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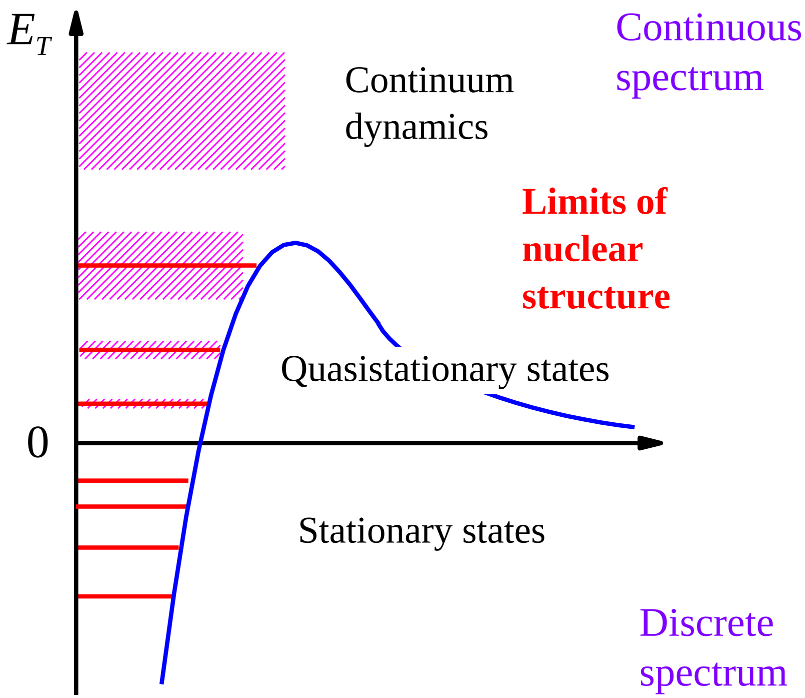
Transition from direct to sequential 2p-decay in theory and in experiment.

NUSTAR meeting, March 2-4, 2016

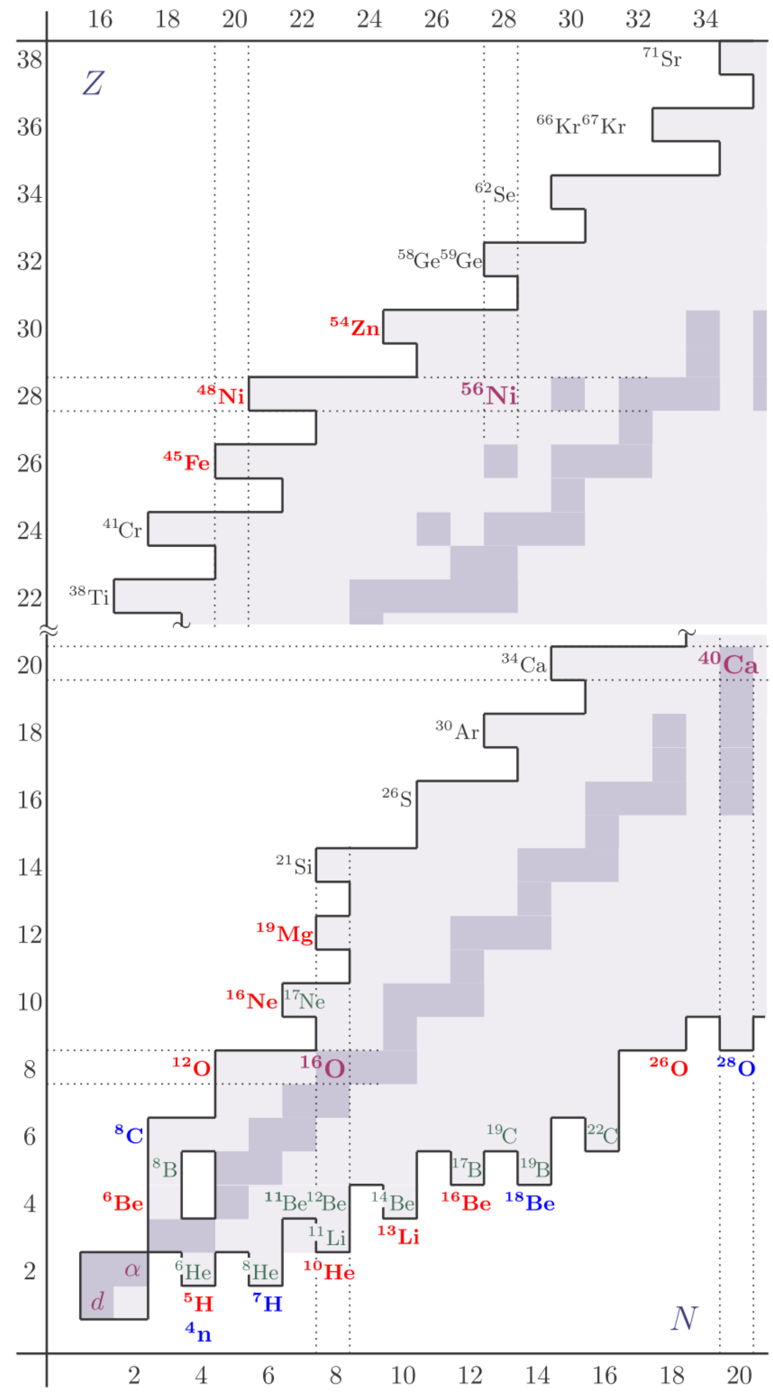
Limits of nuclear structure existence

Dripline is studied for light nuclei

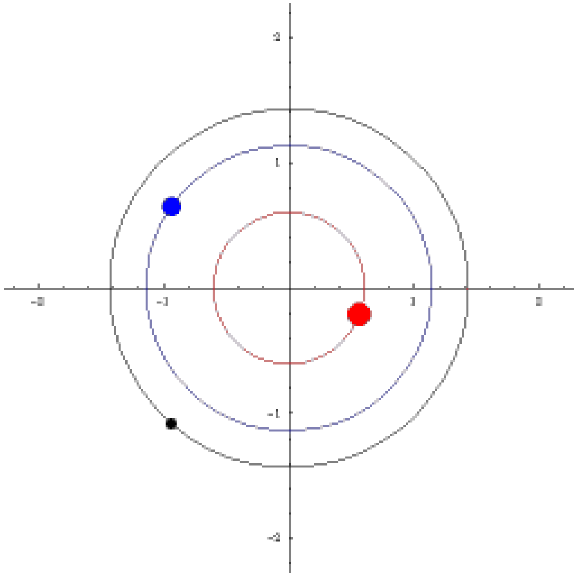
Dripline is achieved for Z<32 and N<22



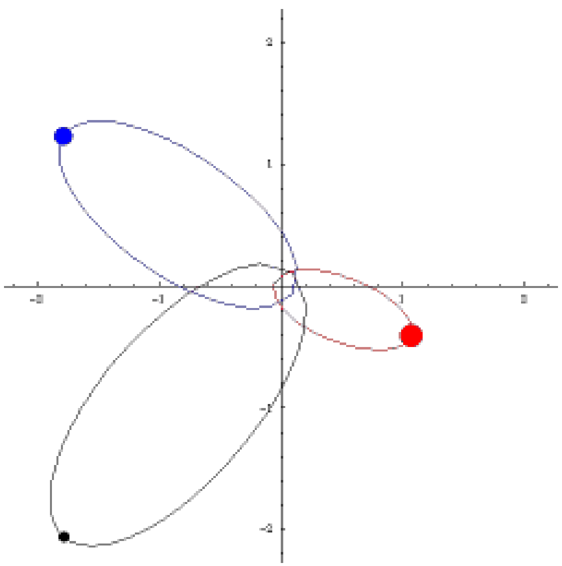
Limits of the nuclear structure are not solidly established even for the lightest isotopes.
^{7}H, ^{12}He, ^{13}Li, ^{5}Be - ???

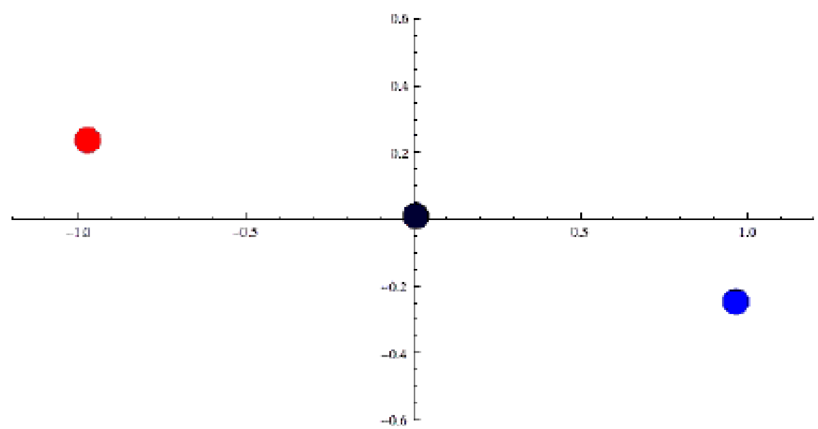


Few-body dynamics



More than 2
First of all three-body
Less than 6-7





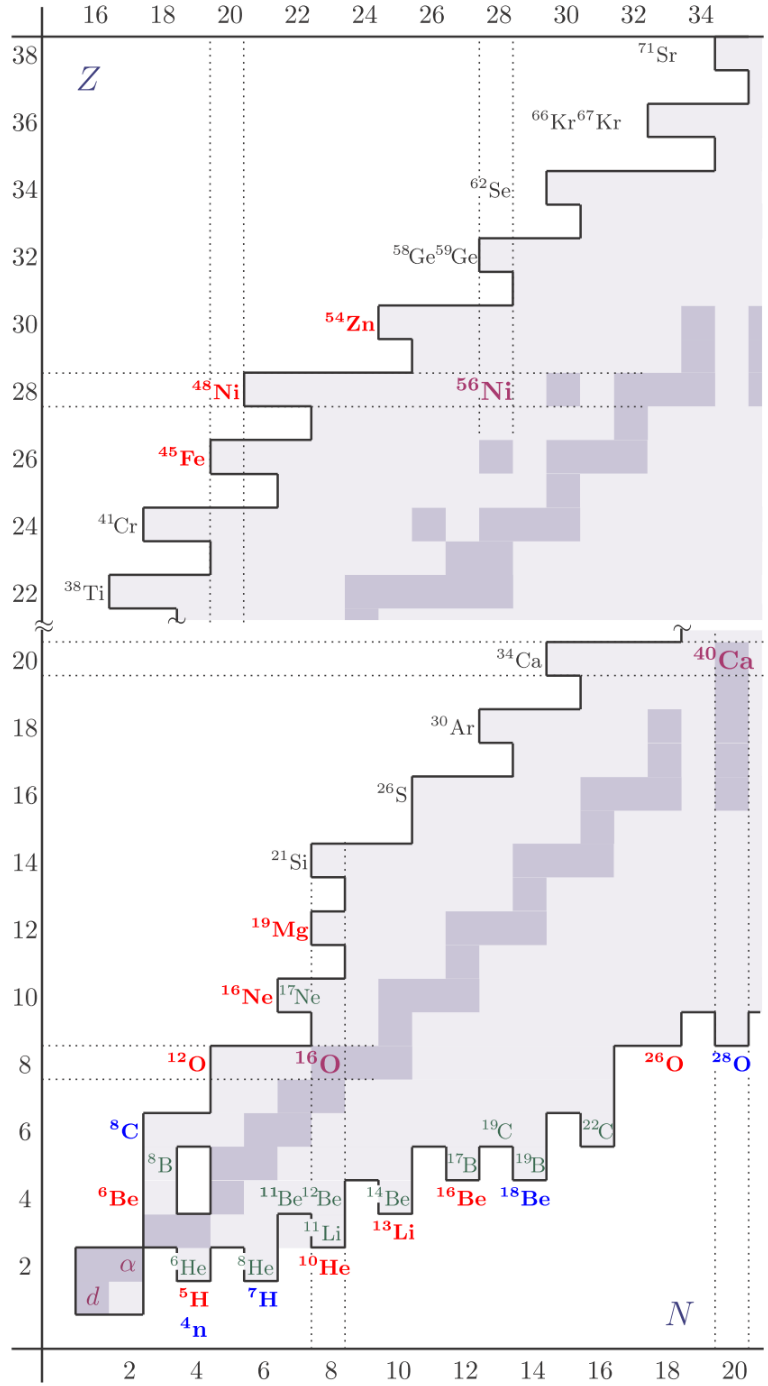
Few-body dynamics at the driplines

Modern RIB research: move towards and beyond the driplines

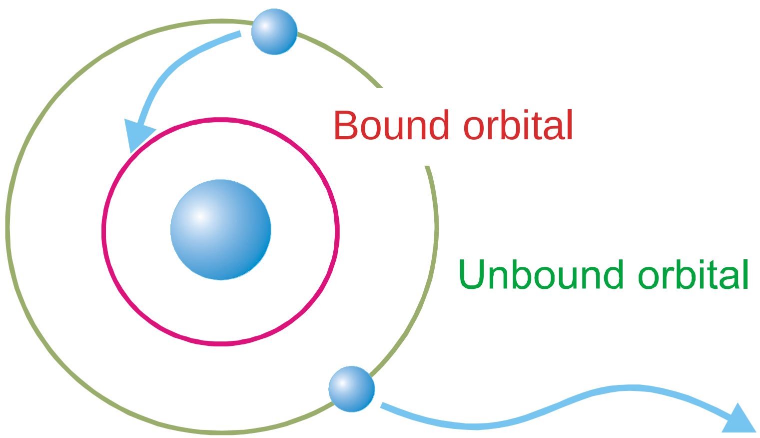
Few-body dynamics at the driplines as consequence of (i) clusterization and (ii) paring

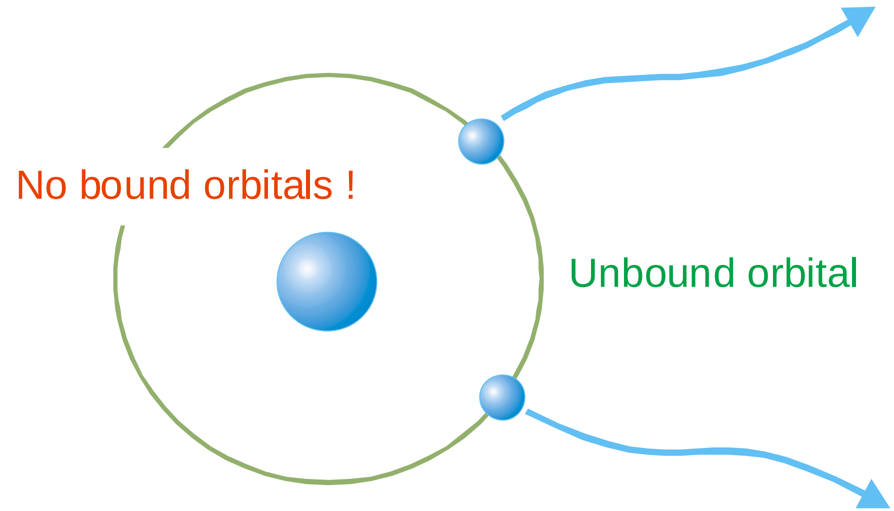
Exotic phenomena in vicinity of driplines:
Haloes (green)
True 2p/2n decays (red)
4p/4n emitters (blue)
NOT INVESTIGATED (gray)

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



Qualitative view of two-proton radioactivity





<u>Classical case:</u>
one particle emission is always possible

<u>Quantum mechanical case:</u>
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**

Three-body correlations.

