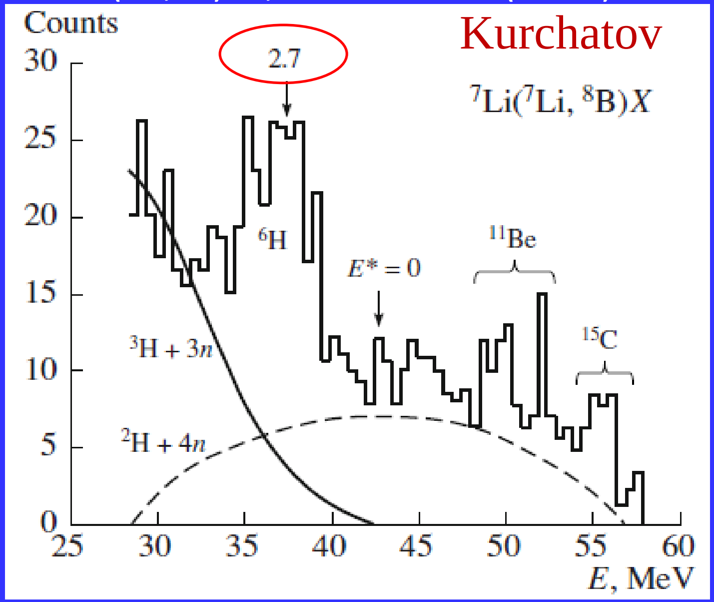


$E = 0.57^{+0.42}_{-0.21}$ MeV, $\Gamma = 0.09^{+0.94}_{-0.06}$ MeV

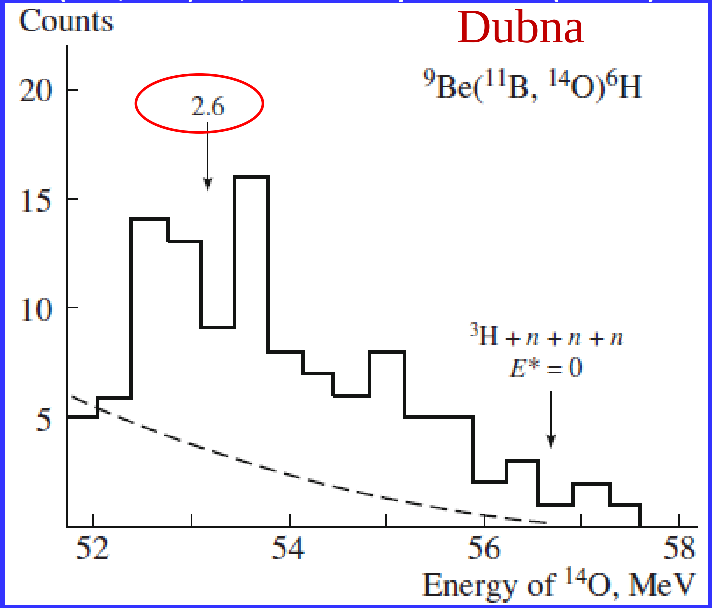
Experiment	*LAB*	*Energy (AMeV)*	*Result*	*Cross section (μb/sr)*
p(^{8}He,pp)	*RIKEN*	61	Very sharp increase from threshold No resonance parameters	~ 30 (E ≤ 3 MeV)
d(^{8}He,^{3}He)	*GANIL*	15.3	Structure near 2 MeV No resonance parameters	—
d(^{8}He,^{3}He)	*Dubna*	25	Few events No resonance parameters	≤ 30 (E ≤ 3 MeV)
^{12}C(^{8}He,^{13}N)	*GANIL*	15.3	7 events $E = 0.57^{+0.42}_{-0.21}$, $\Gamma=0.09^{+0.94}_{-0.06}$ MeV	$40.1^{+58.0}_{-30.6}$
d(^{8}He,^{3}He)	*RIKEN new*	42	Abnormal shape near threshold, shoulder at ~ 2 MeV No resonance parameters	~ 30 (E ≤ 3 MeV)

^{6}H history

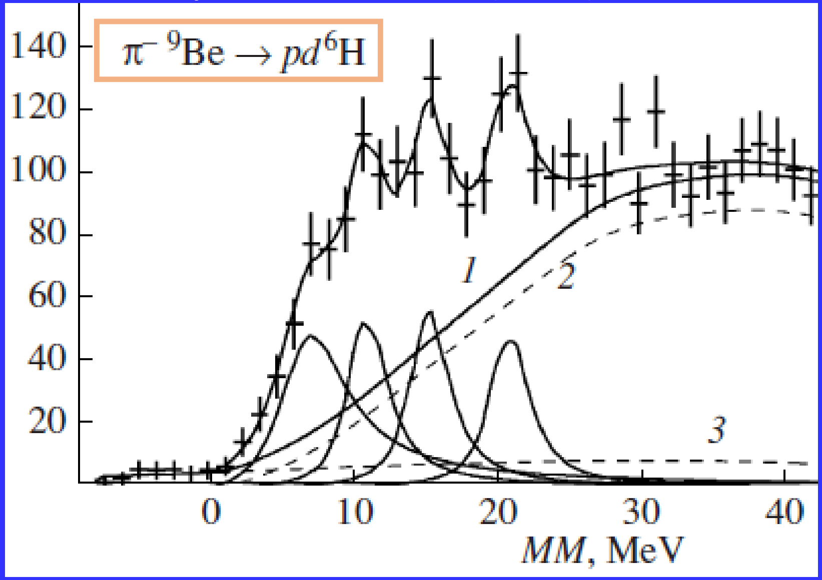
^{7}Li(^{7}Li,^{8}B)^{6}H, Yad.Fiz. т.39 (1984) 513



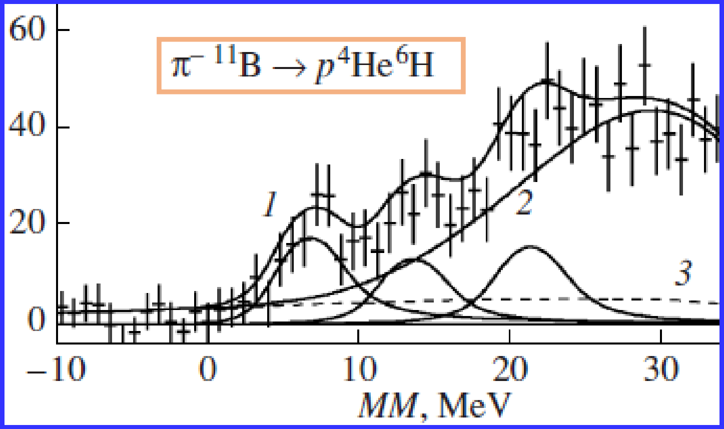
^{9}Be(^{11}B,^{14}O)^{6}H, Nucl.Phys. A460 (1986) 352



