Studies of light exotic nuclei with radioactive beams at FLNR, JINR

E. Yu. Nikolskii [1, 2] (on behalf of ACCULINNA group)

[1] Joint Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions

[2] National Research Center “Kurchatov Institute”

COLLABORATION:

National Research Nuclear University “MEPhI”, 115409 Moscow, Russia

Dubna State University, 141982 Dubna, Russia

Heavy Ion Laboratory, University of Warsaw, 02-093 Warsaw, Poland

Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119991 Moscow, Russia

GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany

II. Physikalisches Institut, Justus-Liebig-Universität, 35392 Giessen, Germany

Laboratory of Information Technologies, JINR, 141980 Dubna, Russia

Institute of Nuclear Physics, 050032 Almaty, Kazakhstan

Nuclear Research Institute, 670000 Dalat, Vietnam

Bogoliubov Laboratory of Theoretical Physics, JINR, 141980 Dubna, Russia

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, 30-059 Krakow, Poland

Institute of Nuclear Physics PAN, Radzikowskiego 152, 31342 Kraków, Poland

Department of Physics, Chalmers University of Technology, S-41296 Göteborg, Sweden

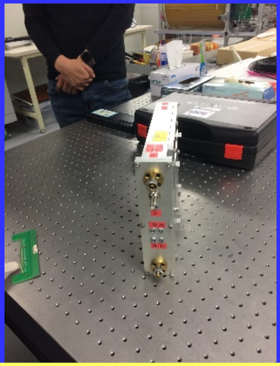
Seoul, April 2019

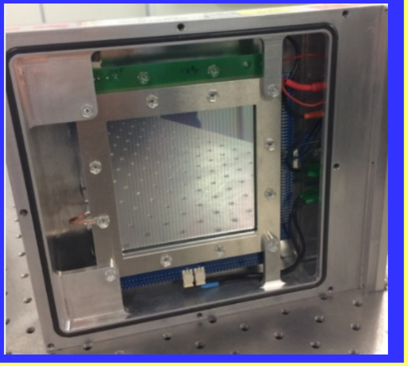
Korea University – JINR MOU Ceremony 2019

RAON, April 2019

Meat restaurant in Daejeon. Delicious!!!

Detector PPAC,
3 of them are in Dubna now





OUTLINE:

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

- Dubna accelerator complex at Flerov Laboratory of Nuclear Reactions, JINR
  - ACCULINNA fragment separator layout
  - Gaseous cryogenic targets, including unique tritium target

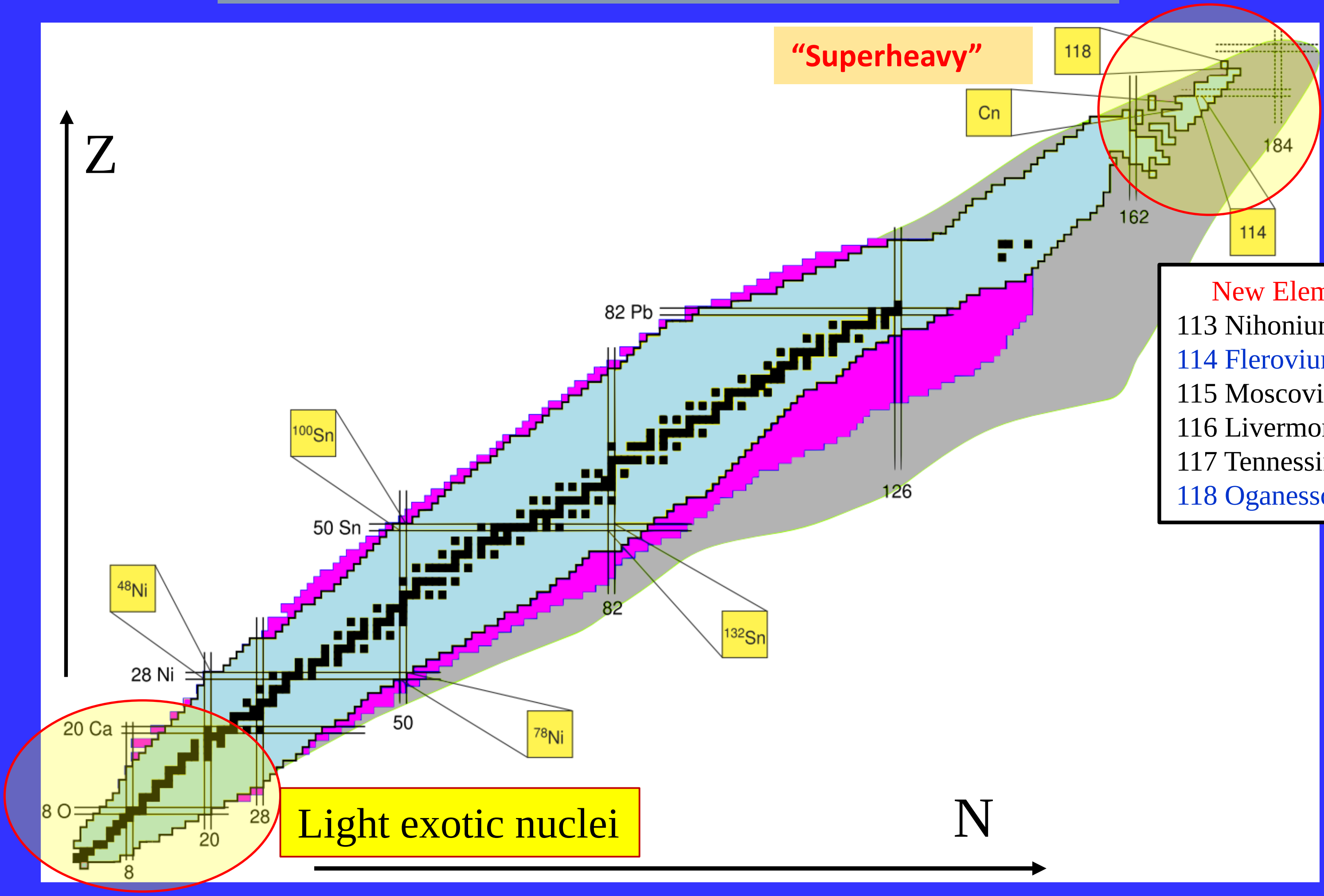
- Short overview of experiments at ACCULINNA fragment separator
  - Elastic scattering (^{6}He+^{4}He). Looking on 2n-transfer
  - Study of ^{6}He nucleus structure by QFS reaction ^{4}He(^{6}He,αα)2n
  - Search for ^{5}H resonances by p(^{6}He,pp)^{5}H, d(^{6}He,^{3}He)^{5}H and t(t,p)^{5}H reactions
  - Correlation measurements to study ^{9}He and ^{10}He systems with ^{8}He beam

- New fragment separator ACCULINNA-2 at FLNR, JINR. Experimental setup.
  - Calibration reactions ^{2}H(^{10}Be,^{3}He)^{9}Li and ^{2}H(^{10}Be,^{4}He)^{8}Li with ^{10}Be beam
  - Study of the ^{7}H system via ^{2}H(^{8}He,^{3}He)^{7}H → t + 4n. Two Runs
  - Satellite study of the ^{6}H system in the reaction ^{2}H(^{8}He,^{4}He)^{6}H → t + 3n

- Looking ahead

- Summary

Main areas of interest at FLNR, JINR

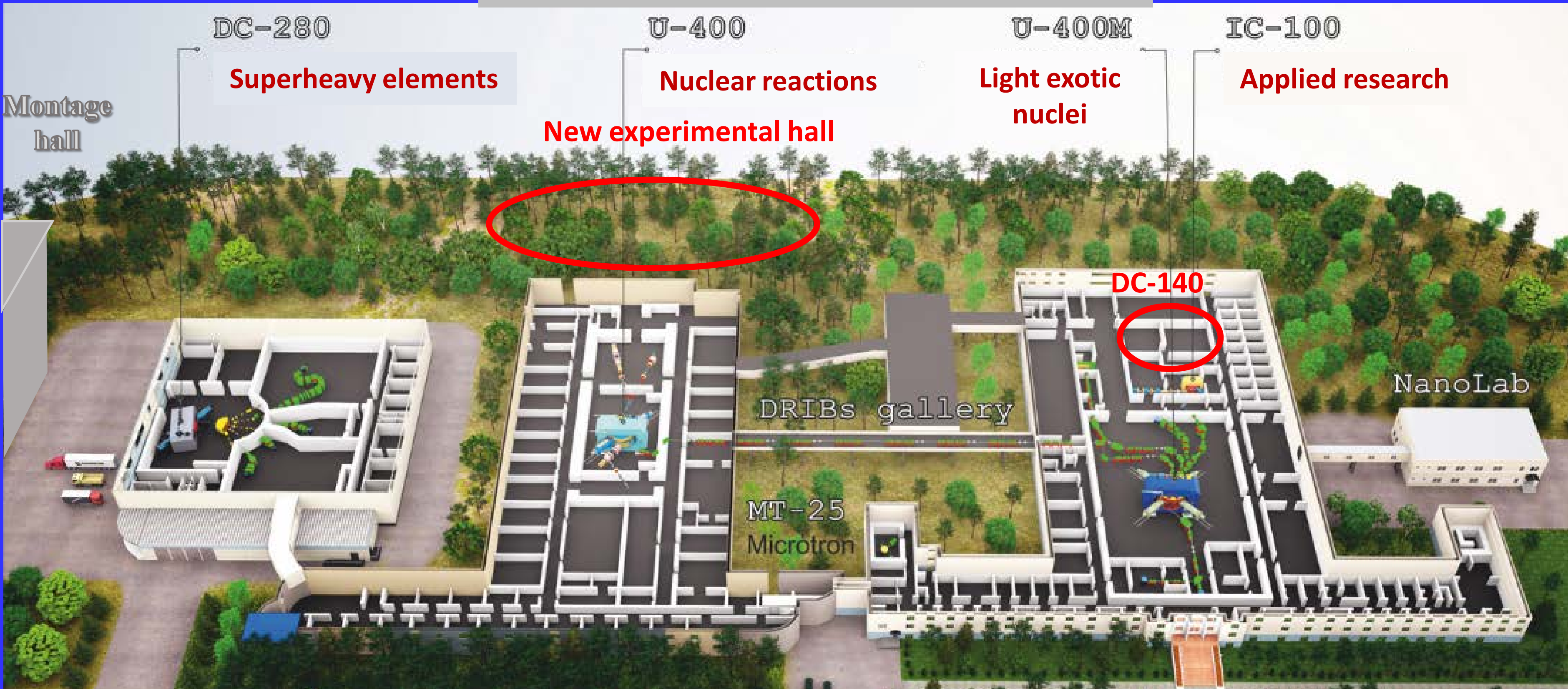


New Elements:
113 Nihonium (2016)
114 Flerovium (2011)
115 Moscovium (2016)
116 Livermorium (2011)
117 Tennessine (2016)
118 Oganesson (2016)

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

DUBNA ACCELERATOR COMPLEX

FLEROV LABORATORY OF NUCLEAR REACTIONS



Setups:
DGFRS-2
GRAND

DC-280

Setups:
SHELS
MAVR
CORSET

U-400

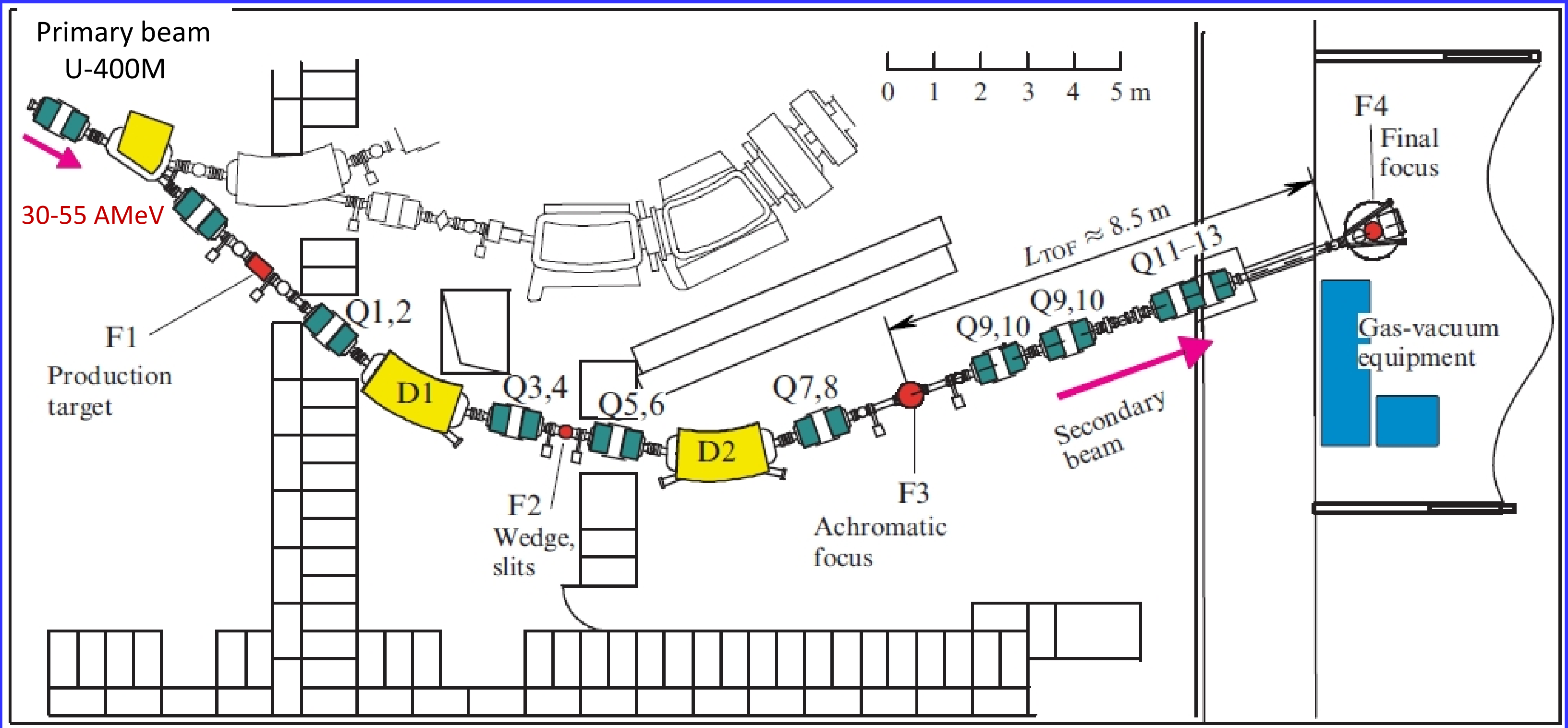
Setups:
ACCULINNA-2
COMBAS
MASHA

U-400M (modernization)

ACCULINNA fragment separator (since 1996)

http://aculina.jinr.ru/

[Rodin A.M. et al. Nucl. Instrum. Meth. Phys. Res. ***B 204*** *114 (2003)]*

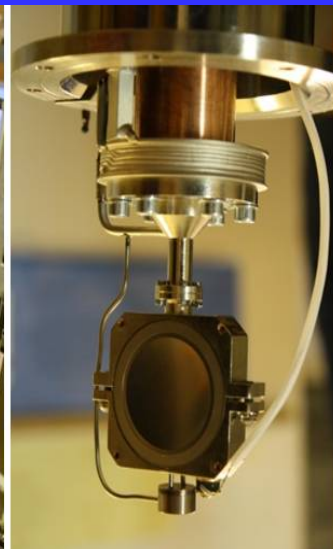


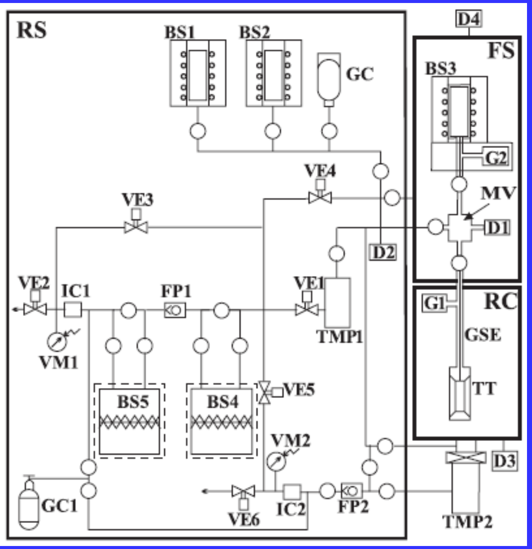
^{6}He (~ 10^6 s^{-1}) and ^{8}He (~ 10^4 s^{-1}) secondary beams at ~ 25 *AMeV*

^{3}H beam (3 x 10^7 s^{-1}) at 58 MeV

- Elastic scattering (^{6}He+^{4}He) & (^{8}He+^{4}He). Looking on 2n & 4n transfers at backward angles
- Study of ^{6}He nucleus structure by QFS reaction on ^{4}He target
- Search for ^{5}H resonances by p(^{6}He,pp)^{5}H, d(^{6}He,^{3}He)^{5}H and t(t,p)^{5}H reactions
- Correlation measurements to study ^{9}He and ^{10}He systems with ^{8}He beam

Unique tritium (^3H) gas/liquid target at ACCULINNA





A.A. Yukhimchuk et al., NIM A 513 (2003) 439

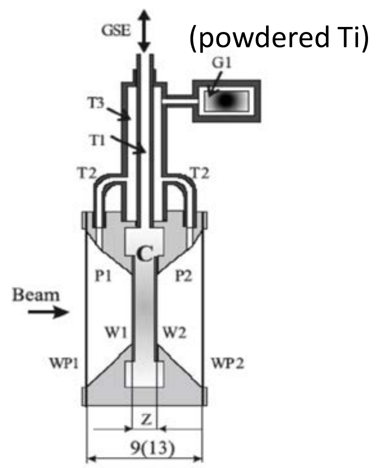
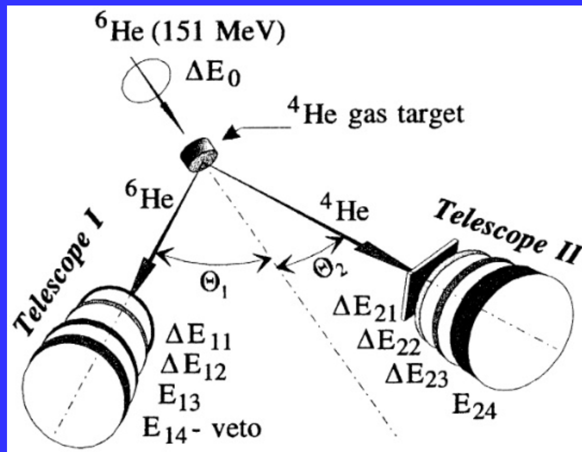


Fig. 2. Schematic drawing of the target. Denoted in the drawing are: C—target cell; W1, W2—cell windows; GSE (tube T1)—gas supply/evacuation path; P1, P2—protection barriers supplied with windows (WP1, WP2) and connected with the getter G1 through the tubes T1, T2 and T3.

