Democratic decay of ^{6}Be studied in direct reactions

I. A. Egorova,
S. N. Ershov,
A. S. Fomichev,
L. V. Grigorenko,
M. S. Golovkov,
Yu. L. Parfenova,
R. Charity

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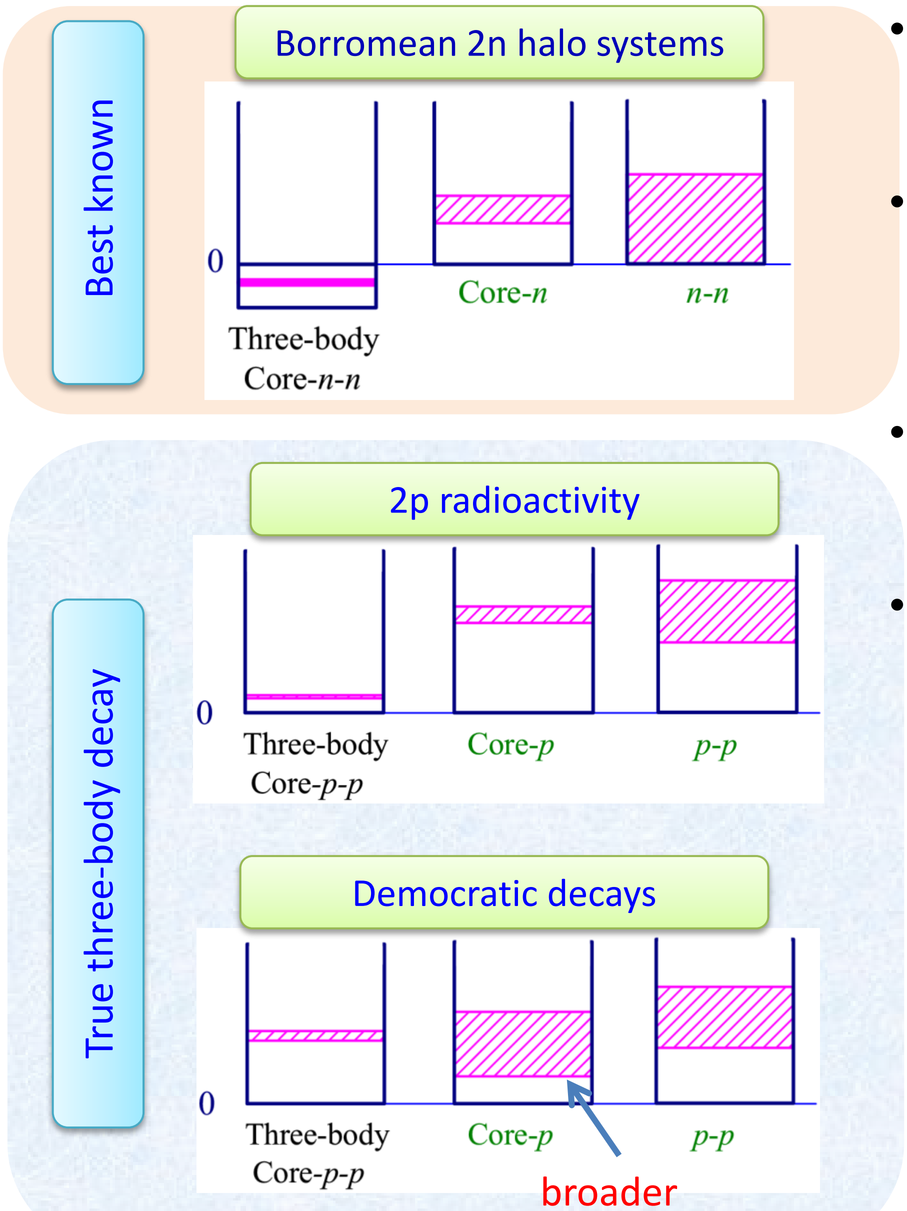
Energy conditions and few-body phenomena



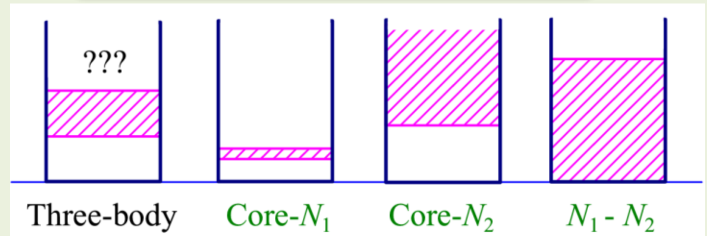
- Different types of few-body phenomena are connected with specific energy conditions, which are illustrated here schematically.
- In even systems close to driplines the lowest threshold is often 3-body core+2ns or core+2ps. In these regions the three-body dynamics becomes important.
- The best known example of such dynamics is “Borromean” 2p or 2n halo systems, where 2body subsystems core+n and n+n are unbound.
- In continuum the partner effects of Borromean halo are true three-body decay. We distinguish 2p radioactivity and democratic decay. Difference between of them is that in Democratic decay the resonance in core+p subsystem is broader and decay via the wings of this resonance is formally allowed. However, now we understand (from the recent experimental and theoretical studies) that the decay mechanism remains essentially 3b. in nature.

Energy conditions and few-body phenomena

- Important and so far not well understood phenomenon is soft excitations. The difference of soft excitations from others mechanism is a kind of asymmetry: nucleons in subsystem are in single-particle states belonging to different shells.
- 3-b Virtual states are a kind of analog of Efimov states in continuum.
- The possibility of novel complicated phenomenon – four-neutron radioactivity was predicted recently.

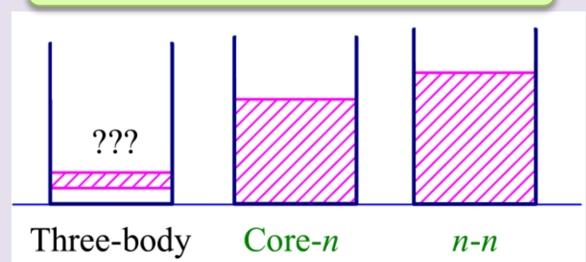
Not well understood

"Soft excitations"

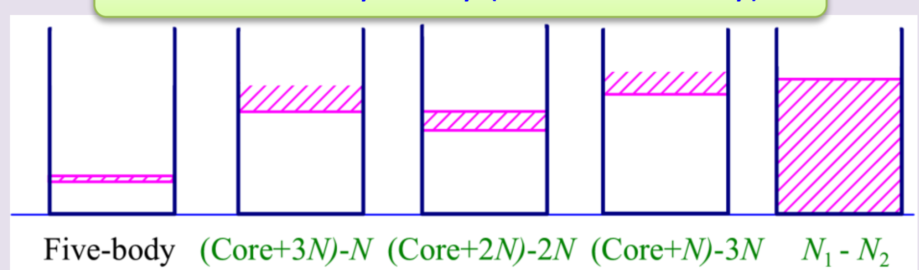


Predicted

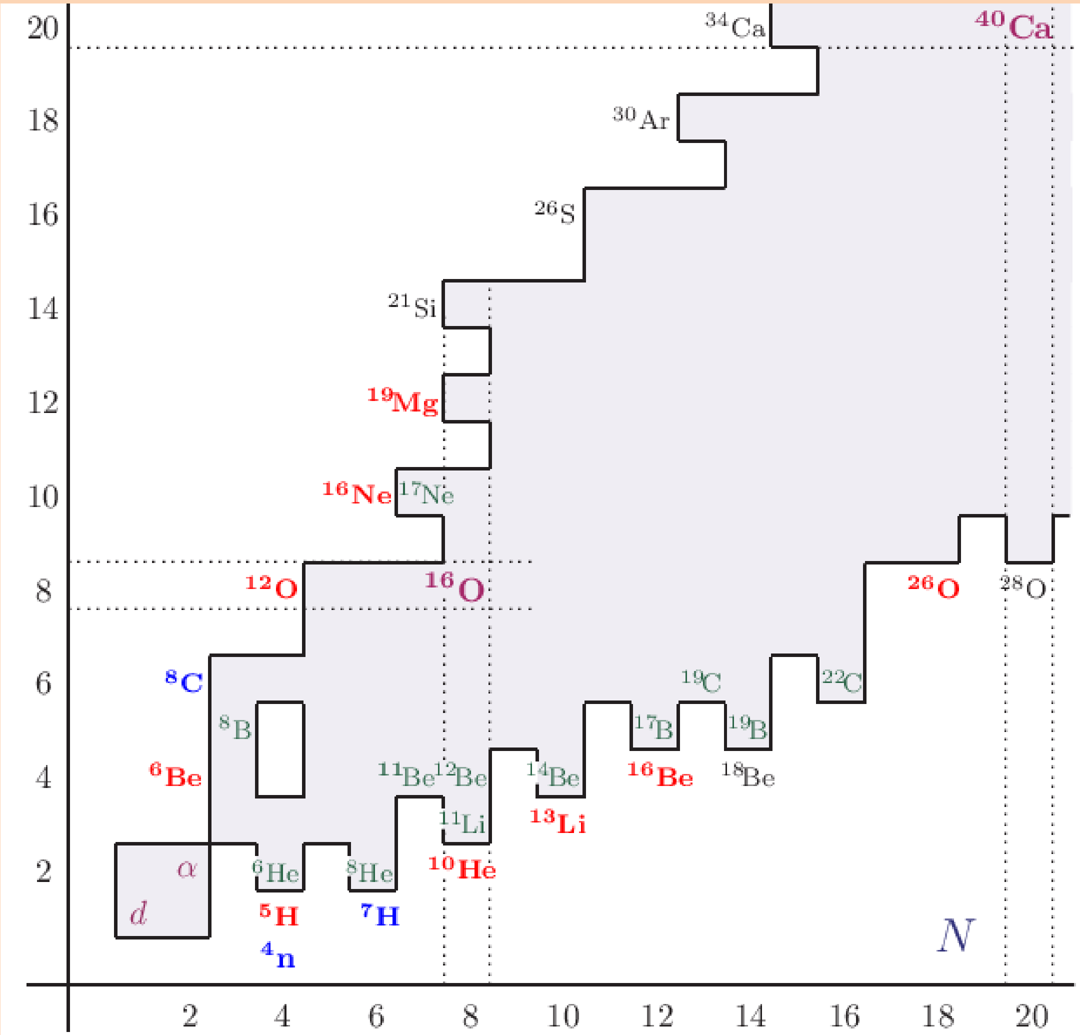
Three-body virtual states



True 5n-body decay (4n radioactivity)



Few-body dynamics at the driplines



Green – halo systems

Red – true 2p/2n emitters

Blue – 4p/4n emitters

Black – few-body decay, but **nothing** is known

Pretending to understand asymmetric nuclear matter EOS, nucleosynthesis, few-body dynamics one need to extend our knowledge as far as possible beyond the driplines.

Every second nucleus beyond the proton dripline is or is expected to be true 2p emitter!

Recently discovered 2p radioactivity cases: ^{19}Mg, ^{45}Fe, ^{48}Ni, ^{54}Zn.

