Leonid Grigorenko

Flerov Laboratory of Nuclear Reactions, JINR, Dubna

Recent FLNR JINR developments and collaboration with FLNR

Few-body dynamics in light exotic nuclei

ACCULINNA-2 fragment separator

EXPERT setup at FAIR

DERICA - Dubna **E**lectron-**R**adioactive **I**sotope **C**ollider f**A**cility

NIIYaF seminar, December 6, 2018

Two-proton radioactivity and three-body decay

L.V. Grigorenko

FLNR, JINR, Dubna
and
RRC “The Kurchatov institute”, Moscow

Few-body dynamics in light exotic nuclei

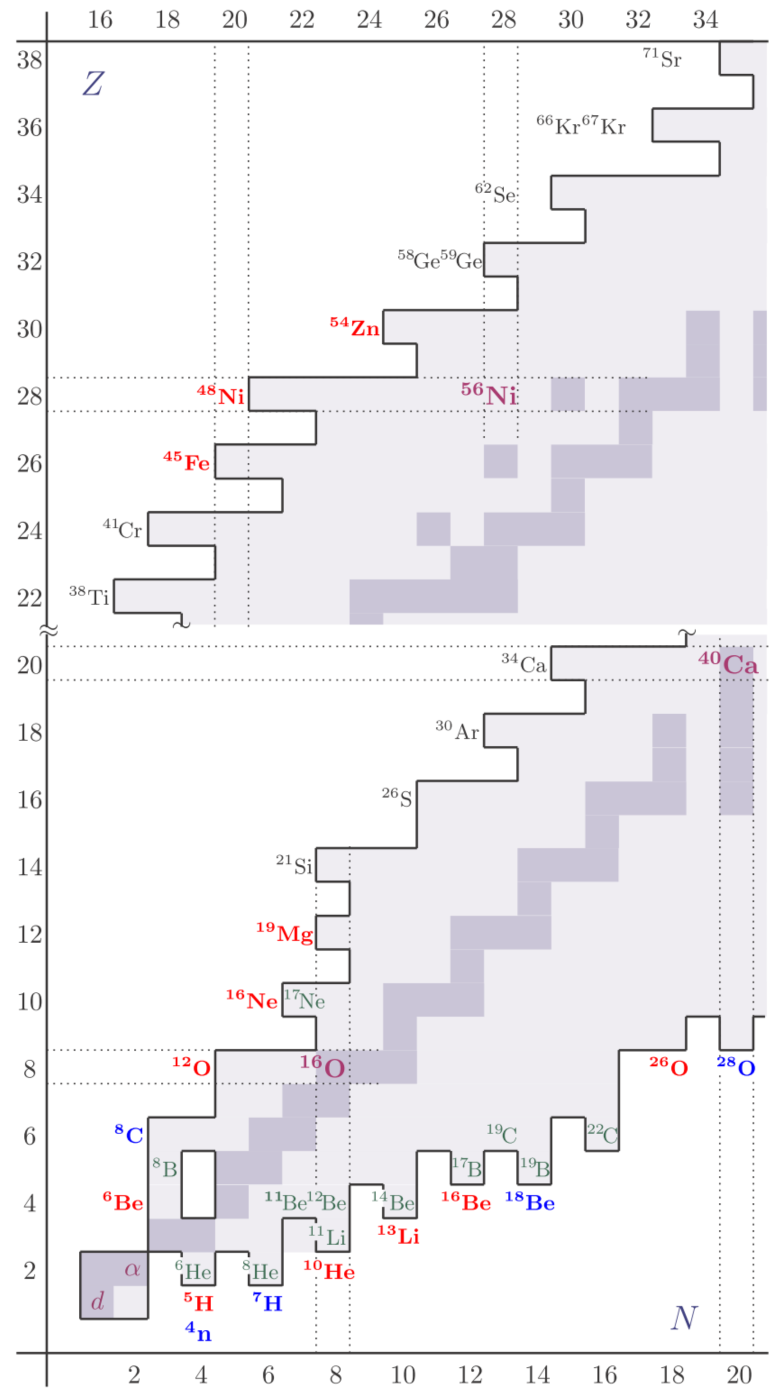
Few-body dynamics at the driplines

Modern RIB research trend: move towards and beyond the driplines

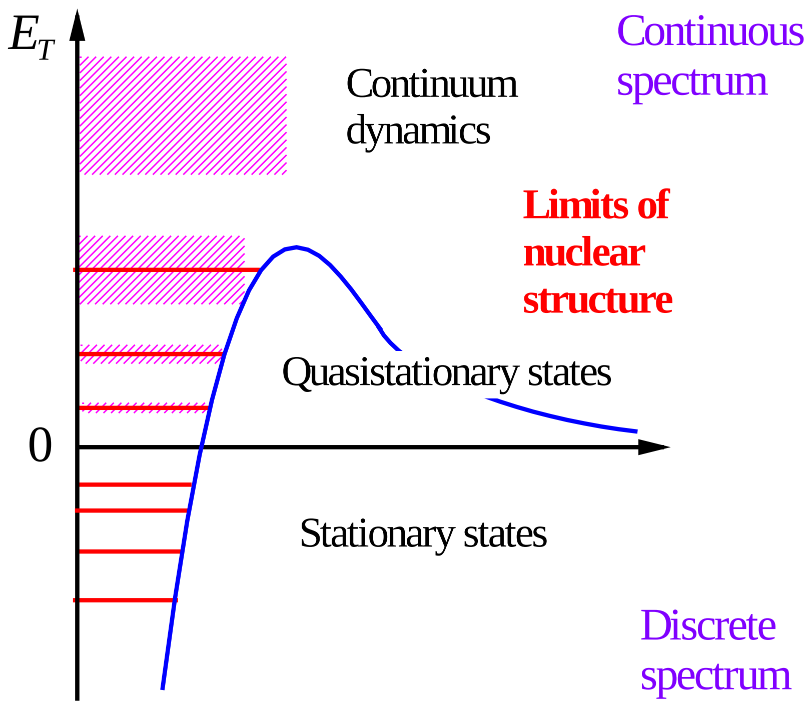
Few-body dynamics at the driplines as consequence of (i) clusterization and (ii) paring

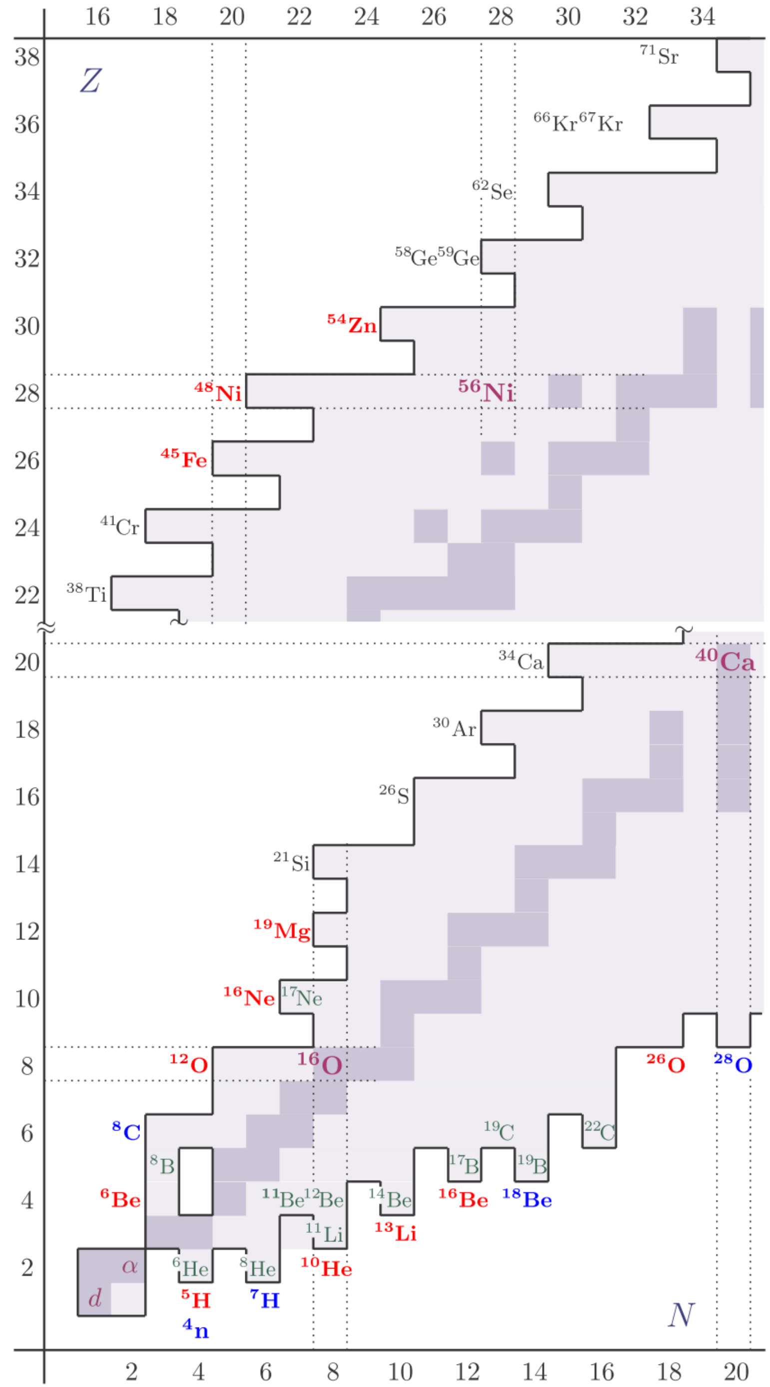
Exotic phenomena in vicinity of driplines:
Haloes (green)
True 2p/2n decays (red)
4p/4n emitters (blue)
NOT INVESTIGATED (gray)

NOT SO EXOTIC: More or less every second isotope in vicinity of the driplines has features connected to few-body dynamics



Limits of nuclear structure existence



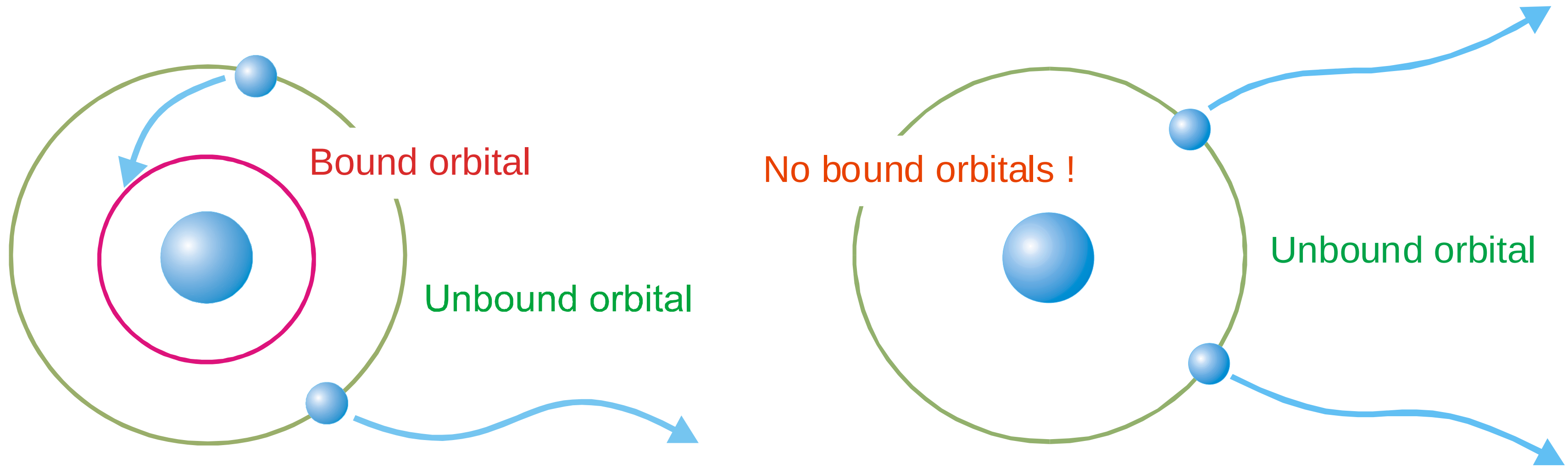


Dripline is achieved for Z<32 and N<22

Dripline is only studied for lightest nuclei

Limits of the nuclear structure are not solidly established even for the lightest isotopes.
^{7}H, ^{12}He, ^{13}Li, ^{5}Be - ???

Qualitative view of two-proton radioactivity



Classical case:
one particle emission is always possible

Quantum mechanical case:
it could be that both particles should be emitted simultaneously

Exclusive Quantum-Mechanical phenomenon

- **No deeper bound orbitals.**
- **The common orbital for two protons exists only when both are "inside".**
- **When one of them goes out, their common orbital do not exist any more and the second HAS to go out instantaneously**

Трёхчастичная кластерная модель

- Метод гиперсферических гармоник
- Для узких состояний

$$\Psi^{(+)}(\rho,\Omega_\rho,t)=\Psi^{(+)}(\rho,\Omega_\rho)\exp[-iE_T t-(\Gamma/2)t]$$

- Уравнение Шрёдингера

$$\left(\hat{H}-E_T+i\Gamma/2\right)\Psi^{(+)}(\rho,\Omega_\rho)=0$$

- Действительно решаемые уравнения

$$\left(\hat{H}-E_{box}\right)\Psi^{(+)}(\rho,\Omega_\rho)=-i(\Gamma/2)\Psi_{box}(\rho,\Omega_\rho)$$

где

$$\left(\hat{H}-E_{box}\right)\Psi_{box}(\rho,\Omega_\rho)=0$$

- «Естественное» определение ширины

$$\Gamma=\frac{j(\rho_{\max})}{N(\rho_{box})}=\frac{\operatorname{Im}\int d\Omega_\rho \Psi^{(+)\dagger}\rho^{5/2}\frac{d}{d\rho}\rho^{5/2}\Psi^{(+)}\Big|_{\rho_{\max}}}{M\int d\Omega_\rho\int_0^{\rho_{box}}d\rho\,\rho^5\left|\Psi^{(+)}\right|^2}$$

- L. V. Grigorenko, R. C. Johnson, I. G. Mukha, I. J. Thompson, and M. V. Zhukov, PRL 85 (2000) 22.
- L. V. Grigorenko, R. C. Johnson, I. G. Mukha, I. J. Thompson, and M. V. Zhukov, PRC 64 (2001) 054002.
- L. V. Grigorenko, I. G. Mukha, I. J. Thompson, and M. V. Zhukov, PRL 88 (2002) 042502.
- L. V. Grigorenko, I. G. Mukha, M. V. Zhukov, NPA 713 (2003) 372.
- L. V. Grigorenko, I. G. Mukha, M. V. Zhukov, NPA 714 (2003) 425.
- L. V. Grigorenko, M. V. Zhukov, PRC 68 (2003) 054005.

Типичная точность: стабильные решения до $\Gamma/E_T > 10^{-30}$

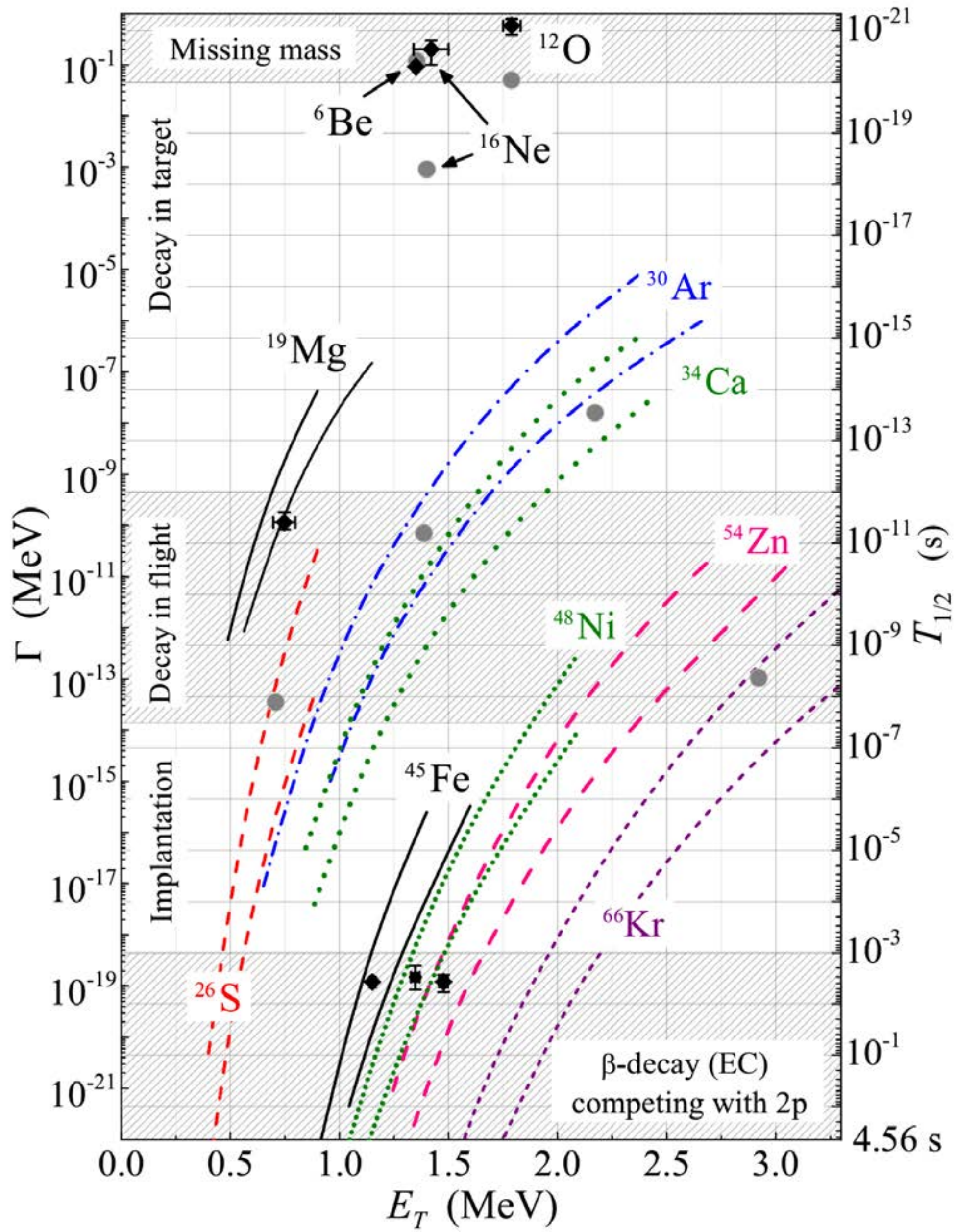
True 2p decay lifetime systematics

20 orders of the magnitude variation of the lifetime

Different experimental techniques are required: implantation, decay in flight, missing mass

In broad lifetime ranges the true 2p lifetime measurements are not accessible

Nice agreement overall. Problem with ^{12}O and ^{16}Ne lifetimes is recently resolved



True 2p decay lifetime systematics

Recent findings

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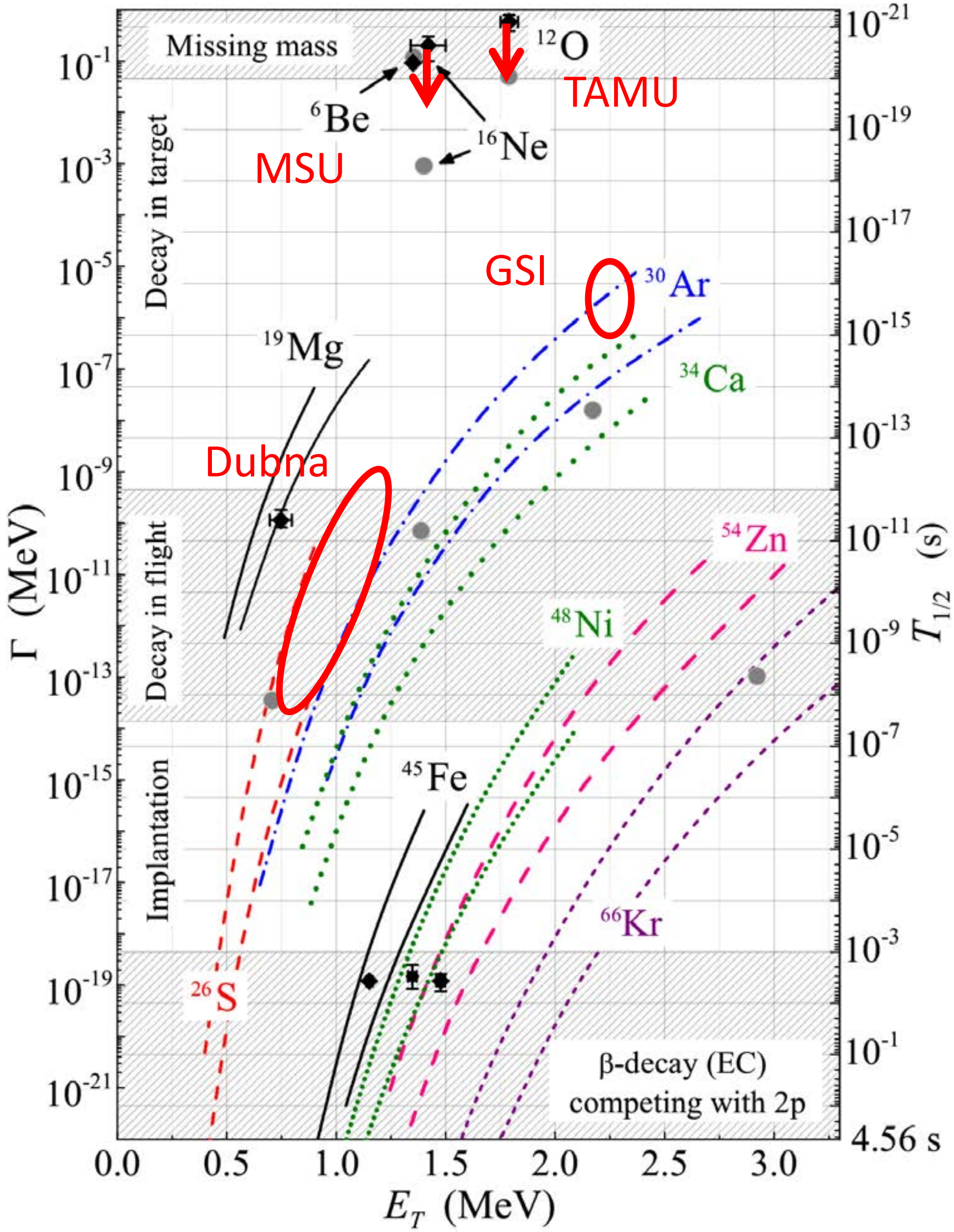


^{45}Fe: the first found and the best studied

Pfützner et al., EPJA **14** (2002) 279

Giovinazzo et al., **89** (2002) 102501

Dossat et al., PRC **72** (2005) 054315

Q_{2p} = 1.154 MeV

Miernik et al., PRL **99** (2007) 192501

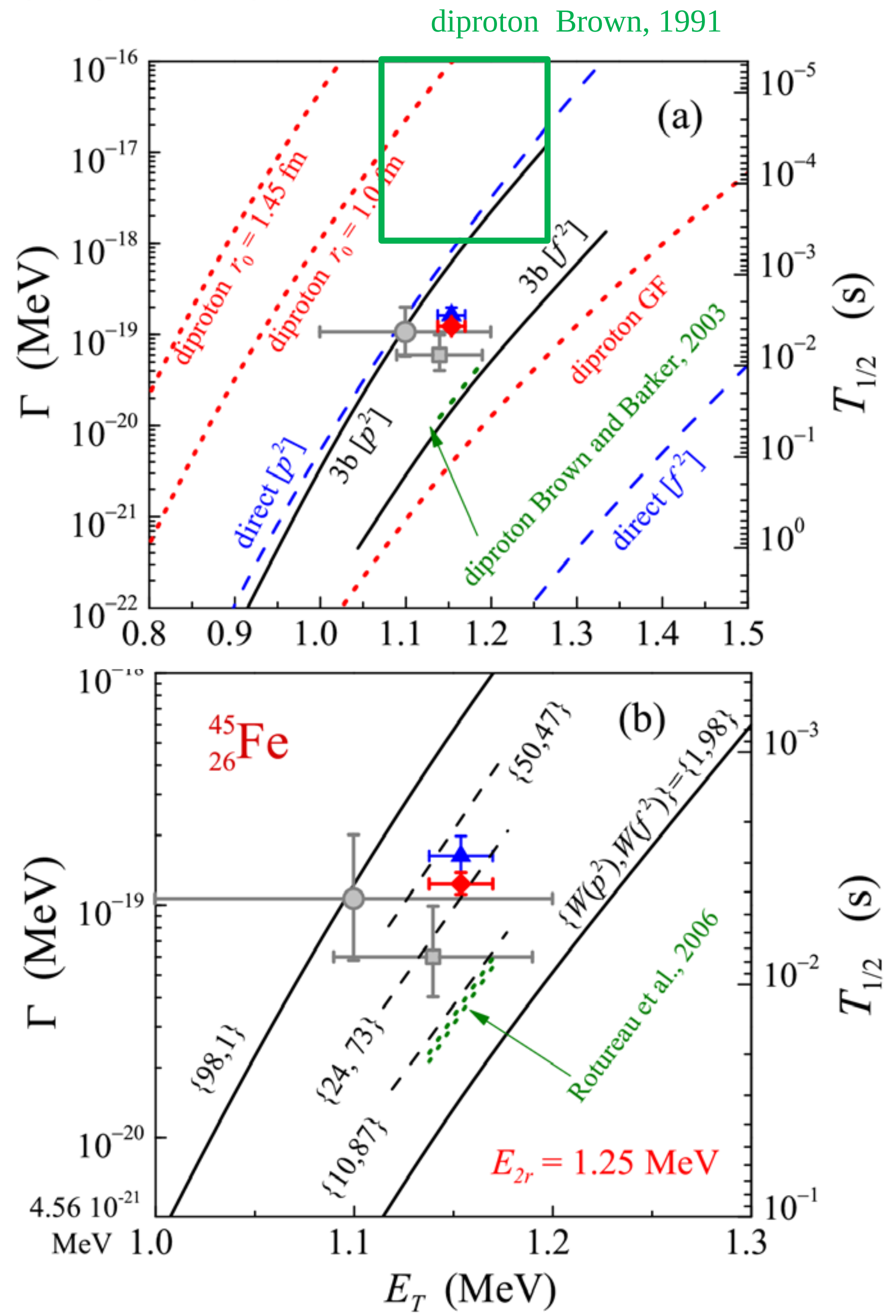
- Special design Optical TPC → nuclear physics “life video”
- Improved lifetime:

$$\Gamma_{2p} = 1.3^{+0.22}_{-0.16} \times 10^{-19} \quad \text{MeV} \qquad T_{1/2}(2p) = 3.5(5) \quad \text{ms}$$

- Complete momentum correlations provided

L.Grigorenko et al., PLB **677** (2009) 30

L.Grigorenko et al., PRC **82** (2010) 014615



Three-body correlations in decays and reactions

2-body decay: state is defined by 2 parameters - energy and width

3-body decays: 2-dimensional “internal” 3-body correlations

3-body continuum in reactions: there is a selected direction. 5-dimensional correlations: “internal” + “external”

For <u>direct reactions</u> the selected direction is momentum transfer vector

Which kind of useful information (if any) can be obtained from three-body correlations?

"Internal" energy of 3-bodies

$\{k_x, k_y\} \rightarrow E_T = E_x + E_y$

"Internal" 3-body correlations

$\{\mathbf{k}_x, \mathbf{k}_y\} \rightarrow$

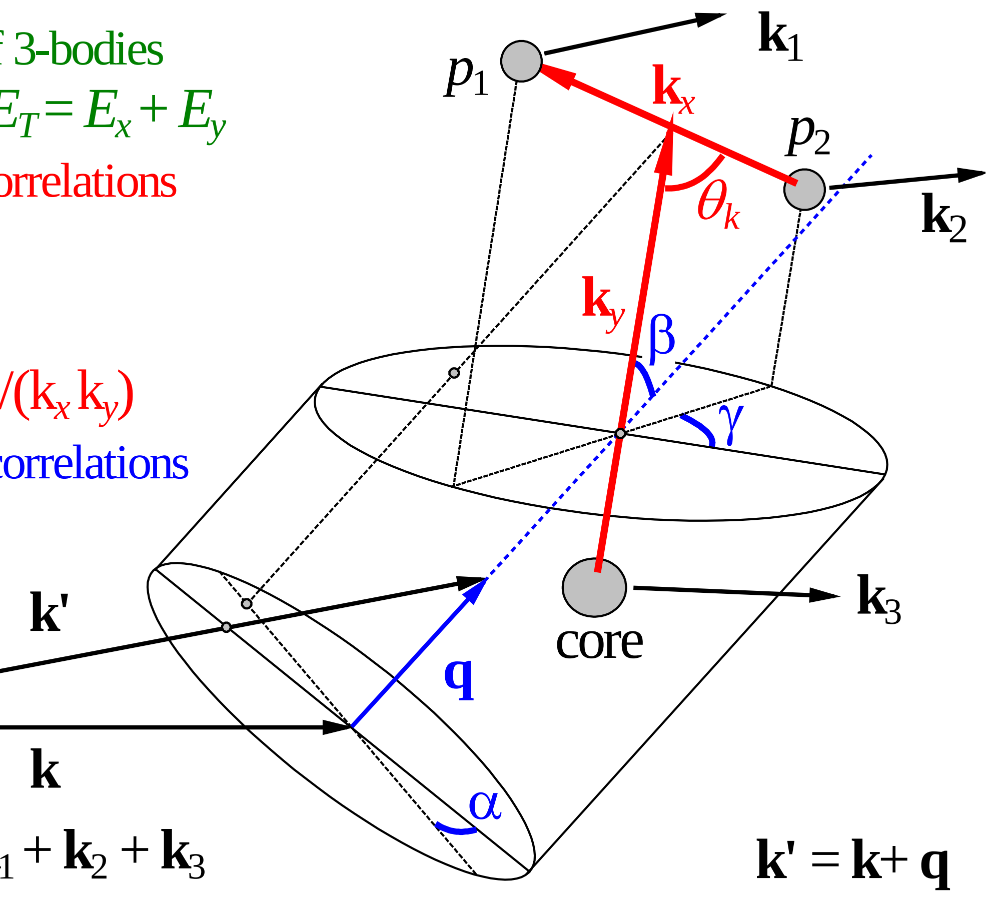
$\varepsilon = E_x / E_T$

$\cos\theta_k = (\mathbf{k}_x, \mathbf{k}_y)/(k_x k_y)$

"External" 3-body correlations

$\{\mathbf{q}, \mathbf{k}_x, \mathbf{k}_y\} \rightarrow$

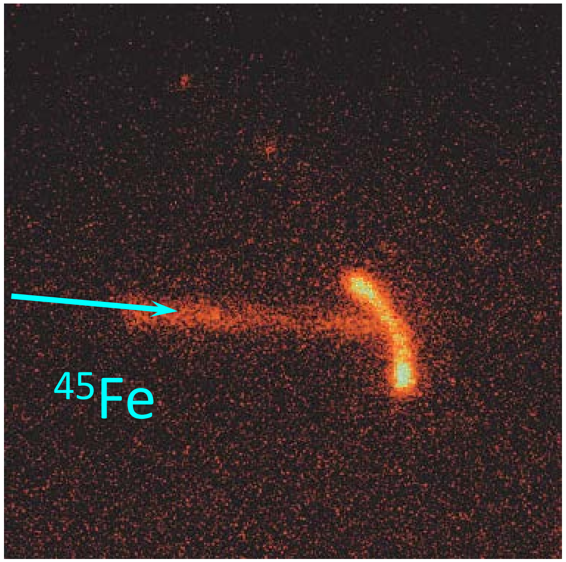
$\{\alpha, \beta, \gamma\}$

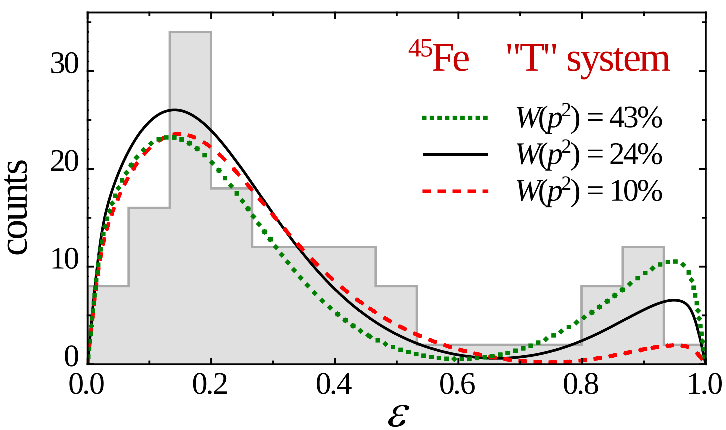


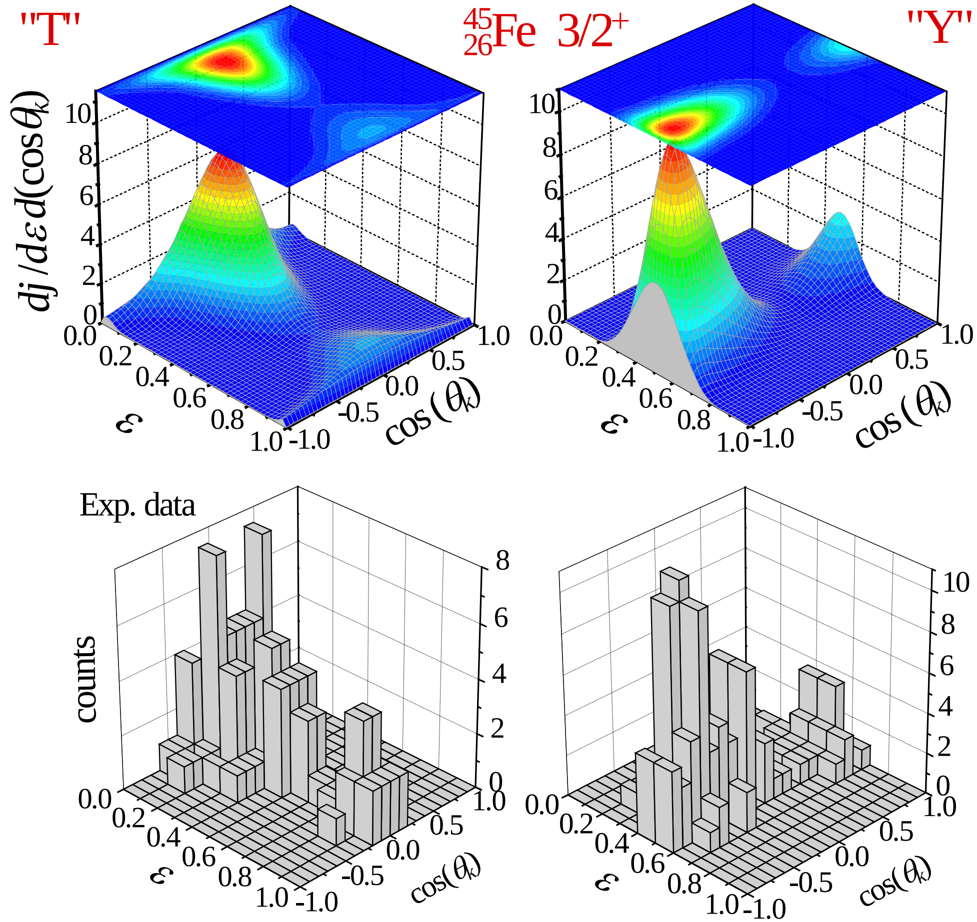
$\mathbf{k}' = \mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3$

