RIB research at FLNR JINR

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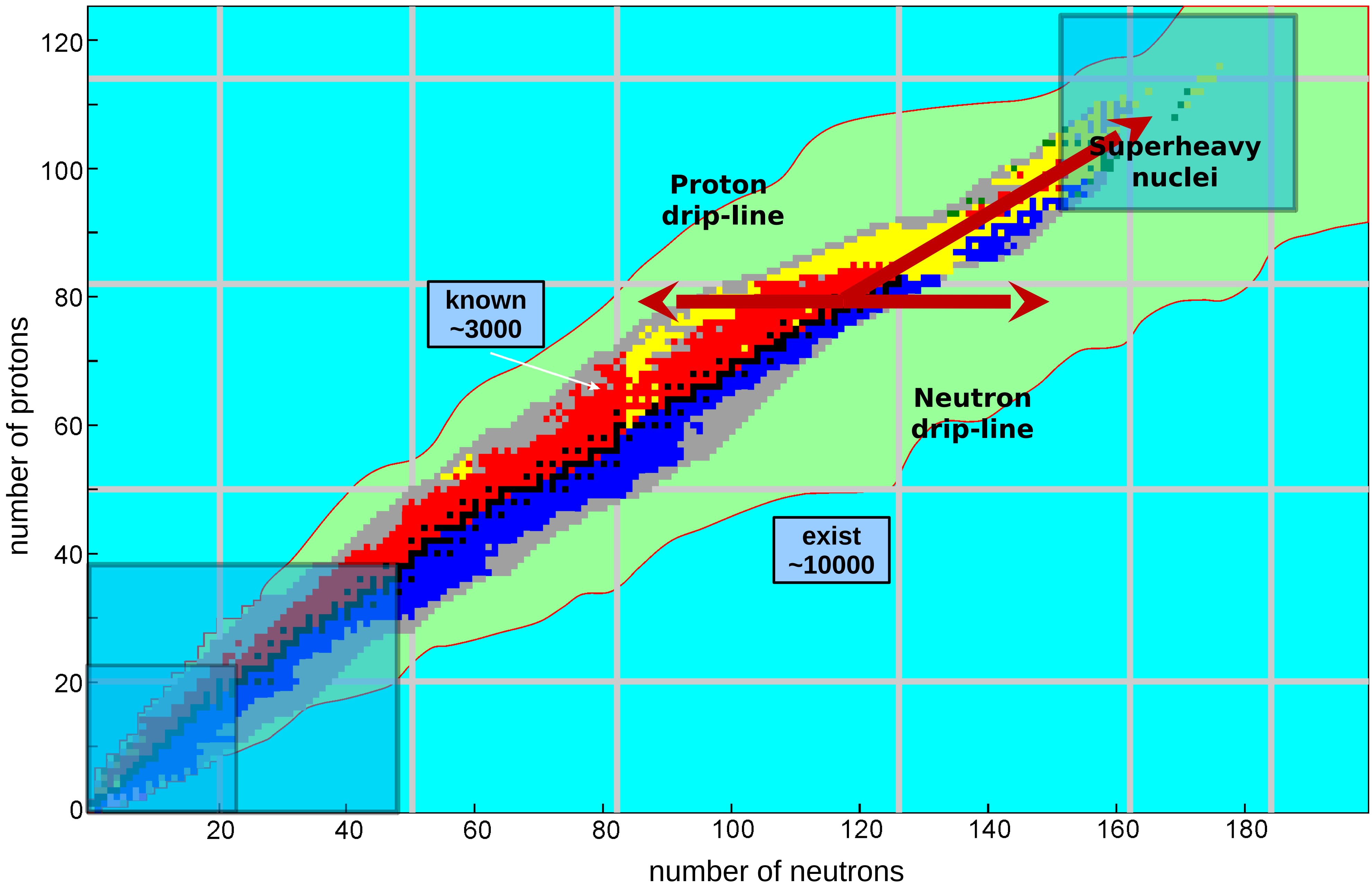
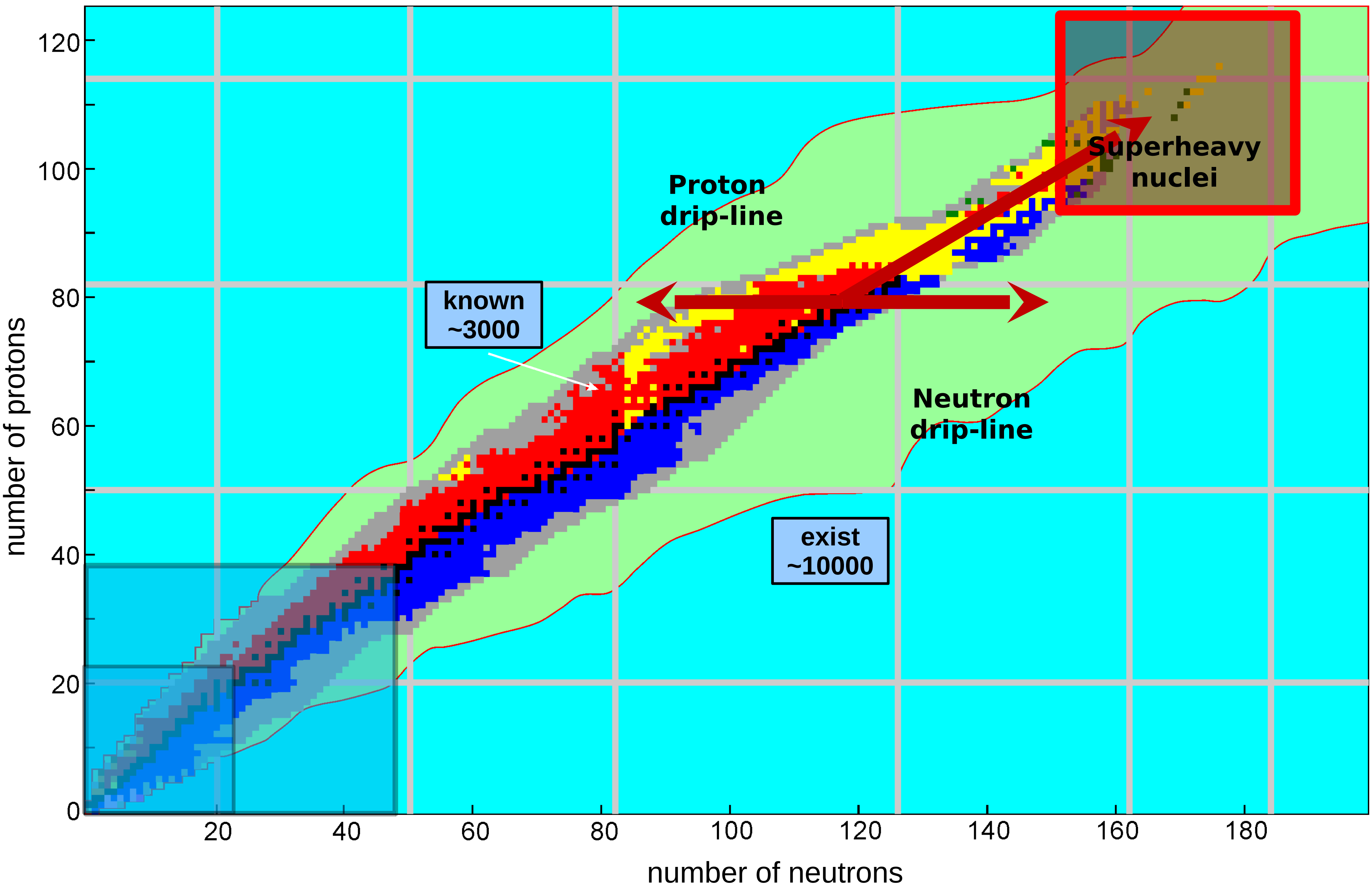
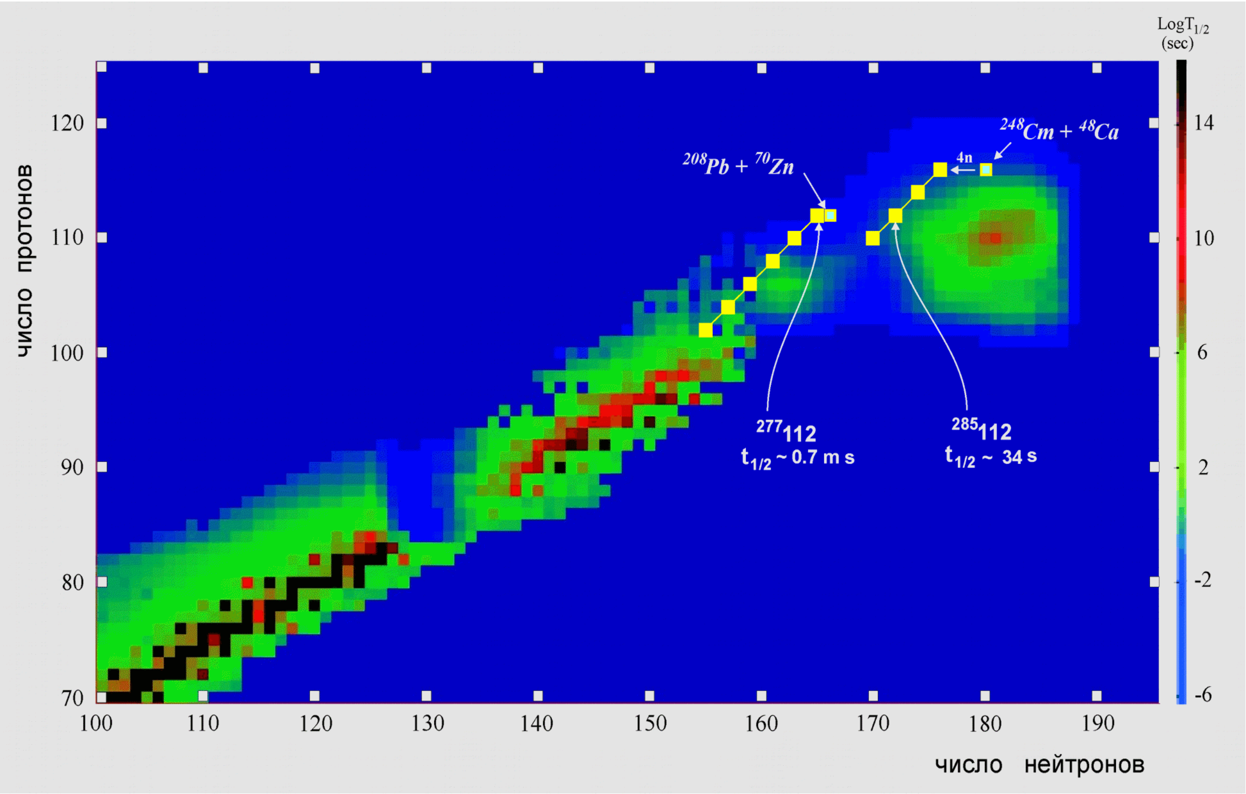
Nuclear physics in FLNR



Nuclear physics: superheavies



SHE: to the Island of Stability



Island of stability

- set of predicted heavy transuranium isotopes
- much more stable than nuclei around uranium
- centered around Z=114 and N=184

synthesis of superheavies

$$Z_1 + Z_2 = Z$$

$$N_1 + N_2 = N + (2 - 4)\text{n}$$

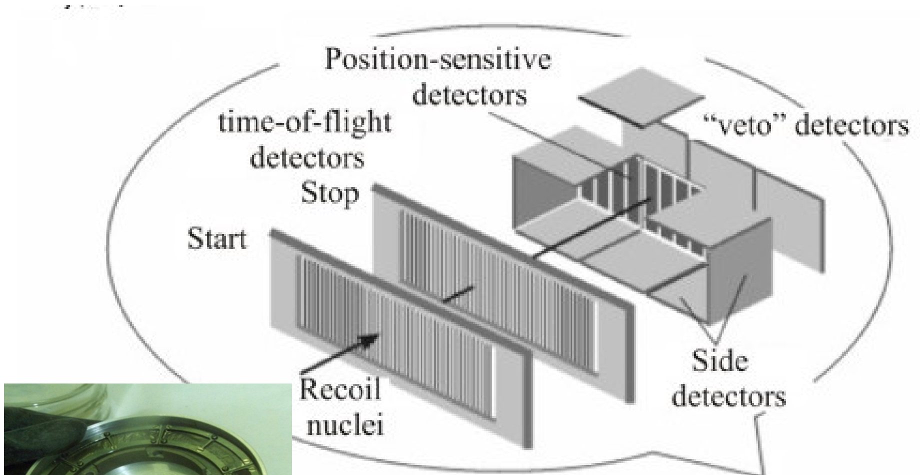
"cold" fusion: Pb + heavy ion

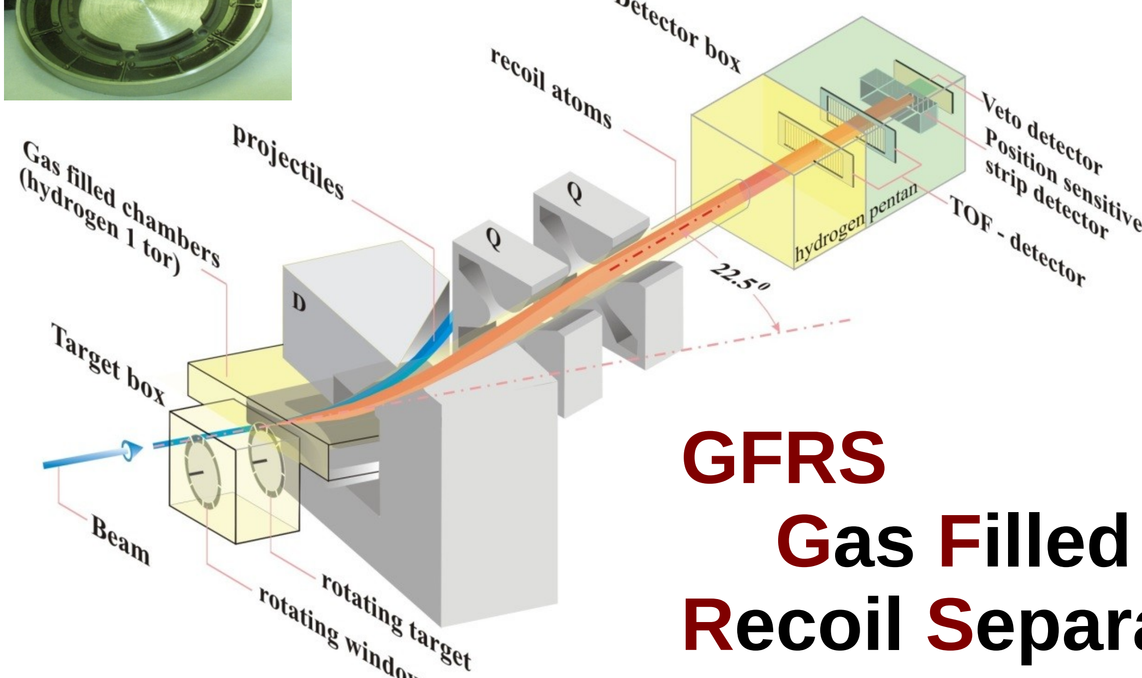
"hot" fusion: light beam + heavy target

- low-energy physics
- compound nucleus
- combination of light nuclei and heavy nuclei gives higher cross sections

SHE: synthesis of superheavies

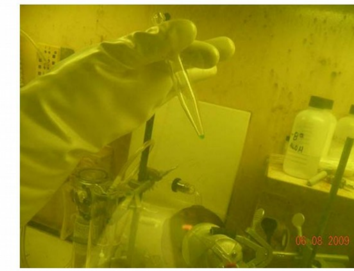
in collaboration with LLNL (USA)





beam

- ^{48}Ca
- 254 MeV; 10^{11} pps
- ~250 000 USD/g



Bk(NO$_3$)$_3$Product

targets

- ^{249}Bk (117), ^{251}Cf (118)
  - $T_{1/2}$ = 330 d, 900 y
- much more expensive than beam
  - delivered by LLNL

