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Структура легких ядер на границе стабильности

Мировый тенденции в исследованиях радиоактивных изотопов

Перспективы исследований на комплексе U-400M/ACCULINNA-2 в 2023-... годах

Совещание по физике тяжелых ионов, 3-9 июня, 2022, Санкт-Петербург

Исследования на пучках радиоактивных изотопов

– Всего существует 256 стабильных изотопов
– 339 изотопов встречается в природе

- На сегодня открыто свыше 3100 ядерно-стабильных изотопов
- По оценкам 2000-3000 предстоит открыть

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

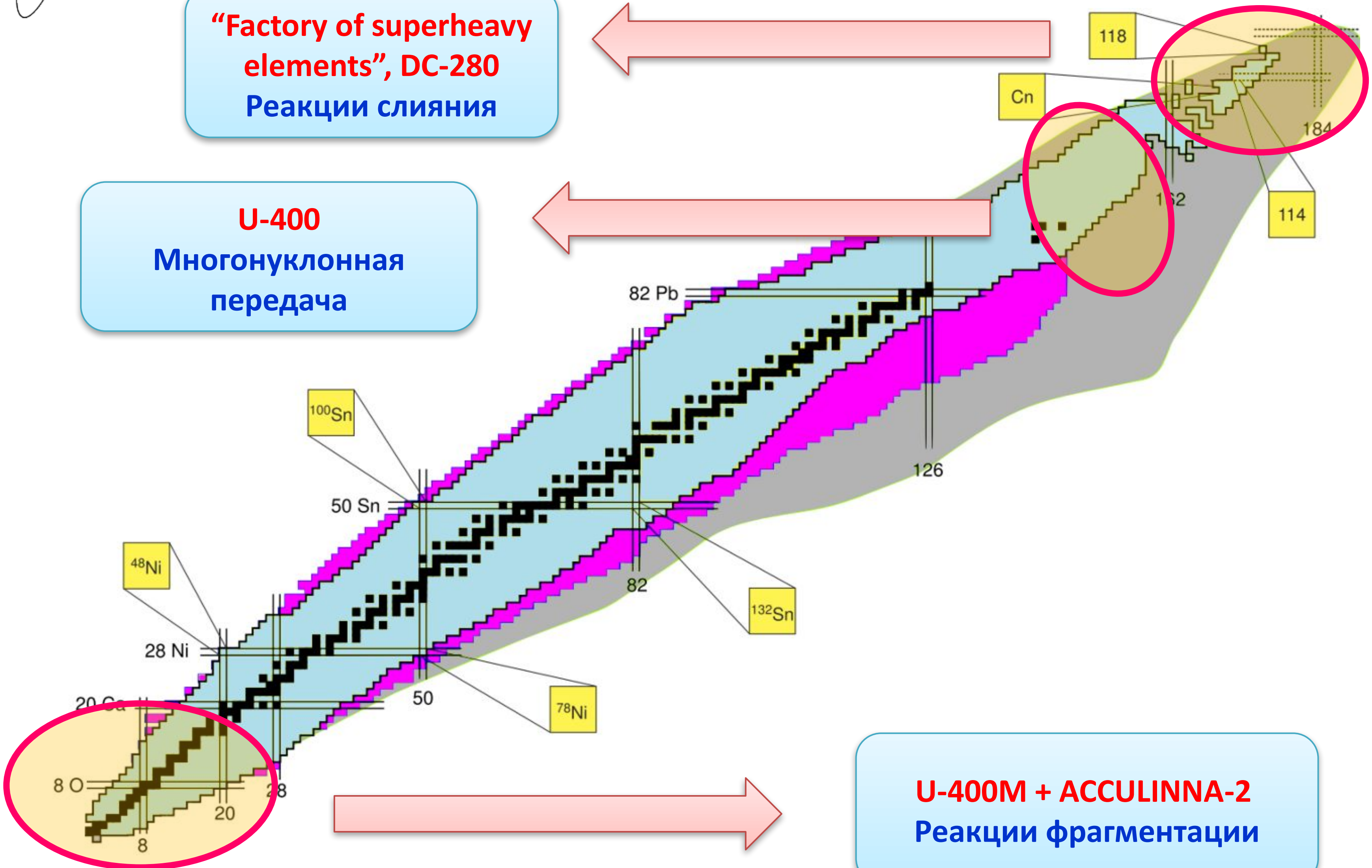
RIKEN	LINAC + Cyclotron	U, 90 AMeV	In-flight, 90 pnA
GSI	LINAC + Syncrotron	U, 900 AMeV	In-flight, 50 pnA
NSCL MSU	Cyclotron + Cyclotron	U, 90 AMeV	In-flight, 70 pnA
GANIL	Cyclotron + Cyclotron	U, 70 AMeV	In-flight, 90 pnA
ISOLDE	LINAC + Syncrotron	p, 1000 MeV	ISOL, ~1.5 kW
FLNR	Cyclotron	B 55 AMeV,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

ЛЯР, области интересов

“Factory of superheavy elements”, DC-280
Реакции слияния

U-400
Многонуклонная передача

U-400M + ACCULINNA-2
Реакции фрагментации



Экзотика в ядрах на границе стабильности

Кластеризация

Разделение характерных масштабов в системе

Не работают привычные концепции насыщения ядерной плотности и насыщения ядерного взаимодействия

Ядерное гало

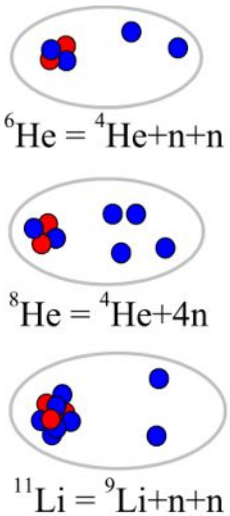
“Нейтронная кожа”

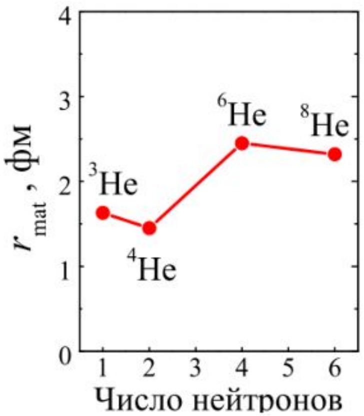
Мягкие моды возбуждения

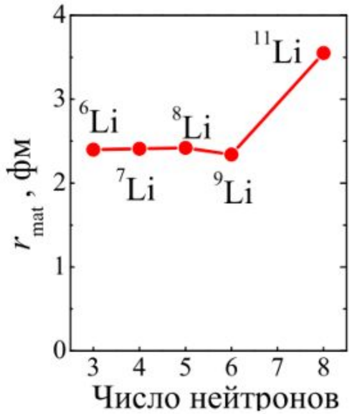
Экзотические виды радиоактивности

Нарушение стандартных оболочечных закономерностей

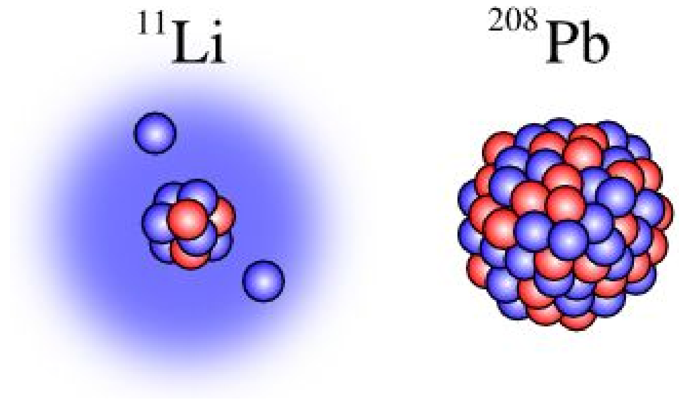
Ядра с гало. Борромиевские ядра



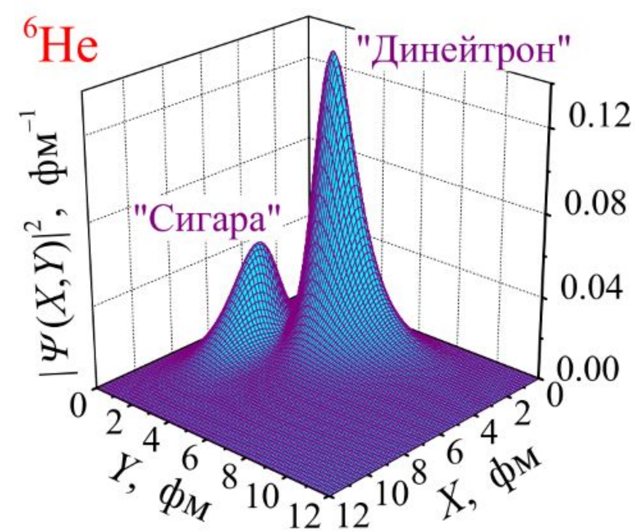




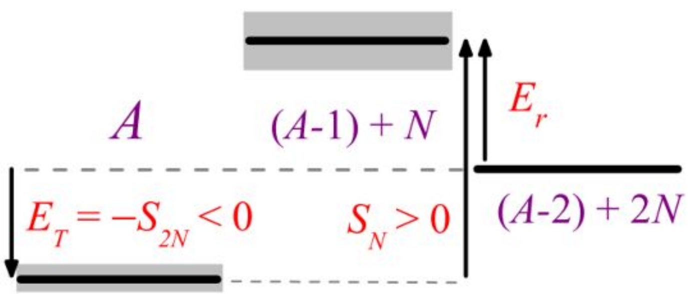
Валентные орбитали аномальных размеров



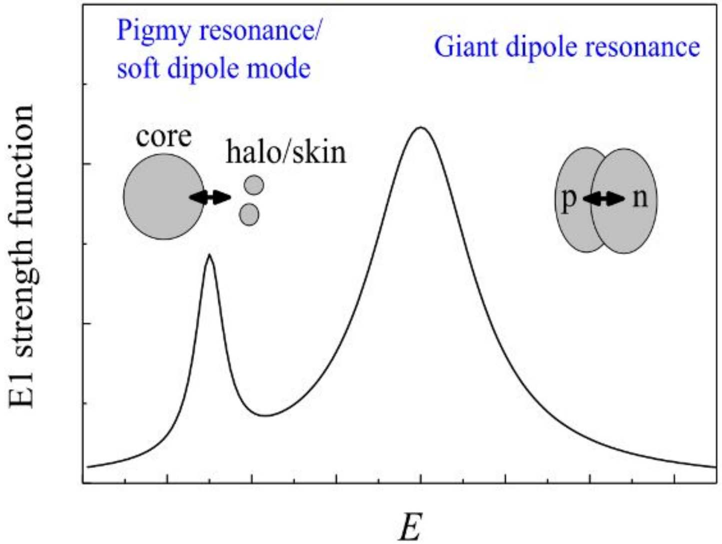
Сложные корреляции

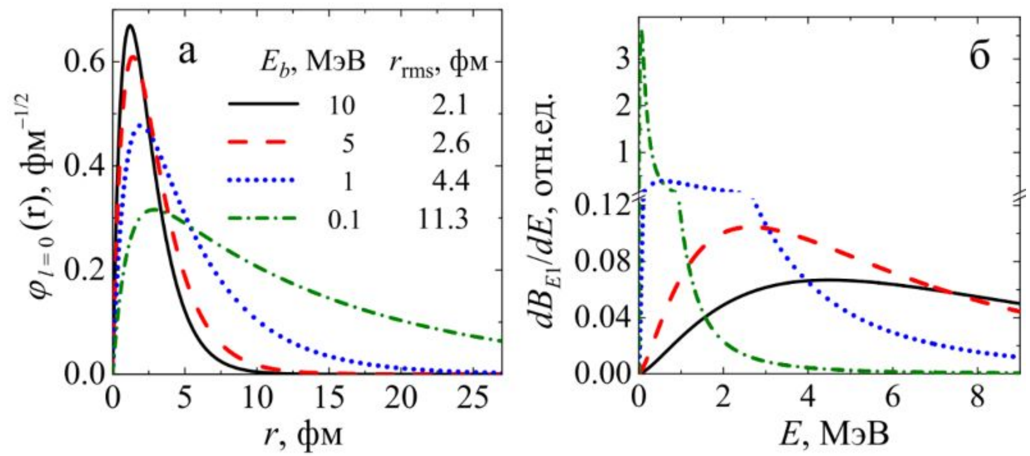


"Борромиевские" системы



Мягкие моды возбуждения (мягкая дипольная мода)





$$\phi_{l=0}(r) = N(\exp[-k_1 r] - \exp[-k_2 r]), \quad k_1 = \sqrt{2ME_b},$$

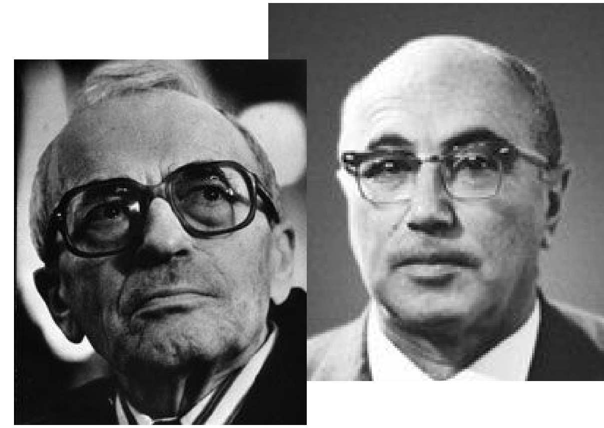
$$M_{E1}(E) = \int_0^\infty dr\,(pr) j_{l=1}(pr)\, r\, \phi_{l=0}(r), \quad p = \sqrt{2ME},$$

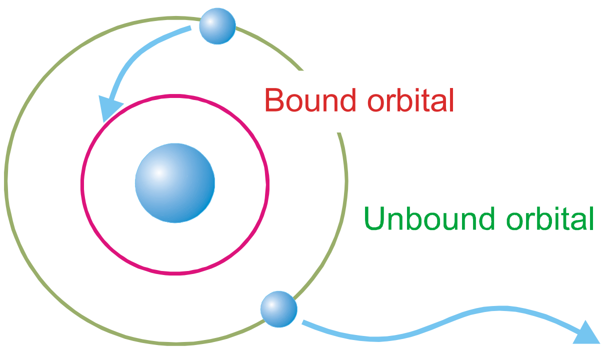
$$\frac{dB_{E1}}{dE} \sim \frac{|M_{E1}(E)|^2}{\sqrt{E}}$$

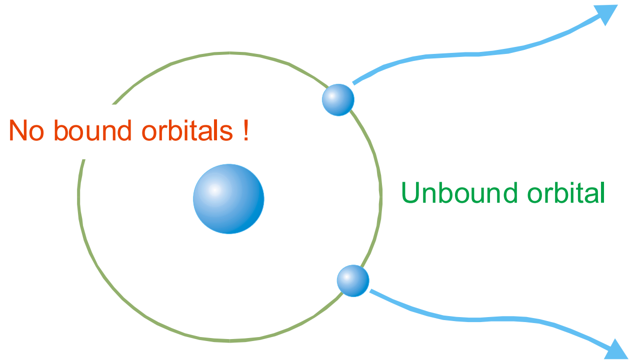
Existance of soft dipole mode strongly influence the nonresonant radiative capture rate in astrophysics

Двухпротонная радиоактивность: родом из СССР

Prediction:
Goldansky and Zeldovich, 1960







Discovery:
Pfutzner et al. and Giovinazzo et al., 2002

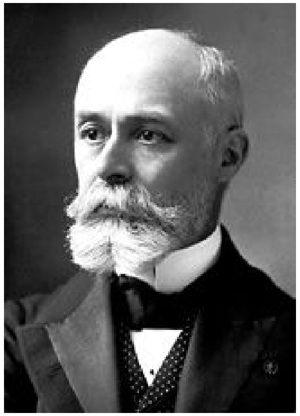
Classical case:
one particle emission is always possible

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

Exclusive Quantum-Mechanical phenomenon

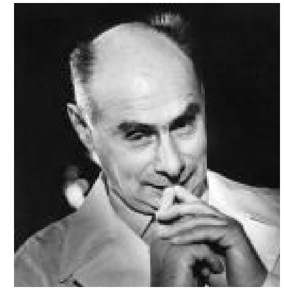
- **No deeper bound orbitals.**
- **The common orbital for two protons exists only when both are “inside”.**
- **When one of them goes out, their common orbital do not exist any more and the second HAS to go out instantaneously**

“Зал славы” явления радиоактивности



Henri Becquerel: three classes of radioactivity - negative, positive, and electrically neutral

F. Jouliot and I. Curie:
β^{+}



G.N. Flerov and K.A. Petrzhak
spontaneous fission

V.A. Karnaukhov and G.M. Ter-Akopian
β-delayed p

S. Hofmann:
p

M. Pfutzner:
2p

?

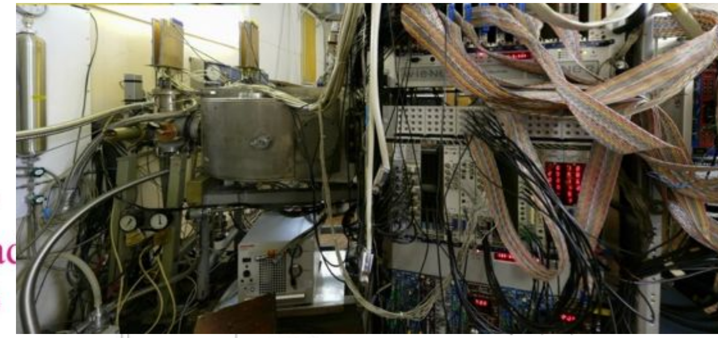
???
2n radioactivity

?

