Research of light neutron-rich nuclei in FLNR

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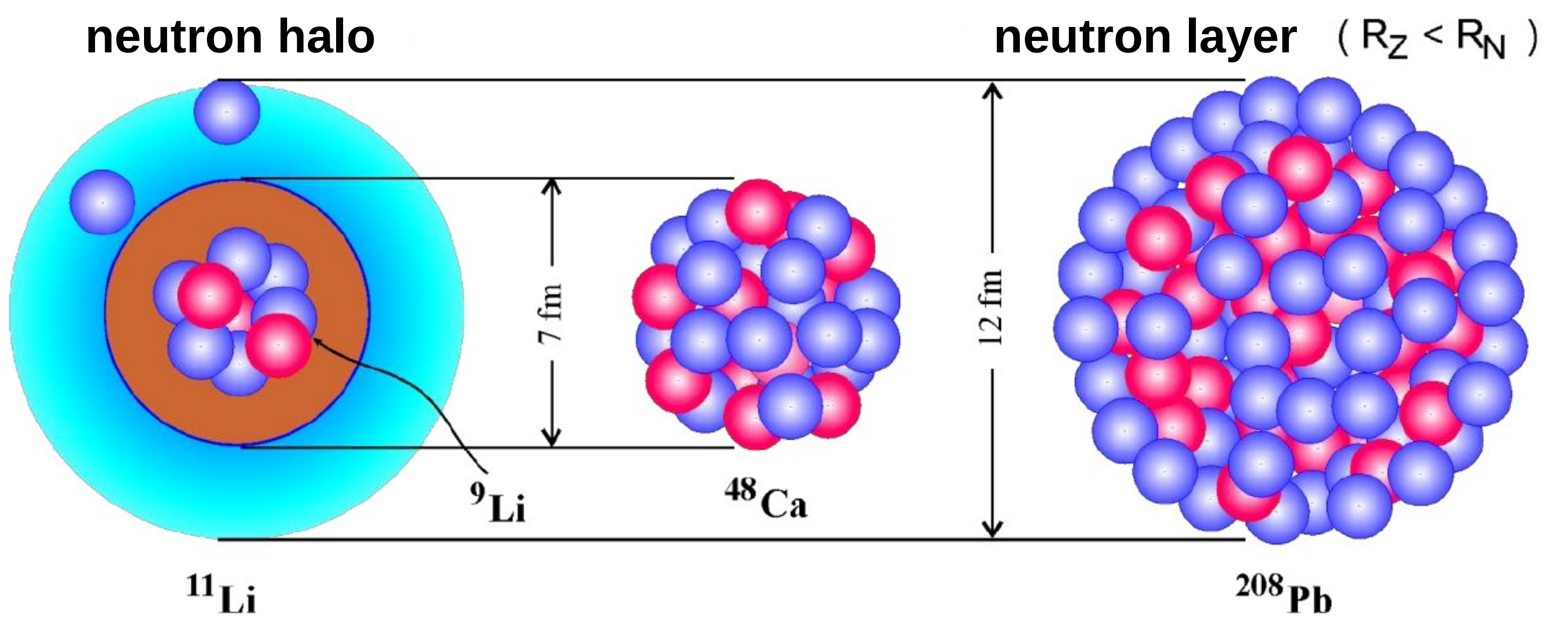
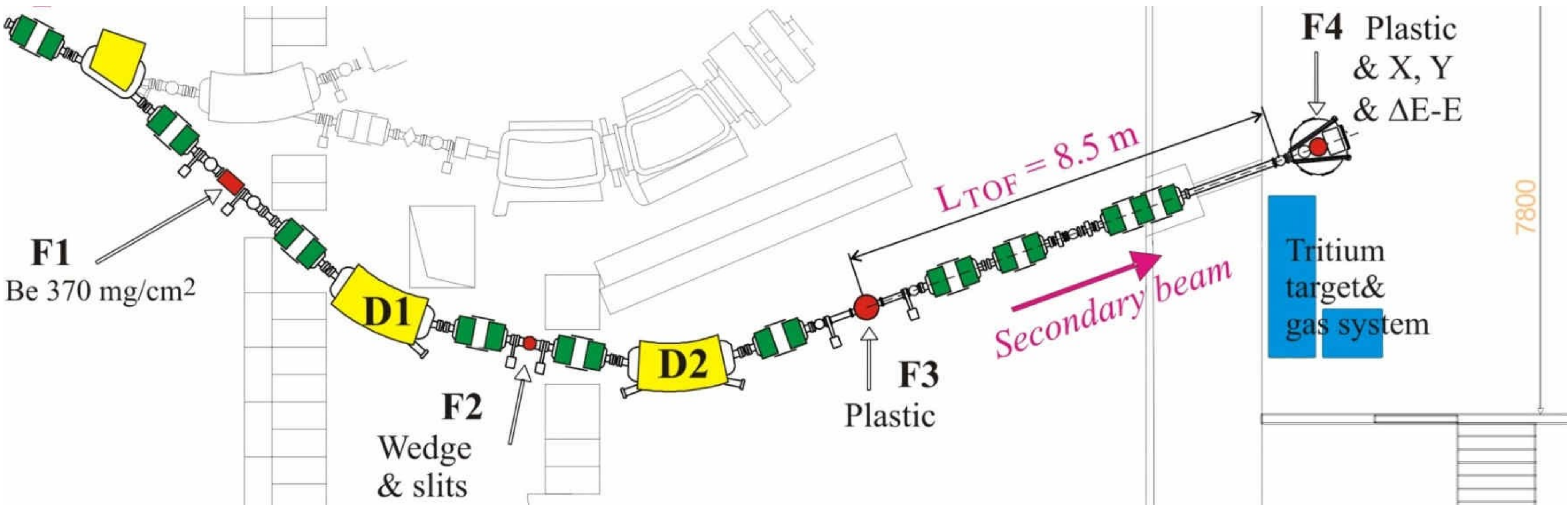
Light exotic nuclei



- *Z* = 1 – 16
- large excess of neutrons or protons
- limits of nuclear stability
- new types of radioactivity
- fundamental information about nuclear matter

Fragment separator ACCULINNA



^{8}He

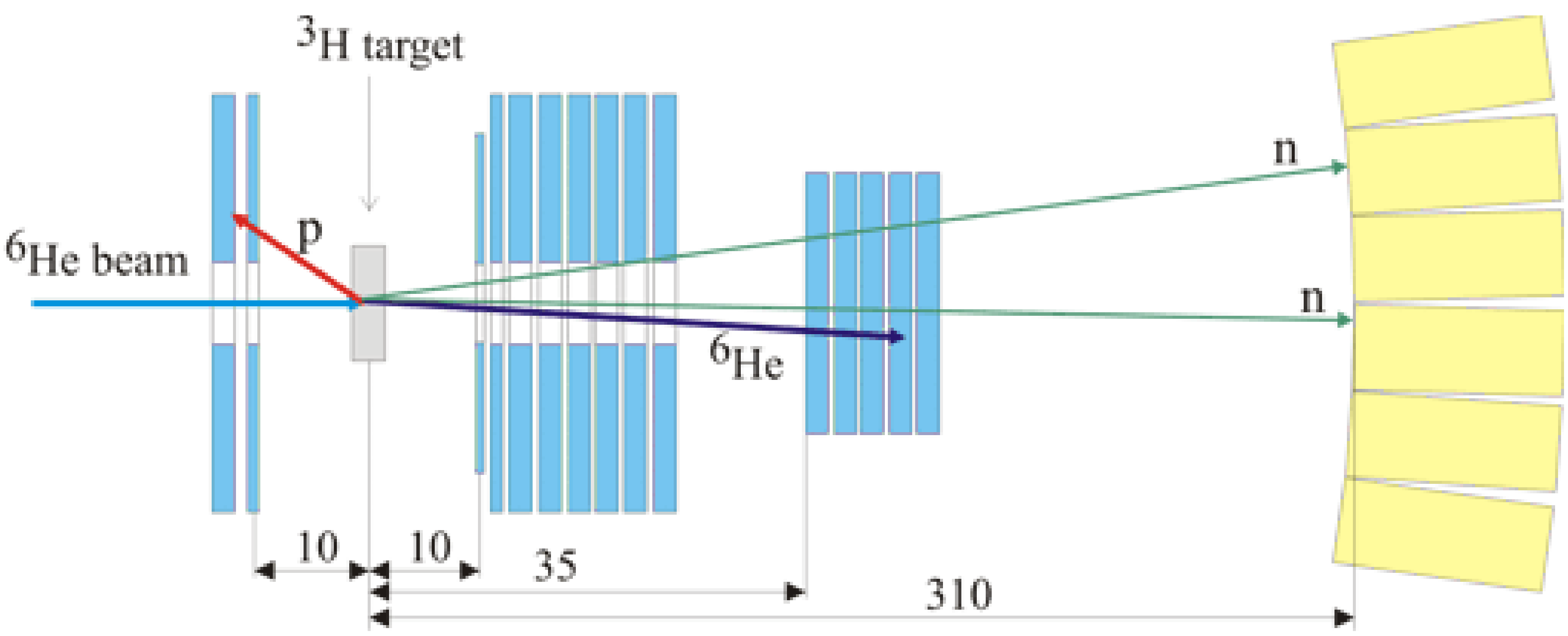
^{8}He: Introduction

- simplicity of the transfer reaction mechanism
- uncertainty of the first excited state energy
- basis for the next, ^{10}He investigation