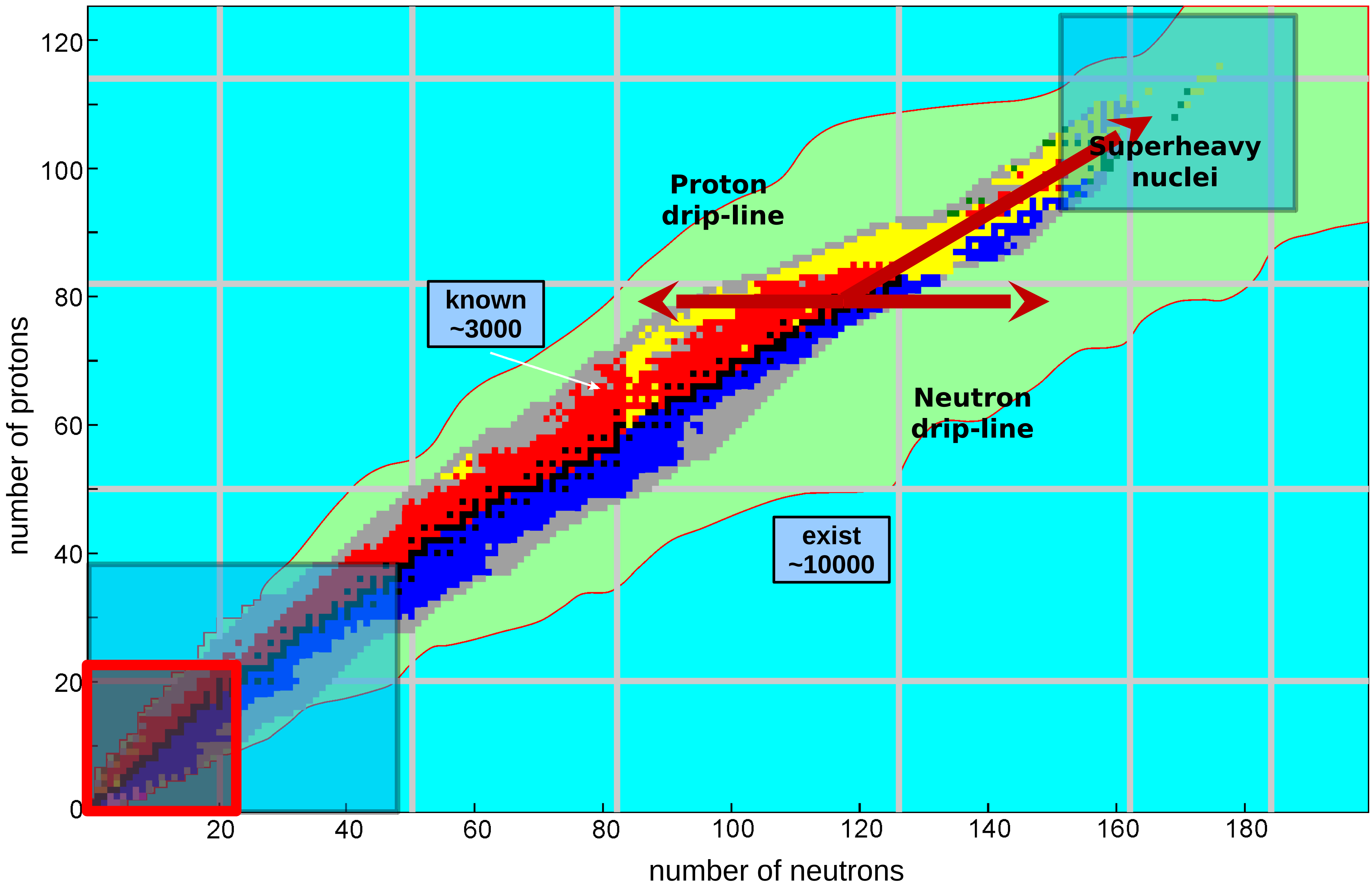
GFRS

Gas Filled Recoil Separator

recently synthesized

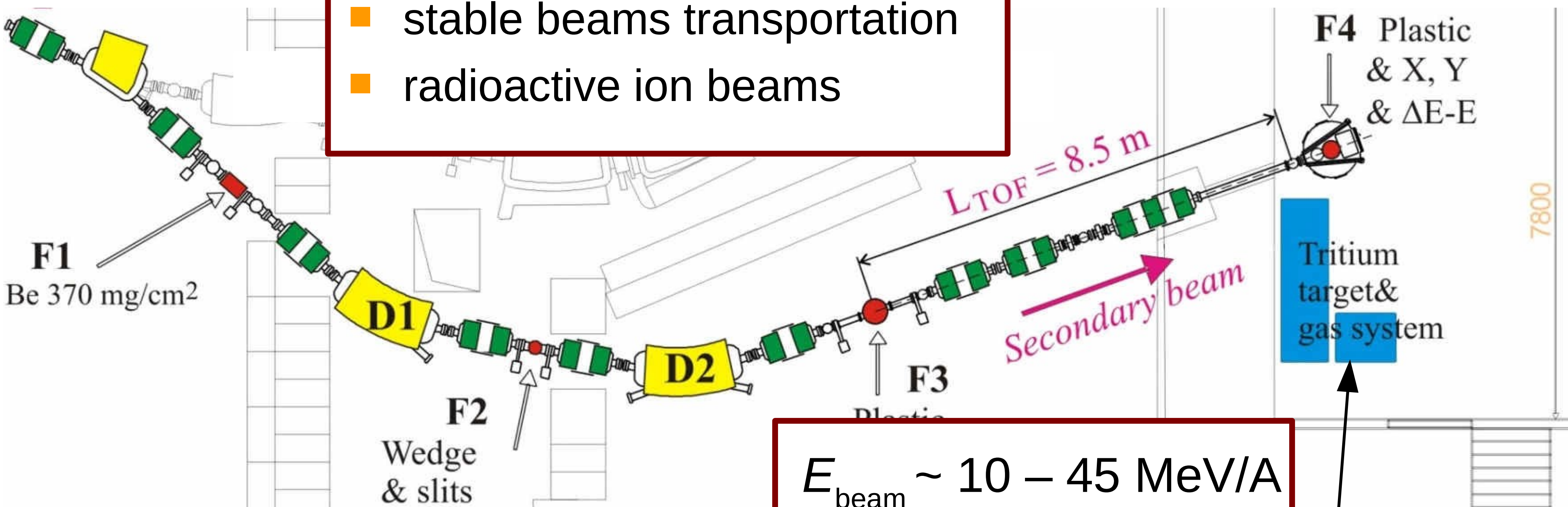
- 2002: 118th element
- 2010: 117th element

Nuclear physics: light exotic nuclei



ACCULINNA facility

- stable beams transportation
- radioactive ion beams



E_{beam} ~ 10 – 45 MeV/A

I_{beam} ~ 10^3 – 10^6 pps

- the only working RIB facility in JINR
- in-flight technique
- beams up to ^{26}S

unique combination of tritium beam and target

Main research directions at ACCULINNA

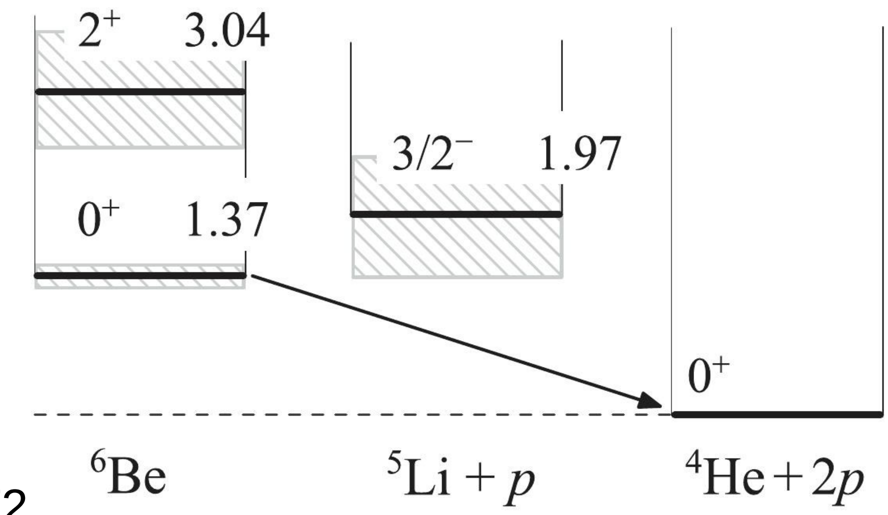
- full range of “ordinary” nuclear physics research
- energy range 5-45 AMeV is especially suitable for spectroscopy by means of direct reactions
- ways to obtain very exotic systems
  - knock-out (the most usual)
  - transfer reaction
  - charge-exchange reactions
  - quasifree scattering
- few-body decays, 2p radioactivity
- strong theoretical background
- complicated correlation measurements and further analysis

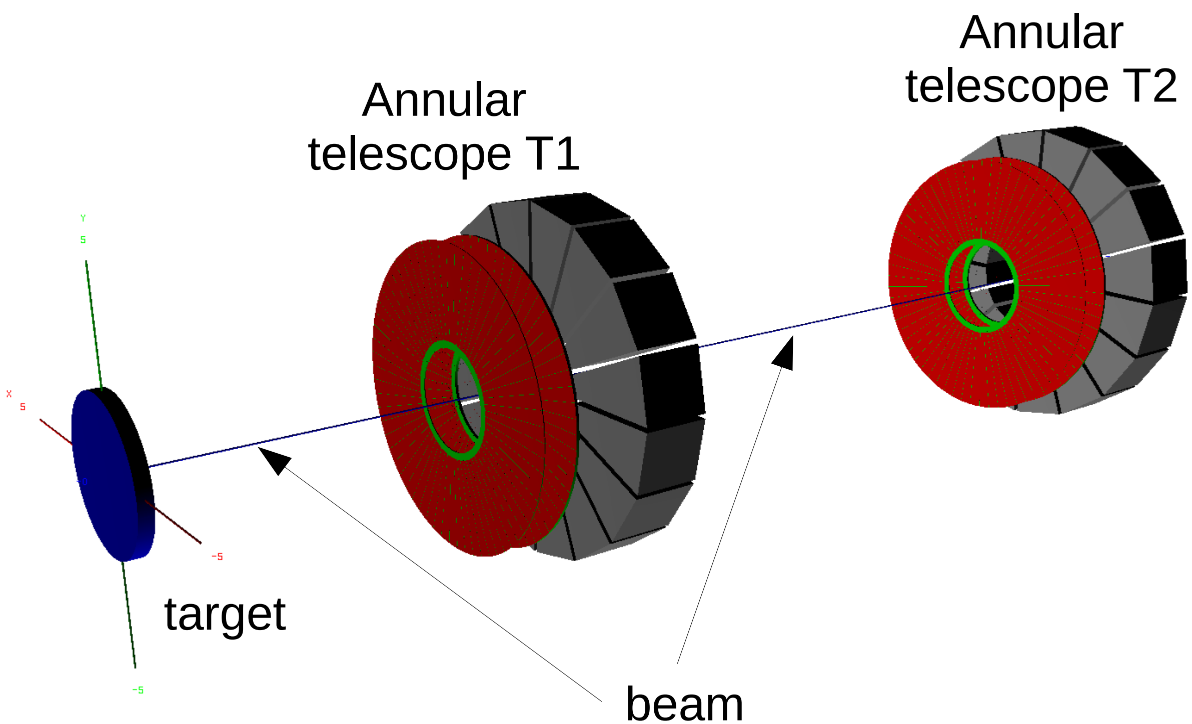
^{6}Be

^{6}Be: Introduction

$$
\begin{aligned}
{}^{6}\mathrm{Li} + \mathrm{p} &\rightarrow {}^{6}\mathrm{Be} + \mathrm{n} \\
{}^{6}\mathrm{Be} &\rightarrow \alpha + \mathrm{p} + \mathrm{p}
\end{aligned}
$$

- alpha core + 2 valence protons
- the lightest true 2p emitter
- mirror nucleus of ^{6}He; access to properties of ^{6}He ground state
- very limited information on correlations



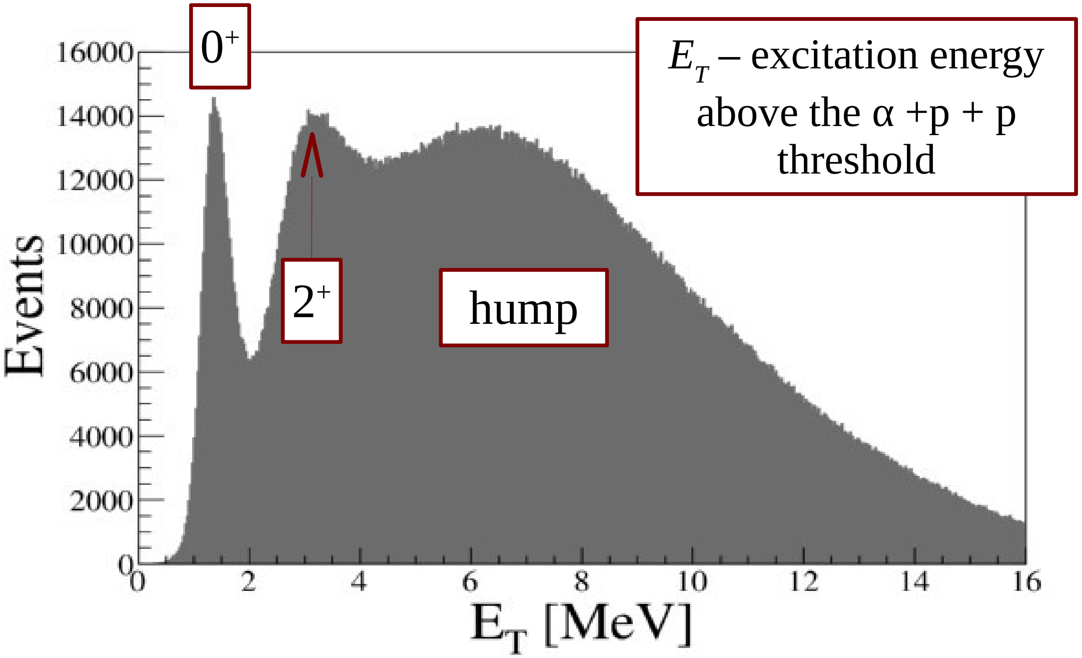


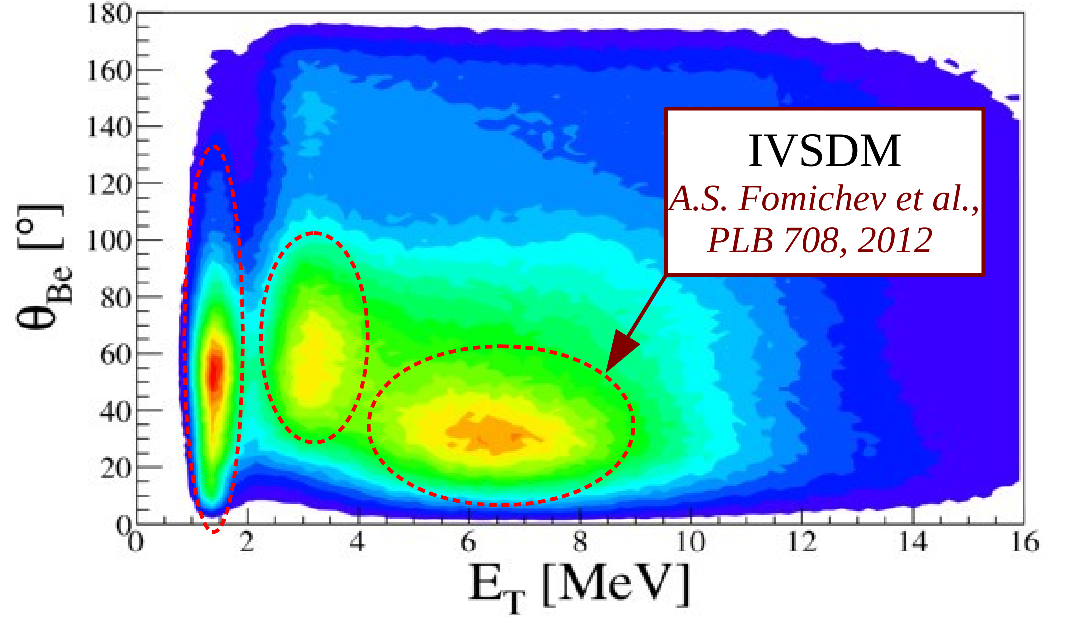
full kinematics measurement

- ^{6}Li beam: 35 MeV/A; 10^7 pps
- ^{1}H gaseous target: d = 4 mm; p ~ 3 bar; T ~ 35 K
- 3-particle (α and 2p) coincidences

^{6}Be: Invariant mass spectrum

- 0^+ , 2^+ states
- broad hump at $E_T > E_T(2^+)$
  - uniform shape; high cross-section
  - interpreted as Isovector soft dipole mode (IVSDM)
- rich information hidden behind IM spectrum

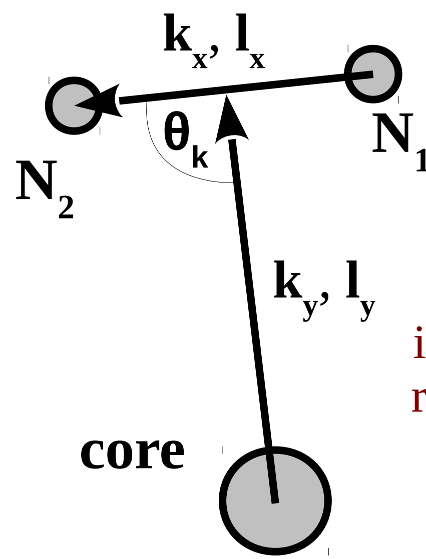




^{6}Be: Correlations

2-body vs. 3-body decay

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



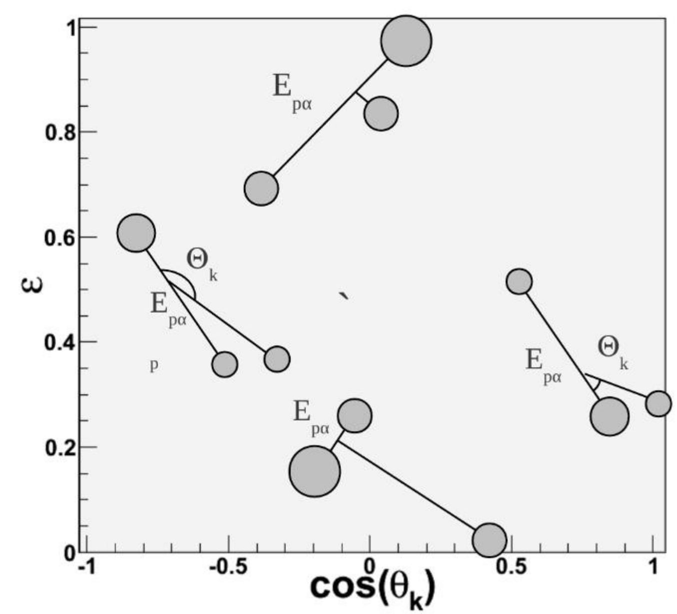
Jacobi coordinates in momentum representation

T-system

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

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

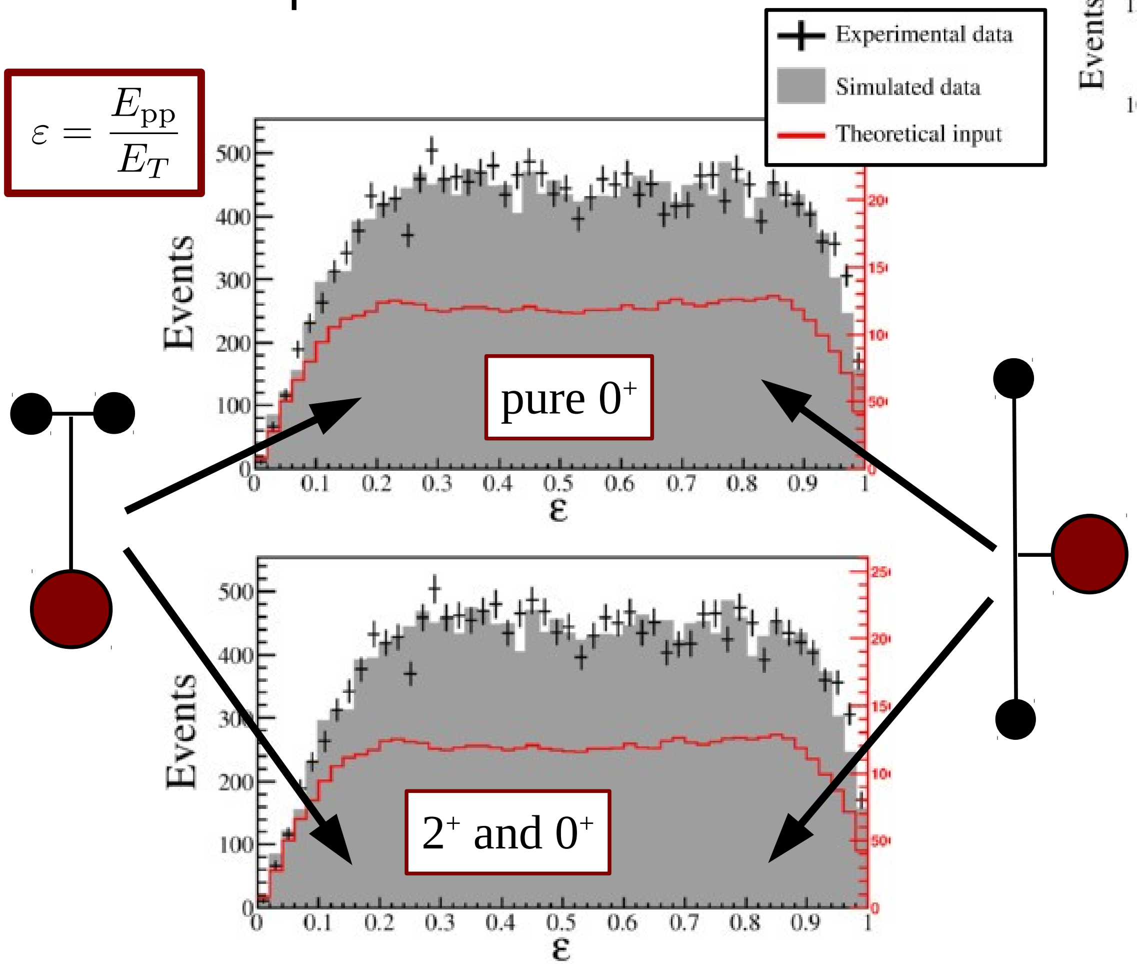
- external correlations: 3-body system orientation