???
4n radioactivity

ACCULINNA и ACCULINNA-2

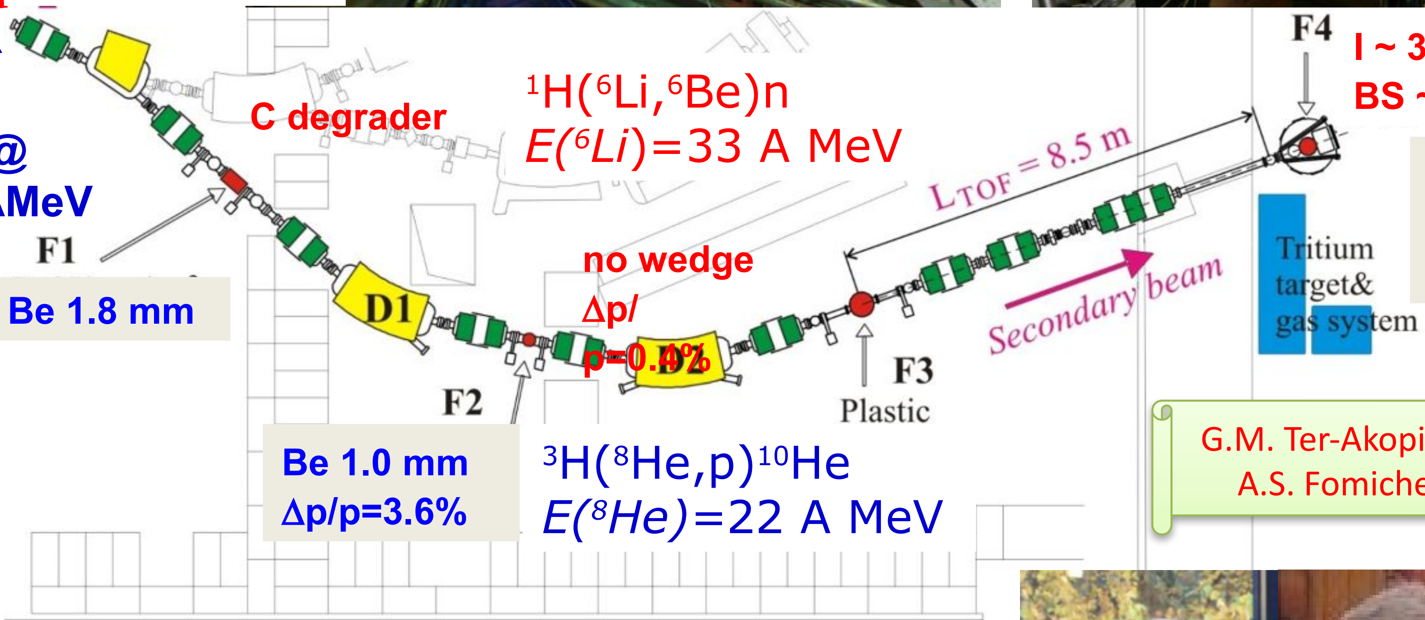
FLNR: Superlights – fragment separator ACCULINNA



U-400M :

^{6}Li @ 47 AMeV

^{11}B @ 34 AMeV



C degrader

^{1}H(^{6}Li,^{6}Be)n
E(^{6}Li)=33 A MeV

no wedge
Δp/p=0.4%

Be 1.8 mm

Be 1.0 mm
Δp/p=3.6%

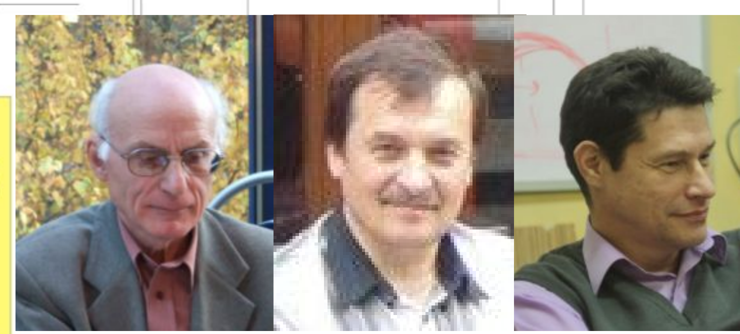
^{3}H(^{8}He,p)^{10}He
E(^{8}He)=22 A MeV

I ~ 3×10^{7} 1/s
BS ~ 5 mm

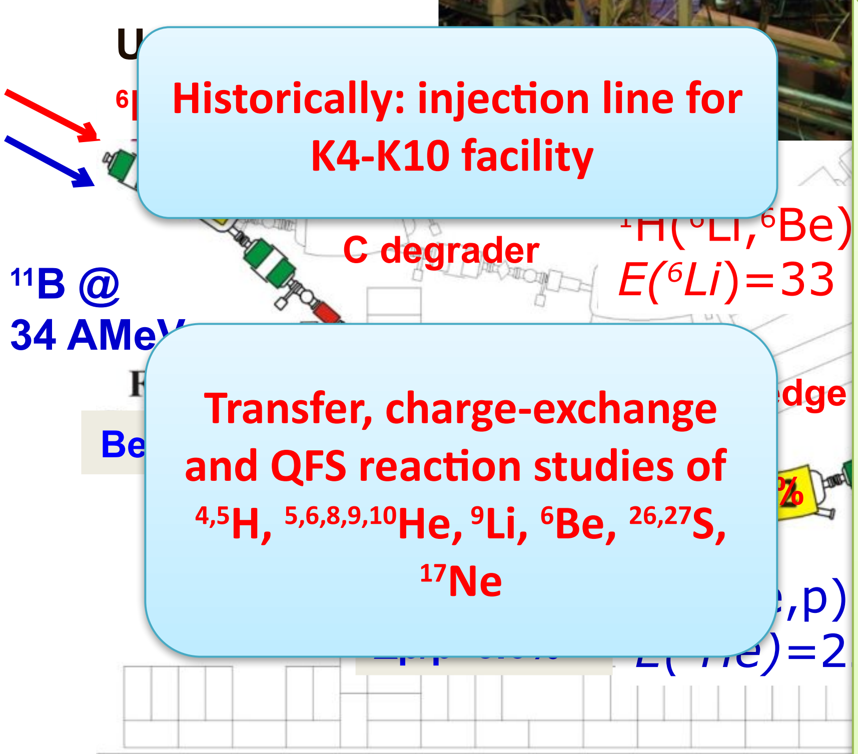
I ~ 2×10^{4} 1/s
BS ~ 15 mm
P ~ 90 %

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



FLNR: Superlights – fragment separator ACCULINNA

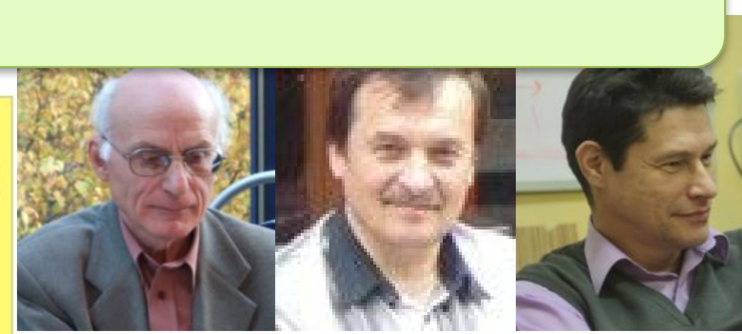


Historically: injection line for K4-K10 facility

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

	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

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.



Competitive light nuclei RIB program at FLNR

Intermediate energy reactions (20-70 MeV/nucleon)

Transfer reactions

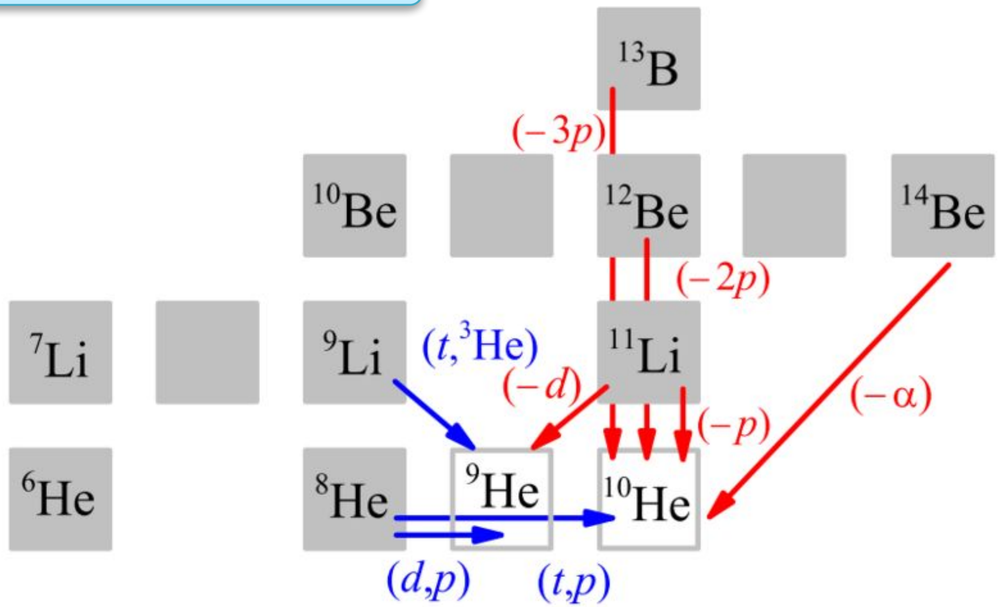
Missing mass, invariant mass, combination

Lower energy – better resolution

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

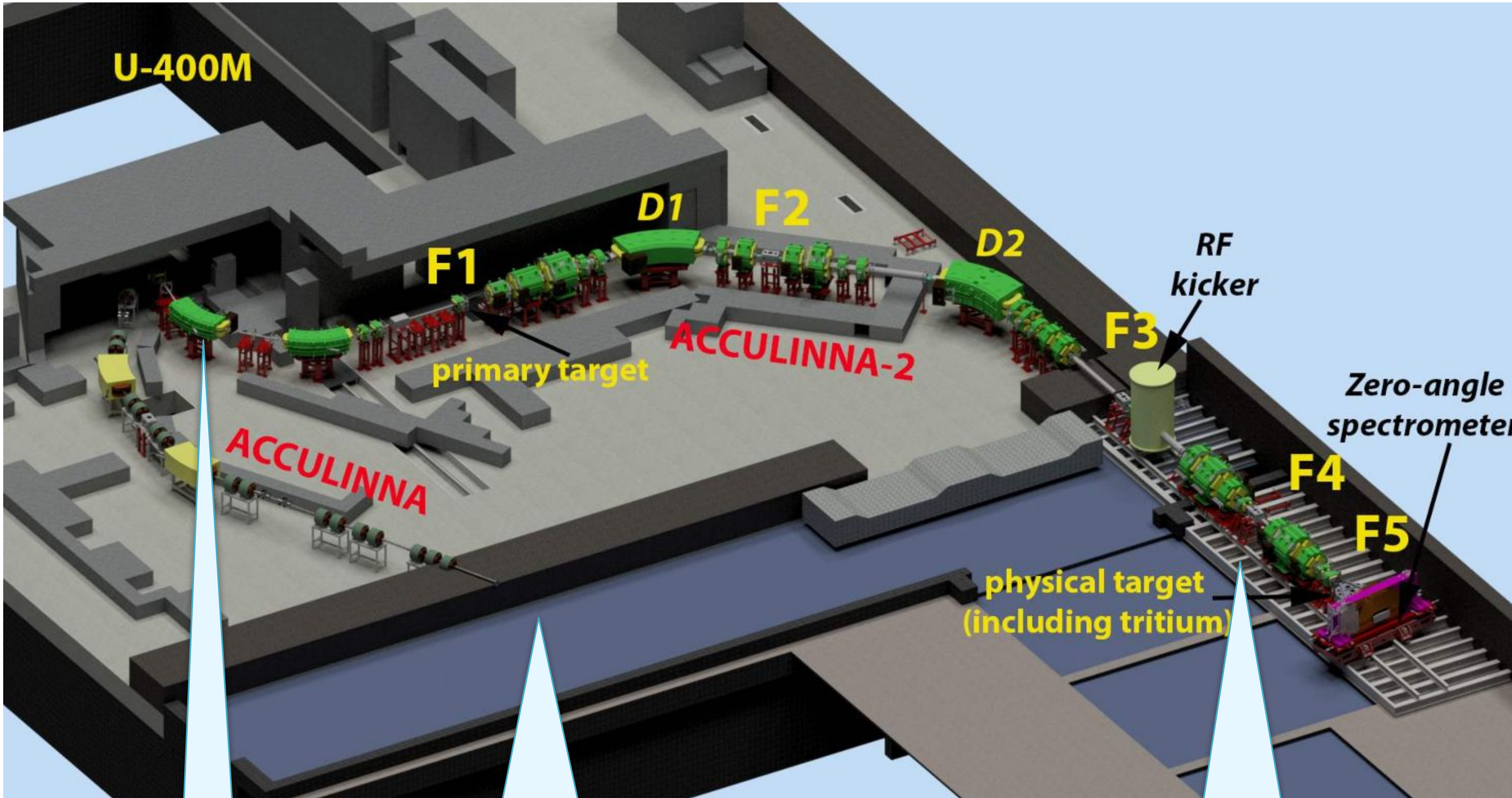
Knockout reactions

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



Importance of complementary reaction studies

2014-2018: от ACCULINNA к ACCULINNA-2
2019-2021: первые эксперименты – ^{7}H, ^{6}H

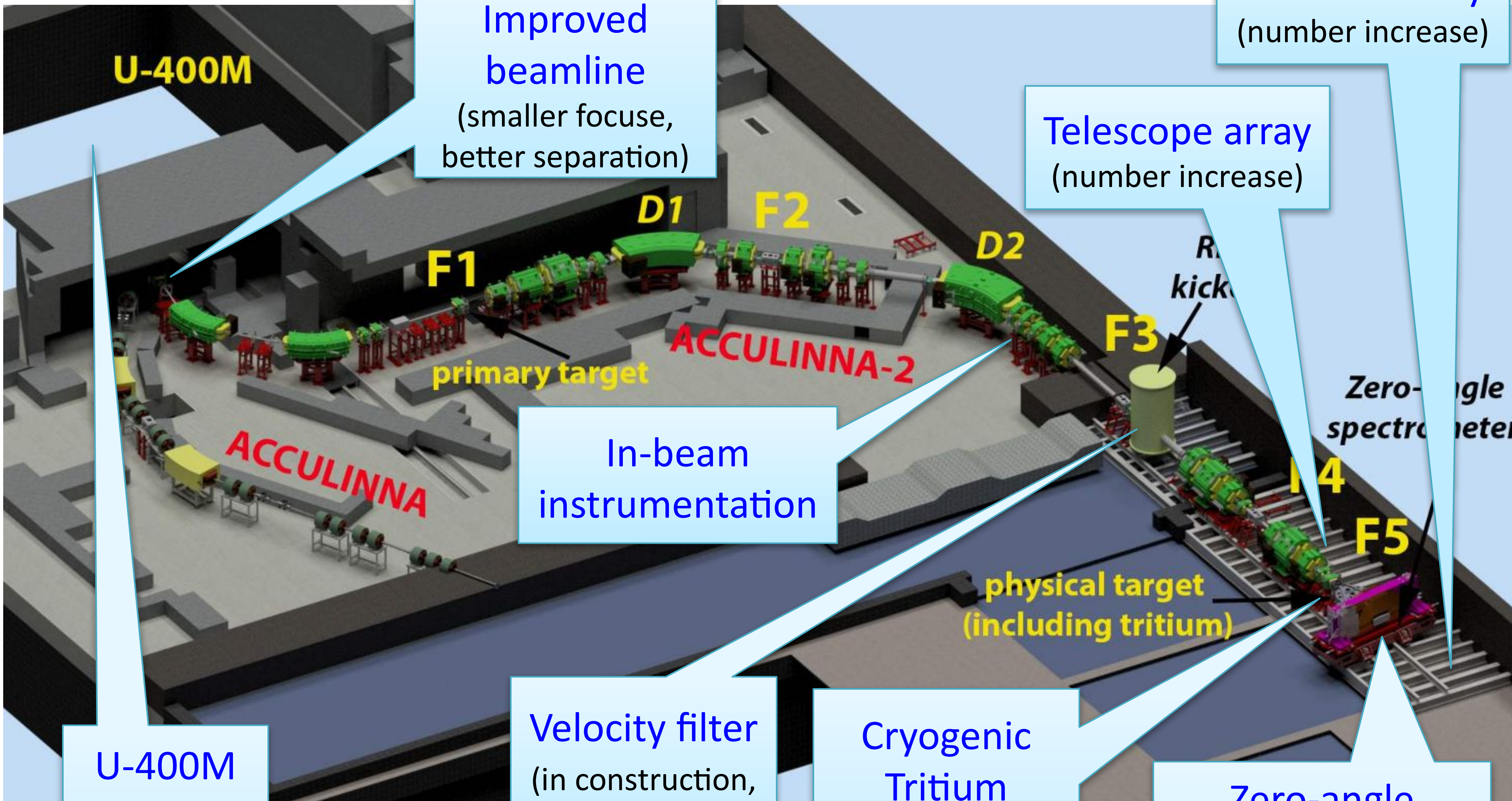


U-400M hall

ACCULINNA experimental hall

ACCULINNA-2 experimental hall

2021-2022: программа развития инструментов



Improved beamline
(smaller focuse, better separation)

Neutron array
(number increase)

Telescope array
(number increase)

In-beam instrumentation

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

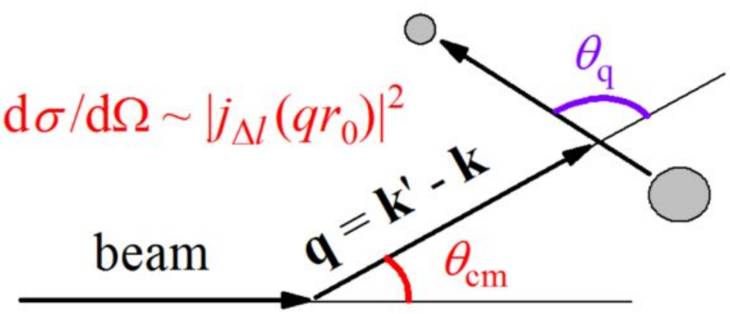
Velocity filter
(in construction, SigmaPhi)