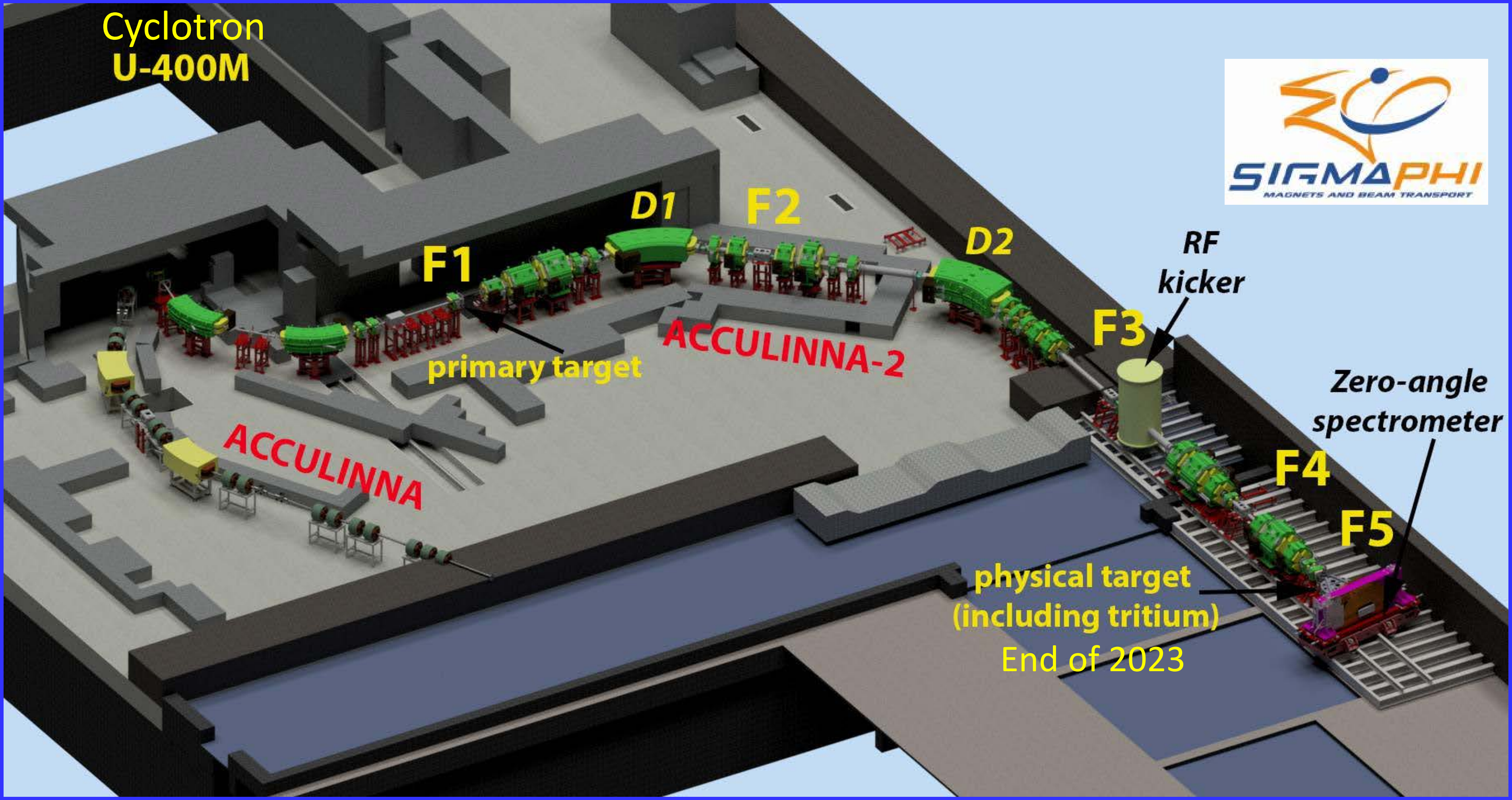
Phys. Part. Nucl. 40 (1990) 558



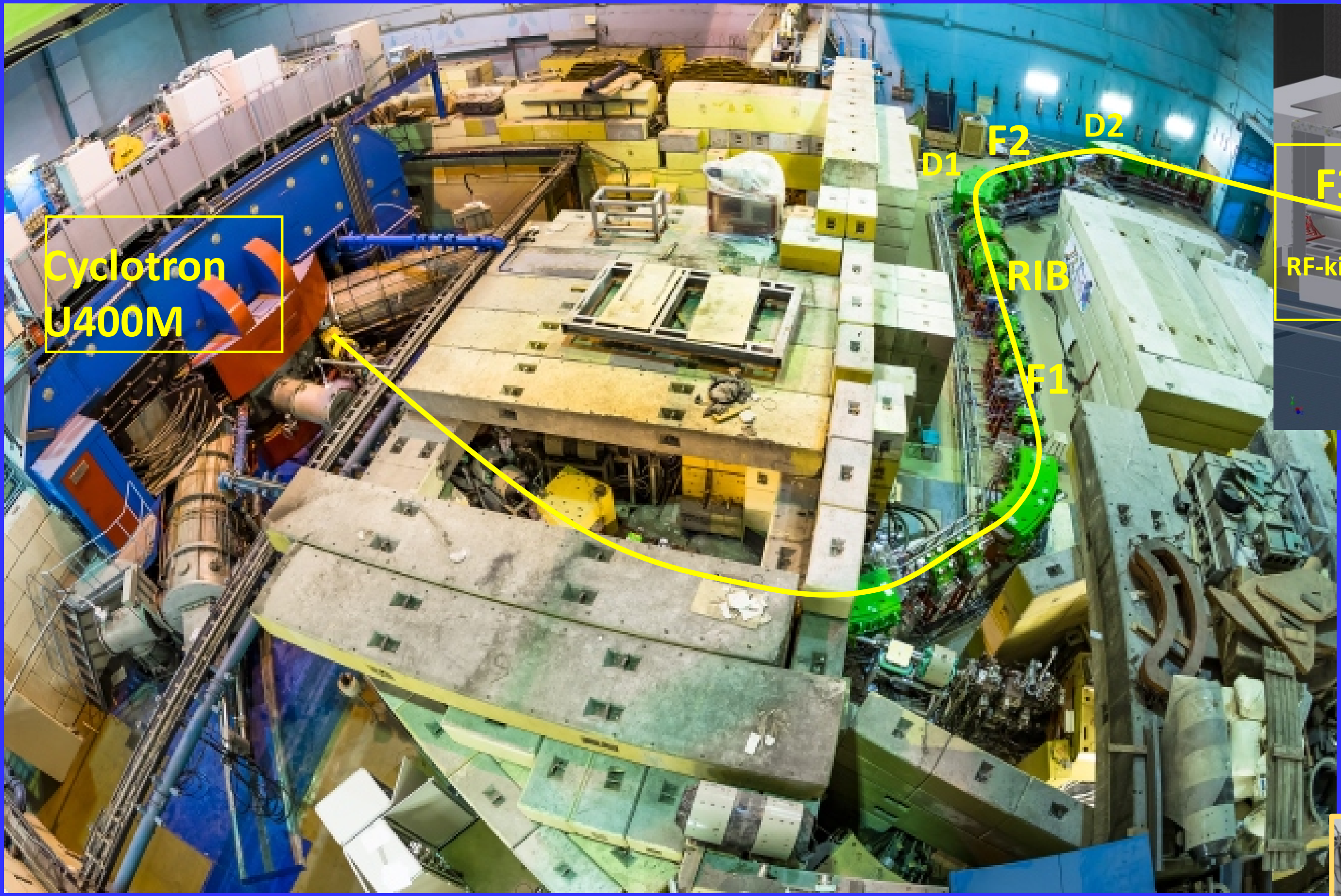
^{9}Be(π^{-}, pd)^{6}H		^{11}B(π^{-}, p^{4}He)^{6}H	
E_r, MeV*	Γ, MeV**	E_r, MeV	Γ, MeV
6.6 ± 0.7	5.5 ± 2.0	7.3 ± 1.0	5.8 ± 2.0
10.7 ± 0.7	4 ± 2	–	–

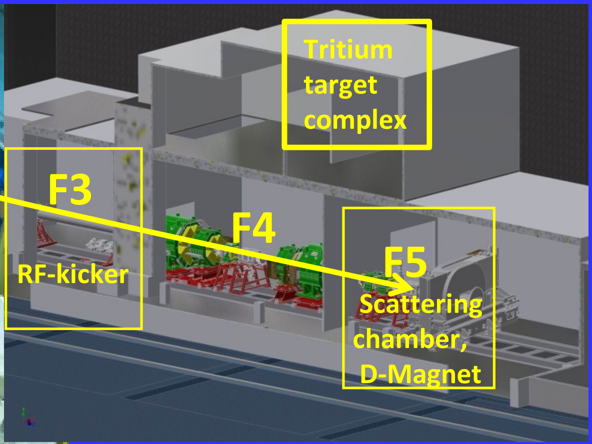


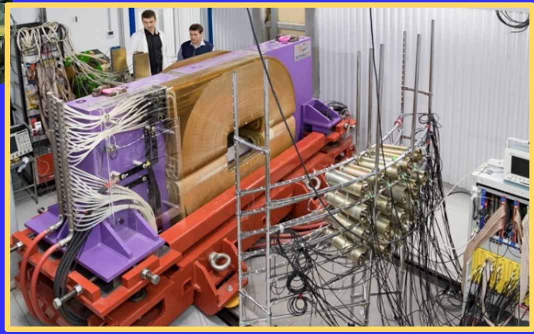
ACCULINNA-2 separator layout



A.S. Fomichev et al., Eur. Phys. J. A (2018) **54**: 97

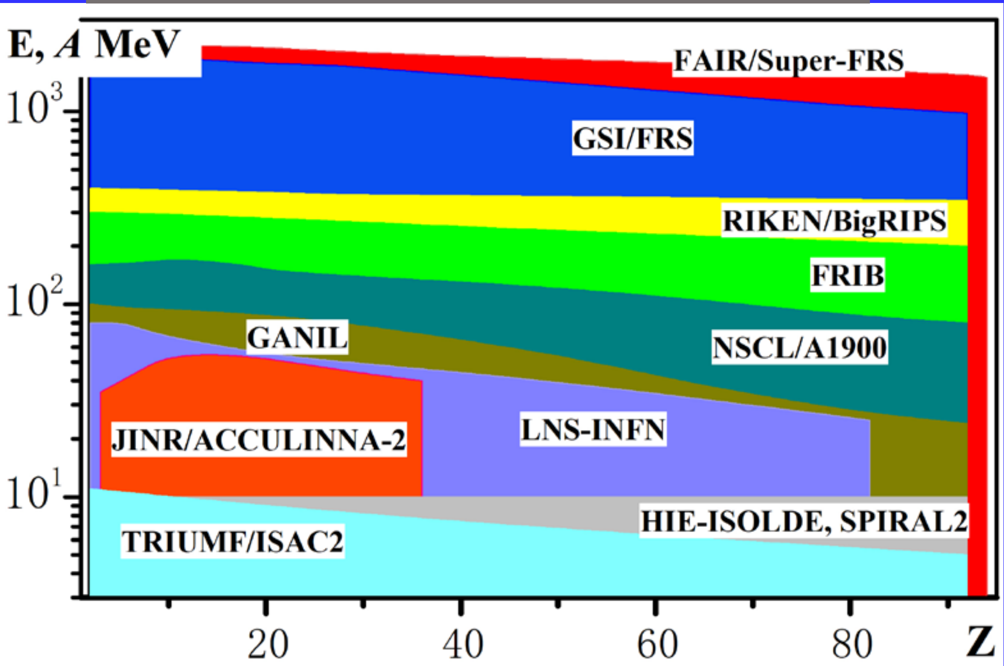






2011: Contract signed with Sigma PHI
2016-17: Full commissioning + Beam
2018-2019: First experiments
2020-2022: Upgrade U400M cyclotron

ACCULINNA-2 and world RIBs centers



Primary beams for ACCULINNA-2:

	I, pμA
^{6}Li @ 46 AMeV	8
^{11}B@ 33 AMeV	5
^{15}N @ 50 AMeV	2
^{20}Ne @ 53 AMeV	1
^{32}S @ 52 AMeV	0.2

Secondary beams from ACCULINNA-2:

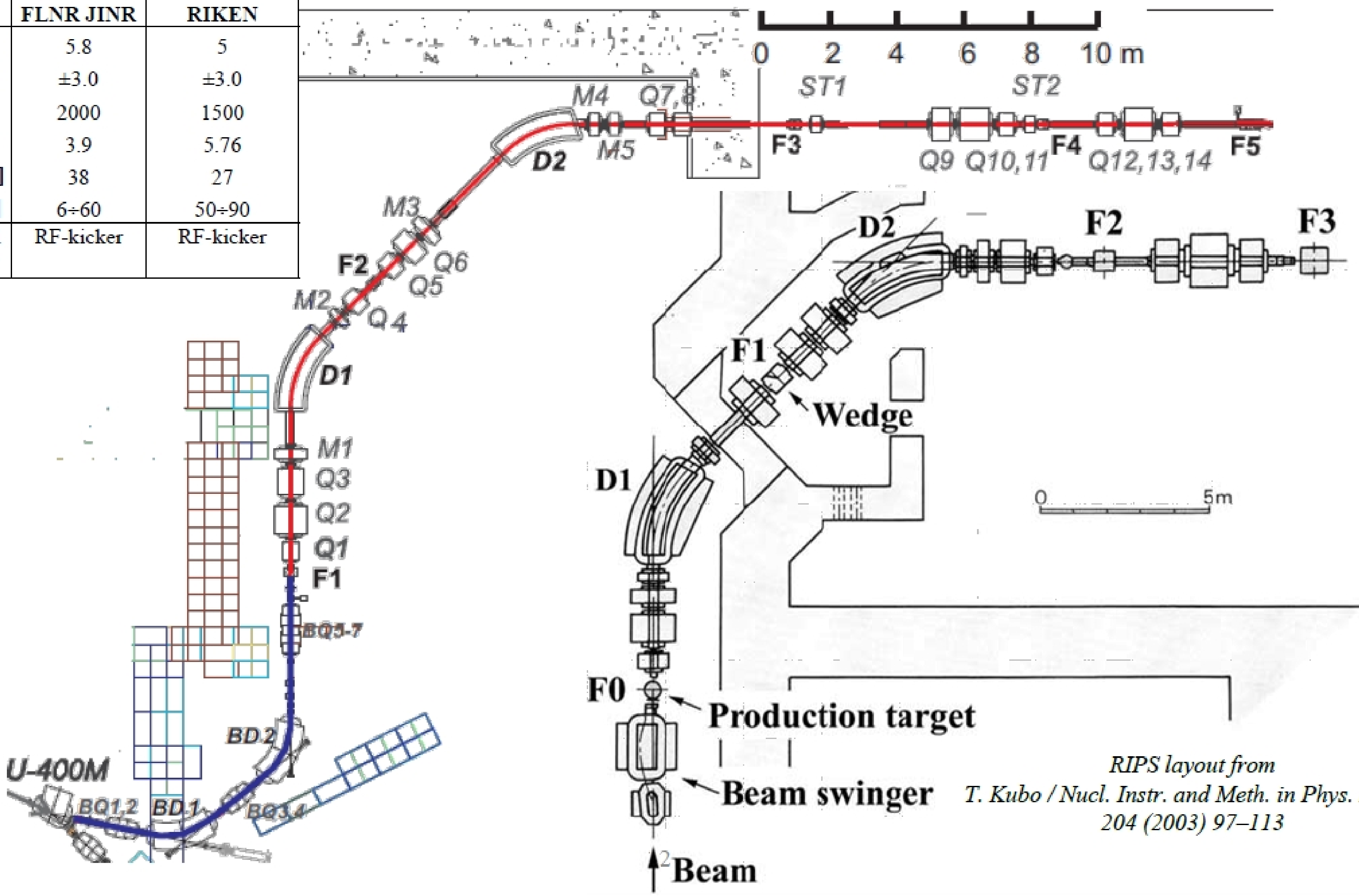
^{6,8}He @ 25÷35 AMeV
^{9,11}Li @ 30 AMeV
^{18}Ne @ 35 AMeV
^{28}S @ 38 AMeV
In-flight separation