Recent studies of democratic decay in ^{6}Be:

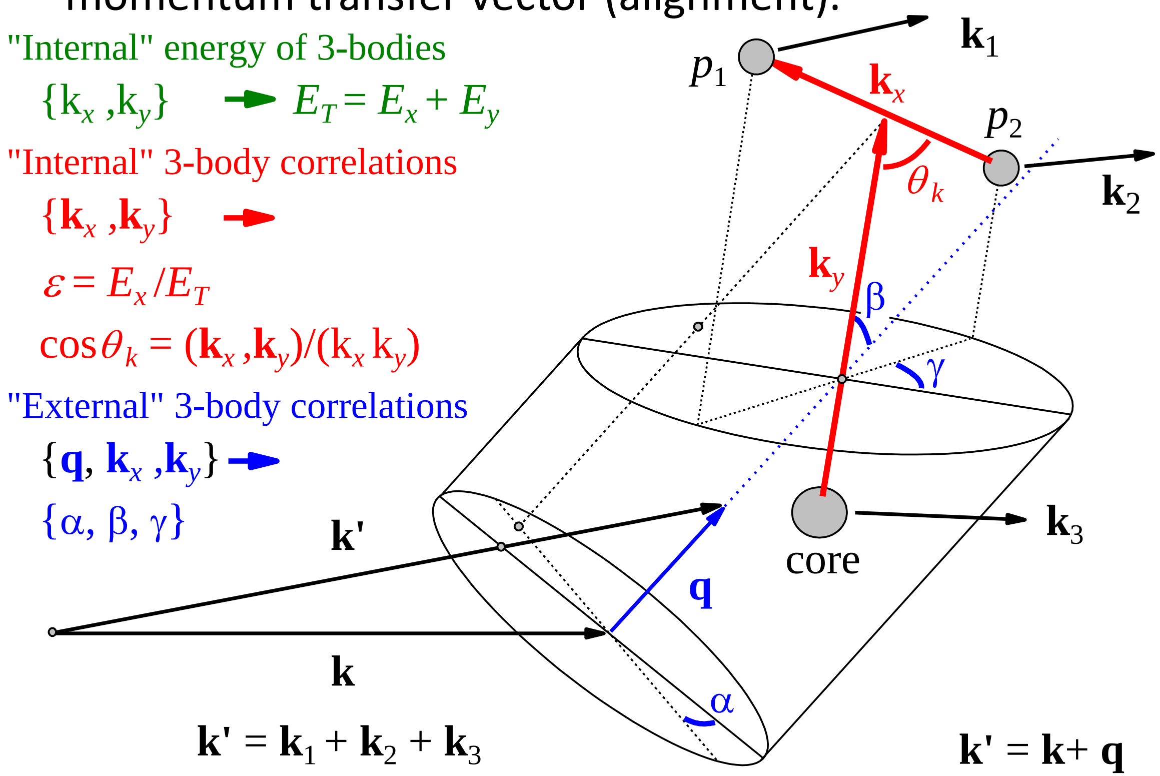
(i) Texas A&M (USA) in transfer reaction

(ii) MSU (USA) in knockout reaction

(iii) Dubna in charge-exchange reaction

Three-body correlations in decays and reactions

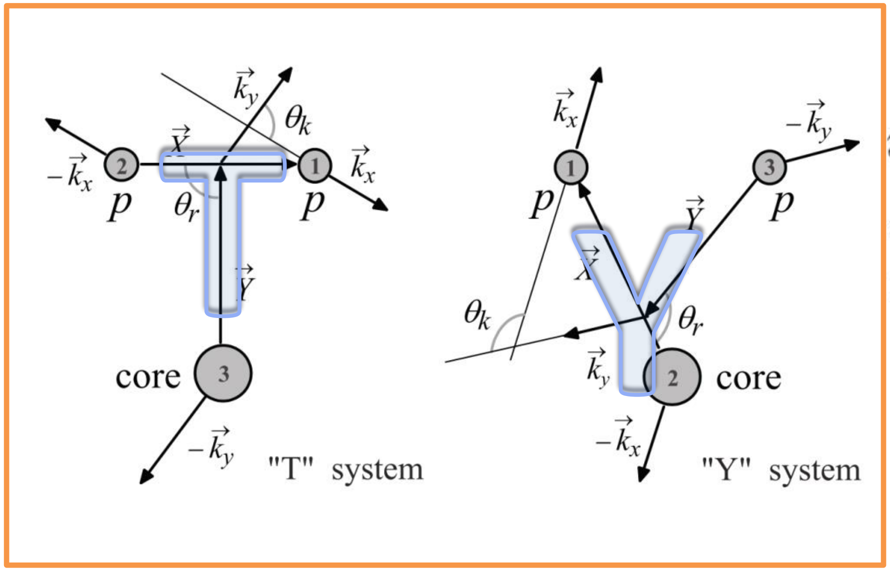
- $\{\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3\}$ (or $\{\mathbf{k}', \mathbf{k}_x, \mathbf{k}_y\}$ in Jacoby system -> 9 degrees of freedom.
- All the degrees of freedom, we split into two groups: 2D “internal” (energy-angular correlations) and 5D “external” (associated with orientation of the whole system).
- Reactions vs. decays: selected direction in reactions (5-dimensional correlations: “internal” + “external”)
- For direct reactions the evident selected direction defining orientation of the system is momentum transfer vector (alignment).



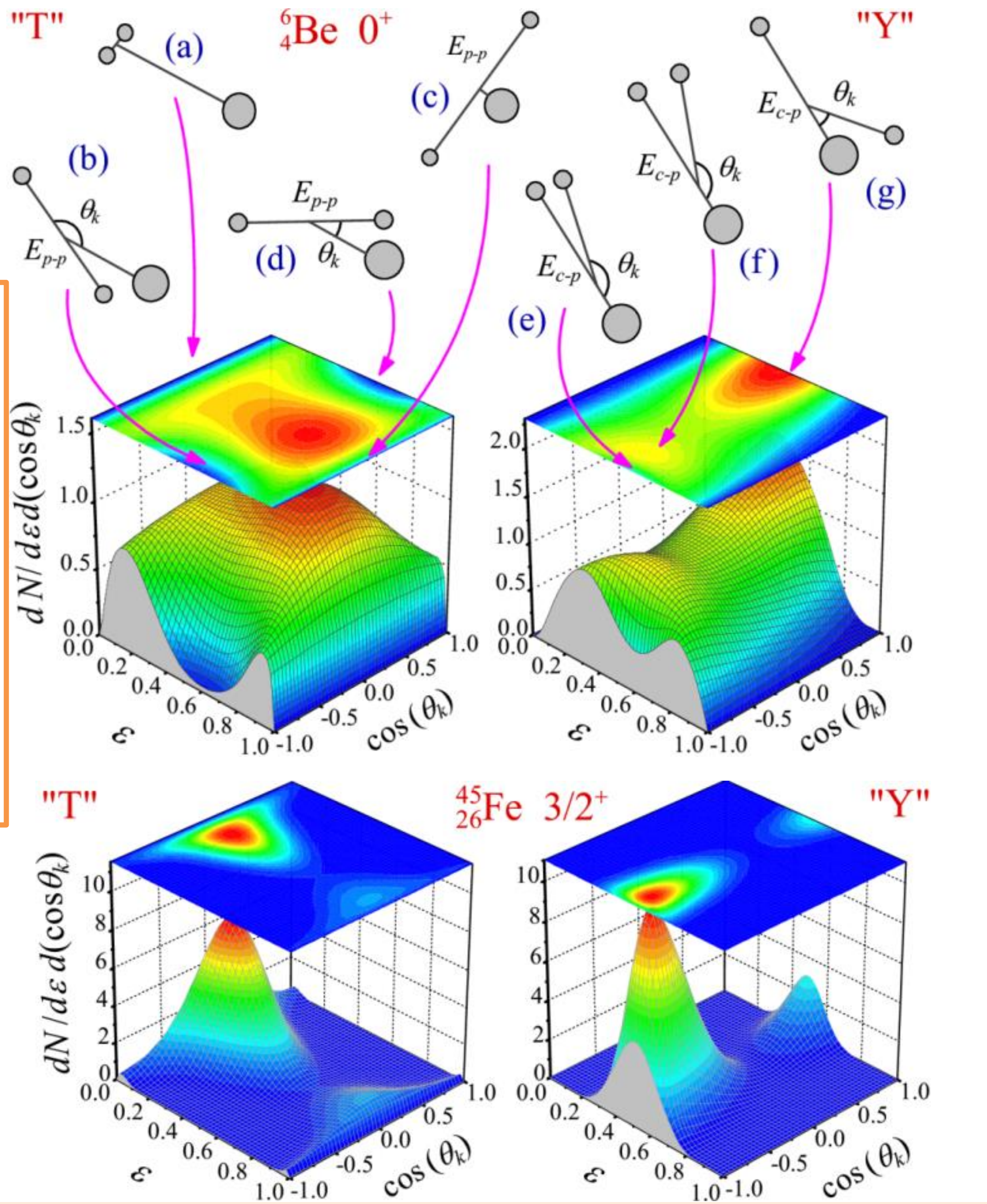
Which kind of useful information (if any) can be obtained from this additional information?

Example of energy-angular correlations

"Internal" three-body or energy-angular correlations for the g.s. of ^6Be and ^{45}Fe

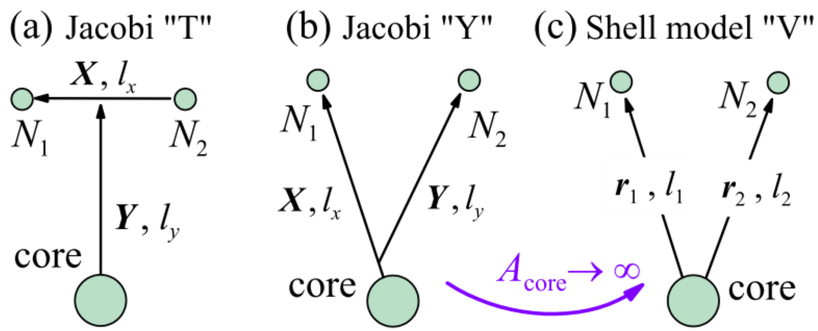


Challenge: Establish 3-body correlation studies as important and reliable "spectroscopic tool"



Differences between democratic and true 2p decays in simplified model. Transition to sequential decay

M. Pfűtzner, L. V. Grigorenko, M. Karny, K. Riisager at al., Rev.Mod.Phys. 84 (2012) 567

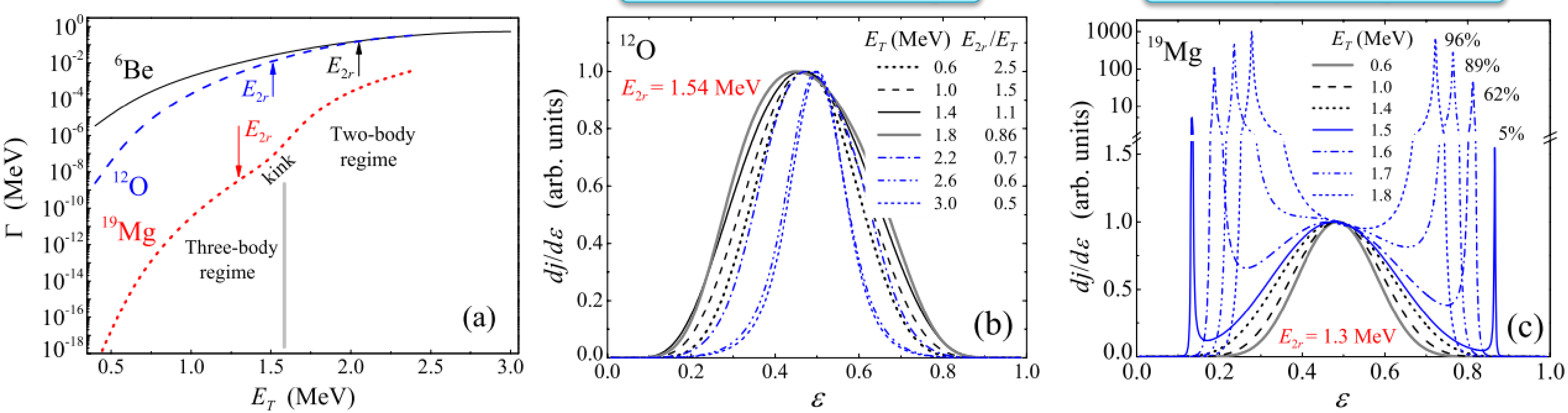


- Based on the factorization of the decay amplitude into the product of two-body terms neglecting some of the FSIs
- Three-body GF can be constructed in an analytical form:

$$\hat{G}^{(+)}_{3E}(\mathbf{XY},\mathbf{X}'\mathbf{Y}') = \frac{E}{2\pi i}\int_0^1 d\varepsilon \hat{G}^{(+)}_{\varepsilon E}(\mathbf{X},\mathbf{X}')\hat{G}^{(+)}_{(1-\varepsilon)E}(\mathbf{Y},\mathbf{Y}')$$