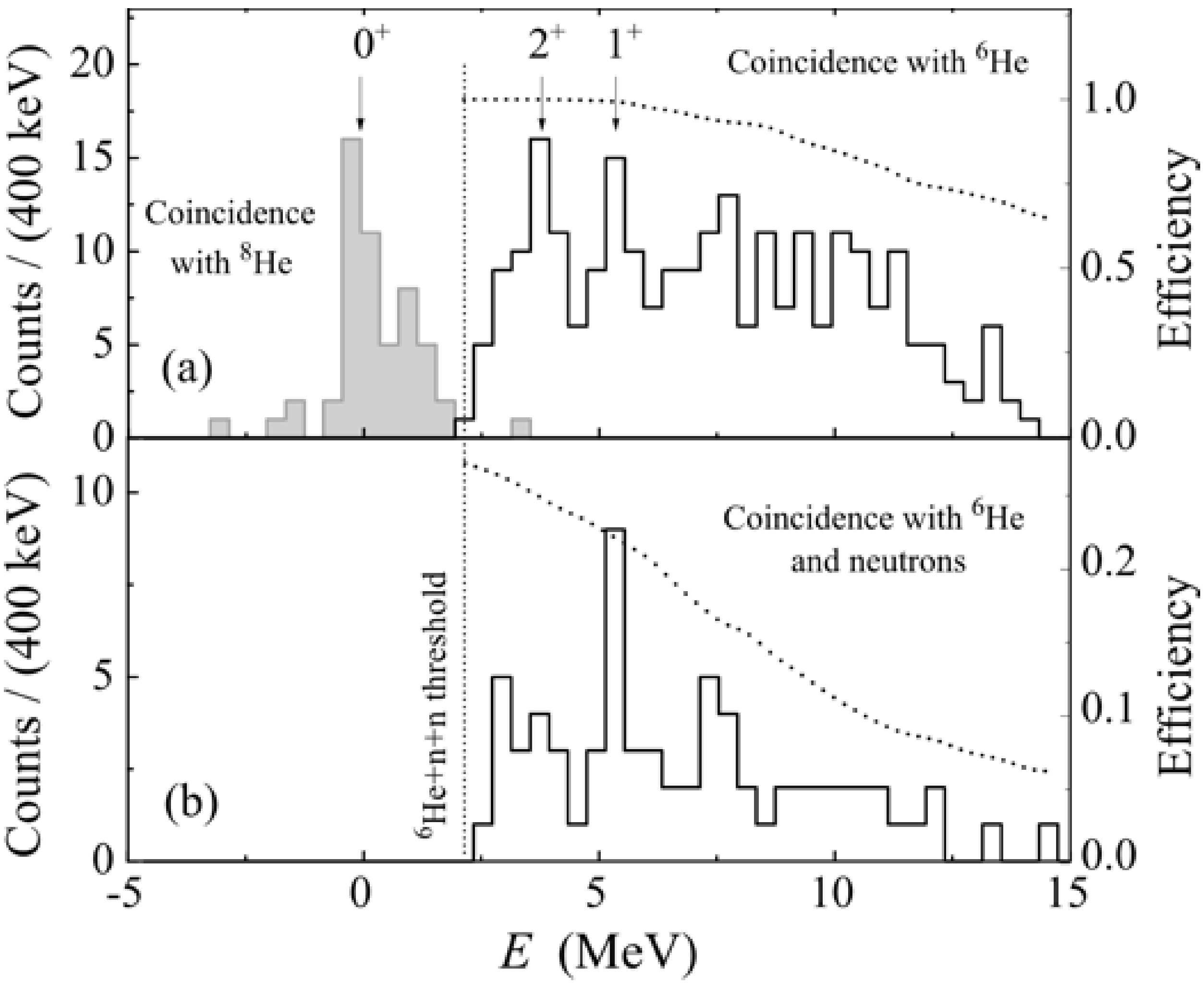
$$^{3}\mathrm{H} + ^{6}\mathrm{He} \rightarrow ^{8}\mathrm{He} + \mathrm{p}$$
$$^{8}\mathrm{He} \rightarrow ^{6}\mathrm{He} + \mathrm{n} + \mathrm{n}$$

beam energy: 25 MeV/A

gaseous target 4 mm, 21K



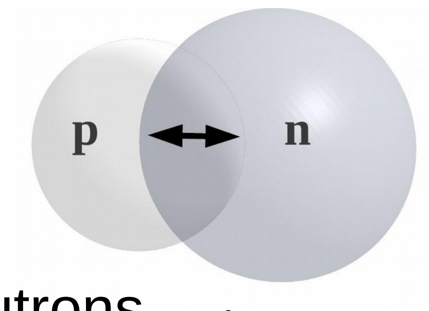
^{8}He: Obtained spectrum



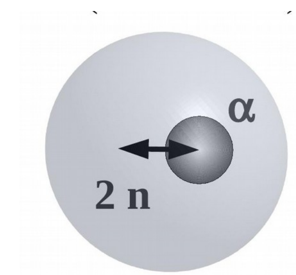
- **ground state**
- **2^{+} state:** 3.6 – 3.9 MeV
- **1^{+} state:** 5.4 MeV
- evidence for state at ~7.5 MeV

- overall agreement with previous experimental data
- peculiar form of the first excited state (2^{+})

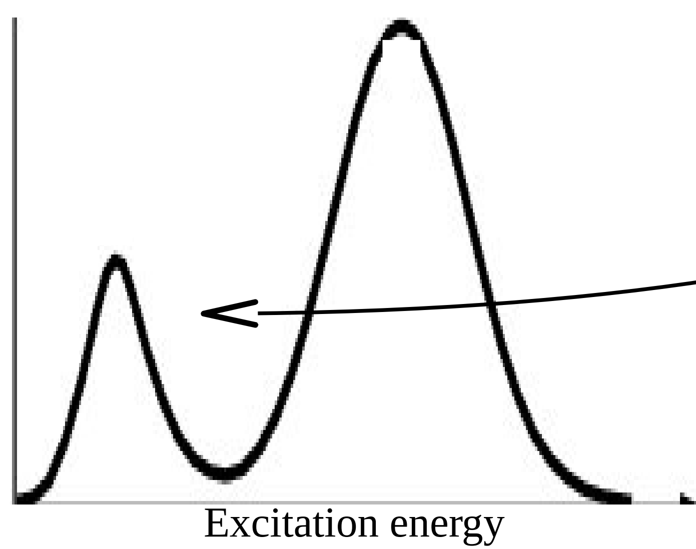
^{8}He: Soft dipole mode (SDM) of giant dipole resonance (GDR)



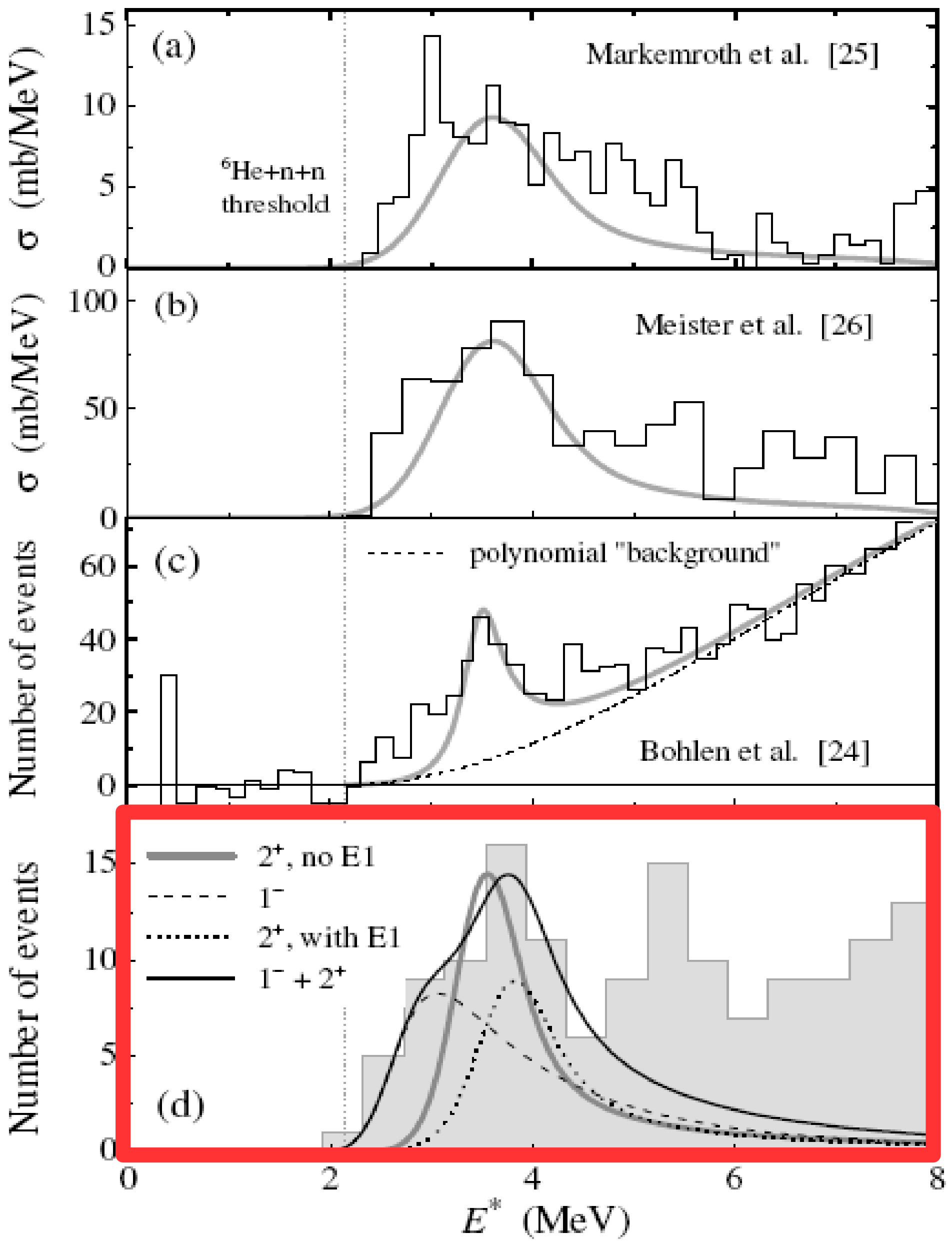
- GDR
  - protons vs. neutrons
  - E_{GDR} ~ 14 – 24 MeV
  - induced by EM excitation



- SDM
  - halo vs. core
  - E_{SDM} lower than E_{GDR}
  - induced by EM excitation and charge-exchange reaction