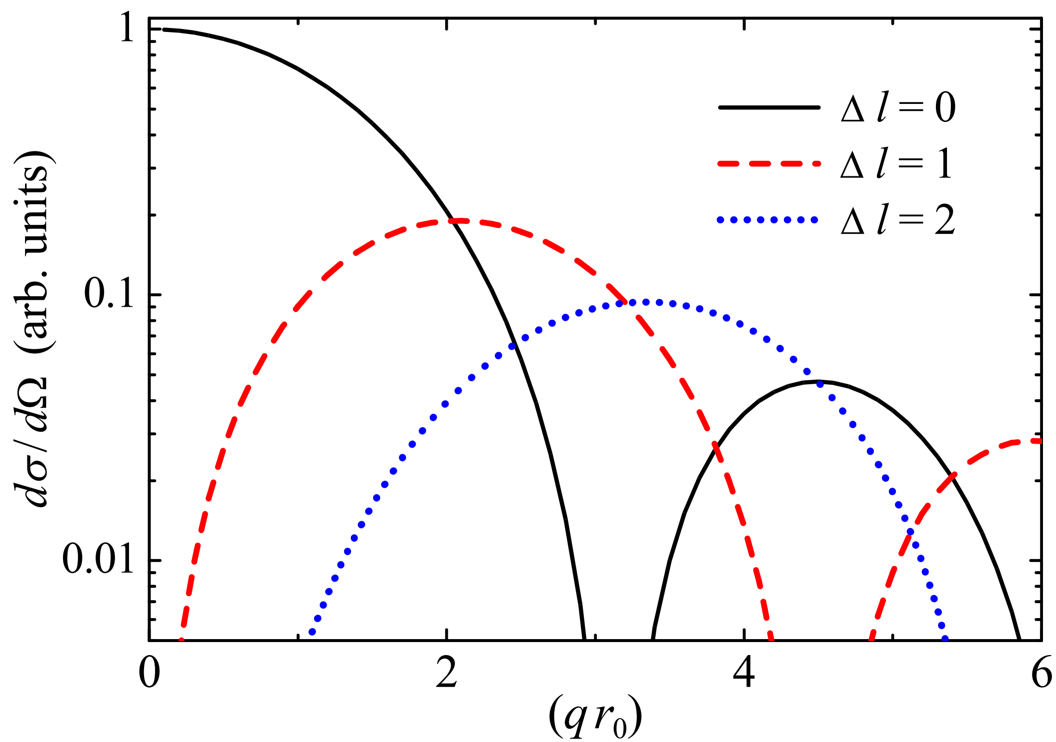
Cryogenic Tritium system
(ordered, R&D)

Zero-angle spectrometer hodoscope
(in development)

Корреляции в состояниях непрерывного спектра заселяемого в прямых реакциях

CMS correlations of the recoils or products





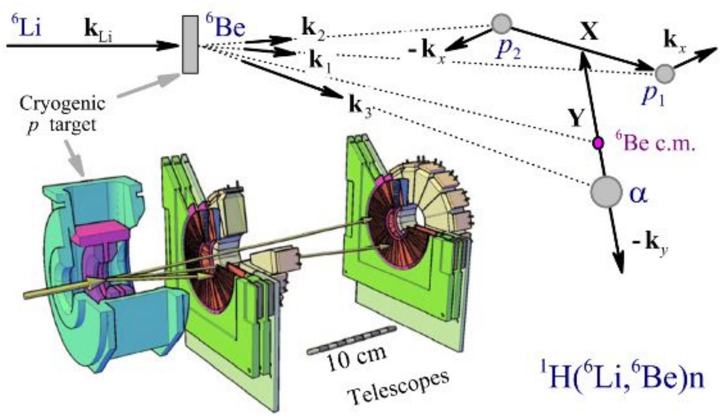
For fixed energy of the product transferred momentum q and cms angle are trivially connected

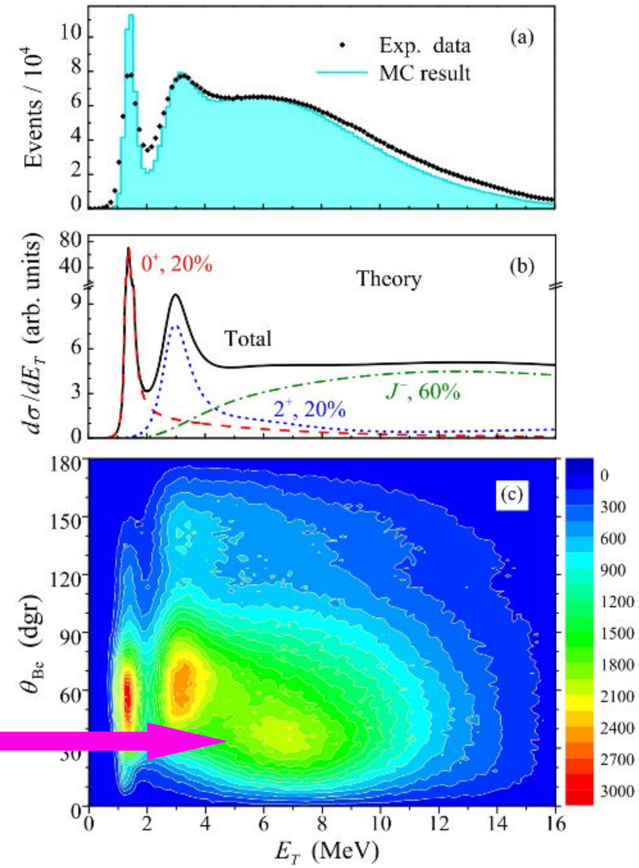
Simple systematics of diffraction minima and maxima as function of the momentum transfer

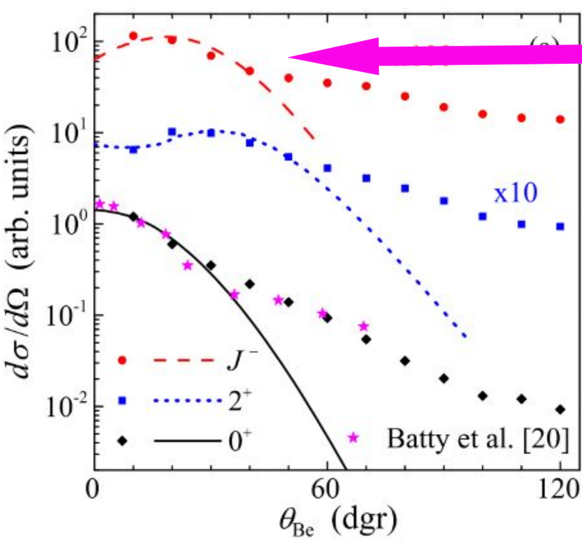
Opportunity of spin-parity identification

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

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

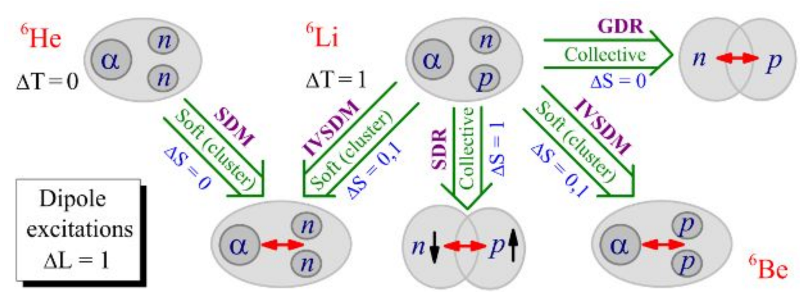






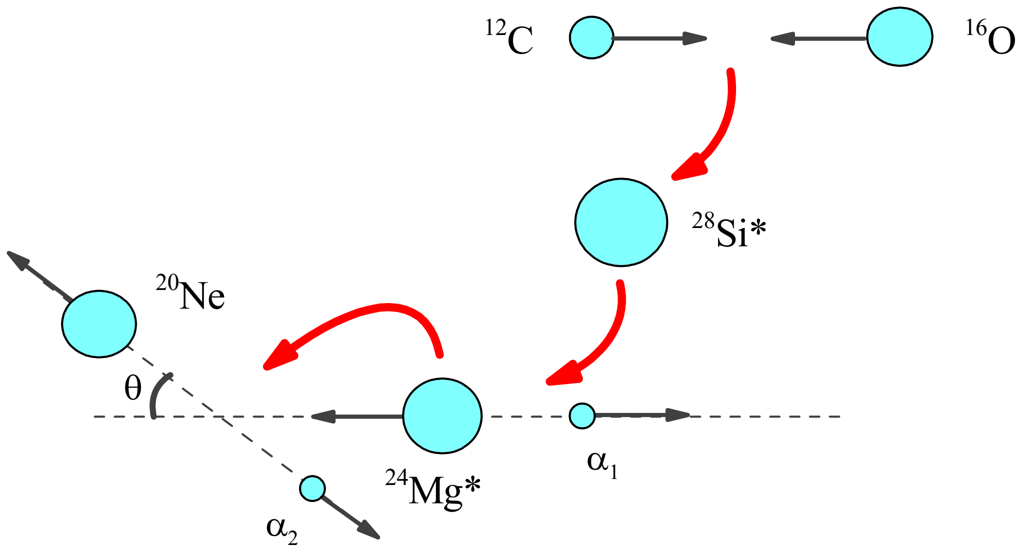
Δ *l* = 1

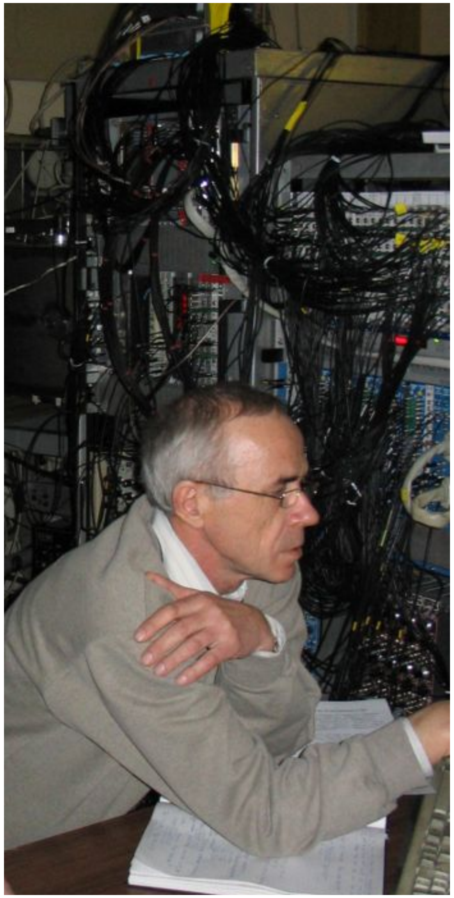
Isovector Soft Dipole Mode identification



Распад выстроенных двухчастичных состояний в системе переданного импульса

Correlations in the “zero geometry” reactions populating continuum states





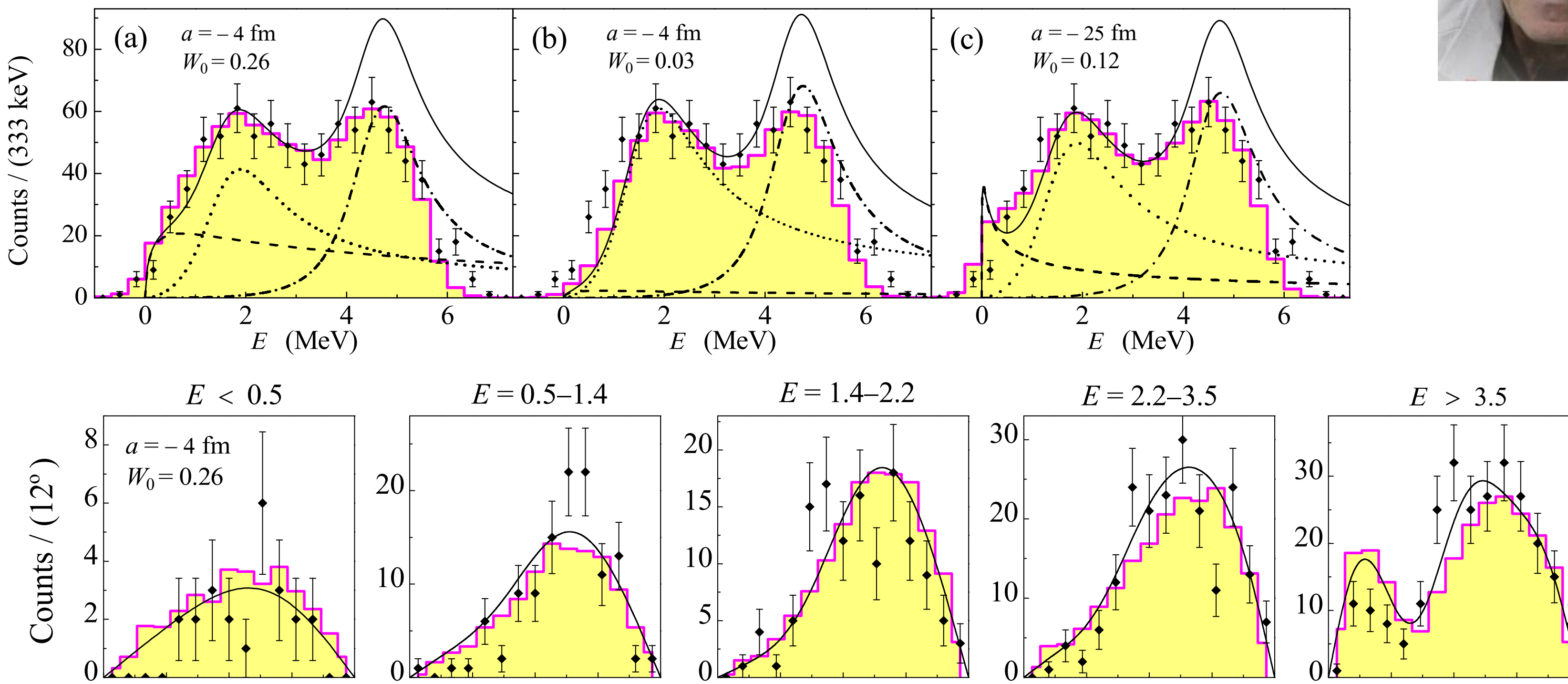
- Correlations in the zero geometry transfer reactions.
- Classics of alpha-cluster state studies
- First alpha-particle is measured at zero angle.
- Then completely aligned intermediate state is populated.
- Then for second alpha-particle the angular distribution is $|P_L^0(\cos\theta)|^2$ where L is angular momentum of intermediate state.

Prof. M. Golovkov pioneered this approach for RIB research

Example: of ^{9}H studied in ^{2}H(^{8}He,p)^{9}H -> ^{8}He+n reaction:

From correlations to spin-parity identification

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



- Due to M = ± 1/2 population the interference leading to backward-forward asymmetry is possible only for { $s_{1/2}$ - $p_{1/2}$, $p_{1/2}$ - $d_{5/2}$, $p_{3/2}$ - $d_{3/2}$ } interference patterns
- Low energy distributions $s_{1/2}$ - $p_{1/2}$ interference → $p_{1/2}$
- Distribution $E > 3.5$ MeV: higher polinomial → d-wave. Asymmetry → $d_{5/2}$
- Set of states is uniquely identified as {$s_{1/2}\, p_{1/2}\, d_{5/2}$}

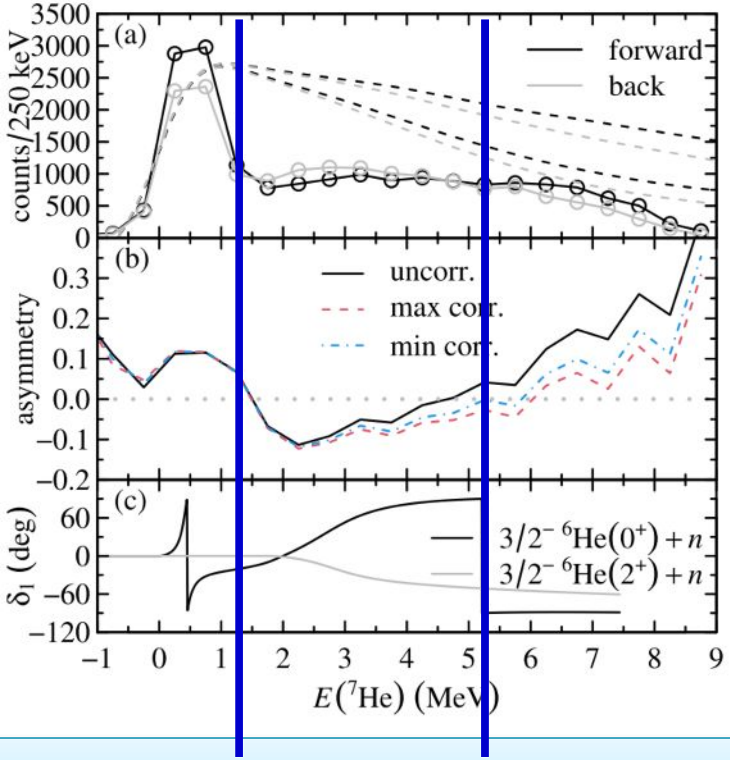
Experimental prospects at ACC-2

^{9}He studies with decisive precision in ^{8}He(d,p) reaction

^{7}He studies with decisive precision in ^{6}He(d,p) reaction

^{10}Li correlations never studied in ^{9}Li(d,p) reaction

^{7}He preliminary data



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

Распад выстроенных трехчастичных состояний в системе переданного импульса

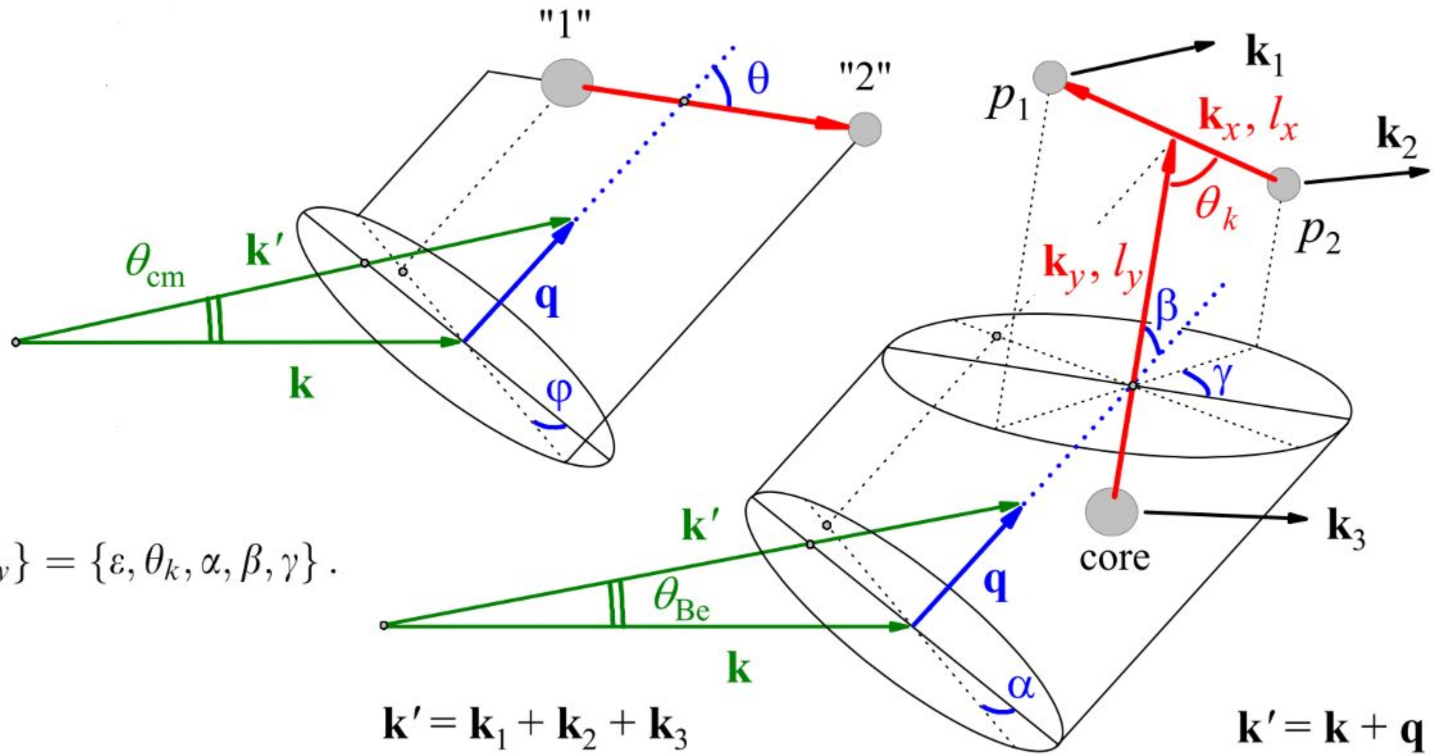
Correlations in the direct reactions populating continuum

