Леонид Григоренко

Лаборатория ядерных реакций
им. Г.Н. Флерова, ОИЯИ, Дубна

Исследования экзотических ядер на установке ACCULINNA-2. Перспективы ядерной физики низких энергии в РФ.

От ACCULINNA к ACCULINNA-2

Экспериментальная “кампания” 2018-2021

Экспериментальная программа ACCULINNA-2 в 2023-2025
Приглашение к сотрудничеству

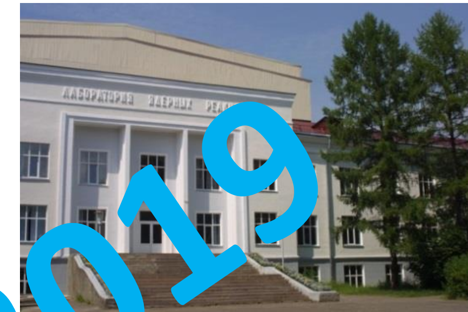
Приглашение к сотрудничеству

Перспективы ядерной физики низких энергий в РФ

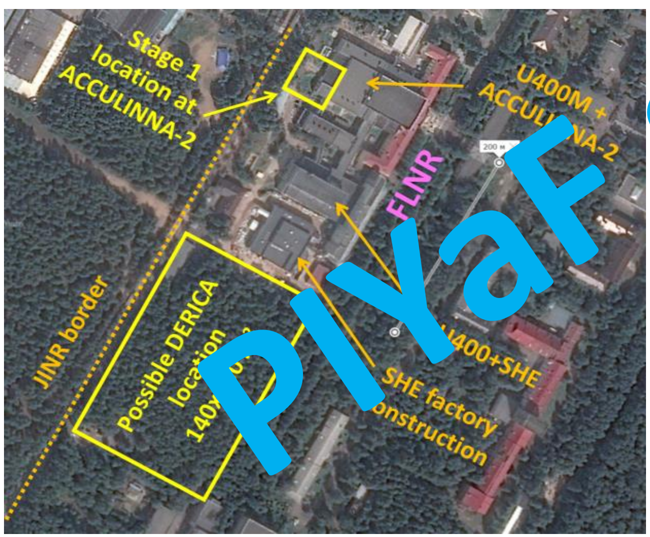
Семинар ПИЯФ, Гатчина, 22 сентября 2022

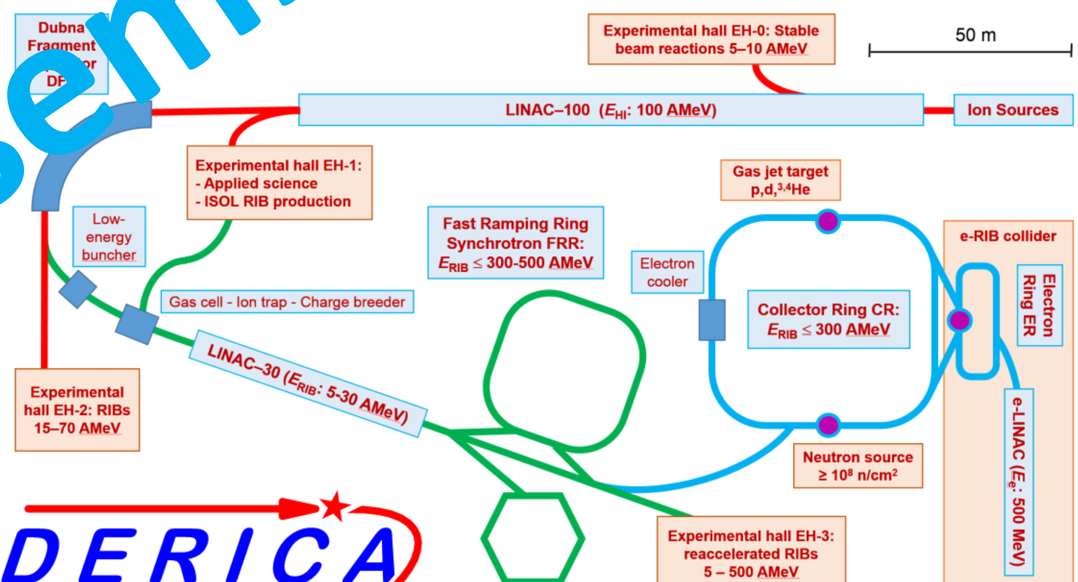
Леонид Григоренко

Лаборатория ядерных реакций
им. Г.Н. Флерова, ОИЯИ, Дубна



Статус и перспективы исследований с пучками радиоактивных изотопов в ЛЯР ОИЯИ





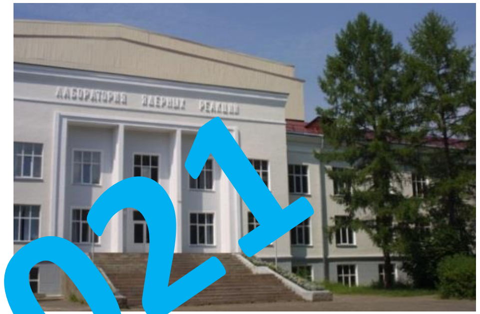
DERICA

http://aculina.jinr.ru/derica.php

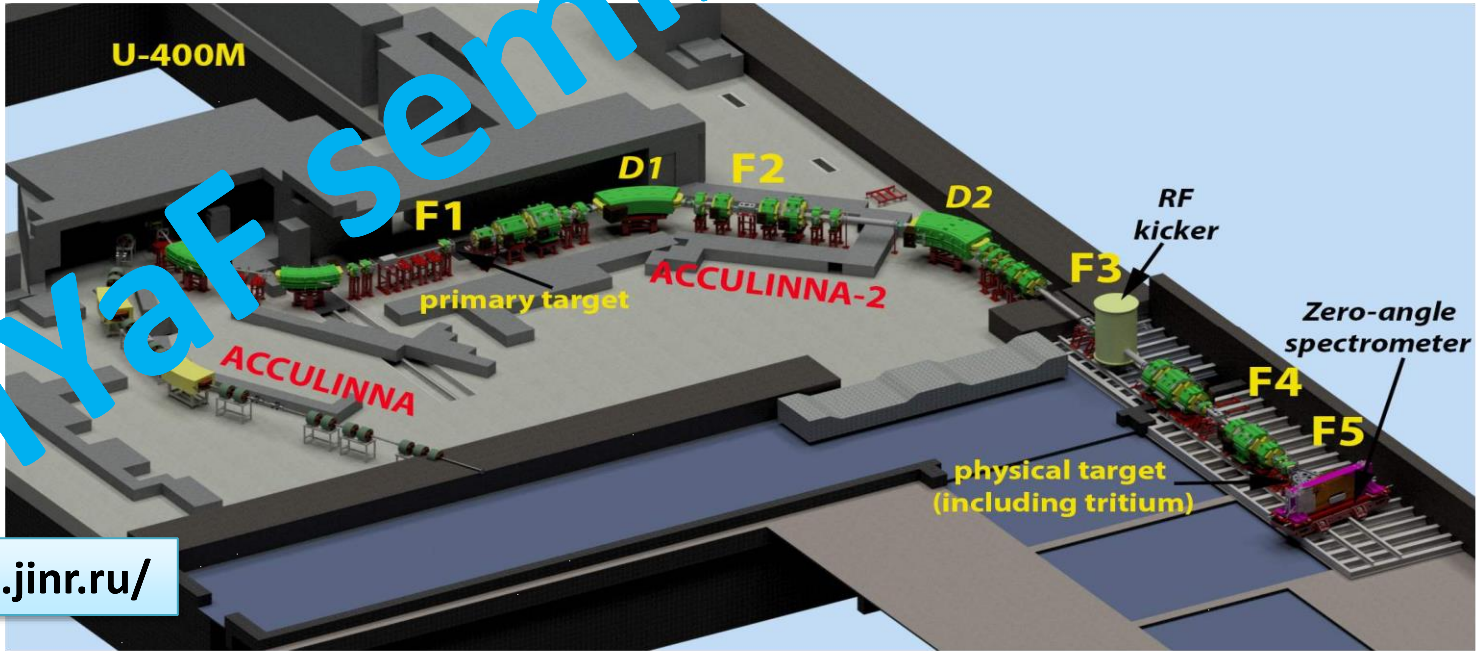
Семинар в ПИЯФ, Гатчина, 28 мая 2019

Leonid Grigorenko

Flerov Laboratory of Nuclear Reactions,
JINR, Dubna



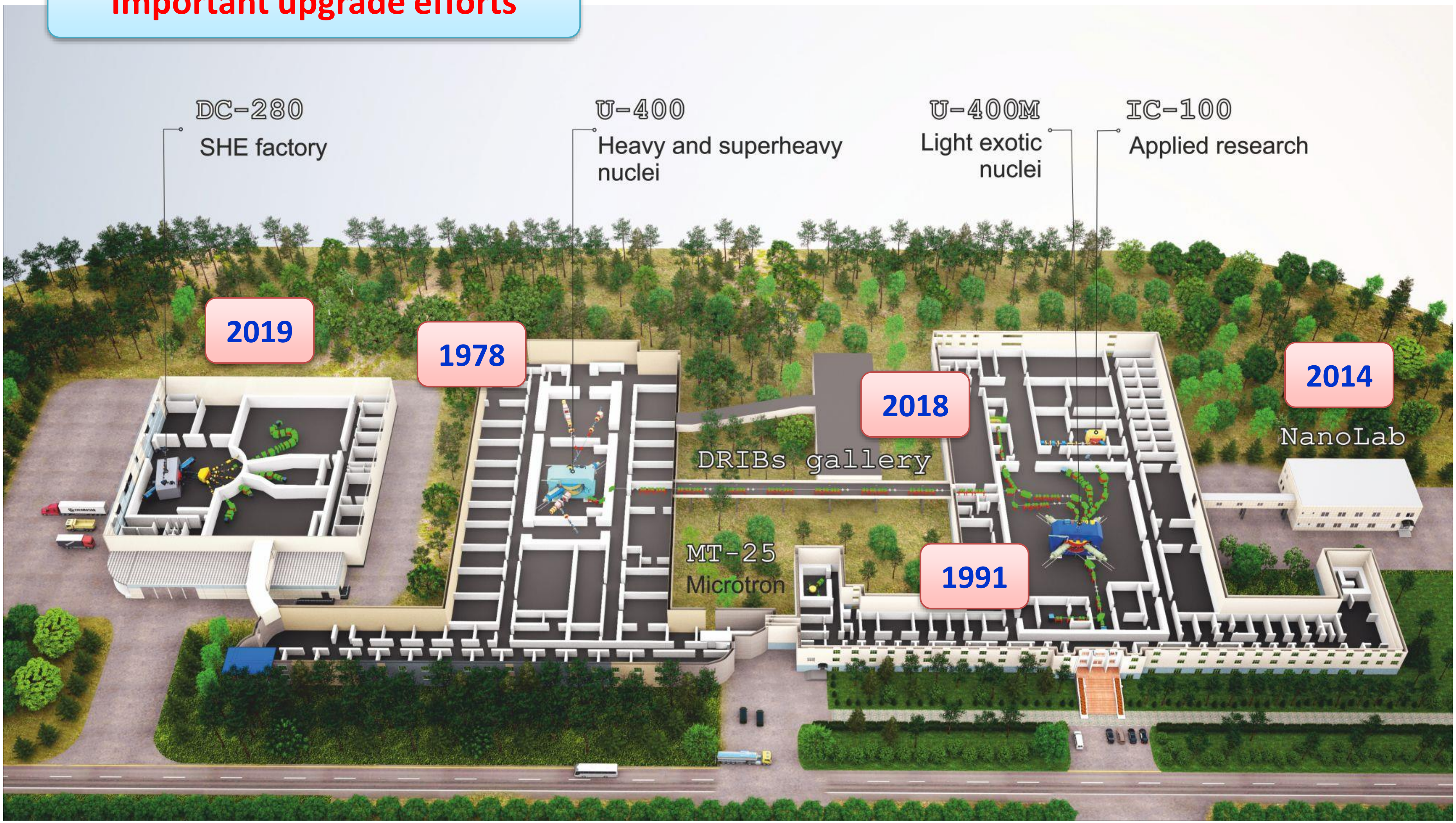
Тяжелейшие изотопы водорода ^{6}H и ^{7}H в экспериментах на установке ACCULINNA-2



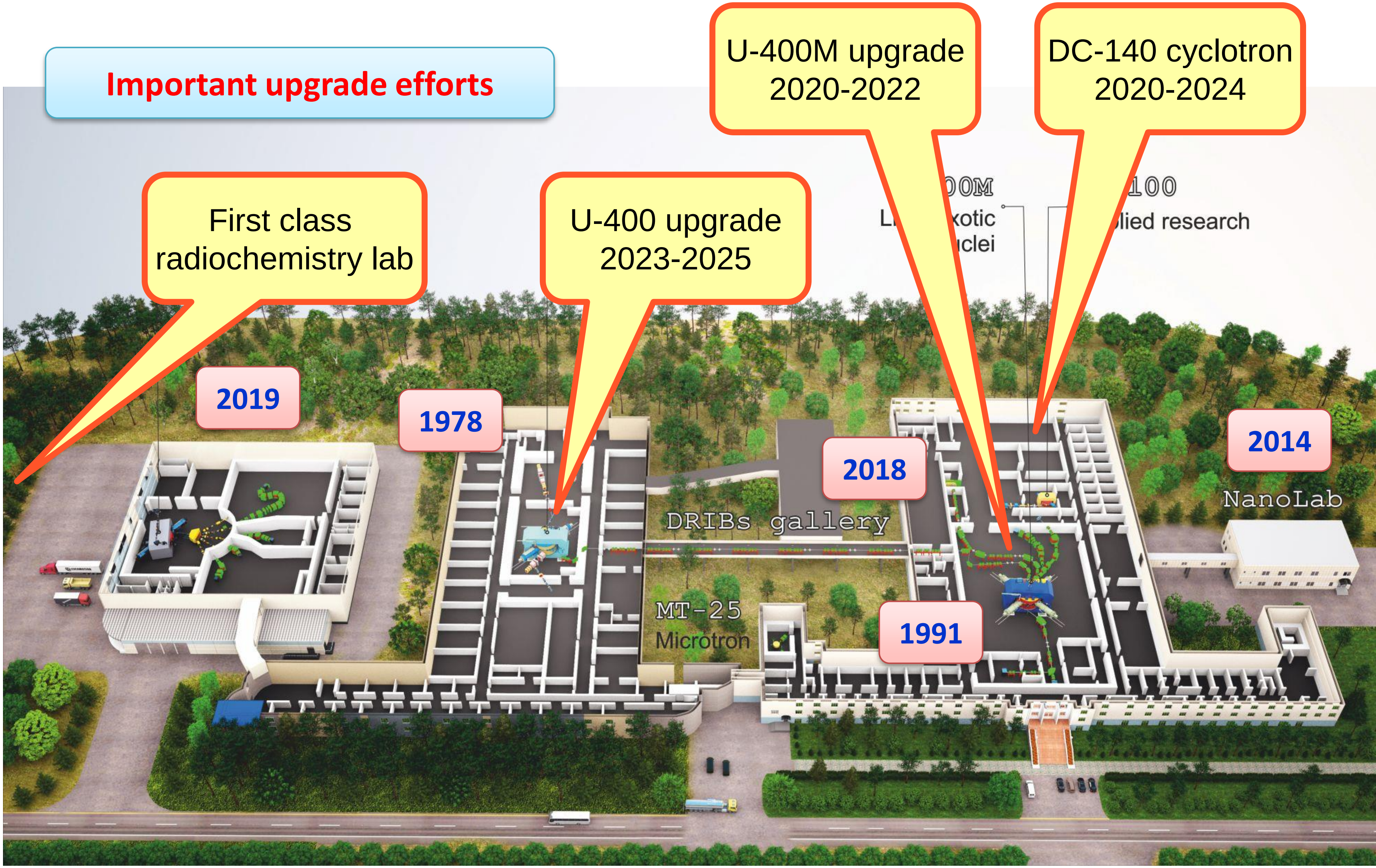
http://aculina.jinr.ru/

Flerov Laboratory of Nuclear Reactions, JINR

Important upgrade efforts



Flerov Laboratory of Nuclear Reactions, JINR



Физика радиоактивных изотопов (РИ) – магистральное направление развития современной ядерной физики

Карта нуклидов – “основной документ” ядерной физики

- **254** стабильных изотопа,
- **339** можно найти в природе
- Свыше **3100** РИ известно
- Свыше **2500** – не открыто…

Экзотические структуры экзотических изотопов:

- Нейтронные/протонные гало
- “Мягкие” моды возбуждения
- Размывание оболочечной структуры
- Новые “магические числа”
- Природа сильного взаимодействия в экзотических системах

Обширные области экстенсивного развития (~40% изотопов пока неизвестно) и прекрасный потенциал неожиданных открытий

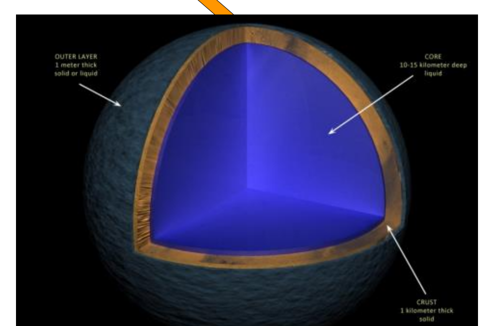
“Остров стабильности” сверхтяжелых: чуть коснулись краешка...

Протонная граница стабильности: изучена до Z<32

Пределы существования ядерной структуры: Известны только в легчайших ядерах

Астрофизика: взрывной нуклеосинтез в r- и rp-процессах

Нейтронная граница стабильности: изучена до Z<20

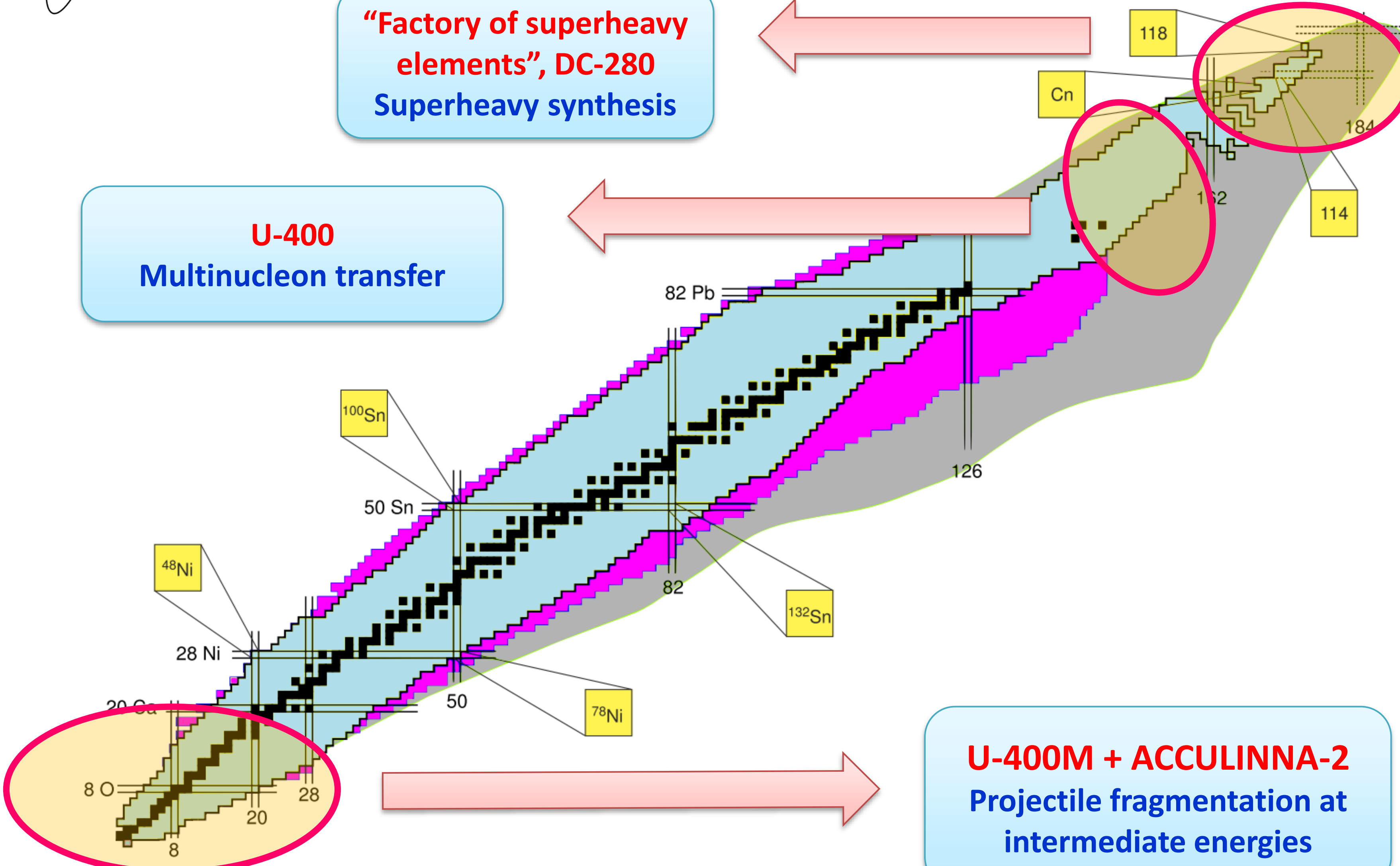


Астрофизика: свойства нейтронной материи и нейтронных звезд

JINR Flerov Lab research agenda

"Factory of superheavy elements", DC-280
Superheavy synthesis

U-400
Multinucleon transfer

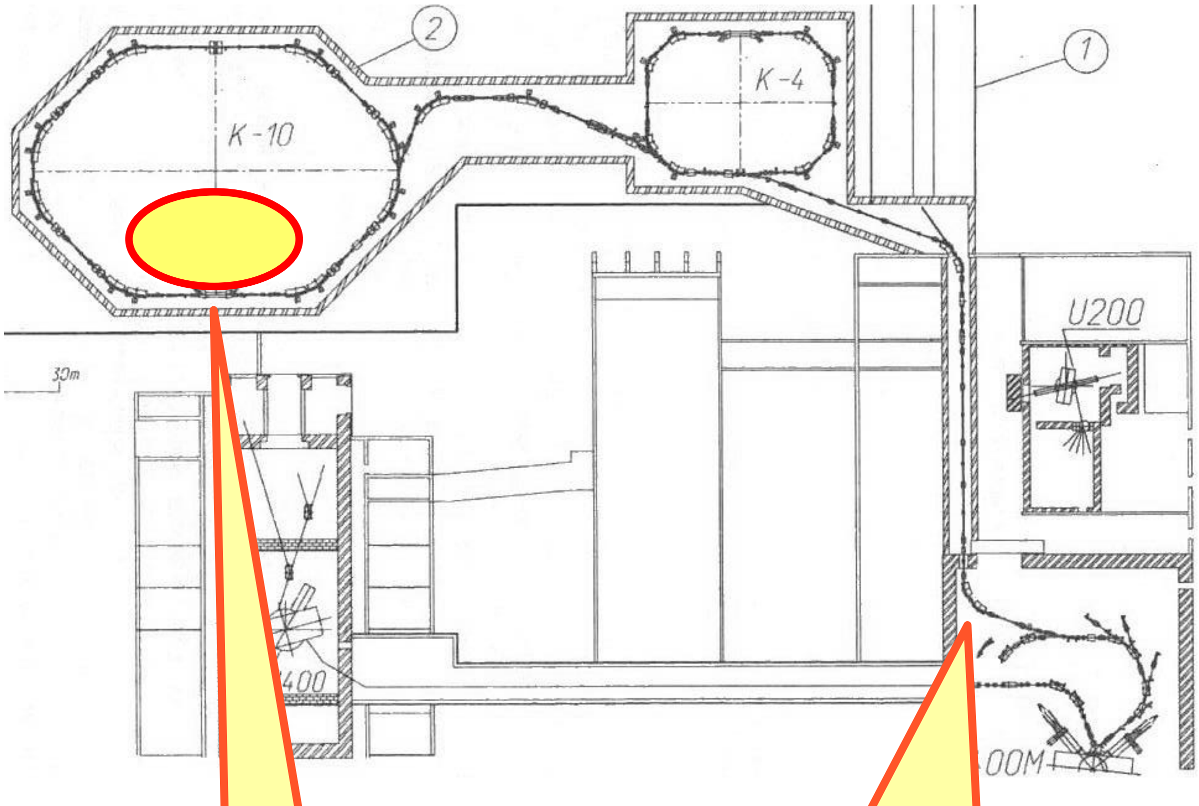


U-400M + ACCULINNA-2
Projectile fragmentation at intermediate energies

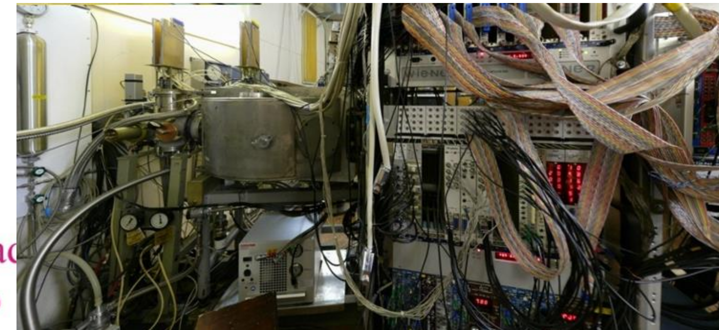
From ACCULINNA to ACCULINNA-2

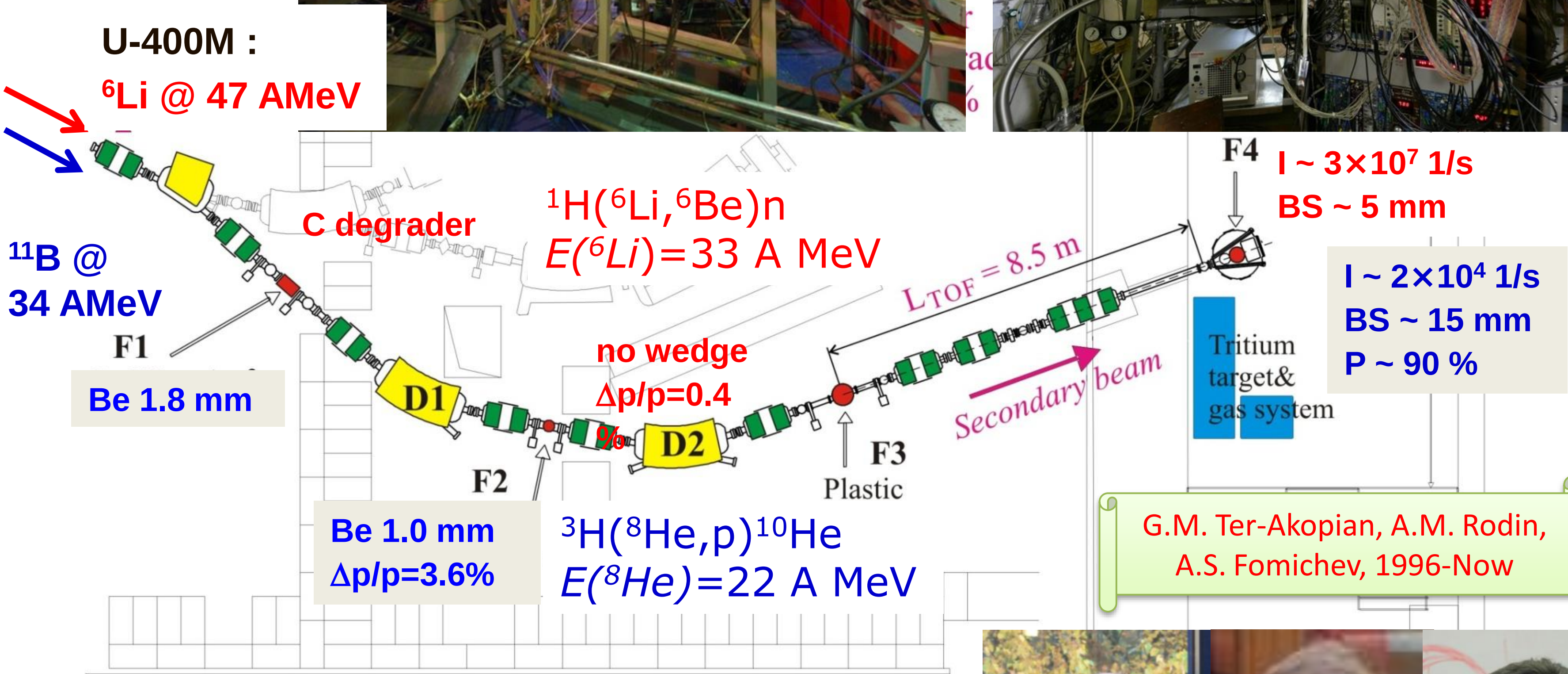
K4-K10 complex at FLNR

Yu. Ts. Oganessian *et. al.*,
Z. Phys. A341 (1992) 217

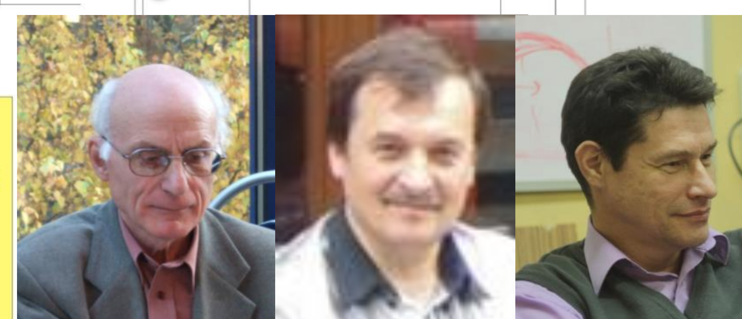


Fragment separator ACCULINNA for light exotic nuclei studies

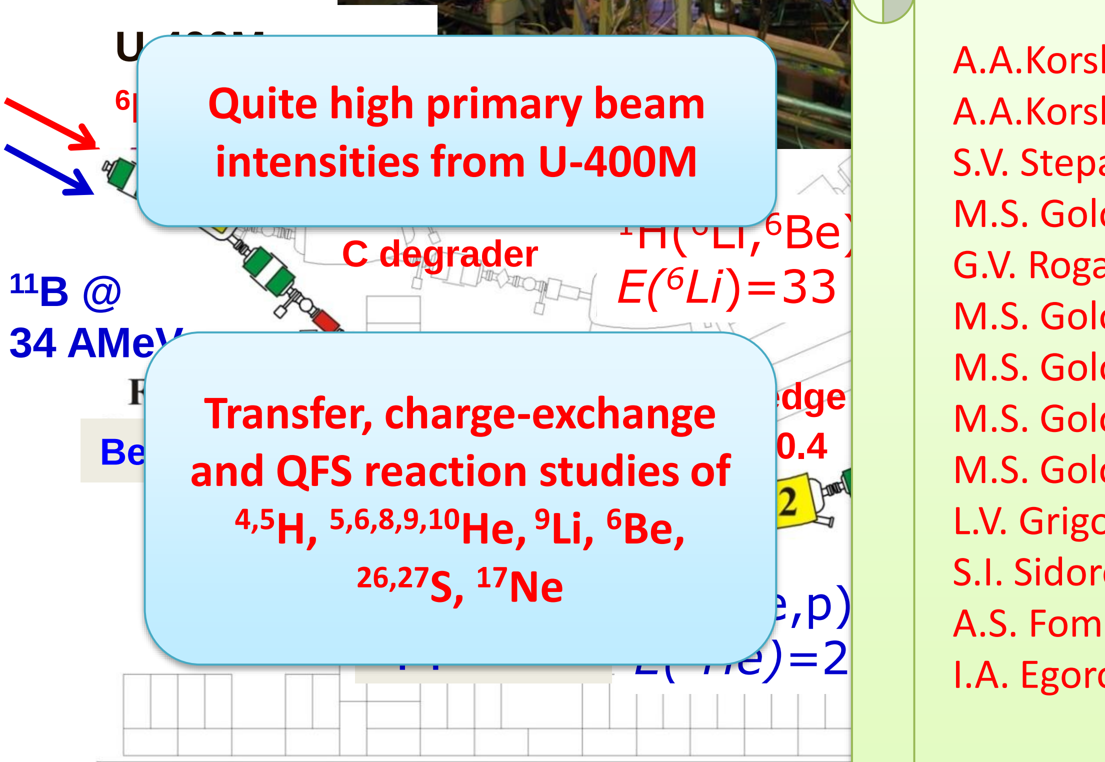




	F2	F3	F4
H/V magnification	0.5/2.0	1.0/1.0	2.25/1.6
Mom. dispersion, mm/%	4.0-18.0	–	–
Mom. resolution	0.003		
H/V RIB size, mm		8/10	20/16