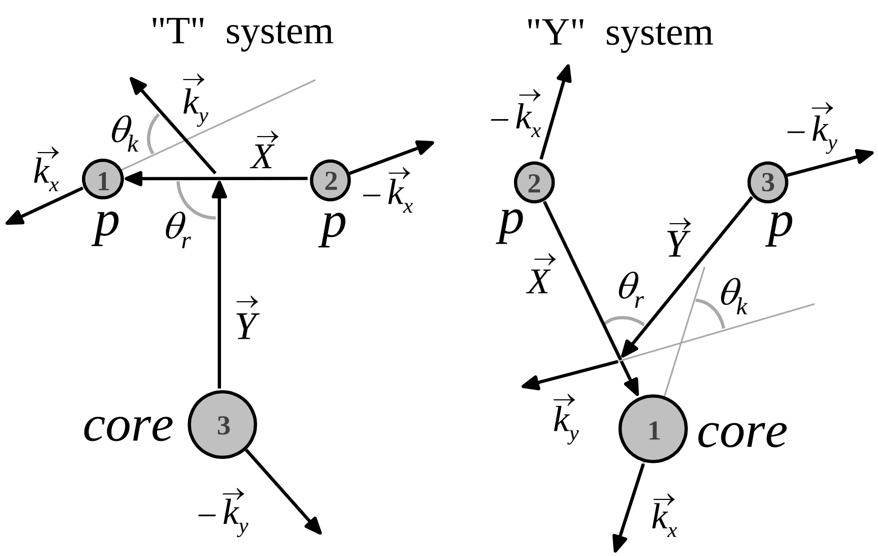
2-body decay: state is defined by 2 parameters - energy and width

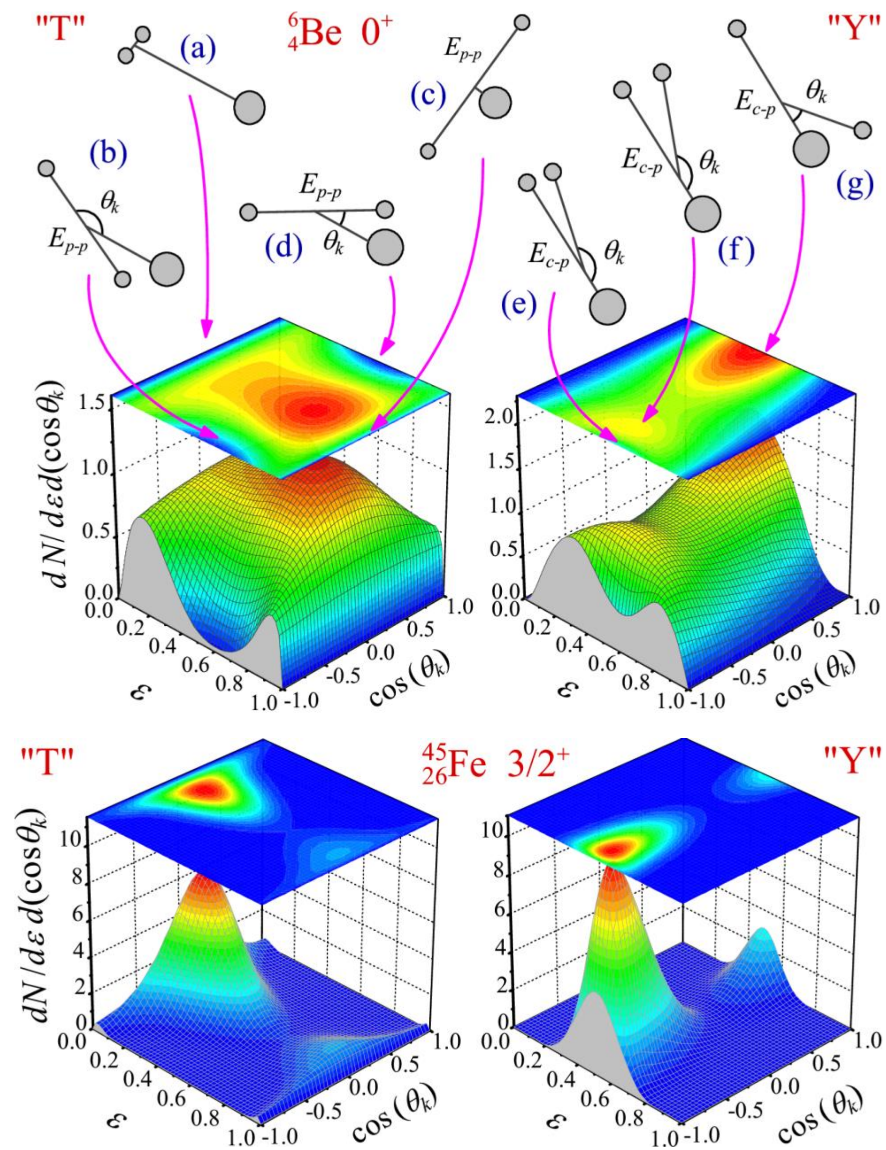
3-body decays: 2-dimensional "internal" 3-body correlations

- 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.





Three-body decay – a lot more **information** than for two-body decay encrypted in the correlations

Which kind of new **knowledge** we can decrypt from that?

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

A. Brown, PRC **41** (1991) R1513.

Brown 1991: energy – yes, lifetime – no

Grigorenko 2001: energy – no, lifetime – yes

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

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

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

Q_{2p} = 1.154 MeV

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

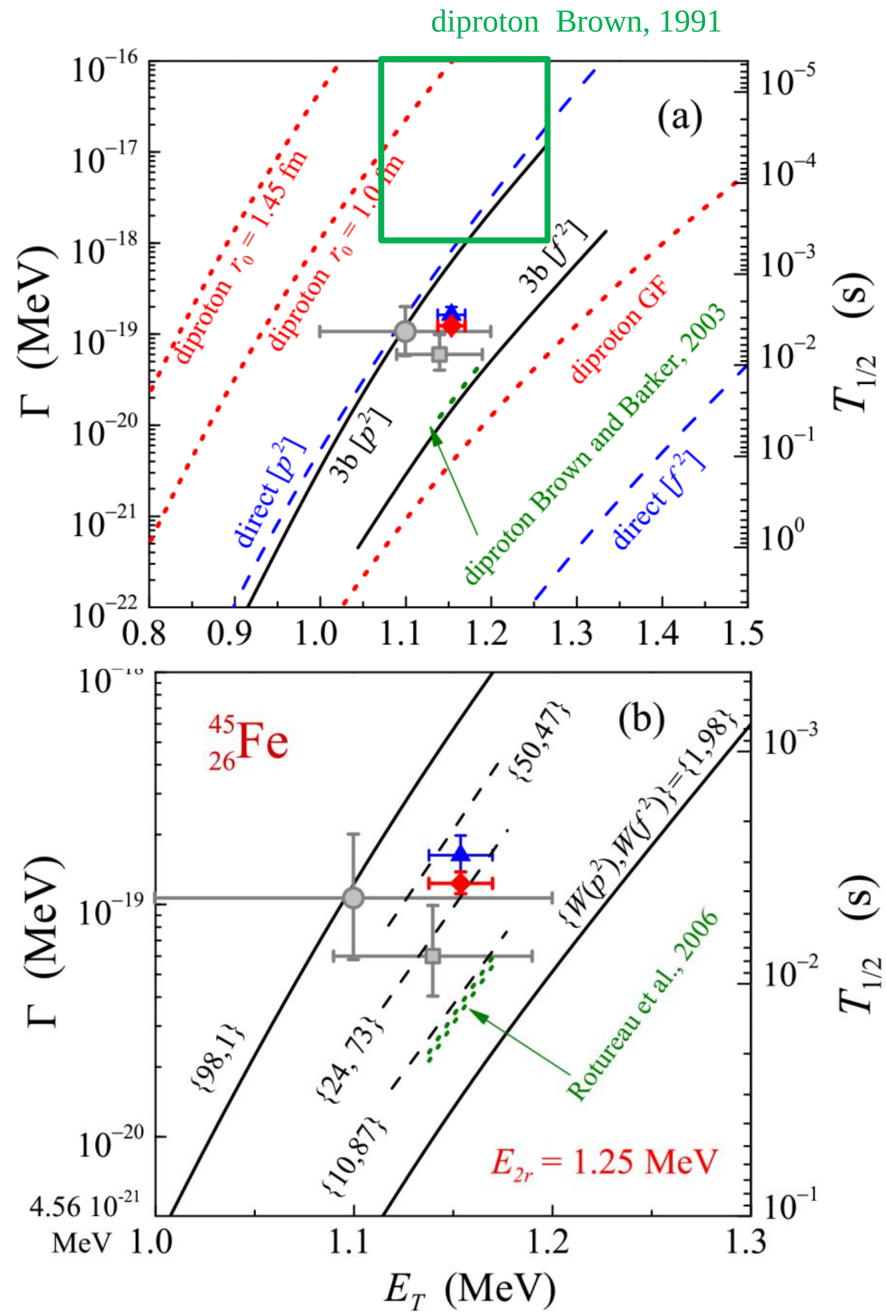
- Special design Optical TPC → nuclear physics "life video"
- Improved lifetime:

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

- Complete momentum correlations provided

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

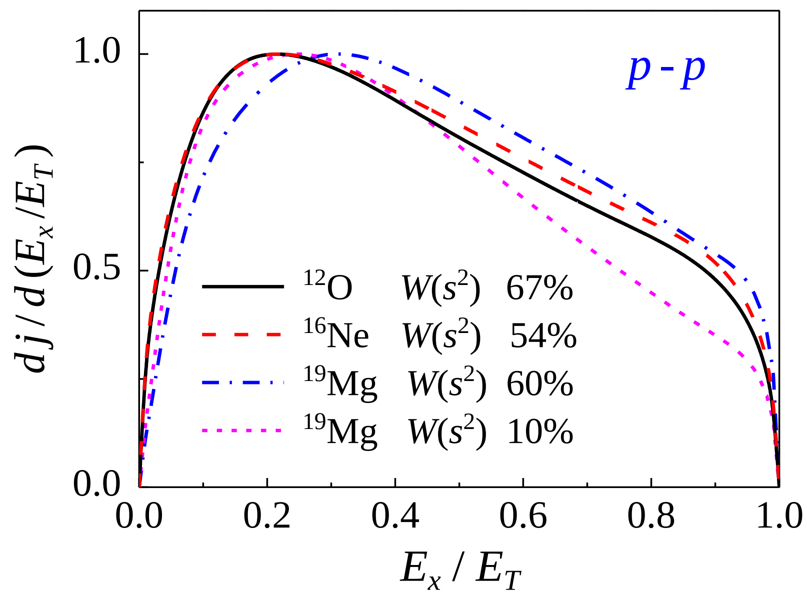
L.Grigorenko et al., PRC **82** (2010) 014615

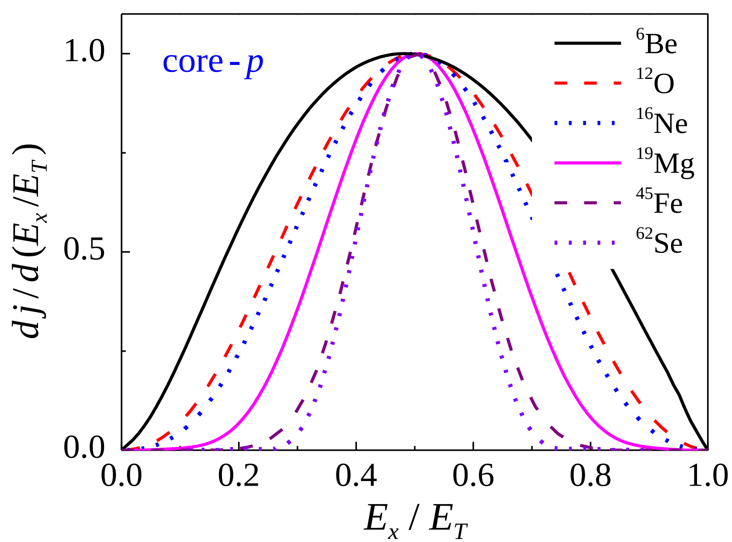


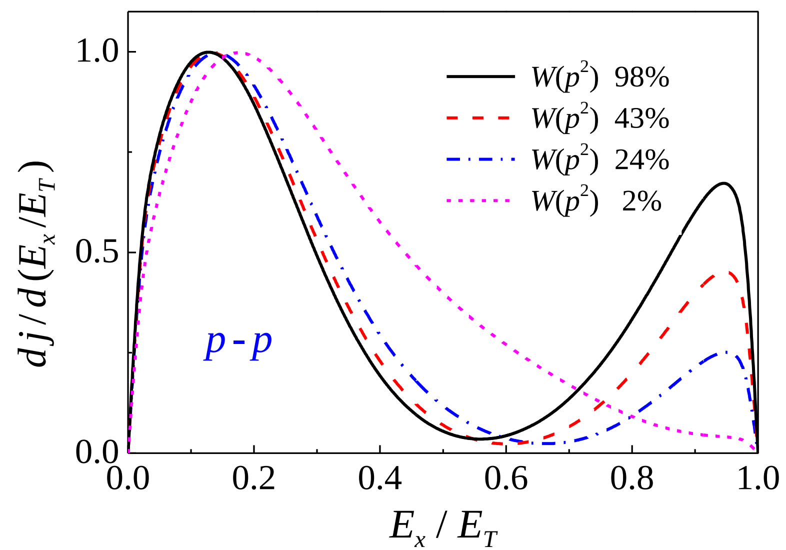
Common properties of correlations

How can we use the correlation information?