2-body decays: are defined by 2 parameters - energy and width

3-body decays: 2-dimensional "internal" 3-body correlations: $\{k_x/k_y, \theta_k\}$

2-body reactions: additional "external" correlation angle θ

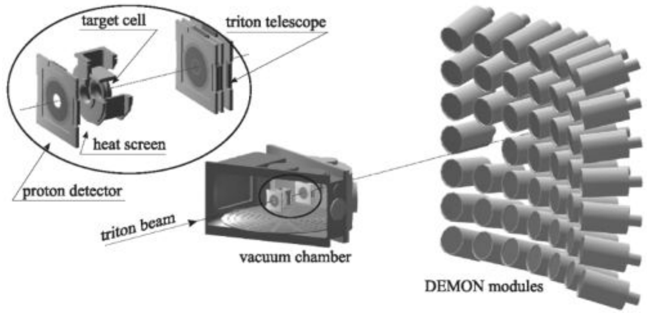
3-body reactions: additional 3-dimensional "external" correlations described by Euler $\{\alpha, \beta, \gamma\}$

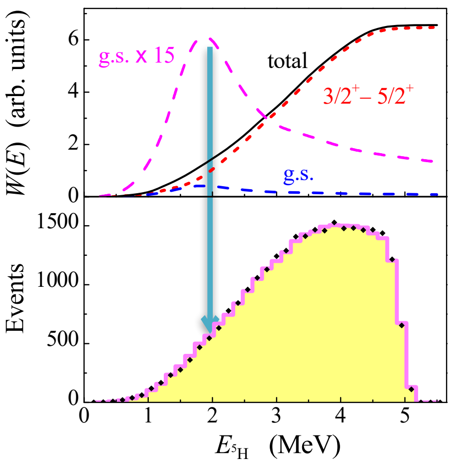


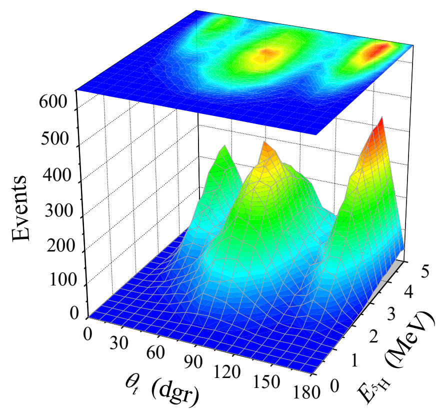
$$\Omega \rightarrow \Omega_2 = \{\theta, \phi\} \,,$$

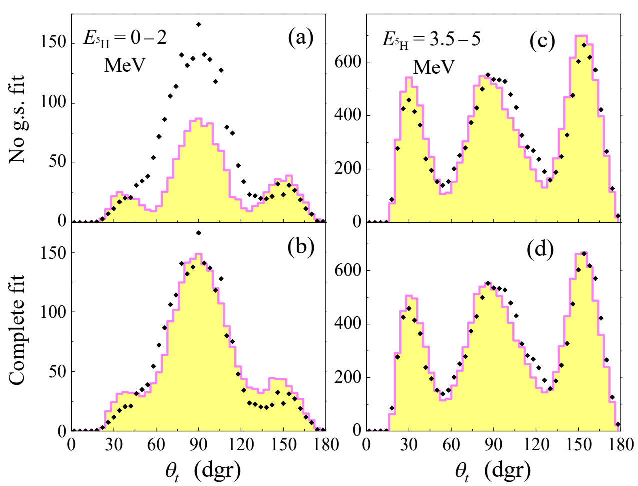
$$\Omega \rightarrow \Omega_5 = \{\varepsilon, \Omega_{kx}, \Omega_{ky}\} = \{\varepsilon, \theta_k, \alpha, \beta, \gamma\} \,.$$

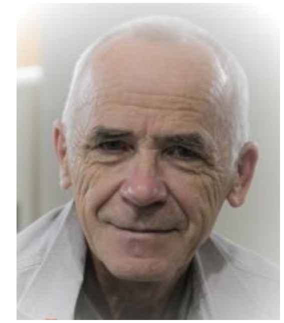
Example: ^{5}H studied in the ^{3}H(t,p)^{5}H -> t+n+n reaction











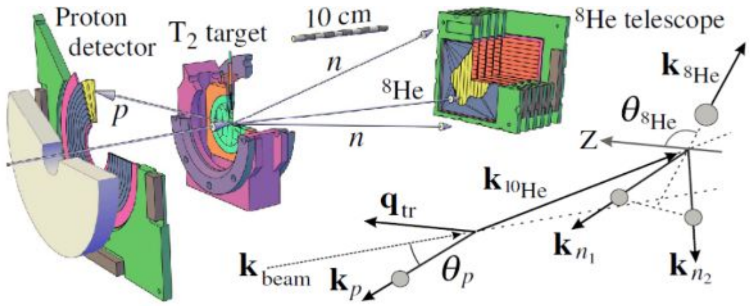
A.A. Korsheninnikov, 2001, ^{6}He(p,2p)^{5}H
Discovery of ^{5}H at FLNR

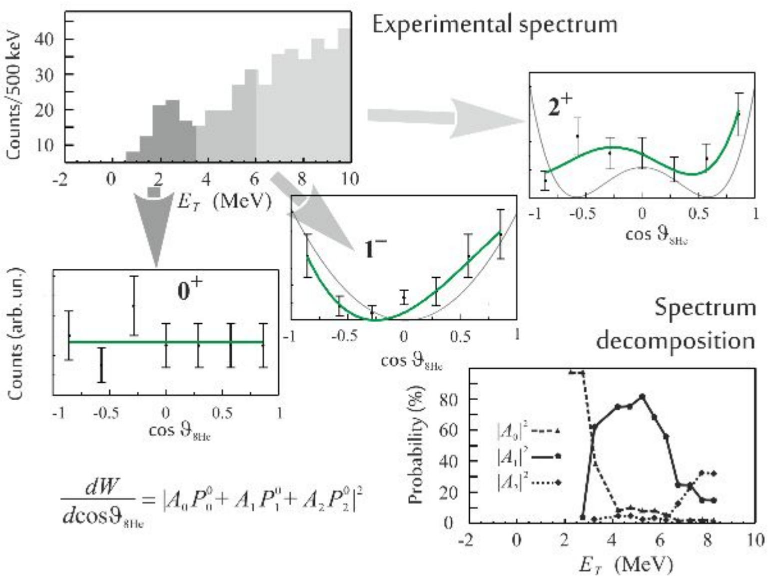
M.S. Golovkov, 2004,
Pioneering correlation studies

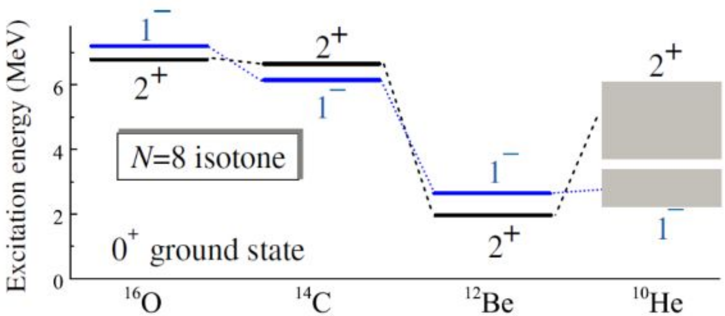
A.A. Korsheninnikov et al., PRL **87** (2001) 92501.
M.S.Golovkov et al., PLB **566** (2003) 70.
M.S.Golovkov et al., PRL **93** (2004) 262501.
S.V. Stepantsov et al., NPA **738** (2004) 436.
M.S.Golovkov et al., PRC **72** (2005) 064612.

- 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 -> ^{8}He+n+n reaction

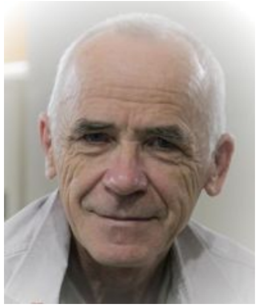






"Conundrum nucleis" second double magic in nuclide chart

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?

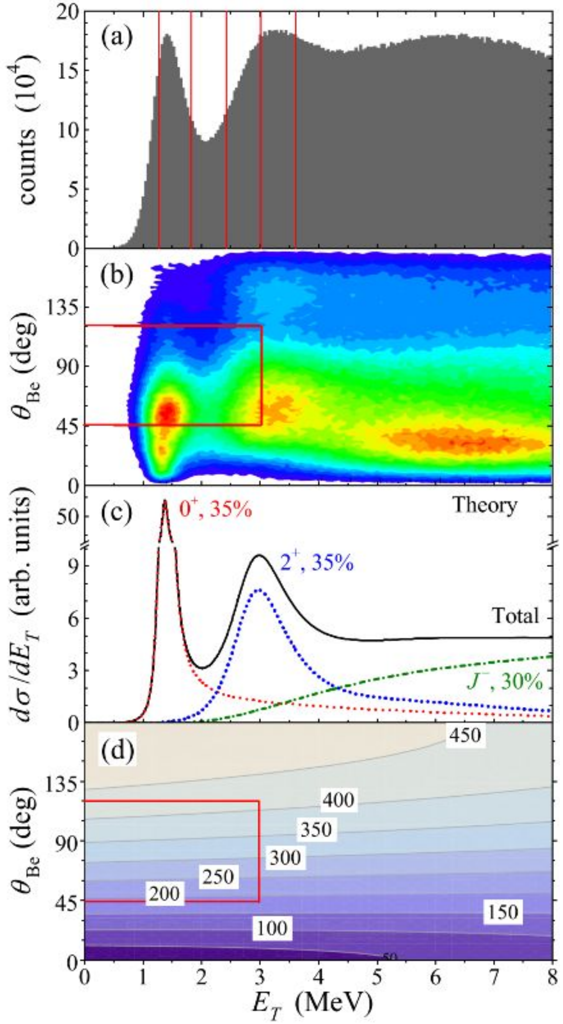
New ground state energy for ^{10}He: E_T=2.0-2.5 MeV

Shell structure breakdown in ^{10}He

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

V. Chudoba *et al.,* PRC C **98**, 054612 (2018)

From known level scheme to complete quantum mechanical information (density matrix parameters as function of energy and cm angle)



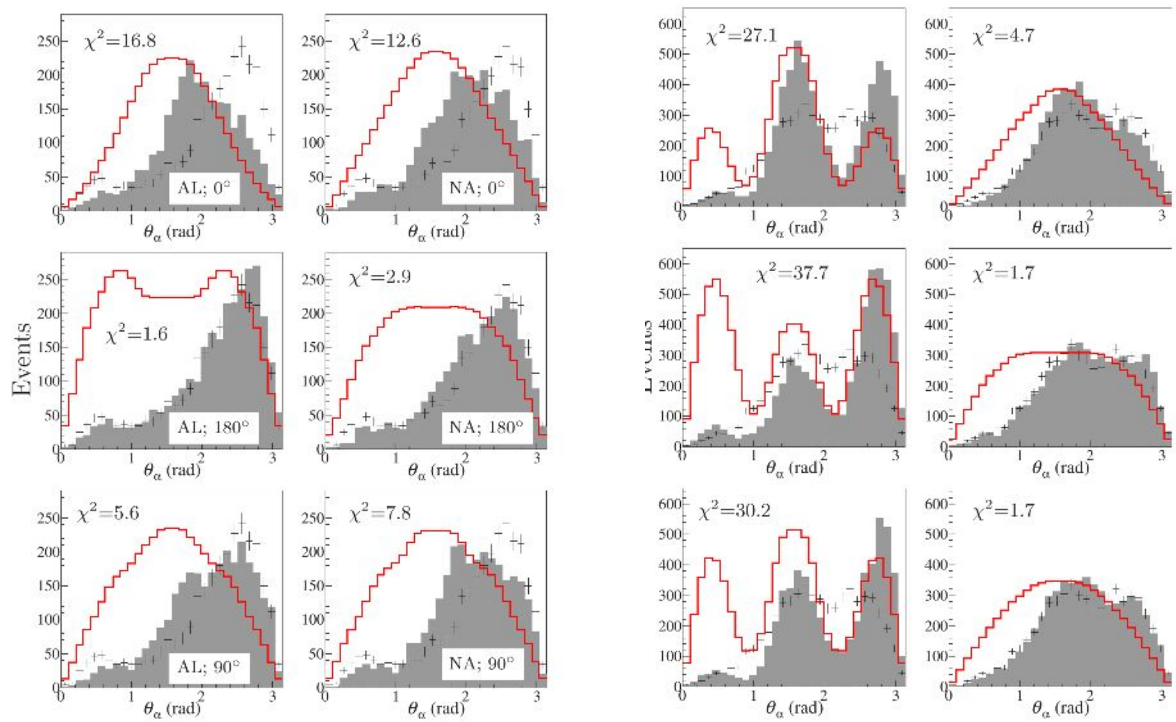


TABLE I. The best fit to experimental data of density matrix parameters for different $\{E_T, \theta_{\rm Be}\}$ ranges. The fits were found using the figures with θ_α distribution for all six configurations of the theoretical model.

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; $\varphi_{02}=135^\circ$	AL + 50% NA; $\varphi_{02}=180^\circ$	AL; $\varphi_{02}=180^\circ$	AL + 20% NA; $\varphi_{02}=180^\circ$
1.9–2.5	AL + 50% NA; $\varphi_{02}=135^\circ$	NA + 10% AL; $\varphi_{02}=180^\circ$	NA; $\varphi_{02}=180^\circ$	AL + 10% NA; $\varphi_{02}=90^\circ$
2.5–3.1	NA + 10% AL; $\varphi_{02}=180^\circ$	AL + 10% NA; $\varphi_{02}=180^\circ$	NA + 30% AL; $\varphi_{02}=90^\circ$	NA; $\varphi_{02}=135^\circ$

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

Изучение изотопической симметрии ядерных реакций в процессах (T,^{3}He) vs. (^{3}He,T)

Заселение двухпротонных распадчиков в реакциях (^{3}He,n)

Двухпротонная радиоактивность

“Внутренние” трехчастичные корреляции

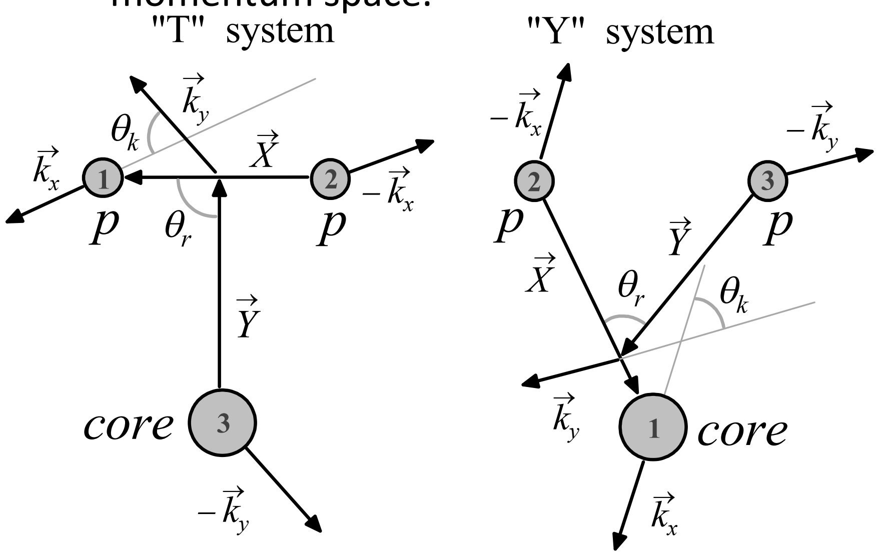
2-body decay: state is defined by 2 parameters - energy and width

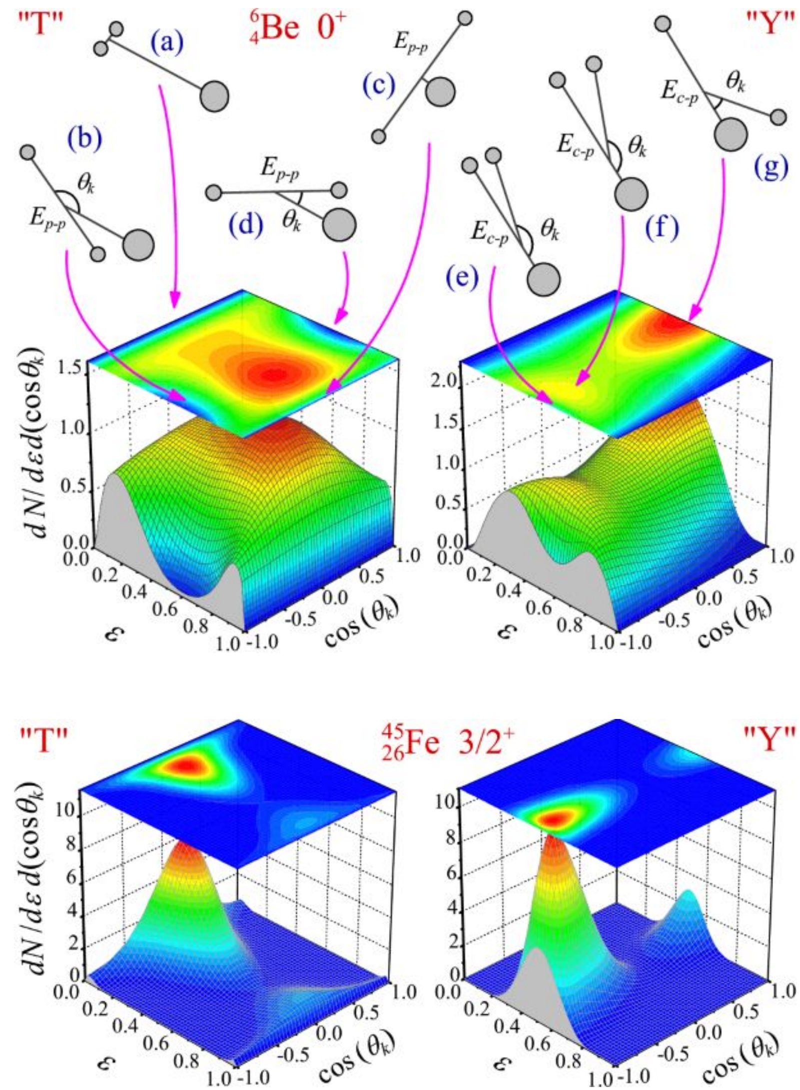
3-body decays: 2-dimensional “internal” 3-body correlations

- 2-dimensional “internal three-body correlations” or “energy-angular correlations”

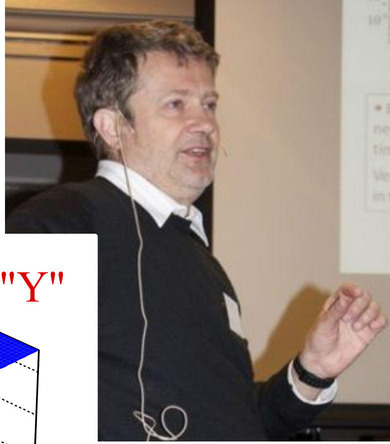
$$\varepsilon = E_x / E_T \qquad \cos(\theta_k) = (\mathbf{k}_x,\mathbf{k}_y)/k_x k_y$$

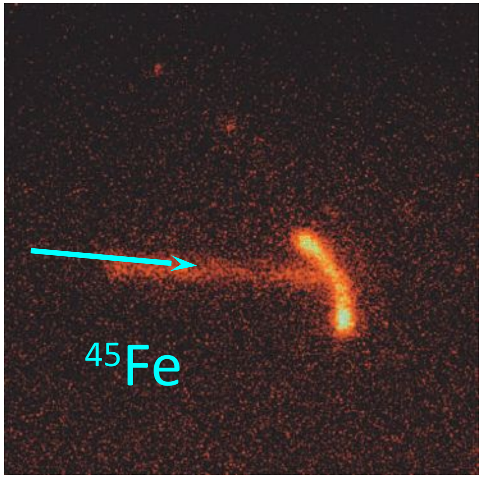
- “T” and “Y” Jacobi systems reveal different dynamical aspects
- Three-body variables in coordinate and in momentum space.