Fragment separator ACCULINNA for light exotic nuclei studies

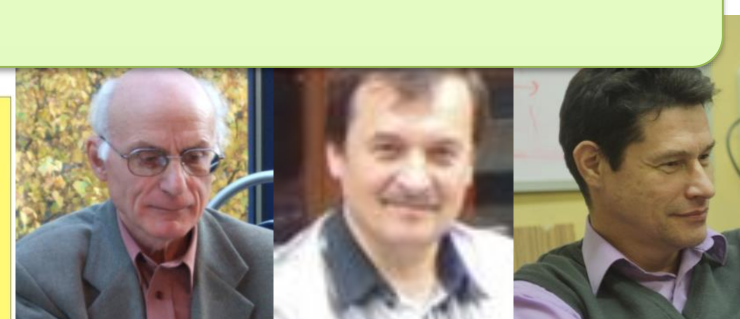


Quite high primary beam intensities from U-400M

Transfer, charge-exchange and QFS reaction studies of ^{4,5}H, ^{5,6,8,9,10}He, ^{9}Li, ^{6}Be, ^{26,27}S, ^{17}Ne

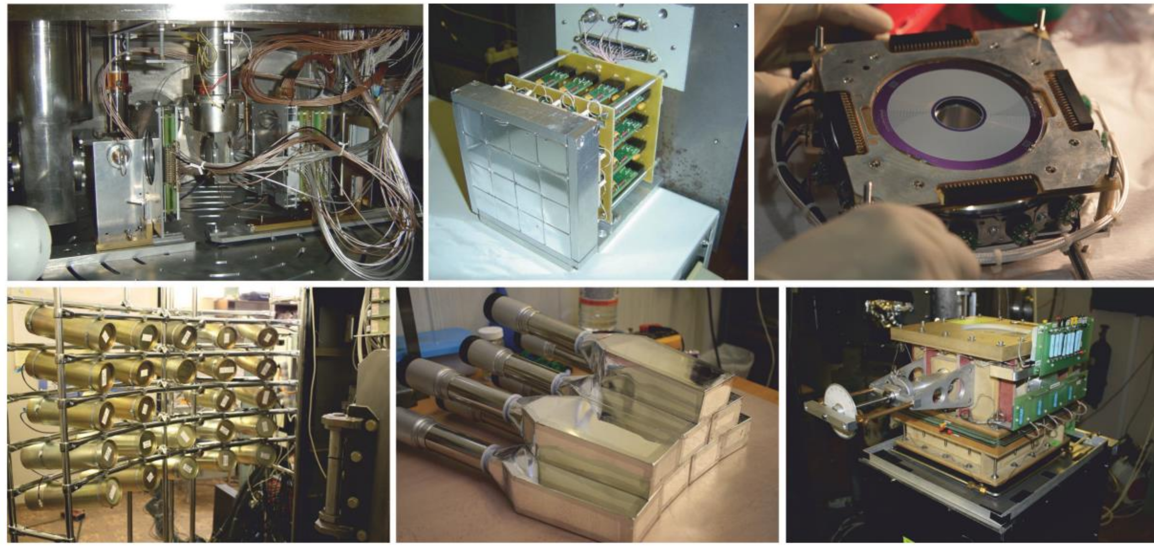
A.A.Korsheninnikov, PRL **82** (1999) 3581.
A.A.Korsheninnikov, PRL **87** (2001) 092501.
S.V. Stepantsov *et al.*, PLB **542** (2002) 35.
M.S. Golovkov *et al.*, PLB **566** (2003) 70.
G.V. Rogachev *et al.* PRC **67** (2003) 041603(R).
M.S. Golovkov *et al.*, PRL **93** (2004) 262501.
M.S. Golovkov *et al.*, PLB **588** (2004) 163.
M.S. Golovkov *et al.*, PRC **76** (2007) 021605(R).
M.S. Golovkov *et al.*, PLB **672** (2009) 22.
L.V. Grigorenko *et. al.*, PLB **677** (2009) 30.
S.I. Sidorchuk *et al.*, PRL **108** (2012) 202502.
A.S. Fomichev *et al.*, PLB **708** (2012) 6.
I.A. Egorova *et al.*, PRL **109** (2012) 202502.

	F2	F3	F4
H/V magnification	0.5/2.0	1.0/1.0	2.25/1.6
Mom. dispersion, mm/%	4.0-18.0	–	–
Mom. resolution	0.003		
H/V RIB size, mm		8/10	20/16



Instrumentation development

- Cryogenic targets
- Telescopes
- Stilbene neutron array
- γ-array GADAST
- Warsaw OTPC
- DAQ – MBS, like GSI



Truly unique item: cryogenic tritium gas system

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

Background free experiments, easy variation of target thickness

Available only in military laboratories

Nice example of military technology conversion for fundamental science conversion

Competitive light nuclei RIB program at FLNR

Intermediate energy reactions (20-70 MeV/nucleon)

Transfer reactions

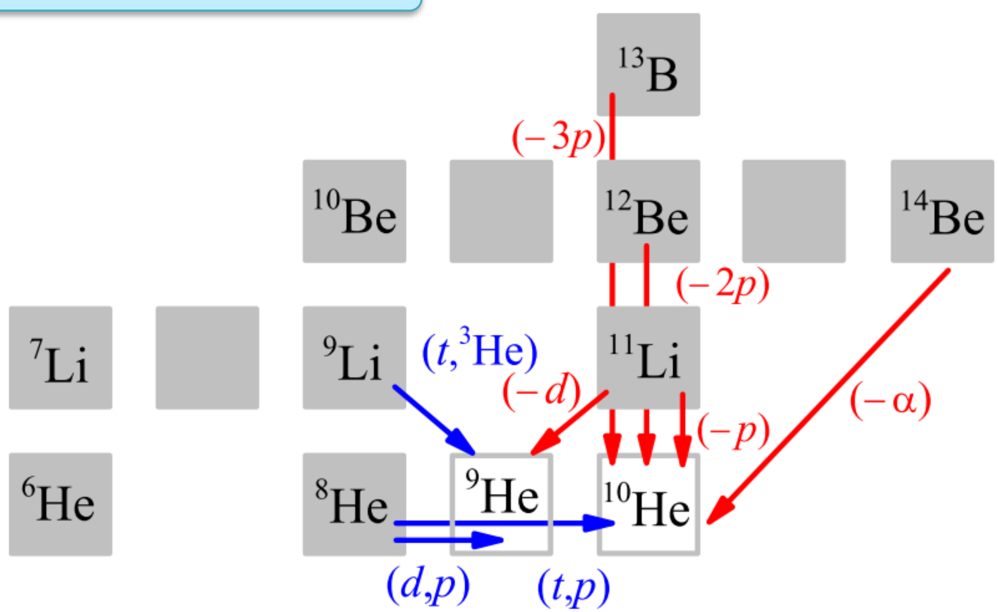
Missing mass, invariant mass, combination

Lower energy – better resolution

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

Knockout reactions

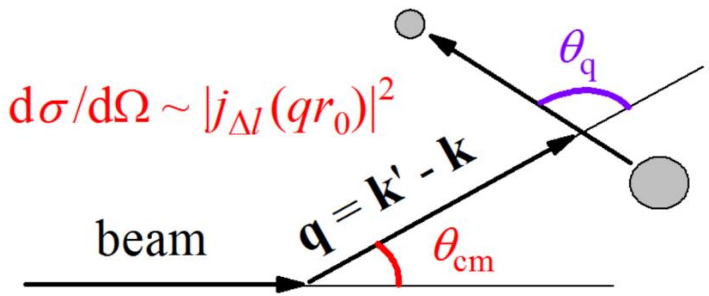
Only invariant mass (exclusion (p,2p) reactions



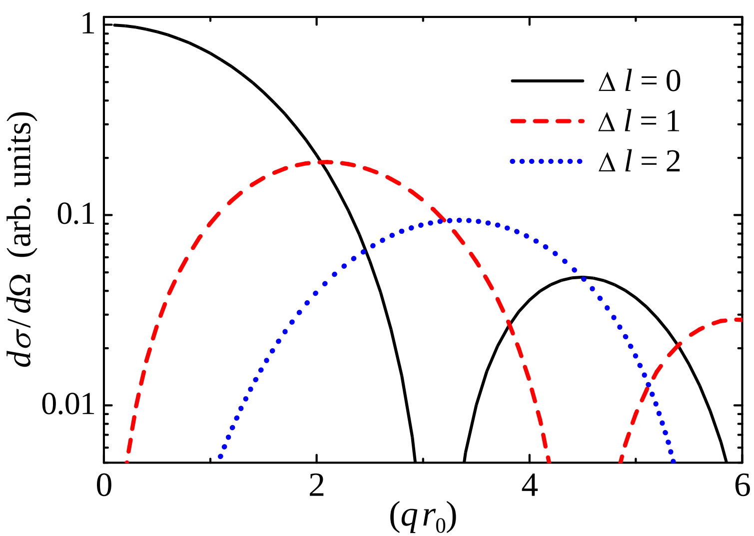
Importance of complementary reaction studies

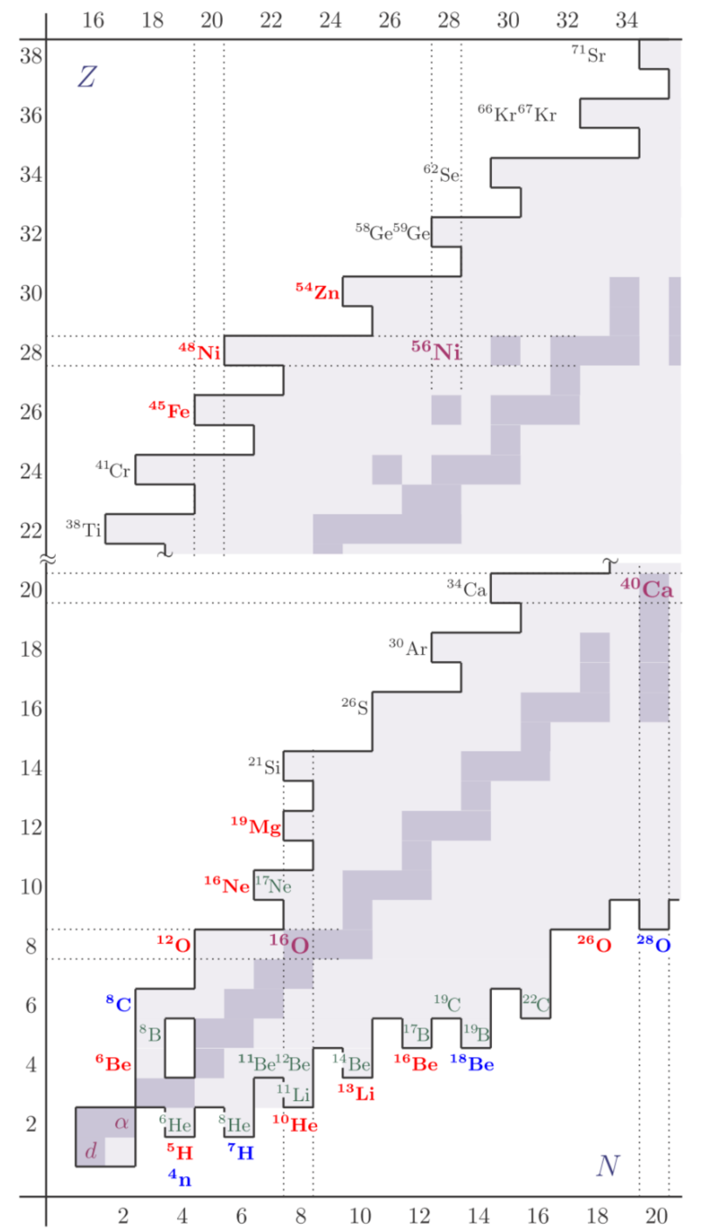
Competitive light nuclei RIB program at FLNR

Correlations for aligned continuum states populated in the direct reactions



Opportunity of spin-parity identification



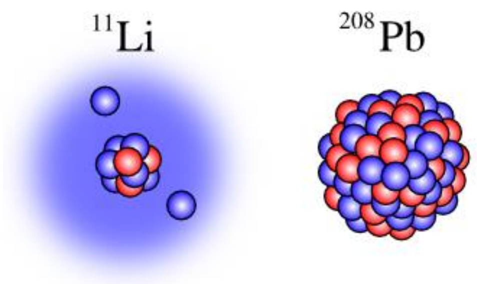


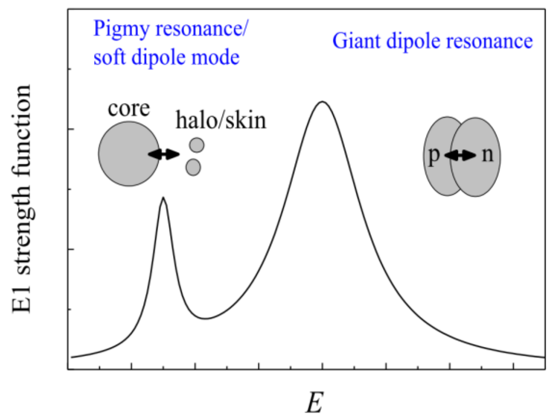
Competitive light nuclei RIB program at FLNR

Few-body dynamics near the driplines,
Correlations in the few-body decays

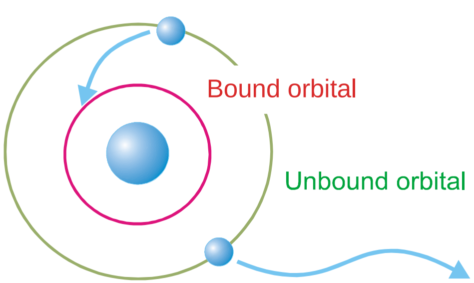
Halo phenomenon

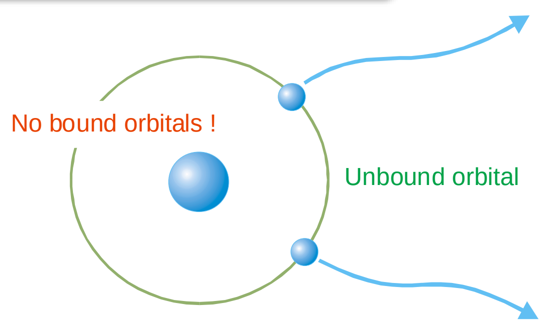
Soft excitation modes

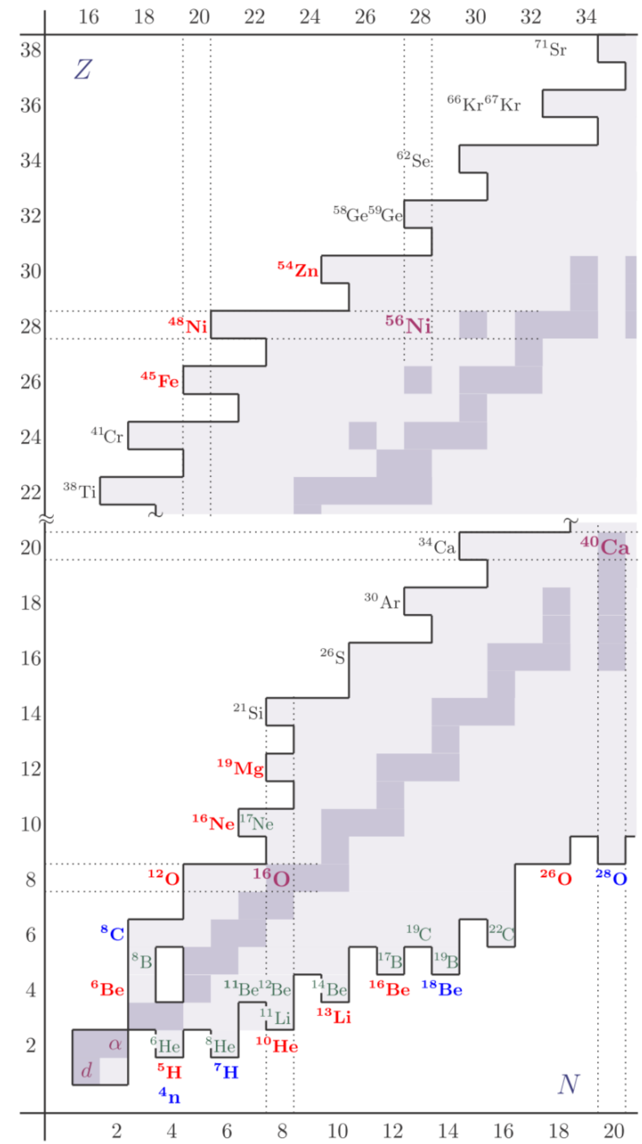




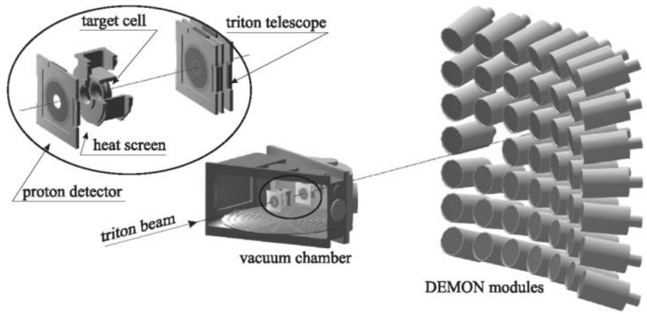
2p radioactivity and few-body decays

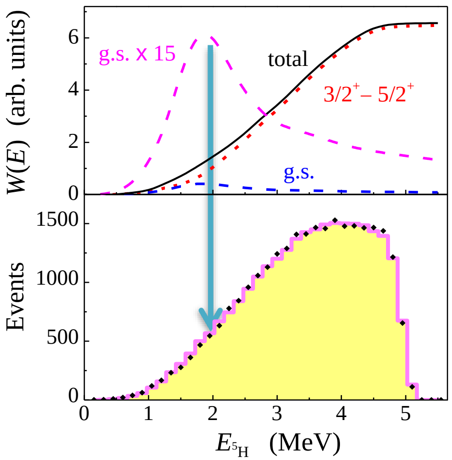


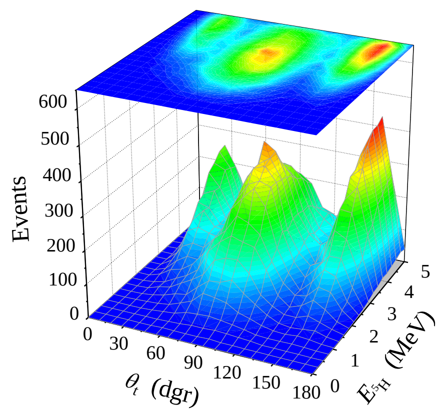


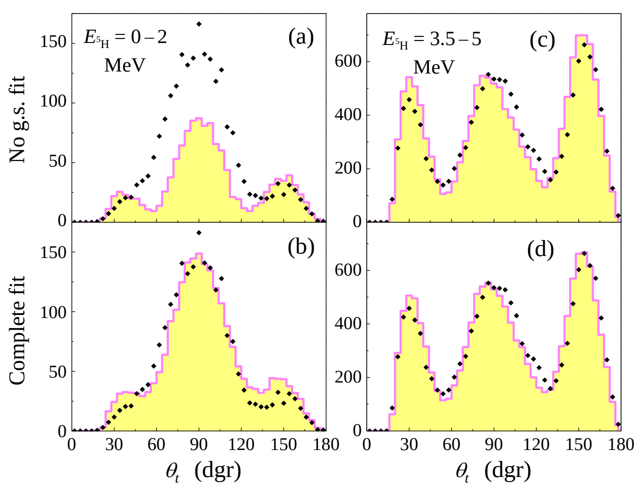


^{5}H studied in the ^{3}H(t,p)^{5}H reaction

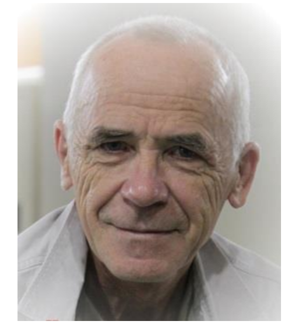








A.A. Korsheninnikov, 2001, ^{6}He(p,2p)^{5}H
Discovery of ^{5}H at FLNR

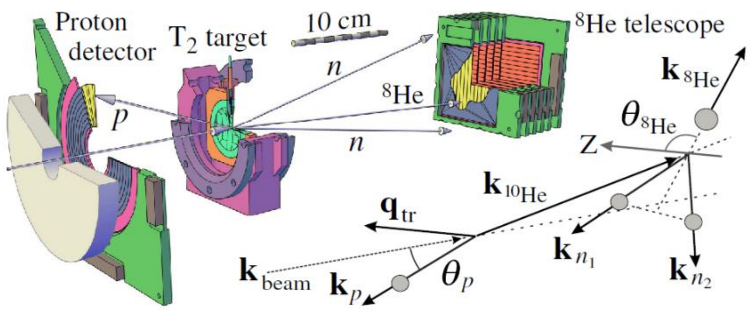


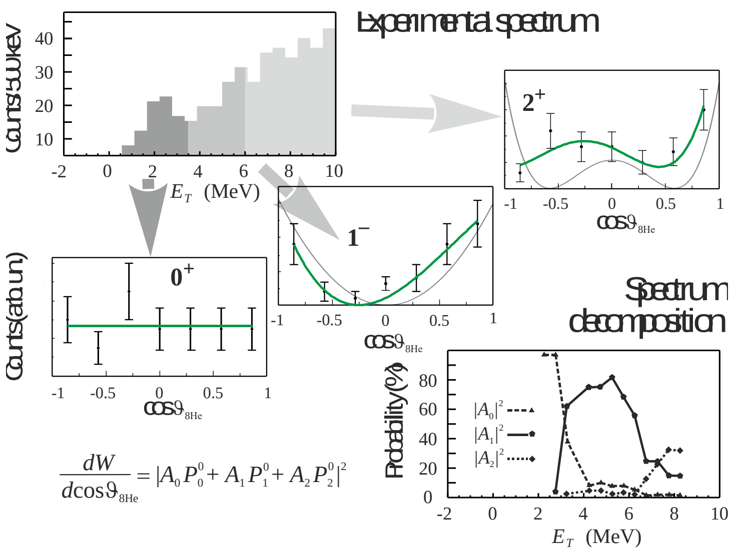
M.S. Golovkov, 2004,
Pioneering correlation studies

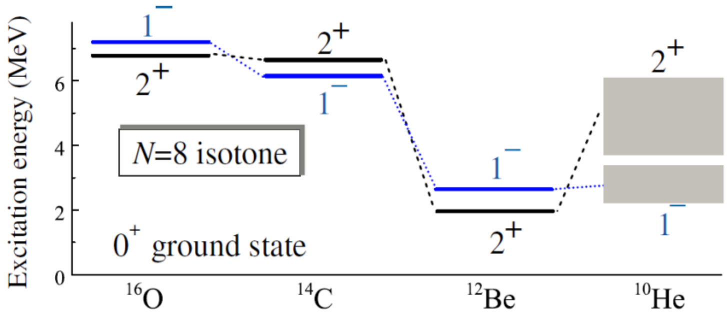
A.A. Korsheninnikov et al., PRL **87** (2001) 92501.
M.S.Golovkov et al., PLB **566** (2003) 70.
M.S.Golovkov et al., PRL **93** (2004) 262501.
S.V. Stepantsov et al., NPA **738** (2004) 436.
M.S.Golovkov et al., PRC **72** (2005) 064612.

- Poor population of ground state. However, correlations provide enough selectivity: quantum amplification
- ^{5}H ground state position is finally established; the excited state is established as $3/2^+$-$5/2^+$ degenerate mixture

^{10}He studied in the ^{8}He(t,p)^{10}He reaction

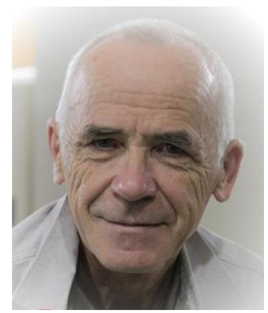






"Conundrum nucleis" second double magic in nuclide chart

Discovered by Korsheninnikov et al. in 1994 in RIKEN giving E_T=1.2 MeV



M.S. Golovkov *et al.*, PLB **672** (2009) 22
S.I. Sidorchuk *et al.*, PRL **108** (2012) 202502

- Three-body correlations were studied in ^{5}H basing on outstanding statistics. Can be something useful done with really exotic systems and limited statistics?

New ground state energy for ^{10}He: E_T=2.0-2.5 MeV

Shell structure breakdown in ^{10}He

Publicity for ^{10}He work

McGRAW-HILL
YEARBOOK OF
SCIENCE &
TECHNOLOGY

2013

Comprehensive coverage of recent events and research as compiled by the staff of the McGraw-Hill Encyclopedia of Science & Technology

McGraw Hill

New York Chicago San Francisco Lisbon London Madrid Mexico City
Milan New Delhi San Juan Seoul Singapore Sydney Toronto

Breakdown of shell closure in helium-10

The study of exotic nuclei at the edges of nuclear stability is one of the most important developments in modern nuclear physics Unusual forms of nuclear dynamics often arise here. One of the most prominent phenomena encountered is shell breakdown—the deviation from the expected shell structure in these exotic nuclei. On the one hand, in the nuclear shell model, helium-10 (^{10}He) is a "double-magic" nucleus with $Z = 2$ and $N = 8$. On the other hand, it has an enormous neutron excess; its neutron number (N) to proton number (Z) ratio equals 4, which brings it to the edge of nuclear matter asymmetry. Thus, the ^{10}He nucleus is an important system for the development of our understanding of nuclei located far from the beta stability valley and even beyond the neutron and proton drip lines. Here we present new insights into the basic properties of this nucleus, illuminating its shell structure and indicating its strong deviation from the simple shell population picture.

Shell structure in nuclei. For more than 100 years the periodic table of elements has provided a basis ...ical laws. The ex- ...nnected with the ...cal atomic shells. "N versus Z," can ...riodic table in the ...gned to treat sys- semi-integer spin.

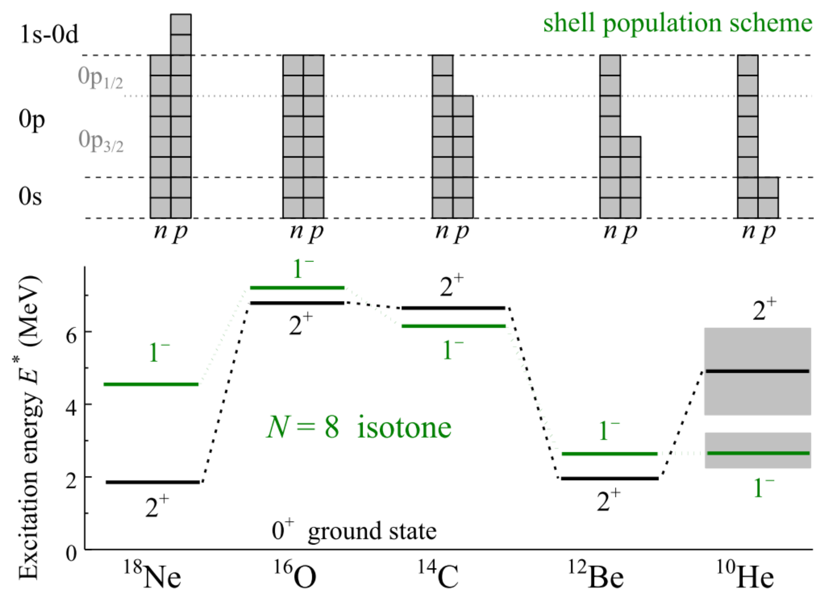


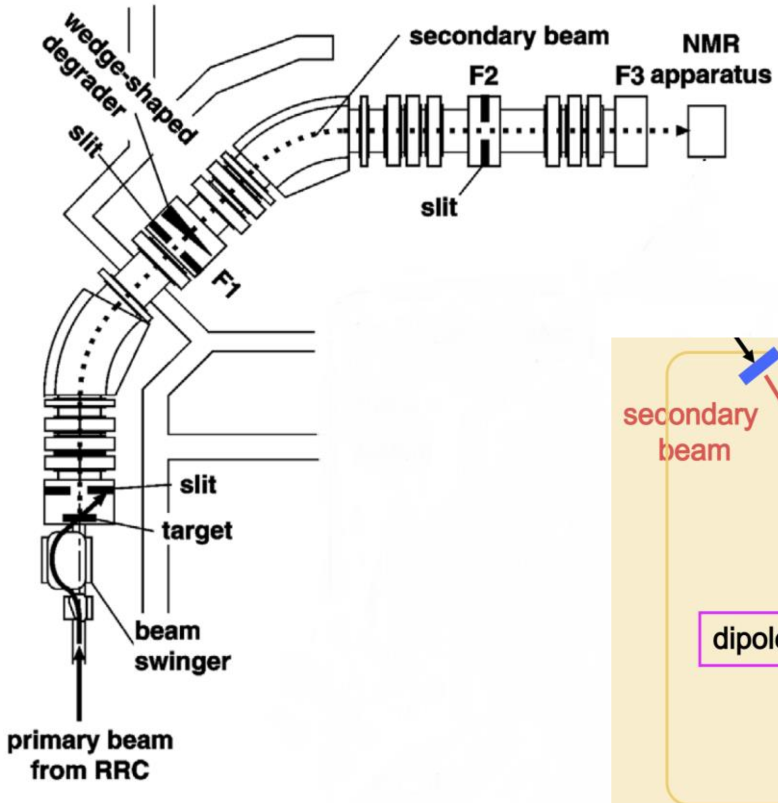
Figure 4. Evolution of excitation energy for the first 2^+ and 1^- states for N = 8 isotone. Shell population is schematically shown on top of the panel. Shaded rectangles indicate the uncertainty of the ^{10}He level positions due to their width.