		ACC FLNR,	ACC-2 JINR	LISE3 GANIL	ARIS[a] FRIB	RIPS	BigRIPS RIKEN
$\Delta\Omega$	msr	0.9	4.2	1.0	5.0	5.0	6.3
δ_P	%	2.5	6.0	5.0	10	6.0	6.0
$P/\Delta P$	a.u.	1000	2000	2200	4000	1500	3300
$B\rho_{max}$	Tm	3.2	3.9	3.2-4.3	8.0	5.76	9.0
Length	m	21	37	19(42)	87	21	77
$E_{\min}$	AMeV	10	5	30	30[b]	30	5[c]
$E_{\max}$	AMeV	40	50	80	300	90	350

ACCULINNA-2 is comparable with RIPS, RIKEN

ACCULINNA-2 layout compared to RIPS (RIKEN)

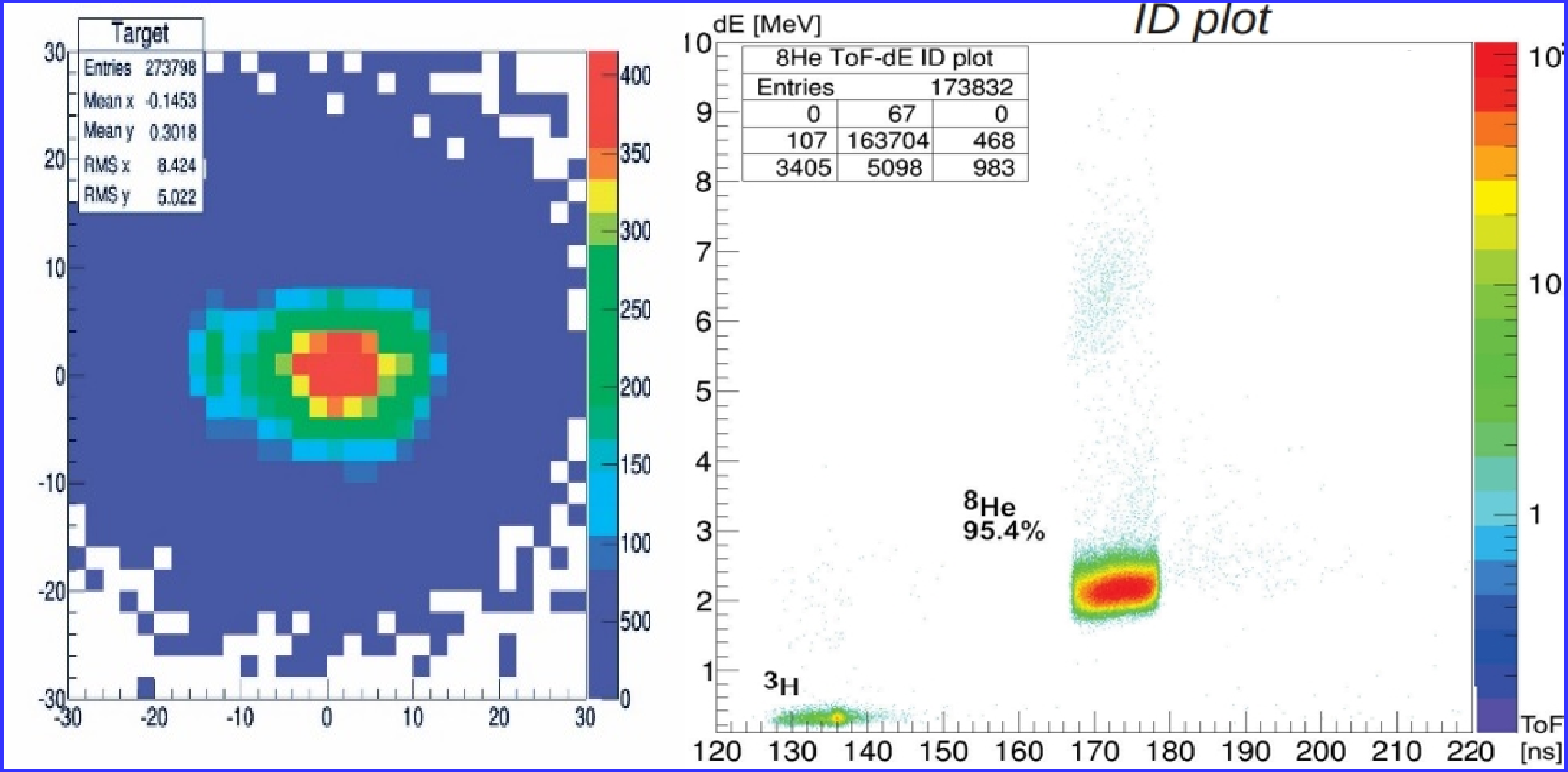
	ACC-2 FLNR JINR	RIPS RIKEN
ΔΩ [msr]	5.8	5
Δp/p [%]	±3.0	±3.0
Rp/Δp	2000	1500
Bρ [Tm]	3.9	5.76
Length [m]	38	27
E [AMeV]	6÷60	50÷90
Additional RIB Filter	RF-kicker	RF-kicker



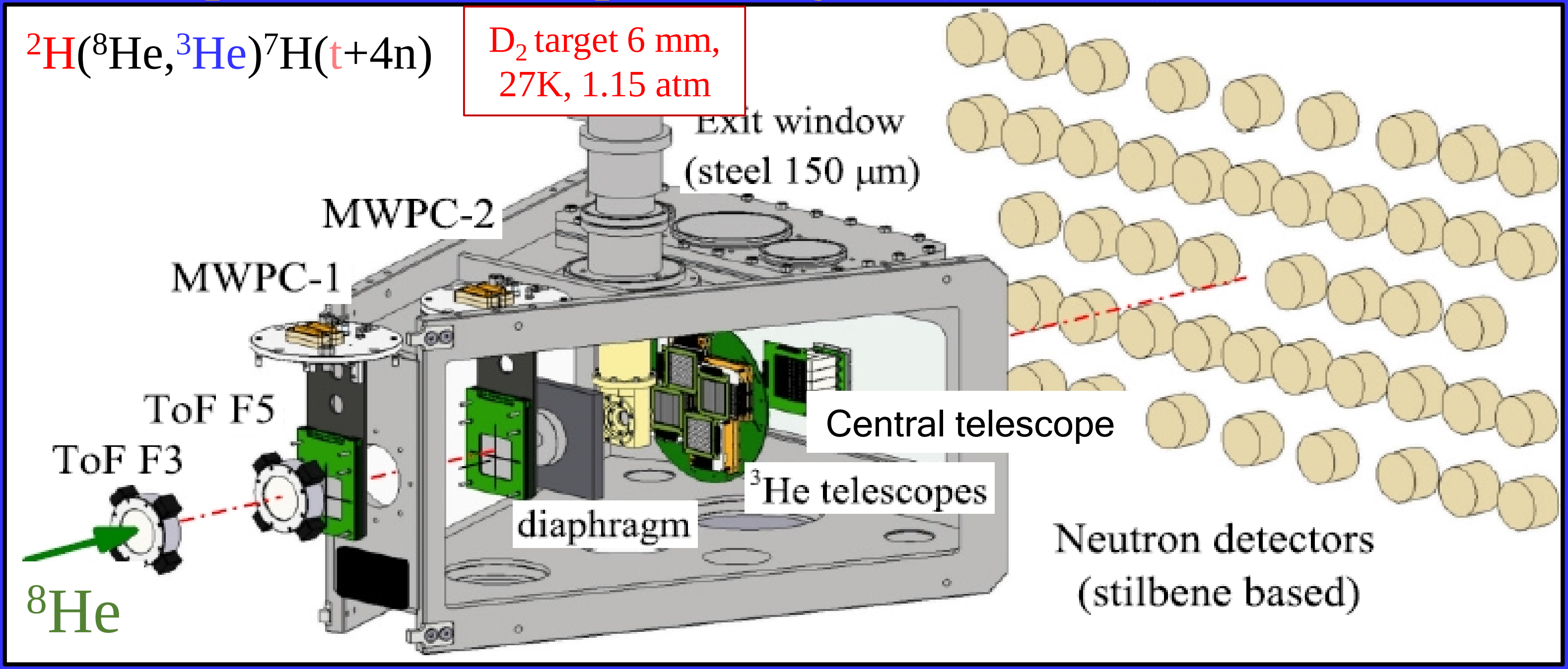
RIPS layout from
T. Kubo / Nucl. Instr. and Meth. in Phys. Res. B 204 (2003) 97–113

^{8}He beam

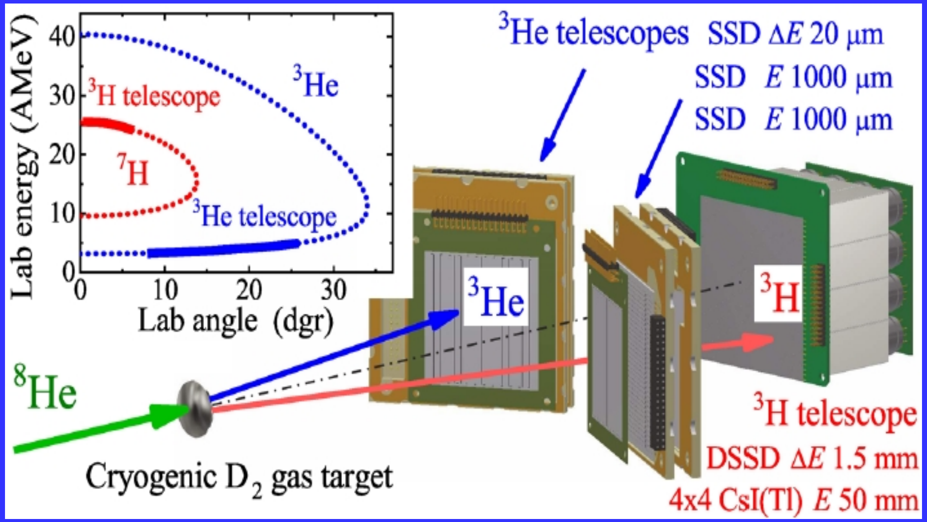
I ~ 3*10^{5} pps, E ~ 26 *A*MeV, P > 90%, Ø ~17 mm



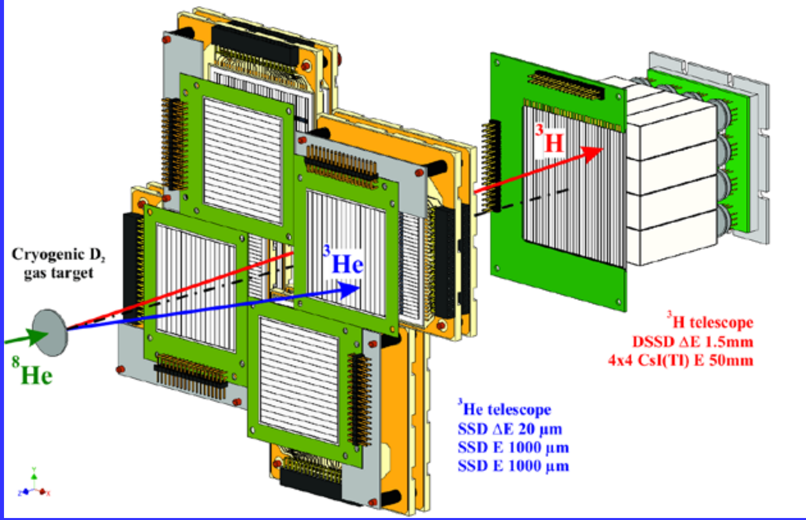
Experimental setup to study $^{2}H(^{8}He,^{3}He)^{7}H$ reaction