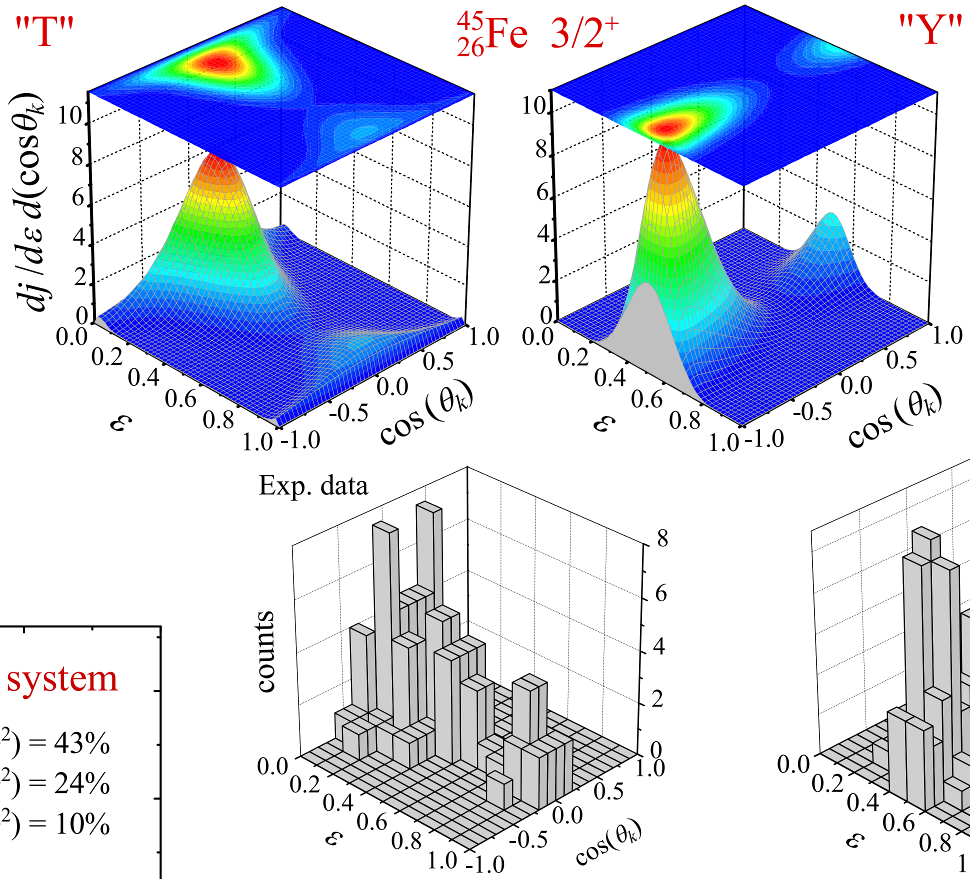


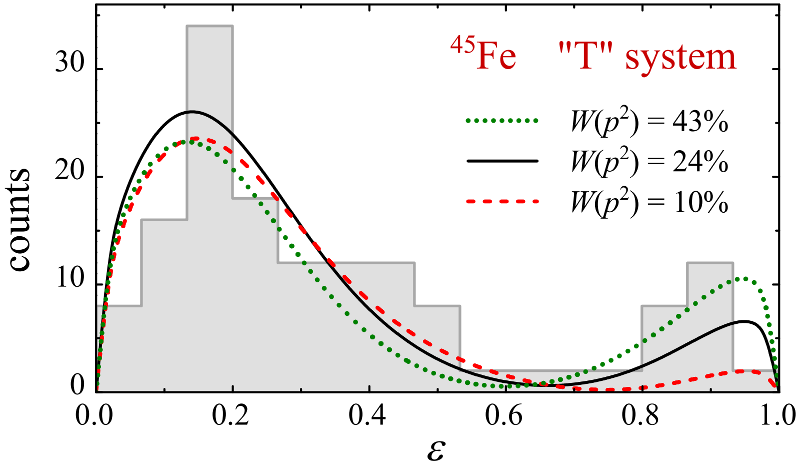


^{45}Fe: “внутренние” трехчастичные корреляции









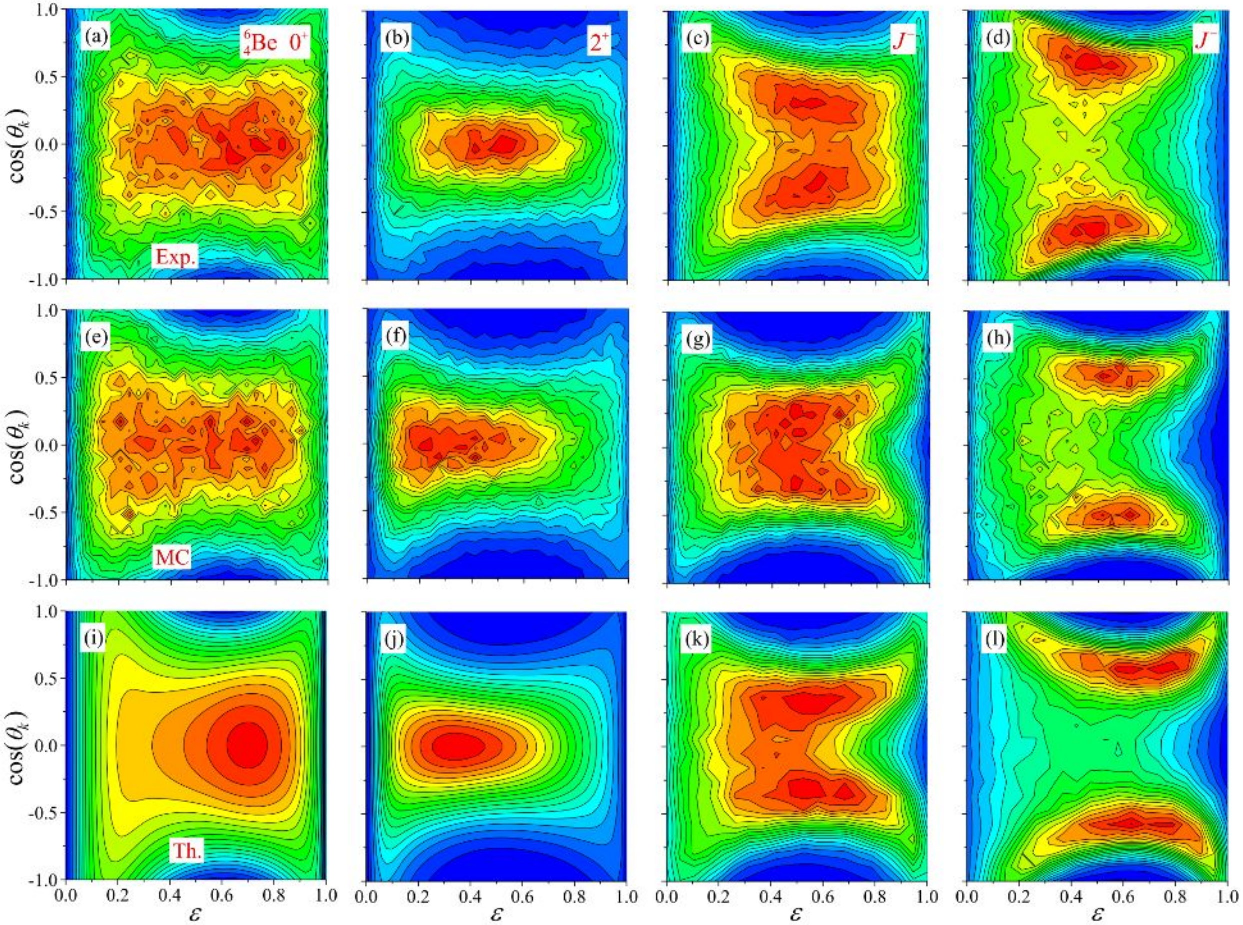
Miernik *et al.*, PRL **99** (2007) 192501

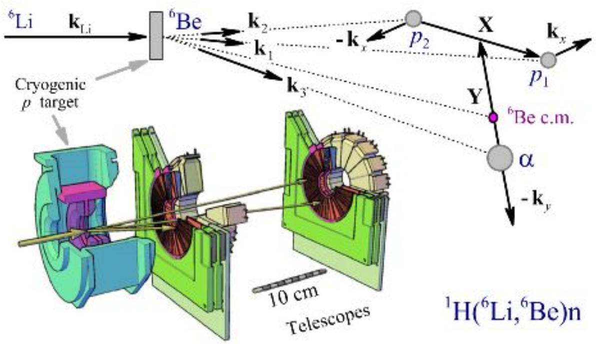
- Complete kinematics reconstructed
- Both lifetime and correlations provide $W(p^2) \sim 30\%$

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





For positive parity states perfect agreement with theoretical predictions

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

Δ *l* = 0 → 0$^+$

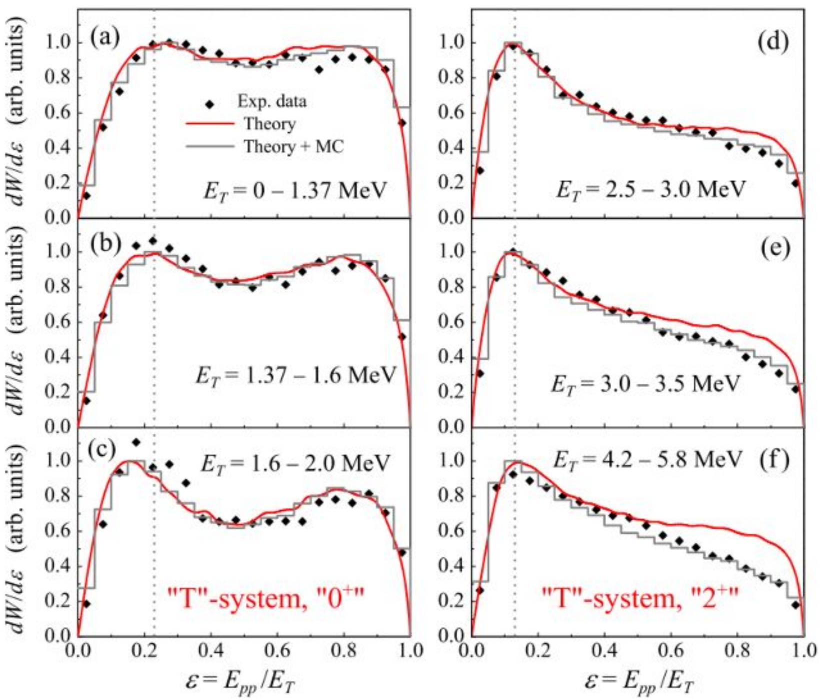
Δ *l* = 2 → 2$^+$

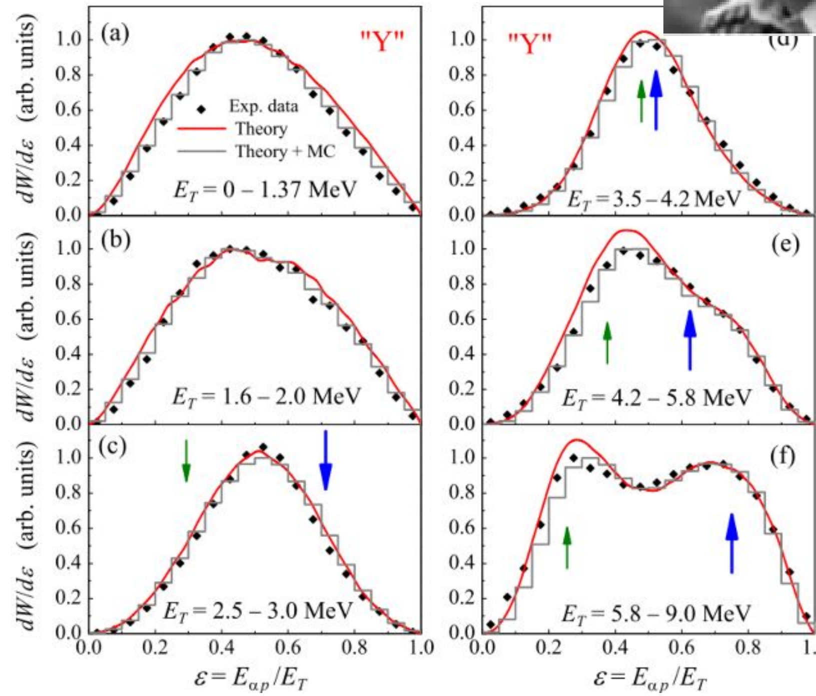
Δ *l* = 1 → *J*$^-$

Example: $^7Be(^9Be,X)^6Be \rightarrow \alpha+p+p$

^{6}Be as a "benchmark" system for three-body decays

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





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 $E_T > 2E_r + \Gamma$

Experimental prospects at ACC-2

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

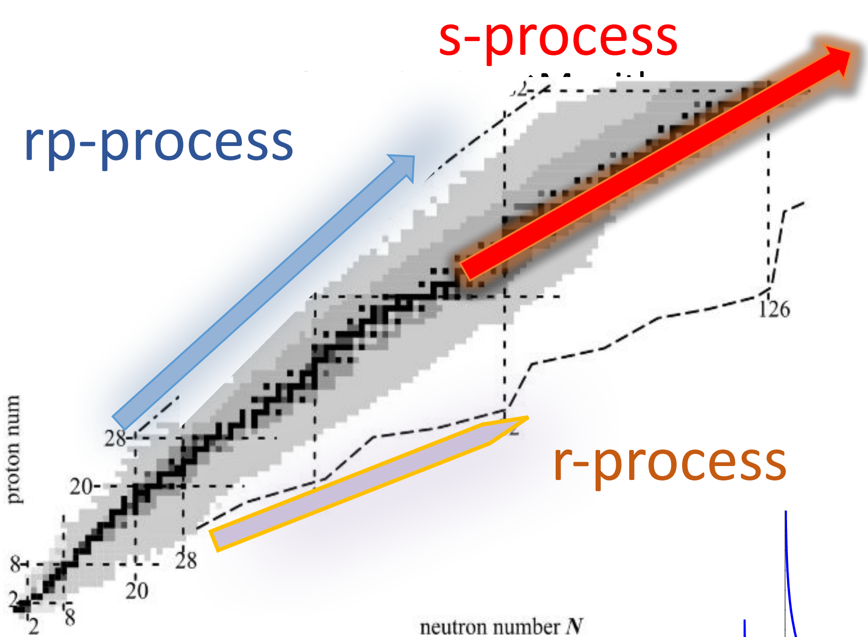
Search for 2p radioactive decay of the first excited state of ^{17}Ne

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

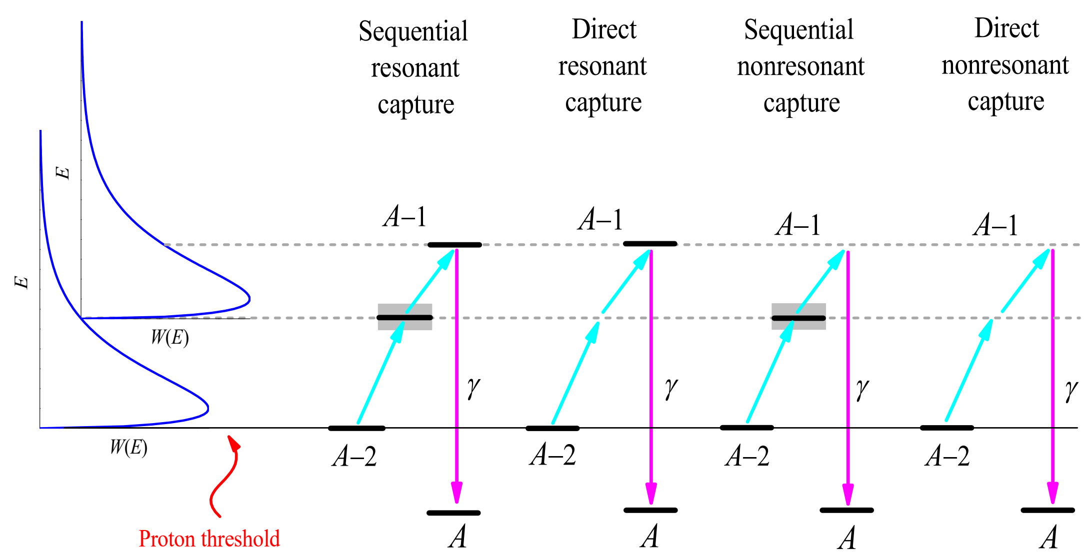
Мягкие дипольные переходы и задачи астрофизического цикла

Three-body radiative capture reactions: where and why?