$\mathbf{k}' = \mathbf{k} + \mathbf{q}$

^{45}Fe: internal correlations







Miernik *et al.*, PRL **99** (2007) 192501

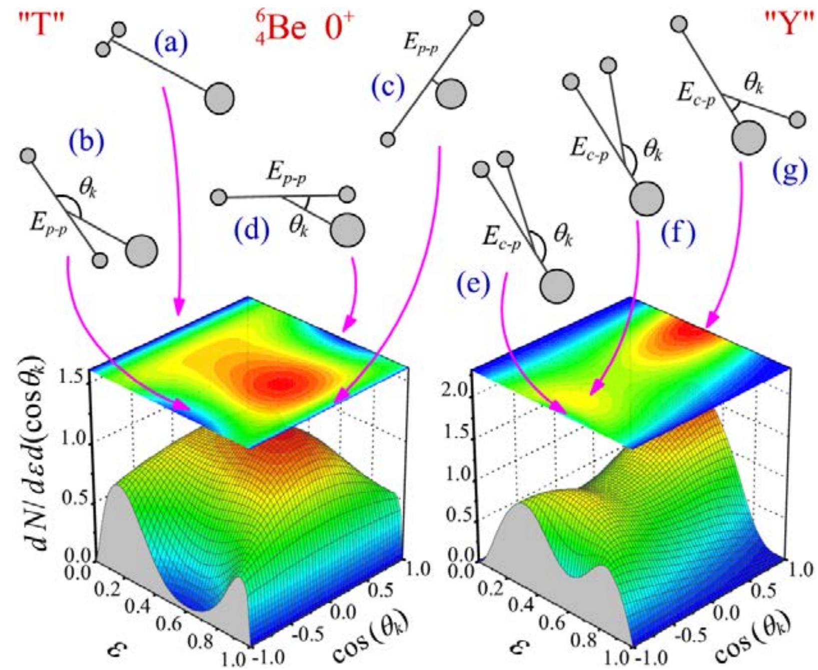
- Complete kinematics reconstructed
- Both lifetime and correlations provide $W(p^2) \sim 30\%$

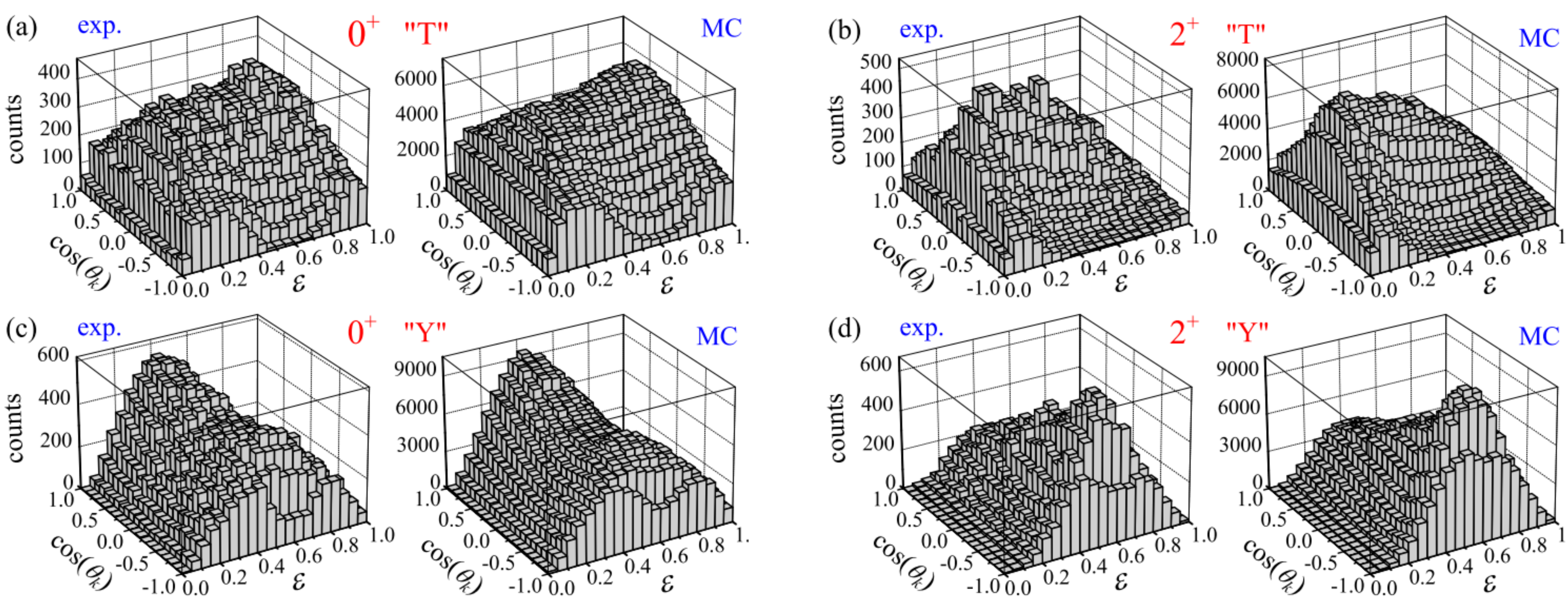
^{6}Be at MSU: correlations on resonance

Experiment:
R. Charity and coworkers, MSU ^{7}Be(^{9}Be,X)^{6}Be

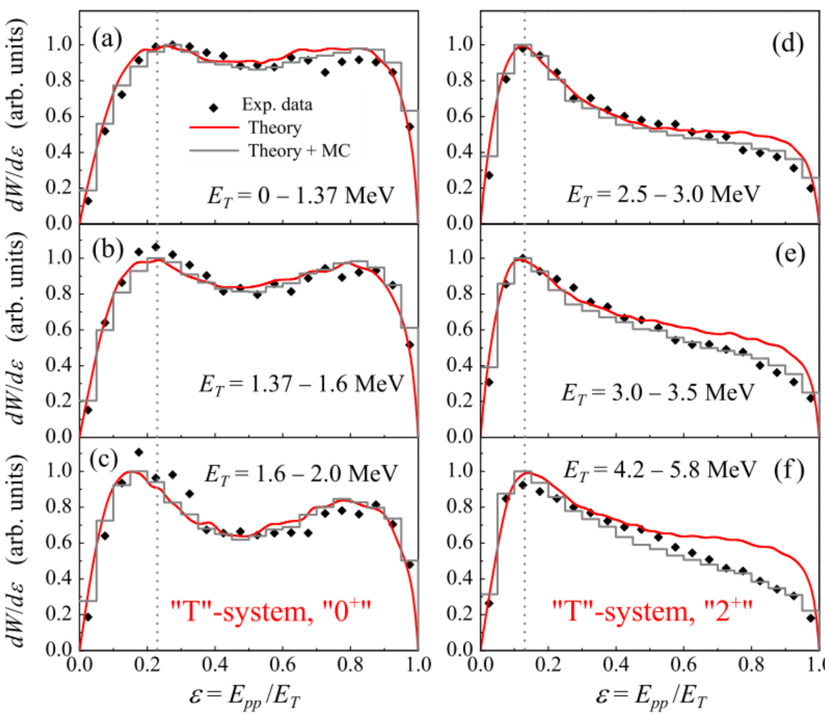
I. Egorova et al., PRL **109** (2012) 202502.

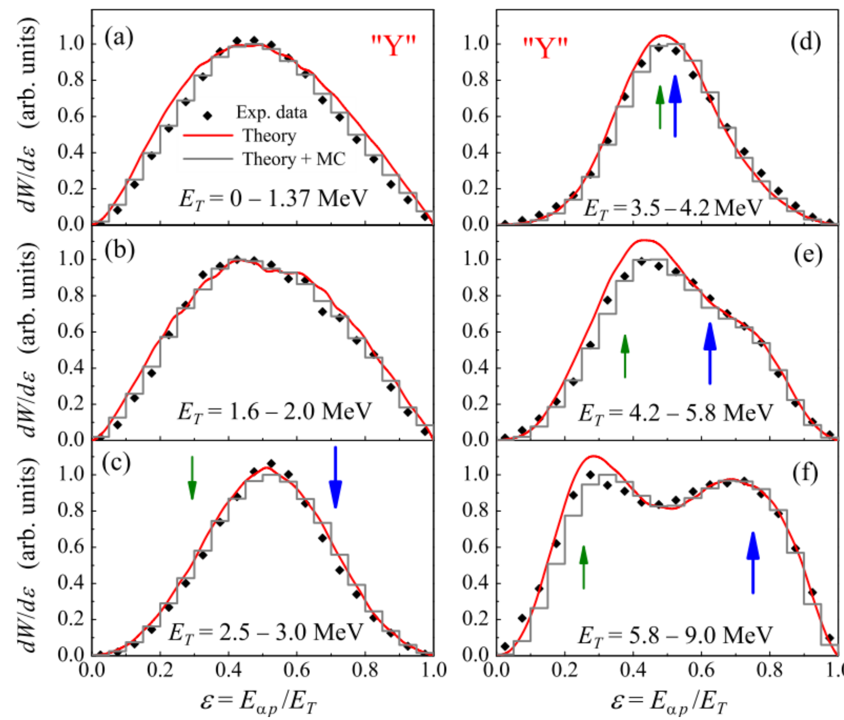
- High statistics (~10^6 events/state)
- High resolution
- Nice agreement with the previous (Texas A&M, Dubna) experimental data





^{6}Be at MSU: energy evolution of correlations





Note: the higher decay energy – the more developed is low-energy p-p correlation (“diproton”)

Note: when two-body states enters the decay window the intensity at expected peak position is suppressed

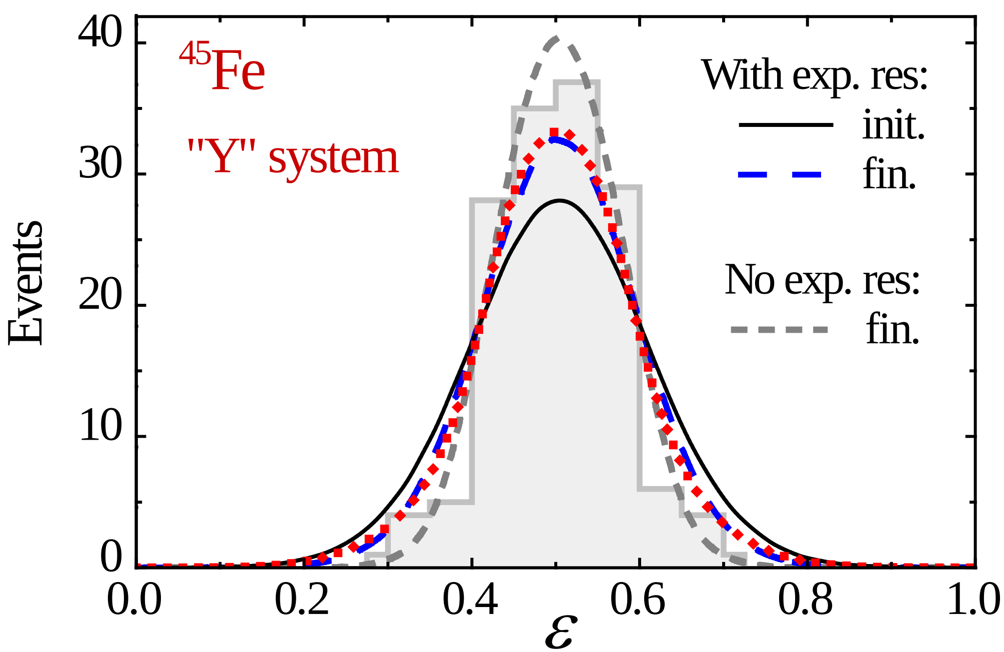
Note: above 2$^+$ the ε distribution is practically insensitive to decay energy

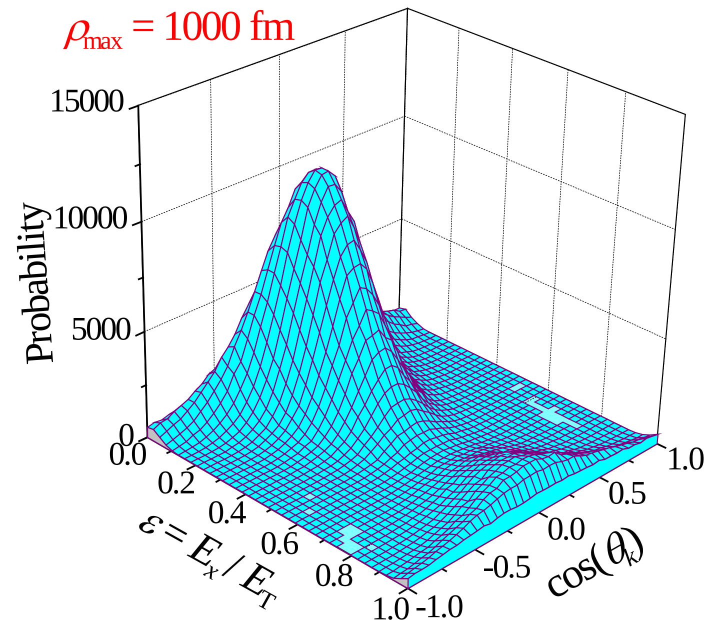
Note: sequential decay patterns appears only for $E_T > 2E_r + \Gamma$

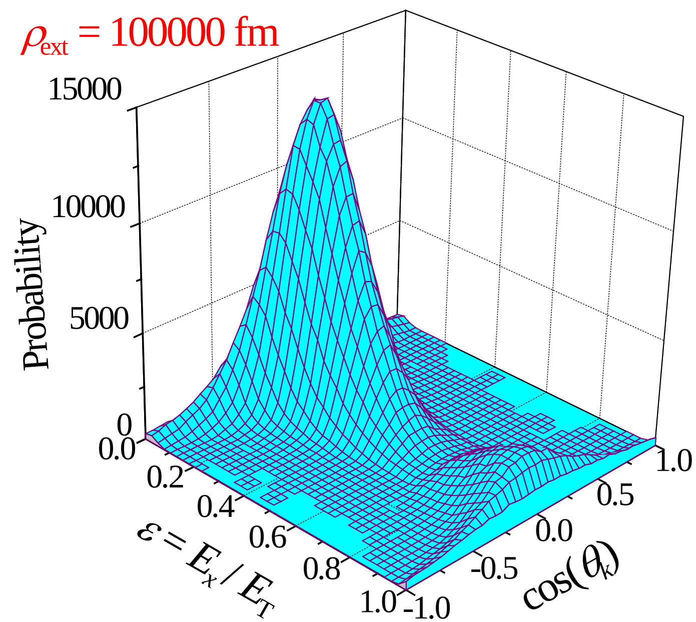
Long-range character of three-body Coulomb by example of ^{45}Fe

^{45}Fe, E_T = 1.154 MeV

- Start point for extrapolation: typical range of 1000 fm in ρ value
- End point for extrapolation: typical range of 100000 fm in ρ value
- Complicated treatment of experimental effects







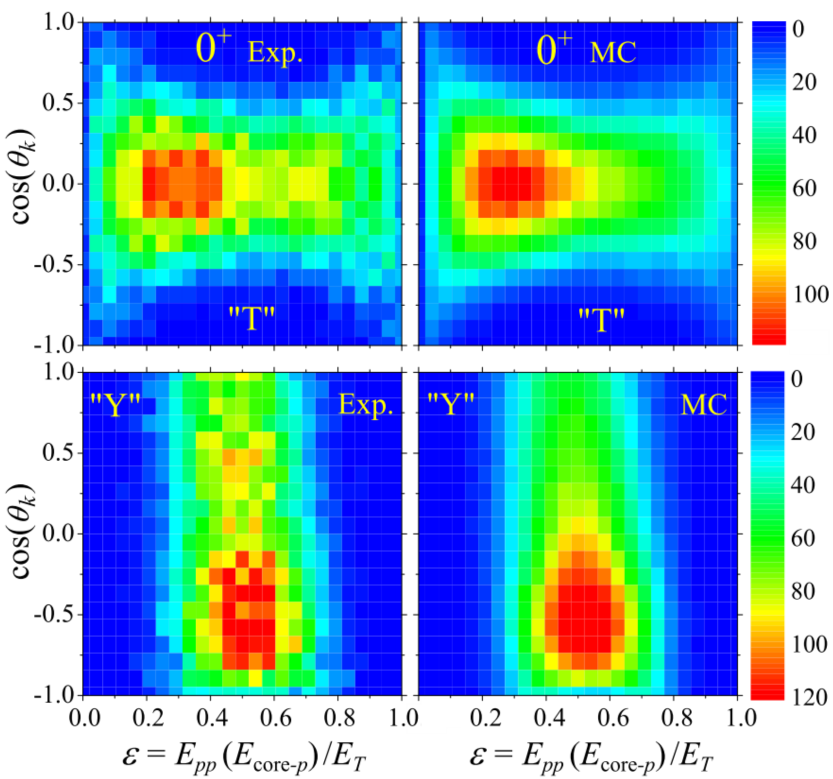
Long-range character of three-body Coulomb by example of ^{16}Ne

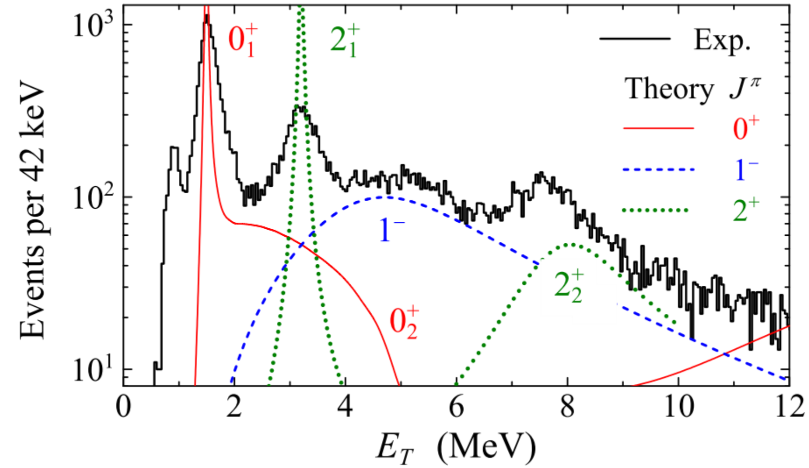
^{16}Ne g.s., E_T = 1.466 MeV

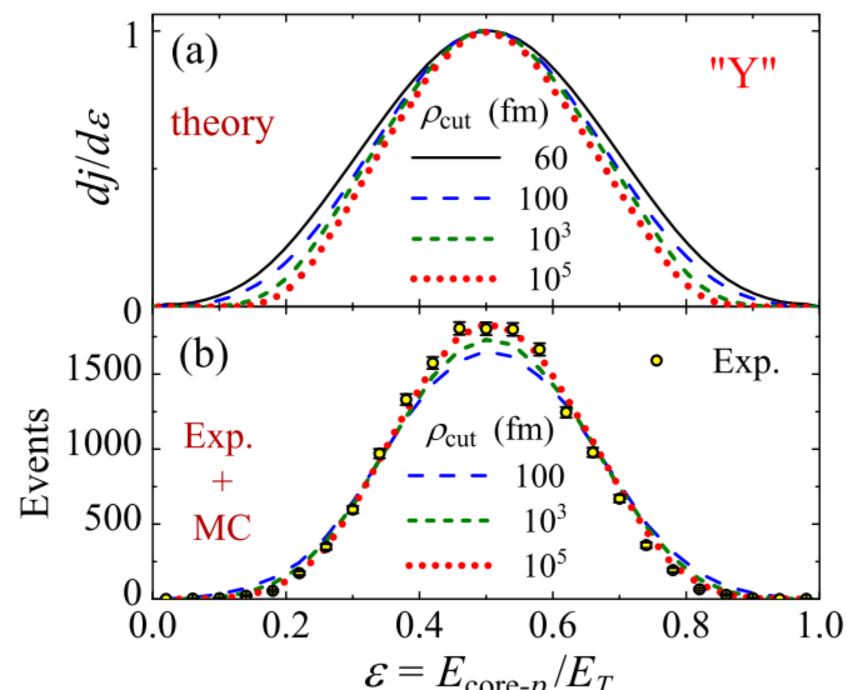
- New level of experimental precision. MSU 2013: ^{16}Ne populated in n knockout from ^{17}Ne

K. Brown et al., PRL **113** (2014) 232501

- The energy distribution in “Y” Jacobi system only reproduced for extreme range of calculation



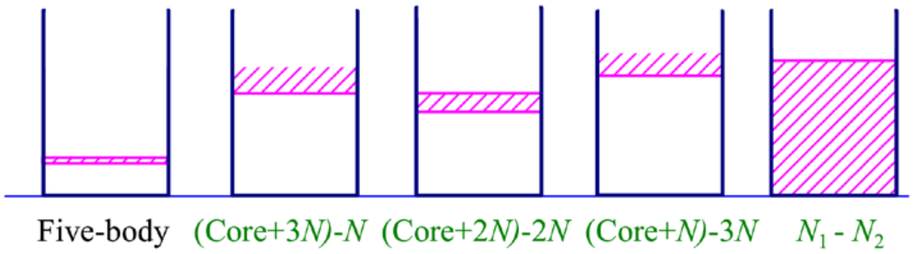


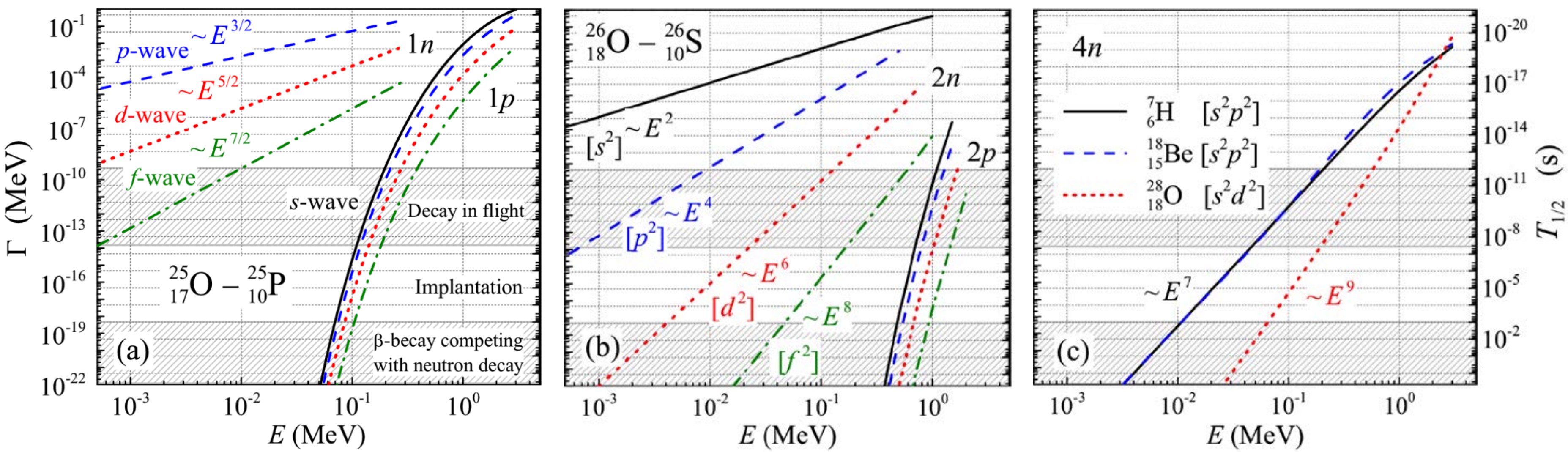


Two- (and more)-neutron radioactivity search prospects

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

Energy conditions for true 4n decay

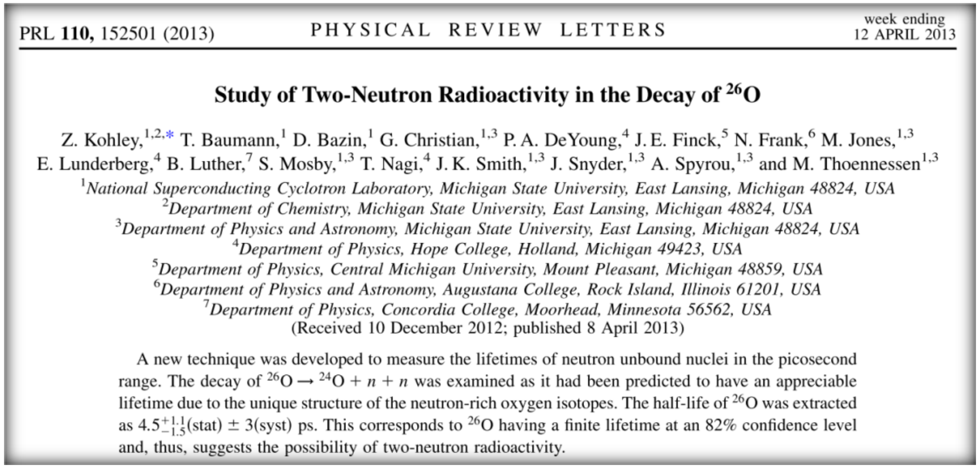




Long-living true four-neutron decay states are most probable.

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

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]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Physics, Hope College, Holland, Michigan 49423, USA*
[5]*Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*
[6]*Department of Physics and Astronomy, Augustana College, Rock Island, Illinois 61201, USA*
[7]*Department of Physics, Concordia College, Moorhead, Minnesota 56562, USA*

(Received 10 December 2012; published 8 April 2013)

A new technique was developed to measure the lifetimes of neutron unbound nuclei in the picosecond range. The decay of $^{26}O \rightarrow {}^{24}O + n + n$ was examined as it had been predicted to have an appreciable lifetime due to the unique structure of the neutron-rich oxygen isotopes. The half-life of ^{26}O was extracted as $4.5^{+1.1}_{-1.5}$(stat) $\pm$ 3(syst) ps. This corresponds to ^{26}O having a finite lifetime at an 82% confidence level and, thus, suggests the possibility of two-neutron radioactivity.