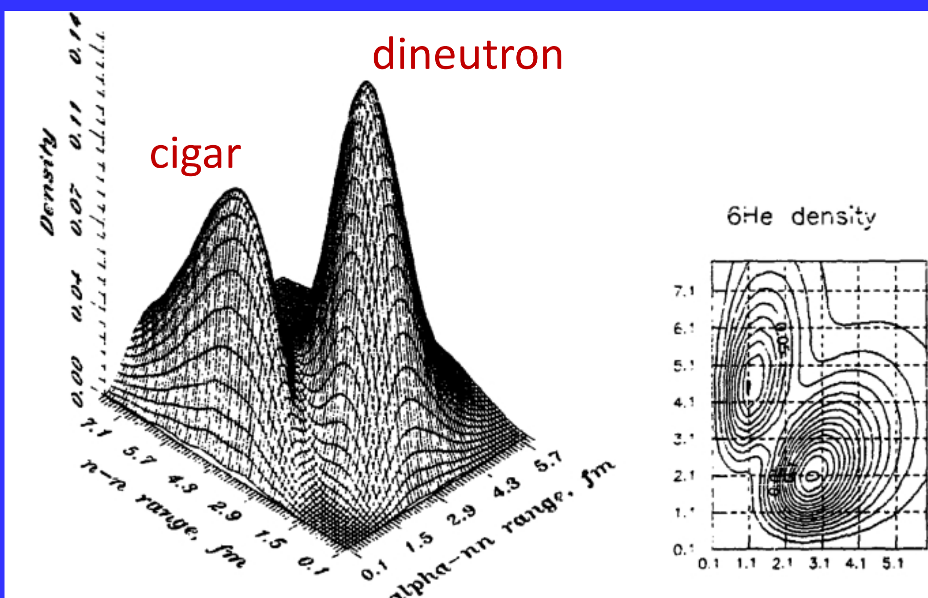
<u>Gas:</u>
ϕ=25 mm, d=3÷6 mm,
T=26 K, P=0.92 atm,
$3*10^{20}$ Atoms/cm^2

<u>Liquid:</u>
ϕ=20 mm, d=0.4÷0.8 mm,
w=2x8.4 μ stainless steel,
$1.1*10^{21}$ Atoms/cm^2
I ≤ 960 Ci ($3.54*10^{13}$ Bq)

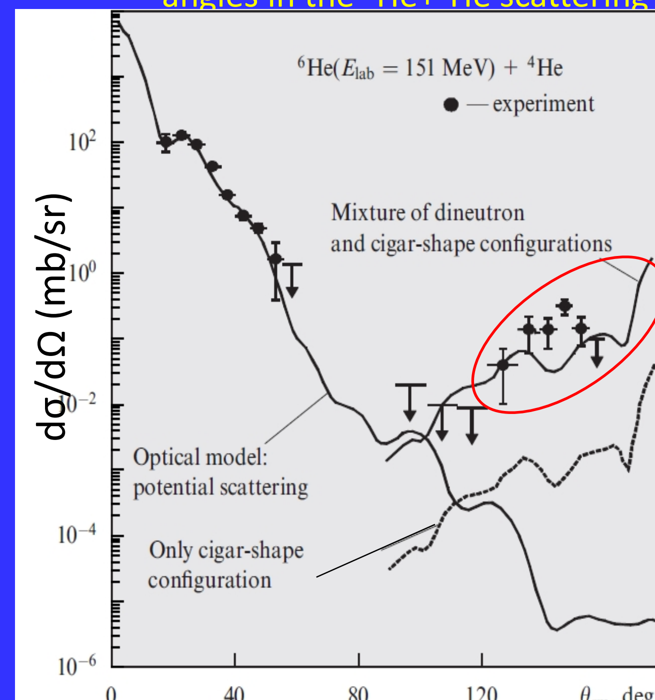
Dineutron structure of the ^{6}He nucleus with neutron halo in the ^{6}He+^{4}He elastic scattering



Spatial structure of ^{6}He nucleus (HH-theoretical calculations)



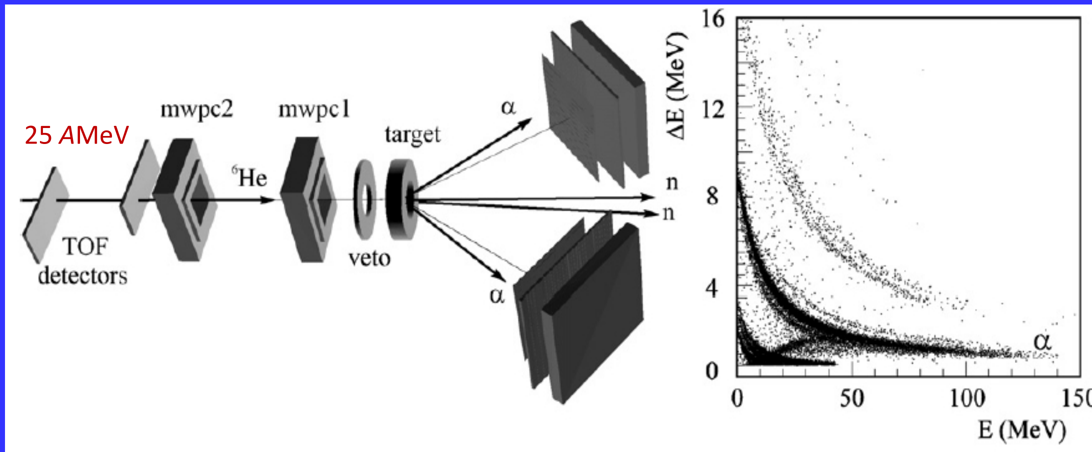
Clear signal of two neutrons exchange at backward angles in the ^{6}He+^{4}He scattering



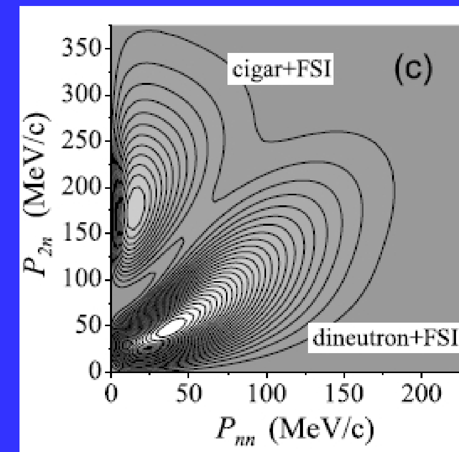
*G.M. Ter-Akopian et al., PLB **426** (1998) 251–256*

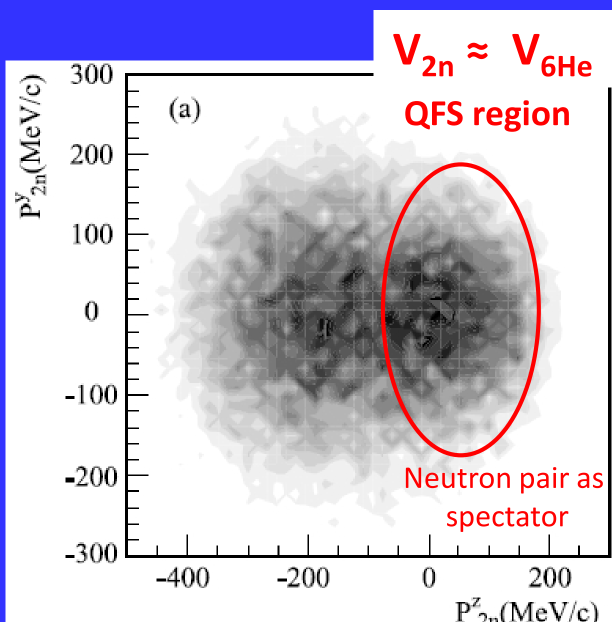
B.V. Danilin et al., Sov. J. Nucl. Phys. 48 766 (1988); Yad. Fiz. 48 1208 (1988)

Study of the ^{6}He structure in the reaction of quasifree scattering ^{4}He(^{6}He, 2α)



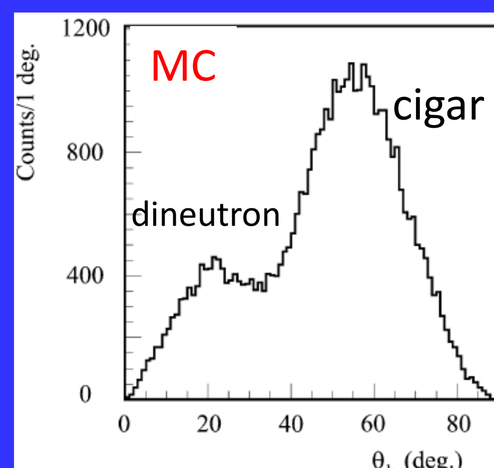
Spectral function ^{6}He $|S(P_{nn},P_{2n})|^2$

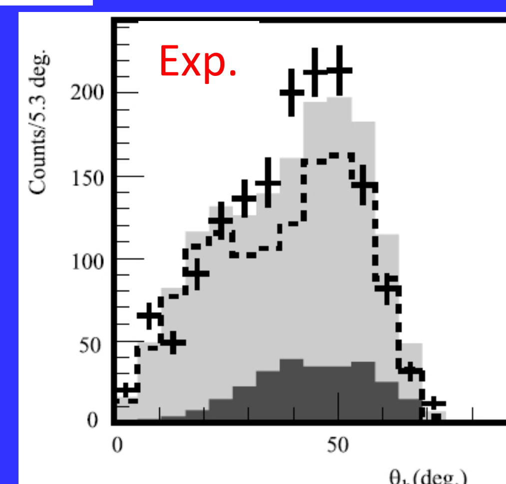




Hyper-angle:

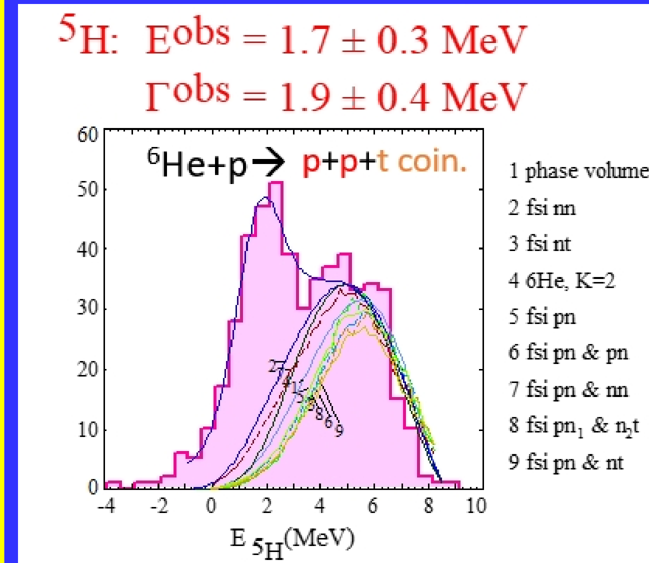
$$\tan\theta_\varkappa = \sqrt{\frac{E_{nn}}{E_{\alpha-2n}}}$$

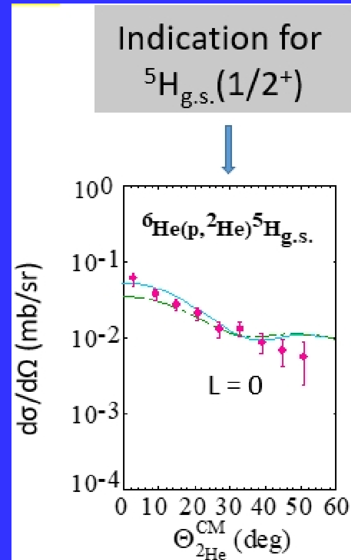




*S.I. Sidorchuk et al., Nucl. Phys. A**840** (2010) 1*

*A.A. Korsheninnikov et al., PRL **87** 092501 (2001)*

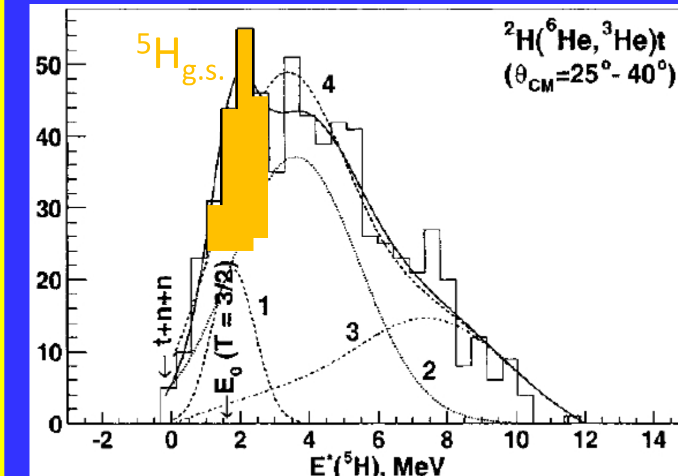




Collaboration: Dubna-Kurchatov-RIKEN-GANIL

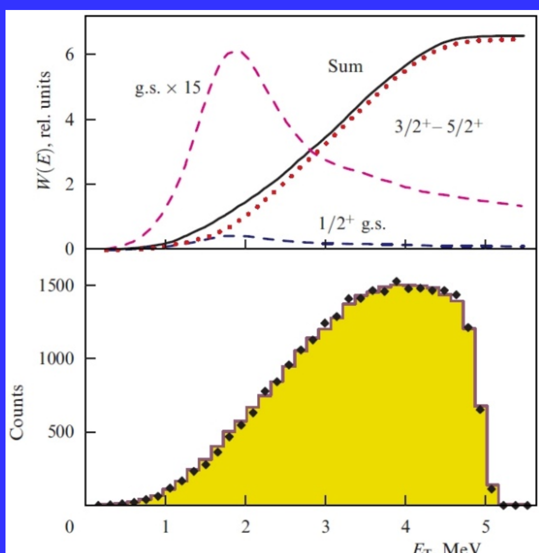
^{2}H(^{6}He,^{3}He)^{5}H

*S.V. Stepantsov et al., Nucl. Phys. A**738** (2004) 436*

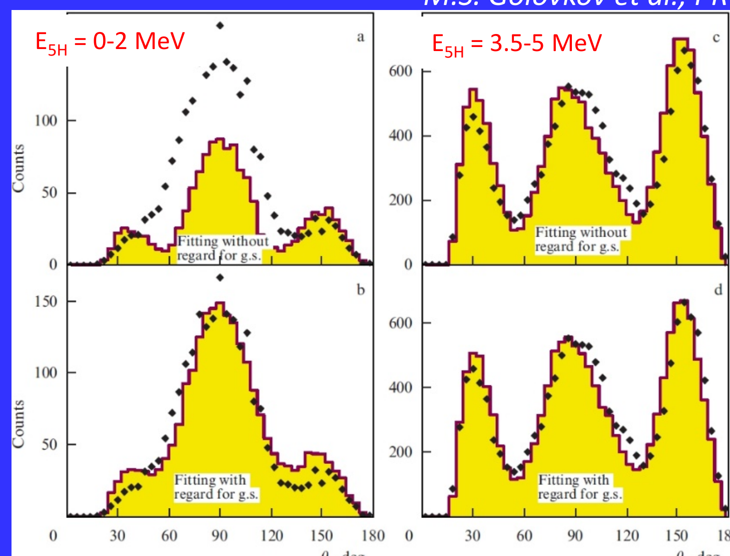


^{3}H(^{3}H,p)^{5}H (p-t-n coincidences, complete kinematics)

*M.S. Golovkov et al., PRL **93**, 262501 (2004)*
*M.S. Golovkov et al., PRC **72**, 064612 (2005)*



Target: T$_2$ gas 4 mm, 25K, 0.86 atm
Beam 58 MeV, 3x10^7 s-1



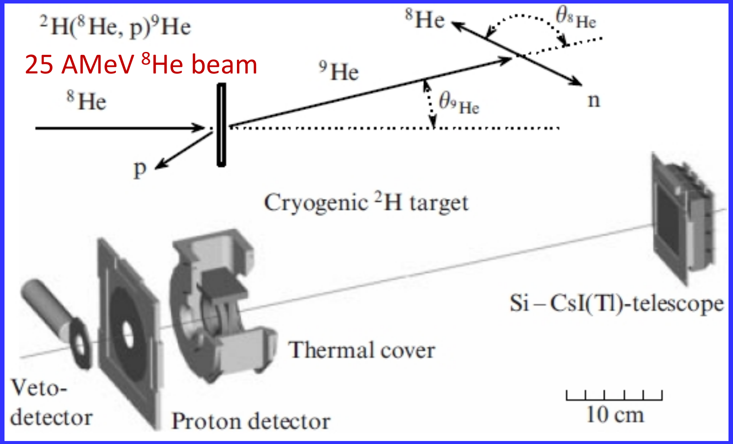
interference of 1/2$^+$, 3/2$^+$ and 5/2$^+$ states

interference of only 3/2$^+$and 5/2$^+$ states

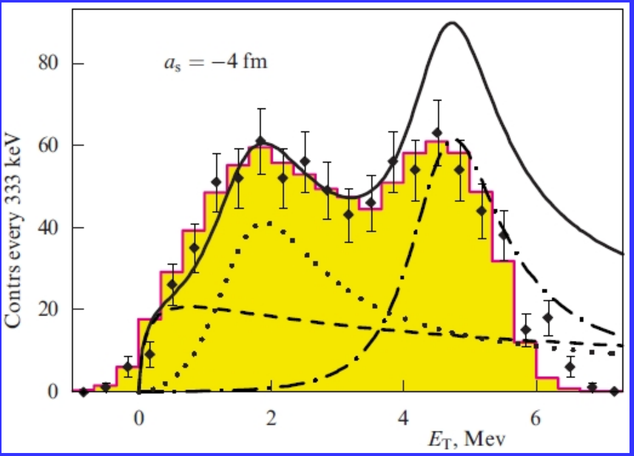
$E_{g.s.} \approx 1.8$ MeV
$\Gamma \approx 1.3$ MeV

Unambiguous spectrum identification of ^{9}He in the d(^{8}He,p)^{9}He reaction

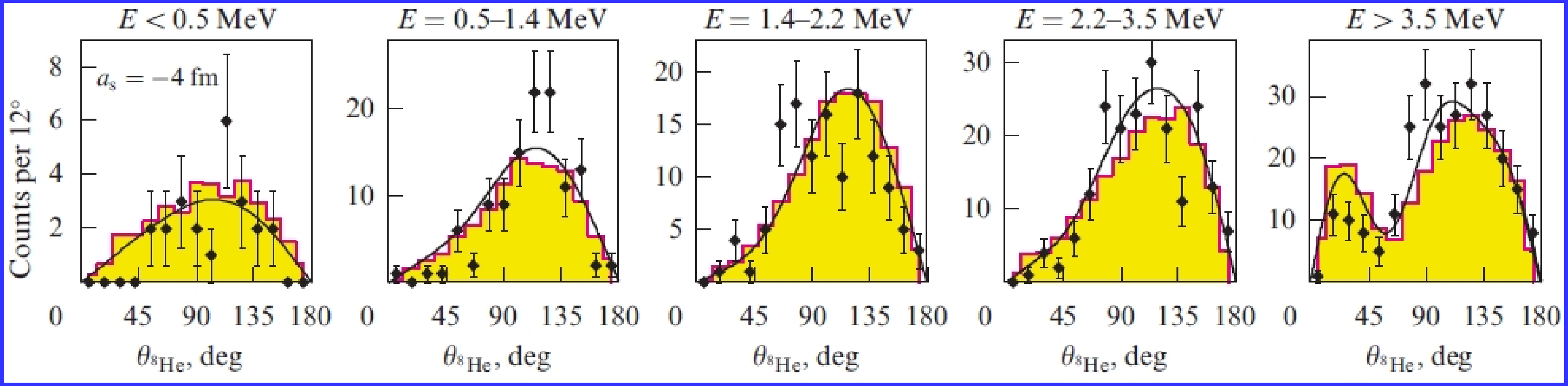
*M.S. Golovkov et al., PRC **76**, 021605(R) (2007)*



Setup: complete kinematics



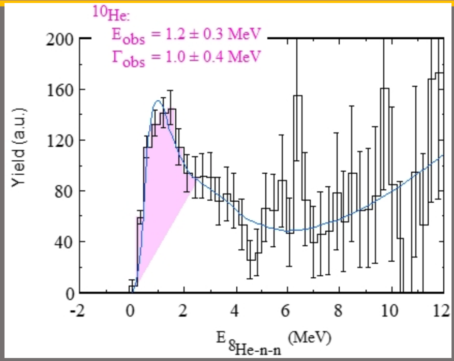
^{9}He missing mass spectrum



Angular distributions of ^{8}He in CM of ^{9}He

Conclusions: the lowest resonant state of ^{9}He is found at 2.0 ± 0.2 MeV with a width of ~2 MeV and is identified as 1/2−. Angular correlations are uniquely explained by the interference of the 1/2− resonance with a virtual 1/2+ state (a limit $a > -20$ fm is obtained for the scattering length), and with a 5/2+ resonance at energy ≥ 4.2 MeV.