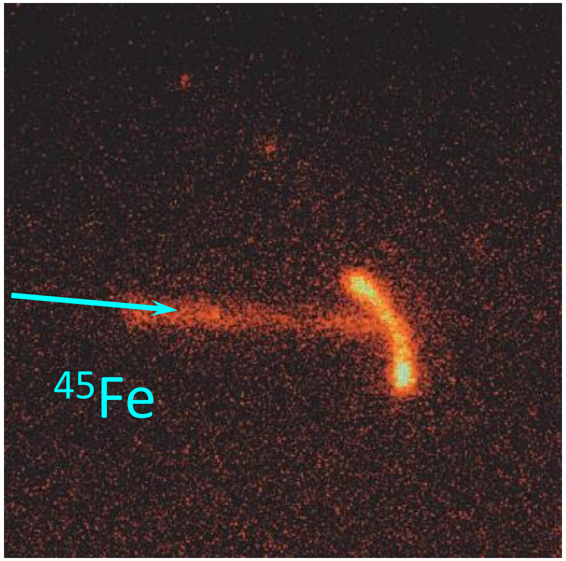
- **Energy correlation in the core-p** channel well corresponds to original prediction of Goldansky: energies of the emitted protons tend to be equal.
- **Energy correlation in the p-p channel** in the s-d shell nuclei quantitatively depend on the structure
- **Energy correlation in the p-p channel**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

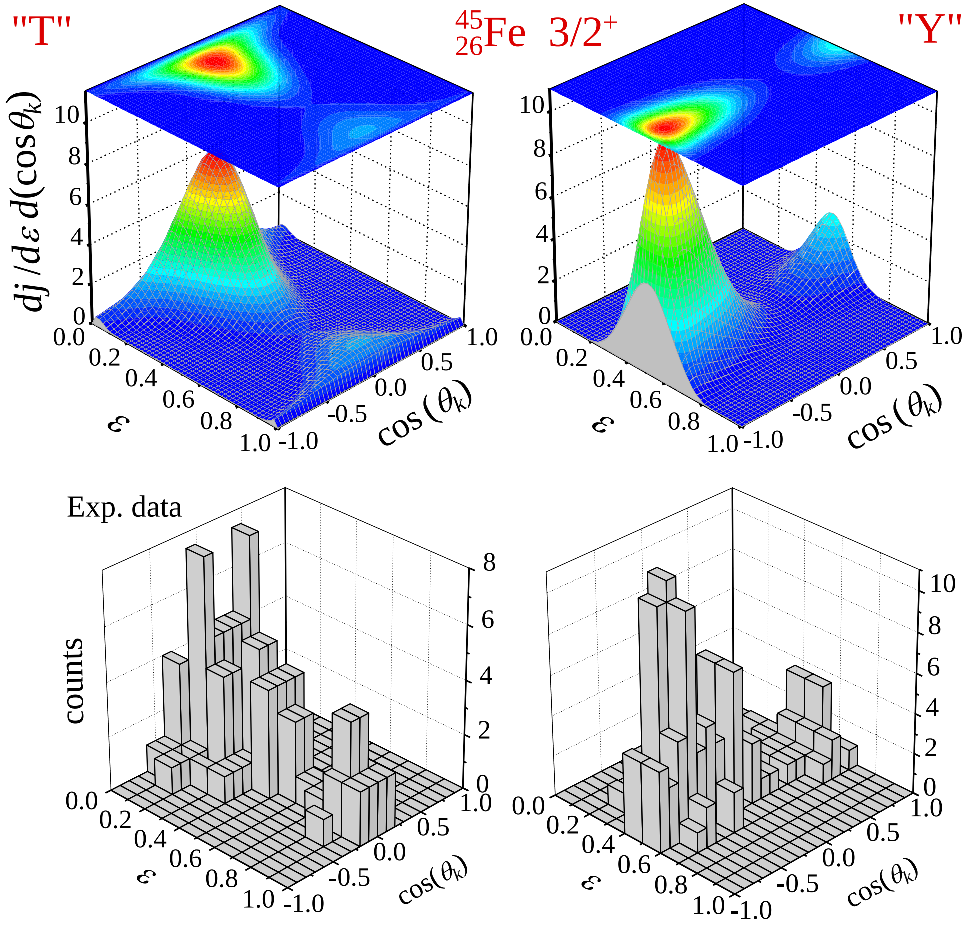


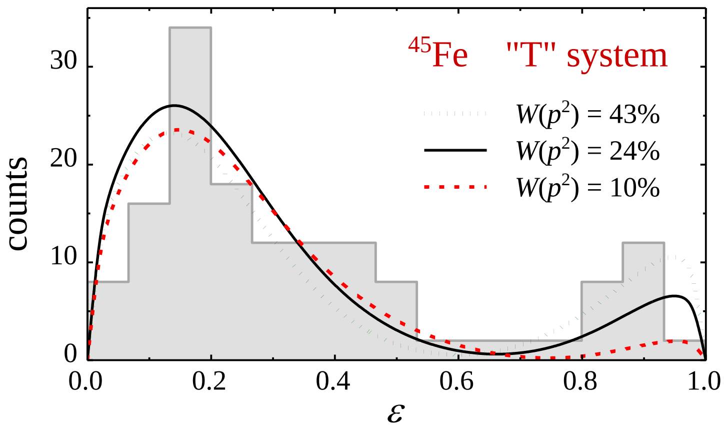




^{45}Fe: internal correlations







Miernik et al., PRL 99 (2007) 192501

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

Growing sophistication of the theoretical methods

Monte-Carlo codes

Observables in reactions:
Nuclear structure +
Reaction mechanism +
Final state interaction

M.S.Golovkov et al., PRL **93** (2004) 262501.
M.S.Golovkov et al., PRC **72** (2005) 064612.
L.V. Grigorenko et al., PRC **82** (2010) 014615.
A.S.Fomichev et al., PLB **708** (2012) 6.
I.A. Egorova et al., PRL **109** (2012) 202502.
I. Mukha et al., PRL **115** (2015) 202501.

- For studies of correlations full quantum-mechanical Monte Carlo simulations are required
- Decompose experimental particle correlation data over hyperspherical amplitudes in the momentum space. HH amplitudes automatically take into account PP, angular momenta in the subsystems and spin. Calculated or parameterized.
- Density matrix formalism:

$$\frac{dW}{dq\,dE\,d\Omega_5} = \sum_{JM,J'M'} \rho_{JM}^{J'M'}(q,E)\,A^{\dagger}_{J'M'}(E,\Omega_5)\,A_{JM}(E,\Omega_5)$$



- Density matrix has especially simple form in the system of transferred momentum for direct reactions
- Three-body decay -> eightfold differential cross section
- People involved: Yu. Parfenova, T. Golubkova, P. Sharov

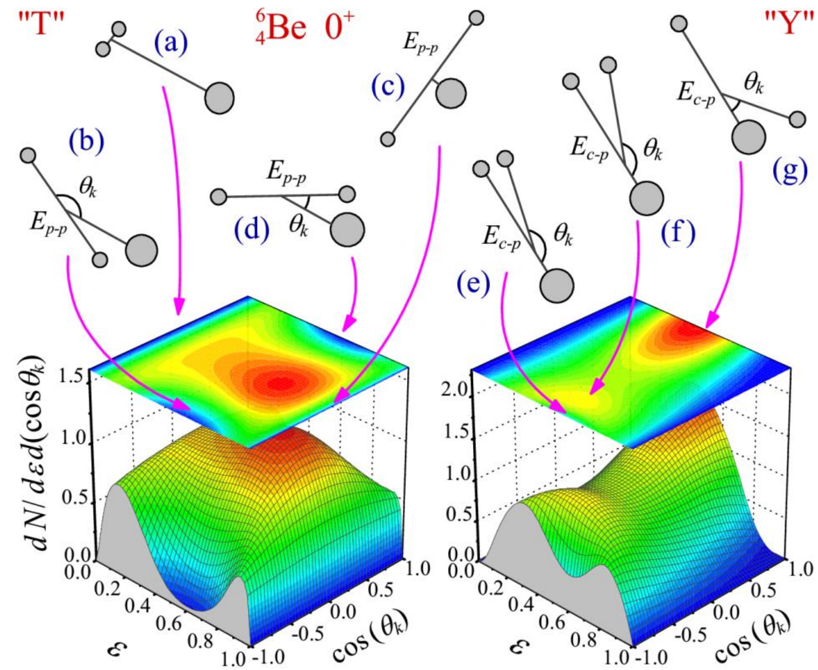
Experimental bias:
Acceptance +
Resolution +
Physical backgrounds

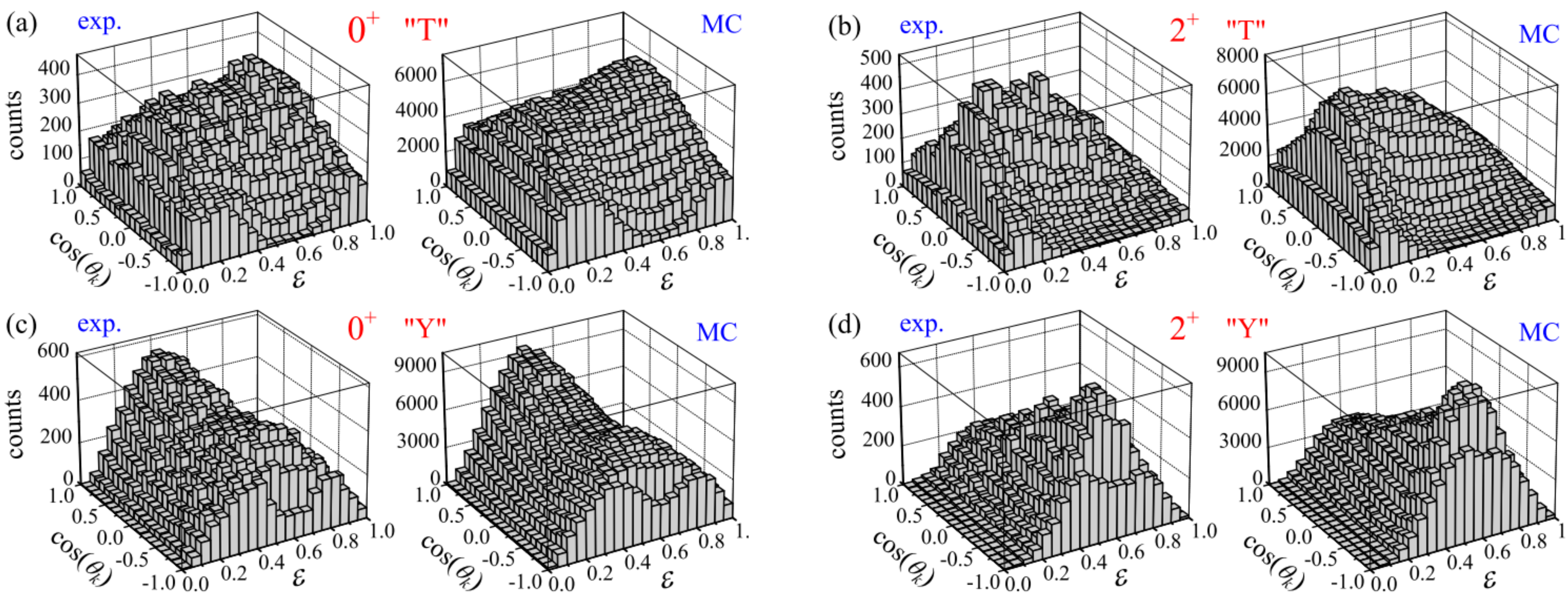
^{6}Be at MSU: correlations on resonance

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

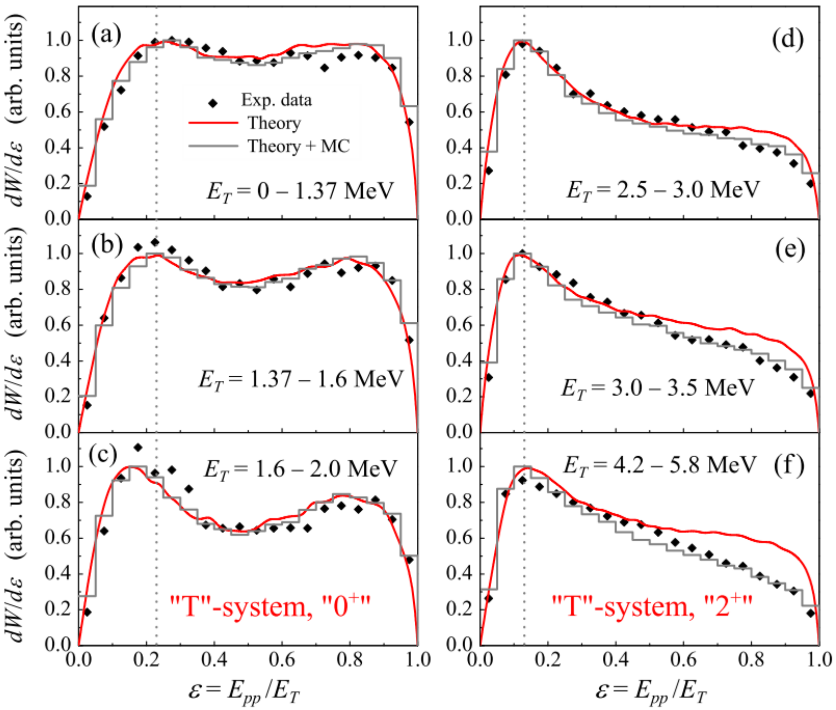
I. Egorova et al., PRL **109** (2012) 202502.