^{8}He: Form of the first peak



energy of the first excited state (2^+) determined with a large uncertainty: 2.7 — 3.6 MeV

steep rise straight from the three-body threshold

low-energy tail of the 2^+ cannot be responsible for the near threshold events

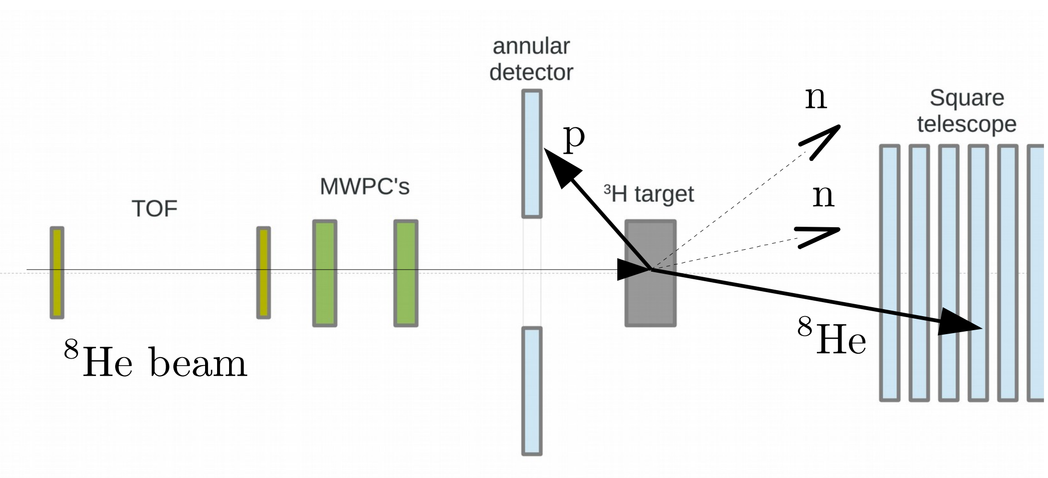
only plausible source of the low-energy events is the population of E1 (1^-) continuum

^{10}He

^{10}He: Introduction

- extremely high excess of neutrons
- the lightest double magic isotope after alpha particle
- inconsistent data on 0^+ ground state energy
- no correlation data

$$^{3}\mathrm{H} + ^{8}\mathrm{He} \rightarrow ^{10}\mathrm{He} + \mathrm{p}$$
$$^{10}\mathrm{He} \rightarrow ^{8}\mathrm{He} + \mathrm{n} + \mathrm{n}$$



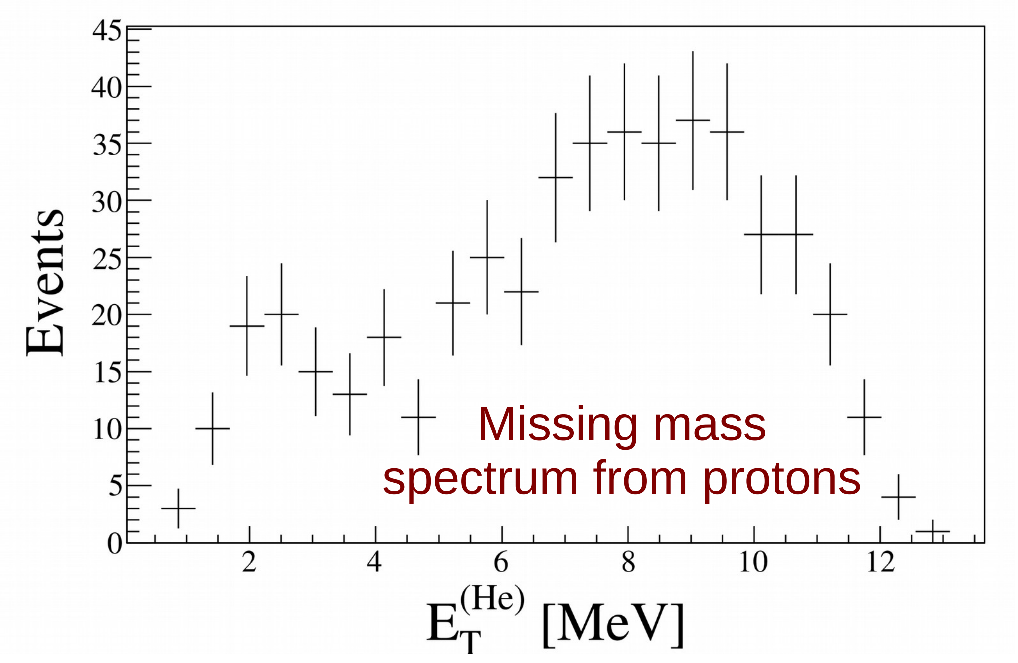
Ground state energy
(above the ^{8}He+n+n threshold)

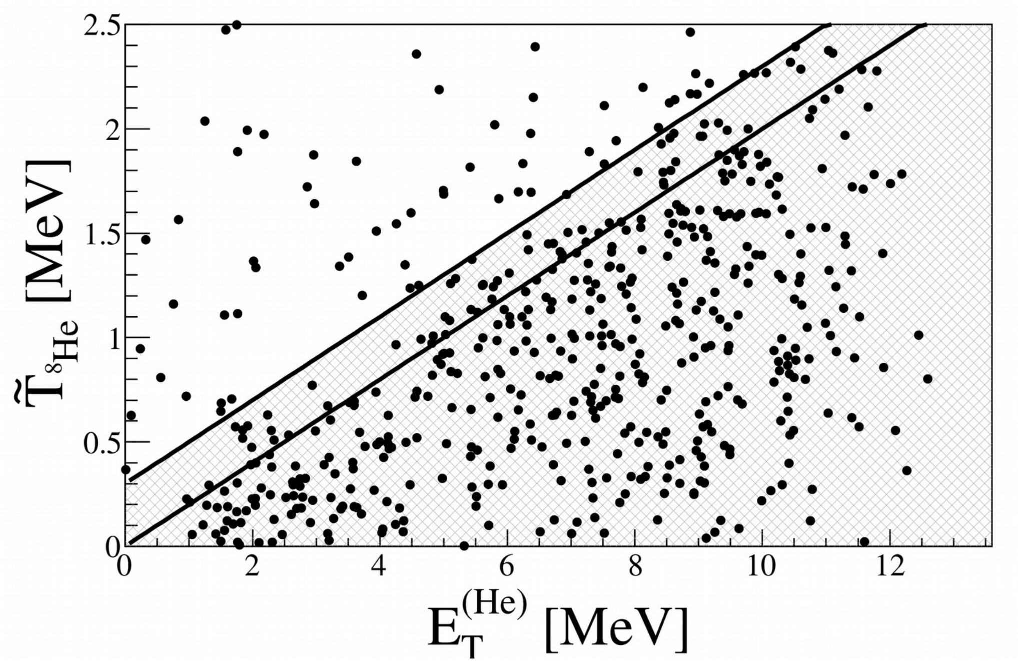
Reference	$E_T^{(He)}$ [MeV]	Γ [MeV]
Korsheninnikov *et al.*	1.2	1.2
Ostrowski *et al.*	1.07	0.3
Chudoba *et al.*, Golovkov *et al.*	~3	N/A
Johansson *et al.* A	1.42	1.11
Johansson *et al.* B	1.54	1.91
Kohley *et al.*	1.60	1.08

- ^{8}He beam: 21.5 MeV/A; 10^5 pps
- ^{3}H target: d ~ 6 mm; p ~ 0.9 bar; T ~ 26 K

^{10}He: Missing mass spectrum

- missing mass spectrum from protons measured in coincidence with ^{8}He
- 479 events found
- population of 0+ ground state with maximum at E_T~2.1 MeV
- structureless spectrum for E_T>4 MeV
- low background from competing processes

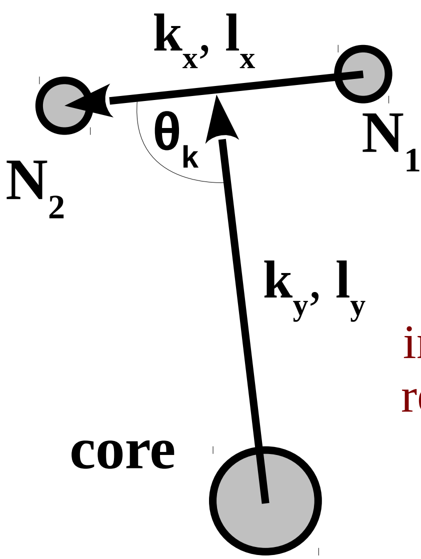




^{10}He: Correlations

2-body vs. 3-body decay

- 2 parameters for 2-body decay (E,Γ)
- 5 additional parameters at given energy for 3-body decay



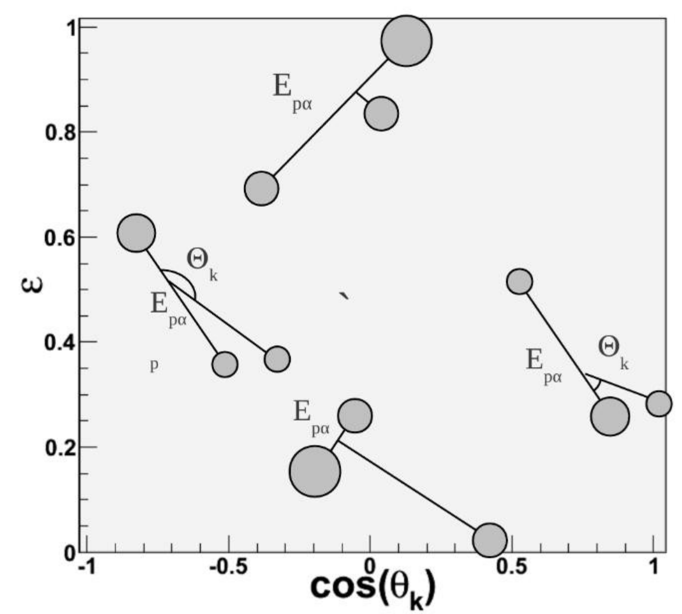
Jacobi coordinates in momentum representation

