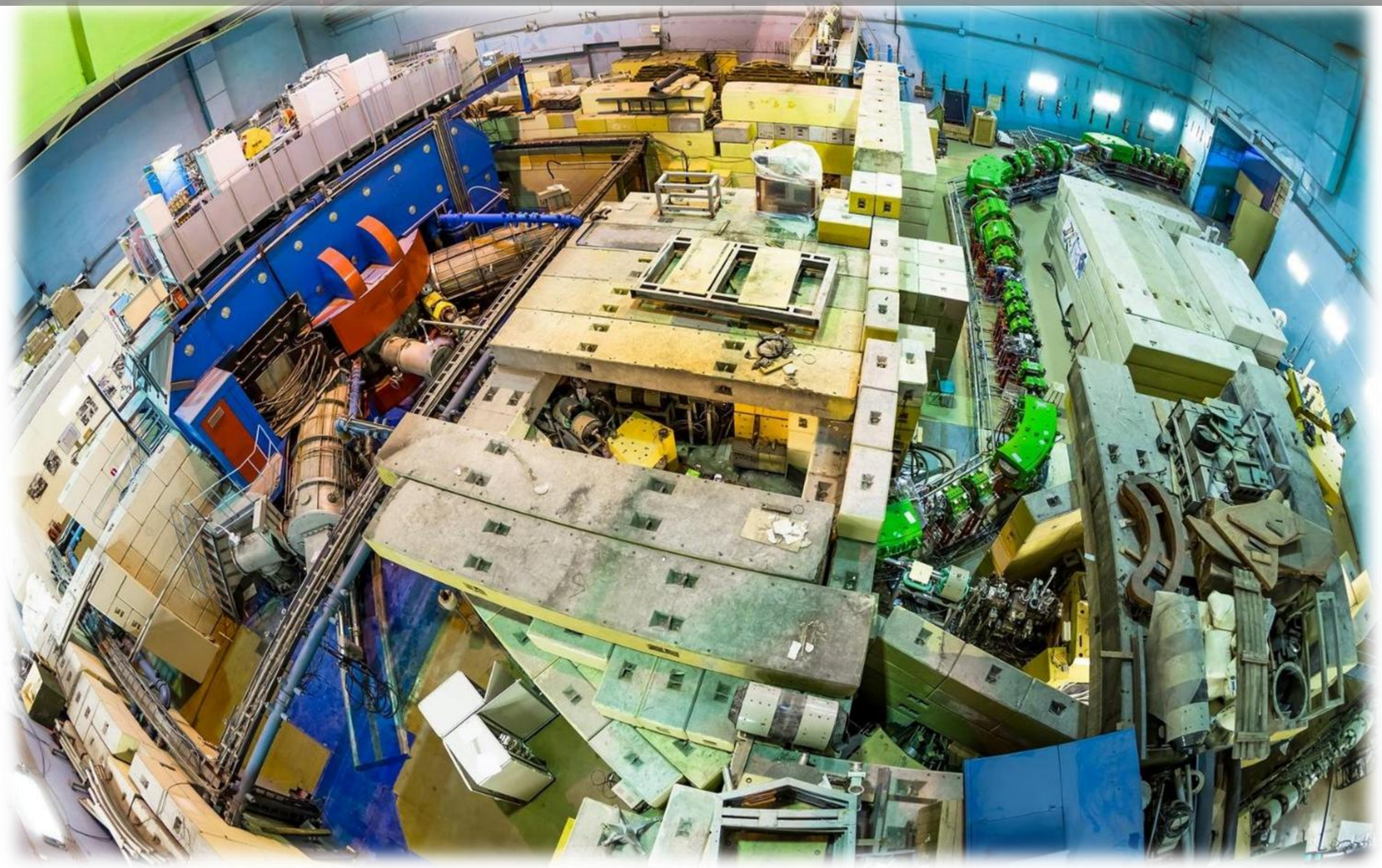
Joint Institute for Nuclear Research
SCIENCE BRINGING NATIONS TOGETHER

JINR
114 Flerovium
FLNR
Dubna

Grzegorz Kaminski
Flerov Laboratory of Nuclear Reactions
JINR, Dubna

New possibilities for JINR – IMP collaboration in nuclear physics research



- One year collaboration
- FLNR setups
- ACCULINNA-2
- Recent results
- Nearest research plans
- Detectors&systems

Institute of Modern Physics CAS, 3rd of September 2025, Huizhou

Research program

Heavy and Superheavy elements

experimental research on synthesis and physical and chemical properties of new superheavy elements

Nuclear reaction studies

experimental research on fusion and fission reactions and multinucleon transfer in heavy ion collisions

Study of exotic nuclei

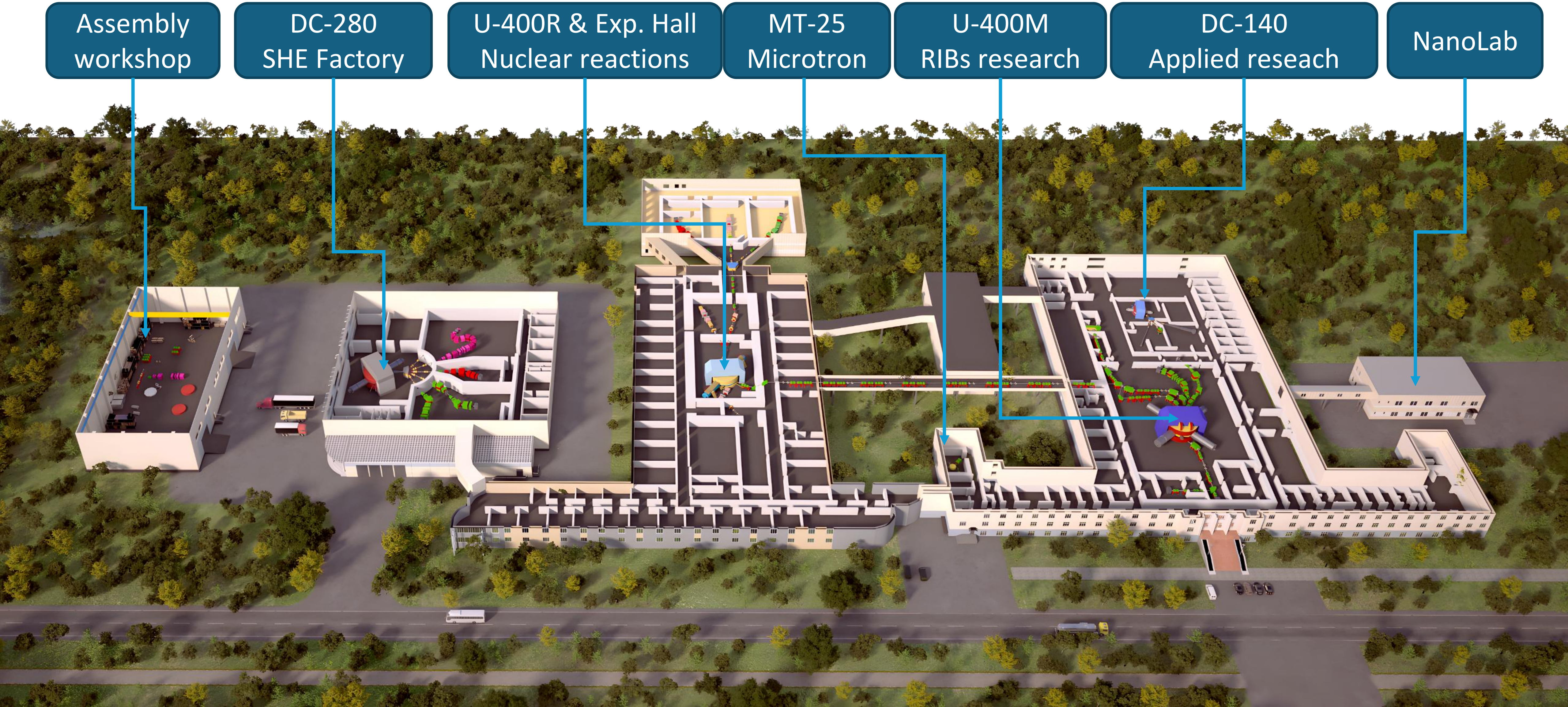
studies of the properties of nuclei on the borders of nucleon stability limits and mechanisms of nuclear reactions with accelerated radioactive nuclei

Applied research

studies of interactions of heavy ions with various materials (polymers, semiconductors, electronic components of space equipment, etc.) and physical groundwork of nanotechnology

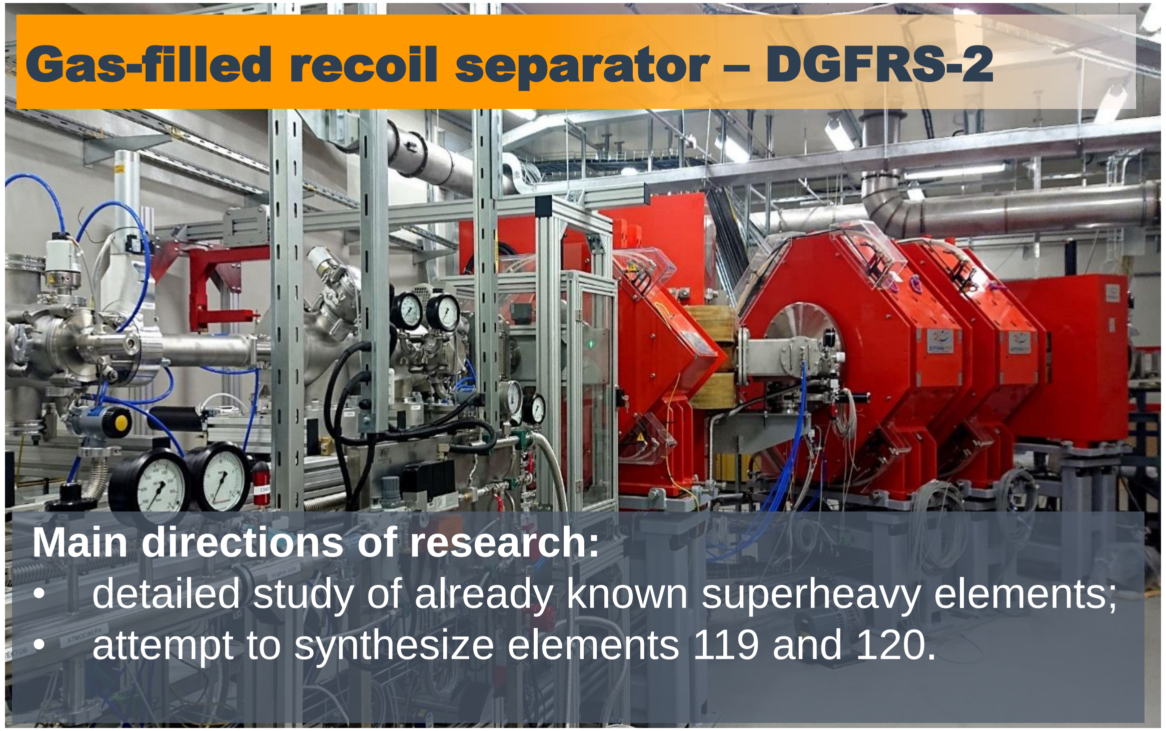
Accelerator technologies

DRIBS-III ACCELERATOR COMPLEX



MAIN SET-UPs OF FLNR

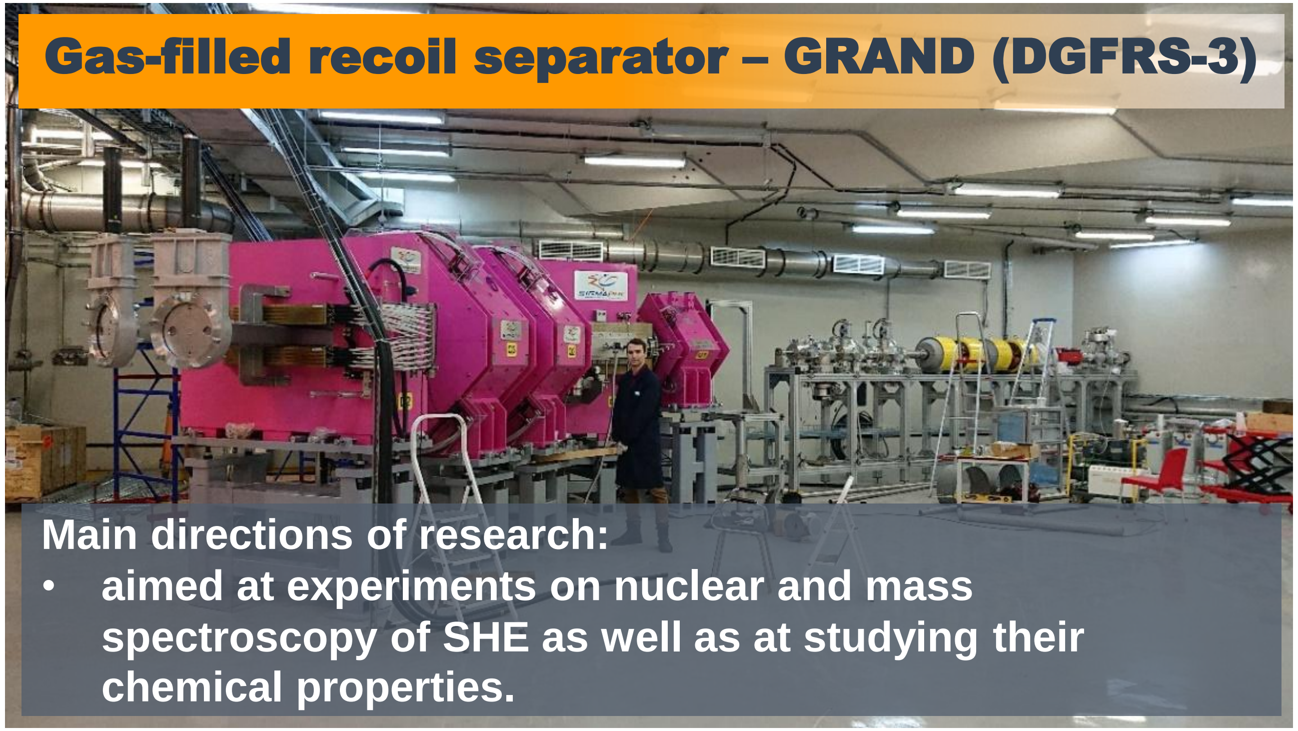
Gas-filled recoil separator – DGFRS-2



Main directions of research:

- detailed study of already known superheavy elements;
- attempt to synthesize elements 119 and 120.

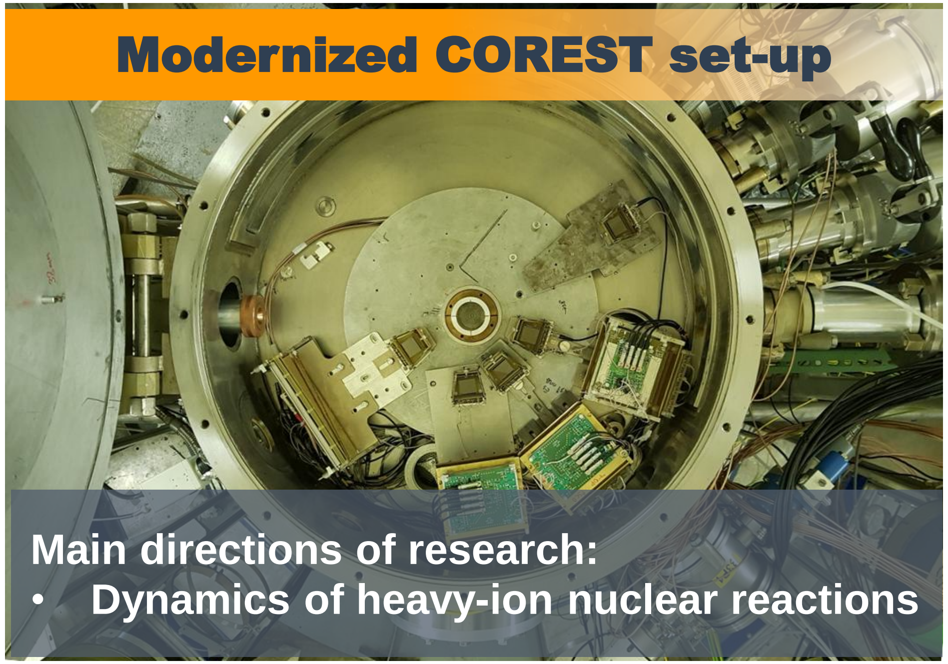
Gas-filled recoil separator – GRAND (DGFRS-3)



Main directions of research:

- aimed at experiments on nuclear and mass spectroscopy of SHE as well as at studying their chemical properties.

Modernized COREST set-up



Main directions of research:

- Dynamics of heavy-ion nuclear reactions

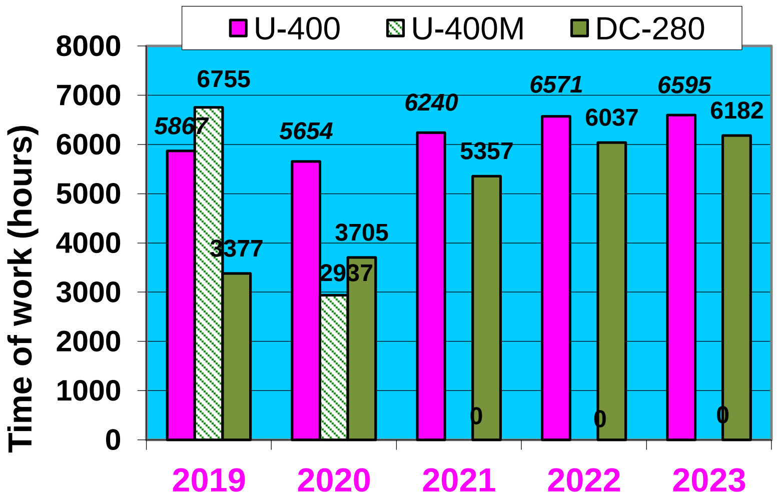
RIB's at the U400M cyclotron (Under modernization. Scheduled to be back in operation in 2024)

Main directions of research:

- Study of the structure of exotic nuclei near and beyond the neutron drip-line in the direct reactions

FLNR Accelerator Complex
operation in 2023

FLNR accelerator complex operation (hours)	2018	2019	2020	2021	2022	**2023**
	16904	20110	15124	15065	16834	**16583**



Modernization of U-400M (since summer 2020):
First beams – end of spring 2024

Expected beam energies and intensities after modernization

Ion	2019		Expected	
	E (MeV/u)	I(pμA)	E (MeV/u)	I(pμA)
^{7}Li	35	5	39	10
^{11}B	30	3	33	6
^{15}N	47	0.5	51	2
^{18}O	36	0.5	40	1.5
^{22}Ne	45	0.3	50	1
^{36}S	40	0.12	44	0.2
^{48}Ca	34	-	38	0.1
$^{56}Fe^{15+}$	36	0.01	40	0.1

Energy increase ~10%

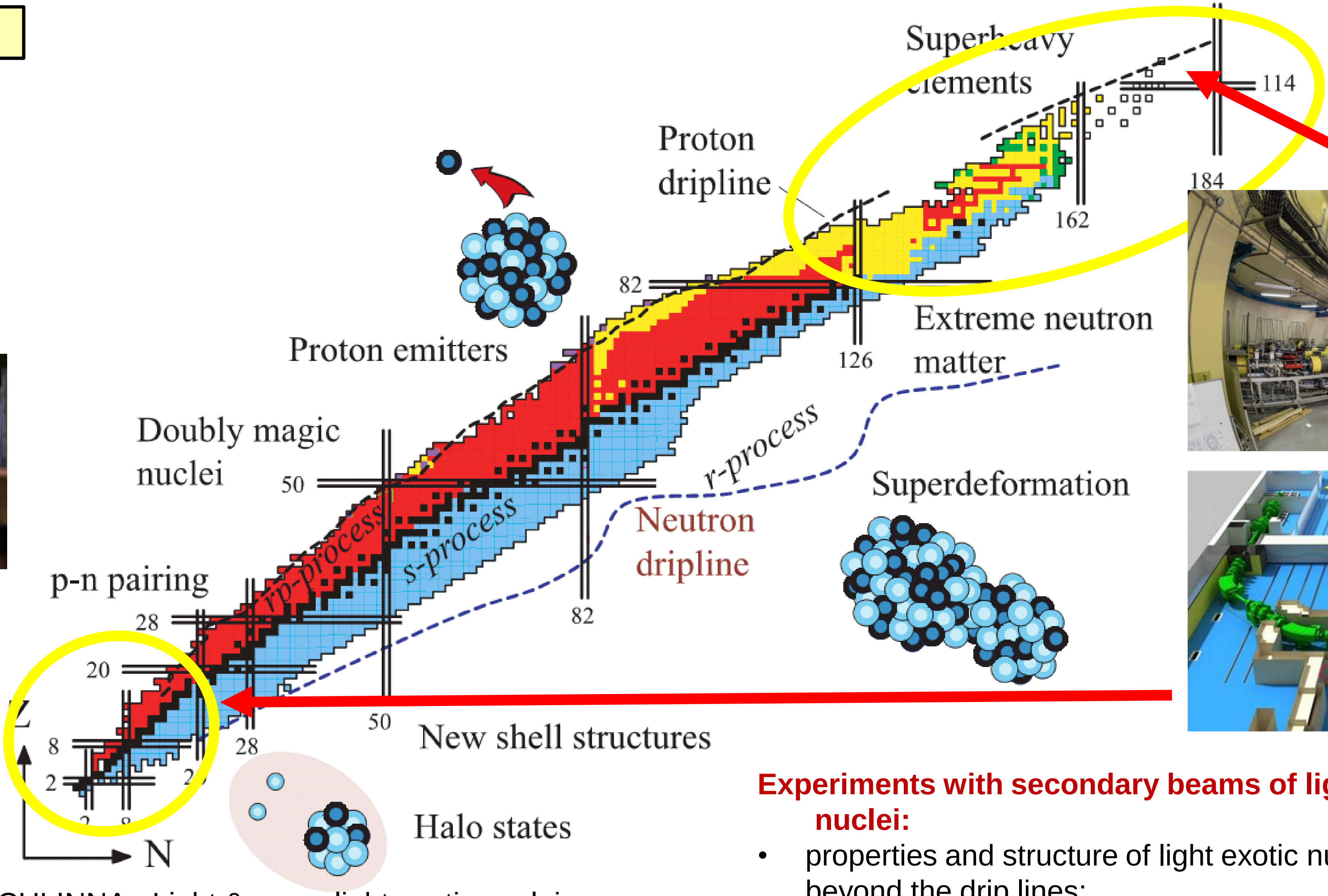
Intensity increase ~2÷10 times

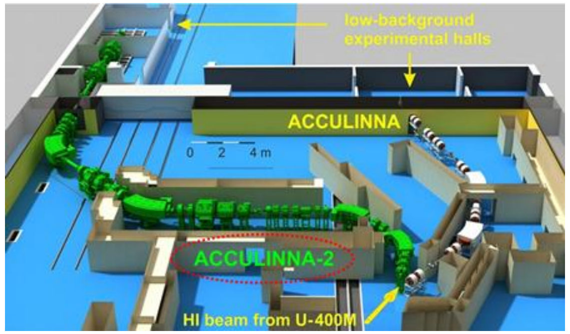
Main areas of interest at the FLNR at nuclide chart

SHE research status

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

Scientific leader of FLNR
Prof. Yu. Ts. Oganessian





ACCULINNA - Light & super light exotic nuclei,
neutron-rich hydrogen ($^{5,7}H$) and helium ($^{8,10}He$) isotopes)

Experiments with secondary beams of light radioactive nuclei:

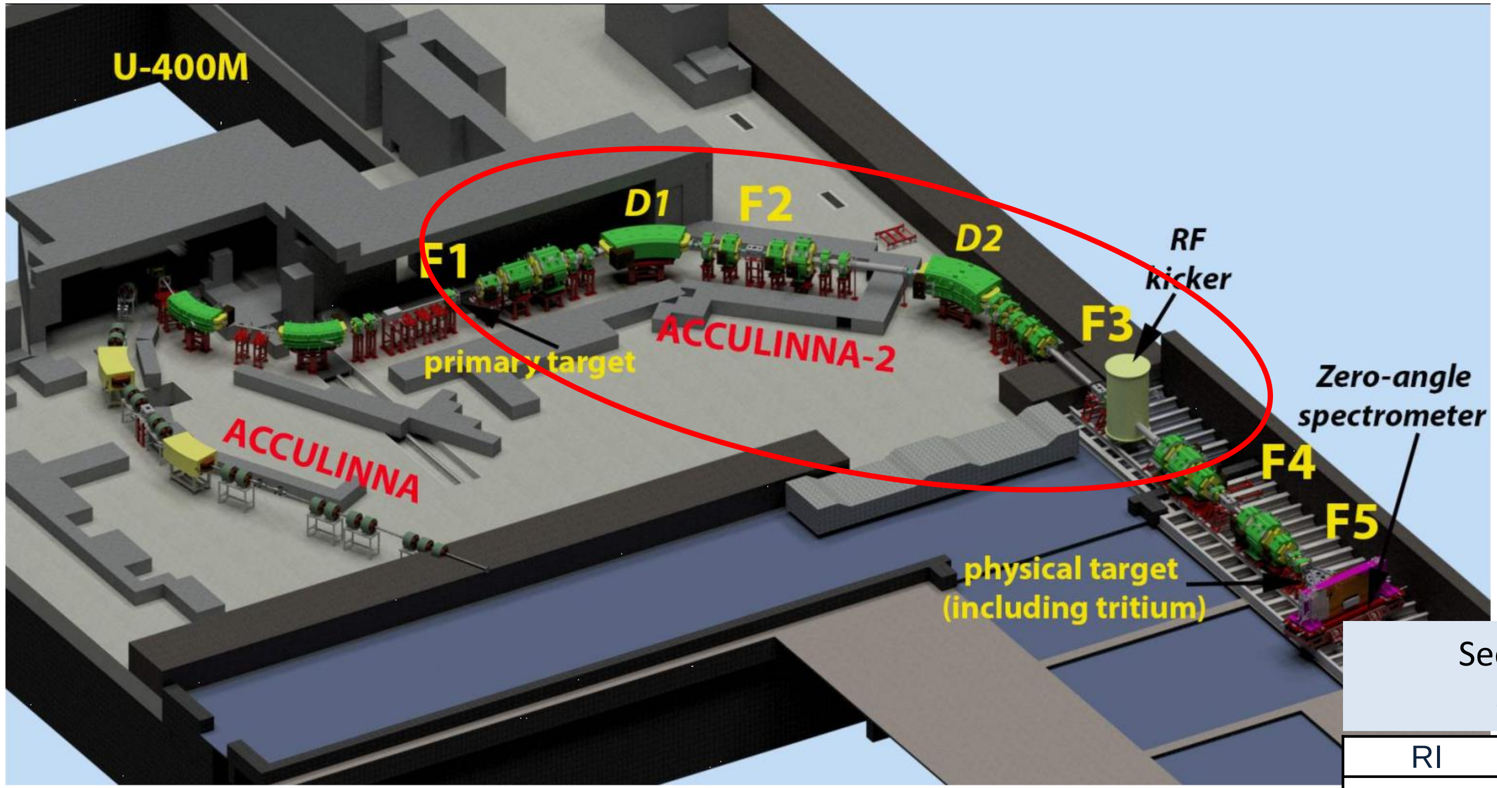
- properties and structure of light exotic nuclei near and beyond the drip lines;
- reactions with exotic nuclei.

Light exotic nuclei at the FLNR
basic facility: modernized U-400M + ACCULINNA-2

Experimental complex for study of light exotic nuclei at the U-400M cyclotron at FLNR

Historical dates:
1991 – commissioning of the U400M cyclotron
1997 – commissioning of the ACCULINNA-1 separator
2003 – upgrade of the ACCULINNA-1 separator

2017 – commissionning of the ACCULINNA-2 separator



		ACC	ACC-2
		FLNR,	JINR
$\Delta\Omega$	msr	0.9	4.2
δ_P	%	2.5	6.0
$P/\Delta P$	a.u.	1000	2000
$B\rho_{max}$	Tm	3.2	3.9
Length	m	21	37
$E_{\min}$	AMeV	10	5
$E_{\max}$	AMeV	40	50

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

Secondary ion beams at ACCULINNA-2

RI	2024	
	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

Expected experimental conditions in 2024

U400M: Improved beam quality, increased intensity, stable operation
ACC-2: intensive, high quality secondary beams
ACC-1: available for tests measurements, detectors testing, applied studies etc.

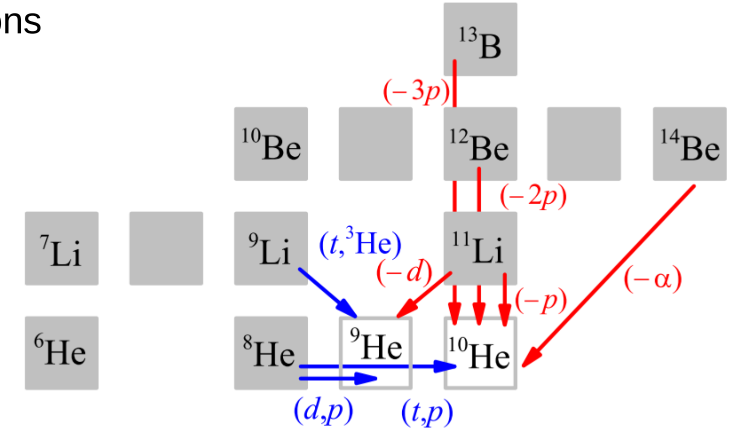
Competitive light nuclei RIB program at ACCULINNA

➢ Energy range and reaction selection

Intermediate energy reactions (20-70 MeV/nucleon)

Transfer reactions

Missing mass, invariant mass, combination



Importance of complementary reaction studies

High energy reactions (>70-100 MeV/nucleon)

Knockout reactions

Only invariant mass (exclusion (p,2p) reactions

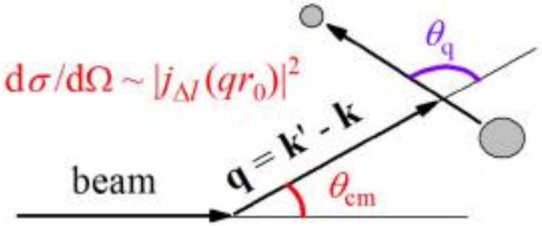
- **Complementary information from different reaction mechanism**
- **Lower reaction energy - easier to get higher energy resolution**

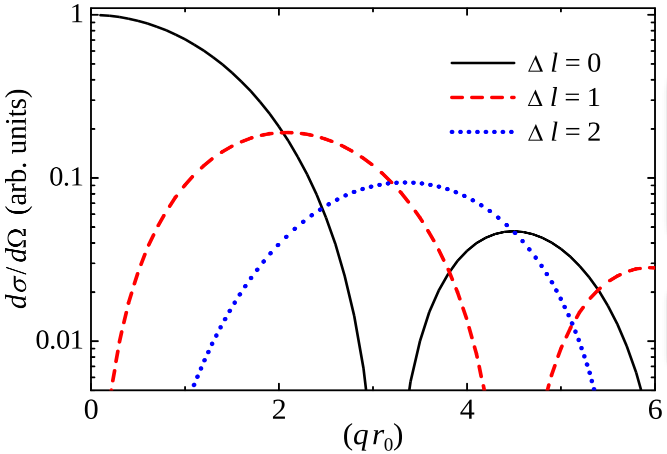
➢ CMS correlations of recoils or products

Correlations for aligned states populated in the direct reactions

- Few-body dynamics near the driplines
- Correlations in the three-body decays: two extra degrees of freedom

For fixed energy of the product transferred momentum q and cms angle are trivially connected





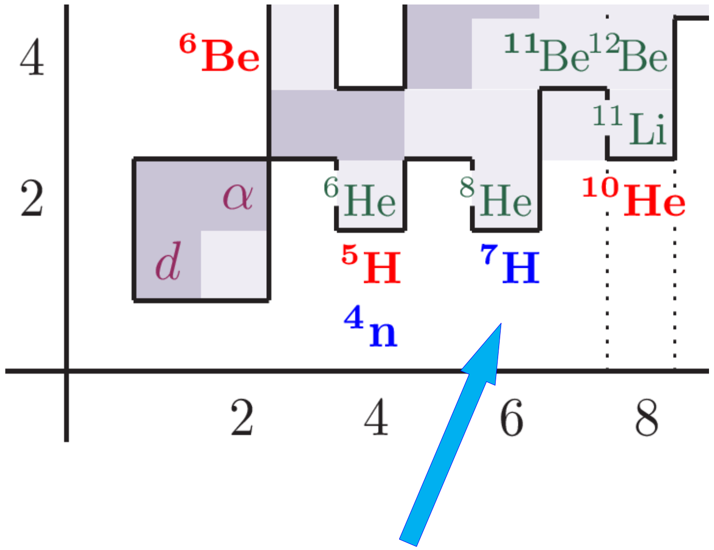
Simple systematics of diffraction minima and maxima as function of the momentum transfer

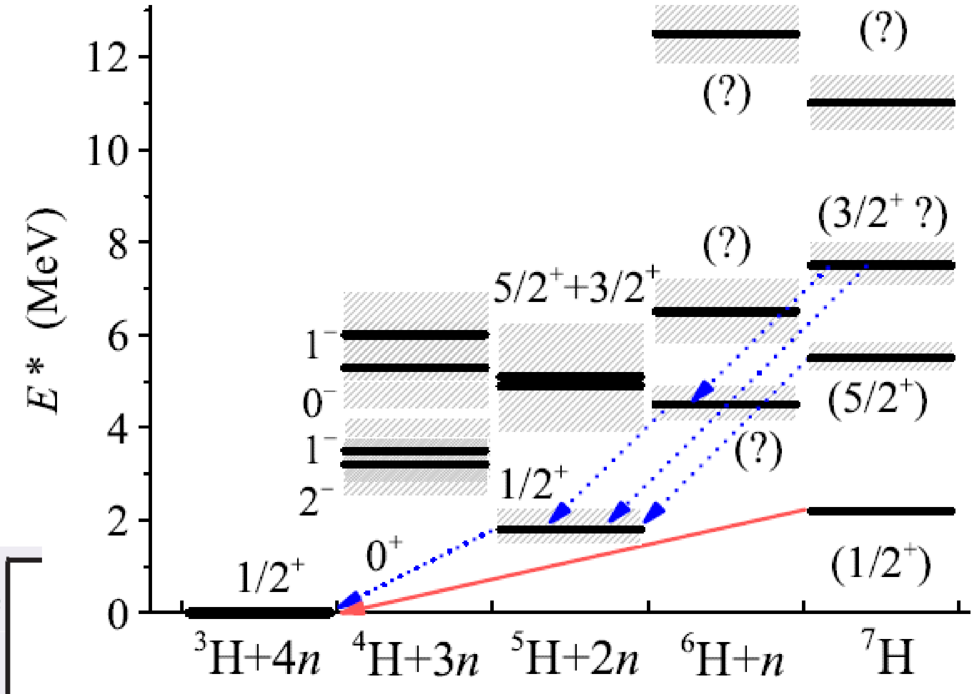
Opportunity of spin-parity identification

Flag ship experiments - ^{6}H and ^{7}H

object of interest: ^{7}H

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





^{7}H level scheme and the decay mechanism of the ground state via true 4n emission (red arrow) and the first excited states as the sequential 2n+2n emission or n+2n via the ^{5}H and ^{6}H states, respectively (blue arrows).