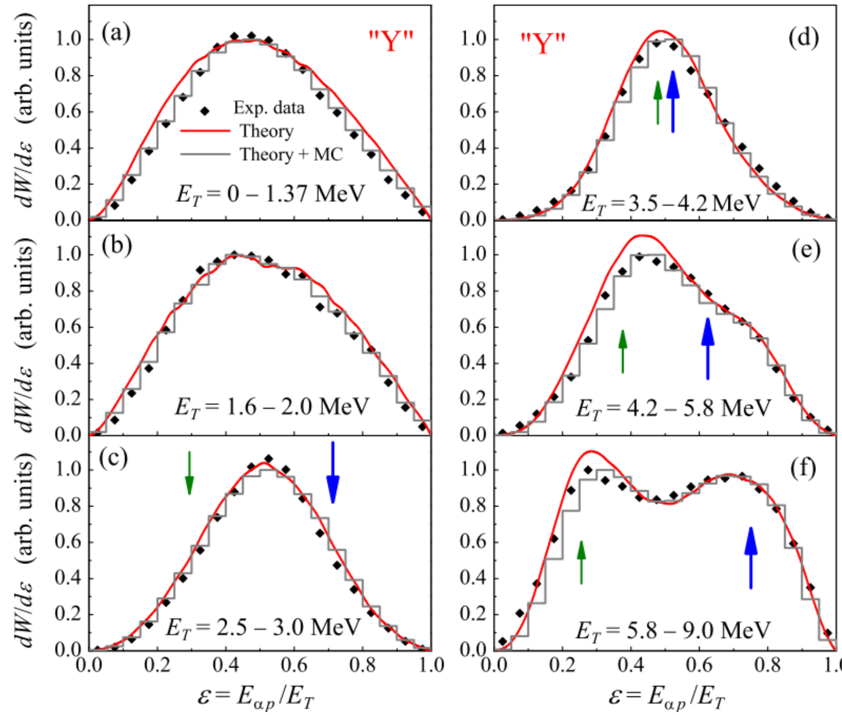
- High statistics (~10^6 events/state)
- High resolution
- Nice agreement with the previous (Texas A&M, Dubna) experimental data





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





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

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

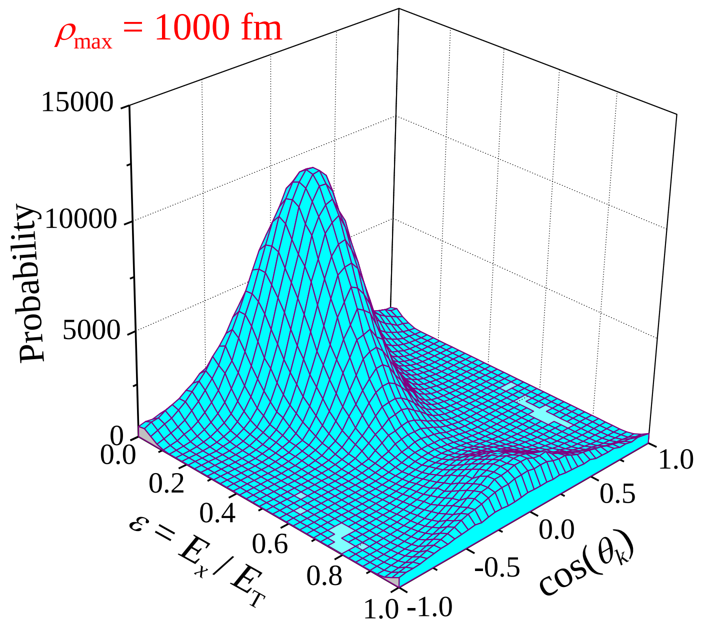
Note: above 2^+ the ε distribution is practically insensitive to decay energy

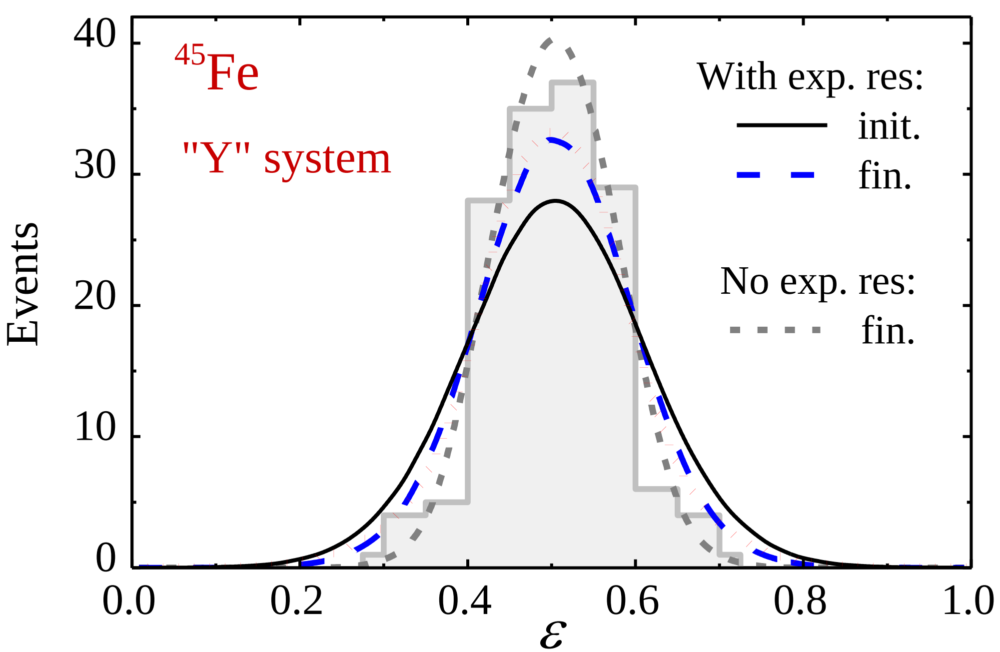
Note: sequential decay patterns appears only for $E_T > 2E_r + \Gamma$

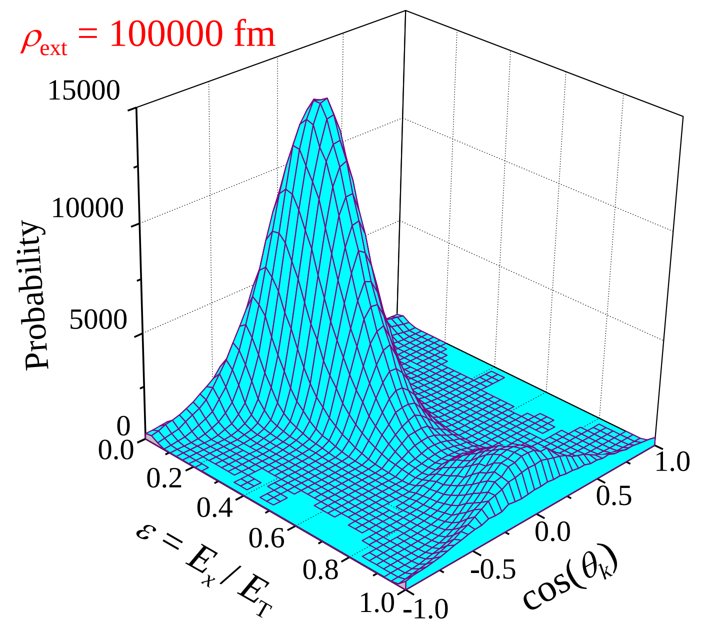
Long-range character of three-body Coulomb by example of ^{45}Fe

^{45}Fe, $E_T = 1.154$ MeV

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







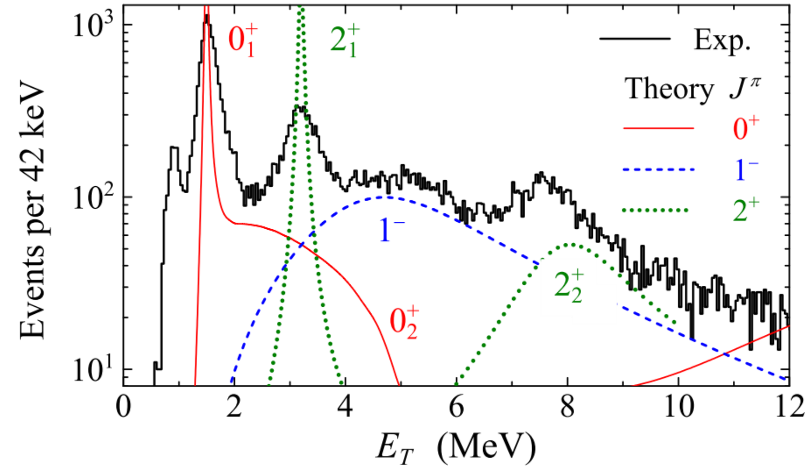
Long-range character of three-body Coulomb by example of ^{16}Ne

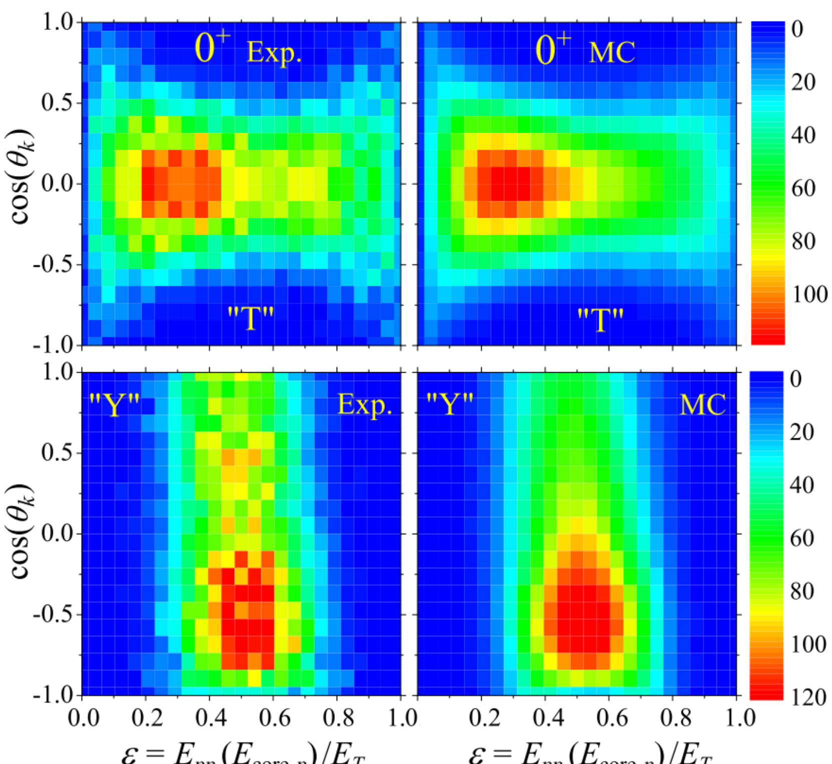
^{16}Ne g.s., $E_T = 1.466$ MeV

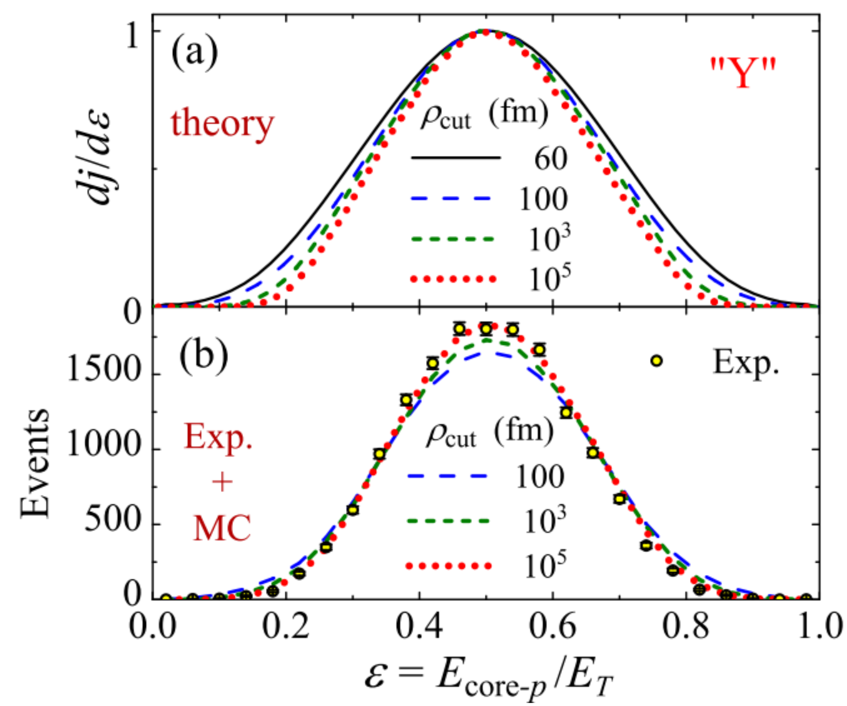
- New level of experimental precision. MSU 2013: ^{16}Ne populated in n knockout from ^{17}Ne

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

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







Two-proton decay of ^{30}Ar

S388 experiment at GSI

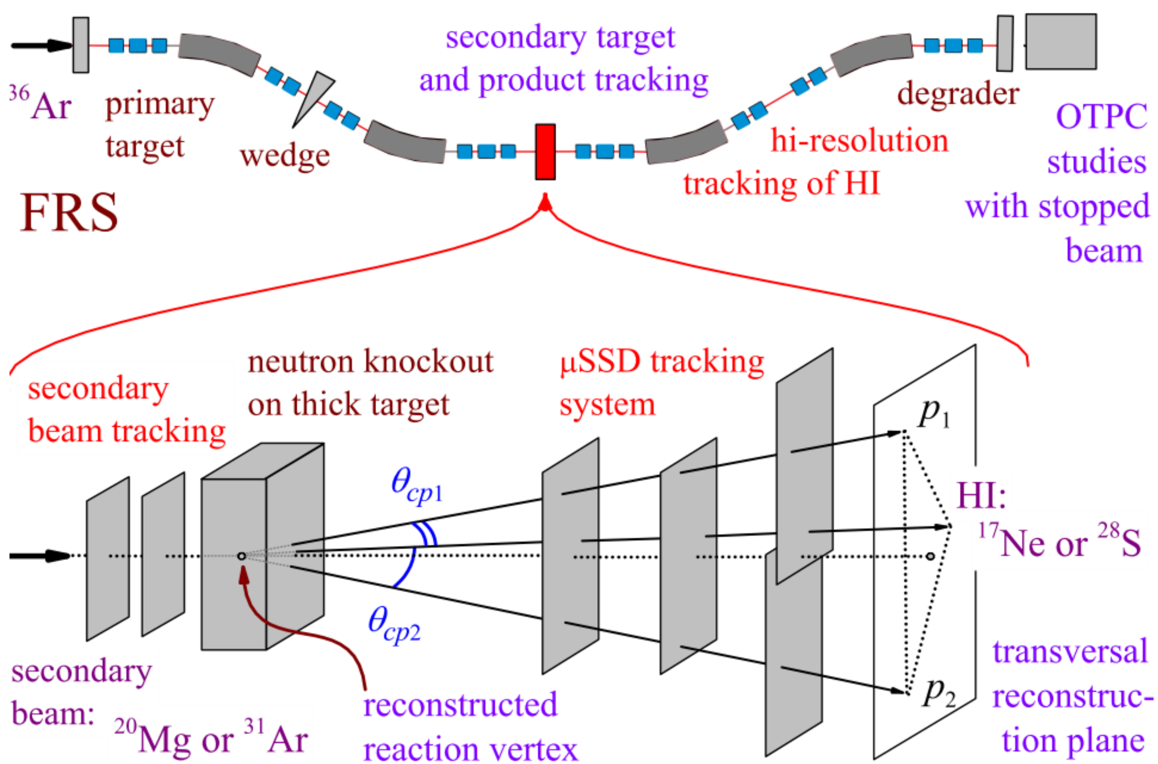
- 2012
- Primary ^{36}Ar beam 885 AMeV
- 8 g/cm^2 primary Be target
- Second. ^{31}Ar beam 620 AMeV
- 50 ions s^{-1}
- 4.8 g/cm^2 secondary Be target

