Леонид Григоренко

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

Использование радиоактивных пучков для изучения экзотических ядер вблизи границ ядерной стабильности

Теория

Интерпретация

Перспективы в РФ (условная DERICA)

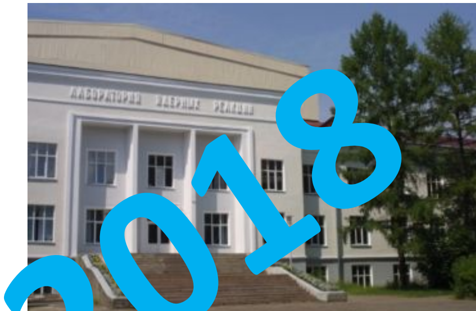
Two-proton radioactivity and three-body decay

L.V. Grigorenko

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

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 Electron-Radioactive Isotope Collider fAcility

Теория

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

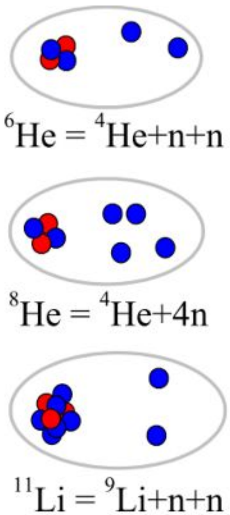
“Нейтронная кожа”

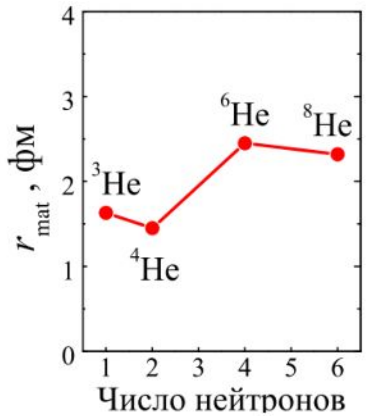
Мягкие моды возбуждения

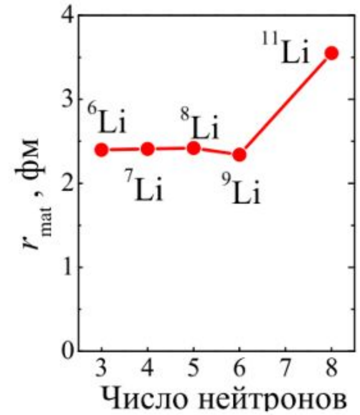
Экзотические виды радиоактивности

Нарушение стандартных оболочечных закономерностей

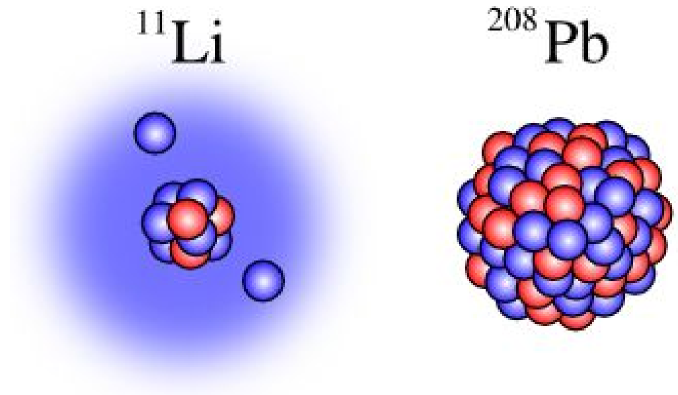
Ядра с гало. Борромиевские ядра



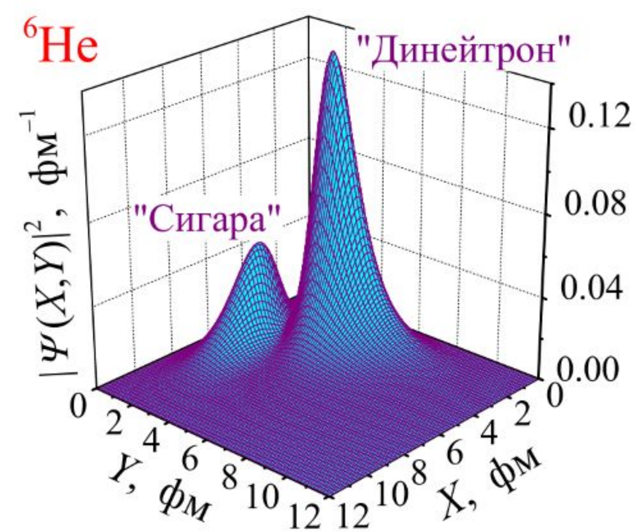




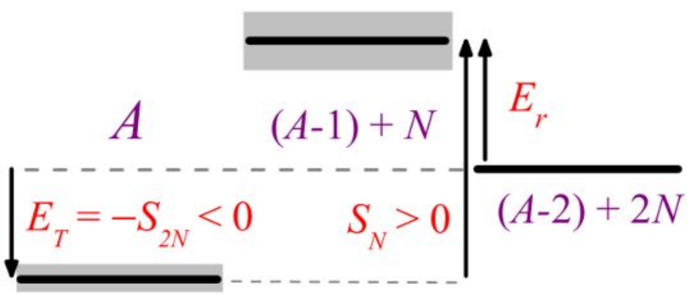
Валентные орбитали аномальных размеров



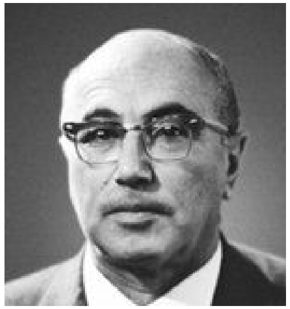
Сложные корреляции

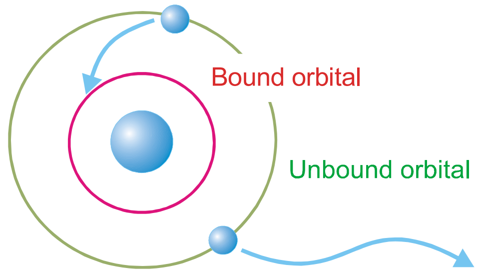


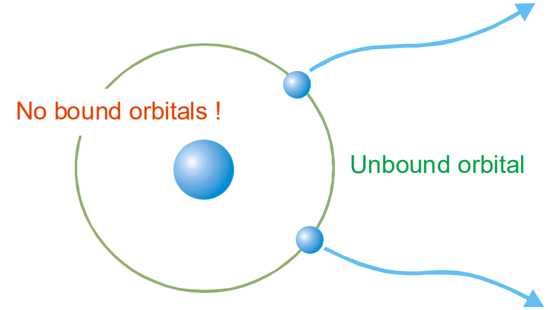
“Борромиевские” системы



Двухпротонная радиоактивность





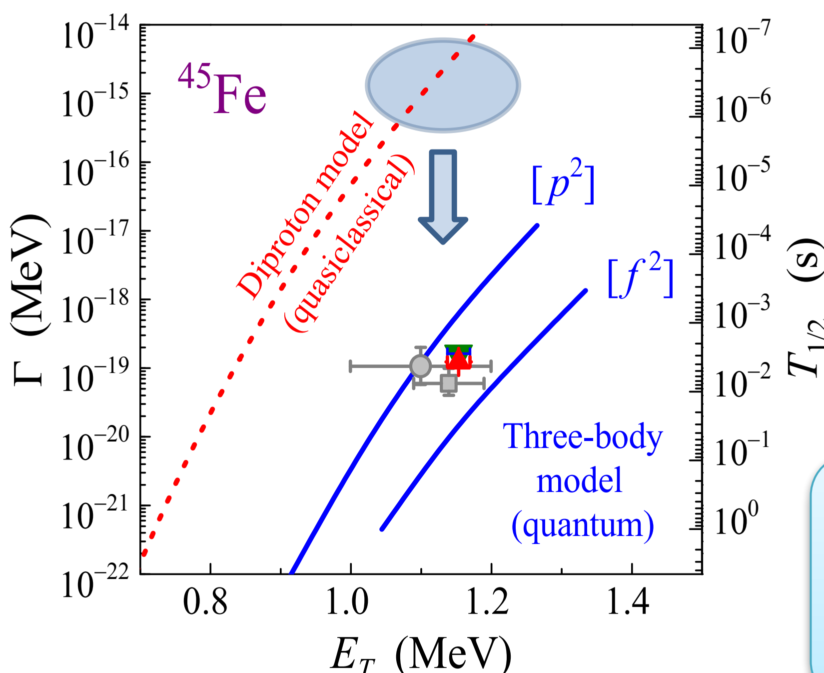


Я.Б. Зельдович и В.И. Гольданский, 1960, предсказание возможности p и 2p радиоактивности

p-радиоактивность – естественное обобщение α-радиоактивности

2p-радиоактивность – необычное и сложное квантовомеханическое явление

Потребовались 4 десятилетия для реализации предсказаний



M. Pfutzner, 2002, GSI: 2p-радиоактивность ^{45}Fe

Л.В. Григоренко, М.В. Жуков, И. Томпсон, Р. Джонсон, 2000, первая последовательная квантово-механическая теория 2p радиоактивности

Правильные теоретические расчеты сыграли критическую роль в открытии 2p радиоактивности

“Внутренние” трехчастичные корреляции

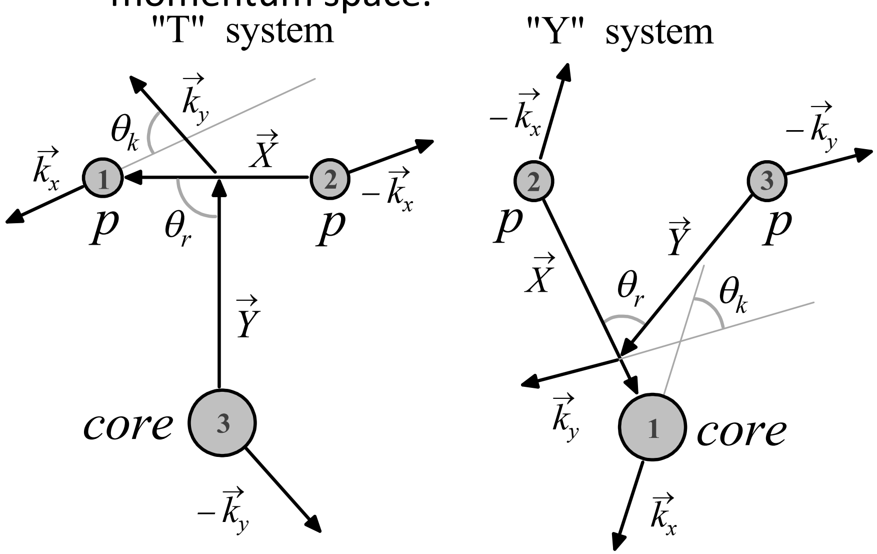
2-body decay: state is defined by 2 parameters - energy and width

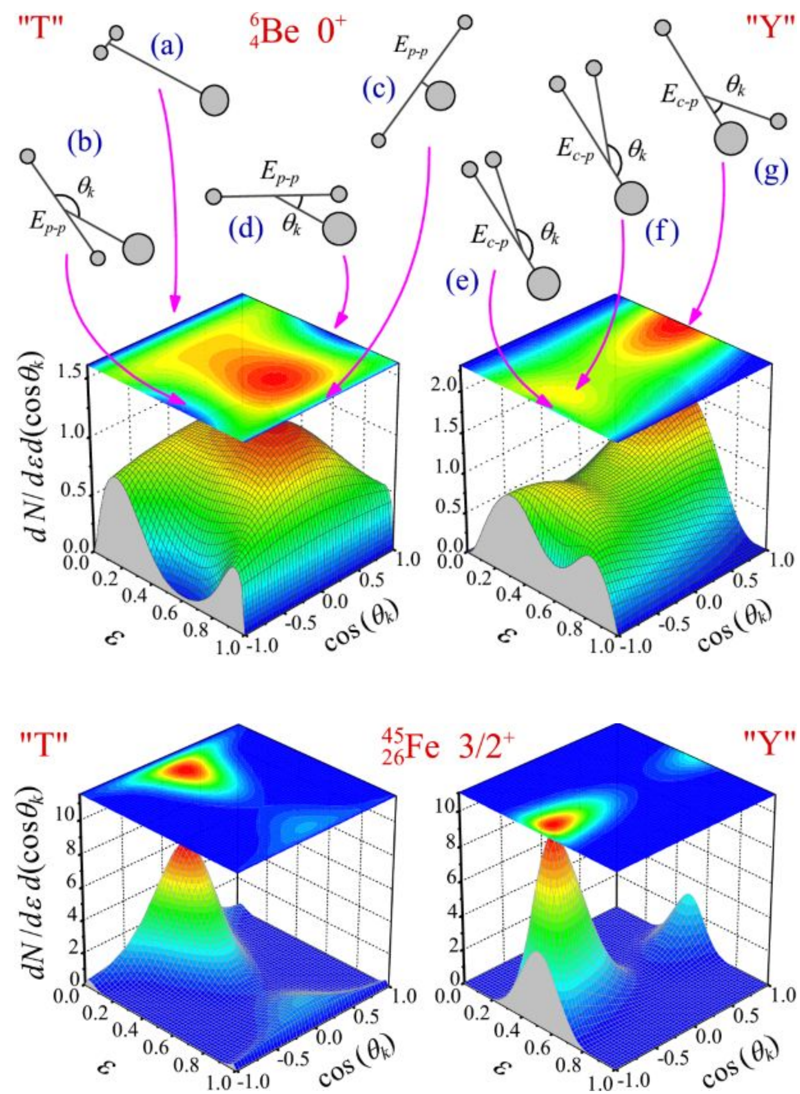
3-body decays: 2-dimensional “internal” 3-body correlations

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

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

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

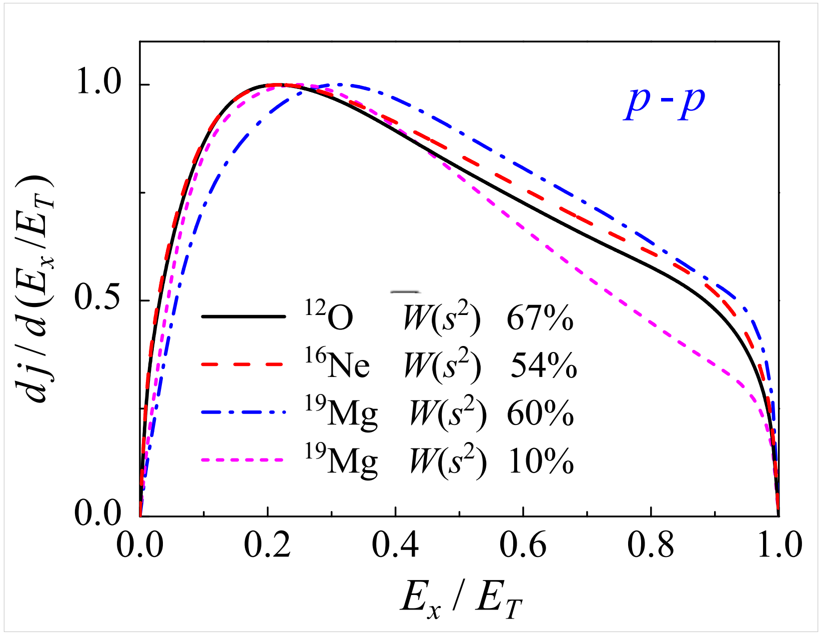


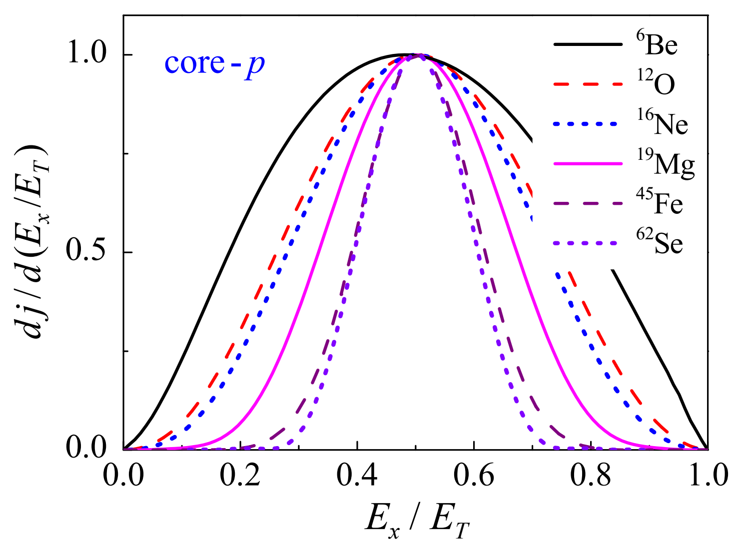


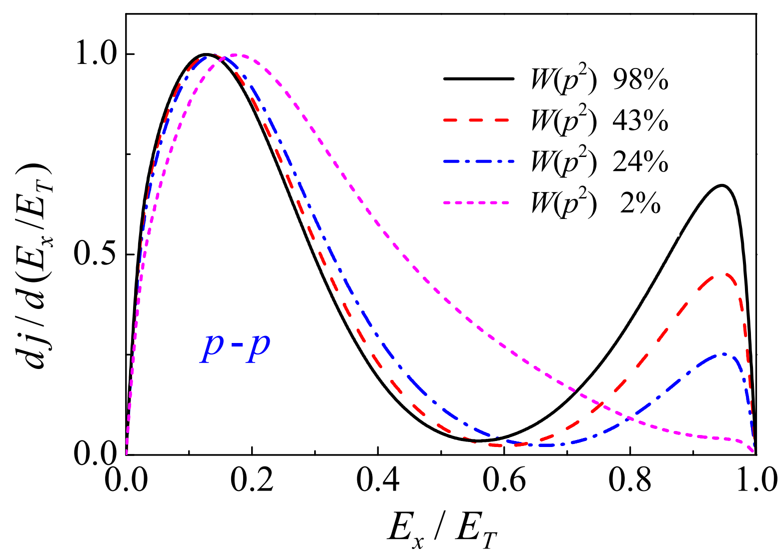
Common properties of correlations for true 2p decays

How can we use the correlation information?

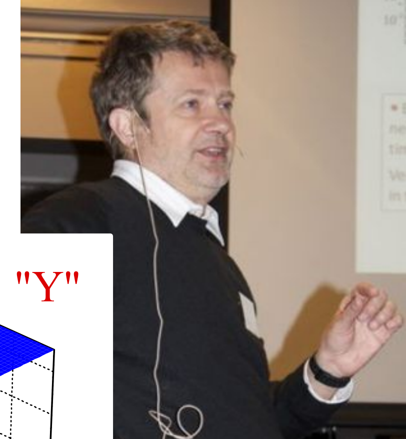
- **Energy correlation in the core-p** channel well corresponds to original prediction of Goldansky: energies of the emitted protons tend to be equal.
- **Energy correlation in the p-p channel** in the s-d shell nuclei quantitatively depend on the structure
- **Energy correlation in the p-p channel** in the p-f shell nuclei qualitatively depend on the structure

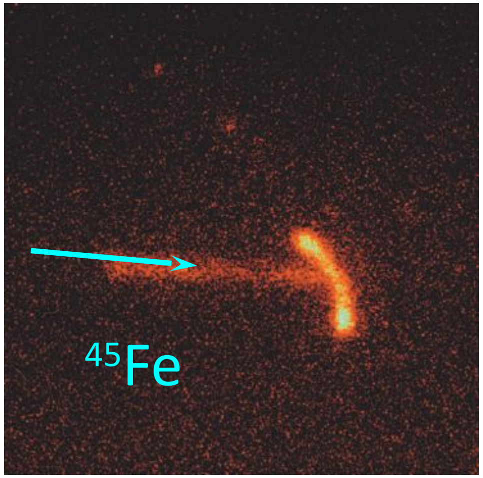


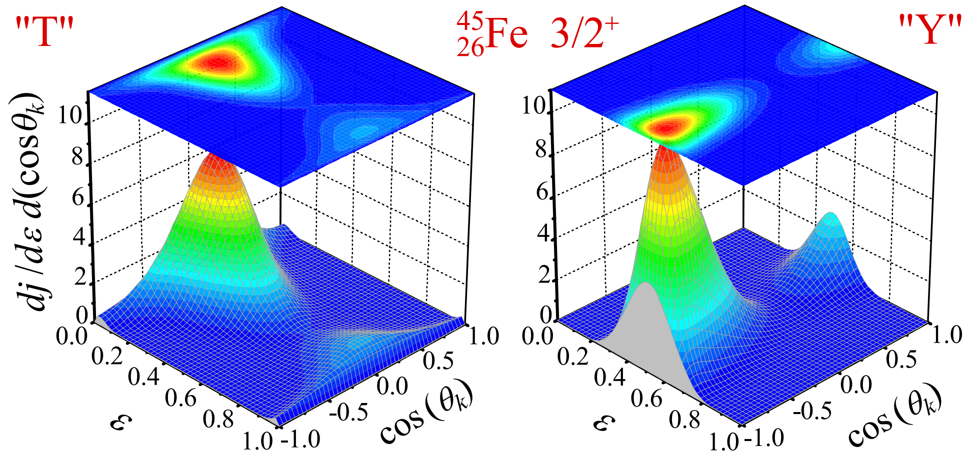


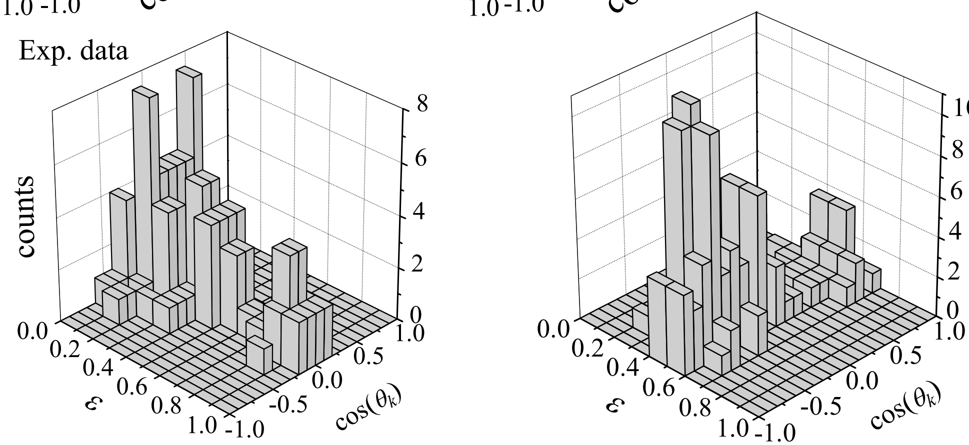


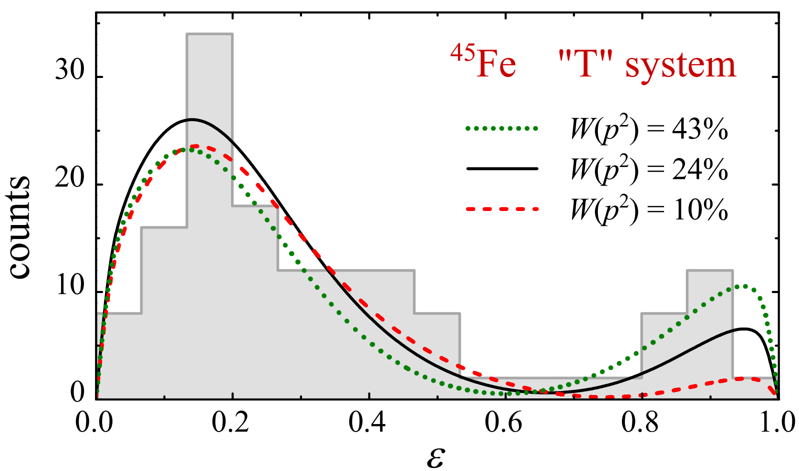
^{45}Fe: “внутренние” трехчастичные корреляции









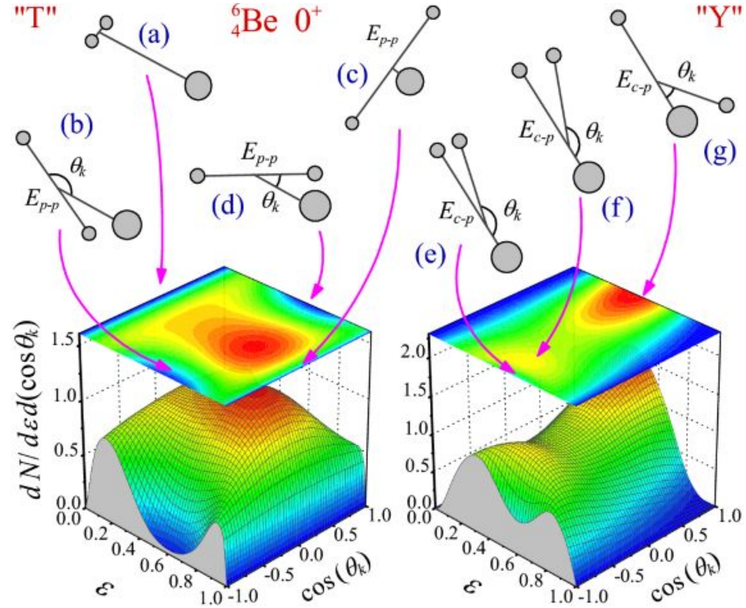


Miernik *et al.*, PRL **99** (2007) 192501

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

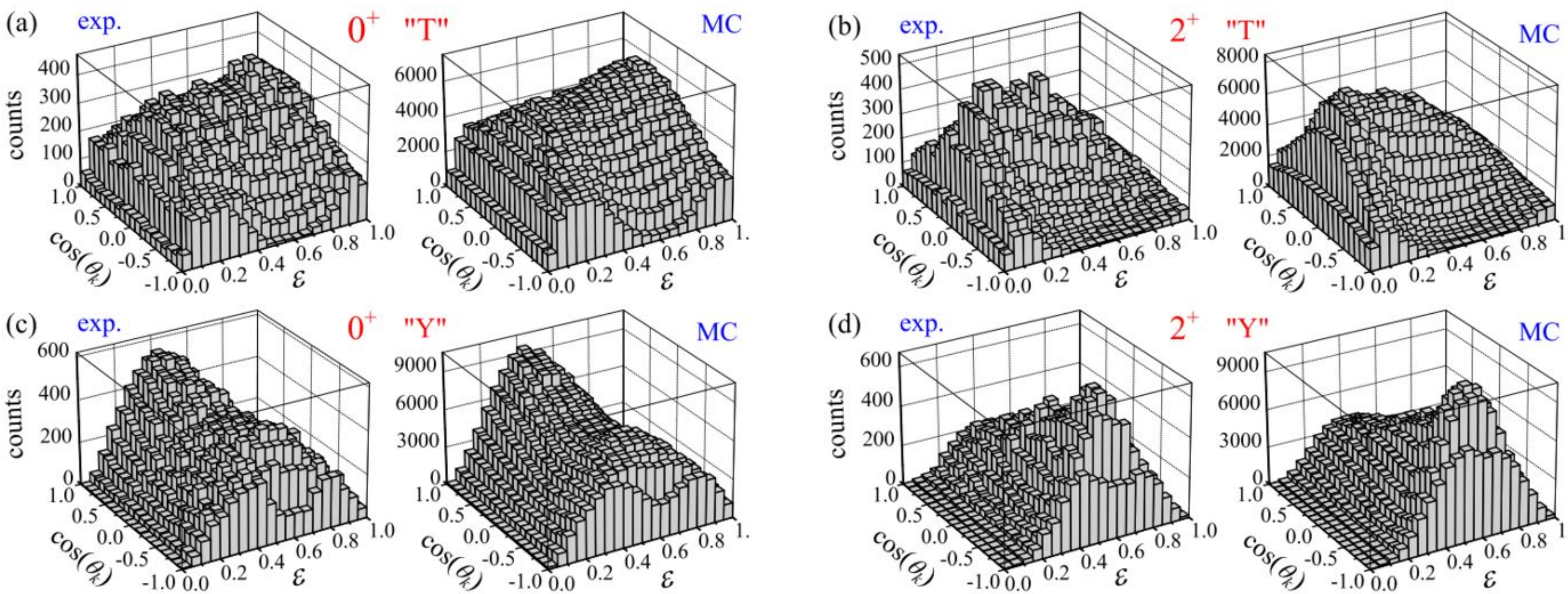
^{6}Be -> α+p+p correlations on resonance