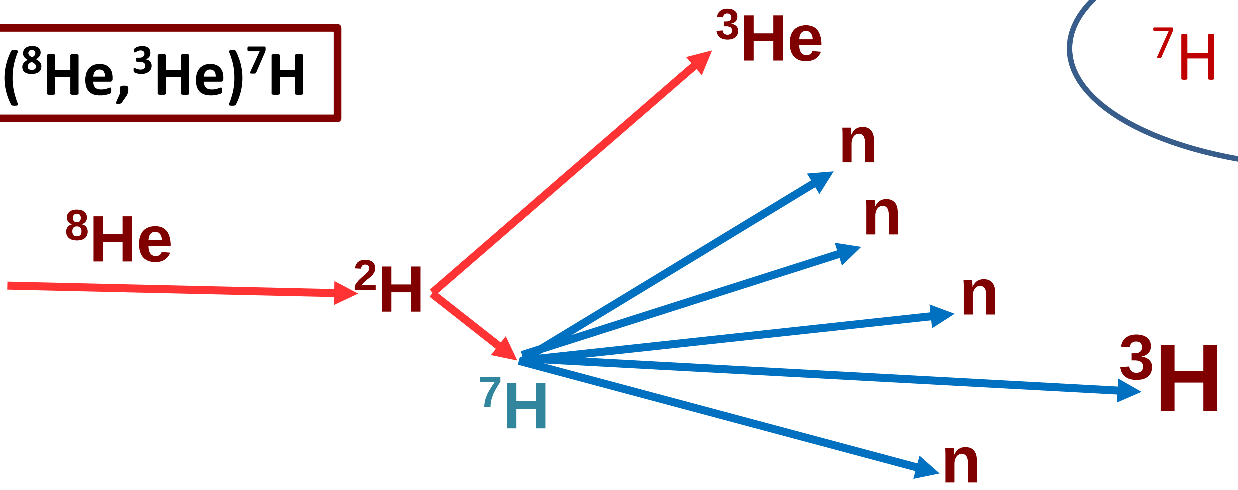
^{7}H is the heaviest hydrogen isotope, which may exist as narrow resonances, 40-year-long search for ^{6}H and ^{7}H, still under the experimental goal at many world leading laboratories

Experimental idea

ACCULINNA-2

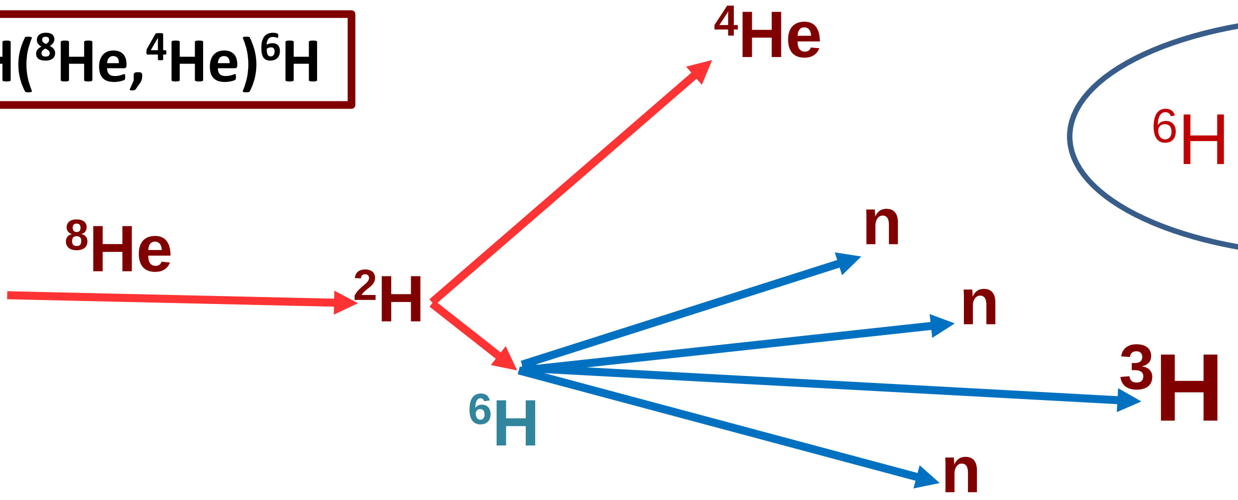
26 AMeV ^{8}He beam:
~10^5 pps,
~90% purity

$^{2}H(^{8}He,^{3}He)^{7}H$



^{7}H channel

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

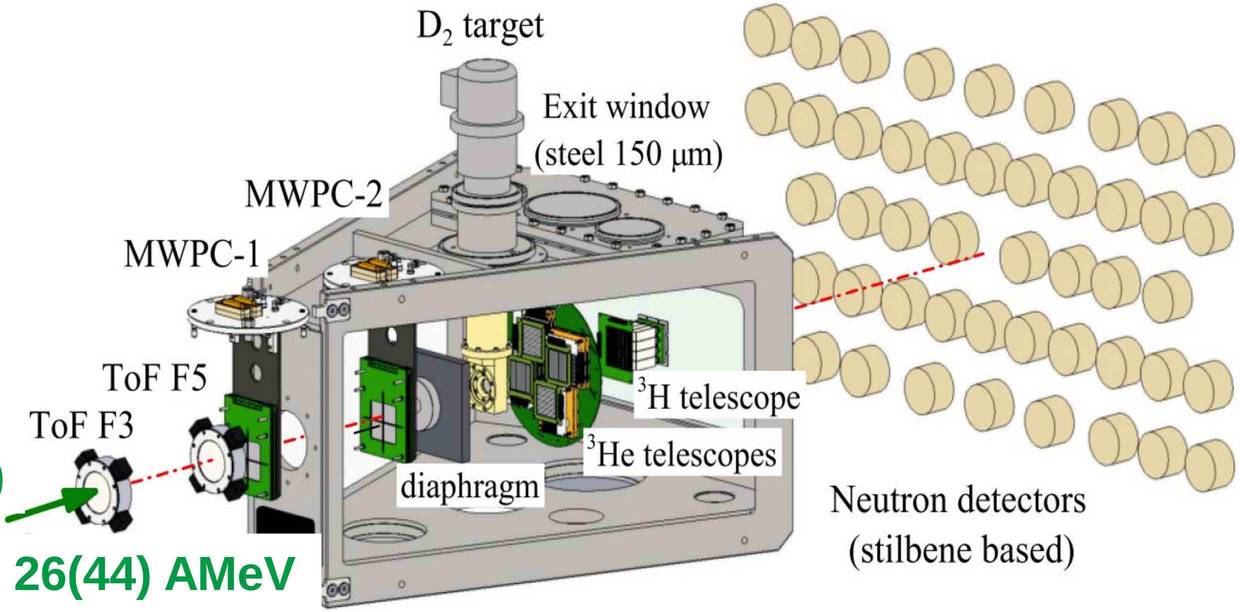


^{6}H channel

^{6}H reconstruction as missing from ^{4}He in coincidence with ^{3}H

Experimental setup

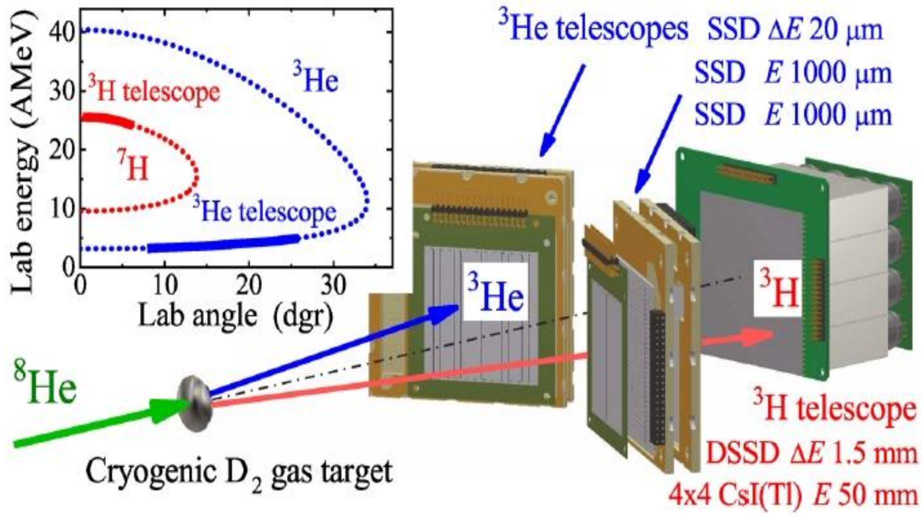
$^2H(^8He,^4He)^6H$, $^2H(^8He,^3He)^7H$ and $^2H(^{10}Be,^4He)^8Li$, $^2H(^{10}Be,^3He)^9Li$ reactions



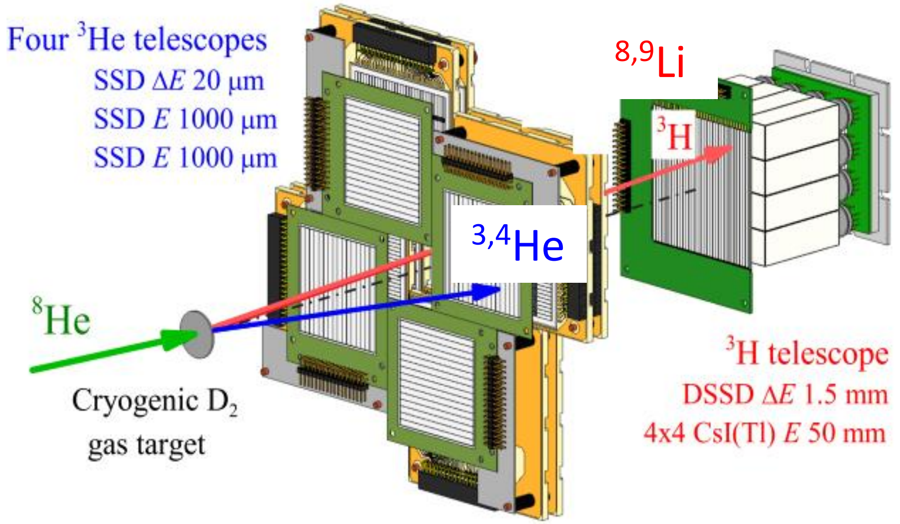
$^8He(^{10}Be)$

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

Experiment 1, (2018), 2 weeks



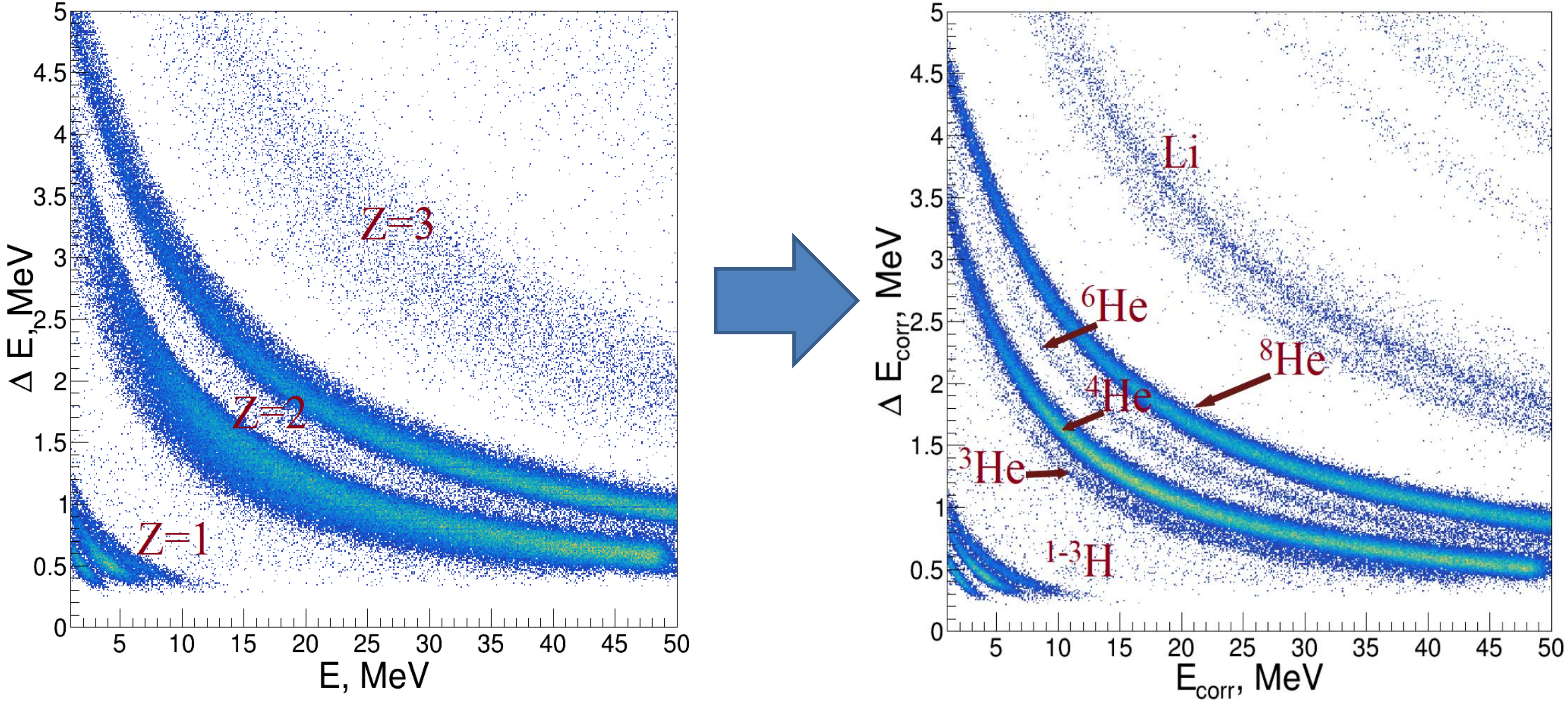
Experiment 2, (2019), 3 weeks



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

^{3}He identificatioin

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



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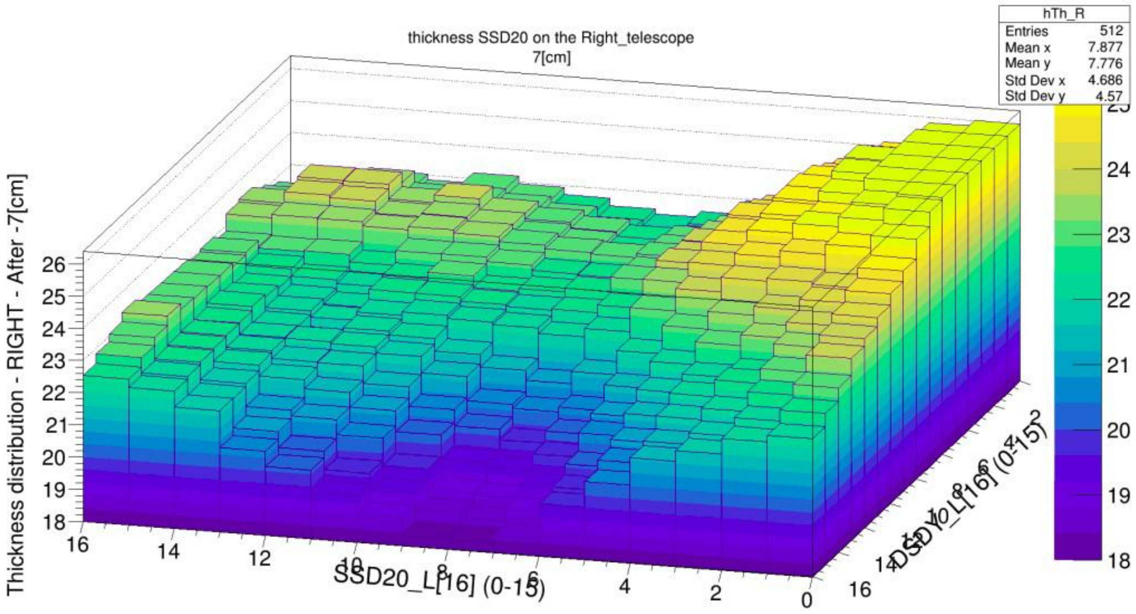
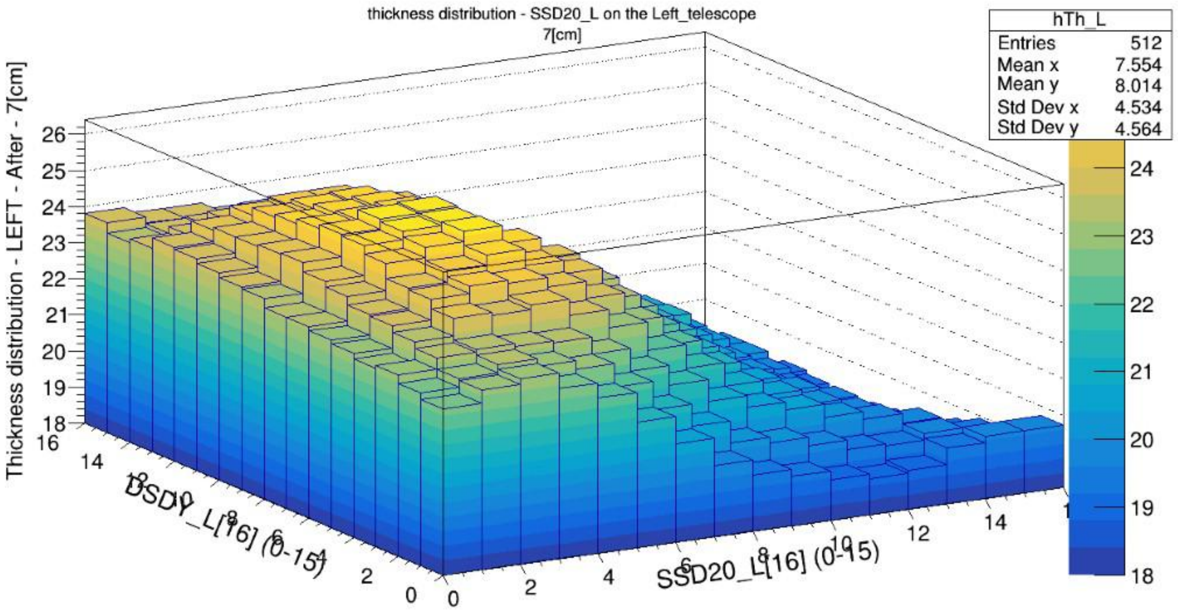
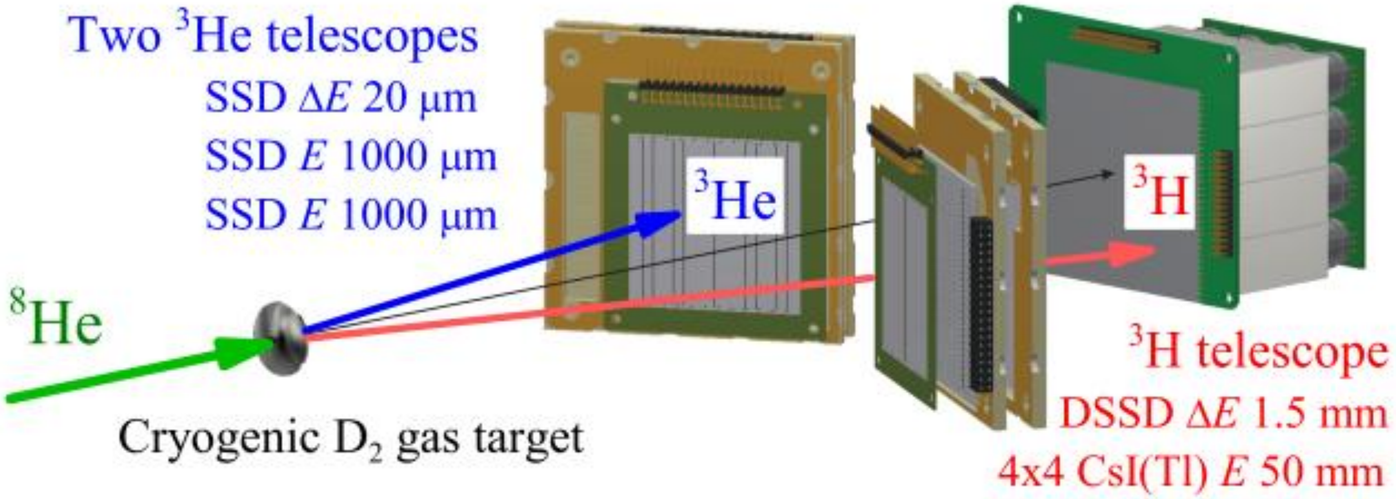




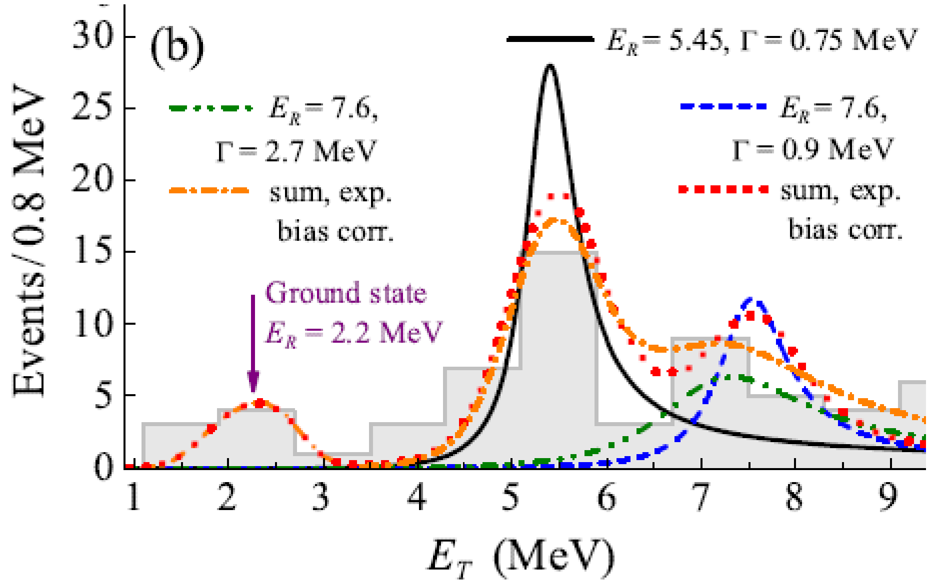


ΔThickness up to 8 μm (30%)!
Should be taken into account!

Spectra of ^7H and ^6H

^7H

Ground state: 2.2 MeV
Excited states: 5.5, 7.5 MeV



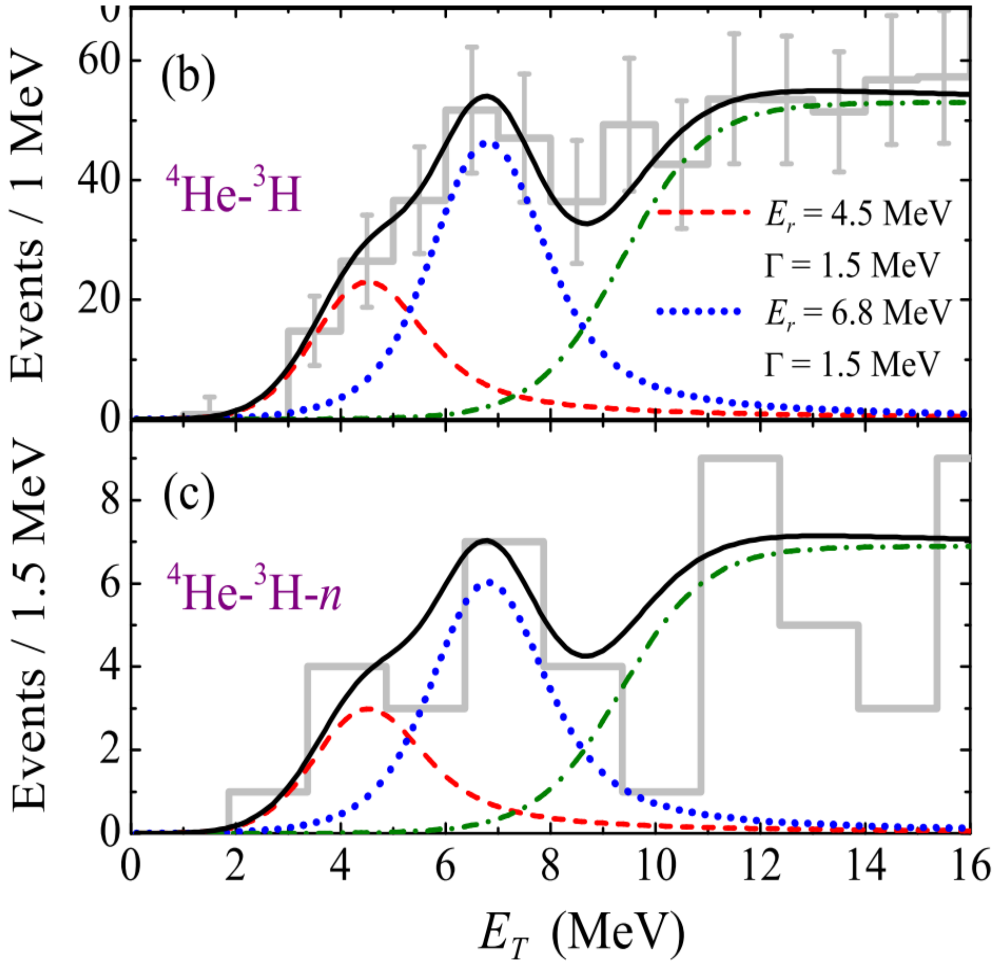
The energy profile of the ground state at 2.2(5) MeV and first excited states at 5.5(3) and 7.5(3) MeV obtained in the $^2H(^8He,^3He)^7H$ reaction [30]; the experimental missing mass spectrum of ^7H is shown by gray histogram.

A.A. Bezbakh et al., Phys. Rev. Lett. 124 (2020) 022502
I.A. Muzalevskii et al., Phys. Rev. C 103 (2021) 044313.

^6H

Ground state: 4.5 MeV
Excited state: 6.8 MeV

Study of ^6H system in the $^2H(^8He,^4He)^6H$ → t + 3n reaction

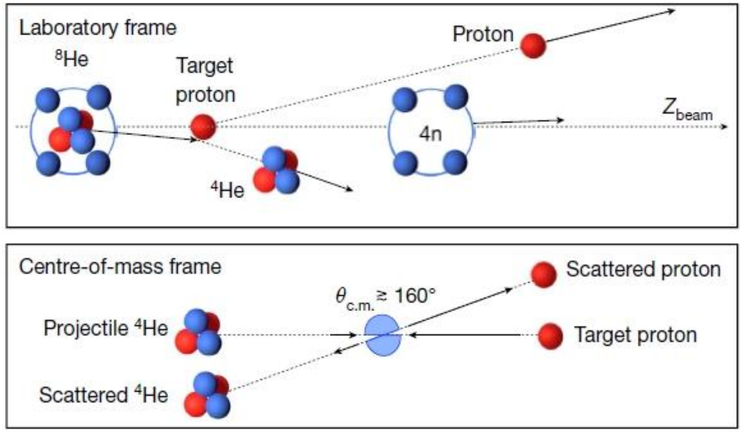


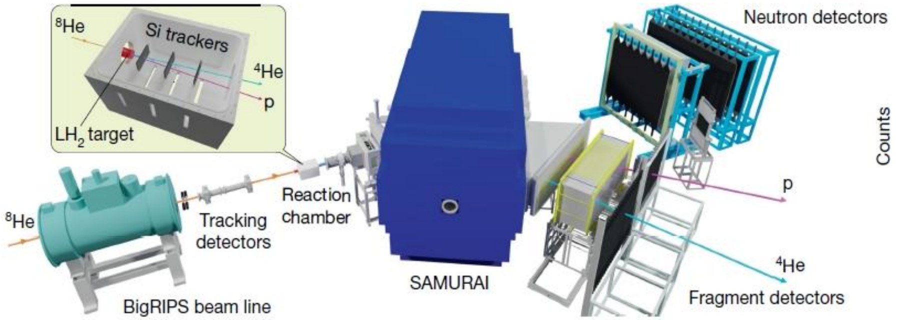
E. Yu. Nikolskii et al. Phys. Rev. C 105, 064605, *The ^6H states studied in the $^2He(^8He,^4He)$ reaction and evidence of extremely correlated character of the ^5H ground state*

"Observation of a correlated free four-neutron system"

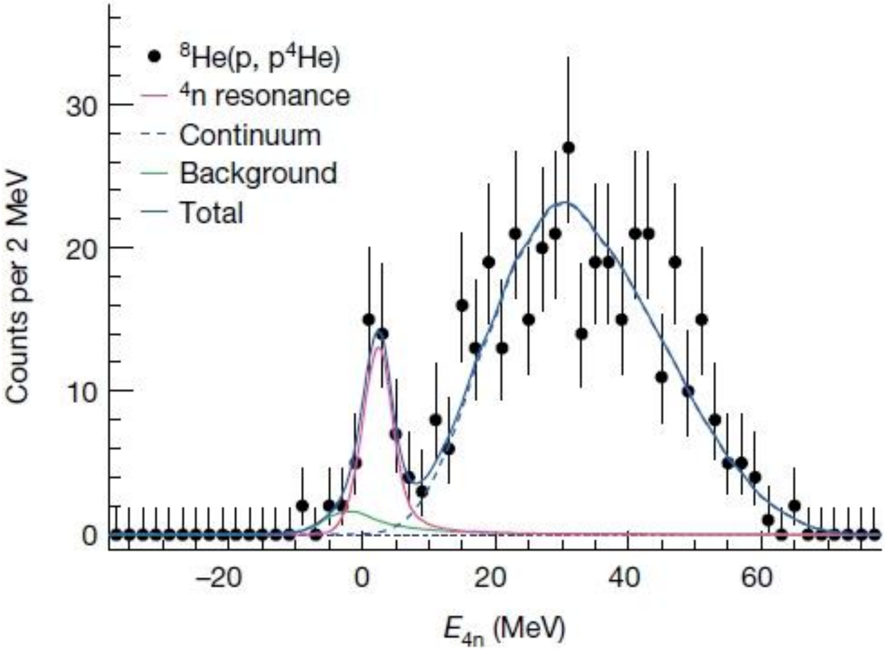
(M. Duer *et al*., 678 | **Nature** | Vol **606** | 23 June 2022)

^{8}He(p, p^{4}He)4n knockout reaction; RIKEN experiment



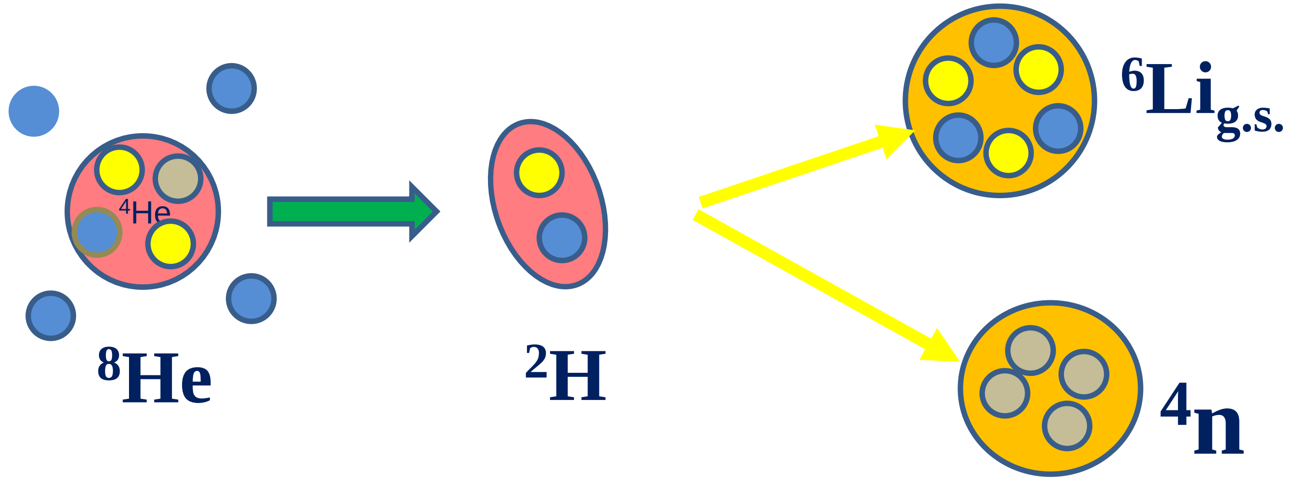


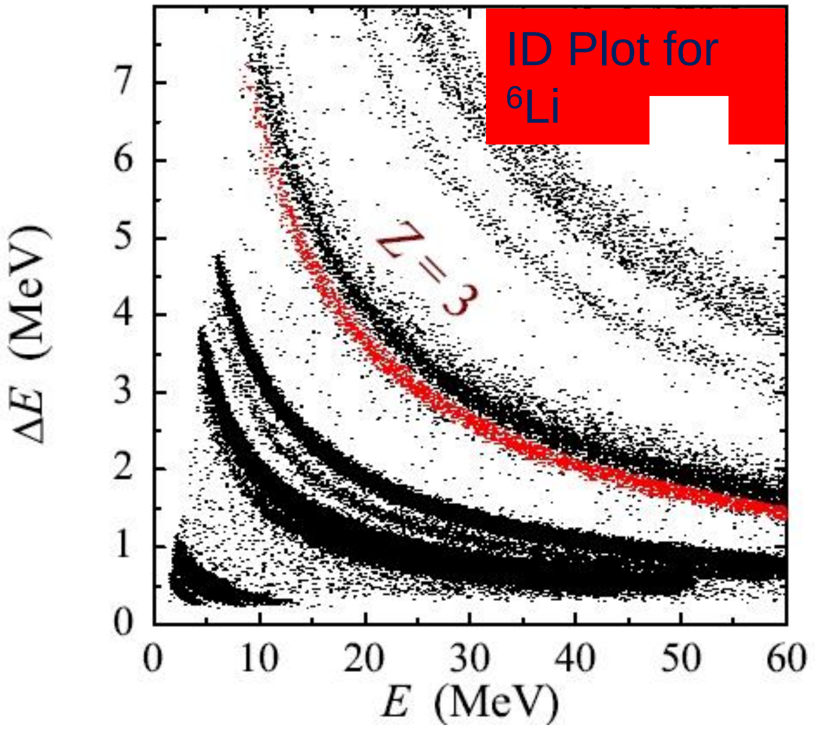
$$E_r = 2.37 \pm 0.38(\text{stat.}) \pm 0.44(\text{sys.})\ \text{MeV},$$
$$\Gamma = 1.75 \pm 0.22(\text{stat.}) \pm 0.30(\text{sys.})\ \text{MeV}.$$