EXP 1, 2018 2 weeks, 107 ^{7}H (^{3}He+t) events

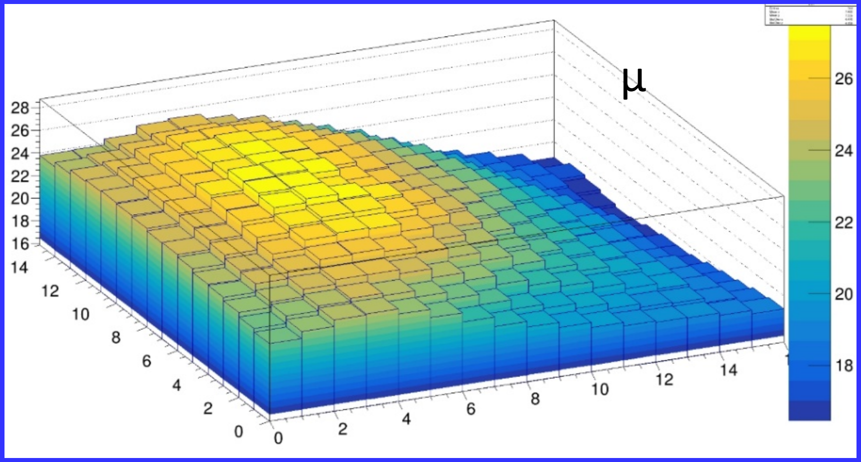


EXP 2, 2019 3 weeks, 404 ^{7}H (^{3}He+t) events

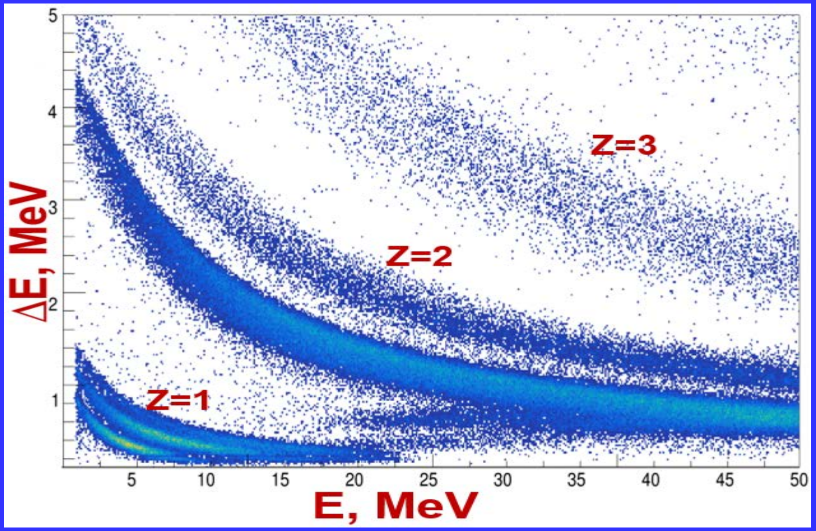


Identification of low-energy ^{3}He is a difficult task!

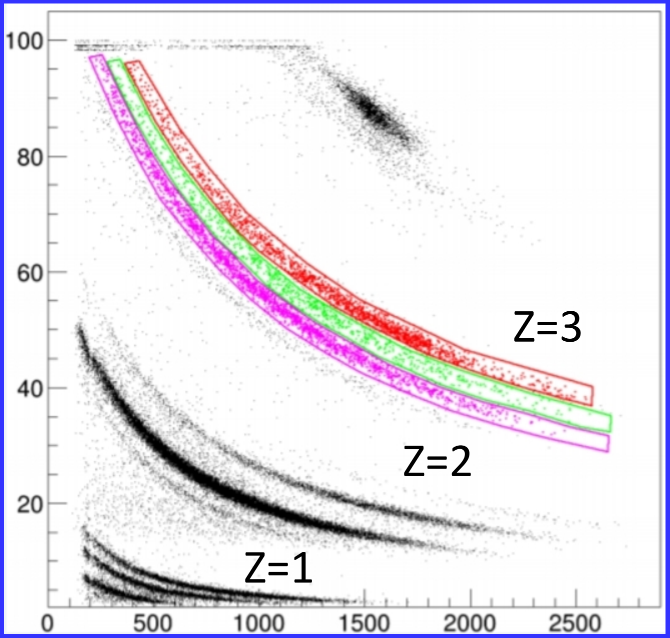
Measured thickness map of one of 20-um detector



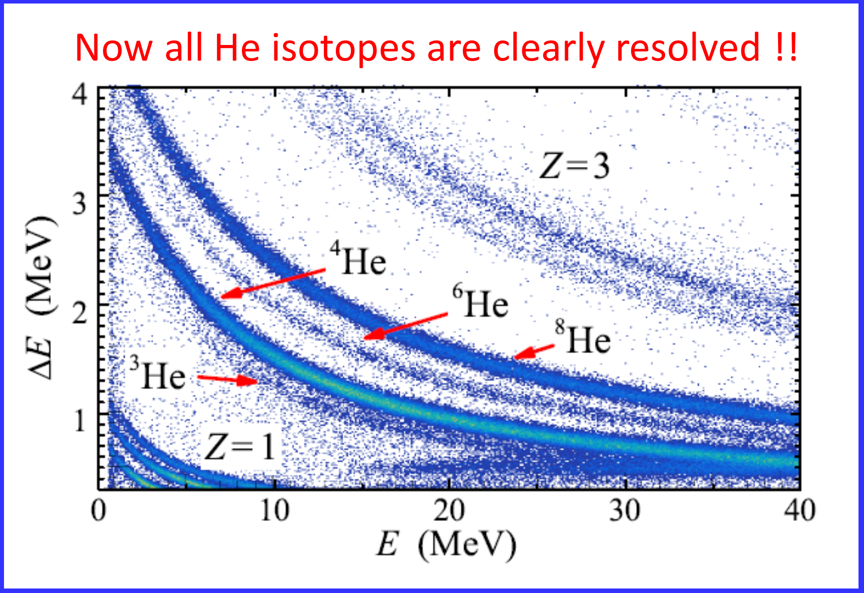
Particle ID w/o thickness correction of 20-um detector



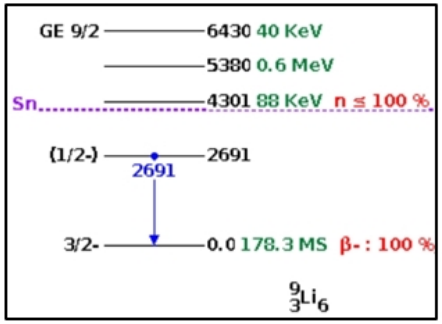
Identification in central telescope (^{10}Be beam)



Particle ID after thickness correction of 20-um detector

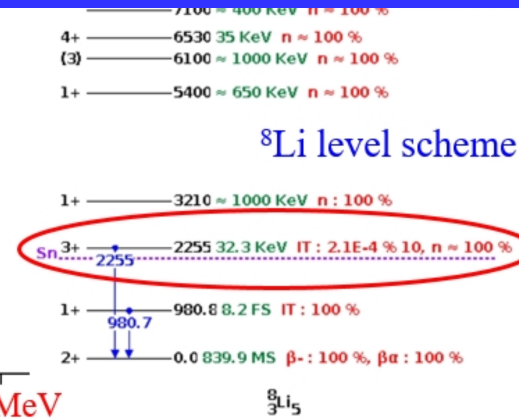


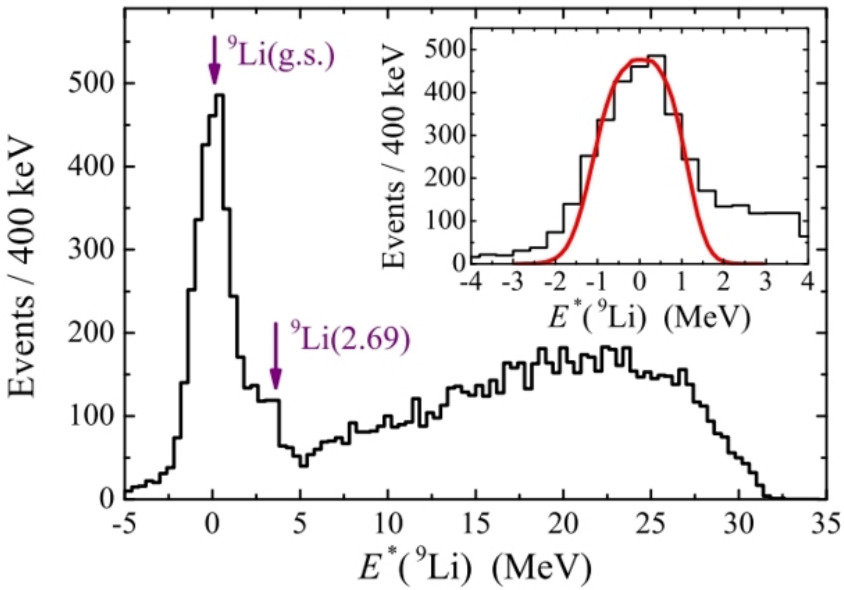
Test reactions $^{2}H(^{10}Be,^{3}He)^{9}Li$ and $^{2}H(^{10}Be,^{4}He)^{8}Li$ with 42 *A*MeV ^{10}Be beam

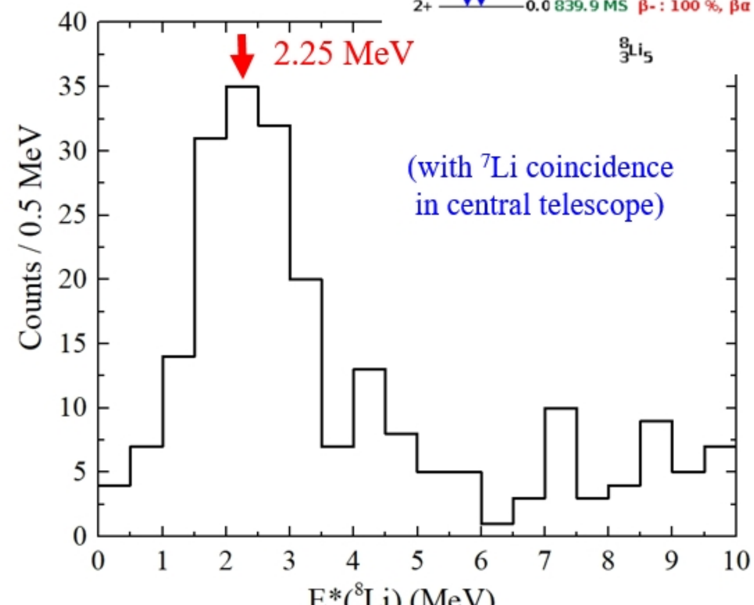


Data for the reference reactions $^{2}H(^{10}Be,^{3}He)^{9}Li$ and $^{2}H(^{10}Be,^{4}He)^{8}Li$:

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

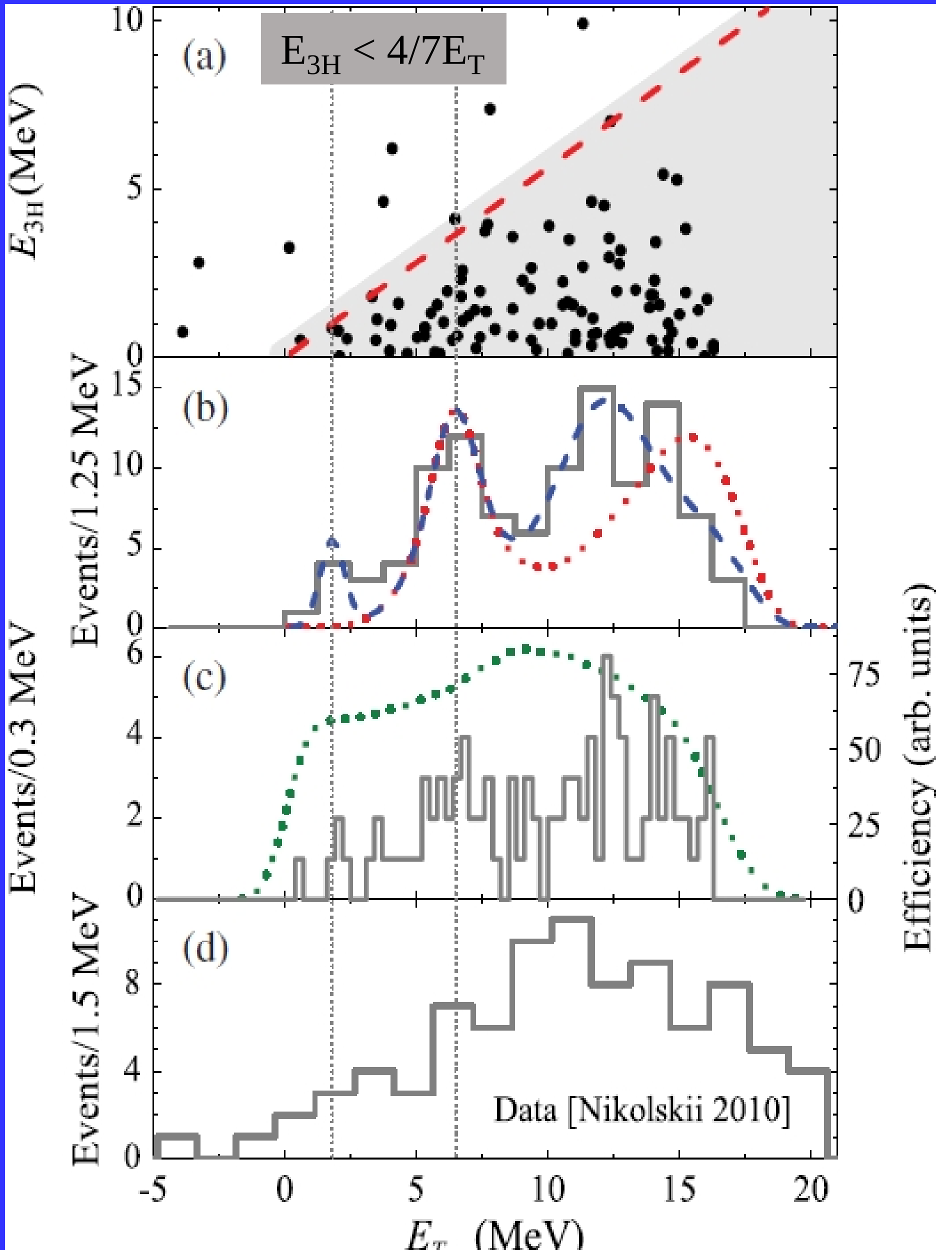


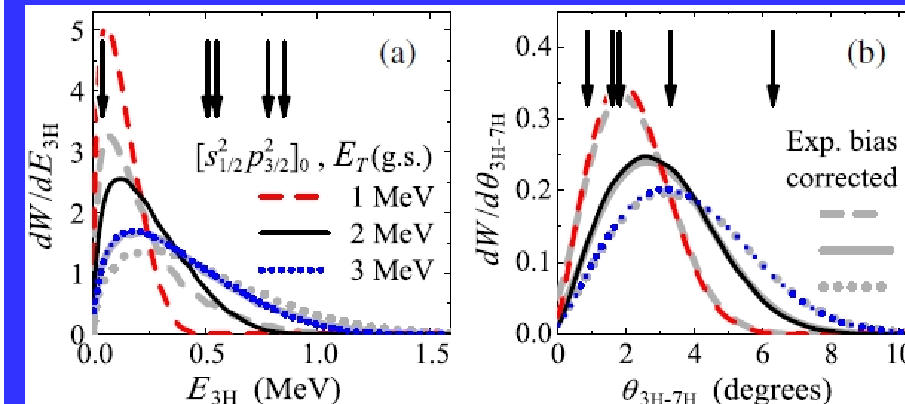




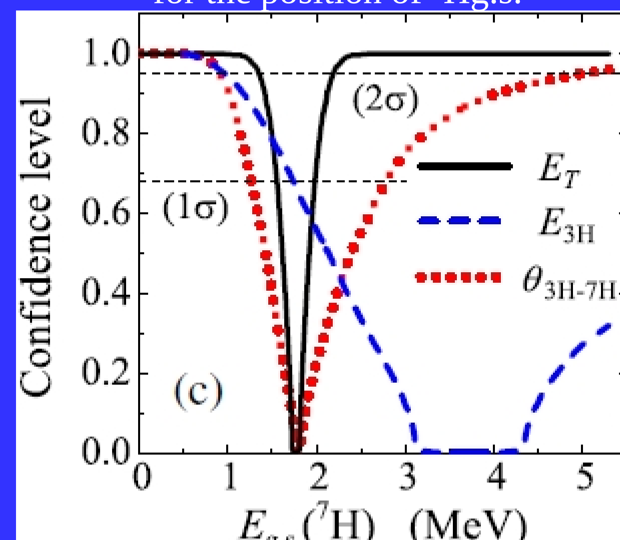
Detailed data of ^{7}H of the 1st Run

[A.A. Bezbakh *et al.*, PRL **124**, 022502 (2020)]





MC likelihood functions of confidence level for the position of ^{7}Hg.s.



Indication of the 1/2$^+$ g.s. of ^{7}H at E =1.8(5) MeV with cs ~25 μb/sr at θcm ≃ 17°–27°.

Conclusion after 1st Run:

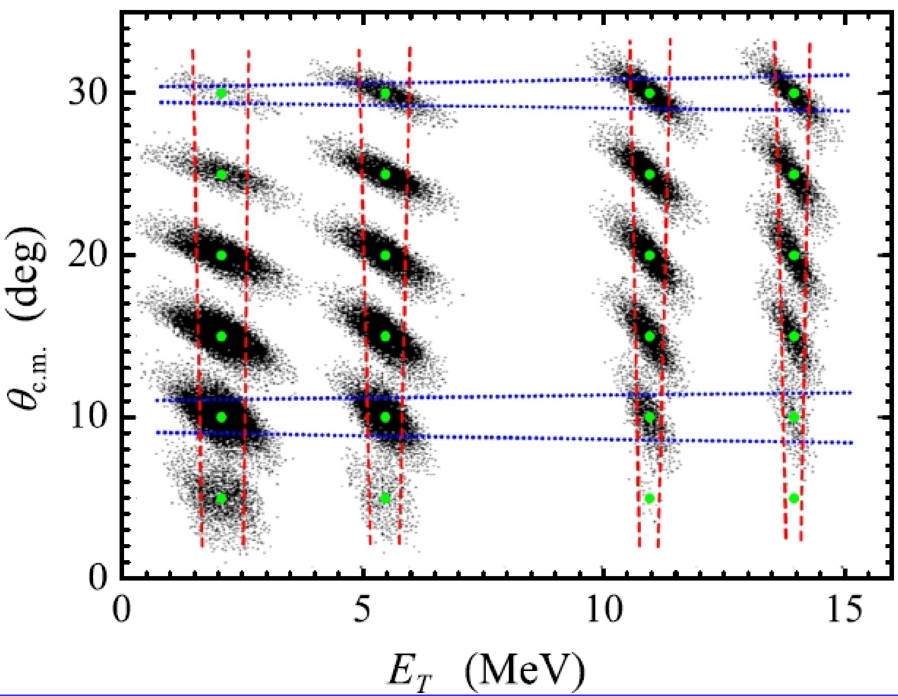
(I) For the first time, the ^{7}H excited state is observed at $E_T = 6.5(5)$ MeV with $\Gamma = 2.0(5)$ MeV. This state can be interpreted as the unresolved 5/2+ and 3/2+ doublet built upon the 2+ excitation of valence neutrons, or one of the doublet states.

(ii) Indications for the ^{7}Hg.s. at $E_T = 1.8(5)$ MeV are found in the measured energy and angular distributions. The cross section obtained for the presumed ^{7}Hg.s. populated in the ^{8}He(d,^{3}He)^{7}H reaction in the $\Theta_{CM} = 7° - 27°$ is ≈ 25 μb/sr. This corresponds to a weak population of the g.s. with experimental SF ~ 0.1, which clarifies why the previous searches for the ^{7}Hg.s. required so much time and efforts without bringing reliable assignments of such a remote isotope.

Monte Carlo calculations of the ^{7}H missing mass energy resolution over Θ_{CM} and ^{7}H energy

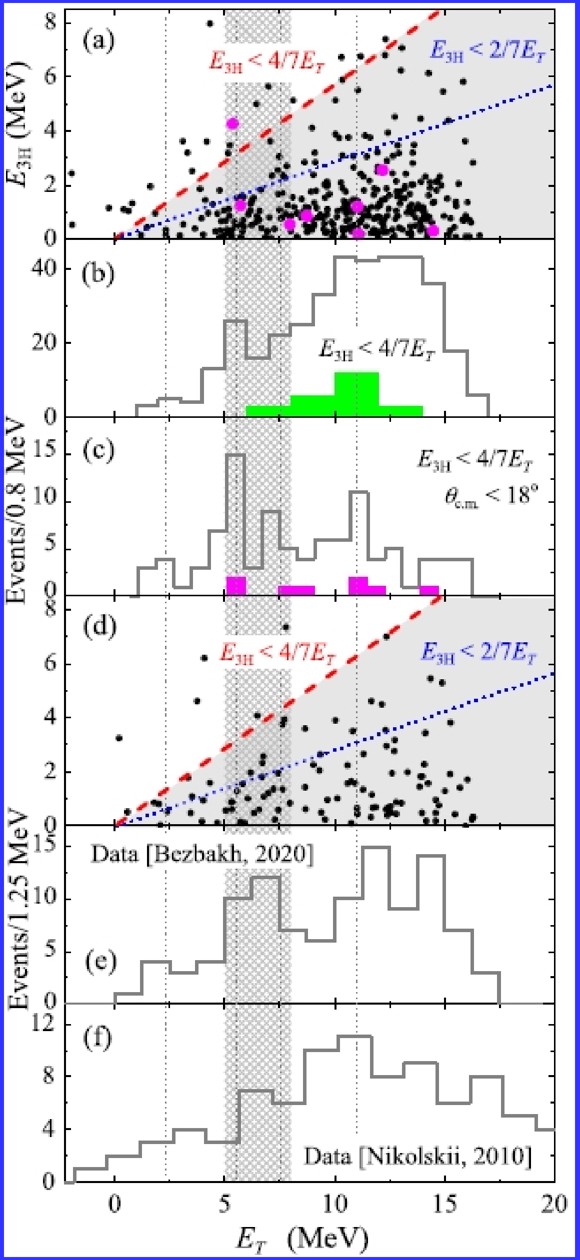
TABLE I. Experimental resolution in the second experiment as a function of the ^{7}H MM energy and center-of-mass angle $\theta_{c.m.}$ based on the MC simulations Fig. 8. The first and second values in each cell are the FWHM energy and the angular resolutions given in MeV and degrees, respectively.