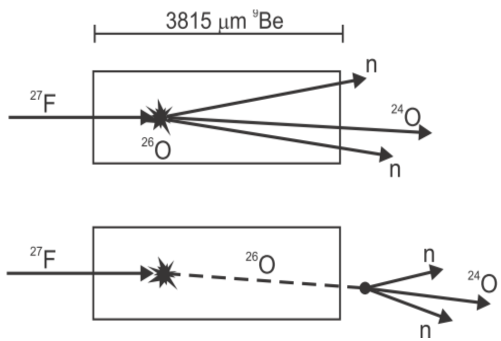
L.V. Grigorenko, I.G. Mukha, M.V. Zhukov,
PRL **111** (2013) 042501

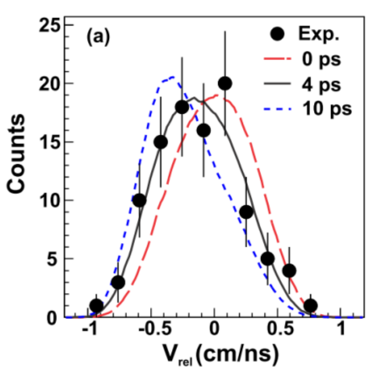
Importance of fine three-body effects

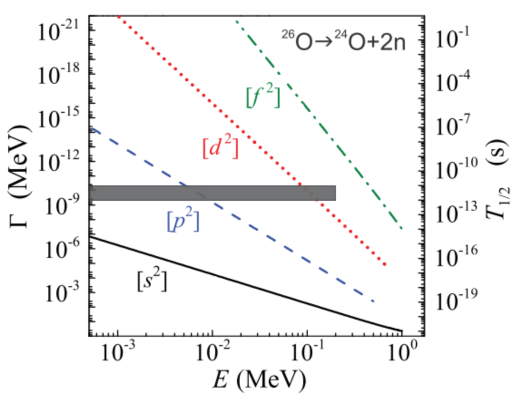
2p radioactivity:
Core recoil – negligible
Paring - factor 200-500

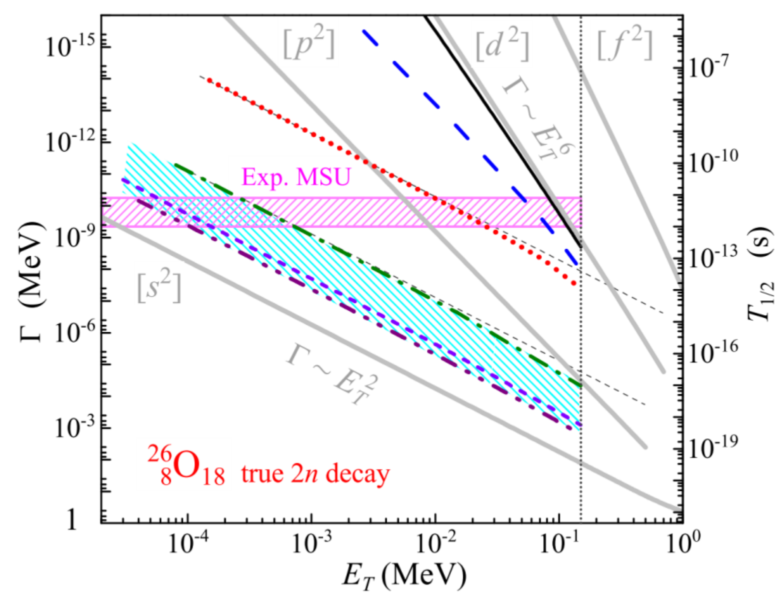
2n radioactivity:
Core recoil – factor 5-10
Paring - factor 2000-10000

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



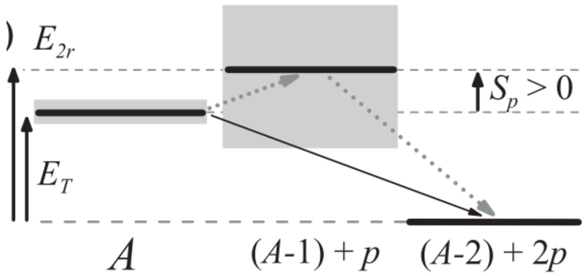


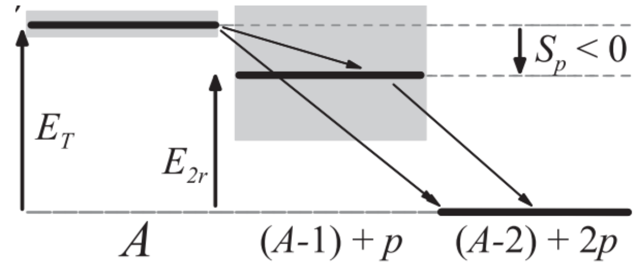




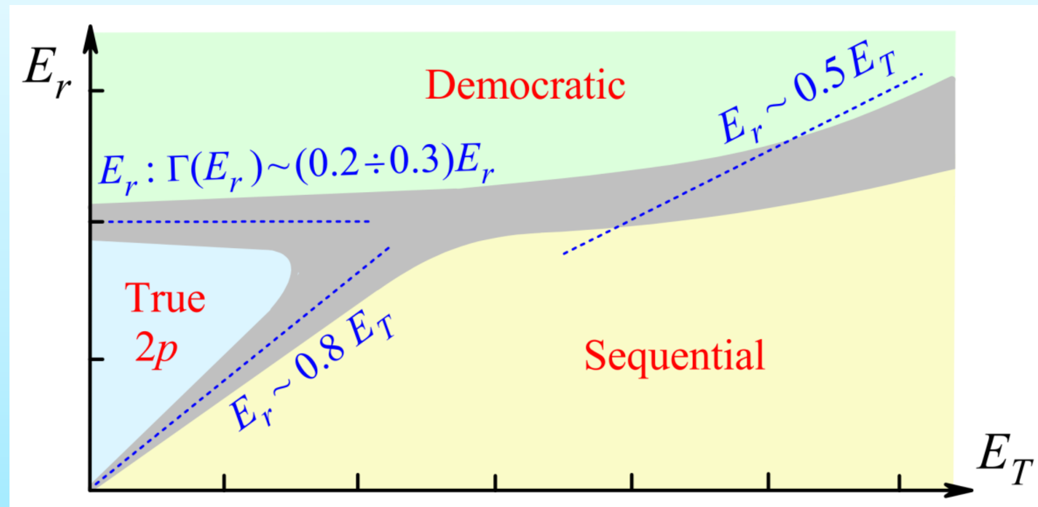
Extreme low-energy decay of ^{26}O should be inferred

Mechanisms of 2p decay defined by separation energies





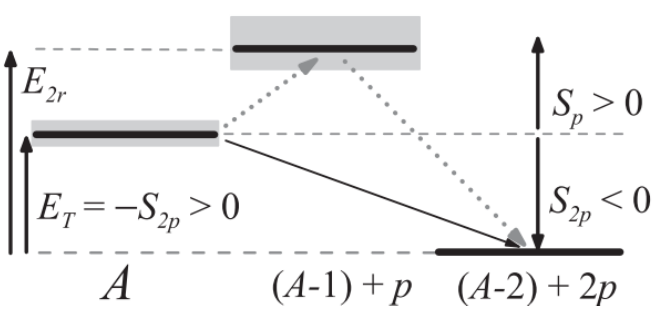
Three major decay mechanisms: True 2p, Democratic 2p Sequential 2p

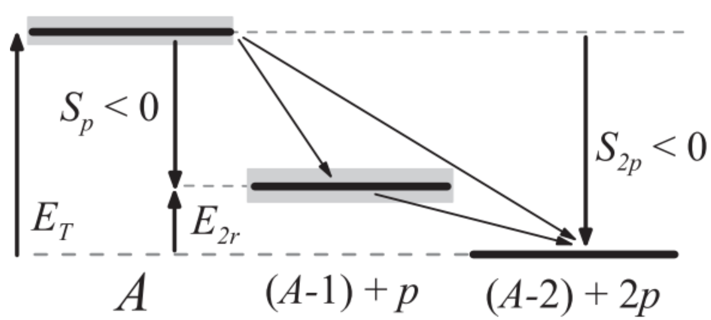


There SHOULD EXIST transition region between them

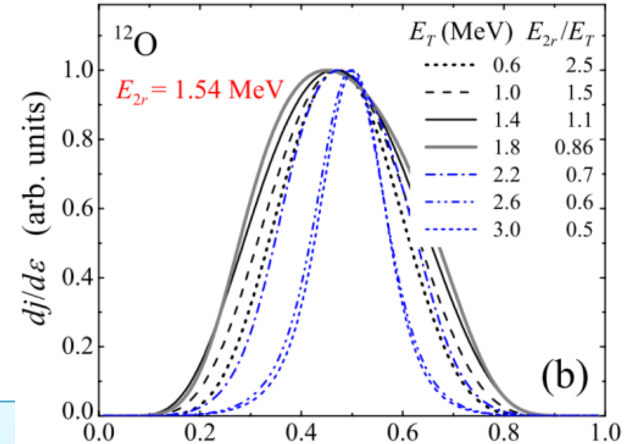
Three principal parameters:

$E_T \quad E_r \quad \Gamma_r$

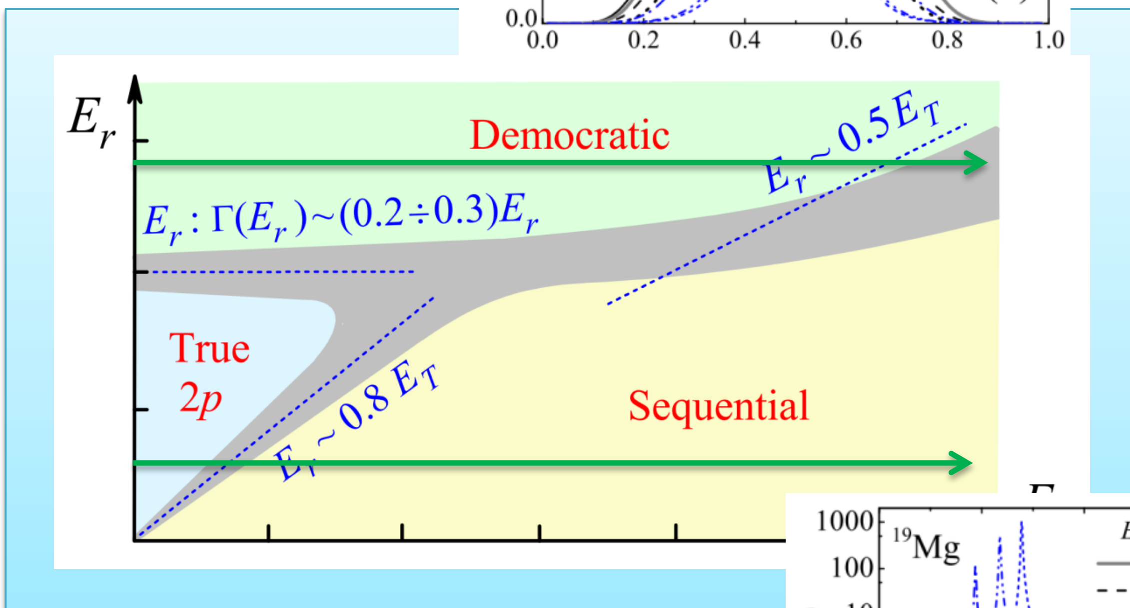




Mechanisms of 2p decay

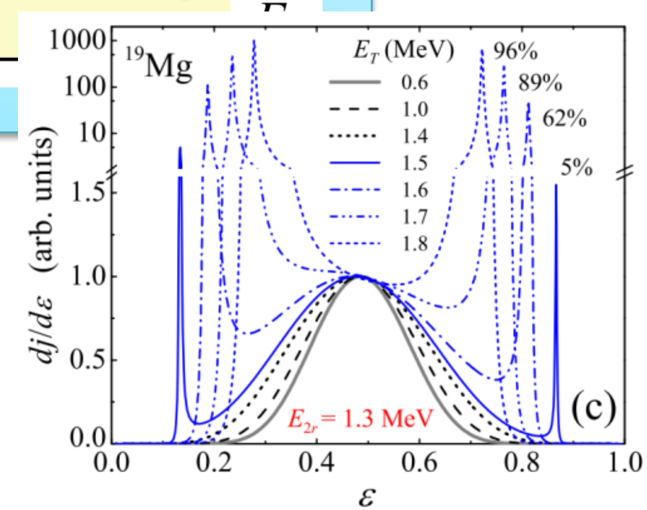


Democratic 2p <-> Sequential 2p



Energy correlations between core and one proton

True 2p <-> Sequential 2p



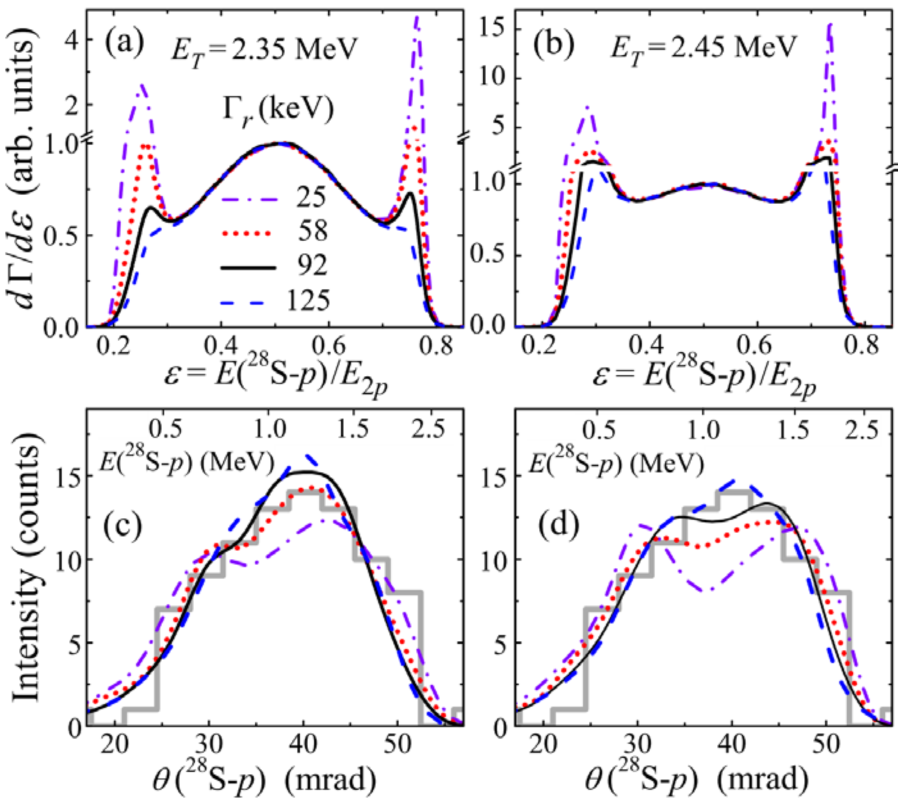
^{29}Cl g.s. width from ^{30}Ar data

Energy is "easy" to measure, width could be very complicated.
From $T_{1/2}$~1 ps to Γ~100-200 keV there is a "blind spot"

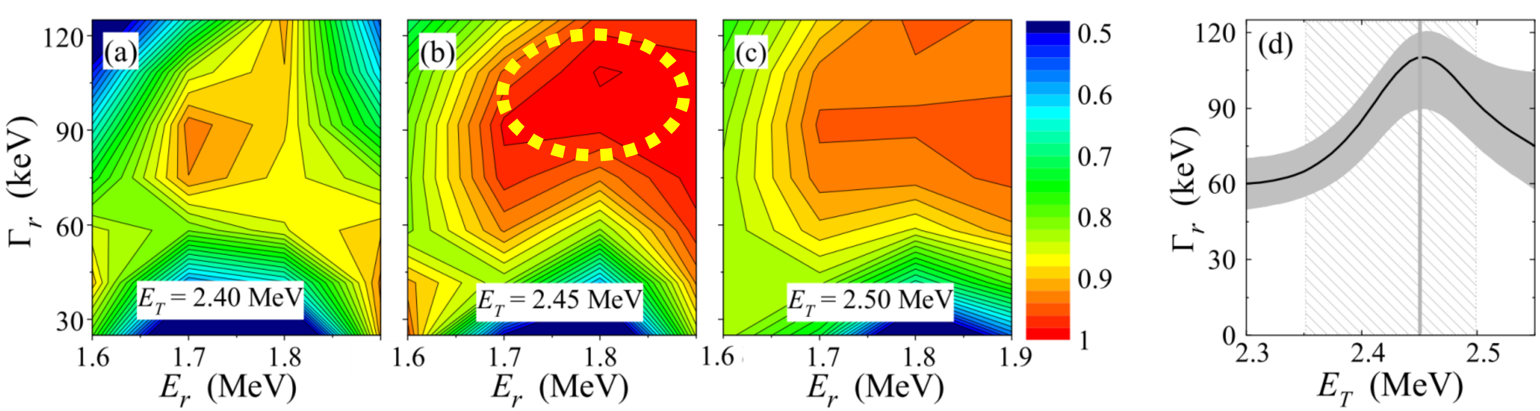
^{30}Ar was found to have transition decay dynamics

Strong dependence of the experimental signal on the g.s. properties of core+p subsystem – ^{29}Cl

Stringent limits for ^{29}Cl g.s. width



T.A. Golubkova *et al.*, PLB **762** (2016) 263



Radioactive ion beam studies
Flerov lab

ACCULINA and ACCULINNA-2

JINR 114 Flerovium FLNR Dubna

What we already have at Flerov lab

Elements 102 - 108 and 113 - 118 were synthesized at FLNR JINR

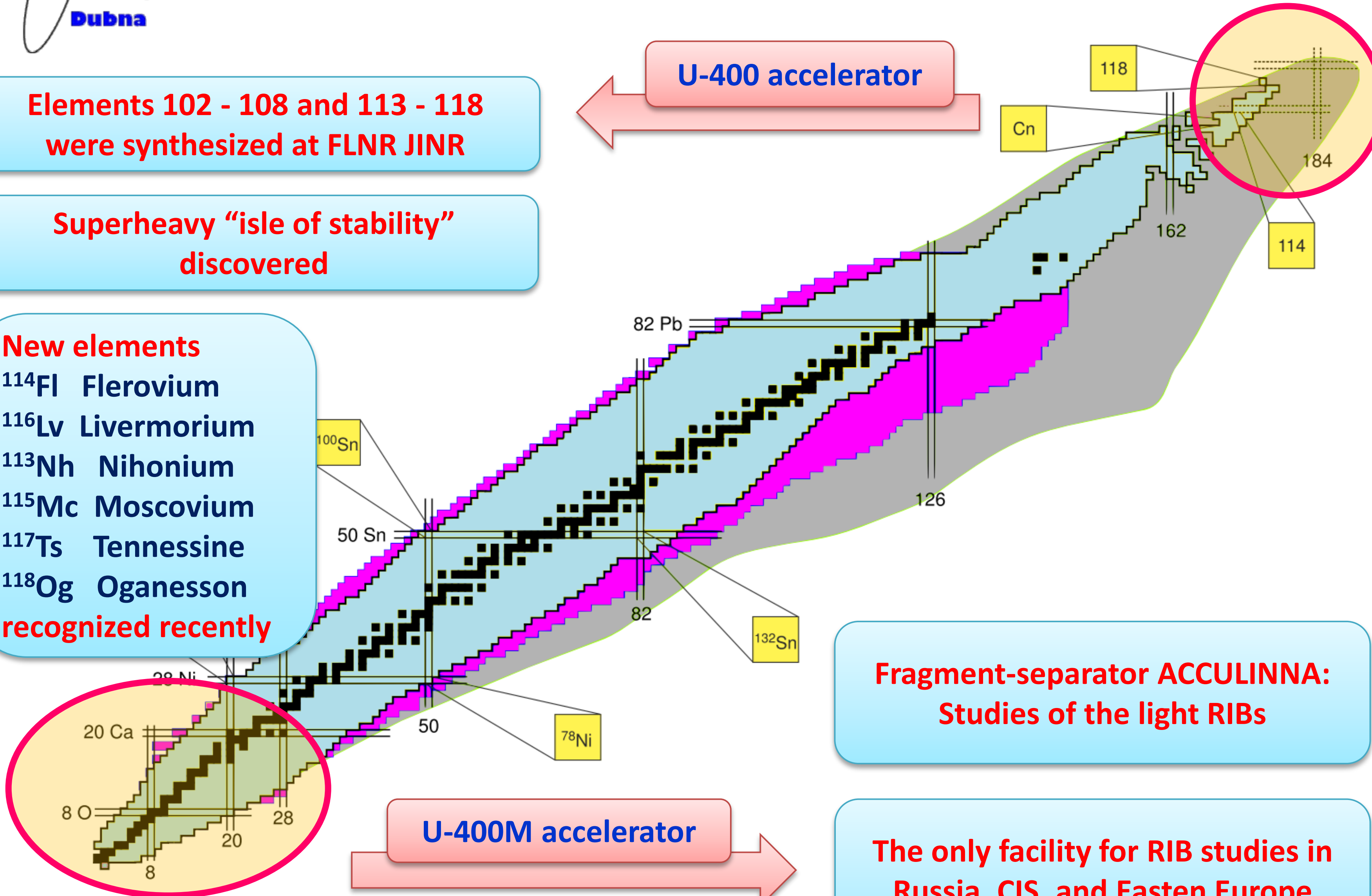
Superheavy "isle of stability" discovered

New elements

- ^{114}Fl Flerovium
- ^{116}Lv Livermorium
- ^{113}Nh Nihonium
- ^{115}Mc Moscovium
- ^{117}Ts Tennessine
- ^{118}Og Oganesson

recognized recently

U-400 accelerator



U-400M accelerator

Fragment-separator ACCULINNA: Studies of the light RIBs

The only facility for RIB studies in Russia, CIS, and Easten Europe

March 30 2018 – The Lomonosov great gold medal is awarded to Yuri Oganessian and Bjorn Jonson

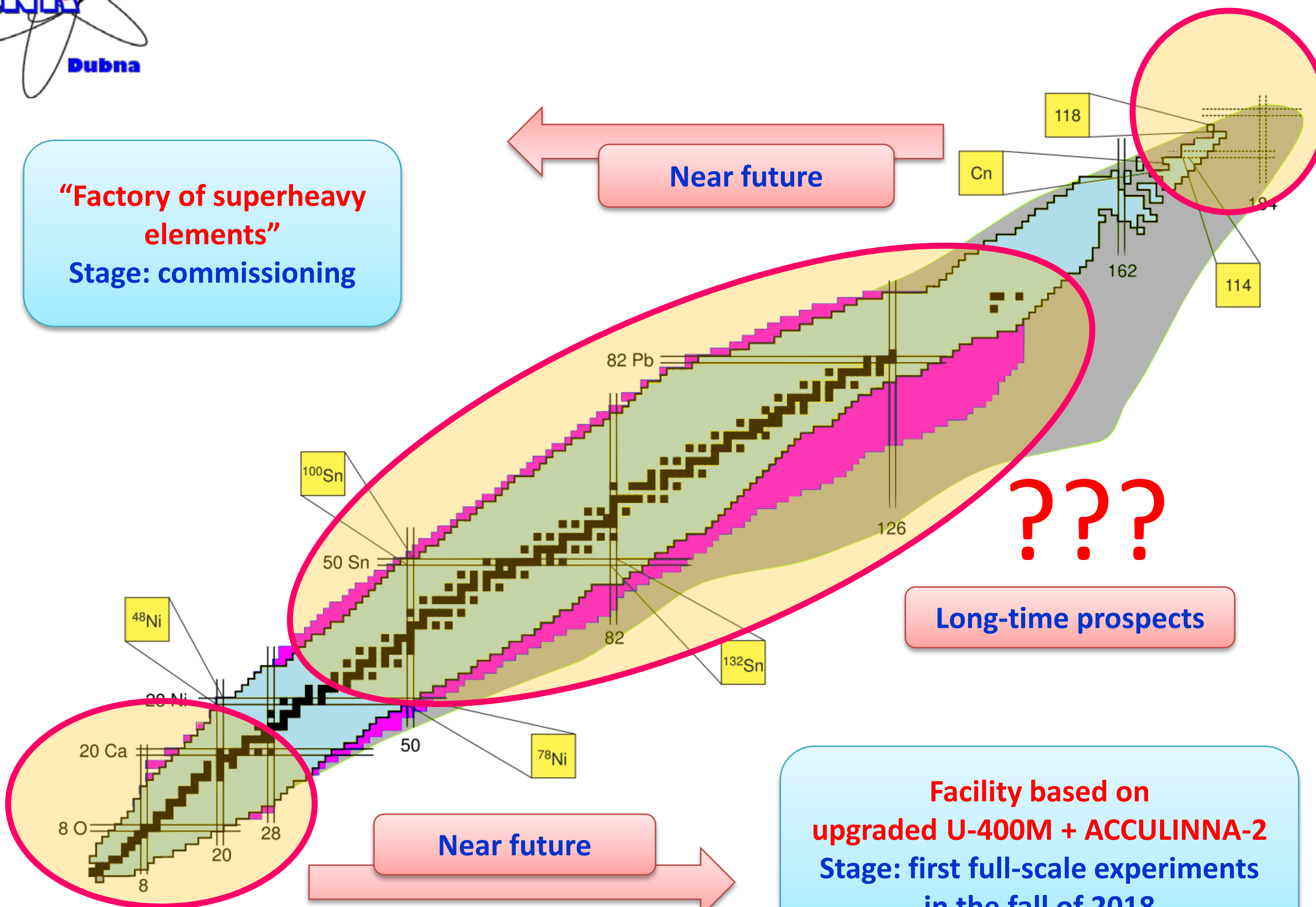
Yu.Ts. Oganessian – **synthesis of superheavy elements**

B. Jonson – **contribution of studies of exotic nuclei (ISOL method and nucleon halo)**

FLNR prospects

“Factory of superheavy elements”
Stage: commissioning

Near future



Long-time prospects

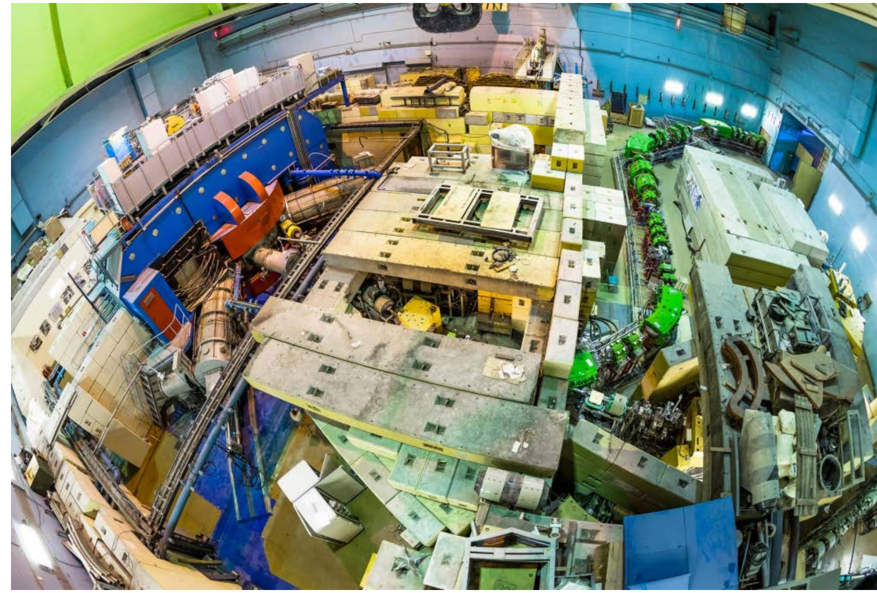
Near future

Facility based on
upgraded U-400M + ACCULINNA-2
Stage: first full-scale experiments
in the fall of 2018

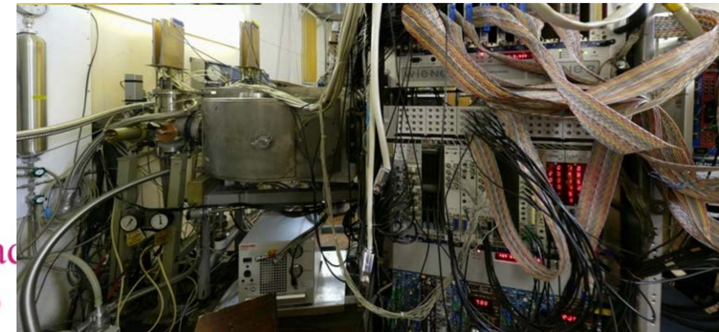
New facilities at FLNR

“Factory of superheavy elements”

ACCULINNA-2 fragment-separator



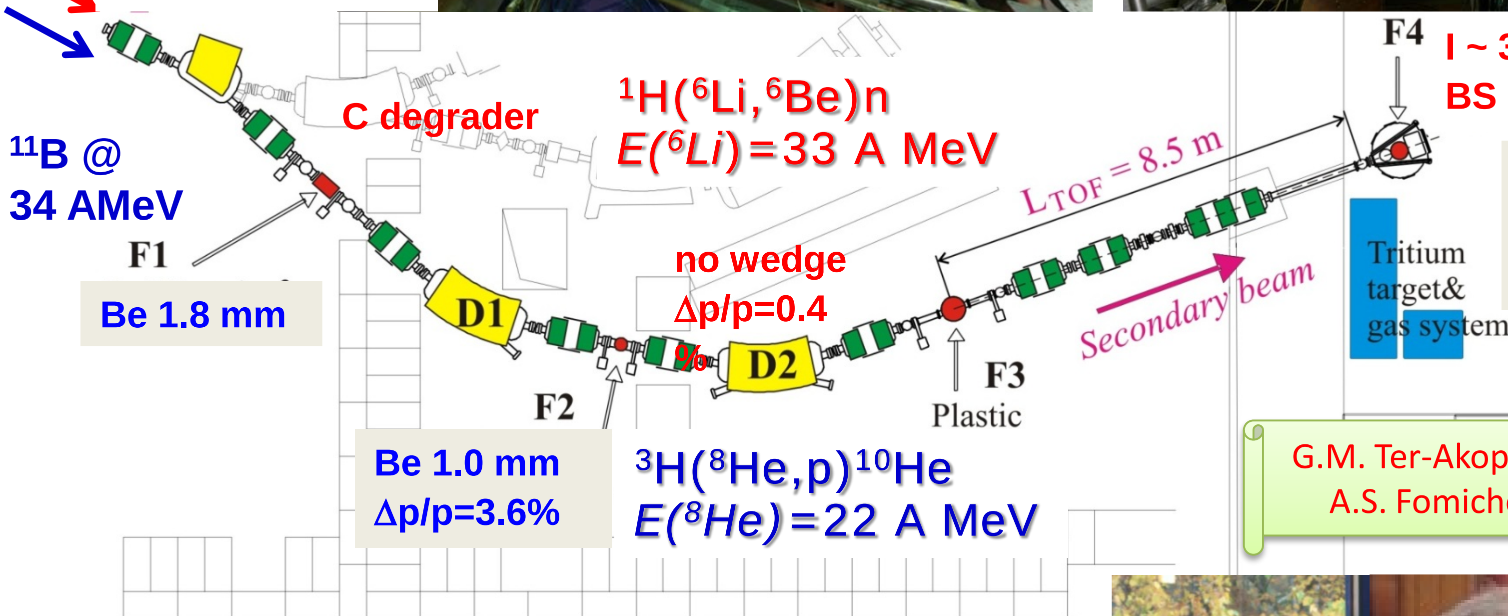
Flerov Lab: “Superlights” – fragment separator ACCULINNA



U-400M :

^{6}Li @ 47 AMeV

^{11}B @ 34 AMeV



^{1}H(^{6}Li,^{6}Be)n

$E(^{6}Li)=33$ A MeV

^{3}H(^{8}He,p)^{10}He

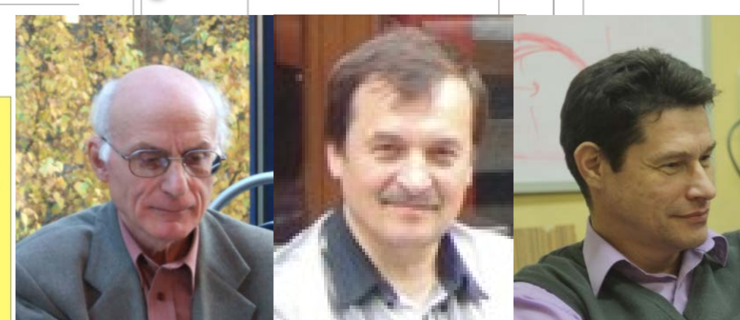
$E(^{8}He)=22$ A MeV

I ~ 3×10^{7} 1/s
BS ~ 5 mm

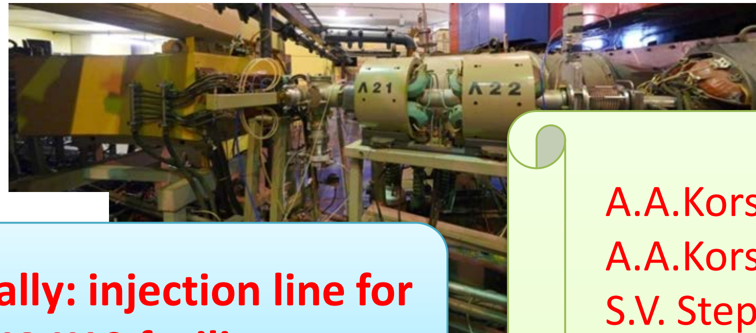
I ~ 2×10^{4} 1/s
BS ~ 15 mm
P ~ 90 %

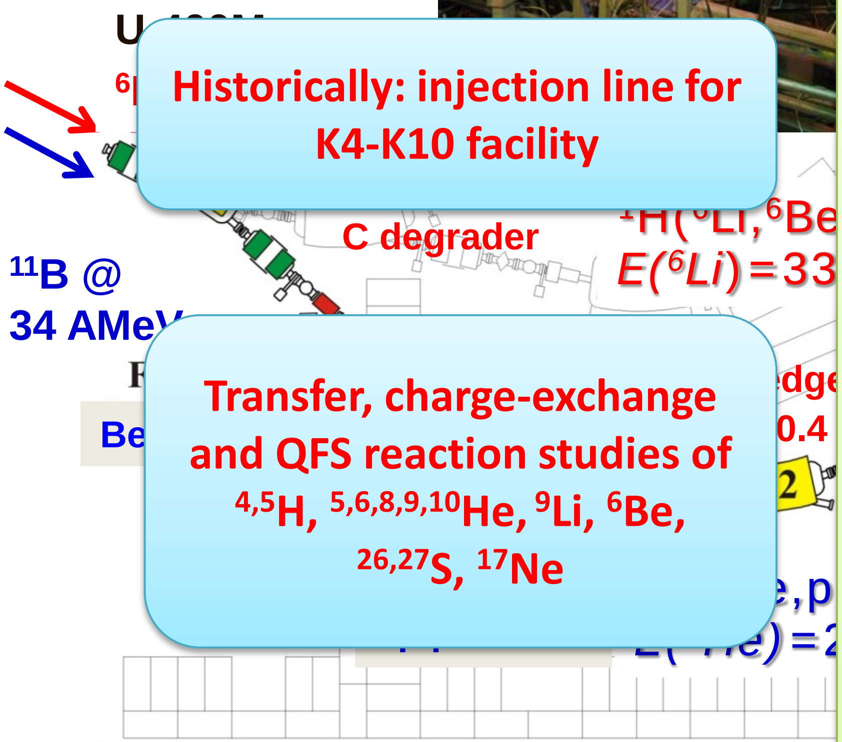
G.M. Ter-Akopian, A.M. Rodin, A.S. Fomichev, 1996-Now

	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



Flerov Lab: Superlights – fragment separator ACCULINNA





Historically: injection line for K4-K10 facility

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.
P. G. Sharov *et al.,* PRC **96** (2017) 025807.
V. Chudoba *et al.,* PRC **98** (2018) 054612.