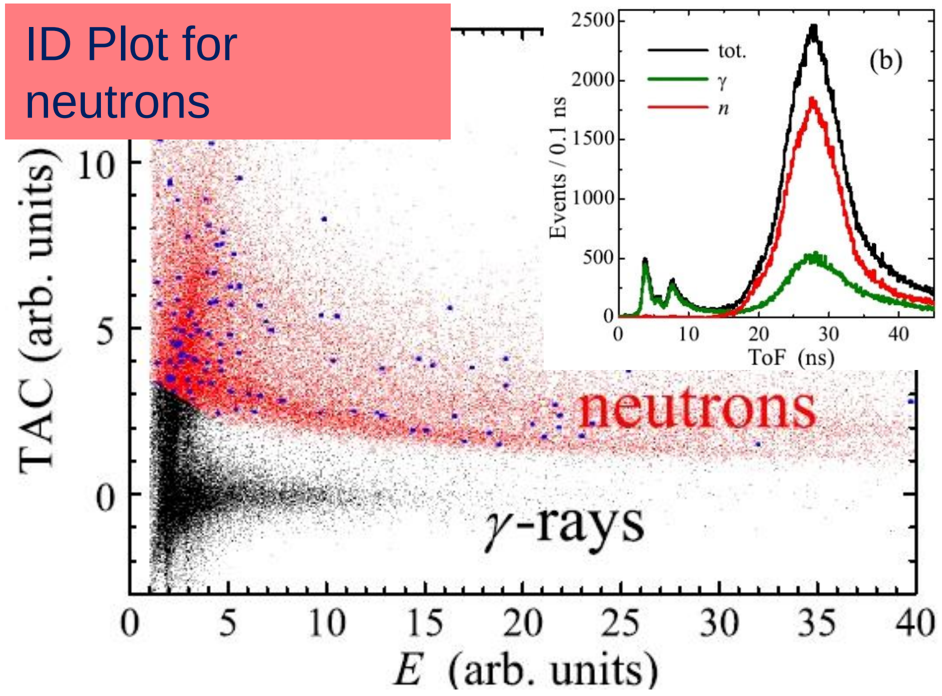


K. Kisamori et l., PRL **116**, 052501 (2016)
"Candidate Resonant Tetraneutron State Populated by the ^{4}He(^{8}He,^{8}Be) Reaction"
E(4n) = 0.83 ± 0.65(stat) ± 1.25(syst) MeV

Study of the ^{4}n system in the reaction ^{2}H(^{8}He,^{6}Li)^{4}n



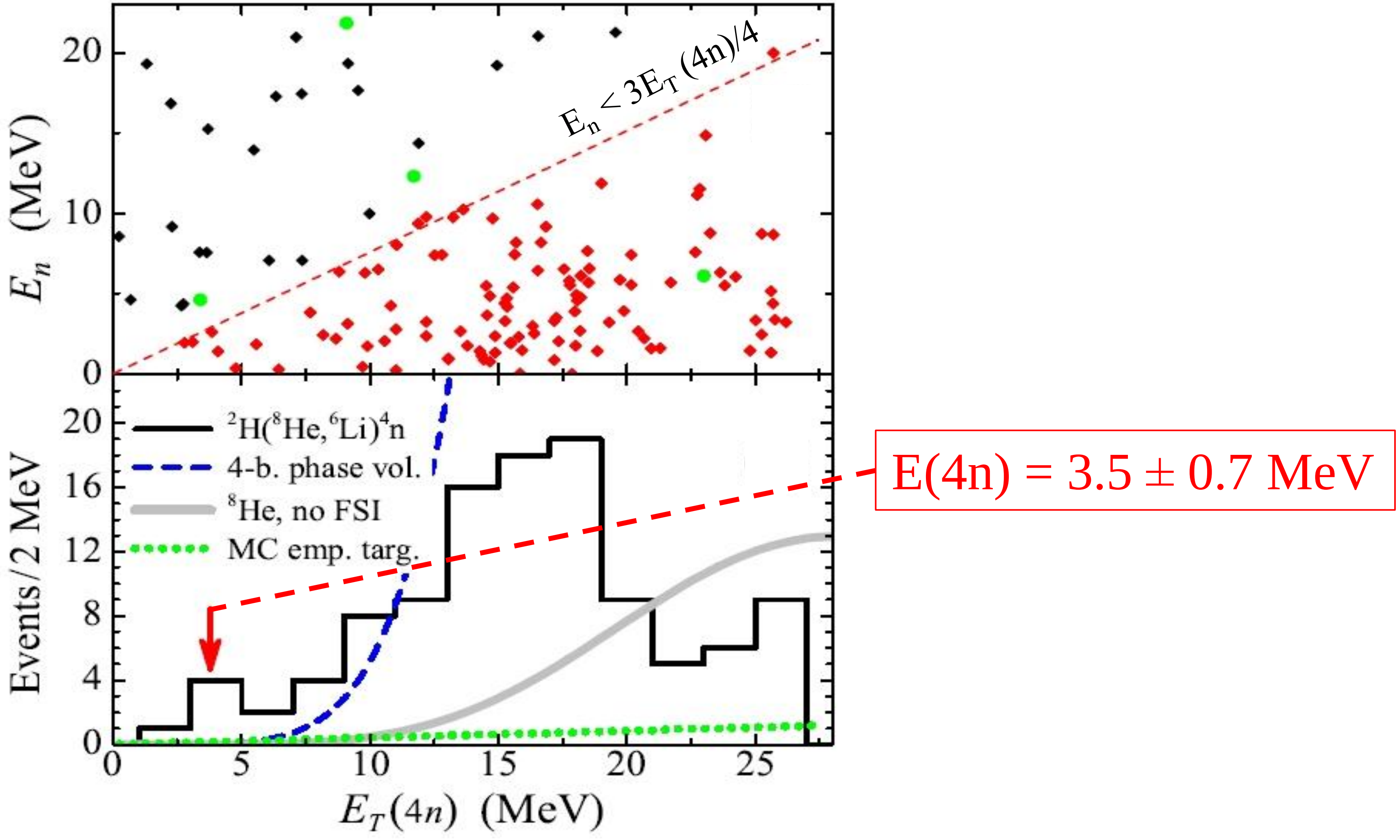


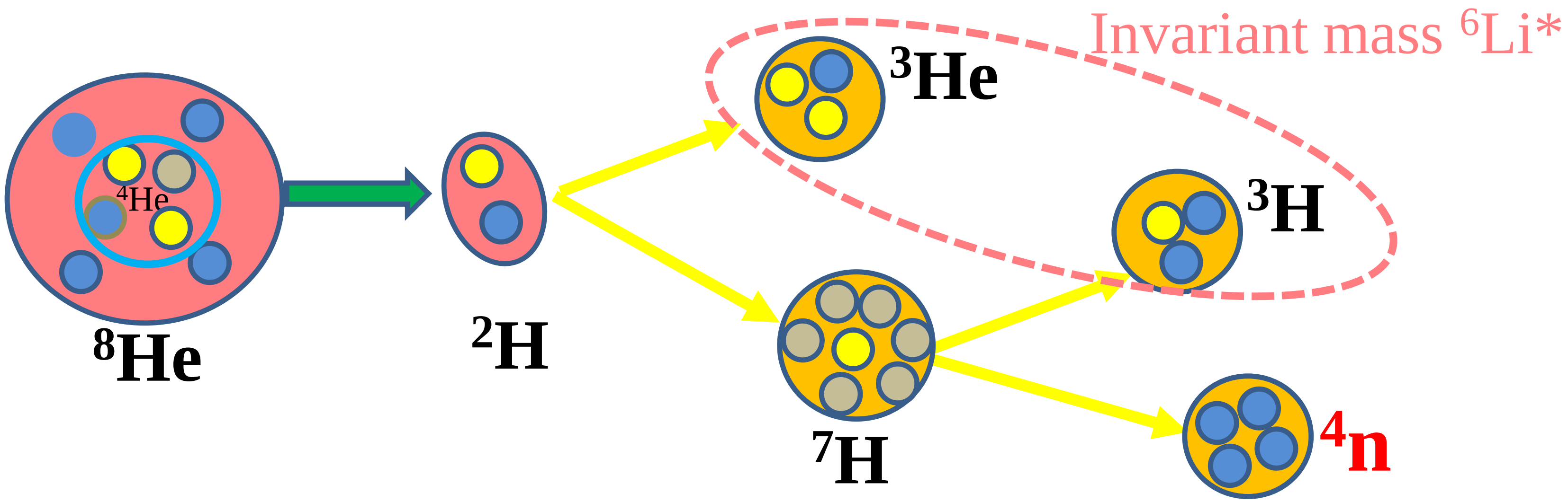


Data from the $^2H(^8He,^6Li)^4n$ reaction

Missing mass spectrum of ^4n derived from ^6Li + n coincidences

Total number of events = 136

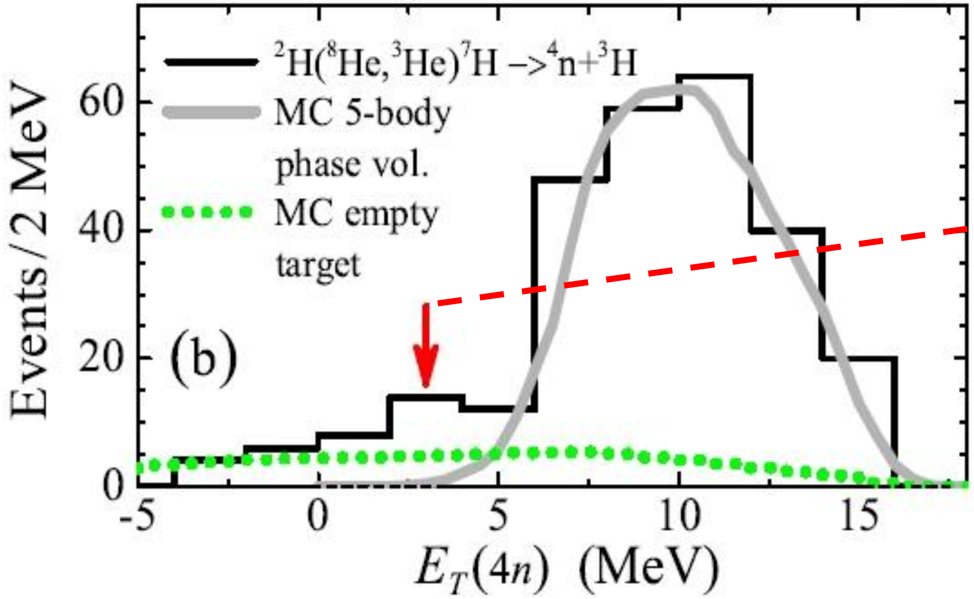




Data from the ^{2}H(^{8}He,^{3}He)^{7}H → ^{3}H + ^{4}n reaction

MM spectrum of ^{4}n derived from ^{3}He+^{3}H = ^{6}Li* data

^{4}n spectrum summed up for E_T (^{7}H) > 8 MeV



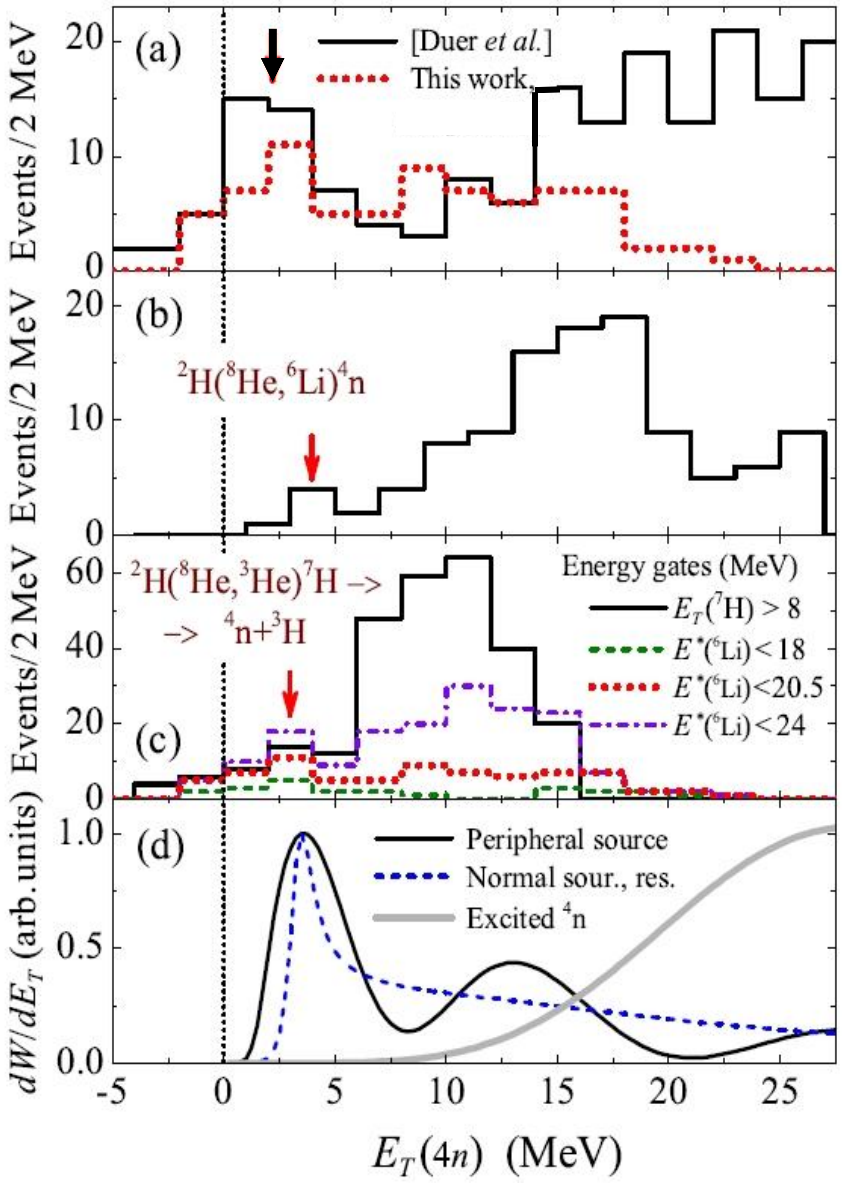
$$\frac{dW}{dE_T(^7\mathrm{H})\,d\varepsilon} \propto E_T^{(\alpha+3)/2}(^7\mathrm{H})\,\sqrt{\varepsilon^\alpha(1-\varepsilon)}$$

$$\varepsilon = E_T(4n)/E_T(^7\mathrm{H})$$

$E_T(4n)$ = 2 - 4 MeV → $\varepsilon \leq 0.5$ → $E_T(^7\mathrm{H}) \geq 8$ MeV

E(4n) = 3.2 ± 0.7 MeV

Summary comparison of experimental data and theory



Duer *et al.*
E(4n) ≈ 2.4 ± 0.6 MeV

This work
E(4n) ≈ 3.5 ± 0.7 MeV

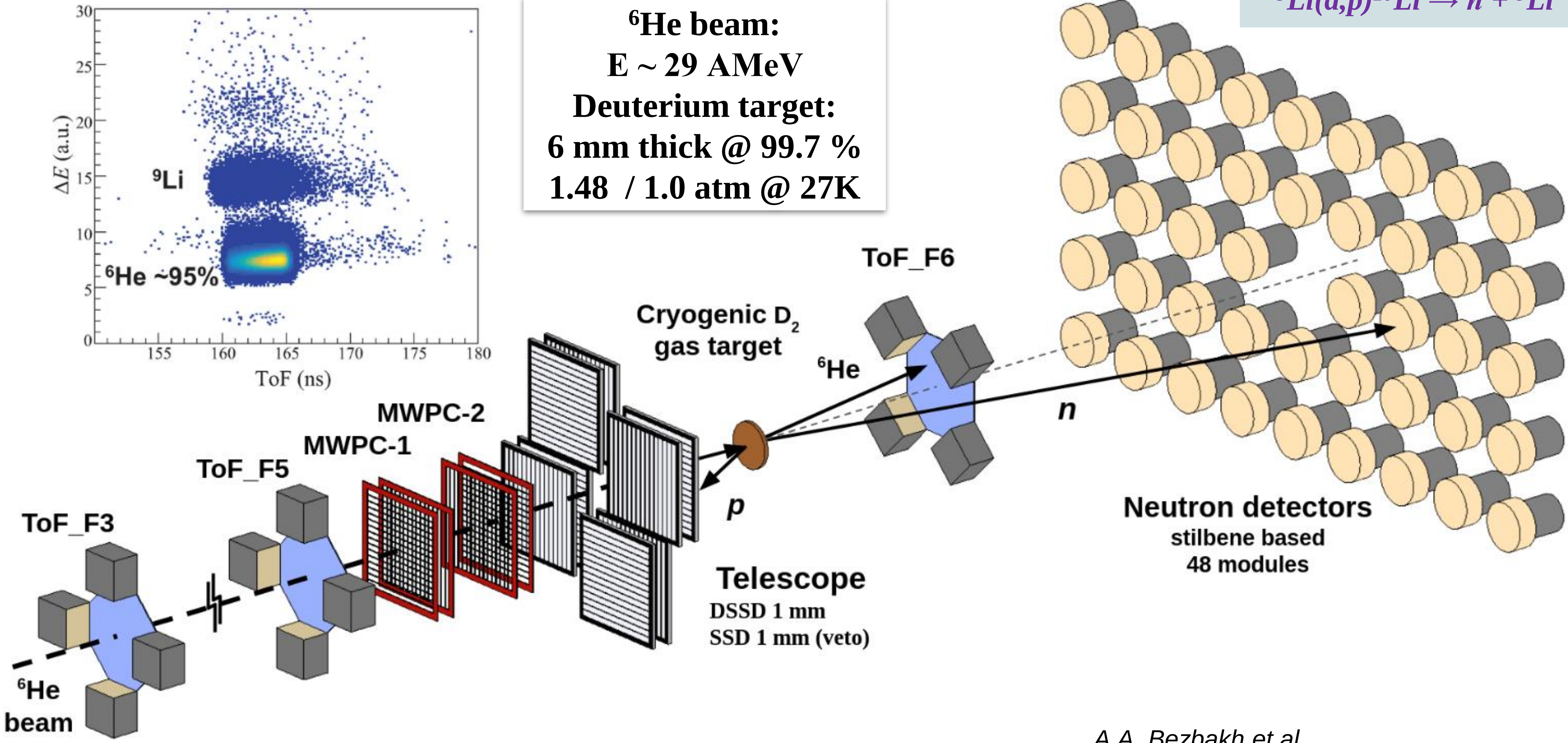
This work
E(4n) ≈ 3.2 ± 0.8 MeV

Extreme peripheral source
or
Real resonant behavior

Experimental scheme. Study of excited states of ^{7}He in the ^{6}He(d,p) reaction

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

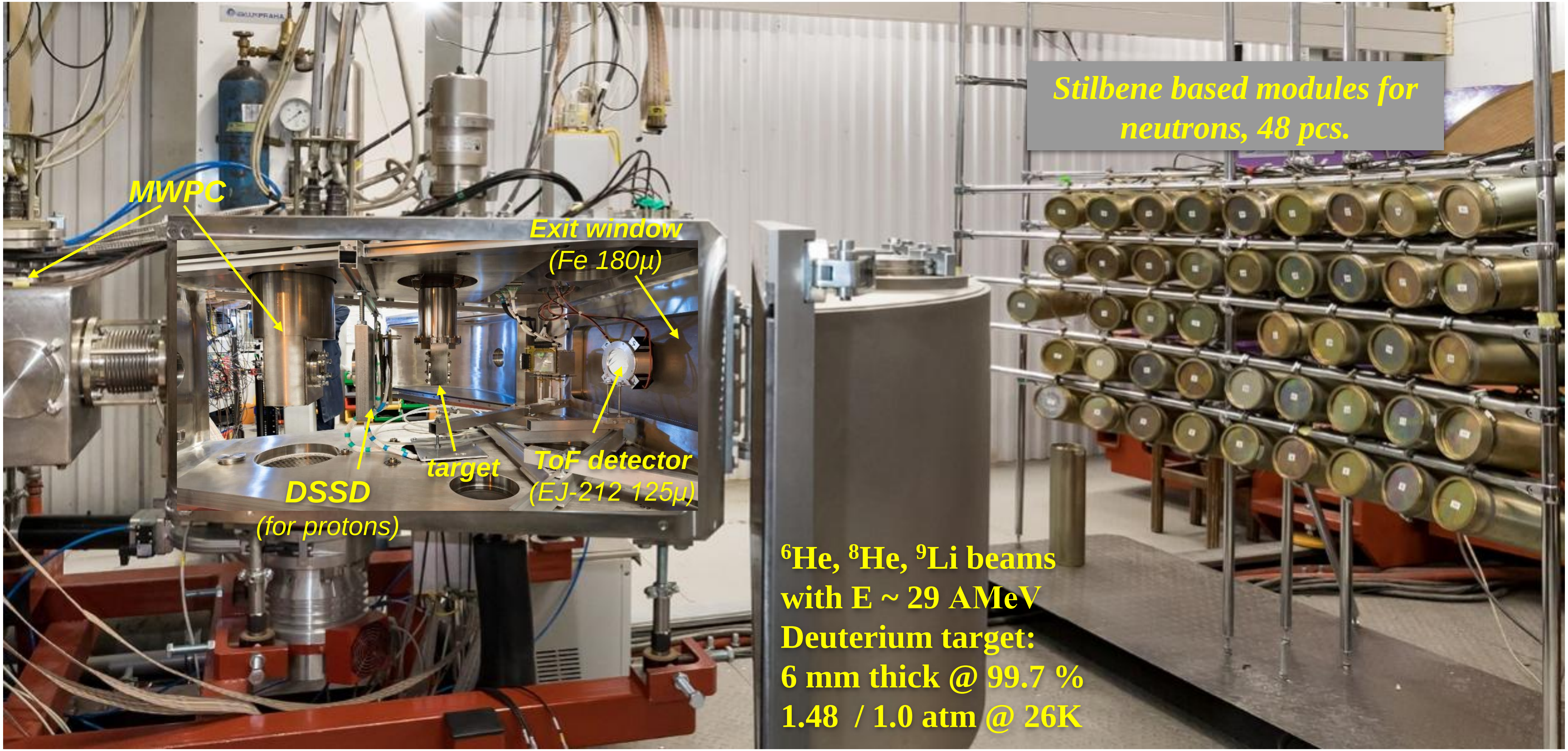
^{6}He beam:
E ~ 29 AMeV
Deuterium target:
6 mm thick @ 99.7 %
1.48 / 1.0 atm @ 27K



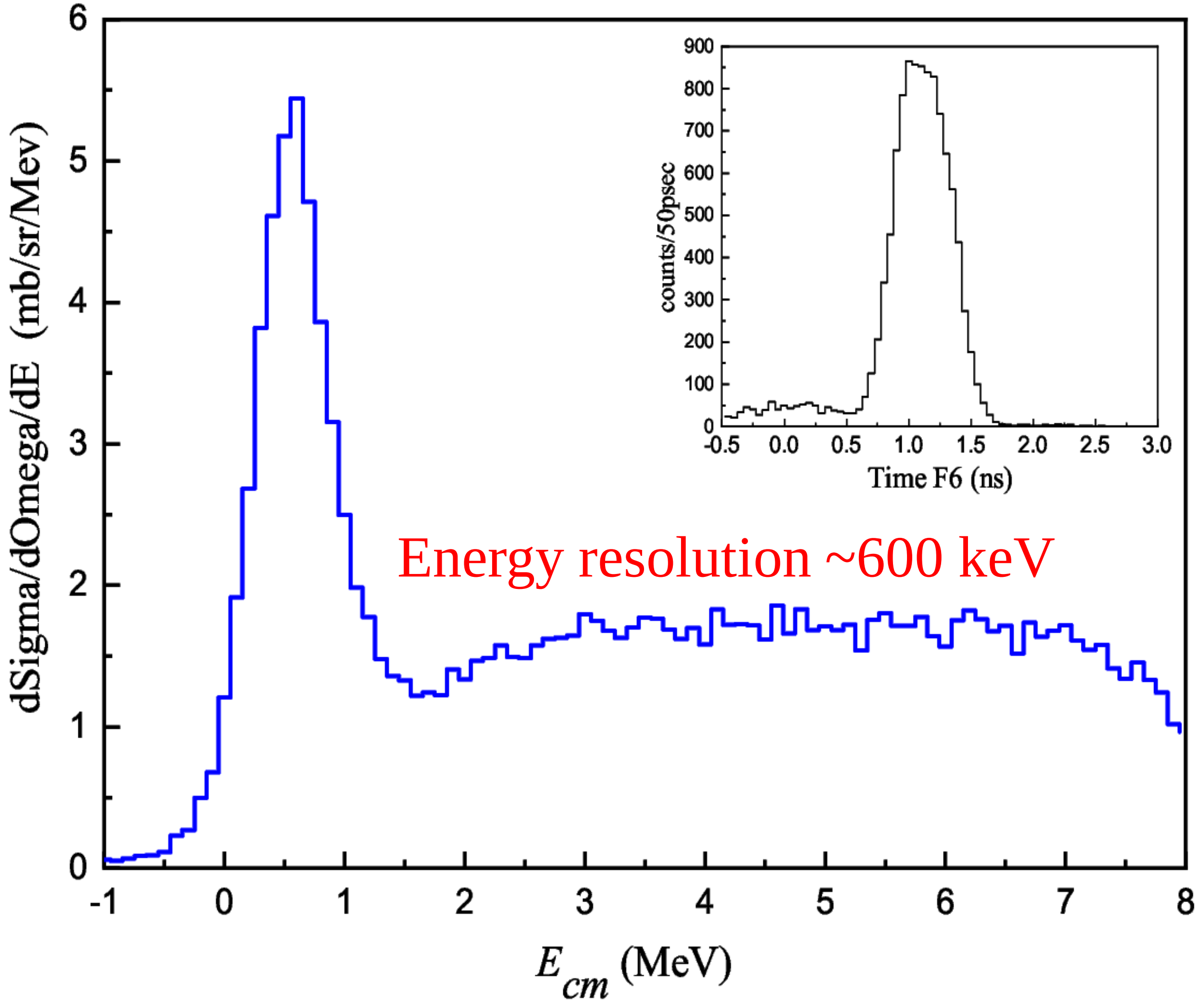
A.A. Bezbakh et al.,
Int. J. Mod. Phys. E 33. (2023) 245002

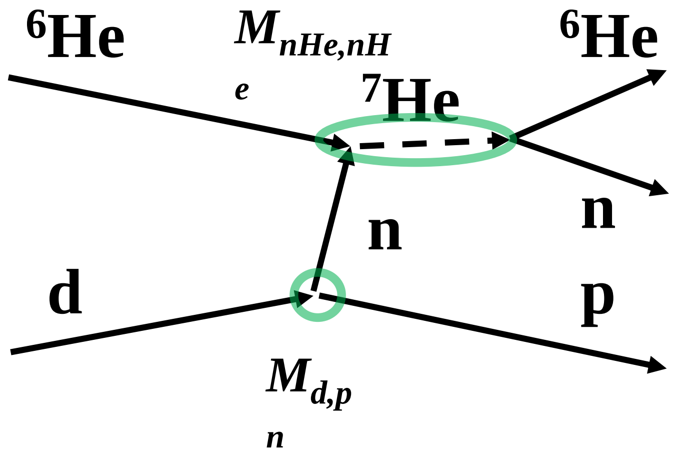
Setup for the study ^{7}He, ^{9}He and ^{10}Li isotopes in the reaction *(d,p)*

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



Experimental missing mass spectrum of ^{7}He from the $^{2}H(^{6}He, p)$ reaction.





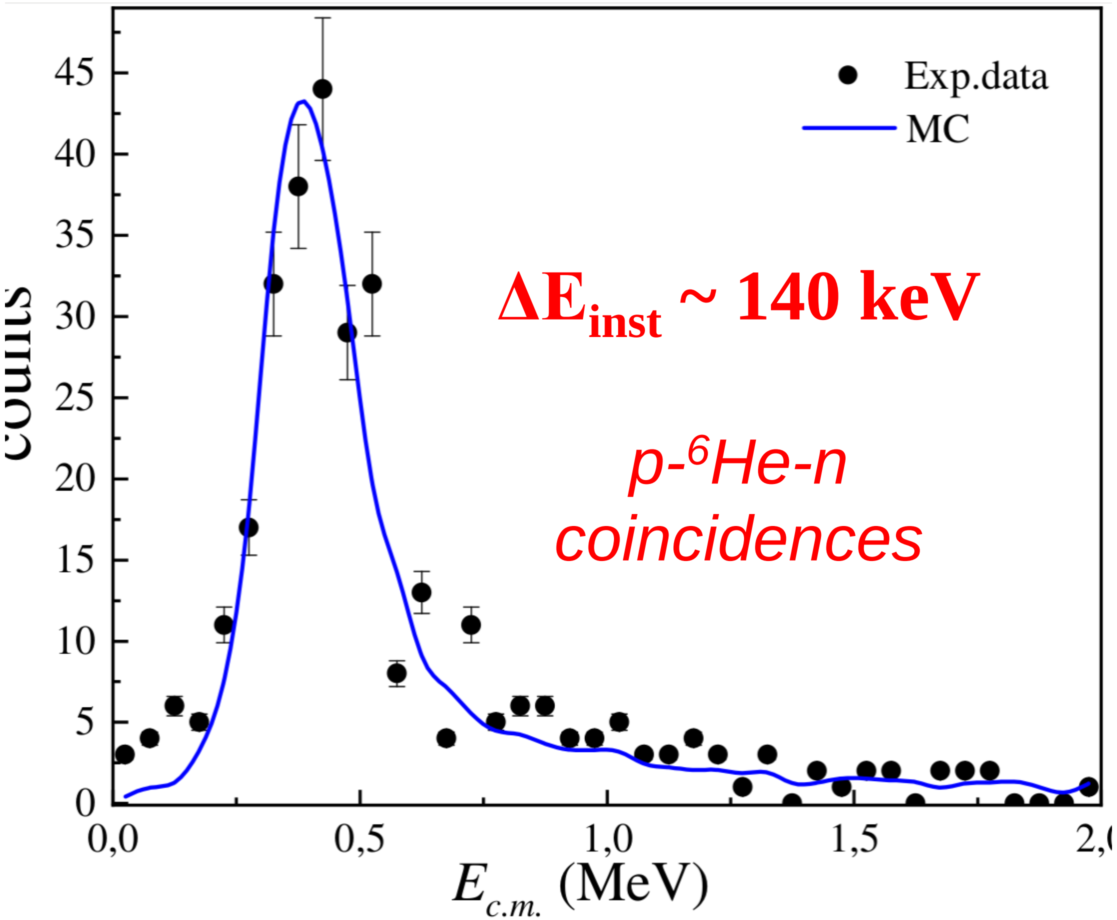
$$M^{PW}_{d,H} = -\frac{M_{d,pn} M_{nHe,nHe}}{E - \mathbf{q}^2/2m + i\epsilon}$$

A model is proposed to describe the spectrum of the transmission response based on the elastic scattering amplitude.

Inset shows the projection of the events corresponding to the population of the ^{7}He ground state. It demonstrates that the background does not exceed a few-percent part of the total number of counts obtained in the region of the ground-state peak.