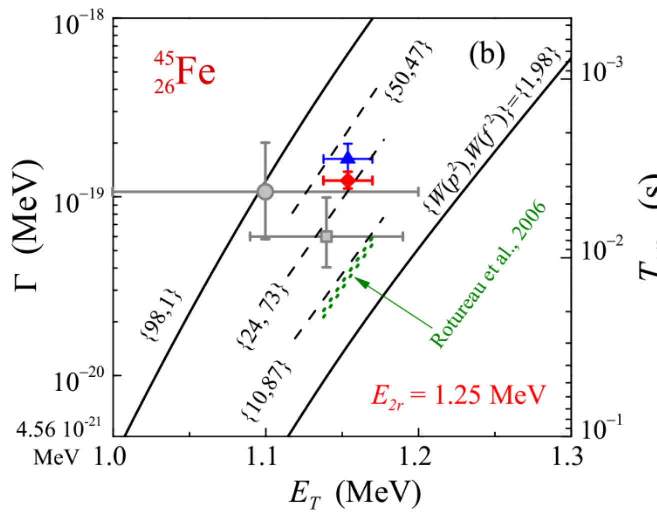
Transition from the true three-body to the sequential decay for ^{6}Be, ^{12}O, and ^{19} Mg in the direct decay approximation:

Democratic decay | **2p decay**



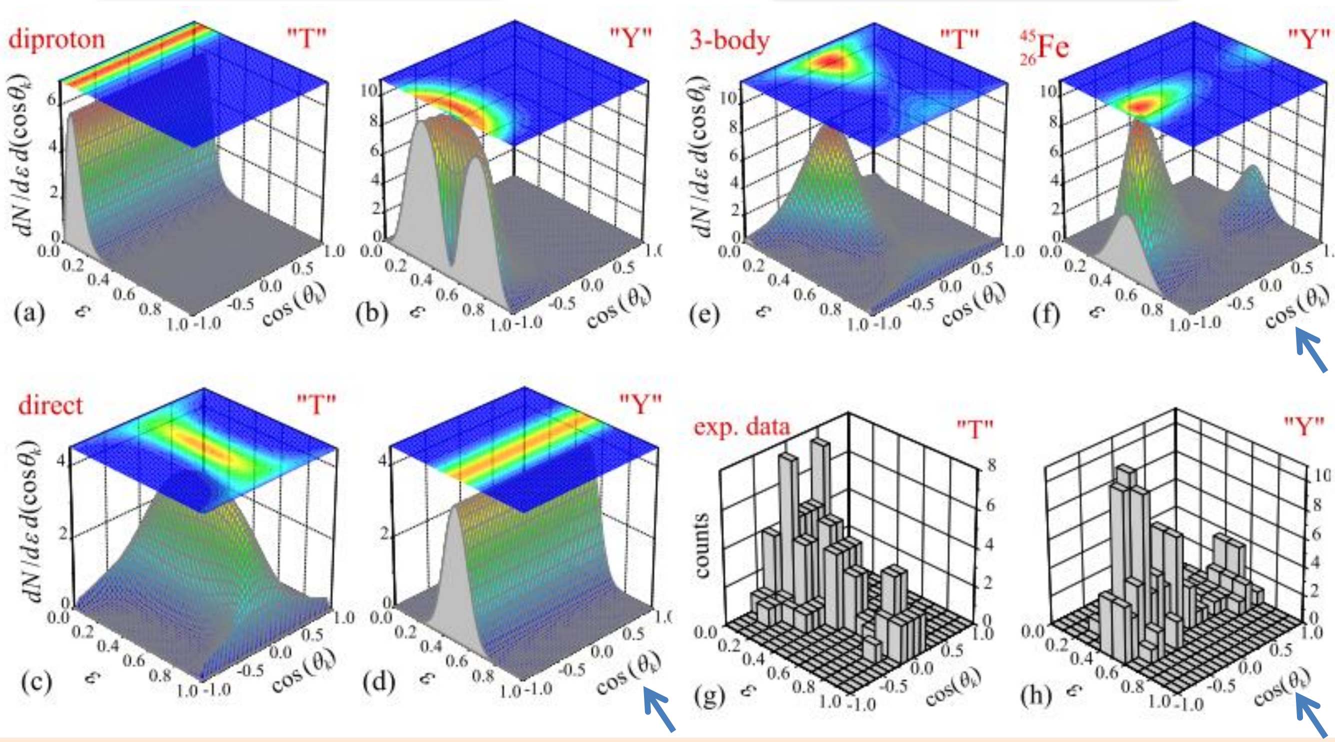
2p decay of ^{45}Fe in different models

- ^{45}Fe: the first found and the best studied 2p emitter
- Improvement of experimental data with the time
- Sequential decay: angular distribution is symmetric
- Asymmetry by angle in experimental data
- Only 3-body model have a good agreement with experimental data



Two-body models

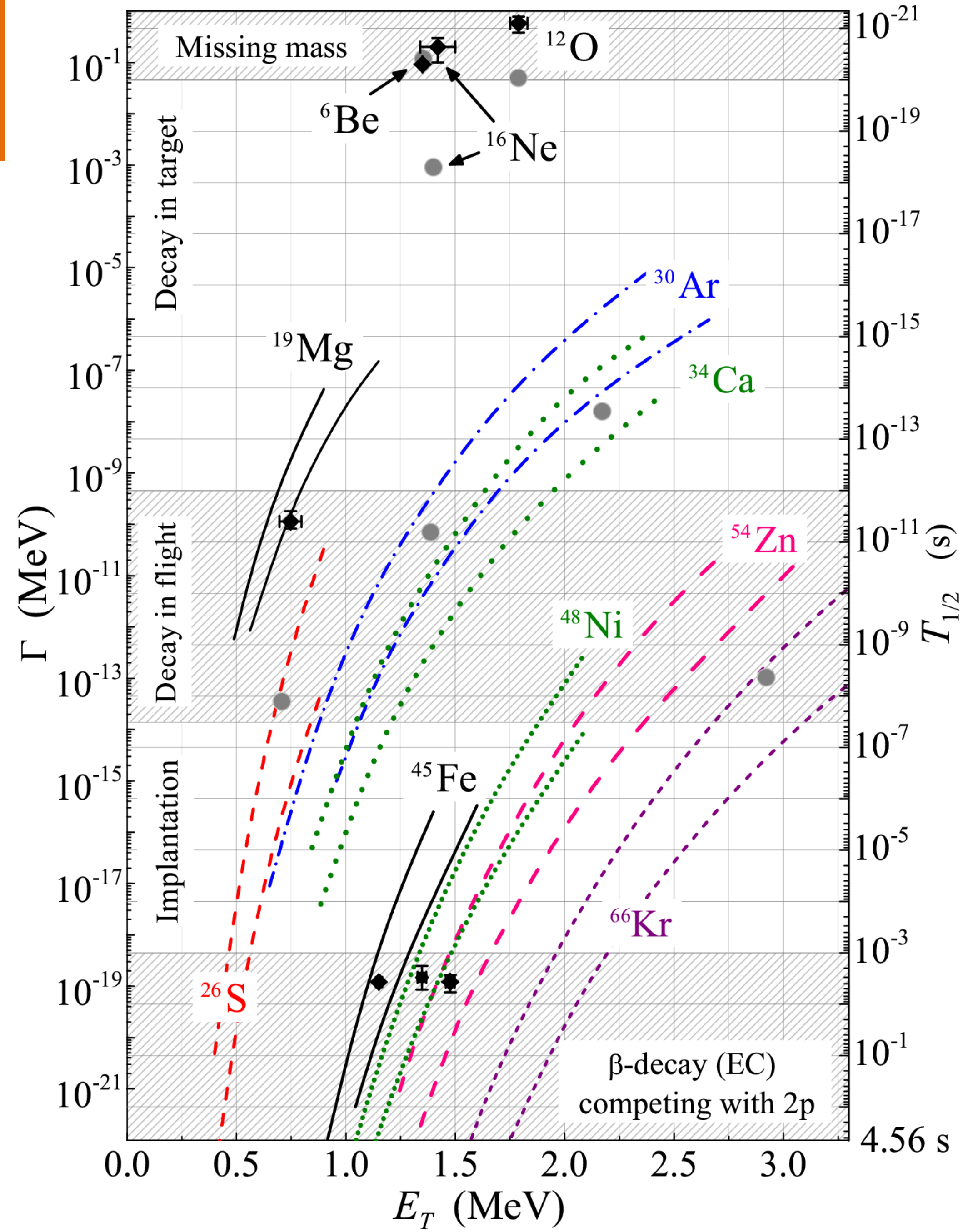
Three-body model



M. Pfűtzner, L. V. Grigorenko, M. Karny, K. Riisager at al., Rev.Mod.Phys. 84 (2012) 567

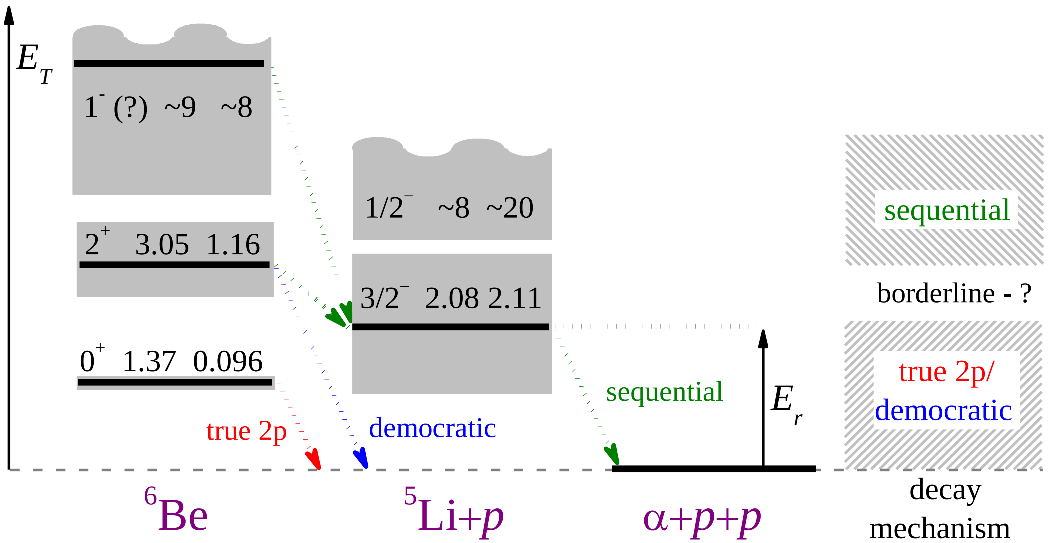
General systematics of 2p lifetimes

- The lifetime range for the known true 2p emitters spans about 20 orders of the magnitude.
- The complexity of the problem requiring a variety of experimental methods to cover the possible lifetime range.



Decay modes of ^{6}Be. Open questions

- 0^+: lightest true 2p emitter.
- 2^+: very limited information
- Quite broad excited states
- Two possibilities - sequential decay (via ^{5}Li) and democratic decay is accessible. How it should be described? (2-body model vs. 3-body model)
- Last experimental data help us to answer on this questions



Questions:

- How are ^{6}Be states populated in reaction mechanism?
- Where is the borderline between three-body and two body decay dynamics?