	F2	F	
H/V magnification	0.5/2.0	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

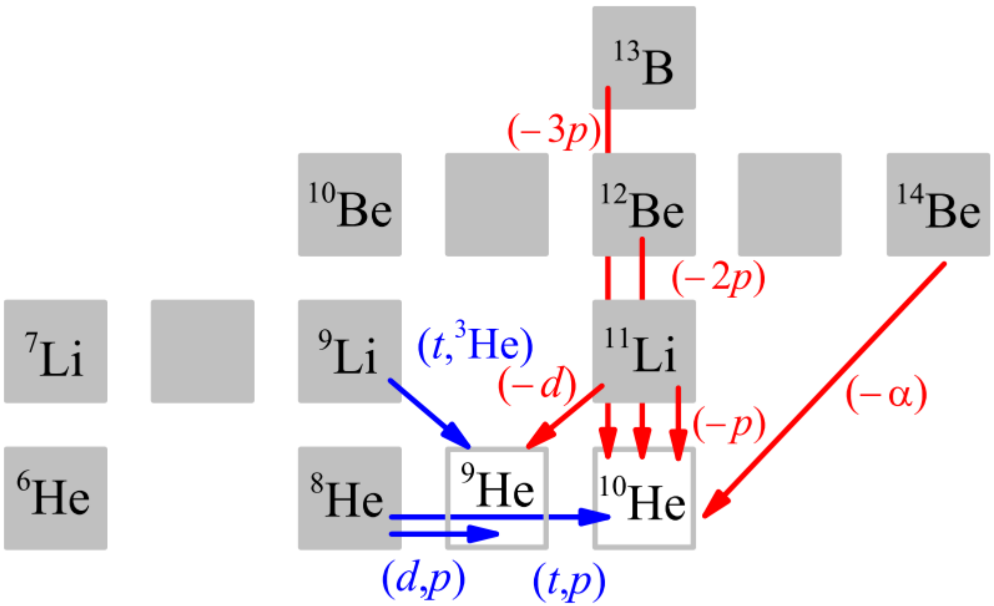
Competitive scientific program at JINR

Intermediate energy reactions (20-70 MeV/nucleon)

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

Transfer reactions

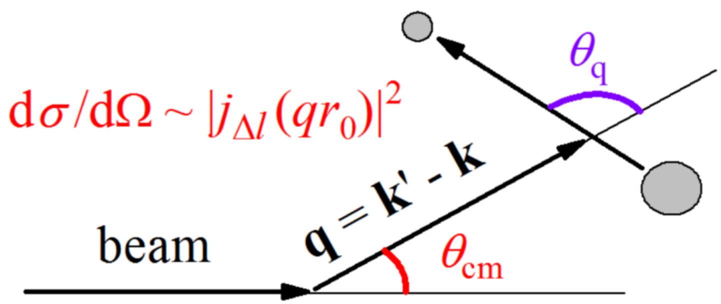
Knockout reactions



Importance of complementary reaction studies

Competitive light nuclei RIB program at FLNR
2. Correlations and few-body dynamics studies

Correlations for aligned states populated in the direct reactions



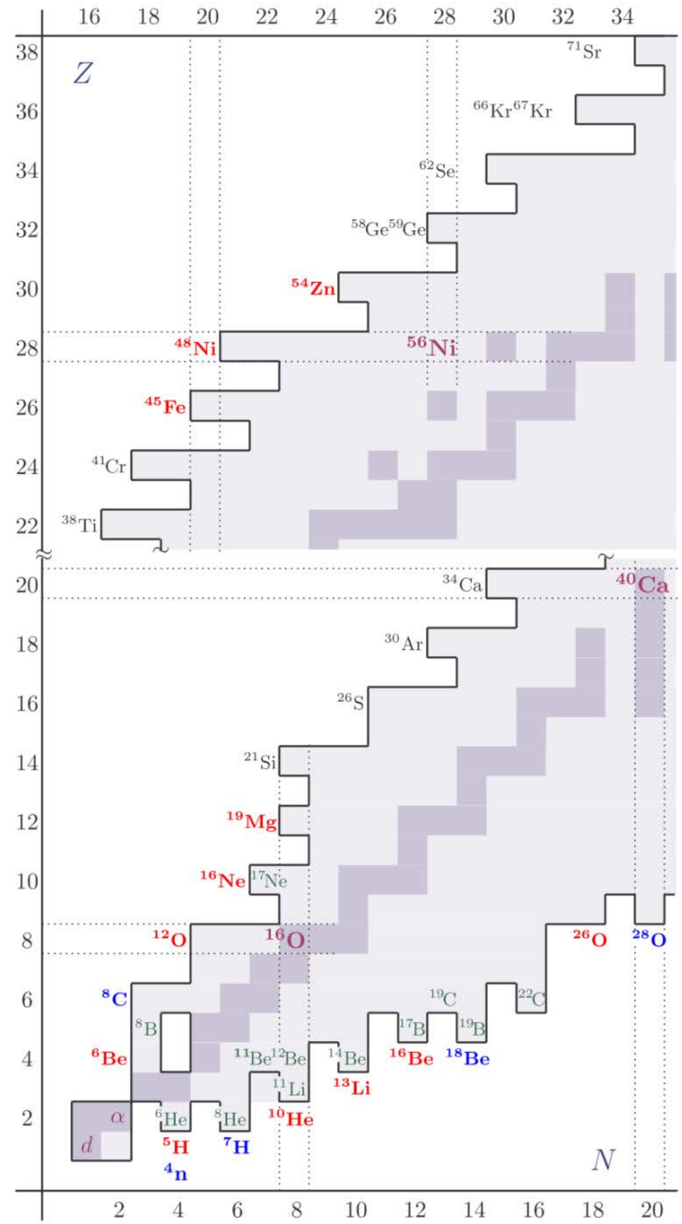
Few-body dynamics near the driplines

Few-body dynamics at the driplines is consequence of (i) clusterization and (ii) paring

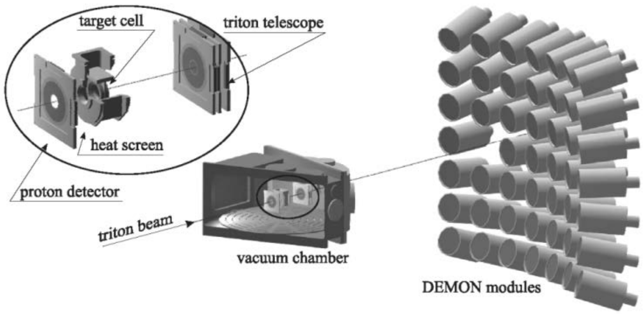
Exotic phenomena near driplines: Haloes (green) True 2p/2n decays (red) 4p/4n emitters (blue) NOT INVESTIGATED (gray)

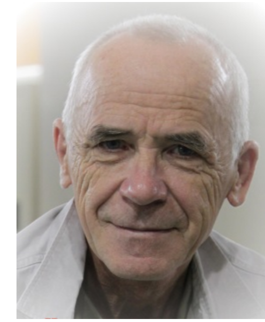
NOT SO EXOTIC: More or less every second isotope in vicinity of the driplines has features connected to few-body dynamics

Correlations in the three-body decays: two extra degrees of freedom



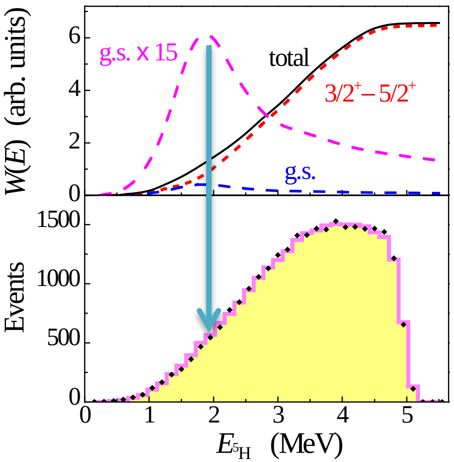
Example: ^{5}H studied in the ^{3}H(t,p)^{5}H reaction

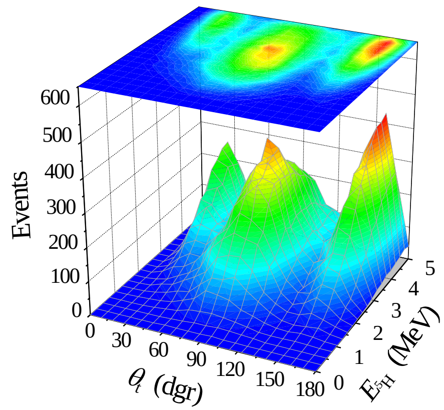




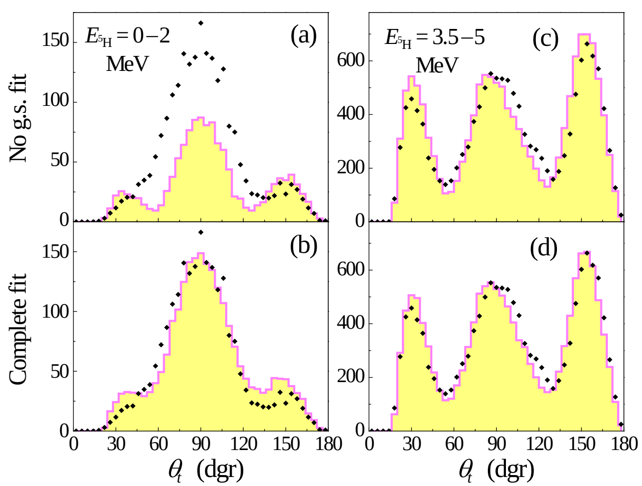
A.A. Korsheninnikov, 2001, ^{6}He(p,2p)^{5}H
Discovery of ^{5}H at FLNR

M.S. Golovkov, 2004,
Pioneering correlation studies



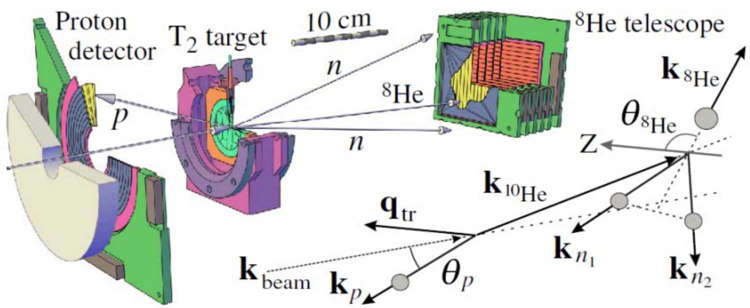


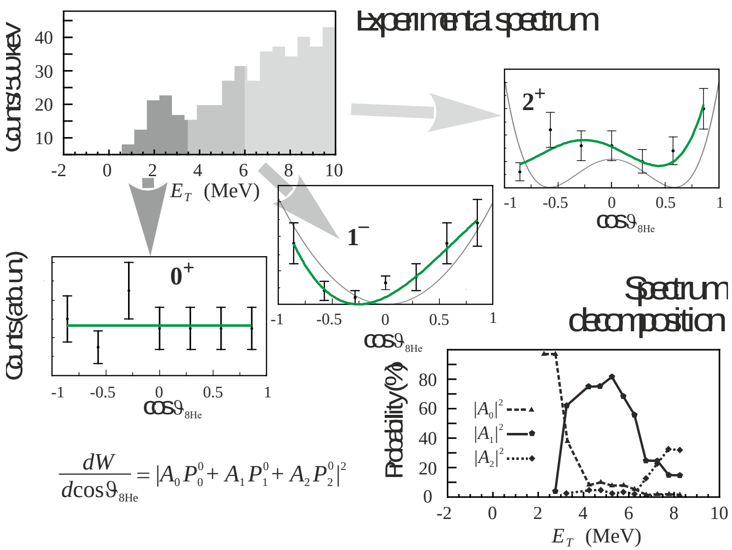
A.A. Korsheninnikov et al., PRL **87** (2001) 92501.
M.S.Golovkov et al., PLB **566** (2003) 70.
M.S.Golovkov et al., PRL **93** (2004) 262501.
S.V. Stepantsov et al., NPA **738** (2004) 436.
M.S.Golovkov et al., PRC **72** (2005) 064612.

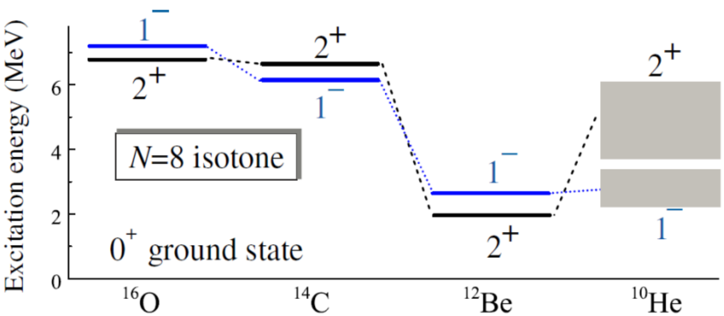


- Poor population of ground state. However, correlations provide enough selectivity: quantum amplification
- ^{5}H ground state position is finally established; the excited state is established as $3/2^{+}$-$5/2^{+}$ degenerate mixture

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

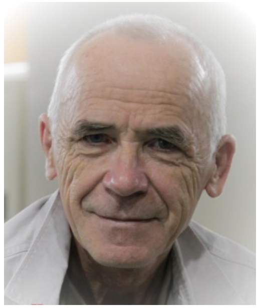






"Conundrum nucleis" second double magic in nuclide chart

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

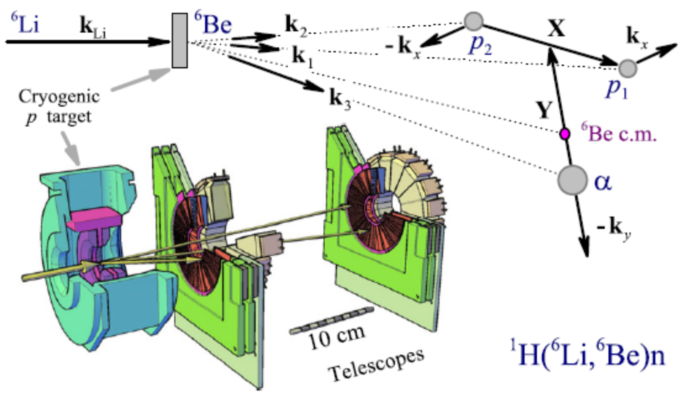
- Three-body correlations were studied in ^{5}H basing on outstanding statistics. Can be something useful done with really exotic systems and limited statistics?

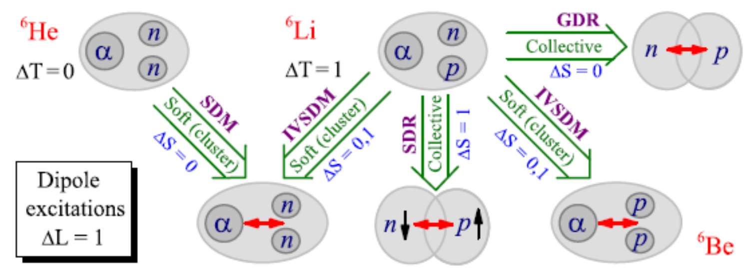
New ground state energy for ^{10}He: E_T=2.0-2.5 MeV

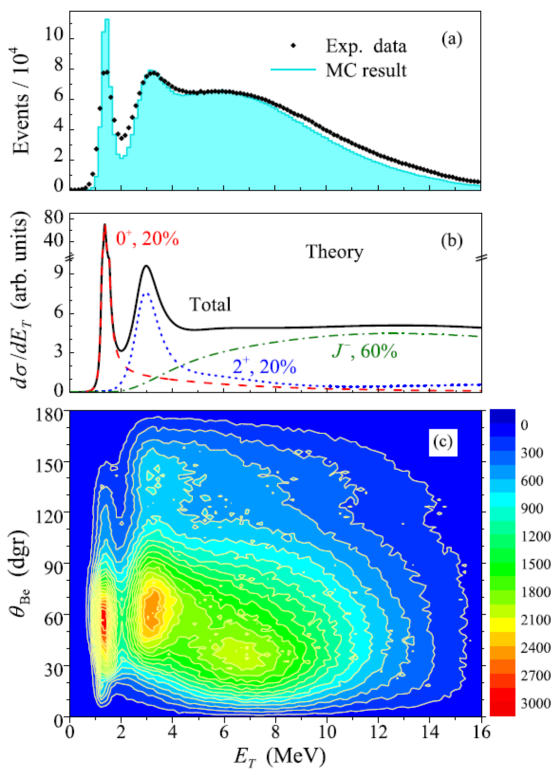
Shell structure breakdown in ^{10}He

IsoVector Soft Dipole Mode in ^{6}Be

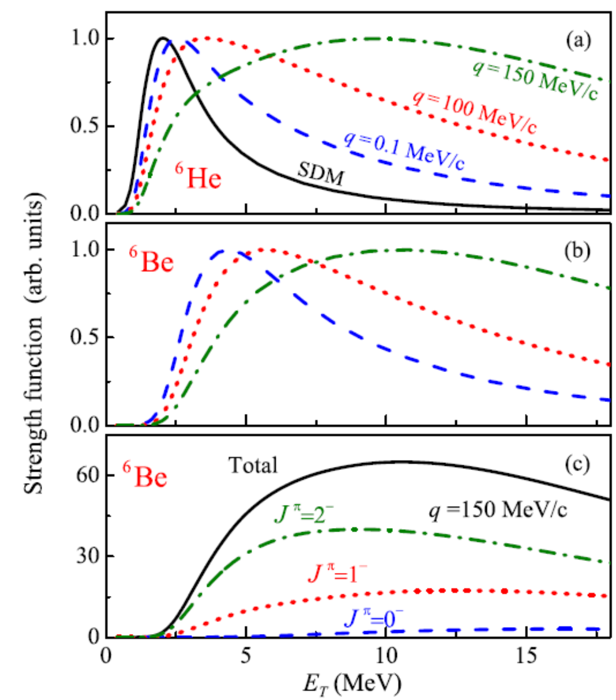
A.S.Fomichev et al., PLB **708** (2012) 6.







- 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 g.s. WF
- Built on the spatially extended ^{6}Li g.s.



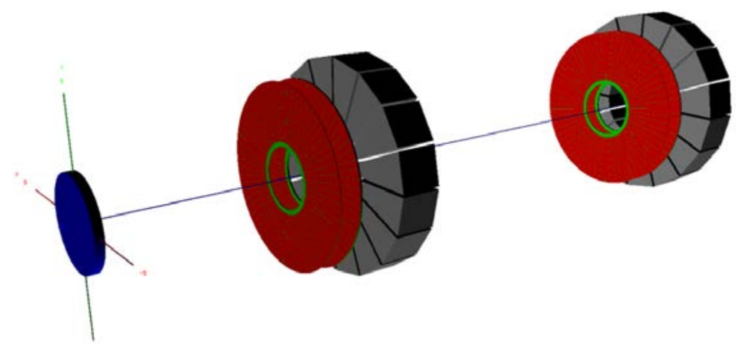
Experimentally observed and theoretically discussed: IVSDM as a specific form of SDM

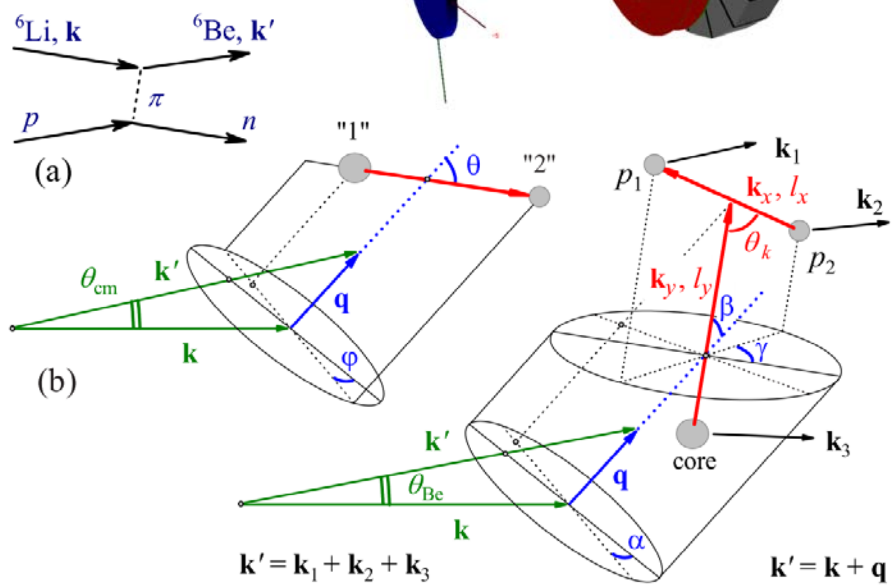
Example: ^{6}Be studied in the ^{6}Li(p,n)^{6}Be reaction

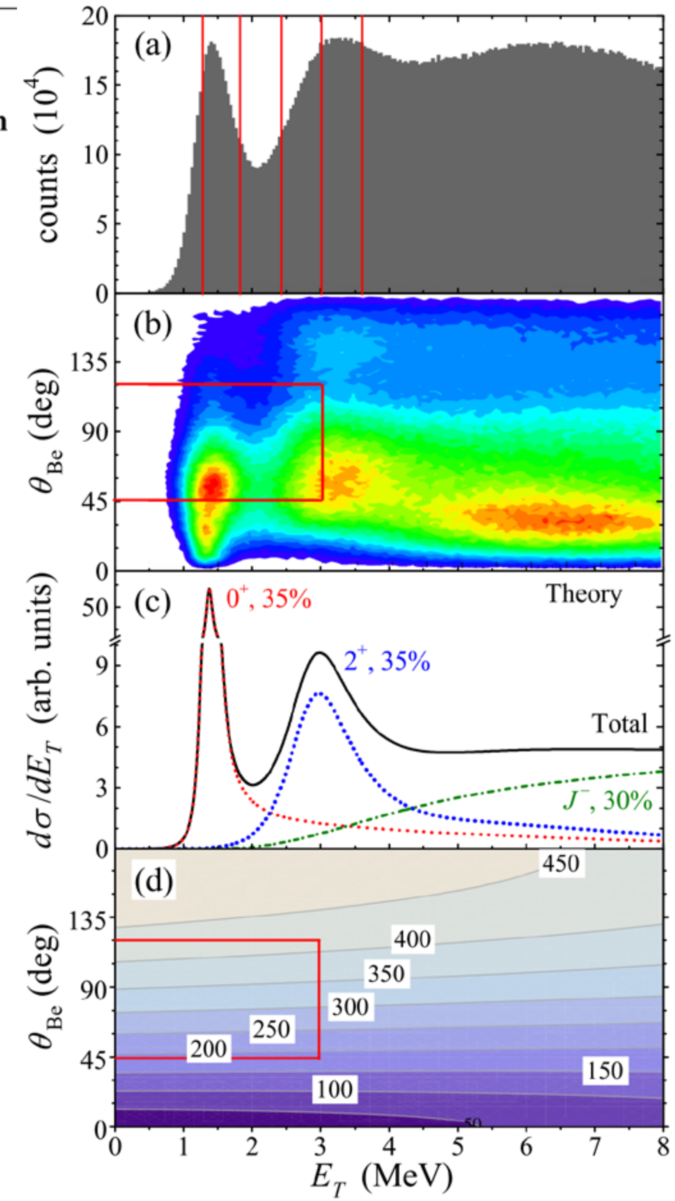
PHYSICAL REVIEW C **98**, 054612 (2018)

Three-body correlations in direct reactions: Example of ^{6}Be populated in the (p, n) reaction

V. Chudoba,[1,2,*] L. V. Grigorenko,[1,3,4] A. S. Fomichev,[1,5] A. A. Bezbakh,[1,2] I. A. Egorova,[6,7] S. N. Ershov,[6] M. S. Golovkov,[1,5] A. V. Gorshkov,[1] V. A. Gorshkov,[1] G. Kaminski,[1,8] S. A. Krupko,[1] I. Mukha,[9] E. Yu. Nikolskii,[1,4] Yu. L. Parfenova,[1] S. I. Sidorchuk,[1] P. G. Sharov,[1,2] R. S. Slepnev,[1] L. Standylo,[10] S. V. Stepantsov,[1] G. M. Ter-Akopian,[1,5] R. Wolski,[1,11] and M. V. Zhukov[12]







^{6}Be in (p,n) reaction: from known level scheme to complete quantum mechanical information (density matrix parameters as function of energy and cm angle)

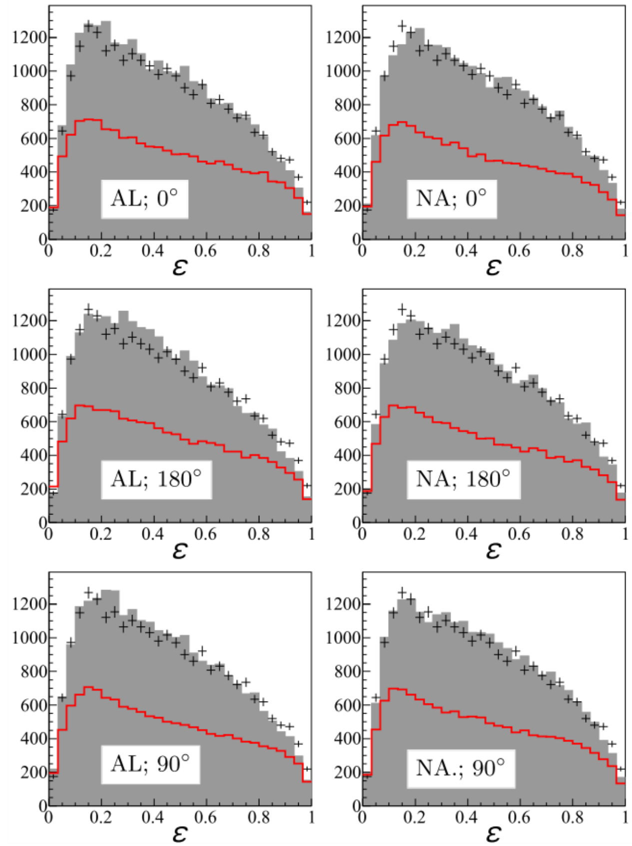


FIG. 13. Energy distribution ε_T for ^{6}Be decay with $2.5 < E_T < 3.1$ MeV (left slope of 2^+) for $75^\circ < \theta_{\rm Be} < 90^\circ$ and different alignment/interference settings, see also Fig. 10 for details.

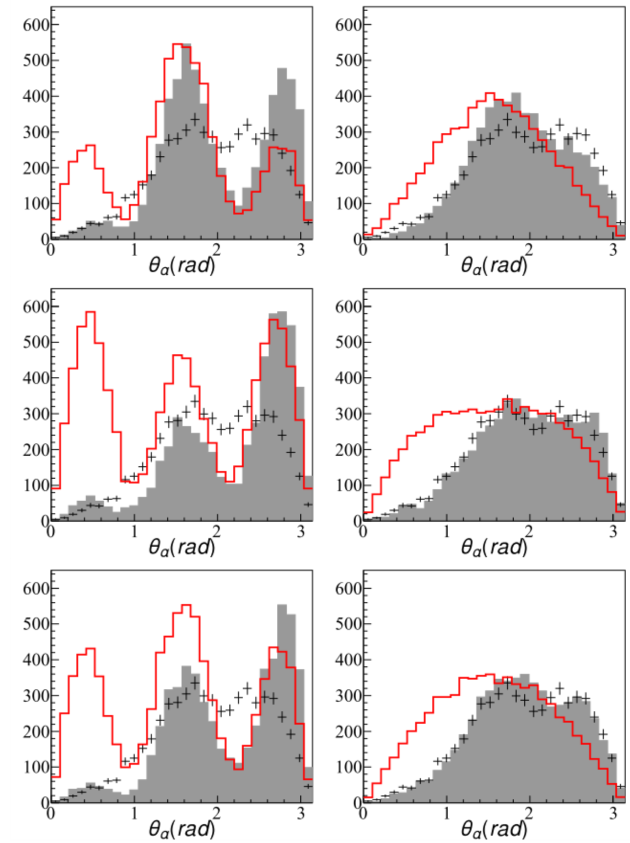


FIG. 15. Angular distributions for the α-particle emission in the momentum transfer frame in the range $2.5 < E_T < 3.1$ MeV and $90^\circ < \theta_{\rm Be} < 120^\circ$. Alignment/interference settings are the same as in Fig. 10.

TABLE I. The best fit to experimental data of density matrix parameters for different $\{E_T, \theta_{\rm Be}\}$ ranges. The fits were found using the figures with θ_α distribution for all six configurations of the theoretical model.