- Extreme pressure and temperature.
- "Classics": $\alpha+\alpha+\alpha \rightarrow {}^{12}C+\gamma$.
- R-process nucleosynthesis: 2n capture.
- Rp-process nucleosynthesis: 2p capture.

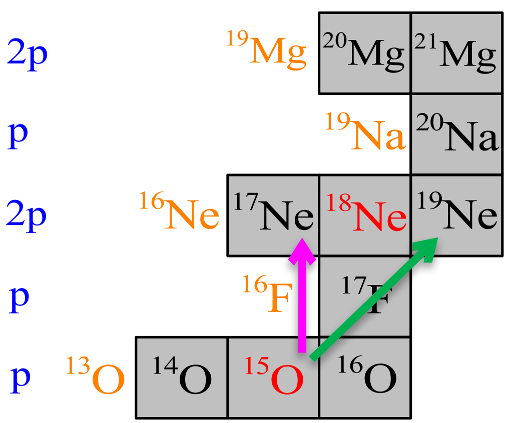


Modes of 2p and 2n radiative capture



Reverse to sequential 2p	Reverse to true 2p decay	Reverse to soft dipole mode

«Waiting points» bypass



Radiative capture reactions: three-body vs. two-body

"Classical" way to determine the three-body capture rate [Fowler, Annu. Rev. Astron. Astrophys. 5 (1967) 525] and recent review [Angulo, Nucl. Phys. A 656 (1999) 3–183].

$$A_1 + A_2 + A_3 \to A_{123} + \gamma,$$

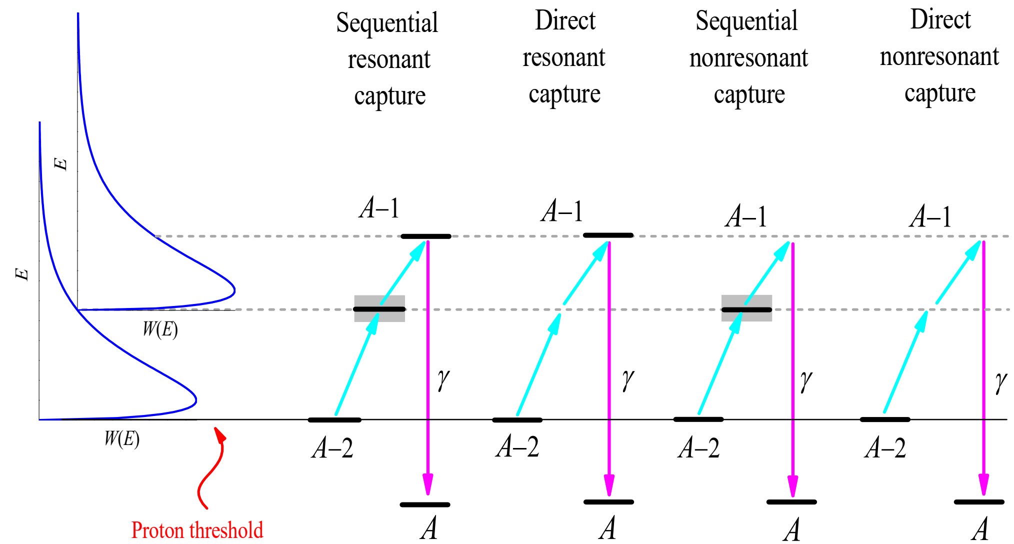
$$\langle \sigma_{A_1 A_2 A_3,\gamma} v \rangle = \sum_i \frac{\langle \sigma_{A_1 A_2,(A_1 A_2)} v \rangle_i}{\Gamma_{(A_1 A_2),i}} \langle \sigma_{(A_1 A_2) A_3,\gamma} v \rangle_i ,$$

Is essentially quasiclassical as it is based on the classical "chemical equilibrium" equations

$$\dot{Y}^{(i)}_{(A_1 A_2)} = N_A \rho \langle \sigma_{A_1 A_2,(A_1 A_2)} v \rangle_i \, Y_{A_1} Y_{A_2} - \Gamma_{(A_1 A_2),i} \, Y^{(i)}_{(A_1 A_2)} ,$$

$$\dot{Y}_{(A_1 A_2 A_3)} = \sum_i N_A \rho \langle \sigma_{(A_1 A_2) A_2,\gamma} v \rangle_i \, Y^{(i)}_{(A_1 A_2)} Y_{A_3} ,$$

Modes of 2p and 2n radiative capture



Sequential	Reverse to true 2p decay	Reverse to soft dipole mode

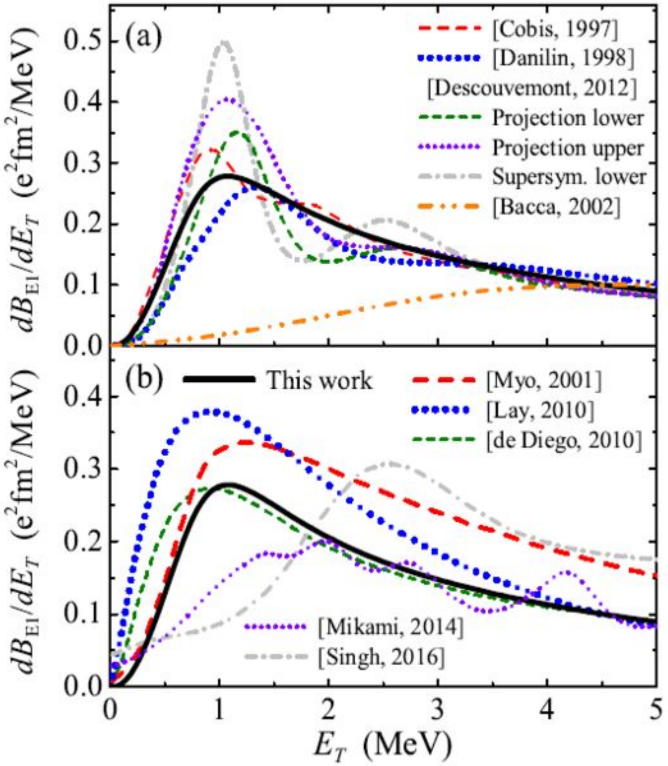
Problems:

(i) "Classical" expression does not contain direct resonant capture. Solved in [Grigorenko and Zhukov, PRC 72 (2005) 015803]).

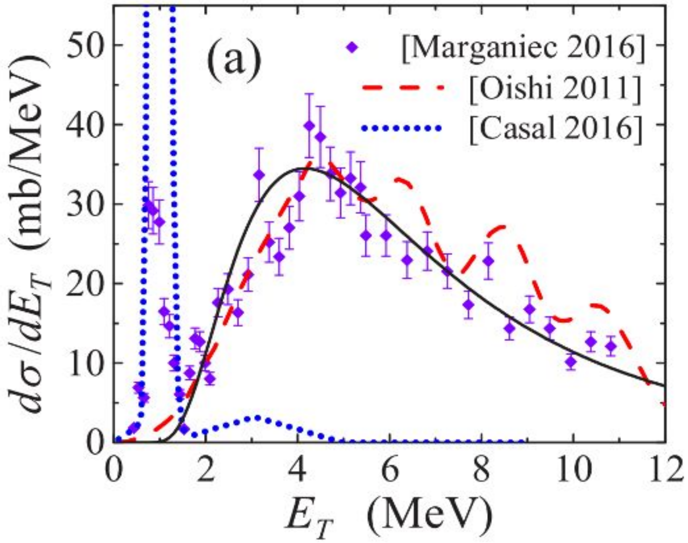
(ii) "Classical" expression for nonresonant capture rates can not be calibrated: violation of E1 sum rule is possible.

E1 SDM strength functions for 2n and 2p processes

Three-body E1 dissociation
$^{6}He \rightarrow {}^{4}He+n+n$



Three-body E1 dissociation
$^{17}Ne \rightarrow {}^{15}O+p+p$

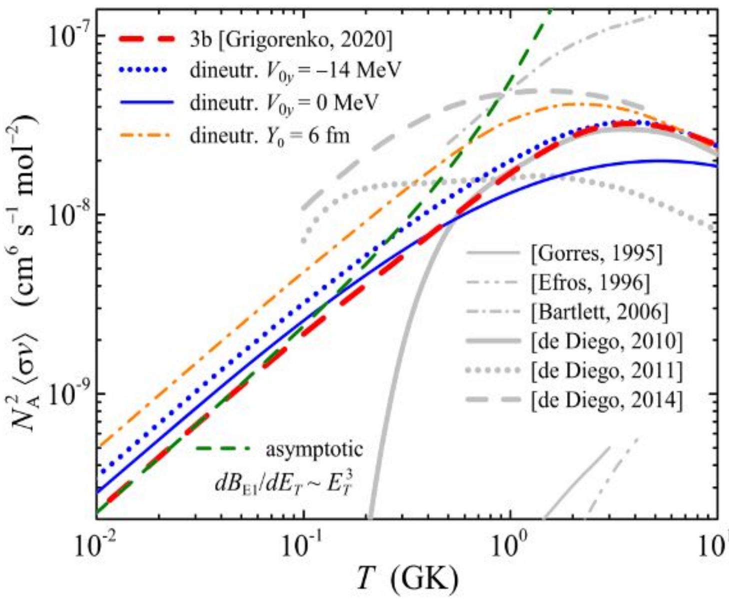


Qualitative changes
compared to previous works

Astrophysical 2p and 2n nonresonant capture rates improved

Nonresonant 2n

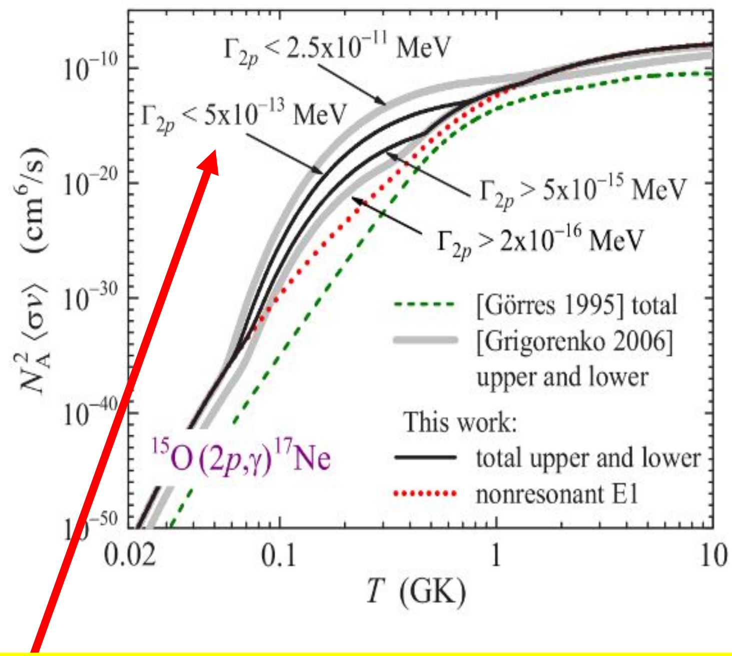
$^4He+n+n \rightarrow {}^6He + \gamma$



Orders of the magnitude improvements compared to previous works

Nonresonant + resonant 2p

$^{15}O+p+p \rightarrow {}^{17}Ne + \gamma$



JINR prize 2017 in experiment!

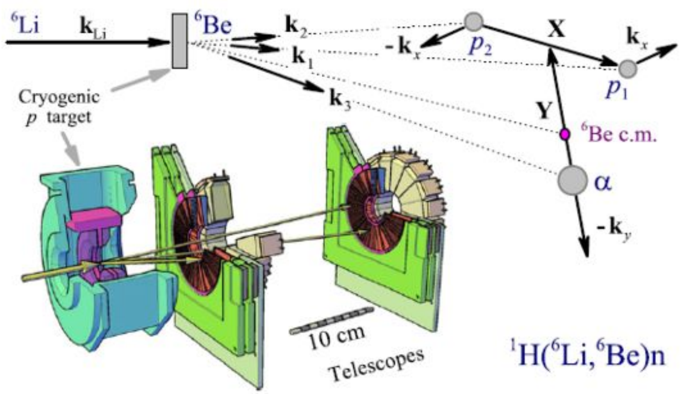
PHYSICAL REVIEW C **96**, 025807 (2017)

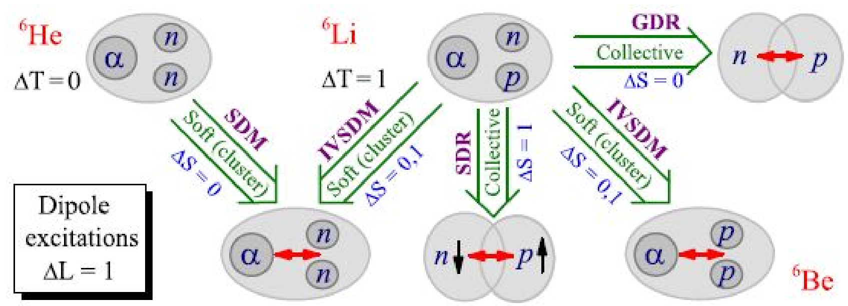
Search for 2*p* decay of the first excited state of ^{17}Ne

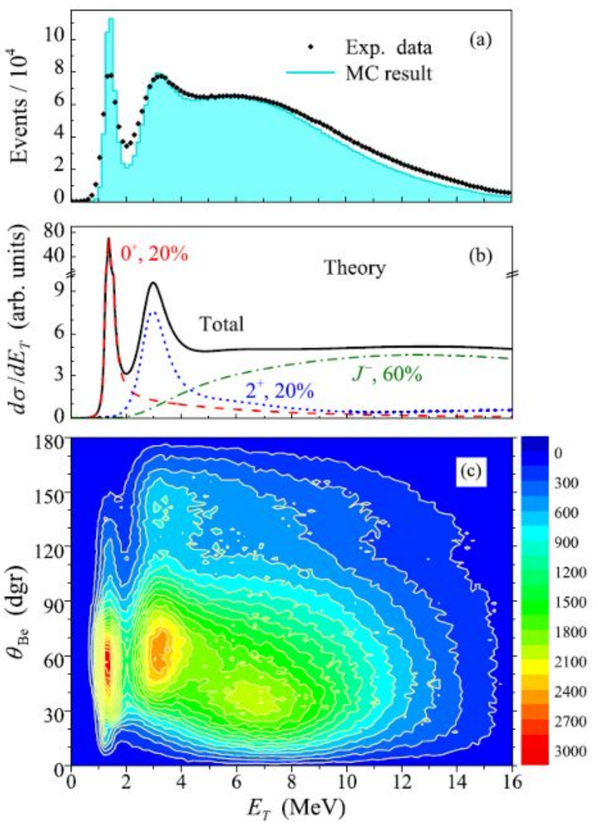
P. G. Sharov,[1,2,*] A. S. Fomichev,[1,3] A. A. Bezbakh,[1,2] V. Chudoba,[1,4] I. A. Egorova,[5,2] M. S. Golovkov,[1,3] T. A. Golubkova,[6,2] A. V. Gorshkov,[1,2] L. V. Grigorenko,[1,7,8] G. Kaminski,[1,9] A. G. Knyazev,[1,2] S. A. Krupko,[1,2] M. Mentel,[1,10] E. Yu. Nikolskii,[7,1] Yu. L. Parfenova,[1,11] P. Pluchinski,[1,10] S. A. Rymzhanova,[1,2] S. I. Sidorchuk,[1] R. S. Slepnev,[1] S. V. Stepantsov,[1] G. M. Ter-Akopian,[1,3] and R. Wolski[1,9]

Isovector Soft Dipole mode in ^{6}Be

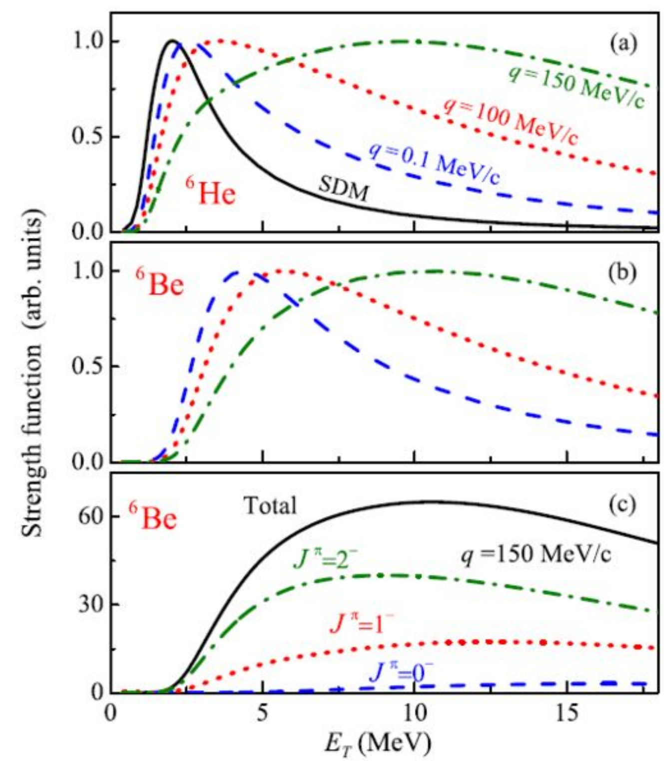
A.S.Fomichev et al., PLB **708** (2012) 6.