Interplay and transition between different decay mechanisms in three-body systems is not completely understood and produce a lot of discussions

^{6}Be population in neutron knockout reaction

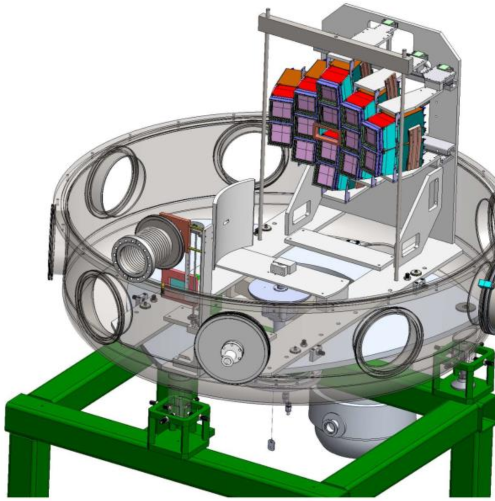
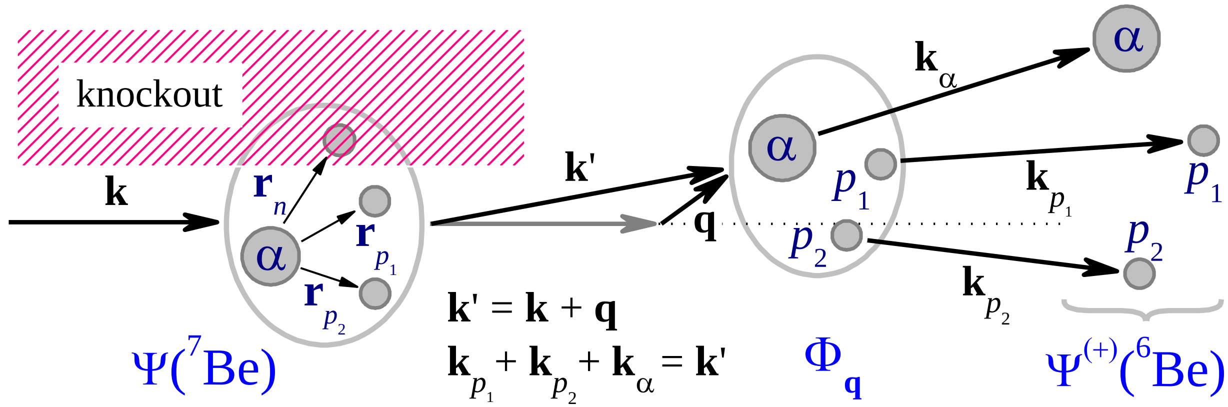


Figure 1: Experimental setup.



- Neutron knockout reaction ^{9}Be(^{7}Be, ^{6}Be)X (MSU, 2009)
- Advanced High Resolution Array
- High-statistics and high-resolution data
- Detailed view of the evolution of correlation patterns up to 10 MeV

I.A. Egorova *et al.*, PRL **109** (2012) 202502.
L.V. Grigorenko *et al.*, PRC **86** (2012) 061602(R).

Theoretical model

$$(\hat{H}_3 - E_T)\Psi^{(+)} = \Phi_{\mathbf{q}}, \quad \Phi_{\mathbf{q}} = \int d^3 r_n e^{i\mathbf{q}\mathbf{r}_n} \langle \Psi_{^4\mathrm{He}} | \Psi_{^7\mathrm{Be}} \rangle .$$

- The knockout of a neutron from ^{7}Be is described as a sudden neutron removal.
- The 7Be WF is constructed as an "inert" α-core plus p-wave neutron and two protons with coupling.

$$\langle \Psi_{^4\mathrm{He}} | \Psi_{^7\mathrm{Be}} \rangle = \alpha [p_{3/2}[p^2_{3/2}]_0]_{3/2} + \beta [p_{3/2}[p^2_{1/2}]_0]_{3/2}$$
$$+\gamma [p_{3/2}[p^2_{3/2}]_2]_{3/2} + \delta [p_{3/2}[\frac{p_{3/2}p_{1/2} - p_{1/2}p_{3/2}}{\sqrt{2}}]_2]_{3/2} .$$

- For single-particle motion, we use the harmonic-oscillator WFs whose radial behavior is (r_0 = 1.8 fm)

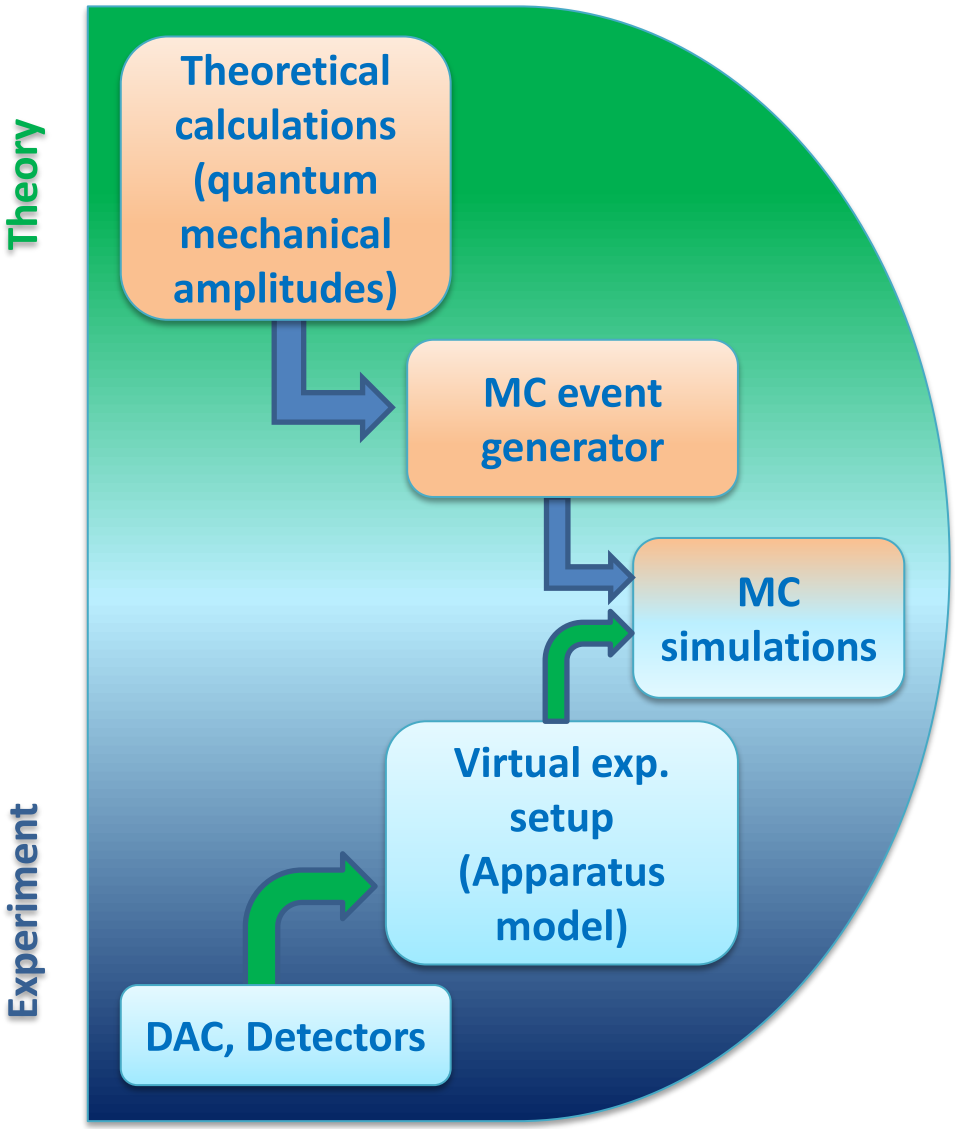
$$\phi(r) = (8/3\sqrt{\pi})^{1/2}(r^2/r_0^{5/2})\exp[-r^2/(2r_0^2)]$$

- Parameterization of source function for (ls) coupling:

$$\Phi_{J,q} \sim \sqrt{1-\eta_J^2}\, |J, S=0\rangle + \eta_J\, |J, S=1\rangle ,$$

- Coefficients η_J , controlling the $W_{S=0}$ /$W_{S=1}$ ratio, can be expressed via { α, β, γ, δ } from (ls) coupling in the source.

Interface between theory and experiment. Monte-Carlo codes.

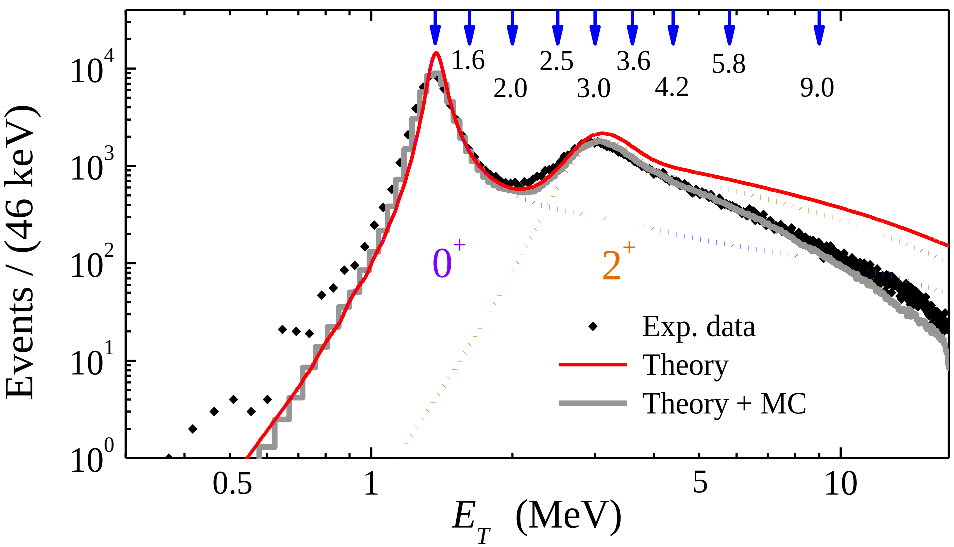


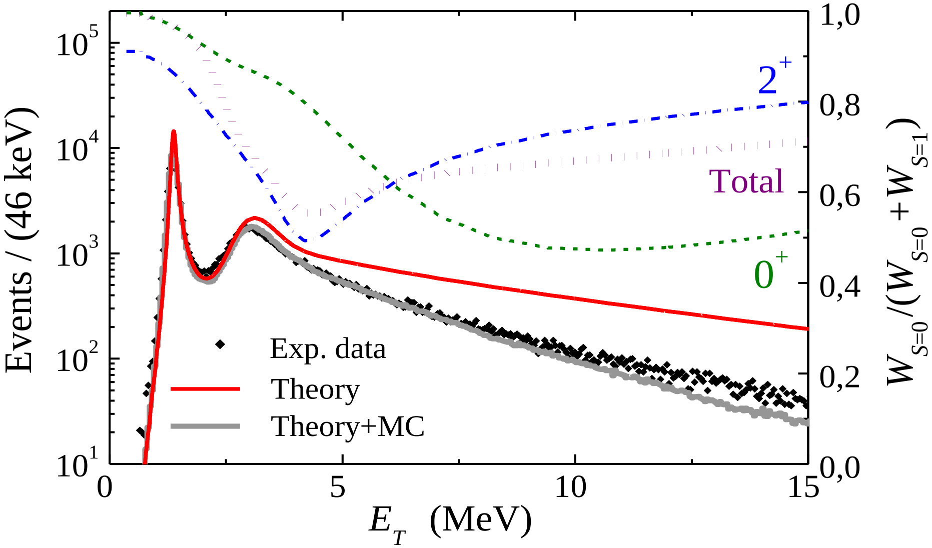
- Density matrix formalism:

$$\frac{d\sigma}{dq\, dE_T\, d\Omega_5} = \sum_{JM,J'M'} \rho_{JM}^{J'M'}(q, E_T) \times A^{\dagger}_{J'M'}(E_T, \Omega_5)\, A_{JM}(E_T, \Omega_5)$$