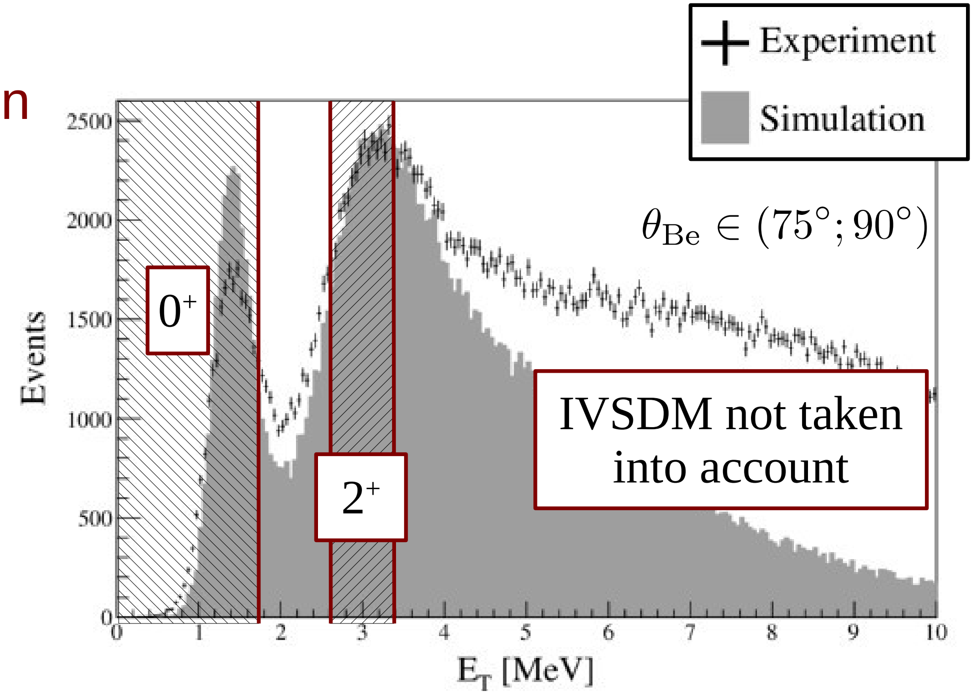


^{6}Be: Data analysis

- **theoretical model:** PWIA in combination with 3-body model
- direct comparison of theoretical model with experimental data

$$\varepsilon = \frac{E_{pp}}{E_T}$$

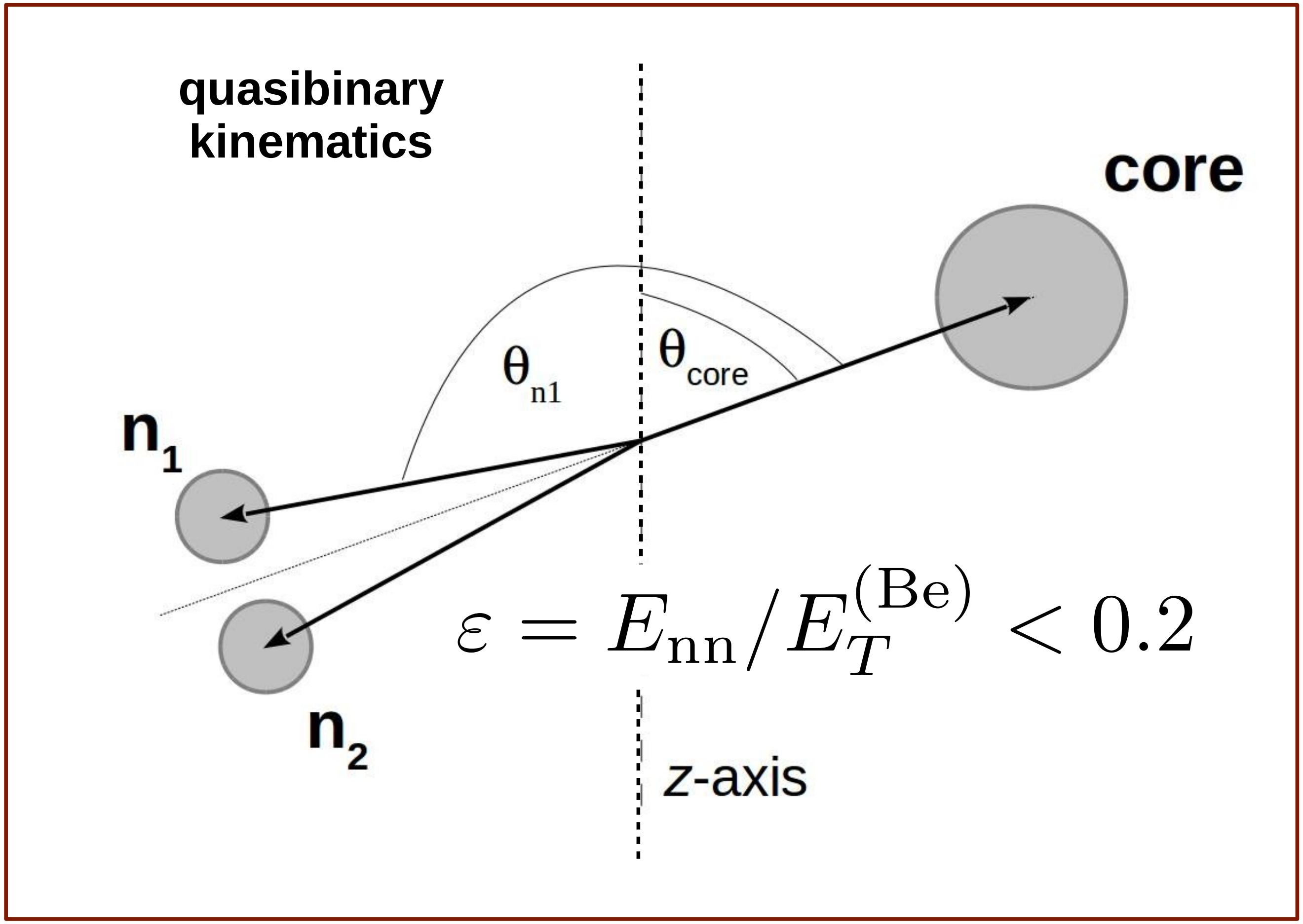


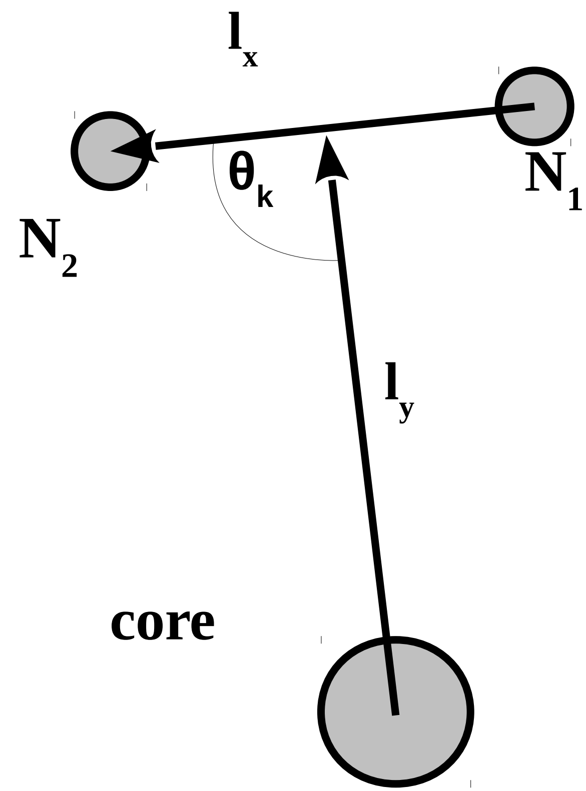


- test on 0^+ ground state (no free parameters)
- two overlapping states 0^+ and 2^+
  - 2^+ can be aligned
  - broad 0^+ and 2^+ can interfere
- low sensitivity of **internal correlations** to model parameters observed

agreement between EXP and THEOR data for E_T<3.2 MeV in full range of θ_{Be}

^{6}Be: Quasibinary kinematics

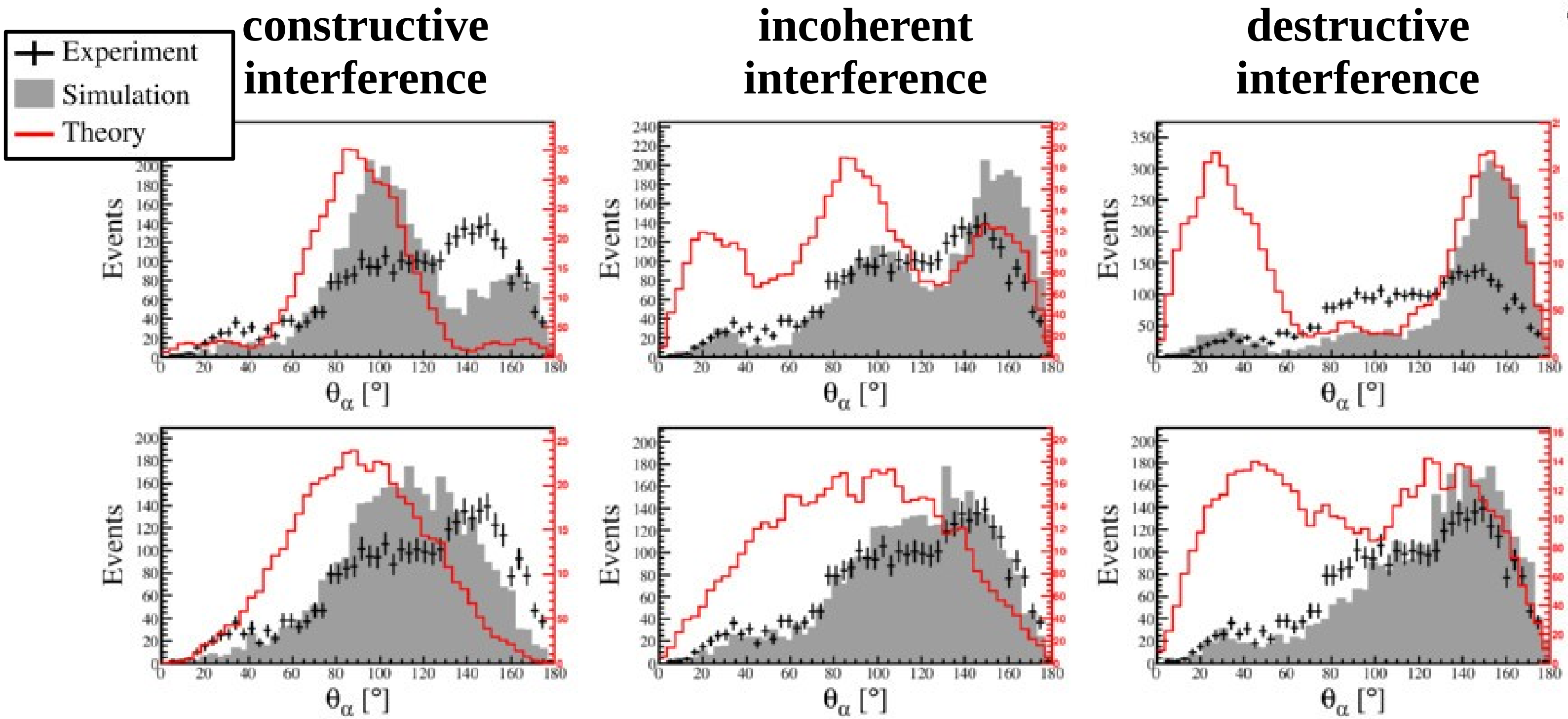


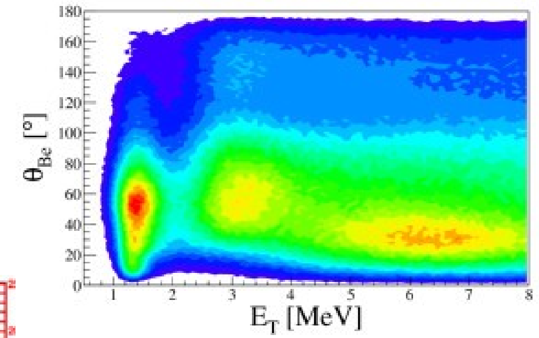


- useful when a few overlapping states present
- total angular momentum is determined emission angle of alpha particle

Legendre polynomials can be visible

^{6}Be: External correlations





aligned

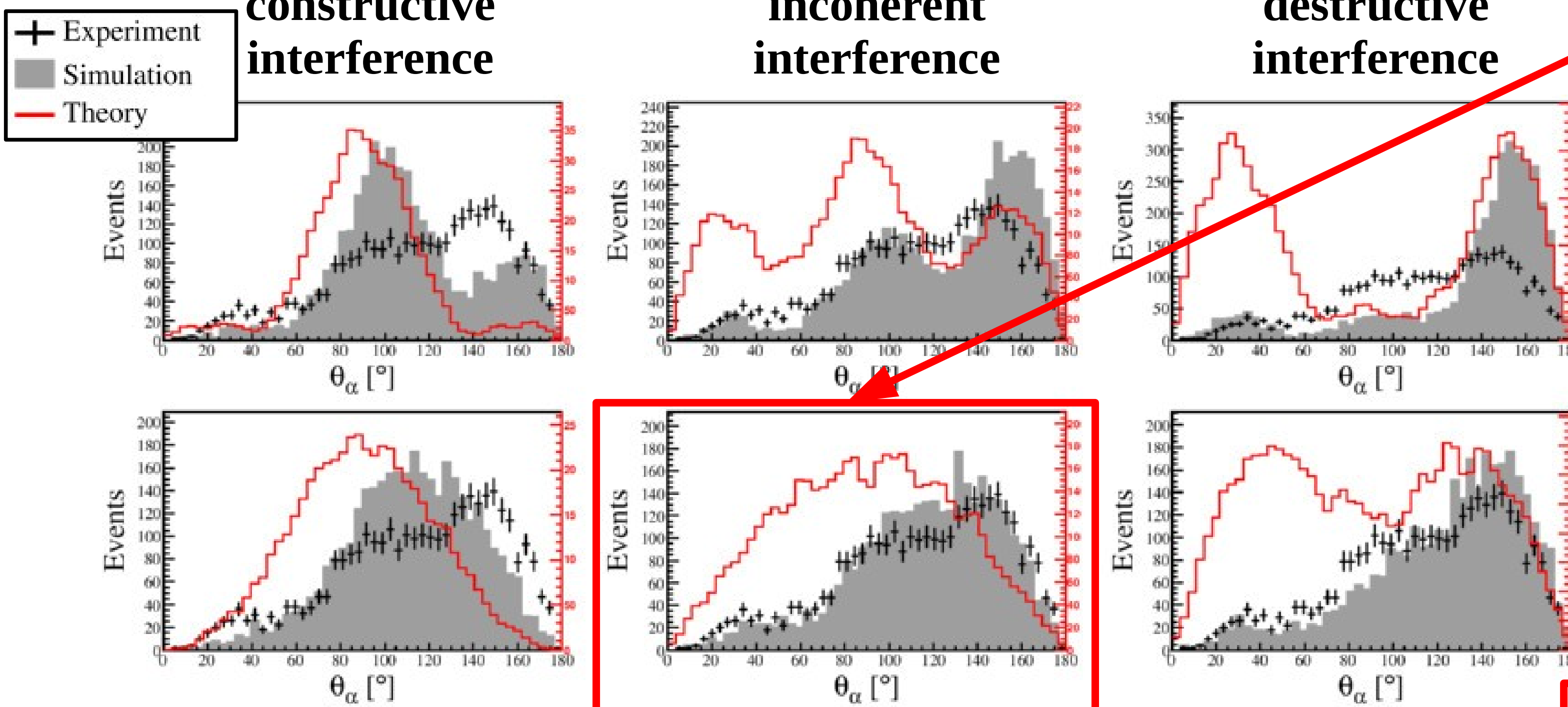
$E_T \in (1.9,2.5)$ MeV
$\theta_{Be} \in (60,75)°$

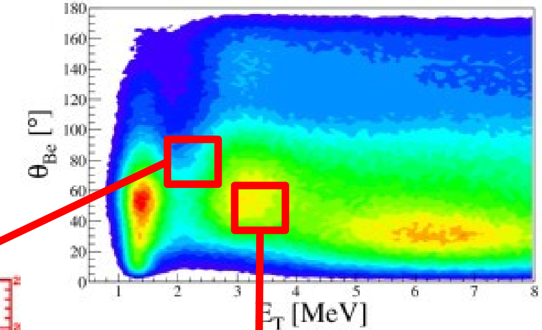
nonaligned

experimental sensibility to J^{π} orientation and interference between 0^+ and 2^+

- dramatic changes of the θ_{α} distributions depending on the model parameters
- level of alignment and interference angle is changing with E_T and θ_{Be}

^{6}Be: External correlations





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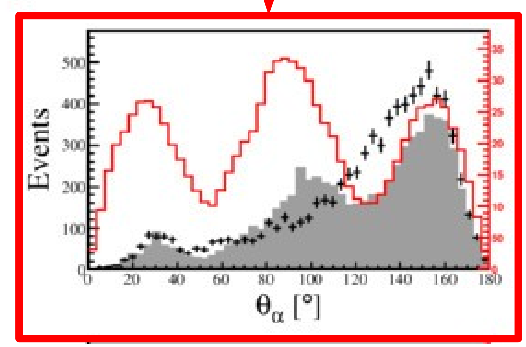


experimental sensibility to J^π orientation and interference between 0^+ and 2^+

- dramatic changes of the θ_α distributions depending on the model parameters
- level of alignment and interference angle is changing with E_T and θ_{Be}

such detailed analysis was done for the first time

^{10}He

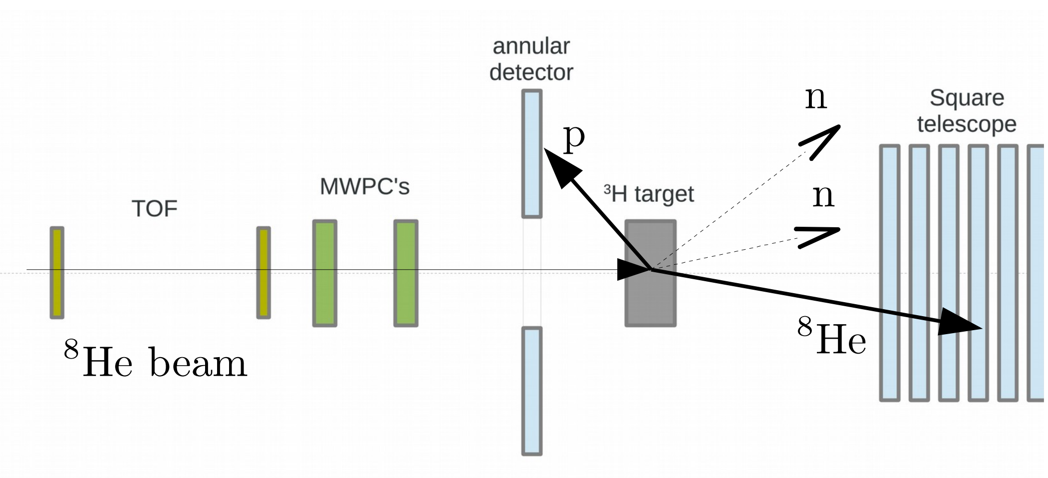
^{10}He: Introduction

- 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)