Structure of ^{10}He low-lying states uncovered by correlations



First observation of ^{10}He (RIKEN)

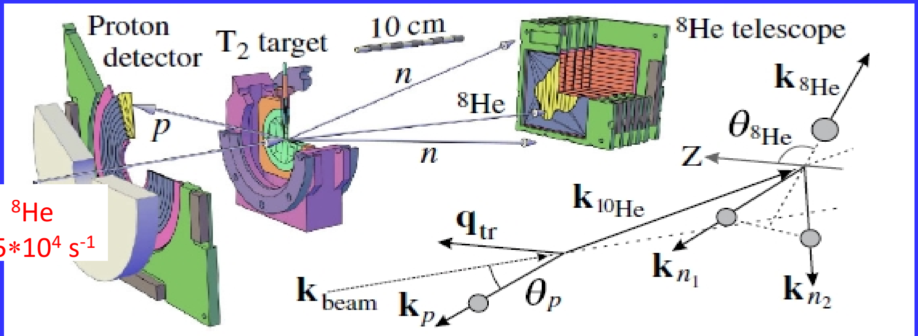
*A. A. Korsheninnikov et al., PLB **326** (1994) 31*

$E_{obs} = 1.2 \pm 0.3$ MeV

$\Gamma_{obs} \leq 1.2$ MeV

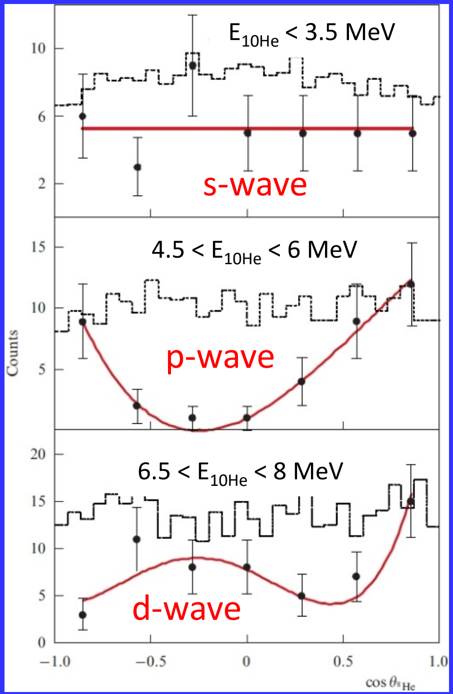
*S.I. Sidorchuk et al., PRL **108**, 202502 (2012)*

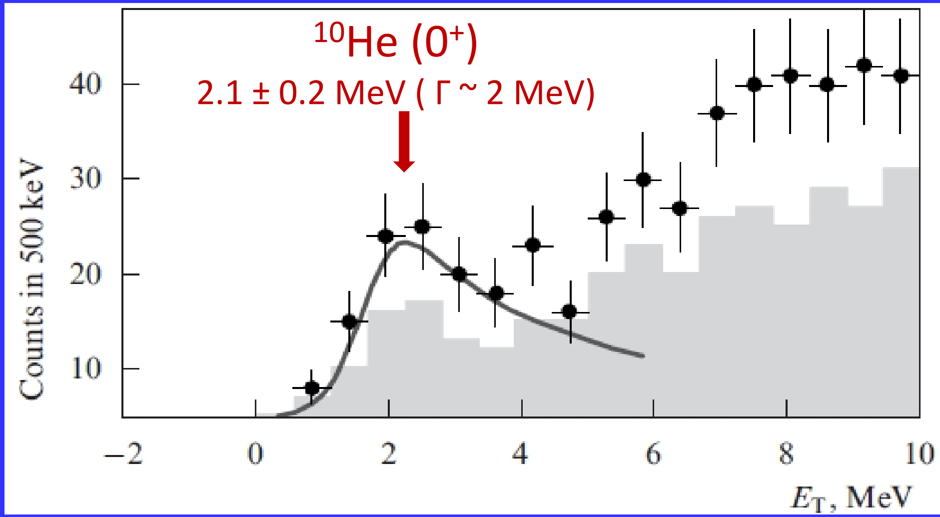
^{3}H(^{8}He,p)^{10}He reaction on tritium gas target with 21.5 *A*MeV ^{8}He beam

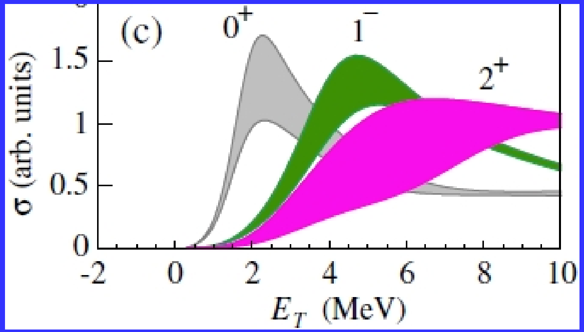


^{8}He
$1.5*10^4$ s^{-1}

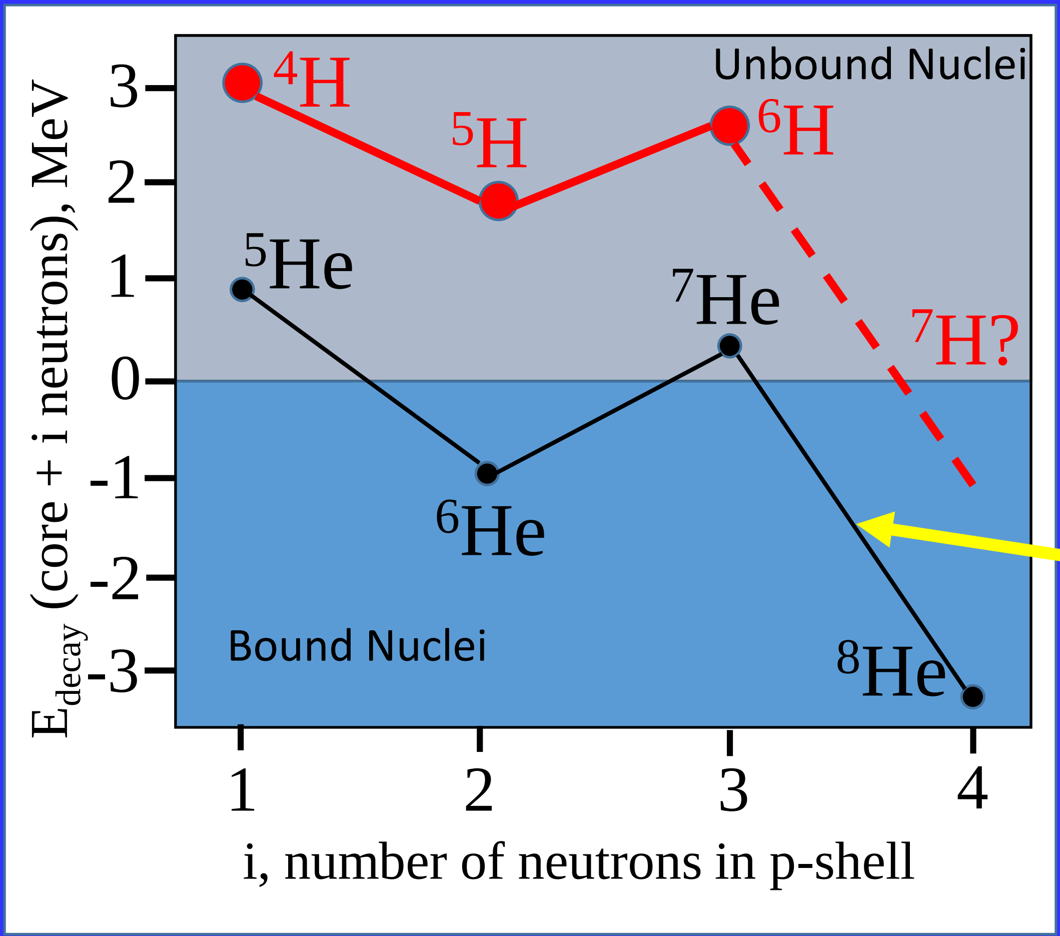
Z-axis: $\mathbf{q}_{tr} = -(1/4)\mathbf{k}_{beam} - \mathbf{k}_p$







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)

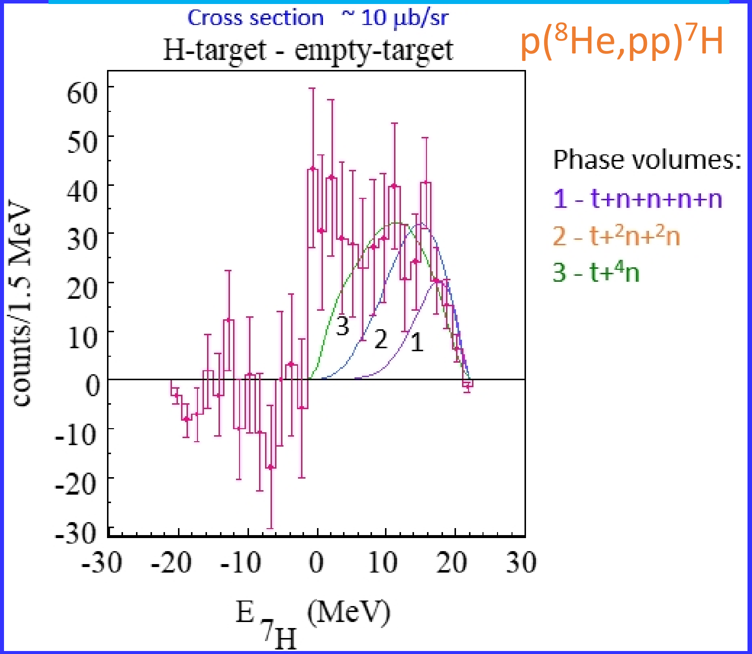
Estimation of width of ^{7}H: **E ≤ 3 MeV ⇔ Γ ≤ 1 MeV**
M.S. Golovkov et al., PL B588 163 (2004)

New Result:

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

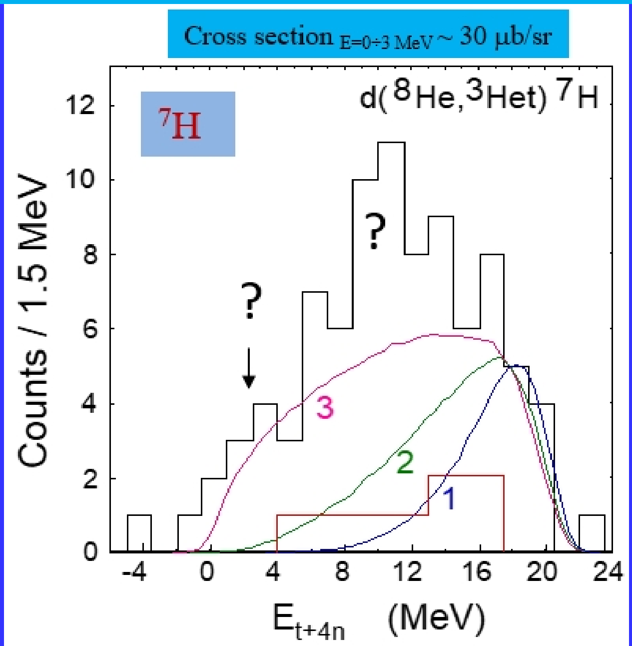
Experiments to search for ^{7}H states

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

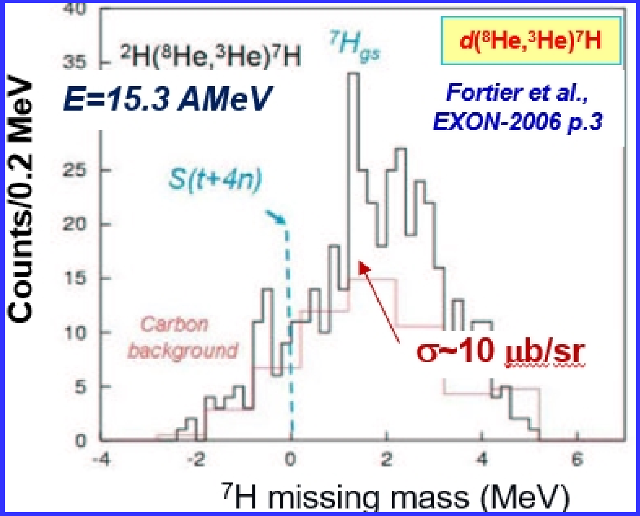


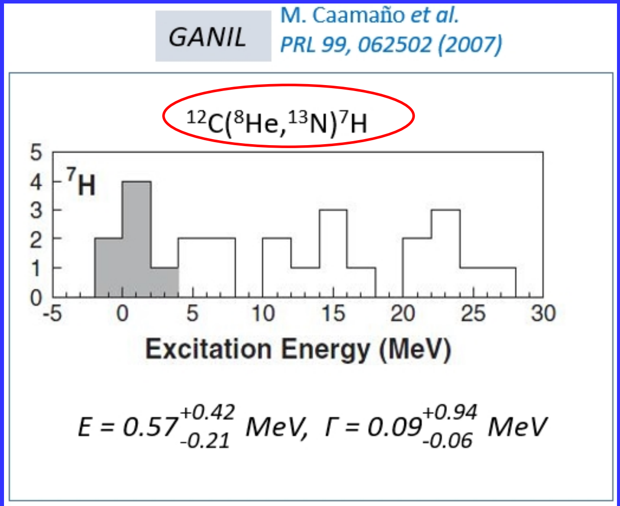
A. A. Korsheninnikov et al. PRL ***90****, 082501 (2003)*

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



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

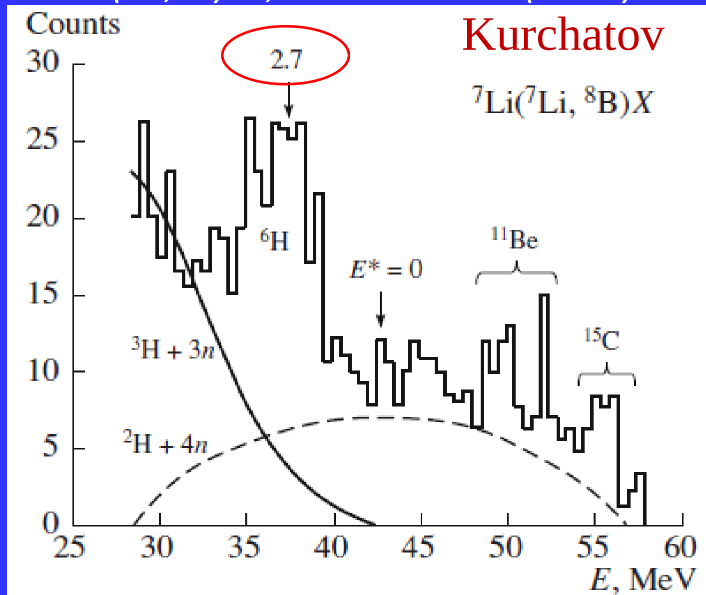




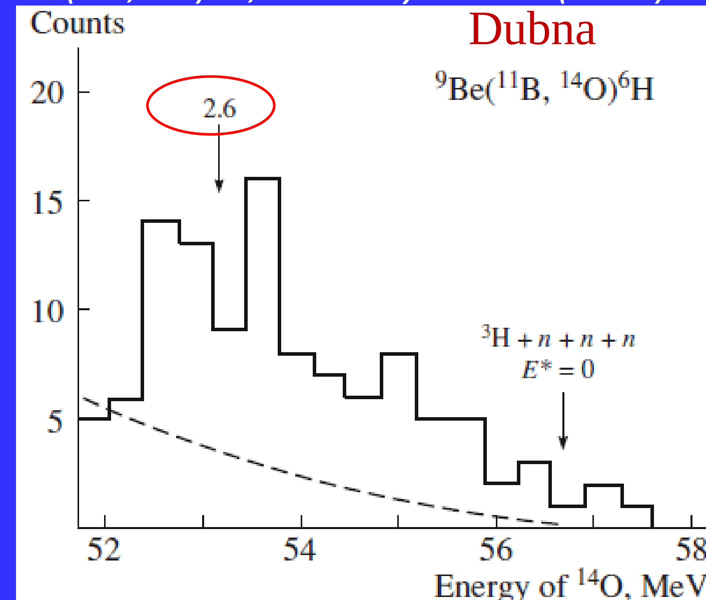
Experiment	*LAB*	*Energy (AMeV)*	*Result*	*Cross section (μb/sr)*
$p(^8He,pp)$	*RIKEN*	61	Very sharp increase from threshold No resonance parameters	~ 30 (E ≤ 3 MeV)
$d(^8He,^3He)$	*GANIL*	15.3	Structure near 2 MeV No resonance parameters	—
$d(^8He,^3He)$	*Dubna*	25	Few events No resonance parameters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

^{6}H search history

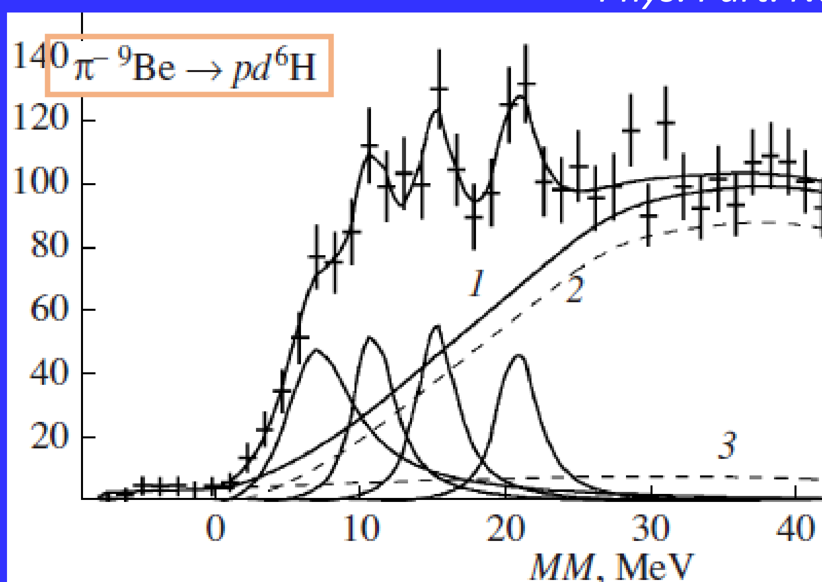
^{7}Li(^{7}Li,^{8}B)^{6}H, Yad.Fiz. m.39 (1984) 513



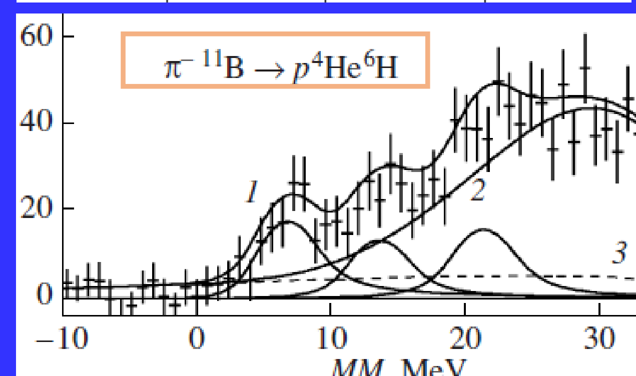
^{9}Be(^{11}B,^{14}O)^{6}H, Nucl.Phys. A460 (1986) 352



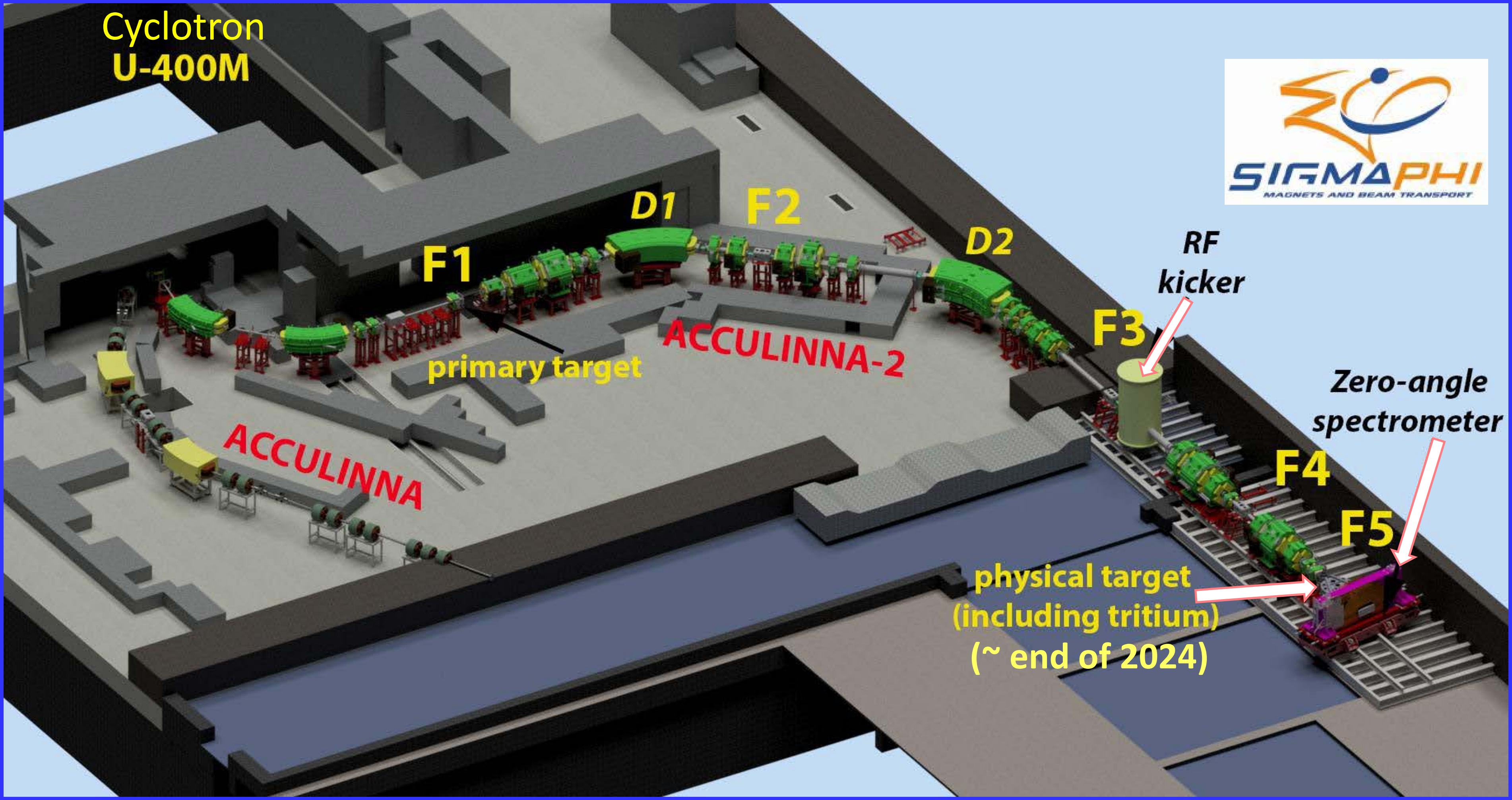
Phys. Part. Nucl. 40 (1990) 558



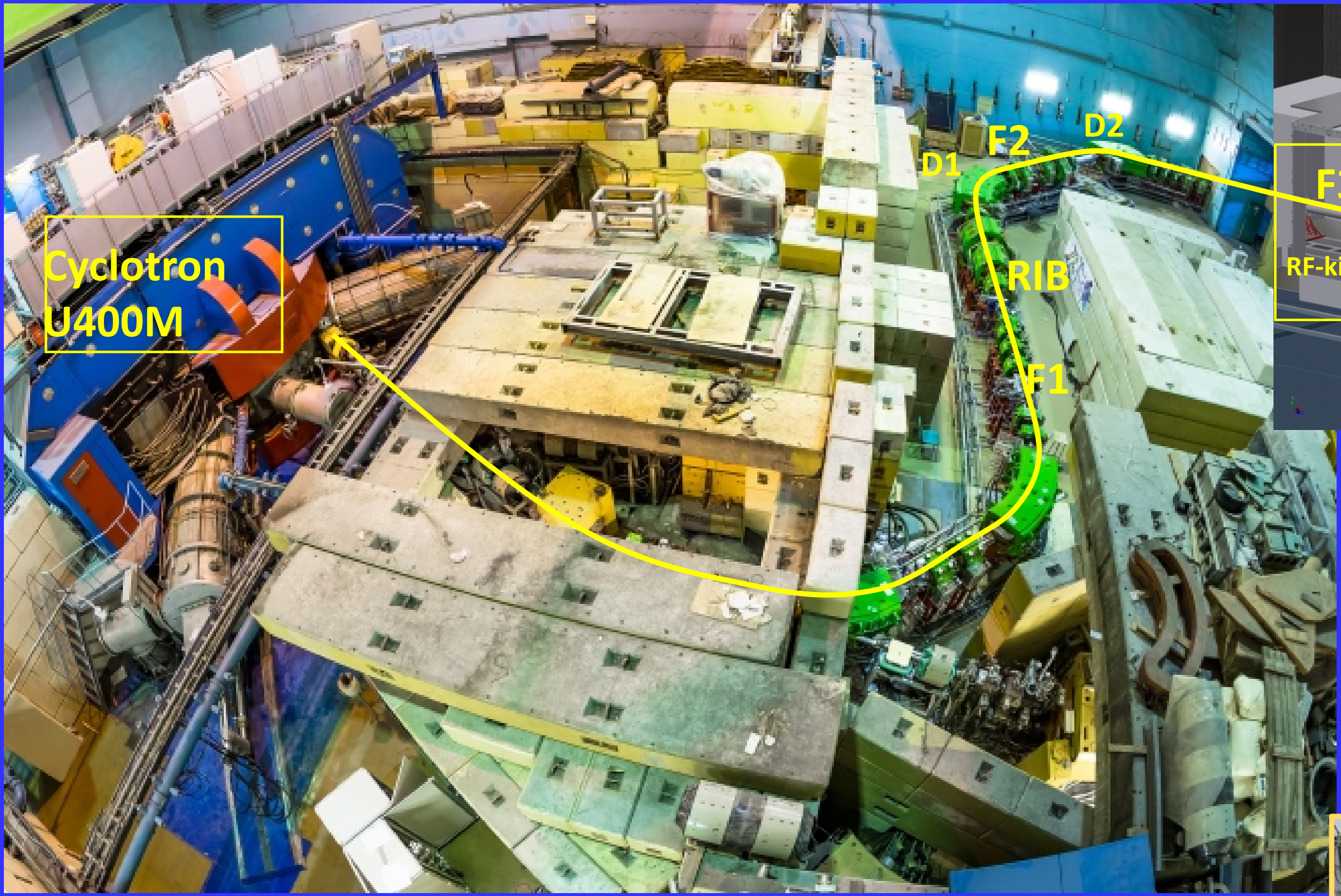
^{9}Be(π^-, pd)^{6}H		^{11}B(π^-, p^{4}He)^{6}H	
E_r, MeV*	Γ, MeV**	E_r, MeV	Γ, MeV
6.6 ± 0.7	5.5 ± 2.0	7.3 ± 1.0	5.8 ± 2.0
10.7 ± 0.7	4 ± 2	–	–