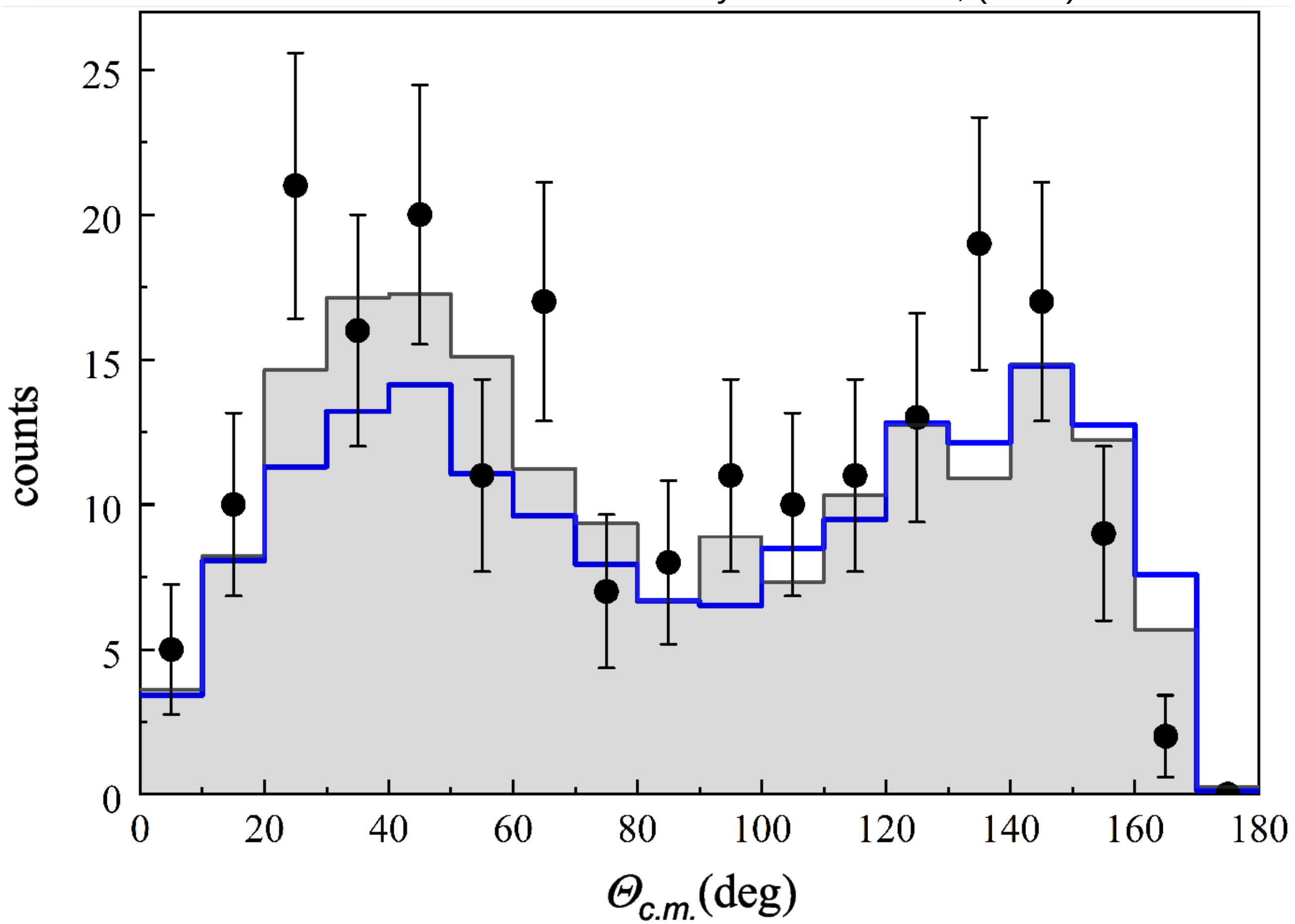
p+^{6}He+n coincidences; complete kinematics, p3/2- the ground state

A.A. Bezbakh et al.,
Int. J. Mod. Phys. E 33. (2023) 245002



^{6}He MM spectrum for events with neutron coincidence

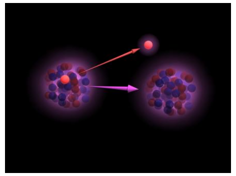
M.S. Golovkov et al.,
Phys. Rev. C. 109, (2024) L061602



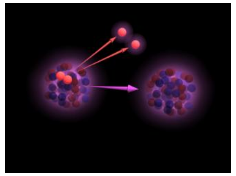
Neutron angular distribution dσ/dθ from the decay of the ^{7}He ground state.

- The instrumental resolution ~140 keV (FWHM), which is comparable to the resonance intrinsic width.
- In the ^{7}He energy spectrum, at ^{7}He gs. energy region an forward-backward asymmetry of the decay neutron emission has been observed.

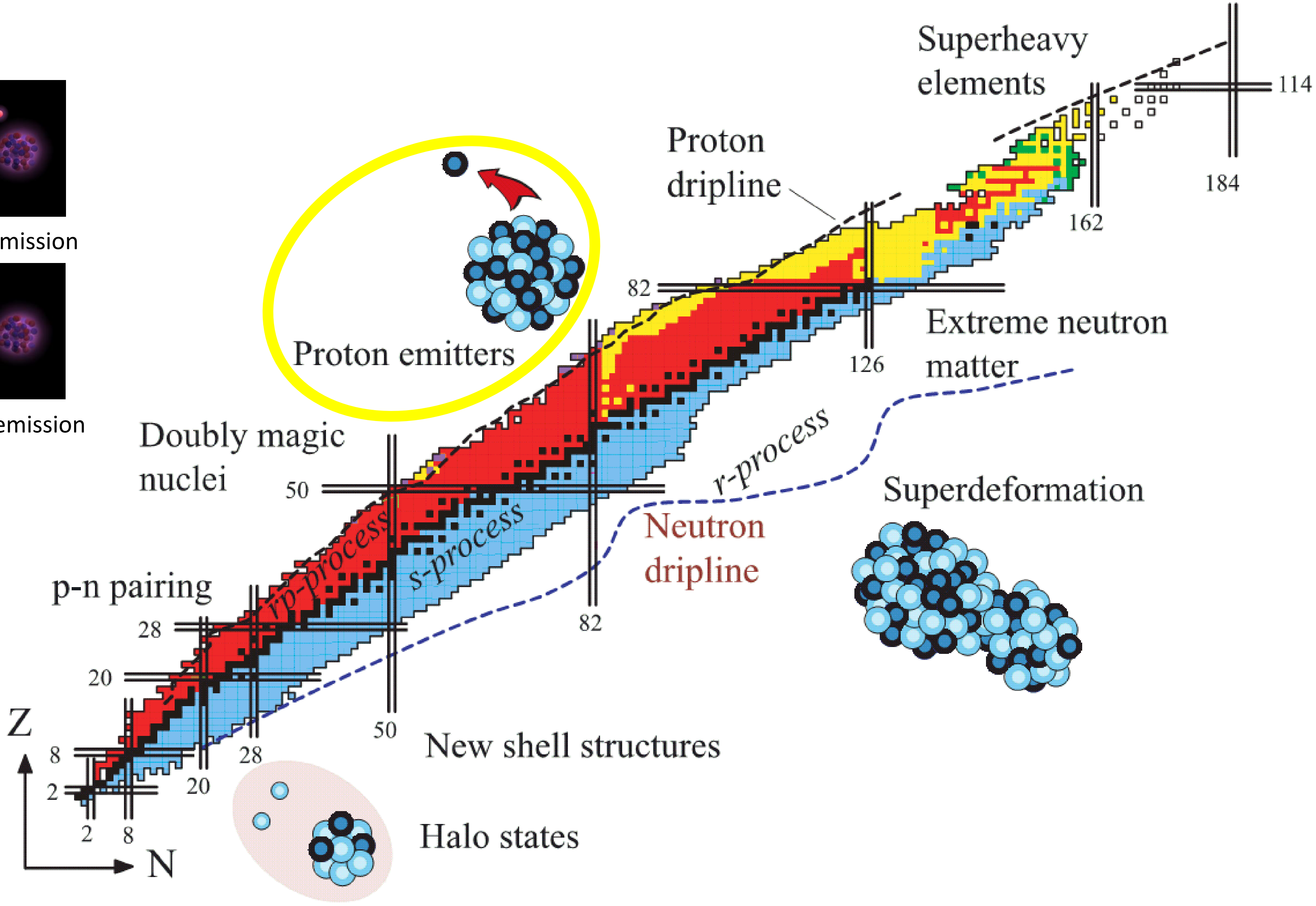
Radioactivity at the nuclear drip-lines (proton-rich nuclei)



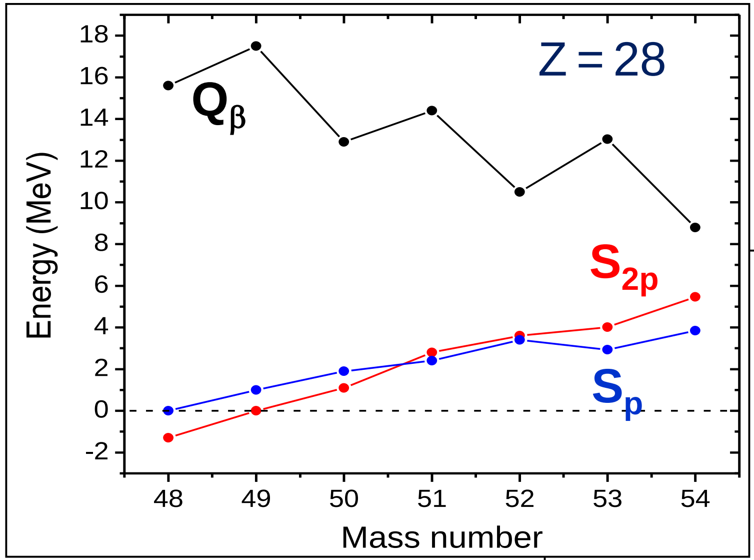
1 proton emission



2 protons emission

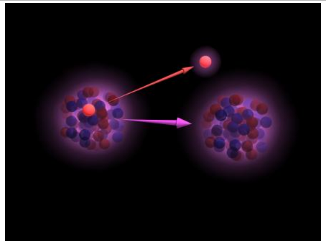


Radioactivity at the nuclear drip-lines (proton-rich nuclei)

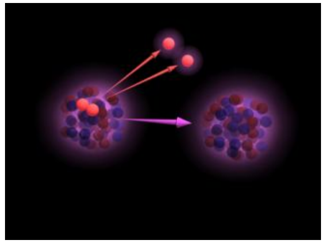


When the β-decay energy is large, many exotic channels are available:

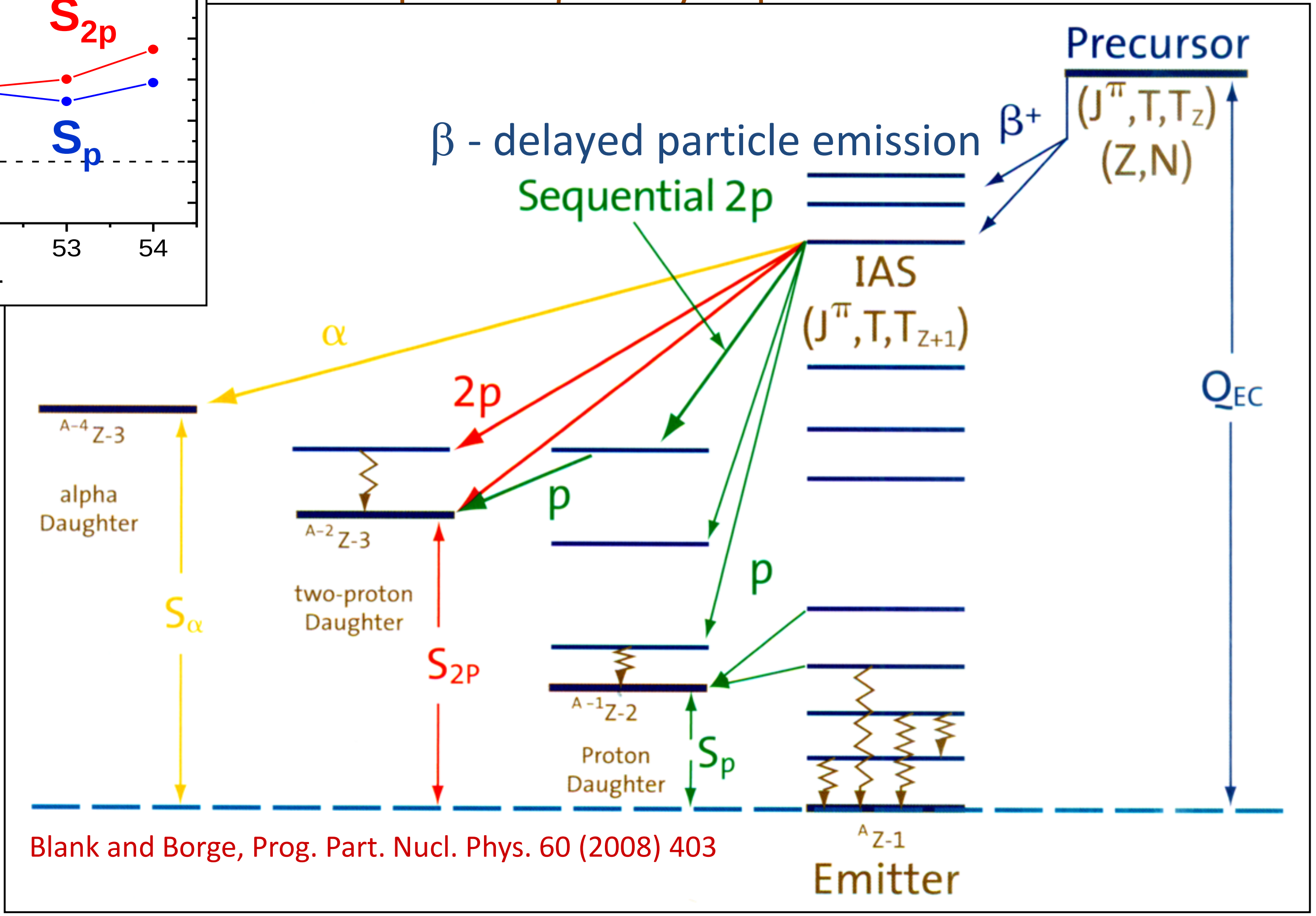
- exotic decay modes (1p, 2p radioactivity)
- multiparticle β-delayed particle emission



1 proton emission



2 proton emission

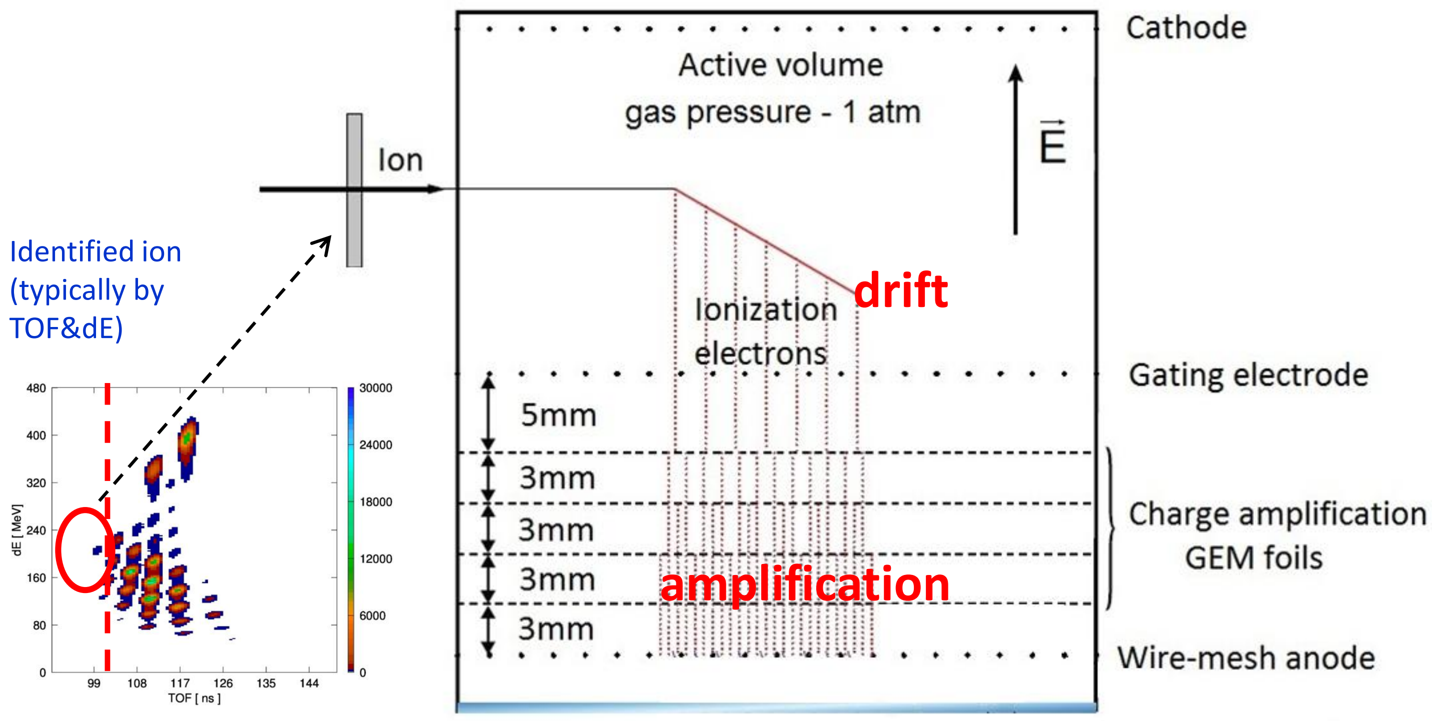


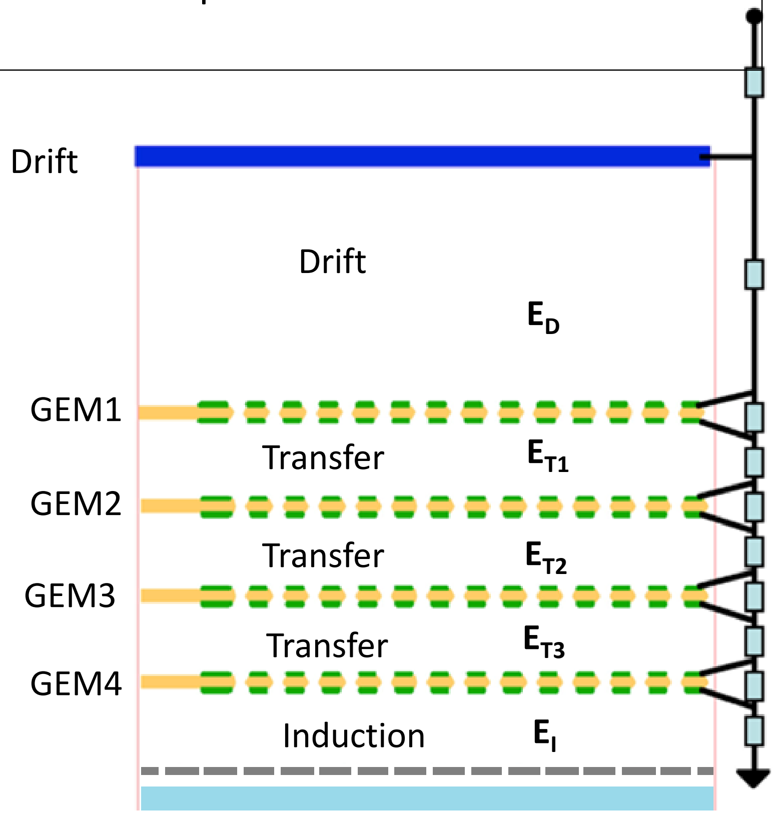
Blank and Borge, Prog. Part. Nucl. Phys. 60 (2008) 403

Experimental tool - Optical Time Projection Chamber

Optical **T**ime **P**rojection **C**hamber (OTPC) - A new type of modern ionization chamber with an optical readout.

***** Collaboration up to 2022, in 2022 terminated …**





Experimental tool - Optical Time Projection Chamber

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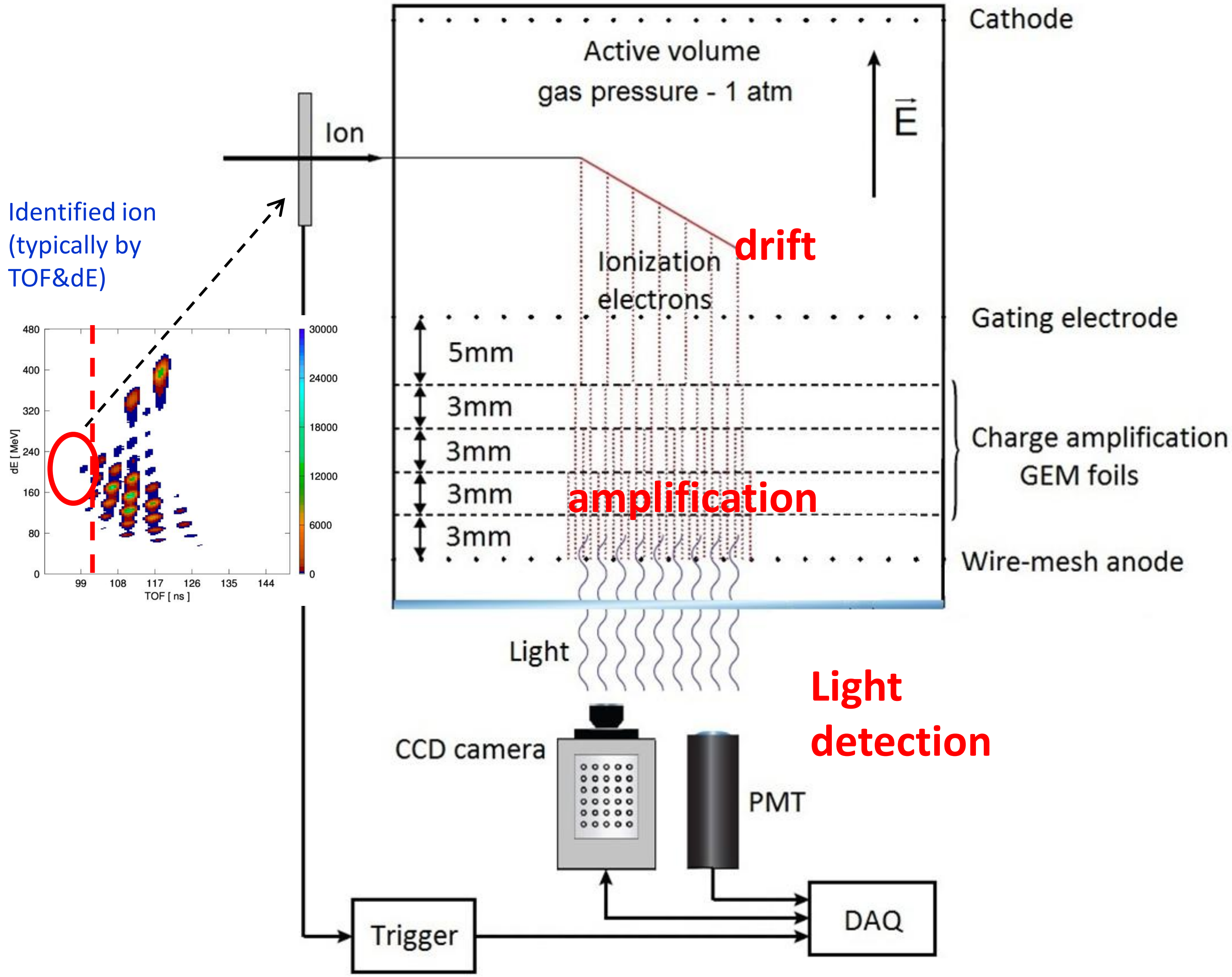
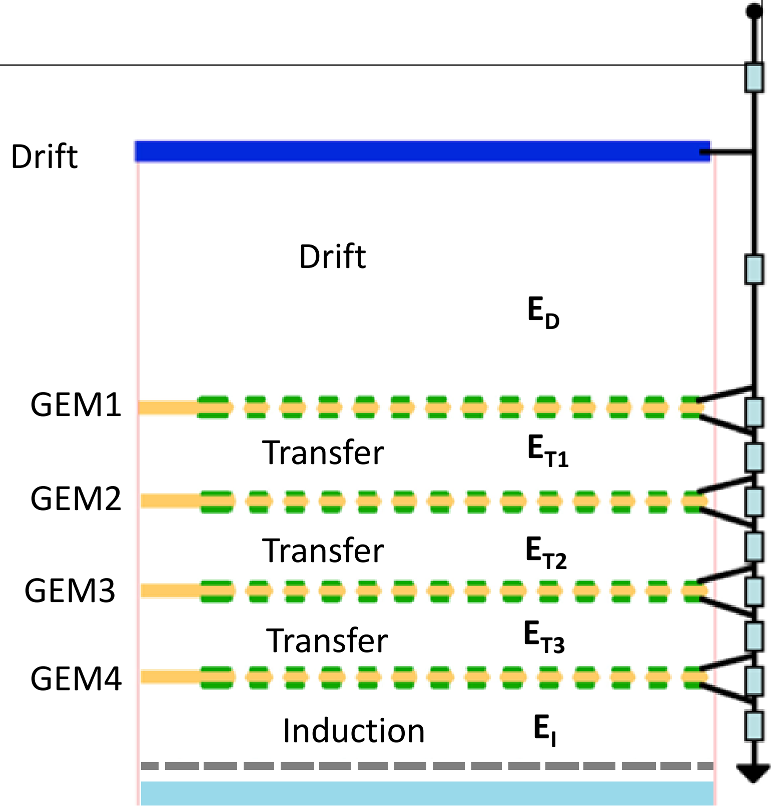
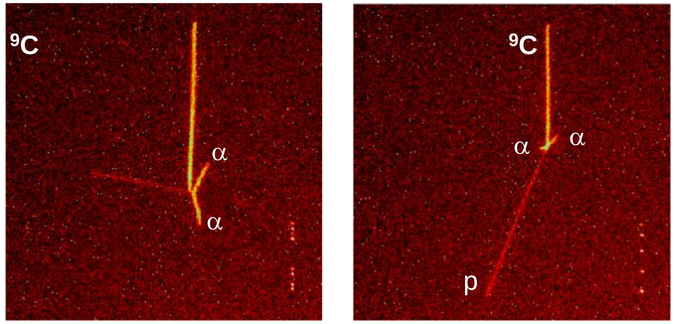




Example cases of β-delayed charged particle emission from ^{9}C

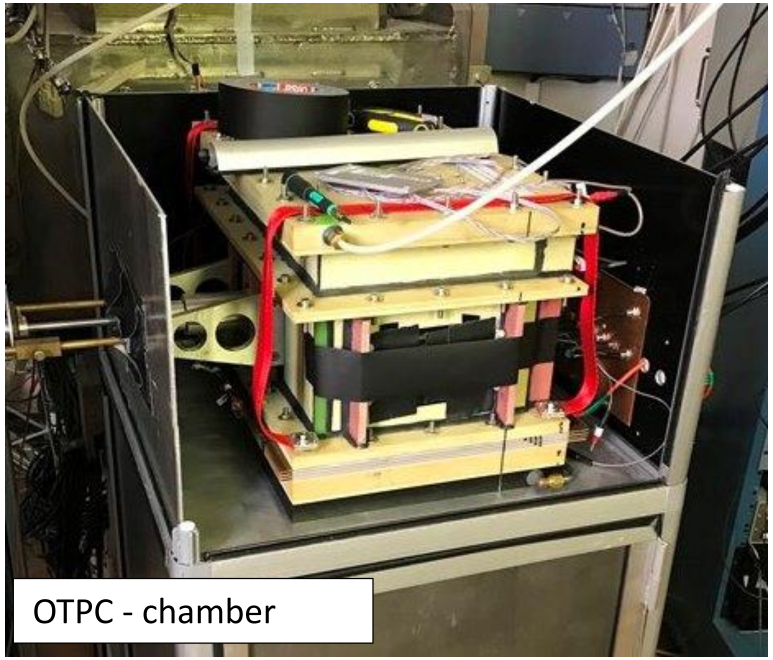


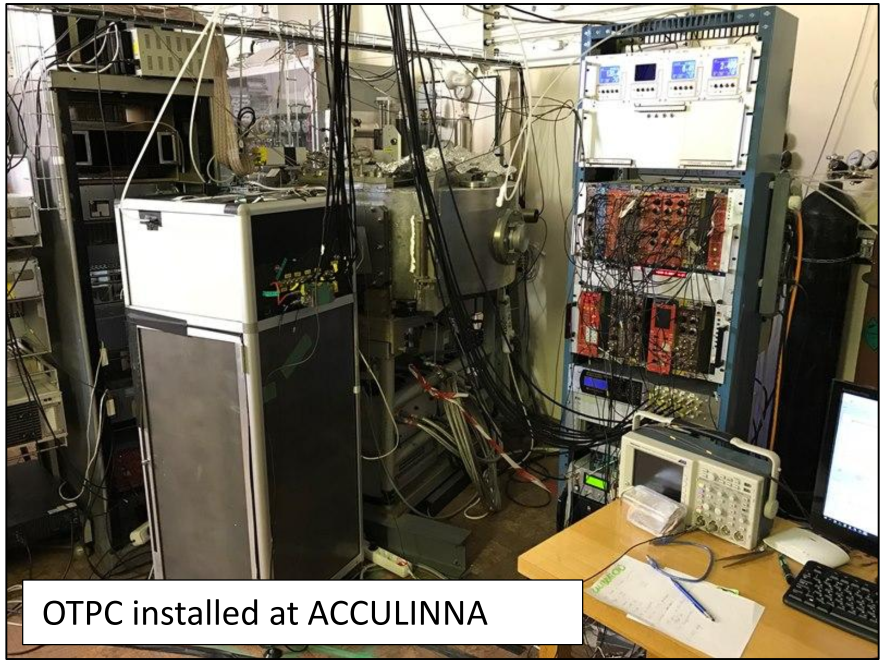
Decay from $^{9}B^{(*)}$ to ^{8}Be.
$^{9}B^{(*)} \rightarrow {}^{8}Be + p$

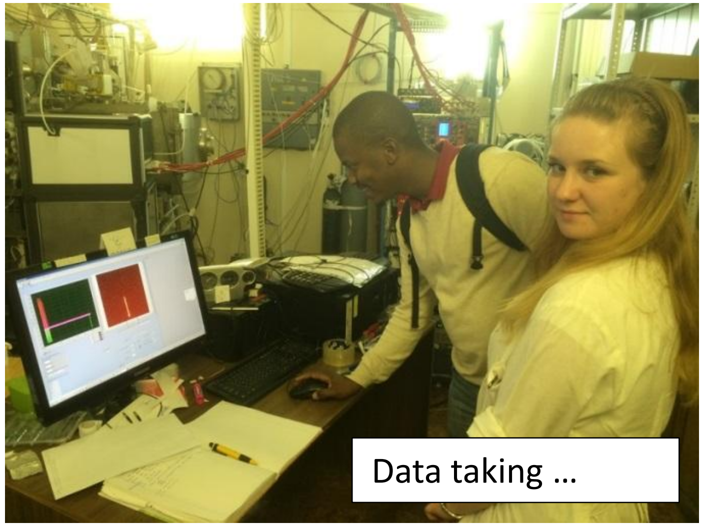
Decay from $^{9}B^{(*)}$ to ^{5}Li
$^{9}B^{(*)} \rightarrow {}^{5}Li + \alpha$

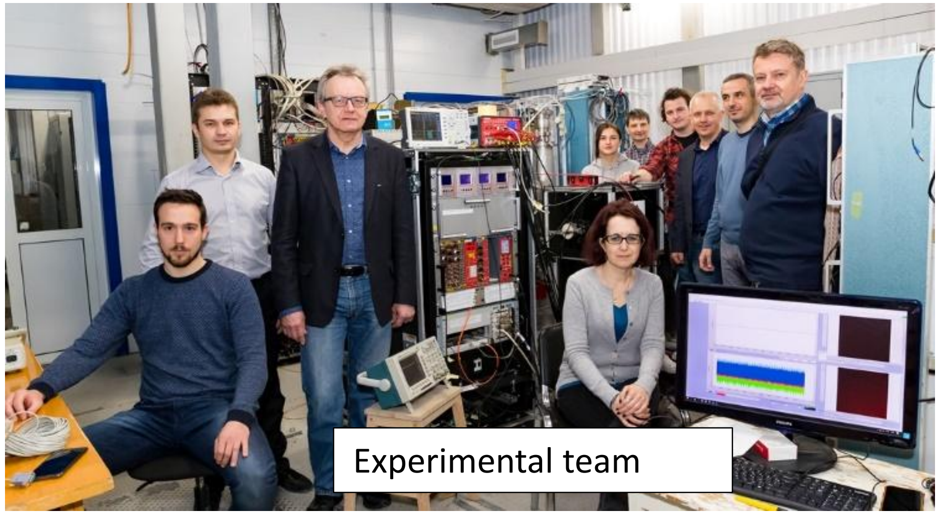
[A. Giska, (2018) Eng. Thesis, University of Warsaw]

Spectroscopy of β-delayed charged particle emission

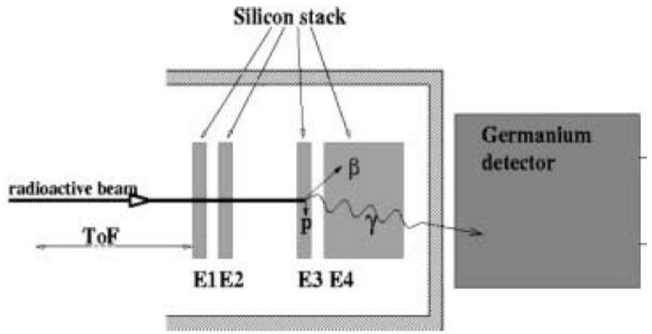

OTPC - chamber

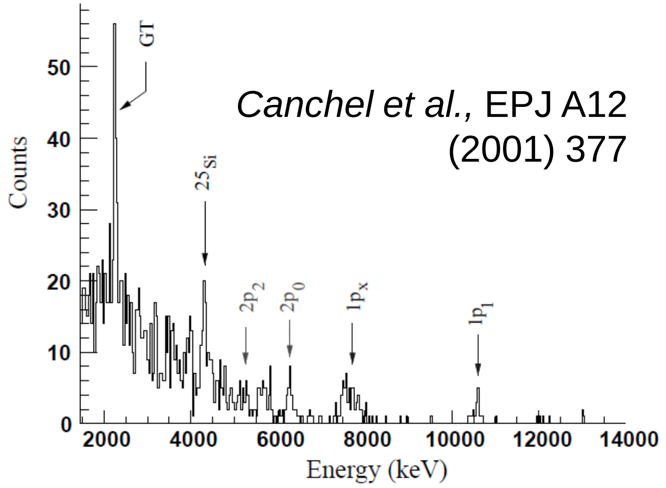

OTPC installed at ACCULINNA


Data taking …


Experimental team

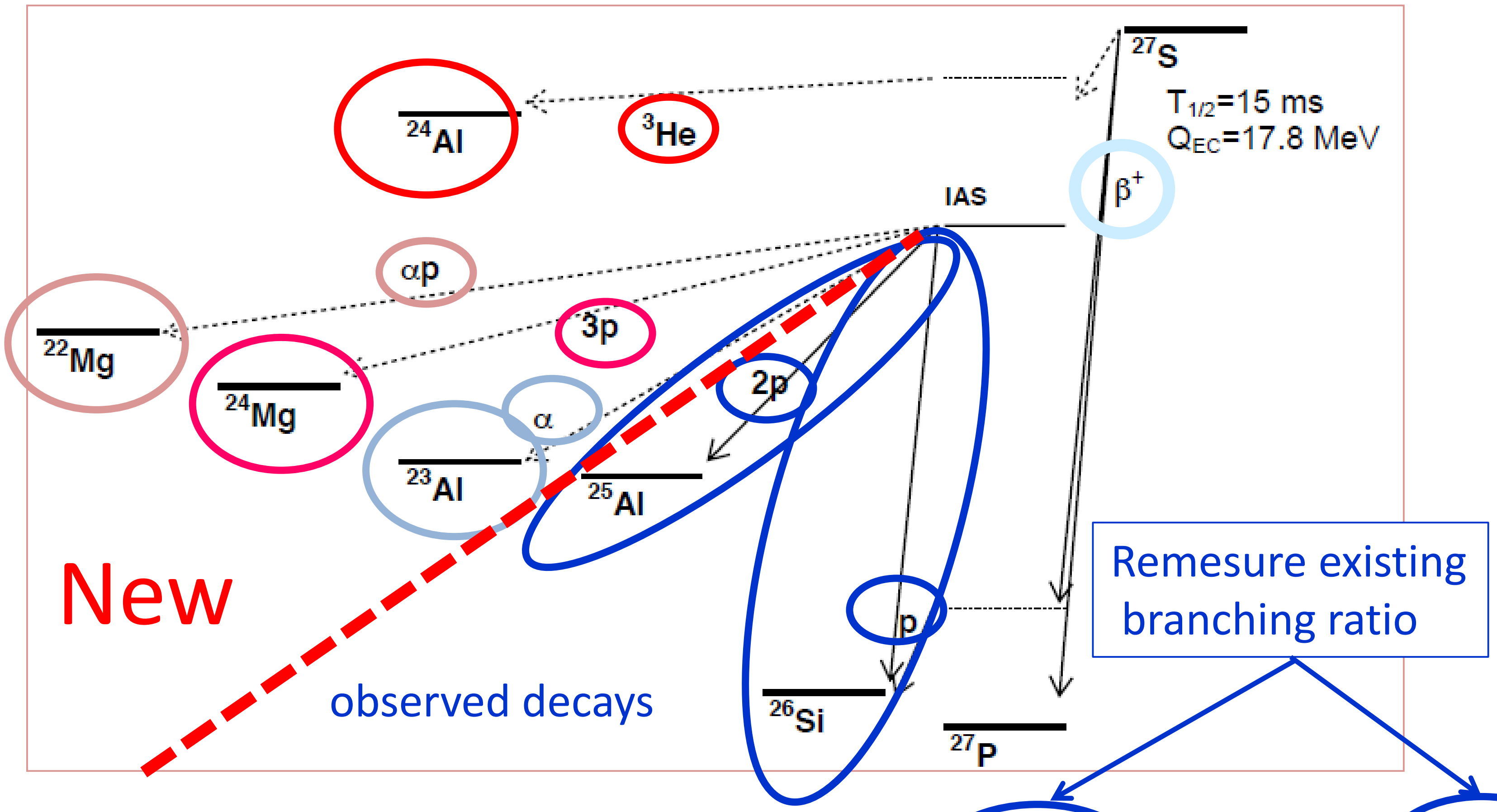
Study of β-delayed charged particle emission from ^{27}S





Canchel et al., EPJ A12 (2001) 377

Fig. 3. Charged-particle spectrum of the decay of ^{27}S nuclei implanted in the E3 silicon detector. Proton groups above about 7 MeV have to be reconstructed by summing the energy signals from detectors E3 and E4.