R. Charity and coworkers, MSU



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

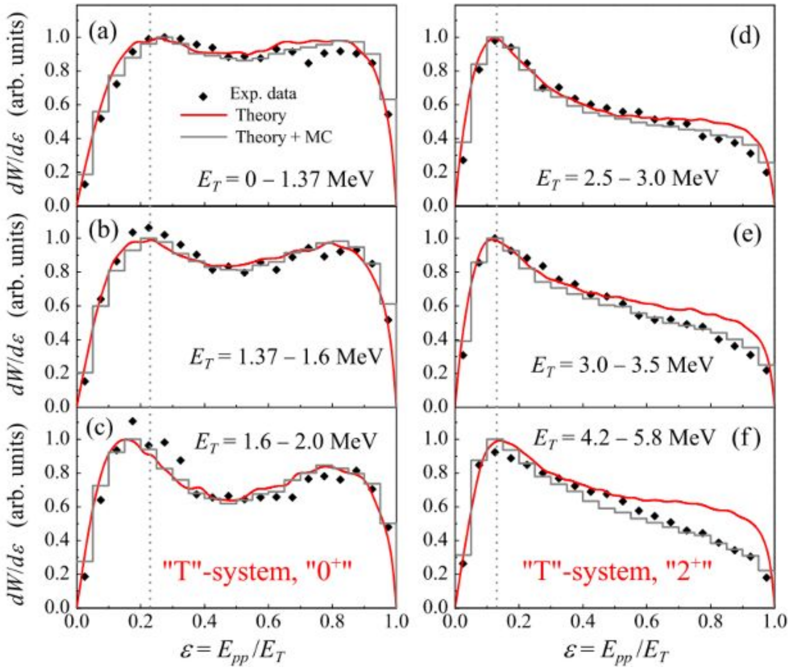
- High statistics (~10^6 events/state)
- High resolution
- Nice agreement with the previous (Texas A&M, Dubna) experimental data

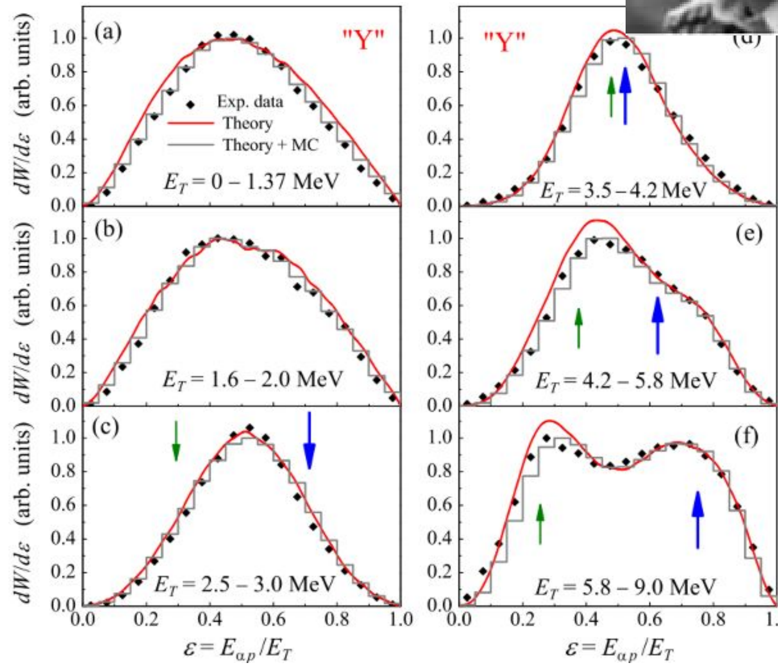


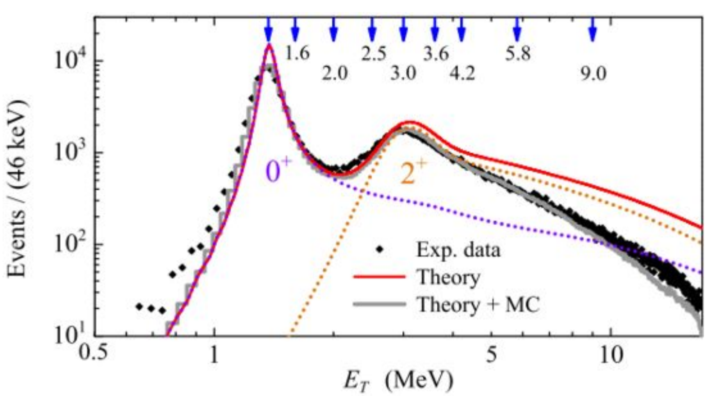
^{6}Be -> α+p+p energy evolution of correlations

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

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







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

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

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

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

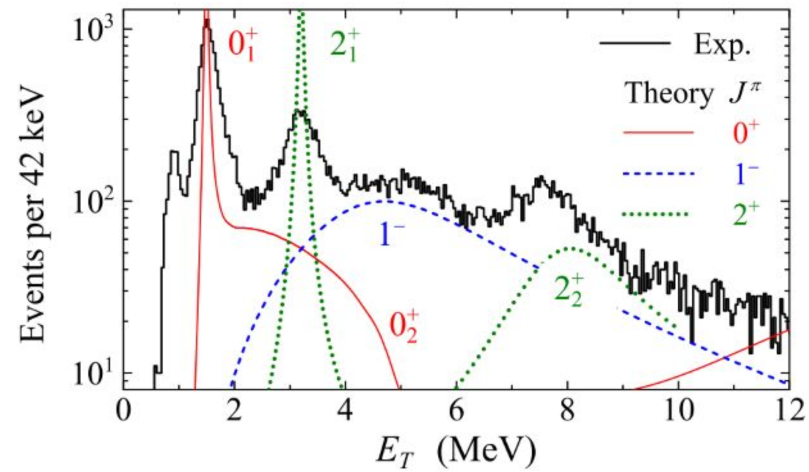
Long-range character of three-body Coulomb by example of ^{16}Ne

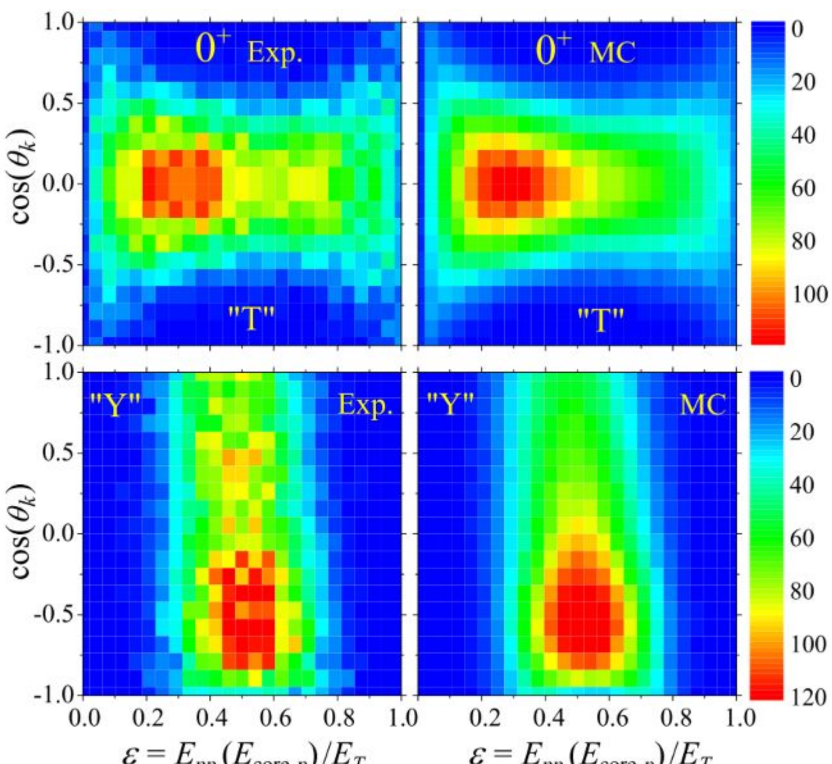
^{16}Ne g.s., E_T = 1.466 MeV

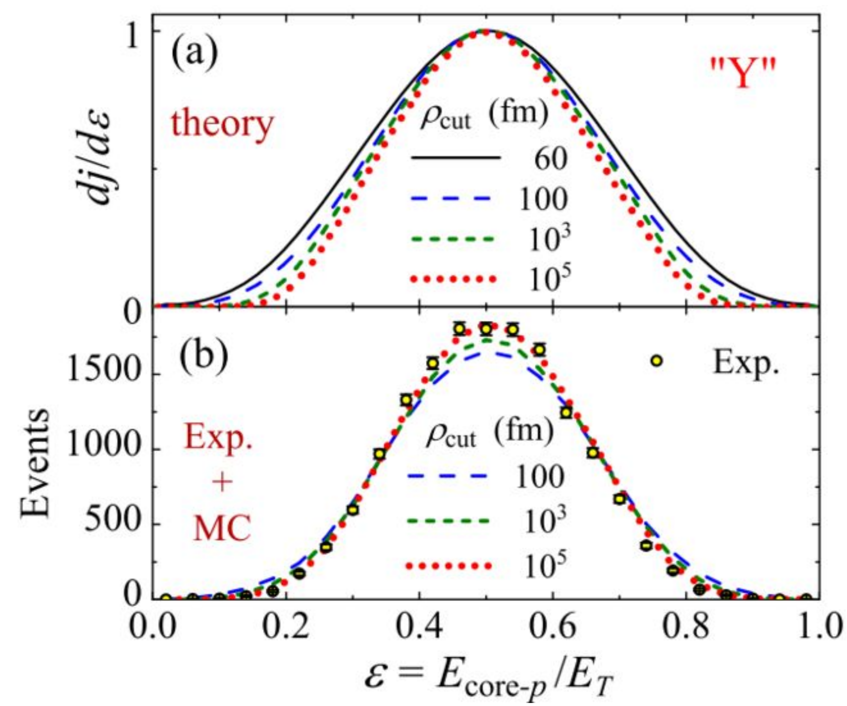
- New level of experimental precision. MSU 2013: ^{16}Ne populated in n knockout from ^{17}Ne

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

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







How to treat 2p radioactivity

Rigorously nontractable problem of the 3-body Coulomb continuum

Practical solution: approximate boundary conditions

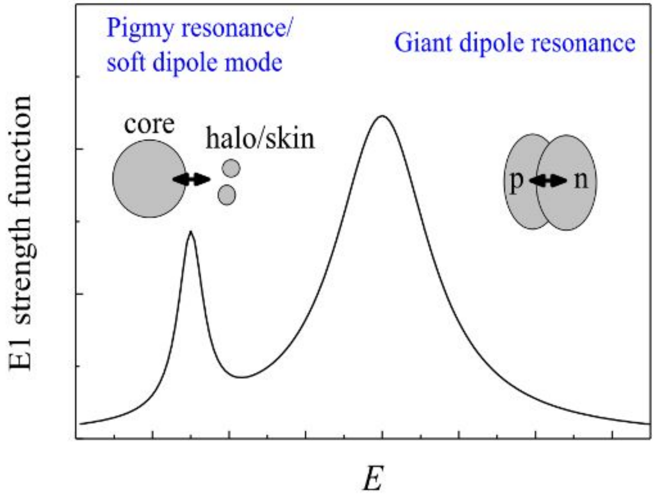
"box"	Any approximate scattering	Diagonalized hyperspherical	Classical extrapolation
Nuclear interior	Subbarrier region	"Abovebarrier" region	Asymptotic region
ρ_{max}~20-30 fm	ρ_{max}~30-100 fm	ρ_{max}~1000-5000 fm	ρ_{max}> 50000 fm
Energy, internal structure	**Resonant width**	**3-body correlations**	**Precision correlations**

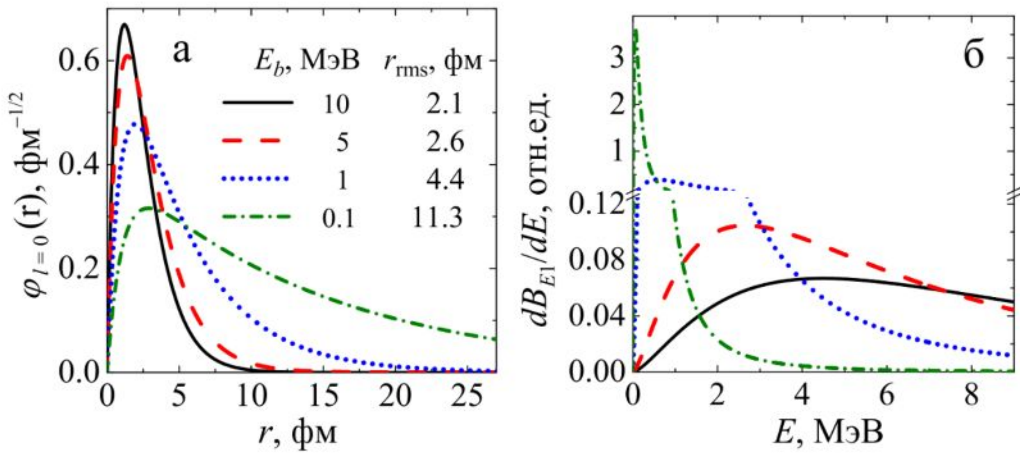
ρ

Мягкие моды возбуждения (мягкая дипольная мода)

A low-energy split-off of the Giant Dipole Resonance, connected with separation of scales of radial degrees of freedom

Soft dipole mode – radius of halo vs. radius of core
Pigmi – resonance – radius of neutron skin vs. radius of nuclear bulk





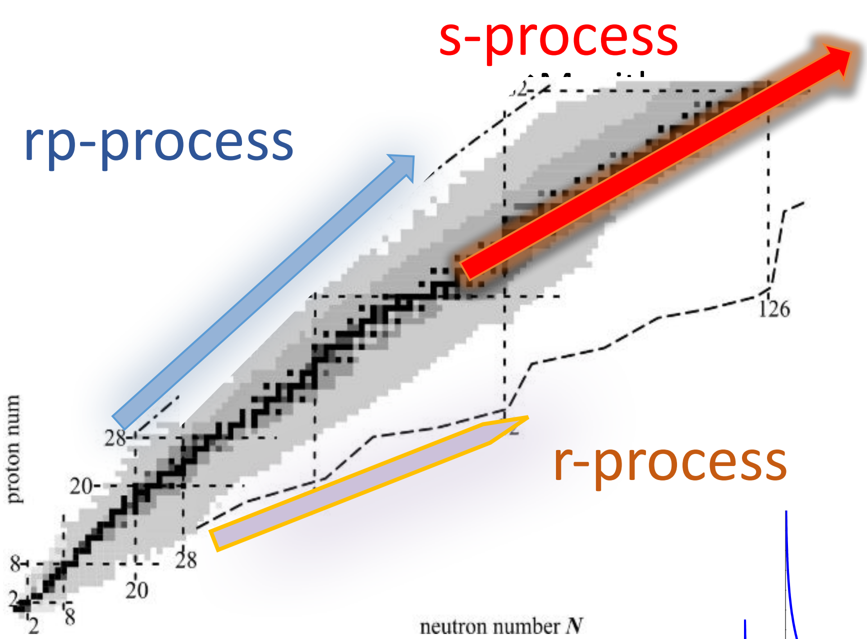
Existance of soft dipole mode strongly influence the nonresonant radiative capture rate in astrophysics

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

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

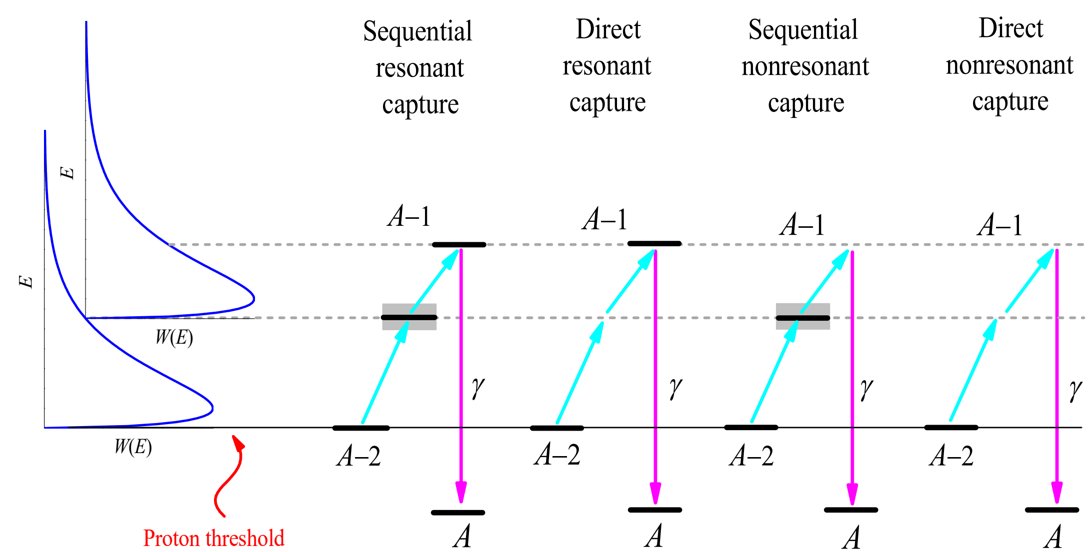
$$\frac{dB_{E1}}{dE} \sim \frac{|M_{E1}(E)|^2}{\sqrt{E}}$$

Three-body radiative capture reactions: where and why?



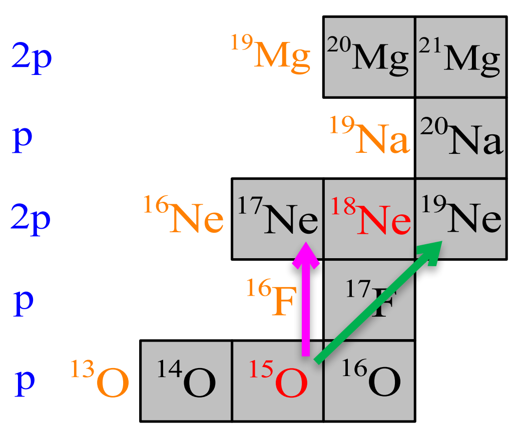
- Extreme pressure and temperature.
- "Classics": $\alpha+\alpha+\alpha \to {}^{12}C+\gamma$.
- R-process nucleosynthesis: 2n capture.
- Rp-process nucleosynthesis: 2p capture.

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].

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

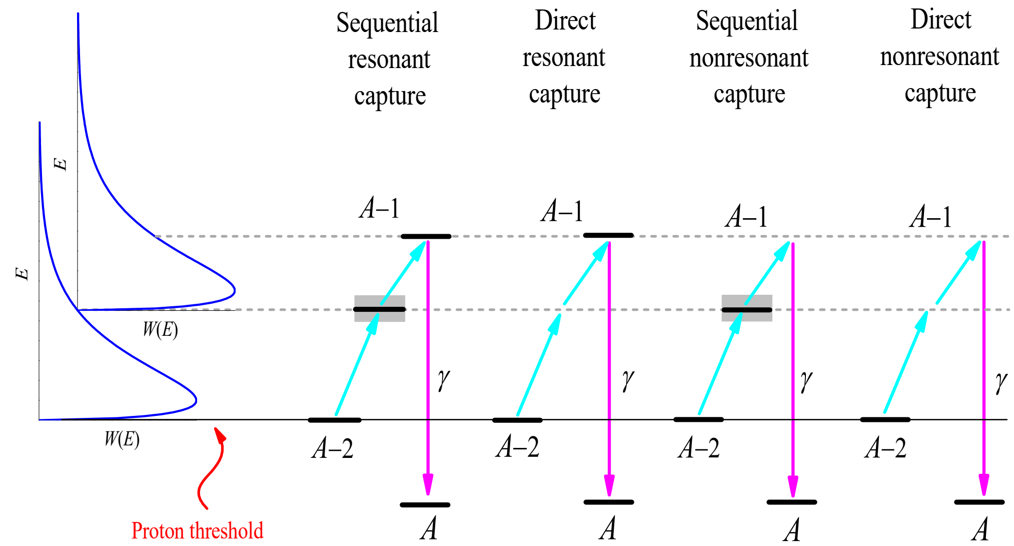
$$\langle \sigma_{A_1 A_2 A_3,\gamma} v \rangle = \sum_i \frac{\langle \sigma_{A_1 A_2,(A_1 A_2)} v \rangle_i}{\Gamma_{(A_1 A_2),i}} \langle \sigma_{(A_1 A_2) A_3,\gamma} v \rangle_i ,$$

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]).

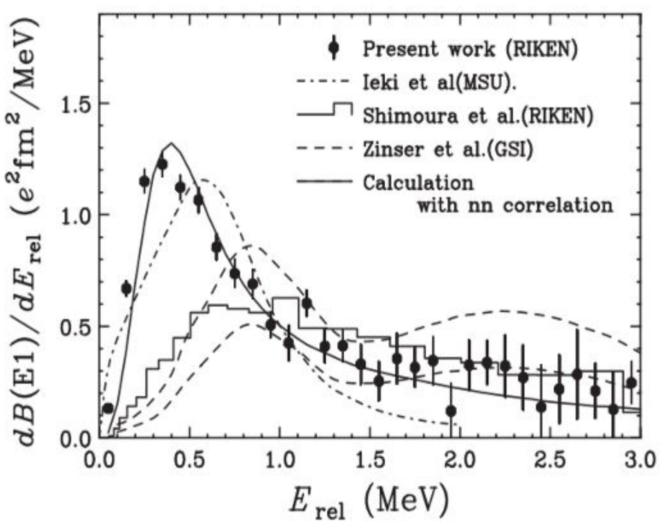
(ii) "Classical" expression for nonresonant capture rates can not be calibrated: violation of E1 sum rule is possible.

Problem of three-body Soft Dipole Mode (SDM)

Experiment

[Nakamura, PRL 96, 252502 (2006)]

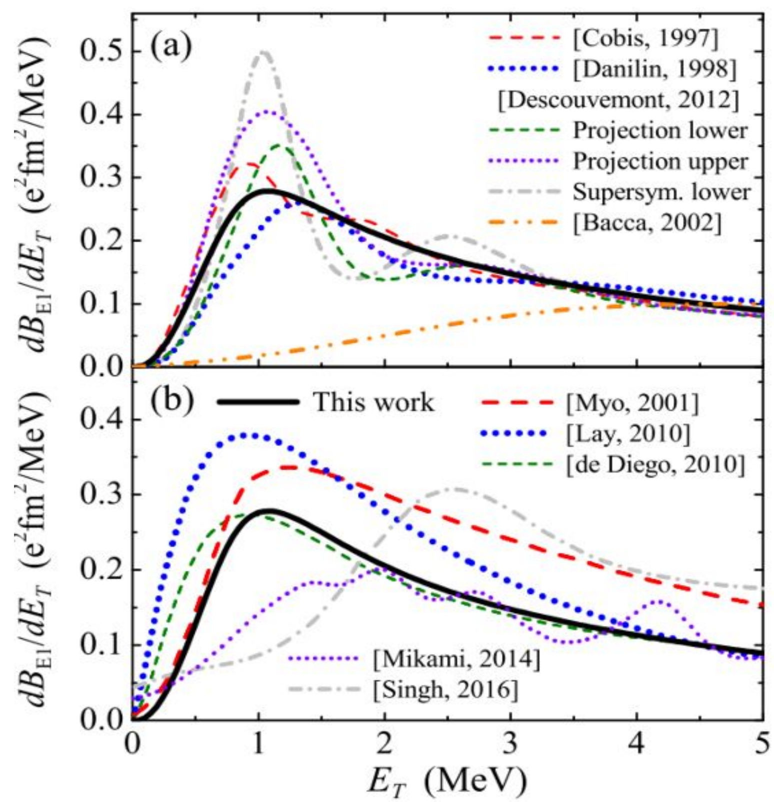
^{11}Li



Theory

[Grigorenko, PRC 102, 014611 (2020)]

^{6}He



There was no reliable understanding of three-body SDM phenomenon.

Neither experimental nor theoretical.