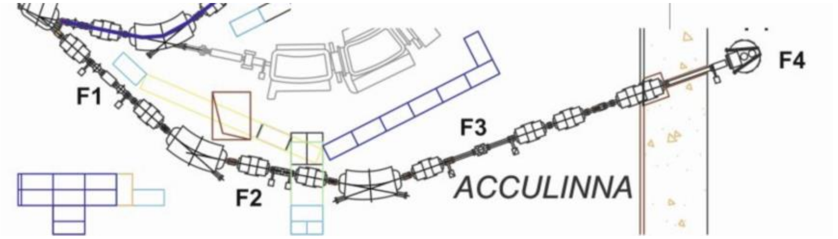
ACCULINNA-2 predecessors and ideology

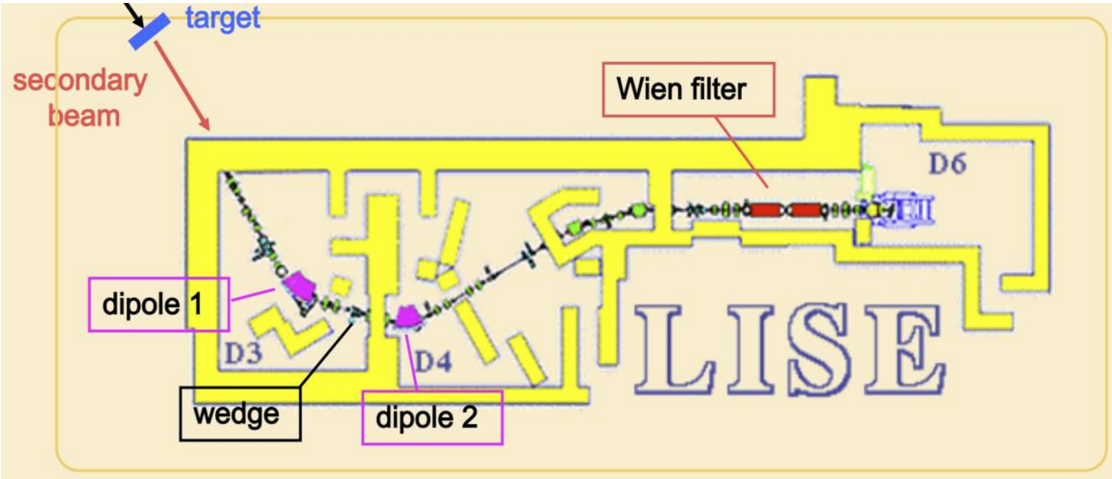
RIPS (RIKEN)

LISE (GANIL)

ACCULINNA (Flerov lab)



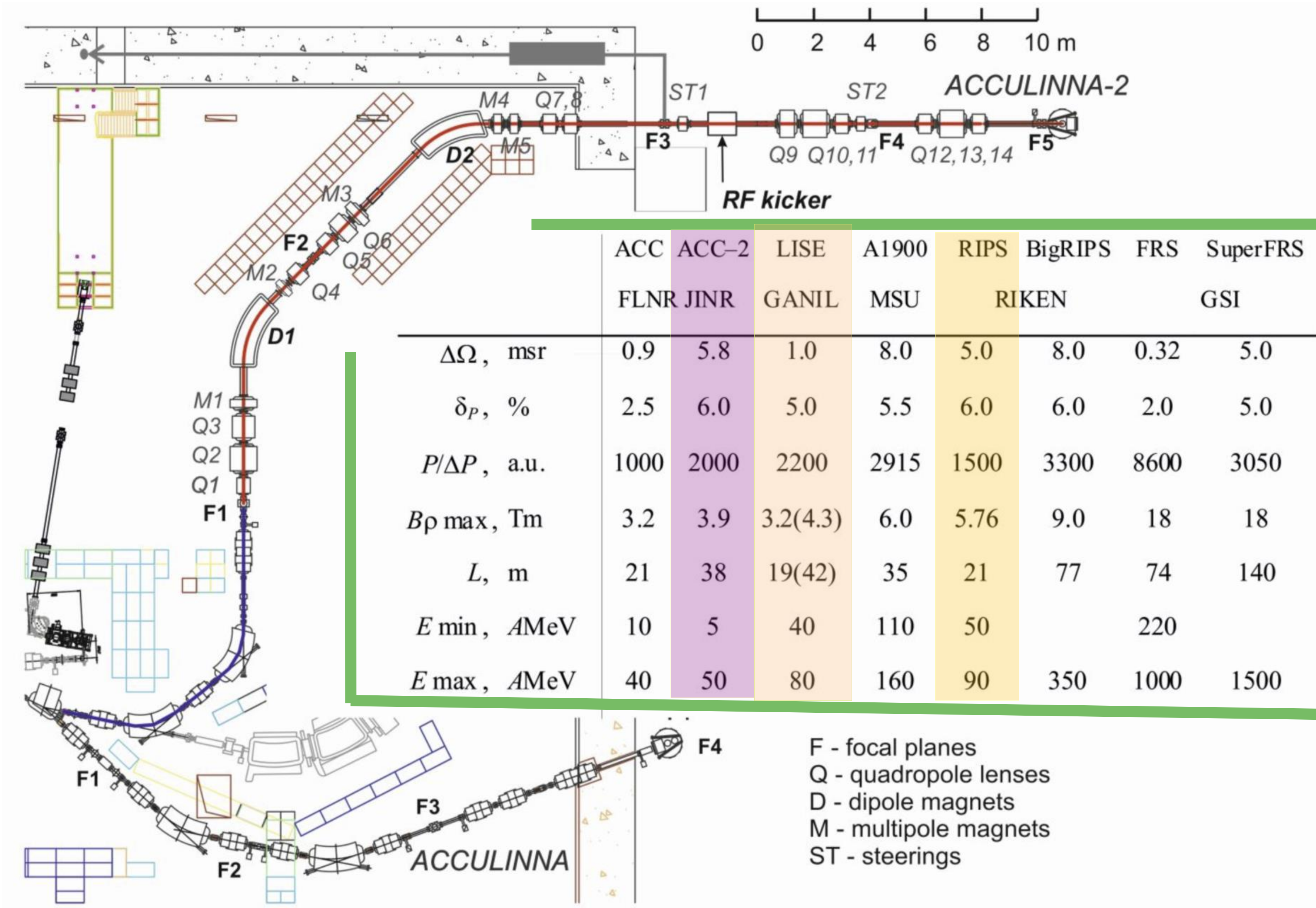




Single achromatic spectrometers

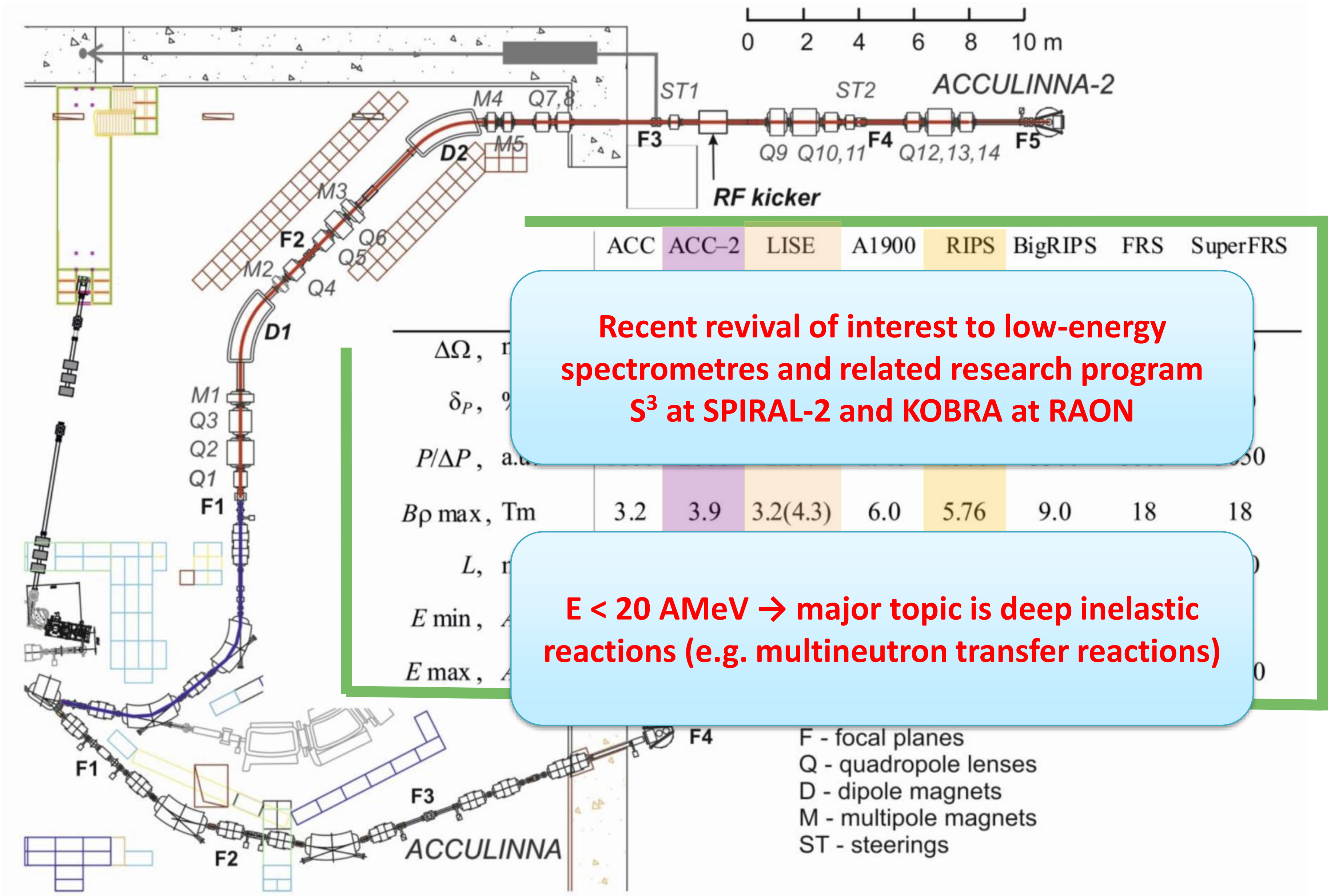
C-type

Acculinna-2 layout (letter of intent, 2012)



		ACC	ACC–2	LISE	A1900	RIPS	BigRIPS	FRS	SuperFRS
		FLNR JINR		GANIL	MSU	RIKEN		GSI	
$\Delta\Omega$,	msr	0.9	5.8	1.0	8.0	5.0	8.0	0.32	5.0
δ_P,	%	2.5	6.0	5.0	5.5	6.0	6.0	2.0	5.0
$P/\Delta P$,	a.u.	1000	2000	2200	2915	1500	3300	8600	3050
$B\rho$ max,	Tm	3.2	3.9	3.2(4.3)	6.0	5.76	9.0	18	18
L,	m	21	38	19(42)	35	21	77	74	140
E min,	AMeV	10	5	40	110	50		220	
E max,	AMeV	40	50	80	160	90	350	1000	1500

Acculinna-2 layout (letter of intent, 2012)



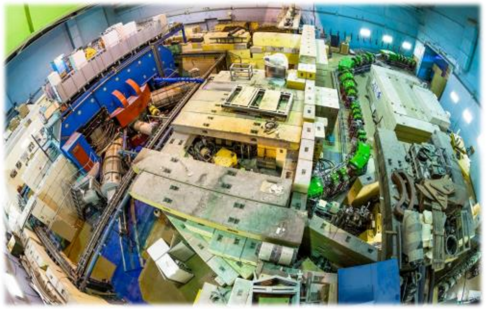
	ACC	ACC–2	LISE	A1900	RIPS	BigRIPS	FRS	SuperFRS
$B\rho$ max, Tm	3.2	3.9	3.2(4.3)	6.0	5.76	9.0	18	18

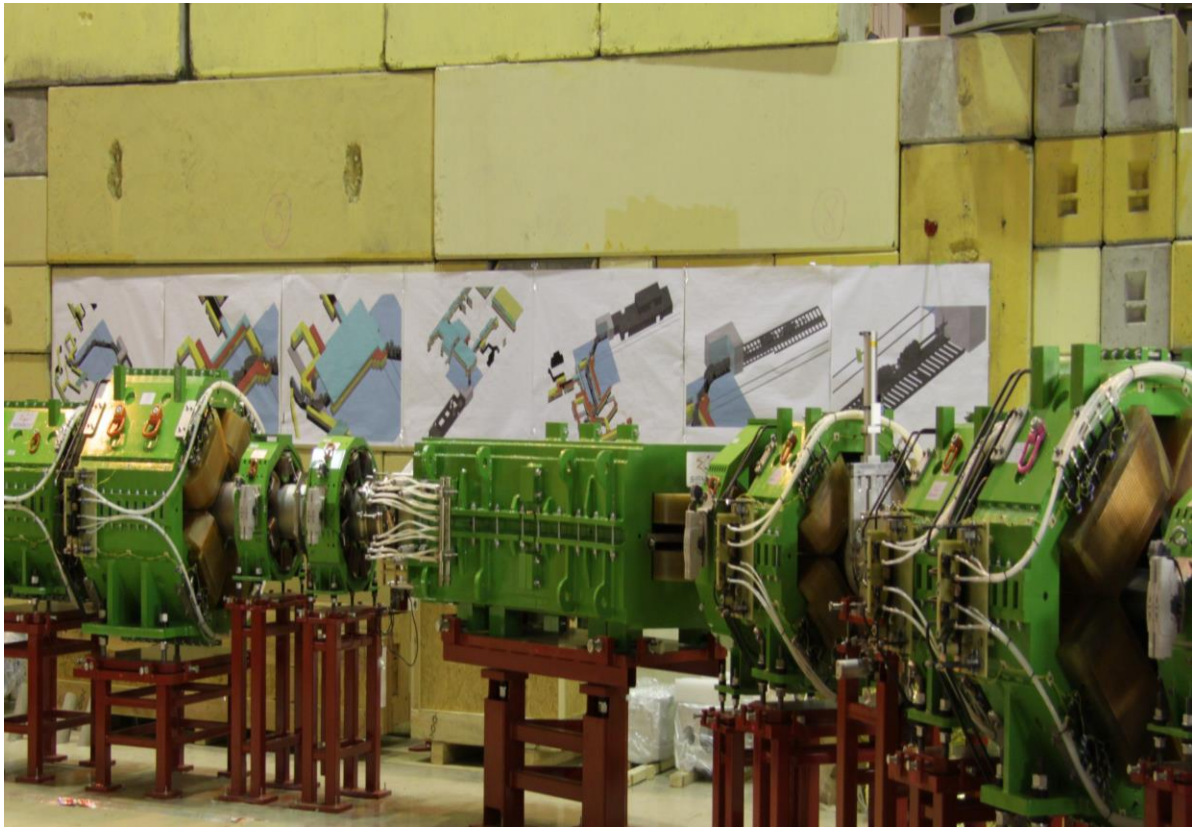
$\Delta\Omega$,
δ_P, %
$P/\Delta P$, a.u.
L,
E min,
E max,

Recent revival of interest to low-energy spectrometres and related research program S^3 at SPIRAL-2 and KOBRA at RAON

E < 20 AMeV → major topic is deep inelastic reactions (e.g. multineutron transfer reactions)

ACCULINNA-2 Construction (2014-2017)

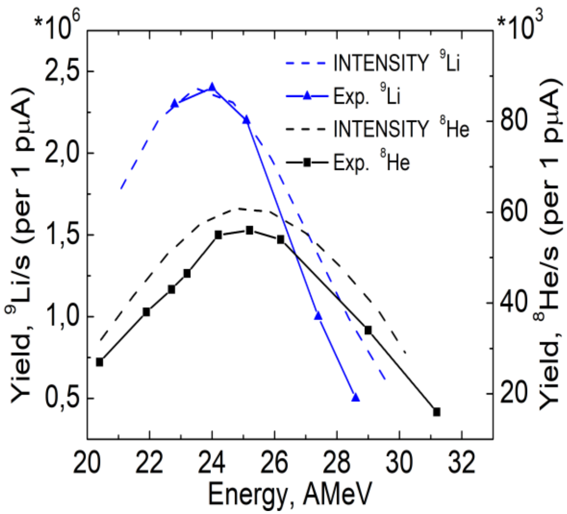


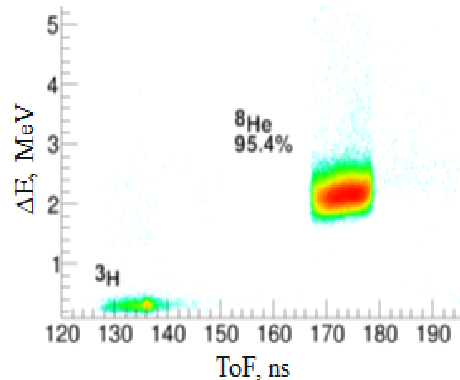


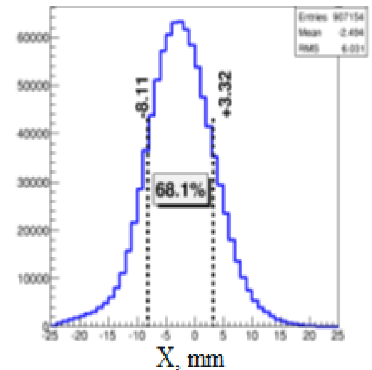
SIGMAPHI
ACCELERATOR TECHNOLOGIES

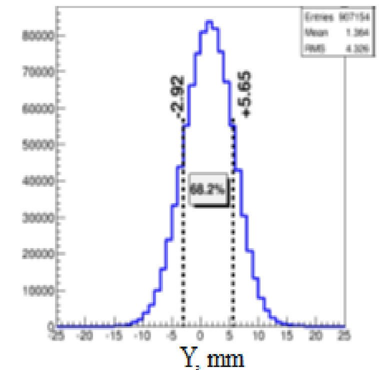
Experimental campaign 2018-2021

Characteristics of RIBs at ACCULINNA-2







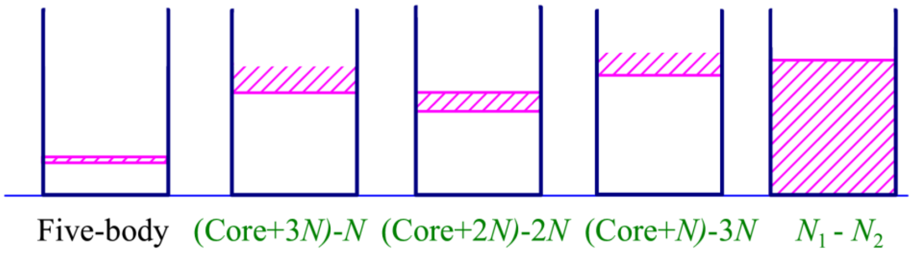


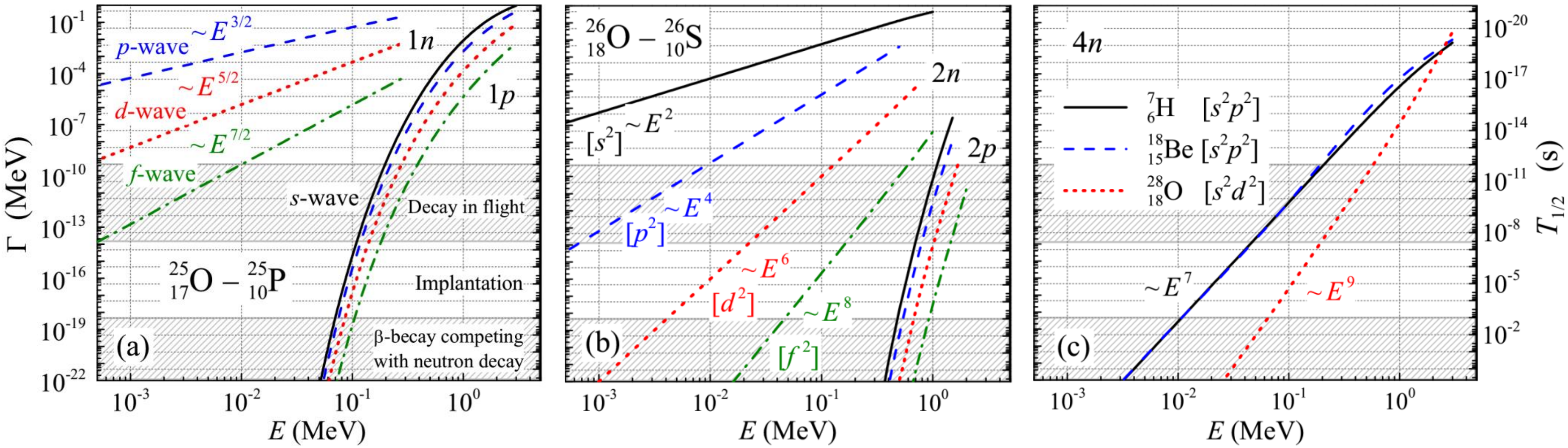
Ион	E МэВ/н	Первичный пучок	Мишень+ Клин	$\pm\Delta p$ %	$I_{эксперимент}$ ион/с/пмкА	$I_{расчет}$ ион/с/пмкА	Чистота %	$X \times Y$, мм (ПШПВ)
^{8}He	27.3	^{11}B 33.6 МэВ/н	Be(1 мм)+ Be(1 мм)	3.25	$5.4 \cdot 10^4$	$5.8 \cdot 10^4$	95.4	14.2×10.2
^{9}Li	25.2			2.00	$2.3 \cdot 10^6$	$2.9 \cdot 10^6$	97.9	13.9×11.1
^{11}Li	17.2			3.25	$1.4 \cdot 10^2$	$1.2 \cdot 10^2$	1.5	12.9×11.3
^{12}Be	15.1			3.25	$9.0 \cdot 10^3$	$1.8 \cdot 10^3$	23.3	16.6×12.9
^{10}Be*	45.0	^{15}N 49.3 МэВ/н	Be(1 мм)+ Be(1 мм)	1.25	$2.3 \cdot 10^6$	$9.0 \cdot 10^5$	78.4	17.7×13.4
^{27}S**	28.2	^{32}S 52.7 МэВ/н	Be(0.5 мм)+ Be(0.5 мм)	0.75	$1.6 \cdot 10^1$	$3.5 \cdot 10^1$	0.002	—
^{26}P	26.7				$8.5 \cdot 10^1$	$3.2 \cdot 10^2$	0.012	—
^{25}Si	25.0				$2.9 \cdot 10^3$	$2.3 \cdot 10^3$	0.56	—

Two- and four-neutron radioactivity search prospects

L.V. Grigorenko, I.G. Mukha, C. Scheidenberger, and M.V. Zhukov, PRC **84** (2011) 021303(R)

Energy conditions for true 4n decay





Long-living true four-neutron decay states are most probable.

Nearest candidates for 4n radioactive decay: ^{7}H, ^{18}Be, ^{28}O

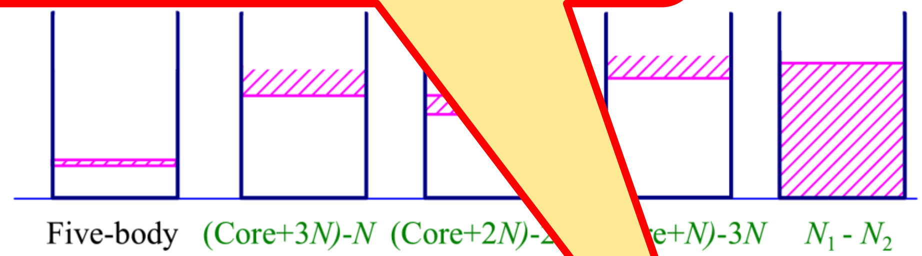
Two- and four-neutron radioactivity search prospects

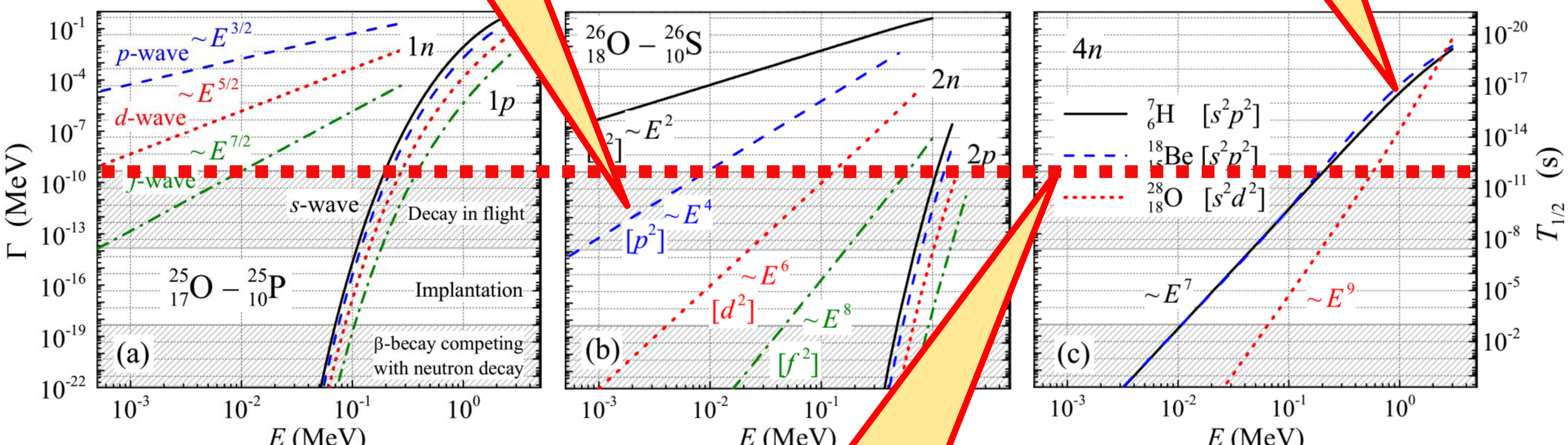
L.V. G… …enberger, and … …3(R)

Energy conditions for … 4n decay

^{26}O — controversial experimental results

^{7}H — four-neutron radioactivity or «true» 5-body decay



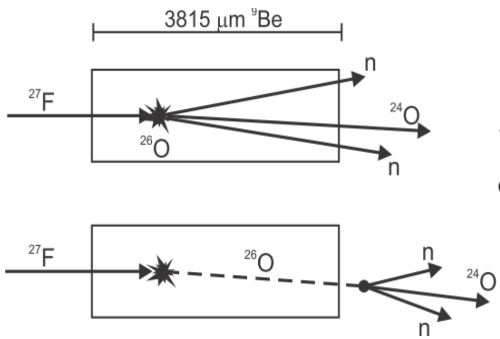


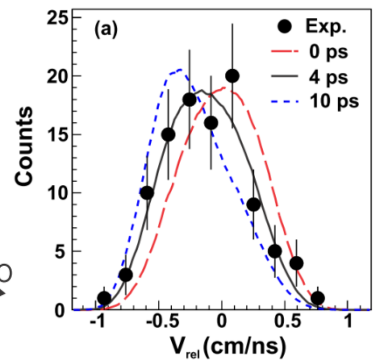
«Radioactivity borderline» $T_{1/2} \sim 1$ ps

Long-living true four-neutron dec… states are most probable.

…st candidates for 4n radioactive decay: ^{7}H, ^{18}Be, ^{28}O

2n radioactivity in ^{26}O ?





PRL 110, 152501 (2013) PHYSICAL REVIEW LETTERS week ending 12 APRIL 2013

Study of Two-Neutron Radioactivity in the Decay of ^{26}O

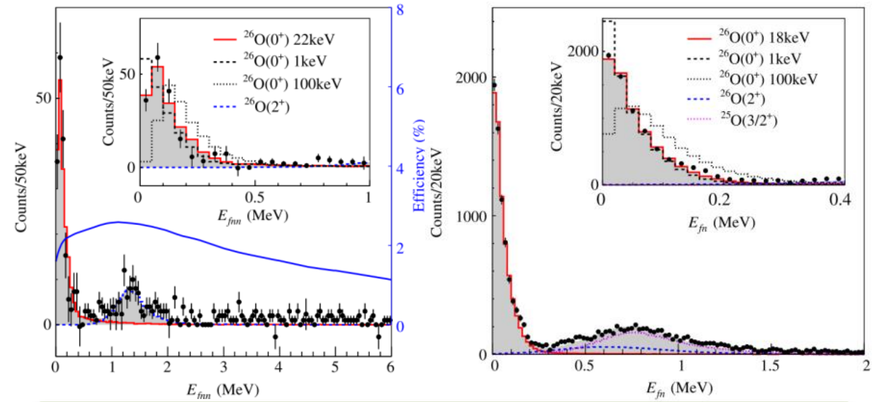
Z. Kohley,[1,2,*] T. Baumann,[1] D. Bazin,[1] G. Christian,[1,3] P. A. DeYoung,[4] J. E. Finck,[5] N. Frank,[6] M. Jones,[1,3] E. Lunderberg,[4] B. Luther,[7] S. Mosby,[1,3] T. Nagi,[4] J. K. Smith,[1,3] J. Snyder,[1,3] A. Spyrou,[1,3] and M. Thoennessen[1,3]

$T_{1/2}$ = 4.5 ps: 2*n* radioactivity discovered?