T-system

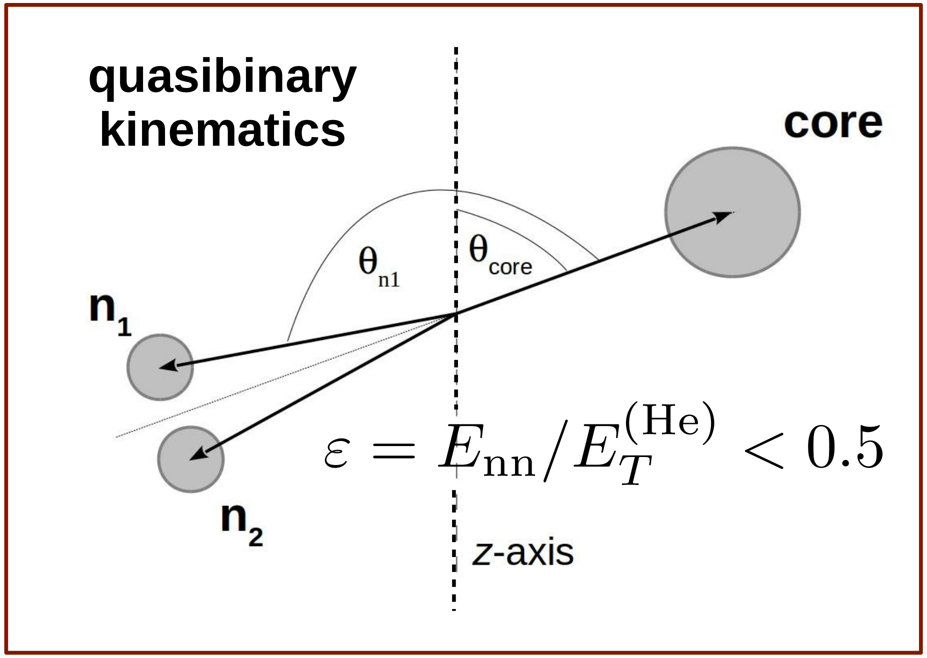
- full description of the internal correlations by parameters ε and θ_k

$$\varepsilon = \frac{E_x}{E_x + E_y} \qquad \cos\theta_k = \frac{\mathbf{k}_x \cdot \mathbf{k}_y}{k_x k_y}$$

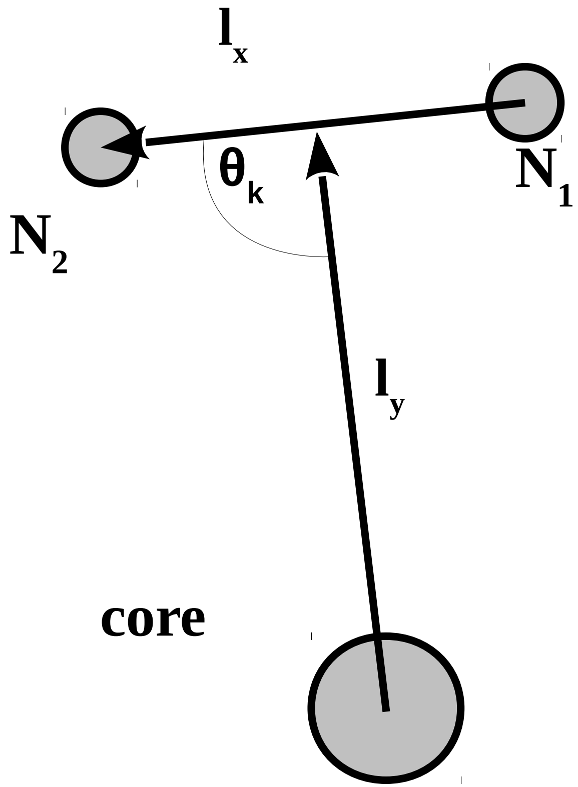
- external correlations: 3-body system orientation



^{10}He: Quasibinary kinematics



$$\varepsilon = E_{\rm nn}/E_T^{\rm (He)} < 0.5$$

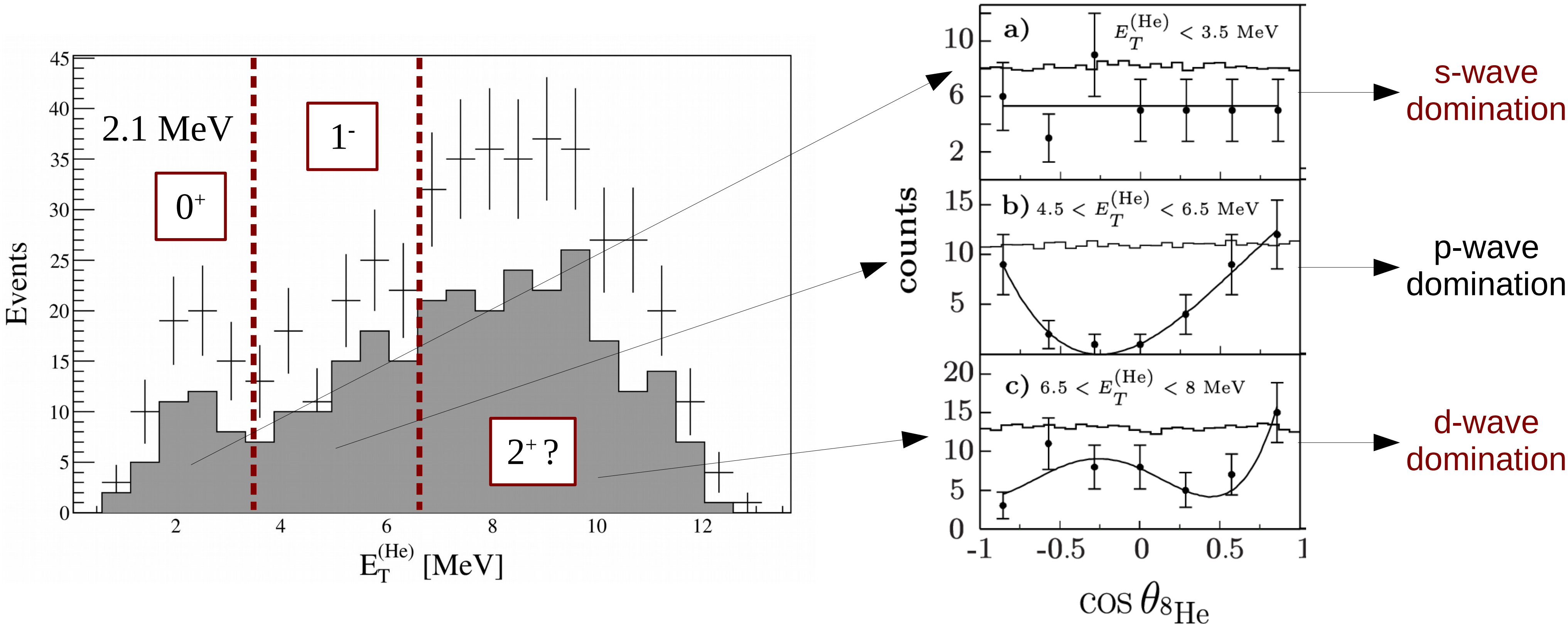


- very useful when a few states present
- ^{10}He total angular momentum is fully determined by angular momentum of ^{8}He

$$[[l_x \otimes l_y]_L \otimes S]_J \to [[0 \otimes l_y]_L \otimes 0]_J \Rightarrow \mathbf{J} = \mathbf{l}_y$$

Legendre polynomials can be visible

^{10}He: Correlation and spectrum decomposition



$$\frac{d\sigma}{d\Omega} = \left[AP_0(x) + B\sqrt{3}P_1(x) + C\sqrt{5}P_2(x)\right]^2 + D^2$$

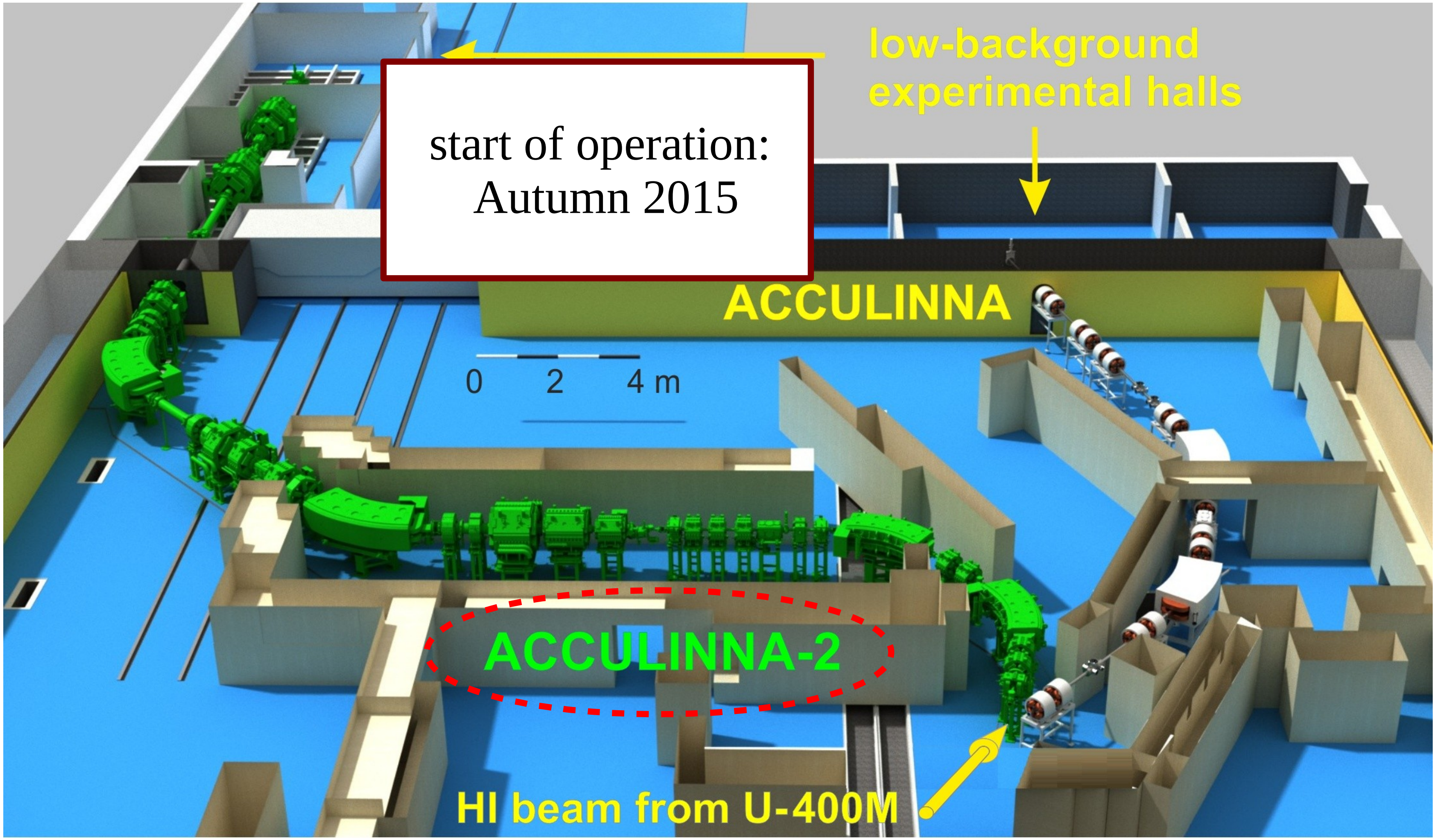
- J^π of the ground state confirmed by the experimental data analysis
- J^π of the ***1***$^-$ states determined from experimental data for the first time
- the spin-parity assignment made for ^{10}He for the first time