Problem of three-body Soft Dipole Mode (SDM)

PHYSICAL REVIEW C **102**, 014611 (2020)

High-precision studies of the soft dipole mode in two-neutron halo nuclei: The ^{6}He case

L. V. Grigorenko,[1,2,3,*] N. B. Shulgina,[3,4] and M. V. Zhukov[5]
[1]*Flerov Laboratory of Nuclear Reactions, JINR, 141980 Dubna, Russia*
[2]*National Research Nuclear University "MEPhI", 115409 Moscow, Russia*
[3]*National Research Centre "Kurchatov Institute", Kurchatov sq. 1, 123182 Moscow, Russia*
[4]*Bogoliubov Laboratory of Theoretical Physics, JINR, 141980 Dubna, Russia*
[5]*Department of Physics, Chalmers University of Technology, 41296 Göteborg, Sweden*

(Received 30 March 2020; accepted 24 June 2020; published 14 July 2020)

Physics Letters B 807 (2020) 135557

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Three-body vs. dineutron approach to two-neutron radiative capture in ^{6}He

L.V. Grigorenko [a,b,c,*], N.B. Shulgina [c,d], M.V. Zhukov [e]

Physics Letters B 811 (2020) 135852

Contents lists available at ScienceDirect

Physics Letters B

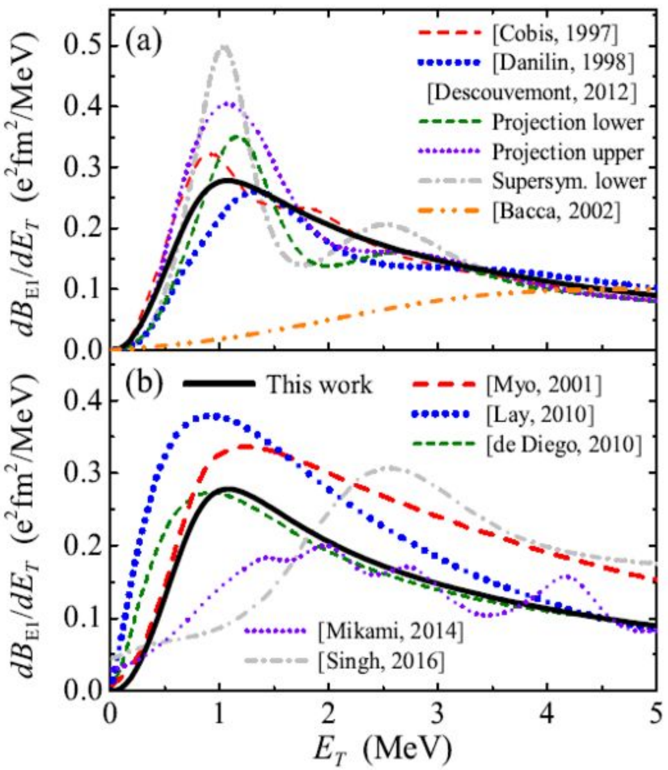
www.elsevier.com/locate/physletb

Asymptotic normalization coefficient method for two-proton radiative capture

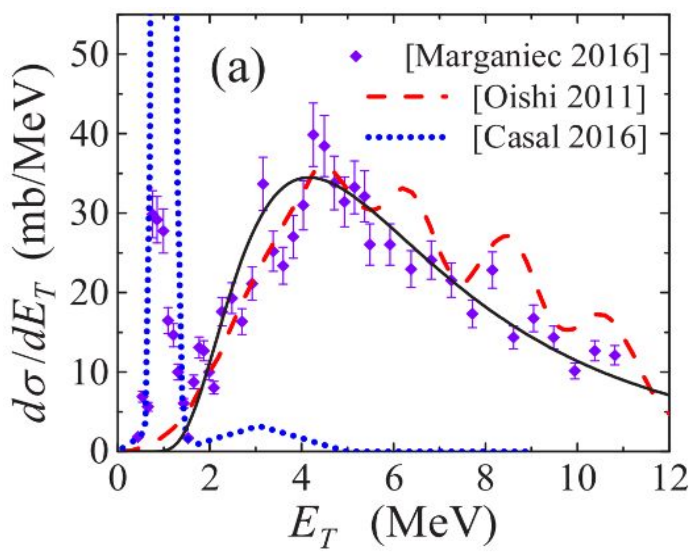
L.V. Grigorenko [a,b,c,*], Yu.L. Parfenova [a], N.B. Shulgina [c,d], M.V. Zhukov [e]

E1 SDM strength functions for 2n and 2p processes

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



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

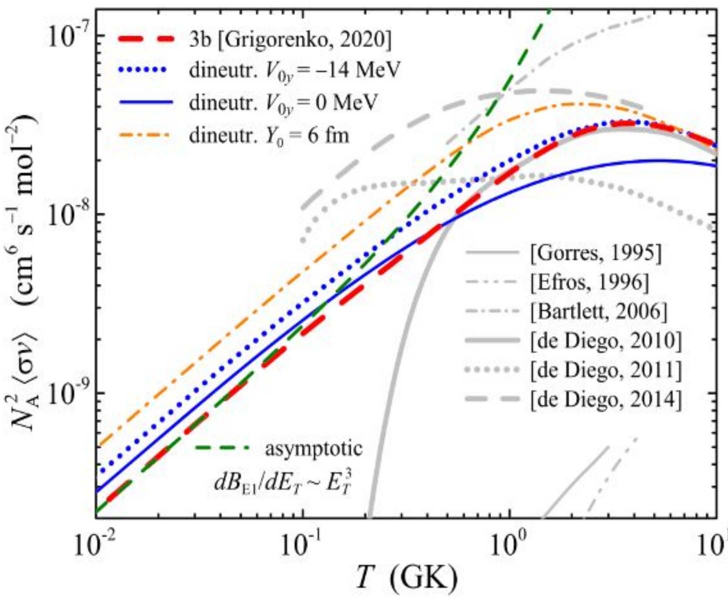


Qualitative changes
compared to previous works

Astrophysical 2p and 2n nonresonant capture rates improved

Nonresonant 2n

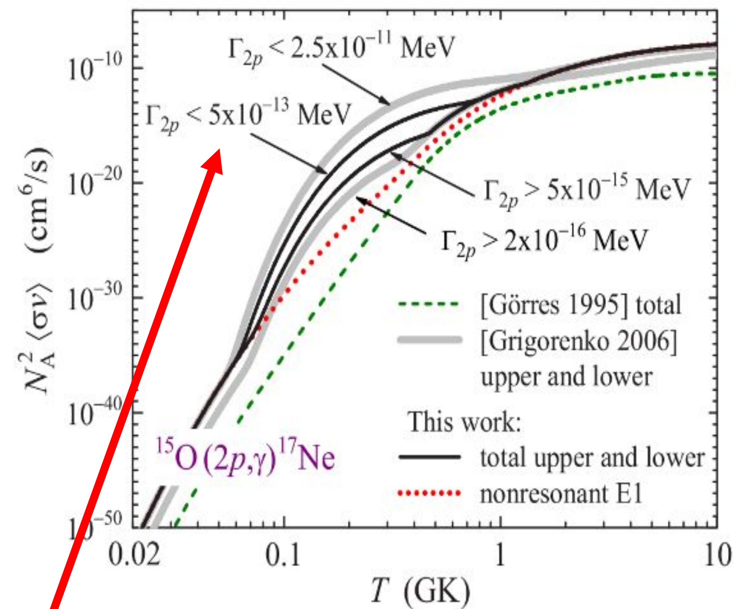
^{4}He+n+n -> ^{6}He + γ



Orders of the magnitude improvements compared to previous works

Nonresonant + resonant 2p

^{15}O+p+p -> ^{17}Ne + γ



JINR prize 2017 in experiment!

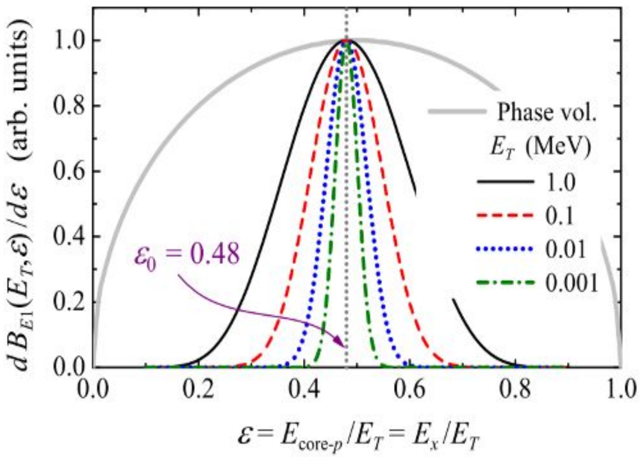
PHYSICAL REVIEW C **96**, 025807 (2017)

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]

ANC3 development: Analytical formula for 2p non-resonant astrophysical capture rate

Energy distribution between captured protons



Highly correlated character of the low-energy 2p capture, analogous to Goldansky correlations in 2p radioactivity.

Lead to wierd low-energy asymptotic

$$\frac{dB_{E1}}{dE_T} \propto E_T^{5/4} \exp(-2\pi\eta_{sh})$$

Fully analytical compact expression for 2p capture

$$\langle\sigma_{2p,\gamma}v\rangle = \left(\frac{\sum_n A_n}{A_1A_2A_3}\right)^{3/2}\left(\frac{2\pi}{mkT}\right)^3 \frac{2J_f+1}{2(2J_i+1)} I_E(T),$$

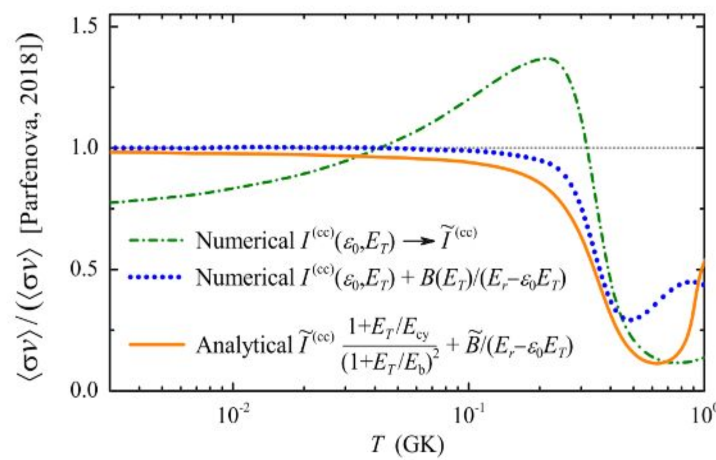
$$I_E(T) = \int dE\, \frac{16\pi}{9} E_\gamma^3 \frac{dB_{E1}(E)}{dE} \exp\left[-\frac{E}{kT}\right],$$

$$I_E(T) \propto \int dE_T (E_b+E_T)^3 I_\varepsilon(E_T) \exp\left[-\frac{E_T}{kT}\right] = \frac{2\pi E_b^3 E_G^{5/2}}{3\gamma\sqrt{R_\varepsilon}}$$

$$\times \frac{1+E_G/E_{cy}}{1+E_G/E_b}\left(\tilde{I}_{10}^{(cc)} + \frac{(1+E_G/E_b)^2}{1-\varepsilon_0 E_G/E_r}\tilde{B}\right)^2 \exp\left[-\frac{3\gamma^{2/3}}{(kT)^{1/3}}\right],$$

$$E_G = (\gamma kT)^{2/3}, \quad \gamma = \pi Z_{sh} e^2 \sqrt{M/2}, \quad \pi\eta_{sh} = \gamma/\sqrt{E_T}.$$

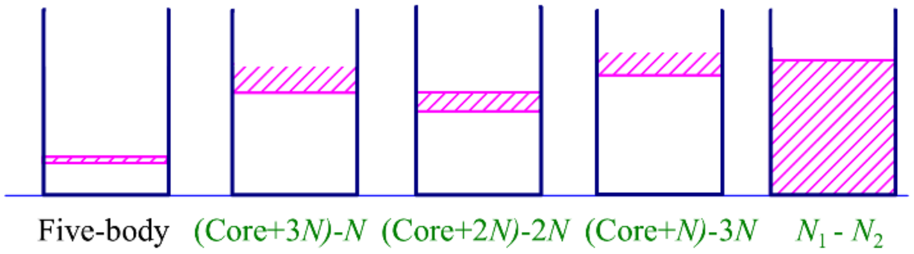
Robust replacement to a very bulky and complicated 3-body calculations



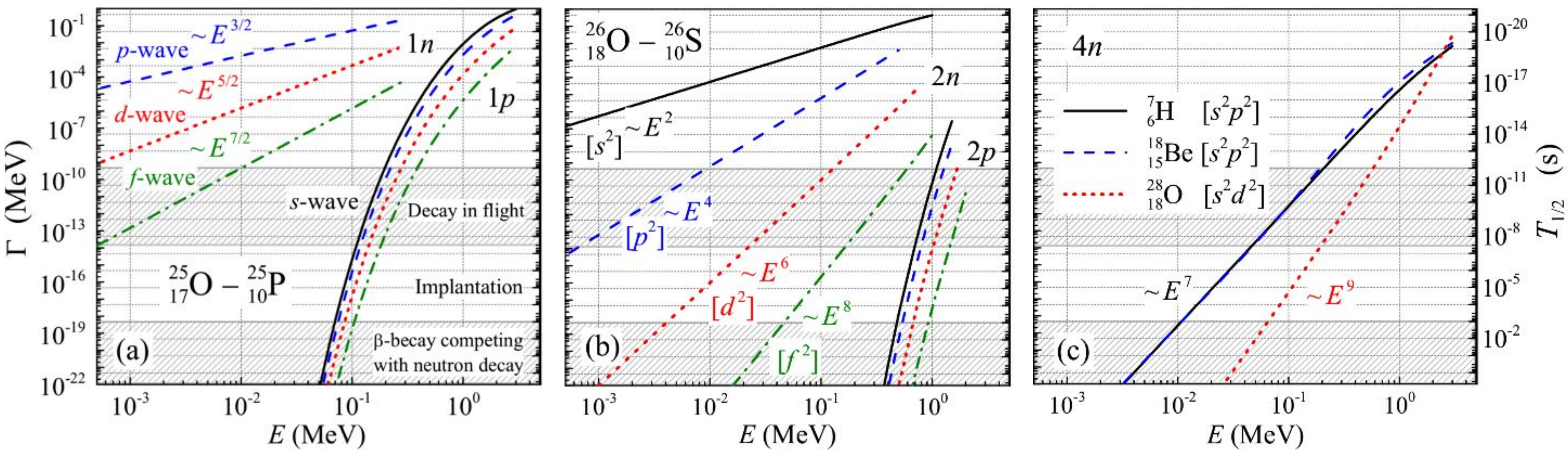
Very precise in a broad range of temperatures

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 ?

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

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)

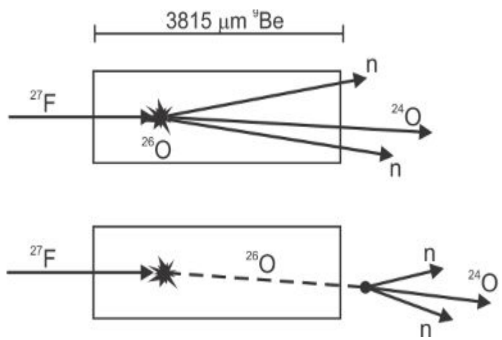
A new technique was developed to measure the lifetimes of neutron unbound nuclei in the picosecond range. The decay of $^{26}O \rightarrow {}^{24}O + n + n$ was examined as it had been predicted to have an appreciable lifetime due to the unique structure of the neutron-rich oxygen isotopes. The half-life of ^{26}O was extracted as $4.5^{+1.1}_{-1.5}$(stat) ± 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.

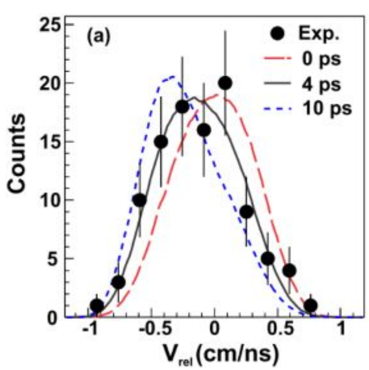
Importance of fine three-body effects

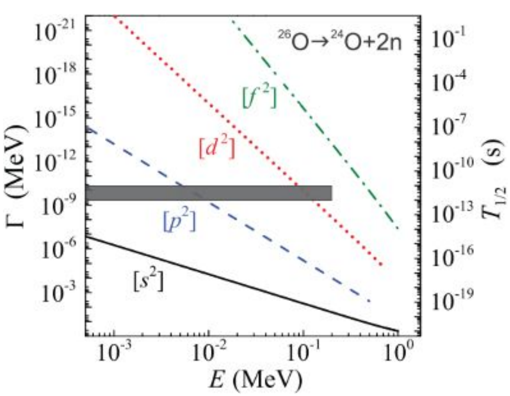
2p radioactivity:
Core recoil – negligible
Paring - factor 200-500

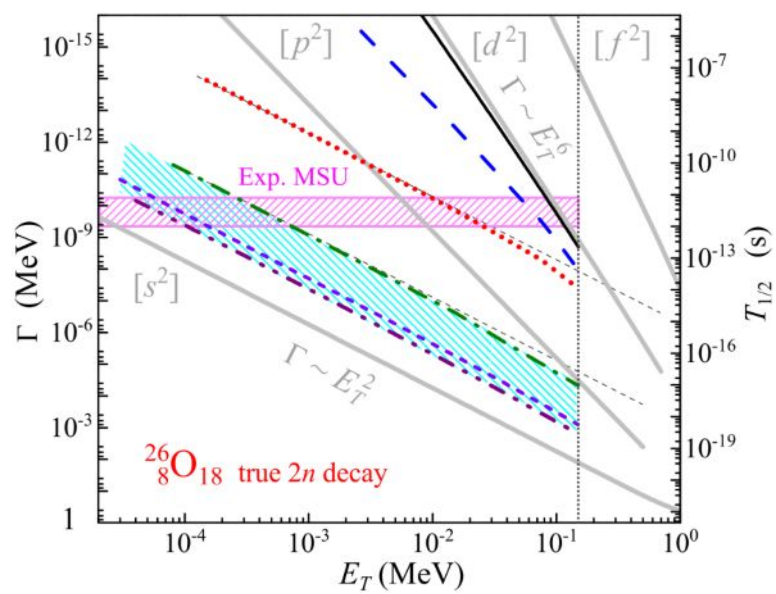
2n radioactivity:
Core recoil – factor 5-10
Paring - factor 2000-10000

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









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

2n radioactivity in ^{26}O ?

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

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

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

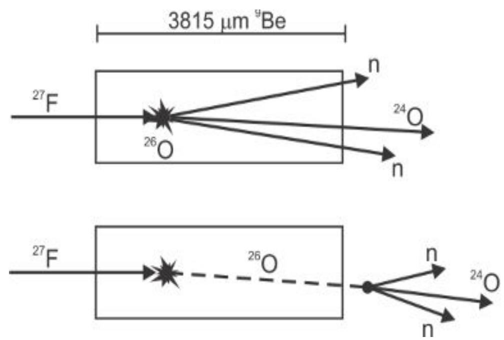
Z. Kohley,[1,2,*] T. Baumann,[1] D. Bazin,[1] G. Christian,[1,3] P. A. DeYoung,[4] J. E. Finck,[5] N. Frank,[6] M. Jones,[1,3] E. Lunderberg,[4] B. Luther,[7] S. Mosby,[1,3] T. Nagi,[4] J. K. Smith,[1,3] J. Snyder,[1,3] A. Spyrou,[1,3] and M. Thoennessen[1,3]

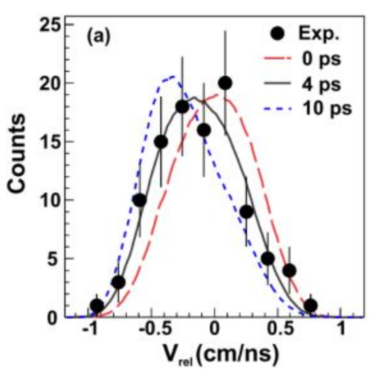
[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, 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*

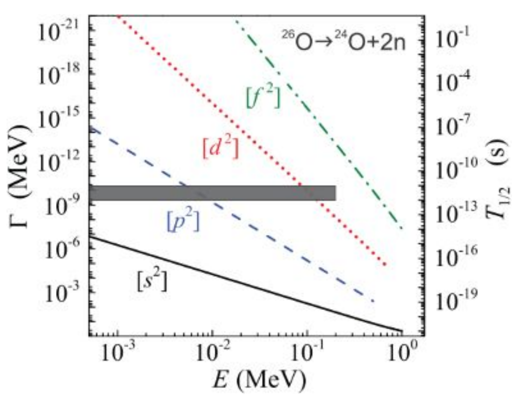
(Received 10 December 2012; published 8 April 2013)

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.

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



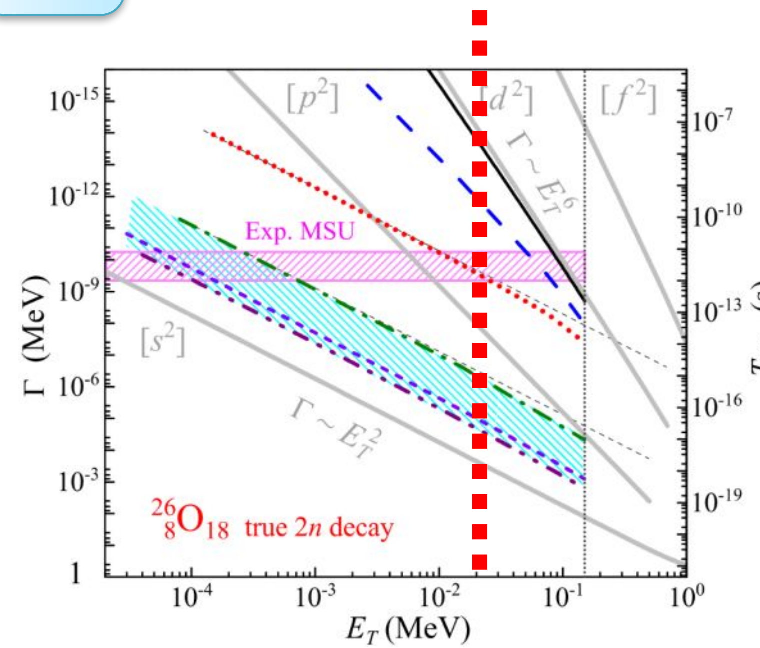




Importance of fine three-body effects

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

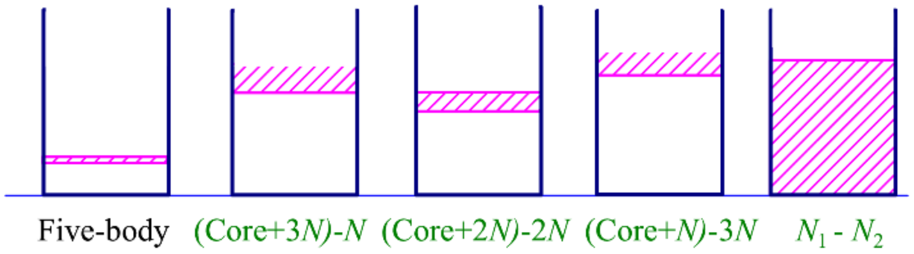
2n radioactivity:
Core recoil – factor 5-10
Paring - factor 2000-10000



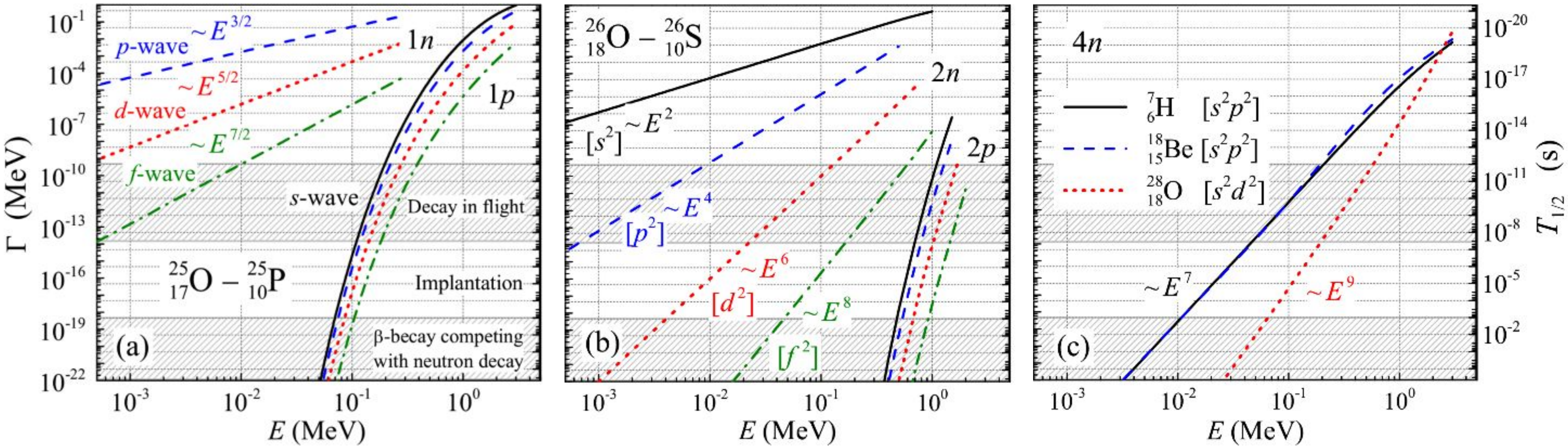
Extreme low-energy decay of ^{26}O should be inferred

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

Can it be useful to study 5-body correlations (4N decay)?

Pauli-focusing for “true” 4N emission

ISSN 0021-3640, JETP Letters, 2019, Vol. 110, No. 1, pp. 5–14. © Pleiades Publishing, Inc., 2019.

FIELDS, PARTICLES, AND NUCLEI

Pauli-Principle Driven Correlations in Four-Neutron Nuclear Decays

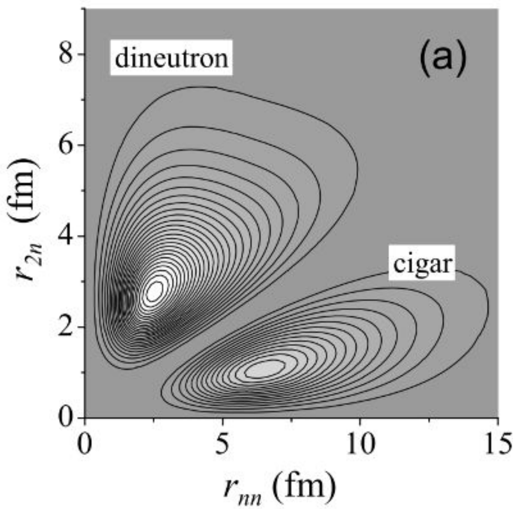
P. G. Sharov[a, *], **L. V. Grigorenko**[a, b, c], **A. N. Ismailova**[a], and **M. V. Zhukov**[d]

[a] *Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna, Moscow region, 141980 Russia*
[b] *National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, 115409 Russia*
[c] *National Research Center Kurchatov Institute, Moscow, 123182 Russia*
[d] *Department of Physics, Chalmers University of Technology, Göteborg, 41296 Sweden*
**e-mail: sharovpavel@jinr.ru*

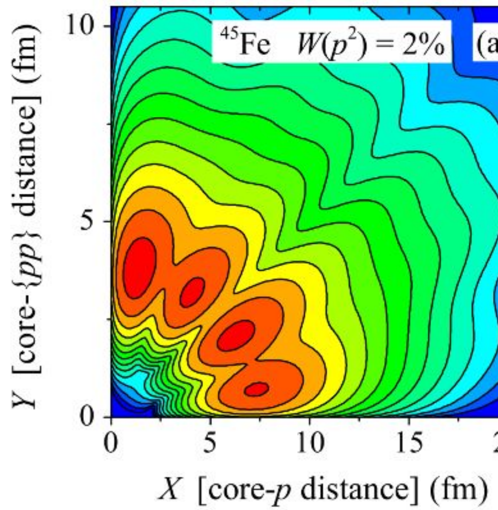
Received March 29, 2019; revised April 24, 2019; accepted May 24, 2019

Pauli focusing in coordinate space 0^+ states

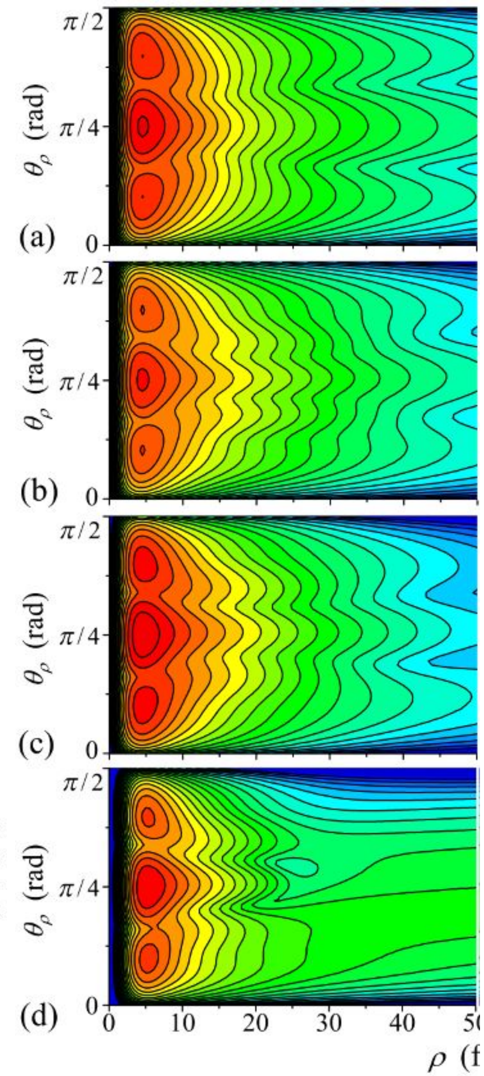
^{6}He $[p^2]_0$



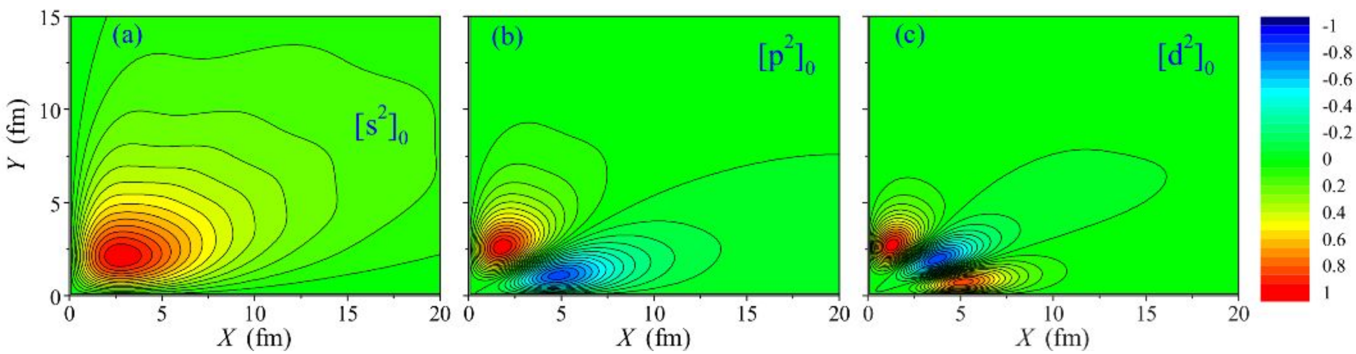
^{45}Fe $[f^2]_0$



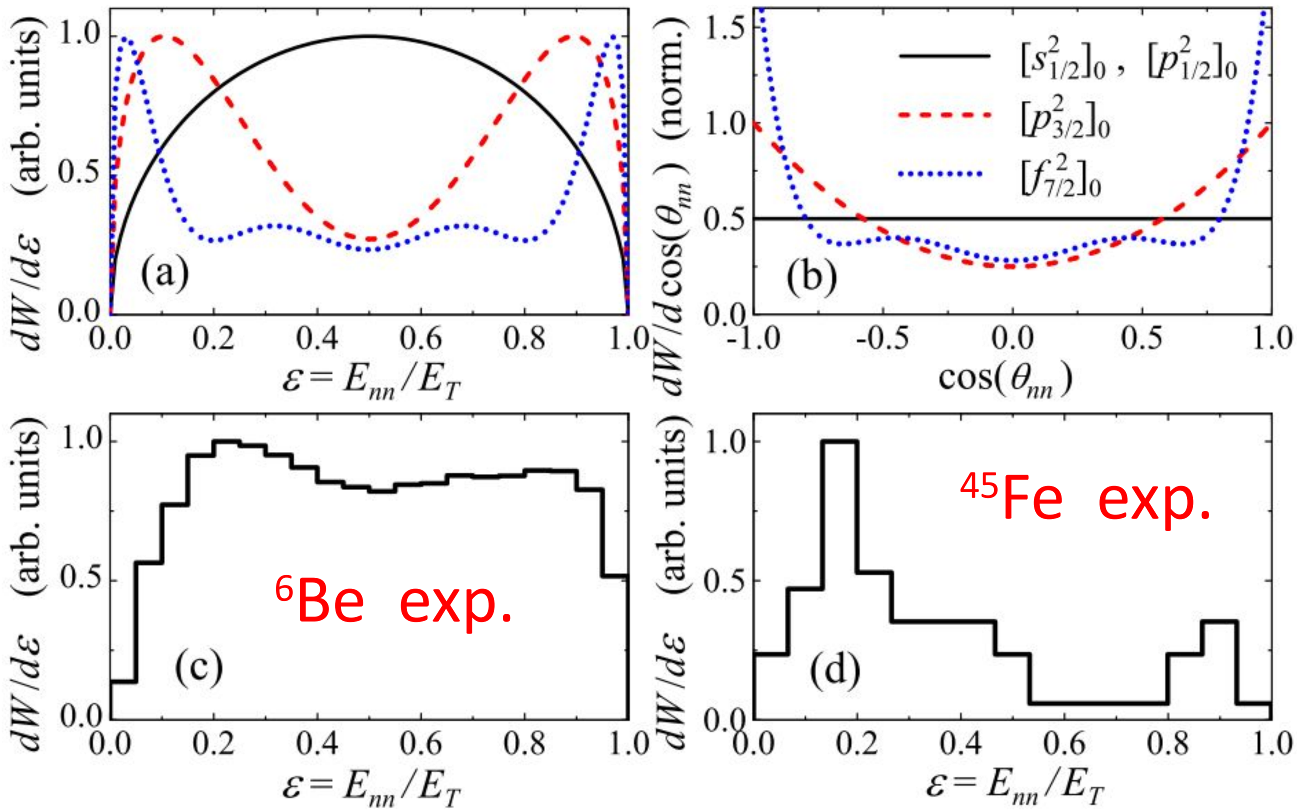
^{26}O $[d^2]_0$



Dineutron approximation structure $[l^2]_0$



From Pauli focusing in coordinate space to correlations in momentum space. Decay.