PRL 116, 102503 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line

Y. Kondo,[1] T. Nakamura,[1] R. Tanaka,[1] R. Minakata,[1] S. Ogoshi,[1] N. A. Orr,[2] N. L. Achouri,[2] T. Aumann,[3,4] H. Baba,[5] F. Delaunay,[2] P. Doornenbal,[5] N. Fukuda,[5] J. Gibelin,[2] J. W. Hwang,[6] N. Inabe,[5] T. Isobe,[5] D. Kameda,[5] D. Kanno,[1] S. Kim,[6] N. Kobayashi,[1] T. Kobayashi,[7] T. Kubo,[5] S. Leblond,[2] J. Lee,[5] F. M. Marqués,[2] T. Motobayashi,[5] D. Murai,[8] T. Murakami,[9] K. Muto,[7] T. Nakashima,[1] N. Nakatsuka,[9] A. Navin,[10] S. Nishi,[1] H. Otsu,[5] H. Sato,[5] Y. Satou,[6] Y. Shimizu,[5] H. Suzuki,[5] K. Takahashi,[7] H. Takeda,[5] S. Takeuchi,[5] Y. Togano,[4,1] A. G. Tuff,[11] M. Vandebrouck,[12] and K. Yoneda[5]



E_T = 18(7) keV is quite large

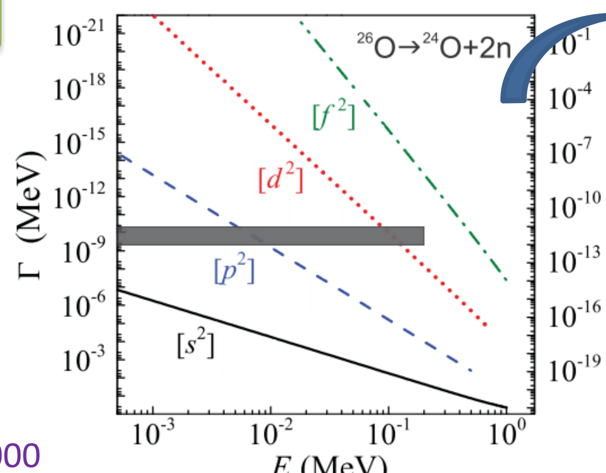
L.V. Grigorenko, I.G. Mukha, M.V. Zhukov, **PRL 111** (2013) 042501

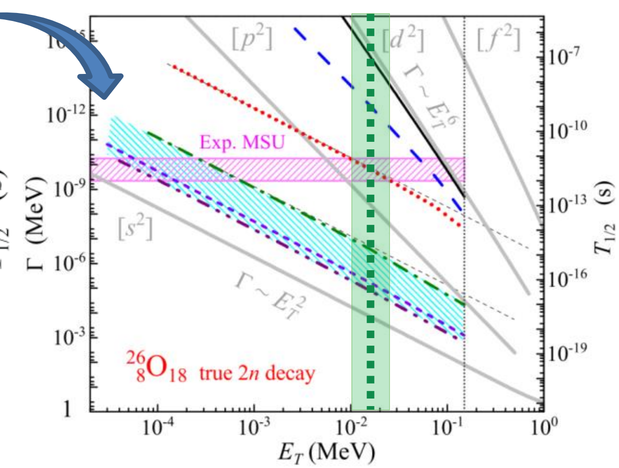
One of three works is wrong

Importance of fine three-body effects

2p radioactivity:
Core recoil – negligible
Paring - factor 200-500

2n radioactivity:
Core recoil – factor 5-10
Paring - factor 2000-10000





What can be interesting in ^{7}H?

^{7}H is the heaviest conceivable hydrogen isotope. The largest A/Z = 7 ratio is closer to the neutron matter than whatever we can imagine in the world of nuclides.

Special stability to ^{7}H is expected to be granted by the closed $p_{3/2}$ neutron subshell. Nothing heavier is expected. Questions of shell evolution in conditions of extreme proton deficiency

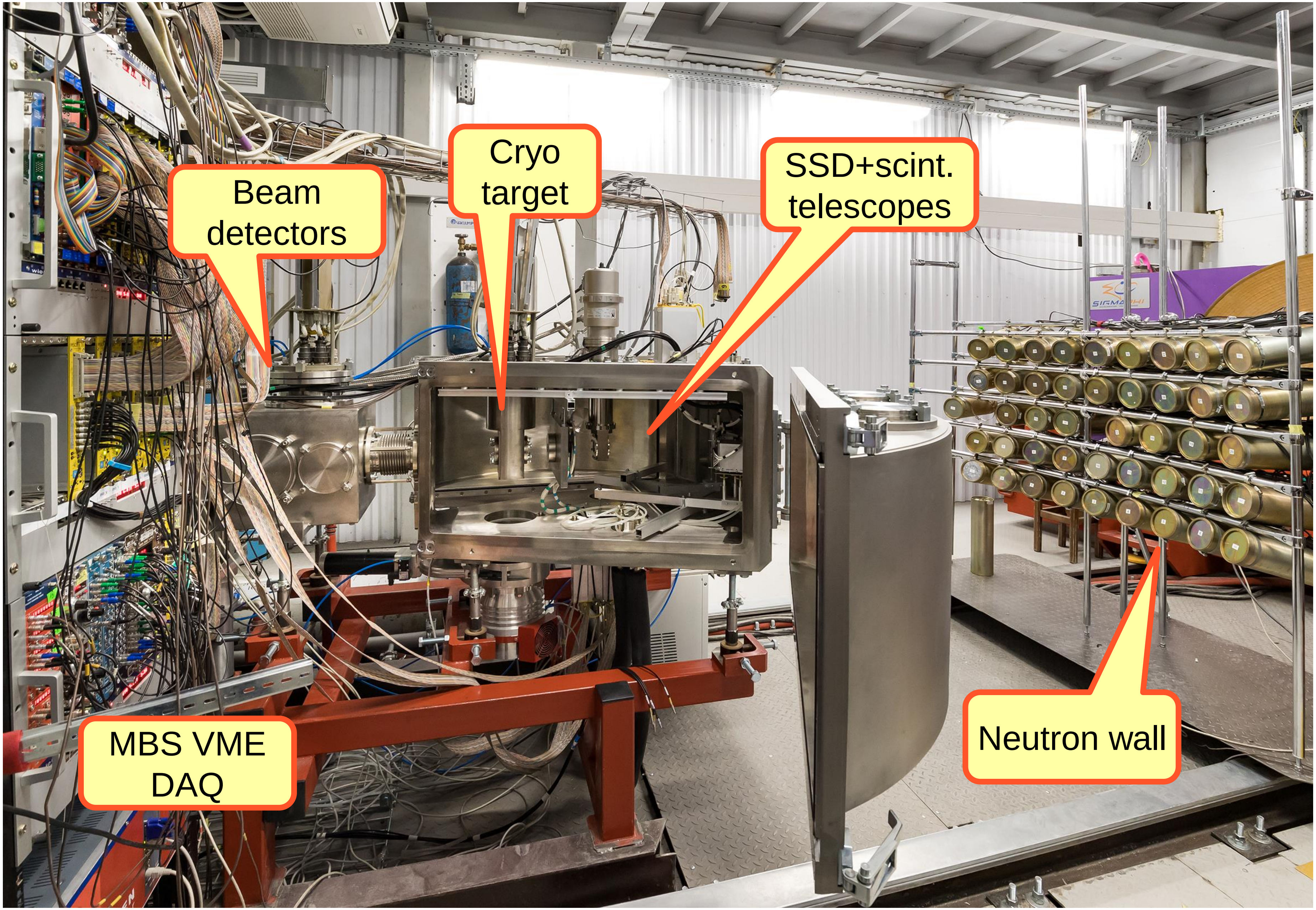
The ^{7}H g.s. is expected to decay only via the unique “true” five-body core+4n decay channel or simultaneous emission of four neutrons:

(i) The ^{7}H g.s. may be extremely long-lived for its decay energy. Candidate for 4n-radioactivity. Radioactivity-scale lifetimes for ET < 100-300 keV.

(iii) Even at ET = 2 MeV the ^{7}H g.s. width can be as small as 0.1-10 keV.

(iv) Specific correlations of fragments can be expected for the “true” five-body core+4n decay.

ACCULINNA-2 F5 setup for ^{7}H experiment



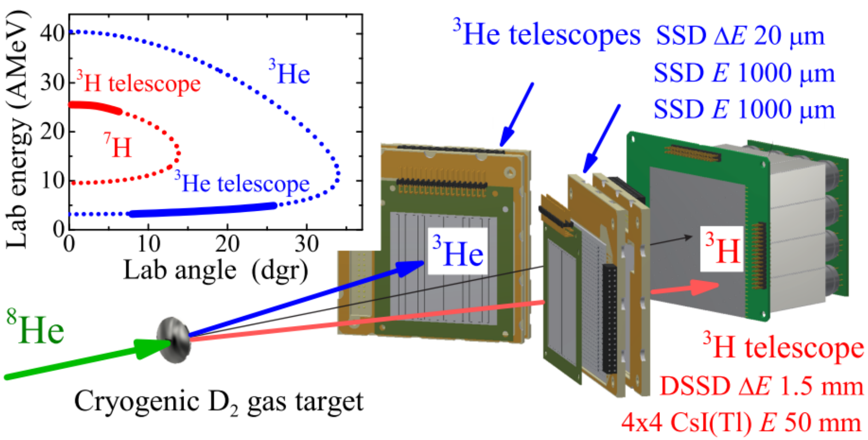
^{7}H studied in the ^{2}H(^{8}He, ^{3}He)^{7}H reaction

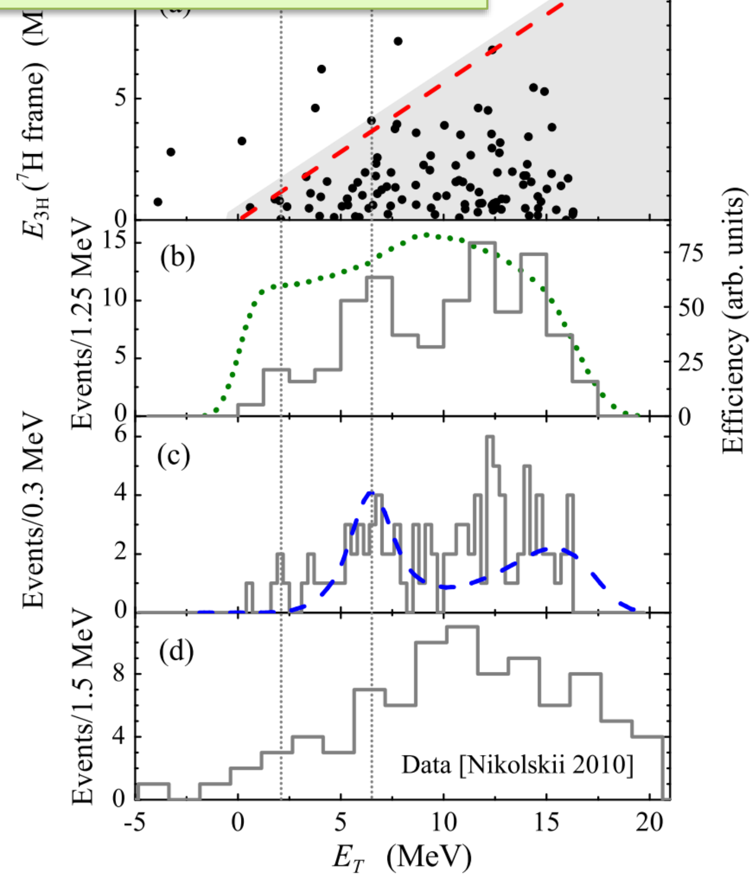
PHYSICAL REVIEW LETTERS **124**, 022502 (2020)

Evidence for the First Excited State of ^{7}H

A. A. Bezbakh,[1,2] V. Chudoba,[1,2,*] S. A. Krupko,[1,3] S. G. Belogurov,[1,4] D. Biare,[1] A. S. Fomichev,[1,5] E. M. Gazeeva,[1] A. V. Gorshkov,[1] L. V. Grigorenko,[1,4,6] G. Kaminski,[1,7] O. A. Kiselev,[8] D. A. Kostyleva,[8,9] M. Yu. Kozlov,[10] B. Mauyey,[1,11] I. Mukha,[8] I. A. Muzalevskii,[1,2] E. Yu. Nikolskii,[6,1] Yu. L. Parfenova,[1] W. Piatek,[1,7] A. M. Quynh,[1,12] V. N. Schetinin,[10] A. Serikov,[1] S. I. Sidorchuk,[1] P. G. Sharov,[1,2] R. S. Slepnev,[1] S. V. Stepantsov,[1] A. Swiercz,[1,13] P. Szymkiewicz,[1,13] G. M. Ter-Akopian,[1,5] R. Wolski,[1,14] B. Zalewski,[1,7] and M. V. Zhukov[15]

^{8}He beam 26 AMeV, 10^{5} pps
2018, two weeks





- Excited state at 6.5 MeV
- Indication of g.s. at 1.8 MeV (5 events)
- May be something at 12 MeV

^{7}H studied in the ^{2}H(^{8}He, ^{3}He)^{7}H reaction. Second run.

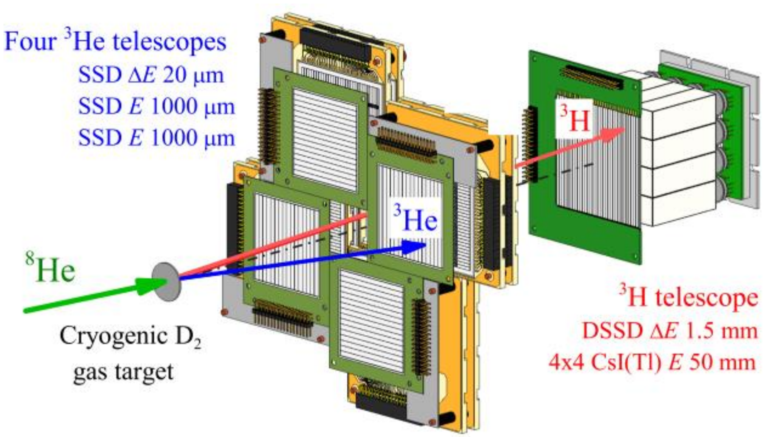
PHYSICAL REVIEW C **103**, 044313 (2021)

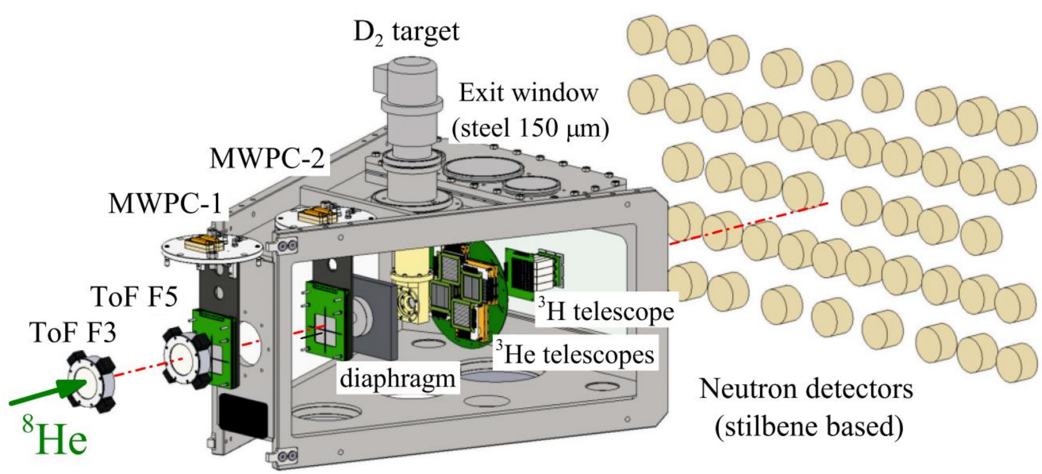
Resonant states in ^{7}H: Experimental studies of the ^{2}H(^{8}He, ^{3}He) reaction

I. A. Muzalevskii,[1,2,*] A. A. Bezbakh,[1,2] E. Yu. Nikolskii,[3,1] V. Chudoba,[1,2] S. A. Krupko,[1] S. G. Belogurov,[1,4] D. Biare,[1] A. S. Fomichev,[1,5] E. M. Gazeeva,[1] A. V. Gorshkov,[1] L. V. Grigorenko,[1,4,3] G. Kaminski,[1,6] O. Kiselev,[7] D. A. Kostyleva,[7,8] M. Yu. Kozlov,[9] B. Mauyey,[1,10] I. Mukha,[7] Yu. L. Parfenova,[1] W. Piatek,[1,6] A. M. Quynh,[1,11] V. N. Schetinin,[9] A. Serikov,[1] S. I. Sidorchuk,[1] P. G. Sharov,[1,2] N. B. Shulgina,[3,12] R. S. Slepnev,[1] S. V. Stepantsov,[1] A. Swiercz,[1,13] P. Szymkiewicz,[1,13] G. M. Ter-Akopian,[1,5] R. Wolski,[1,14] B. Zalewski,[1,6] and M. V. Zhukov[15]

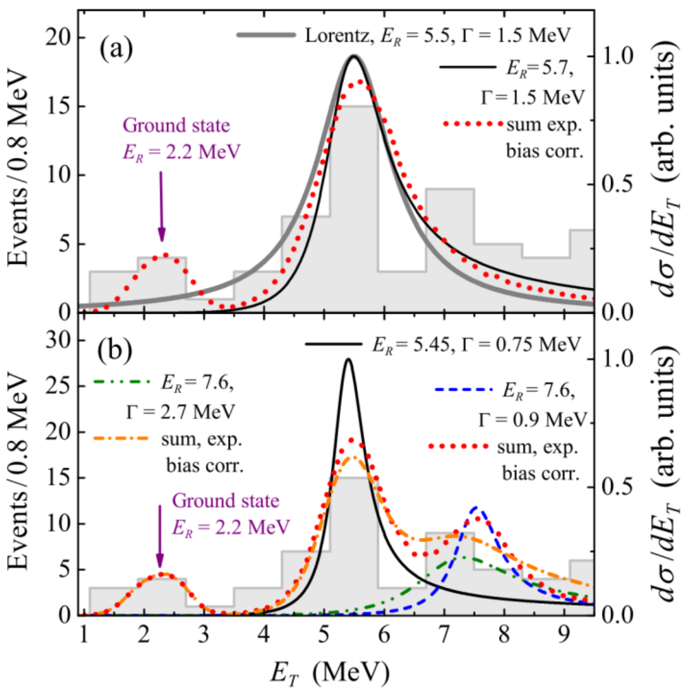
^{8}He beam 26 AMeV, 10^{5} pps
2019, 3 weeks

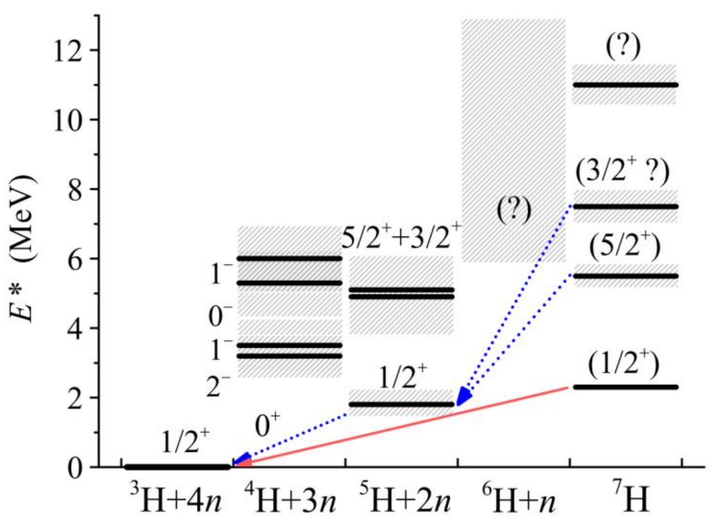
"Comming out party" for the neutron wall

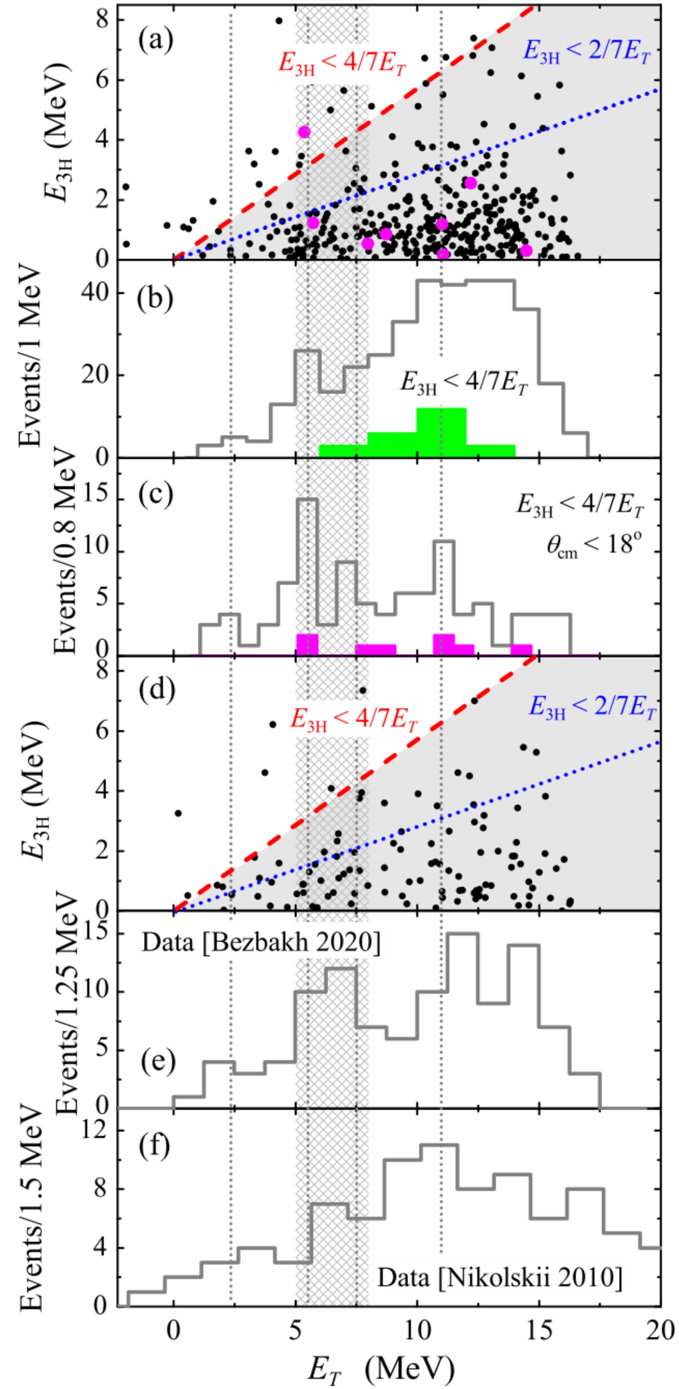




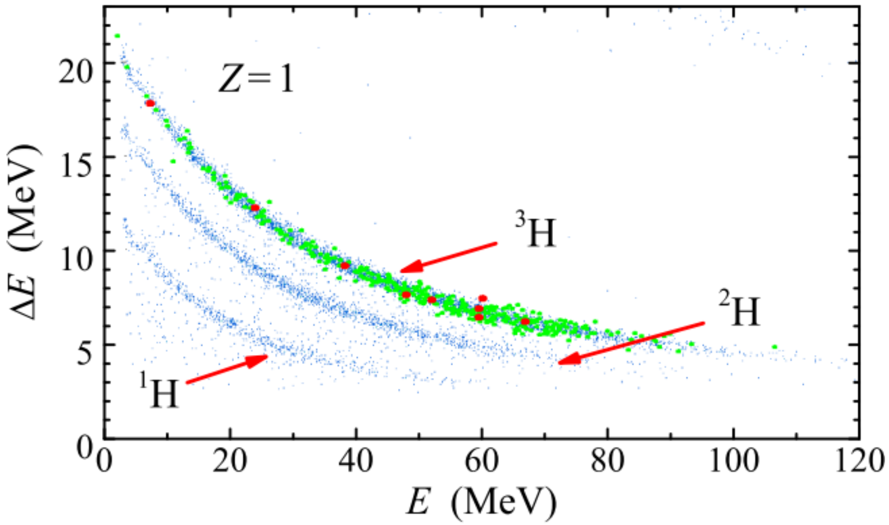
^{7}H data and spectrum

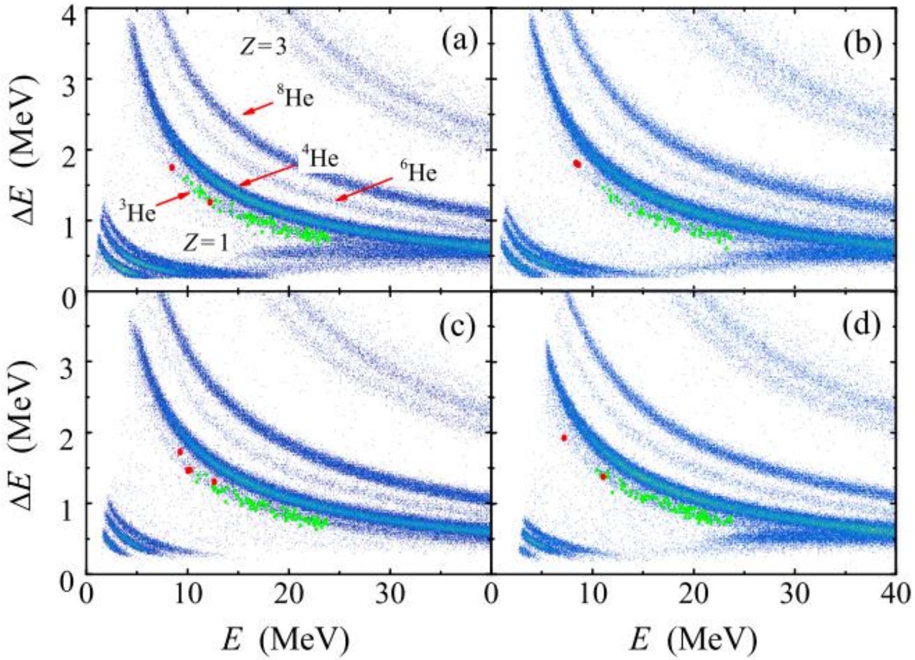






Channel identification





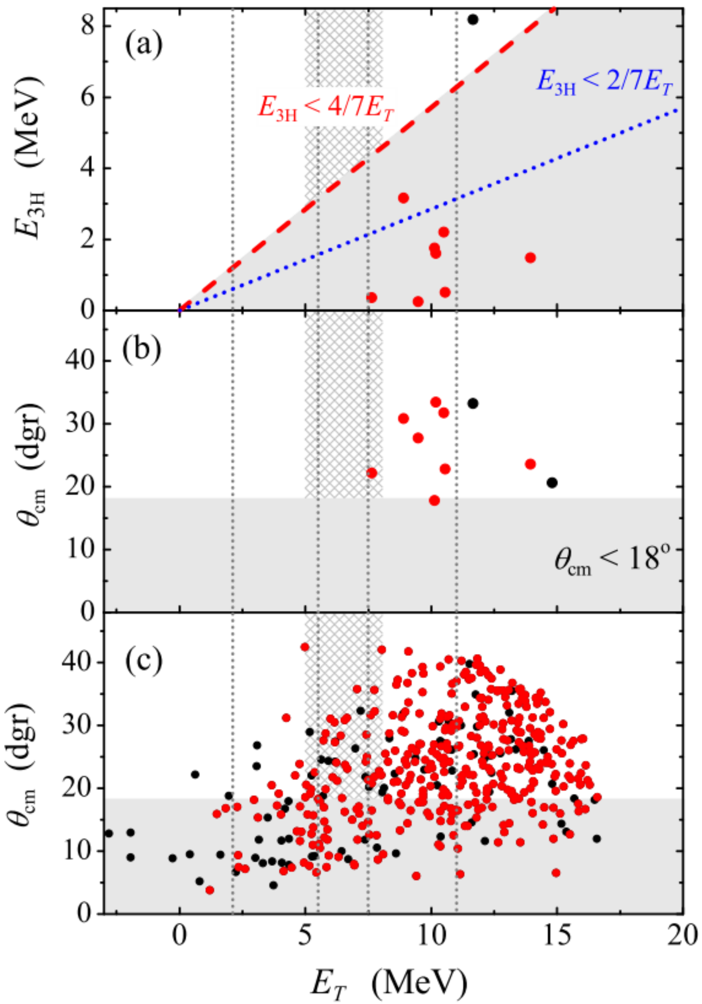
Red dots – ^{7}H g.s. candidate events, individually treated

– Reliable identification of both ^{3}He recoils and ^{3}H fragments

– Special treatment of 20 micron silicon detectors for ^{3}He telescope

– Careful event by event analysis of all candidates for ^{7}H low-lying states

Empty target measurements

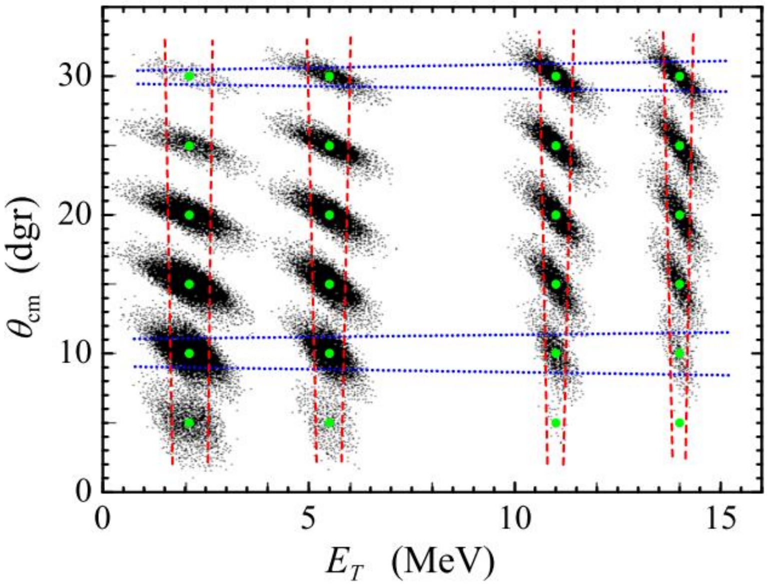


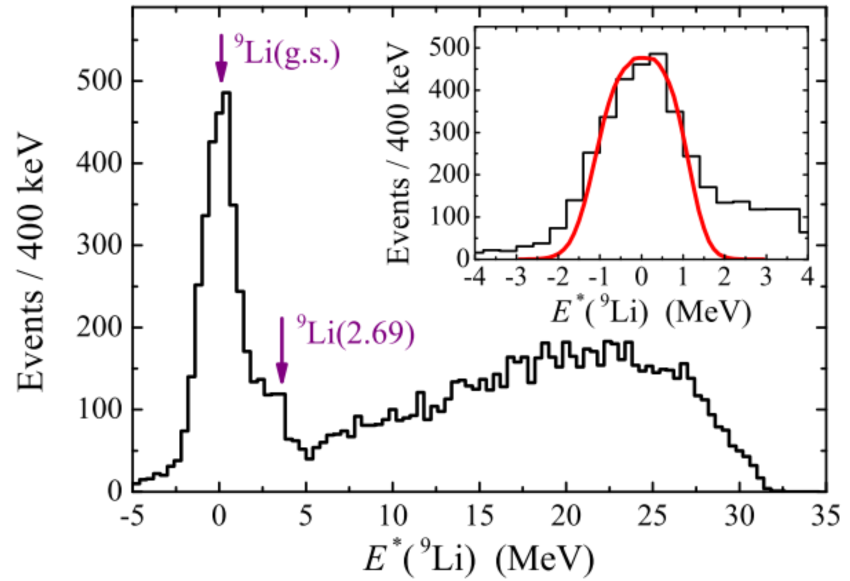
– Empty target events are located mainly outside the energy ranges of interest