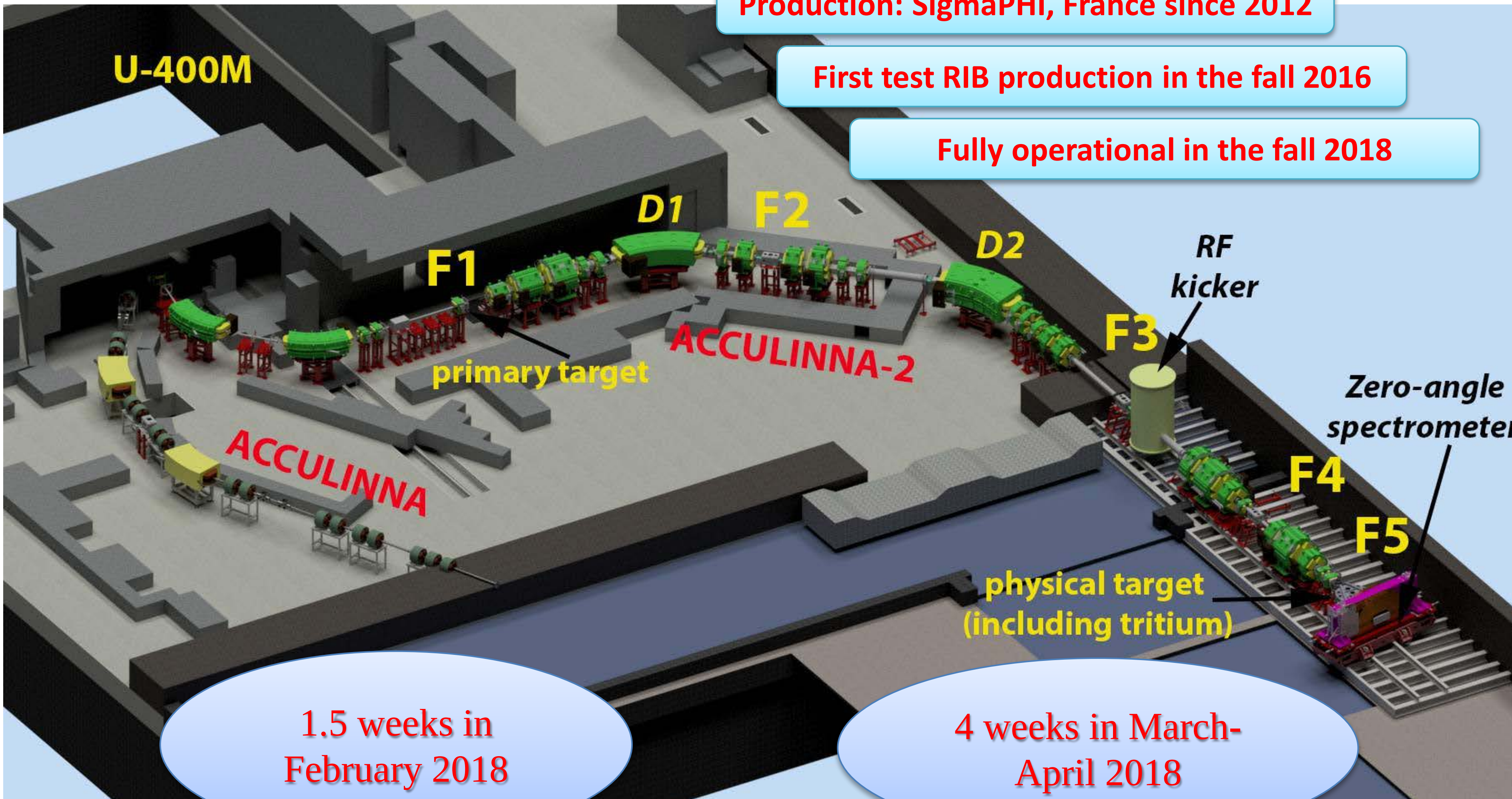
E_T (MeV)	$\theta_{\rm Be}\in(45,60)^\circ$	$\theta_{\rm Be}\in(60,75)^\circ$	$\theta_{\rm Be}\in(75,90)^\circ$	$\theta_{\rm Be}\in(90,120)^\circ$
1.4–1.9	AL; φ_{02}=135°	AL + 50% NA; φ_{02}=180°	AL; φ_{02}=180°	AL + 20% NA; φ_{02}=180°
1.9–2.5	AL + 50% NA; φ_{02}=135°	NA + 10% AL; φ_{02}=180°	NA; φ_{02}=180°	AL + 10% NA; φ_{02}=90°
2.5–3.1	NA + 10% AL; φ_{02}=180°	AL + 10% NA; φ_{02}=180°	NA + 30% AL; φ_{02}=90°	NA; φ_{02}=135°

Layout of ACCULINNA-1 and ACCULINNA-2 setups at U-400M

Production: SigmaPHI, France since 2012

First test RIB production in the fall 2016

Fully operational in the fall 2018



1.5 weeks in February 2018

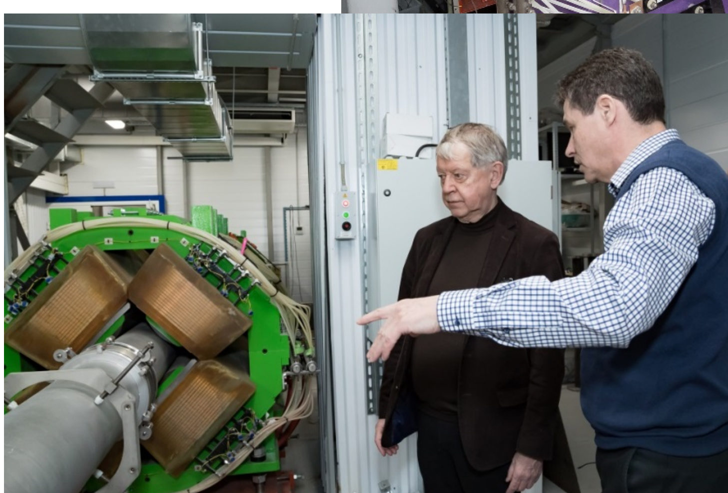
4 weeks in March-April 2018

A.S. Fomichev, L.V. Grigorenko, S.A. Krupko, S.V. Stepantsov and G.M. Ter-Akopian
The ACCULINNA-2 project: The physics case and technical challenges, Eur. Phys. J. A **54**, 97 (2018)

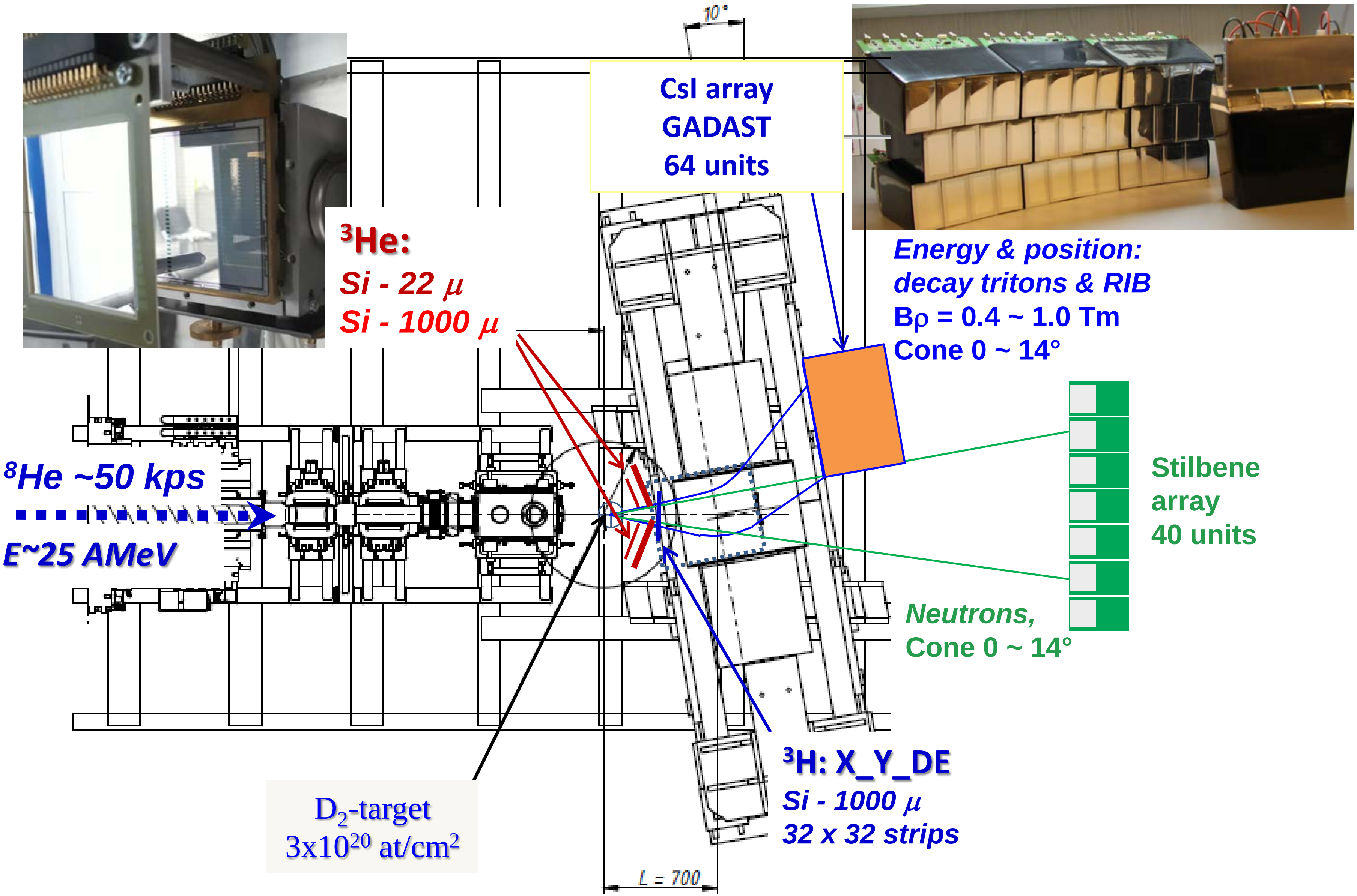
First experiments with ^{6}He and ^{9}Li on CD_2 target

Winter/spring 2018:

- elastic and inelastic scattering of ^{6}He;
- $d(^{6}\text{He},^{3}\text{He})^{5}\text{H}$ reaction;
- $d(^{9}\text{Li},p)^{10}\text{Li} \rightarrow n+^{9}\text{Li}$ run.

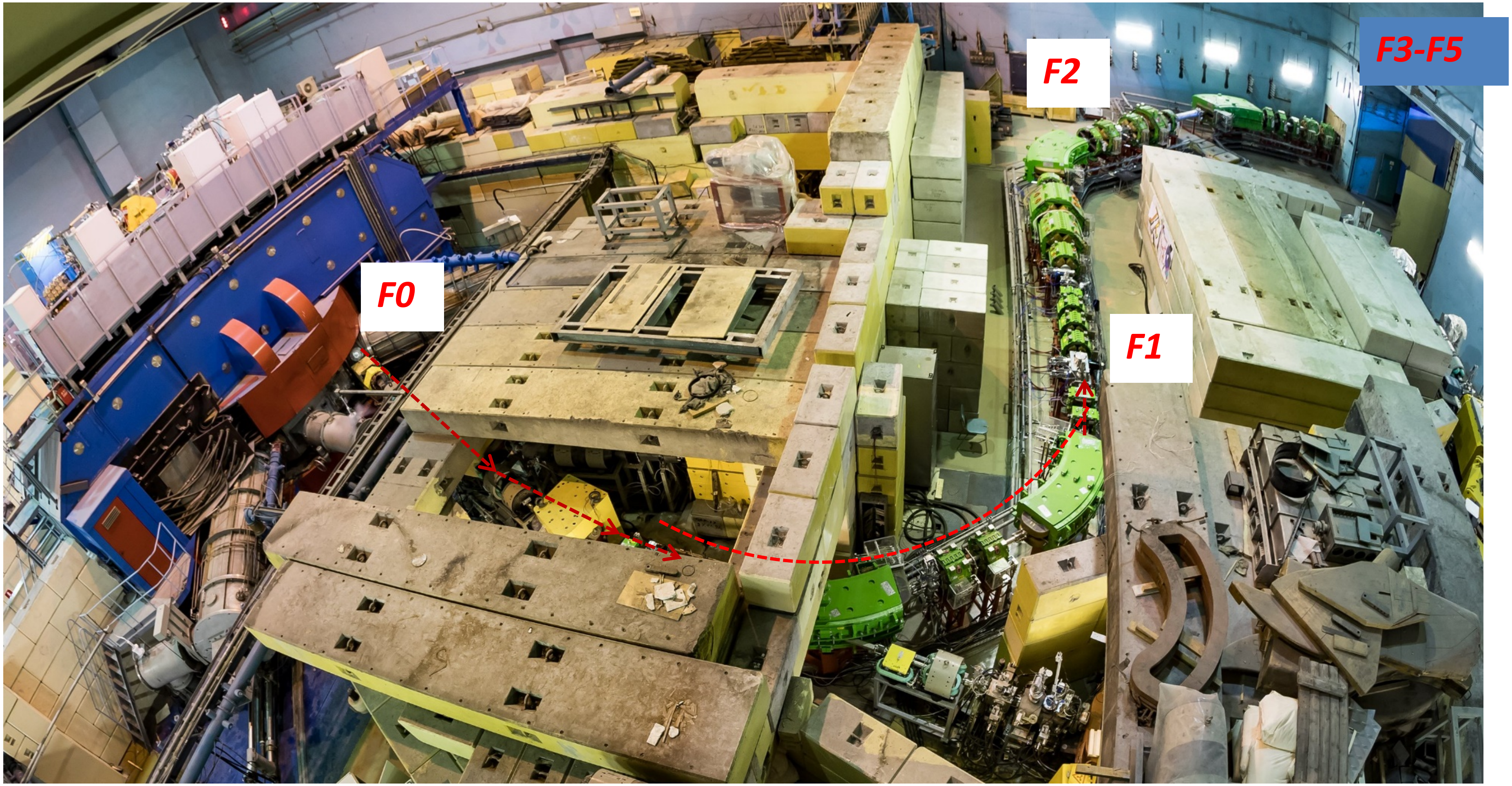


$d(^8He,^3He)^7H$: 2 weeks test run in November, ^8He 7×10^4 pps

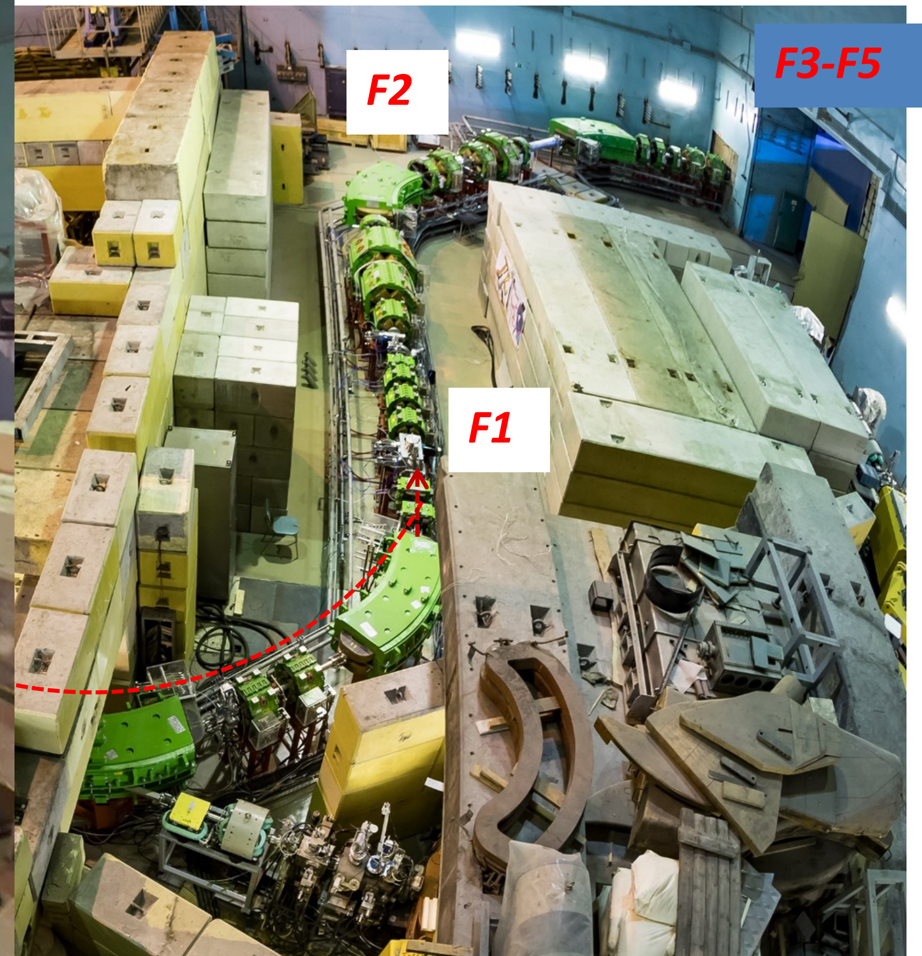


Advantages: good energy resolutions (~1 MeV) & ^{3}He-t-n coins.

Moving ahead to the flagship experiment: ^{7}H search

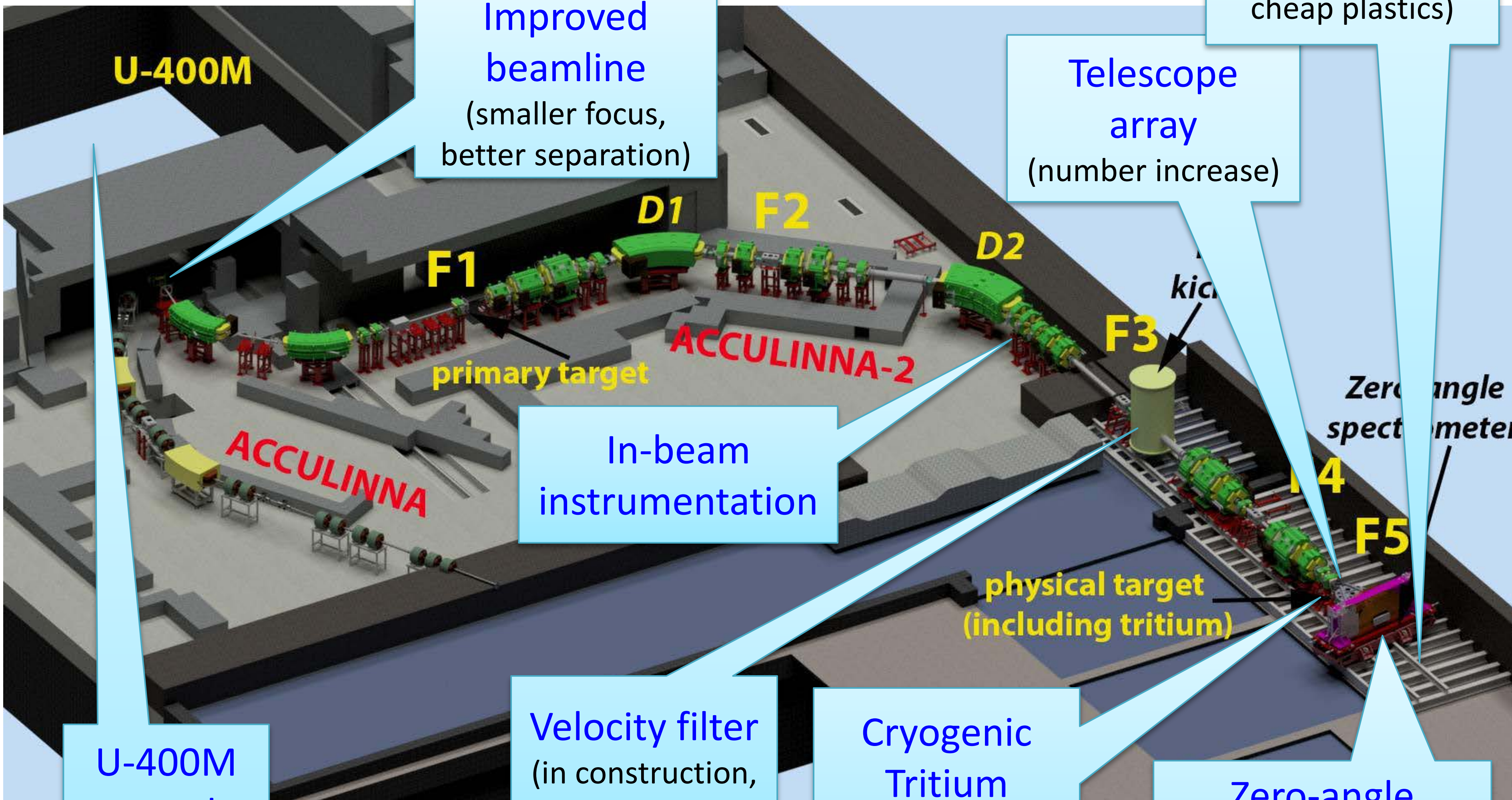


Moving ahead to the flagship experiment: ^{7}H search



Radiation protection shell around F1-F2 area completed in July-August.

2019 upgrade program



Improved beamline
(smaller focus, better separation)

Neutron array
(number increase, cheap plastics)

Telescope array
(number increase)

In-beam instrumentation

U-400M upgrade
(stability, beams, intensities)

Velocity filter
(in construction, SigmaPhi)

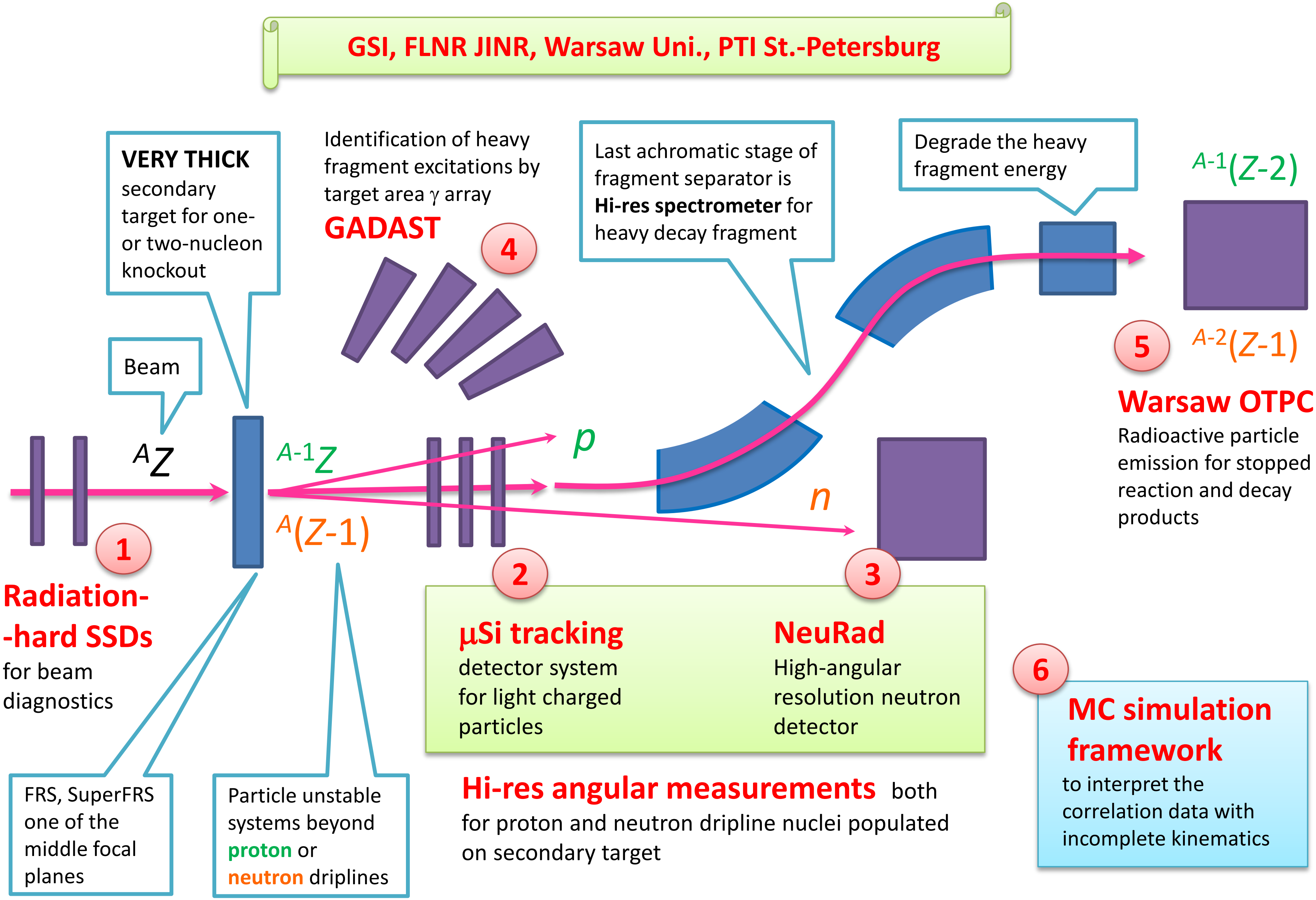
Cryogenic Tritium system
(ordered, R&D)

Zero-angle spectrometer hodoscope
(in development)

EXPERT@SuperFRS

EXotic **P**article **E**mission and **R**adioactivity by **T**racking

EXPERT: EXotic Particle Emission and Radioactivity by Tracking

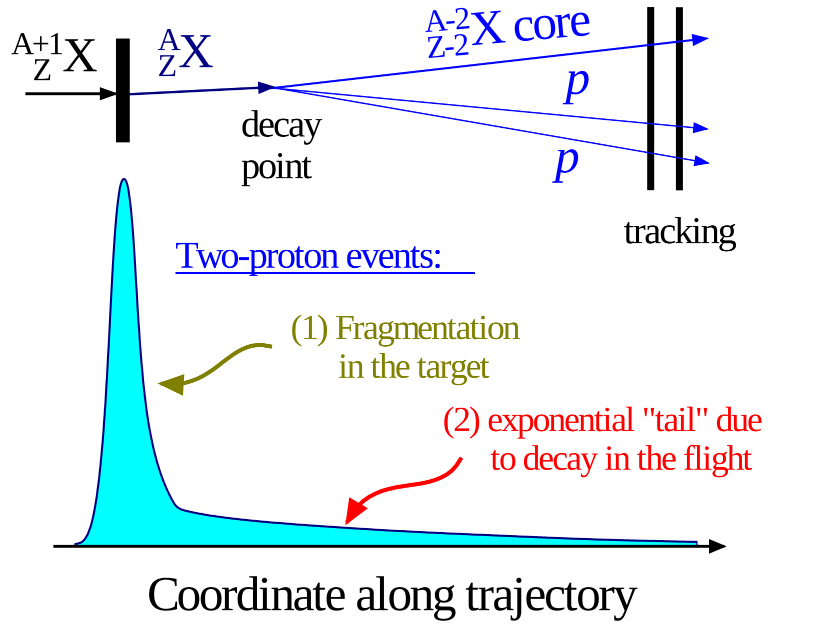


Basic idea

Radioactivity studies

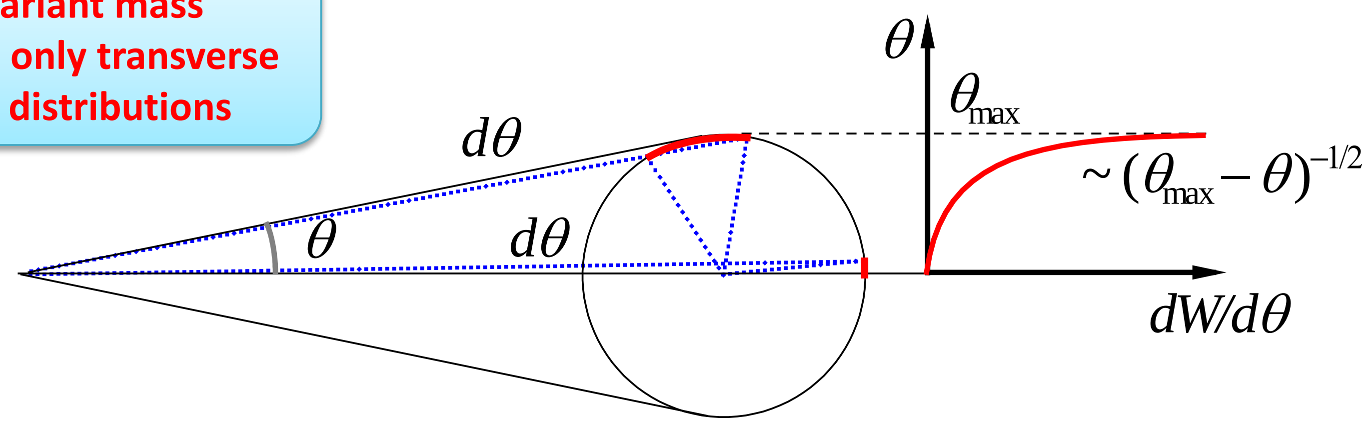
I. Mukha: opportunity to investigate particle radioactivity in fs-ns lifetime range

HOWEVER. Found to be well suited for spectroscopy



Two-body decay

Not an invariant mass measurement: only transverse momentum distributions

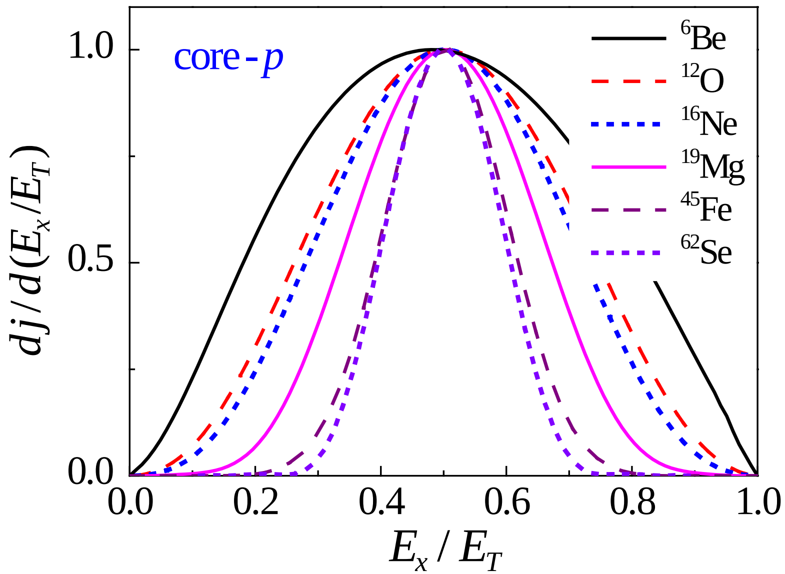


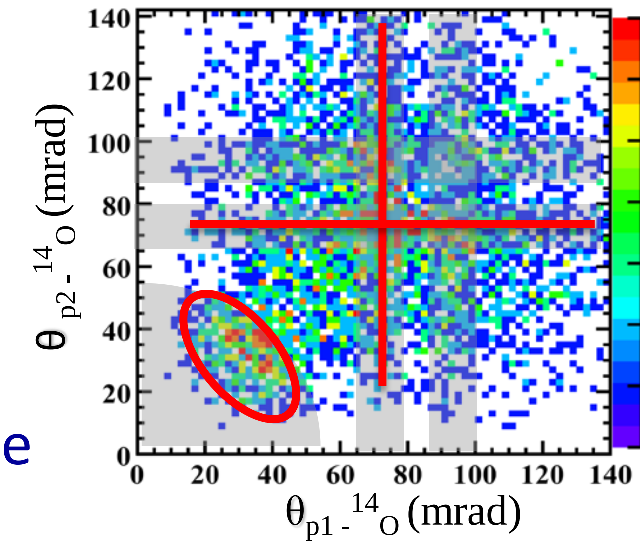
Better than invariant mass method! <u>IF</u> you understand what is happening

Basic idea

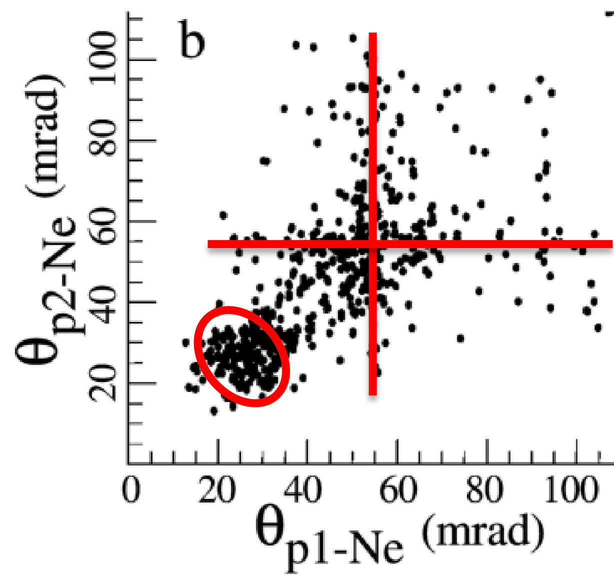
Better than invariant mass method
<u>IF</u> you understand what is happening

True three-body decay





^{16}Ne



^{19}Mg

Energies of protons tend to be almost equal

I. Mukha et al., PRL **99** (2007) 182501.
I. Mukha et al., PRC **77** (2008) 061303.
I. Mukha et al., PRC **79** (2009) 061301.