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

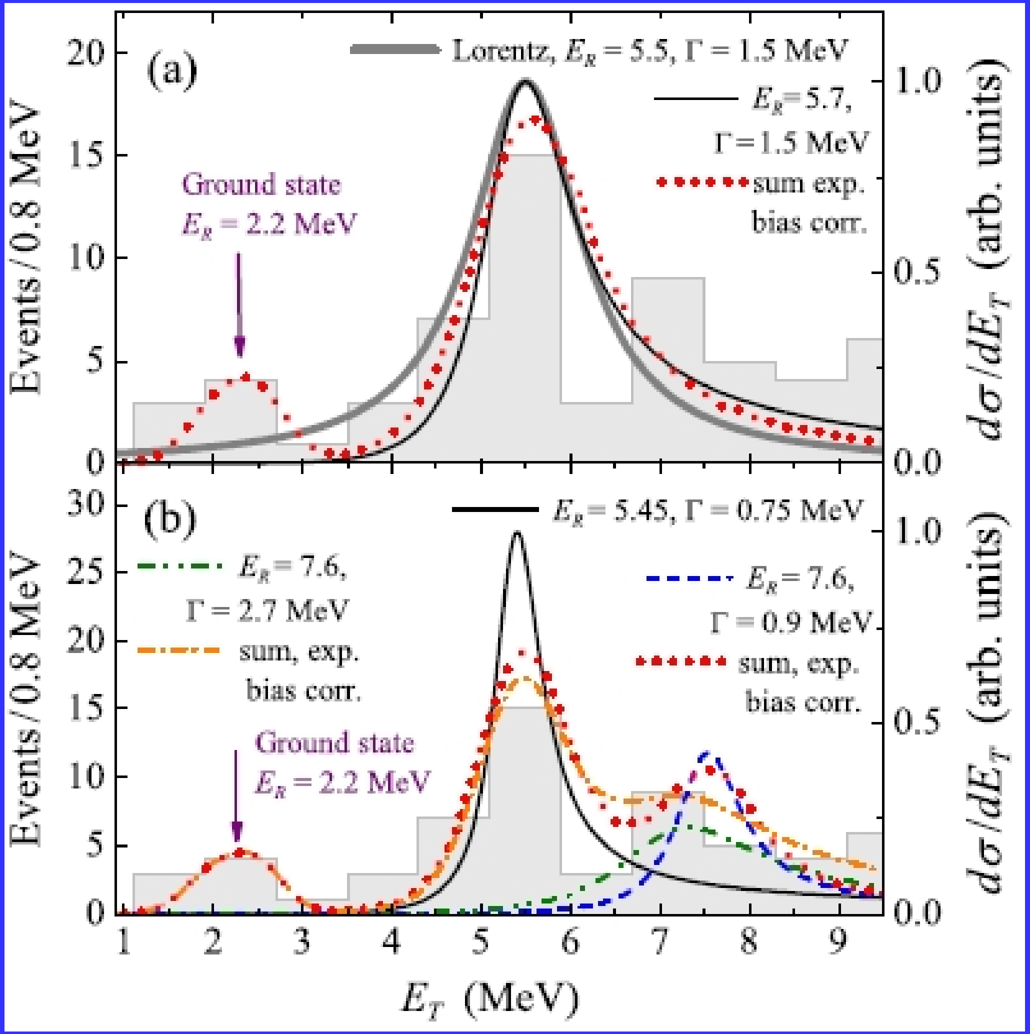


Detailed data of ^{7}H of the 2nd Run

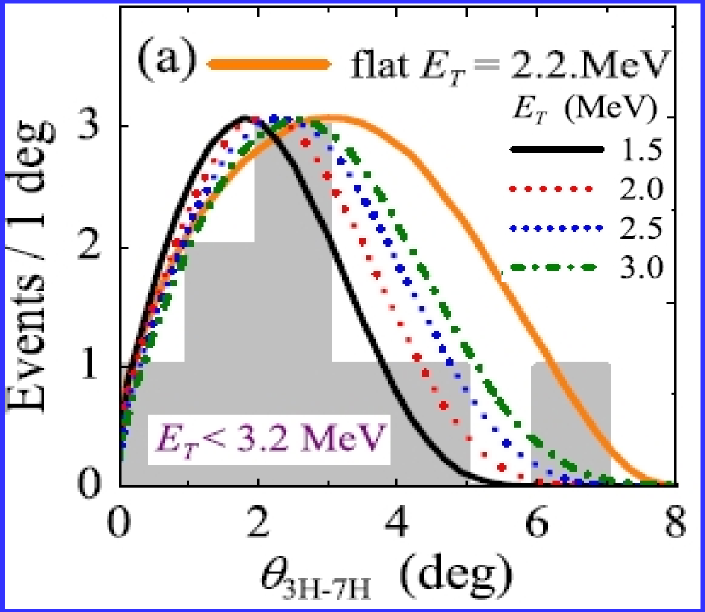
[I. A. Muzalevskii et al, PRC **103**, 044313 (2021)]

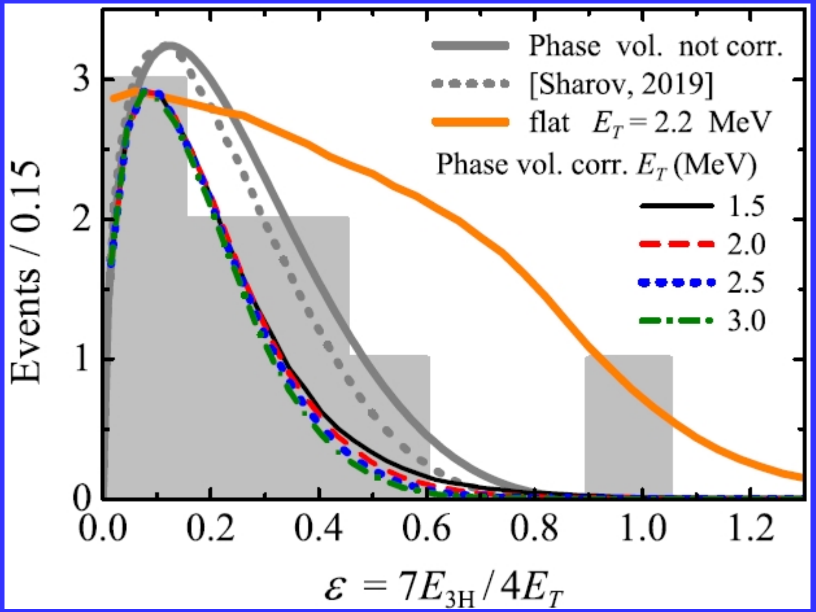


^{7}H spectrum after $E_{3H} < 4/7E_T$ and $\Theta_{CM} < 18^0$ selections



Additional support for the position of ^{7}Hg.s. at E = 2.2(5)MeV comes from the angular and energy distributions of tritons from the ^{7}H decay for the events $E_T < 3.2$ MeV





Value	flat	1.5	2.0	2.5	3.0	Expt.
$\langle\varepsilon\rangle$	0.46(11)	0.28(6)	0.26(6)	0.24(6)	0.23(6)	0.31
$\langle\theta_{3H\text{-}7H}\rangle$	3.5(6)	2.3(4)	2.6(4)	2.8(4)	3.0(4)	2.9

The value ε is consistent with $E_T < 2.2$ MeV. The best fit to the experimental $<\theta_{3H}$-^{7}H> value is obtained at E_T = 2.6(7) MeV. Both values are consistent with E_T = 2.2(5) MeV inferred from the MM data.

Conclusion after 1st and 2nd experiments:

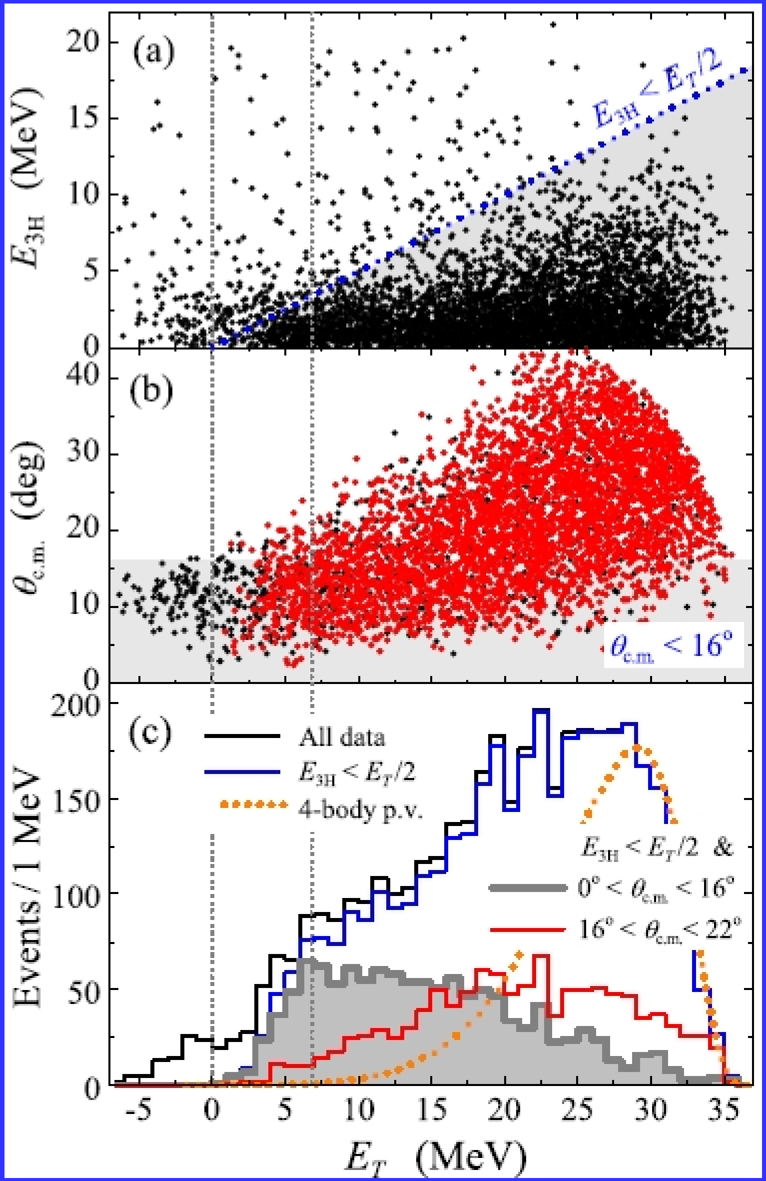
1. A solid experimental evidence is provided that two resonant states of ^{7}H are located in its spectrum at 2.2(5) and 5.5(3) MeV relative to the ^{3}H+4n decay threshold.

2. Based on the energy and angular distributions, obtained for the $^{2}H(^{8}He, ^{3}He)^{7}H$ reaction, the weakly populated 2.2(5)-MeV peak is ascribed to the ^{7}H $1/2^{+}$ ground state.