– Only the hypothetical 11 MeV state can be contaminated by the empty targer background

– Reaction cm angle cutoff θ_{cm} < 18 dgr is expected to provide the ^7H spectrum free from empty target background

Energy resolution and calibration $^2H(^{10}Be,^3He)^9Li$ reaction





– Complete MC simulations of setup

– Higher energy resolution than in the previous experiments (less than 1 MeV) is obtained

– Independent MM calibration with ^{10}Be beam

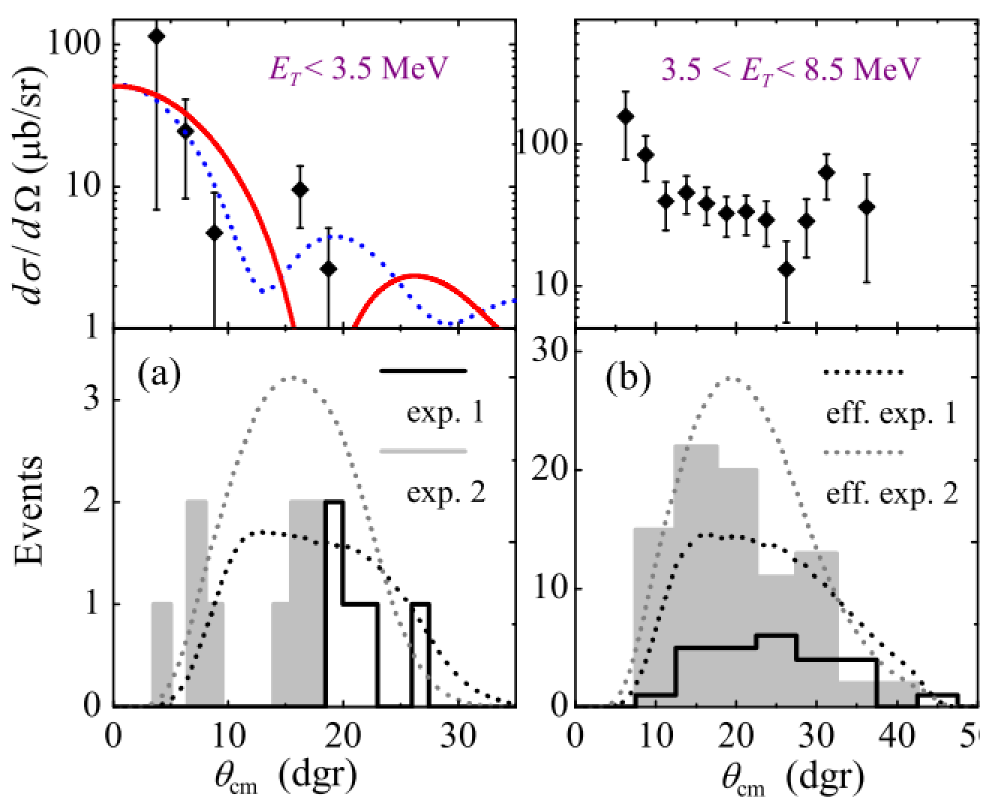
– MC simulations validated by the comparison ^{9}Li data

Energy and angular resolutions

E_T	2.2 MeV		5.5 MeV		11 MeV		14 MeV	
10°	0.95	2.2	0.73	2.3	0.48	2.5	0.38	2.8
20°	1.10	1.6	0.93	1.8	0.64	2.2	0.52	2.6
30°	1.13	1.2	0.99	1.3	0.77	1.8	0.69	2.0

Additional evidence: ^{7}H g.s. CMS angular distributions

– First experiment — second diffraction maximum is populated for the ^{7}H g.s.
– Second experiement was planned to populate the forward peak for the ^{7}H g.s.
– Indeed, the «hole» in the data from 9 to 14 degrees observed in the second data



Theoretical FRESCO calculations

– Standard calculation – diffraction minimum is sitting on top of the maximum in the data.

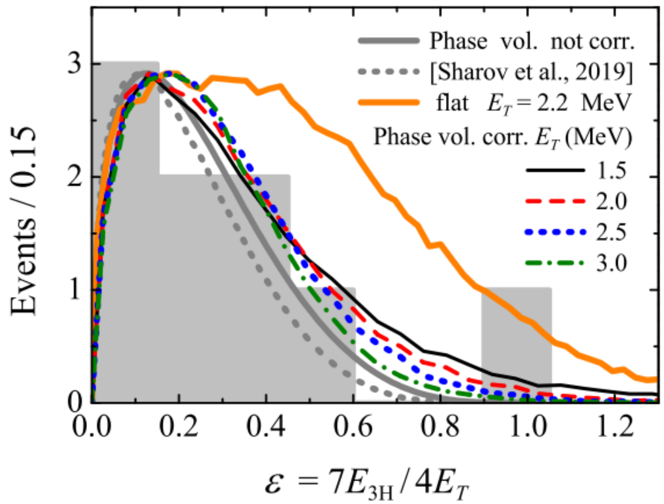
– To fit the position of diffraction minimum the non-standard calculation conditions should be used:

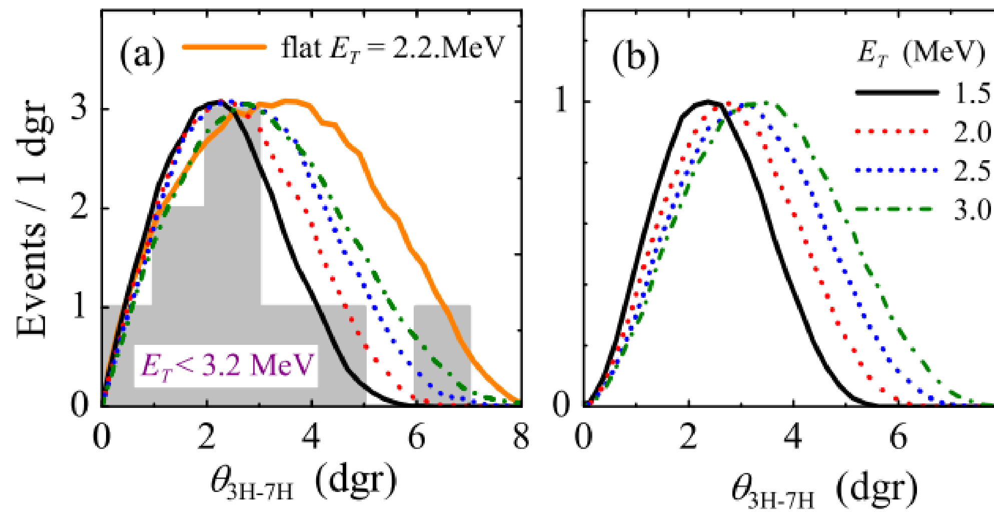
(i) extreme peripheral transfer

(ii) large absorption

Interpretation: observations consistent with expected very "fragile" character of the ^{7}H g.s. and very small g.s. population cross section.

Additional evidence: ^{7}H g.s. energy and angular distributions of tritons





– These distributions should reflect the specific dynamics of true five-body decay

– Theoretically these types of correlations are related

– Experimentally they are obtained in largely independent way

– Simple idea – 5-body phase volume

$$\frac{dW}{d\varepsilon} = \sqrt{\varepsilon(1-\varepsilon)^7}\,, \qquad \varepsilon = \frac{7E_{3H}}{4E_T}$$

TABLE II. Mean values of the ε and $\theta_{3H\text{-}7H}$ variables for the distributions of Figs. 13 and 14.

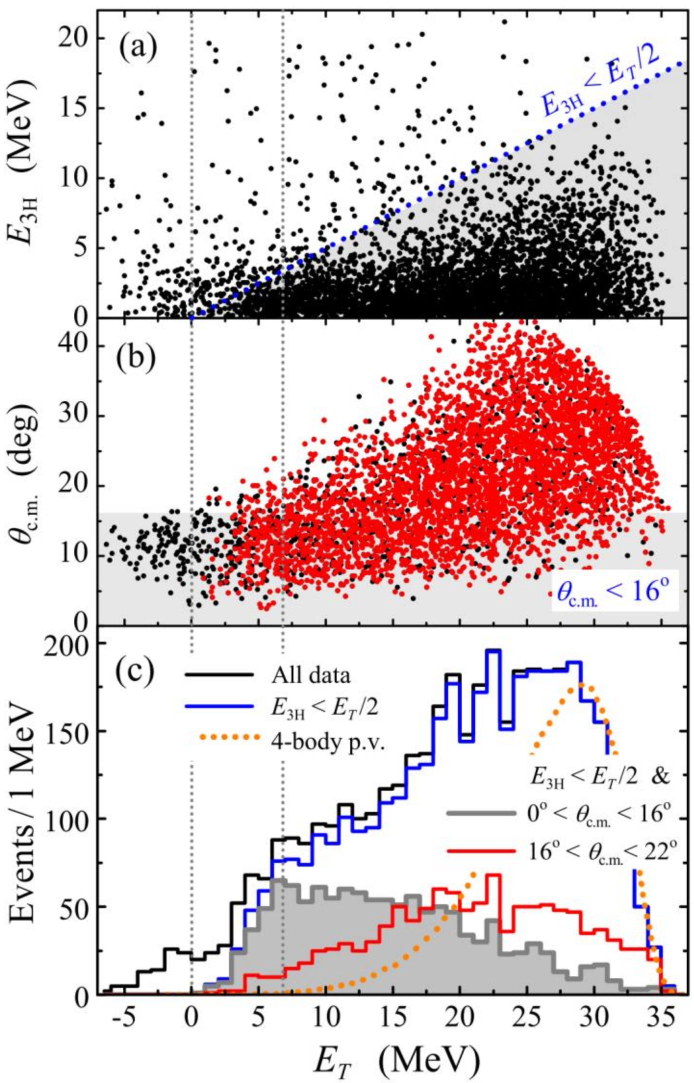
Value	flat	1.5	2.0	2.5	3.0	Exp.
ε	0.464	0.337	0.295	0.272	0.252	0.306
$\theta_{3H\text{-}7H}$	3.38	2.19	2.49	2.78	3.02	2.69

Both patterns are consistent with correlated emission of tritons expected for true five-body decay

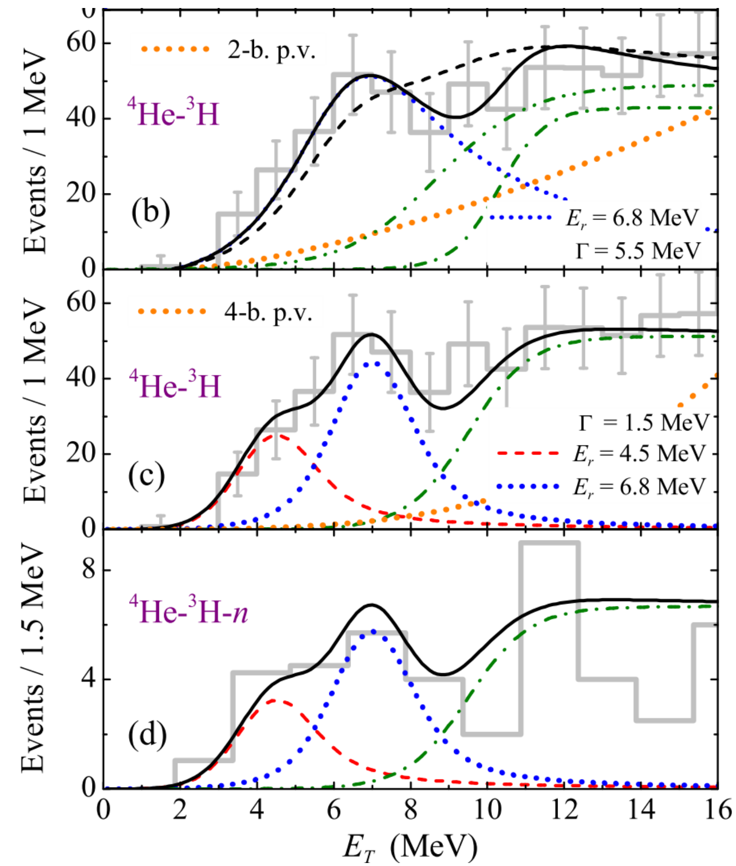
Both patterns are inconsistent with uncorrelated emission of tritons or background character of events

^{6}H data and spectrum

Large statistics, but large backgrounds

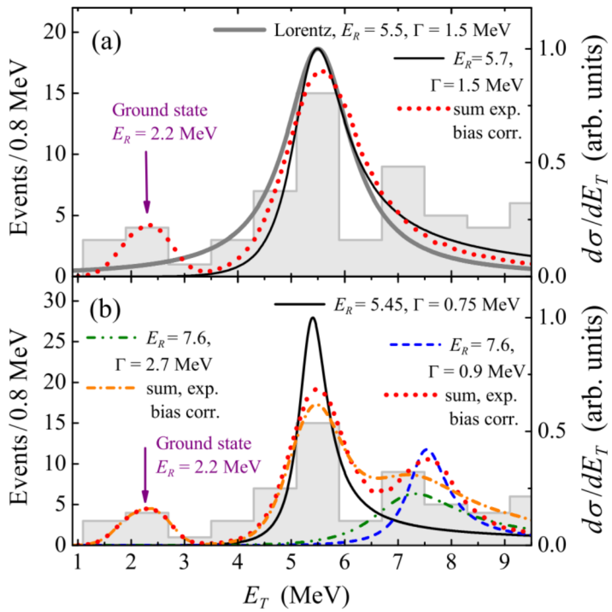


Background-subtracted, efficiency corrected



Reasonable confirmation from the t-α-n coincidence data

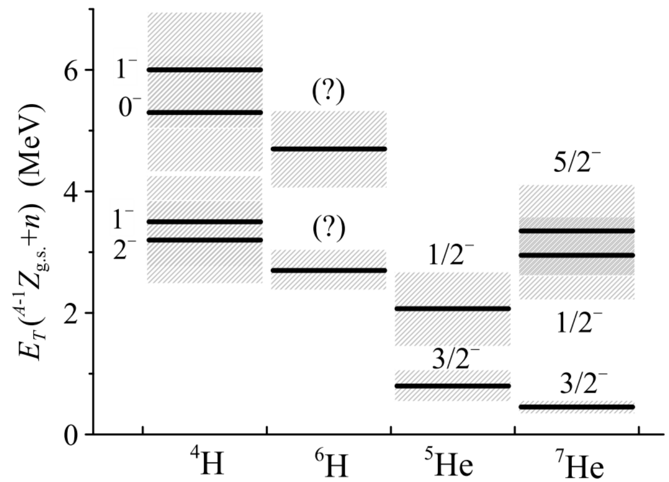
^{7}H and ^{6}H studies summary



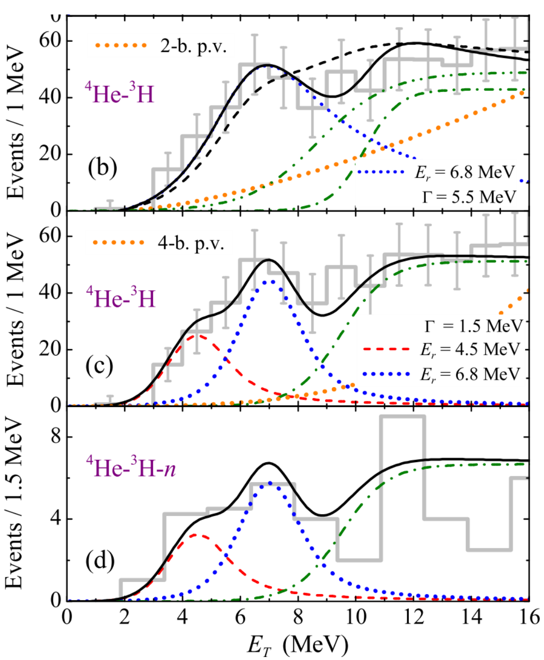
– ^{7}H g.s. at 1.8 MeV

– Resonant states at 5.5, 11 MeV

– Possible resonant state at 7.5 MeV



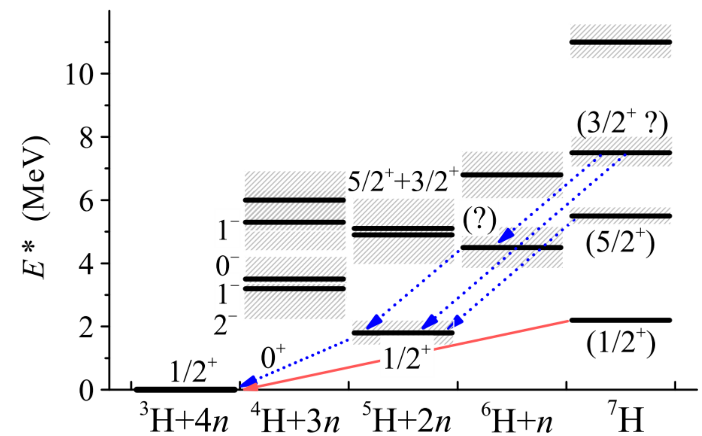
Analogies in the excitation spectra relative ^{3}H and ^{5}H, ^{4}He and ^{6}He ground states



– No ^{6}H g.s. at 2.6-2-7 MeV

– Resonant state at 6.5 MeV

– Possible resonant state at 4.5 MeV



Level scheme for 5 H isotopes: "true" 4n emission off ^{7}H ground state

^{7}H and ^{6}H discussion

Information about ^{6}H ground state seem to be reliable

^{6}H ground state at 2.6-2.7 MeV is excluded with cross section limit 5 μb/sr compared to 100-200 μb/sr for 4.5-6.5 MeV prescription.

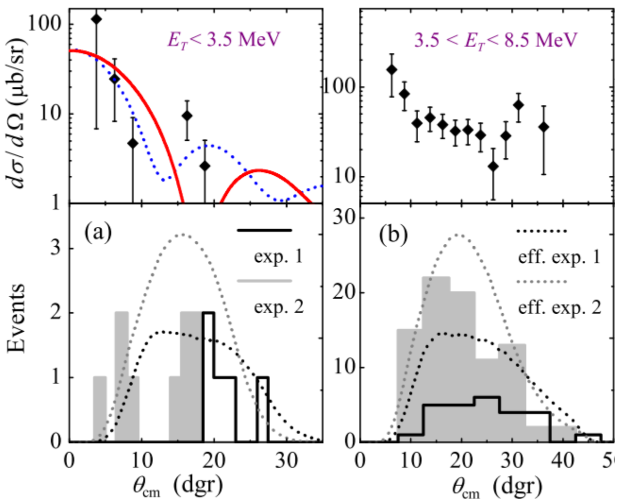
Cross section for ^{6}H ground state at 4.5-6.5 MeV is large and consistent with assumption about direct transfer of deuteron.

Information about ^{7}H ground state has very limited statistics

Could the 5.5 MeV peak be ^{7}H ground state? No

^{7}H ground state at 2.2 MeV has extremely small (for one-nucleon direct transfer) cross section 24 μb/sr

Observation of the 5.5 MeV ^{7}H state is quite reliable, but the cross section is still extremely small (for one-nucleon transfer) 30 μb/sr



Equal populations for 2.2 and 5.5 MeV states is likely to indicate deep structural difference between ^{8}He (expected $[(p_{3/2})^4]_0$ and ^{7}H

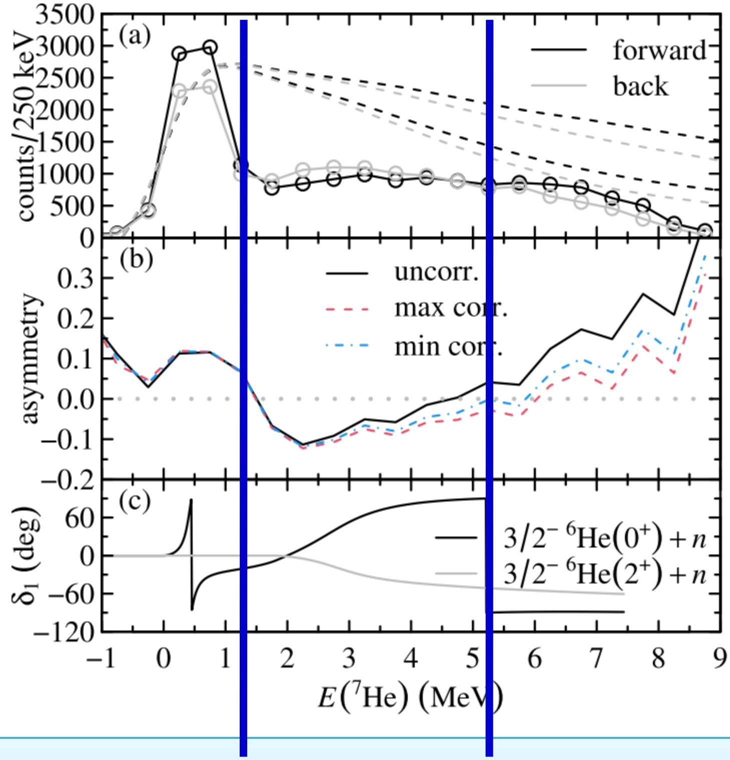
There is deep inconsistency in populations of ^{6}H and ^{7}H

^{6}H seem to be something expected, but ^{7}H does not seem to be as trivial as «proton hole in ^{8}He»

Interesting physics, not yet understood

^{7}He studied in the $^{2}H(^{8}He, p)^{7}He$ reaction

^{7}He preliminary data

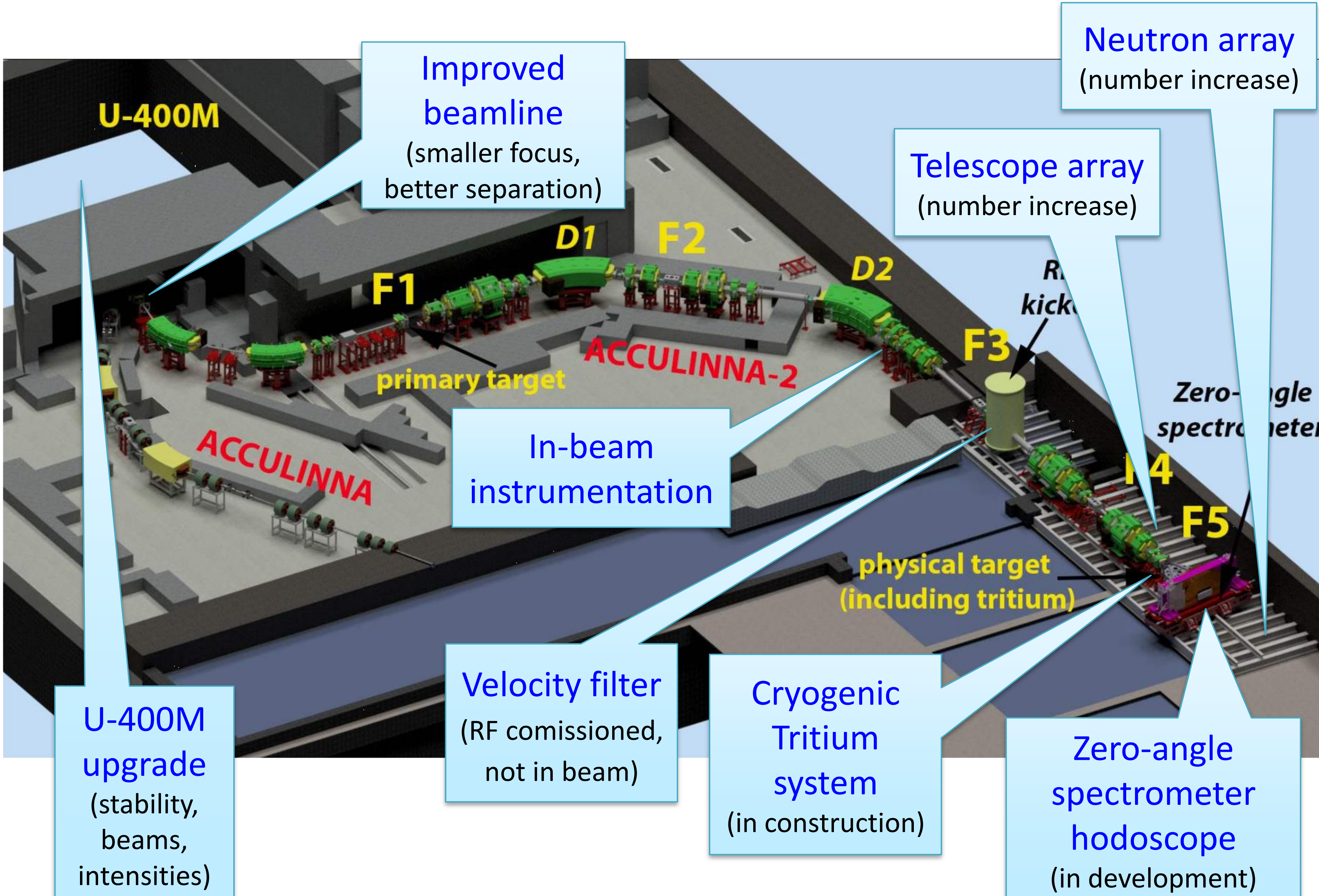


Transition $p_{3/2}$ → $p_{1/2}$ → $p_{3/2}(2)$

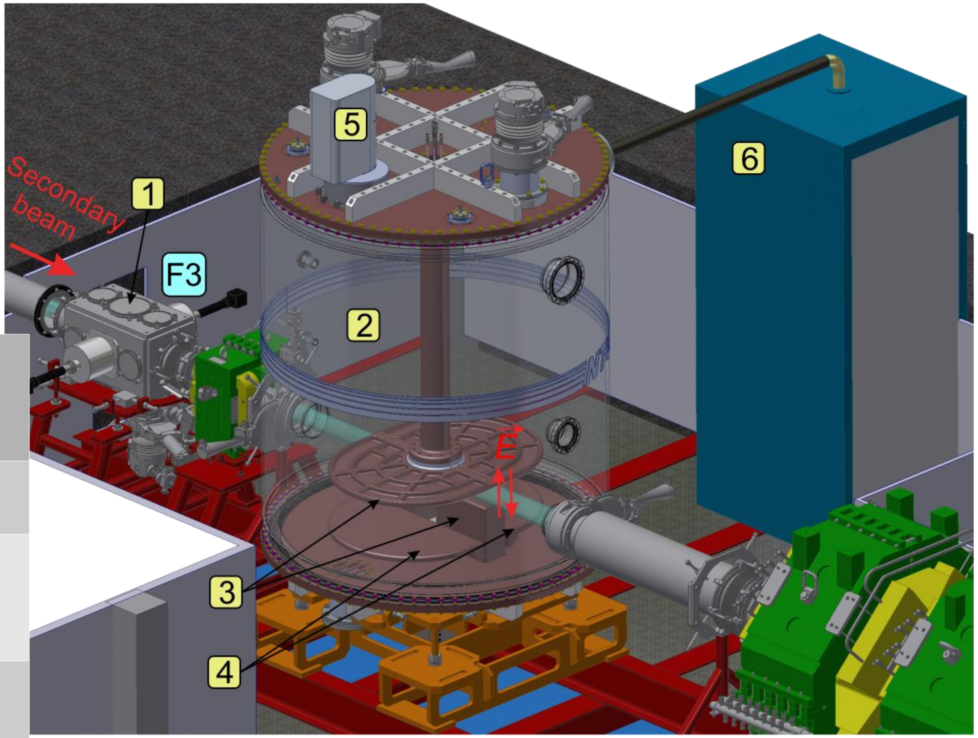
Prospective developments at ACCULINNA-2 for 2023-2025 campaign

In middle 2021 U-400M is stopped for reparation and upgrade. Operation restarts in the beginning 2023