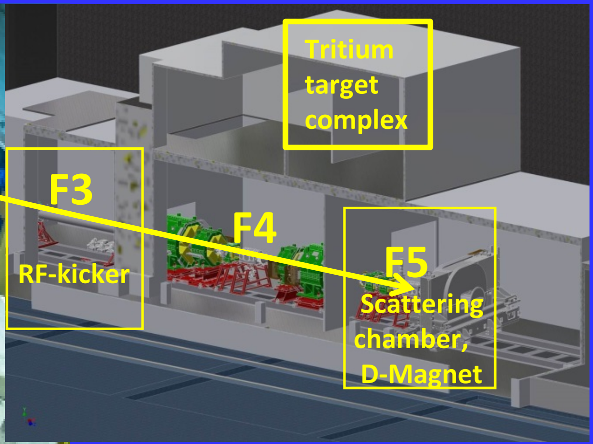


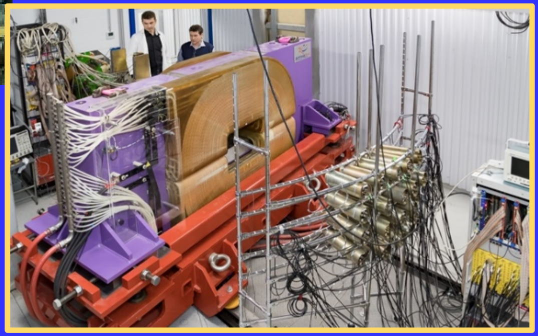
ACCULINNA-2 separator layout (since 2017)



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

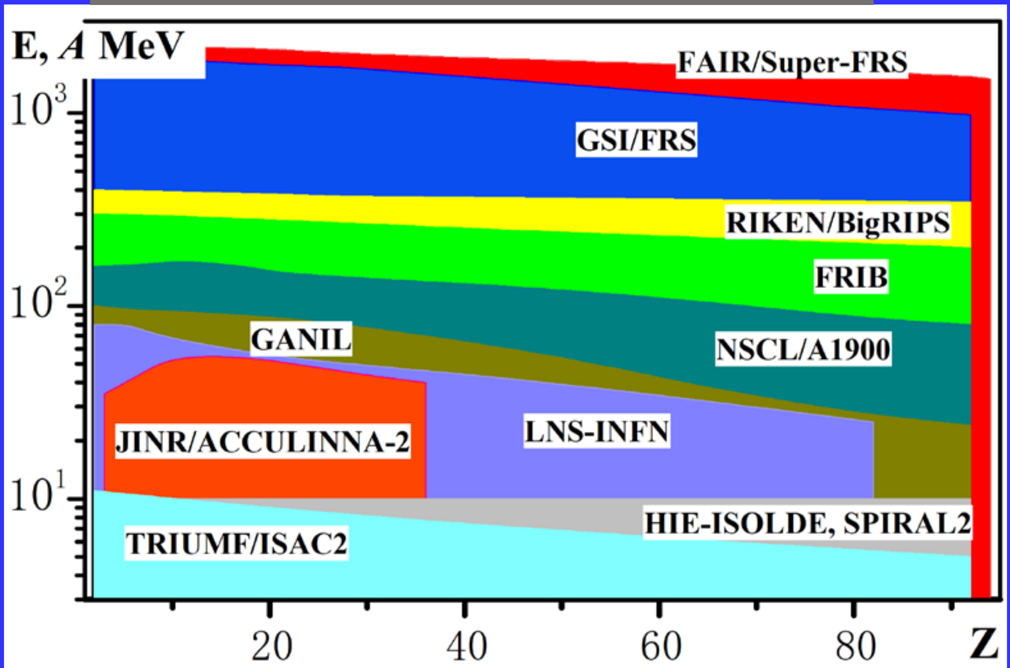






2011: Contract signed with Sigma PHI
2016-17: Full commissioning + Beam
2018-2019: First experiments
2020-2023: Upgrade U400M cyclotron

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

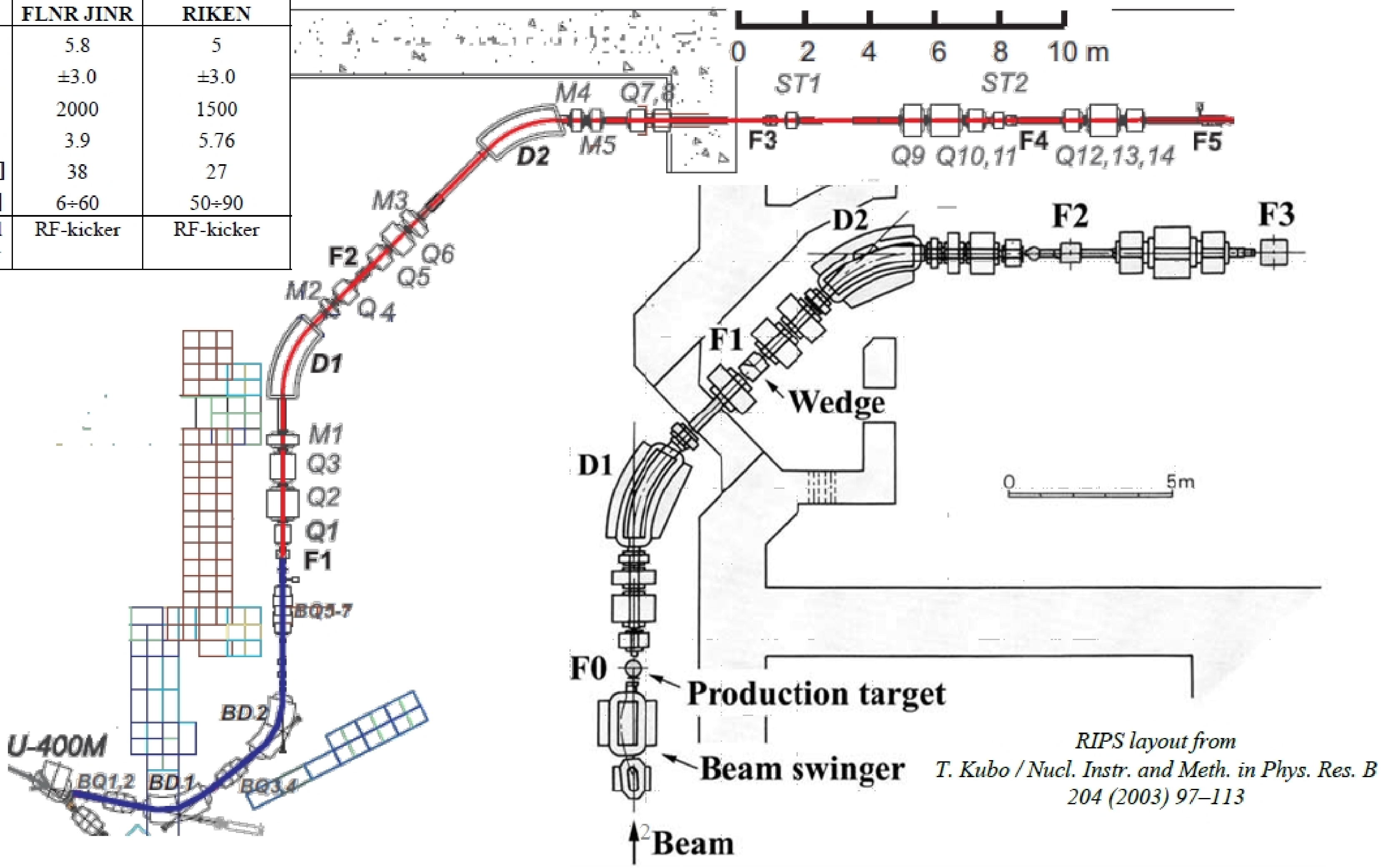
		ACC FLNR,	ACC-2 JINR	LISE3 GANIL	ARIS[a] FRIB	RIPS	BigRIPS RIKEN
$\Delta\Omega$	msr	0.9	4.2	1.0	5.0	5.0	6.3
δ_P	%	2.5	6.0	5.0	10	6.0	6.0
$P/\Delta P$	a.u.	1000	2000	2200	4000	1500	3300
$B\rho_{max}$	Tm	3.2	3.9	3.2-4.3	8.0	5.76	9.0
Length	m	21	37	19(42)	87	21	77
$E_{\min}$	AMeV	10	5	30	30[b]	30	5[c]
$E_{\max}$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

ACCULINNA-2 is comparable with RIPS, RIKEN

Intensities of secondary beams ~ 15-25 times higher than ACCULNNA !!

ACCULINNA-2 layout compared to RIPS (RIKEN)

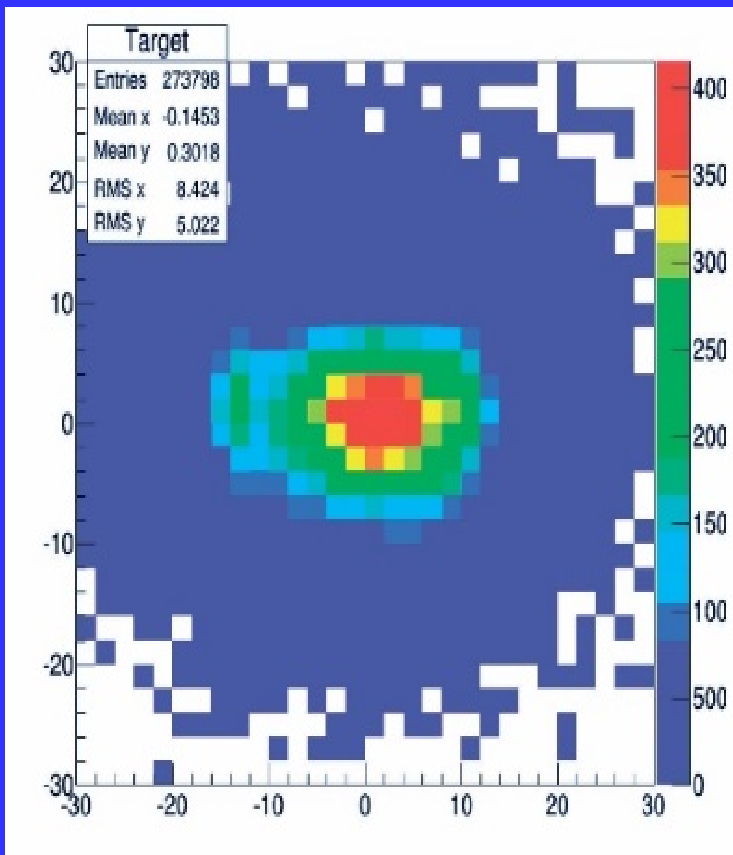
	ACC-2 FLNR JINR	RIPS RIKEN
ΔΩ [msr]	5.8	5
Δp/p [%]	±3.0	±3.0
Rp/Δp	2000	1500
Bρ [Tm]	3.9	5.76
Length [m]	38	27
E [AMeV]	6÷60	50÷90
Additional RIB Filter	RF-kicker	RF-kicker

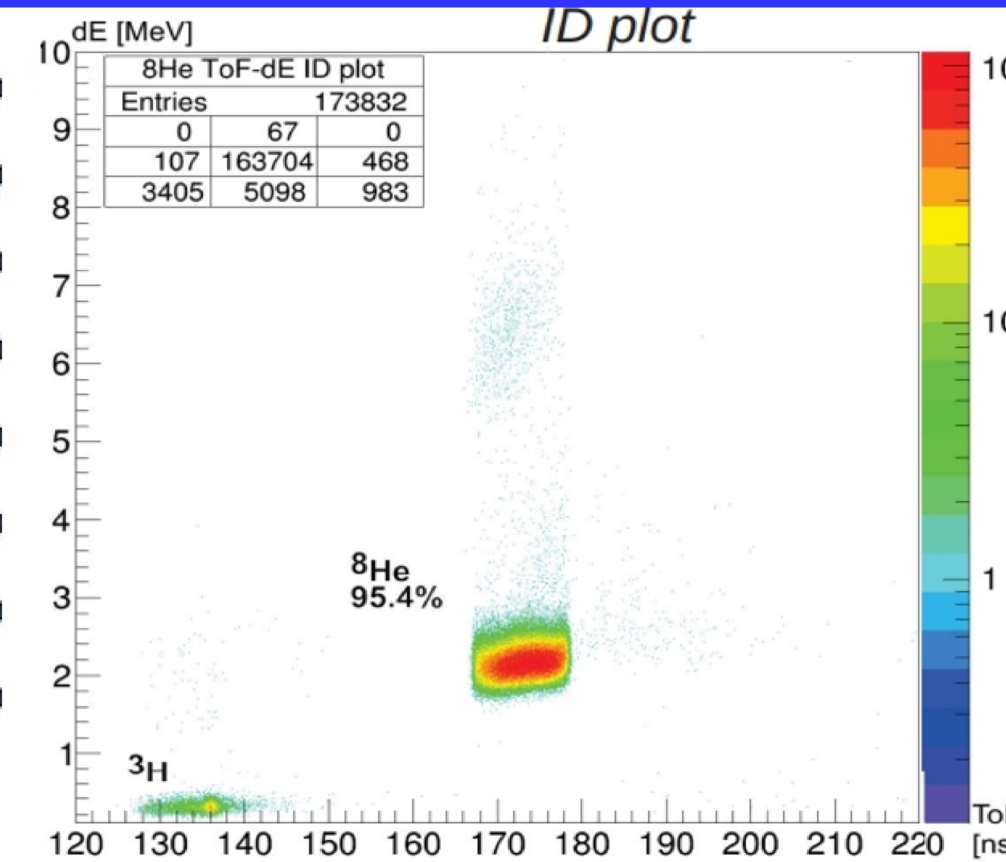


RIPS layout from
T. Kubo / Nucl. Instr. and Meth. in Phys. Res. B 204 (2003) 97–113

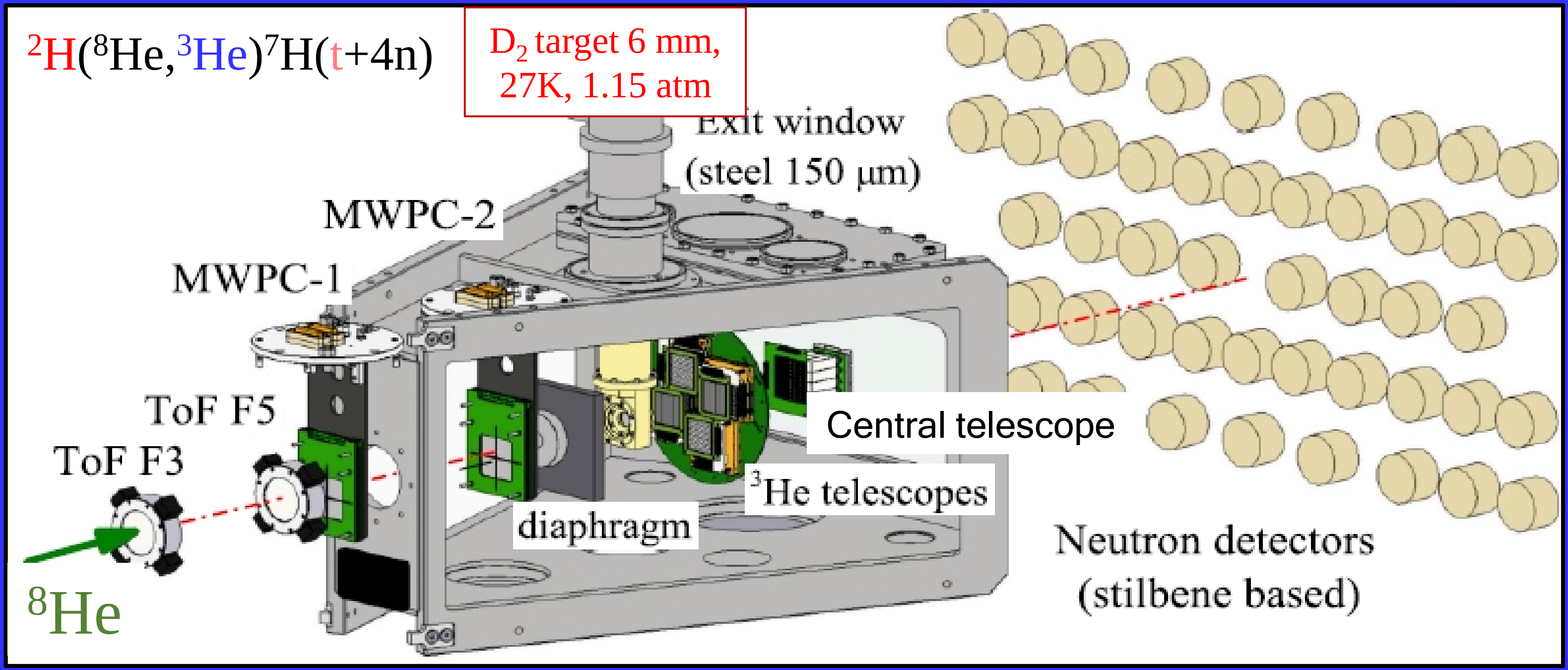
^{8}He beam

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

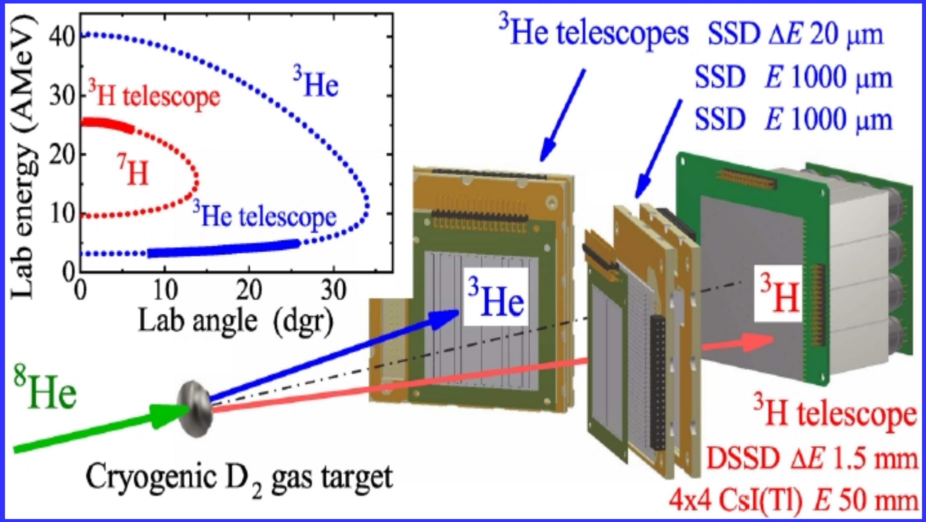




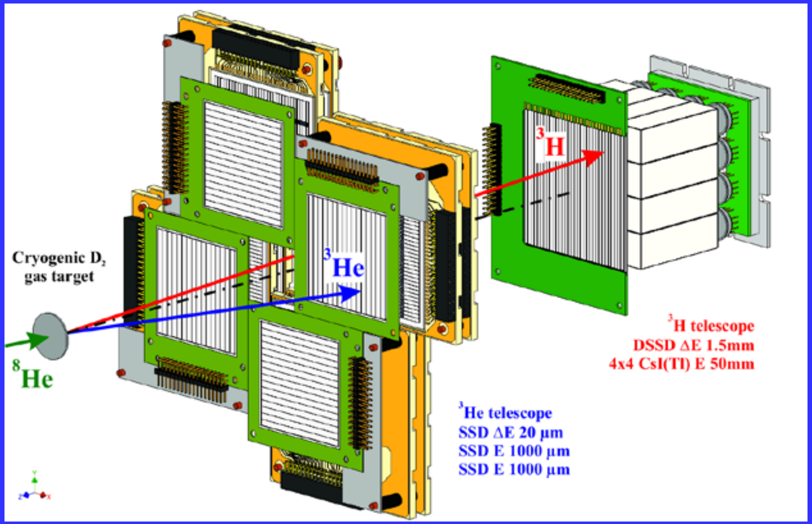
Experimental setup to study ^{2}H(^{8}He,^{3}He)^{7}H reaction