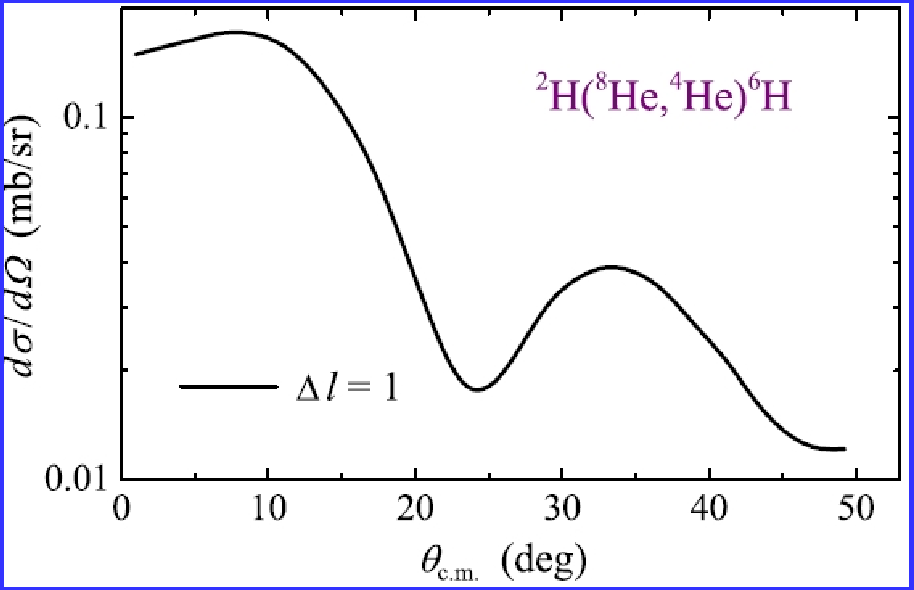
3. There are indications that the resonant states at 7.5(3) and 11.0(3) MeV are present in the measured ^{7}H spectrum.

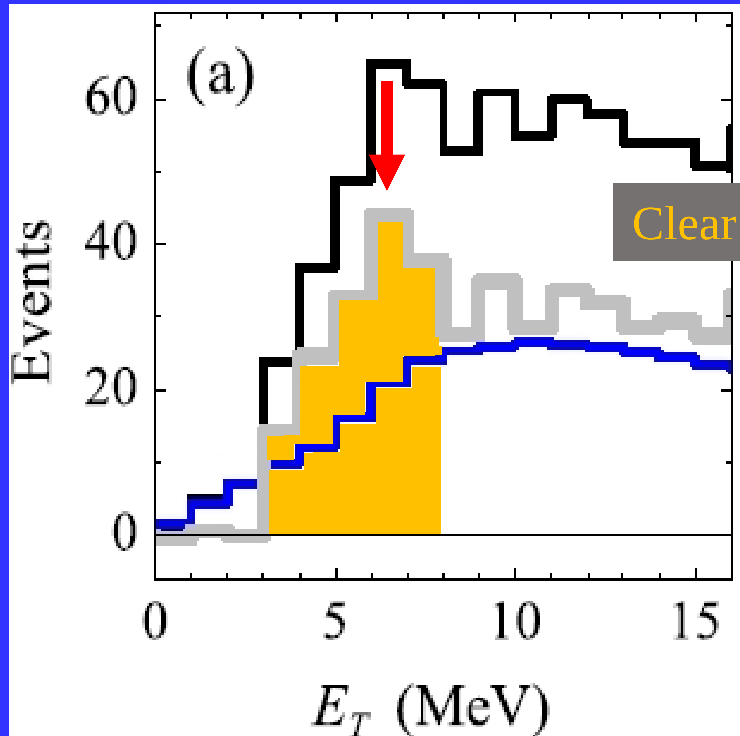
4. It is highly plausible that the firmly ascertained 5.5(3)-MeV state is the $5/2^{+}$ member of the ^{7}H excitation $5/2^{+}$–$3/2^{+}$ doublet, built on the 2^{+} configuration of valence neutrons. The supposed 7.5-MeV state can be another member of this doublet, which could not be resolved in 1st Run.

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

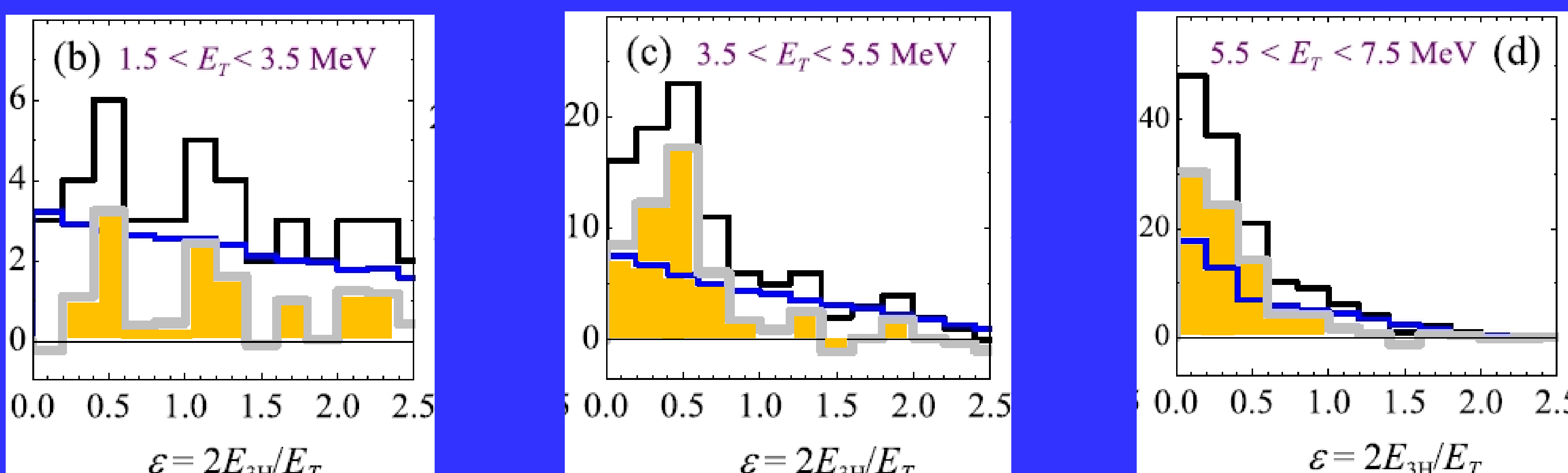


The ΔL = 1 cross section for the ^{2}H(^{8}He, ^{4}He)^{6}H reaction obtained in FRESCO calculations

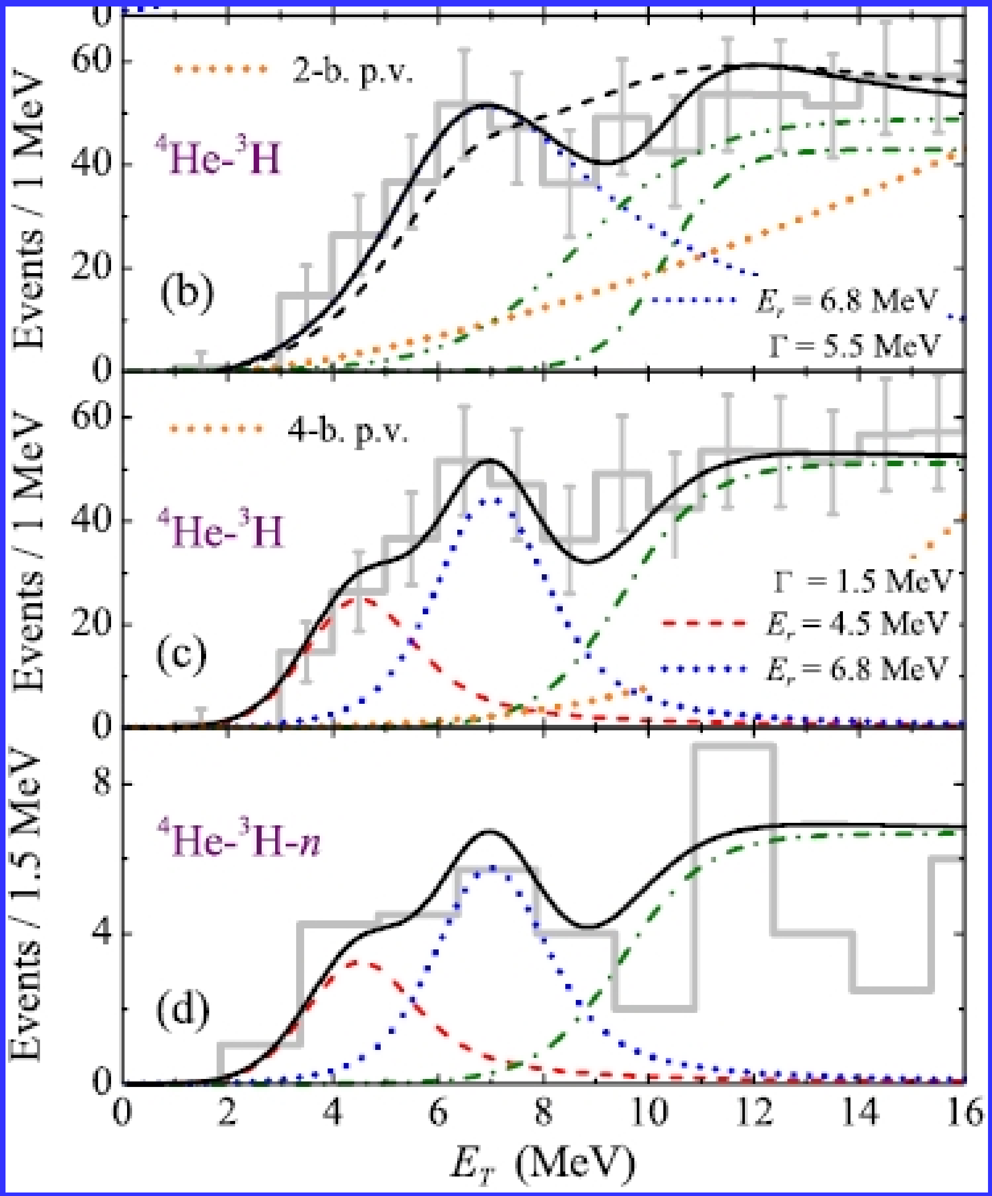




Clear peak was observed at ~ 6.8 MeV !!



Final ^{6}H spectra corrected for the experimental efficiency with cutoff $\Theta_{CM} < 16^0$



$$\frac{d\sigma}{dE_T} \approx \frac{\Gamma(E_T)}{(E_r - E_T)^2 + \Gamma(E_T)^2/4},$$