Major advantages

Specific setup for specific experiments

Unique experiments now and with very small investments

Several experiments in one: (i) cocktail beam, (ii) several sets of detectors

Extremely thick target: (i) can work with poor beams, (ii) can move far from stability in more then one nucleon knockout

Based on very high angular resolution and full characterization of all the decay products (microstrips + high resolution spectrometer for HI)

Important synergy effect among components of the setup

S388 experiment at GSI

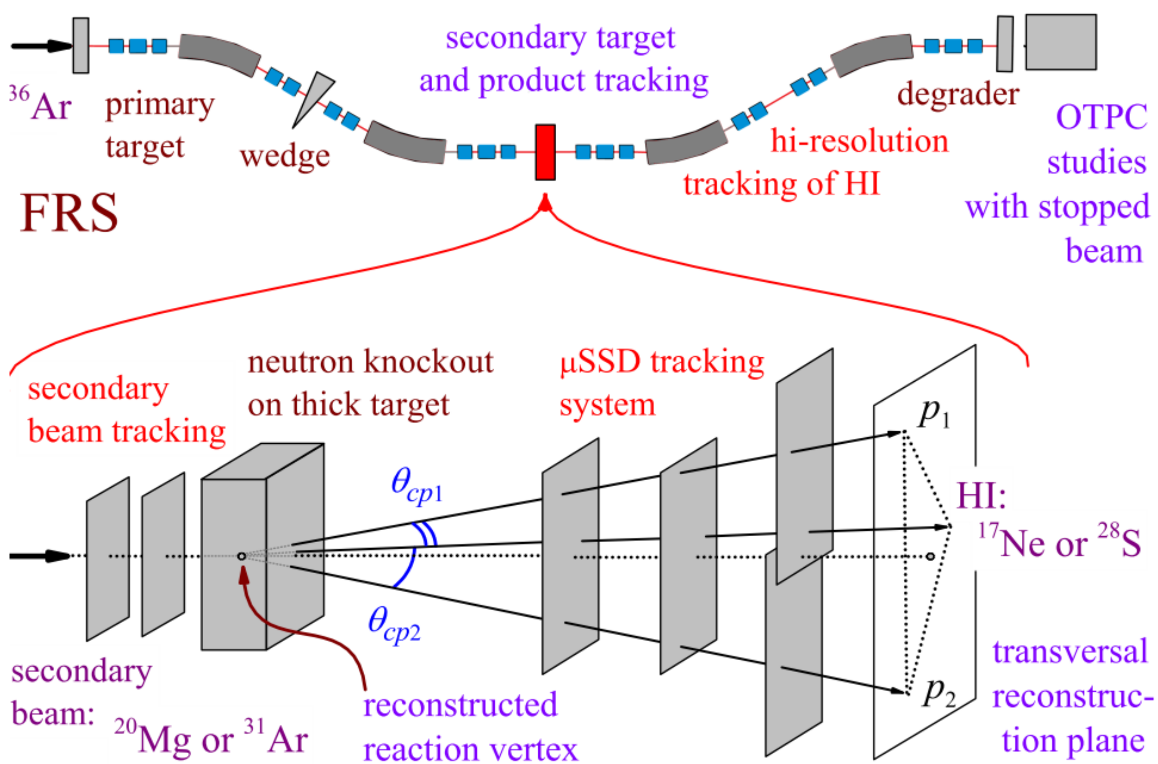
- 2012
- Primary ^{36}Ar beam 885 AMeV
- 8 g/cm^2 primary Be target
- Second. ^{31}Ar beam 620 AMeV
- 50 ions s^{-1}
- 4.8 g/cm^2 secondary Be target

"Search for 2p radioactivity in ^{30}Ar"

I. Mukha et al., PRL **115** (2015) 202501.

"Beta-delayed p decays of ^{31}Ar"

A. Lis et al., PRC **91** (2015) 064309.



Major results

PRL 115, 202501 (2015) PHYSICAL REVIEW LETTERS week ending 13 NOVEMBER 2015

Observation and Spectroscopy of New Proton-Unbound Isotopes ^{30}Ar and ^{29}Cl: An Interplay of Prompt Two-Proton and Sequential Decay

I. Mukha,[1,2] L. V. Grigorenko,[3,4,2] X. Xu,[5,1,6] L. Acosta,[7,8] E. Casarejos,[9] A. A. Ciemny,[10] W. Dominik,[10] J. Duénas-Díaz,[11] V. Dunin,[12] J. M. Espino,[13] A. Estradé,[14] F. Farinon,[1] A. Fomichev,[3] H. Geissel,[1,5] T. A. Golubkova,[15] A. Gorshkov,[3] Z. Janas,[10] G. Kamiński,[16,3] O. Kiselev,[1] R. Knöbel,[1,5] S. Krupko,[3] M. Kuich,[17,10] Yu. A. Litvinov,[1] G. Marquinez-Durán,[11] I. Martel,[11] C. Mazzocchi,[10] C. Nociforo,[1] A. K. Ordúz,[11] M. Pfützner,[10,1] S. Pietri,[1] M. Pomorski,[10] A. Prochazka,[1] S. Rymzhanova,[3] A. M. Sánchez-Benítez,[11] C. Scheidenberger,[1,5] P. Sharov,[3] H. Simon,[1] B. Sitar,[18] R. Slepnev,[3] M. Stanoiu,[19] P. Strmen,[18] I. Szarka,[18] M. Takechi,[1] Y. K. Tanaka,[1,20] H. Weick,[1] M. Winkler,[1] J. S. Winfield,[1] and M. V. Zhukov[21]

PHYSICAL REVIEW C 91, 064309 (2015)

β-delayed three-proton decay of ^{31}Ar

A. A. Lis,[1] C. Mazzocchi,[1,*] W. Dominik,[1] Z. Janas,[1] M. Pfützner,[1,2] M. Pomorski,[1] L. Acosta,[3,4] S. Baraeva,[5] E. Casarejos,[6] J. Duénas-Díaz,[7] V. Dunin,[5] J. M. Espino,[8] A. Estrade,[9] F. Farinon,[2] A. Fomichev,[5] H. Geissel,[2] A. Gorshkov,[5] G. Kamiński,[10,11] O. Kiselev,[2] R. Knöbel,[2] S. Krupko,[5] M. Kuich,[1,12] Yu. A. Litvinov,[2] G. Marquinez-Durán,[7] I. Martel,[7] I. Mukha,[2] C. Nociforo,[2] A. K. Ordúz,[7] S. Pietri,[2] A. Prochazka,[2] A. M. Sánchez-Benítez,[7,13] H. Simon,[2] B. Sitar,[14] R. Slepnev,[5] M. Stanoiu,[15] P. Strmen,[14] I. Szarka,[14] M. Takechi,[2] Y. Tanaka,[2,16] H. Weick,[2] and J. S. Winfield[2]

Physics Letters B 762 (2016) 263–270

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Transition from direct to sequential two-proton decay in *s–d* shell nuclei

CrossMark

T.A. Golubkova[a], X.-D. Xu[b,c,d], L.V. Grigorenko[e,f,g,*], I.G. Mukha[c,g], C. Scheidenberger[b,c], M.V. Zhukov[h]

Major results

PHYSICAL REVIEW C **97**, 034305 (2018)

Spectroscopy of excited states of unbound nuclei ^{30}Ar and ^{29}Cl

X.-D. Xu,[1,2,3] I. Mukha,[3] L. V. Grigorenko,[4,5,6] C. Scheidenberger,[2,3,*] L. Acosta,[7,8] E. Casarejos,[9] V. Chudoba,[4] A. A. Ciemny,[10] W. Dominik,[10] J. Duénas-Díaz,[11] V. Dunin,[12] J. M. Espino,[13] A. Estradé,[14] F. Farinon,[3] A. Fomichev,[4] H. Geissel,[2,3] T. A. Golubkova,[15] A. Gorshkov,[4,16] Z. Janas,[10] G. Kamiński,[4,17] O. Kiselev,[3] R. Knöbel,[2,3] S. Krupko,[4,16] M. Kuich,[10,18] Yu. A. Litvinov,[3] G. Marquinez-Durán,[11] I. Martel,[11] C. Mazzocchi,[10] C. Nociforo,[3] A. K. Ordúz,[11] M. Pfützner,[3,10] S. Pietri,[3] M. Pomorski,[10] A. Prochazka,[3] S. Rymzhanova,[4] A. M. Sánchez-Benítez,[19] P. Sharov,[4] H. Simon,[3] B. Sitar,[20] R. Slepnev,[4] M. Stanoiu,[21] P. Strmen,[20] I. Szarka,[20] M. Takechi,[3] Y. K. Tanaka,[3,22] H. Weick,[3] M. Winkler,[3] and J. S. Winfield[3]

arXiv:1803.10951v5 [nucl-ex] 6 Sep 2018

Deep excursion beyond the proton dripline. I. Argon and chlorine isotope chains

I. Mukha,[1] L.V. Grigorenko,[2,3,4] D. Kostyleva,[5,6,*] L. Acosta,[7,8] E. Casarejos,[9] A.A. Ciemny,[10] W. Dominik,[10] J.A. Dueñas,[11] V. Dunin,[12] J. M. Espino,[13] A. Estradé,[14] F. Farinon,[6] A. Fomichev,[2] H. Geissel,[6,5] A. Gorshkov,[2] Z. Janas,[10] G. Kamiński,[15,2] O. Kiselev,[6] R. Knöbel,[6,5] S. Krupko,[2] M. Kuich,[16,10] Yu.A. Litvinov,[6] G. Marquinez-Durán,[17] I. Martel,[17] C. Mazzocchi,[10] C. Nociforo,[6] A. K. Ordúz,[17] M. Pfützner,[10,6] S. Pietri,[6] M. Pomorski,[10] A. Prochazka,[6] S. Rymzhanova,[2] A.M. Sánchez-Benítez,[18] C. Scheidenberger,[6,5] P. Sharov,[2] H. Simon,[6] B. Sitar,[19] R. Slepnev,[2] M. Stanoiu,[20] P. Strmen,[19] I. Szarka,[19] M. Takechi,[6] Y.K. Tanaka,[6,21] H. Weick,[6] M. Winkler,[6] J.S. Winfield,[6] X. Xu,[22,5,6] and M.V. Zhukov[23]
(for the Super-FRS Experiment Collaboration)

arXiv:1804.01887v5 [nucl-ex] 6 Sep 2018

Deep excursion beyond the proton dripline. II. Toward the limits of existence of nuclear structure

L.V. Grigorenko,[1,2,3] I. Mukha,[4] D. Kostyleva,[5,4,*] C. Scheidenberger,[4,5] L. Acosta,[6,7] E. Casarejos,[8] V. Chudoba,[1,9] A.A. Ciemny,[10] W. Dominik,[10] J.A. Dueñas,[11] V. Dunin,[12] J. M. Espino,[13] A. Estradé,[14] F. Farinon,[4] A. Fomichev,[1] H. Geissel,[4,5] A. Gorshkov,[1] Z. Janas,[10] G. Kamiński,[15,1] O. Kiselev,[4] R. Knöbel,[4,5] S. Krupko,[1] M. Kuich,[16,10] Yu.A. Litvinov,[4] G. Marquinez-Durán,[17] I. Martel,[17] C. Mazzocchi,[10] E.Yu. Nikolskii,[3,1] C. Nociforo,[4] A. K. Ordúz,[17] M. Pfützner,[10,4] S. Pietri,[4] M. Pomorski,[10] A. Prochazka,[4] S. Rymzhanova,[1] A.M. Sánchez-Benítez,[18] P. Sharov,[1] H. Simon,[4] B. Sitar,[19] R. Slepnev,[1] M. Stanoiu,[20] P. Strmen,[19] I. Szarka,[19] M. Takechi,[4] Y.K. Tanaka,[4,21] H. Weick,[4] M. Winkler,[4] J.S. Winfield,[4] X. Xu,[22,5,4] and M.V. Zhukov[23]
(for the Super-FRS Experiment Collaboration)

Major results

New isotopes: ^{30}Ar, ^{29}Ar, ^{30}Cl, ^{29}Cl, ^{28}Cl. Spectroscopy. Will be more

Spectroscopy and g.s. energy of ^{31}Ar. Will be more.

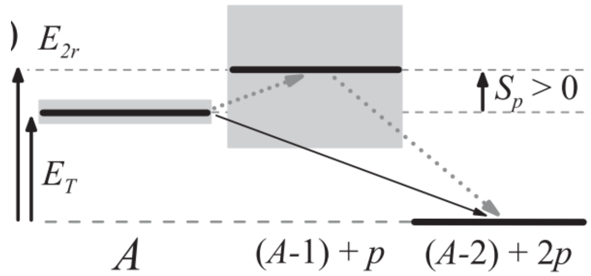
"Phase transition" diagram for 2p decays and transitional dynamics and

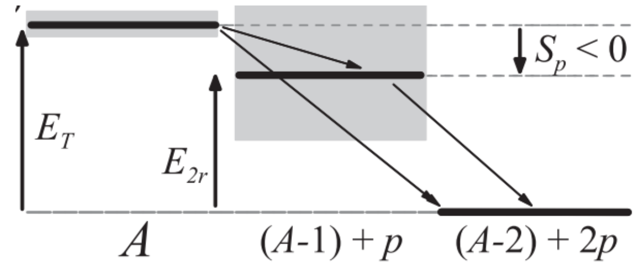
New S_p and S_{2p} systematics for chlorine and argon isotope chains

Limits of nuclear structure existence for chlorine and argon isotope chains

Important synergy effect among components of the setup

Mechanisms of 2p decay defined by separation energies

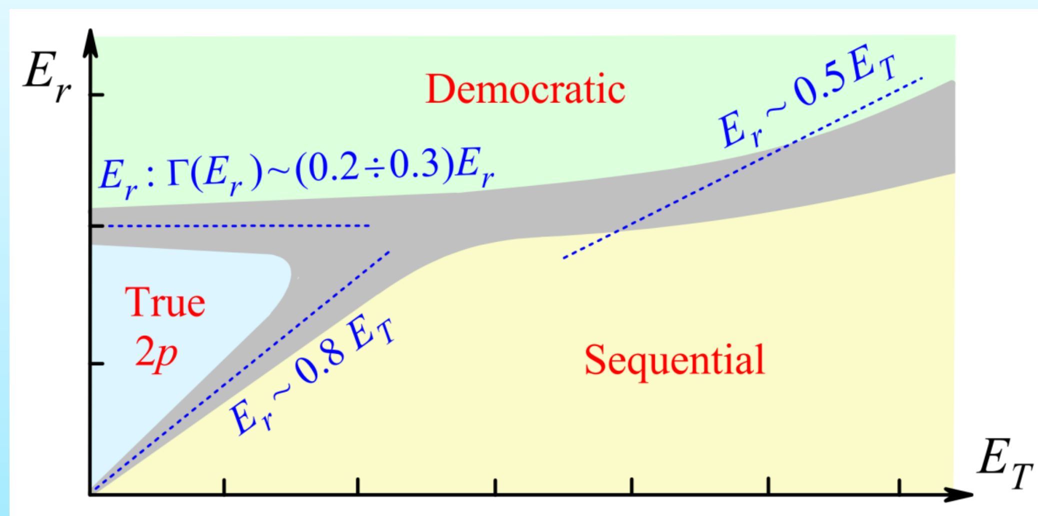




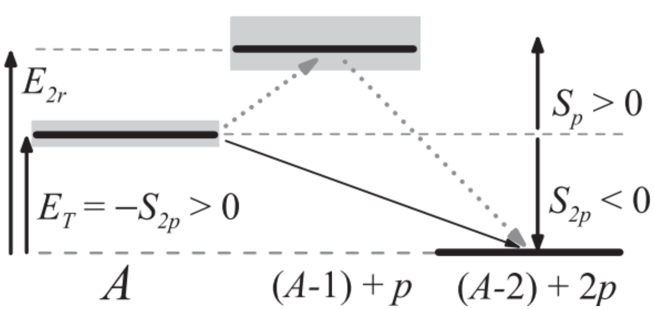
Three major decay mechanisms: True 2p, Democratic 2p Sequential 2p

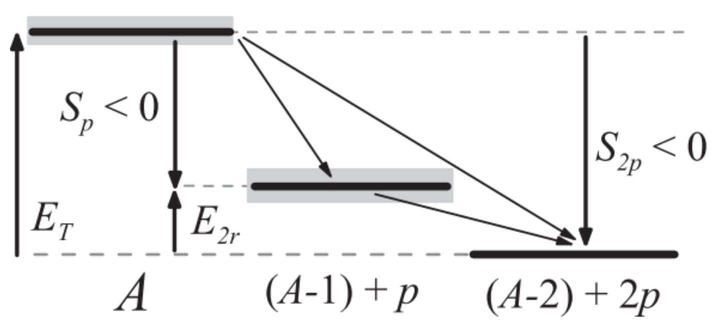
Three principal parameters:

$E_T \quad E_r \quad \Gamma_r$

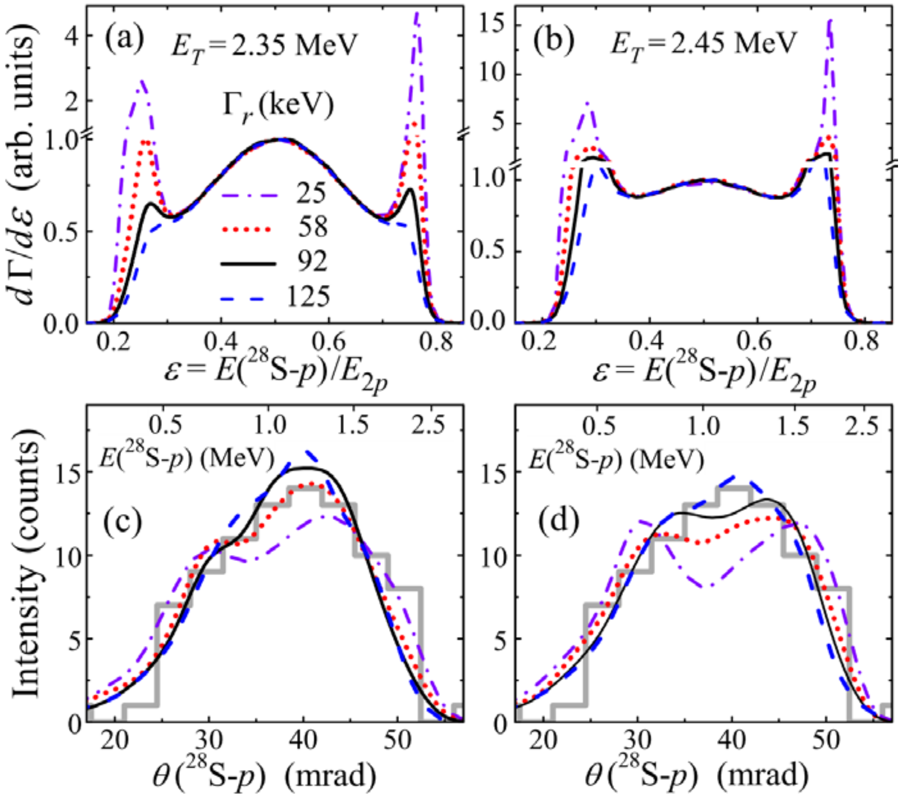


There SHOULD EXIST transition region between them





^{29}Cl g.s. width from ^{30}Ar data



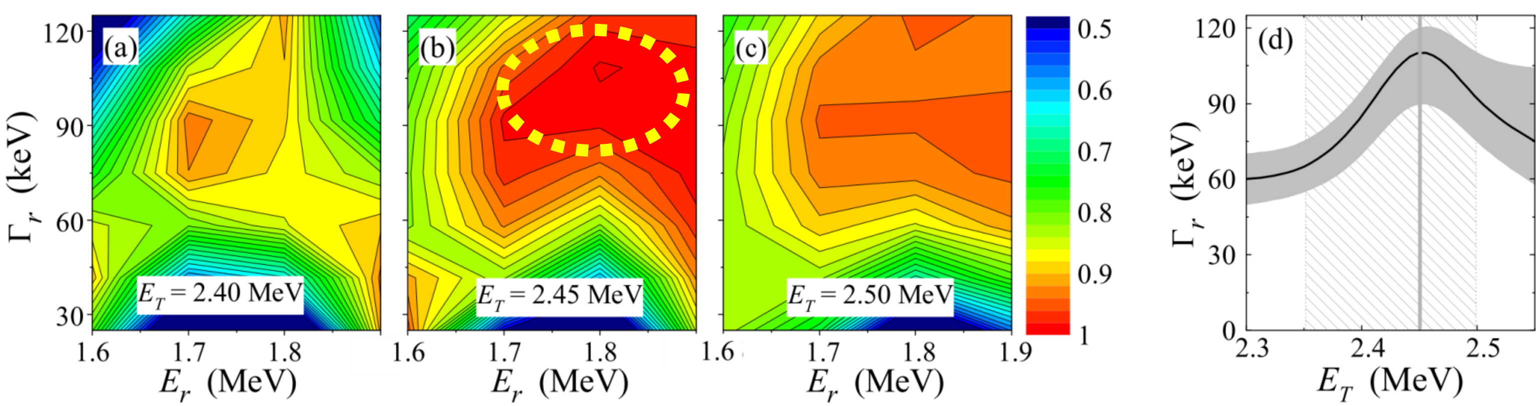
Energy is “easy” to measure, width could be very complicated.
From $T_{1/2}$~1 ps to Γ~100-200 keV there is a “blind spot”

^{30}Ar was found to have transition decay dynamics

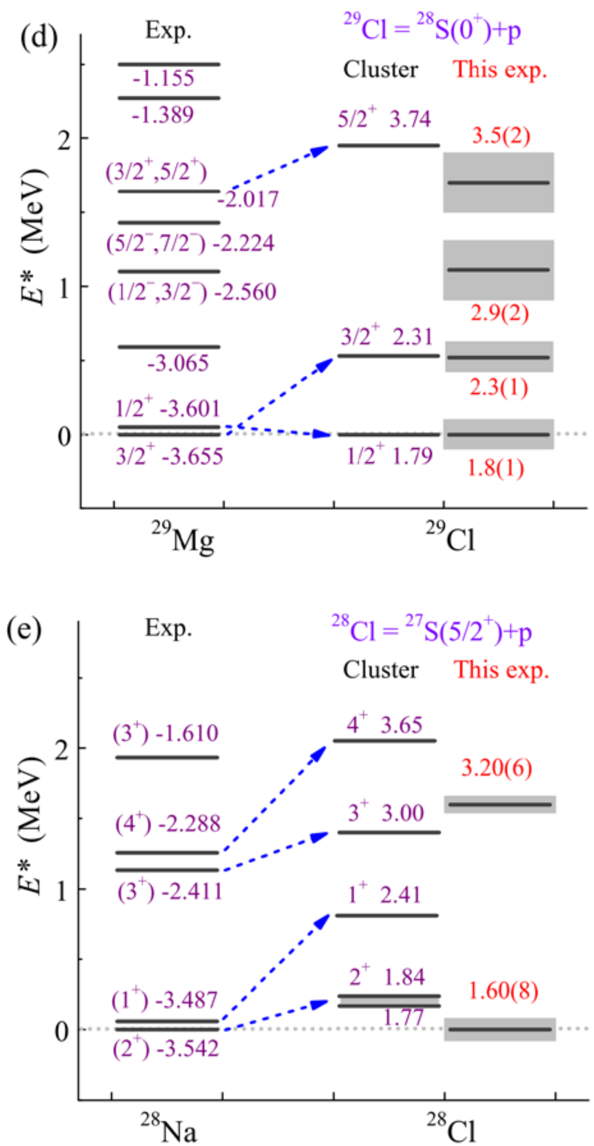
Strong dependence of the experimental signal on the g.s. properties of core+p subsystem – ^{29}Cl

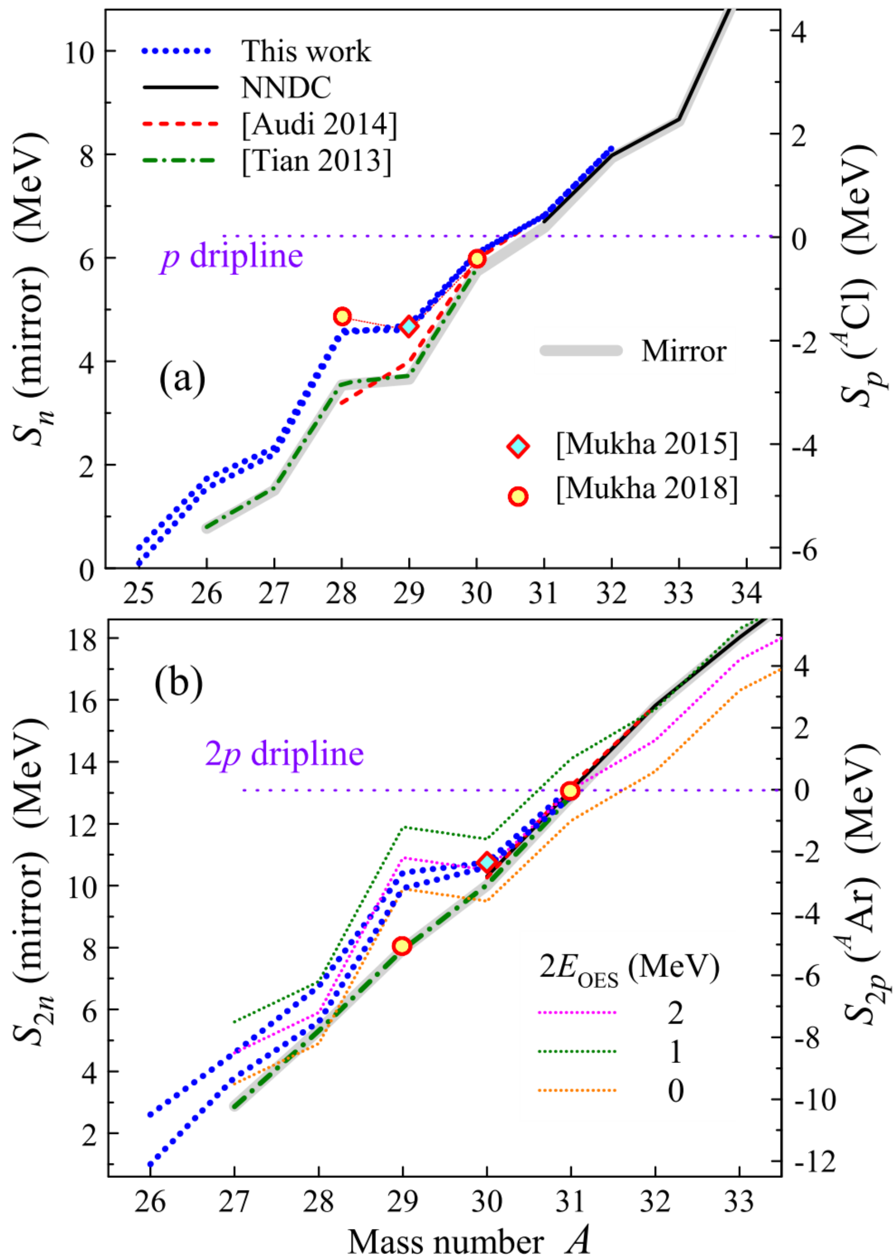
Stringent limits for ^{29}Cl g.s. width

T.A. Golubkova *et al.*, PLB **762** (2016) 263



New energy systematics beyond the dripline





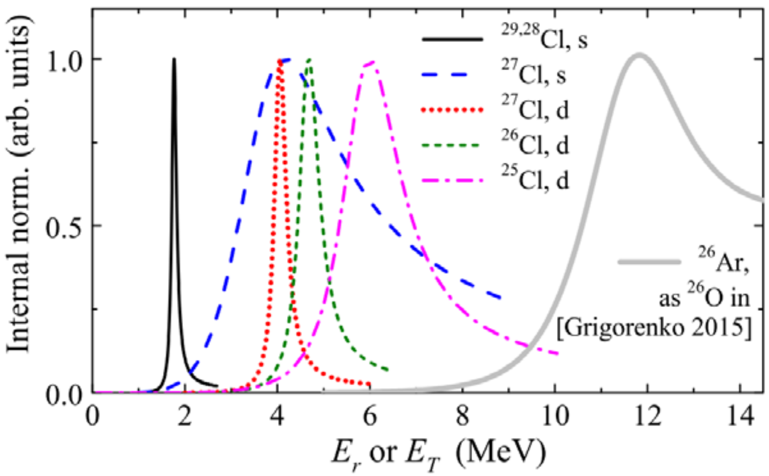
Limits of nuclear structure existence

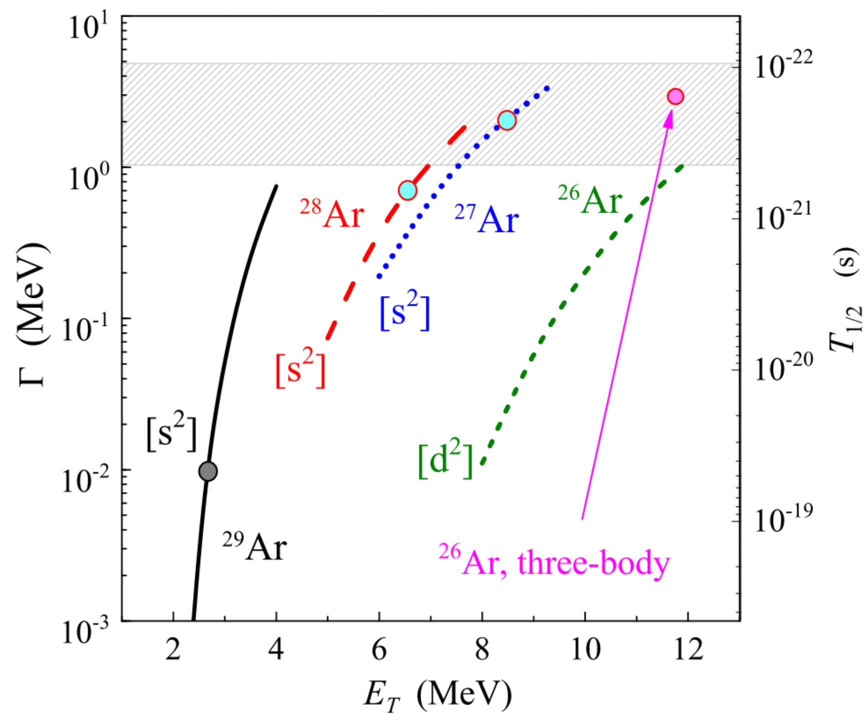
Beyond the proton dripline: quasistationary = stationary for most of purposes

Lifetime as criterium. Γ>3 MeV not a single reflection from the barrier is likely

$$N(E) = \int_0^{r_2} dr\, |\psi(kr)|^2$$

$$\nu = \left(2 \int_{r_1}^{r_2} \frac{dr}{v(r)} \right)^{-1} = \left(\int_{r_1}^{r_2} dr \sqrt{\frac{2M}{E - V(r)}} \right)^{-1}$$

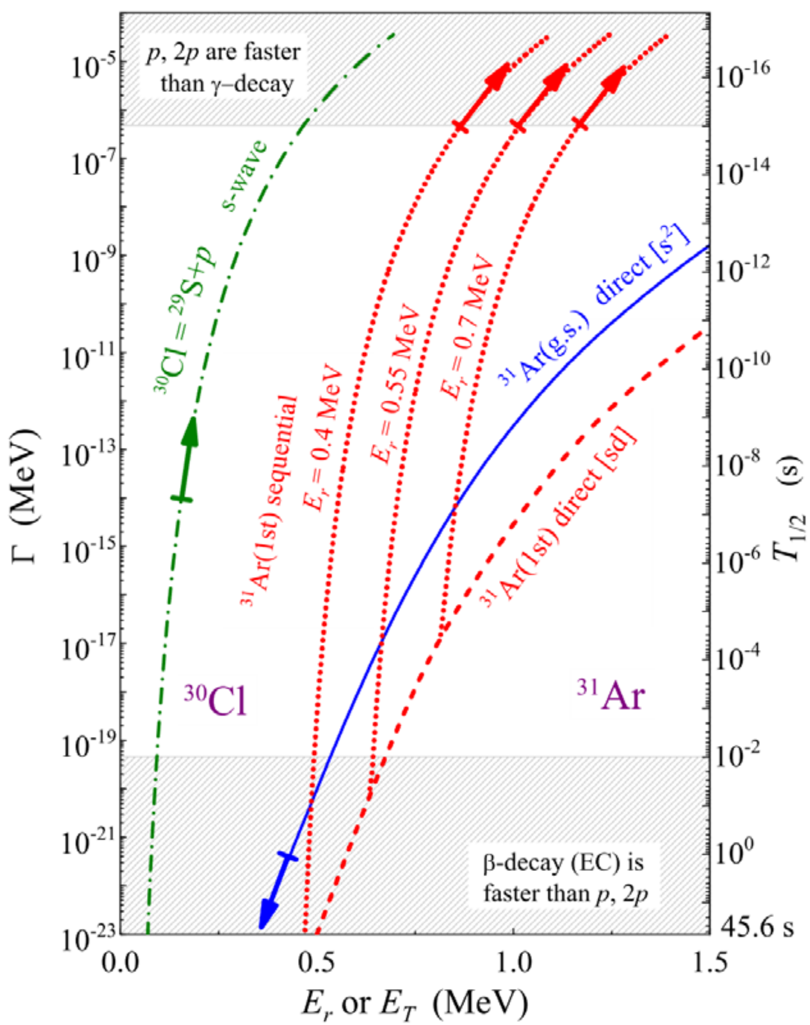


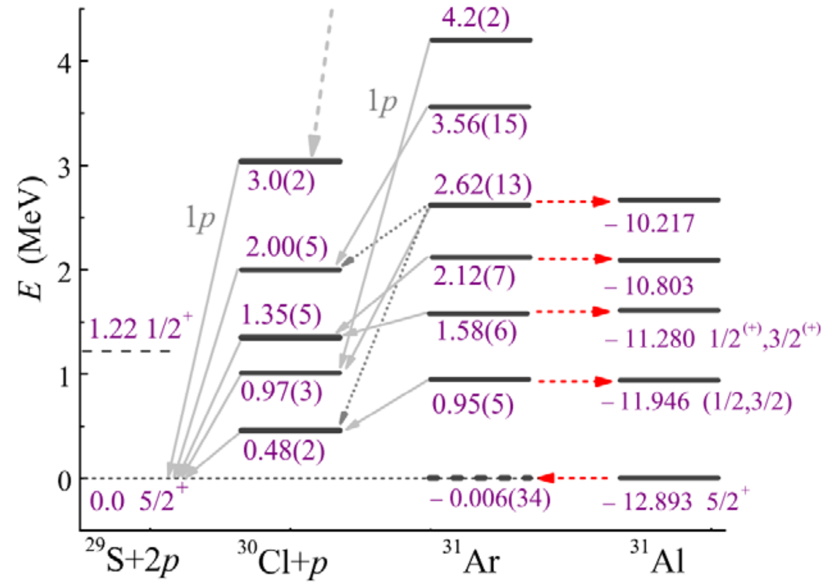


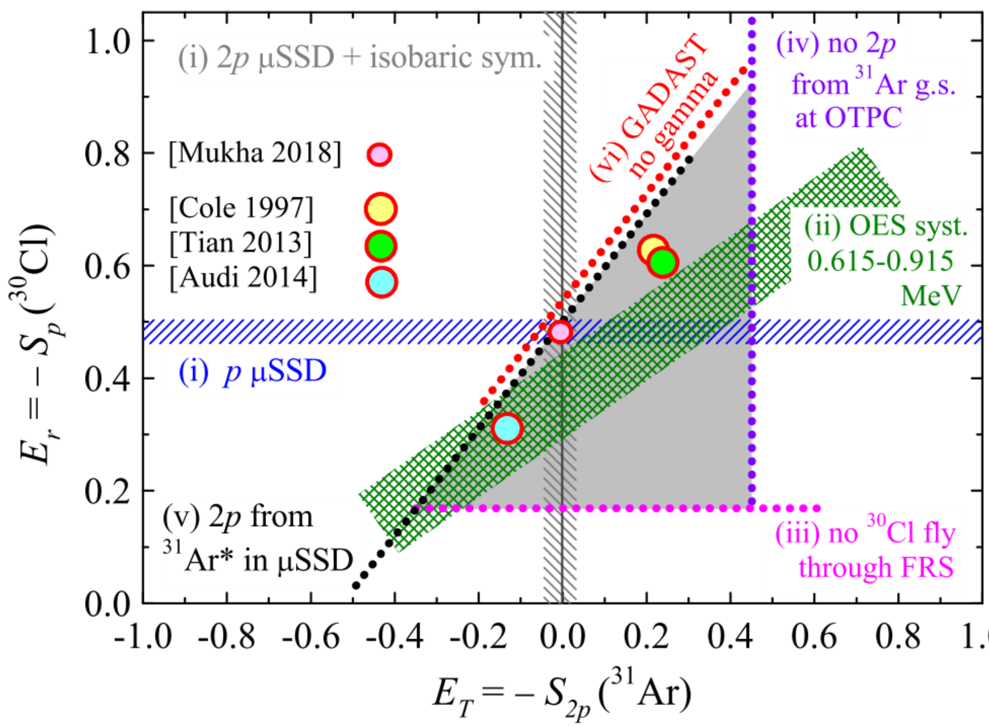
In chlorine and argon isotopic chains the reasonably narrow states can be found down to ^{25}Cl and ^{26}Ar

Synergy at EXPERT

By example of ^{31}Ar g.s.