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

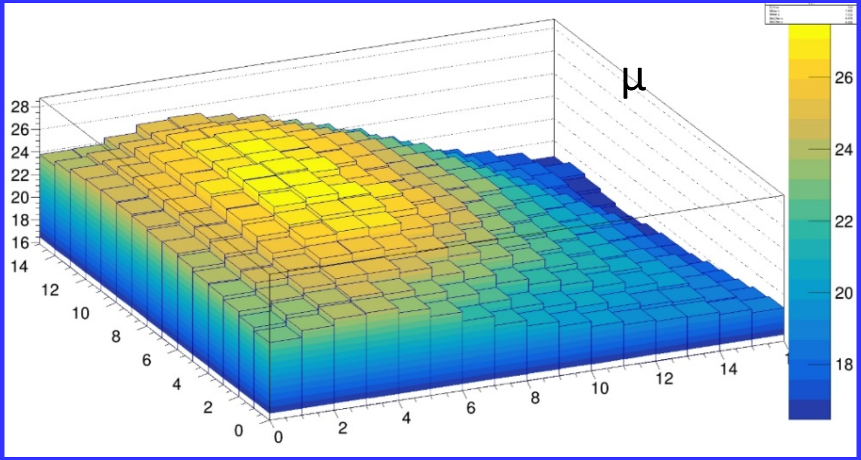


EXP 2, 2019 3 weeks, 404 ^{7}H (^{3}He+t) events

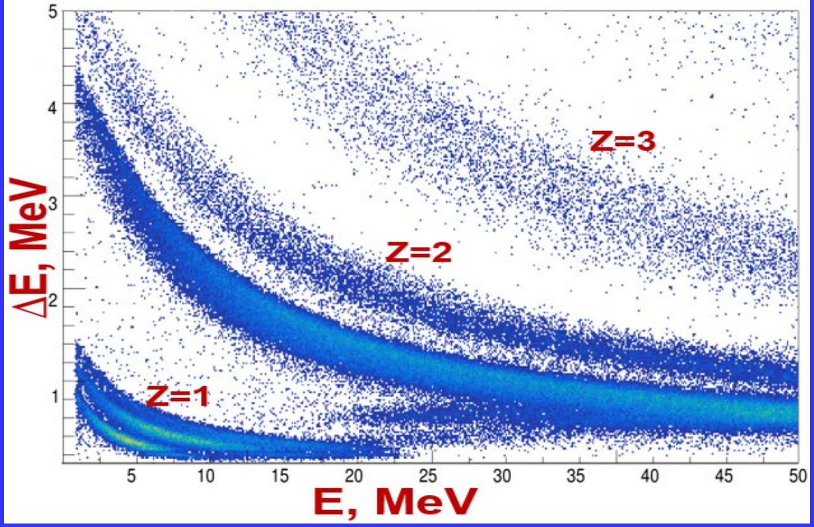


Identification of low-energy ^{3}He is a difficult task!

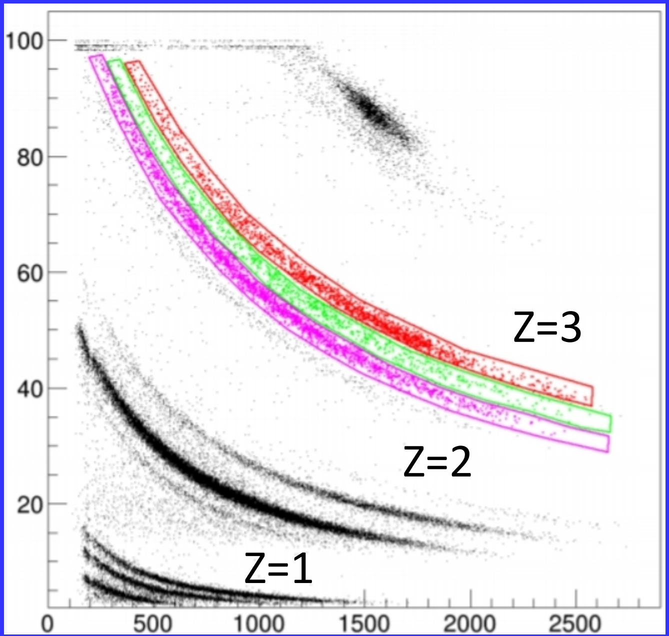
Measured thickness map of one of 20-um detector



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

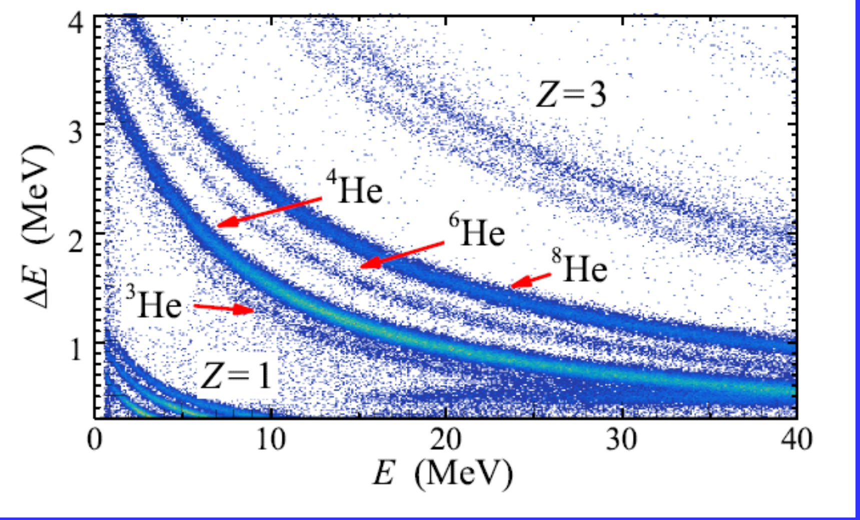


Identification in central telescope (^{10}Be beam)



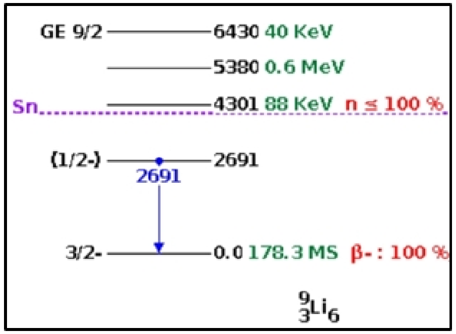
Particle ID after thickness correction of 20-um detector

Now all He isotopes are clearly resolved !!



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

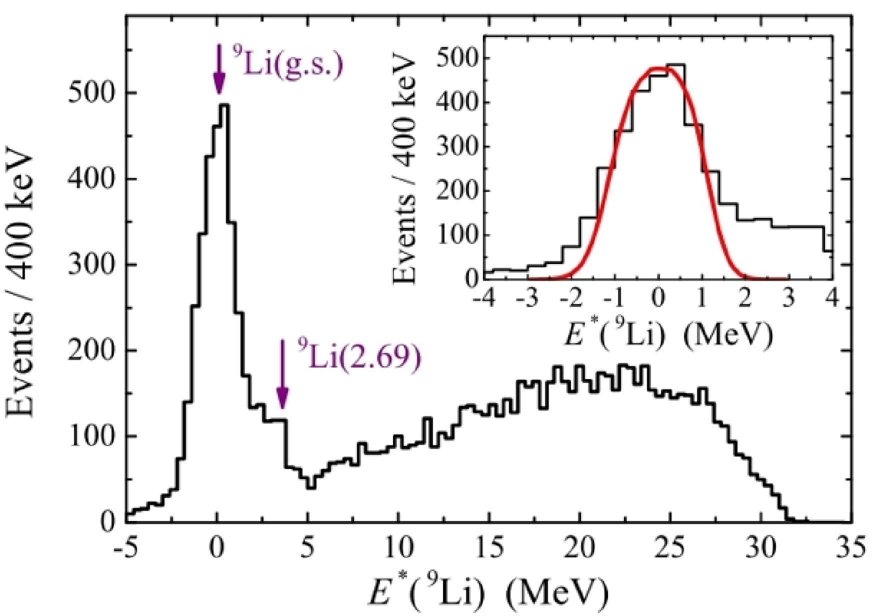
*E. Yu. Nikolskii et al., NIMB **541** (2023) 121*

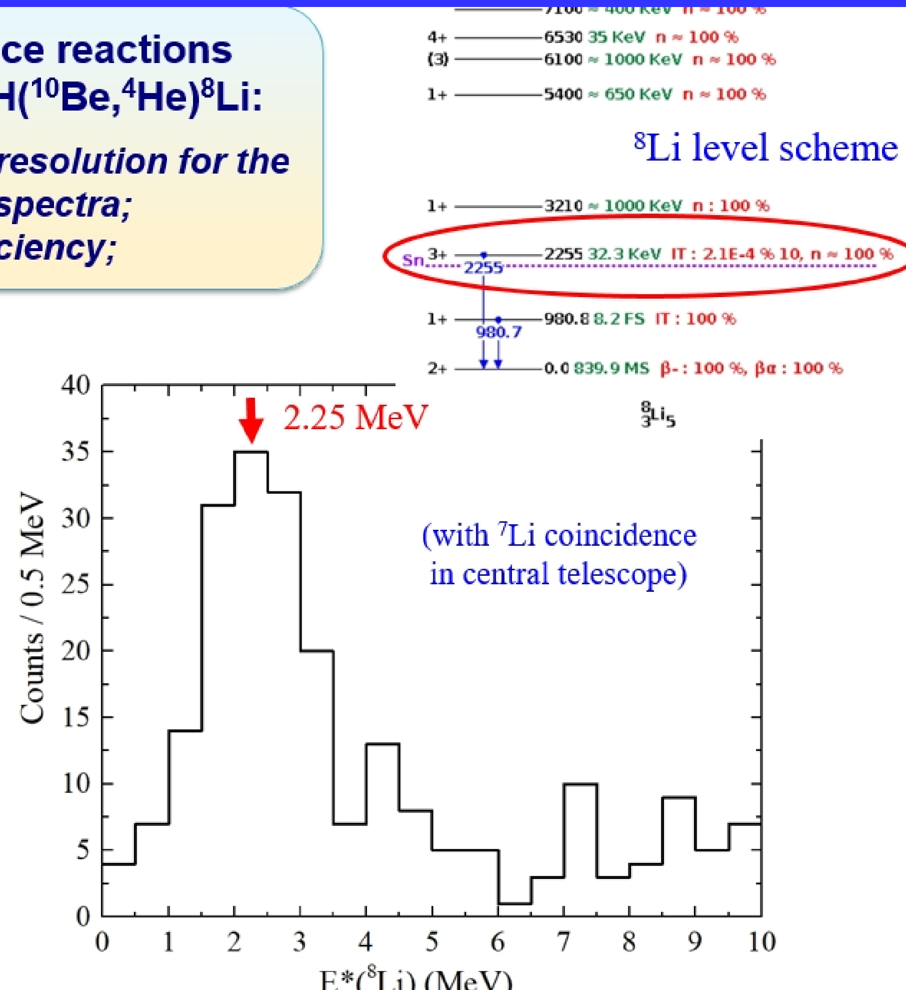


Data for the reference reactions $^{2}H(^{10}Be,^{3}He)^{9}Li$ and $^{2}H(^{10}Be,^{4}He)^{8}Li$:

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

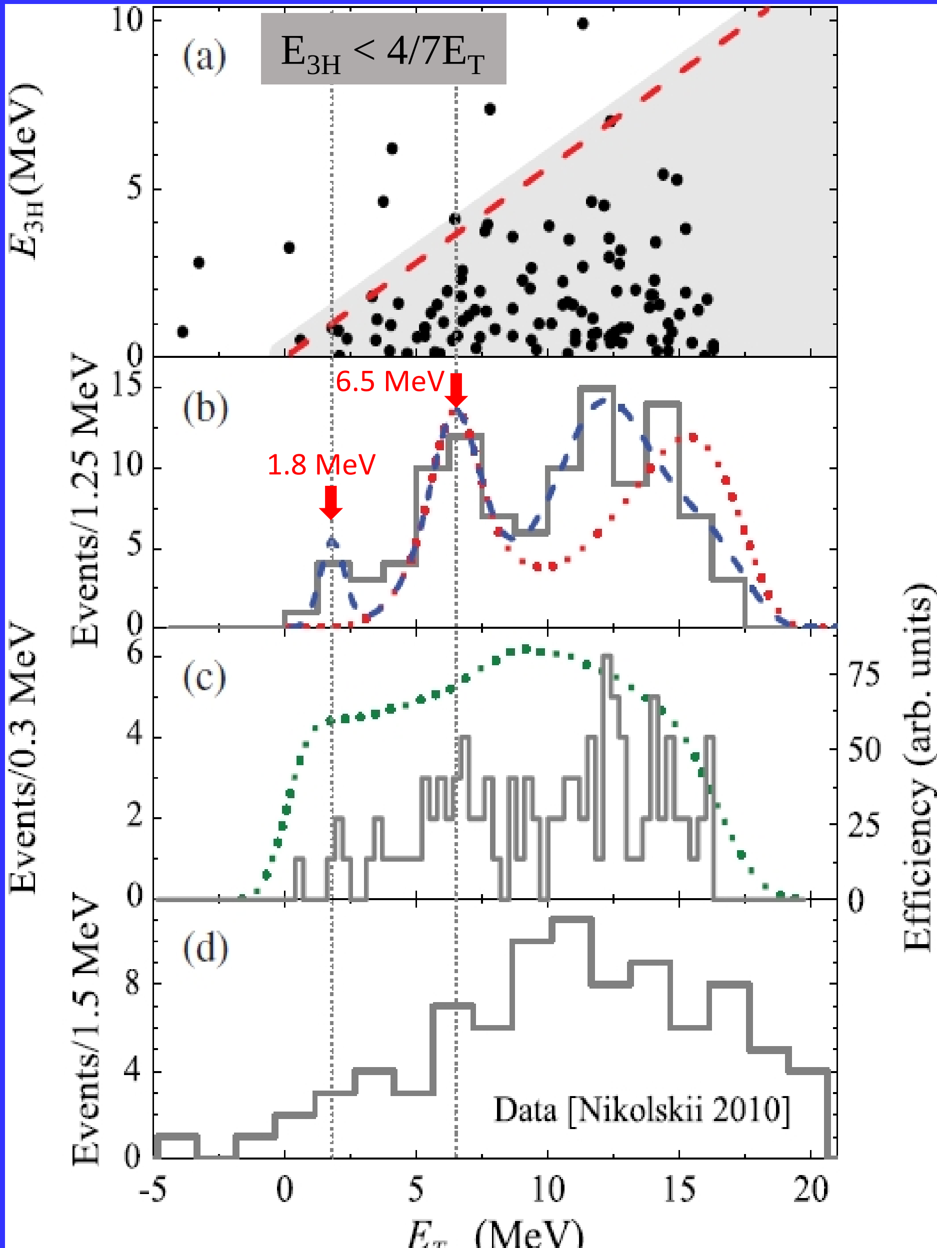
***** detector efficiency;***

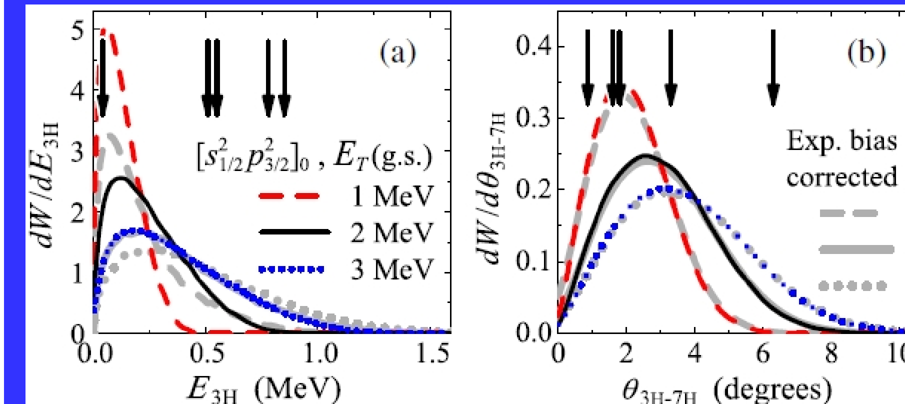




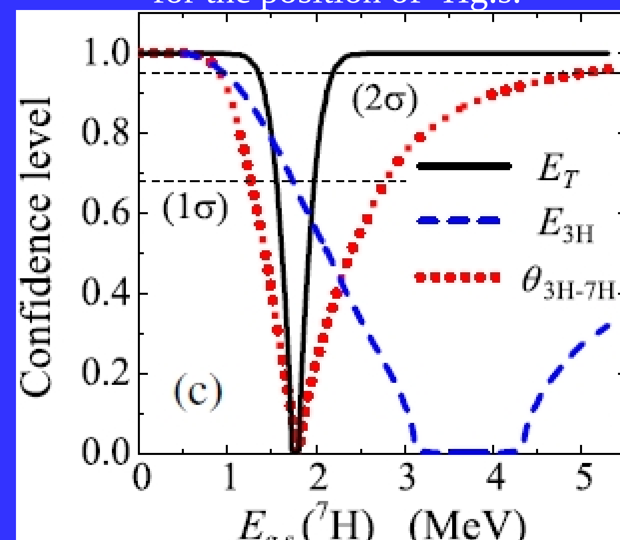
Detailed data of ^{7}H of the 1st Run

[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:

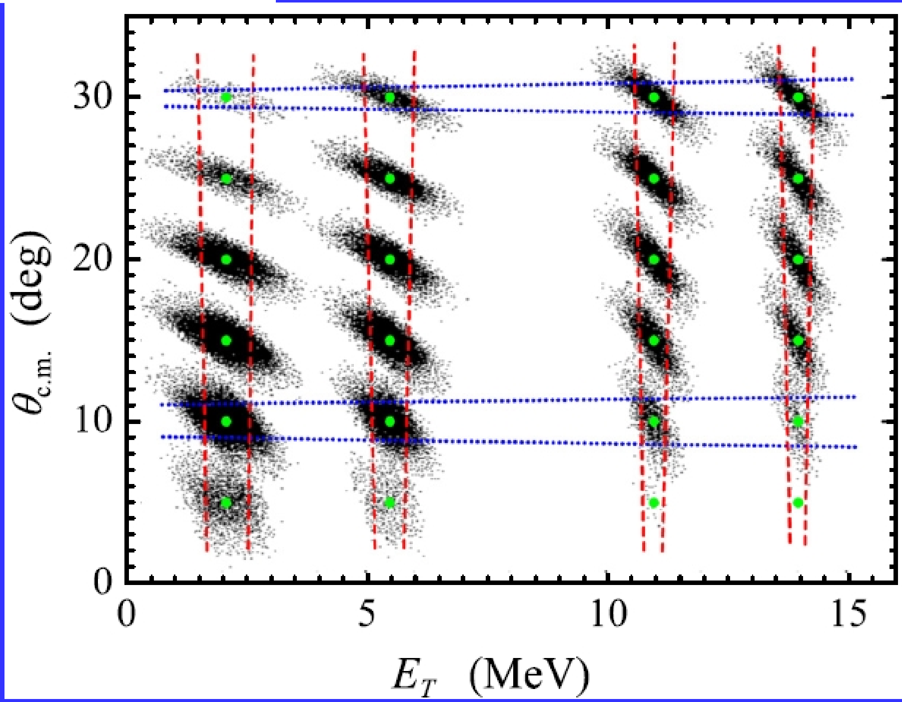
(i) For the first time, the ^{7}H excited state is observed at E_T = 6.5(5) MeV with Γ = 2.0(5) MeV. This state can be interpreted as the unresolved 5/2+ and 3/2+ doublet built upon the 2+ excitation of valence neutrons, or one of the doublet states.