- Large cross section above 2^+ and no resonance
- ΔL=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

^{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

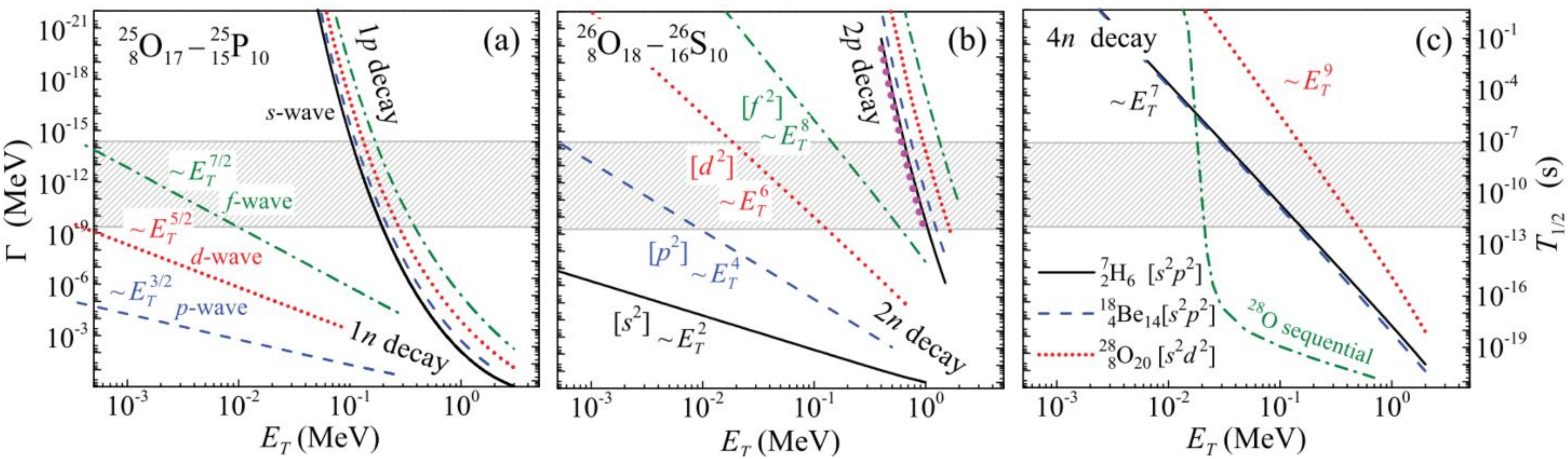
Search for 2p radioactive decay of the first excited state of ^{17}Ne

Сверхтяжелые водороды ^6H, ^7H

Что особенного в ^7H?

- ^7H тяжелейший мыслимый более-менее стабильный изотоп водорода (закрытая $p_{3/2}$ нейтронная подоболочка).
- Отношение A/Z = 7 ближе всего к идее о нейтронной материи чем что-либо в ядерной физике.
- Ожидалось что ^7H g.s. распадается по уникальному 5-частичному core+4n каналу
- Может быть исключительно долгоживущим – кандидат на 4n radioactivity.

Grigorenko, Mukha, Scheidenberger, Zhukov,
PRC 84, 021303(R) (2011)
4n radioactivity prediction



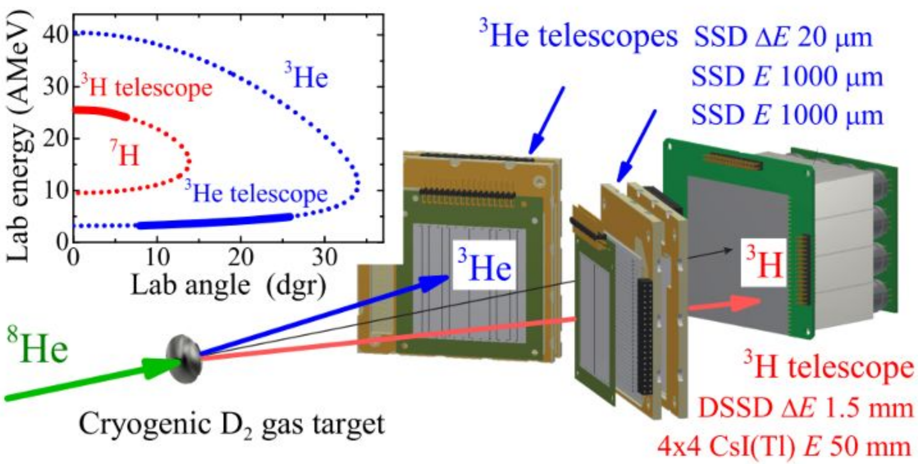
$^{2}H(^{8}He, ^{3}He)^{7}H$ reaction

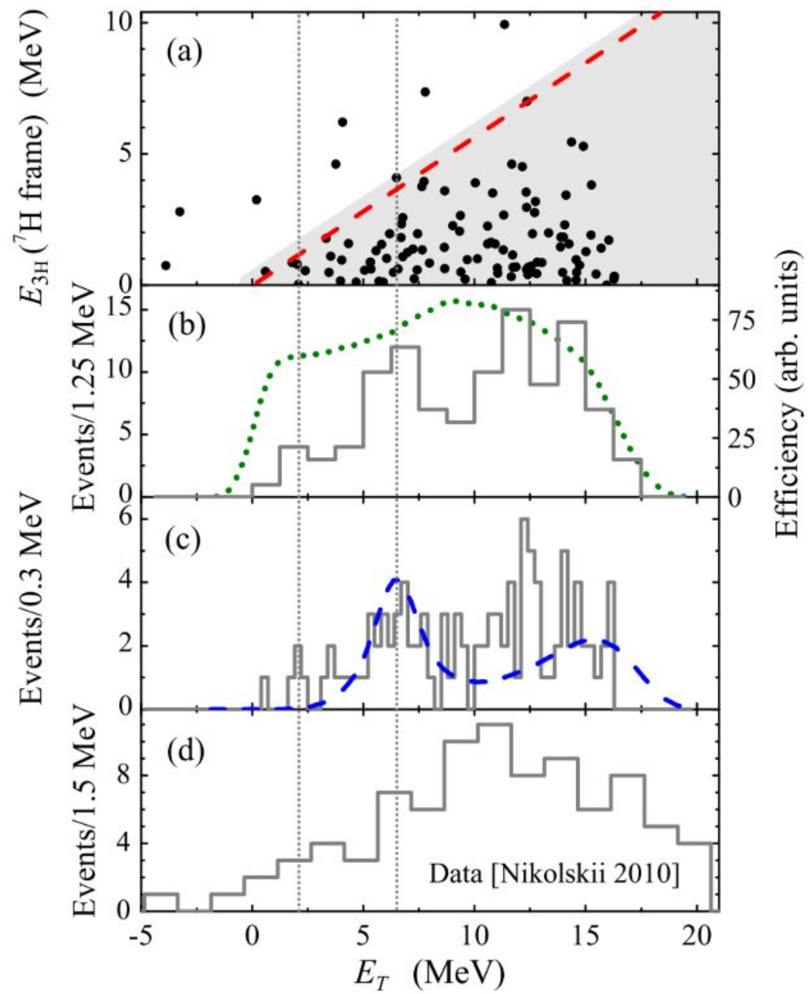
PHYSICAL REVIEW LETTERS **124**, 022502 (2020)

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 ground state at 1.8 MeV
- May be something at 12 MeV

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

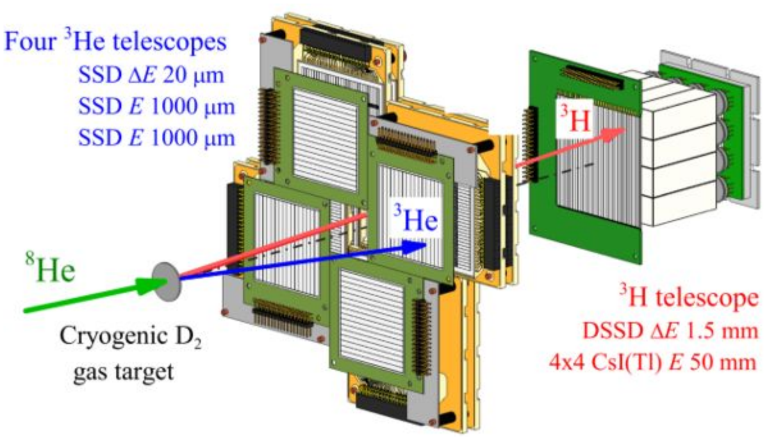
PHYSICAL REVIEW C **103**, 044313 (2021)

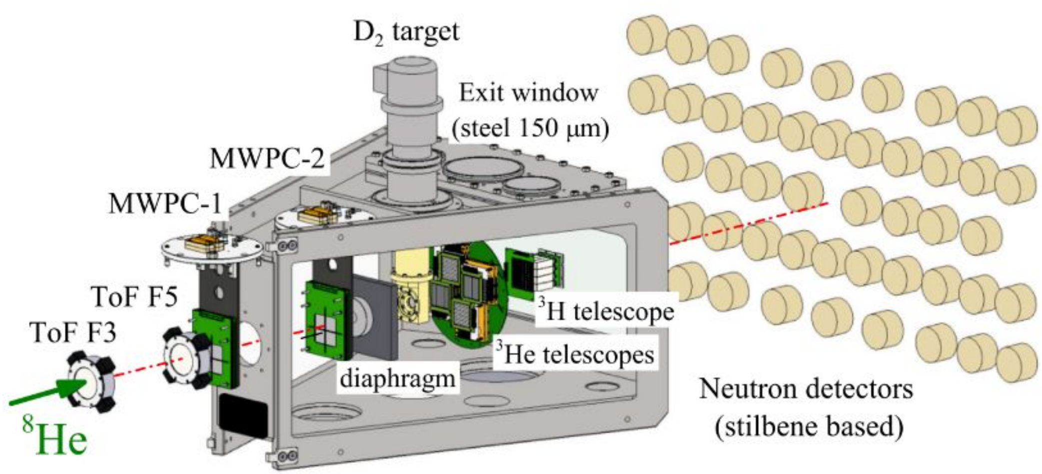
Resonant states in ^{7}H: Experimental studies of the ^{2}H(^{8}He, ^{3}He) reaction

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]

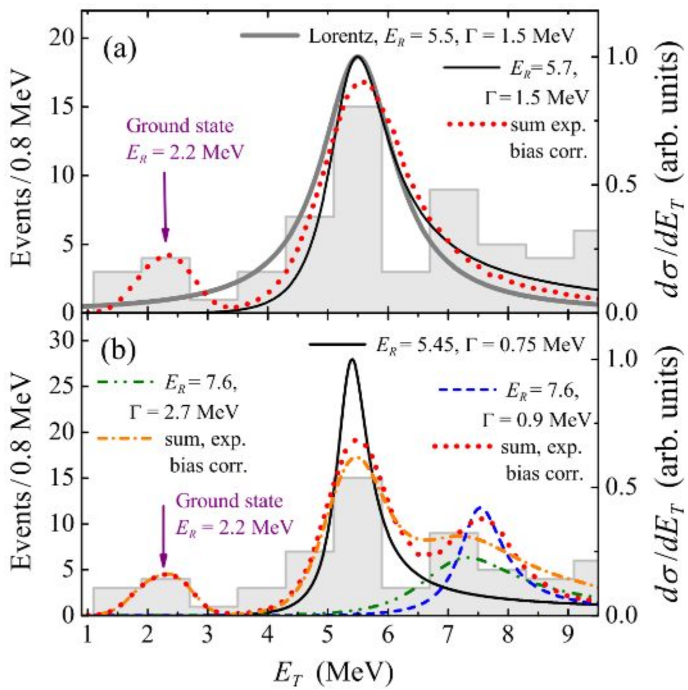
^{8}He beam 26 AMeV, 10^{5} pps
2019, 3 weeks

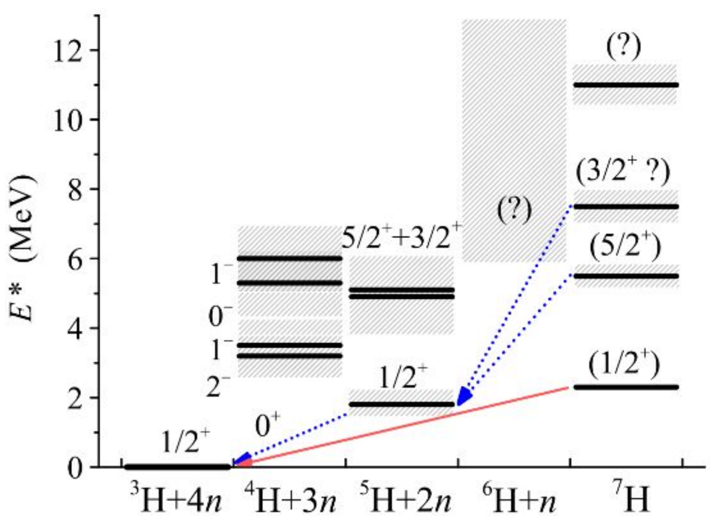
“Comming out party” for the neutron wall

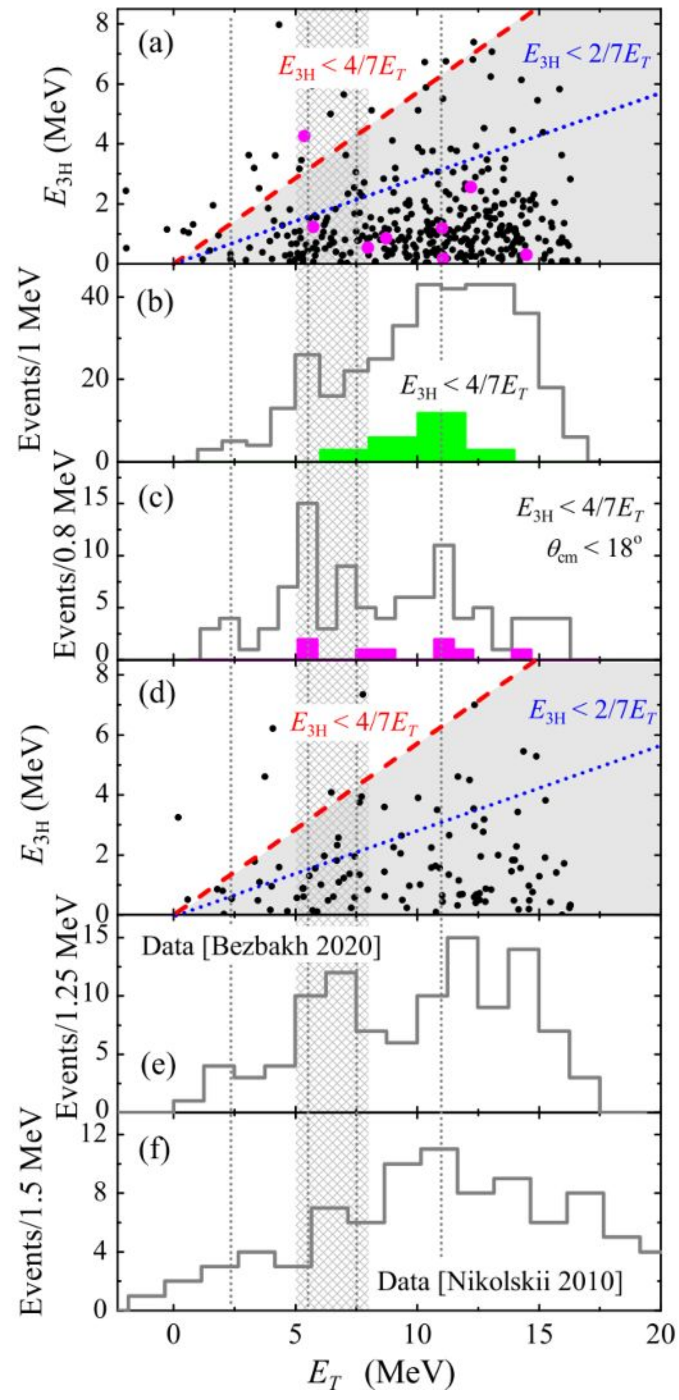




^{7}H data and spectrum



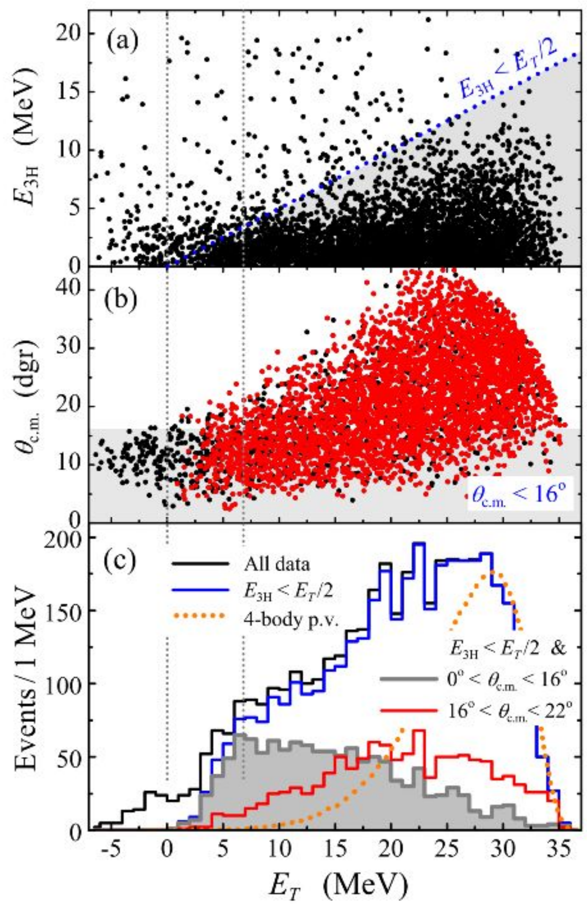




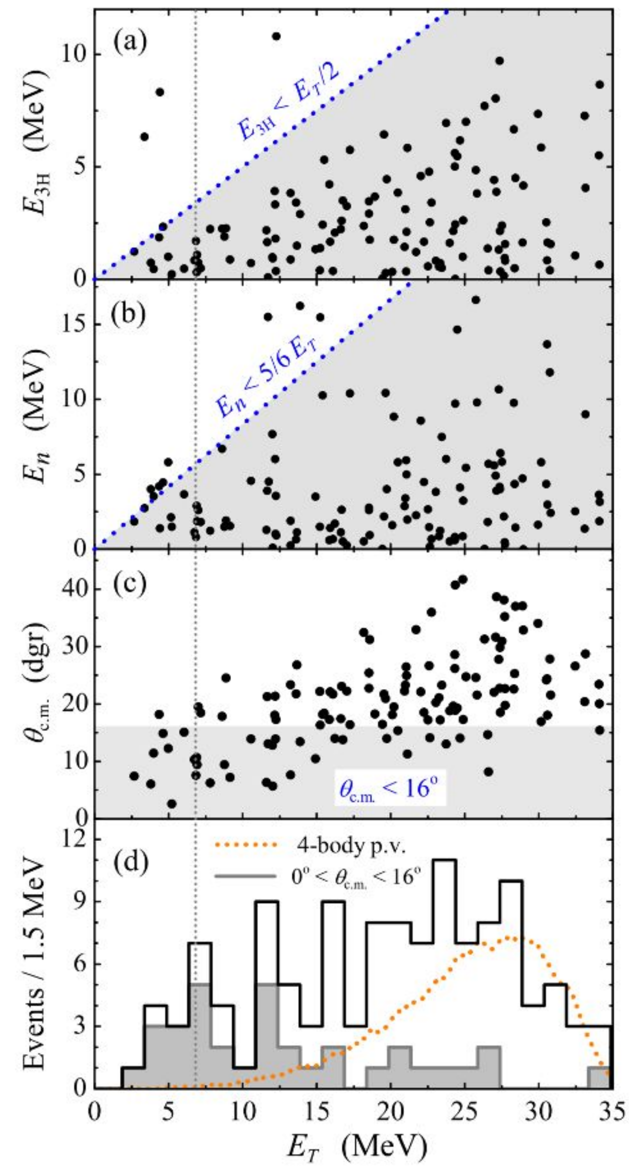
“Satellite” experimental data on ^{6}H from ^{2}H(^{8}He,^{4}He)^{6}H