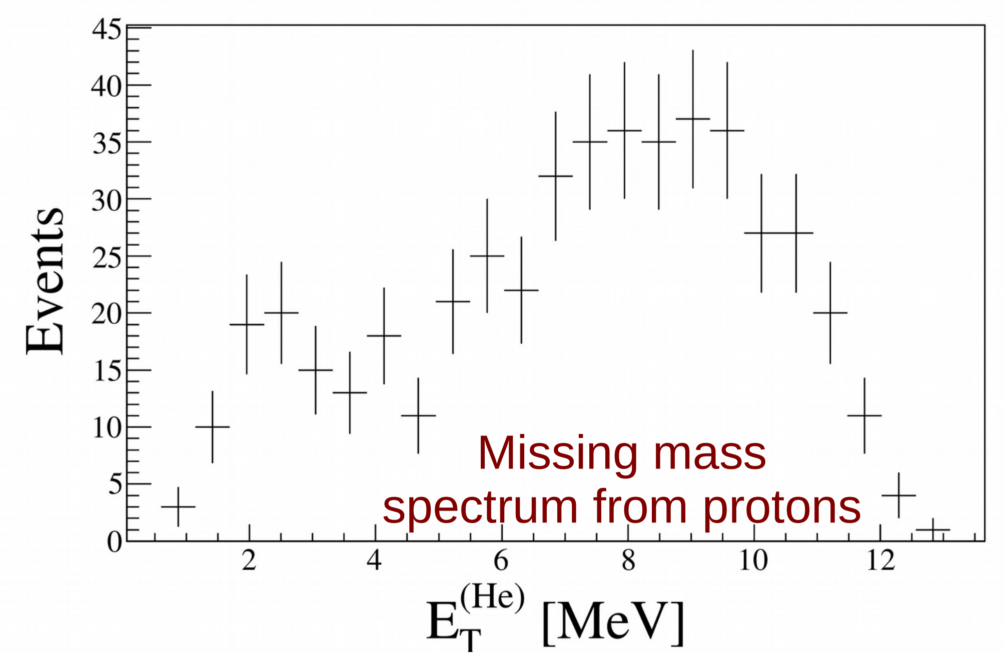
Reference	$E_T^{(\mathrm{He})}$ [MeV]	Γ [MeV]
Korsheninnikov *et al.*	1.2	1.2
Ostrowski *et al.*	1.07	0.3
Chudoba *et al.*, Golovkov *et al.*	$\sim$3	N/A
Johansson *et al.* A	1.42	1.11
Johansson *et al.* B	1.54	1.91
Kohley *et al.*	1.60	1.08

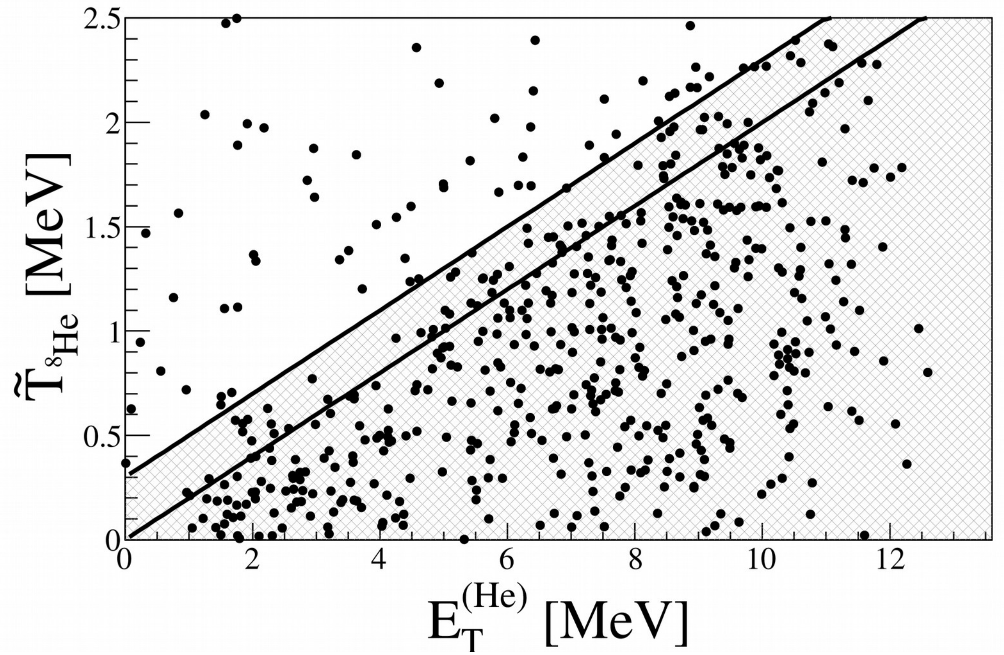


- ^{8}He beam: 21.5 MeV/A; 10^5 pps
- ^{3}H target: d ~ 6 mm; p ~ 0.9 bar; T ~ 26 K

^{10}He: Missing mass spectrum

- missing mass spectrum from protons measured in coincide-nce 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

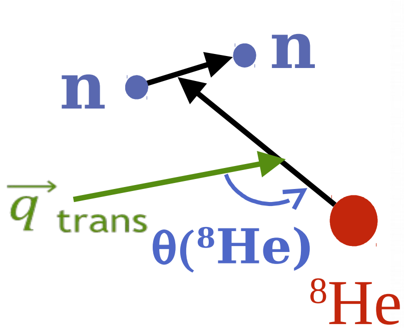


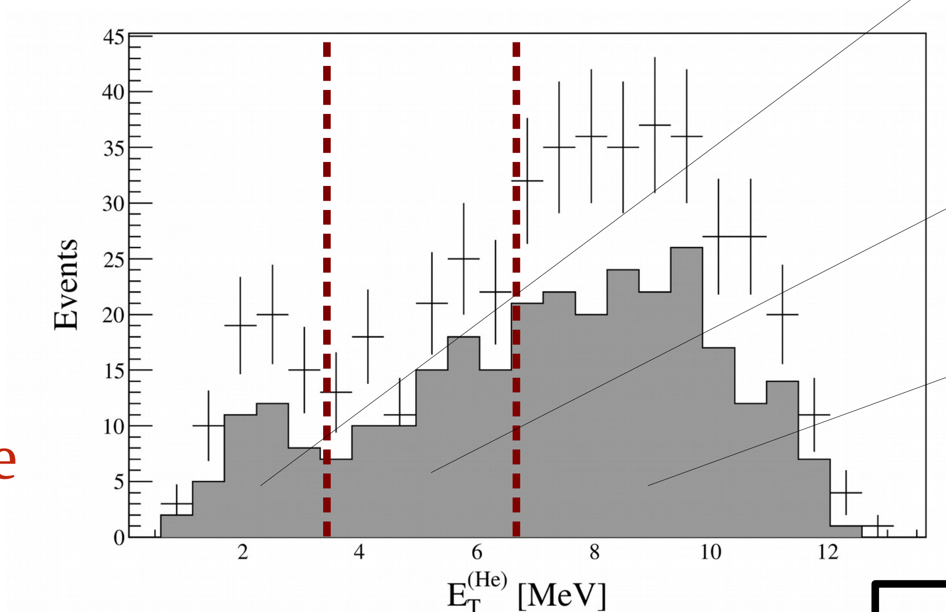


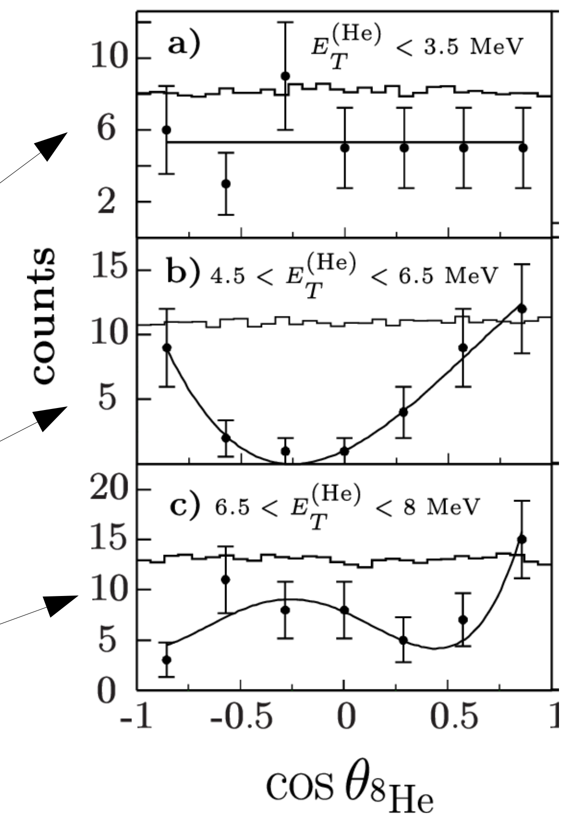
^{10}He: Correlation and spectrum decomposition

- quasibinary kinematics: $\varepsilon = E_{\mathrm{nn}}/E_T^{(\mathrm{He})} < 0.5$
- ^{10}He total angular momentum is fully determined by angular momentum of ^{8}He

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





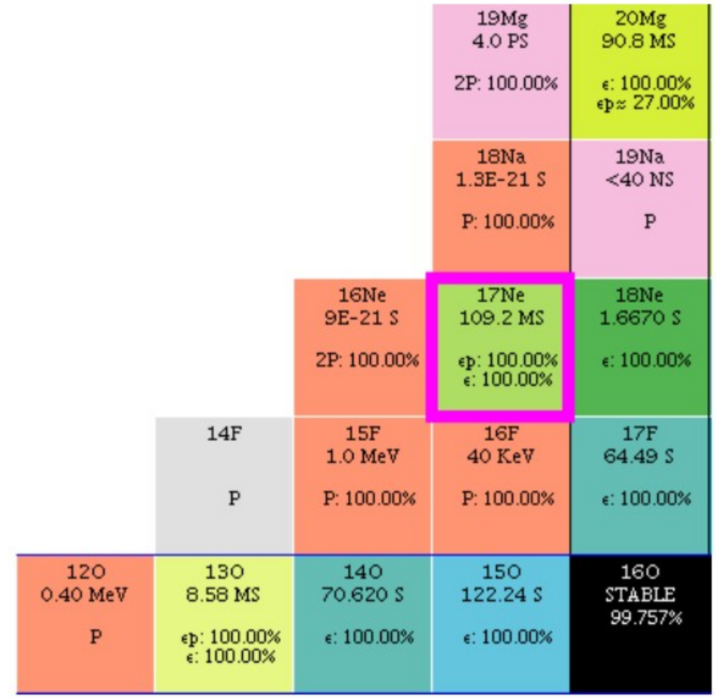


$$\frac{d\sigma}{d\Omega} = \left[AP_0(x) + B\sqrt{3}P_1(x) + C\sqrt{5}P_2(x)\right]^2 + D^2$$

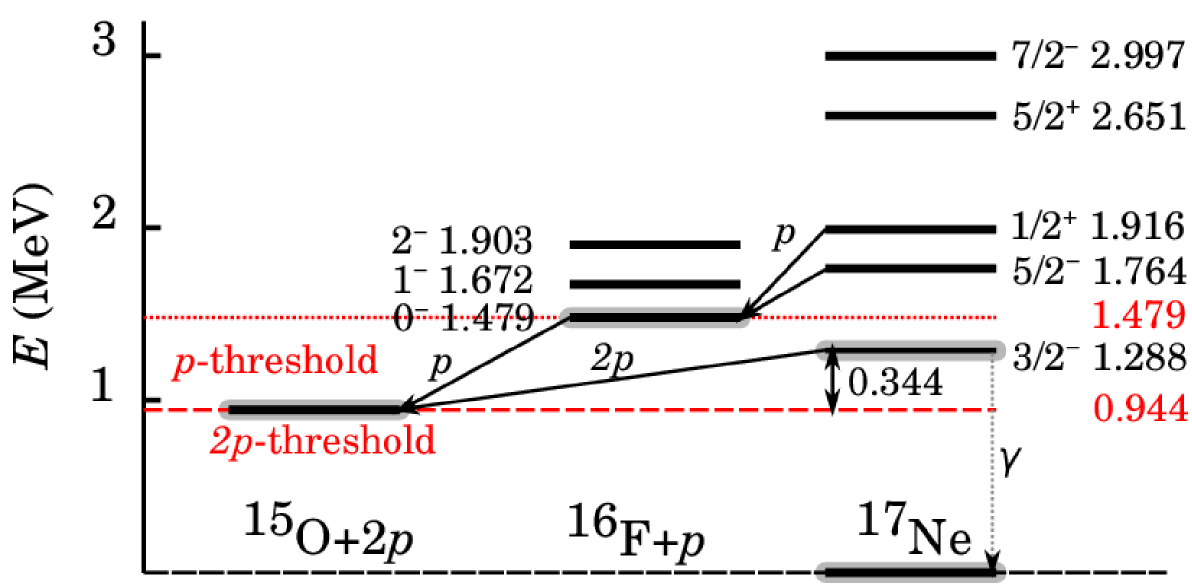
- J^π of the ground state confirmed by the experimental data analysis
- J^π of the ***1***$^-$ states determined from experimental data for the first time

^{17}Ne

^{17}Ne: Introduction



- Borromean system; investigated many times in the past
- possible two-proton halo structure of the g.s.
  (one of the last candidates)
- true 2p decay of the excited state predicted

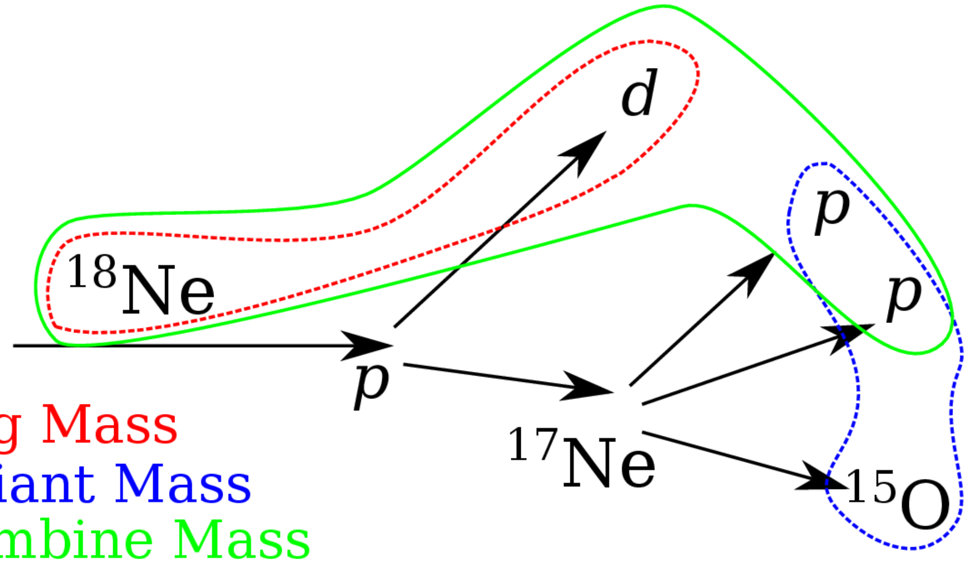


true 2p-decay and γ-decay partial widths ratio:

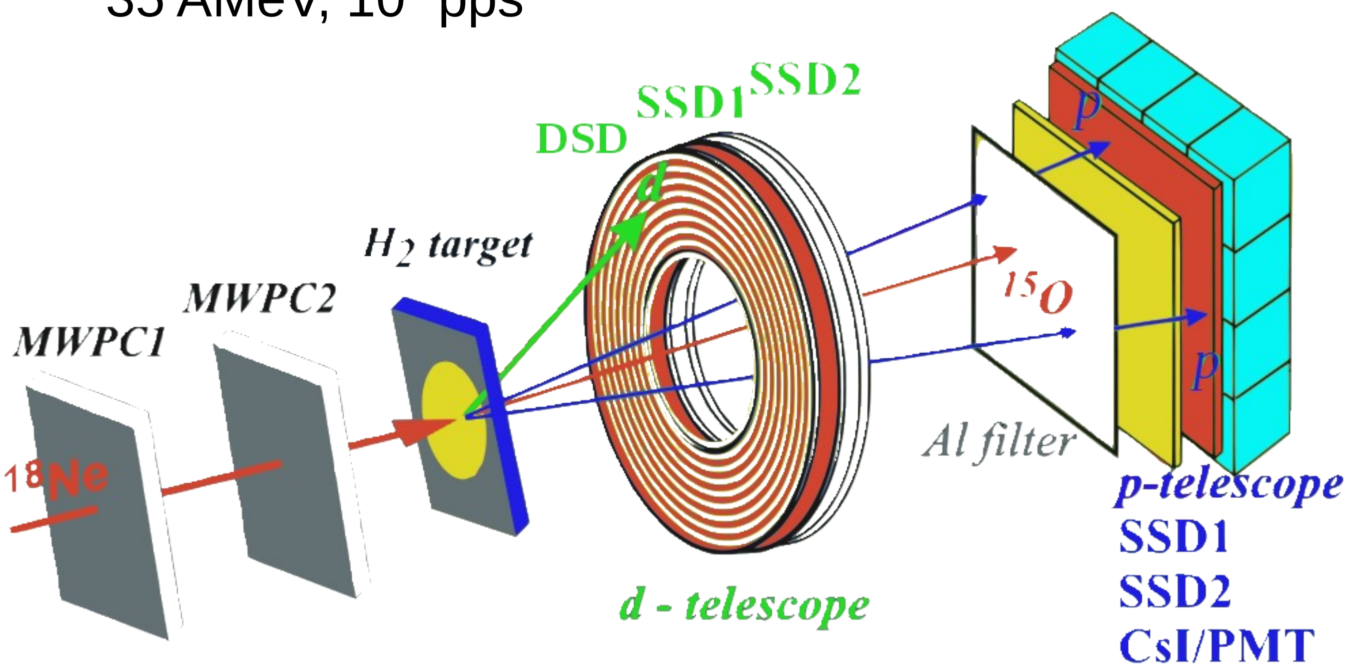
- theoretical predictions (*L.V. Grigorenko and M.V. Zhukov, Phys. Rev. C 76, 014008, 2007*)
  $$\Gamma_{2p}/\Gamma_{\gamma} \leq 5 \times 10^{-7}$$
- experiment (*M.J. Chromik et al., PRC 66, 02413, 2002*)
  $$\Gamma_{2p}/\Gamma_{\gamma} \leq 7.7 \times 10^{-3}$$

^{17}Ne: Measurement and combined mass method

$$^{18}\mathrm{Ne} + \mathrm{p} \rightarrow ^{17}\mathrm{Ne} + \mathrm{d}$$
$$^{17}\mathrm{Ne} \rightarrow ^{15}\mathrm{O} + \mathrm{p} + \mathrm{p}$$