Model validity: Fast "direct decay to continuum"

Model validity: Sequential decay via long-living states

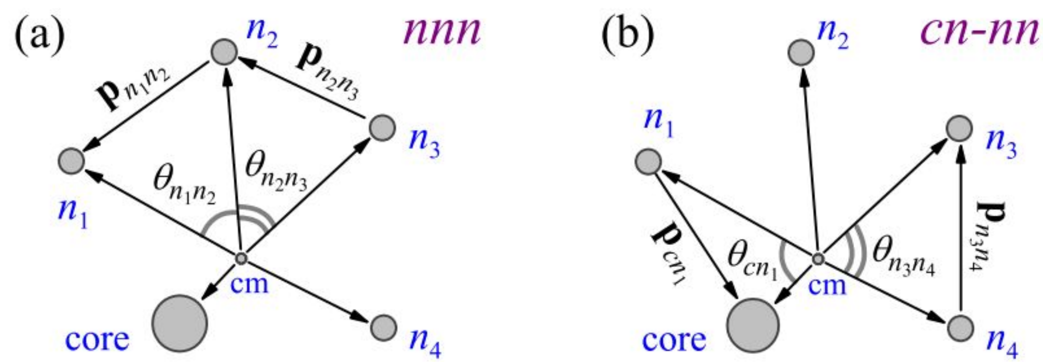
Subbarrier tunneling to low-l configurations

$$^{6}\mathrm{Be}: \qquad [p^2_{3/2}]_0 \rightarrow C_{23}[p^2_{3/2}]_0 + C_{01}[s^2_{1/2}]_0\,,$$

$$^{45}\mathrm{Fe}: \qquad [f^2_{7/2}]_0 \rightarrow C_{67}[f^2_{7/2}]_0 + C_{23}[p^2_{3/2}]_0\,.$$

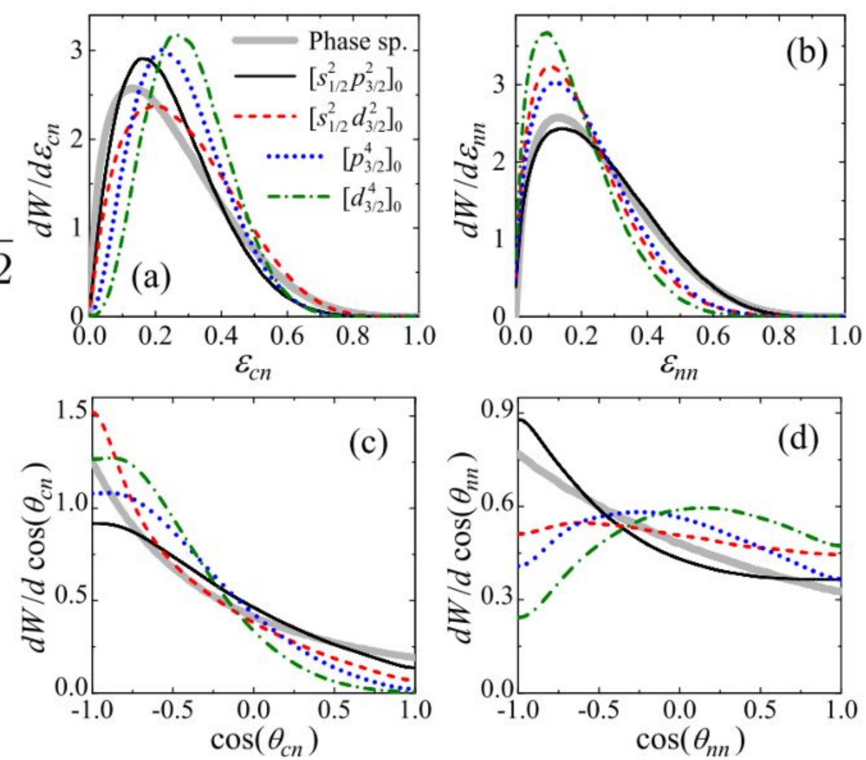
"Minimal" direct decay model for true 4N+core decays

$$dW \sim |T|^2 \, dV_4 \, \prod_{i=1..4} d\Omega_i \, .$$



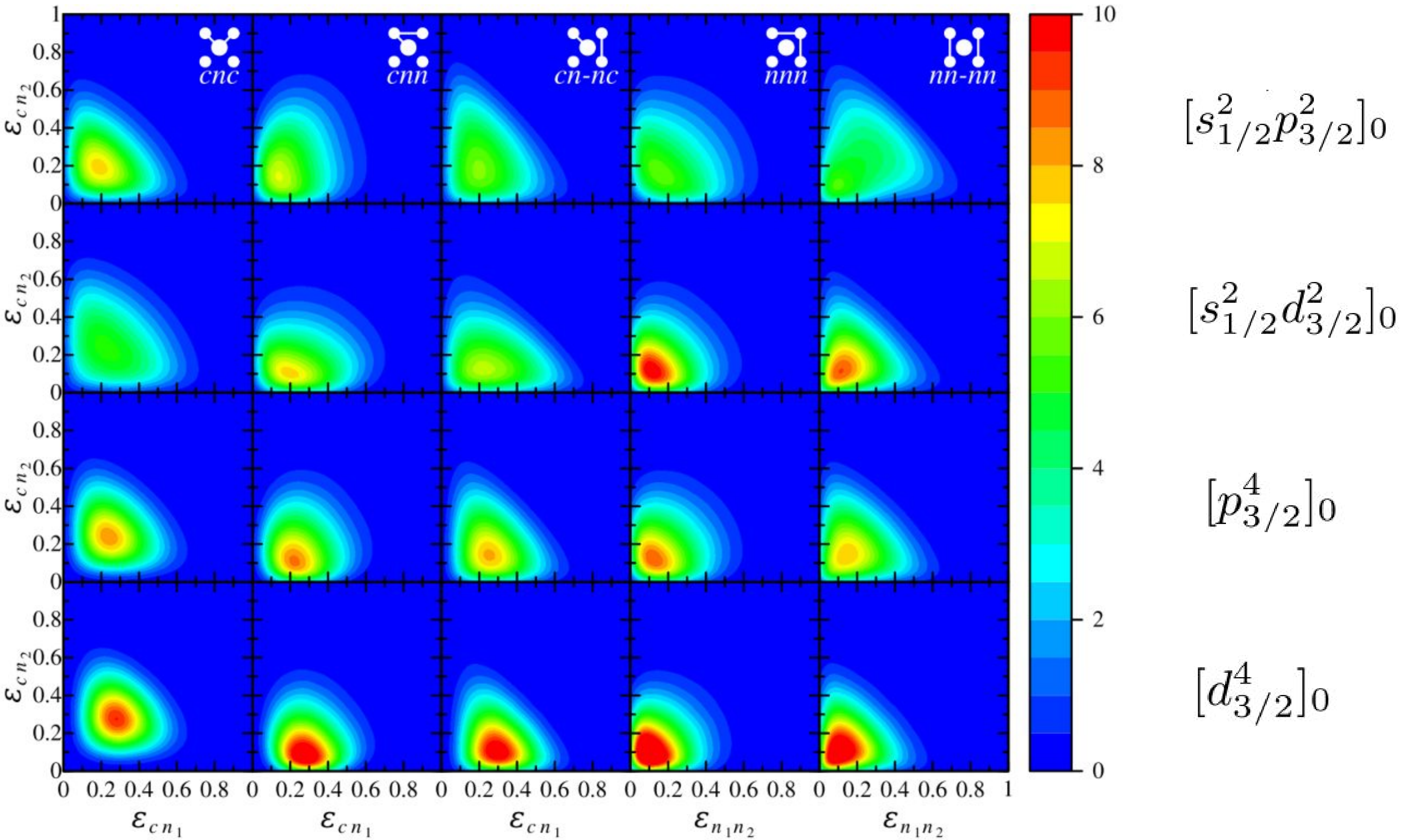
$$T = \mathcal{A} \left[\prod_{i=1..4} A_{cn_i}(l_i, j_i, \mathbf{p}_{cn_i}) \right]_J \, ,$$

$$A_{cn_i}(l_i j_i, \mathbf{p}_{cn_i}) = \frac{1}{2} \frac{a_{l_i j_i} \sqrt{\Gamma_{cn_i}(E_{cn_i})}}{E_{r,cn_i} - E_{cn_i} - i\Gamma_{cn_i}(E_{cn_i})/2}$$



$$\begin{aligned} {}^7\mathrm{H}: \quad [p^4_{3/2}]_0 &\rightarrow \quad C_{2323}[p^4_{3/2}]_0 + C_{0123}[s^2_{1/2}p^2_{3/2}]_0, \\ {}^{28}\mathrm{O}: \quad [d^4_{3/2}]_0 &\rightarrow \quad C_{4343}[d^4_{3/2}]_0 + C_{0143}[s^2_{1/2}d^2_{3/2}]_0 \\ &\qquad + C_{0123}[s^2_{1/2}p^2_{3/2}]_0. \end{aligned}$$

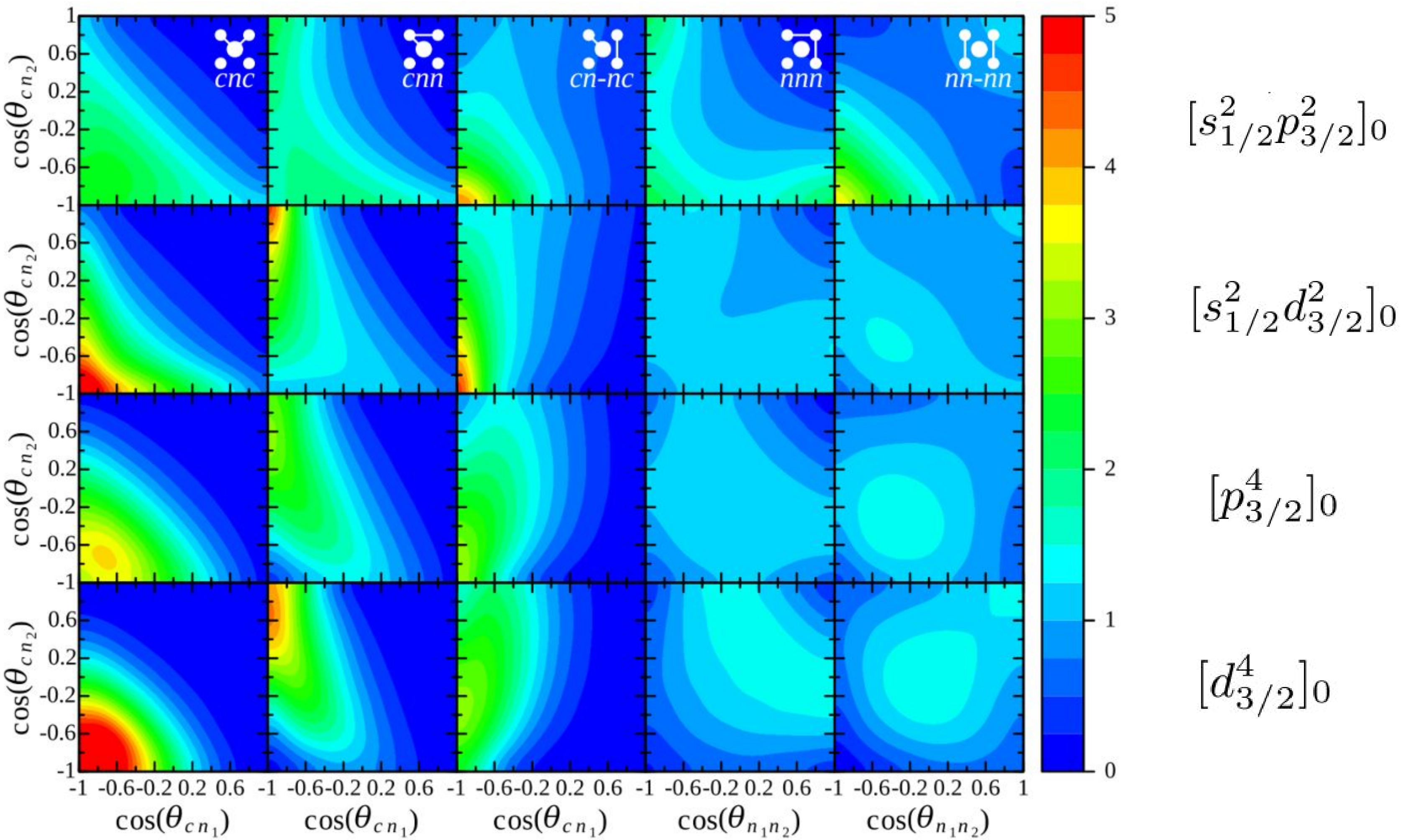
“Pauli focusing” in true 4N+core decays. 2D energy distributions



Full set of correlated 2D distributions form a unique fingerprint of the decaying quantum state

Much more informative situation than in 3body decays

“Pauli focusing” in true 4N+core decays. 2D angular distributions



Full set of correlated 2D distributions form a unique fingerprint of the decaying quantum state

Much more informative situation than in 3body decays

Интерпретация

Competitive light nuclei RIB program at FLNR

Intermediate energy reactions (20-70 MeV/nucleon)

Transfer reactions

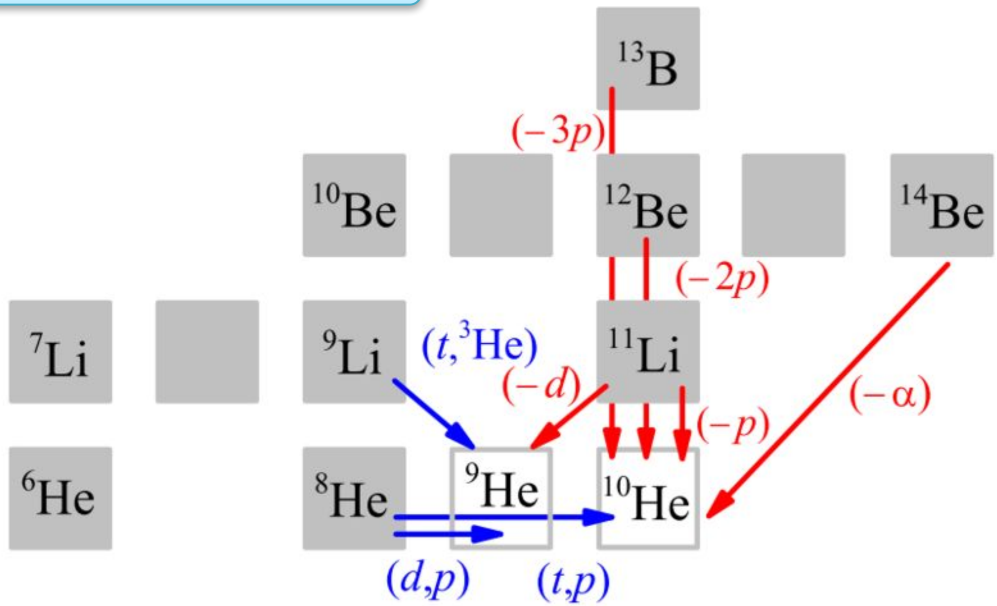
Missing mass, invariant mass, combination

Lower energy – better resolution

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

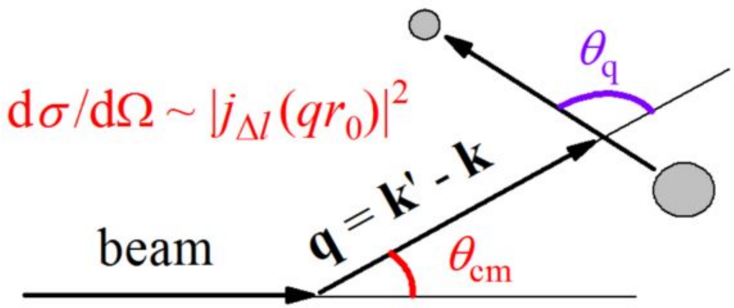
Knockout reactions

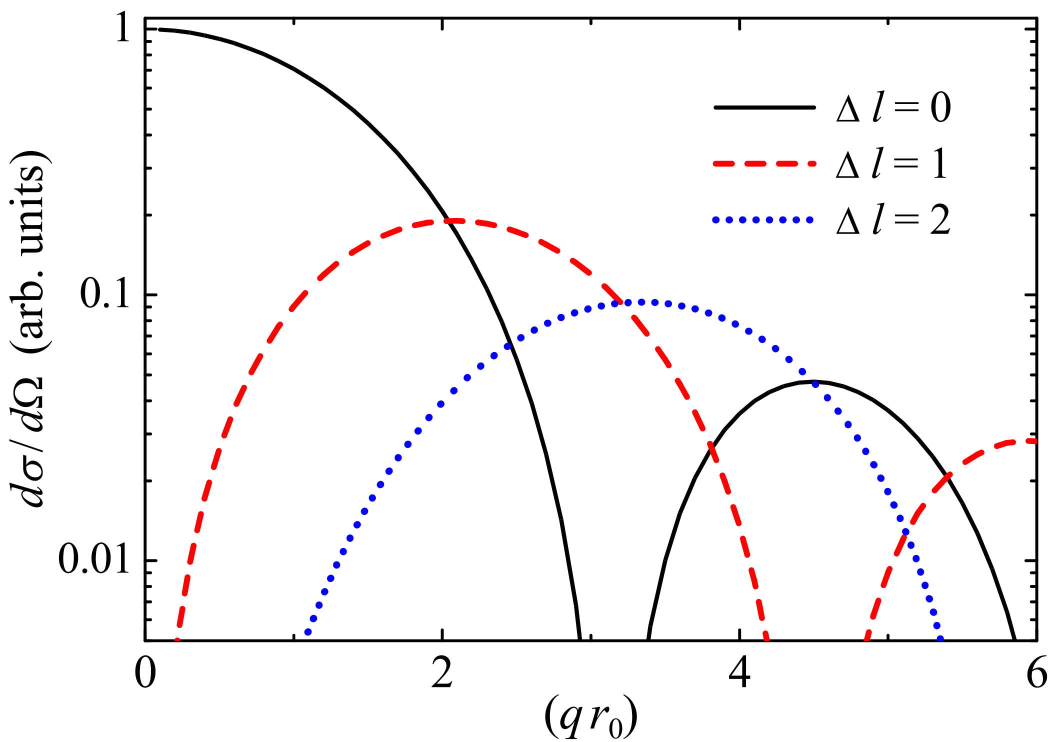
Only invariant mass (exclusion (p,2p) reactions



Importance of complementary reaction studies

CMS correlations of the recoils or products





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

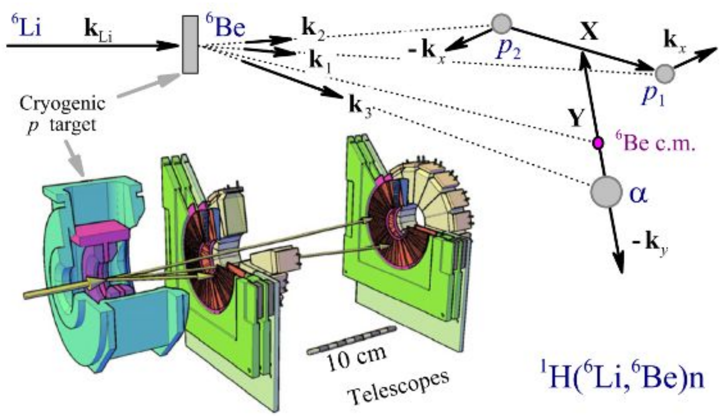
Simple systematics of diffraction minima and maxima as function of the momentum transfer

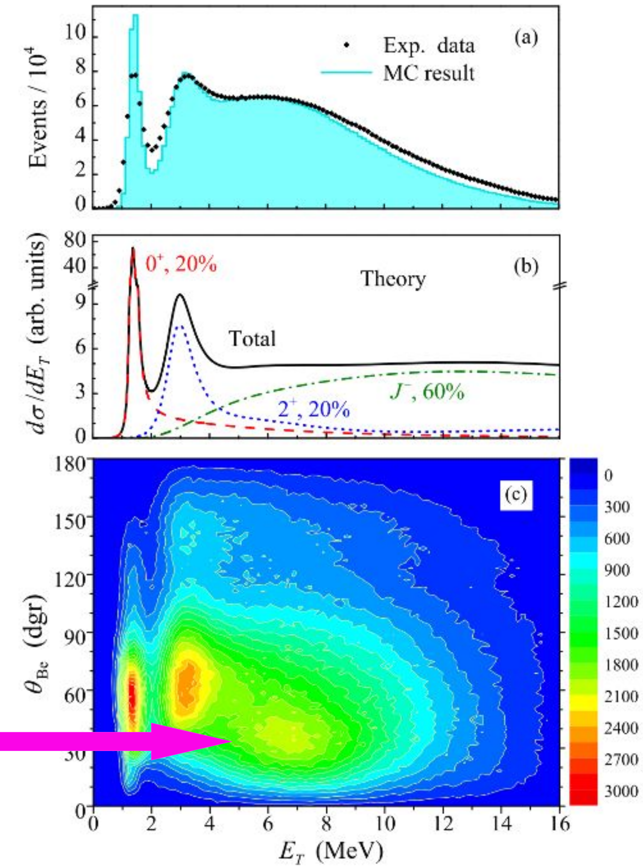
Opportunity of spin-parity identification

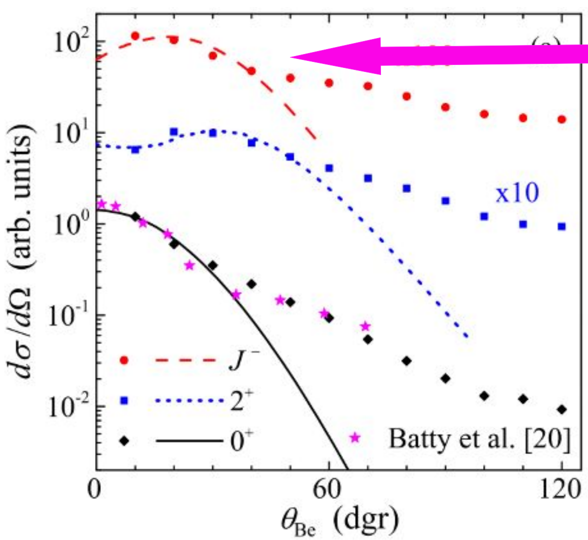
Корреляции в состояниях непрерывного спектра заселяемого в прямых реакциях

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

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

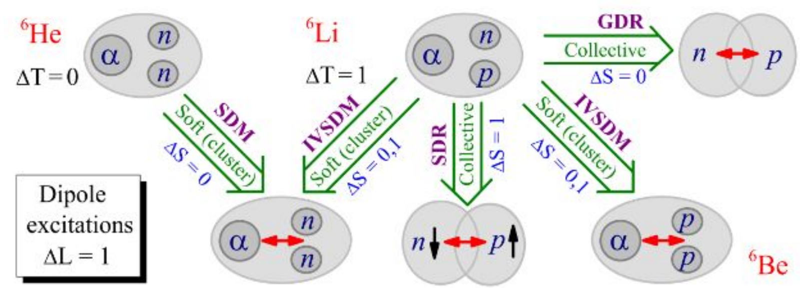






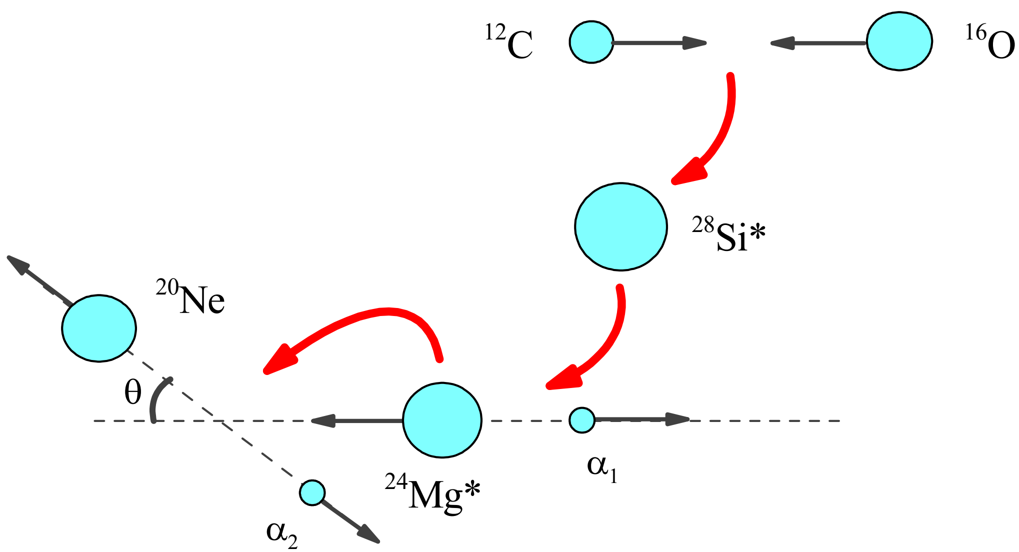
Δ *l* = 1

Isovector Soft Dipole Mode identification

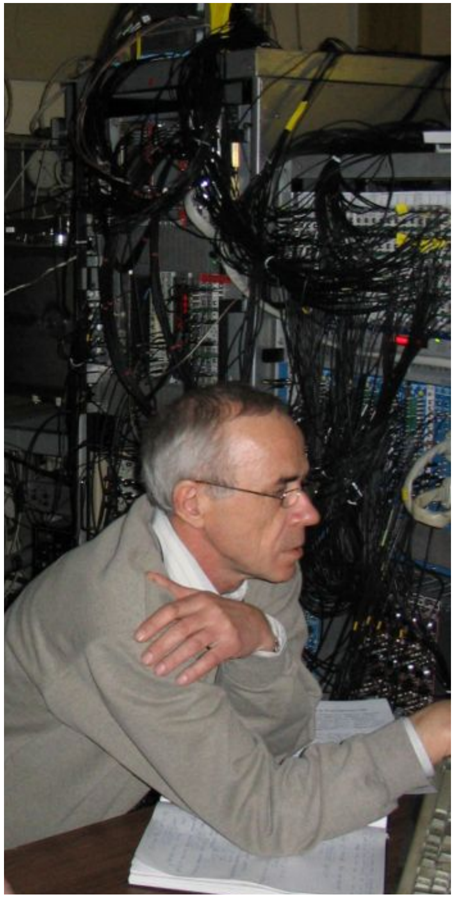


Распад выстроенных двухчастичных состояний в системе переданного импульса

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.