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

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

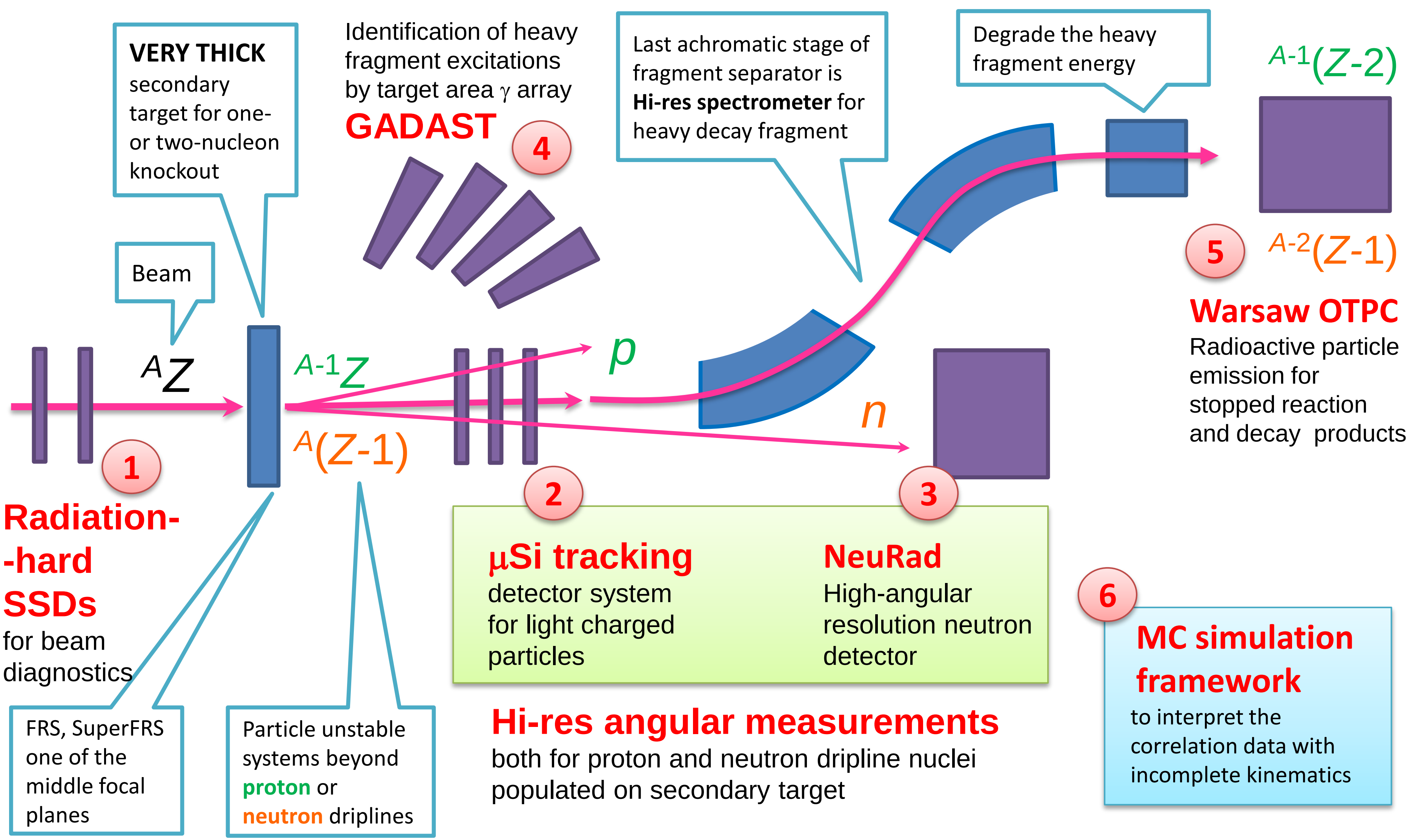
"Beta-delayed p decays of ^{31}Ar"

A. Lis et al., PRC **91** (2014) 064309.



EXPERT: EXotic Particle Emission and Radioactivity by Tracking

GSI, FLNR JINR, Warsaw Uni., PTI St.-Petersburg

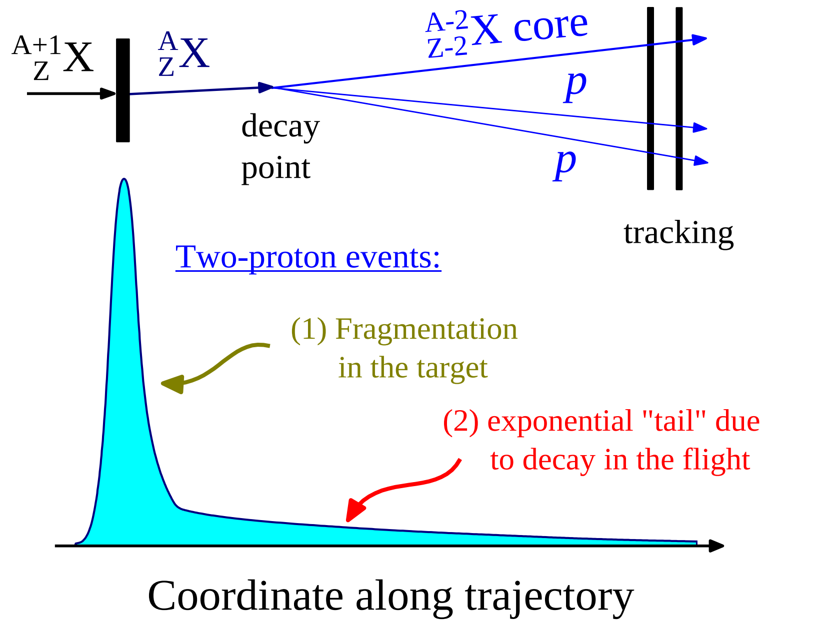


Basic idea

Radioactivity studies

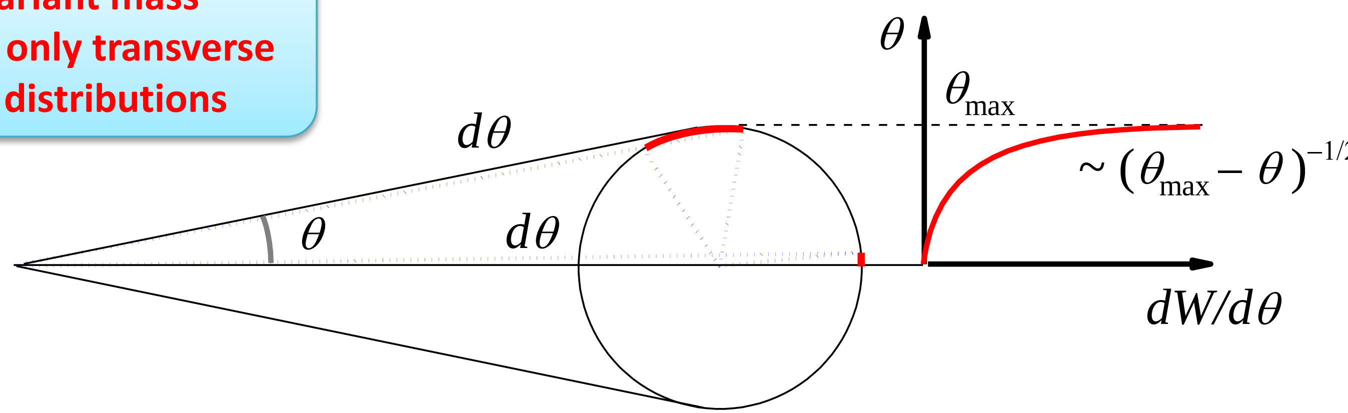
Prof. I. Mukha: opportunity to investigate particle radioactivity in fs-ns lifetime range

HOWEVER. Found to be well suited for spectroscopy



Two-body decay

Not an invariant mass measurement: only transverse momentum distributions

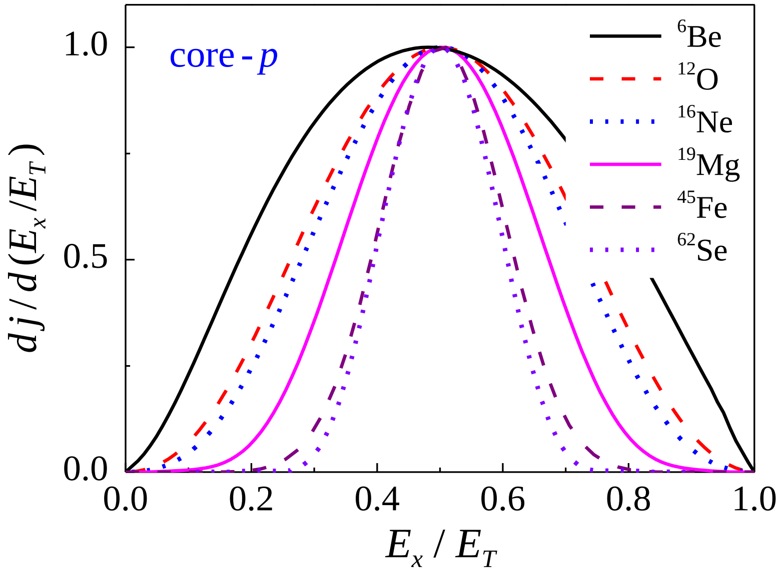


Better than invariant mass method! <u>IF</u> you understand what is happening

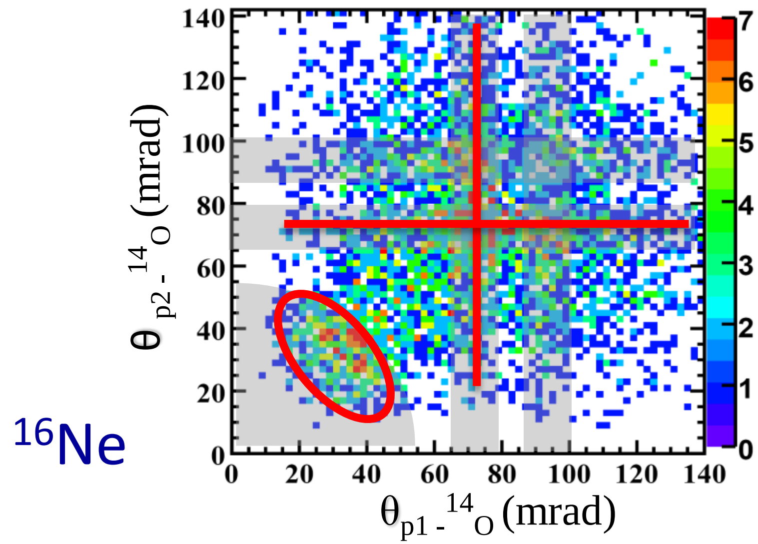
Basic idea

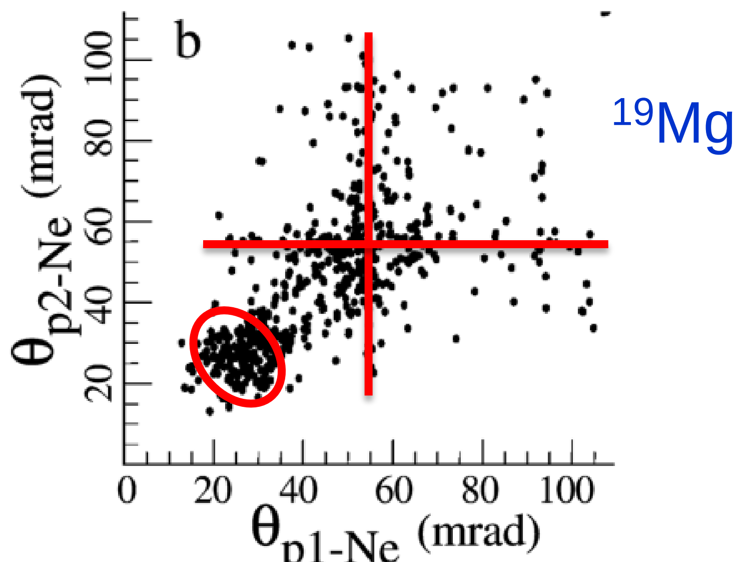
Better than invariant mass method
IF you understand what is happening

True three-body decay



Energies of protons tend to be almost equal

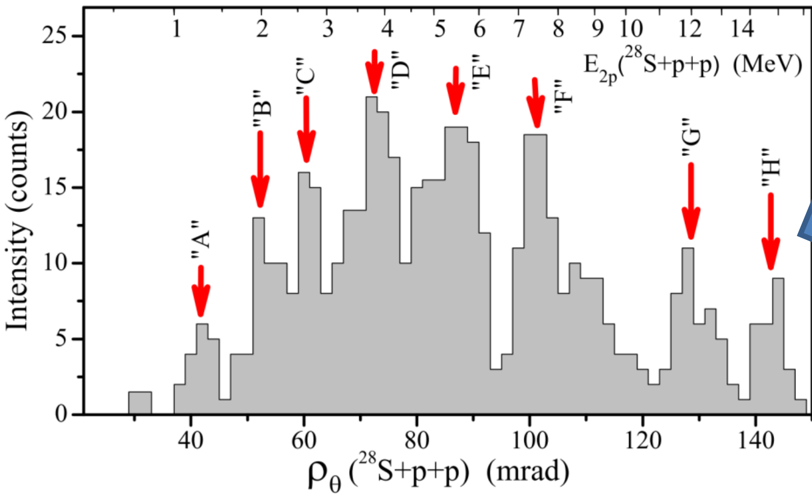


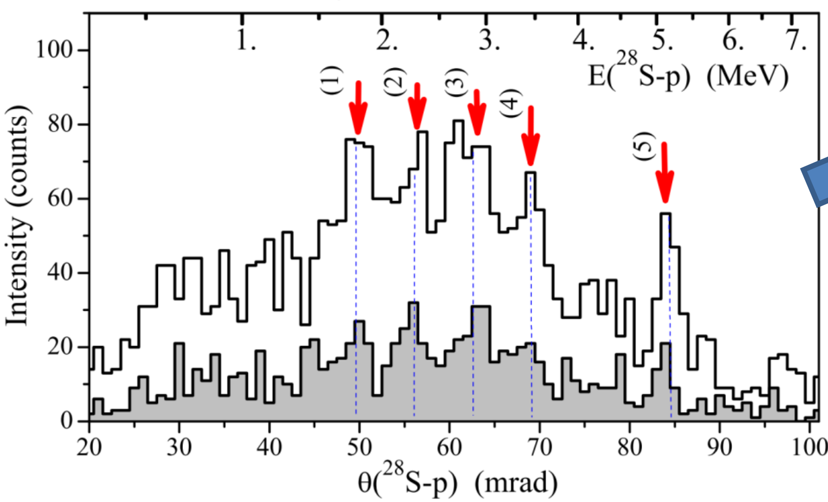


I. Mukha et al., PRL **99** (2007) 182501.
I. Mukha et al., PRC **77** (2008) 061303.
I. Mukha et al., PRC **79** (2009) 061301.