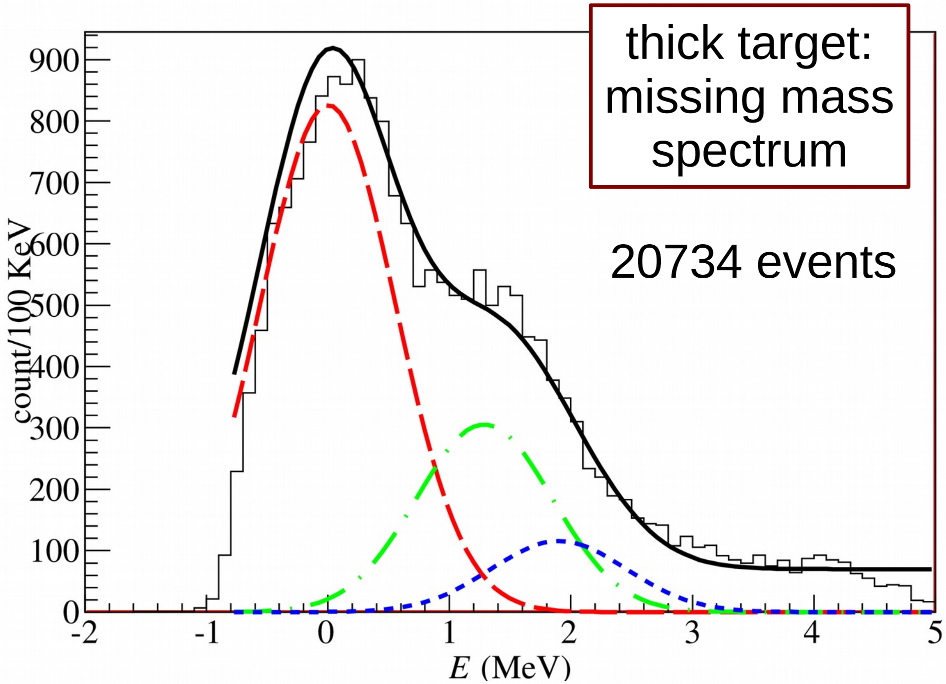
- two measurements on liquid and gaseous target
- ^{18}Ne beam: 35 AMeV, 10^5 pps

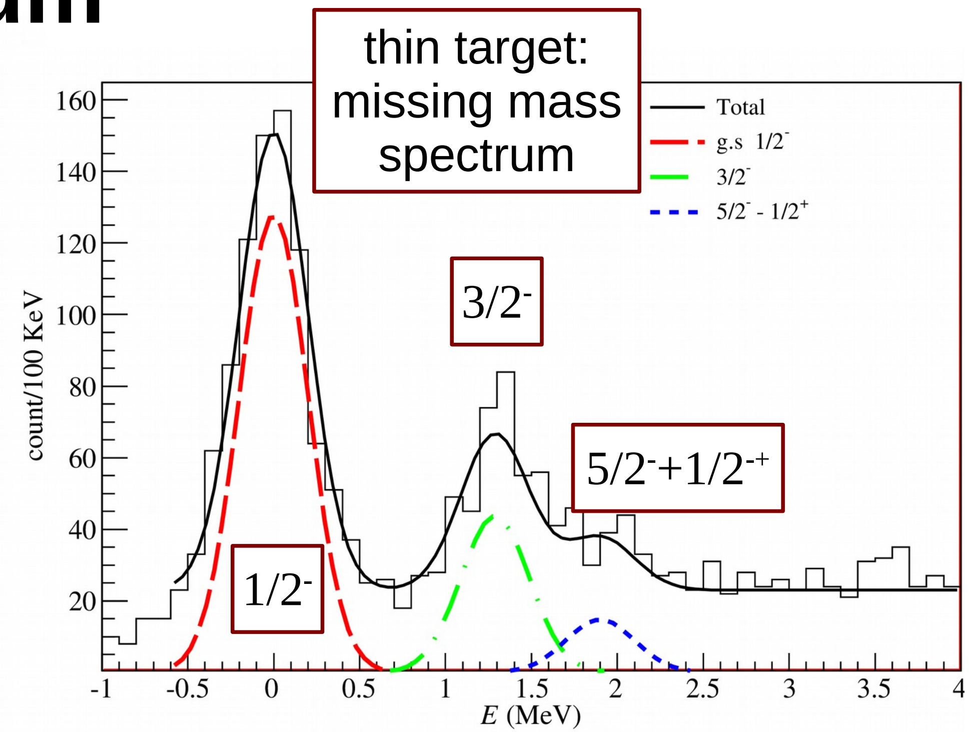


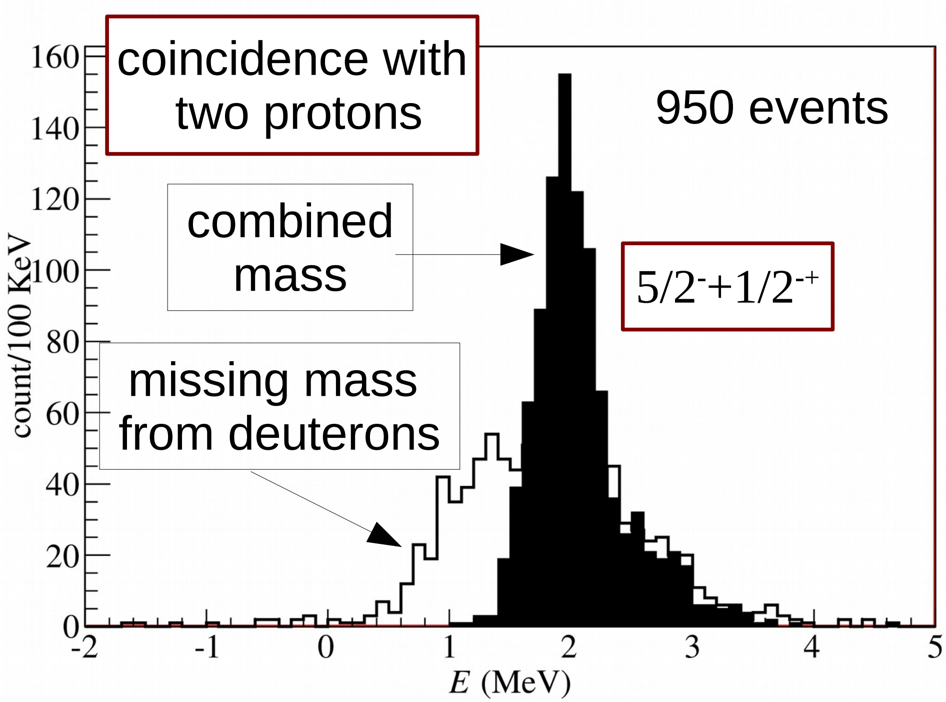
combined mass

- allow to accumulate high statistics
- better resolution compared to missing mass method

^{17}Ne: excitation spectrum







- combined mass method provides much better resolution than missing mass
- no event related to 2p decay of $3/2^-$ state observed
- new limit of 2p partial width

$$\Gamma_{2p}/\Gamma_\gamma \leq 8 \times 10^{-5}$$

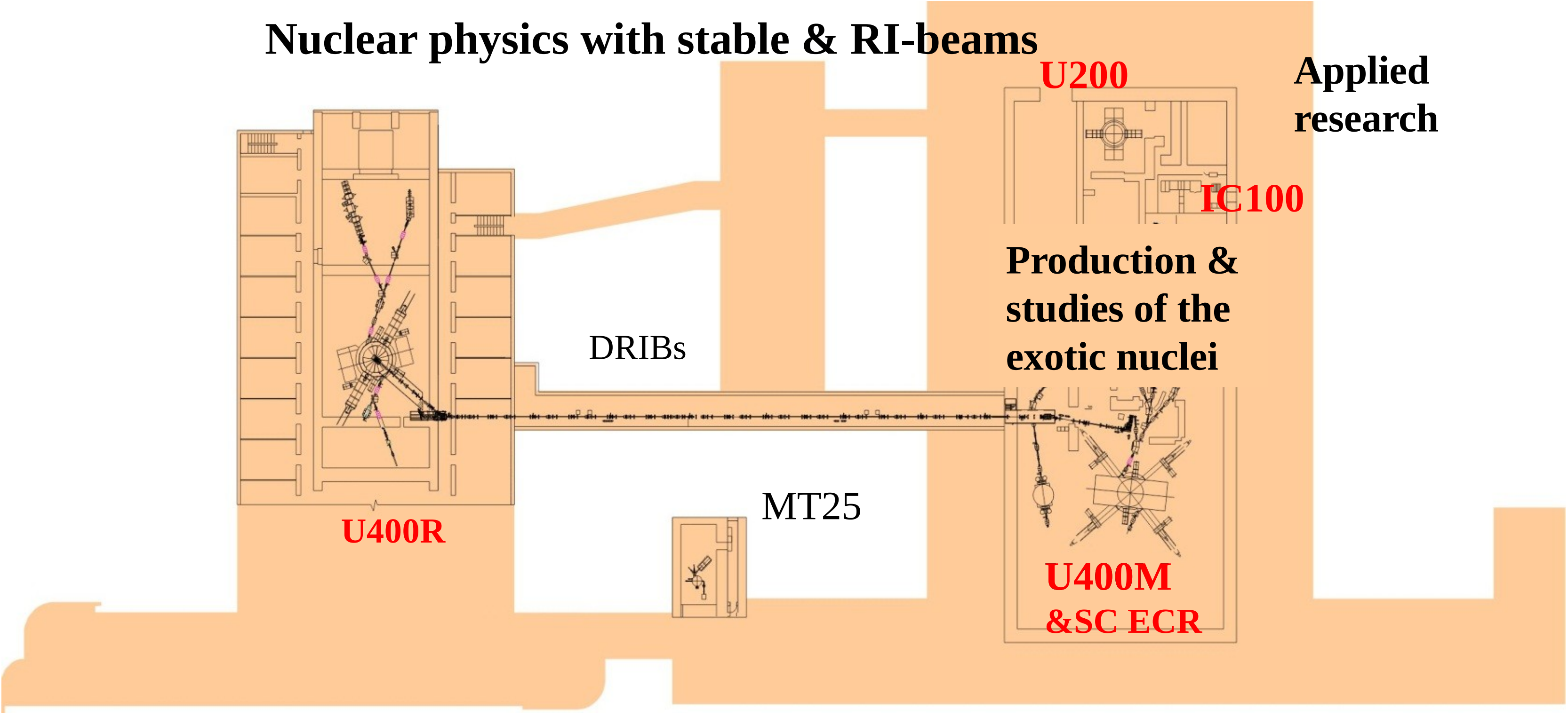
First conclusion

- **^{6}Be**
  - the ground, 2^{+} states populated, manifestation of the Isovector Soft Dipole Mode
  - proper theoretical model developed
  - analysis of external correlations: suitable tool for investigation of reaction mechanism
- **^{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
- **^{17}Ne**
  - experimental resolution significantly enhanced by means of “combined mass” method
  - no events of $3/2^{-}$ state related to true 2p decay
  - new limit upper limit $\Gamma_{2p}/\Gamma_{\gamma} \leq 8 \times 10^{-5}$ established, by 2 orders of magnitude better than existing data

towards the (near) future ...

Superheavy elements factory

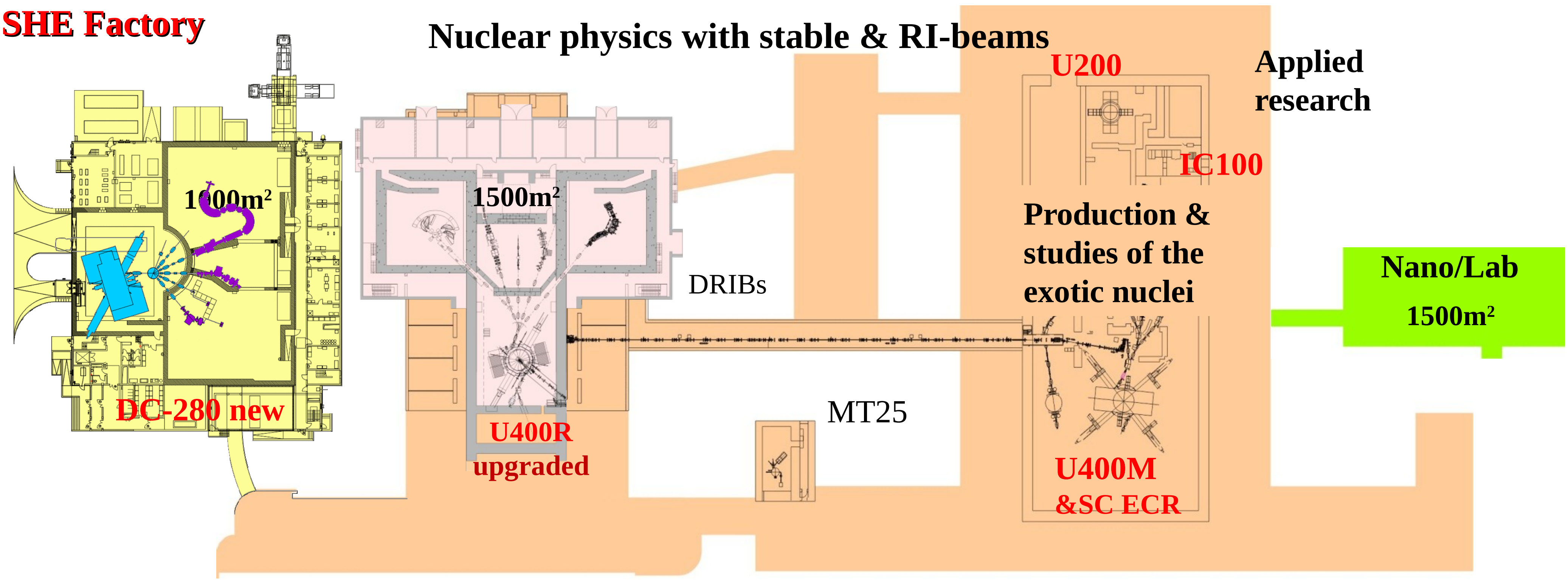
Current state of FLNR



Superheavy elements factory

Full-scale realization off the DRIBs-III

Dubna **R**adioactive **B**eams



targets

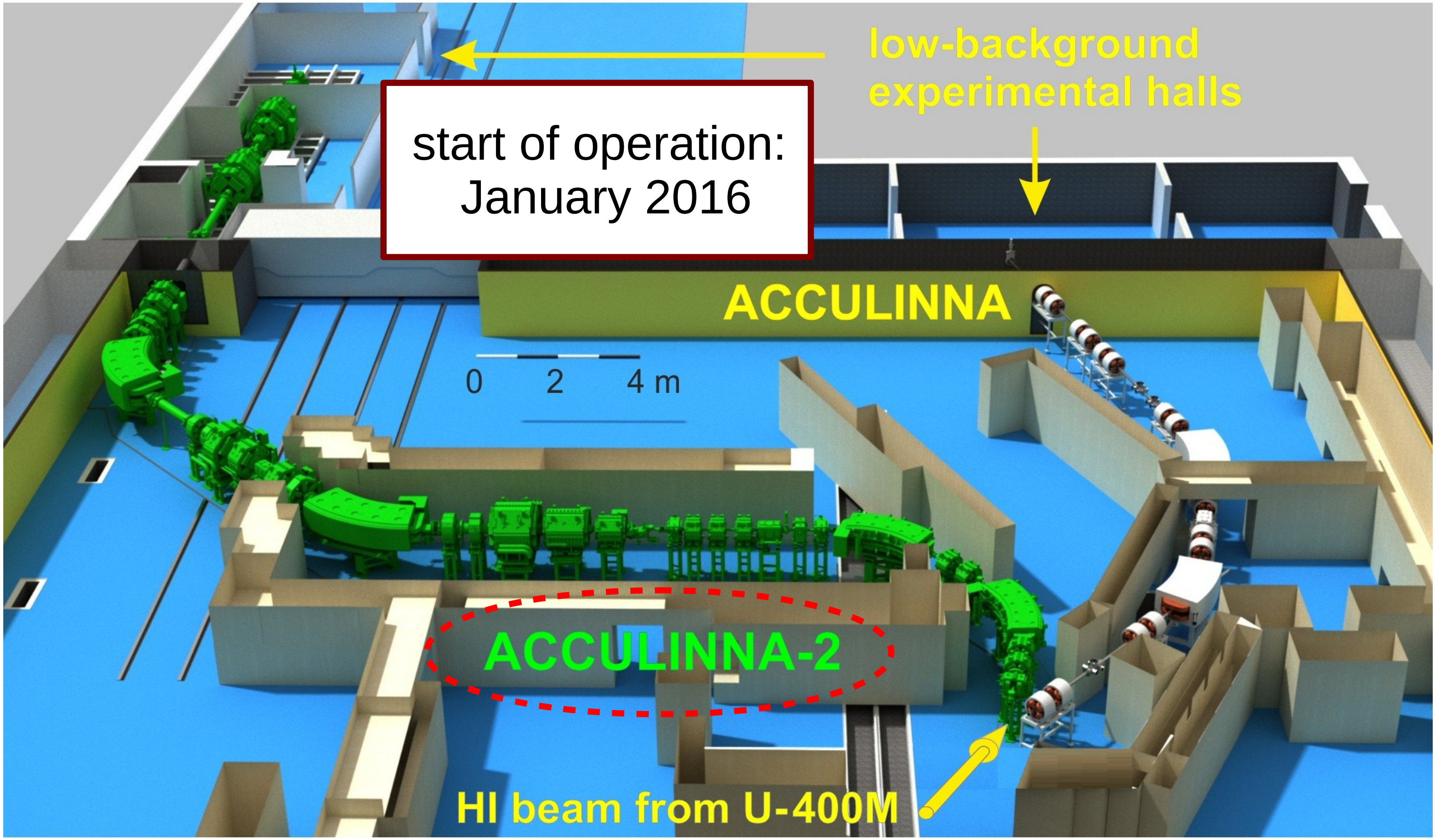
^{251}Cf, ^{254}Es, ...?

beams

^{48}Ca; ^{50}Ti; ^{54}Cr; ^{58}Fe; ^{64}Ni

$I_{beam} > 10^{14}$ pps

LEN: ACCULINNA-2

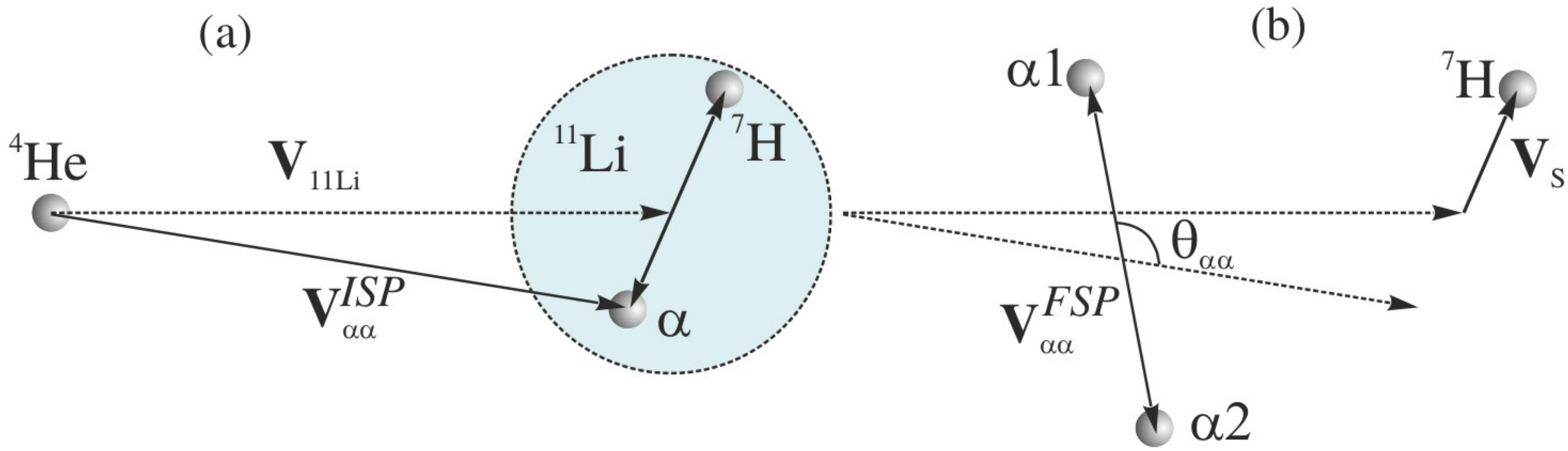


- energy range 6 – 60 MeV/A
- beam intensities higher in 2 orders
- Z_{RIB} ~ 1 – 36