First conclusion

- ^{8}He
  - the ground, 2^{+} (3.6 – 3.9 MeV) and 1^{+} (5.4 MeV) states populated
  - some evidence for a state at energy 7.5 MeV
  - evidence for the manifestation of the SDM with low energy ~3.0 MeV
- ^{10}He
  - new energy of ground state at 2.1 MeV established
  - J^{π} of the 1^{-} states determined from experimental data for the first time
  - evidence for 2^{+} state observed

New perspectives

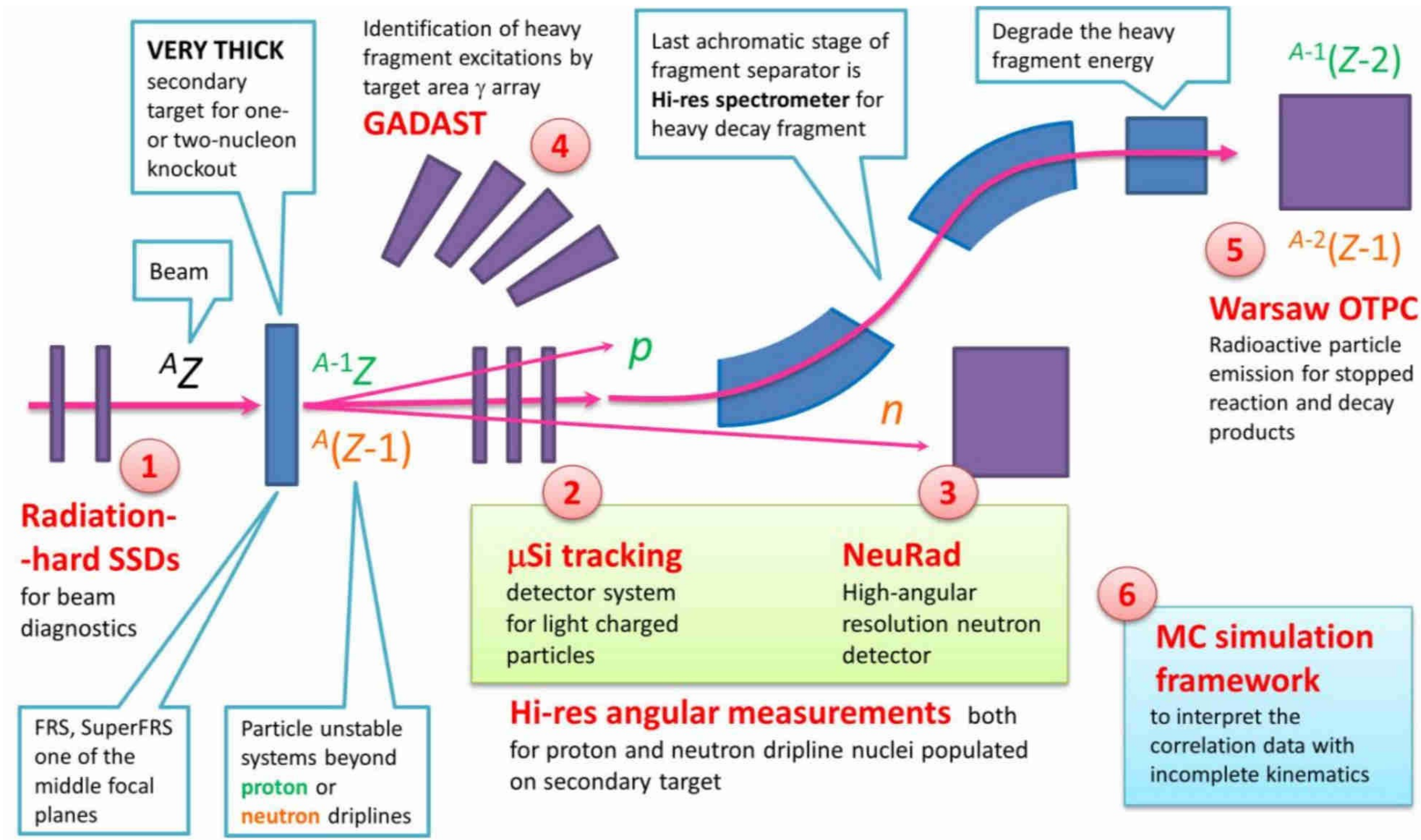
ACCULINNA-2



- energy range 6 – 60 MeV/A
- beam intensities higher in 2 orders
- Z_{RIB} ~ 1 – 36

$$^{4}\mathrm{He}(^{9}\mathrm{Li}, 2\alpha)^{5}\mathrm{H}$$
$$^{4}\mathrm{He}(^{11}\mathrm{Li}, 2\alpha)^{7}\mathrm{H}$$

EXPERT@Super-FRS



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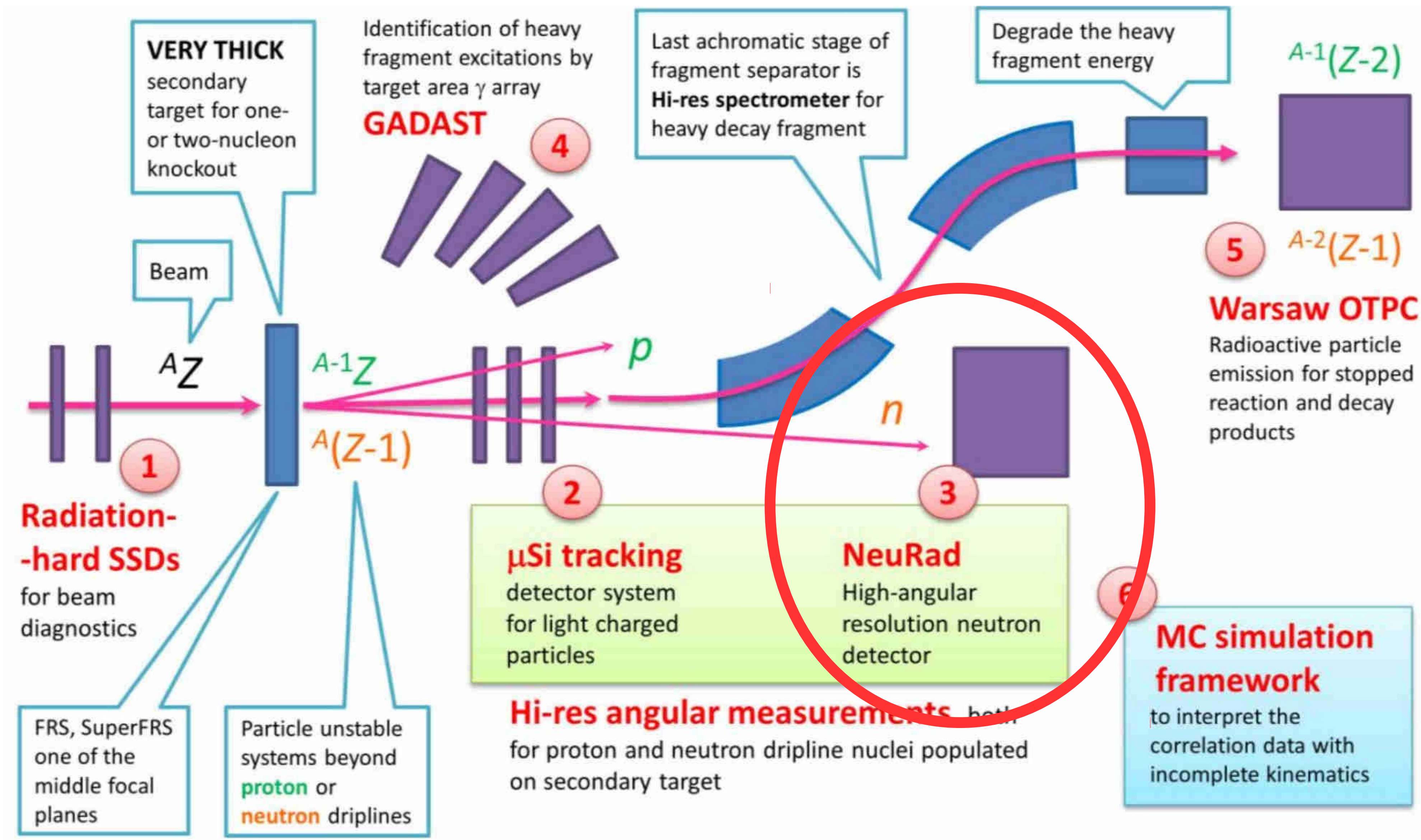