EPJ A12 (2001) 377: $T_{1/2}(^{27}S)$ = 15.5 ms; P(βp) = 2.3 ± 0.9%; P(β2p) = 1.1 ±0.5%

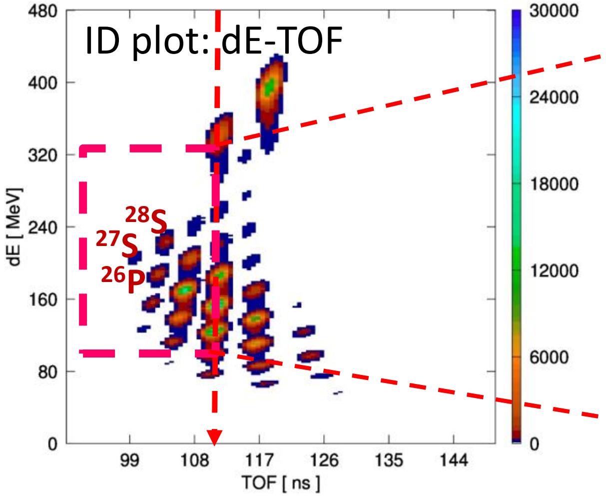
New possible decay channels:
β3p, βα, βαp, $β^3He$

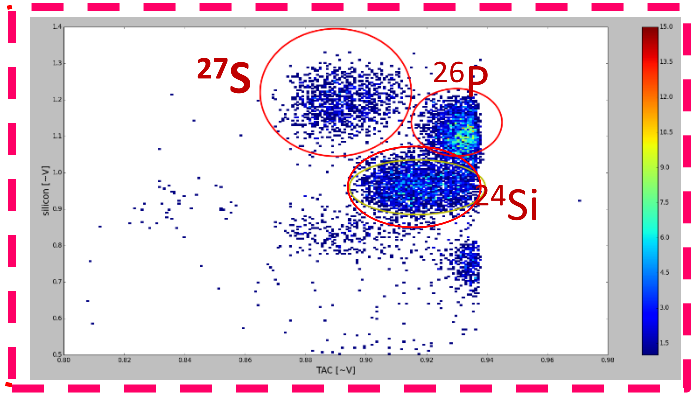
Direct observation of 2p emission
angular correlations between protons

β-delayed charged particles spectroscopy with the OTPC

^{27}S ($T_{1/2}$ = 15.5(15) ms), **^{26}P** ($T_{1/2}$ = 43.7(6) ms)

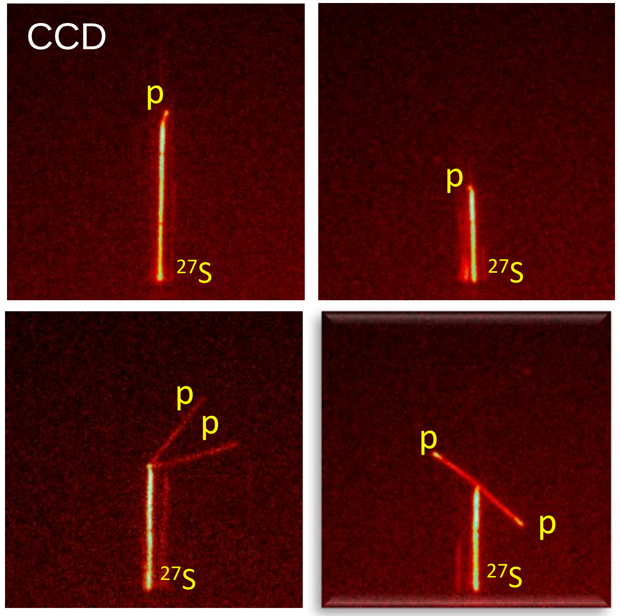
Identification of proton-rich isotopes at ACC-2 adjusted to the maximum yield of the ^{26}P and ^{27}S



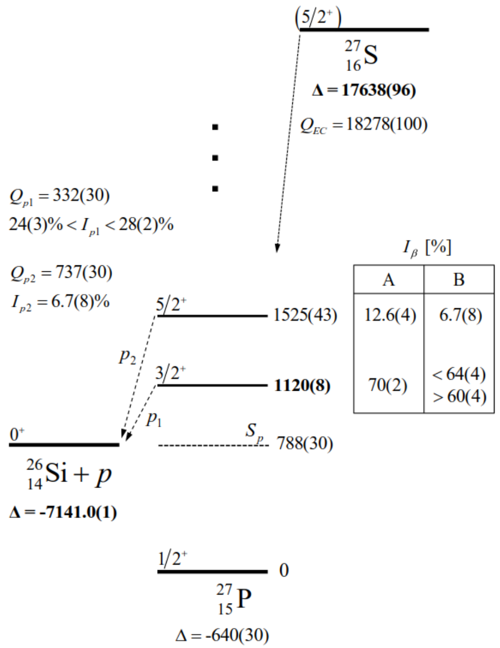


OTPC ID plot: dE-TOF (TOF gate)

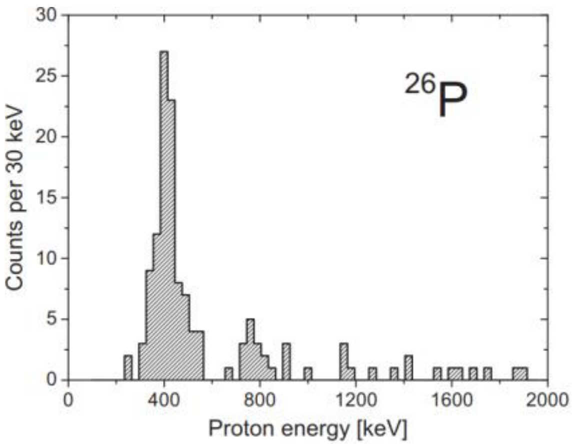
Example events of of 1p, 2p β-delayed emission in the decay of ^{27}S

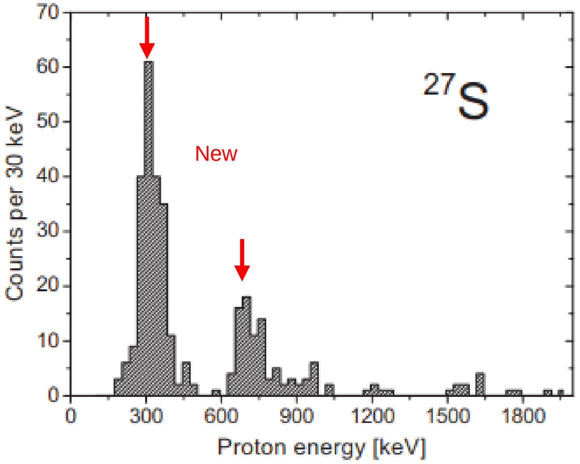


Part of decay scheme of ^{27}S measured with the OTPC at ACC (**L. Janiak et al.,**)



^{26}P				^{27}S			
$P_{\beta p}$ 415 кэВ	$P_{\beta p}$ ~800 кэВ	$P_{\beta 2p}$	P_{tot}	$P_{\beta p}$ 320 кэВ	$P_{\beta p}$ 710 кэВ	$P_{\beta 2p}$	P_{tot}
10.4(9)% ÷ 13.8(10)%	1.1(3)%	1.5(4)%	35(2)%	24(3)% ÷ 28(2)%	> 6.7(8)%	3.0(6)%	64(3) %
17.96(90) %	2.5(3)%	2.2(3)%	39(2)%	2.3±0.9%		1.1±0.5 %	~ 4%
Thomas et al., EPJ A21 (2004) 419				*Canchel et al.*, EPJ A12 (2001) 377			





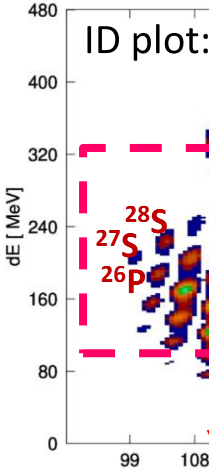
Energy spectrum of β-delayed protons

L. Janiak et al.,
Phys Rev. C 95 (2017) 034315]

β-delayed charged particles spectroscopy with the OTPC

^{27}S ($T_{1/2}$ =

Identificati



$P_{\beta p}$
415 кэВ
10.4(9)% ÷
13.8(10)%
17.96(90)
% Tho

PHYSICAL REVIEW C **103**, L061301 (2021)

Letter

β-delayed two-proton decay of ^{27}S at the proton-drip line

G. Z. Shi (石国柱),[1,2,3,*] J. J. Liu (刘嘉健),[1,*] Z. Y. Lin (林喆阳),[1,2] H. F. Zhu (朱浩钒),[1,4] X. X. Xu (徐新星),[1,5,6,3,7,†] L. J. Sun (孙立杰),[6,8,‡] P. F. Liang (梁鹏飞),[5] C. J. Lin (林承键),[6,9] J. Lee (李晓菁),[5] C. X. Yuan (袁岑溪),[10] S. M. Wang (王思敏),[11] Z. H. Li (李智焕),[11] H. S. Xu (徐瑚珊),[1,3,7] Z. G. Hu (胡正国),[1,3,7] Y. Y. Yang (杨彦云),[1] R. F. Chen (陈若富),[1] J. S. Wang (王建松),[12,1] D. X. Wang (王东玺),[6] H. Y. Wu (吴鸿毅),[11] K. Wang (王康),[1,13] F. F. Duan (段芳芳),[1,2] Y. H. Lam (蓝乙华),[1,3] P. Ma (马朋),[1] Z. H. Gao (高志浩),[1,2] Q. Hu (胡强),[1] Z. Bai (白真),[1] J. B. Ma (马军兵),[1] J. G. Wang (王建国),[1] F. P. Zhong (钟福鹏),[9,6] C. G. Wu (武晨光),[11] D. W. Luo (罗迪雯),[11] Y. Jiang (蒋颖),[11] Y. Liu (刘洋),[11] D. S. Hou (侯东升),[1,3] R. Li (李忍),[1,3] N. R. Ma (马南茹),[6] W. H. Ma (马维虎),[1,14] G. M. Yu (余功明),[1,15] D. Patel,[1,16] S. Y. Jin (金树亚),[1,3] Y. F. Wang (王煜峰),[1,17] Y. C. Yu (余悦超),[1,17] Q. W. Zhou (周清武),[1,18] P. Wang (王鹏),[1,18] L. Y. Hu (胡力元),[15] X. Wang (王翔),[11] H. L. Zang (臧宏亮),[11] P. J. Li (李朋杰),[5] Q. R. Gao (高祺锐),[1] H. Jian (简豪),[1] S. X. Zha (查思贤),[1,3] F. C. Dai (戴凡超),[1,3] R. Fan (范锐),[1,3] Q. Q. Zhao (赵青青),[5] L. Yang (杨磊),[6] P. W. Wen (温培威),[6] F. Yang (杨峰),[6] H. M. Jia (贾会明),[6] G. L. Zhang (张高龙),[19] M. Pan (潘敏),[19,6] X. Y. Wang (汪小雨),[19] H. H. Sun (孙浩瀚),[6] X. H. Zhou (周小红),[1,3,7] Y. H. Zhang (张玉虎),[1,3,7] M. Wang (王猛),[1,3,7] M. L. Liu (柳敏良),[1] H. J. Ong (王惠仁),[1,3,20,21] and W. Q. Yang (杨维青)[1]

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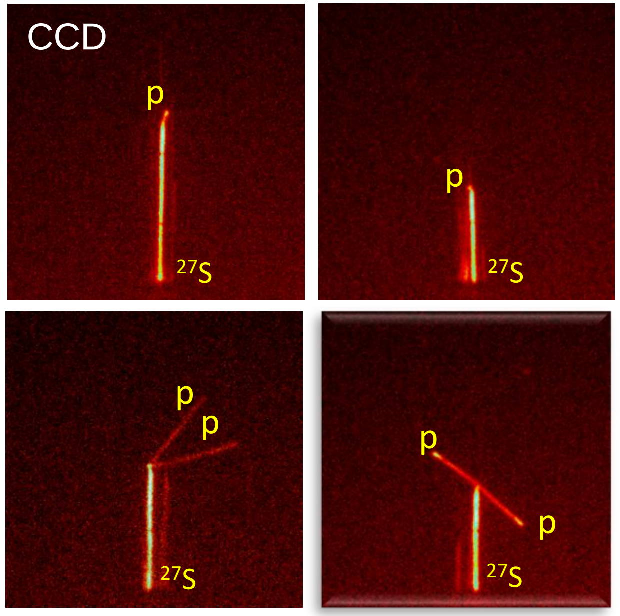
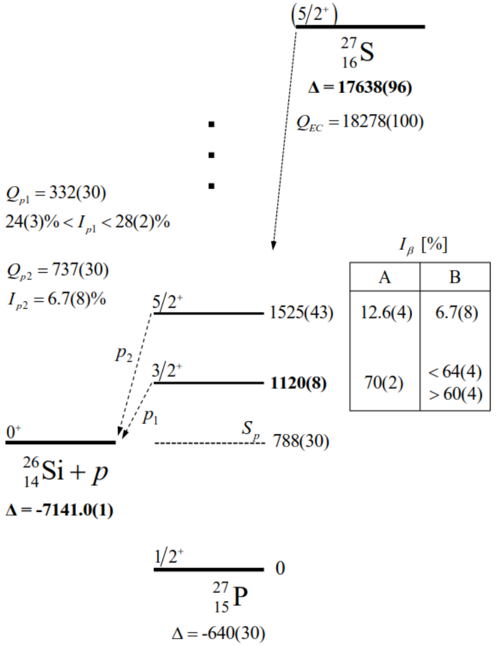
The β-delayed two-proton (β2p) decay of ^{27}S was studied using a state-of-the-art silicon array and Clover-type HPGe detectors. An energy peak at 6372(15) keV with a branching ratio of 2.4(5)% in the decay-energy spectrum was identified as a two-proton transition via the isobaric-analog state in ^{27}P to the ground state of ^{25}Al in the β decay of ^{27}S. Two-proton angular correlations were measured by the silicon array to study the mechanism of two-proton emission. Based on experimental results and Monte Carlo simulations, it was found that the main mechanism for the emission of β2p by ^{27}S is of sequential nature.

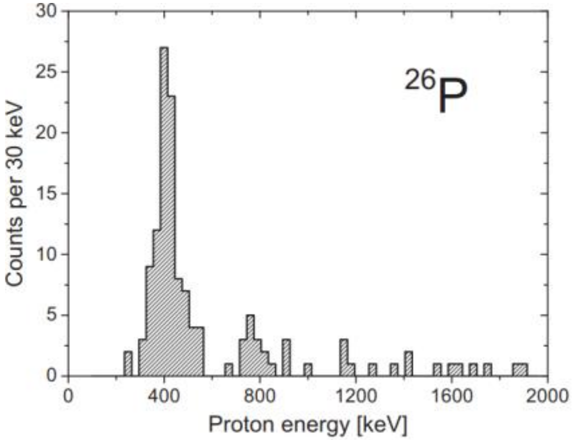
DOI: 10.1103/PhysRevC.103.L061301

Example events of of 1p, 2p β-delayed emission in the decay of ^{27}S

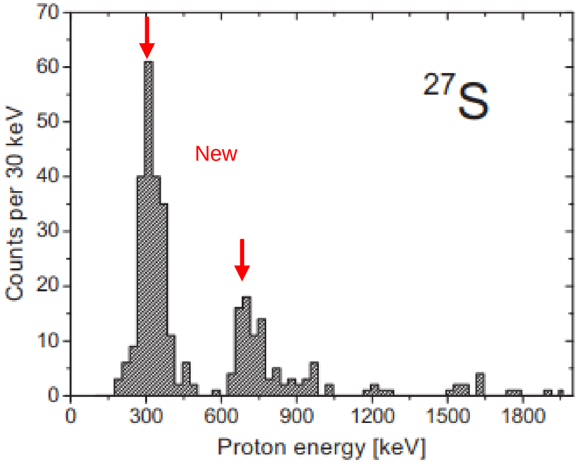


Part of decay scheme of ^{27}S measured with the OTPC at ACC (**L. Janiak et al.,**)

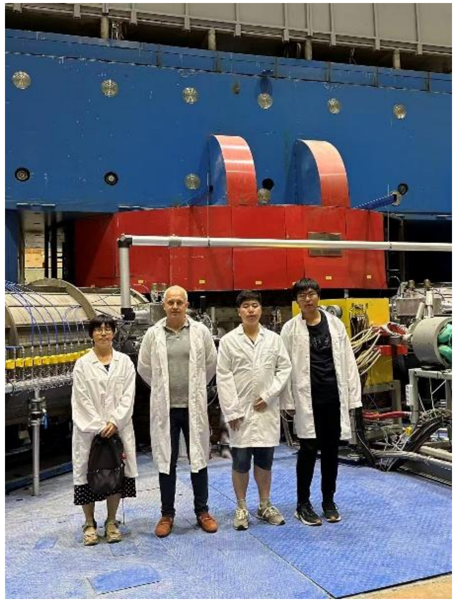




Energy spectrum of β-delayed protons



L. Janiak et al.,
Phys Rev. C 95 (2017) 034315]

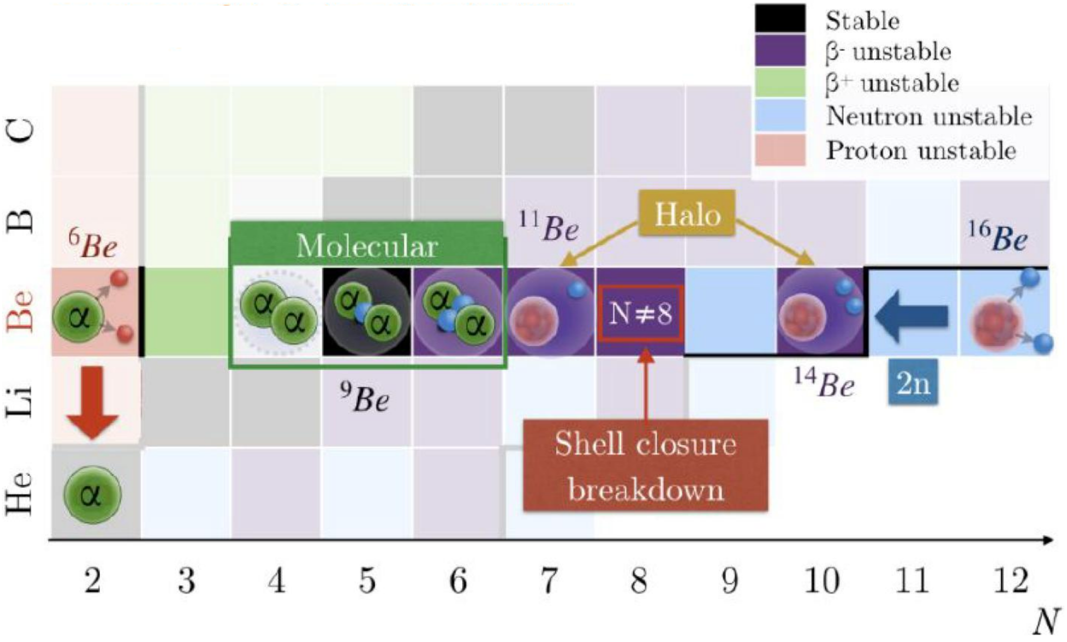


FLNR, JINR, Dubna July 2024

… Common proposal

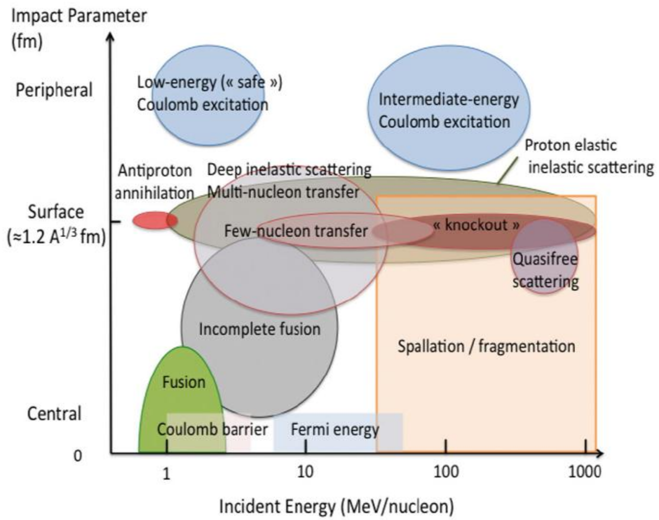
Prof. Jianling Lou, Hongyu Zhu, and Bolong Xia at FLNR, JINR, July 2024

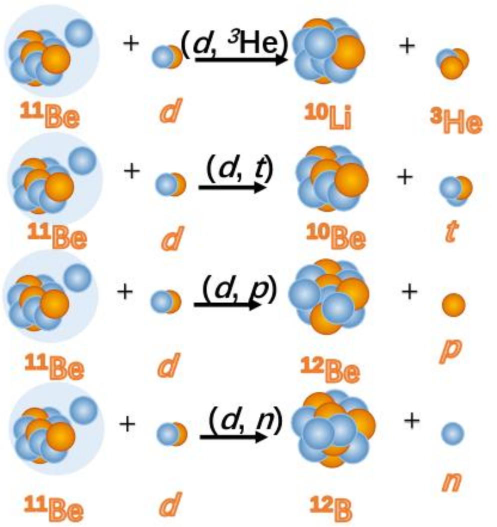
Discussion with Prof. Yuri Oganessian



Direct nuclear reaction

Elastic scattering， inelastic scattering， transfer reactions， knock out, charge change, charge exchange and so on

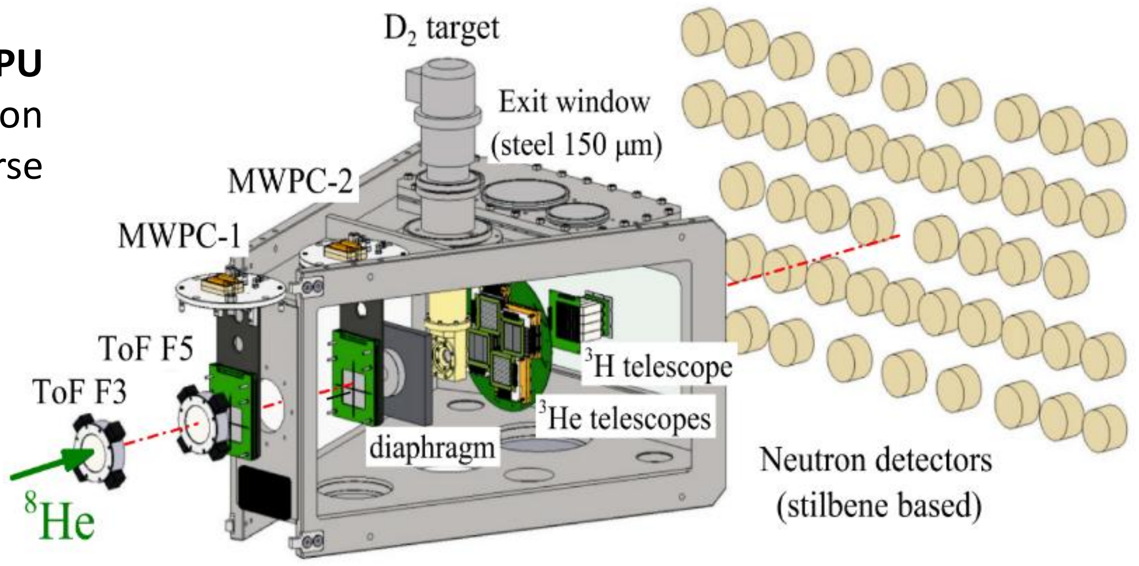


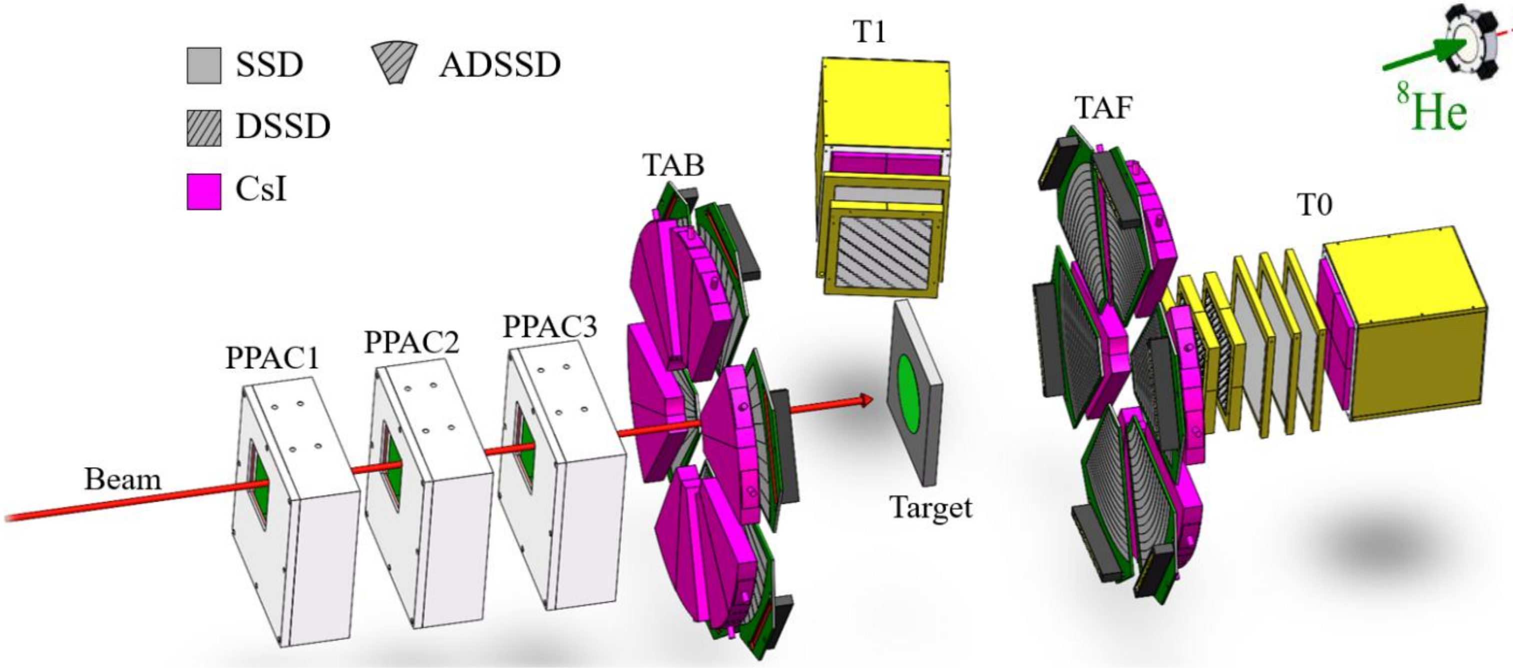


Proposal for a long term common study of ^{10,12,14}Be at ACCULINNA-2

Large **A**cceptance **C**harged particle detector array at **P**eking **U**niversity, **LACPU** dedicated for the simultaneous measurement of various different reaction channels induced by radioactive beams on protons and deuterons in inverse kinematics [1,2].

1. G. Li, J. L. Lou, Y. L. Ye, et al. Nucl Inst & Meth A, 2021, 1013, 165637.
2. H.Y. Zhu, J. L. Lou, Y. L. Ye, et al.Nucl. Sci& Tech, 2023, 34,159.





Schematic view of LACPU (not in scale). The target-like particles from various channels except the $d(^{10}\text{Be},^6\text{Li})^6\text{He}$ channel are measured by the Telescope T1,TAF,and TAB with a one-fold trigger, and at the same time the corresponding projectile-like particles were passively recorded by the telescope T0. For the $d(^{10}\text{Be},^6\text{Li})^6\text{He}$ reaction channel, both ^{6}Li and ^{6}He are coincidently detected by the telescope T0 with a two-fold trigger.