DERICA - is female name of German origin with meaning “beloved leader, ruler of the people”

DERICA - **D**ubna **E**lectron-**R**adioactive **I**sotope **C**ollider f**A**cility

LoI: Russian physics review journal Physics-Uspekhi (2018) in print

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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, V. Chudoba, S.N. Dmitriev, V.K. Eremin, S.N. Ershov, M.S. Golovkov, A.V. Gorshkov, 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. Parhomchuk, M. Pfutzner, S.M. Polozov, C. Scheidenberger, S.I. Sidorchuk, P.G. Sharov, P.Yu. Shatunov, Yu.M. Shatunov, V.N. Shvetsov, N.B. Shulgina, H. Simon, R.S. Slepnev, G.M. Ter-Akopyan, G.V. Trubnikov, A.A. Yukhimchuk, S. Yaramyshev, M.V. Zhukov

Abstract. *Studies of radioactive ions (RI) is the most intensively developing field of the low-energy nuclear physics. In this paper the concept and the scientific agenda of prospective accelerator and storage ring facility for the RI beam (RIB) research are proposed for the large-scale international project based at the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research. The motivation for the new facility is discussed and its characteristics are briefly presented, showing to be comparable to those of the advanced world centers, the so-called "RIB factories". In the project the emphasis is made on the studies with the short-lived RIBs in storage rings. A unique feature of the project is the possibility to study the electron-RI interactions in the collider experiment for determination of fundamental properties of the nuclear matter, in particular, electromagnetic form-factors of exotic nuclei.*

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

April 26, 2018. The is project is submitted to Russian Ministry of Education and Science on the call for «Proposals to build "megascience"-class facilities on the territory of Russian Federation»

Broad support of the project

In 2 weeks we collected 13 official support letters from Russia and abroad

NUSTAR collaboration of FAIR supports “porting” of the delayed ring program to DERICA

Федеральное государственное бюджетное
образовательное учреждение высшего образования
МОСКОВСКИЙ
ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ
имени М.В. ЛОМОНОСОВА

НАУЧНО-ИССЛЕДОВАТЕЛЬСКИЙ
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ
имени Д.В. СКОБЕЛЬЦЫНА
(НИИЯФ МГУ)

Ленинские горы, д. 1, стр. 2, Москва, 119234
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20.04.18. № ИСХ. № 280/14-18/201-1-18
На № ____________

Директору ЛЯР ОИЯИ
профессору С.Н. Дмитриеву

Глубокоуважаемый Сергей Николаевич !

Как известно, в наши дни ключевые эксперименты в ядерной физике с пучками радиоактивных изотопов проводятся в зарубежных исследовательских центрах, таких как RIKEN (Япония), MSU (США), ISOLDE (Швейцария), GANIL (Франция) и GSI (Германия). Лаборатория ядерных реакций им. Г.Н. Флерова в ОИЯИ является одним из немногих мест в России, где проводятся подобные исследования. Дальнейшее развитие в этом направлении за счёт создания современной фабрики пучков радиоактивных ядер на базе ЛЯР ОИЯИ видится совершенно естественным и закономерным.

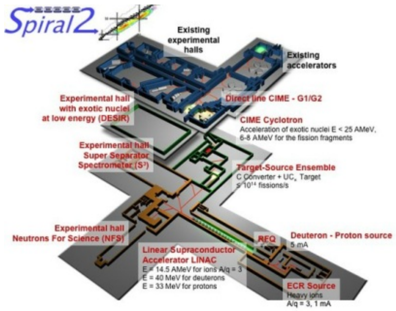
Задача может быть решена в рамках проекта DERICA, где планируется проводить исследования, неохваченные зарубежными лабораториями. Среди таких направлений – прецизионные исследования взаимодействий пучков электронов с радиоактивными ядрами с целью определения фундаментальных свойств ядерной материи. Очевидно, что именно ЛЯР ОИЯИ может стать точкой роста для проекта класса «мегасайенс», поскольку имеется коллектив с долголетним опытом исследований радиоактивных изотопов, есть коллаборации с ведущими западными партнёрами и российскими институтами, а также прочный задел в виде нового фрагмент-сепаратора ACCULINNA-2, на базе которого может проходить поэтапная реализация проекта. Важной особенностью проекта является то, что на всех этапах строительства комплекс DERICA может находиться в рабочем состоянии, позволяя непрерывно проводить разнообразные эксперименты.

НИИЯФ МГУ, будучи базовой кузницей кадров для ОИЯИ, подтверждает свою заинтересованность в создании проекта класса «мегасайенс» DERICA (Dubna Electron-Radioative Ion Collider fAcility). НИИЯФ МГУ готов принять участие в планировании и проведении экспериментов с использованием радиоактивных пучков, нацеленных на фундаментальные исследования в ядерной физике.

Директор НИИЯФ МГУ
профессор /М.И.Панасюк/

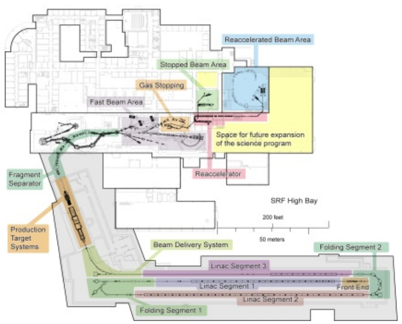
Научно-исследовательский институт ядерной физики имени Д.В. Скобельцына Московского государственного университета имени М.В. Ломоносова
МОСКВА

Фабрики радиоактивных изотопов:
Все больше, и больше, и больше…

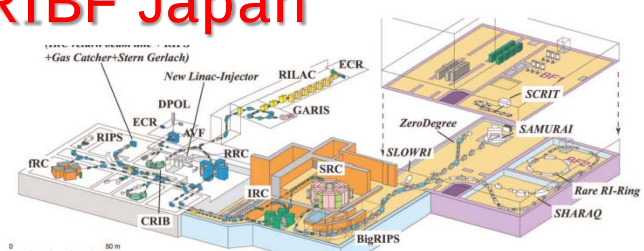


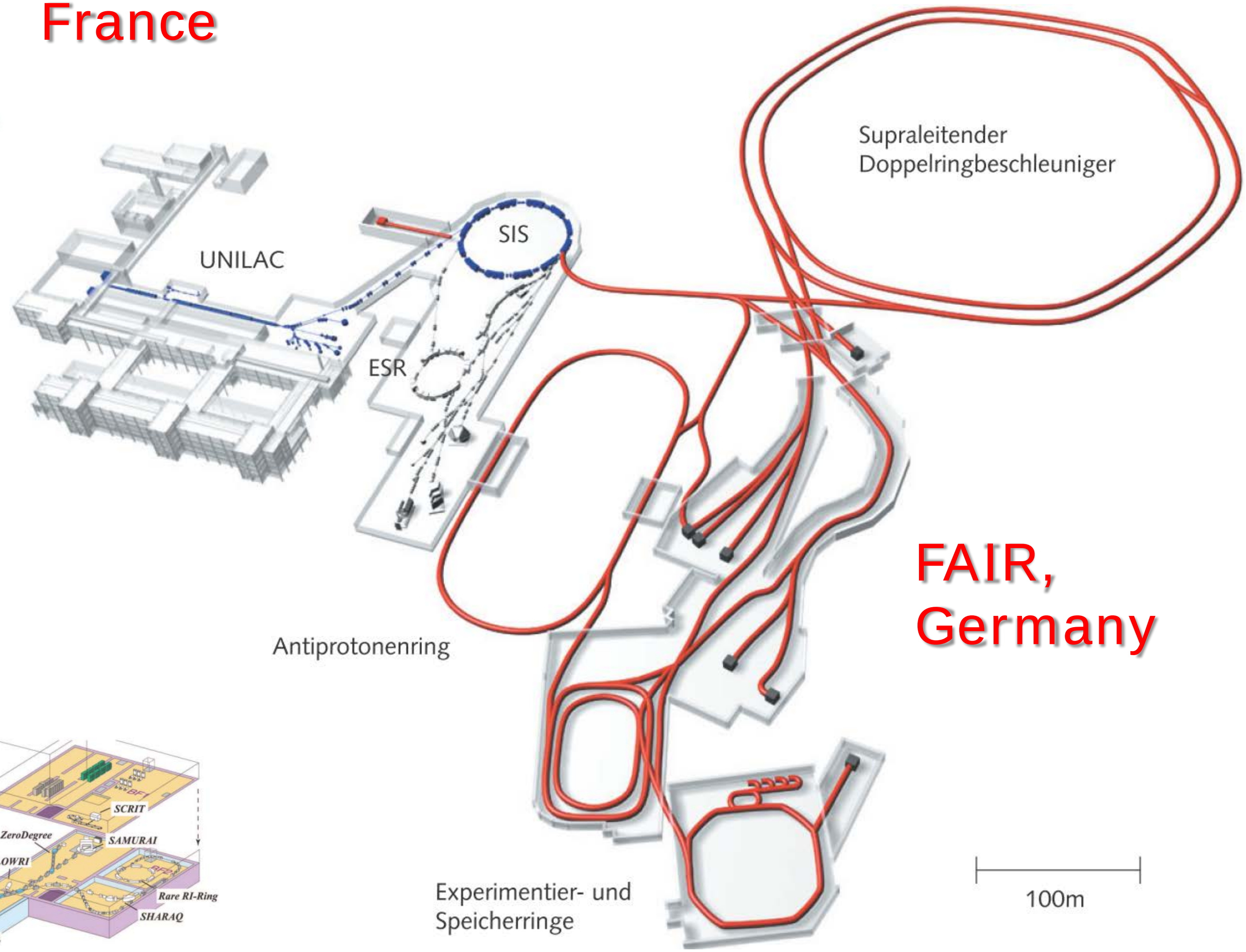
SPIRAL2
France

FRIB USA



RIBF Japan

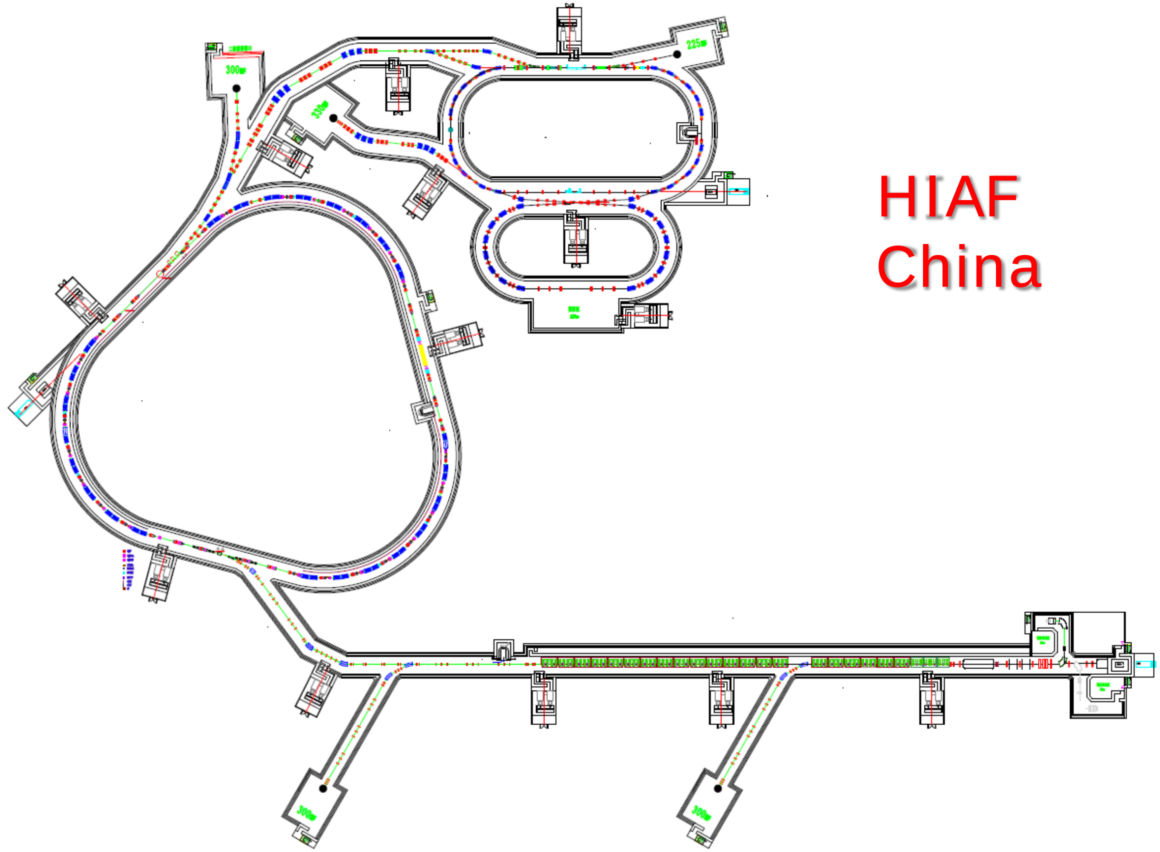




FAIR,
Germany

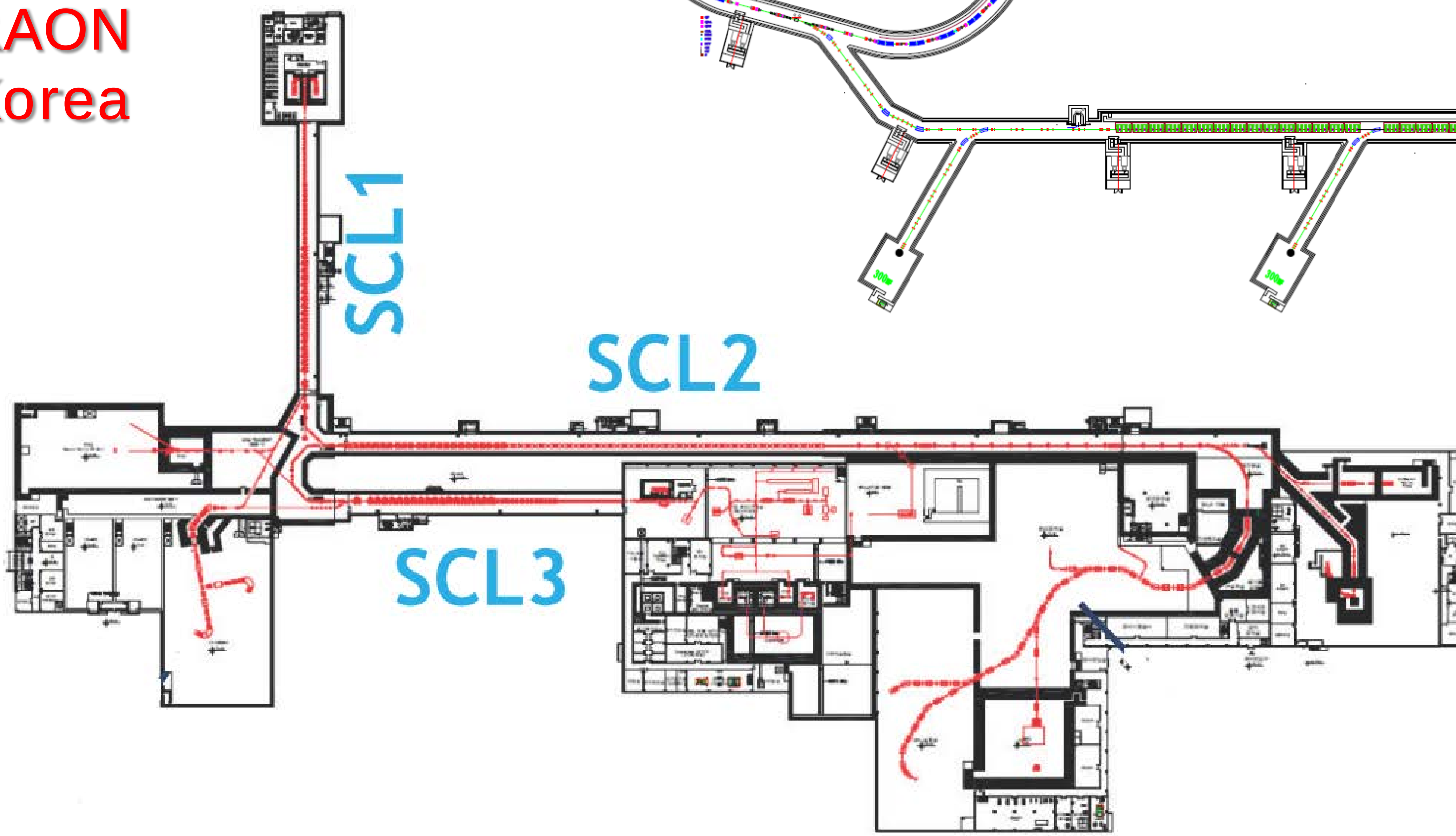
И еще больше…

Горизонтальный размер слайда ~1 км



HIAF
China

RAON
Korea



Empty “ecological niche”

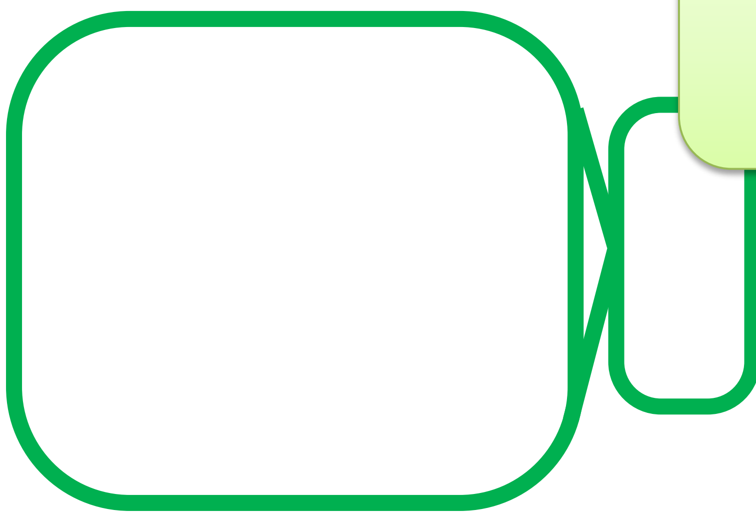
Underdeveloped field: storage ring physics with RIBs

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



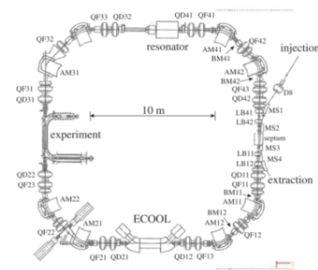
Studies of electromagnetic formfactors of exotic nuclei in e-RIB collider

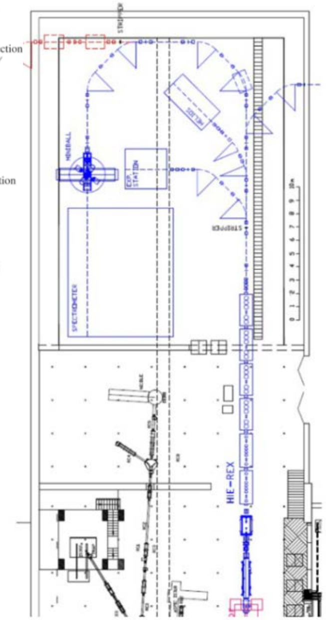
Radioactivity studies with striped ions

Etc….

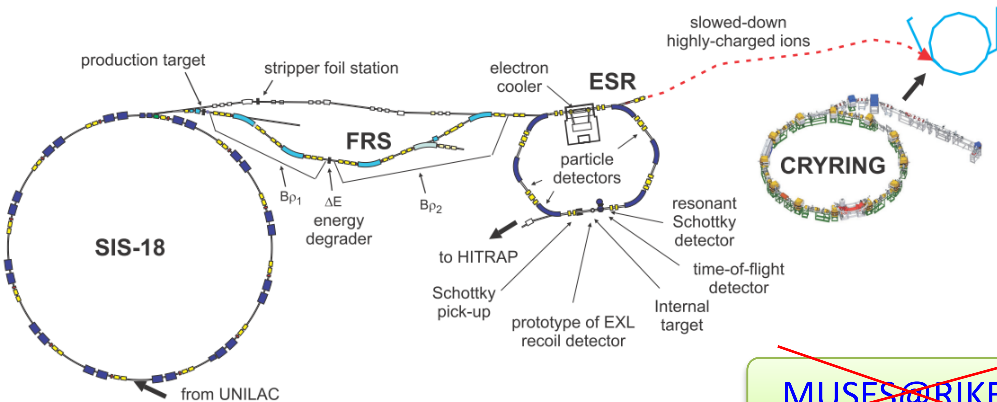
Status of ring projects in the world

~~TSR/ISOLDE@CERN~~

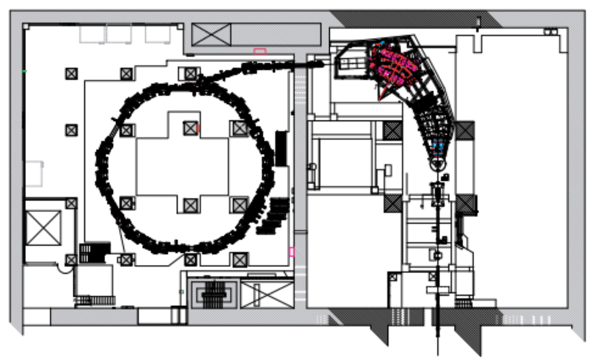




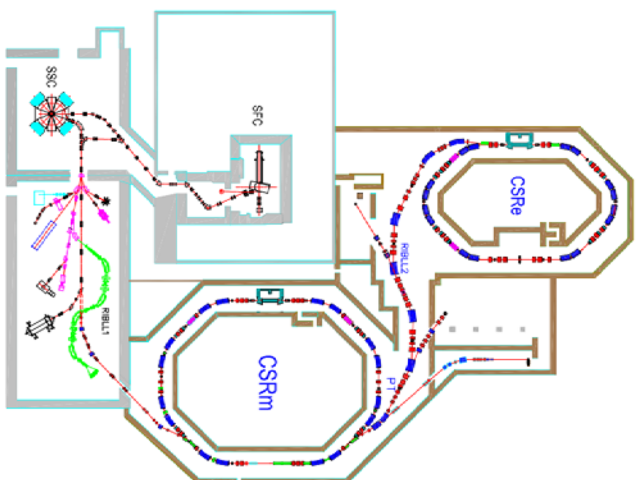
~~ELISe/NESR@FAIR~~ → ESR/CRYRING@GSI



~~MUSES@RIKEN~~ → RI-Ring@RIKEN



~~HIRFL-CSR@Lanzhou~~ → HIAF



Не в масштабе

– A lot of ring projects – serious interest to the topic

– All the ring projects with e-collider abilities were cancelled or indefinitely postponed

Storage ring and e-RIB collider topic in Russia

Expertize in the field especially at Dubna and Novosibirsk

Nuclear Instruments and Methods in Physics Research A 637 (2011) 60–76

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The electron–ion scattering experiment ELISe at the International Facility for Antiproton and Ion Research (FAIR)—A conceptual design study

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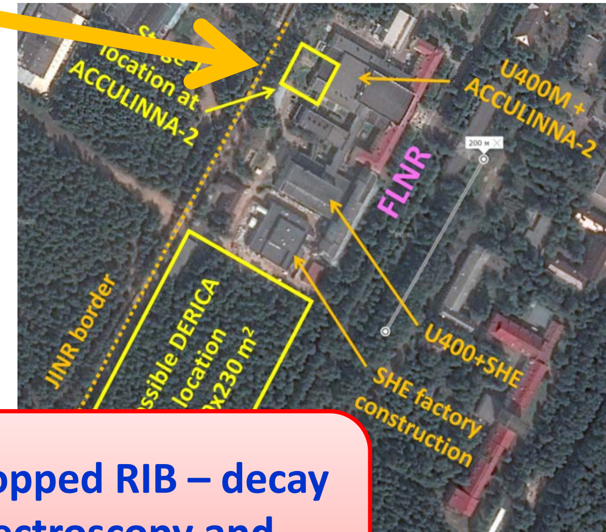
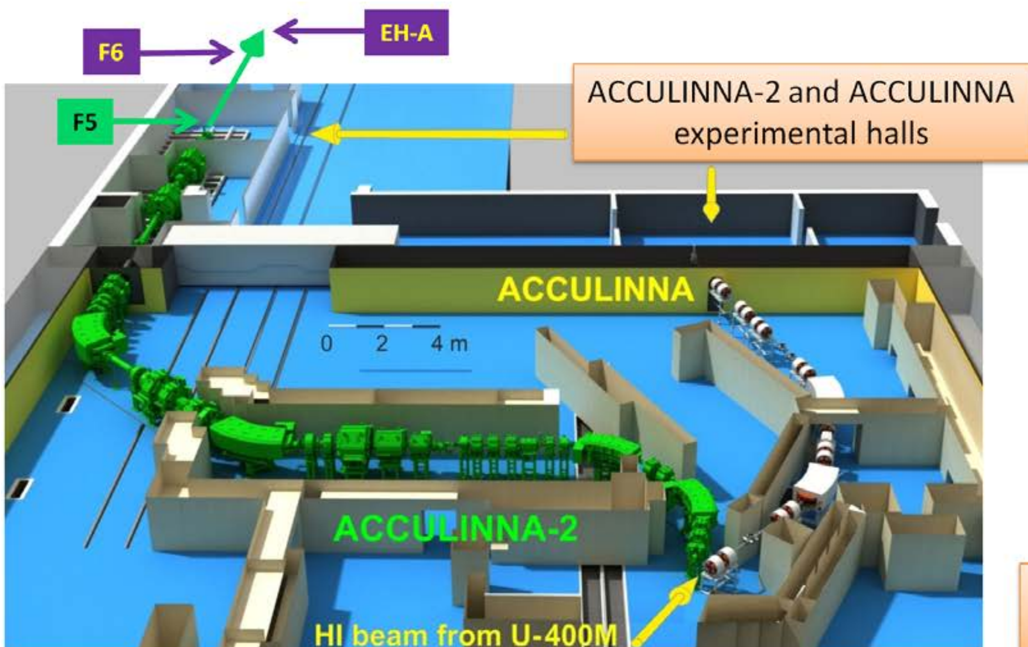
DERICA stages 0 -1

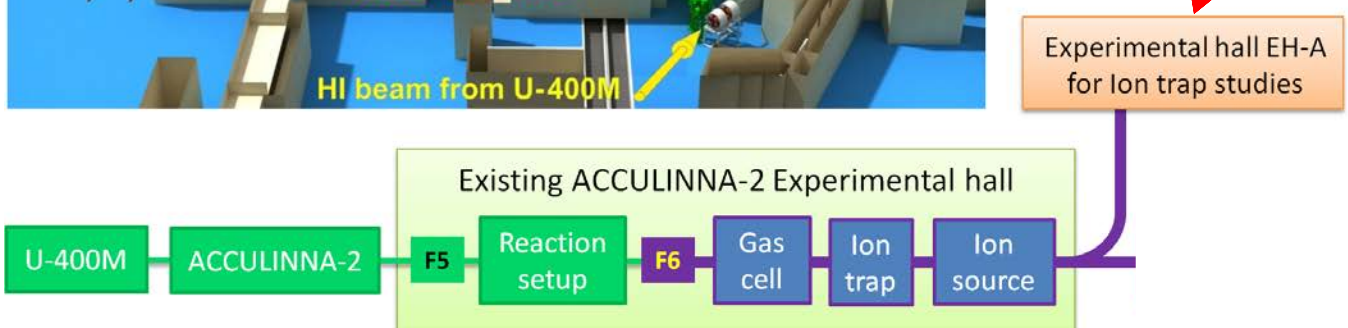
Continuity of scientific program

Minimization of technological risks



Stopped RIB – decay spectroscopy and studies in traps

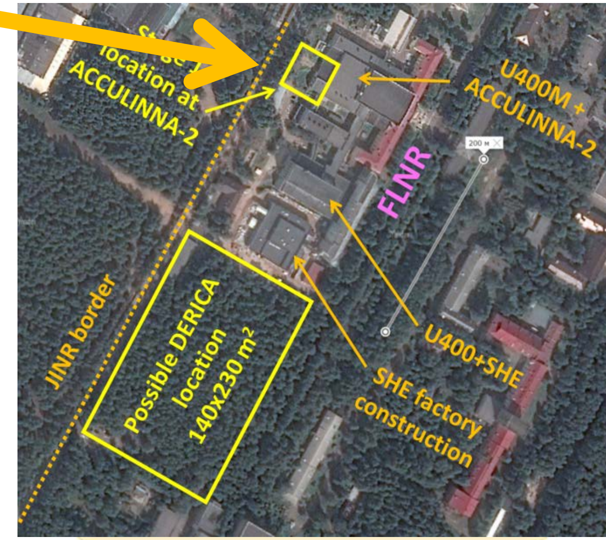


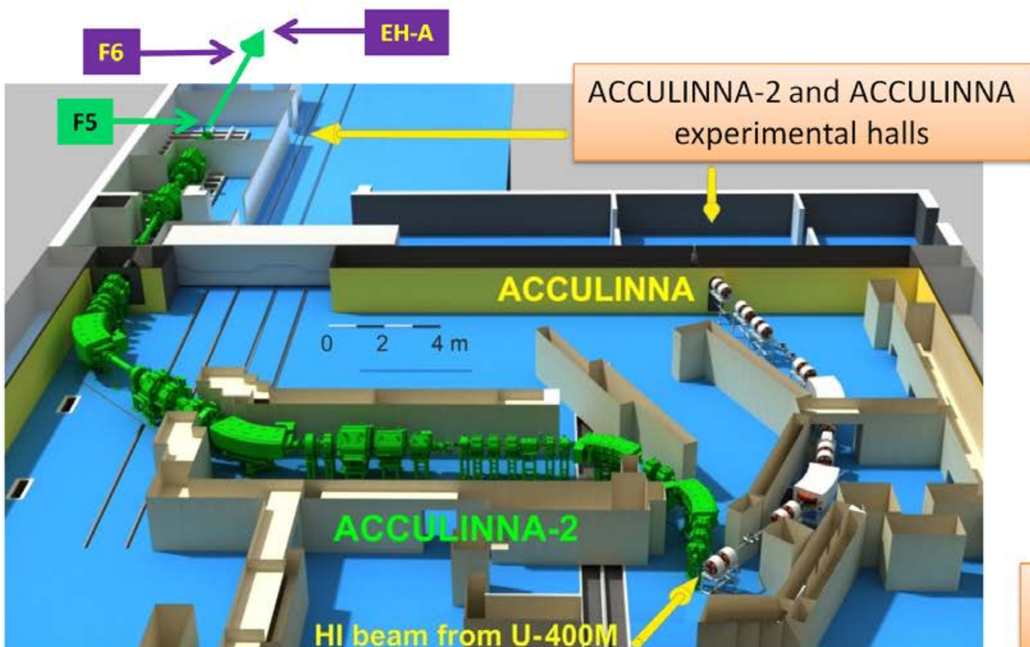


DERICA stages 0 -1

Continuity of scientific program

Minimization of technological risks





Reactions with reaccelerated RIBs around Coulomb barrier energy (5-7 AMeV)