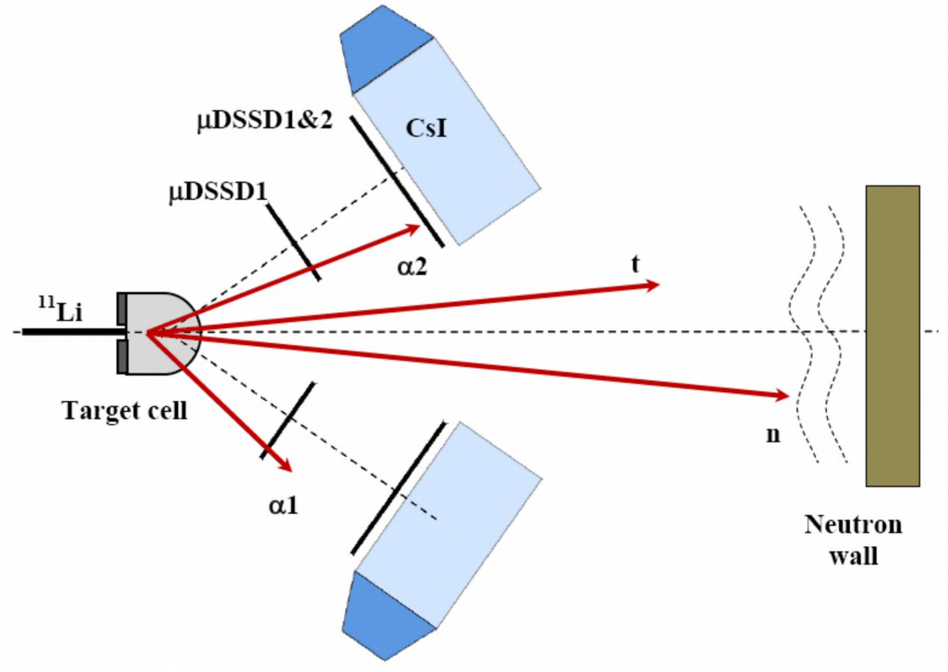
^{5}H and ^{7}H isotopes

quasifree scattering

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

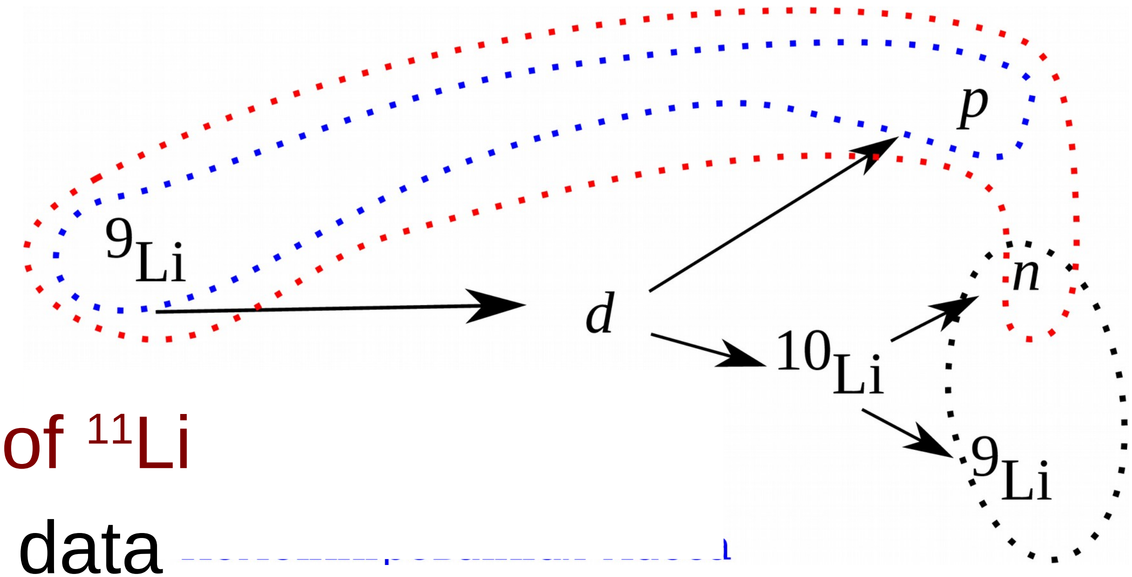


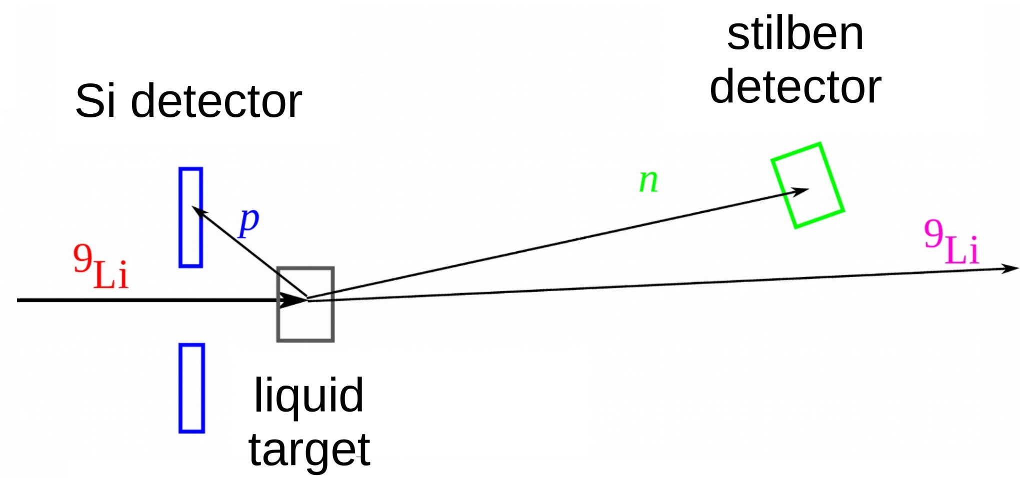
- largest proton-neutron asymmetry among known nuclei
- decay pattern
  - 3-body: t + 2n
  - 5-body: t + 5n !!!!!
- very restricted experimental data

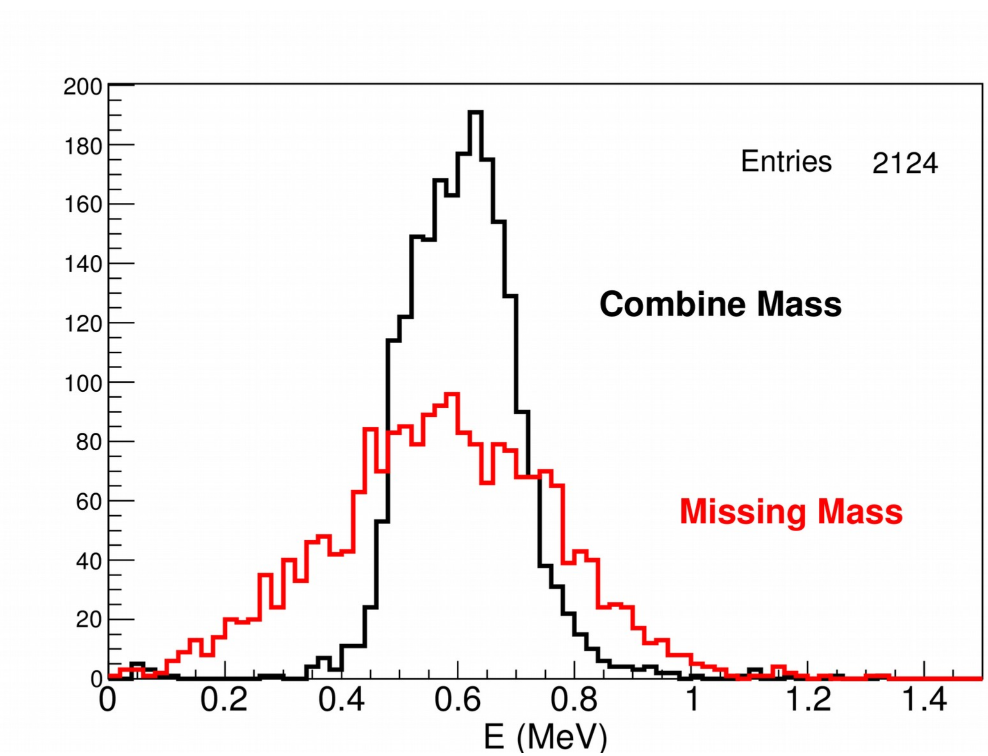


^{10}Li isotope

- subsystem of ^{11}Li
- interaction of ^{10}Li + p needed for description of ^{11}Li
- restricted experimental data

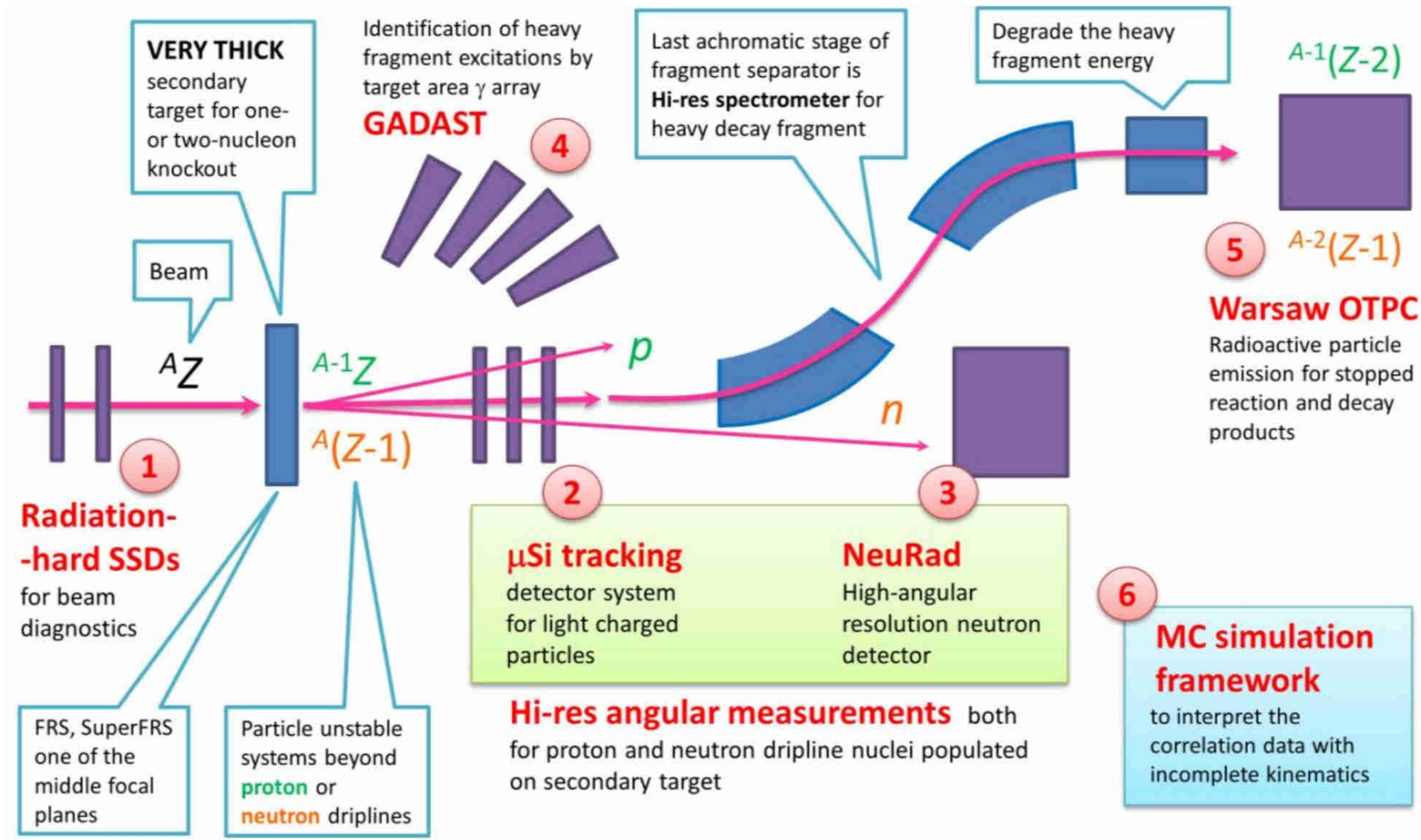






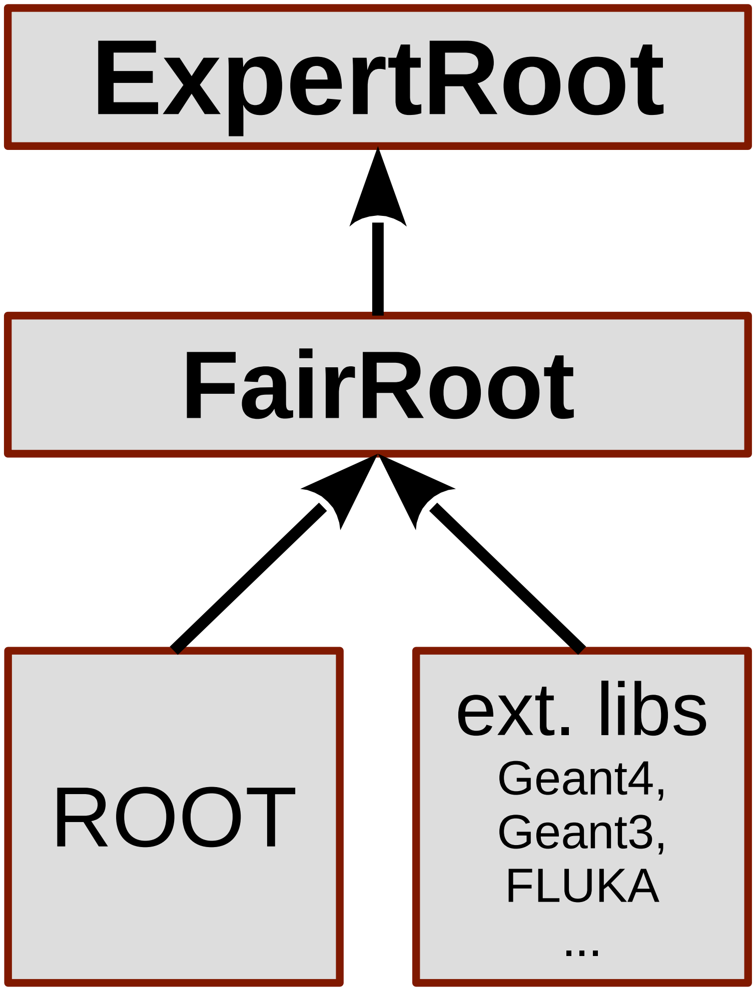
combined mass method provides resolution ~200 keV

EXPERT@SuperFRS@FAIR

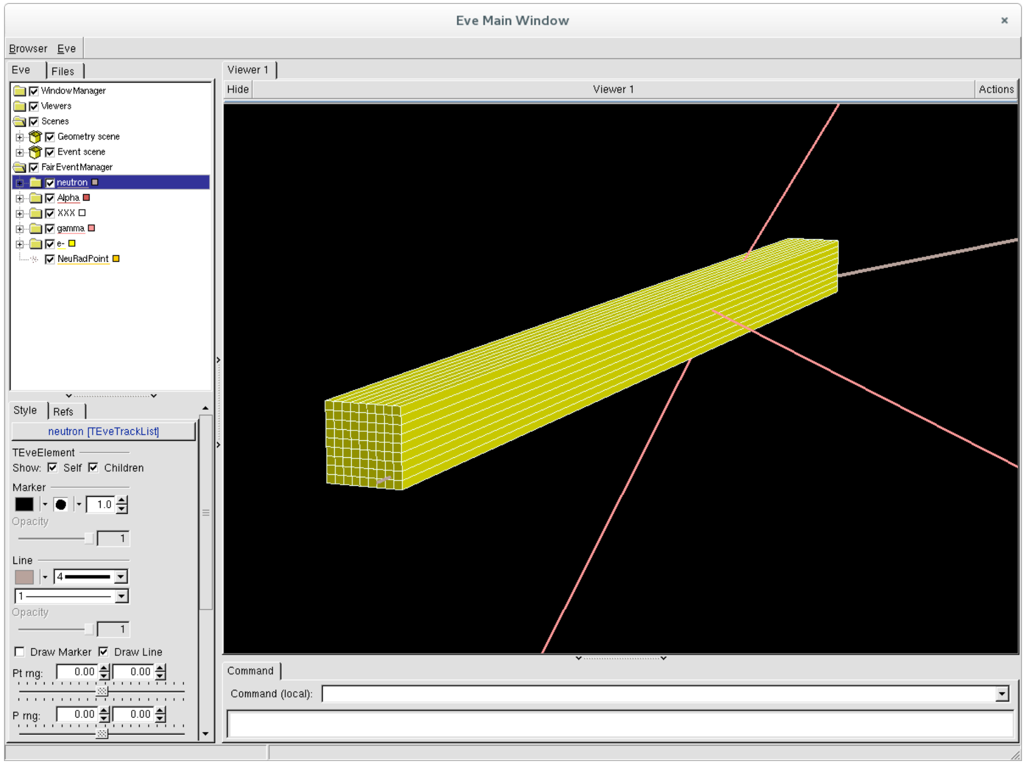


Software to handle the EXPERT and ACCULINNA instrumentation is needed

ExpertRoot: Software for data analysis and simulations



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



Conclusions

- first beam at ACCULINNA-2 expected very soon
- rich experimental program for separators ACCULINNA
- development of software framework ExpertRoot in process