2021-2022: программа развития инструментов



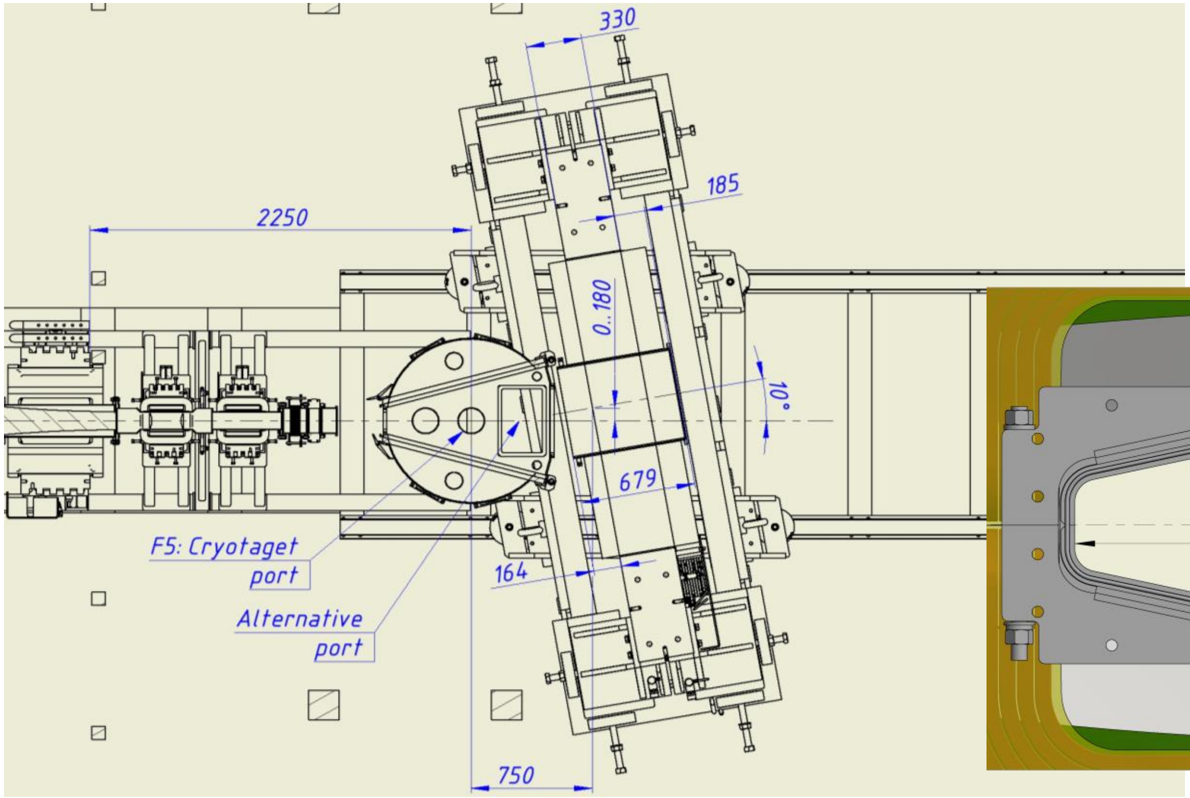
Velocity filter “RF-kicker“

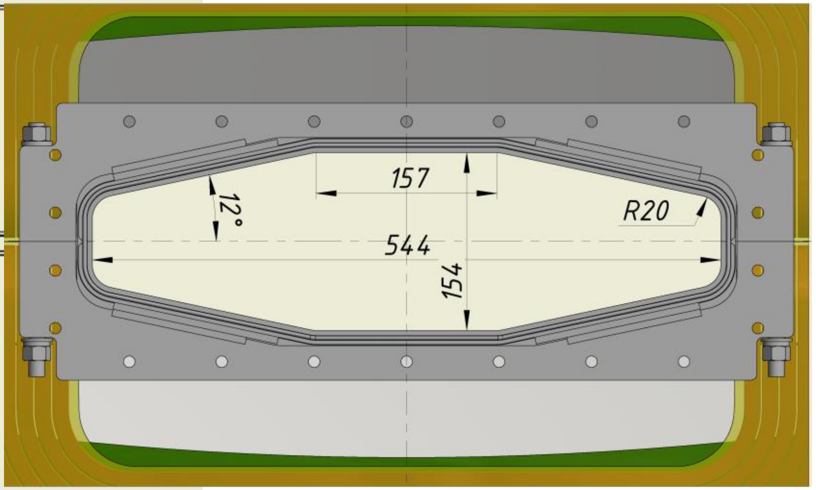


Frequency range (MHz)	14.5 – 20.5
Peak voltage (KV)/ Gap (mm)	120/ 70
Length(mm)/Width (mm) of electrodes	700/120
Cylinder Internal diameter (mm)	1400
Stem diameter (mm)	120
Length of coaxial line from beam axis (mm)	1830
Current at junction (A)	990
Current in short-cut (A)	1200
RF power (Watts)	15 000
Reactance Q	>10000
Df (RF tuning) (MHz)	0.66

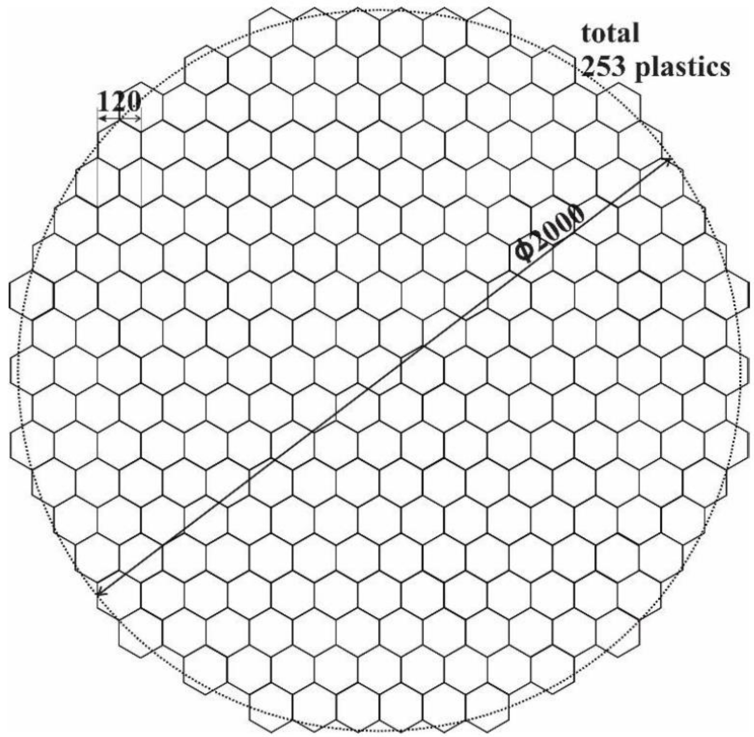
Zero-angle spectrometer “sweeper-magnet“

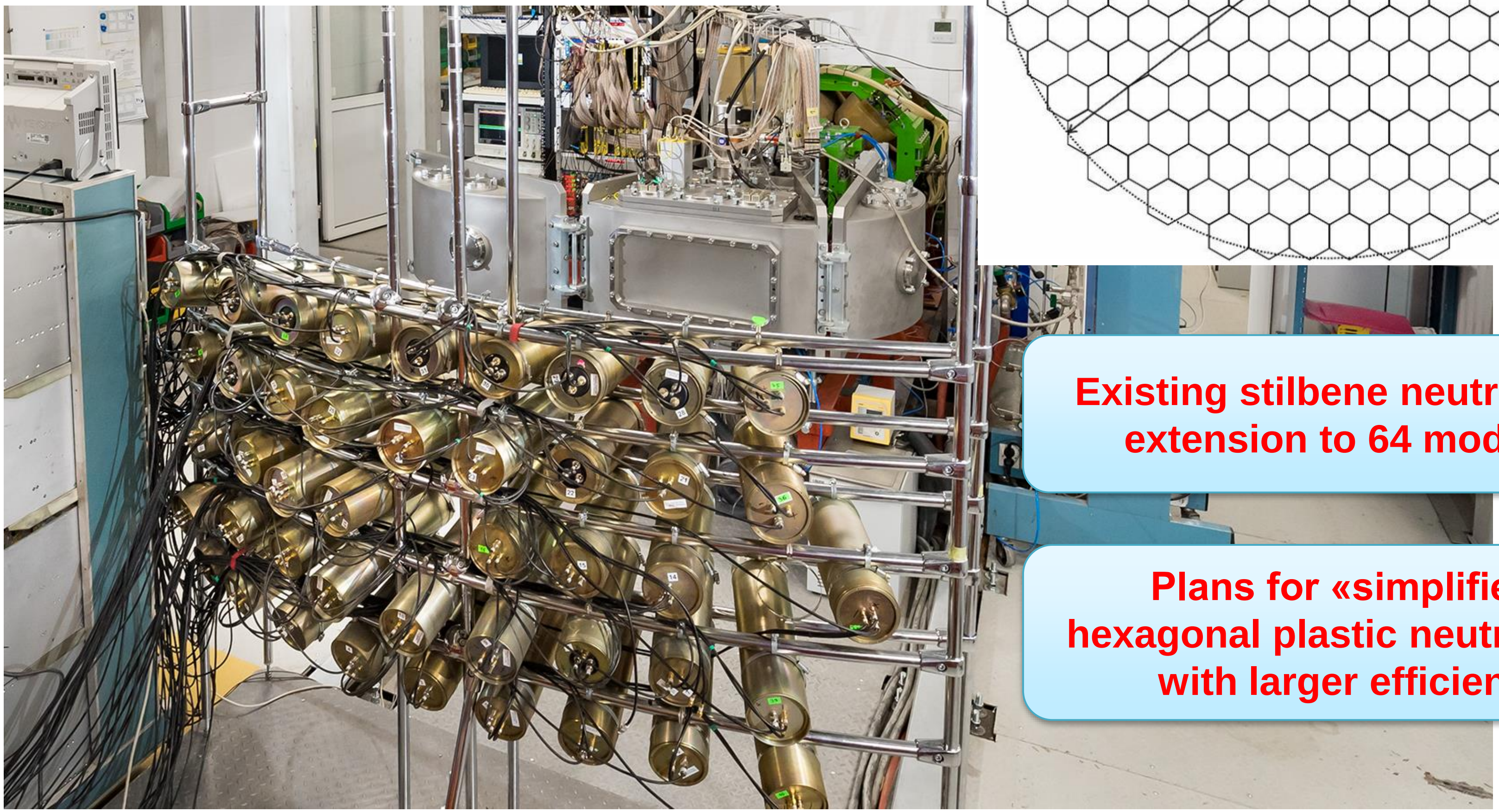
Hodoscope construction of large area silicons and GADAST modules





Neutron wall development





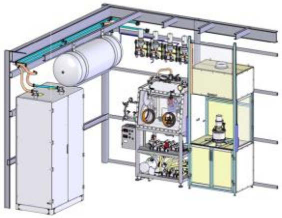
Existing stilbene neutron wall extension to 64 modules

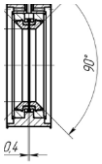
Plans for «simplified» hexagonal plastic neutron wall with larger efficiency

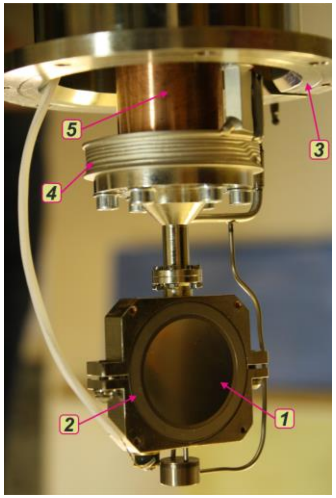
Cryogenic tritium target

If certification of facility goes as planned the next experimental campaign at ACCULINNA-2 is with tritium target

- 10^{14} Bq (1000 cm^3) T_2 >10^{21} n/cm^2
- 30 K for gas, 10 K for solid state
- Zero emission of T_2
- Ø25 mm, 0.8-4 mm cells
- SS foil windows 8 mkm each with double volume







ACCULINNA-2 scientific program for 2023-2025 campaign

"User facility" aspect of ACCULINNA-2

Invitation to contribute this scientific program

Experimental prospects at ACC-2

Tritium «campaign»

^{10}He studies with decisive precision in $^{8}He(t,p)$ reaction

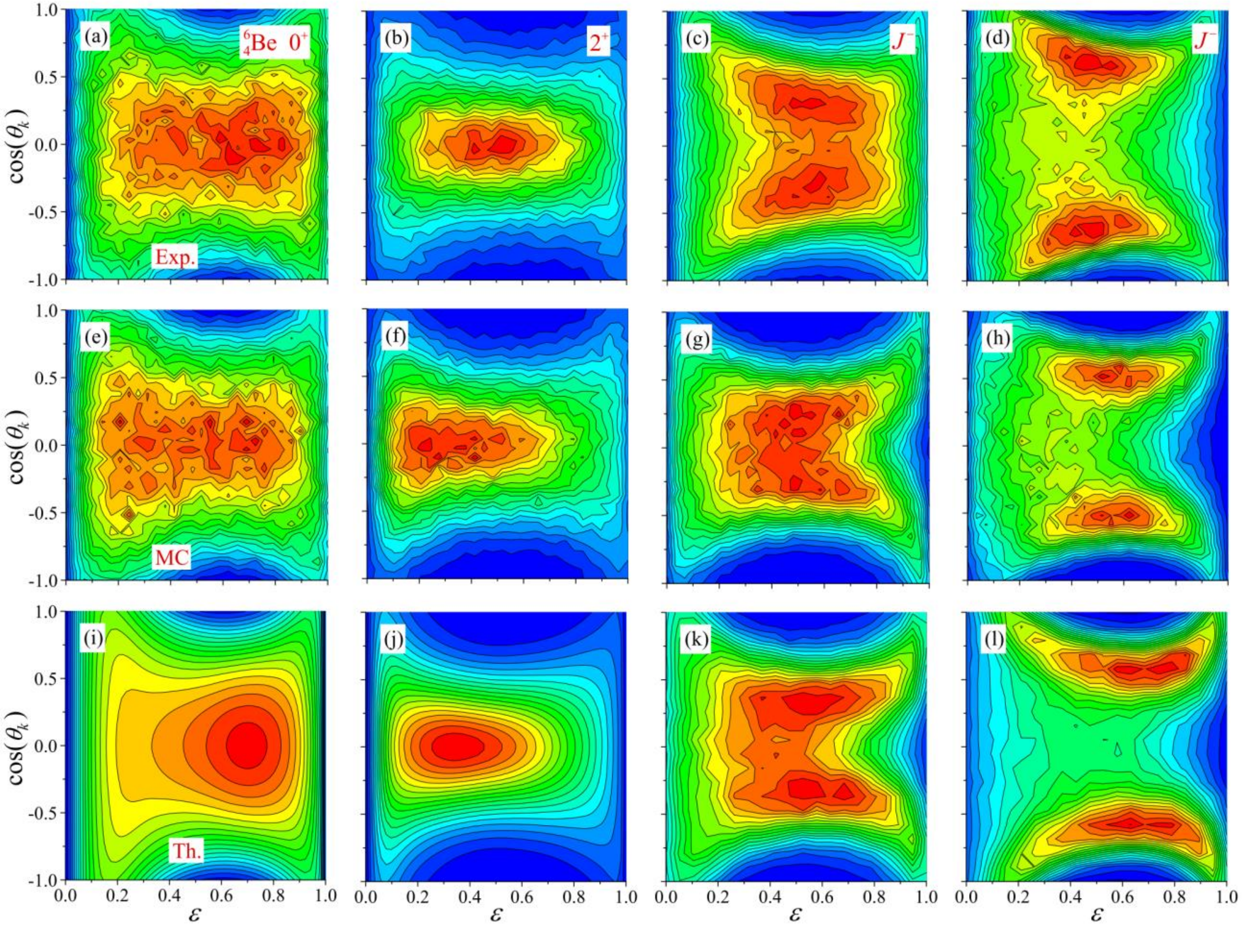
^{13}Li studies in $^{11}Li(t,p)$ reaction

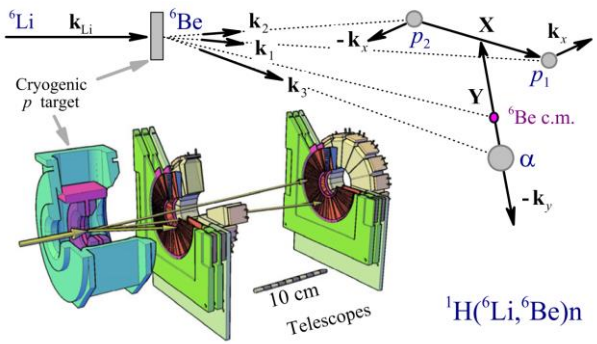
^{16}Be studies in $^{14}Be(t,p)$ reaction

Example: ^{6}Be studied in the ^{6}Li(p,n)^{6}Be -> α+p+p reaction

A. Fomichev *et al.*, PLB **708** (2012) 6

Isovector Soft Dipole Mode identification





Δ l = 0 → 0$^+$

Δ l = 2 → 2$^+$

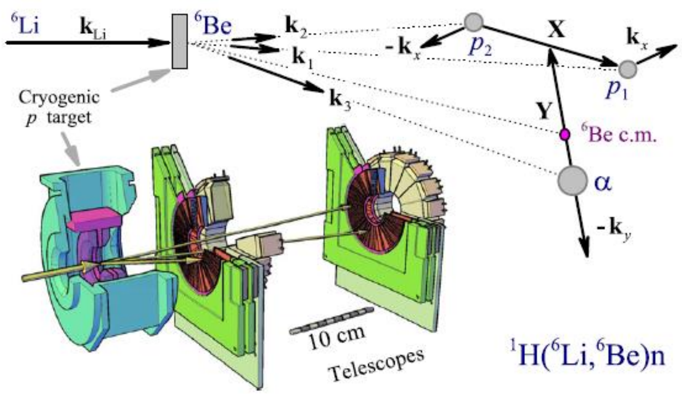
Δ l = 1 → J^-

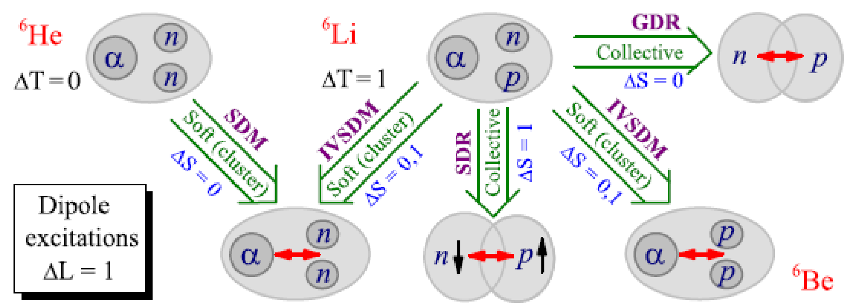
For positive parity states perfect agreement with theoretical predictions

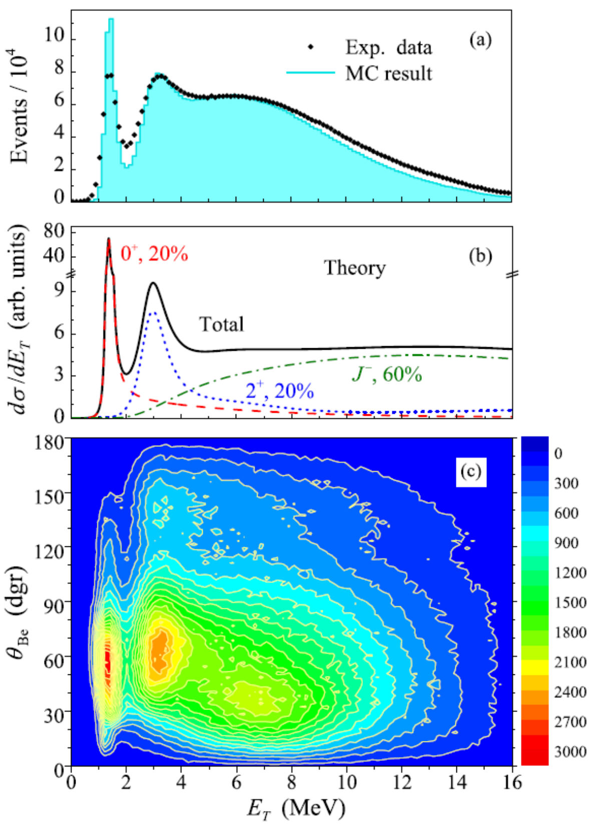
The three-body correlations for soft dipole excitations observed for the first time

Isovector Soft Dipole mode in ^{6}Be

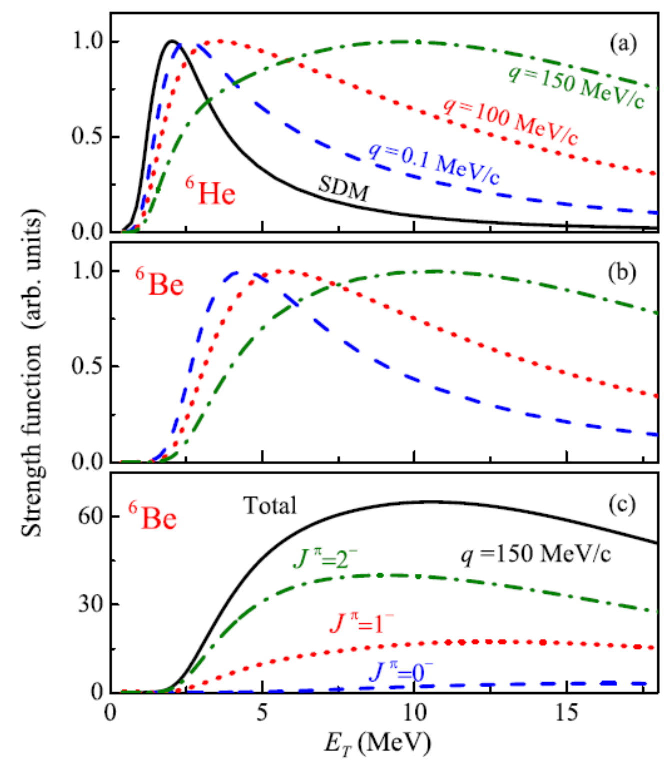
A.S.Fomichev et al., PLB **708** (2012) 6.







- Large cross section above 2^+ and no resonance
- $\Delta L=1$ identification – some kind of dipole response
- No particle stable g.s. – can not be built on spatially extended WF
- Built on the spatially extended ^{6}Li g.s.



Experimental prospects at ACC-2

2p radioactivity

2p radioactivity search in new isotope ^{26}S

Search for 2p radioactive decay of the first excited state of ^{17}Ne

Transitional dynamics studies for the 2p decay of ^{15}Ne

Experimental prospects at ACC-2

Soft excitation modes and
"isobaric symmetry" reactions with ^{3}He target

^{6}He IVSDM studies in ^{6}Li(t,^{3}He) reaction

^{6}H IVSDM studies in ^{6}He(t,^{3}He) reaction

^{7}B IVSDM studies in ^{7}Be(^{3}He,t) reaction

^{17}Na IVSDM studies in ^{17}Ne(^{3}He,t) reaction

Low-energy nuclear physics in Russia

Крупные научные/прикладные проекты в РФ

- Комплекс сверхпроводящих колец на встречных пучках тяжёлых ионов NICA («Комплекс NICA»)
- Международный центр нейтронных исследований на базе высокопоточного исследовательского реактора ПИК (МЦНИ ПИК)
- Токамак с сильным магнитным полем (Игнитор)
- Ускорительный комплекс со встречными электрон-позитронными пучками (Супер Чарм-Тау фабрика)
- Международный центр исследований экстремальных световых полей (ЦИЭС)
- Рентгеновский источник синхротронного излучения четвертого поколения (СКИФ)
- Радиографический центр (Снежинск)
- Тяжелоионный ускорительно-накопительный комплекс для тестирования электроники (Саров)

Состояние дел в ядерной физике низких энергий

САНКТ-ПЕТЕРБУРГСКИЙ ФЕДЕРАЛЬНЫЙ
ИССЛЕДОВАТЕЛЬСКИЙ ЦЕНТР
РОССИЙСКОЙ АКАДЕМИИ НАУК

«ДОРОЖНАЯ КАРТА» В ОБЛАСТИ ЯДЕРНОЙ ФИЗИКИ

Редактор Л.В. Григоренко

Москва
2021

Авторский коллектив:

Лаборатория ядерных реакций им. Г.Н. Флёрова, Объединенный институт ядерных исследований: Л.В. Григоренко, А.С. Деникин, С.Н. Дмитриев, А.В. Карпов, С.А. Крупко, Ю.Ц. Оганесян, С.И. Сидорчук, А.С. Фомичев; **Национальный исследовательский ядерный университет МИФИ:** Л.В. Григоренко, С.М. Полозов, С.В. Попруженко; **Национальный исследовательский центр «Курчатовский институт»:** Л.В. Григоренко, А.Л. Барабанов; **Лаборатория теоретической физики им. Н.Н. Боголюбова, Объединенный институт ядерных исследований:** Н.В. Антоненко, Р.В. Джолос; **Национальный исследовательский центр «Курчатовский институт» — Петербургский институт ядерной физики им. Б.П. Константинова:** А.С. Воробьёв, В.Н. Пантелеев, А.П. Серебров; **Санкт-Петербургский государственный университет:** С.В. Григорьев, С.Ю. Торилов; **Государственный университет «Дубна»:** А.С. Деникин; **Научно-исследовательский институт ядерной физики им. Д.В. Скобельцына Московского государственного университета:** Д.О. Ерёменко, Б.С. Ишханов, А.А. Кузнецов; **Российский федеральный ядерный центр — Всероссийский научно-исследовательский институт экспериментальной физики:** Н.В. Завьялов, Р.И. Илькаев; **Институт ядерных исследований Российской академии наук:** Л.В. Кравчук; **Национальный исследовательский центр «Курчатовский институт» — Институт теоретической и экспериментальной физики им. А.И. Алиханова:** Т.В. Кулевой; **GSI Helmholtz Centre for Heavy Ion Research, Дармштадт, Германия:** И.Г. Муха; **Федеральный исследовательский центр «Институт прикладной физики Российской академии наук»:** В.А. Скалыга; **Институт ядерной физики им. Г.И. Будкера Сибирского отделения Российской академии наук:** С.Ю. Таскаев; **Объединенный институт ядерных исследований:** Б.Ю. Шарков; **Лаборатория нейтронной физики им. И.М. Франка, Объединенный институт ядерных исследований:** В.Н. Швецов.

Состояние дел в ядерной физике низких энергий

Печальное

Исчерпание к концу 80-х научной повестки со стабильными пучками

Исчерпание ресурса и устаревание советской научной инфраструктуры

Исчерпание советских кадровых запасов

Светлые пятна на темном фоне

ACCULINNA-2 (ОИЯИ)

Фабрика сверхтяжелых элементов (ОИЯИ)

ИРИНА (ПИЯФ)

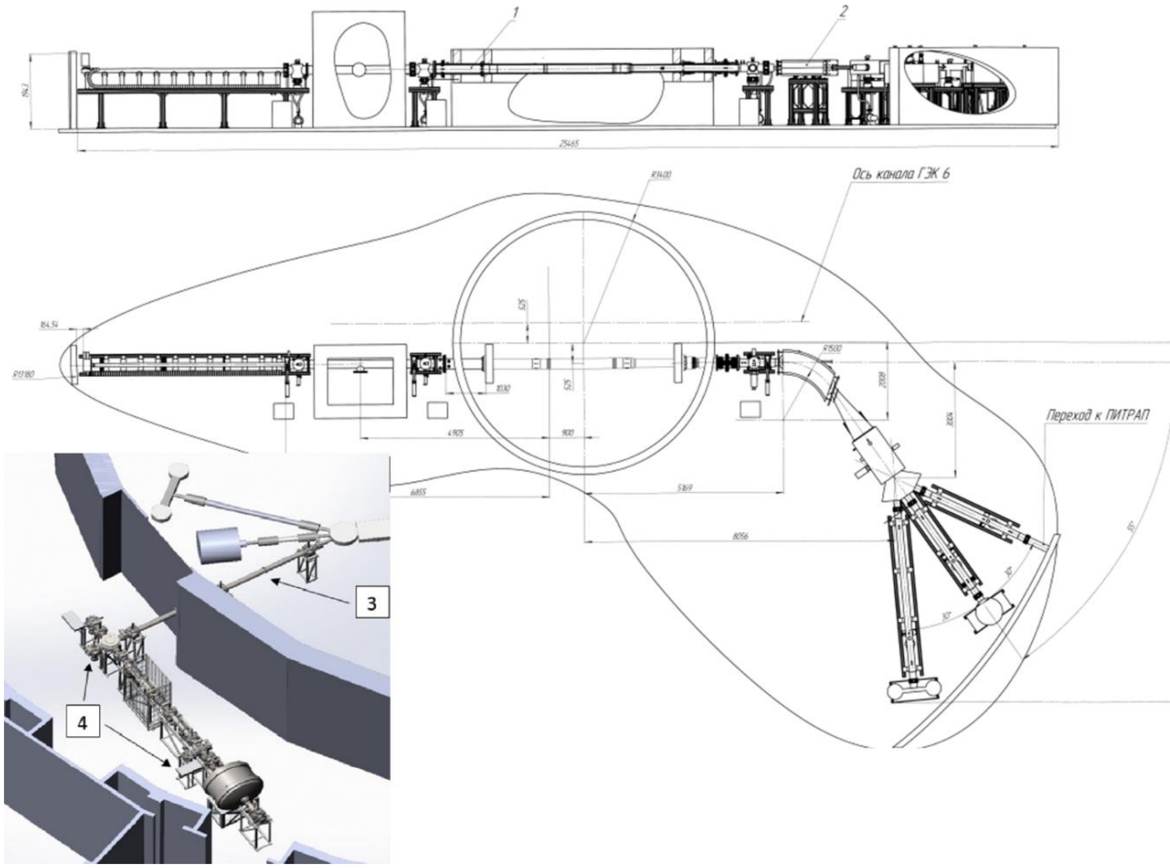
Участие в FAIR (Росатом)

Перспективный тяжелоионный комплекс (DERICA?)