- Density matrix has especially simple form in the system of transferred momentum for direct reactions
- Three-body decay -> eightfold differential cross section

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

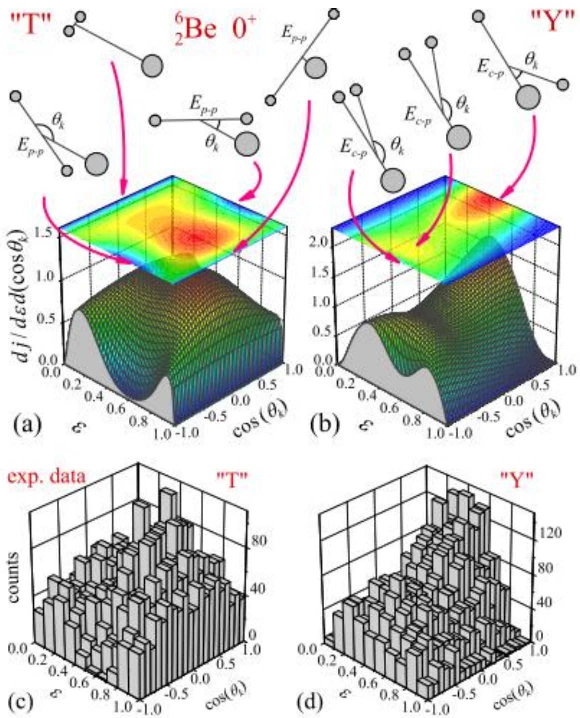




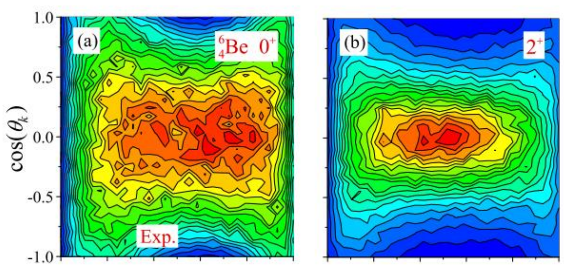
- Experimental invariant-mass spectrum of 6Be and the fitted theoretical result presented here in two scales.
- Very good agreement theory with experiment in the broad range up to 10 MeV by total energy was obtained using fit by parameters: { α, β, γ, δ }= {0.42, 0.3, 0.49, 0.7}.
- We can see also that experimental efficiency considerably influences observed spectrum above 3 MeV.

Correlation studies on 0+ and 2+ resonances.

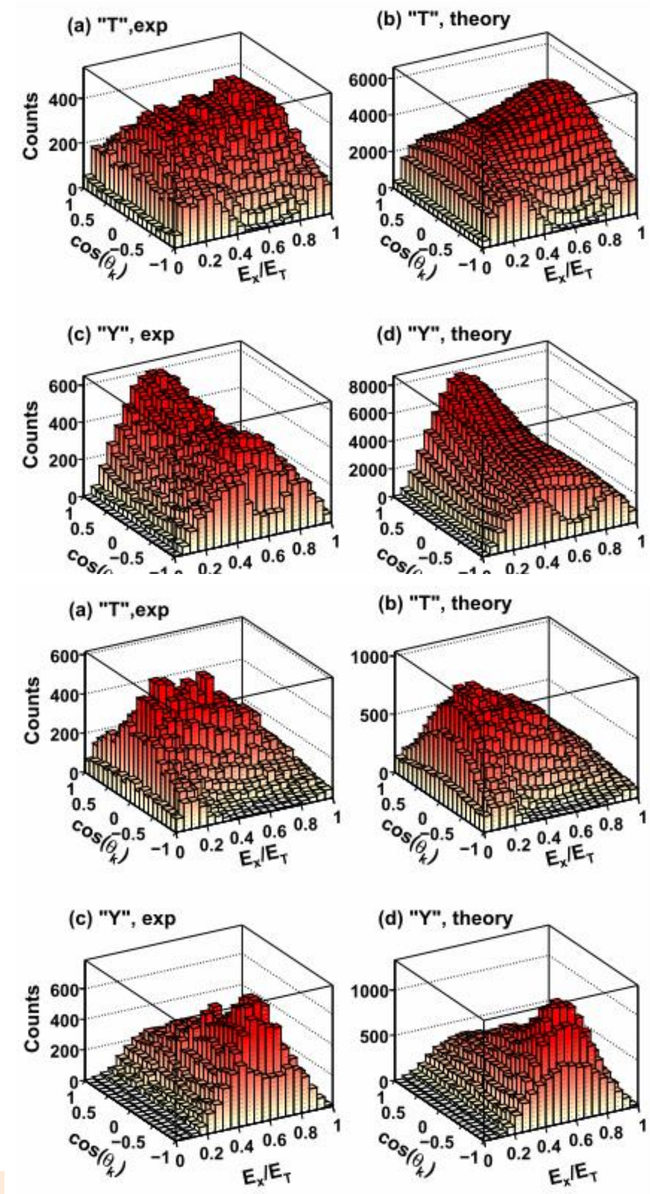
- L. V. Grigorenko et al., PLB 677, 30 (2009)



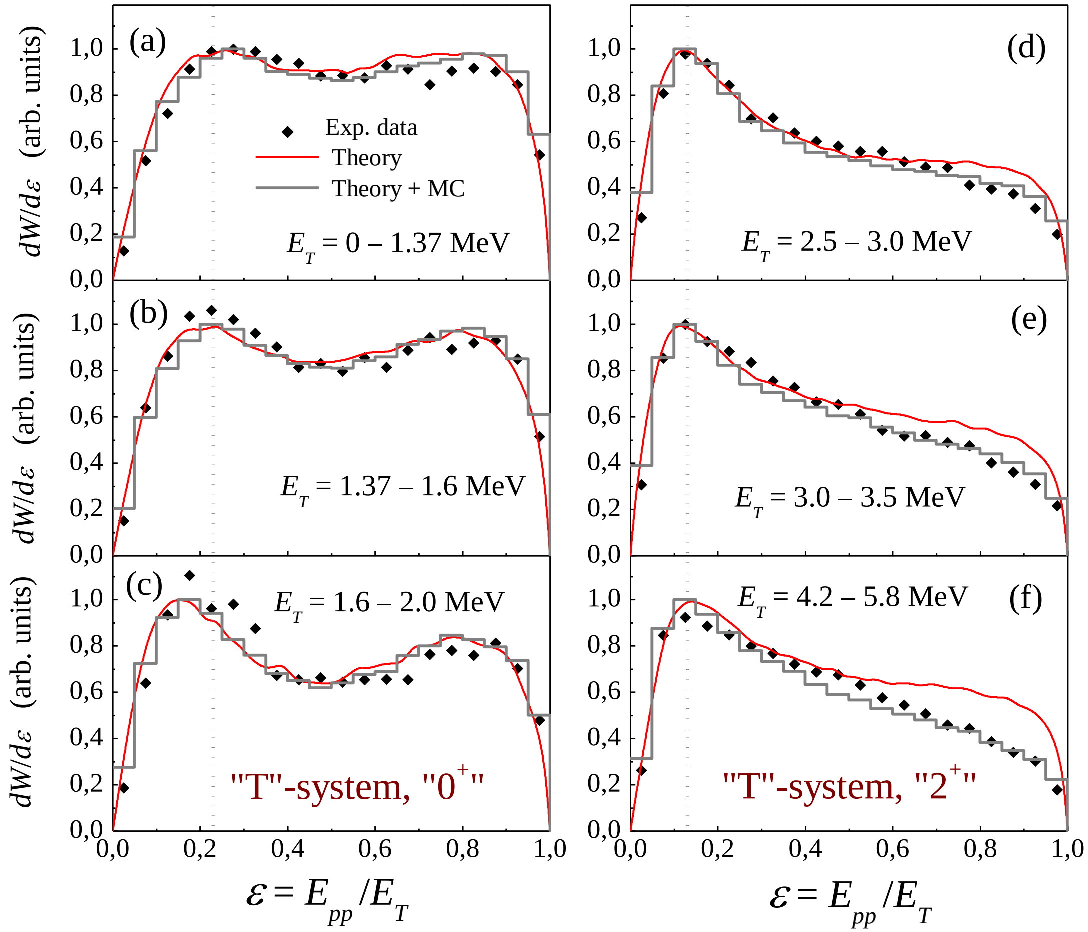
- A. S. Fomichev et al., PLB 708, 6 (2012)



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



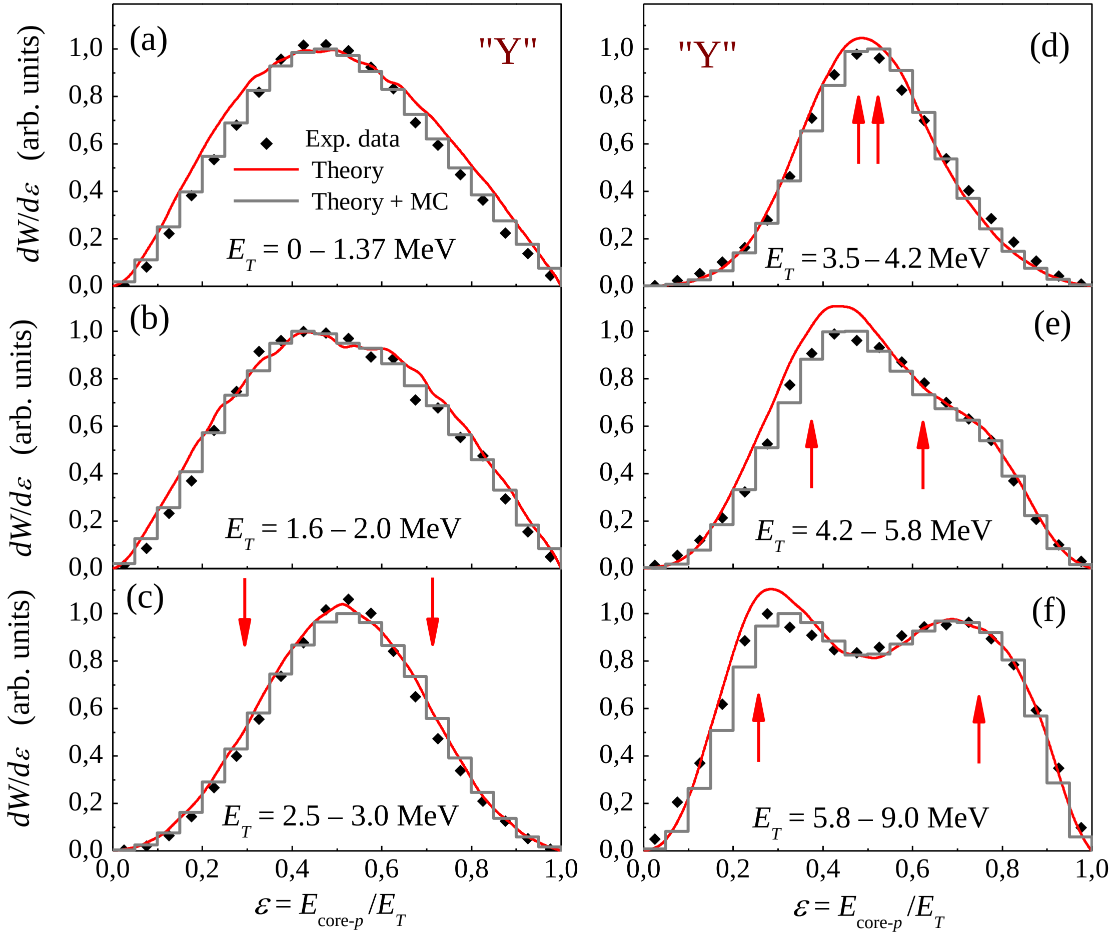
Correlation studies in a broad energy range.