^{30}Ar and ^{29}Cl spectra and decay schemes

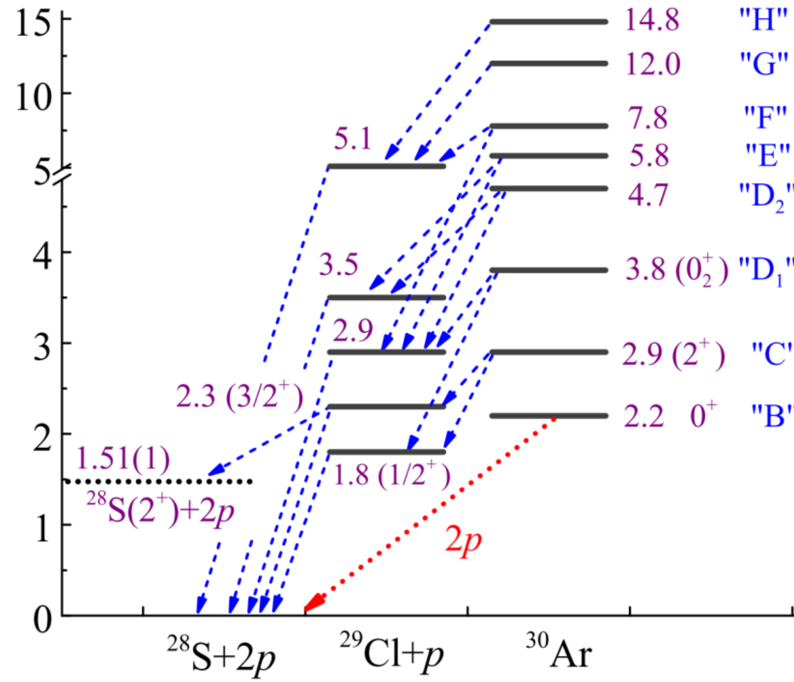
I. Mukha et al., PRL **115** (2015) 202501.





Statistics is limited

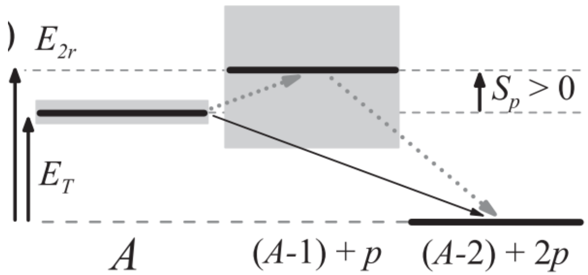
Complex and rich decay picture. A lot of information!

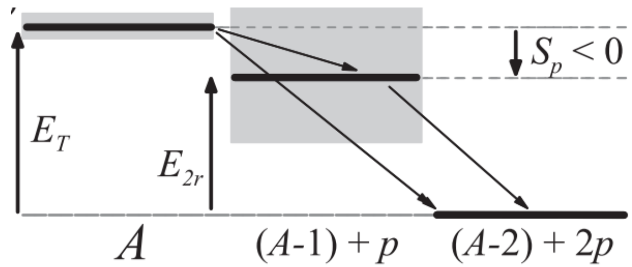


Special bonus: evidence for "transition" dynamics of ^{30}Ar g.s. decay, never seen before

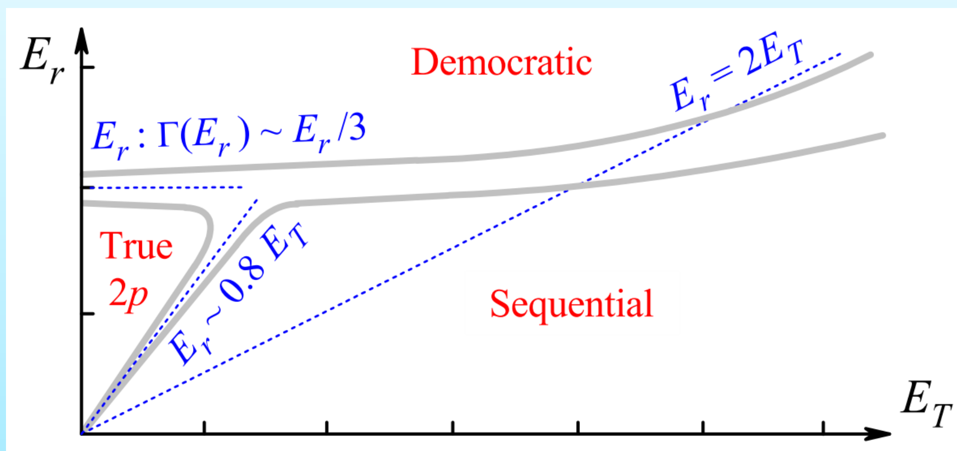
“Transition” decay dynamics

Mechanisms of 2p decay





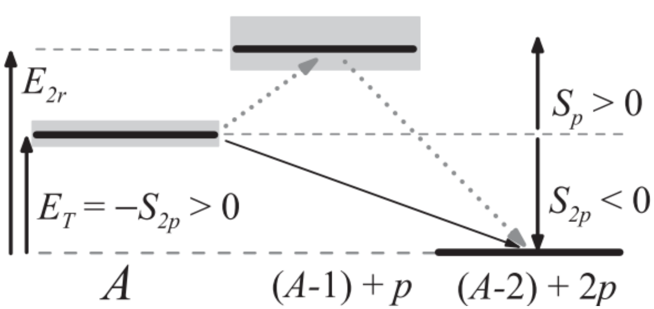
Three major decay mechanisms: True 2p, Democratic 2p Sequential 2p

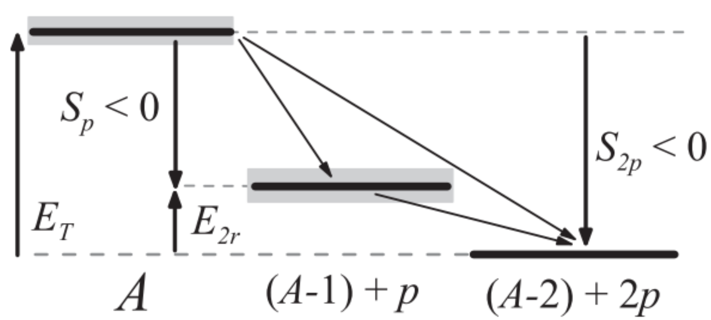


There SHOULD EXIST transition region between them

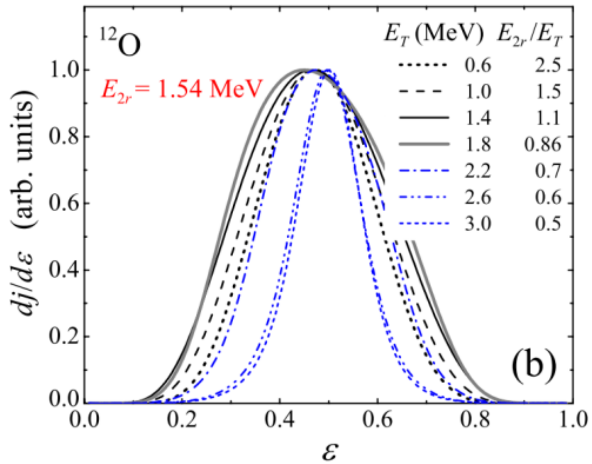
Three principal parameters:

$E_T \quad E_r \quad \Gamma_r$

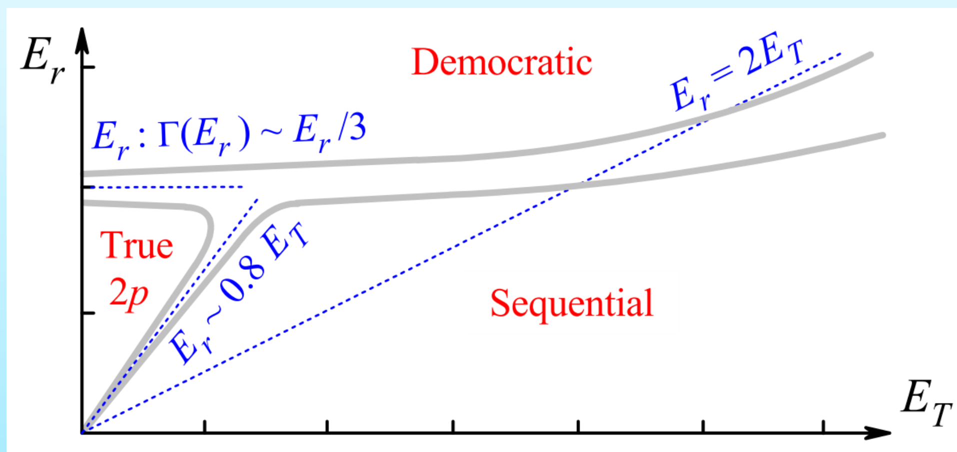




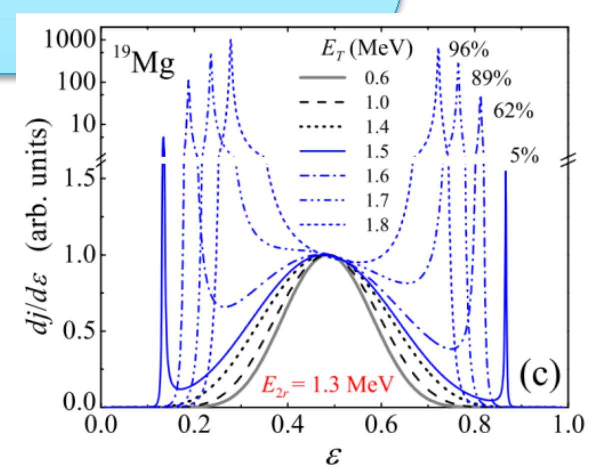
Energy core-p correlations for for fifferent mechanisms