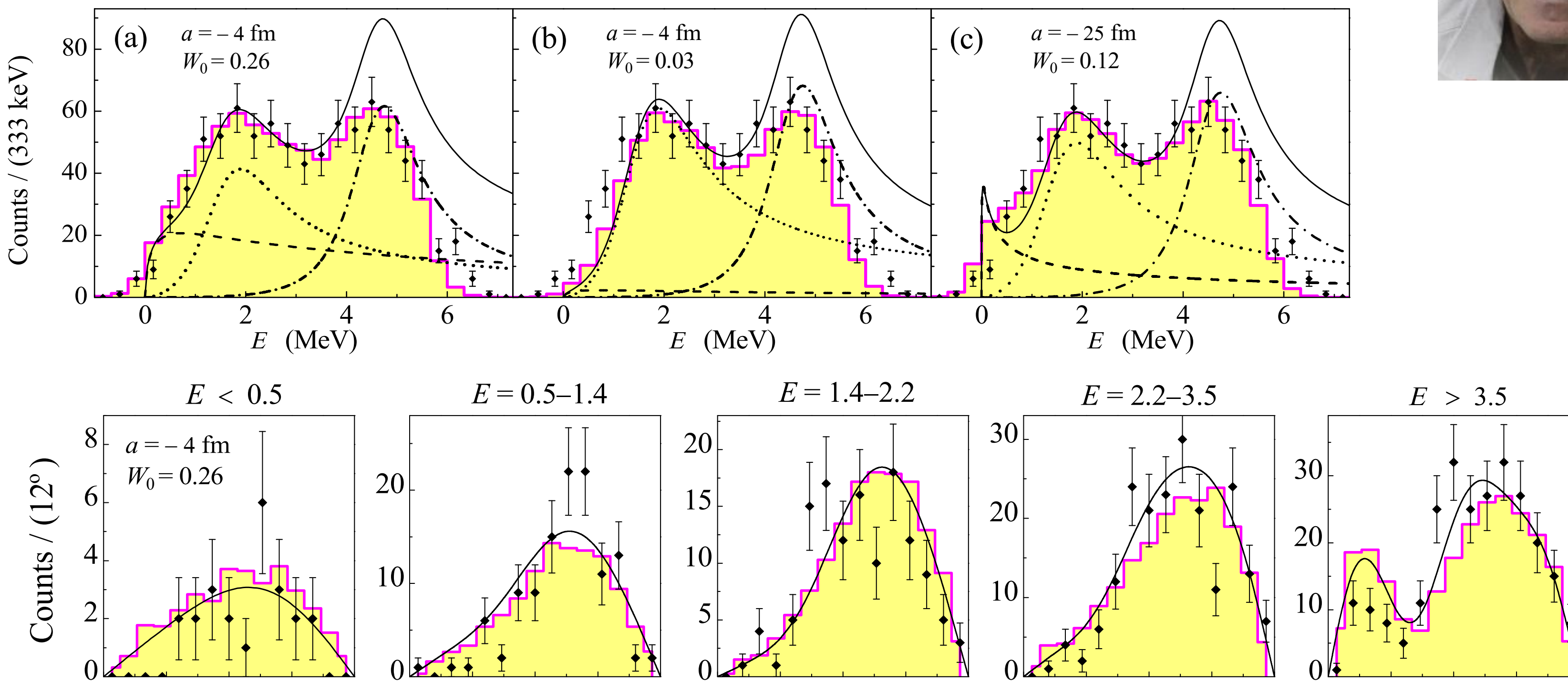


Prof. M. Golovkov pioneered this approach for RIB research

Example: of ^9H studied in $^2H(^8He,p)^9H \rightarrow {}^8He+n$ 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 $\{s_{1/2} p_{1/2} d_{5/2}\}$

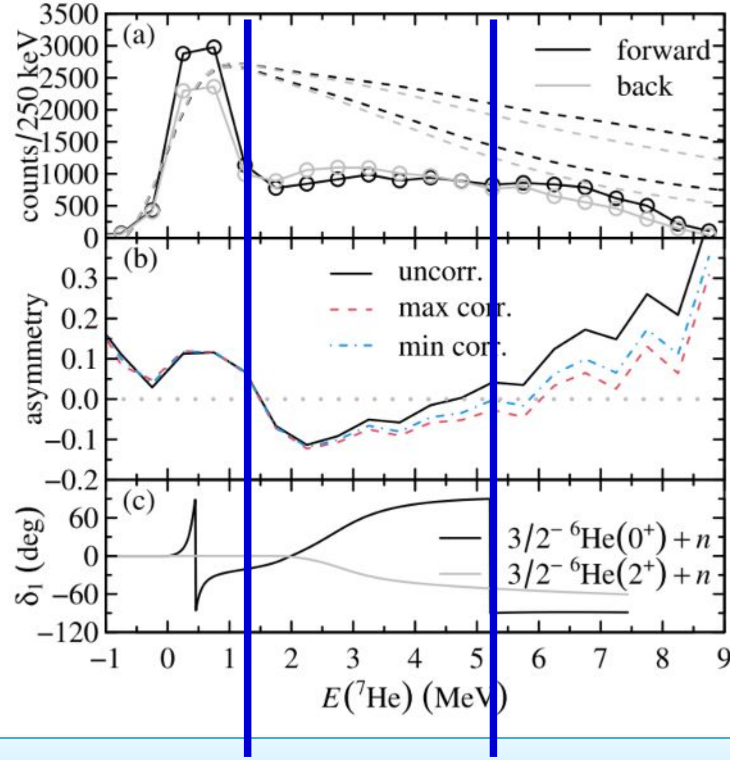
Experimental prospects at ACC-2

^{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

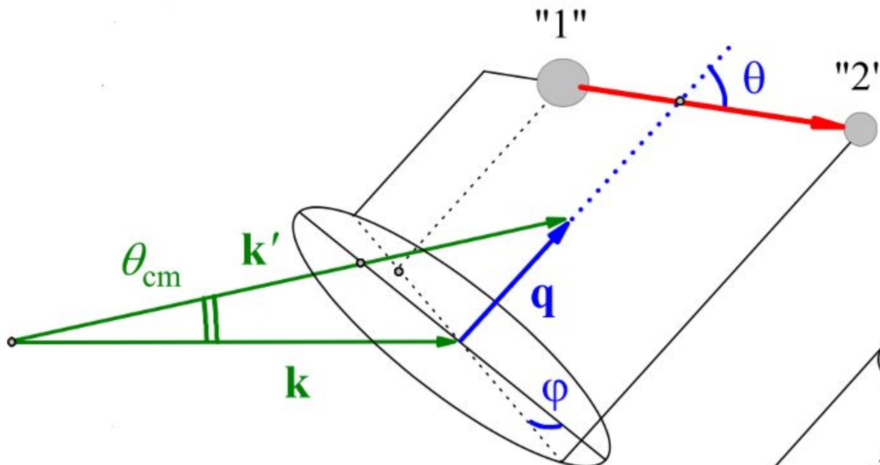
Correlations in the direct reactions populating continuum

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

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

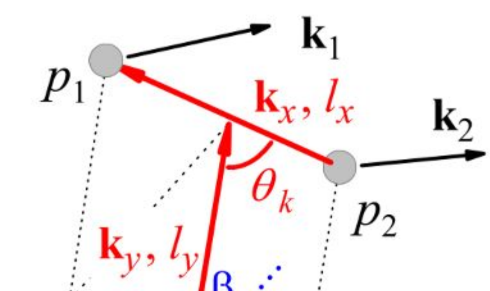
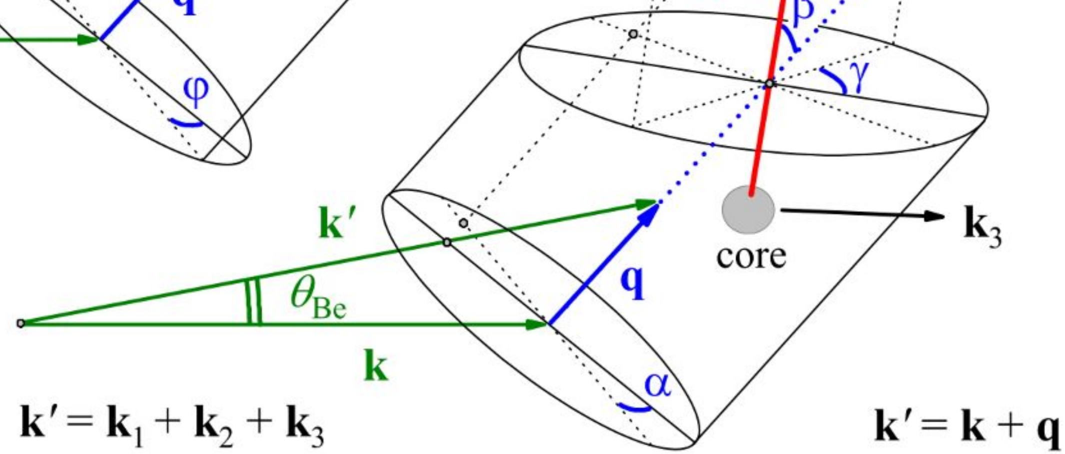
2-body reactions: additional "external" correlation angle θ

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

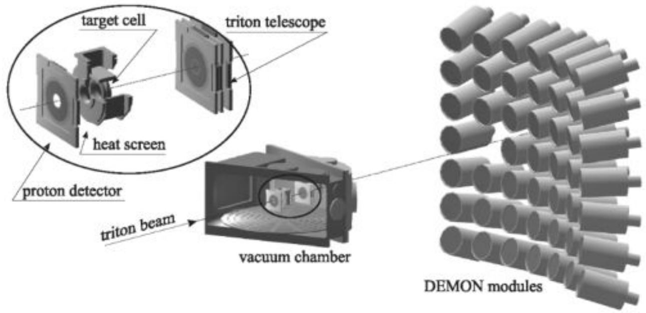


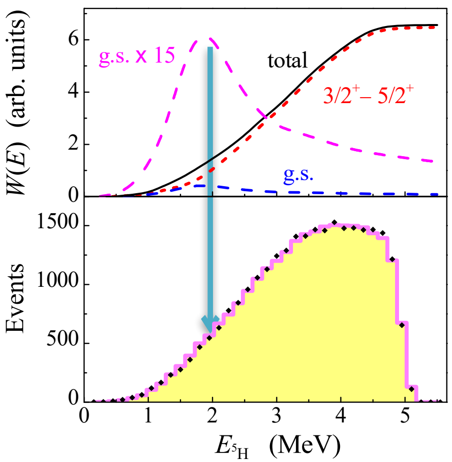
$$\Omega \rightarrow \Omega_2 = \{\theta, \phi\} \, ,$$

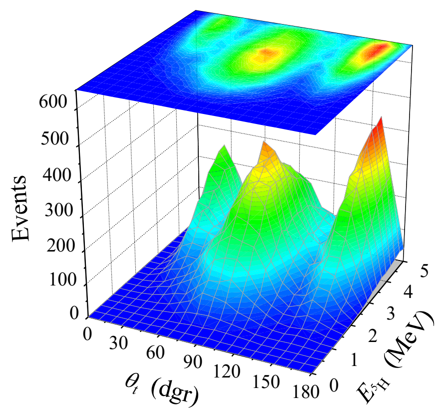
$$\Omega \rightarrow \Omega_5 = \{\varepsilon, \Omega_{kx}, \Omega_{ky}\} = \{\varepsilon, \theta_k, \alpha, \beta, \gamma\} \, .$$

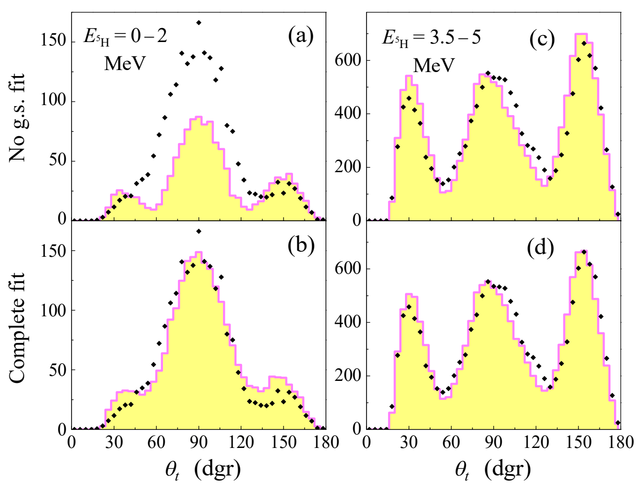



Example: ^{5}H studied in the ^{3}H(t,p)^{5}H -> t+n+n reaction









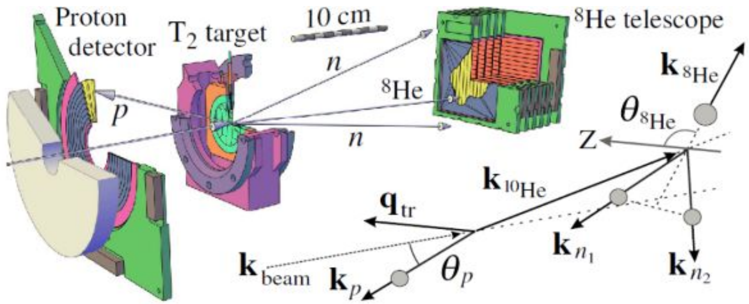
A.A. Korsheninnikov, 2001, ^{6}He(p,2p)^{5}H
Discovery of ^{5}H at FLNR

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.

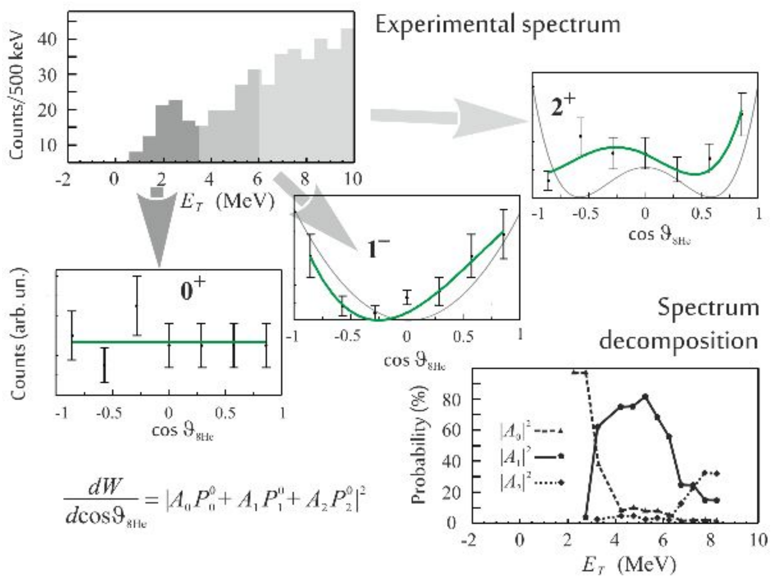
- Poor population of ground state. However, correlations provide enough selectivity: quantum amplification
- ^{5}H ground state position is finally established; the excited state is established as $3/2^{+}$-$5/2^{+}$ degenerate mixture

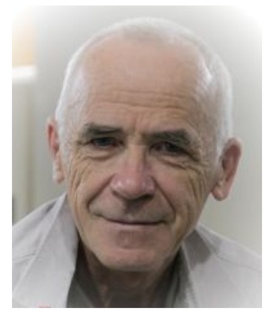
Example: ^{10}He studied in the ^{8}He(t,p)^{10}He -> ^{8}He+n+n reaction



"Conundrum nucleis" second double magic in nuclide chart

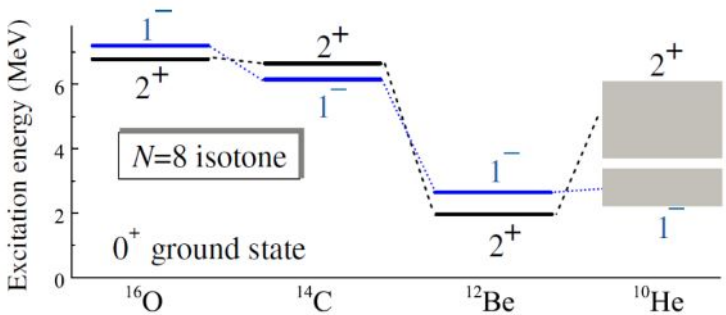
Discovered by Korsheninnikov et al. in 1994 in RIKEN giving E_T=1.2 MeV





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?



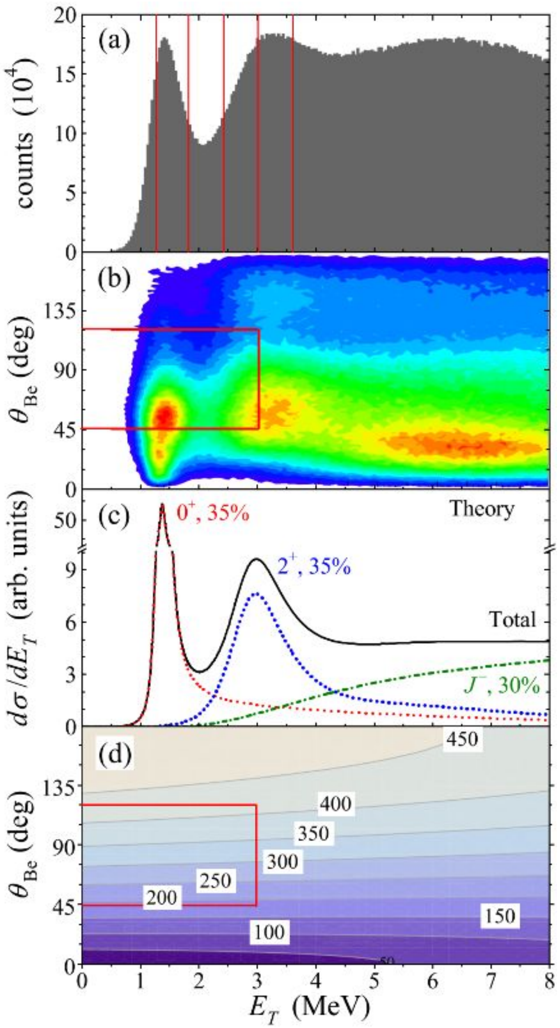
New ground state energy for ^{10}He: E_T=2.0-2.5 MeV

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)



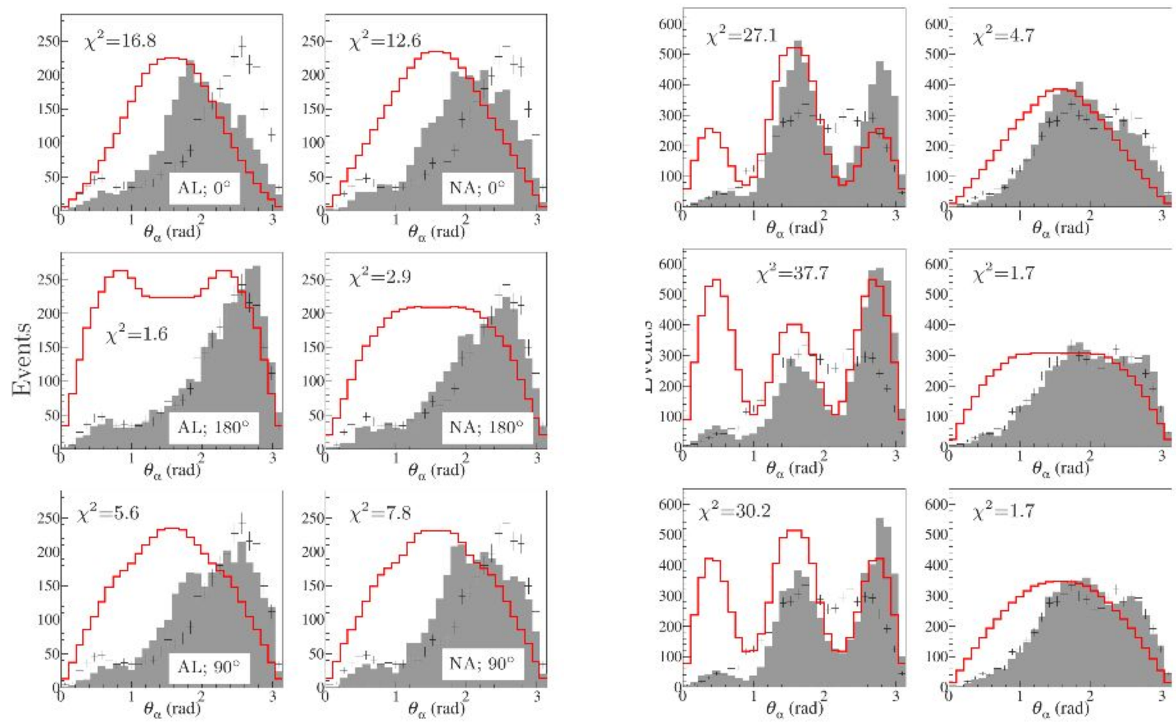


TABLE I. The best fit to experimental data of density matrix parameters for different $\{E_T, \theta_{Be}\}$ ranges. The fits were found using the figures with θ_α distribution for all six configurations of the theoretical model.

E_T (MeV)	$\theta_{Be}\in(45,60)°$	$\theta_{Be}\in(60,75)°$	$\theta_{Be}\in(75,90)°$	$\theta_{Be}\in(90,120)°$
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°