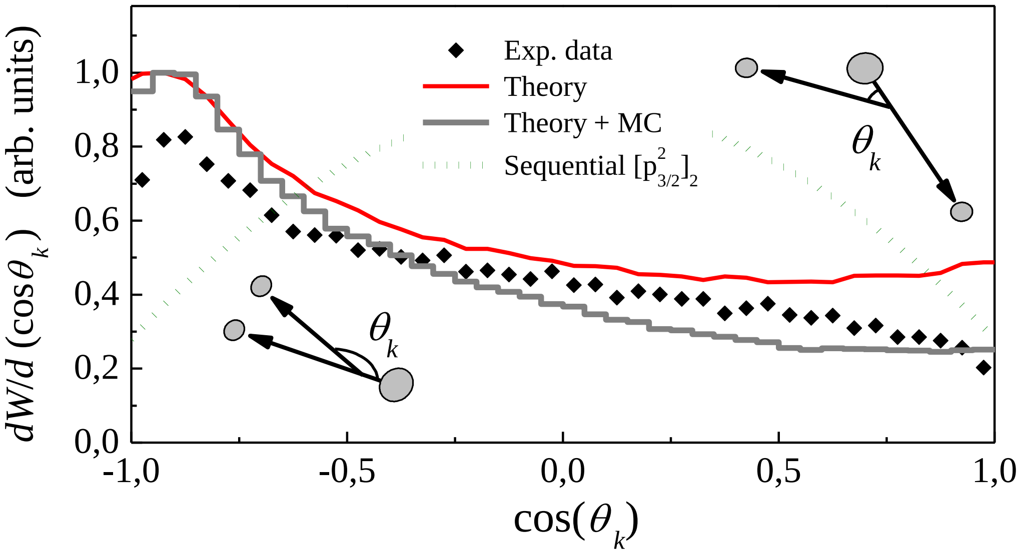


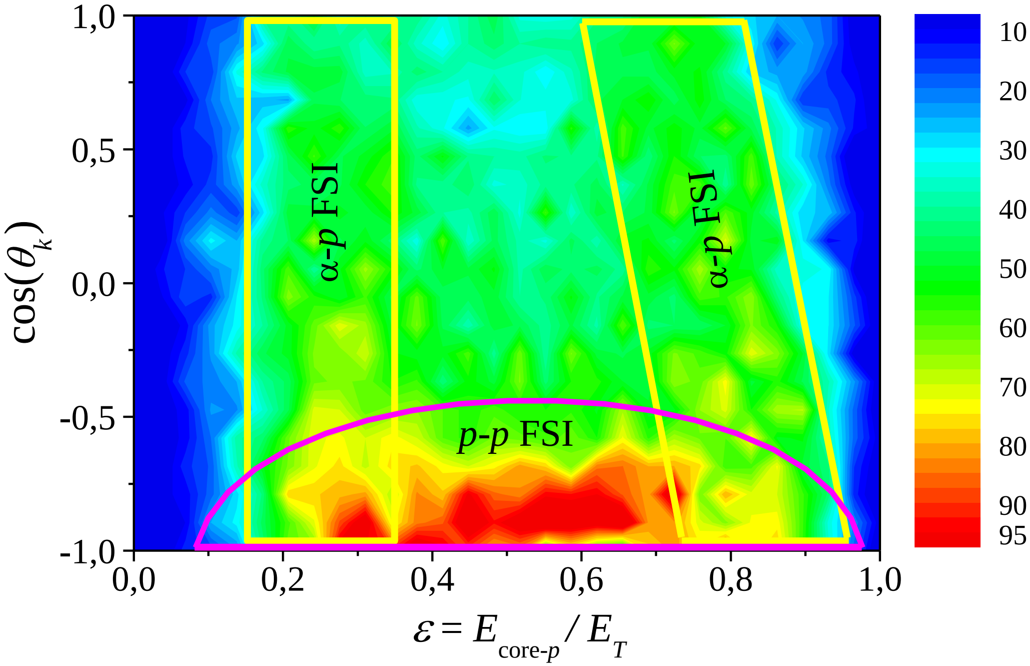
- Relative energy between two protons. Evolution of the distribution with ETotal.
- There are can be seen qualitative difference between the distributions for the 0^+ and 2^+ states.

Correlation studies in a broad energy range.

- Let us consider the energy correlation in the alpha-p channel, which should reflect the ^{5}Li ground-state resonance in the case of sequential decay.
- At low energy the shape of the distribution is relatively broad bell-like profile, typical for true 2p decay
- With increasing of energy E_{total} the profile becomes significantly narrower (c)
- ^{5}Li energy correlation is very well seen only at high energy E_{total} (f) –sequential decay?







- If the decay is really sequential we should have got symmetric shape
- Angular correlations: strong asymmetry of experimental data
- To understand that has happened we can study complete energy-angular distribution in this energy region.
- Complete distributions comprise the regions clearly identified with p-p, α-p FSIs, and broad transition regions
- Surprise! In reality up to high decay energy a complex dynamics is conserved and cannot be described as the sequential decay!

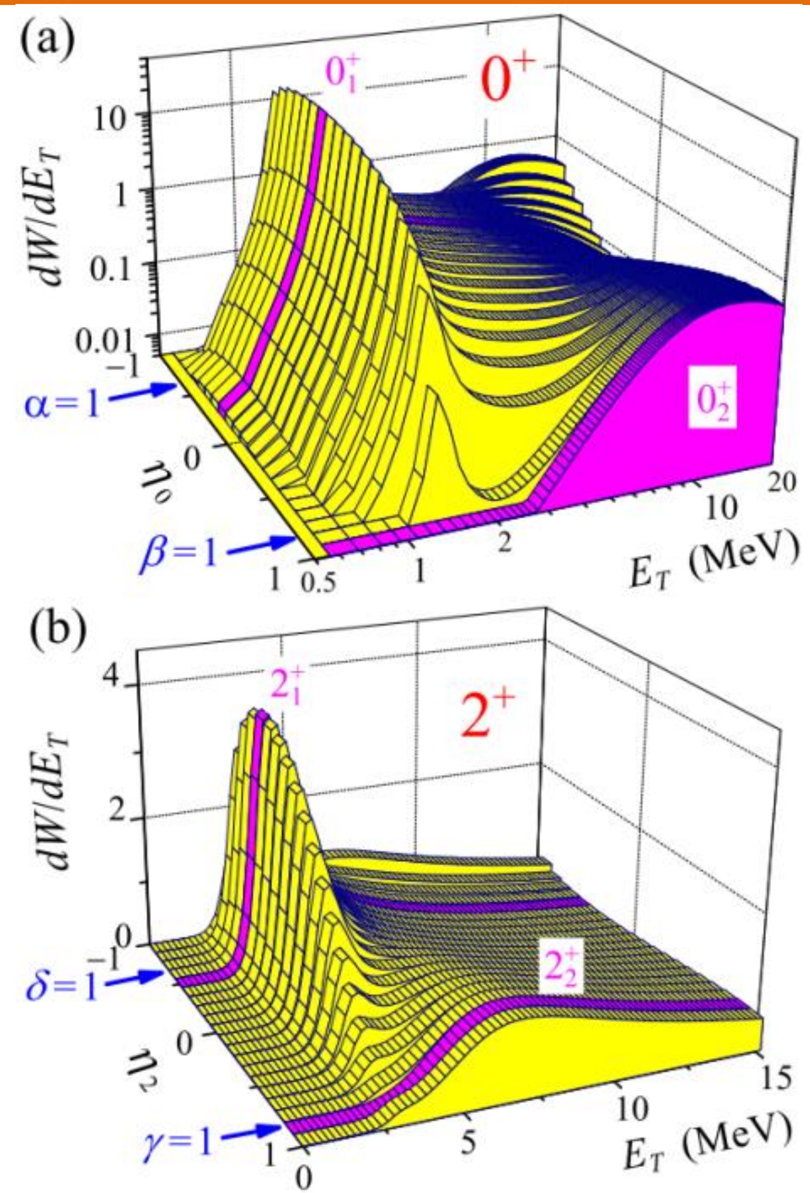
Sensitivity of ^{6}Be spectrum to $W_{S=0}/W_{S=1}$

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

- Dependence of excitation spectra of ^{6}Be from variation of coefficients η_J, controlling spin contents in source function, was studied.
- As result: the "normal" states of ^{6}Be "fade" and even completely disappear.
- New broad peaks arise for these two states at ~12 and ~7 MeV, respectively.
- Model is schematic but allows important qualitative insights:

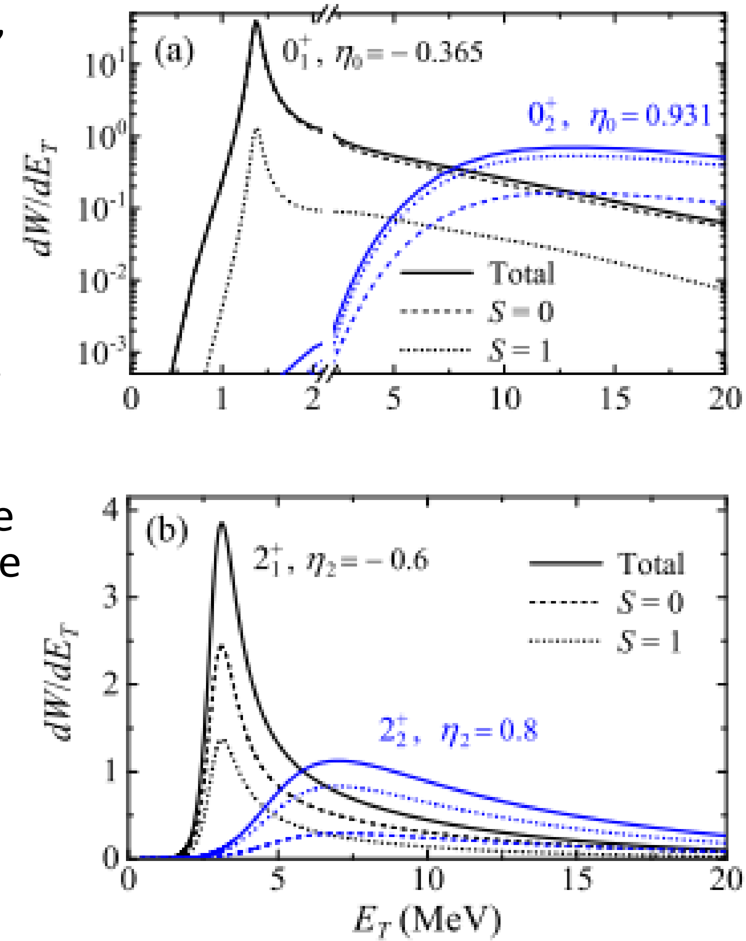
- High sensitivity of ^{6}Be spectrum to structure of ^{7}Be

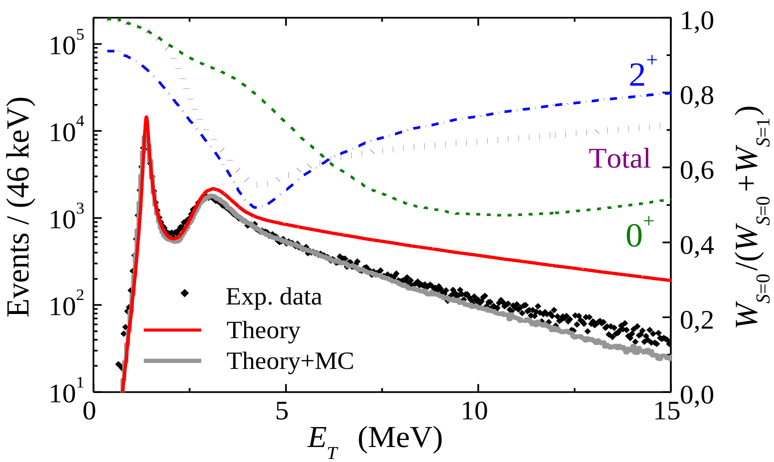
- Allows to infer positions of second 0^+ and 2^+ states



Second 0^+ and 2^+ states

- An important feature of "pure" first and second states, illustrated here: is that the spin composition depends weakly on energy.
- It allows us to interpret the first and second states as different states, although they can be represented by (relatively) broad overlapping structures.
- This property of "pure" states is in sharp contrast with the spin evolution for the "composite" situation in this picture.
- The spin-content ratios $0^+_1/0^+_2$ and $2^+_1/2^+_2$ provide a simple structural idea: These states are partners, in the sense that they are the orthogonal combinations of the S = 0 and S = 1 configurations.