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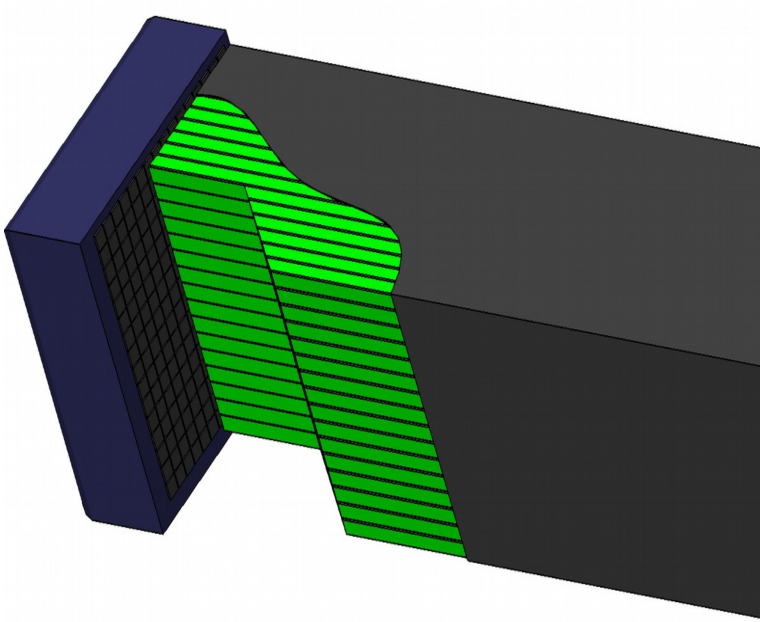
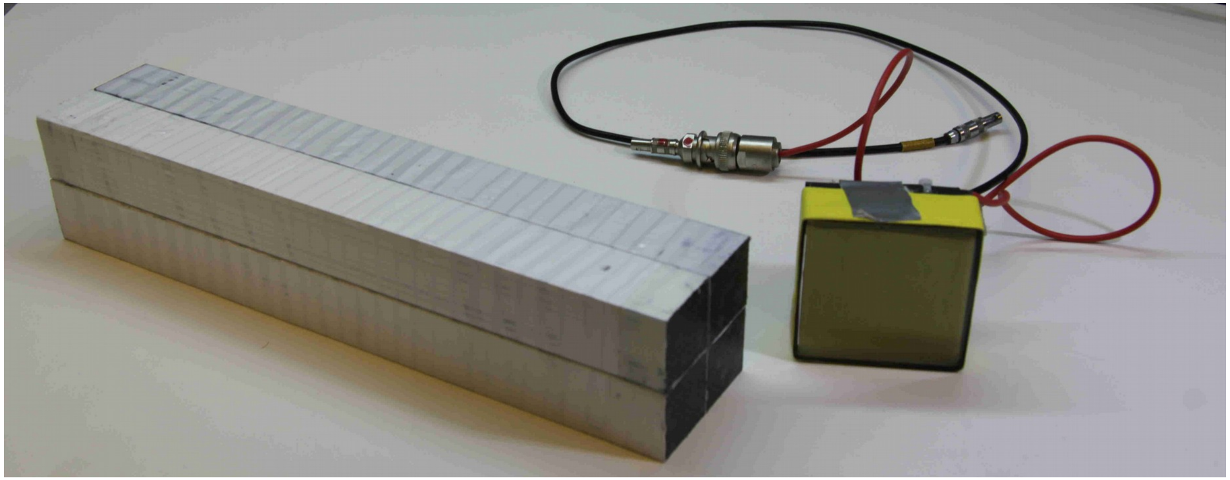
NeuRad

- neutron radioactivity studies:
  search of n, 2n, 4n, (6n?) radioactivity
- E_n ~ 200 – 800 MeV in LAB
- low transverse momentum
  0.1 – 100 keV
- precise information on angular correlations of decay neutrons with a charged fragment



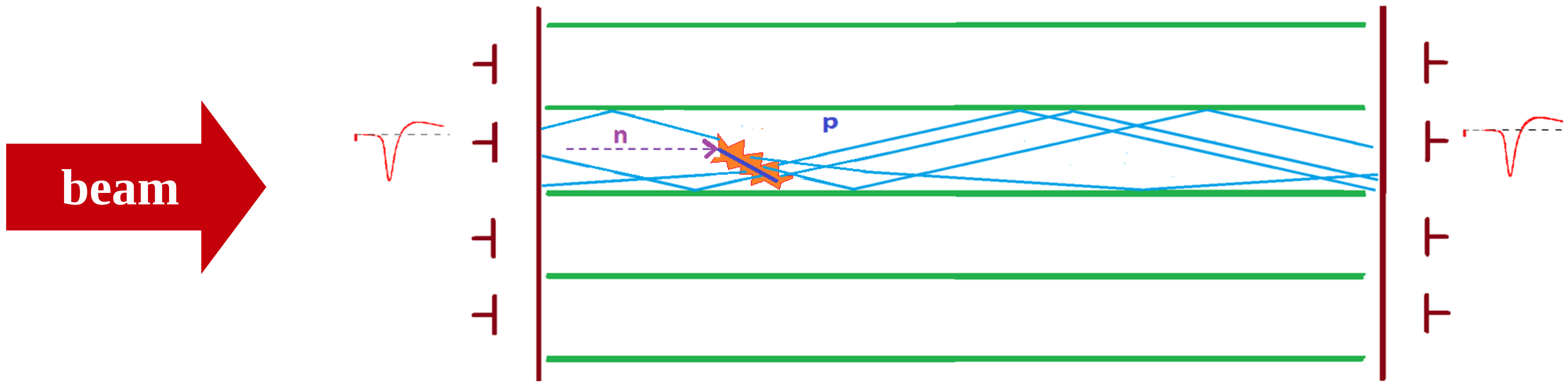


28 m from the target in FMF2

at least 64 modules
40 x 40 x 100 cm^3

NeuRad: principle of work

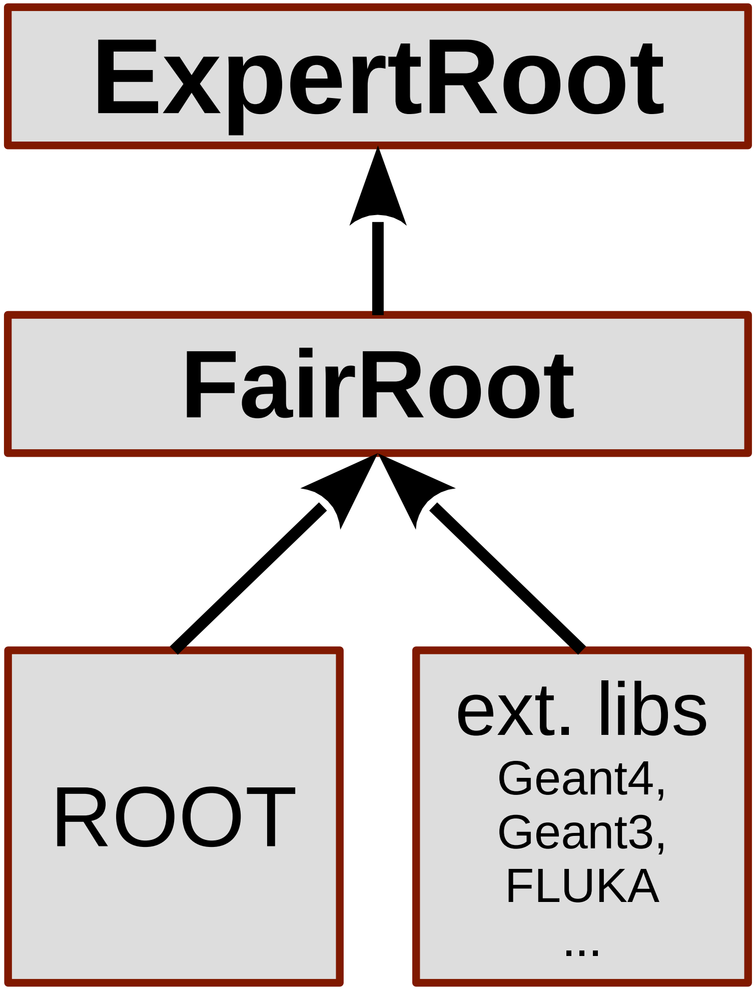
- bundles
  - 3 x 3 mm scintillation fibers BCF12 (Saint-Gobain)
  - 48 x 48 x 1000 mm
  - 2 MAPMT from each side



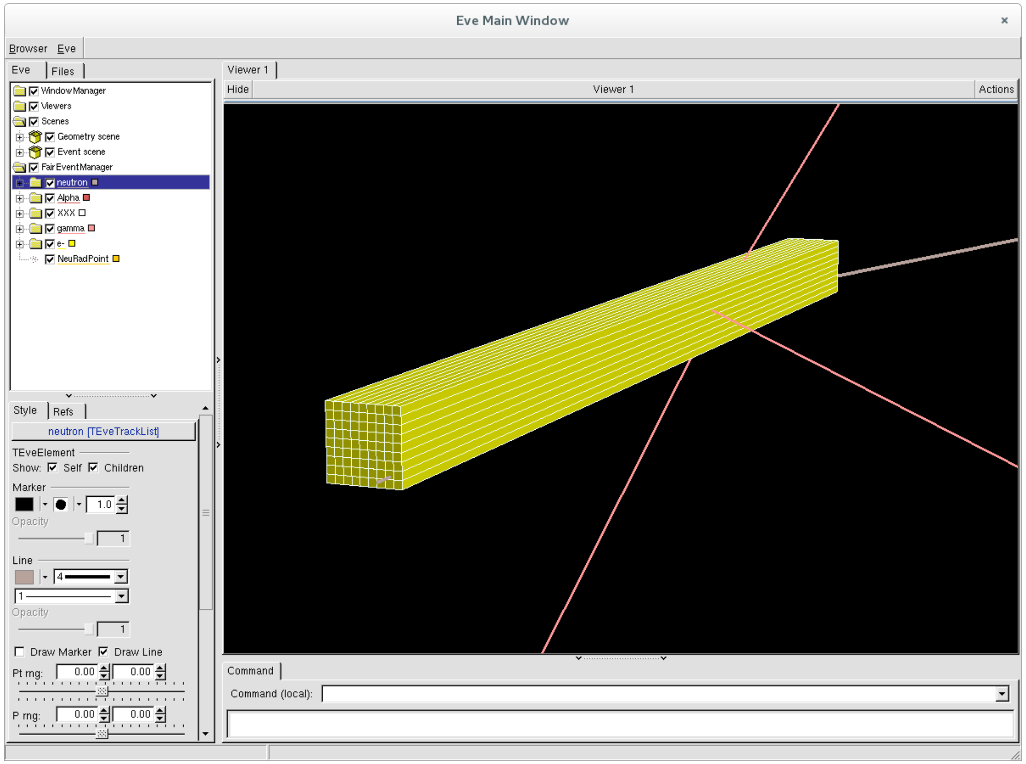
- test modules (25 cm long)
- first tests on gammas
- neutron tests in preparation in FLNP or VBLHEP (neutron generator (d,n))