Thank you for your attention

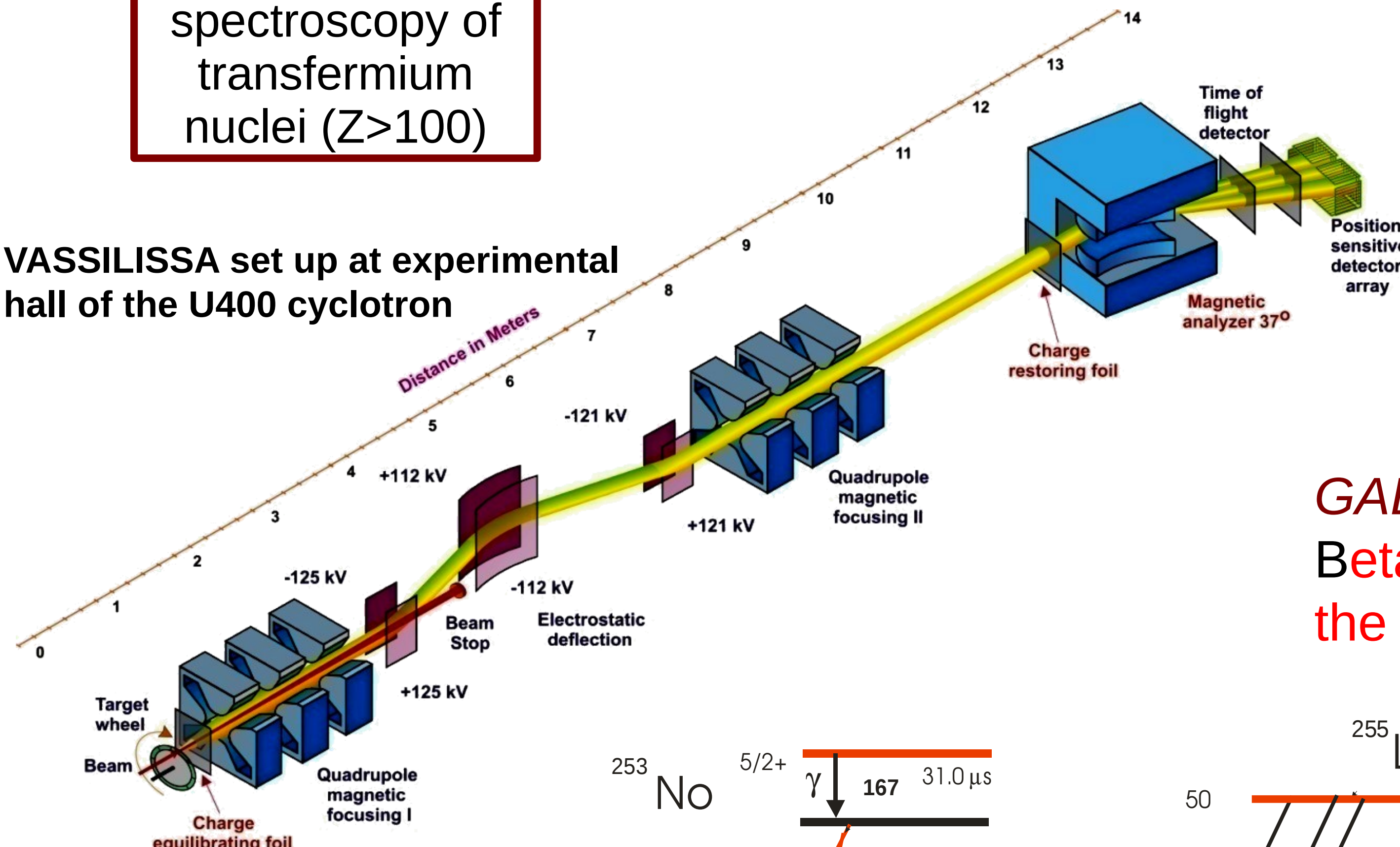
Thank you for your attention

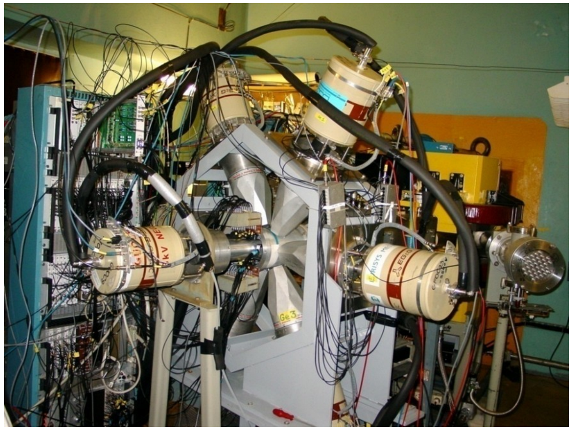
Appendices

SHE: spectroscopy

spectroscopy of transfermium nuclei (Z>100)

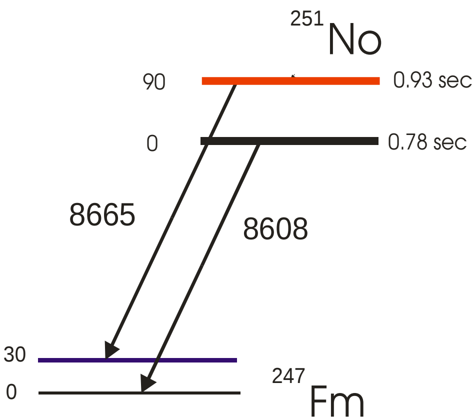
VASSILISSA set up at experimental hall of the U400 cyclotron

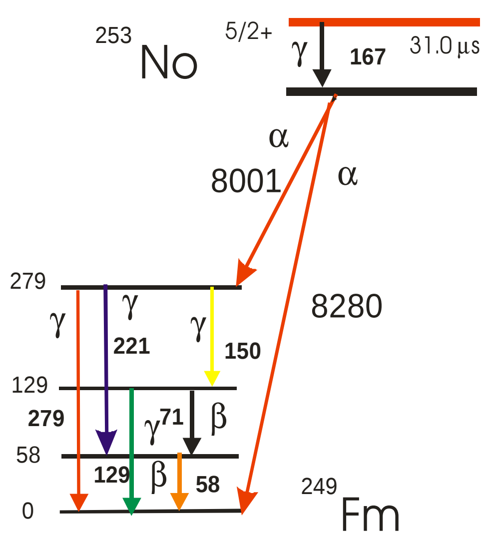


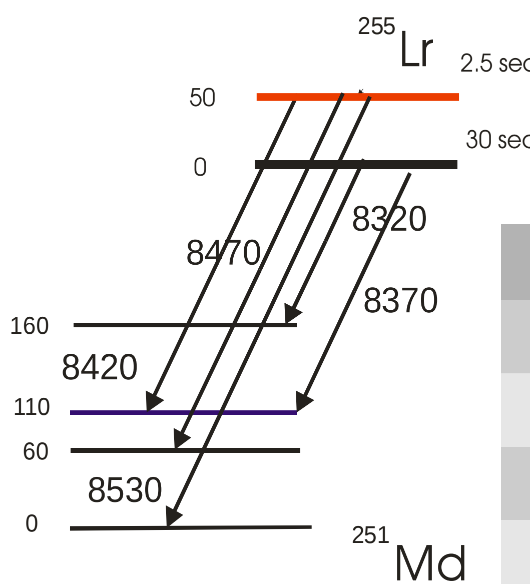


GABRIELA: Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser

in collaboration with CRN (France)

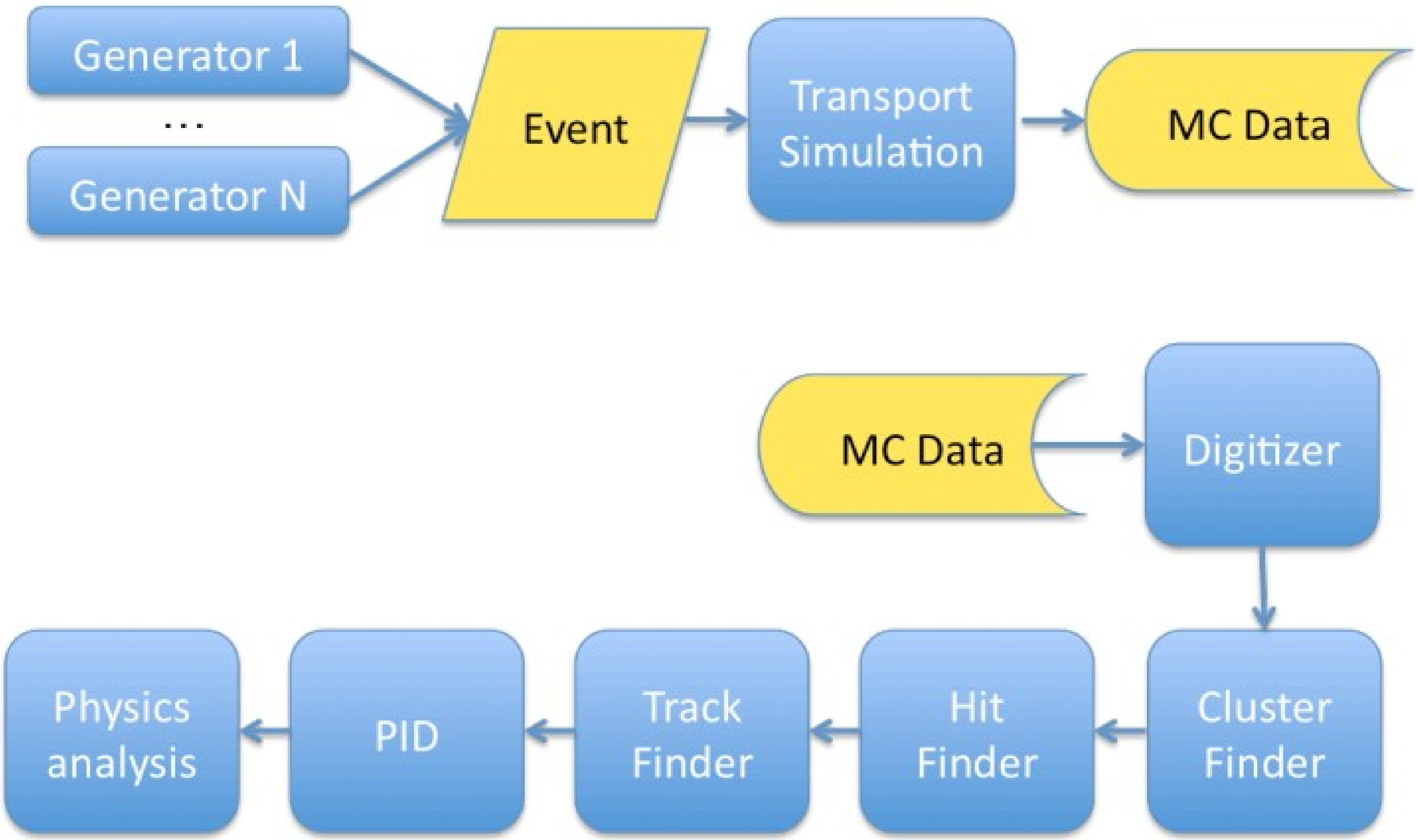






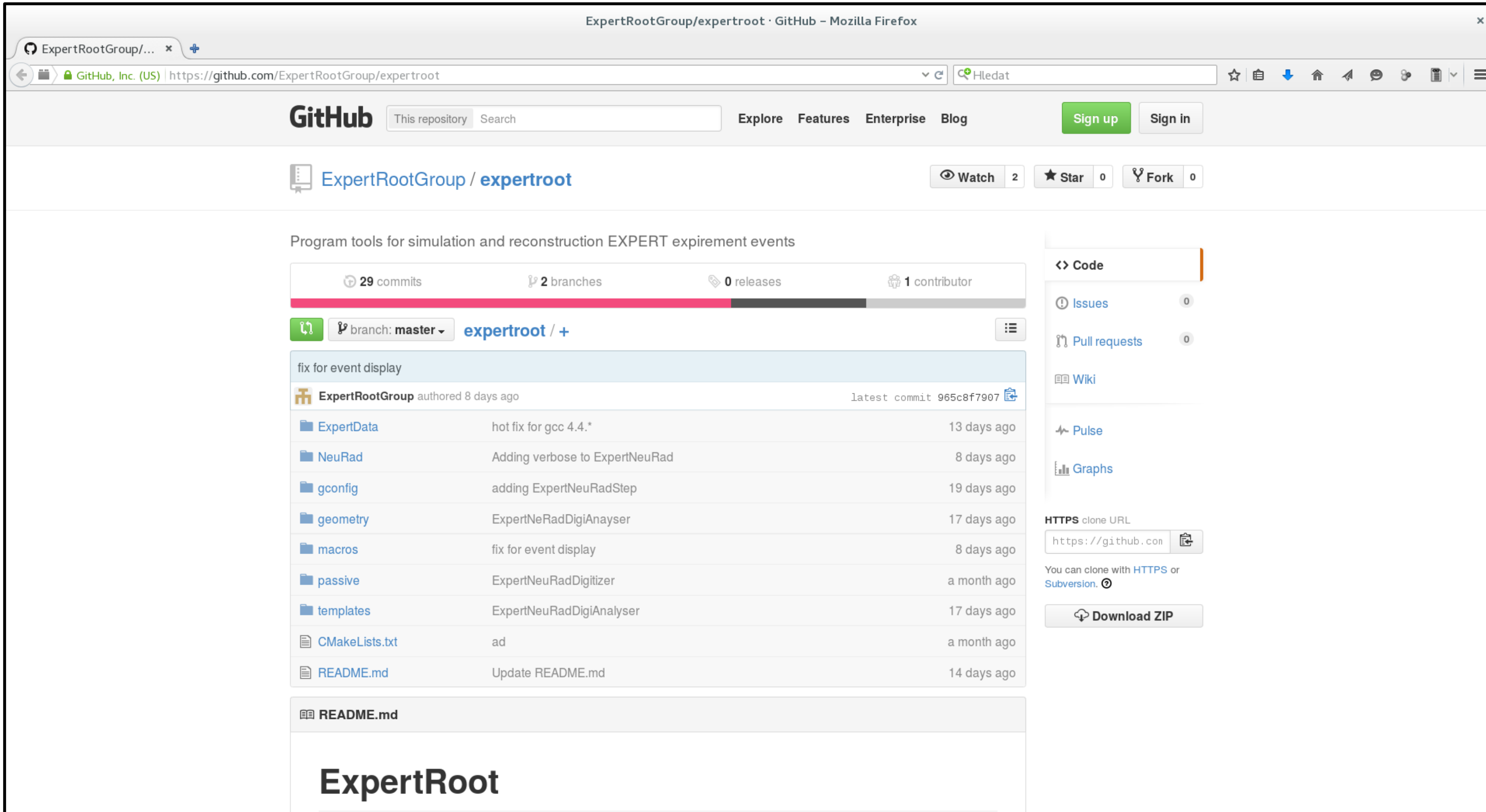
Experiments in 2014
^{22}Ne(^{197}Au,5n)^{214}Ac
^{22}Ne(^{206}Pb,4n)^{224}U
^{40}Ar(^{208}Pb,3n)^{245}Fm
^{50}Ti(^{208}Pb,2n)^{256}Rf

ExpertRoot: Inherited workflow

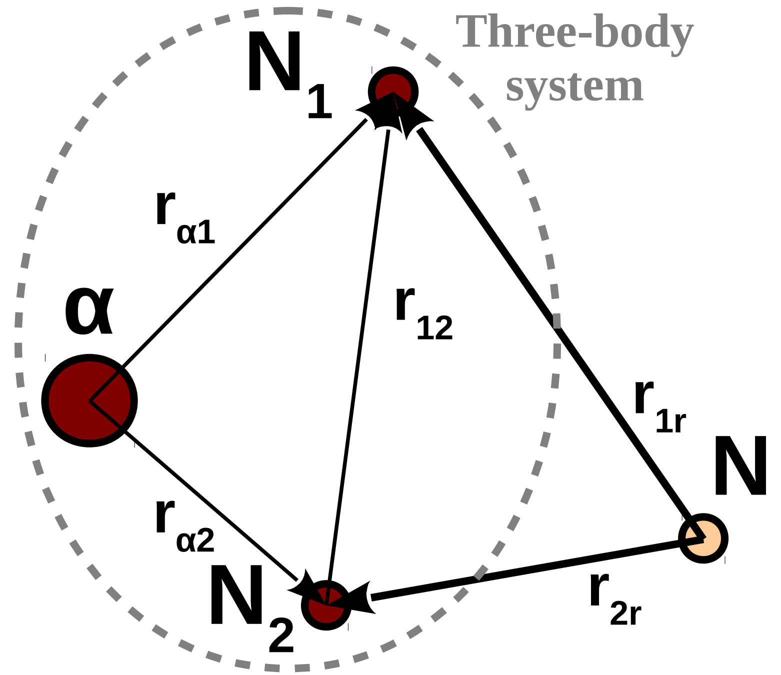


ExpertRoot: How to get?

https://github.com/ExpertRootGroup/expertroot



^{6}Be: theoretical model



- **PWIA** in combination with **3-body model**
- our task is reduced to solving of inhomogenous Schroedinger equation with source on the right side

$$(\hat{H}_3 - E_T)\Psi^{JM(+)}_{^6\mathrm{Be}} = \hat{\mathcal{O}}_{\mu'\mu}\Psi^{J^{(\mathrm{in})}M^{(\mathrm{in})}}_{^6\mathrm{Li}}$$

- transition operator (function of ***q***) contains information about population of ^{6}Be from ^{6}Li

$$\hat{\mathcal{O}}_{\mu'\mu} = \sum_{i=1,2}\sum_{lm} f_l(q,r_i)Y_{lm}(\hat{r}_i)Y^*_{lm}(\hat{q})\ \tau^{(i)}_{-}\ \sum_{\nu}(-1)^{\nu}\sigma^{(i)}_{\nu}C^{\frac{1}{2}\mu'}_{\frac{1}{2}\mu 1\nu}$$

- transition operator takes a “simple” analytical form thanks to the choice of the N-N potential used in PWIA calculations

$$\hat{V}_{ir}(r_{ir}) \quad = \quad (\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_r)(\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_r)\ V_0\exp\left[-\left((\mathbf{r}+\mathbf{r}_i)^2/r_0^2\right)\right]$$

External correlations

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

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

"slow" degrees of freedom: 3-body motion of ^{6}Be decay products

"fast" degrees of freedom: the population of the states in ^{6}Be via the reaction mechanism

parametrization of density matrix:

$$\rho^{J'M'}_{JM} = \begin{Bmatrix} W_{0,0} & 0 & 0 & \sqrt{W_{0,0}W_{2,0}}\cos(\varphi_{02}) & 0 & 0 \\ 0 & W_{2,-2} & 0 & 0 & 0 & 0 \\ 0 & 0 & W_{2,-1} & 0 & 0 & 0 \\ \sqrt{W_{0,0}W_{2,0}}\cos(\varphi_{02}) & 0 & 0 & W_{2,0} & 0 & 0 \\ 0 & 0 & 0 & 0 & W_{2,1} & 0 \\ 0 & 0 & 0 & 0 & 0 & W_{2,2} \end{Bmatrix}$$

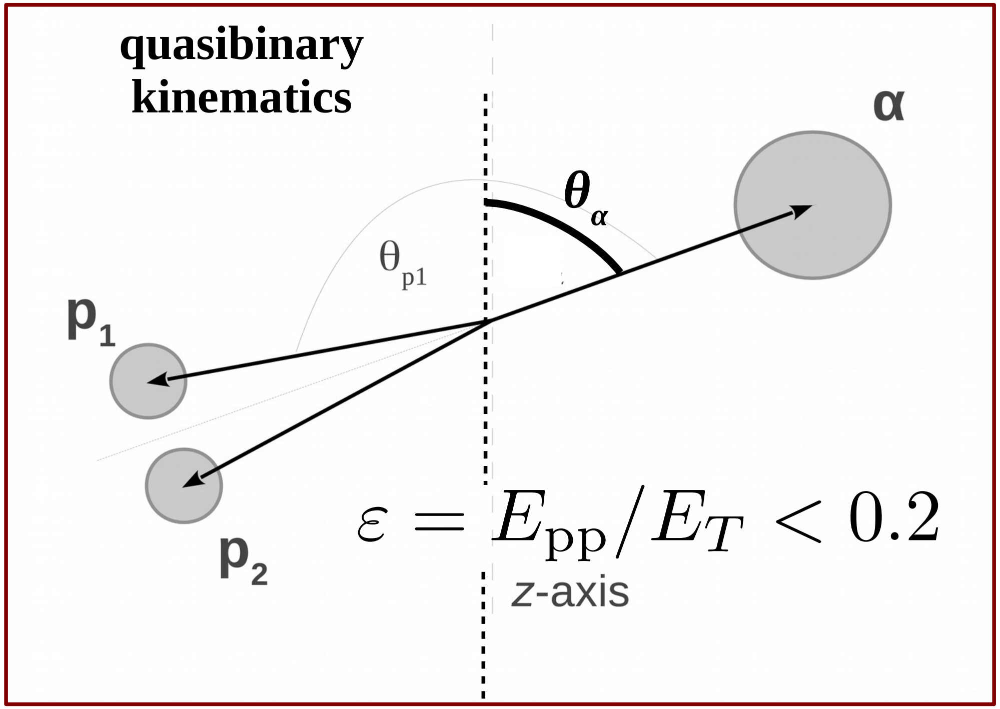
- "slow" degrees of freedom: internal correlations describing the 3-body decay
- "fast" degrees of freedom related to reaction mechanism
  - external correlations: 3-body system orientation
  - interference of 0^+ and 2^+ states