Democratic 2p <-> Sequential 2p



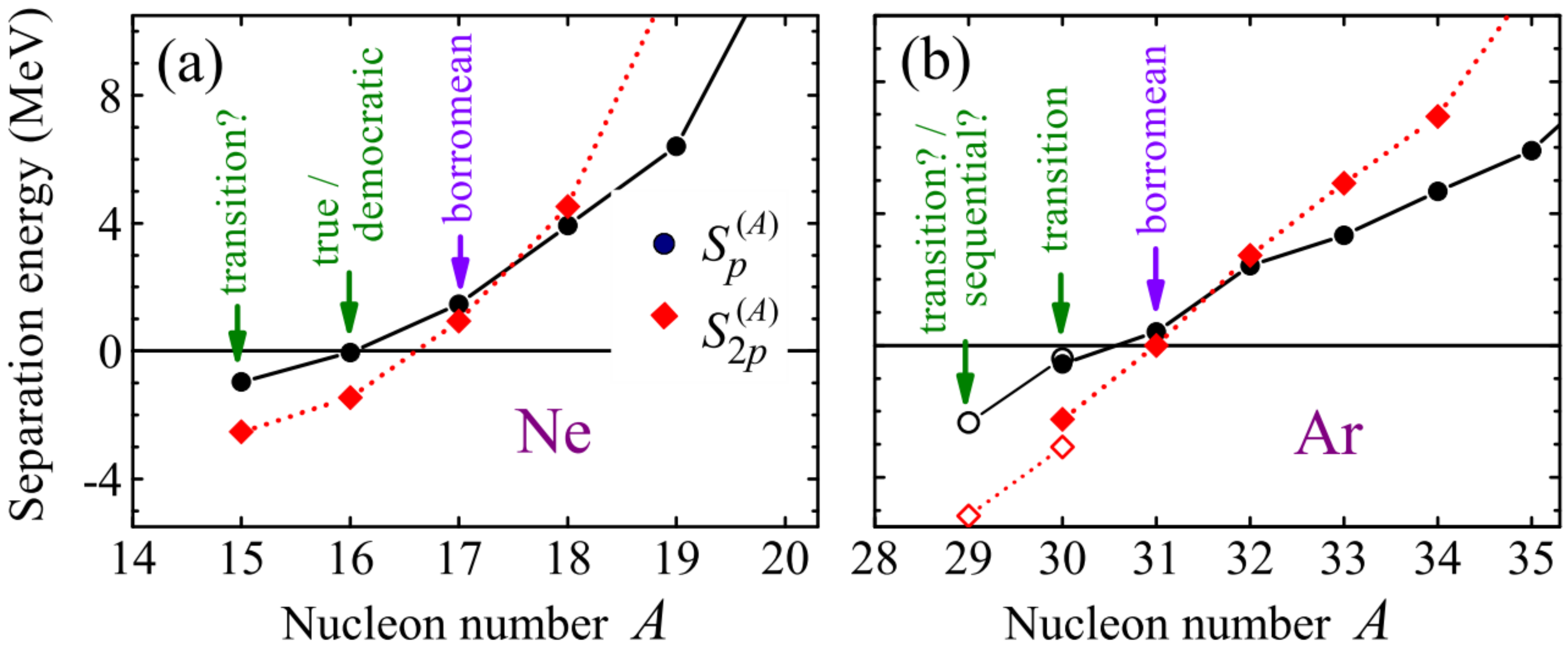
True 2p <-> Sequential 2p



Transition decay mechanism beyond the dripline

Systematics of proton and two-proton separation energies

Upper and lower s-d shell

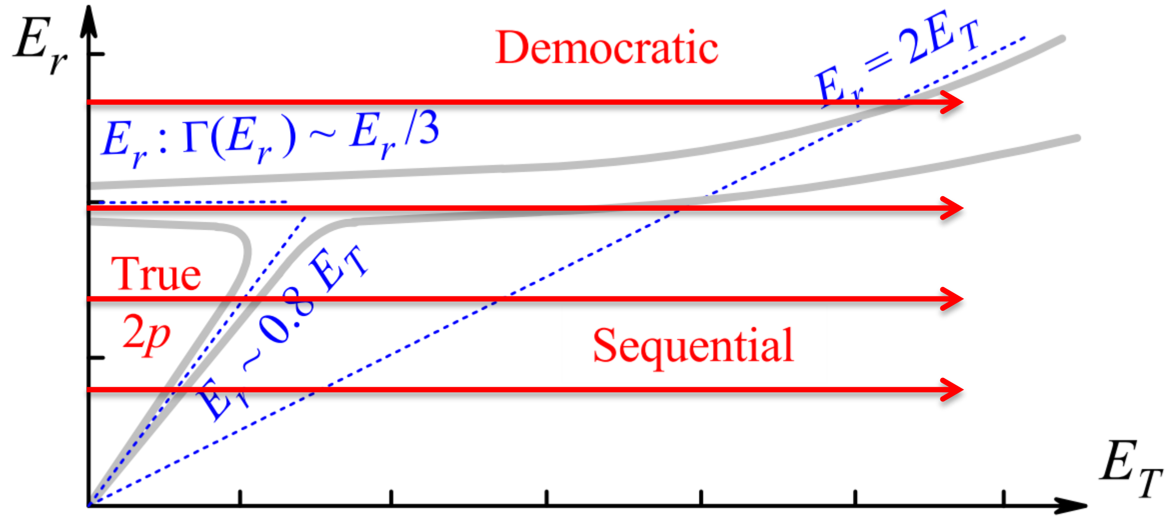


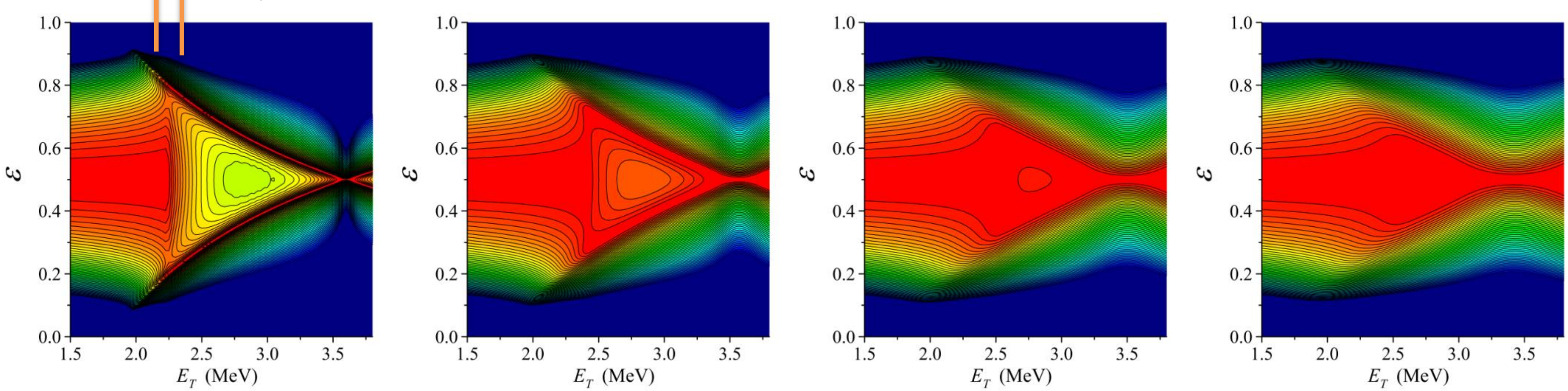
All three mechanisms of 2p emission as well as transition situation change each other on the move away from the dripline

General view of transition dynamics

"^{30}Ar"

Energy correlations between core and one proton

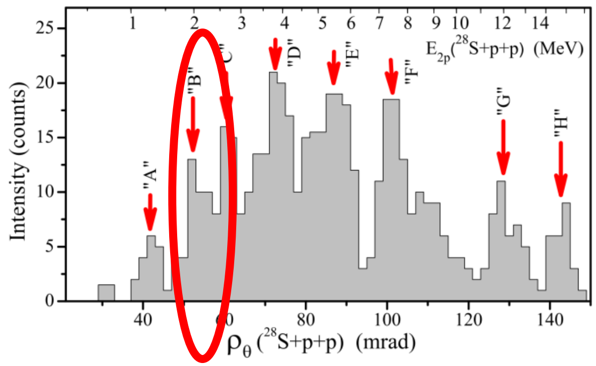


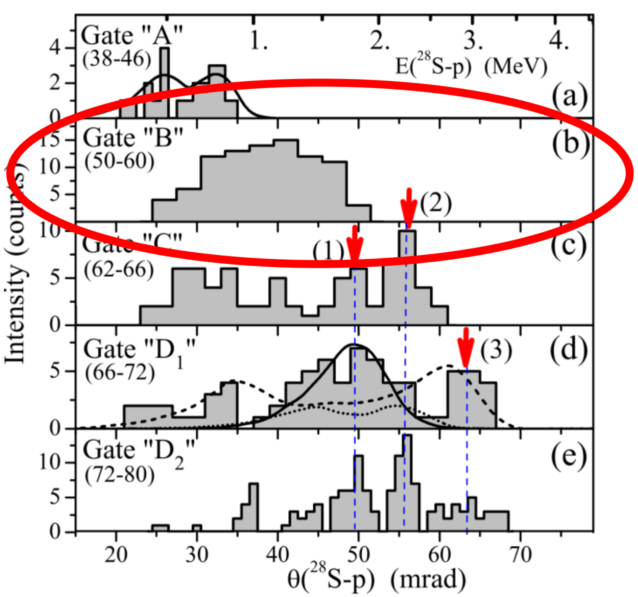


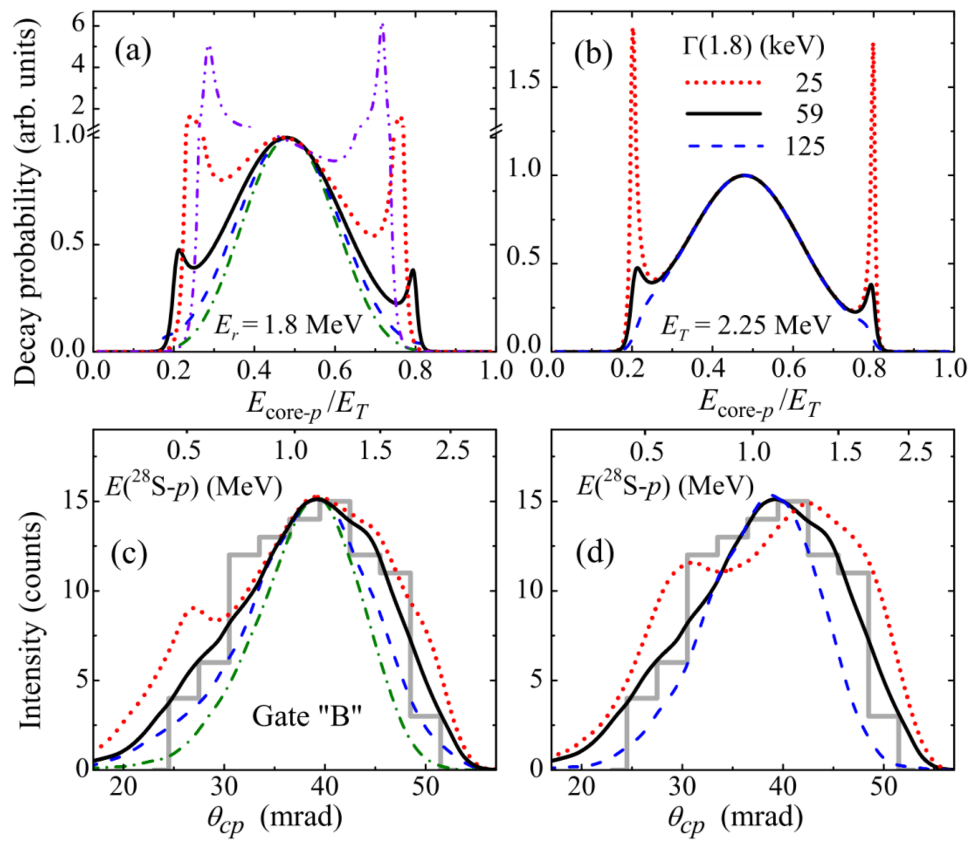
Phase transition like behaviour ->
Strong sensitivity to parameters ->
Opportunity to define them
precisely

^{30}Ar: ground 2.25 MeV state decay

E_T from 2.0 to 2.5 MeV







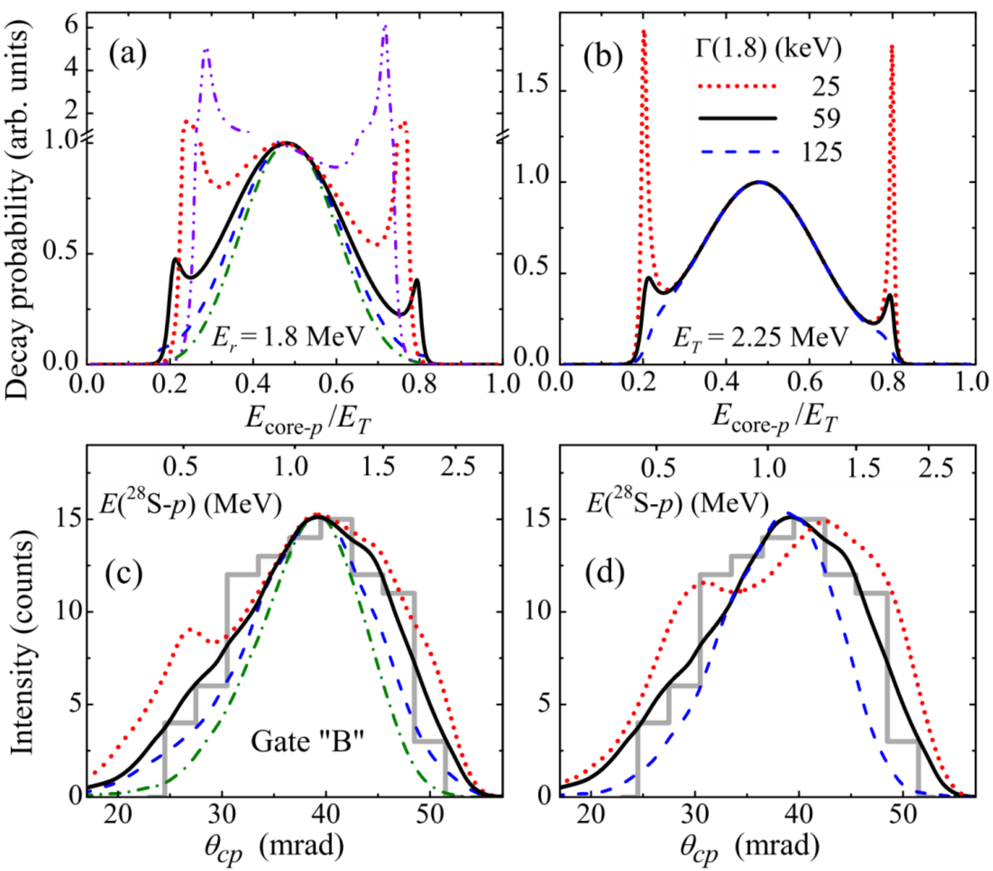
Seen for the first time for the ground state decays

Strong sensitivity to parameters -> sensitive “tool” for fixing parameters

^{29}Cl ground state width

$$\Gamma_{j_1 j_2}(E_T) = \frac{E_T \langle V_3 \rangle^2}{2\pi} \int_0^1 d\varepsilon \frac{\Gamma_{j_1}(\varepsilon E_T)}{(\varepsilon E_T - E_{j_1})^2 + \Gamma_{j_1}(\varepsilon E_T)^2/4}$$

$$\times \frac{\Gamma_{j_2}((1-\varepsilon)E_T)}{((1-\varepsilon)E_T - E_{j_2})^2 + \Gamma_{j_2}((1-\varepsilon)E_T)^2/4}$$



Theory – simplified semianalytical model of 2p decay

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

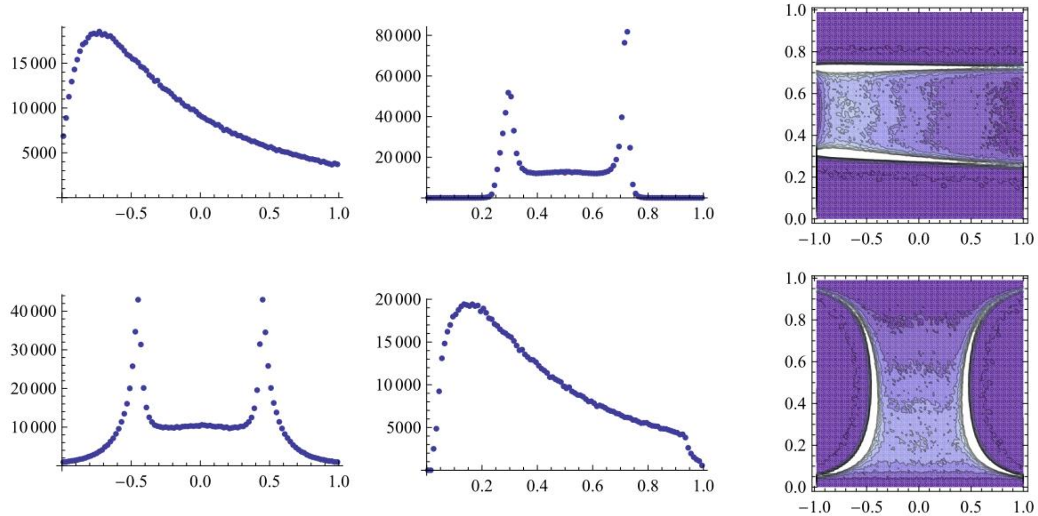
Energy is "easy" to measure, width could be very complicated.
From $T_{1/2}$~1 ps to Γ~100-200 keV there is a "blind spot"