Software to handle the EXPERT instrumentation is needed

ExpertRoot: General concept



- simulation and digitization of one NeuRad module realized
- comparison with stand-alone GEANT4 simulations in process
- next step: detector GADAST



Conclusions

- preparation for the first-day experiments on ACCULINNA-2 started
- works on project EXPERT@FAIR
- development of software framework **ExpertRoot** in process
- we are looking forward the future

Thank you for your attention

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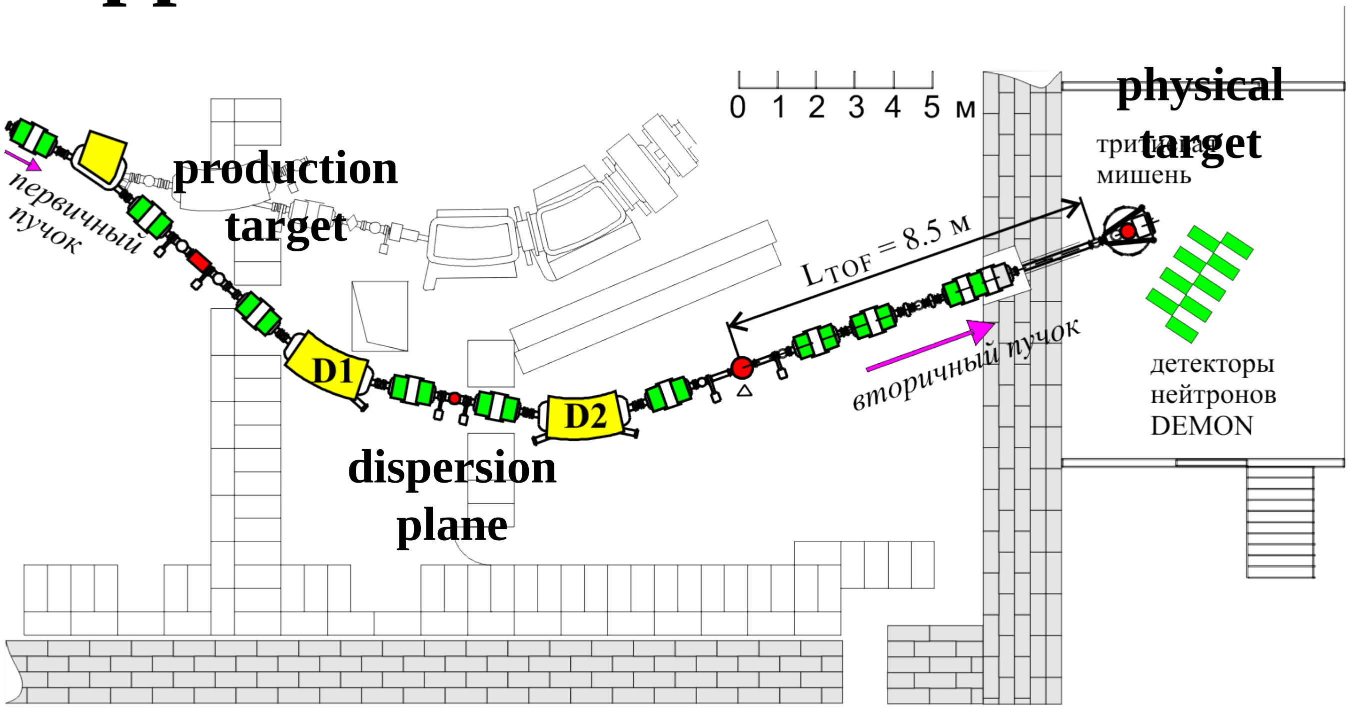
Appendix: LEN



RIB = Radioactive ion beam

Fragment-separator ACCULINNA at FLNR

In-Flight Production:

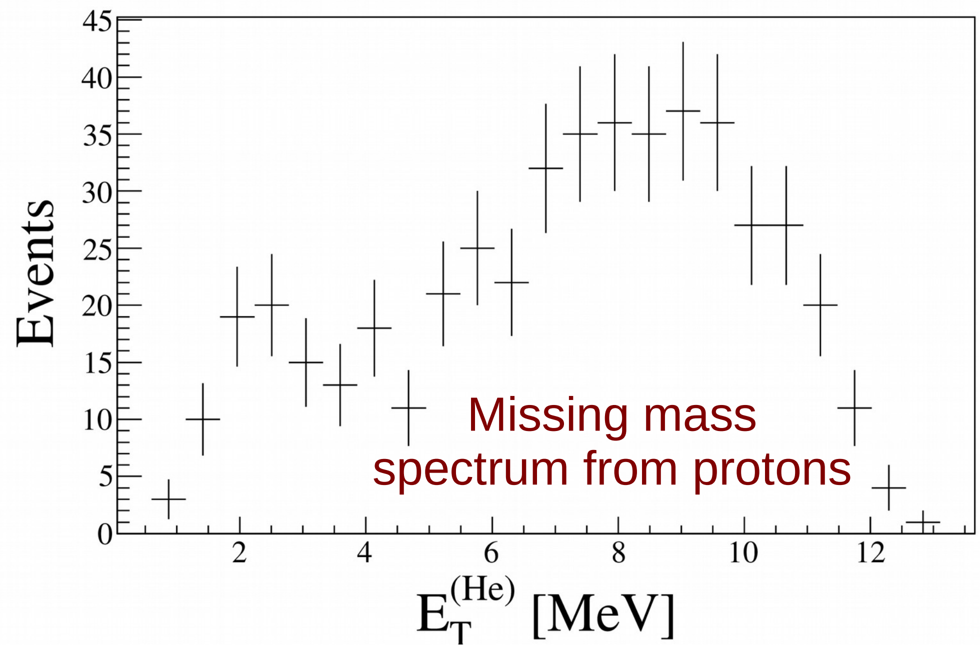
- acceleration of a primary beam ($I \sim 10^{12}$ pps)
- reactions on a thin production target
- secondary beam: fragment-separator ($I < 10^{6}$ pps)
- reactions on a physical target.

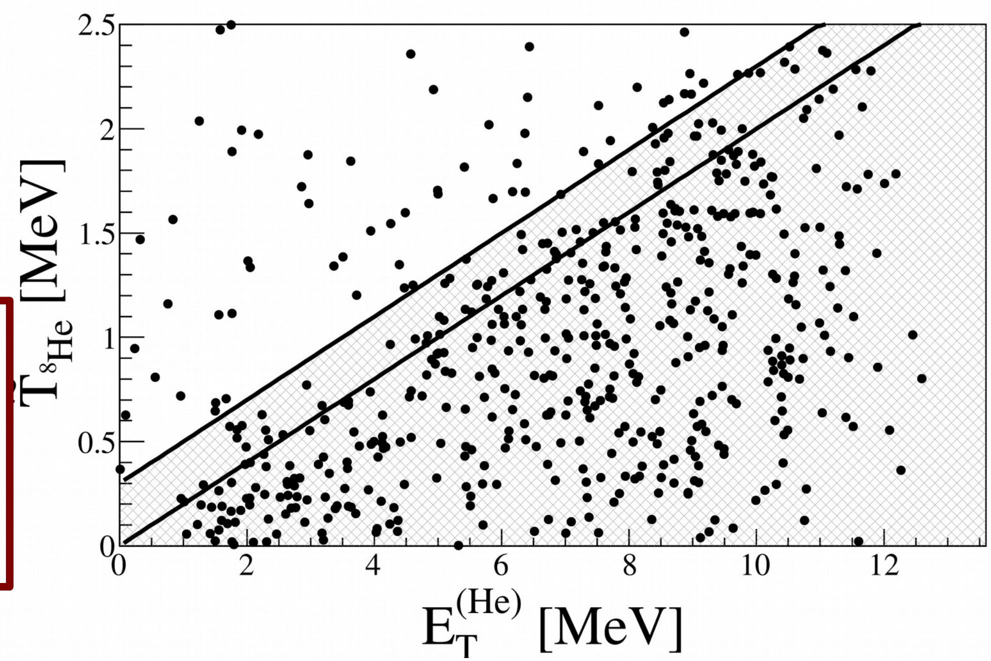
ISOL technique:

- acceleration of a primary beam ($I \sim 10^{12}$ pps)
- reactions in a thick production target: (fast production – slow release) → reaction products to be extracted, ionized and reaccelerated
- secondary beam: ($I < 10^{8}$ pps)
- reactions on a physical target