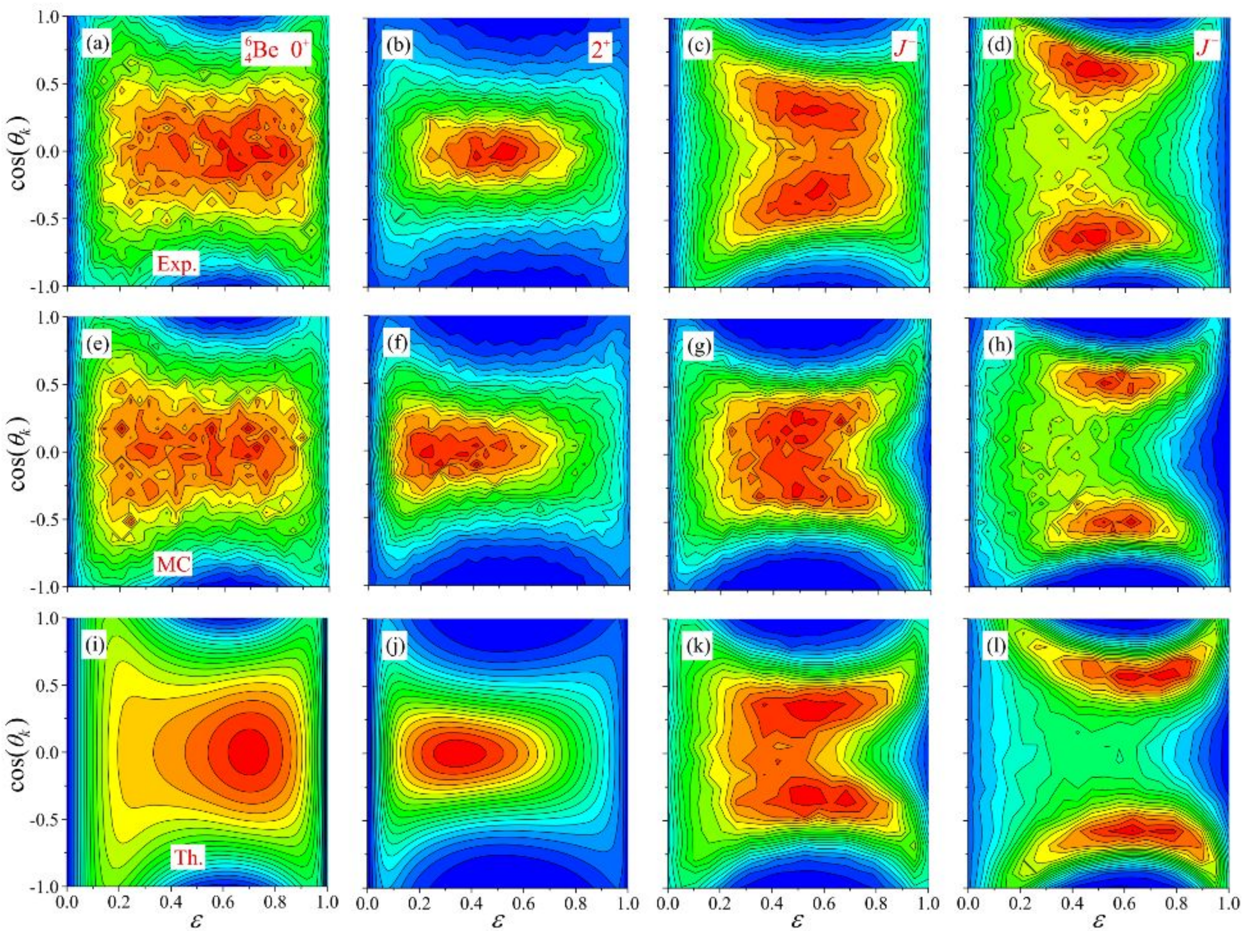
Двухпротонная радиоактивность

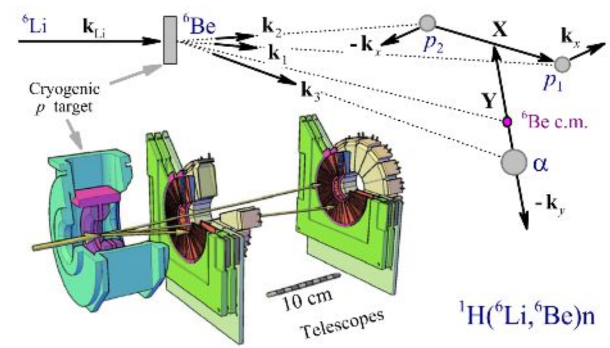
и мягкие моды возбуждения

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

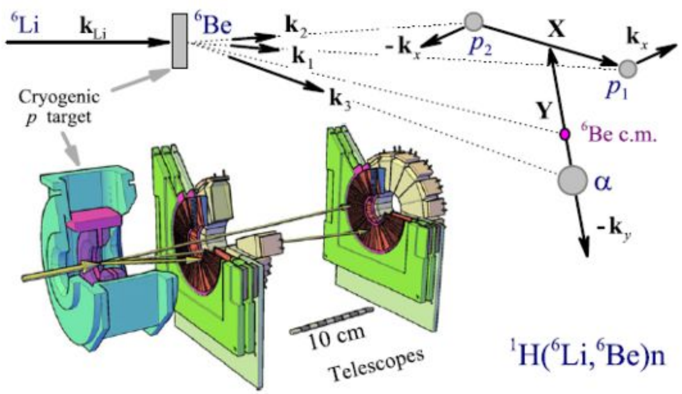
Δ l = 0 → 0⁺

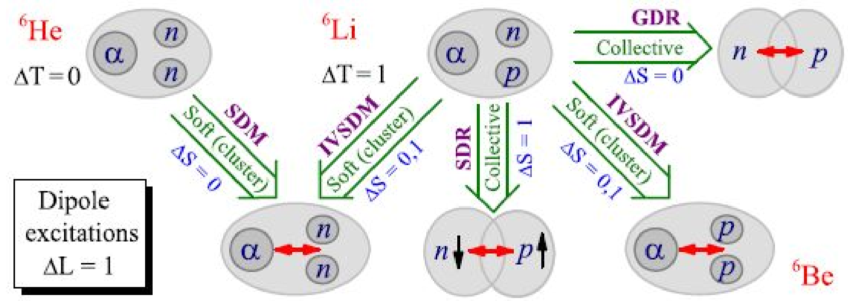
Δ l = 2 → 2⁺

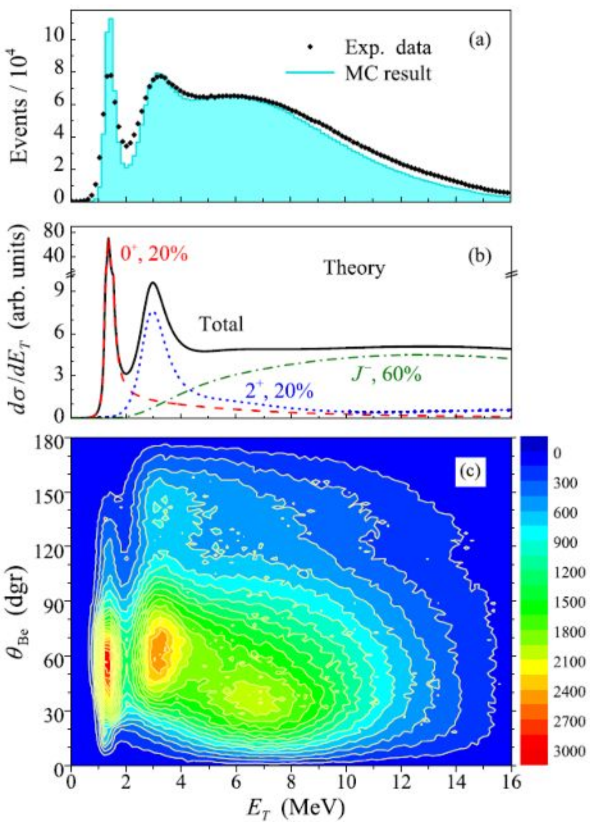
Δ l = 1 → J⁻

Isovector Soft Dipole mode in ^{6}Be

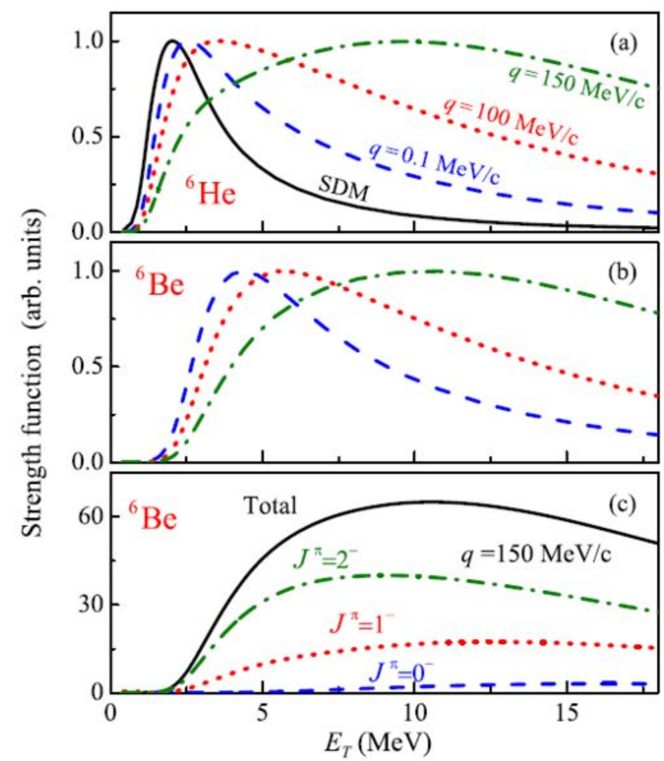
A.S.Fomichev et al., PLB **708** (2012) 6.





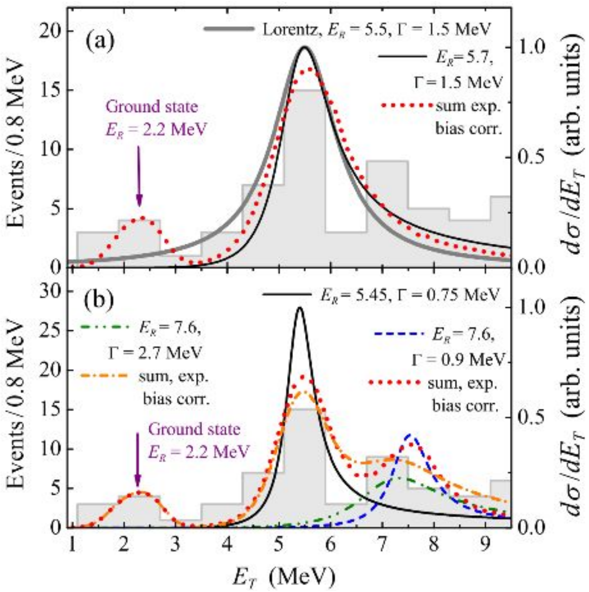


- Large cross section above 2^+ and no resonance
- ΔL=1 identification – some kind of dipole response
- No particle stable g.s. – can not be built on spatially extended WF
- Built on the spatially extended ^{6}Li g.s.

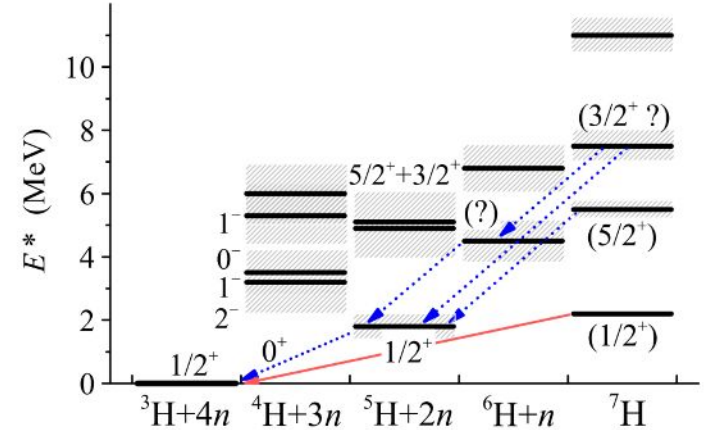


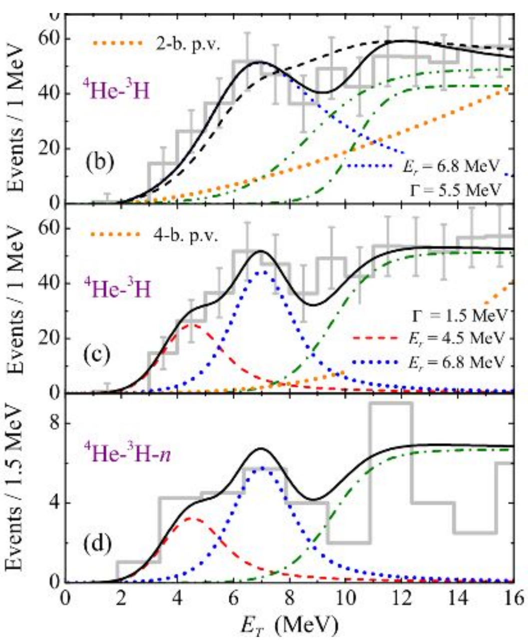
^{7}H and ^{6}H studies summary

Excitation spectra relative ^{3}H ground state

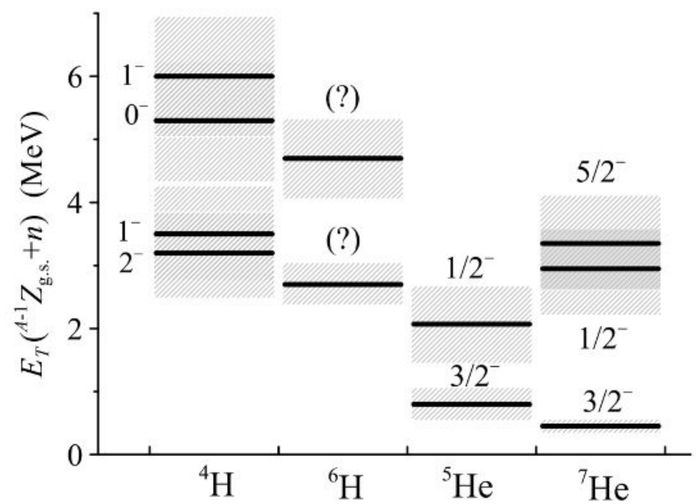


- ^{7}H g.s. at 1.8 MeV
- Resonant states at 5.5, 11 MeV
- Possible resonant state at 7.5 MeV





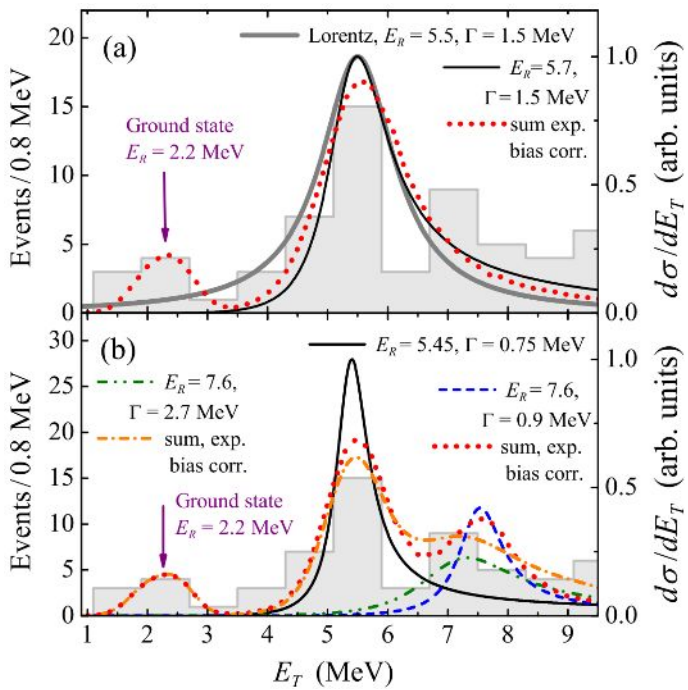
- No ^{6}H g.s. at 2.6-2-7 MeV
- Resonant state at 6.5 MeV
- Possible resonant state at 4.5 MeV

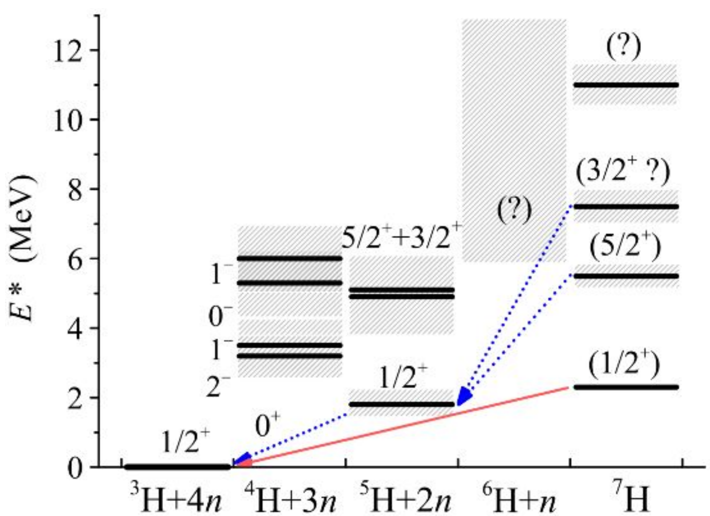


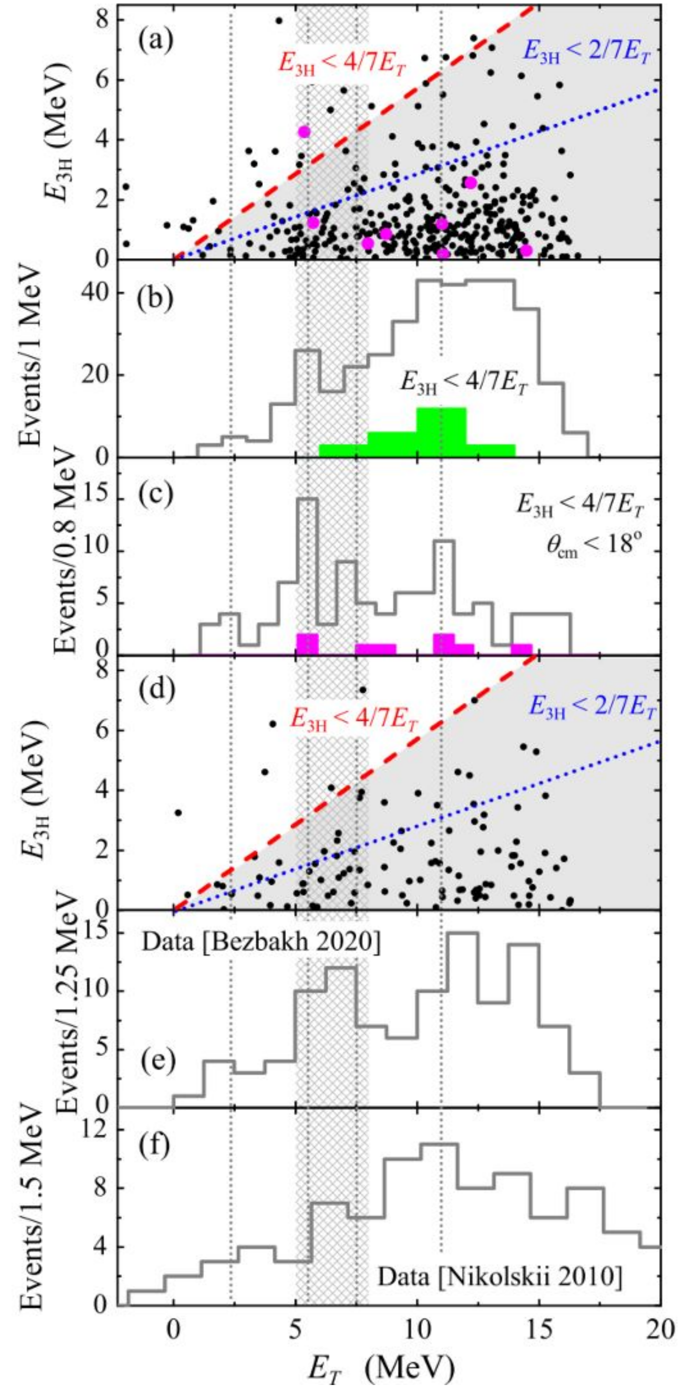
Analogies in the excitation spectra relative ^{3}H and ^{5}H, ^{4}He and ^{6}He ground states

Сверхтяжелые водороды ^{6}H, ^{7}H

^{7}H data and spectrum

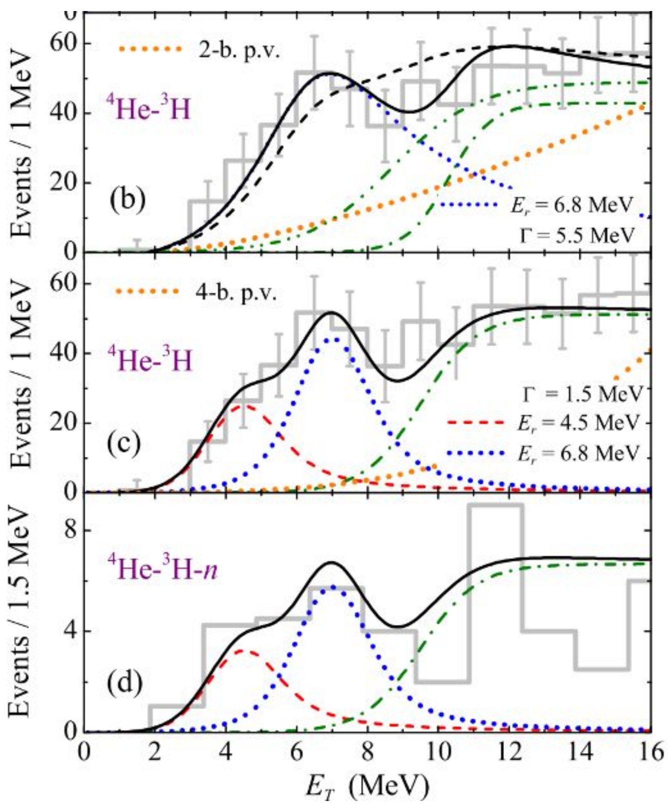






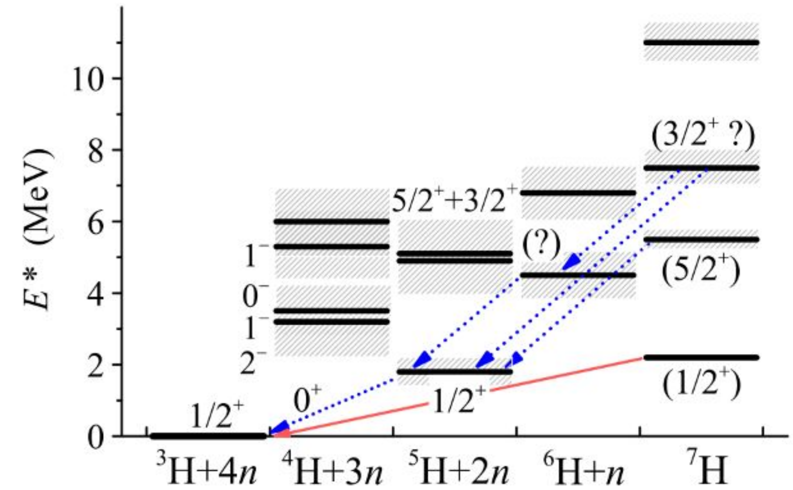
^{6}H data and spectrum

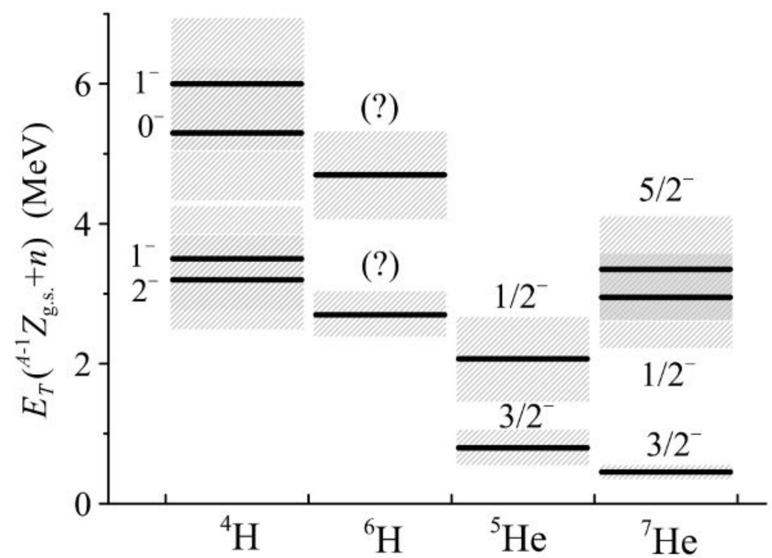
Background-subtracted, efficiency corrected



- 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



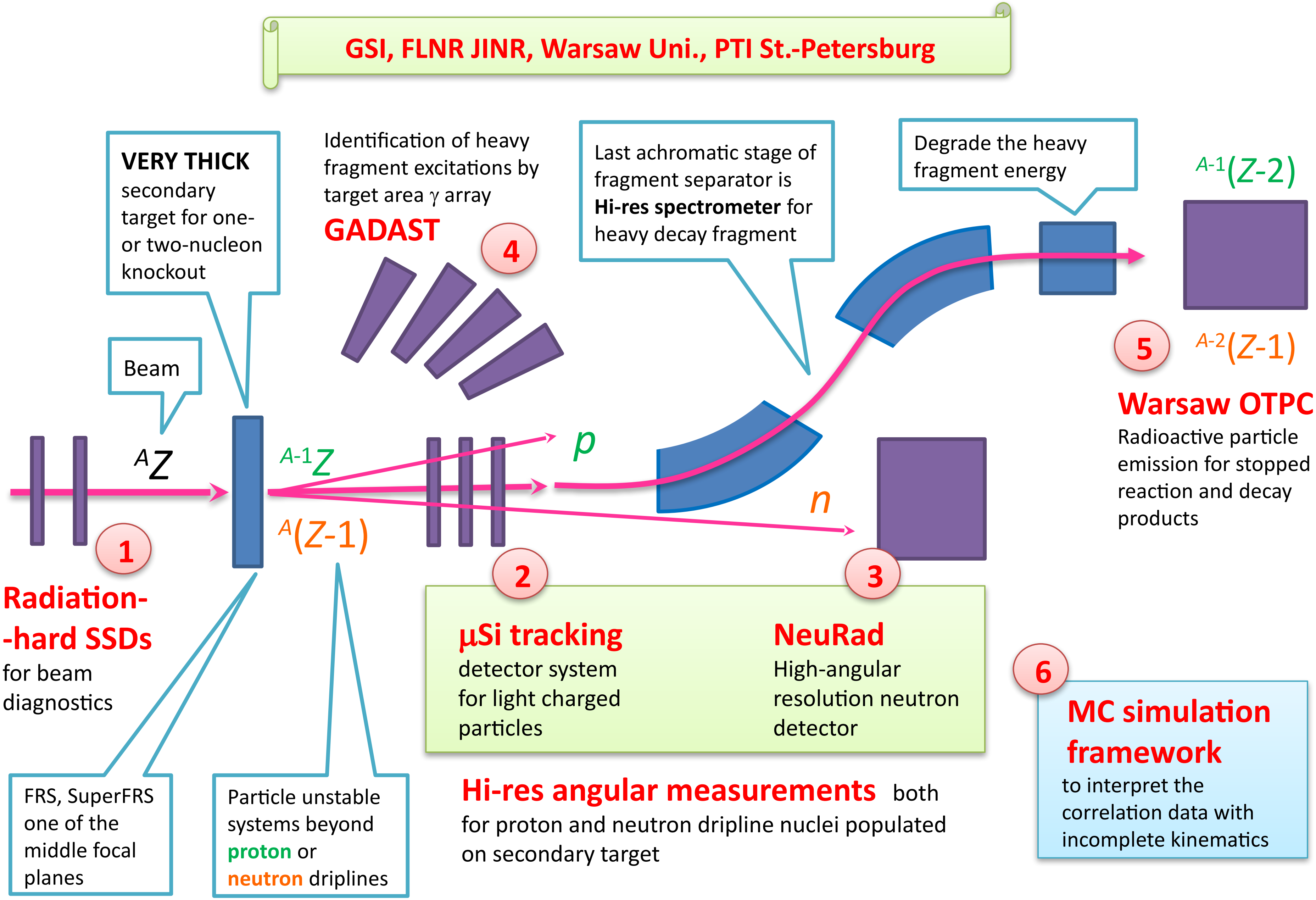


Analogies in the excitation spectra relative ^{3}H and ^{5}H, ^{4}He and ^{6}He ground states

EXPERT@SuperFRS

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

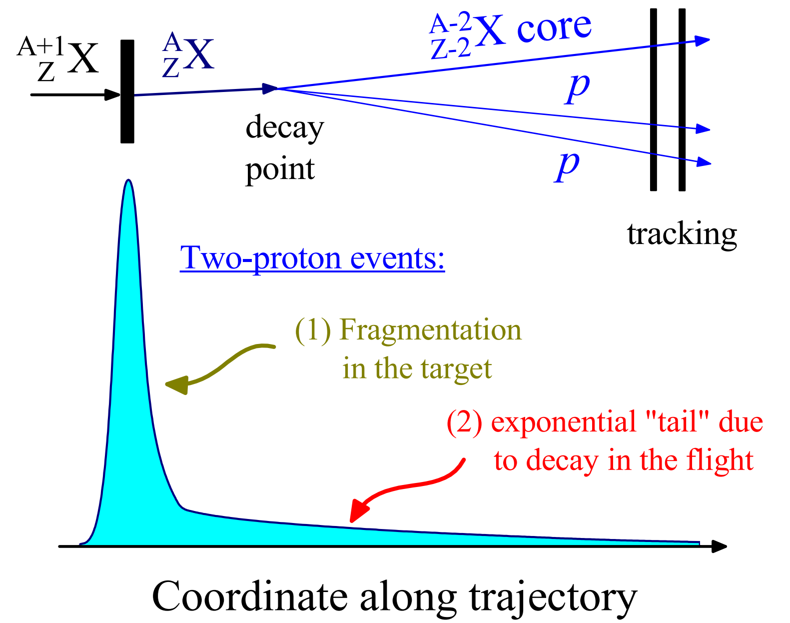
EXPERT: EXotic Particle Emission and Radioactivity by Tracking



Basic idea

Radioactivity studies

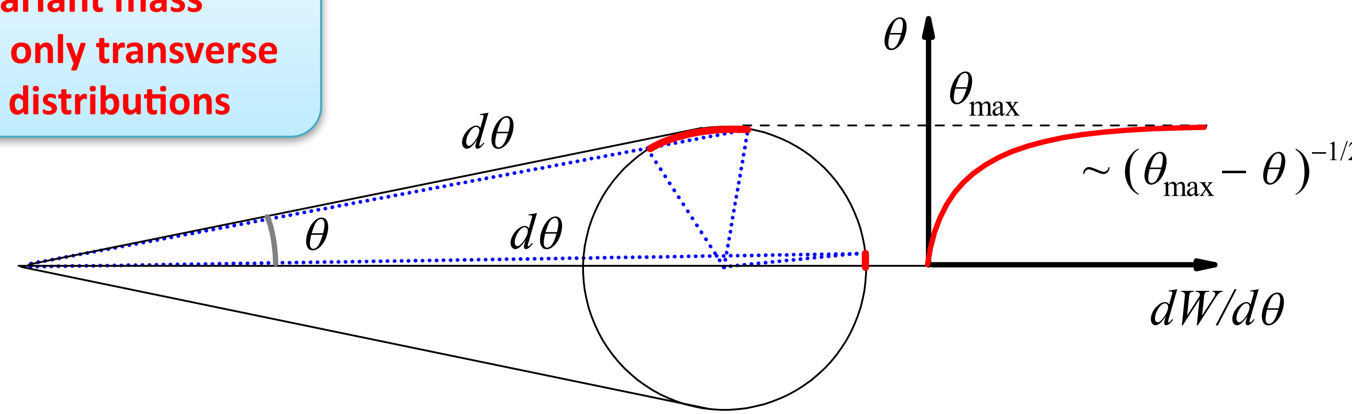
I. Mukha:
opportunity to investigate particle radioactivity in fs-ns lifetime range



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! IF you understand what is happening

Major results for 2007 experiment

PRL 99, 182501 (2007) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2007

Observation of Two-Proton Radioactivity of ^{19}Mg by Tracking the Decay Products