Prospects to establish this kind of measurements for width determination

Systematic studies by variation of all decay parameters

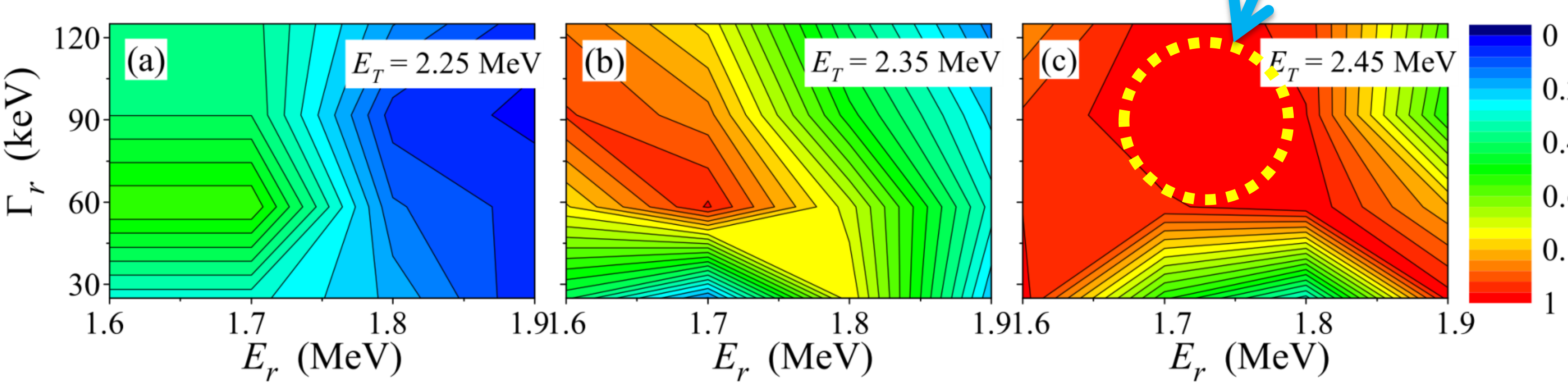
Three principal parameters:
$E_T \quad E_r \quad \Gamma_r$

$$\Gamma_{j_1 j_2}(E_T) = \frac{E_T \langle V_3 \rangle^2}{2\pi} \int_0^1 d\varepsilon \, \frac{\Gamma_{j_1}(\varepsilon E_T)}{(\varepsilon E_T - E_{j_1})^2 + \Gamma_{j_1}(\varepsilon E_T)^2/4} \times \frac{\Gamma_{j_2}((1-\varepsilon) E_T)}{((1-\varepsilon)E_T - E_{j_2})^2 + \Gamma_{j_2}((1-\varepsilon)E_T)^2/4}$$



Kolmogorov test: probability to match the experimental pattern

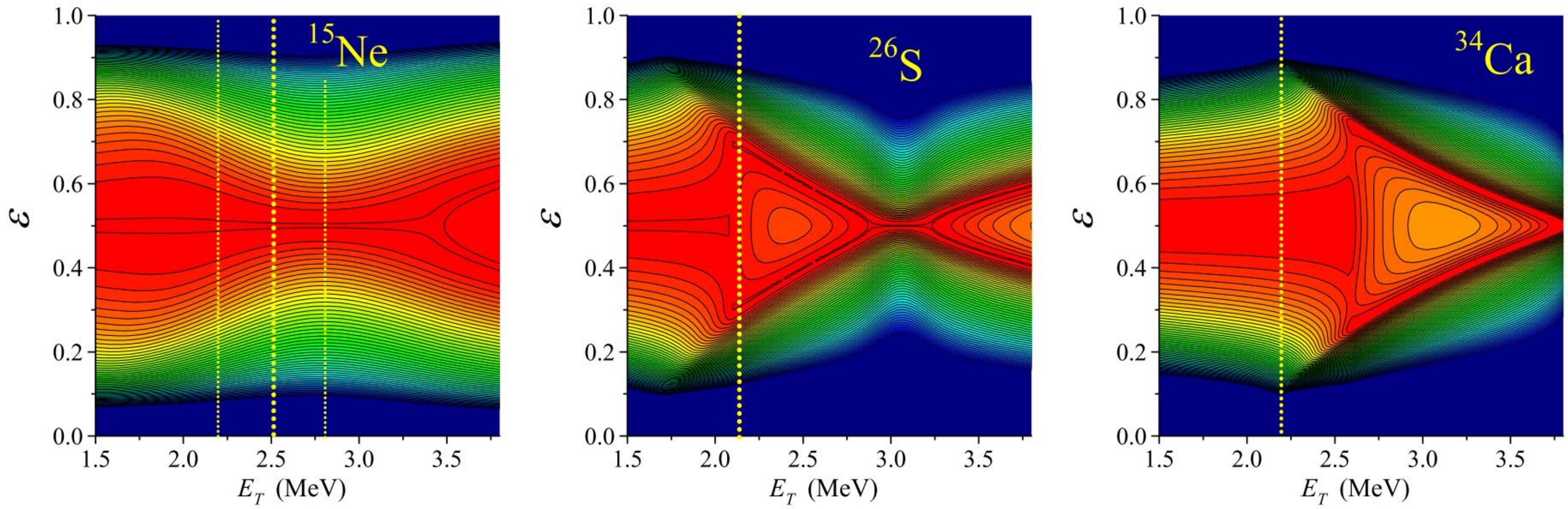
I. Mukha, X. Xu: confinement in parameter space.



Possibility to study transition dynamics in ^{15}Ne

Nearest transition candidates in s-d shell: ^{15}Ne, ^{26}S, ^{34}Ca

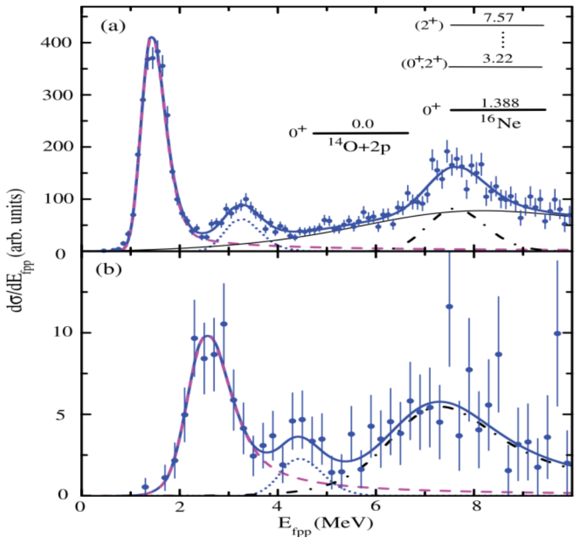
Energy correlations between core and one proton



Prospects to observe transition dynamics in ^{15}Ne

F. Wamers et al., PRL **112** (2014) 132502

^{16}Ne, ^{16}Ne, GSI

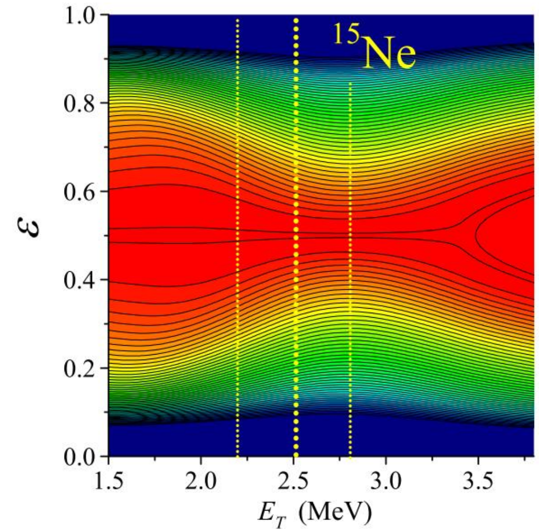


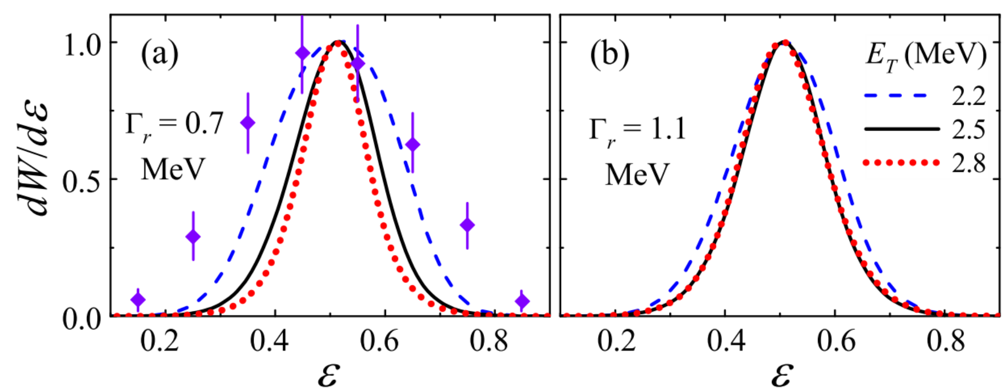
V. Goldberg et al., PLB **692** (2010) 307

^{14}F, TEXAS A&M

Levels in ^{14}F.

E_R (MeV)[a]	E_x[b]	J^π	Γ (keV)	Γ/Γ_{sp}
1.56 ± 0.04	0.00	2^-	910 ± 100	0.85
2.1 ± 0.17	0.54	1^-	~ 1000	0.6
3.05 ± 0.060	1.49	3^-	210 ± 40	0.55
4.35 ± 0.10	2.79	4^-	550 ± 100	0.5



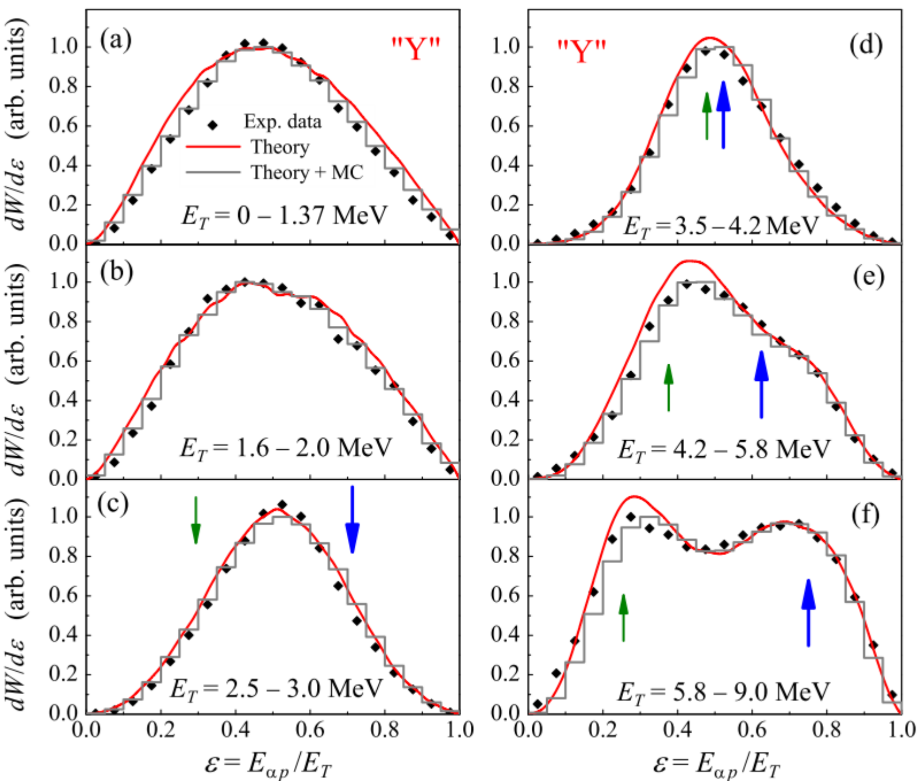


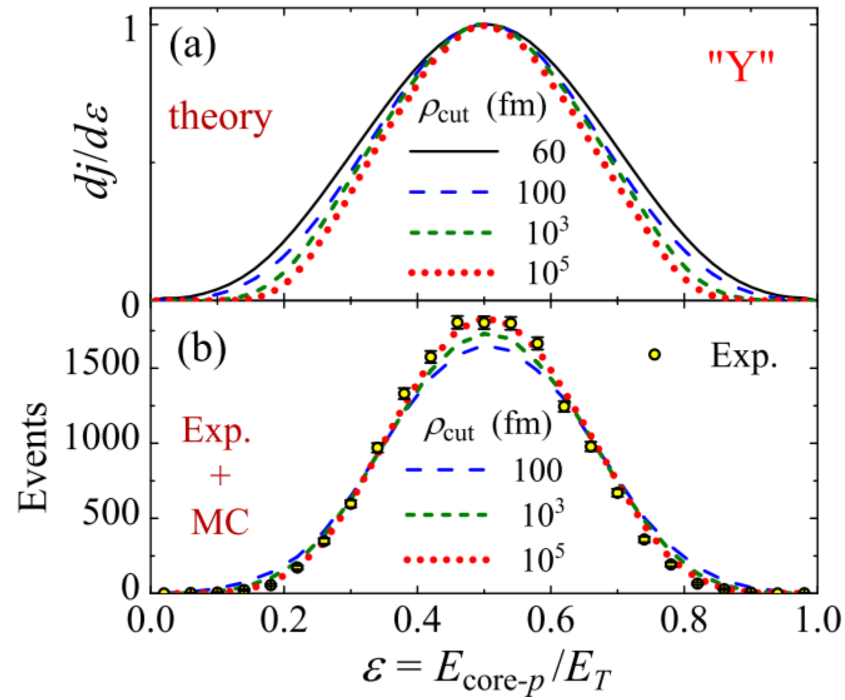
Proposal: to study energy evolution of correlations across broad g.s. of ^{15}Ne to extract ^{14}F width

Prospects to observe transition dynamics in ^{15}Ne

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

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





^{16}Ne, MSU

^{6}Be, MSU

Evolution of energy distributions with total decay energy E_T really exists

Fine differences in energy distributions are extractable from data

Conclusions

- Few-body dynamics is widespread beyond the driplines. ~ 1/2 of the proton-rich nuclei located by 1-2 atomic numbers beyond the proton dripline decay by 2p emission.
- Three major mechanisms of 2p emission: true 2p, democratic 2p, sequential. Major dependence on just three parameters: E_T E_r Γ_r
- Crossing of S_p and S_{2p} curves beyond the dripline – high probability of transition dynamics.
- In the transition region sensitivity to parameters become very high. Pragmatically most interesting is extraction of Γ_r – the width of the g.s. in core-p subsystem.
- Feasibility of such studies is demonstrated by example of ^{30}Ar and ^{15}Ne decays