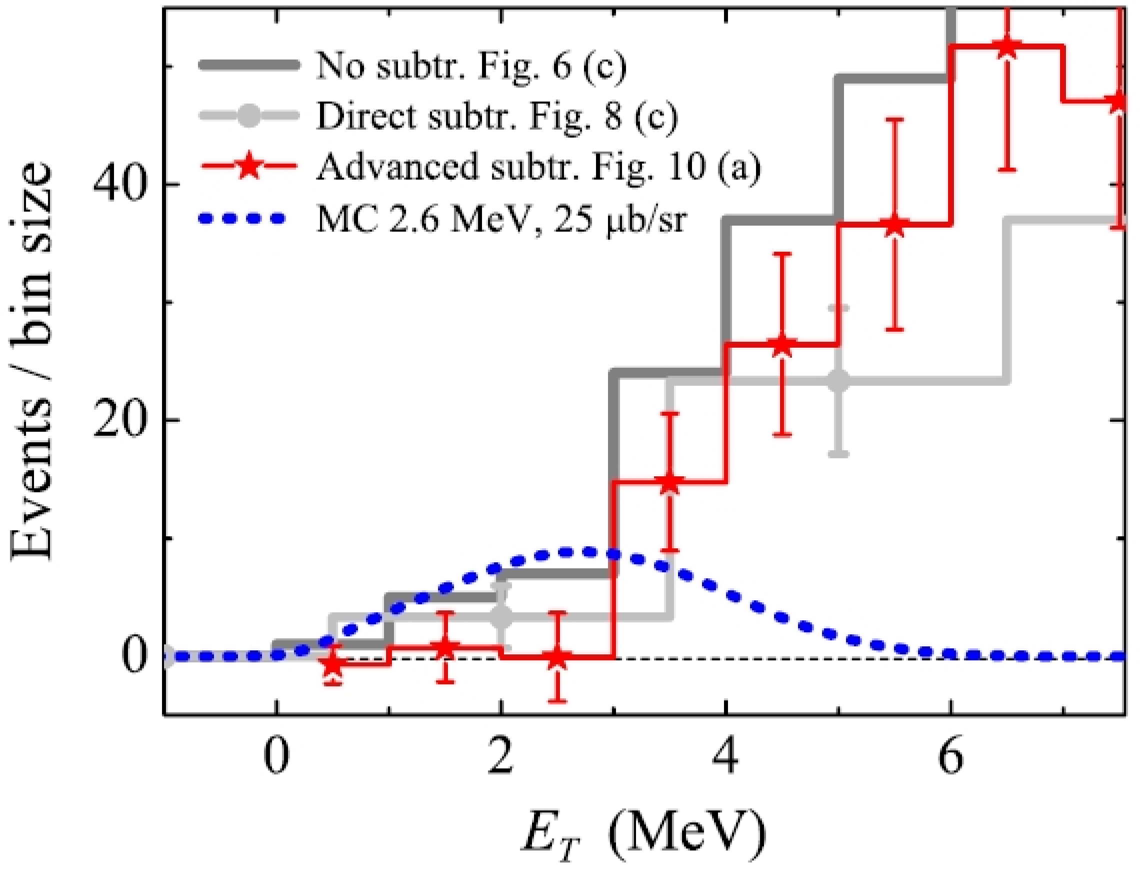
One state interpretation

Two states interpretation

Two states interpretation of the spectrum with neutron coincidences

No indications for the ^6H state at E ~ 2.7 MeV with cross section limit $d\sigma/d\Omega_{CM} \leq$ 5 μb/sr !!

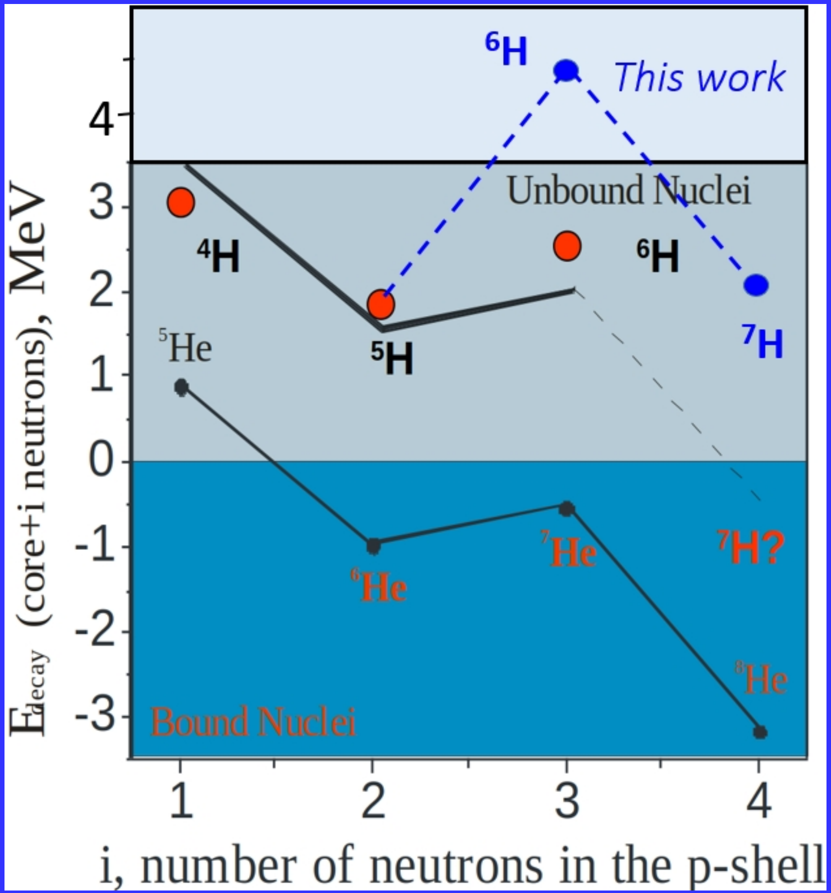
Instead, we observed the population cross section of $d\sigma/d\Omega_{CM} \approx$ 190 μb/sr for the 6.8 MeV broad state at angular range $5^0 < \Theta_{CM} < 16^0$

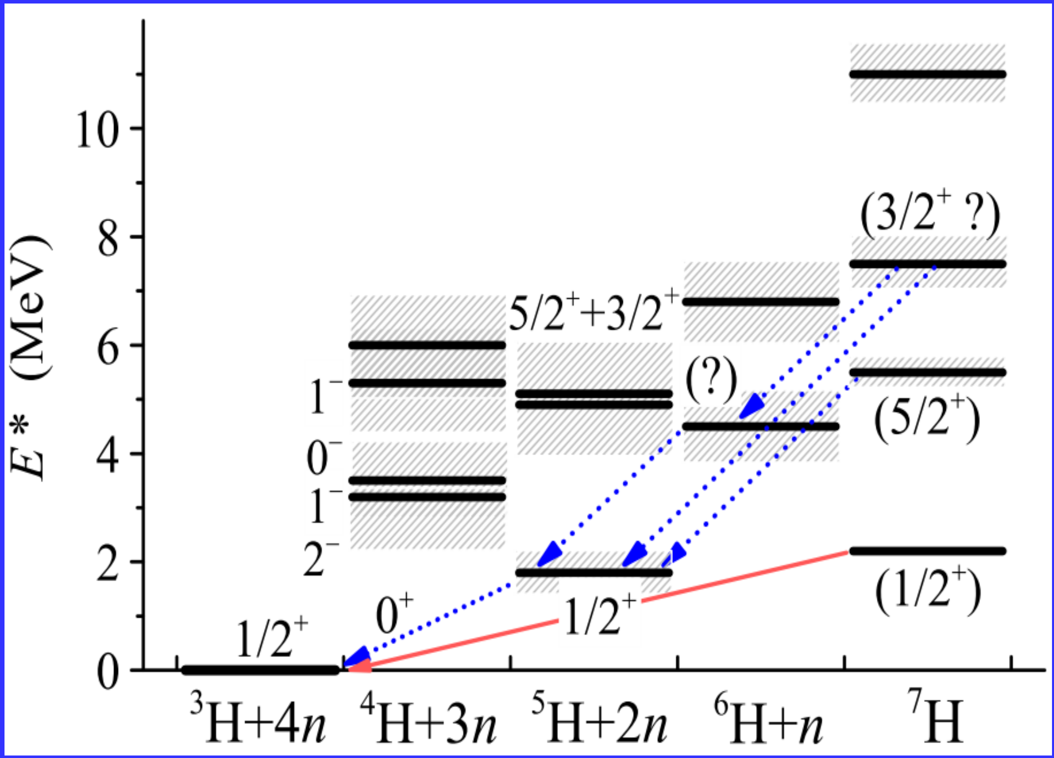


Hydrogen and helium chains: today status

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

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





Summary

1. The ^{7}H system was studied in two experiments in the ^{2}H(^{8}He, ^{3}He)^{7}H transfer reaction with a 26*A*MeV secondary ^{8}He beam. The missing mass (MM) spectrum and center-of-mass angular distributions of ^{7}H, as well as the momentum distribution of the ^{3}H fragments in the ^{7}H frame, were reconstructed.

2. A solid experimental evidence is provided that two resonant states of ^{7}H are located in its spectrum at 2.2(5) and 5.5(3) MeV relative to the ^{3}H+4n decay threshold. There are indications that the resonant states at 7.5(3) and 11.0(3) MeV are also present in the measured ^{7}H spectrum.

3. Based on the energy and angular distributions, obtained for the studied ^{2}H(^{8}He, ^{3}He)^{7}H reaction, the weakly populated 2.2(5)-MeV peak is ascribed to the ^{7}H ground state. It is highly plausible that the firmly ascertained 5.5(3)-MeV state is the $5/2^+$ member of the ^{7}H excitation of $5/2^+ – 3/2^+$ doublet, built on the 2^+ configuration of valence neutrons. The supposed 7.5-MeV state can be another member of this doublet, which could not be resolved in 1st experiment.

4. The ^{6}H spectrum was populated in the ^{2}H(^{8}He, ^{4}He)^{6}H transfer reaction. The broad bump in the ^{6}H MM spectrum at E = 6.8(5) MeV with $\Gamma \sim 5.5$ MeV is reliably identified with the population cross section $d\sigma/d\Omega_{CM} \approx 190$ μb/sr in the $5^0 < \Theta_{CM} < 16^0$ angular range.

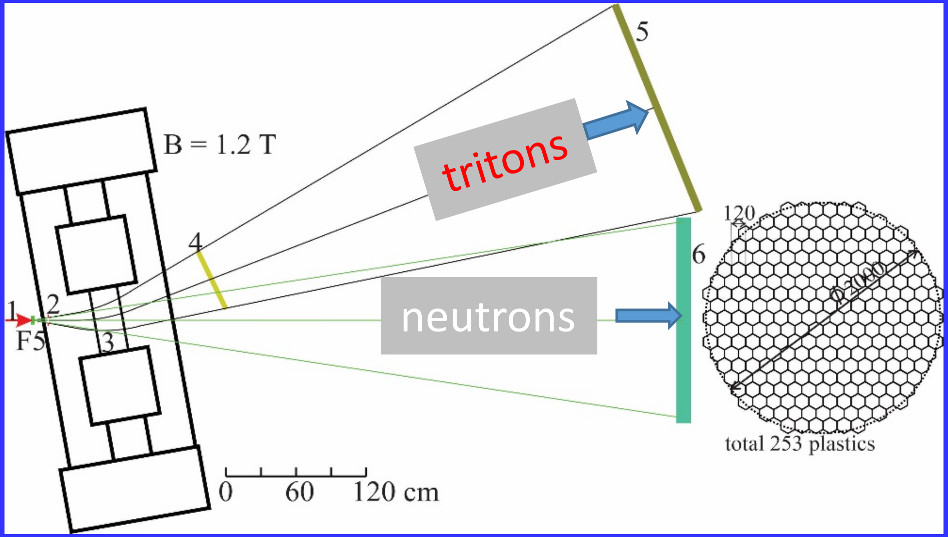
5. We have found *no evidence* of the ≈2.6–2.9 MeV state in ^{6}H, which was reported in 3 previous works. The cross section limit $d\sigma/d\Omega_{CM} \leq 5$ μb/sr is set for the population of possible states with $E <$ 3.5 MeV. We suggest that the position of the ^{6}H g.s. is not yet established, and discussion of this issue should be continued.

6. The ^{7}H and ^{6}H experiments were cross-checked by the studies of the ^{2}H(^{10}Be, ^{3}He)^{9}Li and ^{2}H(^{10}Be, ^{4}He)^{9}Li reactions where calibration and resolution over ^{6,7}H excitation energies were derived that were found to be closed to complete Monte Carlo simulations.

Very short outlook…

1. Tritium Target !! **Liquid T_2 ~ $3*10^{21}$ cm^{-2}**

^{8}He+T_2(liquid) → ^{4}He(stopped) + ^{7}H(t+4n) invariant mass



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**
$^7H_{g.s.}$ counting rate: ~5 per day

2. p(^{11}Li,p^{4}He)^{7}H ^{11}Li – new "source" to make ^{7}H

Quasi-free alpha knockout from ^{11}Li possibly has larger cross section
^{7}H could have [s^2p^2] component of WF that already exist in ^{11}Li

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ACCULINNA-2 team

Thank you for your attention!