Experimental hall EH-A for Ion trap studies

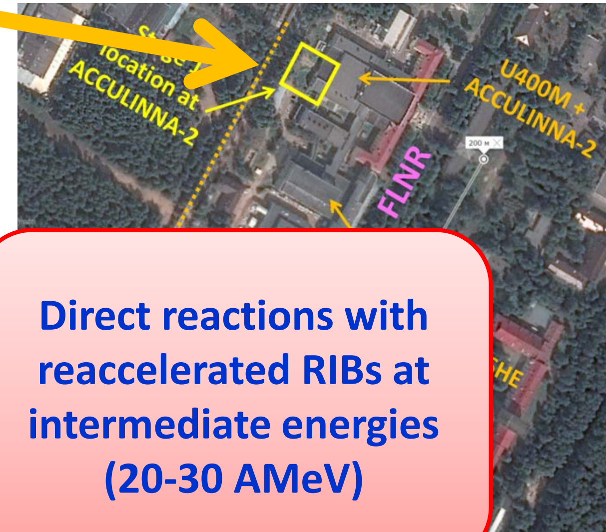
Existing ACCULINNA-2 Experimental hall

U-400M → ACCULINNA-2 → F5 → Reaction setup → F6 → Gas cell → Ion trap → Ion source → LINAC-30 5-10 AMeV → Experimental hall EH-B for Coulomb barrier reaction studies 5-10 AMeV

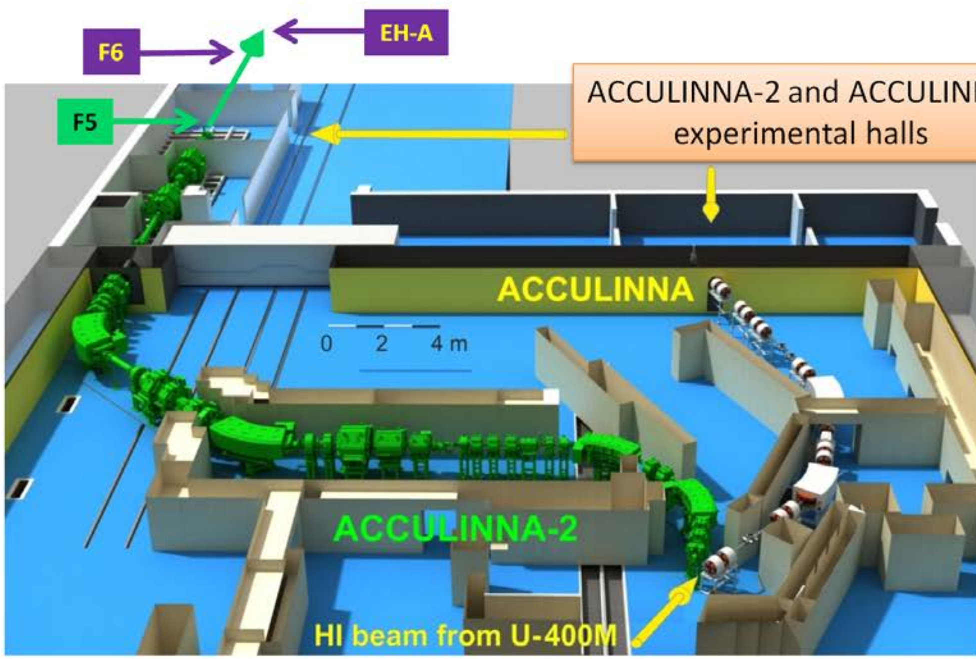
DERICA stages 0 -1

Continuity of scientific program

Minimization of technological risks



Direct reactions with reaccelerated RIBs at intermediate energies (20-30 AMeV)



Experimental hall EH-C for intermediate energy high-precision reaction studies 20-30 AMeV

LINAC-30 10-30 AMeV

Experimental hall EH-A for Ion trap studies

Existing ACCULINNA-2 Experimental hall

U-400M → ACCULINNA-2 → F5 → Reaction setup → F6 → Gas cell → Ion trap → Ion source → LINAC-30 5-10 AMeV

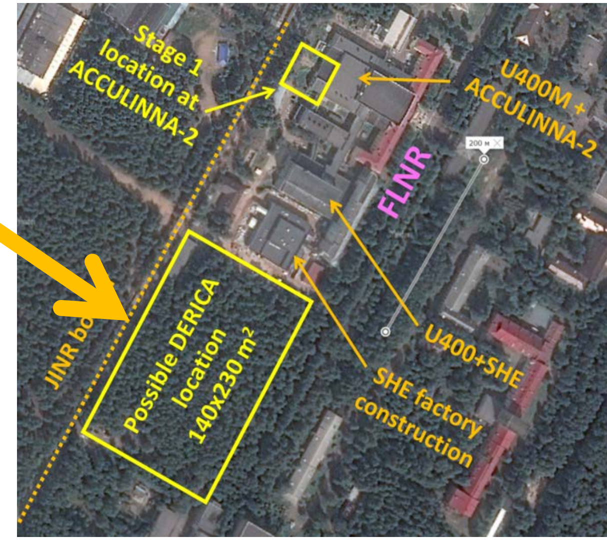
Experimental hall EH-B for Coulomb barrier reaction studies 5-10 AMeV

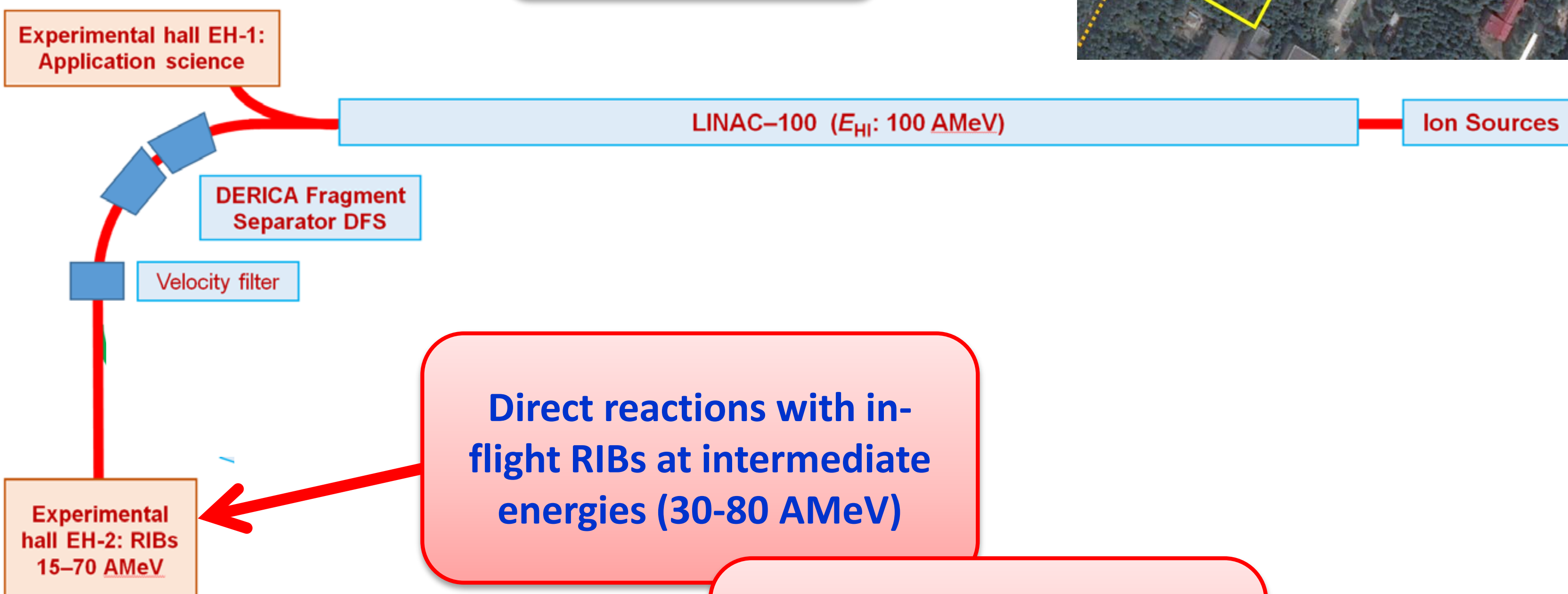
DERICA stages 2 - 4

New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects





Direct reactions with in-flight RIBs at intermediate energies (30-80 AMeV)

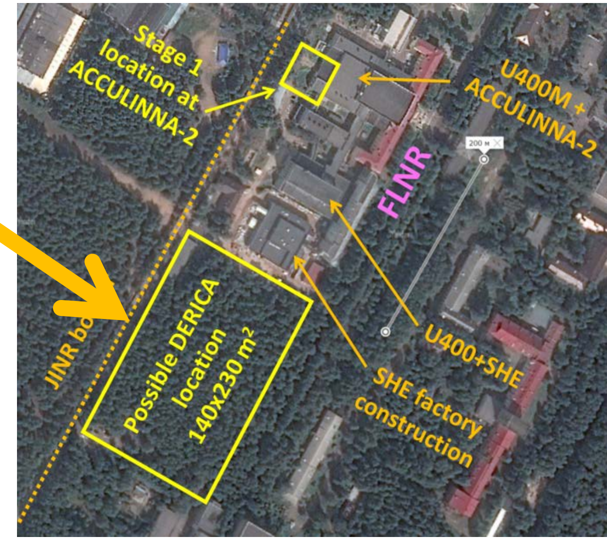
World-leading intencities are expected for this energy range

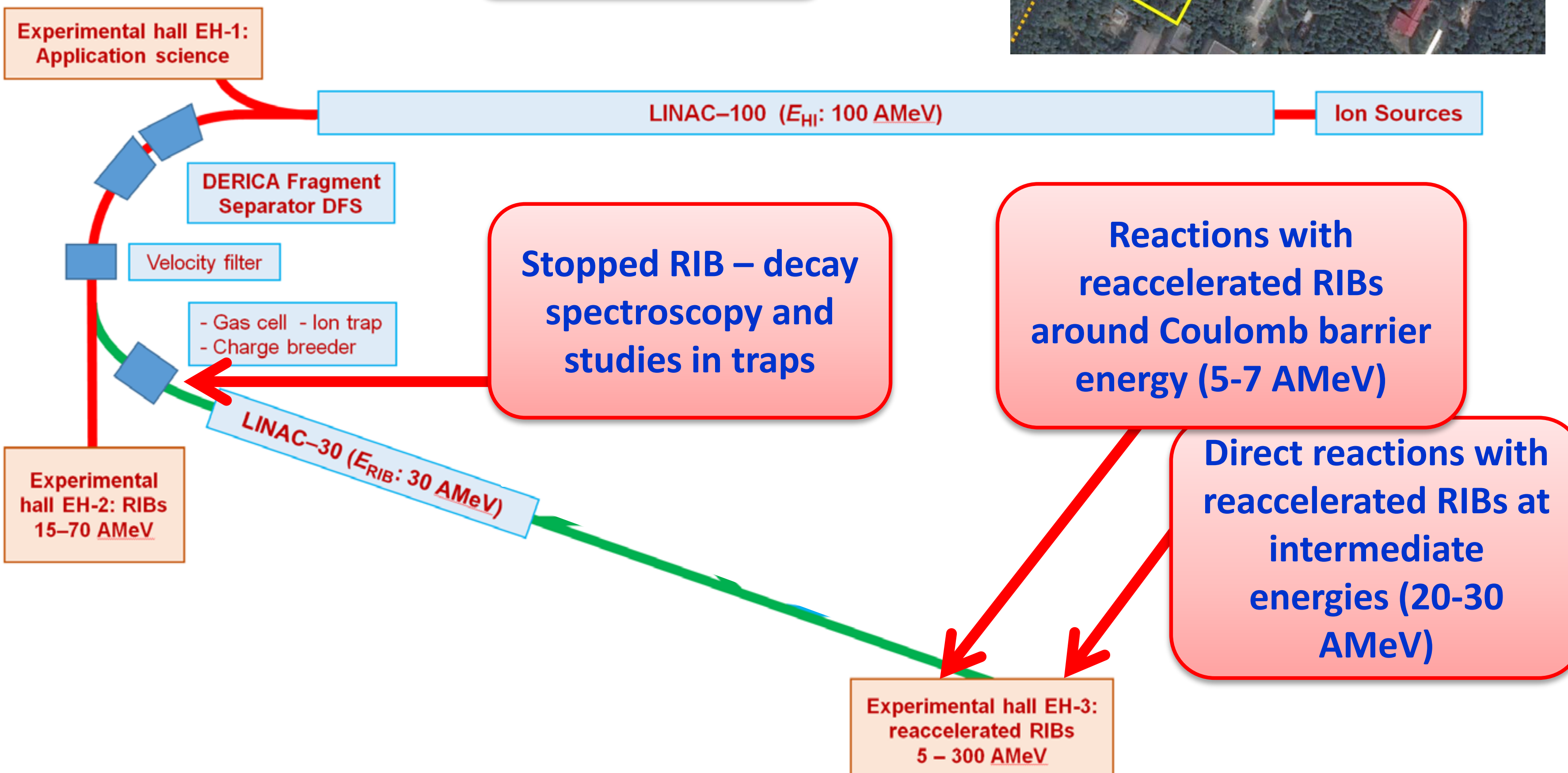
DERICA stages 2 - 4

New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects



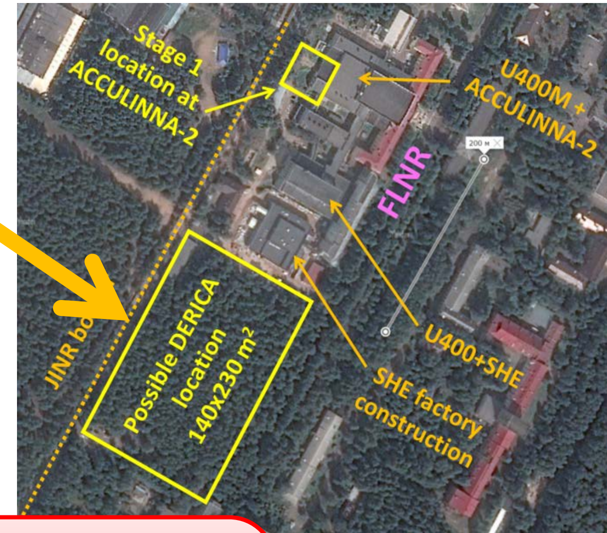


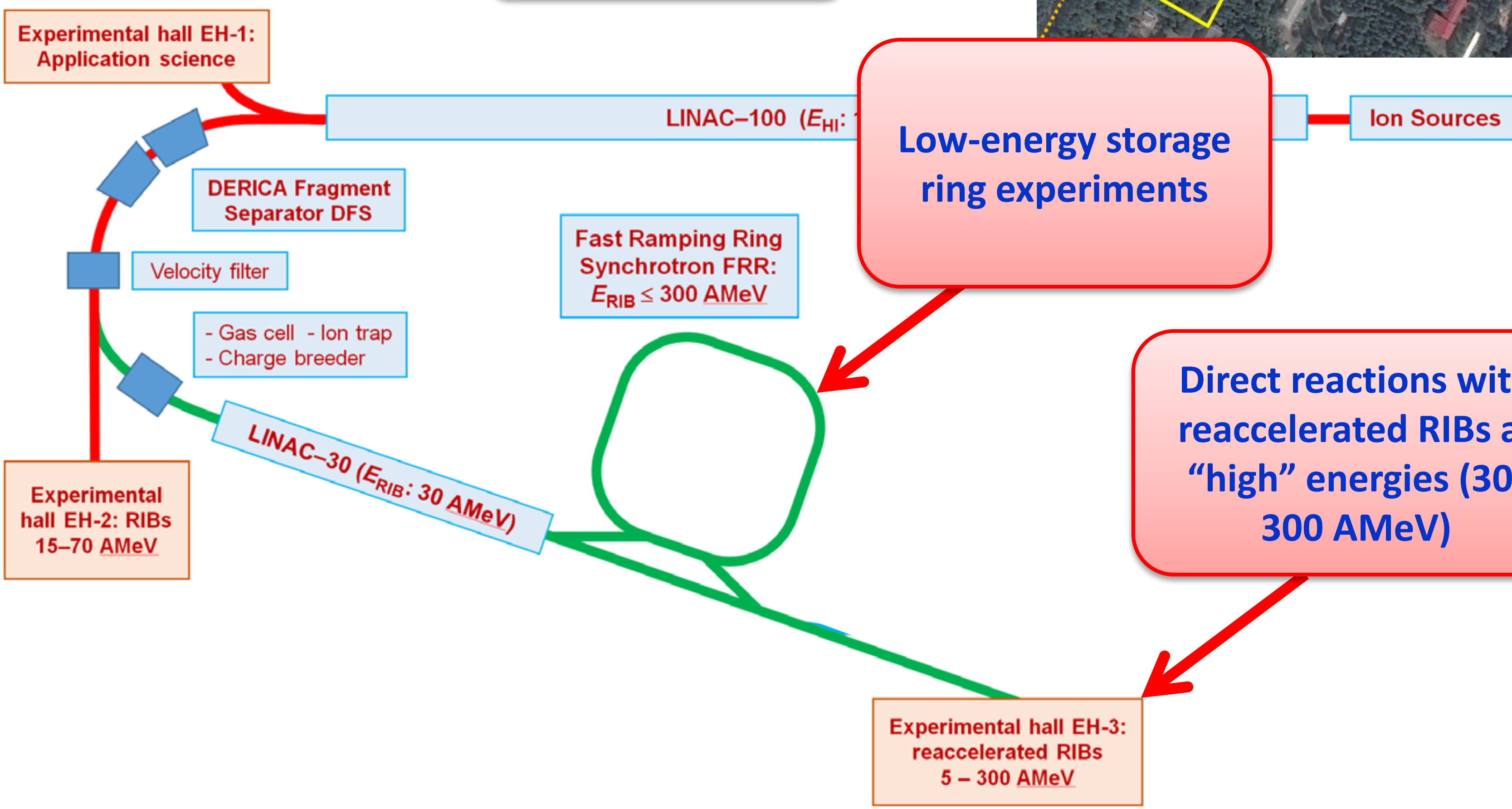
DERICA stages 2 - 4

New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects





Low-energy storage ring experiments

Direct reactions with reaccelerated RIBs at “high” energies (30-300 AMeV)

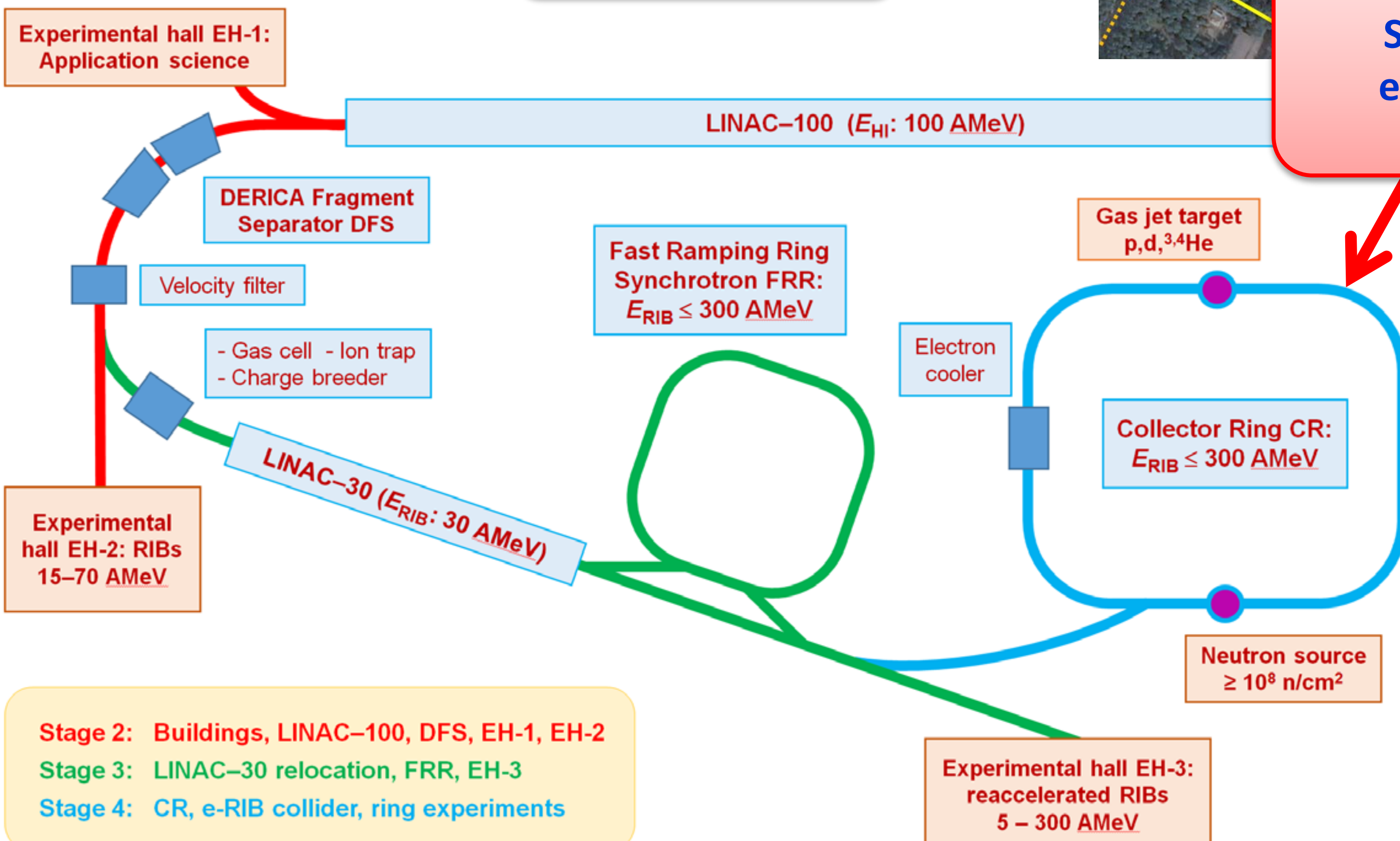
DERICA stages 2 - 4

New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects

Storage ring experiments

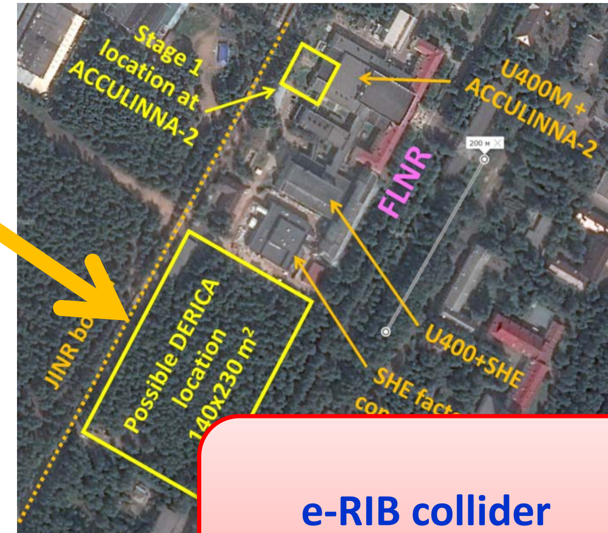


DERICA stages 2 - 4

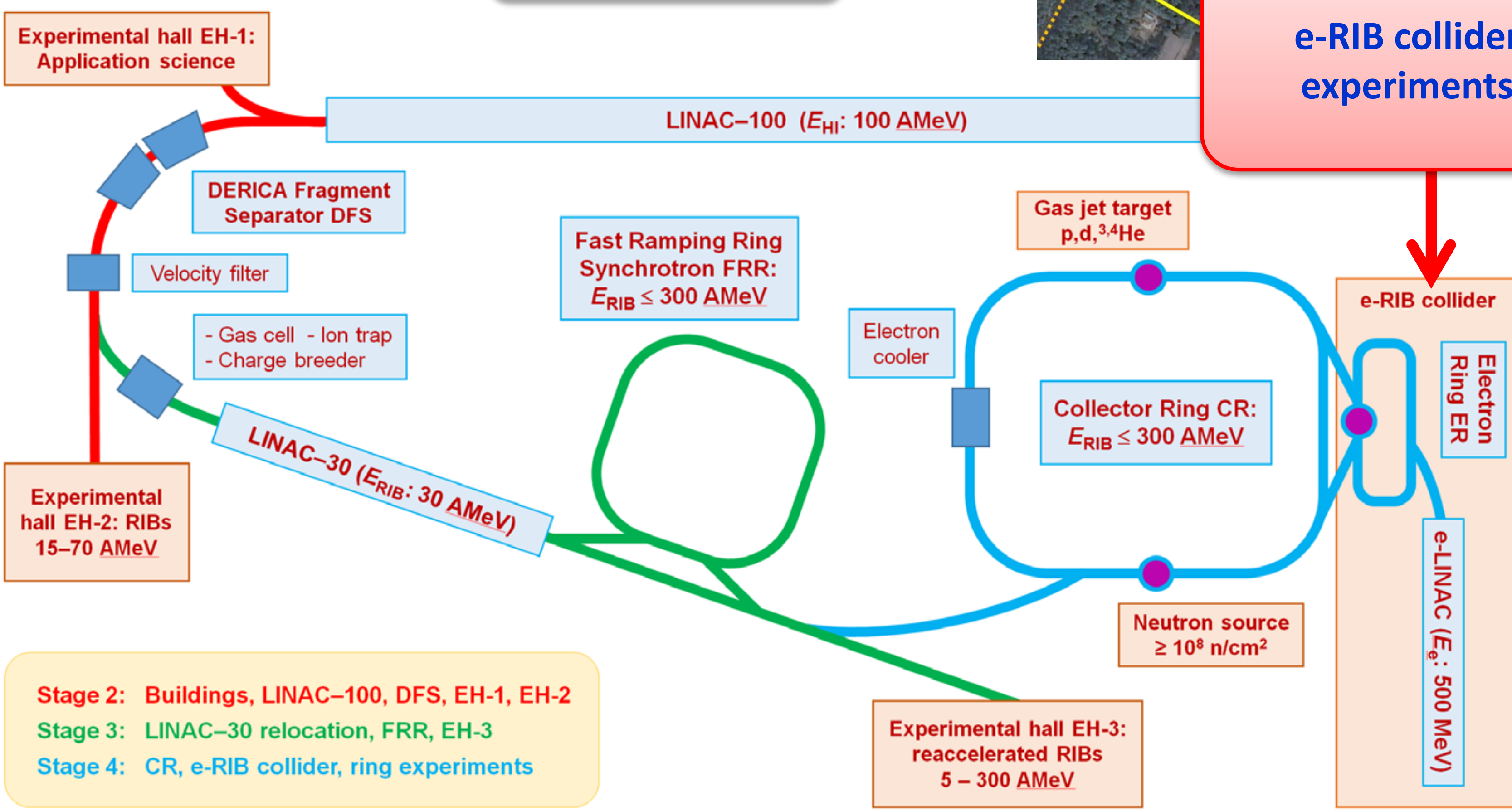
New experimental opportunities on each stage

Spacious cite for development

Good upgrade prospects



e-RIB collider experiments



Stage 2: Buildings, LINAC–100, DFS, EH-1, EH-2

Stage 3: LINAC–30 relocation, FRR, EH-3

Stage 4: CR, e-RIB collider, ring experiments

Advantages of the proposed facility

Unusual facility layout

Ordinary approach 1:
ISOL RIB production ->
problem to reaccelerate RIBs

Ordinary approach 2:
In-flight RIB production ->
Problem to stop/cool RIBs

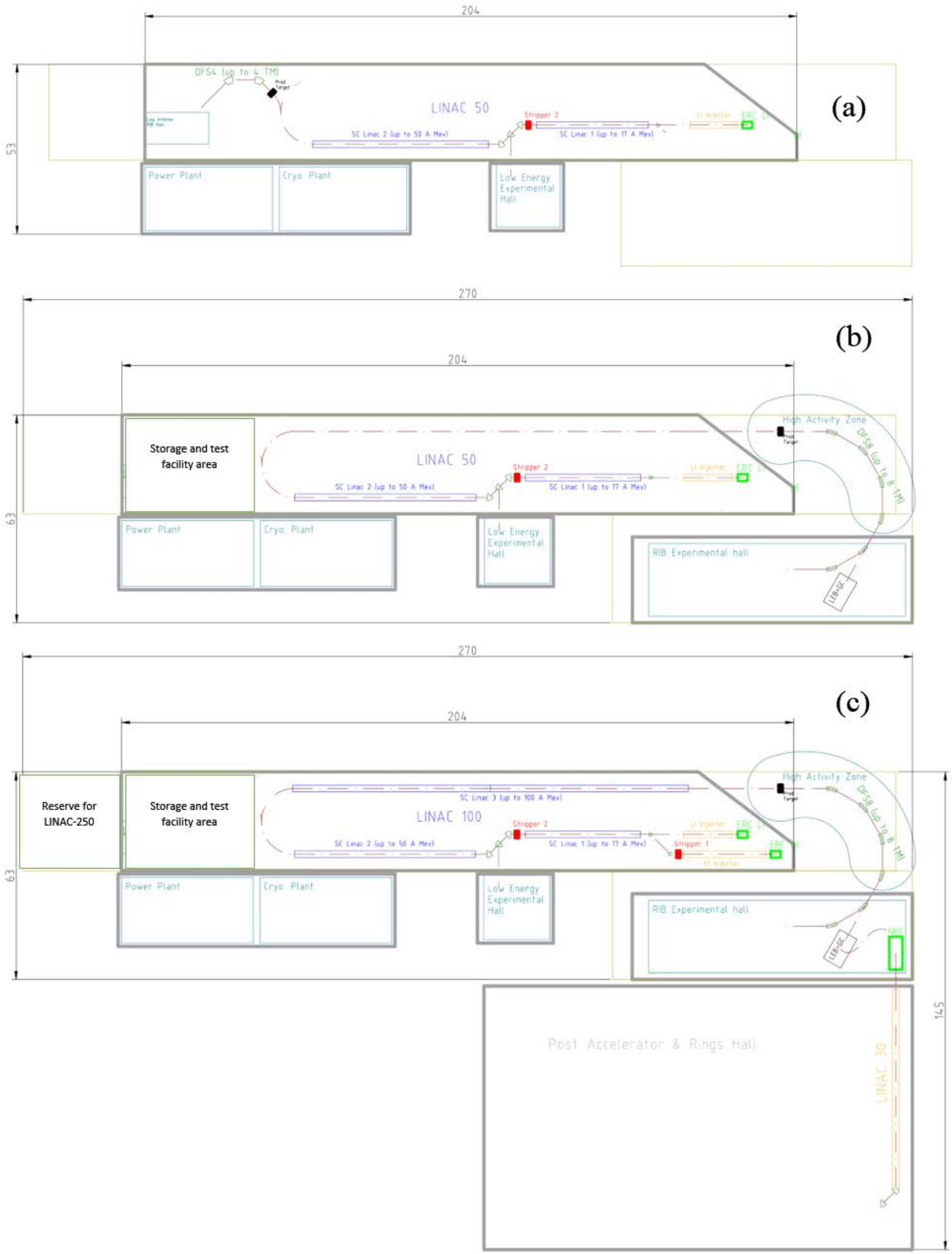
DERICA approach:
In-flight RIB production + RIB "cooling" in gas cell + reaccelerated RIBs up to 300 AMeV

Staged development
- Continuity and flexibility of the research program
- Low technological risks
- Highly upgradable facility design

Unique opportunities
- World most intense RIBs with intermediate energy (20-70 AMeV) for reaction studies
- Reaccelerated RIBs up to 300 AMeV
- e-RIB collider experiment

Realistic scenario

DERICA workshop
4-5 or 7-8 February
2018



Collaboration opportunities with FLNR

Personal interest: few-body dynamics in light exotic nuclei

Theoretical studies are experiment-motivated. Between theory and experiment

Experimental program and instrumentation development for ACCULINNA-2@FLNR

Experimental program and instrumentation development for EXPERT@FAIR

DERICA developments – long-term prospects for the whole Russian low-energy nuclear science

DERICA workshop 4-5 or 7-8 February 2019