Nikolskii *et al.*,
PRC 105, 064605
(2022)

Double coincidences ^{4}He-^{3}H



Triple coincidences ^{4}He-^{3}H-n



– Setup is not specially suited for this experiment

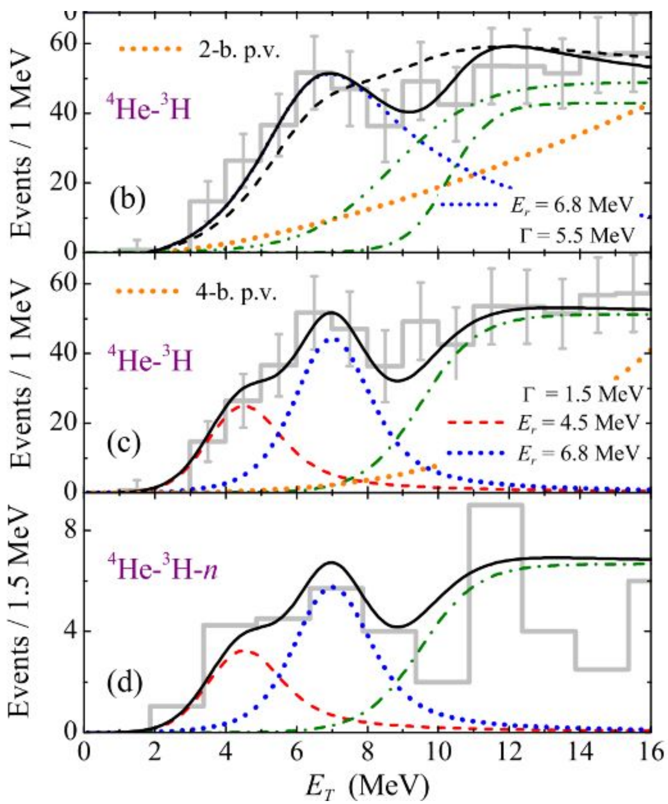
– Higher cross section and high statistics (factor 10)

– Large backgrounds (accidental alphas)

– Neutron coincidence data

Preliminary results

Background-subtracted, efficiency corrected

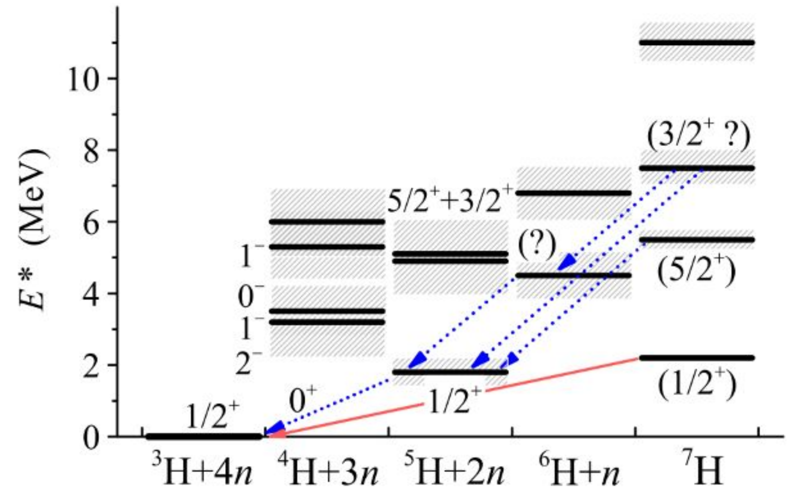


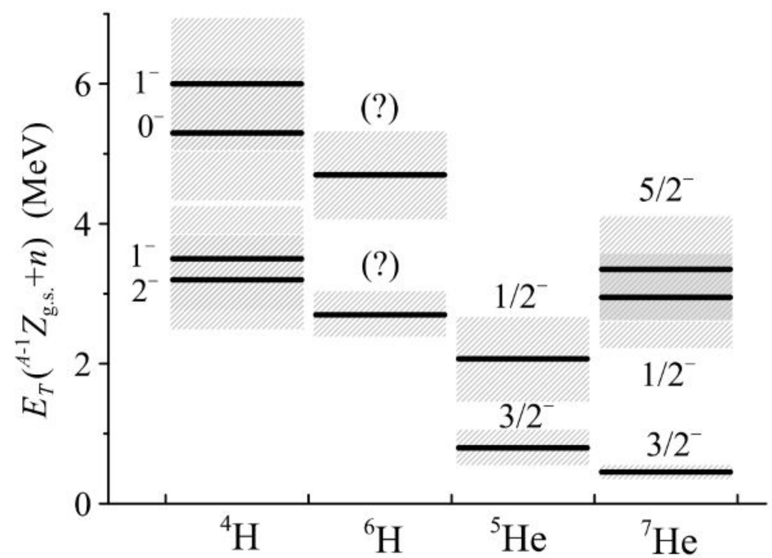
– No ^{6}H g.s. at 2.6-2-7 MeV

– Resonant state at 6.5 MeV

– Possible resonant state at 4.5 MeV

Excitation spectra relative ^{3}H ground state





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

Experimental prospects at ACC-2

^{7}H studies with decisive precision in $^{8}He(d,^{3}He)$ reaction

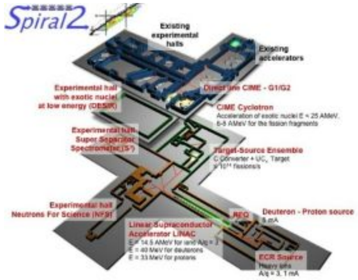
^{6}H studies with decisive precision in $^{8}He(d,^{4}He)$ reaction

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

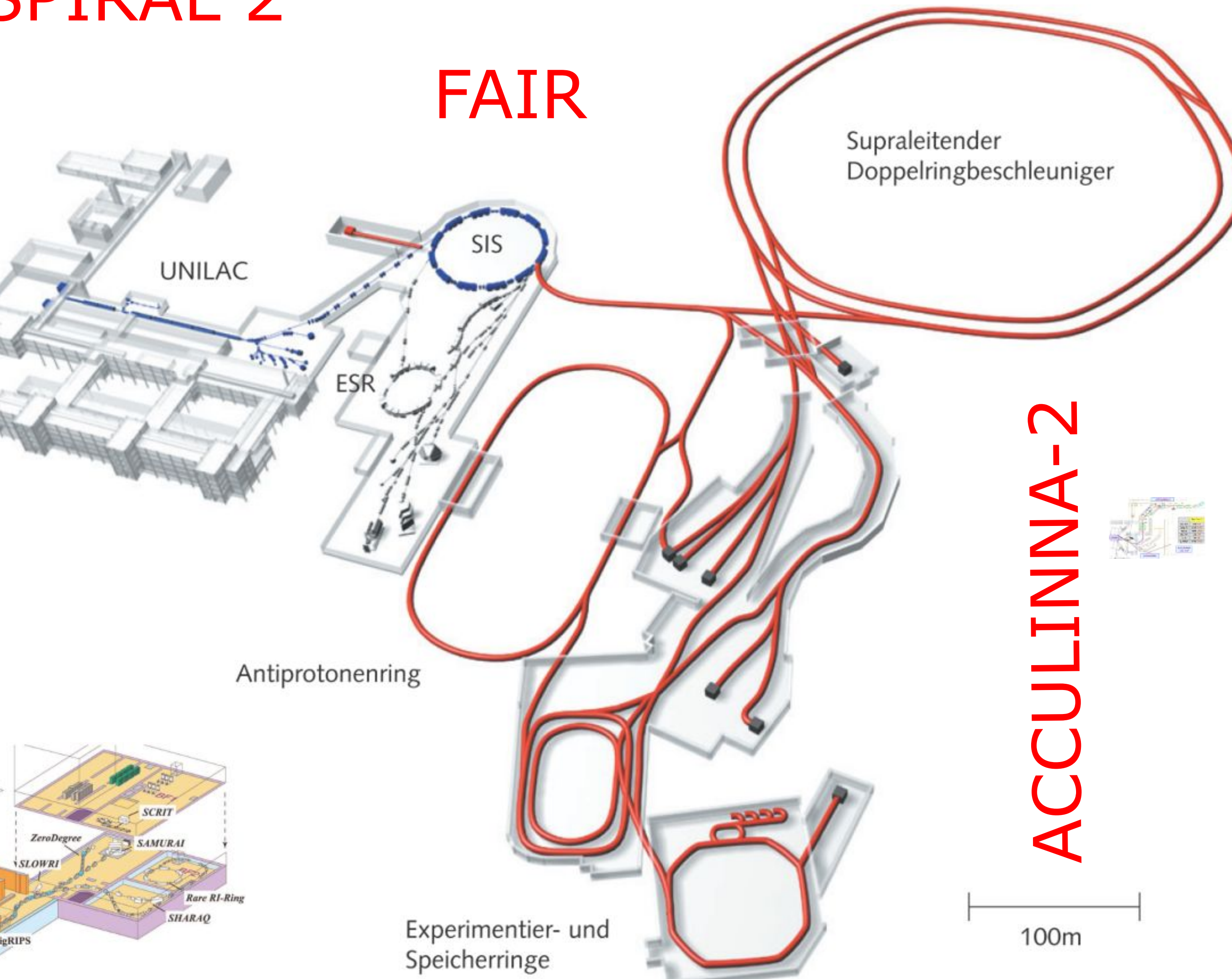
Более далекое будущее?

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

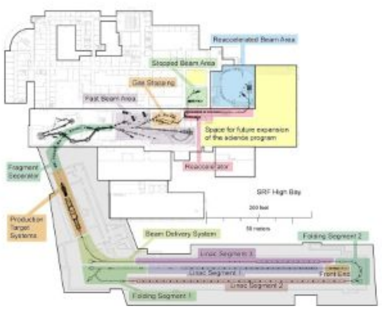
SPIRAL 2



FAIR

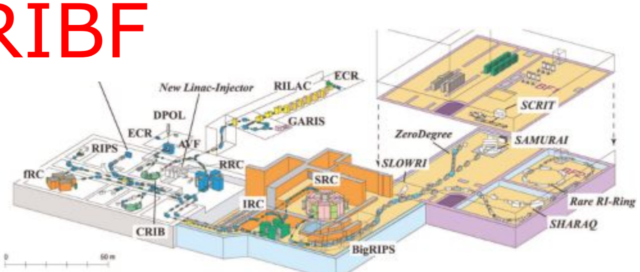


FRIB



ACCULINNA-2

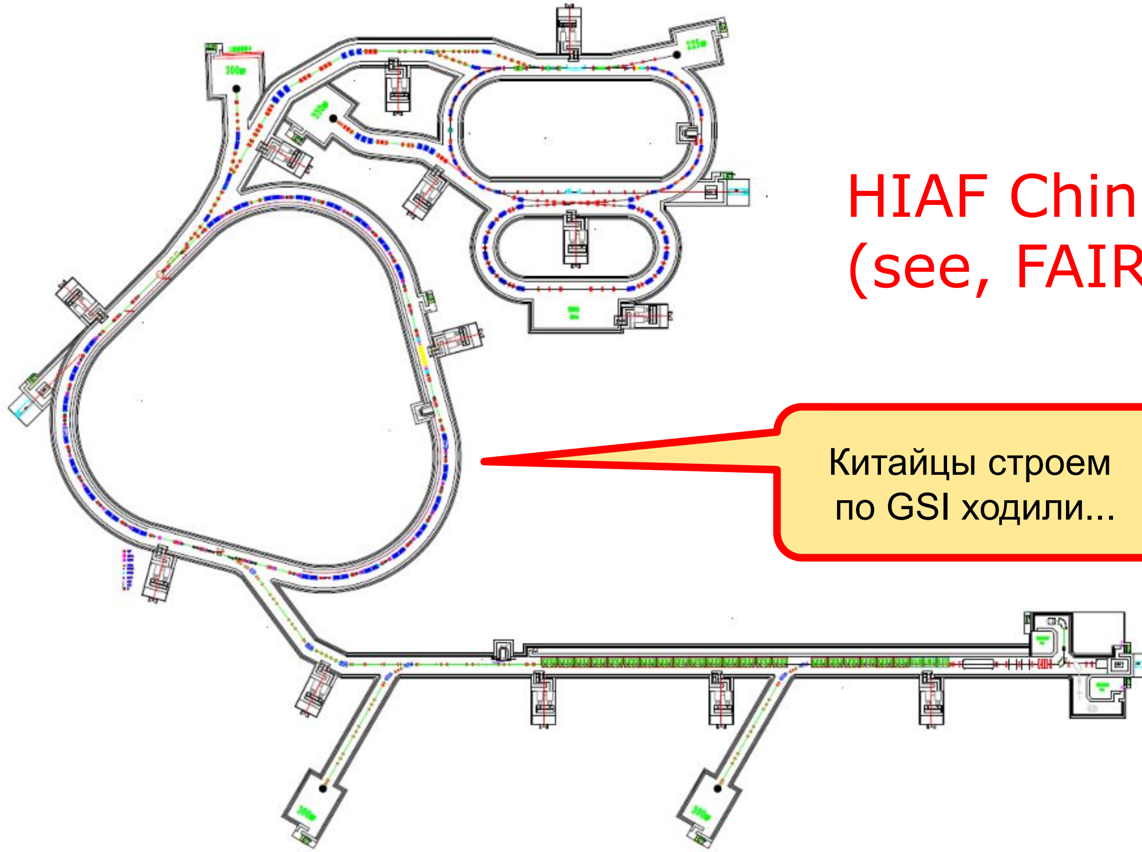
RIBF



However,
even bigger…

Horizontal size of the slide ~1 km

HIAF China
(see, FAIR)



Китайцы строем по GSI ходили…

RAON
Korea
(see. FRIB)

Даешь корейскую Нобелевскую премию!

LINAC-100 + DFS

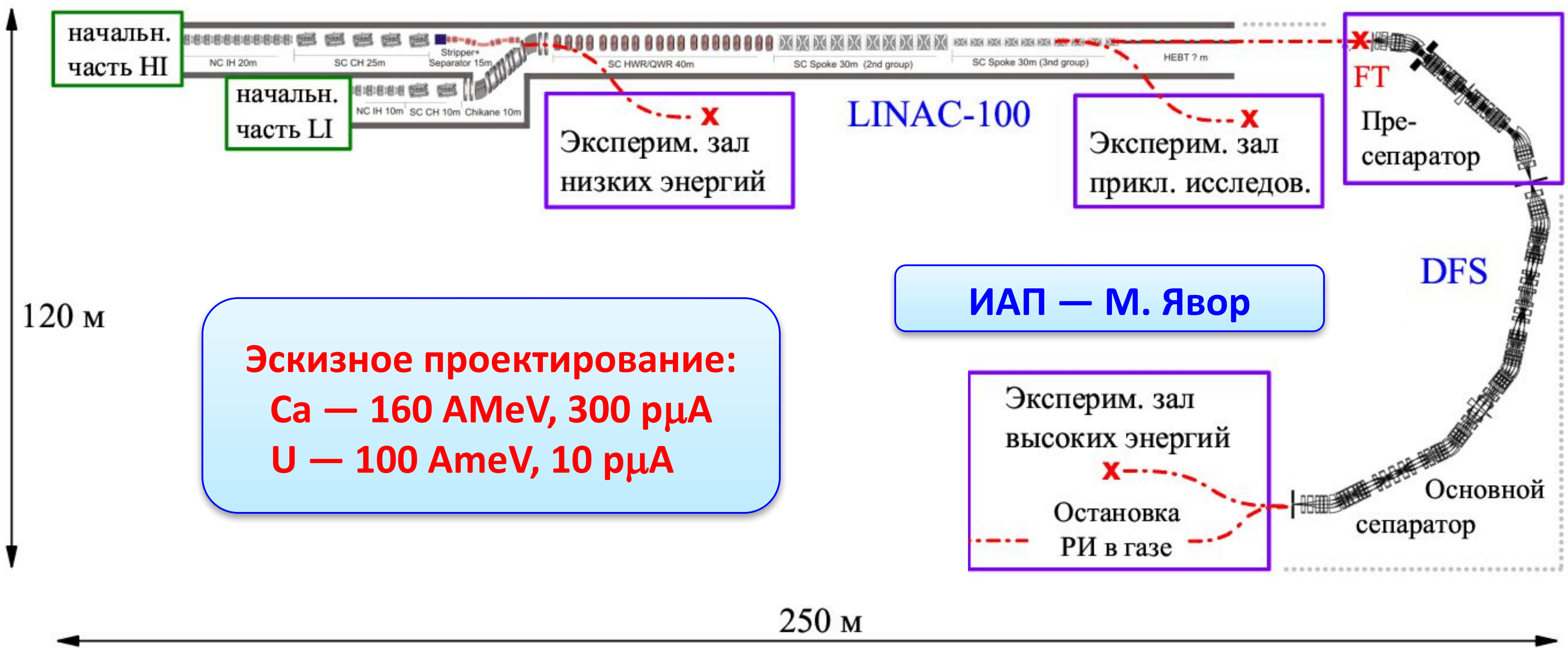
Высокоточный линейный сверхпроводящий ускоритель непрерывного действия

Теплый фрагмент-сепаратор на исключительно высокие токи

ИТЭФ — Т.Кулевой

МИФИ — С.Полозов

???



ИАП — М. Явор

Эскизное проектирование:
Ca — 160 AMeV, 300 pμA
U — 100 AmeV, 10 pμA

Заключение

Связка модернизированный U-400M + ACCULINNA-2 «крепкая» установка «предыдущего» поколения.

- Местами мы способны иметь рекордные или близкие к тому интенсивности пучков РИ и уникальные возможности (тритий). И способны решать задачи на лучшем мировом уровне.

- Ориентировочно 5-7 следующих лет. До массового вступления в строй фабрик радиоактивных изотопов следующего поколения.

Это не разгром, характерный для многих областей отечественной науки, это «золотая осень»

Чтобы «золотая осень» не перешла в состояние «зима близко» необходимо развитие перспективной базы физики радиоактивных изотопов – мощных современных ускорителей тяжелых ионов

Прорабатывался комплекс “рекордный” высокоточный непрерывного действия LINAC-100 и “теплый” двухстадийный фрагмент-сепаратор DFS