- Investigate the α cluster configurations in the ground state of **^{10,12,14}Be** using the transfer reaction **(d,^{6}Li)** in inverse kinematics for the first time
- Identify α cluster configuration from overwhelming 1p,1n single-particle configurations

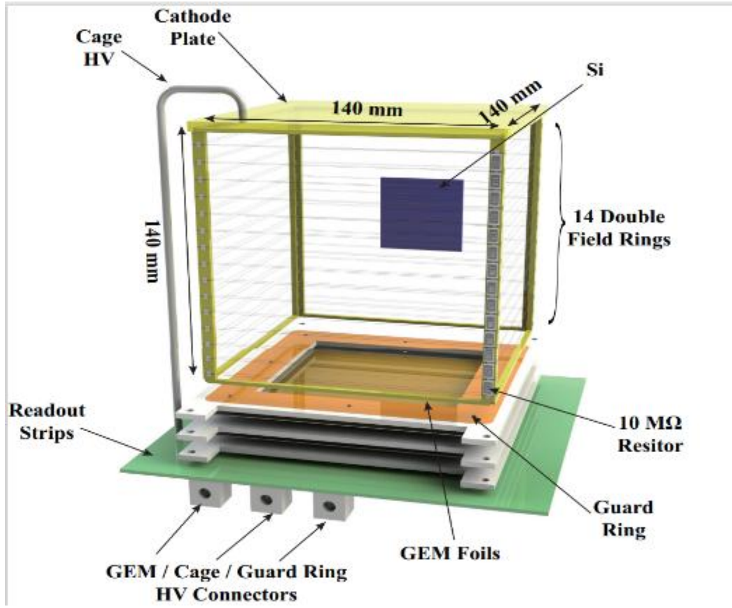
✓ (d,^{3}He),**(d,p)** and (d,^{4}He) will be measured at the same experiment

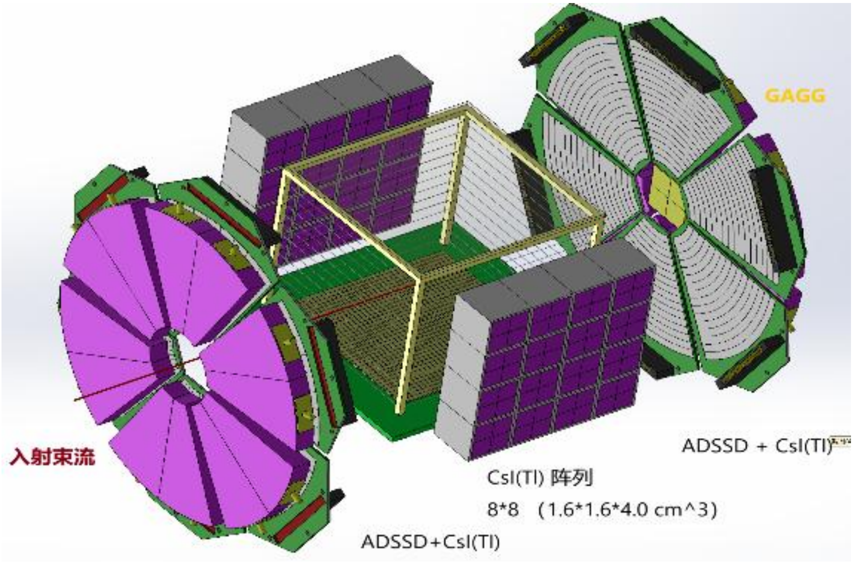
✓ to investigate shell evolution in Be, Li isotopes

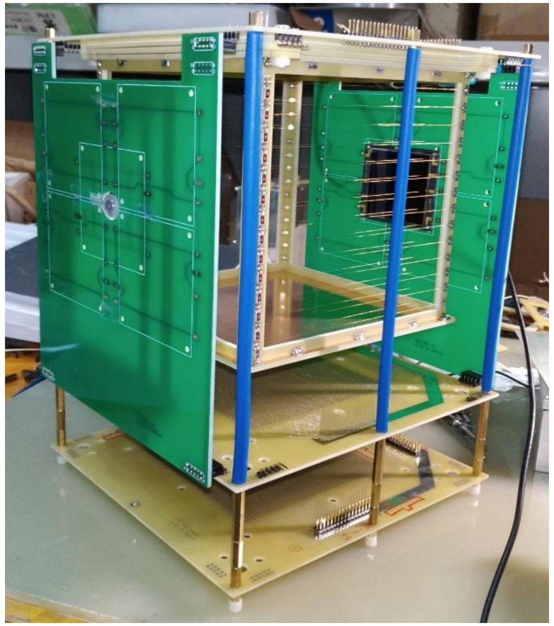
✓ quenching of spectroscopic factor, nucleon-nucleon correlations

Proposal for a long term common study of ^{10,12,14}Be at ACCULINNA-2

Future plans – implementation of AT-TPC technique

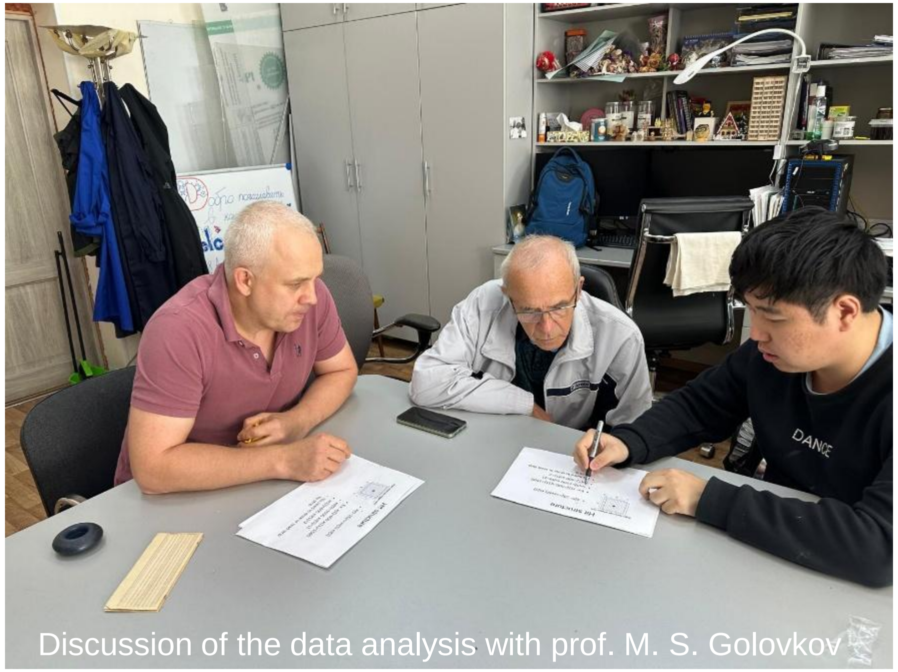






Cluster structure of Be ground state.
First steps:
- Performing a test run: ^{10}Be + d $\to$ ^{6}Li + ^{6}He (May 2025)
- Openning a post doc fellow a position.

August 2025 - Hongyu Zhu from PKU visiting FLNR as a postdoc fellow at FLNR, JINR for common experiment planning with PKU, Beijing


Discussion of the data analysis with prof. M. S. Golovkov

Second step:
- Full time measurement of the reaction: ^{10}Be + d $\to$ ^{6}Li + ^{6}He (May 2026)

With collaborators from PKU.

Planned research areas: 2025 - 2028

- Structure of neutron-rich isotopes in **(d,p), (d,t), (d,^{3}He)** reactions
- Impact of the reaction mechanism on population of low energy spectra of exotic nuclear systems
- Exotic radioactivity - formation of **2*p*** radioactive nuclei in **(^{3}He,n)** and **(p,d)** reactions
- Study of production cross sections of exotic nuclei
- Beyond the nucleon stability line with **2n**-transfer **^{10}He,^{13}Li,^{16}Be** using tritium-target. Lighter neutron-rich isotopes like **^{6,8}He, ^{11}Li, $^{11-14}$Be** are also in the zone of interest
- Study the energy dependence of total reaction cross section in the reactions **$^{10-14}$Be+^{28}Si, $^{12-15}$B+^{28}Si, etc.**

Transfer reactions via ^{2}H target

- ^{6}He(d,^{3}He)^{5}H
- ^{6}He(d,t)^{5}He
- ^{6}He(d,p)^{7}He

Transfer reactions on H target

- ^{7}Be(p,d)^{6}Be
- ^{8}B(p,d)^{7}B
- ^{9}C(p,d)^{8}C

$\sigma_R(E)$ and $\sigma_\Sigma(E)$

- $^{10-14}$Be+^{28}Si
- $^{12-15}$B+^{28}Si

Transfer reactions on ^{3}He target

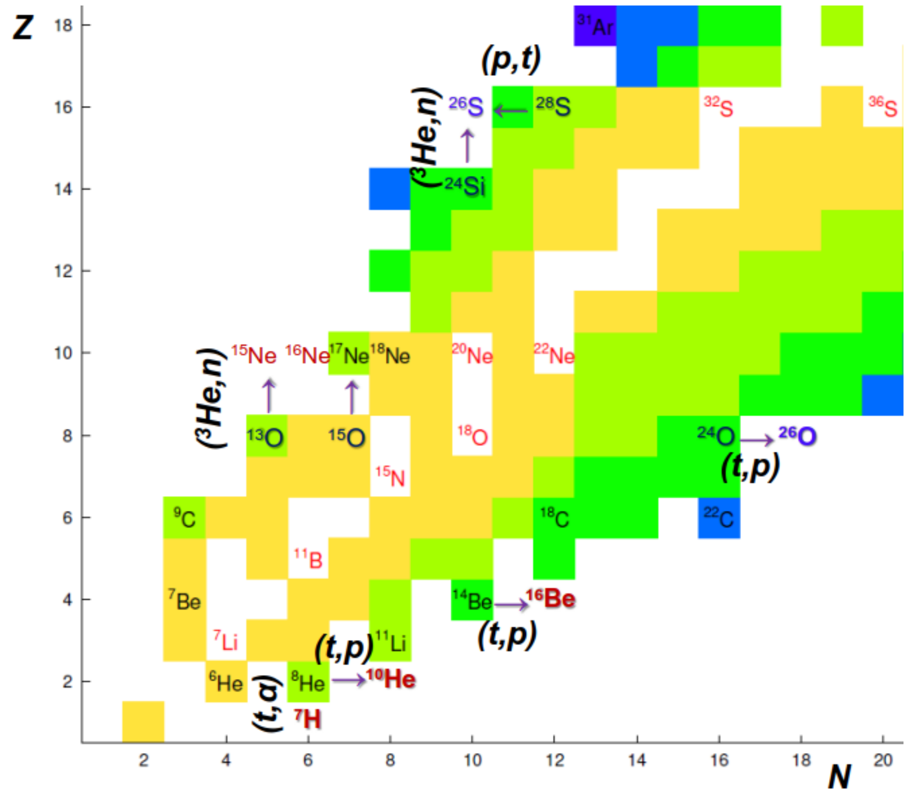
- ^{13}O(^{3}He,n)^{15}Ne
- ^{24}Si(^{3}He,n)^{26}S

Transfer reactions on ^{3}H target

- ^{8}He(t,p)^{10}He
- ^{14}Be(t,p)^{16}Be
- ^{8}He(t,α)^{7}H

Charge-exchange reactions

- (p,n),(^{3}He, ^{3}H),(^{3}He, ^{3}H)

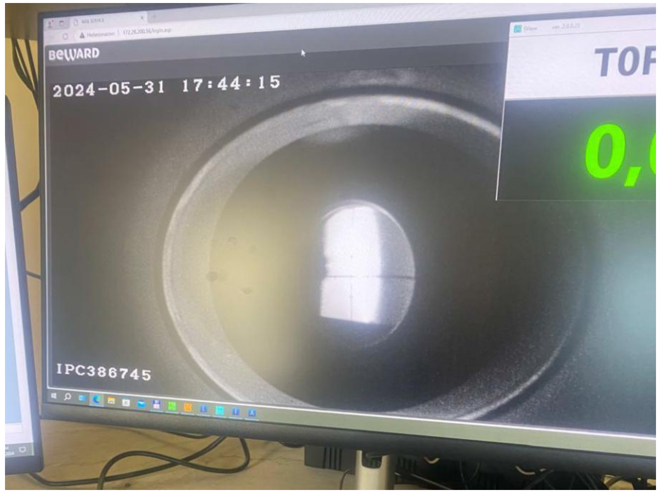


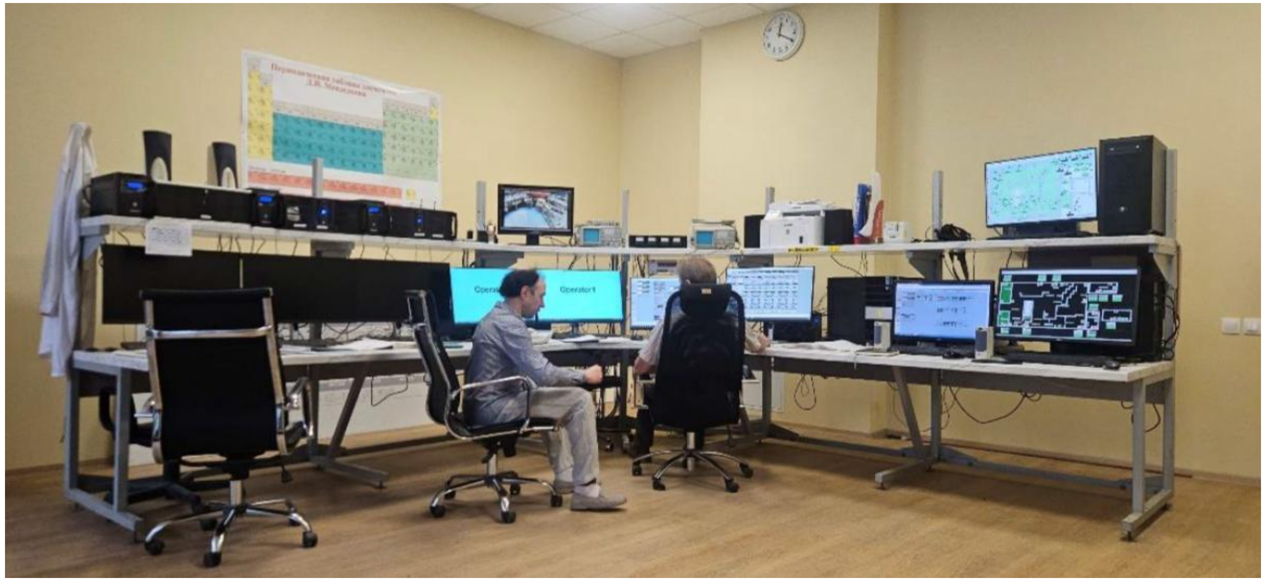
U400M commissioning with accelerated beam

Start 13.05.2024

First beam: $^{40}Ar^{11+}$ **(E=39.2 MeV/n)**

First extracted beam: **31.05.2024**



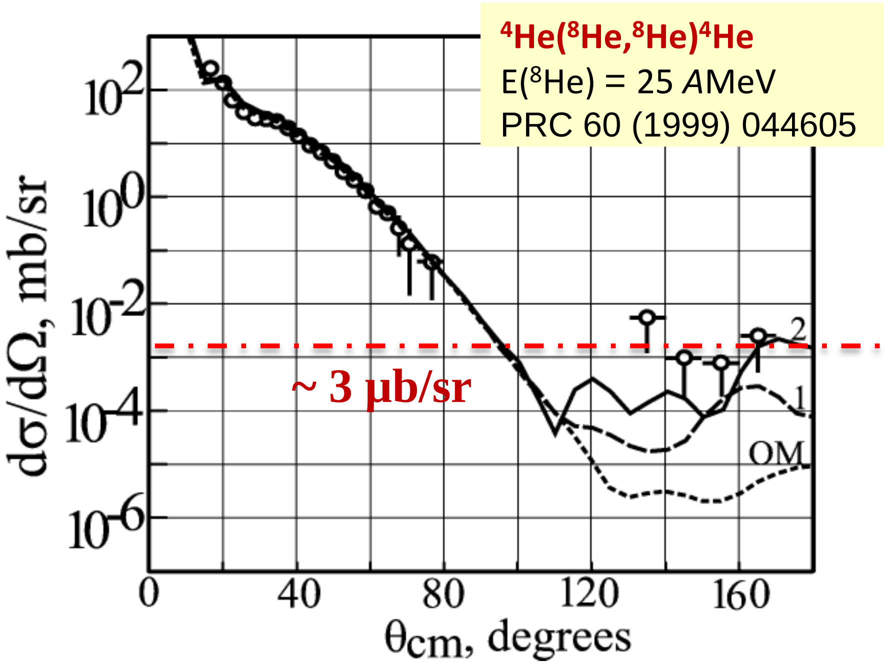


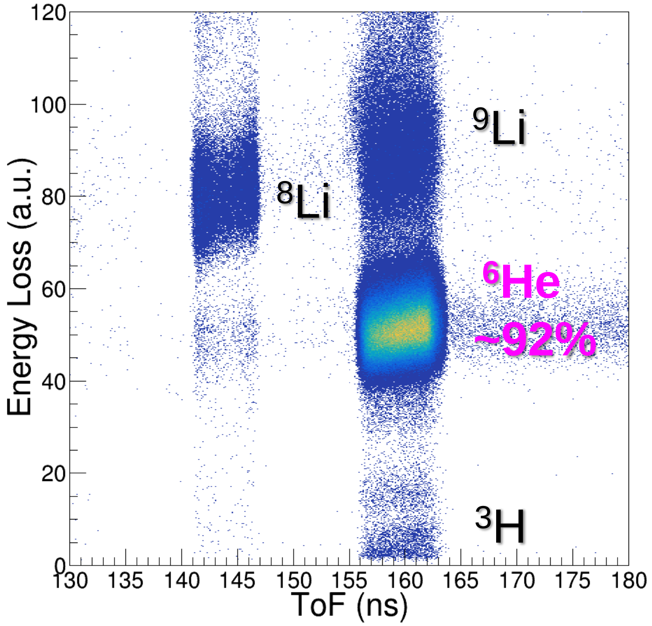
Program of commissioning methodological-technical works for 2024-2025 (2024-2025)

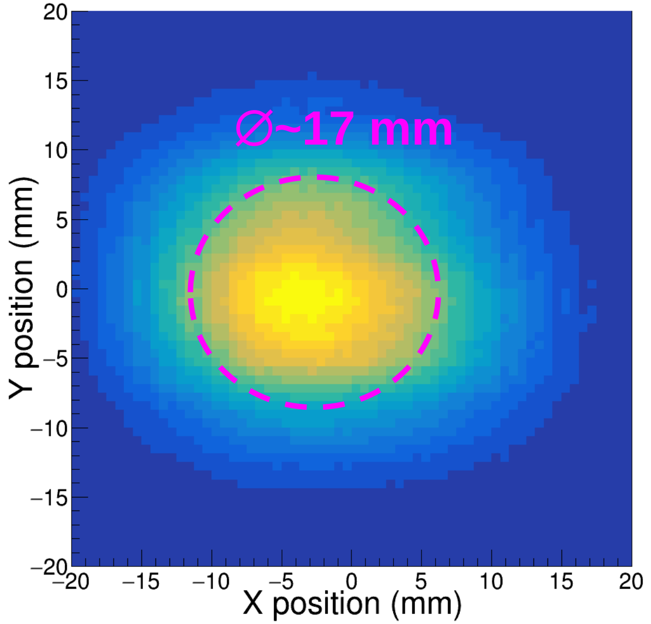
1. Testing of ACCULINNA-2 systems (production target-Be, slits, particle tracking, TOF, cryogenic targets ^{4}He, D_2 ..)
2. Yields measurements of ^{6}He, ^{8}He, ^{12}Be beams in the ^{15}N(51 *A*MeV) и ^{18}O(49 *A*MeV) reactions at ^{9}Be (2 мм) in a wide energy region(E ~ 25 ÷ 55 *A*MeV)
3. Study of the ^{4}He(^{6}He,^{6}He)^{4}He reaction at E(^{6}He) ~ 32 *A*MeV as a preparation for ^{4}He(^{8}He,^{8}He)^{4}He
4. Other measurements (spring 2025) :

^{2}H(^{6}He,^{1}H)^{7}He, ^{2}H(^{10}Be,^{6}Li)^{6}He, ...

(at I_{beam} ~ 10^5 1/s)

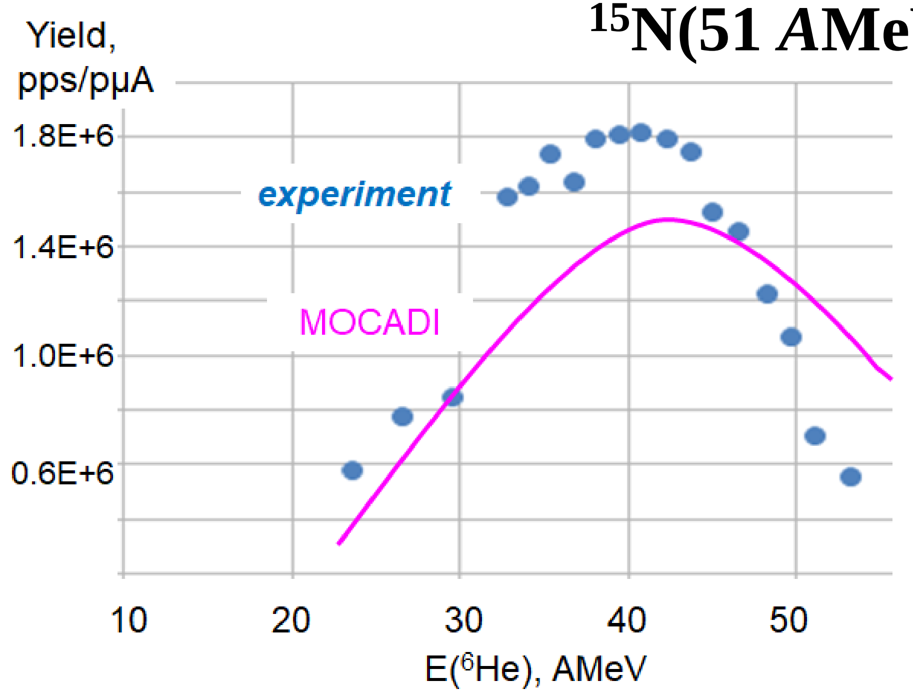


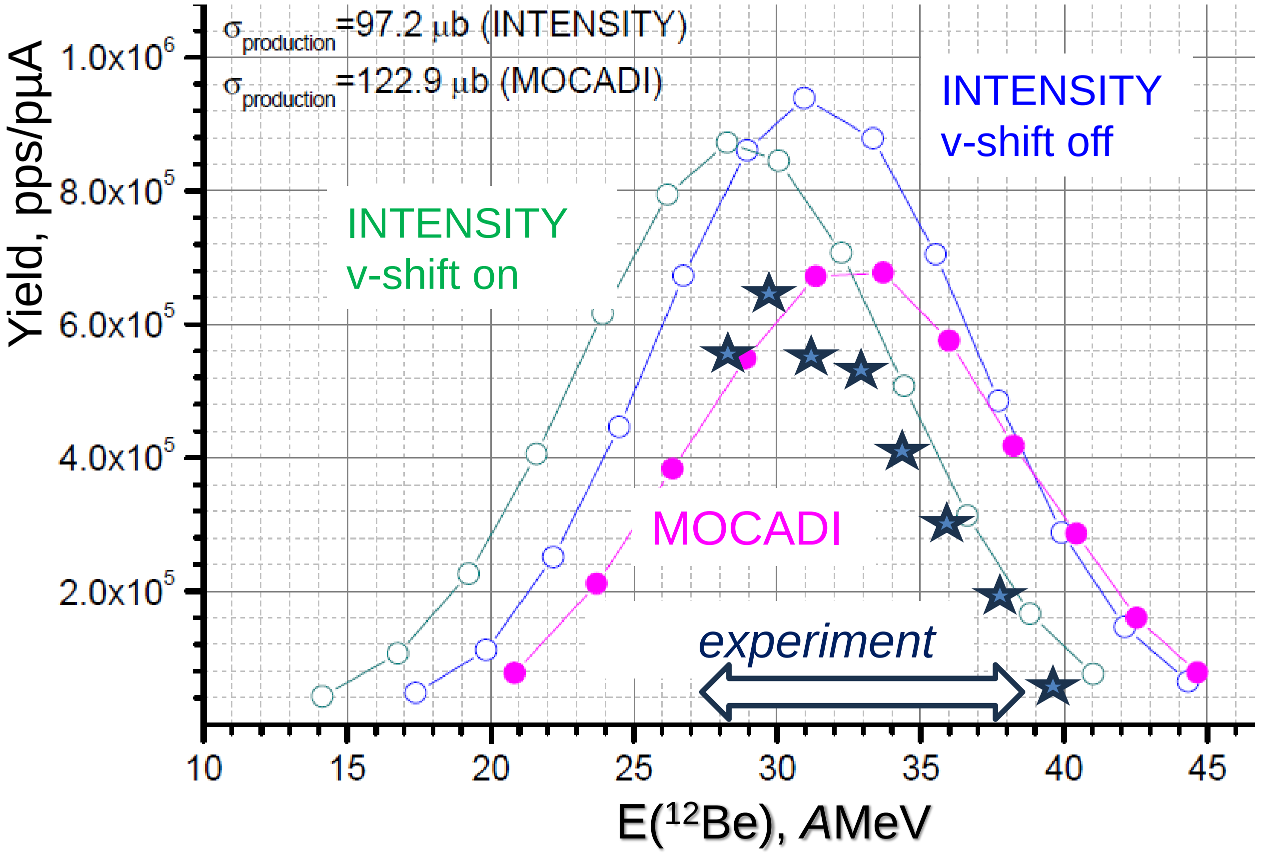


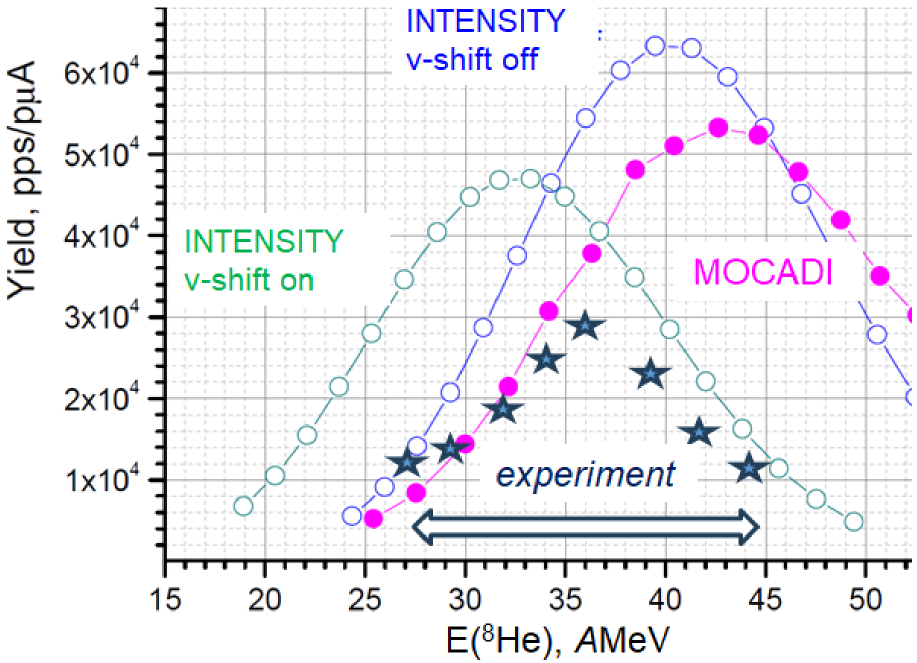


E(^{6}He) ~ 32 *A*MeV, I ~ 10^6 1/s

^{15}N(51 *A*MeV) + Be(2 mm) → ^{6,8}He and ^{12}Be







	^{6}He	^{8}He	^{12}Be
I_{max}, pps	1.8*10^{6}	3.1*10^{4} / 5.2*10^{4}	6.2*10^{5}
E, *A*MeV	40	36	30

^{18}O@49 *A*MeV(!)

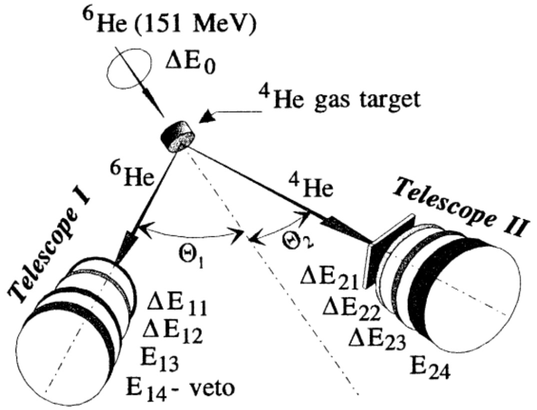
First experiments at ACCULINNA-2 since in 2024

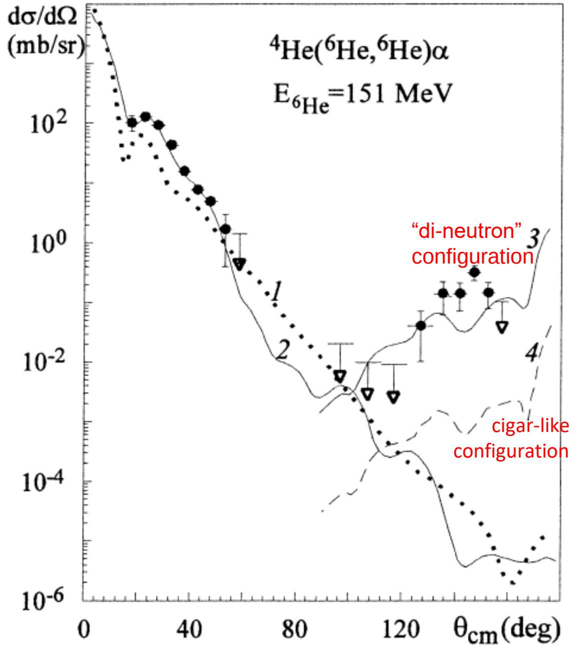
Search for the „di-neutron” configuration of the ^{6}He - a kind of “performance test”
of the new upgraded U400M complex and the ACCULINNA-2 separator

^{4}He(^{6}He,^{6}He)^{4}He: ACCULINNA-1

Physics Letters B 426 (1998) 251,
Two-neutron exange observed in the ^{6}He + ^{4}He reaction.
Search for the „di-neutron” configuration of the ^{6}He

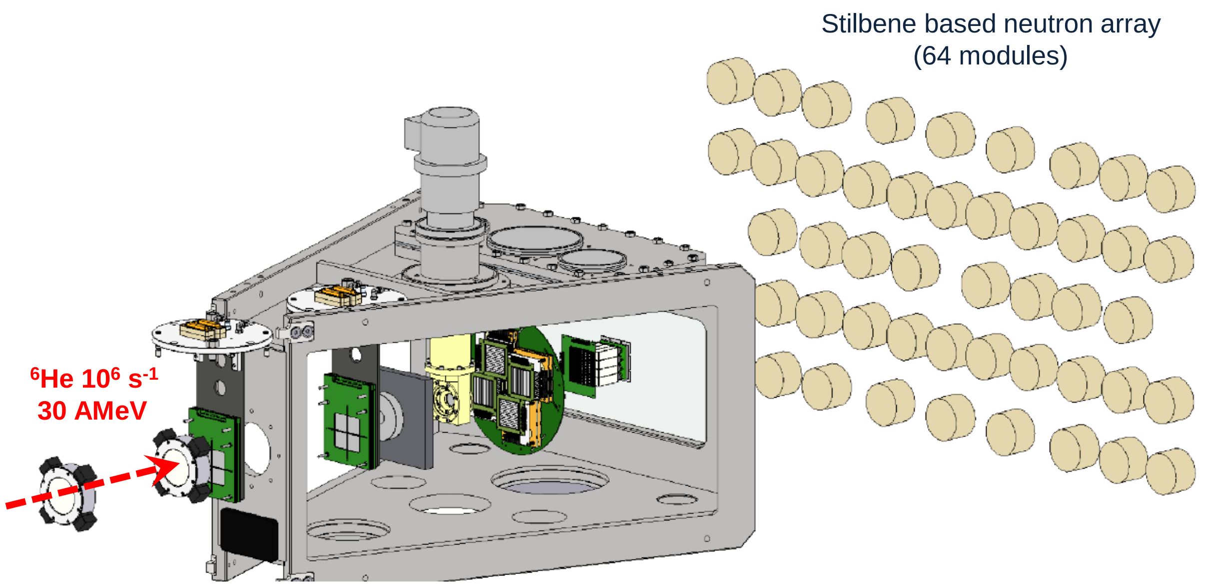
G.M. Ter-Akopian, A.M. Rodin, A.S. Fomichev, S.I. Sidorchuk, S.V. Stepantsov, R. Wolski, M.L. Chelnokov, V.A. Gorshkov, A.Yu. Lavrentev, V.I. Zagrebaev, Yu.Ts. Oganessian





Cigar-like configuration of ^{6}He (4) could contribute negligibly to the obtained 2*n* exchange, which is ~100% due to the di-neutron configuration (3).