^{10}He: Missing mass spectrum

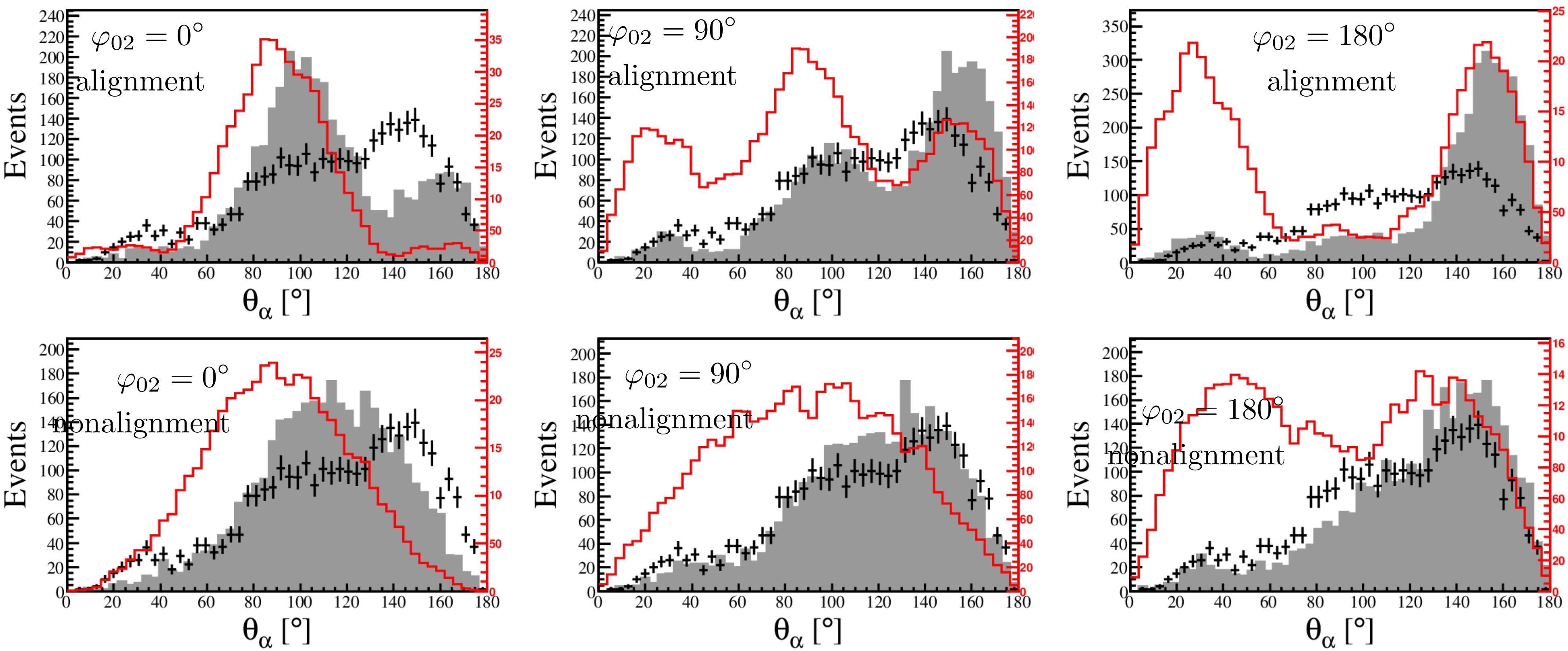
- missing mass spectrum from protons measured in coincidence with ^{8}He
- 479 events found
- population of 0+ ground state with maximum at E_T~2.1 MeV
- structureless spectrum for E_T<4 MeV
- low background from competing processes





Kinematical condition:

$$E_T^{(\mathrm{He})} \geq \left(\frac{m_{^8\mathrm{He}} + 2m_\mathrm{n}}{2m_\mathrm{n}} \right) \tilde{T}_{^8\mathrm{He}} \simeq 5\,\tilde{T}_{^8\mathrm{He}}$$

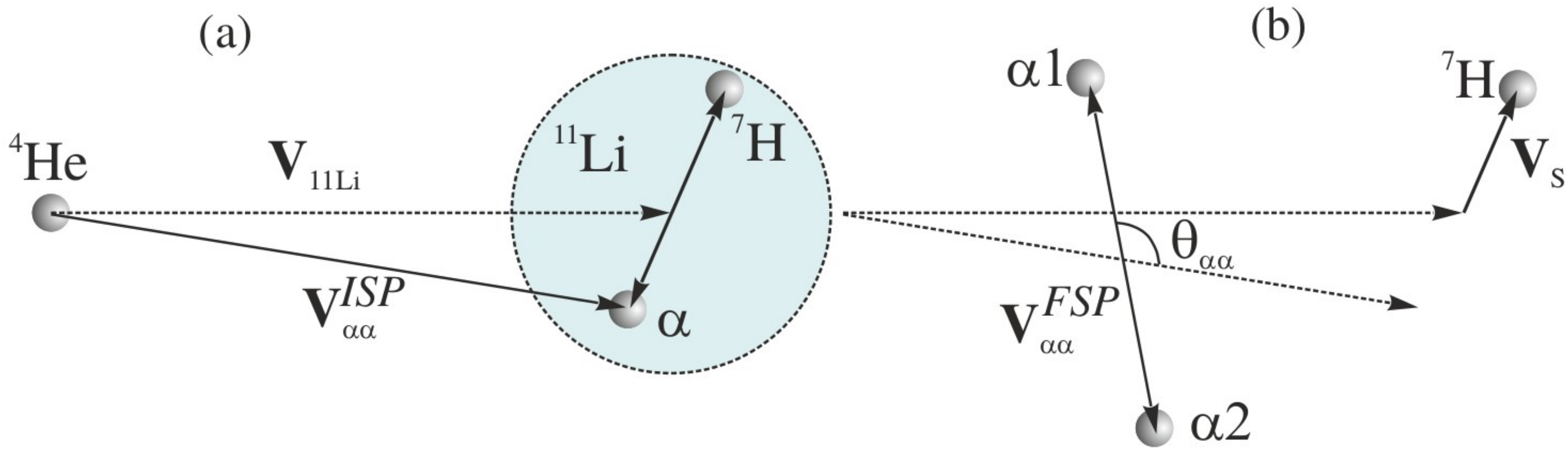


$\varphi_{02} = 0°$
alignment
$\varphi_{02} = 90°$
alignment
$\varphi_{02} = 180°$
alignment
$\varphi_{02} = 0°$
nonalignment
$\varphi_{02} = 90°$
nonalignment
$\varphi_{02} = 180°$
nonalignment
Events
θ_α [°]

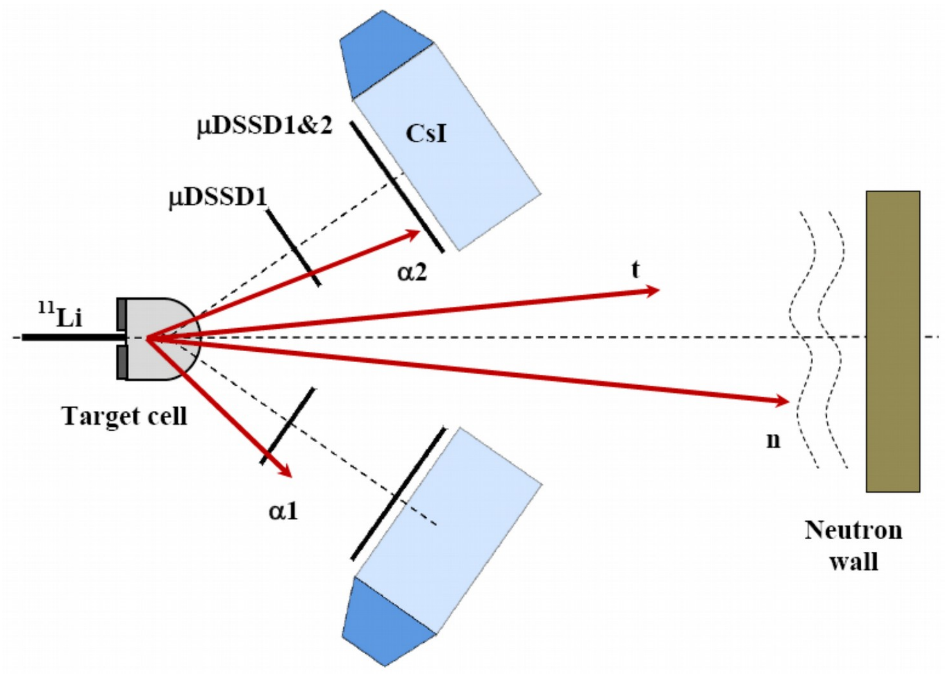
^{5}H and ^{7}H isotopes

$$^4\mathrm{He}(^9\mathrm{Li}, 2\alpha)^5\mathrm{H}$$
$$^4\mathrm{He}(^{11}\mathrm{Li}, 2\alpha)^7\mathrm{H}$$

quasifree scattering



- largest proton-neutron asymmetry among known nuclei
- decay pattern
  - 3-body: t + 2n
  - 5-body: t + 5n !!!!!
- very restricted experimental data



^{6}Be: Correlations

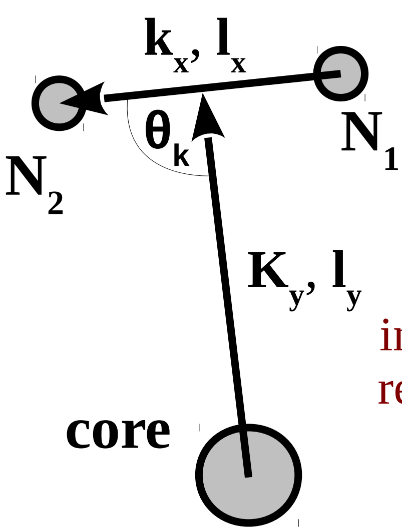
fast: reaction mechanism; determines

$$\frac{d\sigma}{d\Omega_{\varkappa} d\Omega_{k'} dE_T} =$$

$$= \sum_{S M_S S_x} \sum_{J M J' M'} \mathrm{Im}\left[\underbrace{A^{J'M'\dagger}_{S M_S S_x}}(E_T,\Omega_{\varkappa})\, \rho^{J'M'}_{JM}(E_T,\hat{k})\; \underbrace{D^{JM}_{S M_S S_x}}(E_T,\Omega_{\varkappa}) \right],$$

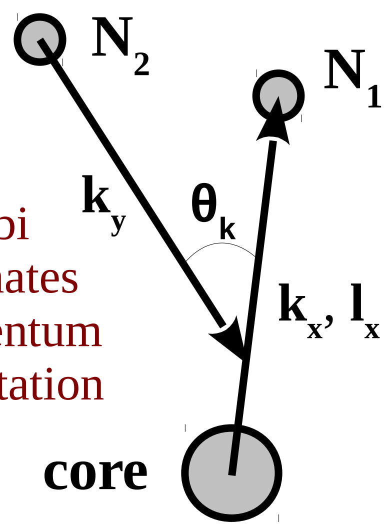
slow: asymptotes of 3-body decay (structure of Be)

T-system



Jacobi coordinates in momentum representation

Y-system



- Three-body task calculated by theory using **hyperspherical harmonics** method
- External correlations: 3-body system orientation
- full description of the internal correlations by parameters ε and θ_k

$$\varepsilon = \frac{E_x}{E_x + E_y} \qquad \cos\theta_k = \frac{\mathbf{k}_x \cdot \mathbf{k}_y}{k_x k_y}$$