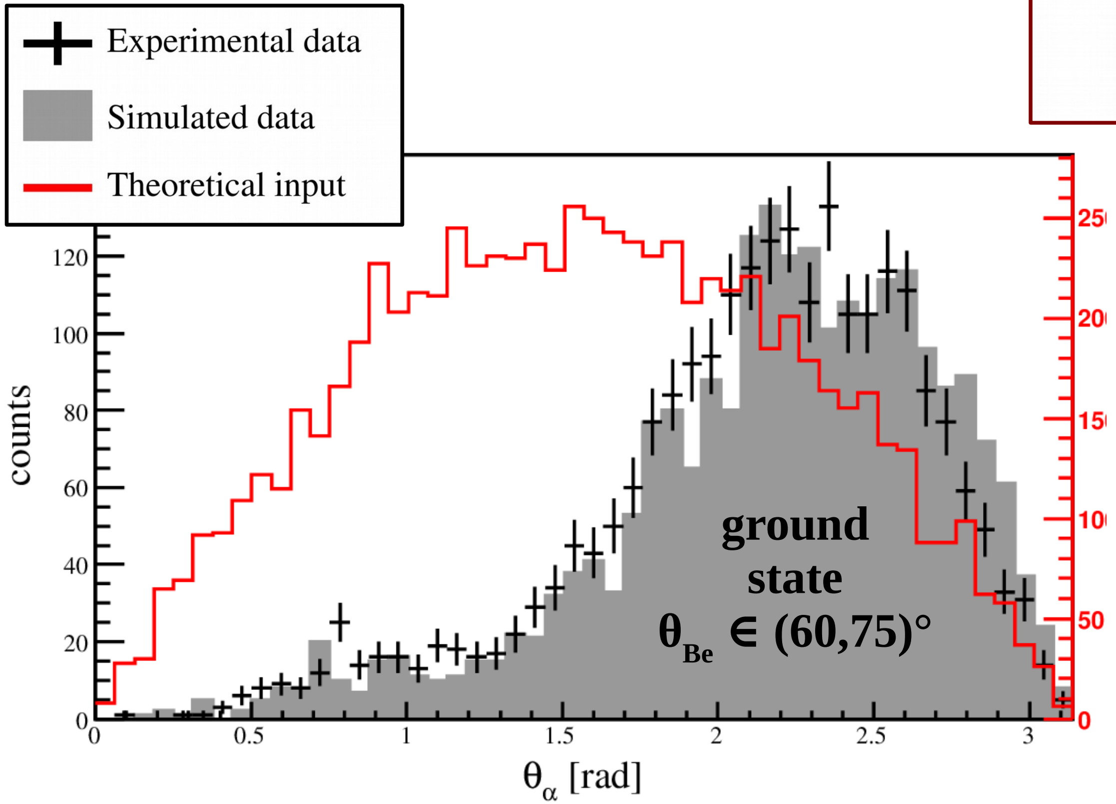
model parameters for extreme cases

- orientation
  - alignment: $|\rho_{00}|^2 \sim 1$, $|\rho_{2m}|^2 \sim \delta_{m0}$
  - nonalignment: $|\rho_{00}|^2 \sim 1$, $|\rho_{2m}|^2 \sim 1/5$
- interference
  - constructive ($\varphi_{02} = 0°$), incoherent ($\varphi_{02} = 90°$), destructive ($\varphi_{02} = 180°$)

External correlations: Data analysis

- model parameters reveal themselves in 3-body system orientation
- structure is fixed ($\varepsilon<0.2$)
  - “quasibinary” decay
  - chance to observe distributions of angular momenta of 0^+ and 2^+



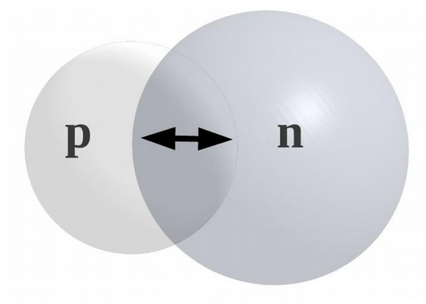


ground state

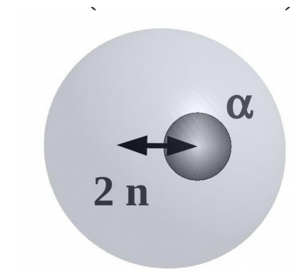
- no free model parameters
- good agreement between experimental and simulated data
- spectrum strongly affected by efficiency

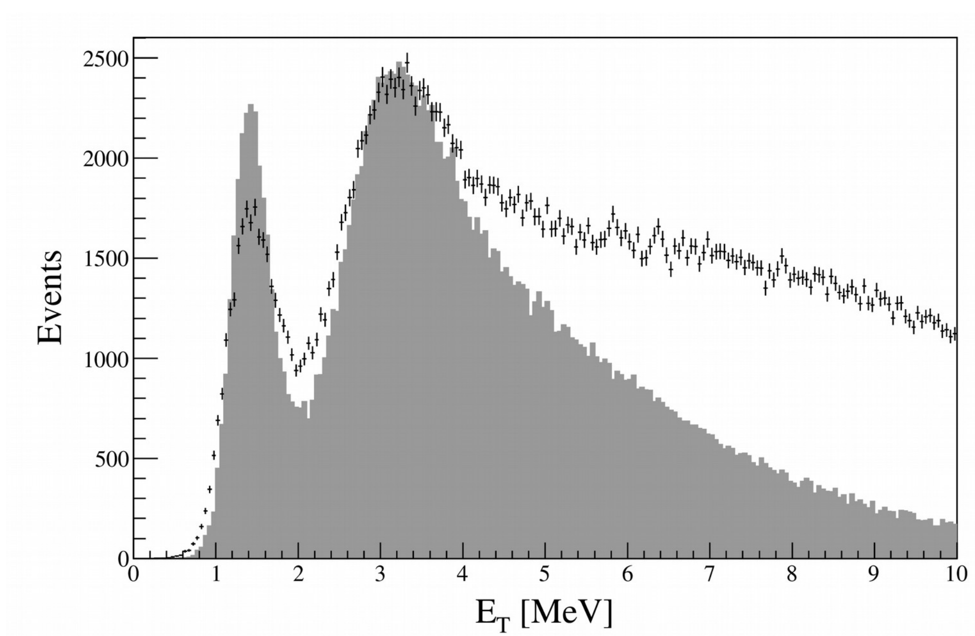
^{6}Be: Soft dipole mode (SDM) of giant dipole resonance (GDR)

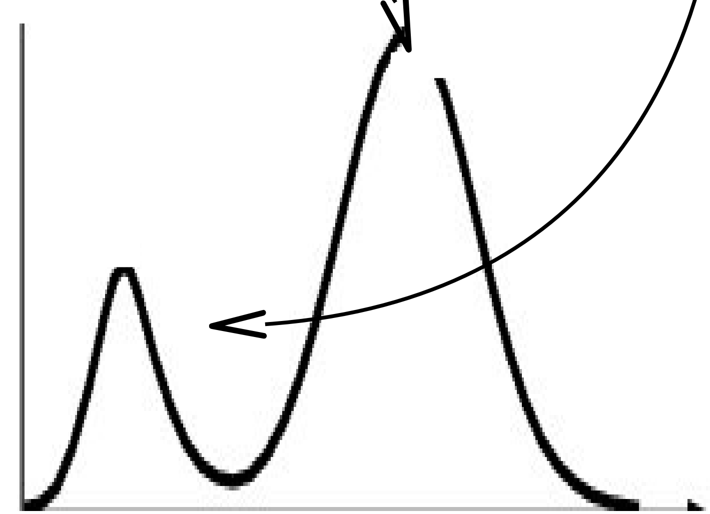
- GDR
  - protons vs. neutrons
  - $\Delta L=1$, $\Delta T=1$
  - E_{GDR} ~ 14 – 24 MeV
  - induced by EM excitation



- SDM
  - halo vs. core
  - $\Delta L=1$
  - E_{SDM} lower than E_{GDR}
  - induced by EM excitation and charge-exchange reaction







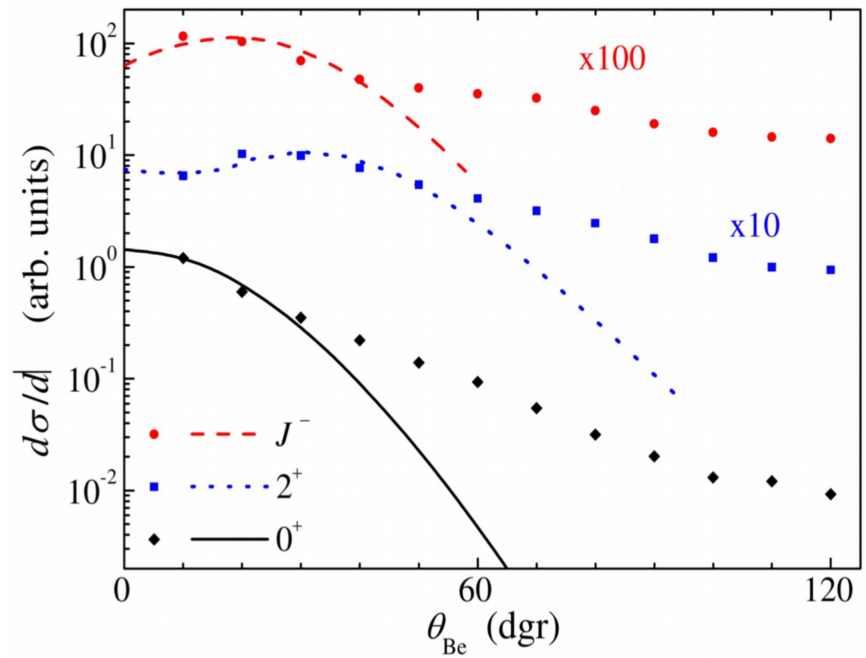
^{6}Be: Isovector SDM

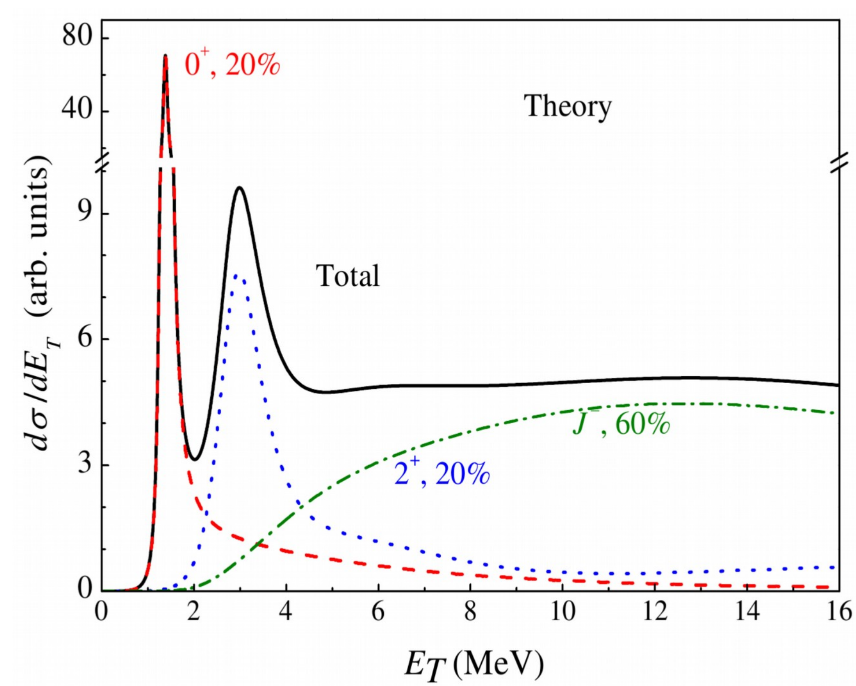
- broad hump above the 2^+ state observed also in other experiments
- analysis of angular distributions allowed us to assign ΔL=1 to this structure
- cross section of the hump is comparable with cross section of resonance states
- interpreted as an isovector soft dipole mode (IVSDM)

resonance	vs.	mode
property of particular nucleus		characteristic for specific reaction
its population does not depend on reaction mechanism		its population is given by reaction mechanism

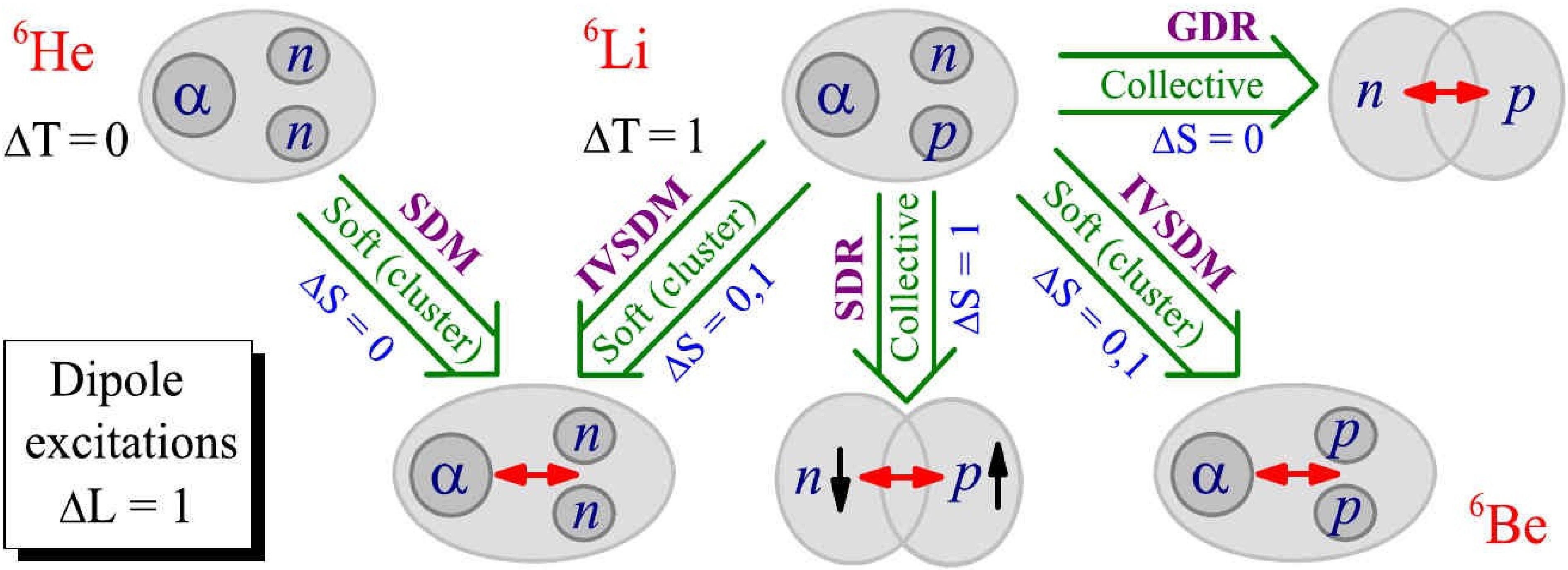
IVSDM population in ^{6}Be:

$$\hat{O} \sim \sum_i f_l(q, r_i) \left[\alpha + \beta \sigma_\mu^{(i)}\right] \tau_\pm^{(i)} Y_{1m}(\hat{r}_i)$$

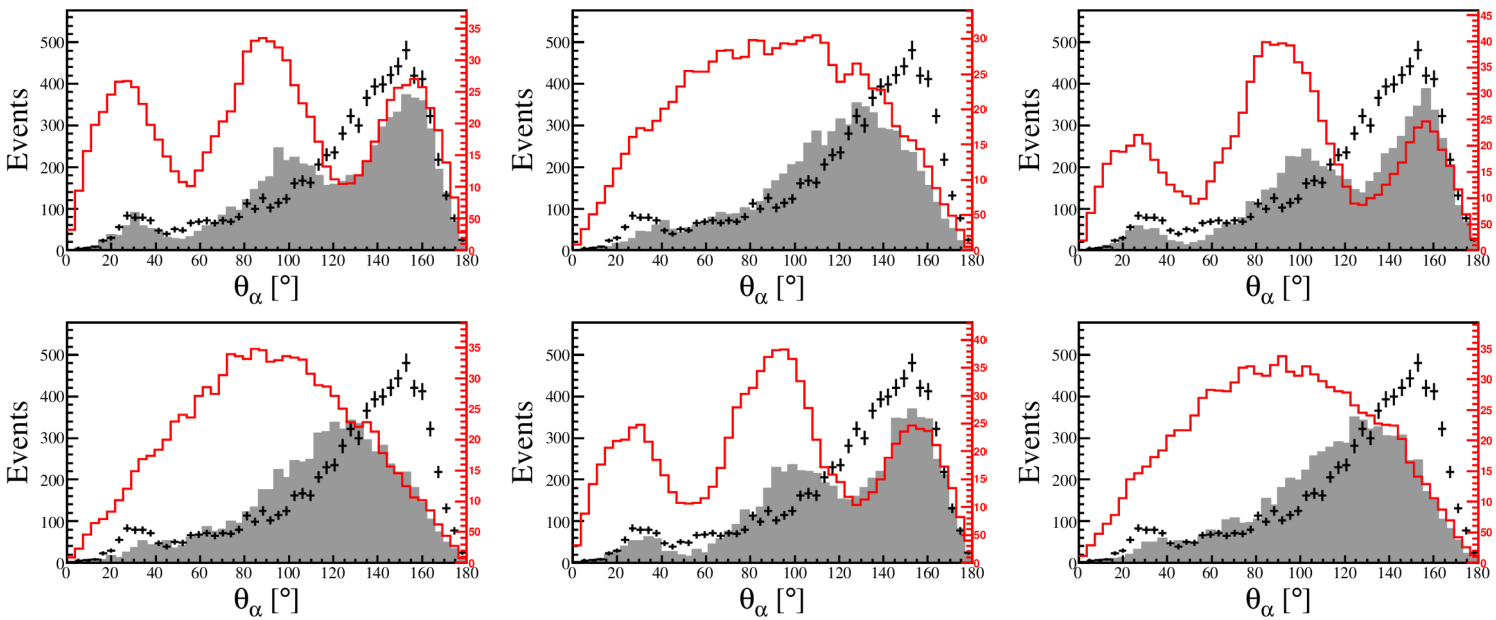




IVSDM



⁶He
ΔT = 0
α
n
n
⁶Li
ΔT = 1
α
n
p
GDR
Collective
ΔS = 0
n
p
SDM
Soft (cluster)
ΔS = 0
IVSDM
Soft (cluster)
ΔS = 0,1
SDR
Collective
ΔS = 1
IVSDM
Soft (cluster)
ΔS = 0,1
Dipole excitations
ΔL = 1
α
n
n
n
p
α
p
p
⁶Be


Events
θα [°]
0 20 40 60 80 100 120 140 160 180
0 100 200 300 400 500

^{17}Ne: 2p-decay of the 3/2$^-$ state