^{4}He(^{6}He,^{6}He)^{4}He, ^{4}He(^{8}He,^{8}He)^{4}He : more statistics at ACCULINNA-2 with high quality, event by event mode ($I_{^6He}$< 3*10^6 s^{-1})

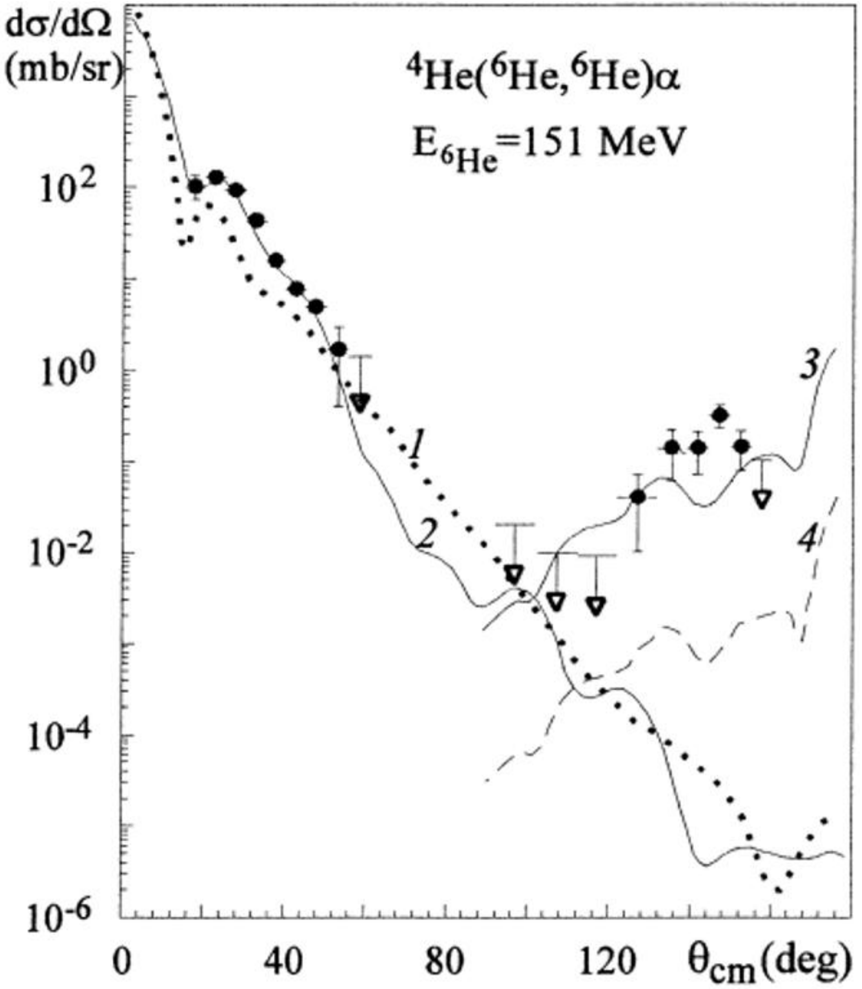


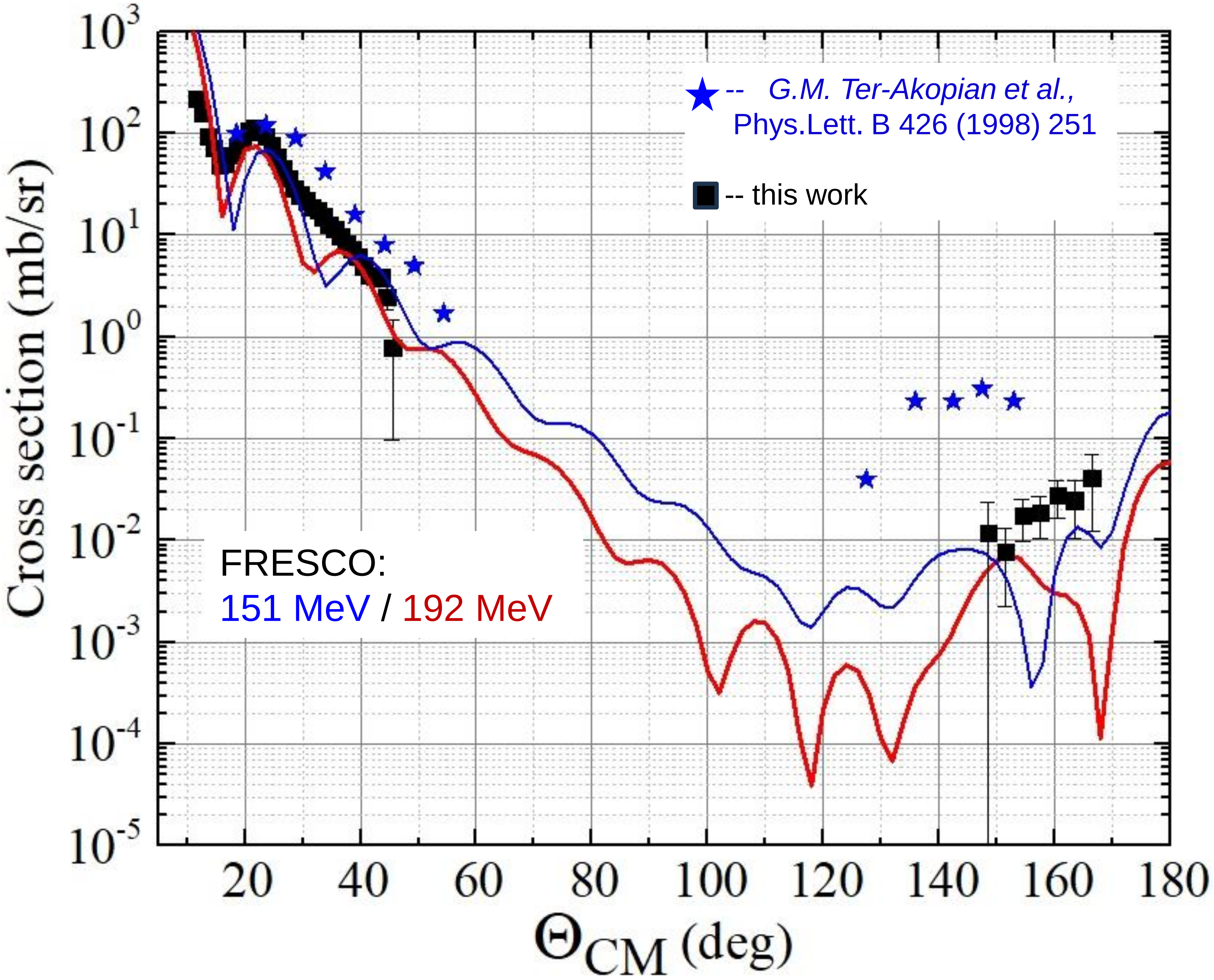
^{6}He beam: I ~ 10^5 s^{-1} (6.5 mm beam spot without tracking)
^{4}He target: ~ 5.6*10^{20} cm^{-2} (5 atm @ 78K, 12 mm thick)
Detectors: two units with ~ 75 msr solid angle

< Factor ~100 >

^{6}He beam: I ~ 2*10^6 s^{-1} (X,Y ~ 1.5 mm, DE/E ~ 1 %)
^{4}He target: ~ 0.6*10^{20} cm^{-2} (2 atm @ 10K, 4 mm thick)
Detectors: four units ~ 100 msr solid angle each

$^4He(^6He,^6He_{g.s.})^4He$ @ $E(^6He)$=192 MeV and $E(^6He)$=151 MeV :

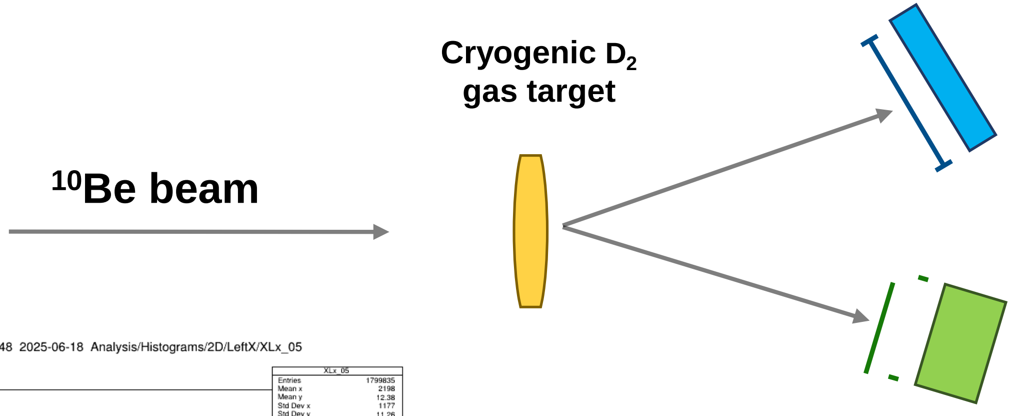




SPRING 2025 - pilot measurements

1. Cluster structure of Be ground state
2. Cluster structure of Be excited states
3. Proton transfer reaction

Left telescope
ΔE - DSSD_300 μm
E - 3x3 LYSO_30 mm



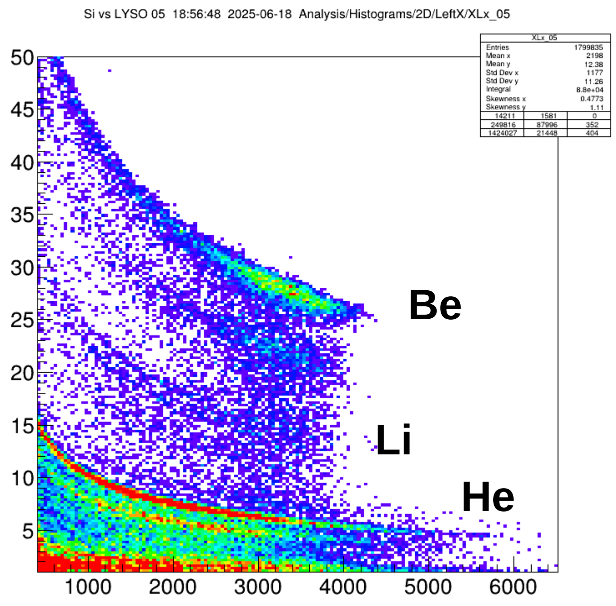
Right telescope
ΔE - DSSD_300 μm
E - 4x4 CsI(Tl)_50 mm

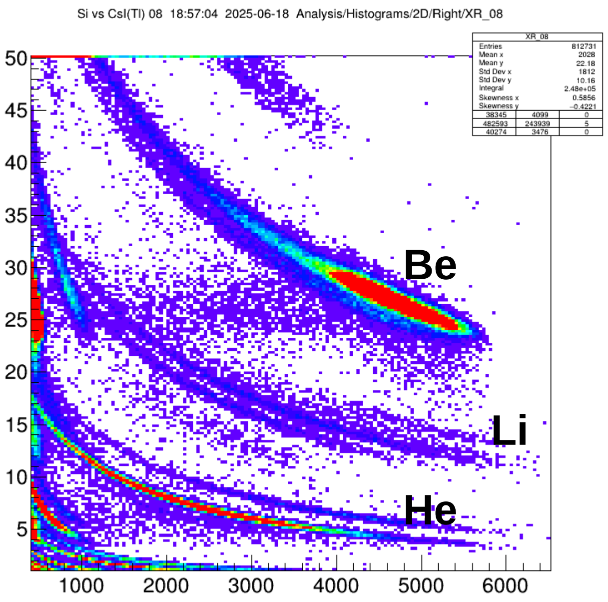
1. Cluster structure of Be ground state

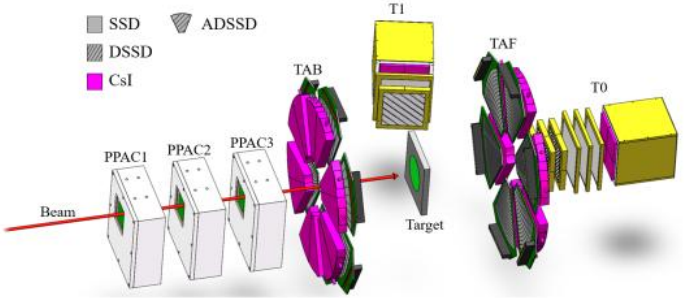
$^{10,12,14}\mathrm{Be} + d \rightarrow {}^{6}\mathrm{Li} + {}^{x}\mathrm{He}$

CHINESE PROPOSAL FOR EXPERIMENT
SPOKESPERSON: Jianling Lou

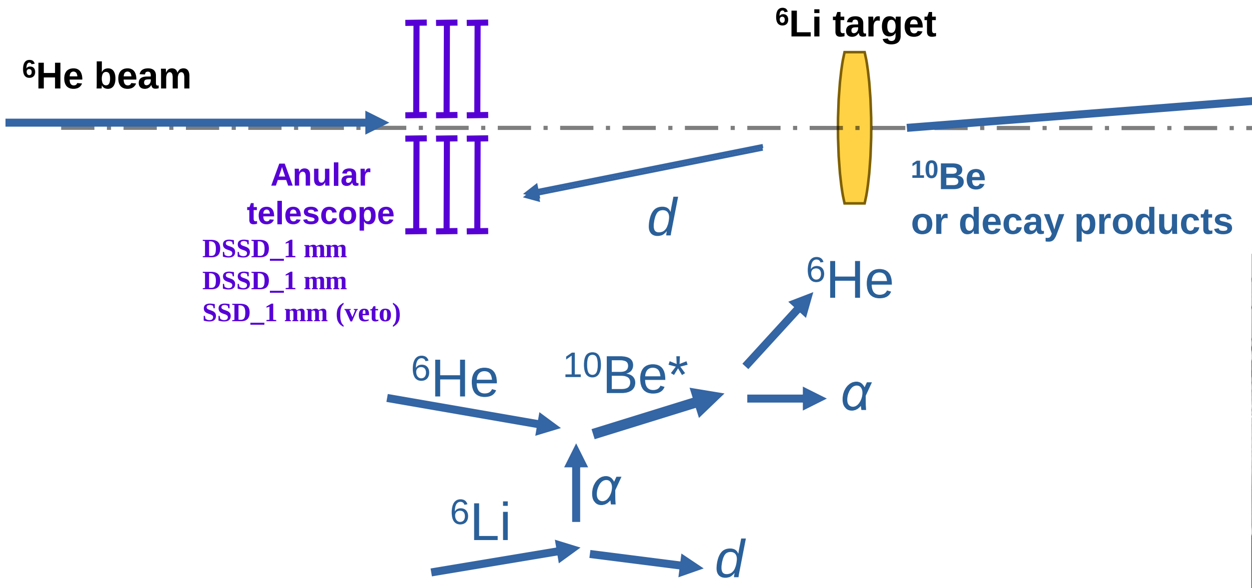
TITLE:Investigation of cluster structures in neutron-rich ^{10,12,14}Be via transfer reactions

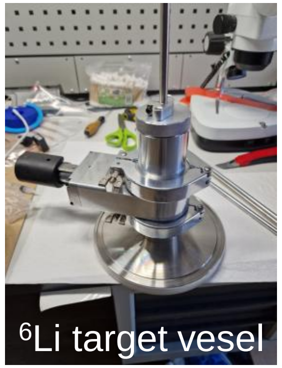


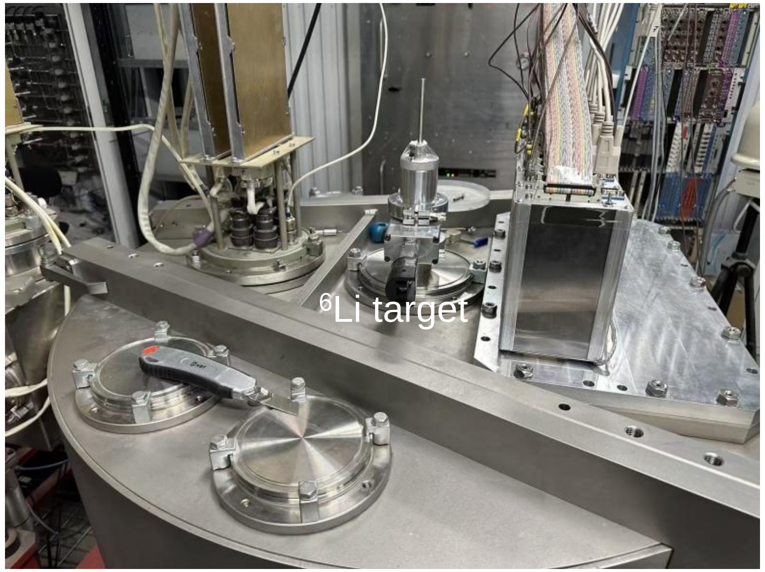




2. Cluster structure of Be excited states ^{6}He(^{6}Li,*d*)^{10}Be in inverse kinematics



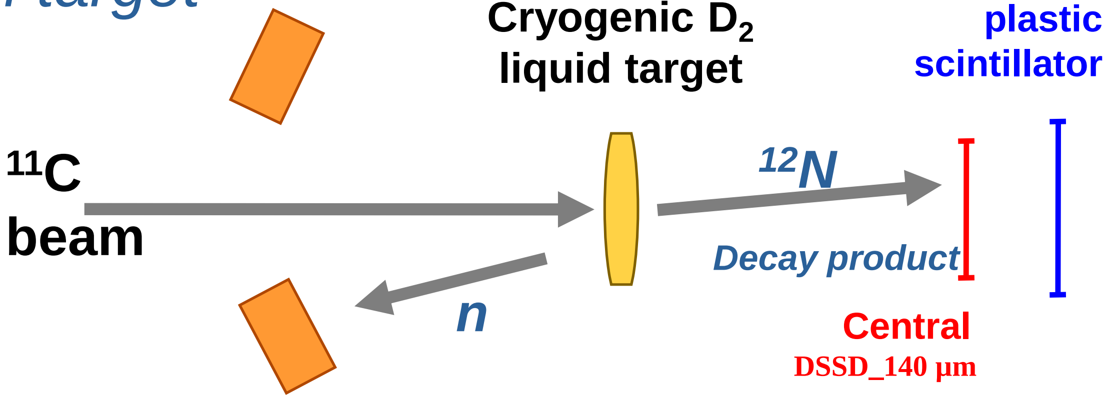


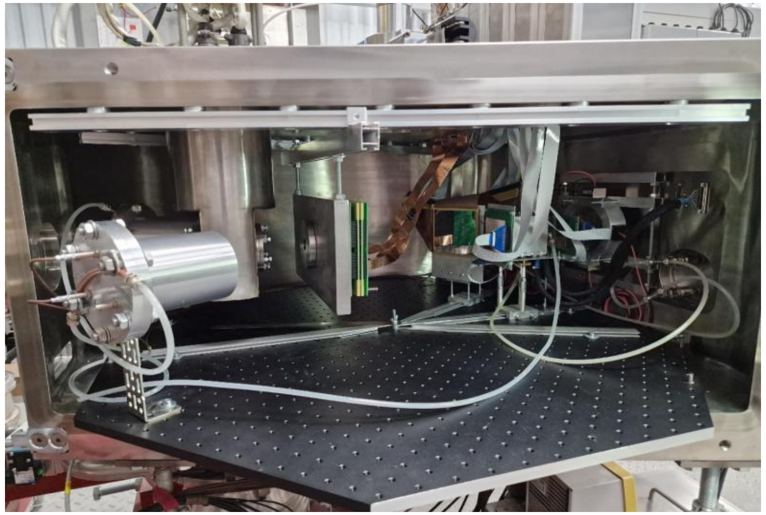


3. Proton transfer reaction

$^{11}C + d \rightarrow ^{12}N + n$

liquid deuterium target





Flagship experiments at ACCULINNA-2 since 2025

1. ^{6,8}He + ^{4}He $\rightarrow$ elastic/inelastic scattering and 2*n*, 4*n* transfer

2. ^{8}He + ^{2}H $\rightarrow$ *4n via* ^{2}H(^{8}He, ^{6}Li)^{4}n, ^{2}H(^{8}He, ^{6}Li*)^{4}n, ^{2}H(^{8}He, ^{3}He)^{7}H$\rightarrow$^{3}H+^{4}n

3. ^{10,12,14}Be + ^{2}H $\rightarrow$ ^{6}Li + ^{6,8,10}He molecular configurations in ^{10,12,14}Be states

4. ^{12}Be + ^{9}Be $\rightarrow$ ^{9}C + ^{12}He double charge exchange

5. ^{14}Be + ^{3}H $\rightarrow$ ^{5}Li + ^{12}He 2*p* transfer / ^{14}Be + ^{4}He $\rightarrow$ ^{6}Be + ^{12}He /
$\rightarrow$ ^{7}Li + ^{10}He α transfer / ^{14}Be + ^{4}He $\rightarrow$ ^{8}Be + ^{10}He /

6. ^{14}Be + ^{3}H $\rightarrow$ *p* + ^{16}Be 2*n* transfer / ^{8}He + ^{3}H $\rightarrow$ *p* + ^{10}He, ^{11}Li + ^{3}H $\rightarrow$ *p* + ^{13}Li /

7. ?

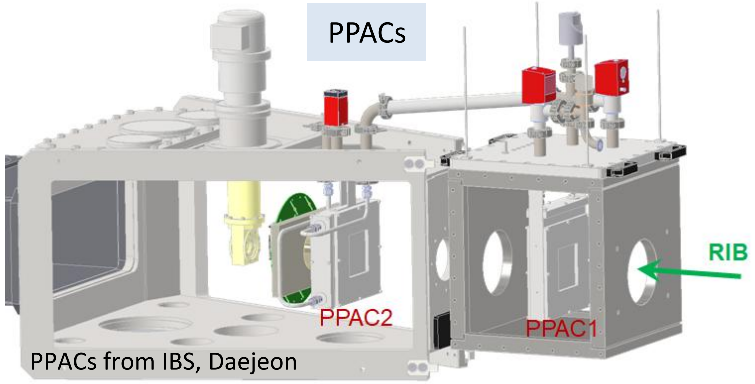
^{18}O@49 *A*MeV(!)

	^{6}He	^{8}He	^{12}Be	^{14}Be
I_{max}, pps@1 pμA	1.8*10^{6}	3.1*10^{4} / 5.2*10^{4}	6.2*10^{5}	1.2*10^{3}
E, *A*MeV	40	36	30	25

^{15}N@51 *A*MeV

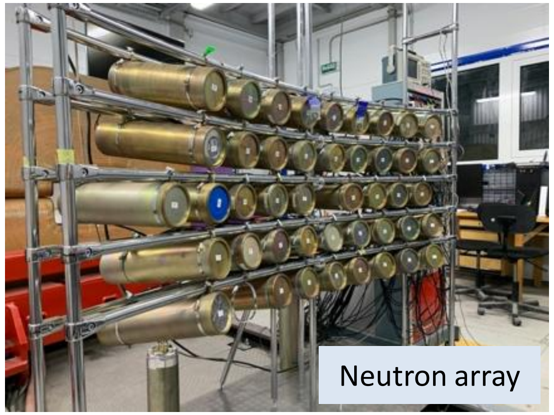
Instrumentation development

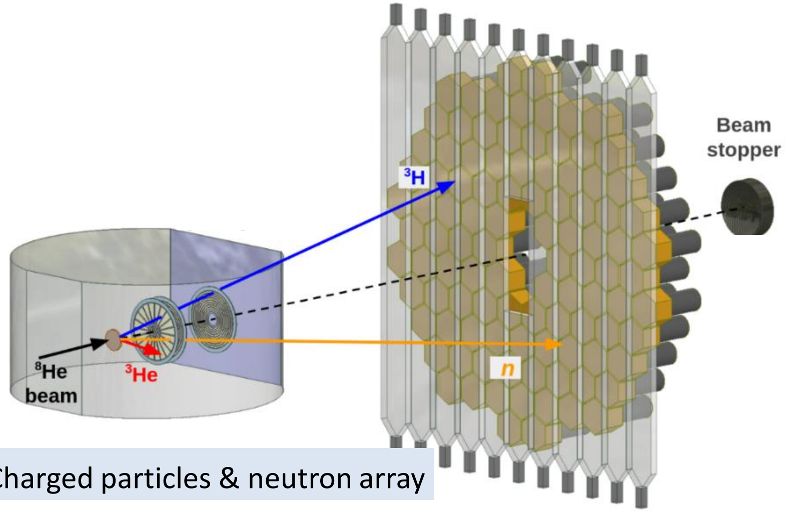
- RF-kicker (operational run with ion beam)
- Zero-angle spectrometer hodoscope
- Neutron detector array (increase in number of modules)
- In-beam detectors
- Charged particles detector arrays (angular and energy acceptance)
- Multiparametric detectors setups
- Others



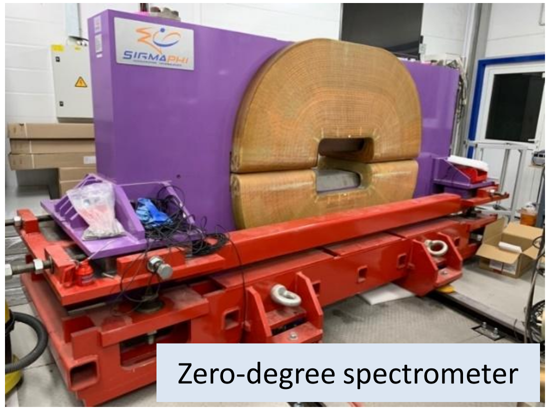
PPACs
PPACs from IBS, Daejeon


RF-Kicker


Neutron array



Charged particles & neutron array


Zero-degree spectrometer

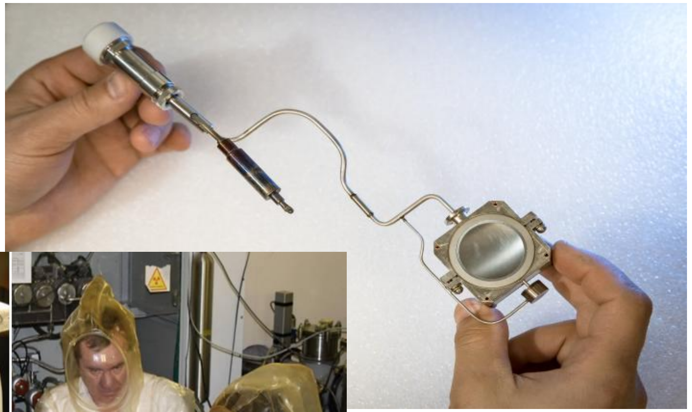

Cryogenic target cell & detectors

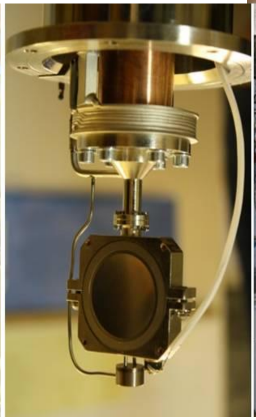
Cryogenic tritium target complex

Old tritium target cell at ACCULINNA-1

Two units move to the neutron-rich region in (t,p) reaction

Background free experiments, easy variation of target thickness





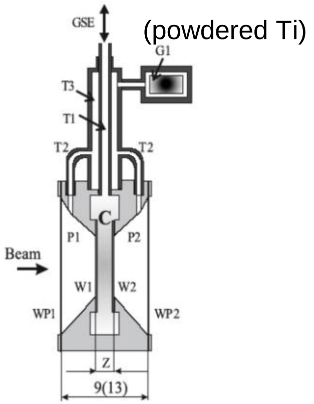
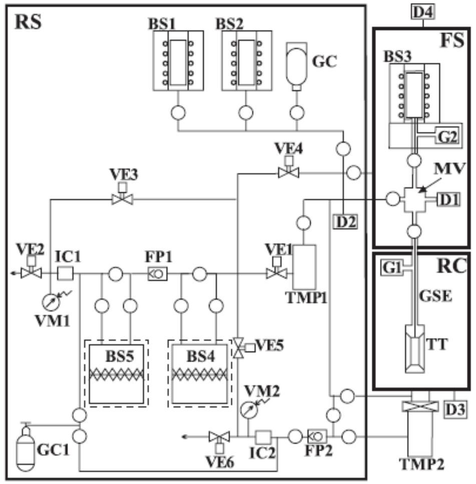


Fig. 2. Schematic drawing of the target. Denoted in the drawing are: C—target cell; W1, W2—cell windows; GSE (tube T1)—gas supply/evacuation path; P1, P2—protection barriers supplied with windows (WP1, WP2) and connected with the getter G1 through the tubes T1, T2 and T3.



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

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

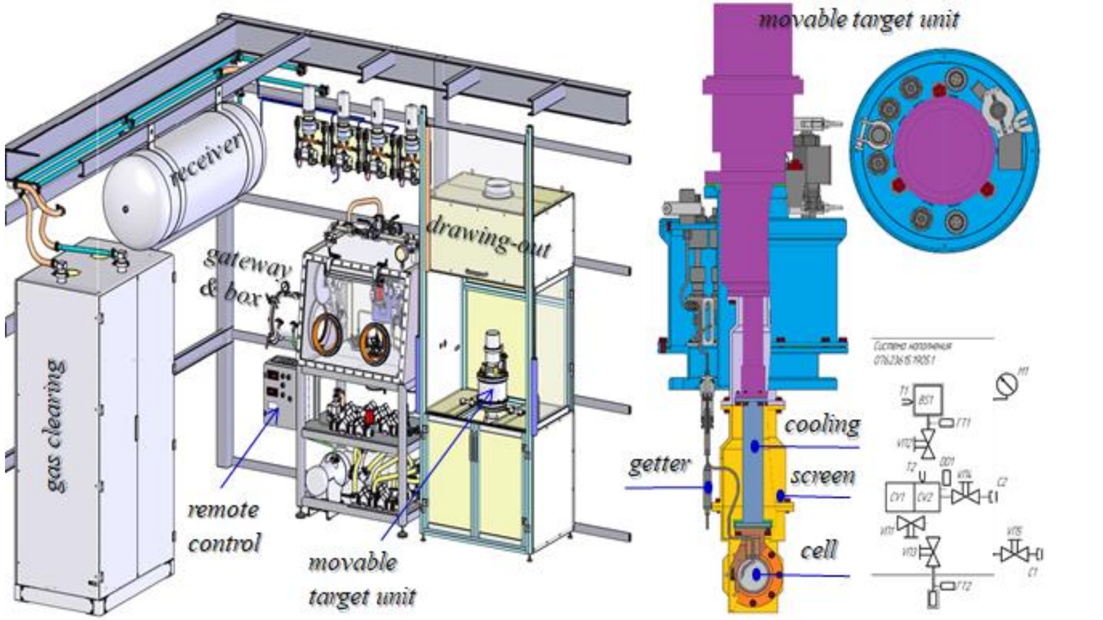
Liquid:
ϕ=20 mm,
d=0.4÷0.8 mm,
w=2x8.4 μ stainless steel,
$1.1*10^{21}$ Atoms/cm^2
I ≤ 960 Ci
($3.54*10^{13}$ Bq)

New cryogenic tritium target complex at ACCULINNA-2

Truly unique item providing important scientific opportunities

Technical specification:

- 2.7 kCi **T_2**;
- Liquid (T~25 K): h=0.4 mm;
  Gas: h=4 mm;
- Three stages of radiation protection;
- Radiation safety control;
- Automatic control and parameter setting;
- The cell can also be filled with **H_2, D_2, ^{3}He, ^{4}He;**
- Thickness in a wide range **~10^{20} ÷ $5*10^{21}$** atoms/cm^2

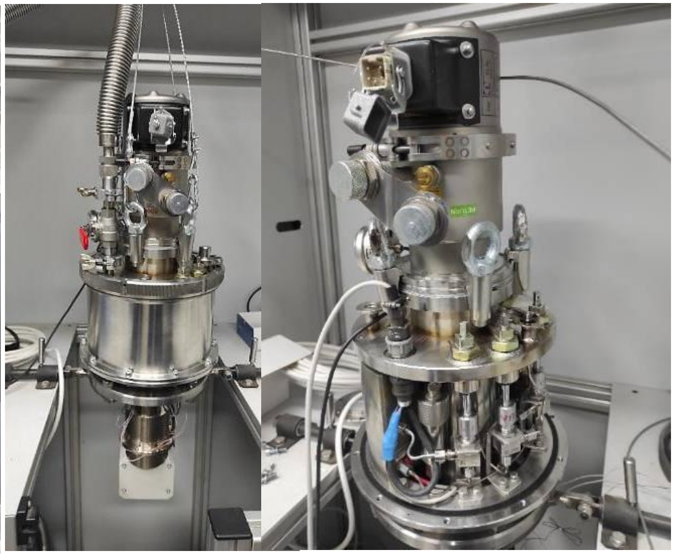


Cryogenic tritium target complex

Tritium target infrastructure:

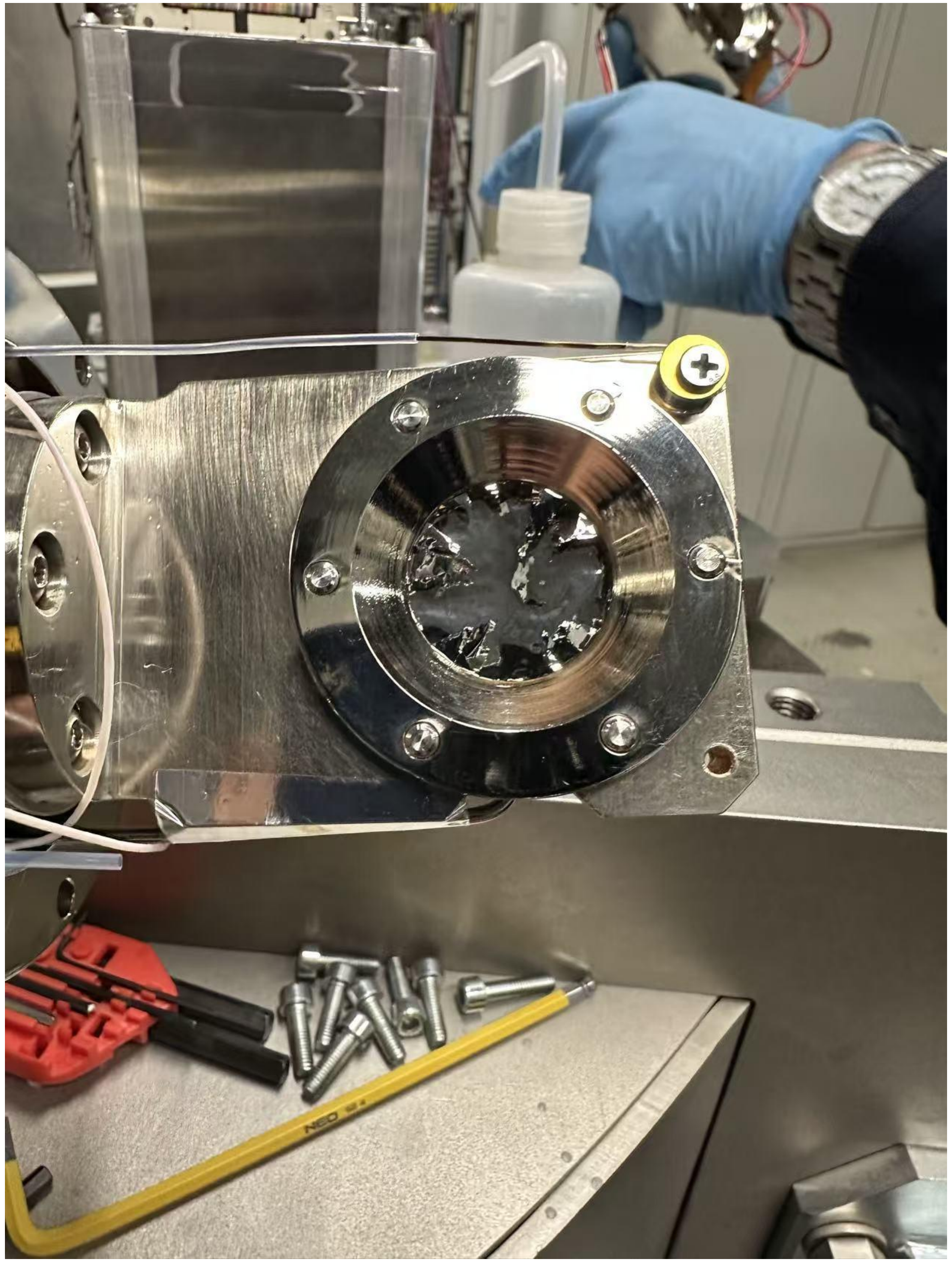
- Completion of work on special ventilation and liquid radioactive waste - 2024
- Certificate for work in the 2nd class room – **2025-2026**

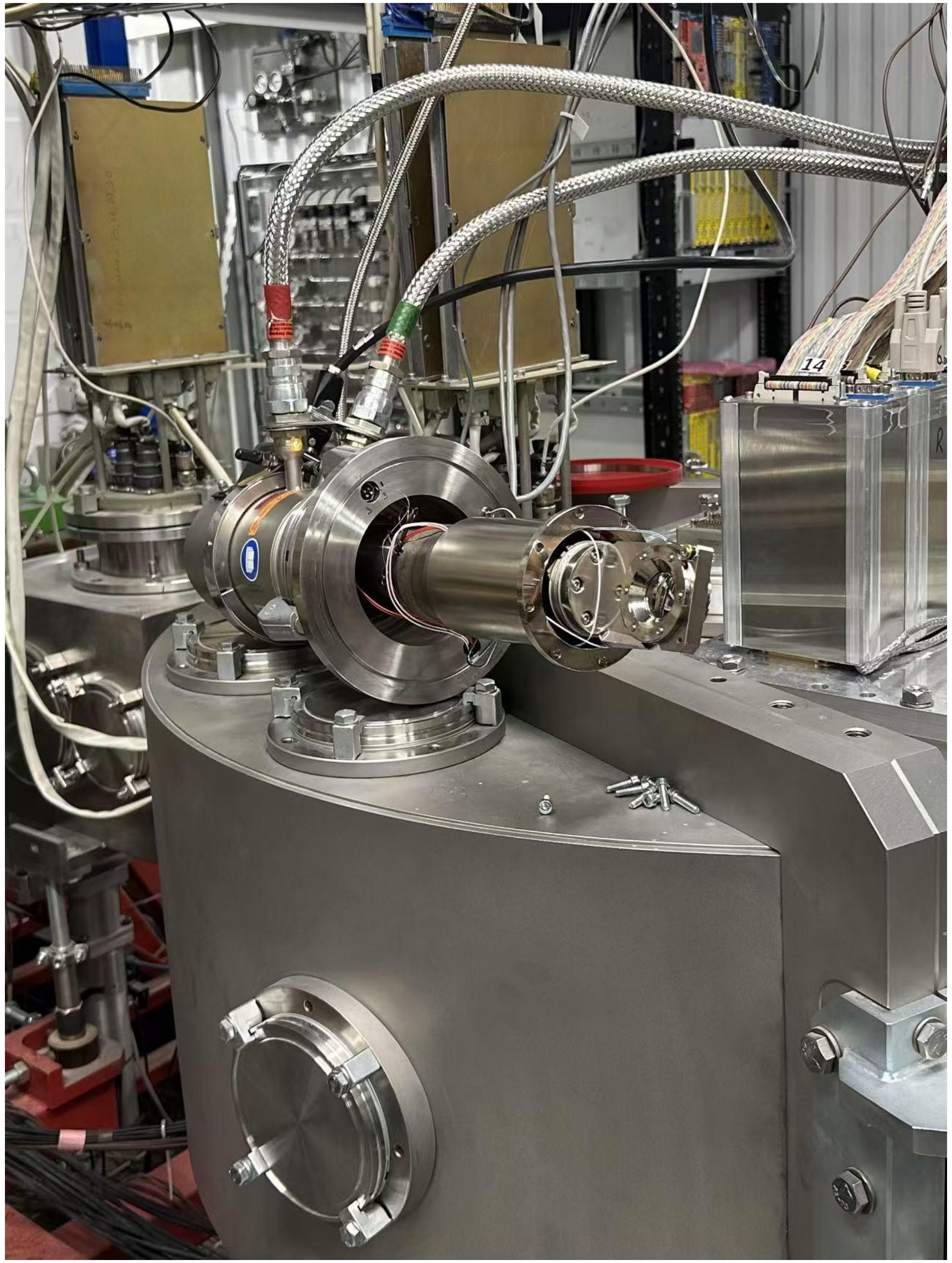
New generation tritium target to be commissioned 2025



Availability for study of cryogenic tritium target (expected in 2026) will be a kind of turning point of the research programme !