(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 Θ_{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

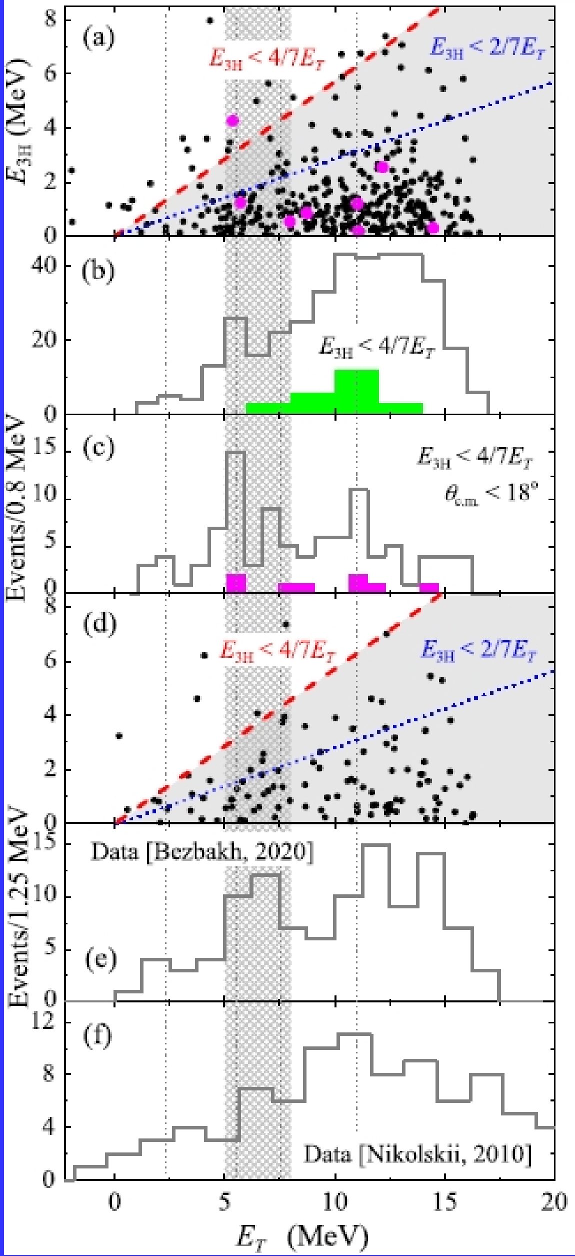
TABLE I. Experimental resolution in the second experiment as a function of the ^{7}H MM energy and center-of-mass angle $\theta_{c.m.}$ based on the MC simulations Fig. 8. The first and second values in each cell are the FWHM energy and the angular resolutions given in MeV and degrees, respectively.

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

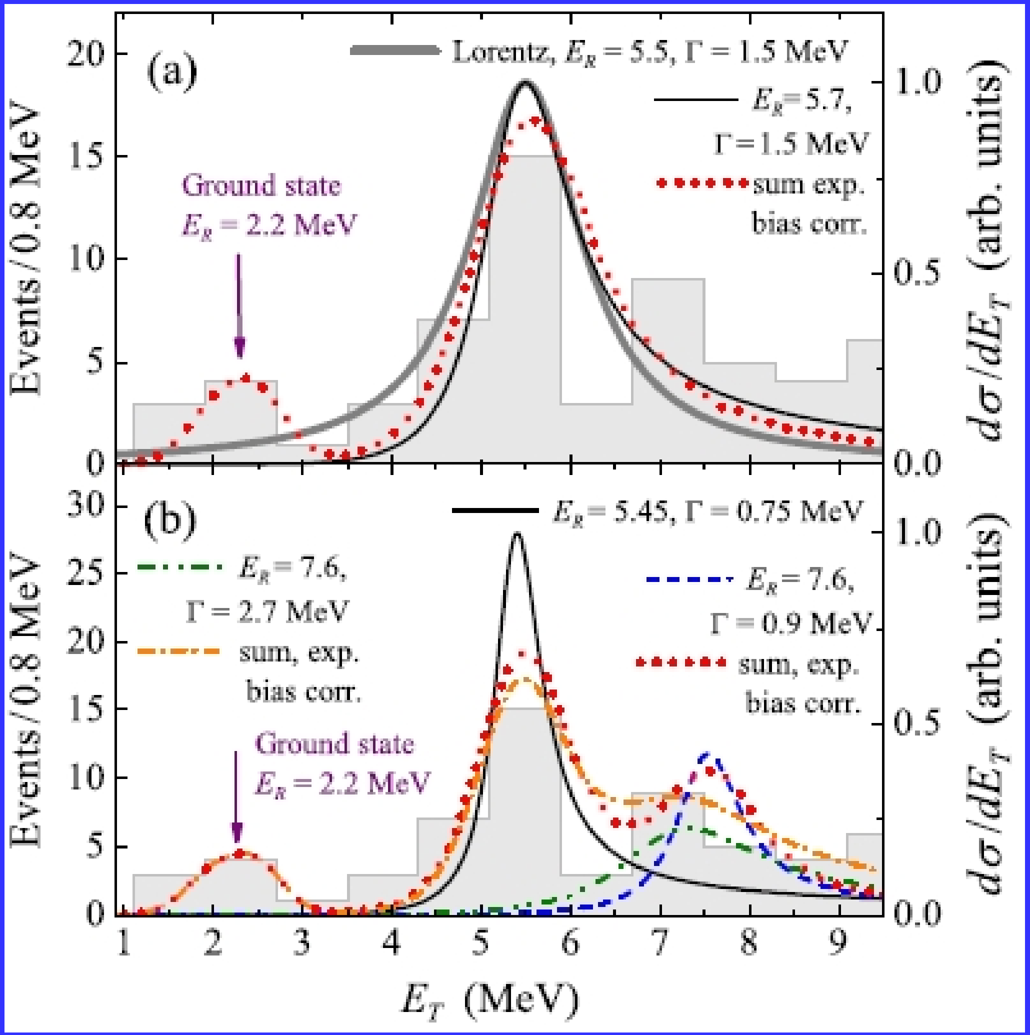


Detailed data of ^{7}H of the 2nd Run

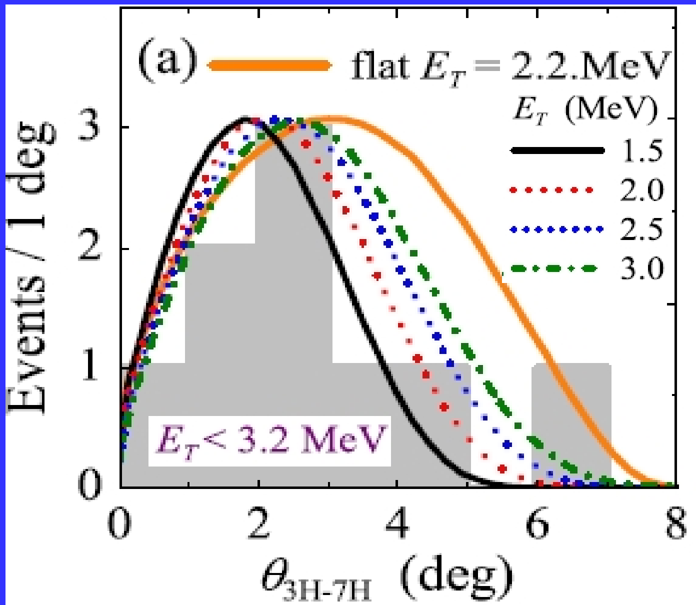
[I. A. Muzalevskii et al, PRC **103**, 044313 (2021)]

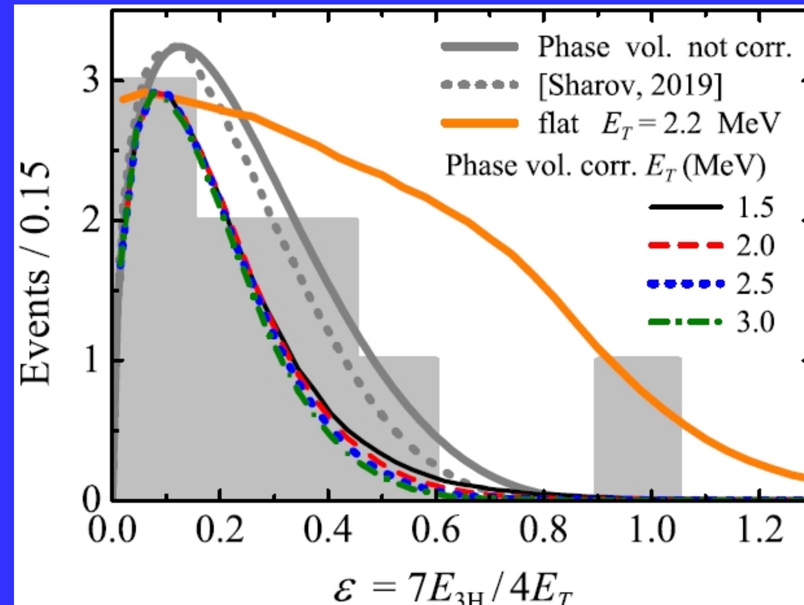


^{7}H spectrum after $E_{3H} < 4/7E_T$ and $\Theta_{CM} < 18^0$ selections



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:

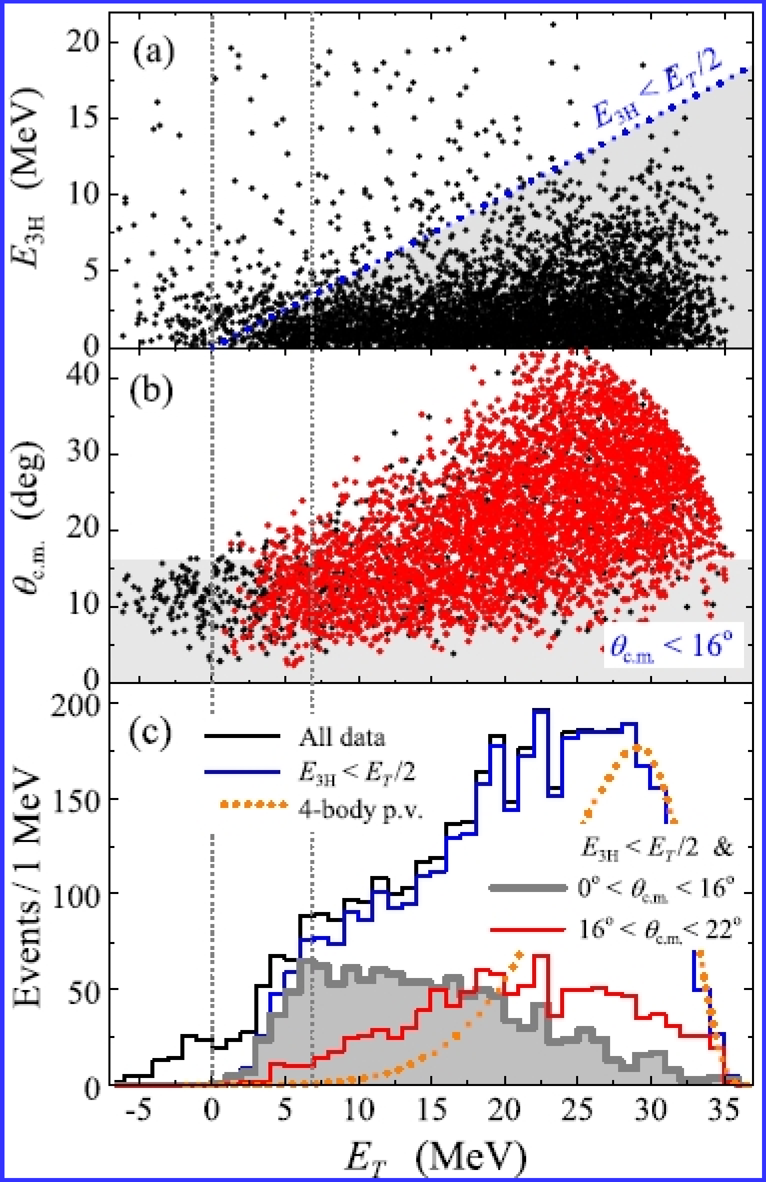
1. A solid experimental evidence is provided that two resonant states of ^{7}H are located in its spectrum at 2.2(5) and 5.5(3) MeV relative to the ^{3}H+4n decay threshold.

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.

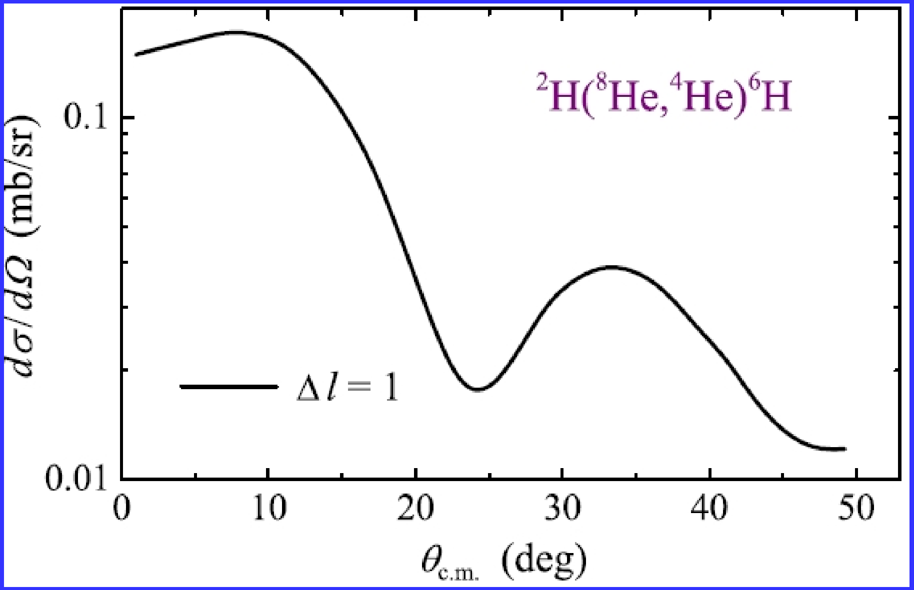
3. There are indications that the resonant states at 7.5(3) and 11.0(3) MeV are present in the measured ^{7}H spectrum.

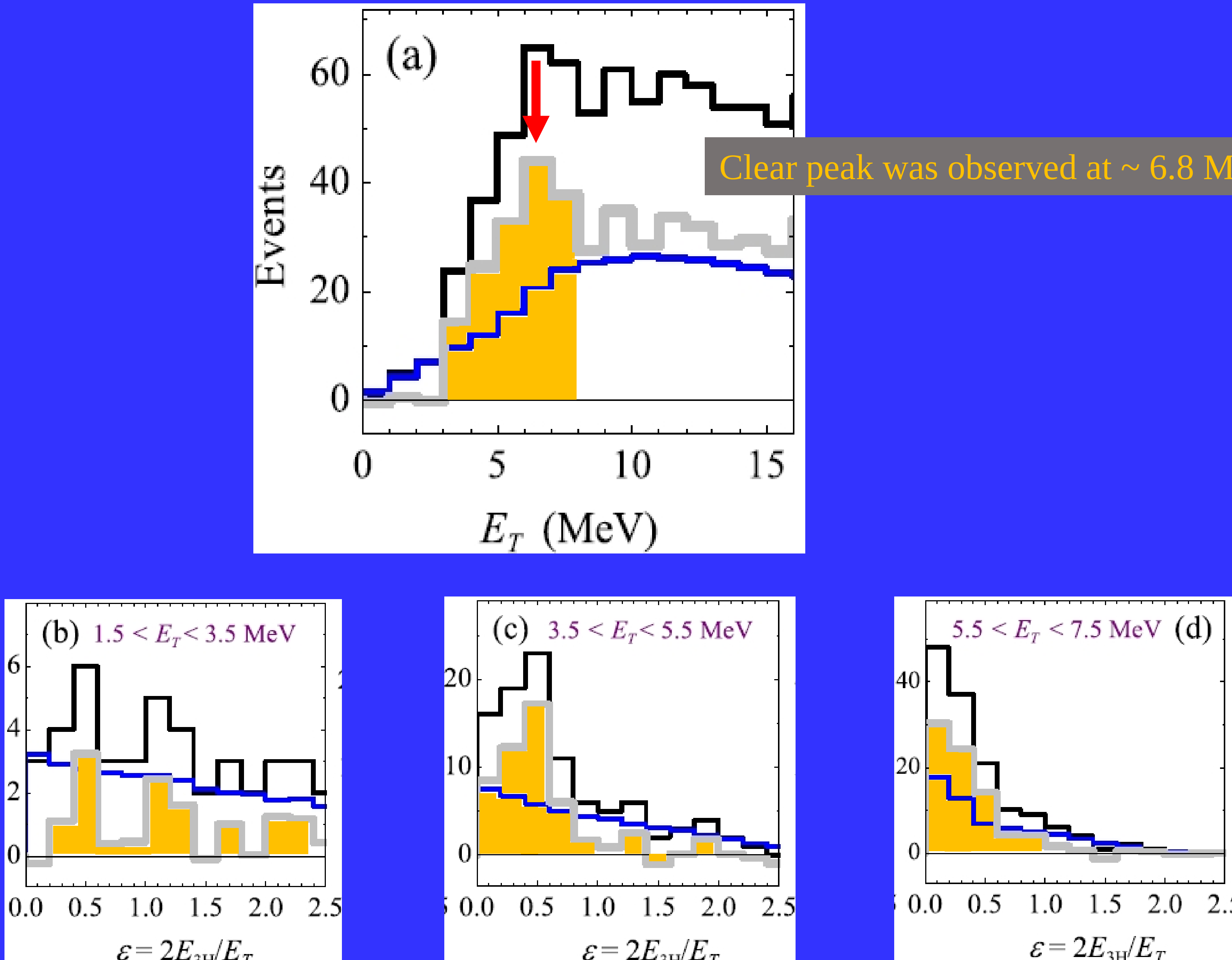
4. It is highly plausible that the firmly ascertained 5.5(3)-MeV state is the $5/2^{+}$ member of the ^{7}H excitation $5/2^{+}$–$3/2^{+}$ doublet, built on the 2^{+} configuration of valence neutrons. The supposed 7.5-MeV state can be another member of this doublet, which could not be resolved in 1st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

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



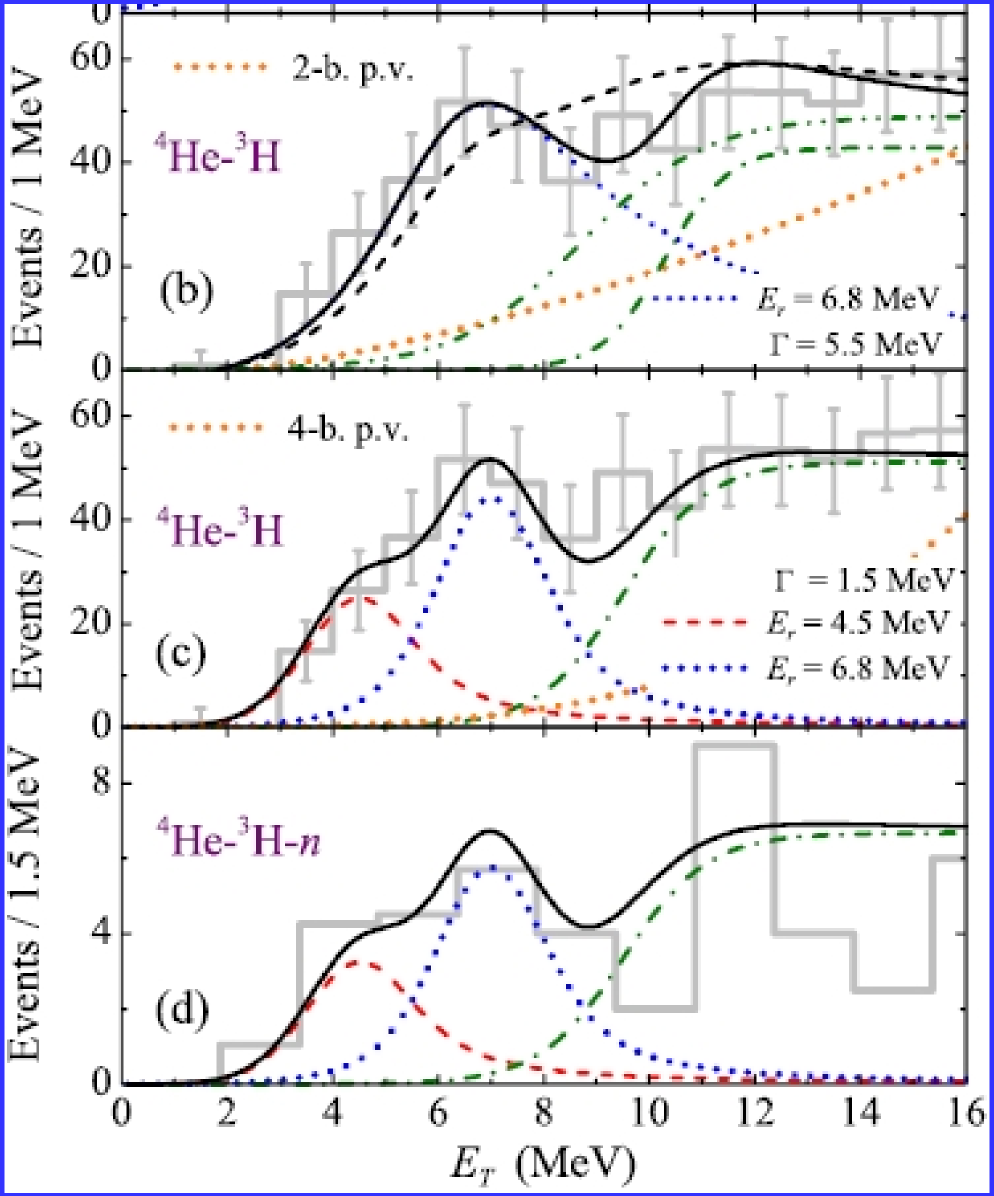
The ΔL = 1 cross section for the ^{2}H(^{8}He, ^{4}He)^{6}H reaction obtained in FRESCO calculations





Clear peak was observed at ~ 6.8 MeV !!