I. Mukha,[1,*] K. Sümmerer,[2] L. Acosta,[3] M. A. G. Alvarez,[1] E. Casarejos,[4] A. Chatillon,[2] D. Cortina-Gil,[4] J. Espino,[1] A. Fomichev,[5] J. E. García-Ramos,[3] H. Geissel,[2] J. Gómez-Camacho,[1] L. Grigorenko,[5,6,2] J. Hoffmann,[2] O. Kiselev,[2,7] A. Korsheninnikov,[6] N. Kurz,[2] Yu. Litvinov,[2] I. Martel,[3] C. Nociforo,[2] W. Ott,[2] M. Pfützner,[8] C. Rodríguez-Tajes,[4] E. Roeckl,[2] M. Stanoiu,[2,9] H. Weick,[2] and P. J. Woods[10]

PHYSICAL REVIEW C 79, 061301(R) (2009)

Observation of narrow states in nuclei beyond the proton drip line: ^{15}F and ^{16}Ne

I. Mukha,[1,2] N. K. Timofeyuk,[3] K. Sümmerer,[4] L. Acosta,[5] M. A. G. Alvarez,[1] E. Casarejos,[6] A. Chatillon,[4] D. Cortina-Gil,[6] J. M. Espino,[1] A. Fomichev,[7] J. E. García-Ramos,[5] H. Geissel,[4] J. Gómez-Camacho,[1] L. Grigorenko,[4,7] J. Hofmann,[4] O. Kiselev,[4,8] A. Korsheninnikov,[2] N. Kurz,[4] Yu. Litvinov,[4,9] I. Martel,[5] C. Nociforo,[4] W. Ott,[4] M. Pfützner,[10] C. Rodríguez-Tajes,[6] E. Roeckl,[4] M. Stanoiu,[4,11] H. Weick,[4] and P. J. Woods[12]

RAPID COMMUNICATIONS

PHYSICAL REVIEW C 77, 061303(R) (2008)

Proton-proton correlations observed in two-proton decay of ^{19}Mg and ^{16}Ne

I. Mukha,[1,2] L. Grigorenko,[3,4] K. Sümmerer,[4] L. Acosta,[5] M. A. G. Alvarez,[1] E. Casarejos,[6] A. Chatillon,[4] D. Cortina-Gil,[6] J. M. Espino,[1] A. Fomichev,[3] J. E. García-Ramos,[5] H. Geissel,[4] J. Gómez-Camacho,[1] J. Hofmann,[4] O. Kiselev,[4,7,8] A. Korsheninnikov,[2] N. Kurz,[4] Yu. Litvinov,[4] I. Martel,[5] C. Nociforo,[4] W. Ott,[4] M. Pfützner,[9] C. Rodríguez-Tajes,[6] E. Roeckl,[4] M. Stanoiu,[4,10] H. Weick,[4] and P. J. Woods[11]

PHYSICAL REVIEW C 82, 054315 (2010)

Spectroscopy of proton-unbound nuclei by tracking their decay products in-flight: One- and two-proton decays of ^{15}F, ^{16}Ne, and ^{19}Na

I. Mukha,[1,2,3,*] K. Sümmerer,[1] L. Acosta,[4] M. A. G. Alvarez,[5] E. Casarejos,[6,7] A. Chatillon,[1] D. Cortina-Gil,[6] I. A. Egorova,[8] J. M. Espino,[5] A. Fomichev,[9] J. E. García-Ramos,[4] H. Geissel,[1] J. Gómez-Camacho,[5] L. Grigorenko,[1,9] J. Hofmann,[1] O. Kiselev,[1,10] A. Korsheninnikov,[3] N. Kurz,[1] Yu. A. Litvinov,[1,11] E. Litvinova,[1,12] I. Martel,[4] C. Nociforo,[1] W. Ott,[1] M. Pfützner,[13] C. Rodríguez-Tajes,[6,14] E. Roeckl,[1] M. Stanoiu,[1,15] N. K. Timofeyuk,[16] H. Weick,[1] and P. J. Woods[17]

PHYSICAL REVIEW C 85, 044325 (2012)

New states in ^{18}Na and ^{19}Mg observed in the two-proton decay of ^{19}Mg

I. Mukha,[1,*] L. Grigorenko,[1,2,3] L. Acosta,[4] M. A. G. Alvarez,[5] E. Casarejos,[6,7] A. Chatillon,[1] D. Cortina-Gil,[6] J. M. Espino,[5] A. Fomichev,[2] J. E. García-Ramos,[4] H. Geissel,[1] J. Gómez-Camacho,[5] J. Hofmann,[1] O. Kiselev,[1] A. Korsheninnikov,[3] N. Kurz,[1] Yu. A. Litvinov,[1] I. Martel,[4] C. Nociforo,[1] W. Ott,[1] M. Pfützner,[1,8] C. Rodríguez-Tajes,[6,9] E. Roeckl,[1] C. Scheidenberger,[1] M. Stanoiu,[1,10] K. Sümmerer,[1] H. Weick,[1] and P. J. Woods[11]

PRL + 2 PRC(R) + 2 PRC

Major results for 2007 experiment

New isotope: ^{19}Mg. Spectroscopy.

Spectroscopy of ^{16}Ne, ^{18}Na, ^{15}F.

The lightest 2p radioactivity case – ground state decay of ^{19}Mg.

First correlation studies in the s-d-shell 2p emitters

Major results for S388

Physics Letters B 762 (2016) 263–270

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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

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]

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]

PHYSICAL REVIEW C 98, 064309 (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]

2 PRL + 1 PLB + 4 PRC + …

(data analysis continues)

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

:. 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] -énas-Díaz,[7] V. Dunin,[5] J. M. Espino,[8] A. Estrade,[9] F. Farinon,[2] A. Fomichev,[5] H. Geissel,[2] A. Gorshkov,[5] ;ki,[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] ıa,[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] epnev,[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]

PHYSICAL REVIEW C 98, 064308 (2018)

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

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

PHYSICAL REVIEW LETTERS 123, 092502 (2019)

Towards the Limits of Existence of Nuclear Structure: Observation and First Spectroscopy of the Isotope ^{31}K by Measuring Its Three-Proton Decay

D. Kostyleva,[1,2,*] I. Mukha,[1] L. Acosta,[3,4] E. Casarejos,[5] V. Chudoba,[6,7] A. A. Ciemny,[8] W. Dominik,[8] J. A. Dueñas,[9] V. Dunin,[10] J. M. Espino,[11] A. Estradé,[12] F. Farinon,[1] A. Fomichev,[6] H. Geissel,[1,2] A. Gorshkov,[6] L. V. Grigorenko,[6,13,14] Z. Janas,[8] G. Kamiński,[15,6] O. Kiselev,[1] R. Knöbel,[1,2] S. Krupko,[6] M. Kuich,[16,8] Yu. A. Litvinov,[1] G. Marquinez-Durán,[17] I. Martel,[18] C. Mazzocchi,[8] C. Nociforo,[1] A. K. Ordúz,[25] M. Pfützner,[8,1] S. Pietri,[1] M. Pomorski,[8] A. Prochazka,[1] S. Rymzhanova,[6] A. M. Sánchez-Benítez,[19] C. Scheidenberger,[1,2] H. Simon,[1] B. Sitar,[20] R. Slepnev,[6] M. Stanoiu,[21] P. Strmen,[20] I. Szarka,[20] M. Takechi,[1] Y. K. Tanaka,[1,22] H. Weick,[1] M. Winkler,[1] J. S. Winfield,[1] X. Xu,[23,2,1] and M. V. Zhukov[24]

Major results for S388

Beta-delayed 3p decay of ^{31}Ar.

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

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

"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

Перспективы в РФ
(условная DERICA)

Состояние дел в ядерной физике низких энергий

САНКТ-ПЕТЕРБУРГСКИЙ ФЕДЕРАЛЬНЫЙ
ИССЛЕДОВАТЕЛЬСКИЙ ЦЕНТР
РОССИЙСКОЙ АКАДЕМИИ НАУК

**«ДОРОЖНАЯ КАРТА»
В ОБЛАСТИ ЯДЕРНОЙ ФИЗИКИ**

Редактор Л.В. Григоренко

Москва
2021

Авторский коллектив:

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

Исследования на пучках радиоактивных изотопов

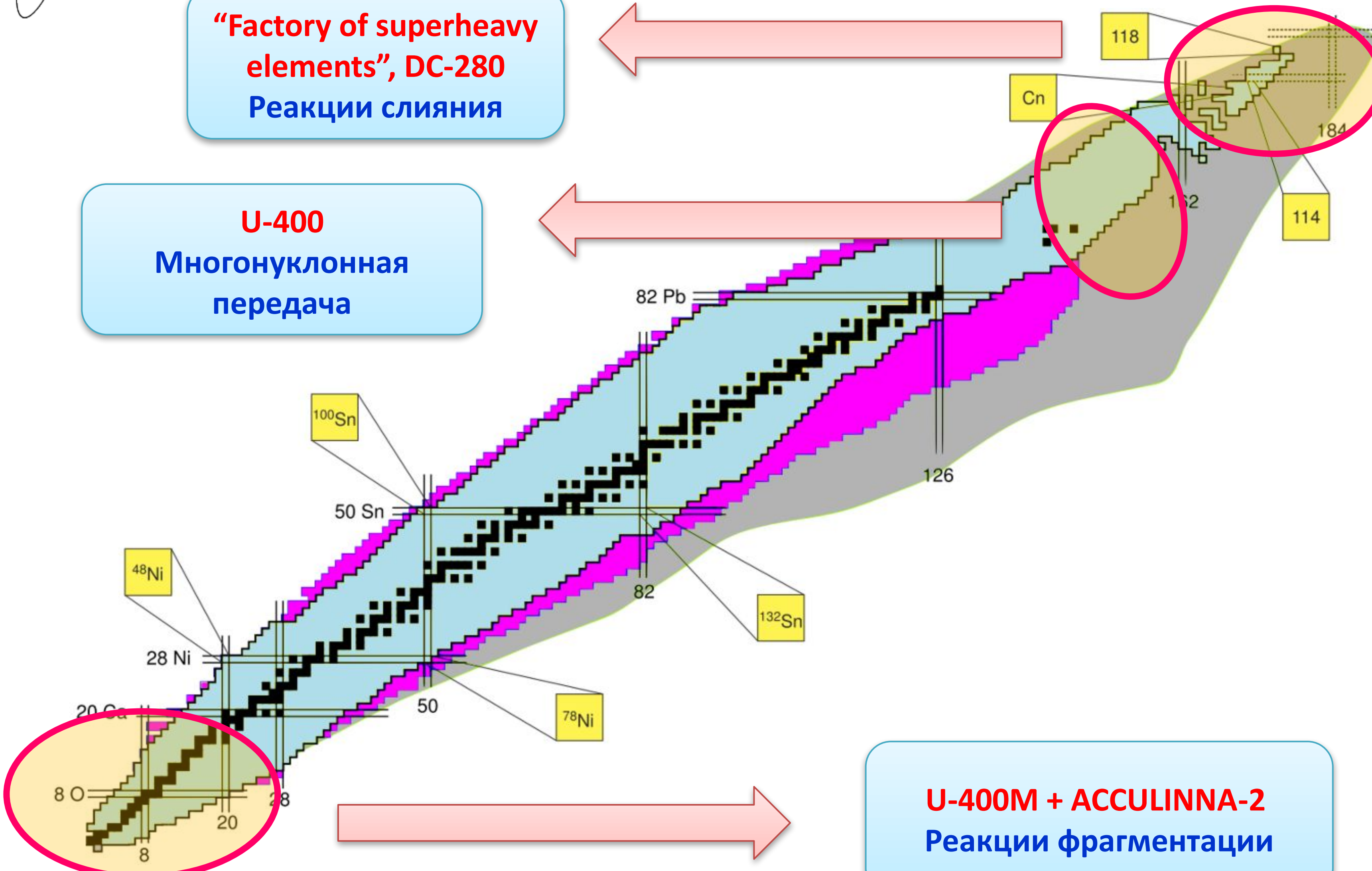
– Всего существует 256 стабильных изотопов
– 339 изотопов встречается в природе

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

ЛЯР, области интересов

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

U-400
Многонуклонная передача

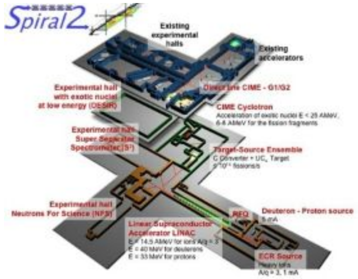


U-400M + ACCULINNA-2
Реакции фрагментации

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

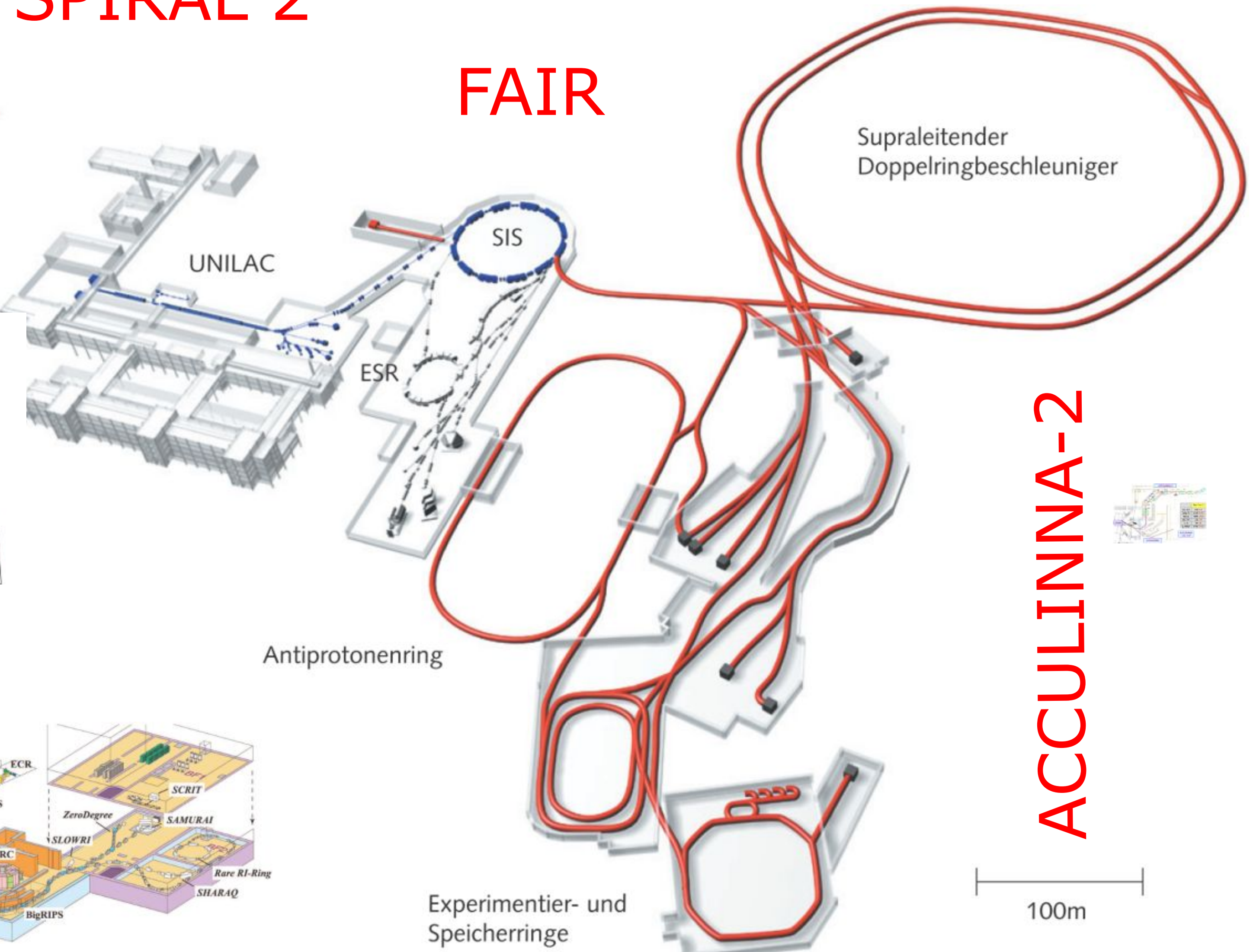
RIKEN	LINAC + Cyclotron	U, 90 AMeV	In-flight, 90 pnA
GSI	LINAC + Syncrotron	U, 900 AMeV	In-flight, 50 pnA
NSCL MSU	Cyclotron + Cyclotron	U, 90 AMeV	In-flight, 70 pnA
GANIL	Cyclotron + Cyclotron	U, 70 AMeV	In-flight, 90 pnA
ISOLDE	LINAC + Syncrotron	p, 1000 MeV	ISOL, ~1.5 kW
FLNR	Cyclotron	B 55 AMeV,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

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

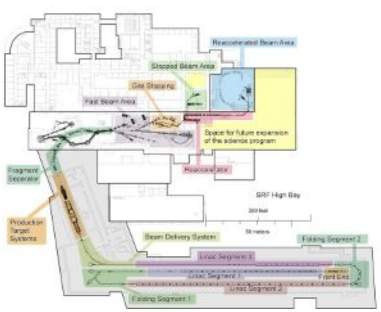


SPIRAL 2

FAIR

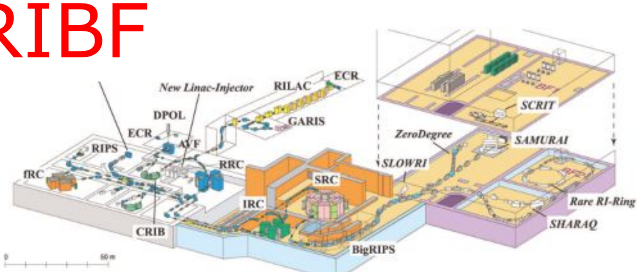


FRIB



ACCULINNA-2

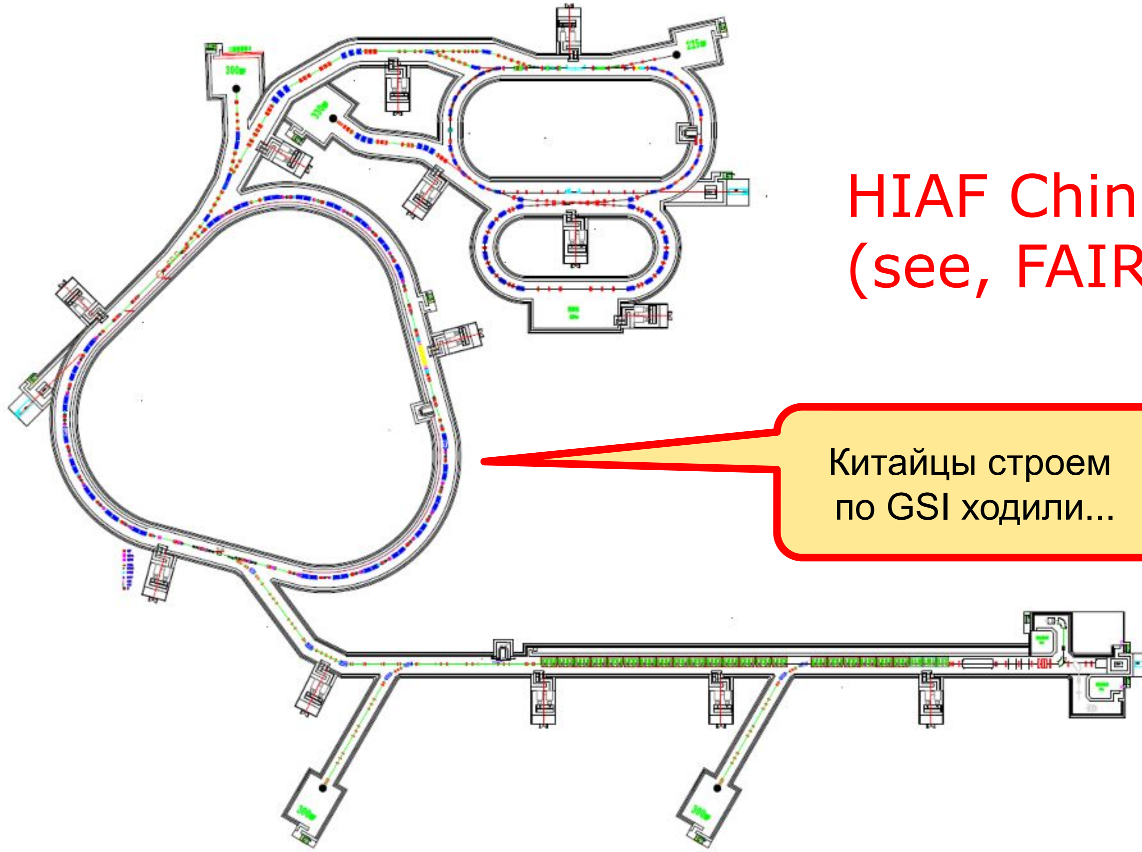
RIBF



However,
even bigger…

Horizontal size of the slide ~1 km

HIAF China
(see, FAIR)



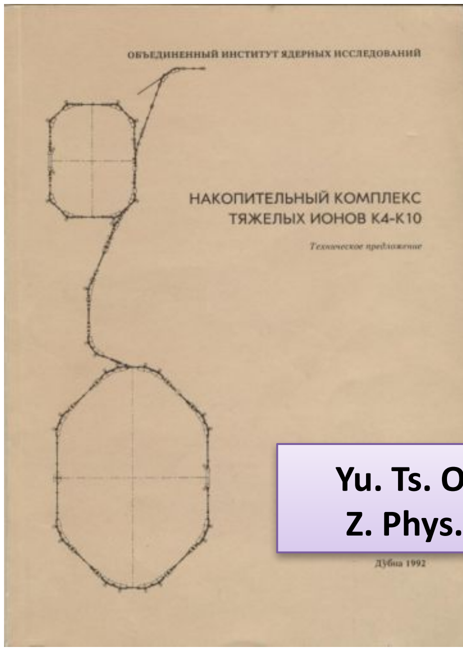
Китайцы строем по GSI ходили…

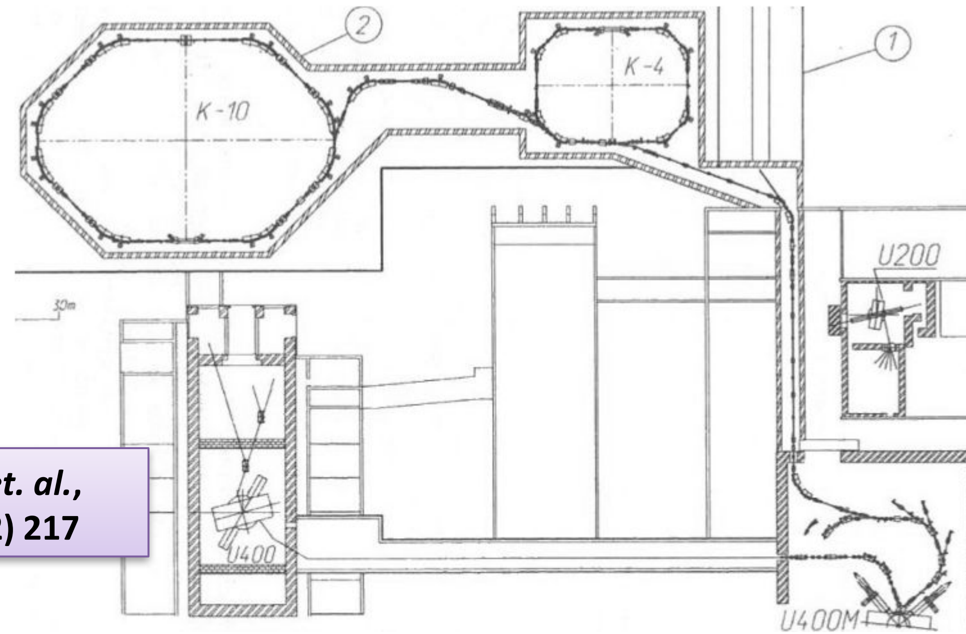
RAON
Korea
(see. FRIB)

Даешь корейскую Нобелевскую премию!

В современном виде физика радиоактивных изотопов утвердилась в начале 1990. А что у нас?