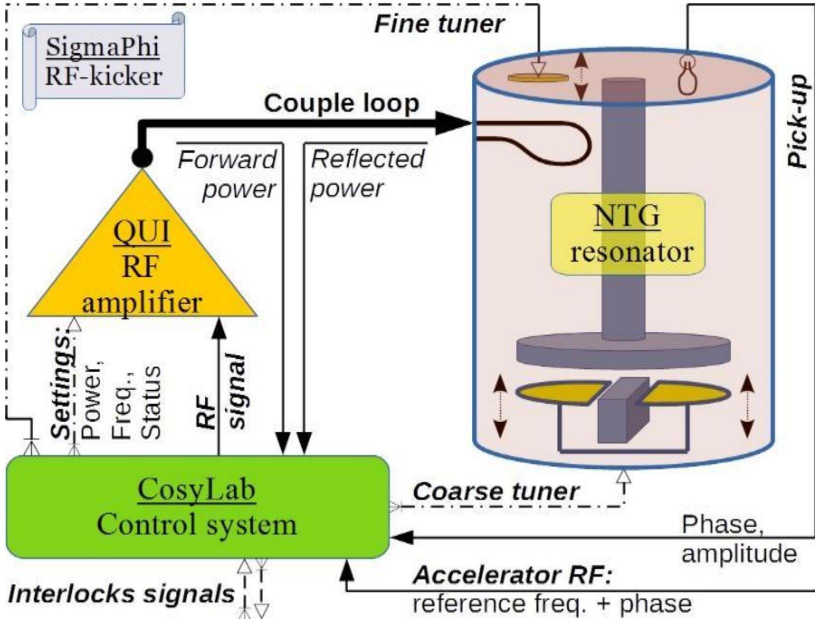
No work – no failures





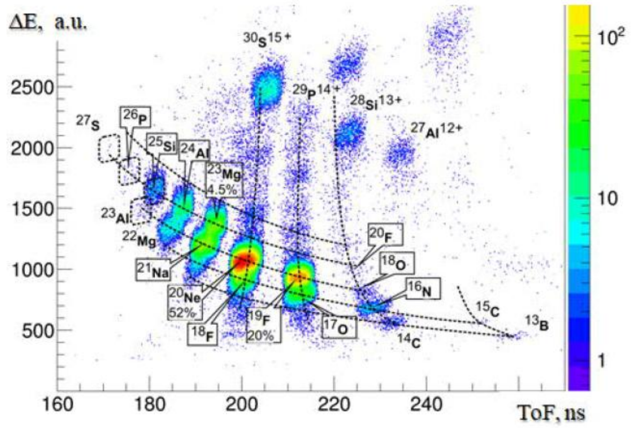
ACCULINNA-2: RF kicker

Frequency range (MHz)	15 – 22,5
Peak voltage (KV)/ Gap (mm)	120/ 70
Length(mm)/Width (mm) of electrodes	700/120
Cylinder Internal diameter (mm)	1400
Stem diameter (mm)	120
Length of coaxial line from beam axis (mm)	1370
Current at junction (A)	990
Current in short-cut (A)	1200
RF power (Watts)	15 000
Reactance Q	>12000
Df dV=1% (Hz)	80-110

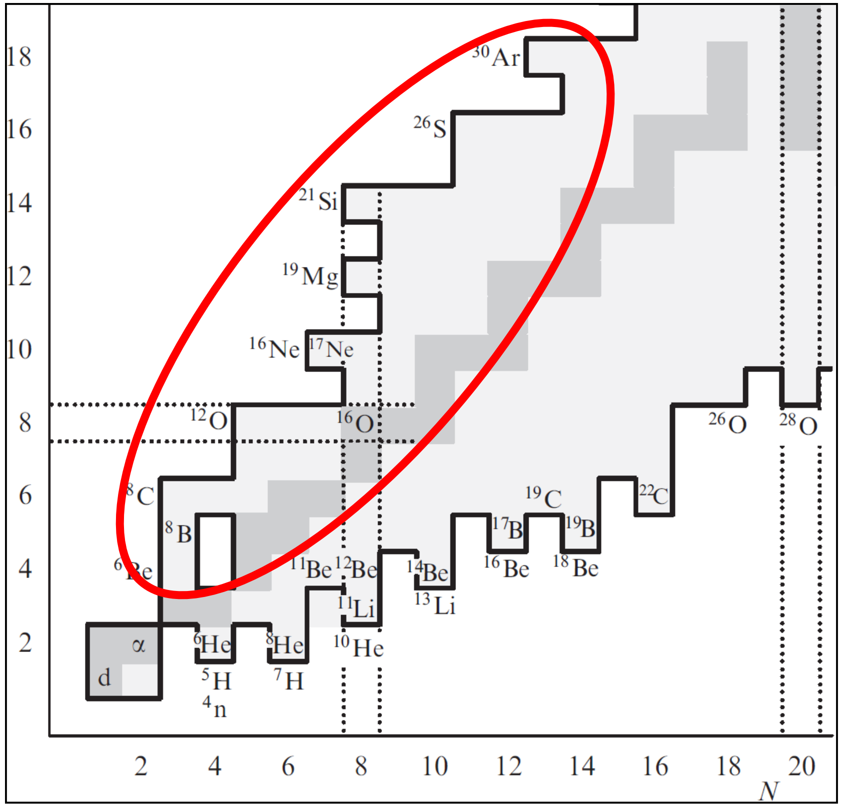


details: Eur. Phys. J. A (2018) 54: 97

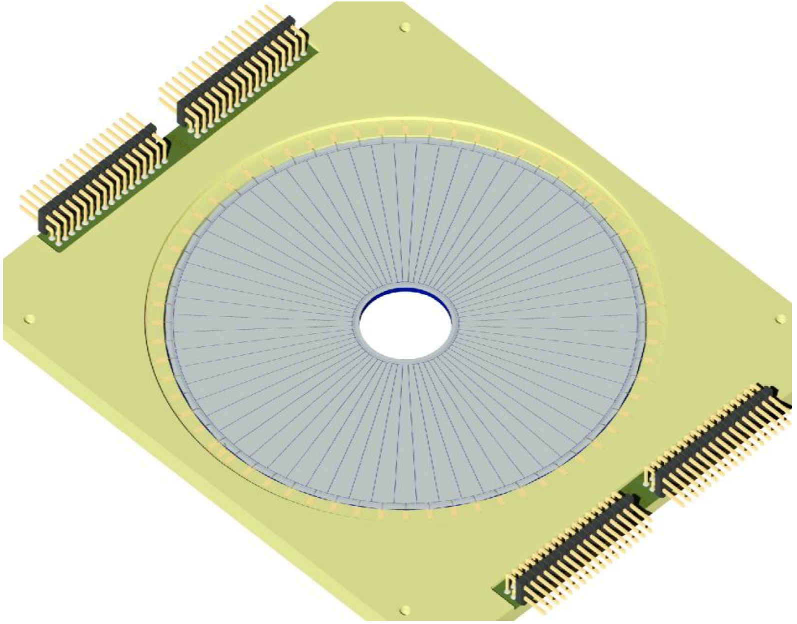
RF kicker installed



Main application of RF kicker: improvement of neutron-deficient RIB purity

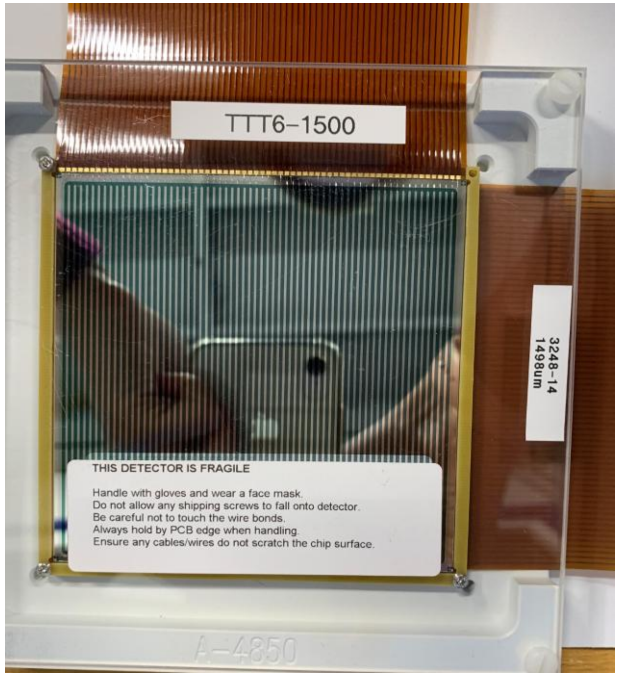


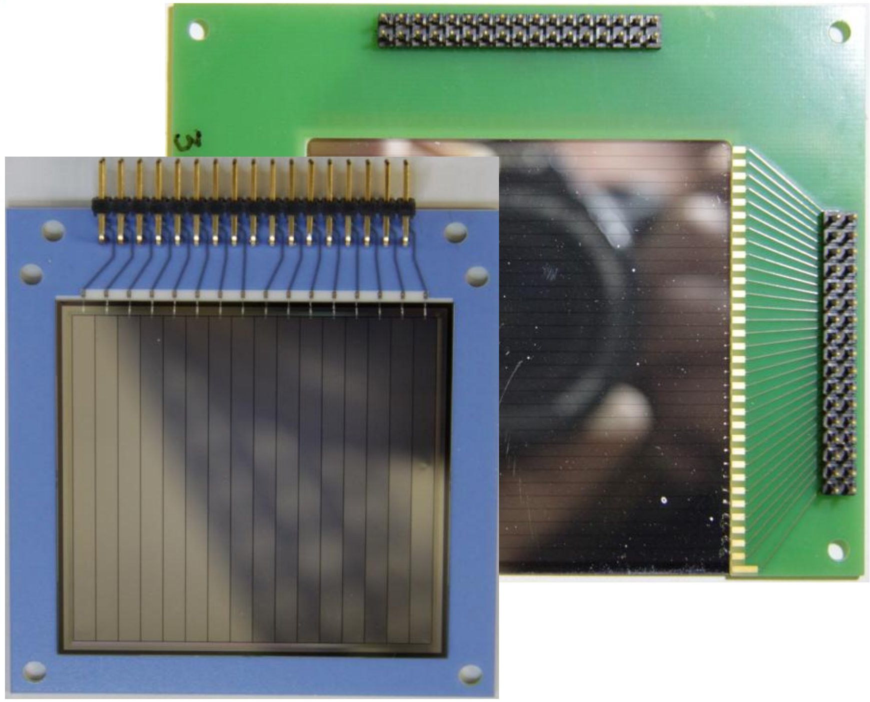
Methods developing: commissioned detector system for detecting charged particles



New anular DSSD (S12)

- *Micron semiconductor*
- *64 Sectors x 64 Rings*
- *Active area Ø125 – Ø32 mm*
- *Central hole Ø28 mm*
- *Thickness 140, 300 and 1500 mkm*





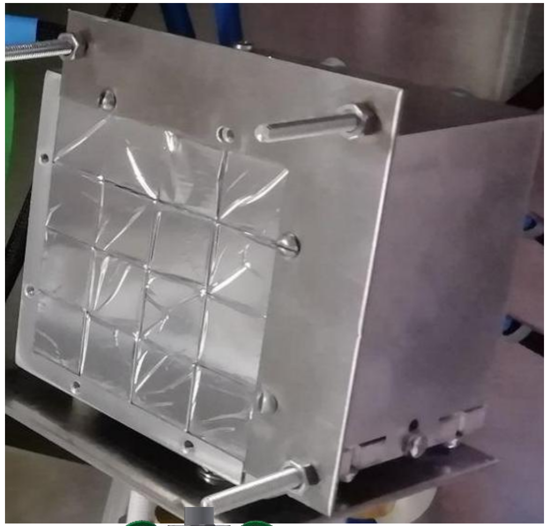
New DSD (TTT6)

- *Micron semiconductor*
- *Strip detectors*
- ***Frameless technology***
- *Active area 100x100 mm*
- *Thickness 140, 300, and 1500 mkm*

Thin SSD (W1)

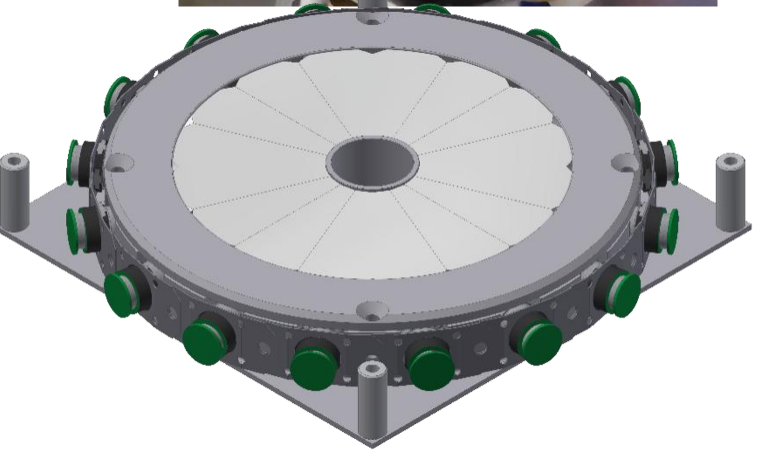
- *Micron semiconductor*
- *Strip detectors*
- *Active area 50x50 mm*
- *Thickness **20 mkm***

Methods developing: detector system for detecting charged particles



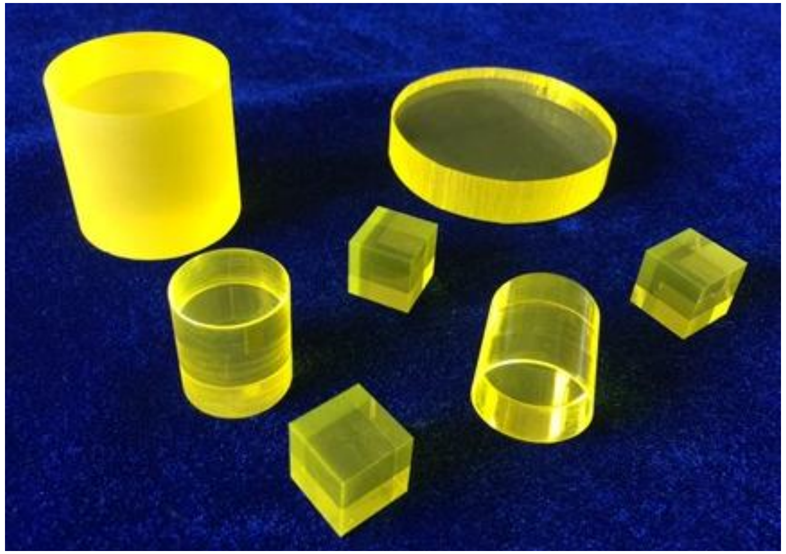
CsI (Tl)

- *Ring and square geometry*
- *Density 4.53 g/cm3*
- *Relatively high light output*
- *Thickness 20 or 50 mm*



LYSO (Lu 1.8Y.2SiO5:Ce)

- *High density*
- *Fast, single exponential decay time*
- *Non-hygroscopic*
- *Three to four times the light emission of BGO*

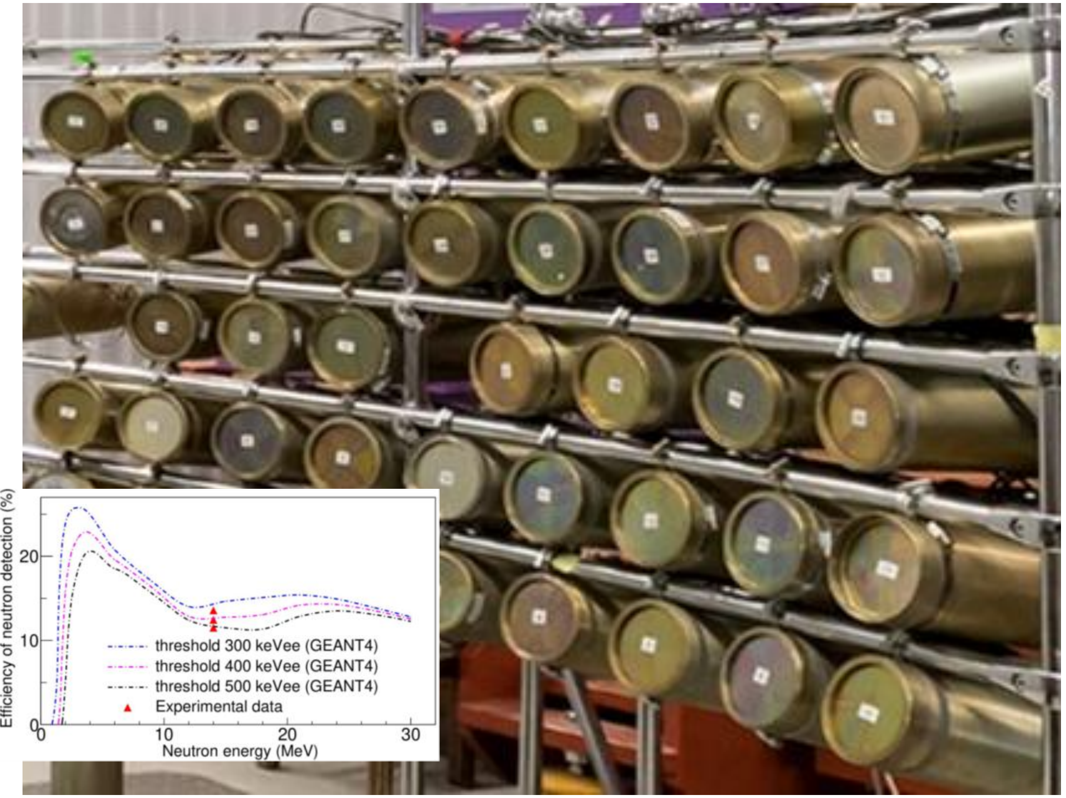


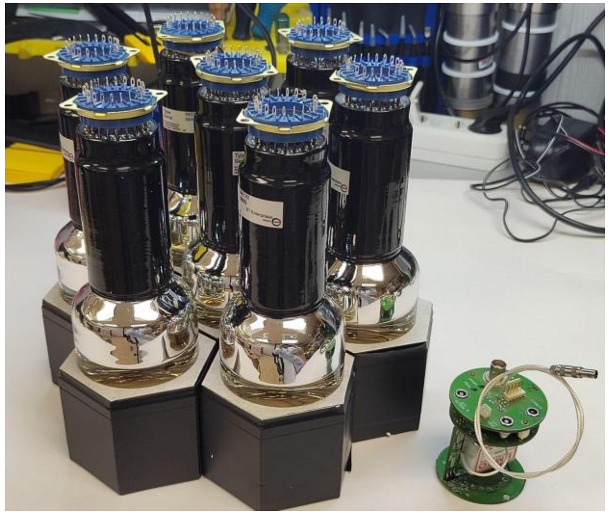
New scintillator materials for telescopes alternative to CsI(Tl)

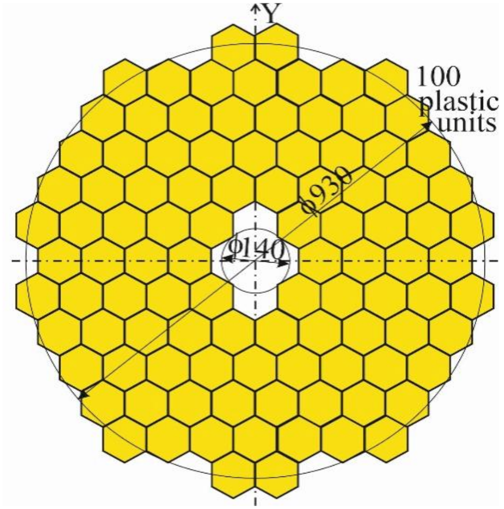
Ce:GAGG (Gd3Al2Ga3O12:Ce)

- *Fomos materials company*
- *Custom size and thickness*
- *Fast, durable*
- *Relatively high light output*
- *High density*
- *High spatial resolution detection*
- *No self-count*

Methods developing: detector system for neutron detection





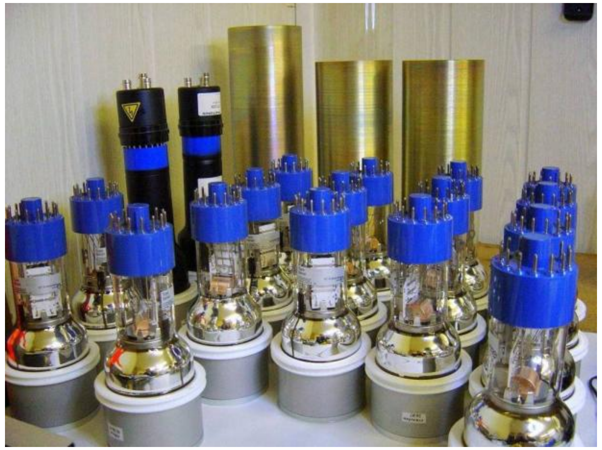


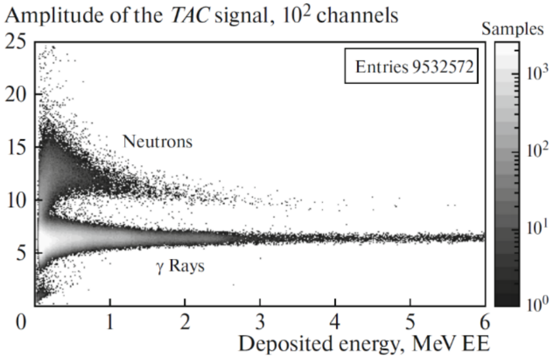
Stilbene

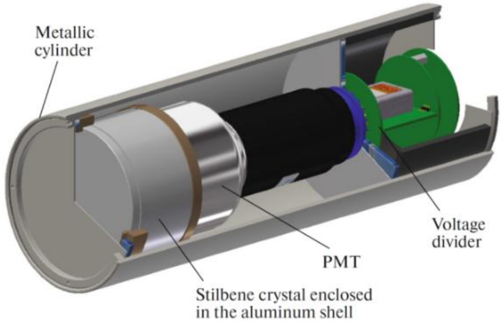
- *Array 48 units (50 mm, Ø 80 mm)*
- *Neutron detection efficiency ~ 12%*
- *Pulse-shape discrimination (MPD-4/Mesytec)*
- *Increase in quantity from 48 to 64 pcs.*
- *Re-encapsulation to reduce n - rescattering*

New scintillator BC-404

- *Hexagonal shape*
- *PMT (ET 9822B)*
- *Thickness 75 mm*
- *High density layout*
- *new neutron ToF spectrometer*







Bezbakh et al., Instr. Exp. Tech. V.61 (2018) 631.

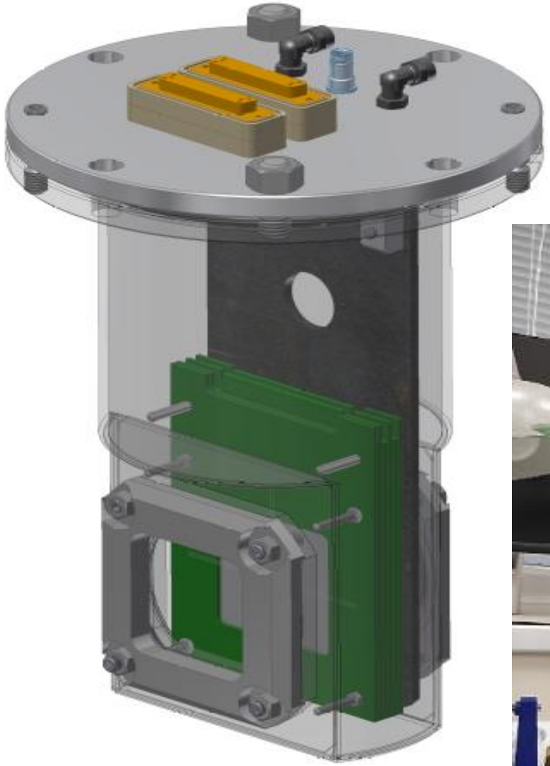
New scintillator EJ-276D

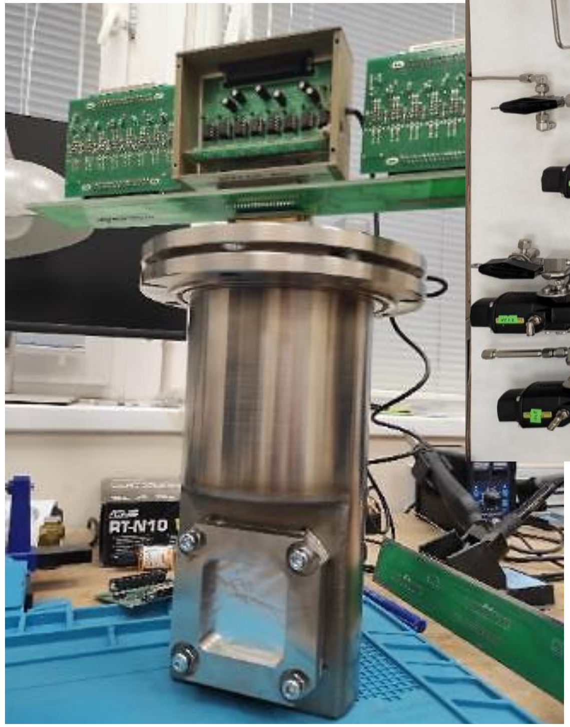
- *PSD plastic scintillator*
- *Size 50 mm, Ø 80 mm*
- *3-inch PMT*
- *PCB with voltage divider, HV source(EMCO) and shaper*
- *Digitizing the signal (V1725/CAEN)*

Methods developing: new beam tracking detector system (PPAC or MWPC)

- Tests with alpha source and RIB were carried out
- Design including mechanical supports and gas-vacuum distribution system was fully developed

PPAC 10x10 cm^2



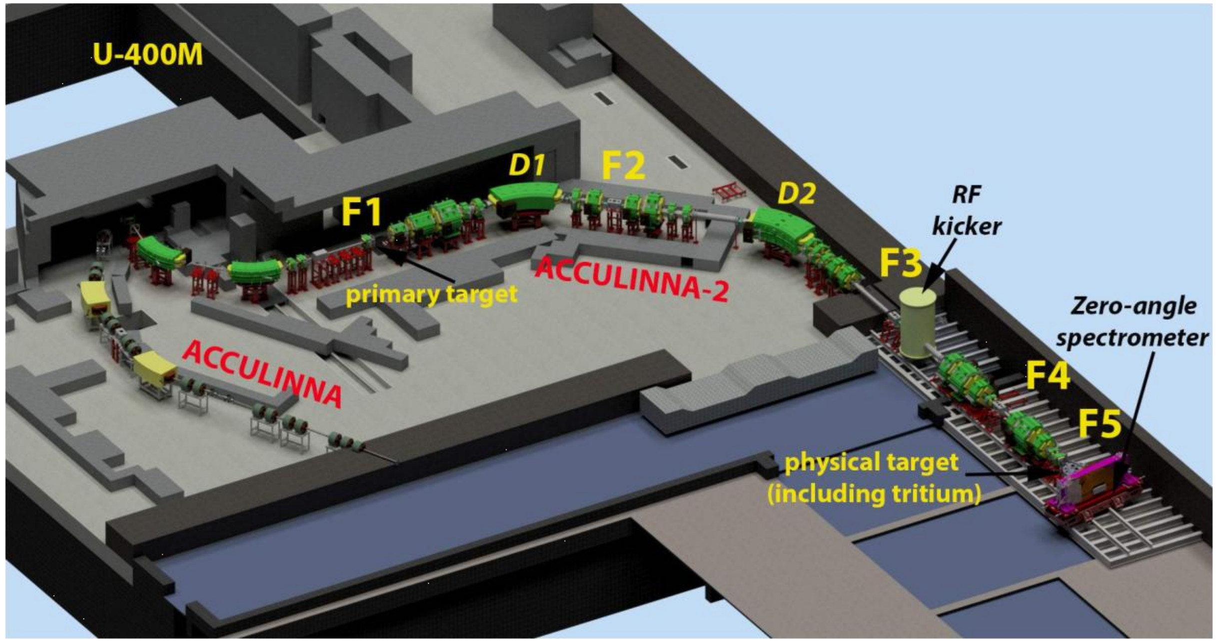


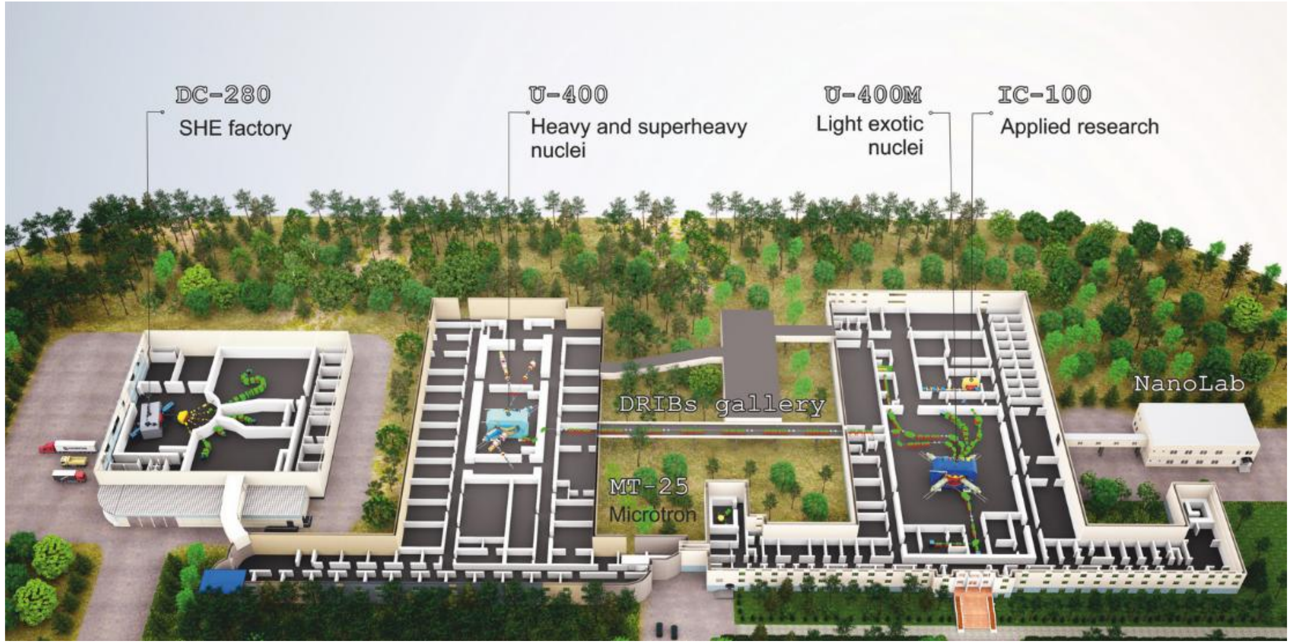
Charles Akers et al.,
Journal of the Korean Phys. Society,
Vol. 70, No.7, 2017, p. 682.

- Redesign completed. Entrance window enlarged.
- New electronics developed.
- Commissioned gas system

Summary

- ACCULINNA-2 is a perspective place for study of nuclear structure in a transfer reactions at low energies (20-50 MeV/A)
- Study of RIB at driplines stimulates of new novel instrumentation and engineering inventions
- Many new technical solutions have arisen during ACCULINNA-2 project realization
- New research program focused on exploring of light exotic nuclei and unbound states will be started in 2025/2026.
- We are open for collaboration and innovative solutions
- Students are international researchers are welcome to attend our projects and collaborations
- Looking for the partners to carry on research with Active Target TPC for precise angular correlations measurements.





Thank you for your attention