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



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

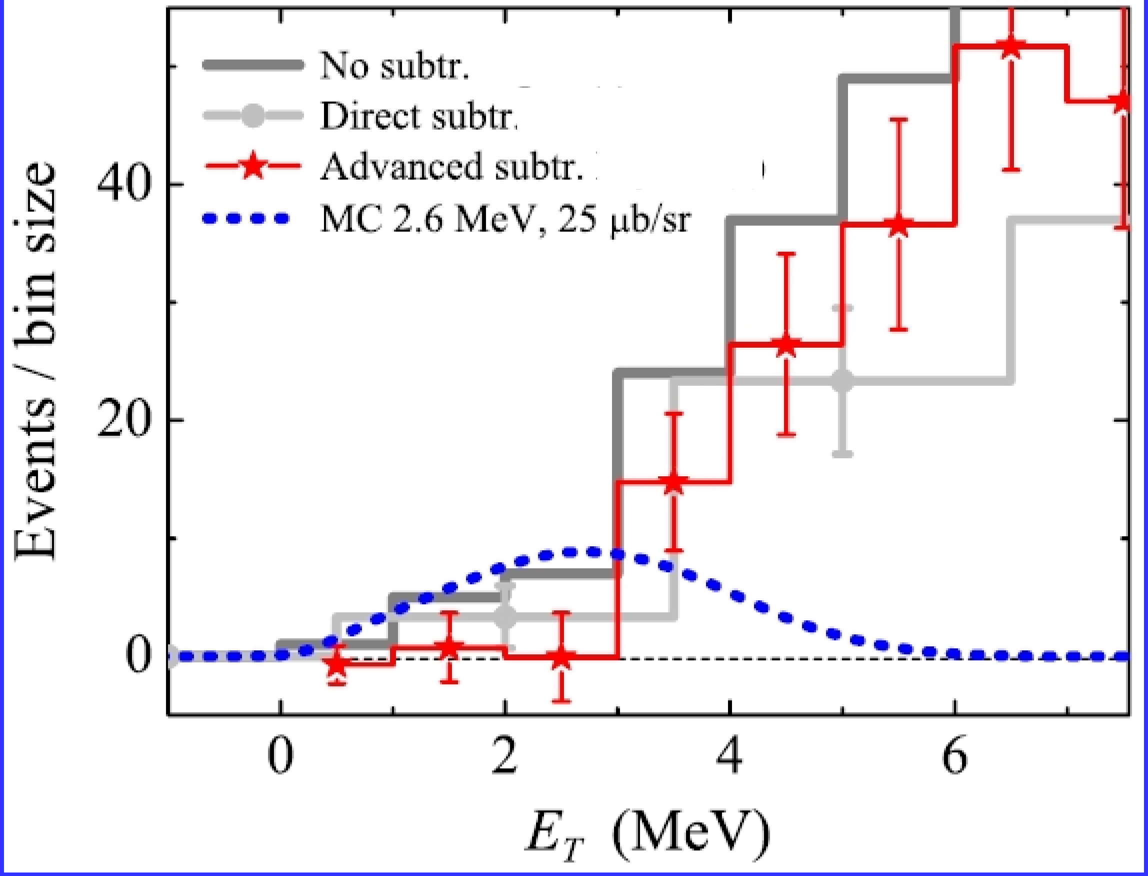
One state interpretation

Two states interpretation

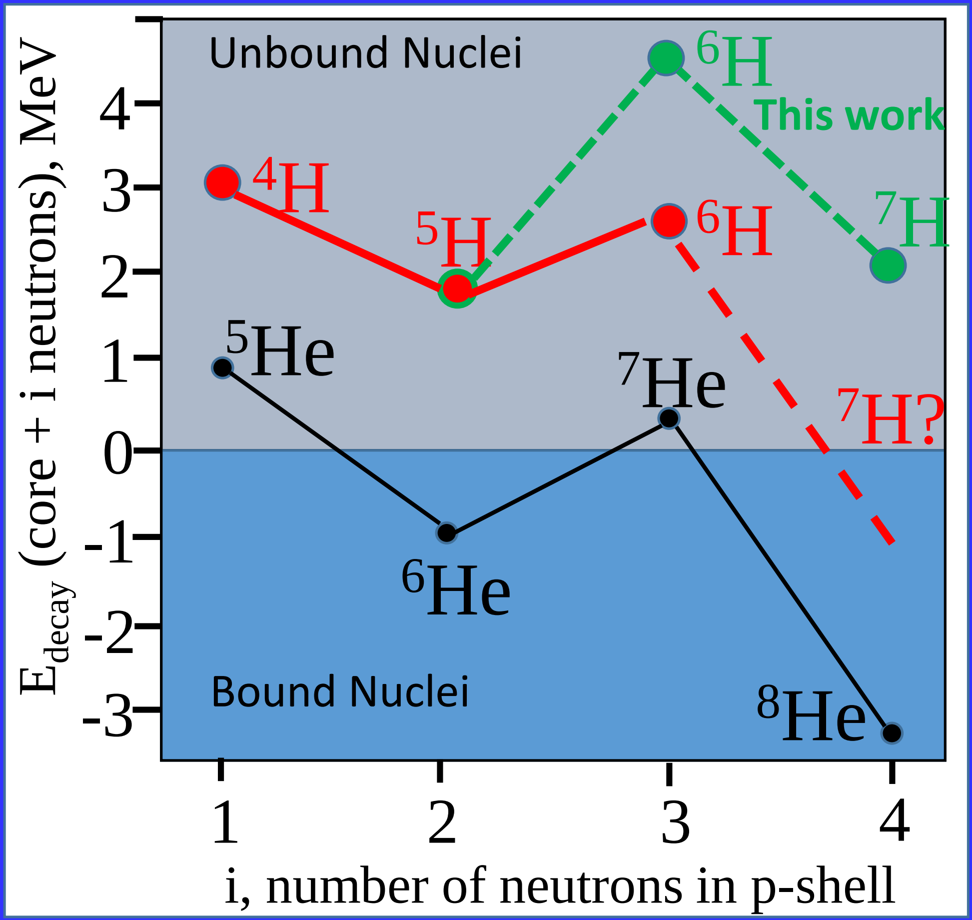
Two states interpretation with neutron coincidences

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 $5^0 < \Theta_{CM} < 16^0$

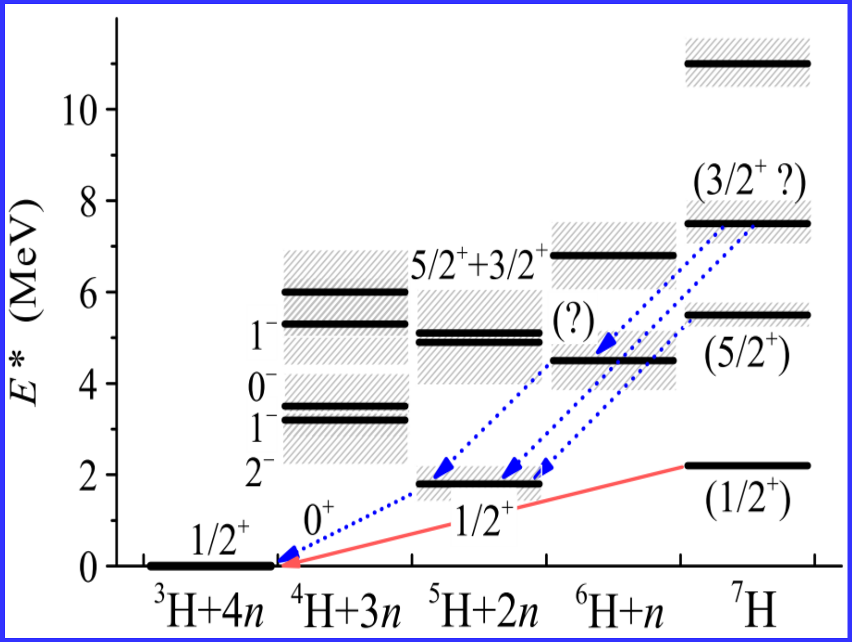


Hydrogen and helium chains: today status

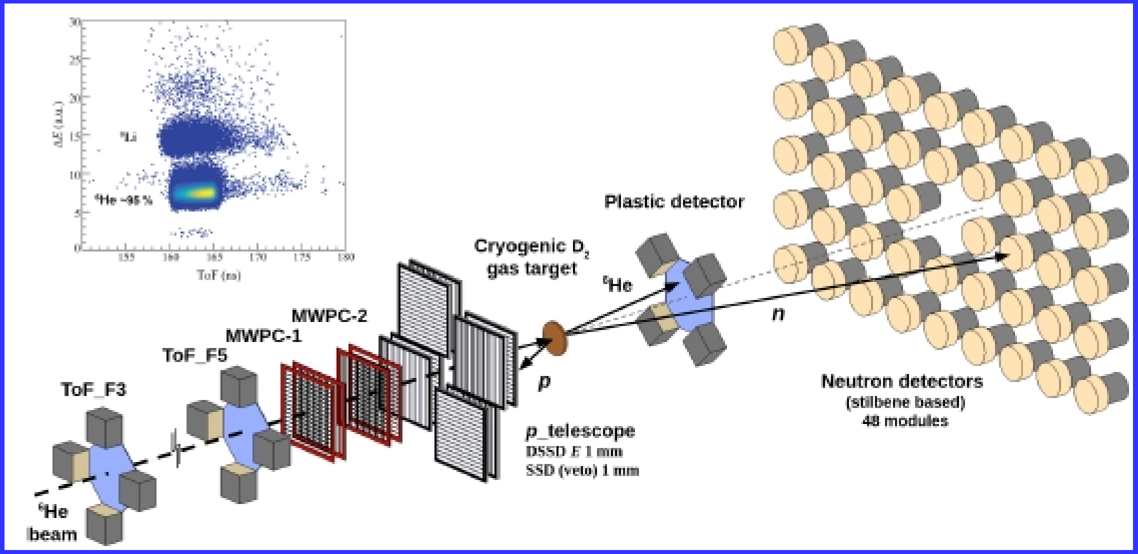


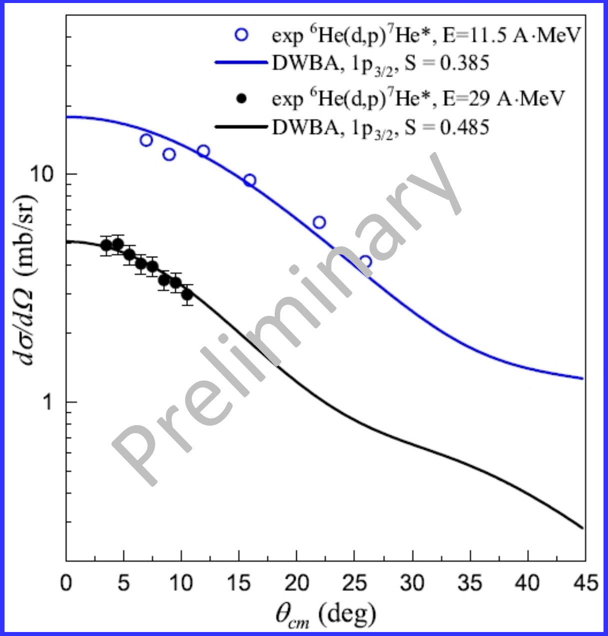
* New level schemes for chain ^{4}H ÷ ^{7}H

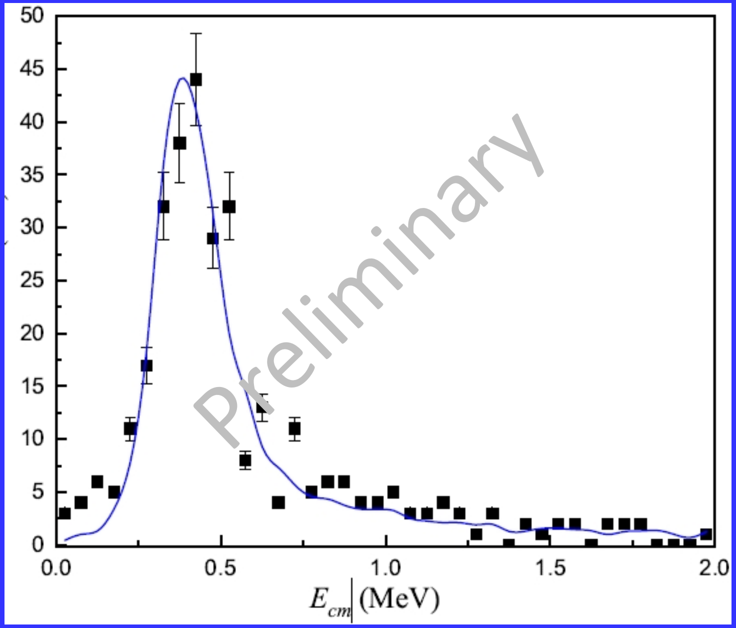
** The unique true *4n*-decay mechanism is proved to be realized for ^{7}H. *This is the first such case found in the nuclide map.*



^{7}He spectrum studied by the ^{6}He(d,p)^{7}He reaction



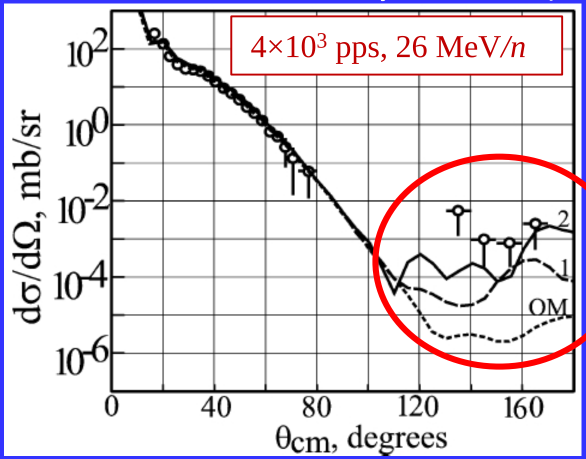




Going ahead…

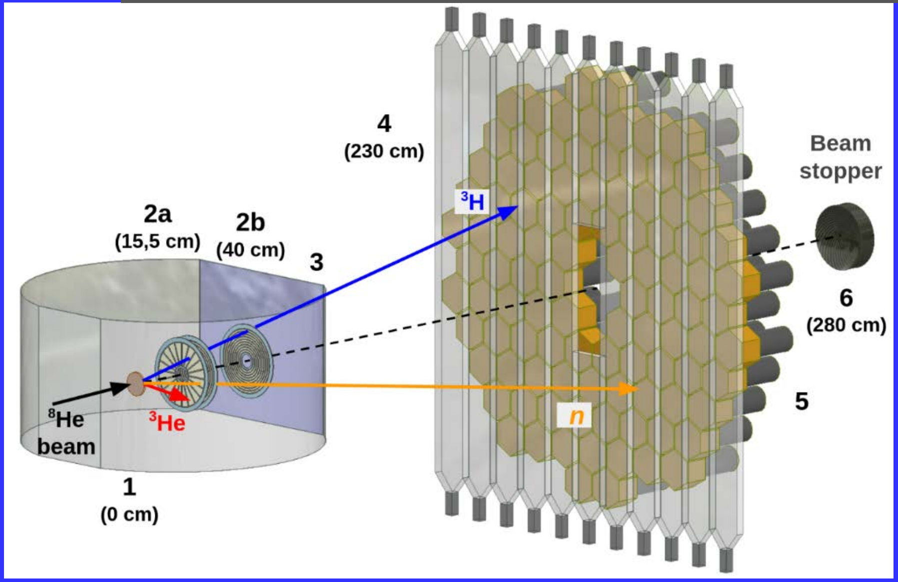
Search for 4n transfer in the ^{8}He+^{4}He scattering

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



~ 5 counts per 10 days are expected for the ^{8}He+^{4}He elastic scattering at $d\sigma/d\Omega = 10^{-5}$ mb/sr in the θcm range 150° – 175°

Isobar-analogue states in ^{5}H and ^{5}He in the ^{6}He+d collisions



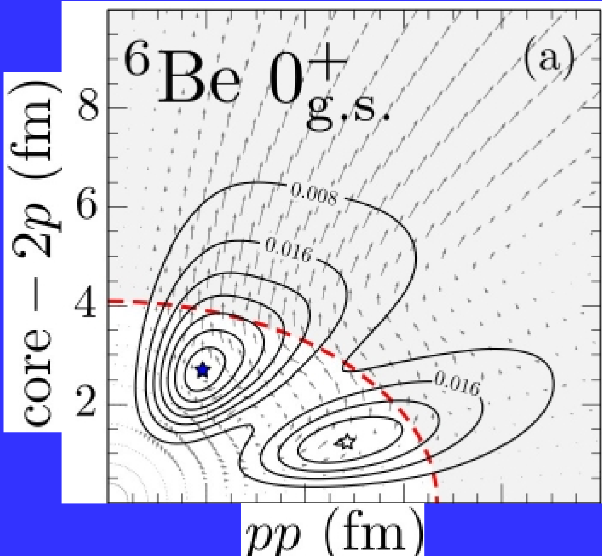
Invariant mass measurements
D_2 target 1×10^{21} cm^{-2}
85 counts per 10 days for ^{3}He+t+2n events
FWHM resolution of ~ 400 keV

Going ahead… (2)

Light proton-rich nuclei ^{6}Be, ^{7}B, ^{8}C studied by the (p,d) reaction

^{6}Be states	E_T (MeV)	Γ (MeV)	
0_1^+	1.383 (1.370)	0.041 (0.092)	
0_2^+	5.95	11.21	
1^+	4.76	7.75	*Exp.*
2_1^+	2.90 (3.04)	1.05 (1.16)	
2_2^+	4.63	5.67	

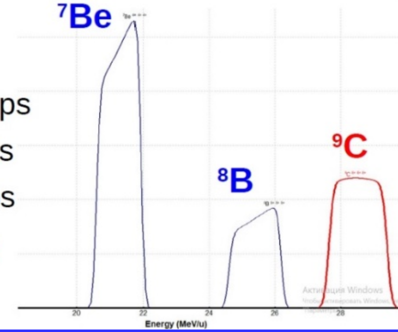
Myo and K. Kato, Phys. Rev. C **107** (2023) 014301.



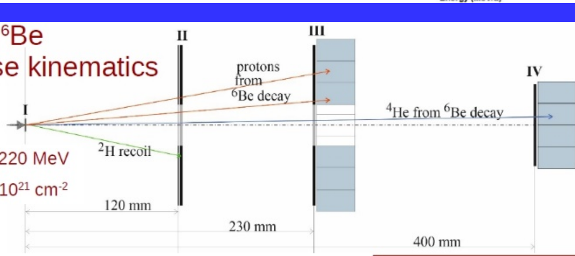
S. M. Wang et al., PRC ***99****, 054302 (20*

Tuning ACCULINNA-2 for ^{7}Be, ^{8}B, ^{9}C beams

- primary beam of ^{12}C, 50 MeV/A, 2 pμA:
  - ^{7}Be, ~27 MeV/A, 1.1e5 pps
  - ^{8}B, ~32 MeV/A, 4.4e4 pps
  - ^{9}C, ~36 MeV/A, 6.8e4 pps
- All component available in one beam mixture



^{7}Be(p,d)^{6}Be in inverse kinematics



E(^{7}Be)~180-220 MeV

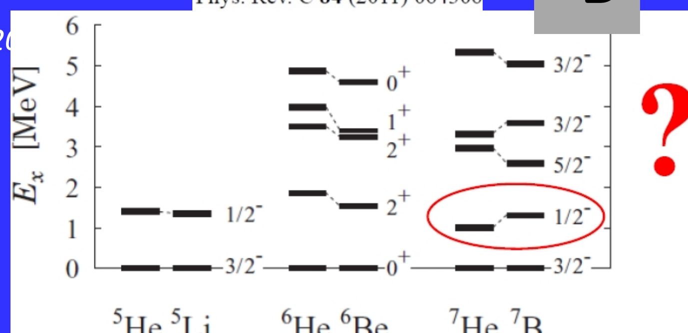
^{1}H target: 2x10^{21} cm^{-2}

- missing mass
- combined mass

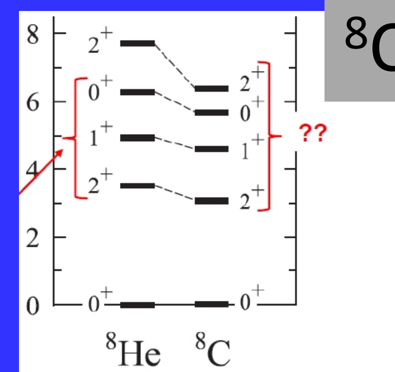
- ΔE~0.16 MeV
- L~6x10^{26} cm^{-2}s^{-1} ~6000 events/d

T. Myo, Y. Kikichi and K. Kato, Phys. Rev. C **84** (2011) 064306

^{7}B



^{8}C



Myo, Odsuren, and Kato, Phys. Rev. C 104, 044306 (2021)

Summary

1. Effective methods for the study of light exotic nuclear systems near and beyond nucleon drip-line were developed in experiments at the ACCULINNA fragment separator, JINR FLNR.
New important results on the structure and level scheme of exotic nuclei as ^{6}He, ^{5}H, ^{9}He, ^{10}He were obtained. These techniques are based on intense radioactive beams (^{6}He, ^{8}He, ^{3}H), unique targets (including tritium) and correlation methods especially efficient for direct reactions studies at intermediate energies.