ЛЯР ОИЯИ: Ускорительно-накопительный комплекс К4-К10





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

Суперколлайдер в Протвино

Нейтронный комплекс ИЯИ, Троицк

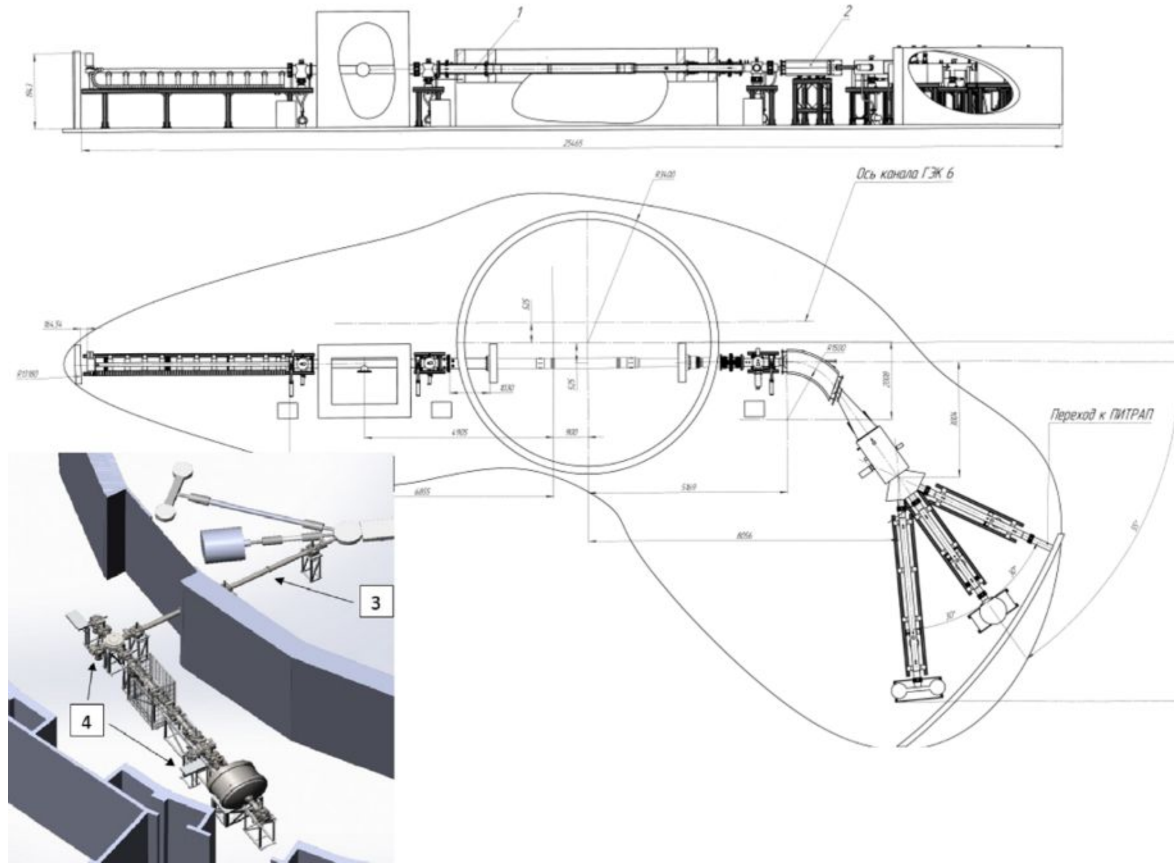
Реактор ПИК, Гатчина

Крупные научные/прикладные проекты в РФ

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

ИРИНА (ПИЯФ)

Для изотопов производимых методом ISOL – рекордные в мире интенсивности



В стороне от задач ПИК, мало места для научных инструментов

LINAC-100 + DFS

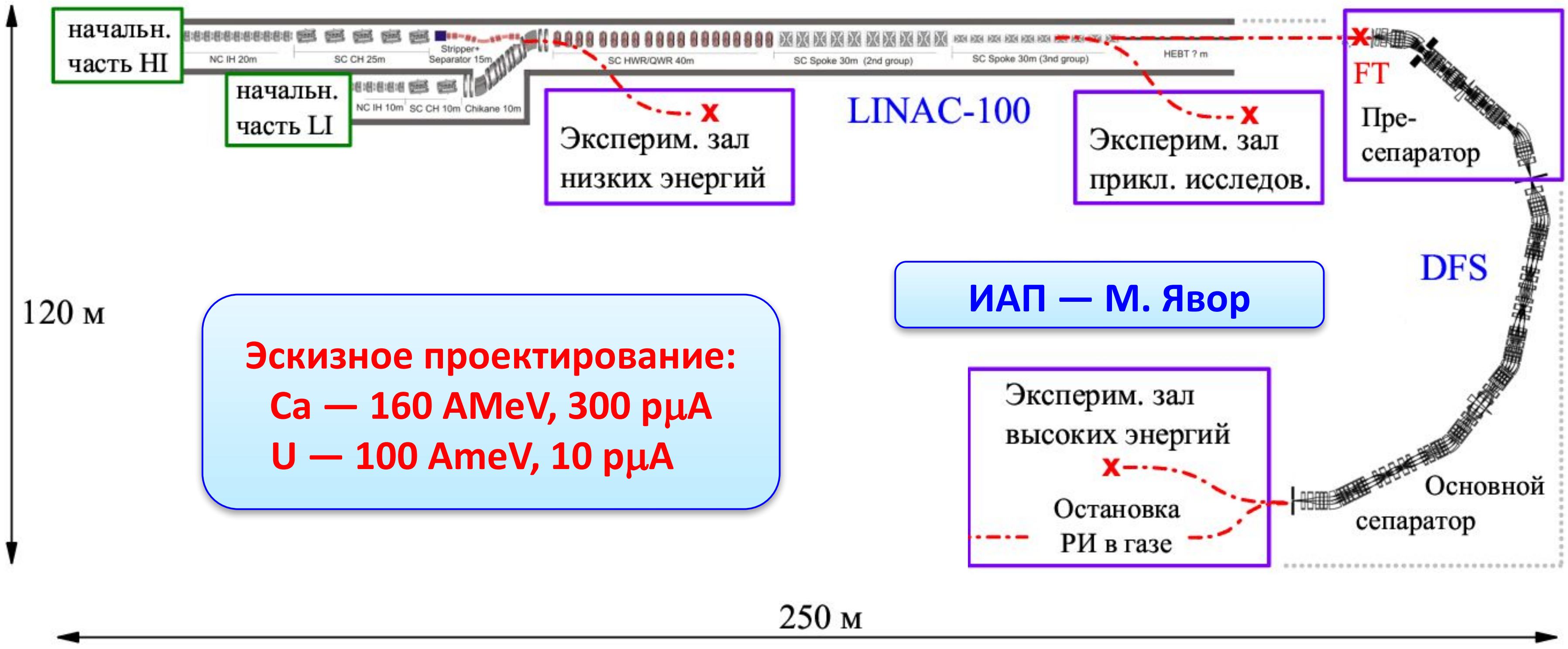
Высокоточный линейный сверхпроводящий ускоритель непрерывного действия

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

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

Underdeveloped field: storage ring physics with RIBs

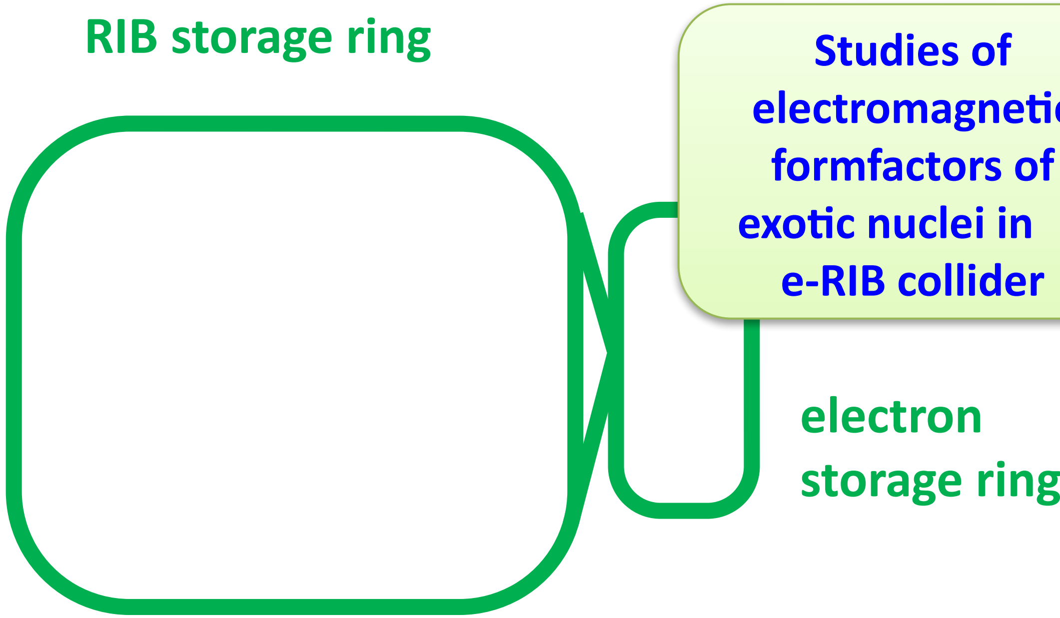
Empty field: studies of RIBs in electron-RIB collider

Isochronous mass spectromentry

Precision reaction studies on internal gas jet target

Atomic physics studies with striped ions

Radioactivity studies with striped ions



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

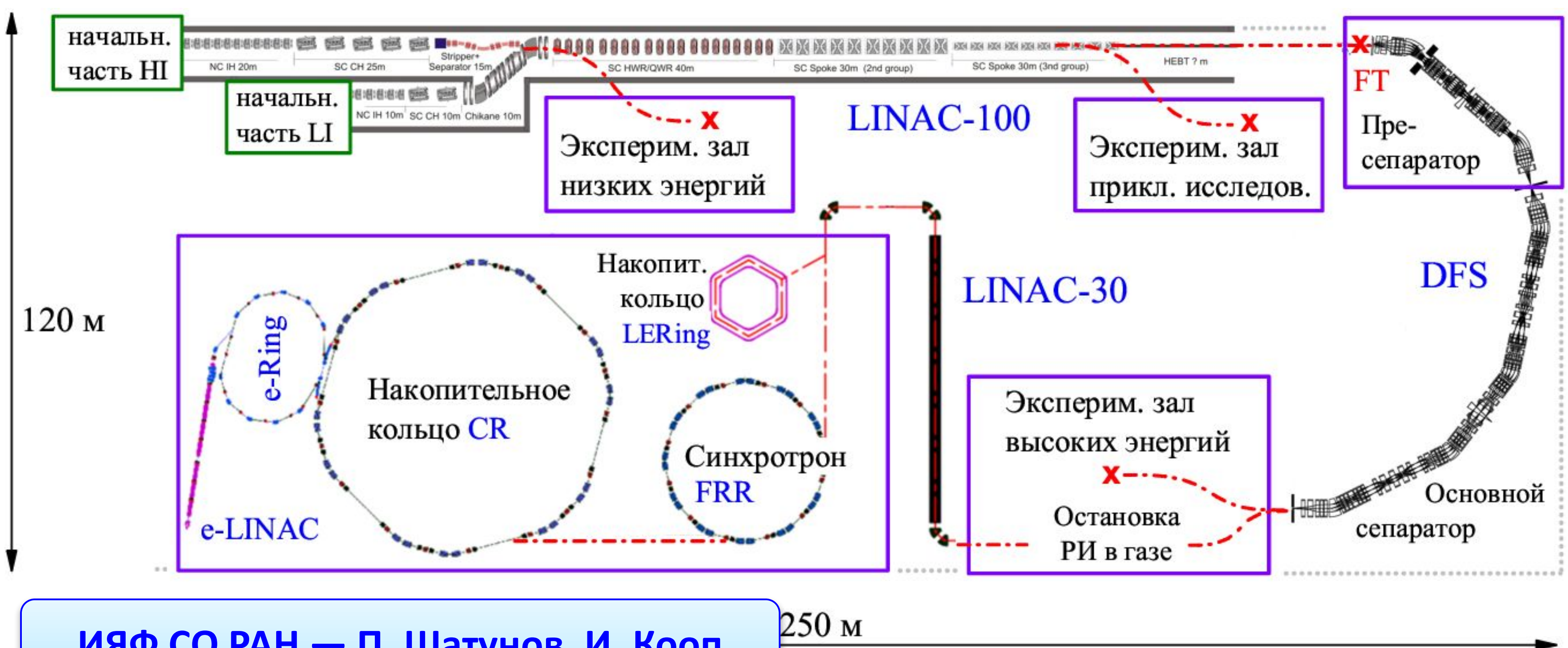
Etc….

DERICA —
Dubna Electron Radioactive Ion Collider fAcility

Facility with world-unique scientific program

Underdeveloped field: storage ring physics with RIBs

Empty field: studies of RIBs in electron-RIB collider



ИЯФ СО РАН — П. Шатунов, И. Кооп

Есть что почитать

http://derica.jinr.ru/

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

INSTRUMENTS AND METHODS OF INVESTIGATION

PACS numbers: 21.10.Ft, **29.20.–c**, 29.25.Rm

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

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

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

ISSN 1063-7788, Physics of Atomic Nuclei, 2021, Vol. 84, No. 1, pp. 68–81.

ELEMENTARY PARTICLES AND FIELDS
Experiment

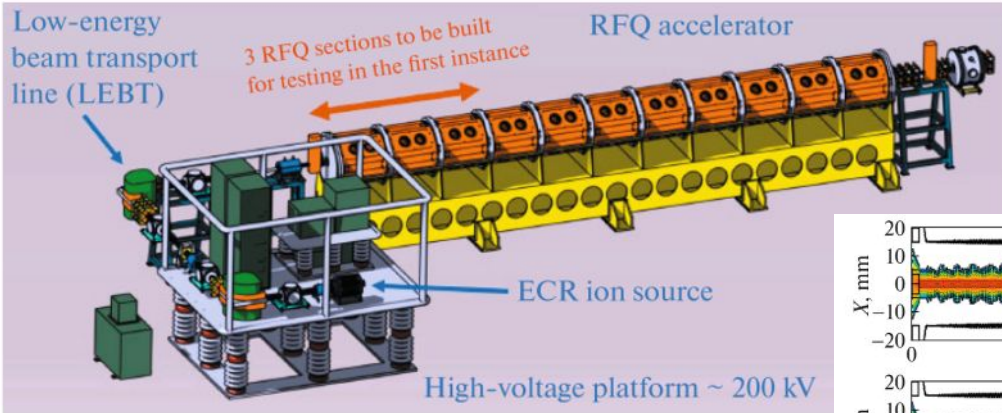
DERICA Project and Strategies of the Development of Low-Energy Nuclear Physics

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

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

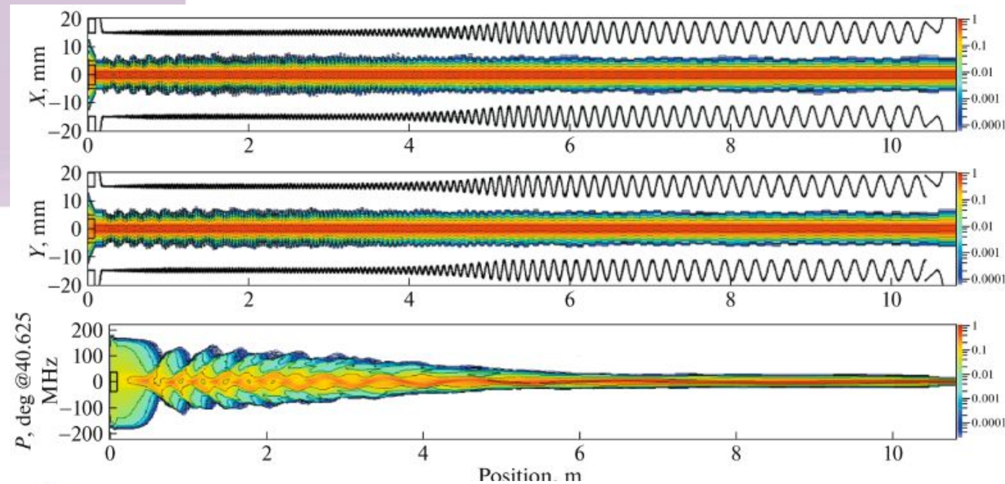
http://www.jinr.ru/wp-content/uploads/JINR_Docs/JINR_Strategy_2030.pdf

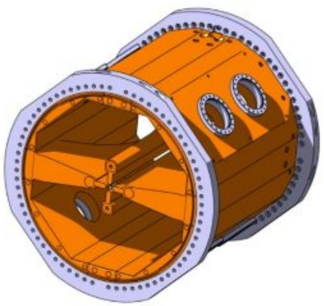
Проверить: Front end LINAC-100



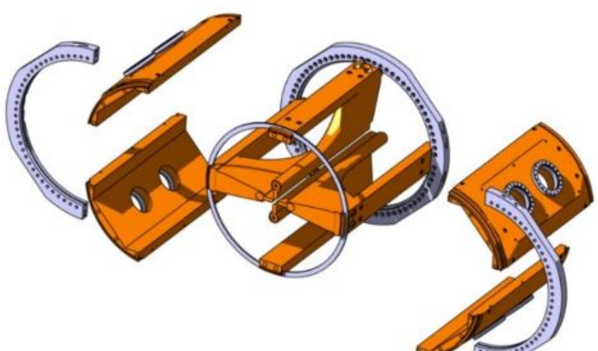
Challenges of LINAC-100 front end

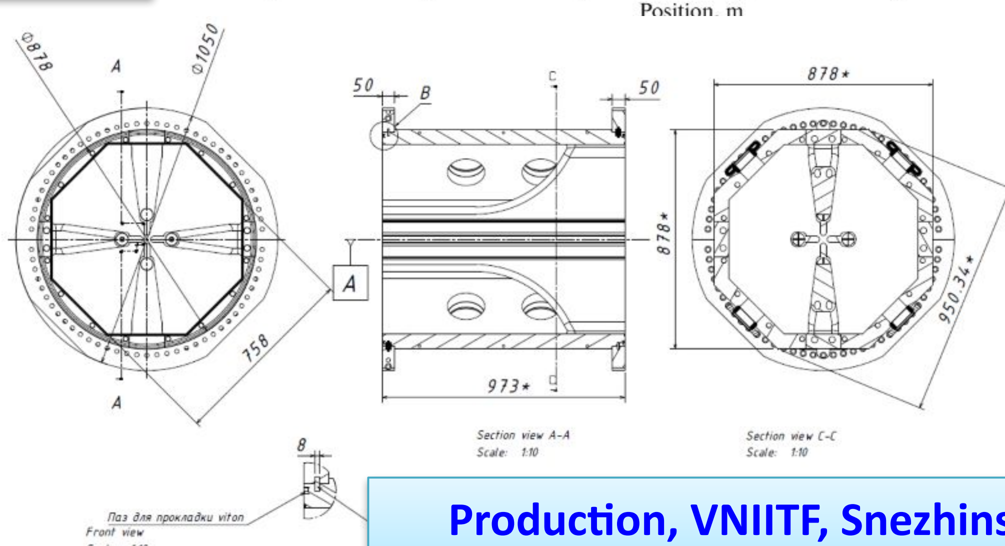
- Ca beam ~3 emA, U beam ~1 emA
- Practically "lossless" RFQ operation





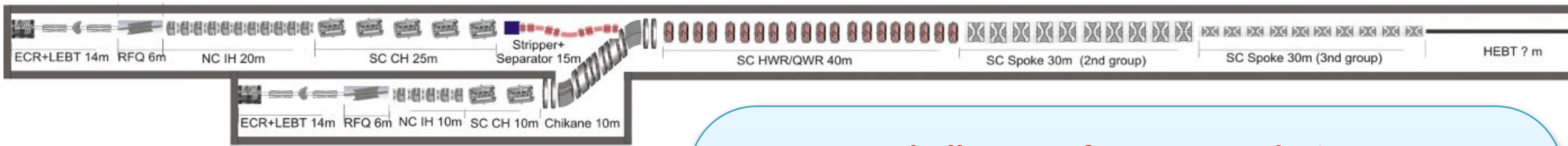
Design: T.V. Kulevoy, G.N. Kropachev, ITEPh, Moscow





Production, VNIITF, Snezhinsk (?)

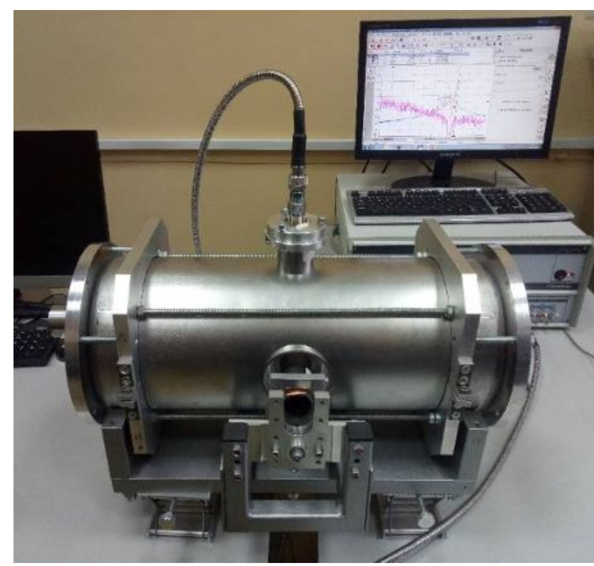
LINAC-100



Challenges of LINAC-100 design

- Ratio of normal/superconducting
- Strippers (1,2 ?), stripping energies
- Acceleration of several charge states
- One or two front ends
- Ca beam ~3 emA ~300 pμA 1500 kW beam
- U beam ~1 emA ~30 pμA 600 kW beam
- Lossless operation

Design: S.M. Polozov, MEPhI



“Recovery” of RF superconductivity technology in Russia

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

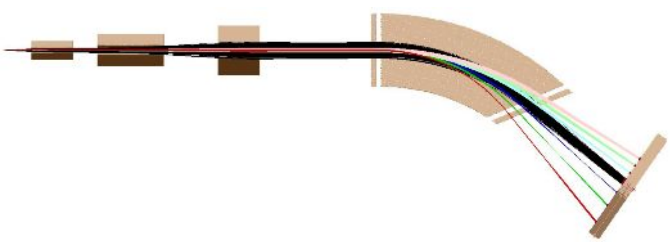
DFS

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

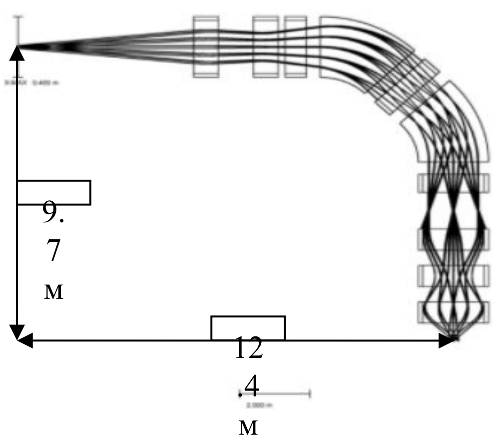
Challenges of DERICA fragment separator

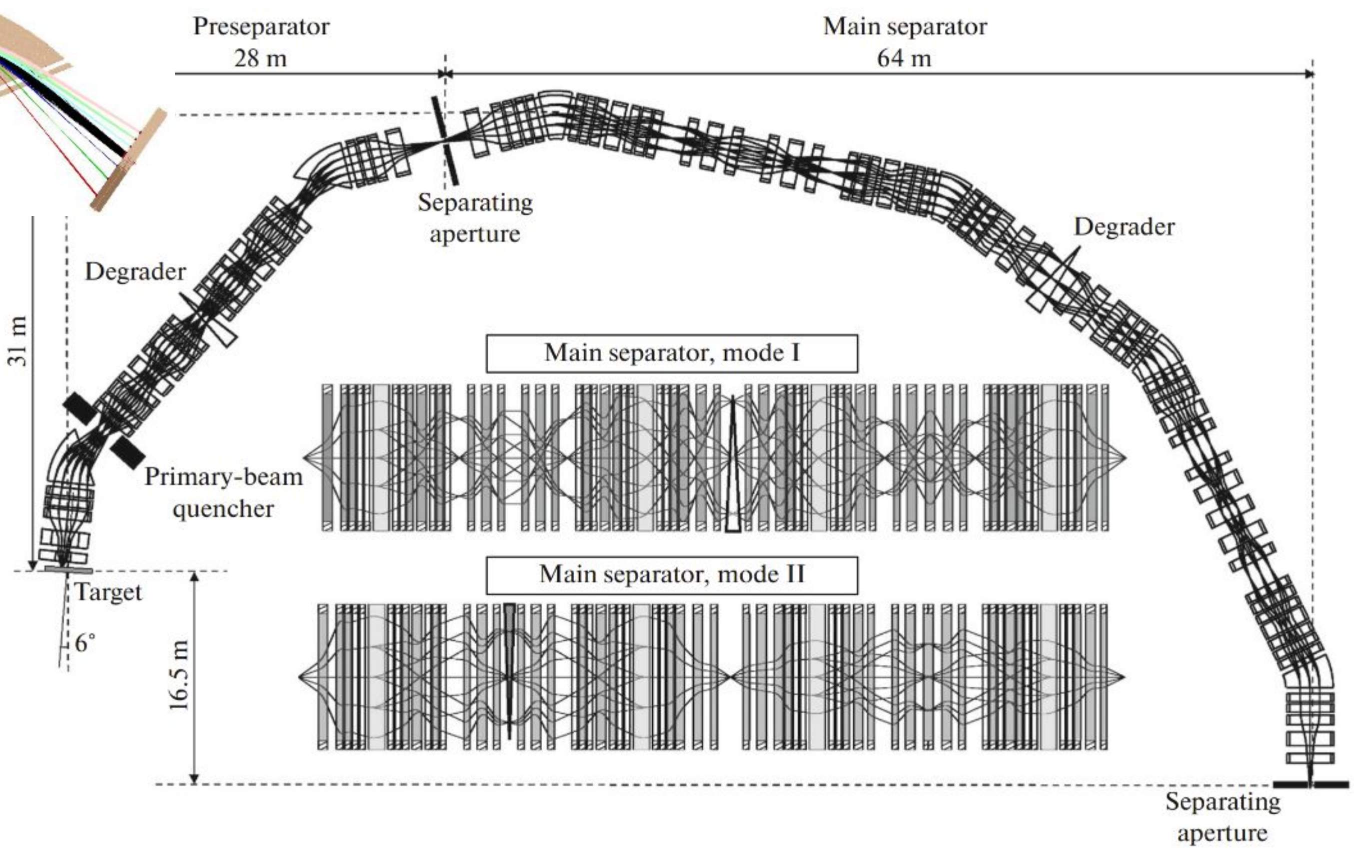
- **Not well investigated energy rangy – 100-160 AMeV**
- **Room-temperature design requested**
- **Momentum acceptance is ΔP/P = ±3% (FWHM)**
- **Resolution is P/ΔP = 1500-3000**
- **Ca beam ~3 emA ~250 pμA 1500 kW beam**
- **U beam ~1 emA ~30 pμA 600 kW beam**

Beam dump problem



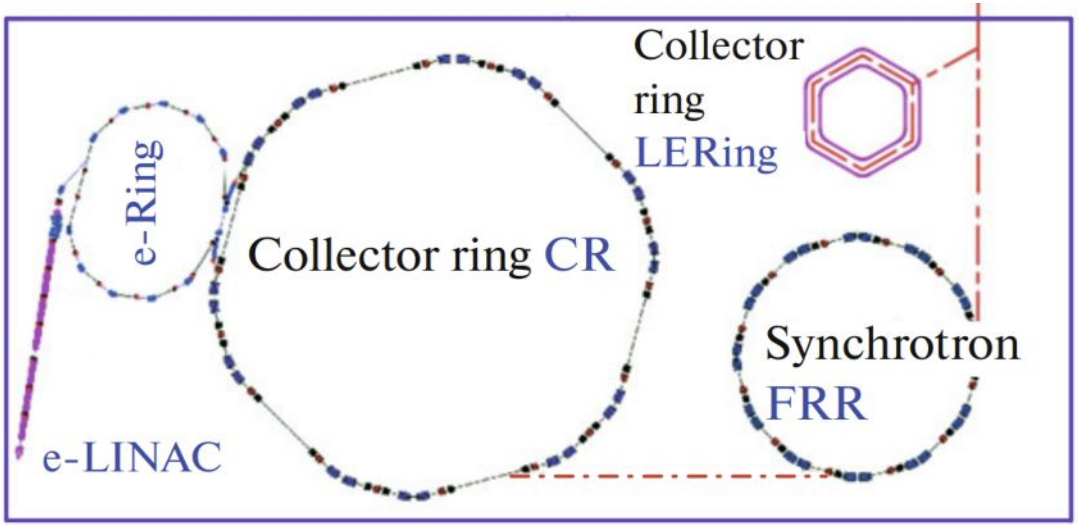
Low-energy buncher for ISOL program





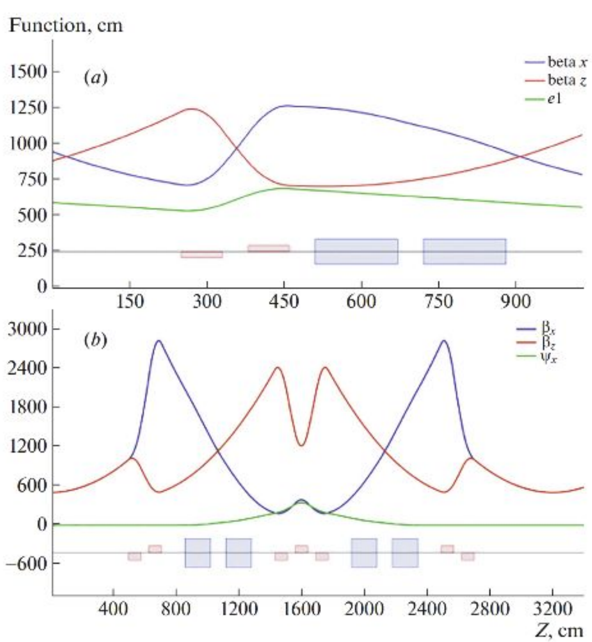
Ring branch design

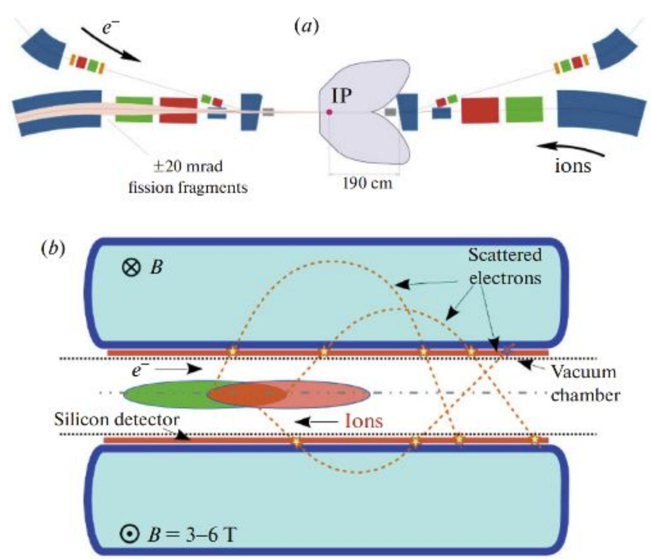
Design: P.Yu. Shatunov, I.A. Koop, BINP, Novosibirsk



Challenges of DERICA ring branch

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





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

Прорабатывается комплекс из “рекордного” высокоточного непрерывного действия LINAC-100 и “теплый” двухстадийный фрагмент-сепаратор DFS

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

Статус многих проектов прояснится к началу 2023