Тяжелоионный центр в ВНИИЭФ

ИРИНА (ПИЯФ)

Для изотопов производимых методом ISOL – рекордные в мире интенсивности



В стороне от задач ПИК, мало места для научных инструментов

Prospective thinking about possible future RIB facility in Russia

Фабрики радиоактивных изотопов ”второго поколения” ~ 1985-2007 гг

RIKEN	LINAC + Cyclotron Cyclot. + Cyclotron	U, 90 AMeV	In-flight, 90 pnA
GSI	LINAC + Syncrotron	U, 900 AMeV	In-flight, 50 pnA
NSCL MSU	Cyclotron + Cyclotron	U, 90 AMeV	In-flight, 70 pnA
GANIL	Cyclotron + Cyclotron	U, 70 AMeV	In-flight, 90 pnA
ISOLDE	LINAC + Syncrotron	p, 1000 MeV	ISOL, ~1.5 kW
FLNR	Cyclotron	B 55 AMeV, S 32 AMeV	In-flight, 3 pμA

Joke about construction business

Build fast

Build cheap

High quality standard

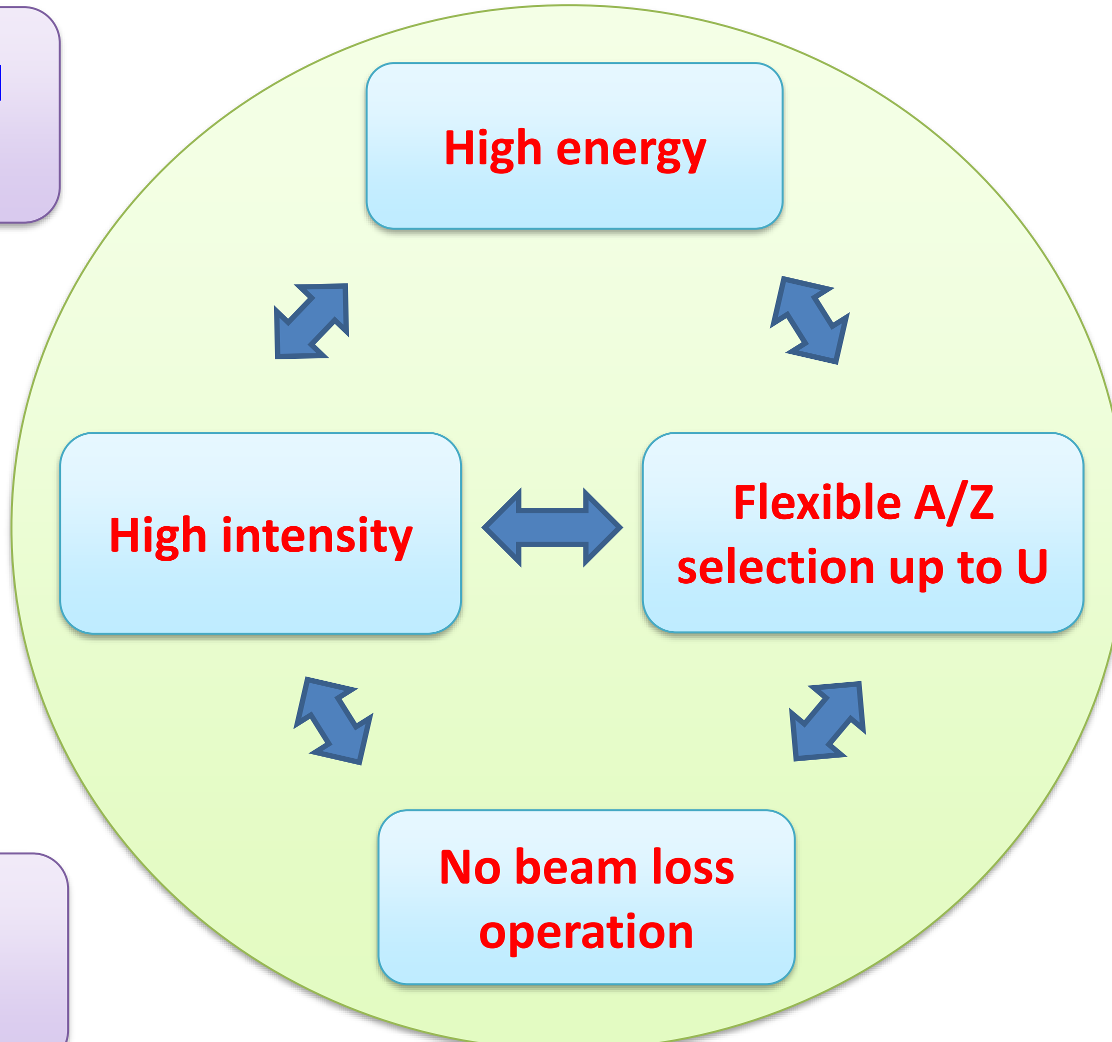
Just select any two of three options!

Problem of heavy-ion acceleration for RIB physics

4 conditions to be fulfilled simultaneously

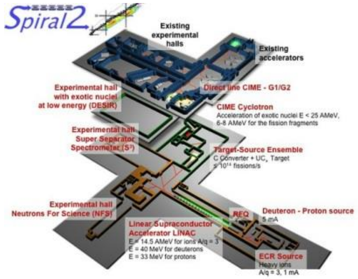
Compromise search as any three are strongly controversial

Complicated acceleration “tactics”

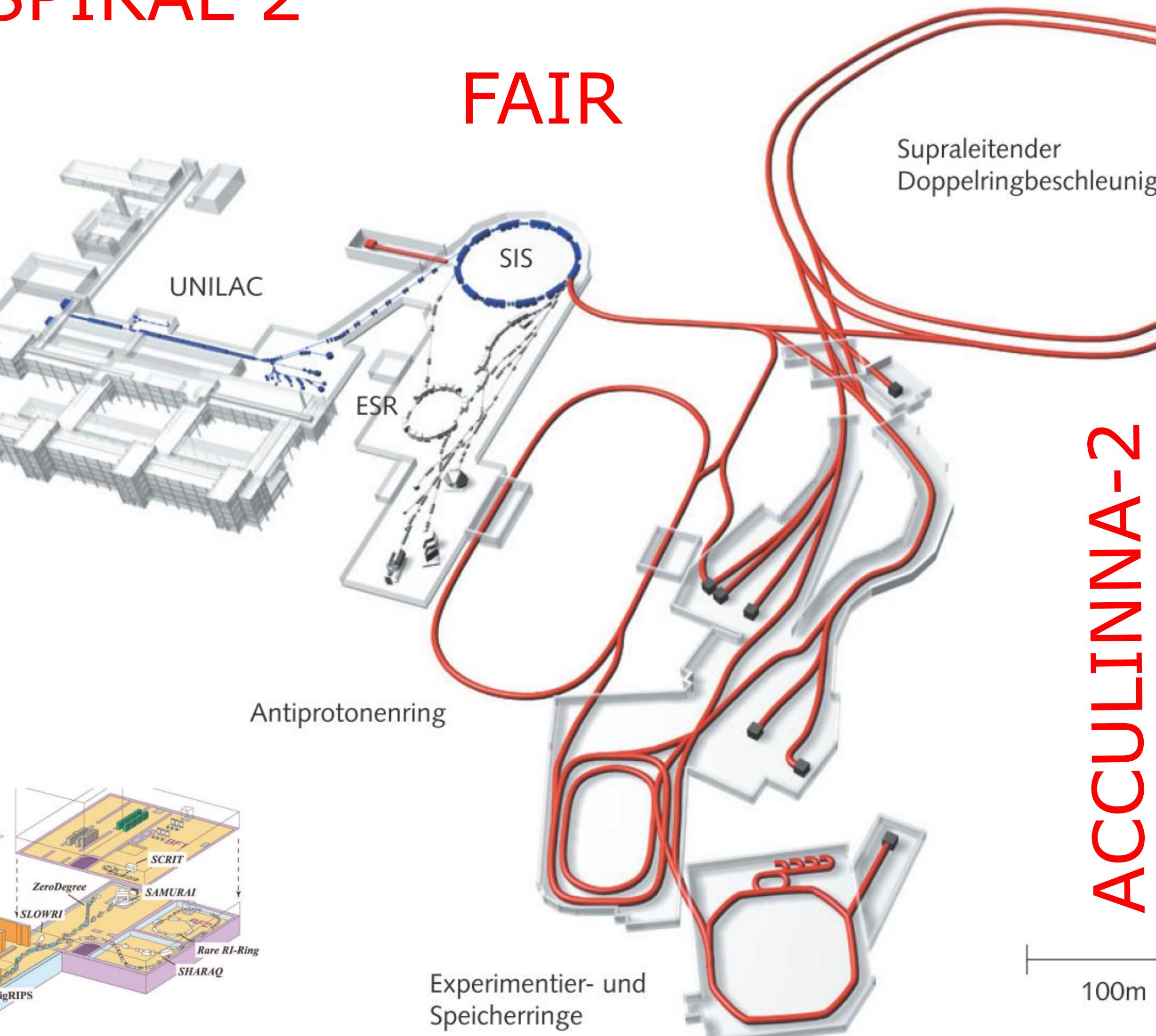


Big, bigger, the biggest – фабрики РИ «третьего поколения» 2007+

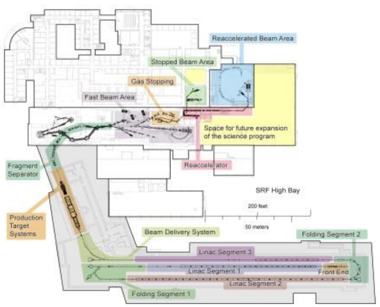
SPIRAL 2



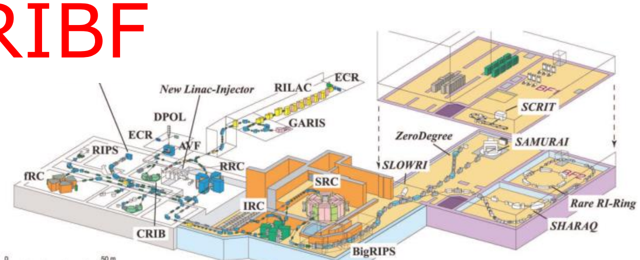
FAIR



FRIB



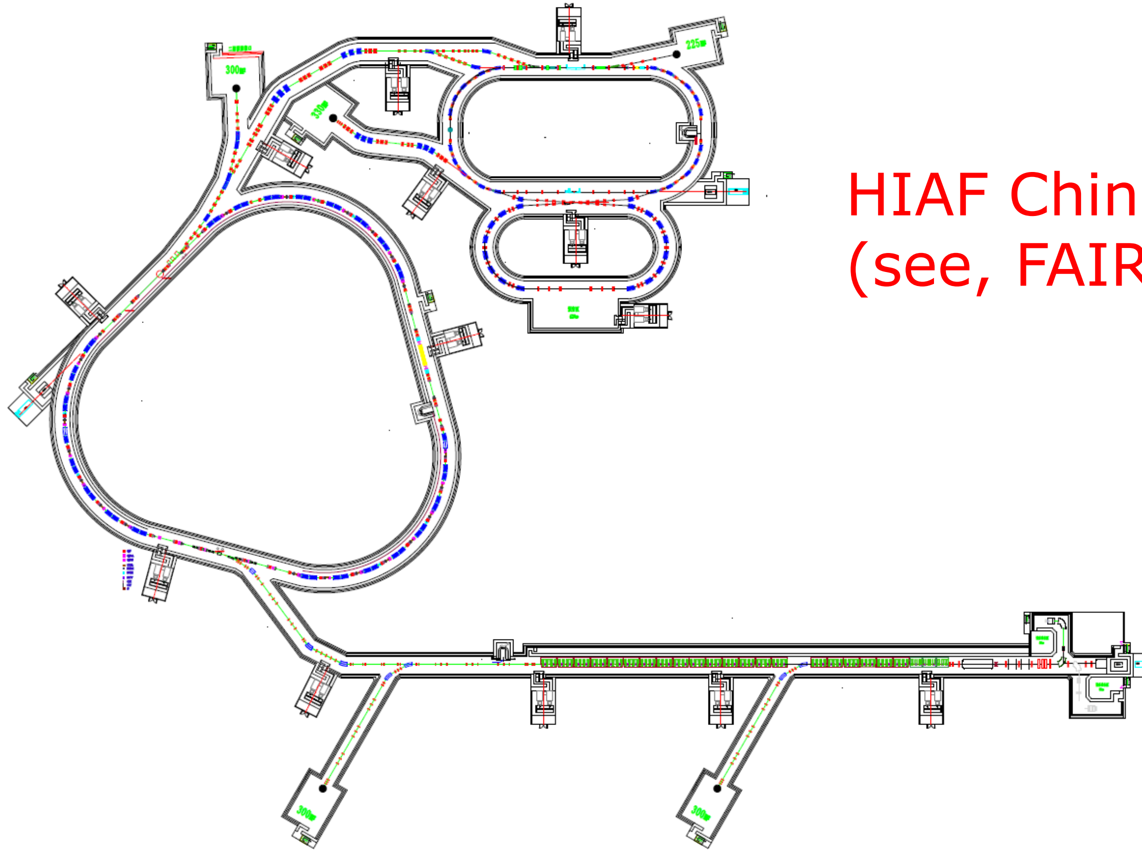
RIBF



ACCULINNA-2

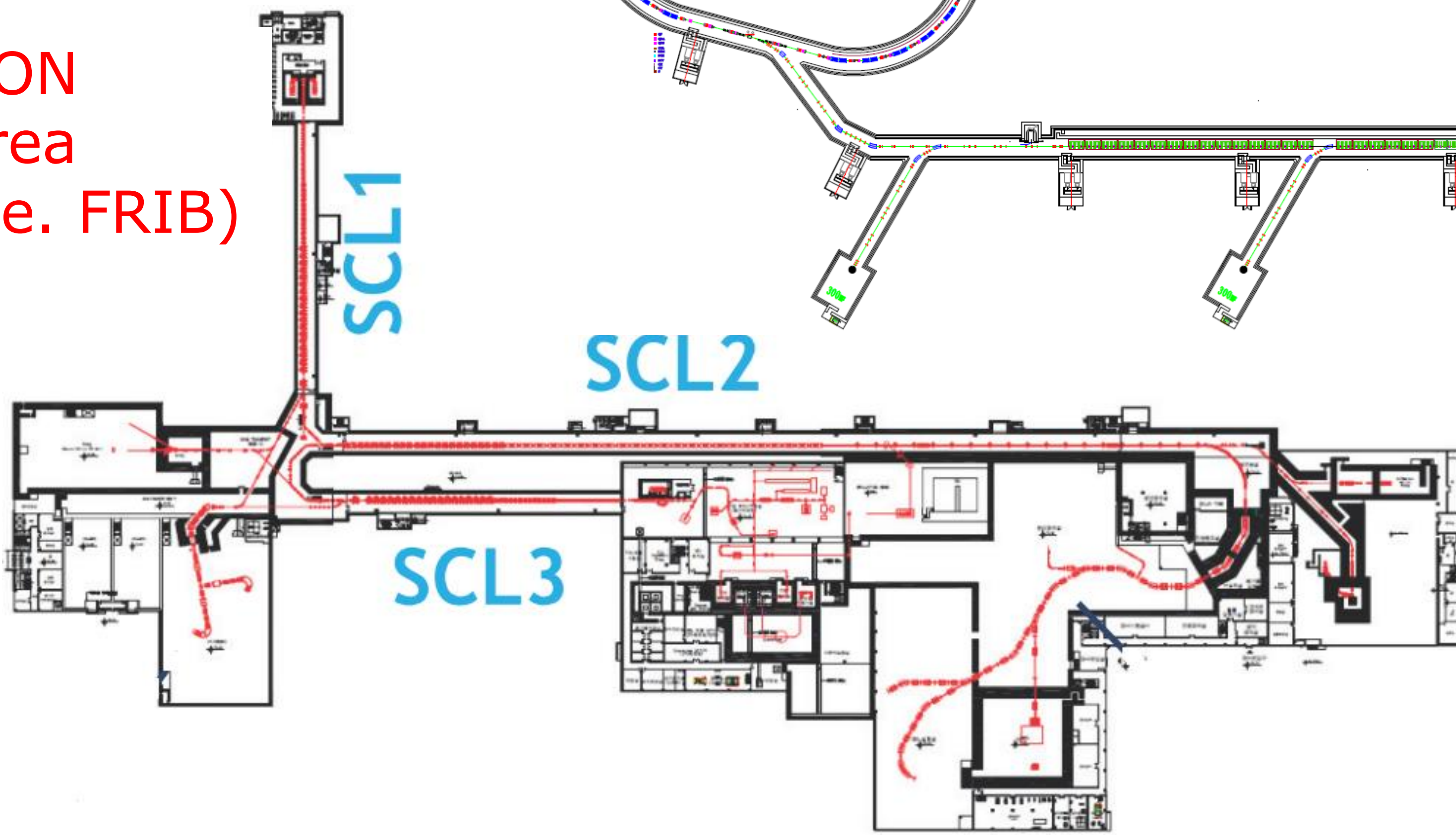
However,
even bigger…

Horizontal size of the slide ~1 km



HIAF China
(see, FAIR)

RAON
Korea
(see. FRIB)



Prospective facility based on LINAC-100 + DFS

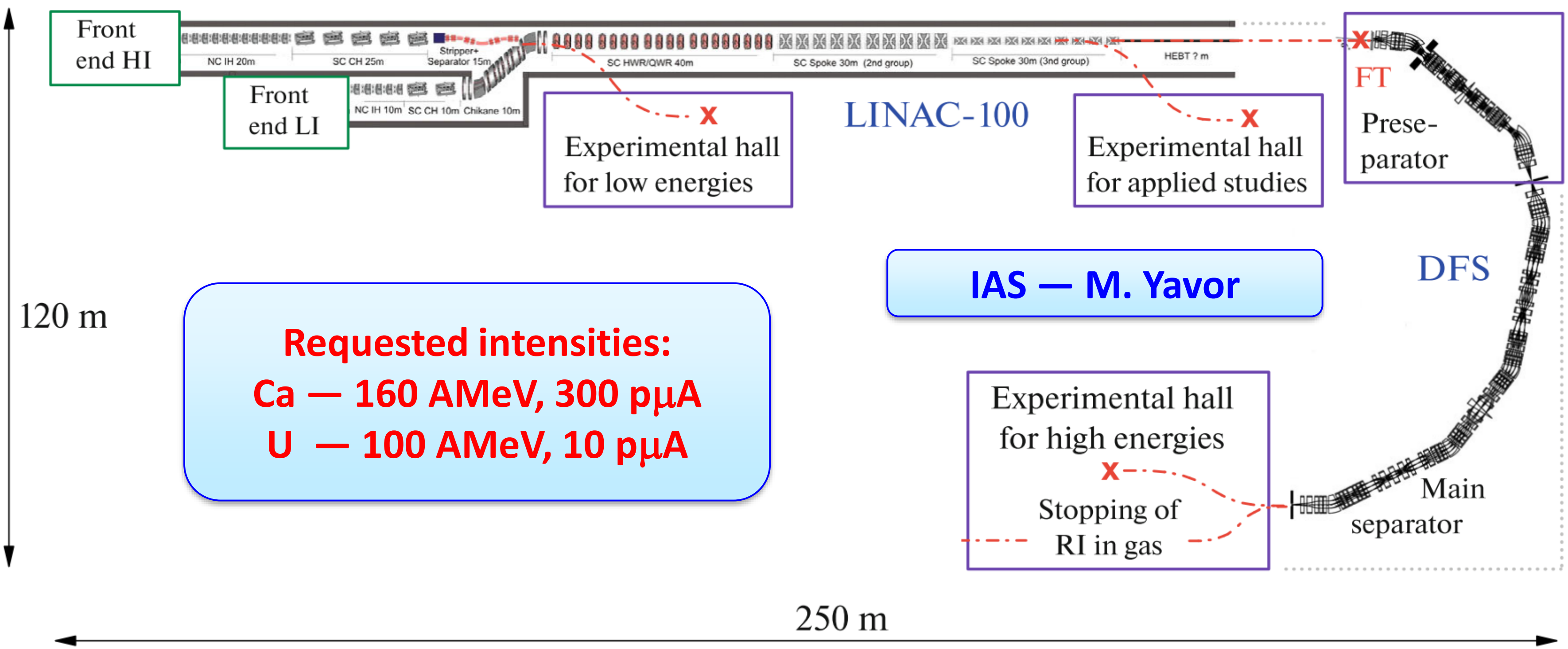
High-intensity universal superconducting CW heavy-ion accelerator LINAC-100

Room-temperature fragment separator DFS for high-intensity primary beams

ITEPh — T.Kulevoy

MEPhI — S.Polozov

???



IAS — M. Yavor

Requested intensities:
Ca — 160 AMeV, 300 pμA
U — 100 AMeV, 10 pμA

Empty "ecological niche" in modern low-energy nuclear physics

Underdeveloped field: storage ring physics with RIBs

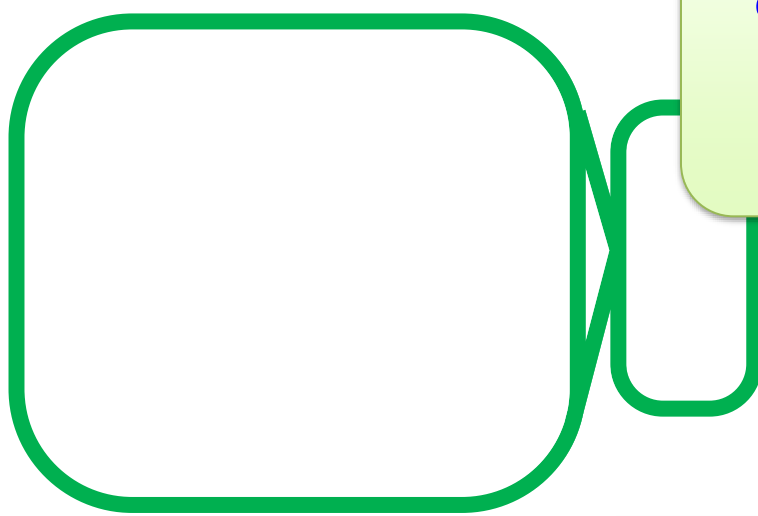
Empty field: studies of RIBs in electron-RIB collider

Isochronous mass spectromentry

Precision reaction studies on internal gas jet target

Atomic physics studies with striped ions

Radioactivity studies with striped ions



Studies of electromagnetic formfactors of exotic nuclei in e-RIB collider

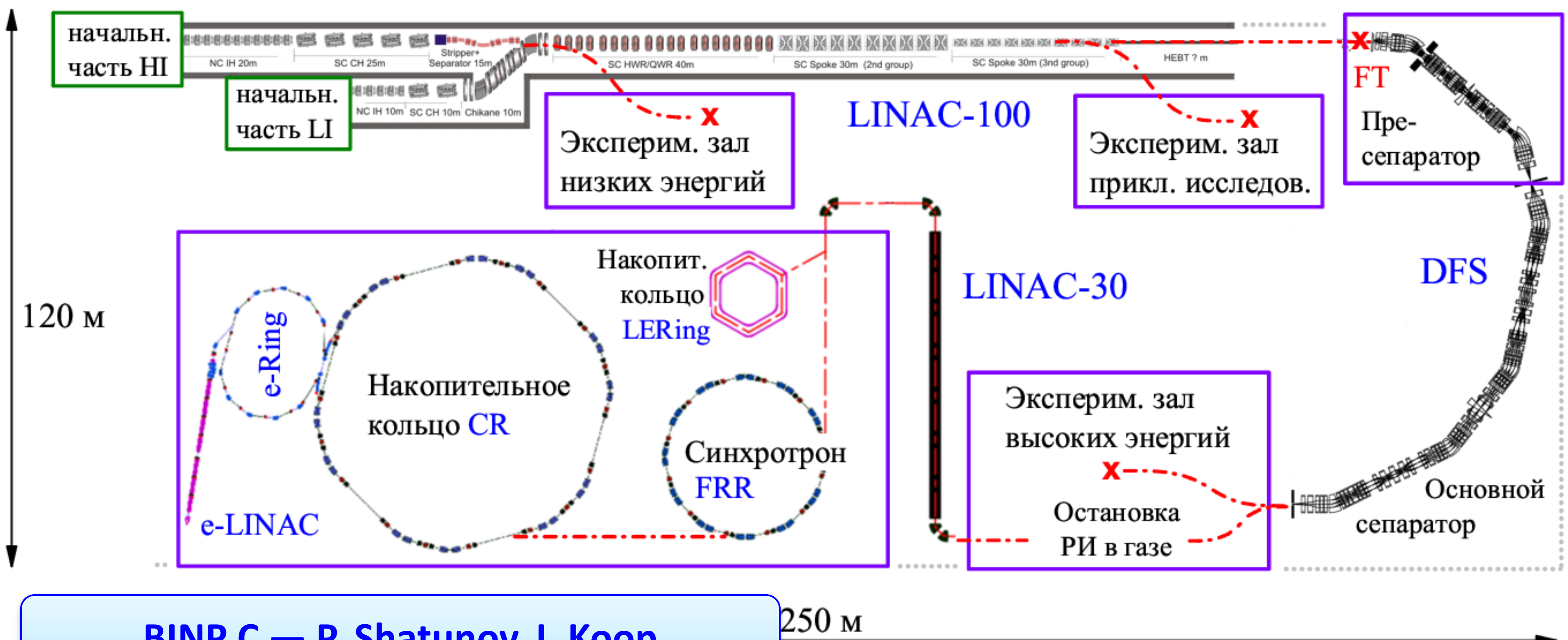
Etc....

DERICA —
Dubna Electron Radioactive Ion Collider fAcility

Facility with world-unique scientific program

Underdeveloped field: storage ring physics with RIBs

Empty field: studies of RIBs in electron-RIB collider



BINP C — P. Shatunov, I. Koop

Публикации

http://derica.jinr.ru/

Научная программа

Physics – Uspekhi **62** (7) 675 – 690 (2019)

INSTRUMENTS AND METHODS OF INVESTIGATION PACS numbers: 21.10.Ft, **29.20.–c**, 29.25.Rm

Scientific program of DERICA — prospective accelerator and storage ring facility for radioactive ion beam research

L V Grigorenko, B Yu Sharkov, A S Fomichev, A L Barabanov, W Barth, A A Bezbakh, S L Bogomolov, M S Golovkov, A V Gorshkov, S N Dmitriev, V K Eremin, S N Ershov, M V Zhukov, I V Kalagin, A V Karpov, T Katayama, O A Kiselev, A A Korsheninnikov, S A Krupko, T V Kulevoy, Yu A Litvinov, E V Lychagin, I P Maksimkin, I N Meshkov, I G Mukha, E Yu Nikolskii, Yu L Parfenova, V V Parkhomchuk, S M Polozov, M Pfutzner, S I Sidorchuk, H Simon, R S Slepnev, G M Ter-Akopian, G V Trubnikov, V Chudoba, C Scheidenberger, P G Sharov, P Yu Shatunov, Yu M Shatunov, V N Shvetsov, N B Shulgina, A A Yukhimchuk, S Yaramyshev

DOI: https://doi.org/10.3367/UFNe.2018.07.038387

Эскизный проект

ISSN 1063-7788, Physics of Atomic Nuclei, 2021, Vol. 84, No. 1, pp. 68–81. © Pleiades Publishing, Ltd., 2021.
Russian Text © The Author(s), 2021, published in Yadernaya Fizika, 2021, Vol. 84, No. 1, pp. 53–66.

ELEMENTARY PARTICLES AND FIELDS
Experiment

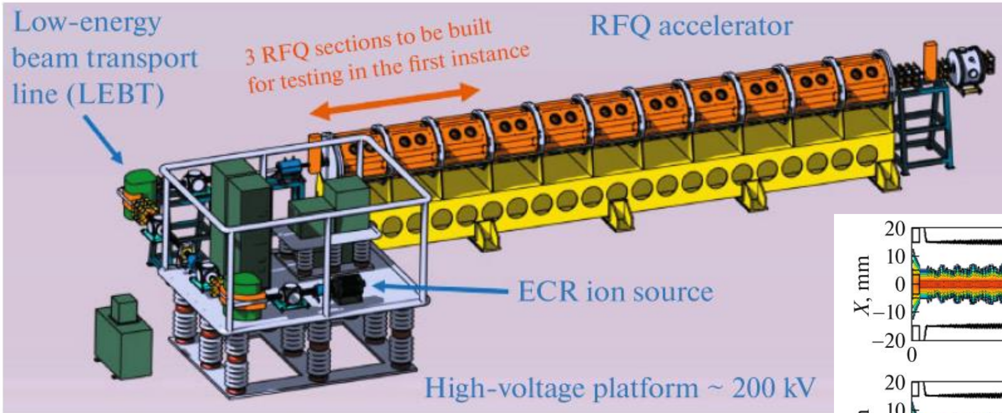
DERICA Project and Strategies of the Development of Low-Energy Nuclear Physics

L. V. Grigorenko[1),2),3)*], G. N. Kropachev[4),1)], T. V. Kulevoy[4)], I. N. Meshkov[5),6),7)], S. M. Polozov[2)], A. S. Fomichev[1),8)], B. Yu. Sharkov[9),2)], P. Yu. Shatunov[10)], and M. I. Yavor[11)]

Received May 24, 2020; revised May 24, 2020; accepted May 24, 2020

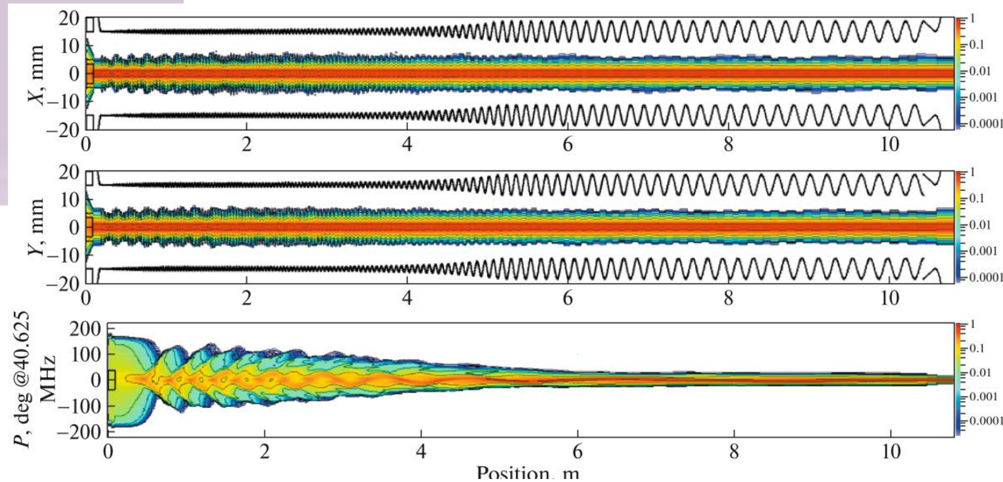
http://www.jinr.ru/wp-content/uploads/JINR_Docs/JINR_Strategy_2030.pdf

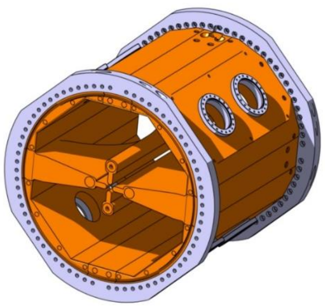
Front end LINAC-100



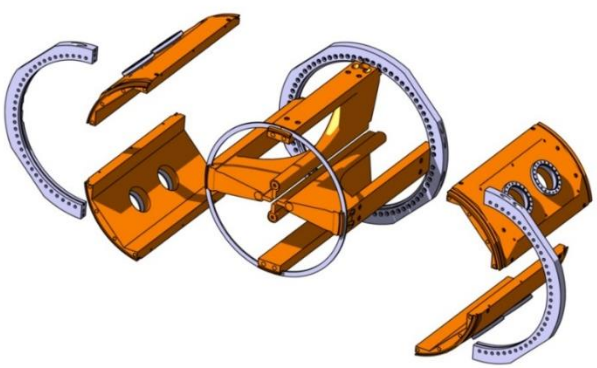
Challenges of LINAC-100 front end

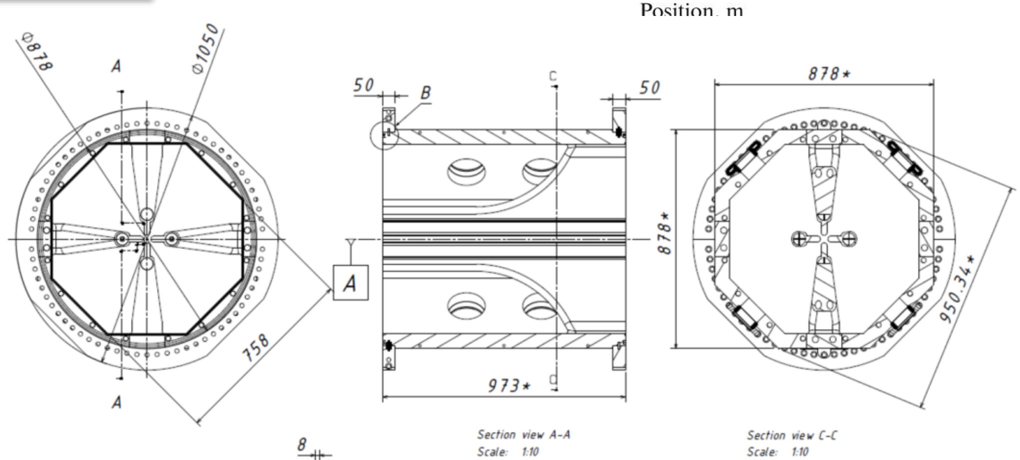
- Ca beam ~3 emA, U beam ~1 emA
- Practically "lossless" RFQ operation

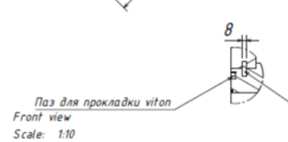




Design: T.V. Kulevoy, G.N. Kropachev, ITEPh, Moscow

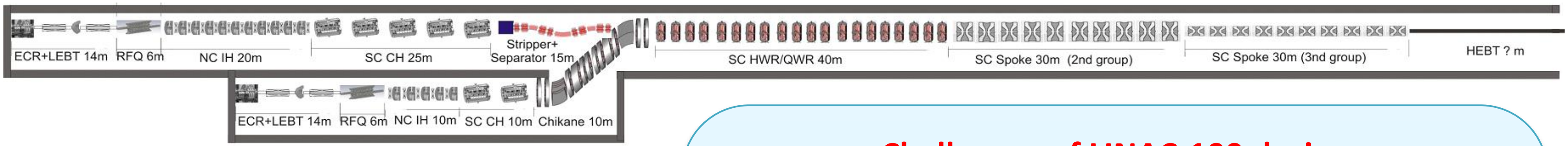






Production, VNIITF, Snezhinsk (?)