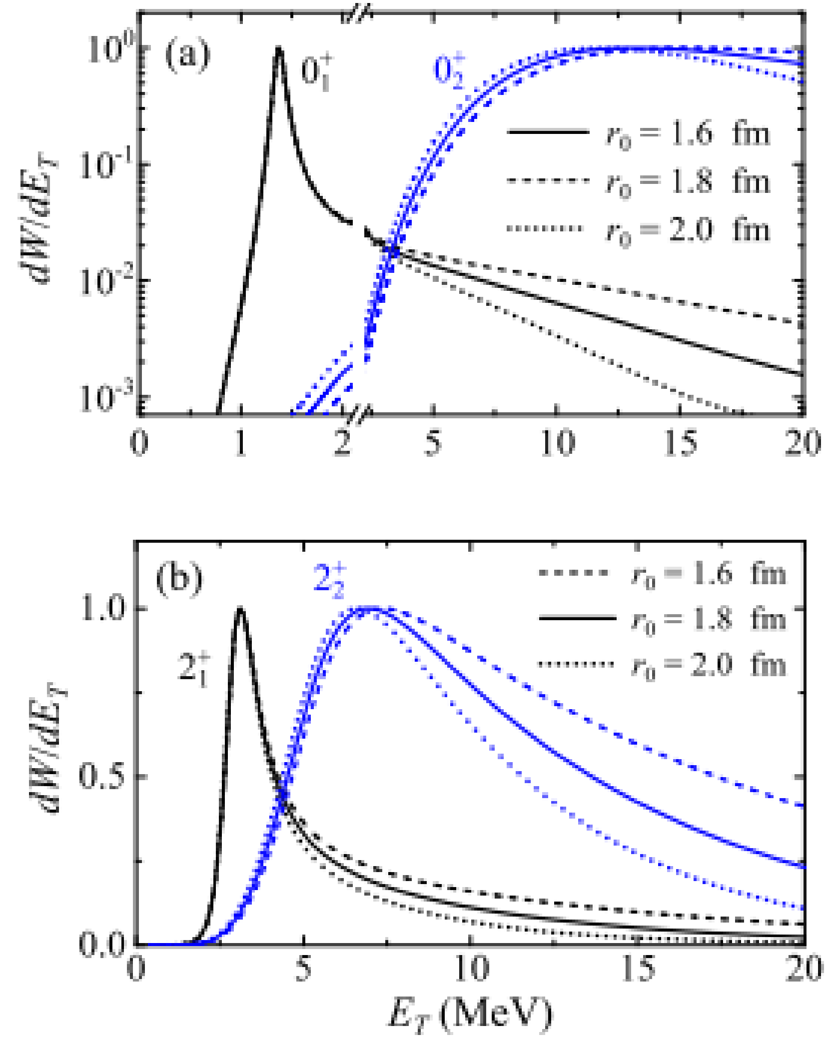




Guidelines for experimental searches: reaction mechanism should populates S=1 component in the final state.

Radial dependence

- The sensitivity to the radial characteristics of the source is presented here.
- It is practically nonexistent for first 0^+: Variations take place only in the “tail,” a few decay widths higher than the resonance position.
- The first 2^+ sensitivity is quite small: The resonance width is affected on the level of 15%.
- With increasing excitation energy of the states (and hence with increasing decay width) the effect grows.
- There is about 0.8-MeV uncertainty of the second 2^+ position connected with the radial extent of the source, and the profile of the cross section is strongly affected. Variation of second 0^+ properties is so large (few million electron volts in peak position) that the properties of such a state cannot be discussed without a detailed account of the reaction mechanism.



Alignmemt and interference effects demonstration

- Information about reaction mechanism is also concluded in density matrix in cross section.
- In the sudden-removal model : there is no alignment of the final state. However, it is clear that some alignment should be introduced by a realistic reaction mechanism.
- Two limiting forms of the density matrix are used, which correspond to the no alignment of the final state and the completely alignment case:

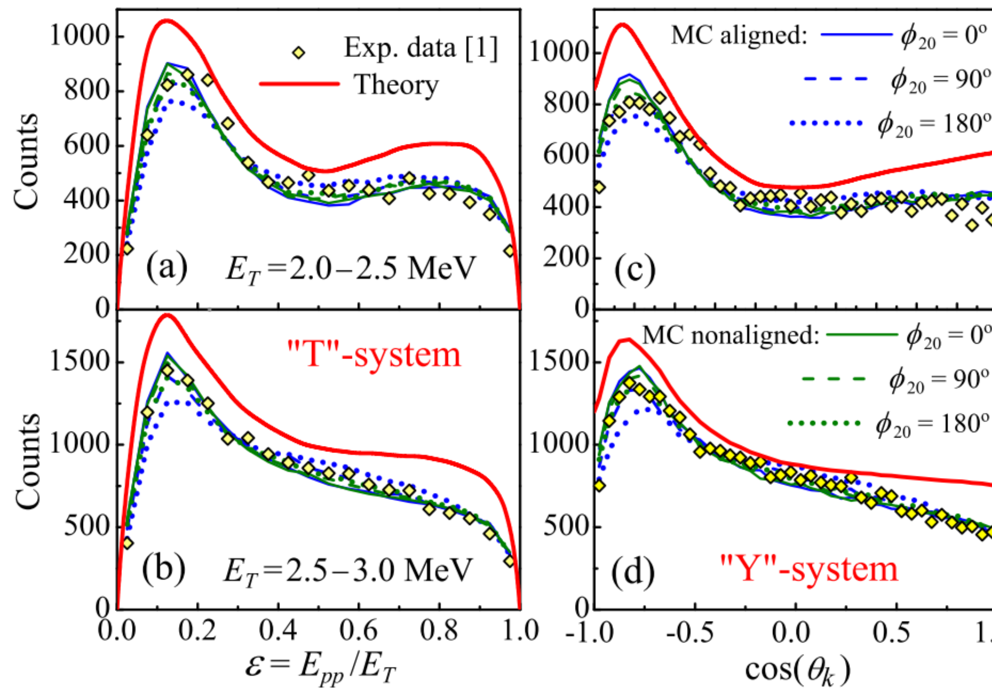
No alignment case

$$\rho_{00}^{00} = 1\,, \quad \rho_{2M}^{2M} = 1/5\,, \quad \rho_{20}^{00} = \rho_{00}^{20} = \cos(\phi_{20})/\sqrt{5},$$

Completely alignment case

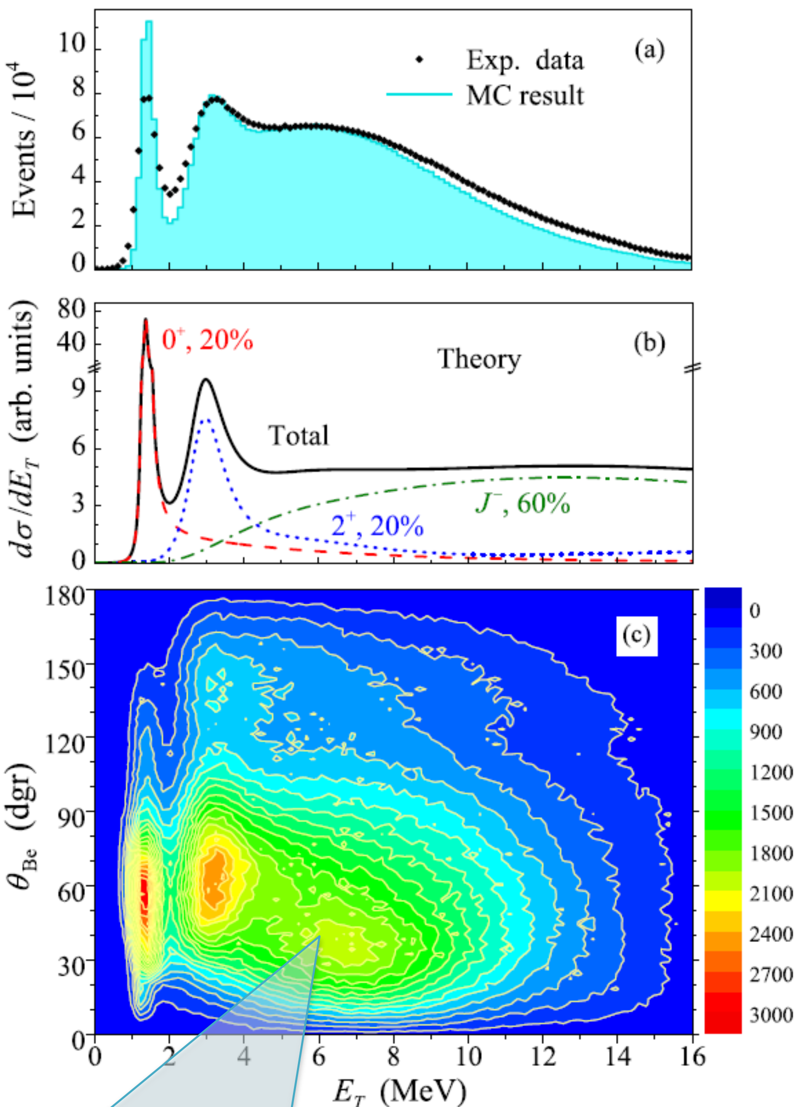
$$\rho_{00}^{00} = 1\,, \quad \rho_{20}^{20} = 1\,, \quad \rho_{20}^{00} = \rho_{00}^{20} = \cos(\phi_{20}).$$

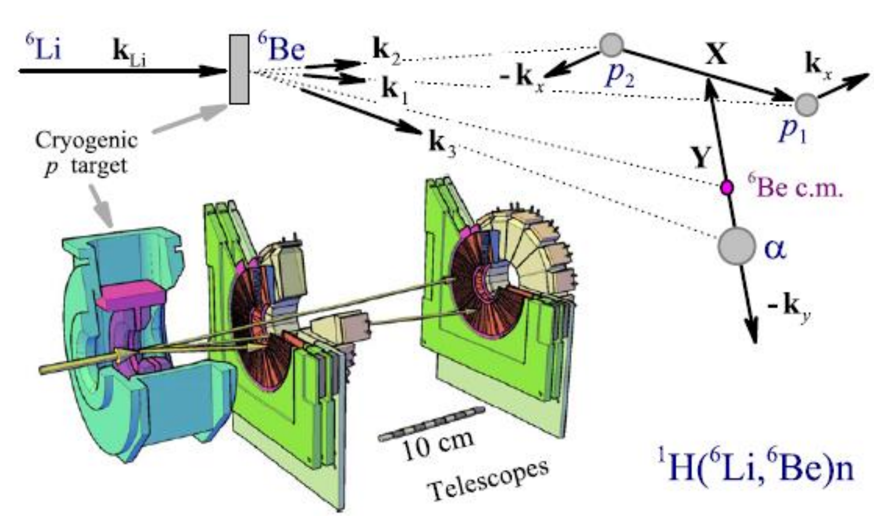
- We kept ϕ_{20} as a parameter in both cases.
- Alignment and interference effects are observable in experimental data due to the unavoidable experimental bias.
- They were found to have an important impact on the measured three-body correlations.
- The scale of local variations in the MC distributions is about 20%.