2. In two experiments at newly commissioned fragment separator ACCULINNA-2 a solid experimental evidence for two resonant states of ^{7}H are located at 2.2(5) and 5.5(3) MeV relative to the ^{3}H+4n decay threshold is provided. There are indications that the resonant states at 7.5(3) and 11.0(3) MeV. 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 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

3. 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 Γ ~ 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.

4. No *evidence* for the ≈2.6–2.9 MeV state in ^{6}H was found, 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.

5. After U400M cyclotron modernization, the future planes of the possible experiments are discussed.
Most likely that could be study of ^{8}He+^{4}He scattering, the detailed spectroscopy of ^{5}H-^{5}He, the further research of ^{6}Be nucleus and search for isobar-analogue states in proton-rich nuclei ^{7}B and ^{8}C.

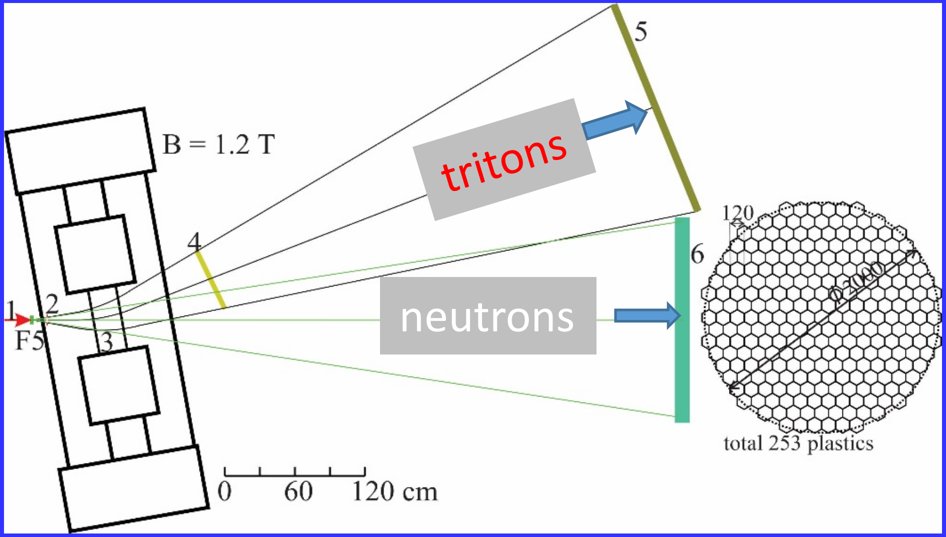
A. S. Fomichev, I. A. Muzalevskii , A. A. Bezbakh, E. Yu. Nikolskii, V. Chudoba, S. A. Krupko, S. G. Belogurov, D. Biare, E. M. Gazeeva, M.S. Golovkov, A. V. Gorshkov, L. V. Grigorenko, G. Kaminski, , D. A. Kostyleva, M. Yu. Kozlov, B. Mauyey, Yu. L. Parfenova, W. Piatek, A. M. Quynh, V. N. Schetinin, A. Serikov, S. I. Sidorchuk, P. G. Sharov, R. S. Slepnev, S. V. Stepantsov, A. Swiercz, P. Szymkiewicz, G. M. Ter-Akopian, R. Wolski, B. Zalewski

ACCULINNA-2 team

Thank you for your attention!

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

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

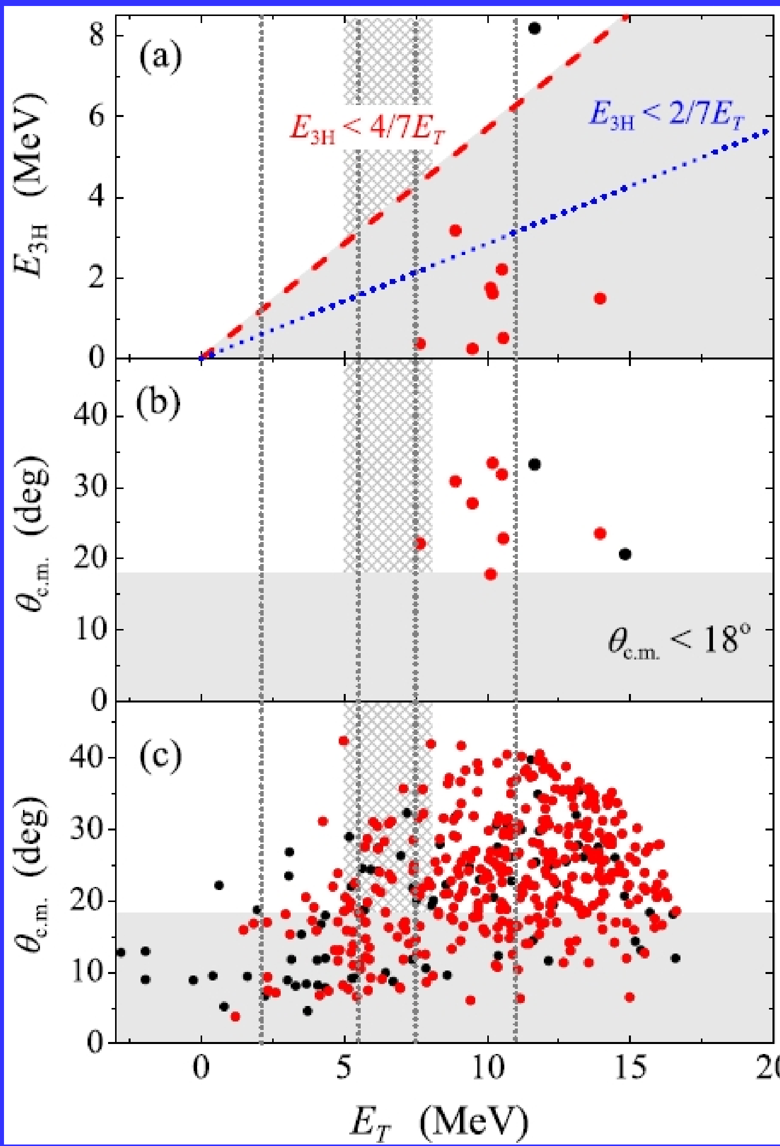


Ground-state energy resolution ~400 keV
Liquid T_2 ~$3*10^{21}$ cm^{-2}
Intensity of ^8He ~10^5 1/s
Reaction cross section ~0.1 mb/sr
Triton trigger eff. ~0.7
***t+4n* detection eff. ~0.015**
$^7H_{g.s.}$ counting rate: ~5 per day

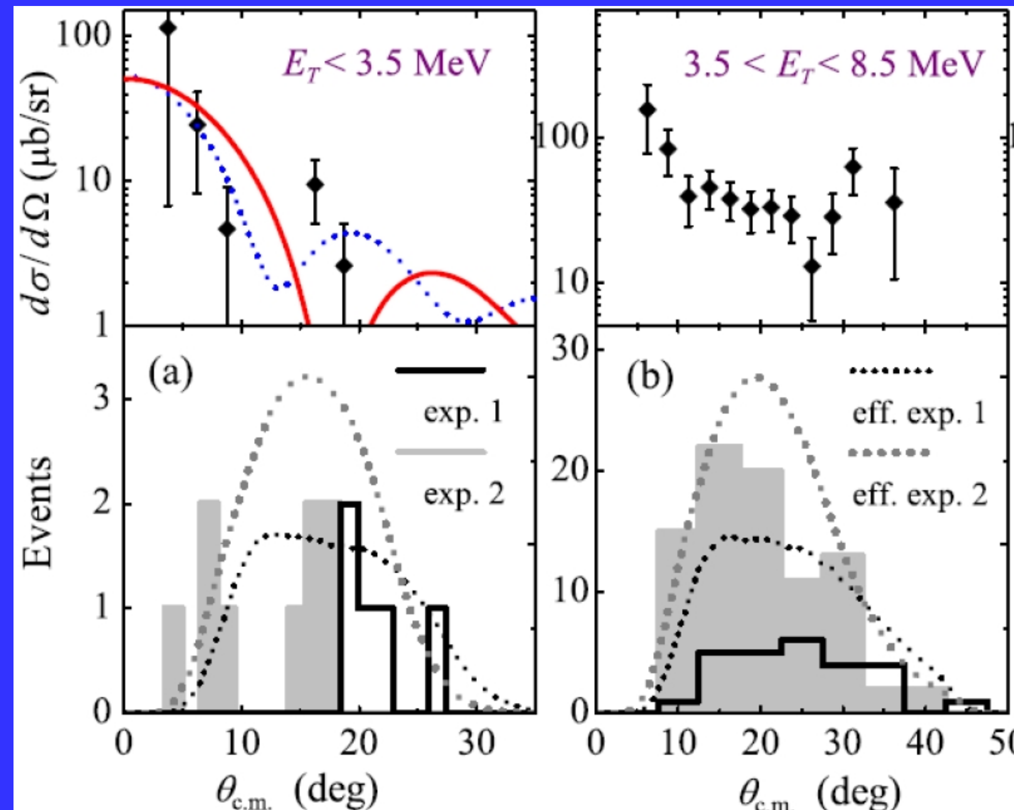
2. $p(^{11}Li,p^4He)^7H$ ^{11}Li – new "source" to make ^7H

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

Empty target from the 2nd Run

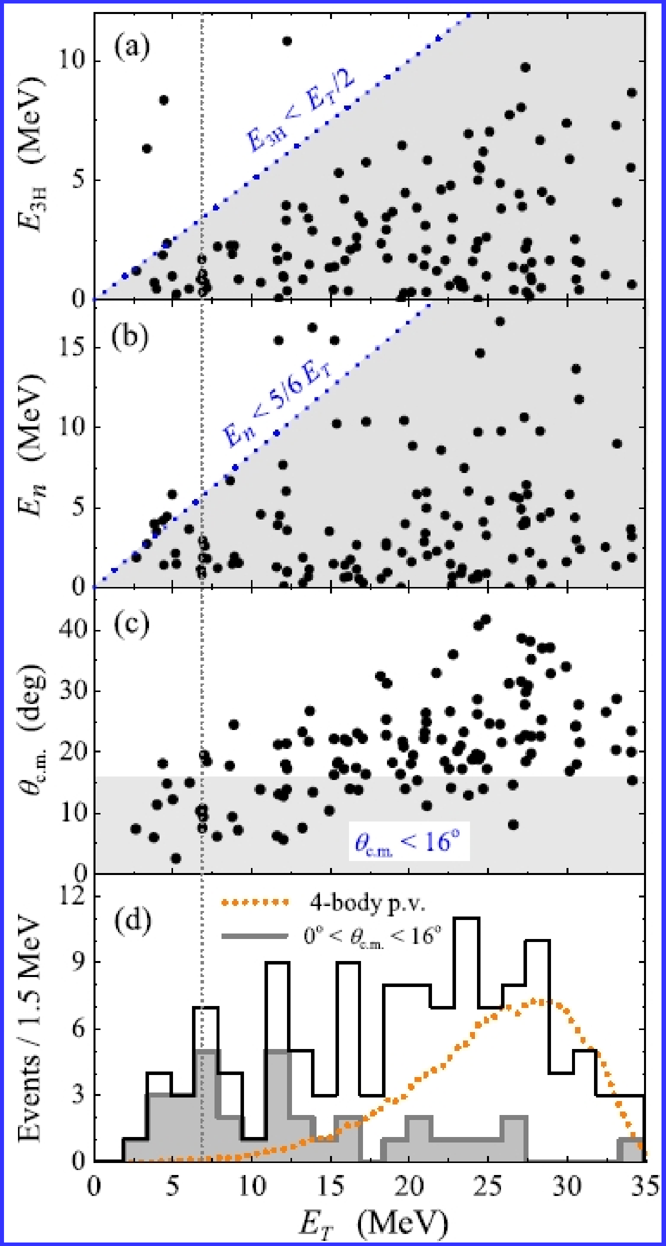


The c.m. angular distributions for the 2H(8He, 3He)7H reaction in different 7H MM energy ranges

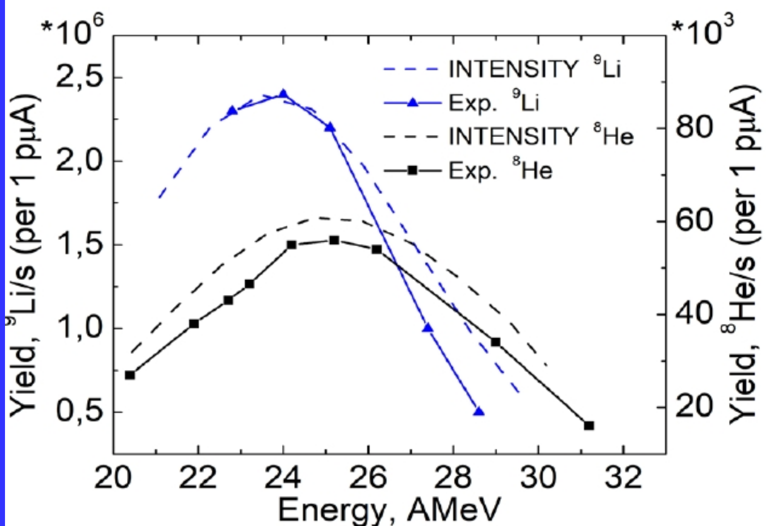


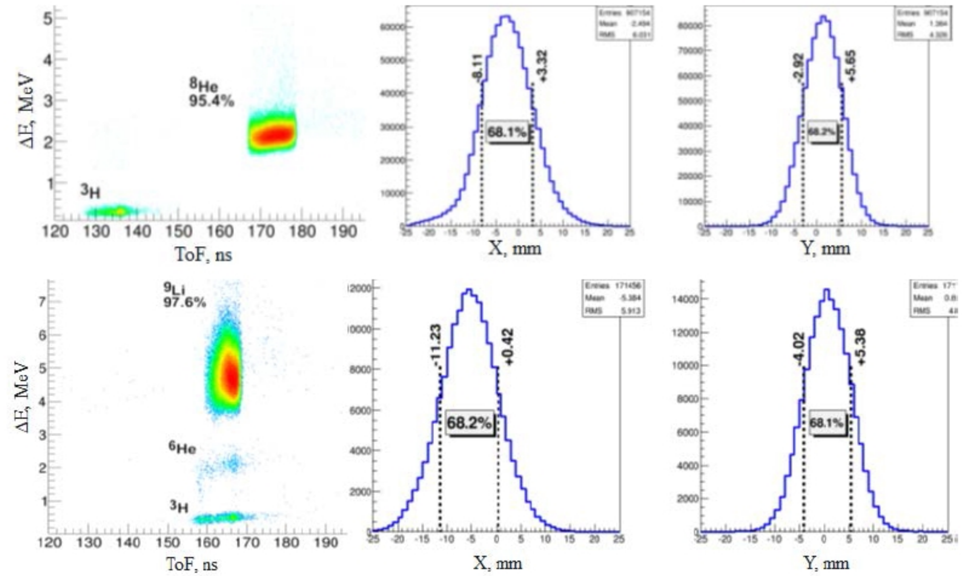
red – FRESCO calculations with standard parameters;
blue – assuming the extreme peripheral transfer → low cross section for the ^{7}H_g.s.

4He+t+n coincidences



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

ACCULINNA-2 Parameters:

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

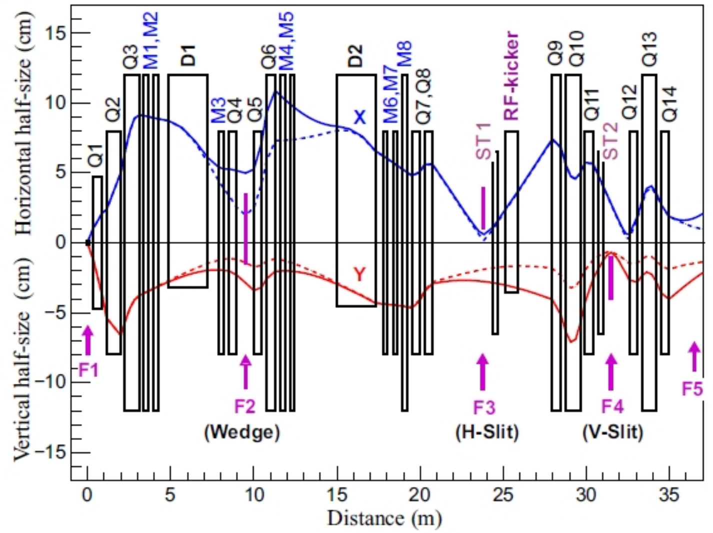


Fig. 4. Envelopes of the beam in horizontal (X) and vertical (Y) planes. F1 object slit is $2 \times 2\,\mathrm{mm}^2$, capture angles are ± 30 and ± 35 mrad in X and Y planes, respectively. Solid lines are for $\delta_P = \pm 2.5\%$ and dashed ones for $\delta_P = \pm 1.0\%$.

Table 3. Main ion-optical parameters of ACCULINNA-2.

Primary beam spot size	F1	2×2	mm^2
Momentum acceptance		6.0	%
θ_{0x} angular acceptance		60	mrad
θ_{0y} angular acceptance		70	mrad
X momentum dispersion	F1 $\rightarrow$ F2	2.0	cm/%$B\rho$
θ_x angul. mom. disper.	–	0.5	mrad/%$B\rho$
X magnification	–	-1.0	
Y magnification	–	-7.4	
X momentum dispersion	F2 $\rightarrow$ F3	3.3	cm/%$B\rho$
X magnification	–	-1.7	
Y magnification	–	-2.0	
X magnification	F1 $\rightarrow$ F3	1.7	
Y magnification	–	5.0	
Length	F1 $\rightarrow$ F2	9.51	m
Length	F2 $\rightarrow$ F3	14.35	m
Length	F3 $\rightarrow$ F4	7.63	m
Length	F3 $\rightarrow$ F5	13.25	m
Length	F1 $\rightarrow$ F5	37.1	m

Table 4. Ion-optical parameters of ACCULINNA-2 magnetic dipoles $D1$, $D2$ and steering (correcting) magnets $ST1$, $ST2$.

Value		Units	$D1$	$D2$	$ST1$, $ST2$
Bending direction			horizontal	horizontal	vertical
Type			sector	sector	rectangular
Gap height	$2h$	cm	6.4	9.0	11.2
Bending mean radius	R	m	3.0	3.0	–
Bending field	B_{nom}	T	1.3	1.3	0.053
Length	L_{eff}	m	2.356	2.356	0.283
Working width	$2w$	cm	20	20	10
Bending angle	Φ	dgr	45	45	–
Entrance angle	τ_{entr}	dgr	0	0	0
Exit angle	τ_{exit}	dgr	0	20	0

Table 5. Ion-optical parameters of ACCULINNA-2 magnetic quadrupoles.

Value		units	$Q1$	$Q2$	$Q3$, 10, 13	$Q4$, 5, 7, 8, 11, 12, 14	$Q6$, 9
Aperture	$2r$	cm	9.4	16	24	16	24
Length	L_{eff}	cm	54.3	87.1	85.9	47.6	51.8
Field gradient	G_{nom}	T/m	9.2	7.2	7.2	9.8	6.4

Table 6. Ion-optical parameters of magnetic multipoles. They all have an effective length $L_{\mathrm{eff}} = 28.6\,\mathrm{cm}$.

Multipole	Aperture	Sextupole	Octupole
	$2r$, cm	B''_{nom}, T/m^2	B'''_{nom}, T/m^3
$M1$, $M2$, $M4$, $M5$, $M8$	24	3.9	195
$M3$, $M6$, $M7$	16	39	

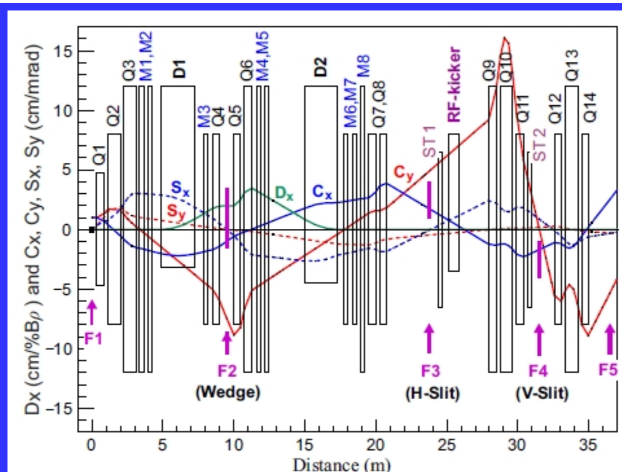


Fig. 6. Momentum dispersion $D_x = (x/\delta_P)$ and main first-order cosine-like, $C_x = (x/x_0)$, $C_y = (y/y_0)$ and sine-like $S_x = (x/\theta_{0x})$, $S_y = (y/\theta_{0y})$ trajectories.

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

The ID plot for neutron spectrometer