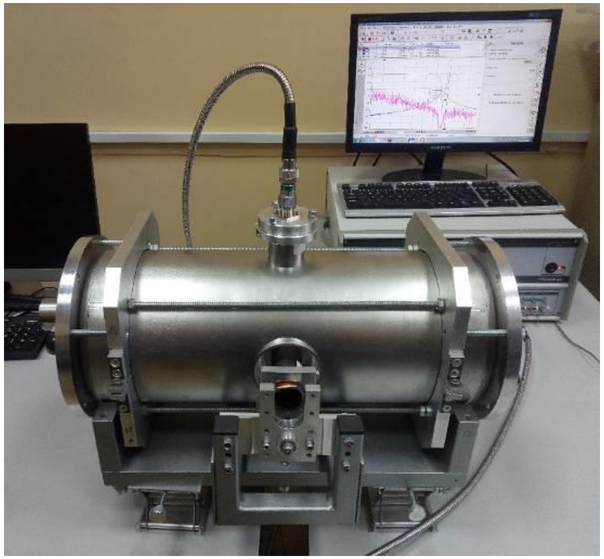
Superconductivity at LINAC-100



Challenges of LINAC-100 design

- Half-wave prototypes exist
- Quarter-wave prototypes to be built within 3 years
- Beam dynamics
  - One or two front ends
  - Ca beam ~3 emA ~300 pμA 1500 kW beam
  - U beam ~1 emA ~10 pμA 200 kW beam
  - Lossless operation

Design: S.M. Polozov, MEPhI



"Recovery" of RF superconductivity technology in Russia

Production: V.G. Zelesski, FTI NAB, Minsk

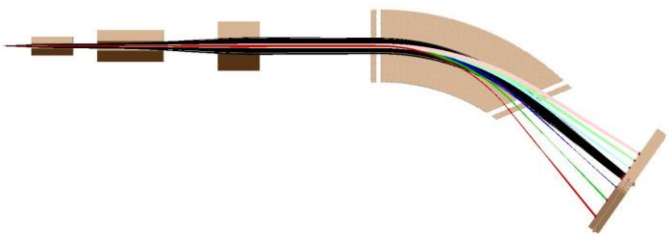
DFS

Design: M.I. Yavor,
IAP RAS, St.-Peterburg

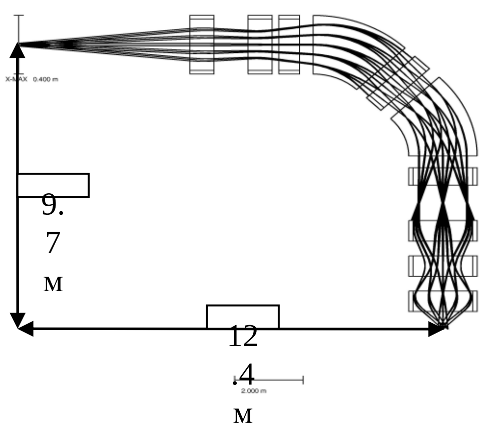
Challenges of DERICA fragment separator

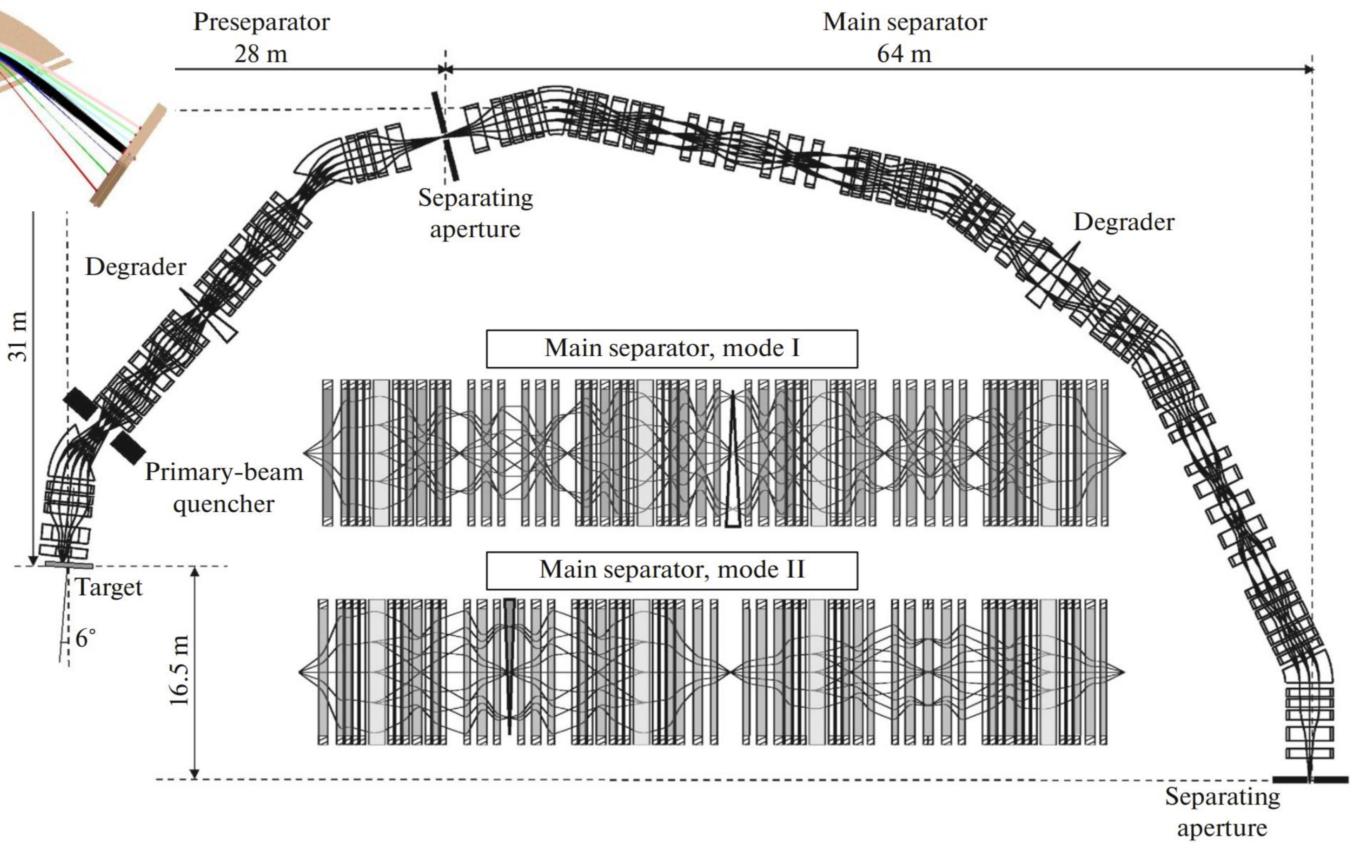
- Not well investigated energy rangy – 100-160 AMeV
- Room-temperature design requested
- Momentum acceptance is ΔP/P = ±3% (FWHM)
- Resolution is P/ΔP = 1500-3000
- Ca beam ~3 emA ~300 pμA 1500 kW beam
- U beam ~1 emA ~10 pμA 200 kW beam

Beam dump problem



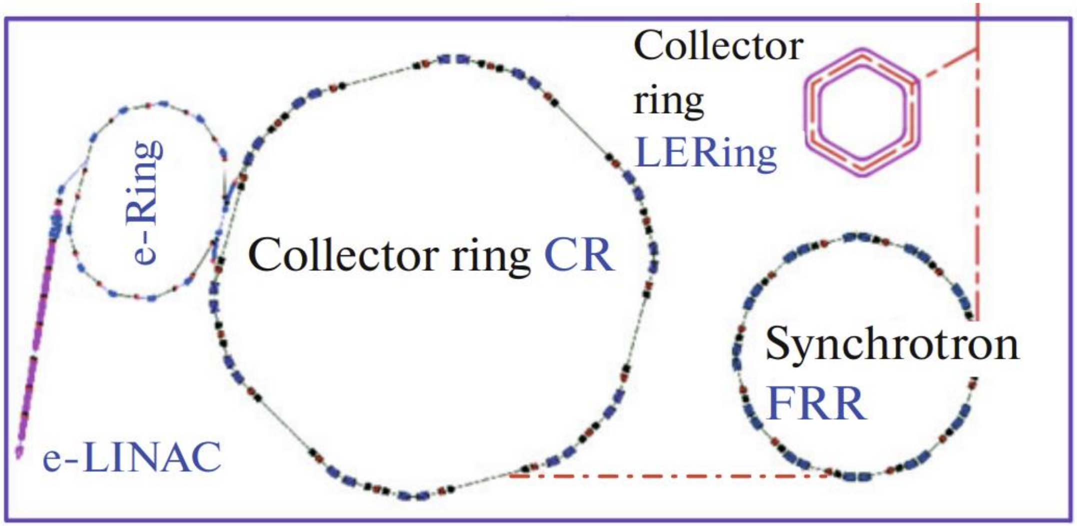
Low-energy buncher for ISOL program





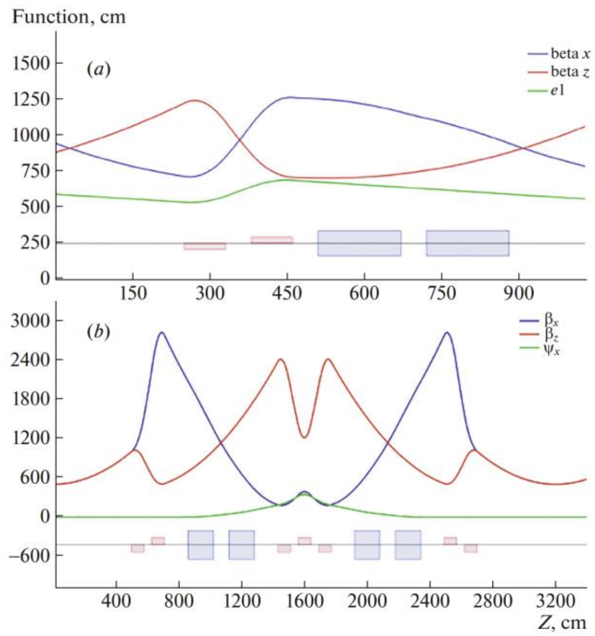
Ring branch design

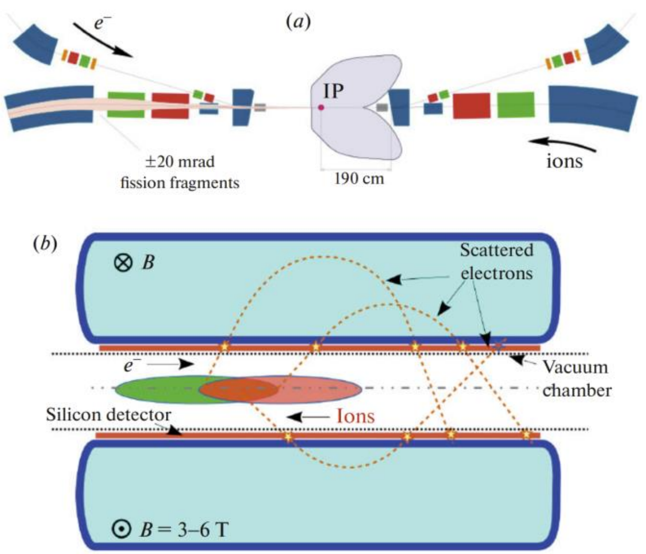
Design: P.Yu. Shatunov,
I.A. Koop, BINP, Novosibirsk



Challenges of DERICA ring branch

- 3-4 rings of different types
- Three ion storage rings are to be equipped with electron cooling system
- Novel developments for electron spectrometer may make scientific objectives of the DERICA project easier to achieve





Conclusion

The ACCULINNA-2 facility provides the world-leading opportunities in its domain – direct reactions with light exotic nuclei at 20-50 AMeV

The new results, possibly resolving the puzzle of the «superheavy» hydrogen isotopes ^{6}H and ^{7}H, were obtained during the first experimental campaign in 2018-2020

ACCULINNA-2 continues scientific operation in the beginning 2023, after U-400M upgrade. New «massive» instruments will become available in the ACCULINNA-2 experimental area including unique tritium cryogenic target complex

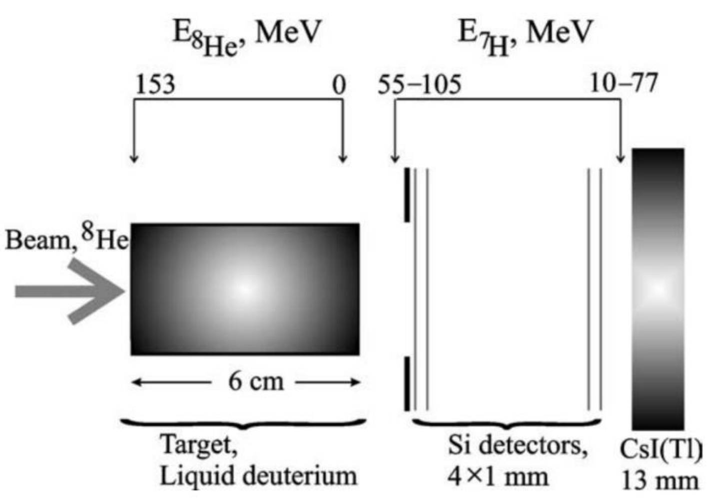
Continues the design and prototype development for prospective radioactive ion beam facility based on the universal high-intensity superconducting CW accelerator LINAC-100

Backup

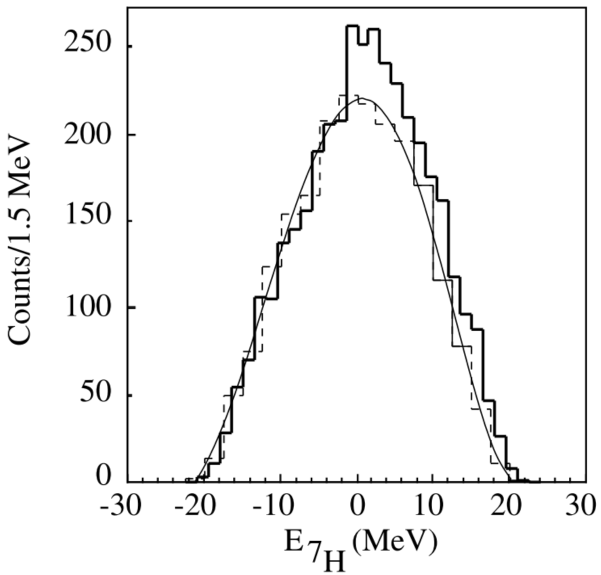
40-year-long quest for ^7H

It could be quite amusing that such a "fundumental" nuclide was left unexplored for such a long period of time

- K. Seth, "Pionic probes for exotic nuclei," (1981). $^7Li(\pi^-,\pi^+)$ NOTHING
- V. Evseev *et al.*, Nuclear Physics A 352, 379 (1981). $^7Li(\pi^-,\pi^+)$ NOTHING
- D. Aleksandrov *et al.*, Yad. Fiz. 36, 1351 (1982). ^{252}Cf ternary fission NOTHING
- Y. Gurov *et al.*, The EPJ A 32, 261 (2007); PPN 40, 558 (2009). $^{11}B(\pi^-,p\ ^3He)$ NOTHING
- M. S. Golovkov *et al.*, Phys. Lett. B 588, 163 (2004). d(^{8}He,^{7}H) $T_{1/2} > 1$ ns NOTHING



More recent data on ^{7}H



A. A. Korsheninnikov, PRL 90, 082501 (2003).

p(^{8}He,2p)^{7}H

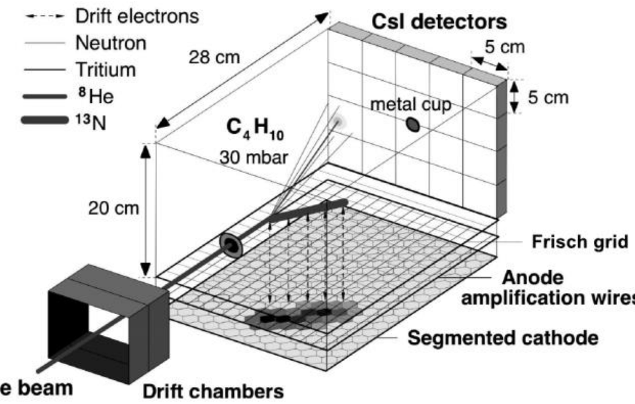
– Missing mass only → 90% of background

– Many events with negative MM energy

– 1.9 MeV MM resolution

Declaraiton:

there is something at the threshold



M. Caamano et al.,

PRL 99, 062502 (2007);

PRC 78, 044001 (2008).

^{12}C(^{8}He,^{13}N)^{7}H

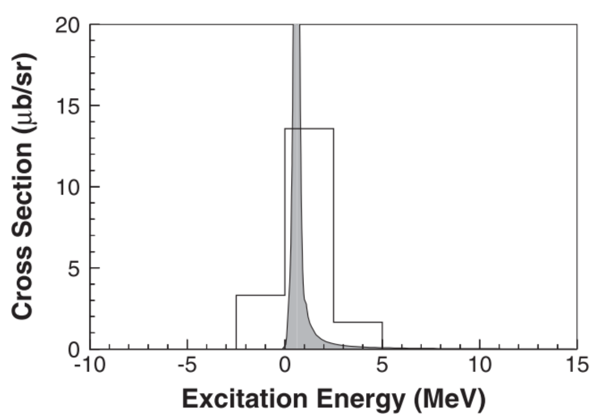
– Mixed material active target

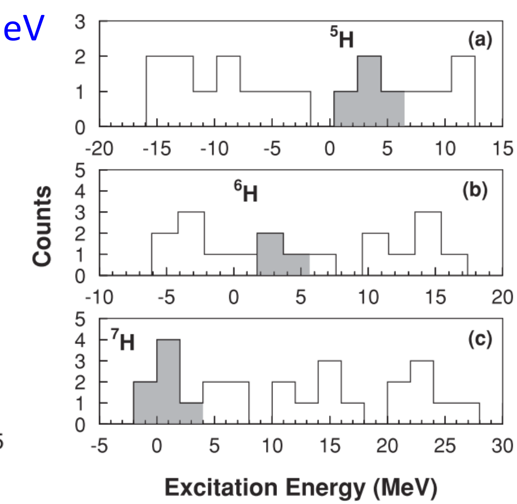
– Missing mass with ^{3}H coincidences

– No channel identification: ^{5}H, ^{6}H, or ^{7}H

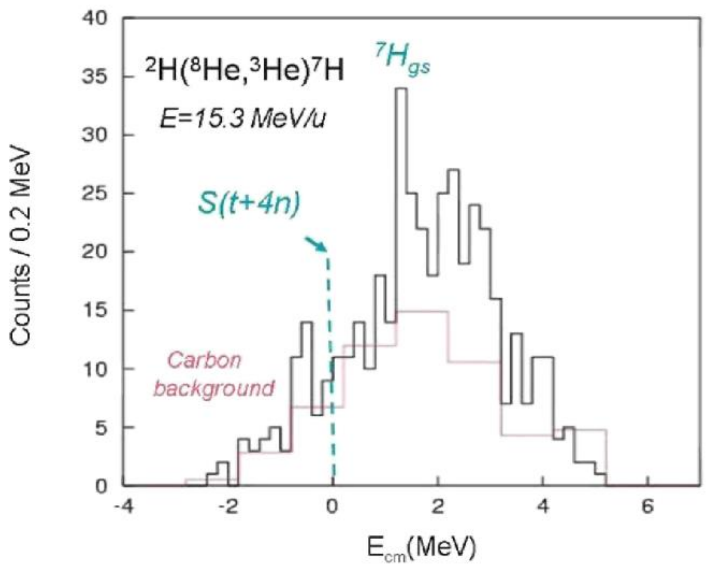
Declaration:

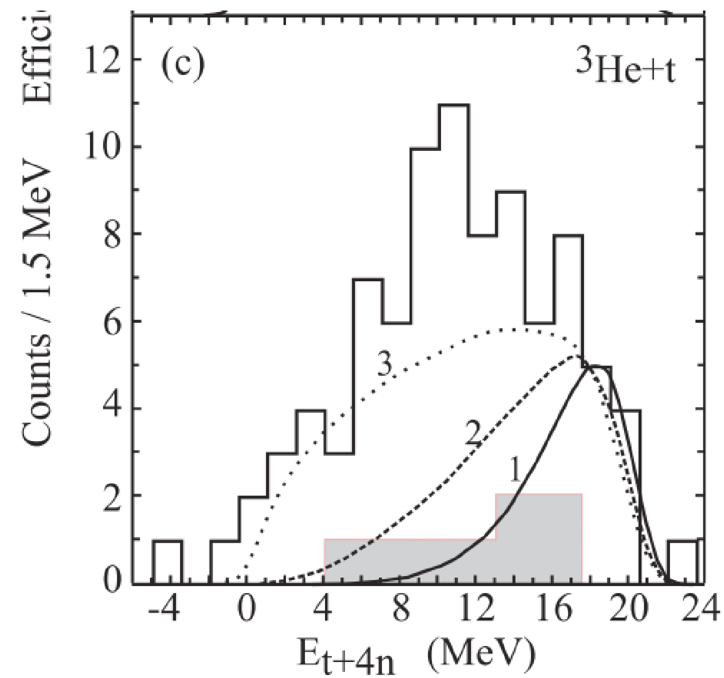
E_T = 0.3-1 MeV, Γ = 0.09-1 MeV





More recent data on ^{7}H





S. Fortier et al., AIP CP 912, 3 (2007)

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

– Missing mass only → 70% of background

– Many events with negative MM energy

– Low energy cutoff (E_T < 5 MeV)

Declaration: in this experiment there should be a peak at about E_T = 2 MeV in any case

E. Y. Nikolskii et al., Phys. Rev. C 81, 064606 (2010).

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

– Missing mass with 3H coincidences

– Some events with negative MM energy

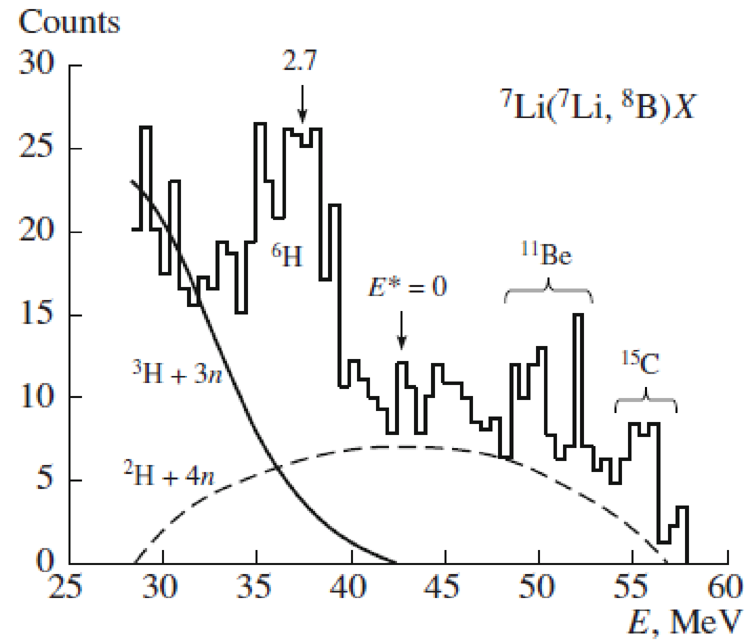
– 1.7 MeV MM resolution

Declaration: there is something at E_T = 2 MeV, and maybe a resonant state at E_T = 11 MeV,

Available information on ^6H

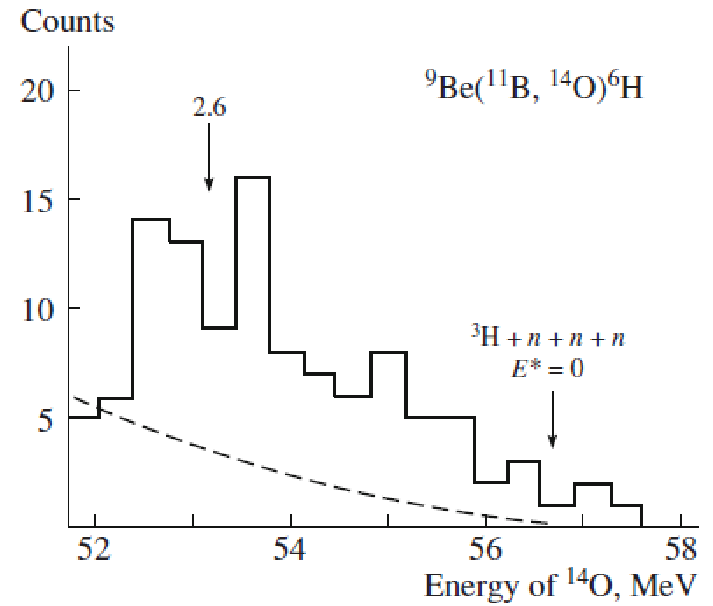
– D. Aleksandrov *et al.*,
Yad. Fiz. 39 (1984) 513.

$^7Li(^7Li, ^8B)\,^6H$ $E_T = 2.7(4)$ MeV



– A. Belozyorov *et al.*,
Nuclear Physics A 460 (1986) 352.

$^9Be(^{11}B,^{14}O)^6H$ $E_T = 2.6(5)$ MeV

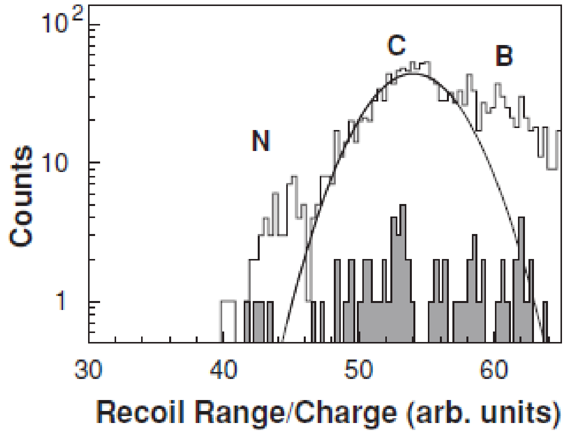


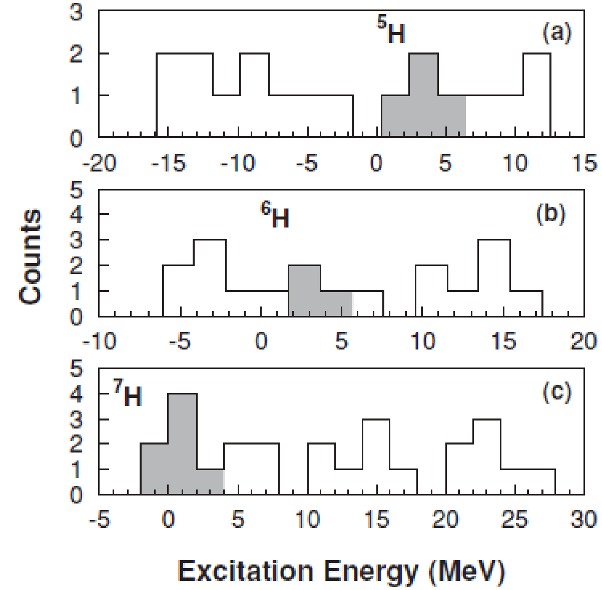
Available information on ^{6}H

– Caamano et al.,
PRL 99, 062502 (2007);
PRC 78, 044001 (2008).

$^{12}C(^8He,^{13}N)^7H$

E_T = 2.7(5) MeV





– Y. Gurov *et al.*, The EPJ A 32, 261 (2007).

$^9Be(\pi^-,p\ d)^6H$

Reaction channel			
$^9Be(\pi^-, pd)^6H$		$^{11}B(\pi^-, p^4He)^6H$	
E_r	Γ	E_r	Γ
6.6 ± 0.7	5.5 ± 2.0	7.3 ± 1.0	5.8 ± 2.0
10.7 ± 0.7	4 ± 2	–	–
15.3 ± 0.7	3 ± 2	14.5 ± 1.0	5.5 ± 2.0
21.3 ± 0.4	3.5 ± 1.0	22.0 ± 1.0	5.5 ± 2.0