IsoVector Soft Dipole Mode in ^{6}Be

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





IVSDM as a specific form of SDM

- Studies of ^{6}Be spectra excitation in charge-exchange reaction at FLNR, JINR (Dubna)
- Excellent agreement with the previous data for the resonant 0^+ and 2^+ states.
- Broad structure above 2^+ state is identified as combination of dipole $\{0^-,1^-,2^-\}$ excitations.
- Surprise! Nonresonant dipole continuum has much higher integral cross section than the expectedly dominant resonant 0^+ and 2^+ contributions.

Formalism for change-exchange reaction

- Three-body dynamics from

$$(\hat{H}_3 - E_T)\Psi_3^{JM(+)} = \hat{O}\Psi_{\rm gs}^{J'M'}.$$

The "source function" $\hat{O}\Psi_{\rm gs}^{J'M'}$ can be constructed in a PWIA approximation :

- For dipole excitations: $\Psi_{\rm gs} \to \Psi_{^6{\rm He}}, \qquad \hat{O} \sim \sum_i Z_i r_i Y_{1m}(\hat{\mathbf{r}}_i),$
- For change-exchange reactions :

$$\Psi_{\rm gs} \to \Psi_{^6{\rm Li}}, \qquad \hat{O} \sim \sum_i f_l(q, r_i)\left[\alpha + \beta\sigma_\mu^{(i)}\right]\tau_\pm^{(i)} Y_{lm}(\hat{\mathbf{r}}_i),$$

- Resonance part: HH method with consistent three-body Hamiltonian
- Soft contribution: simplified Hamiltonian, providing analytical GF

$$\hat{G}_{3E}^{(+)}(\mathbf{XY}, \mathbf{X}'\mathbf{Y}') = \frac{E}{2\pi i}\int_0^1 d\varepsilon\, \hat{G}_{\varepsilon E}^{(+)}(\mathbf{X}, \mathbf{X}')\hat{G}_{(1-\varepsilon)E}^{(+)}(\mathbf{Y}, \mathbf{Y}'). \qquad \Psi_3^{JM(+)} = \hat{G}_{3E_T}^{(+)}\hat{O}\Psi_{\rm gs}^{J'M'},$$

IVSDM vs. SDM

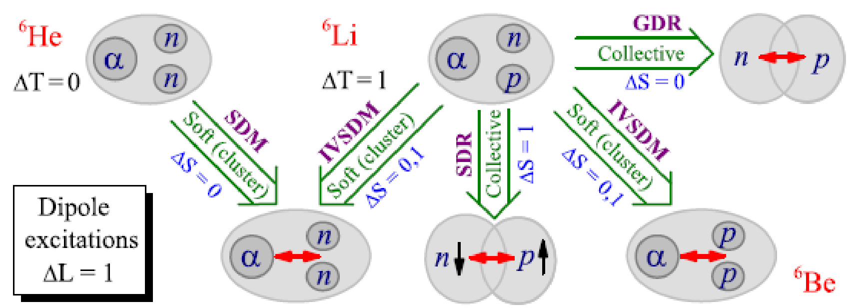
Mode vs. resonances: Large cross section above 2^+ but no resonance

SDM vs. IVSDM:

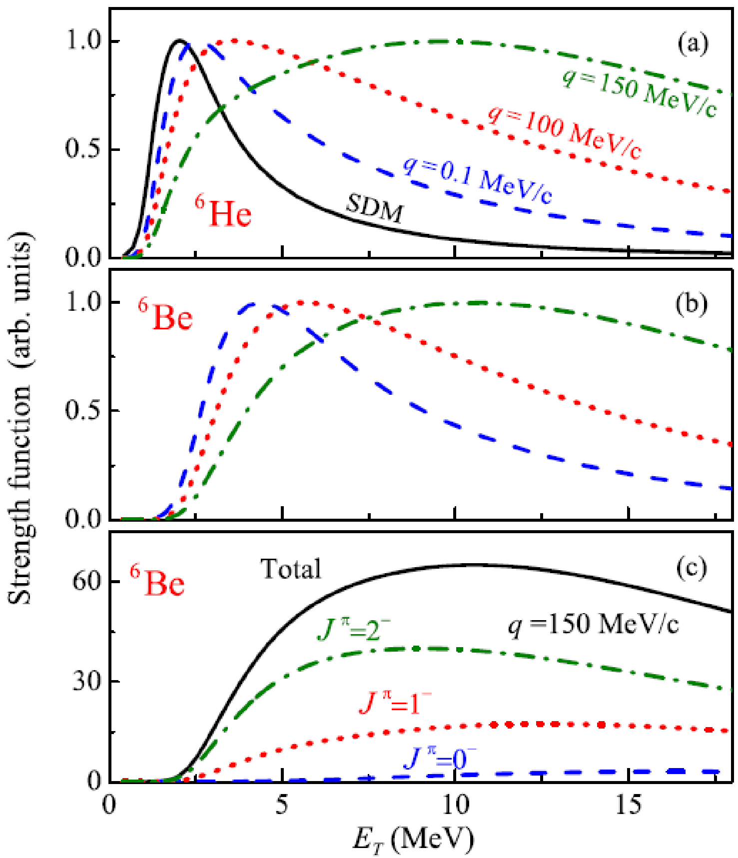
- SDM: based on spatially extended g.s. WF.
- IVSDM: No particle stable g.s. – cannot be built on spatially extended g.s. Built on the spatially extended ^{6}Li g.s by isovector dipole operator.
- SDM in ^{6}He: only 1^- state
- IVSDM in ^{6}Be: 0^-, 1^-, 2^- states
- IVSDM: dependence on ***q***

Isobaric symmetry aspect:

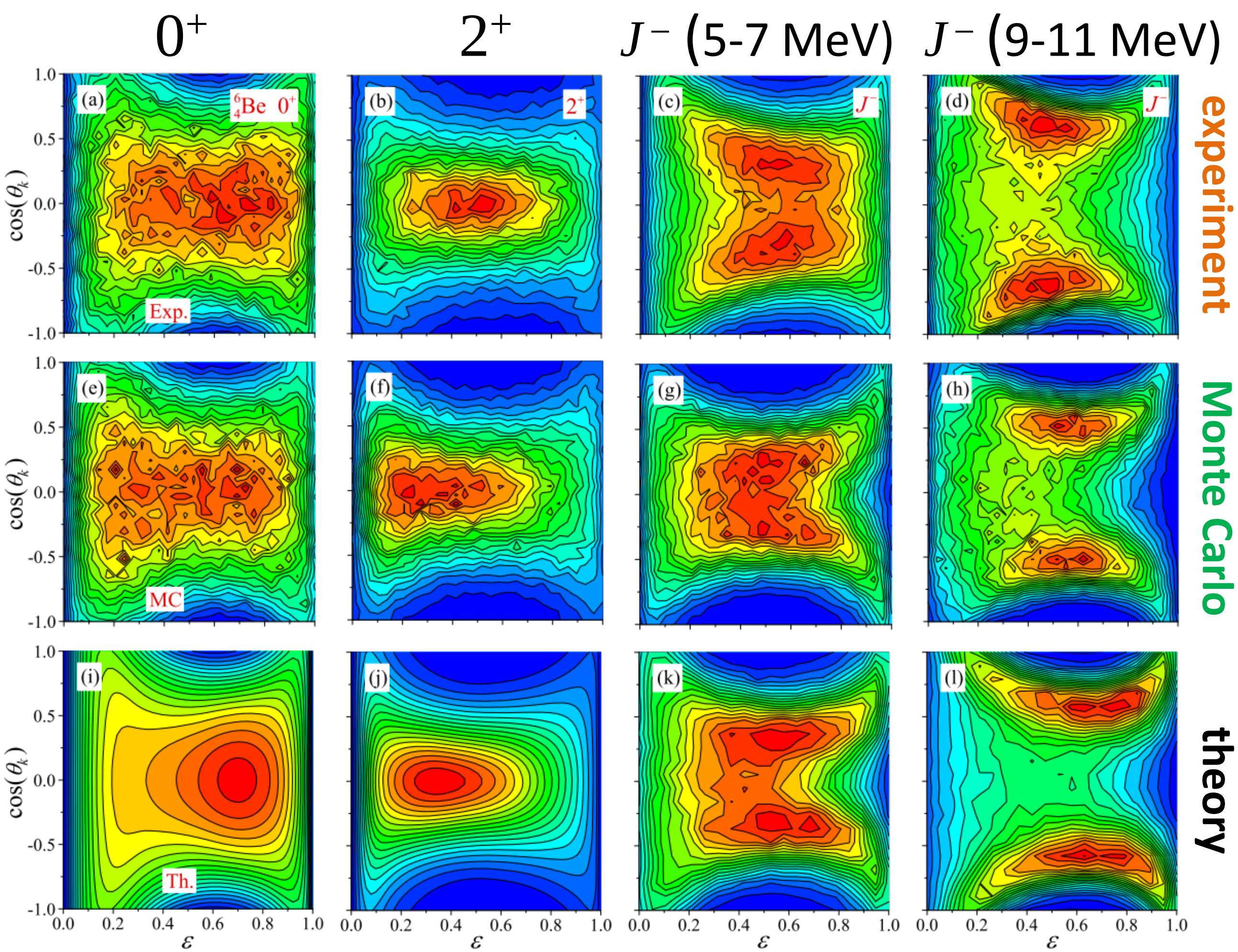
- Differences between SDM in ^{6}He and IVSDM in ^{6}He
- Differences between IVSDM in ^{6}He and IVSDM in ^{6}Be



Important dipole excitation modes in A=6 isobar



Internal energy-angular correlations in ^{6}Be



- Very good agreement with previous experimental data on 0^+ and 2^+ resonant states. Nice agreement between theory and experiment.
- Major features of the J^- excitations are reproduced.

Conclusions

- Theoretical methods for studies of the Coulomb three-body continuum populated in direct reactions was developed for the first time. This allows to study the excitation spectra of exotic systems near dripline in a broad energy range.

- The fully quantum-mechanical MC generator was developed for comparison between theory and experiment for complicated correlation data. So far this development is unique in the world. We collaborate with several groups from world- leading scientific centers helping to analyze and interpret data.

Main result obtained in the MSU experiment:

- Up to high energy excitation decay of ^{6}Be has a complex dynamics.
- The population of the 6 Be 0^{+}_{1} ground state is very stable to variations of the initial-state structure and the reaction mechanism. However, the latter effects become increasingly important with increasing excitation.
- The excitation spectrum of the three-body continuum of 6 Be up to 15–20 MeV is found to be very sensitive to the spin composition of the source function.
- A procedure to identify the second 0^{+}_{1} and 2^{+}_{1} states of ^{6}Be is proposed , providing a guideline for their experimental observation.

Main result obtained in the experiment @FLNR: the spectrum above 2^{+} state of ^{6}Be was interpreted as providing evidence for novel phenomenon – **I**so**V**ector **S**oft **D**ipole **M**ode build on the ^{6}Li g. s.

THANK YOU FOR ATTENTION!