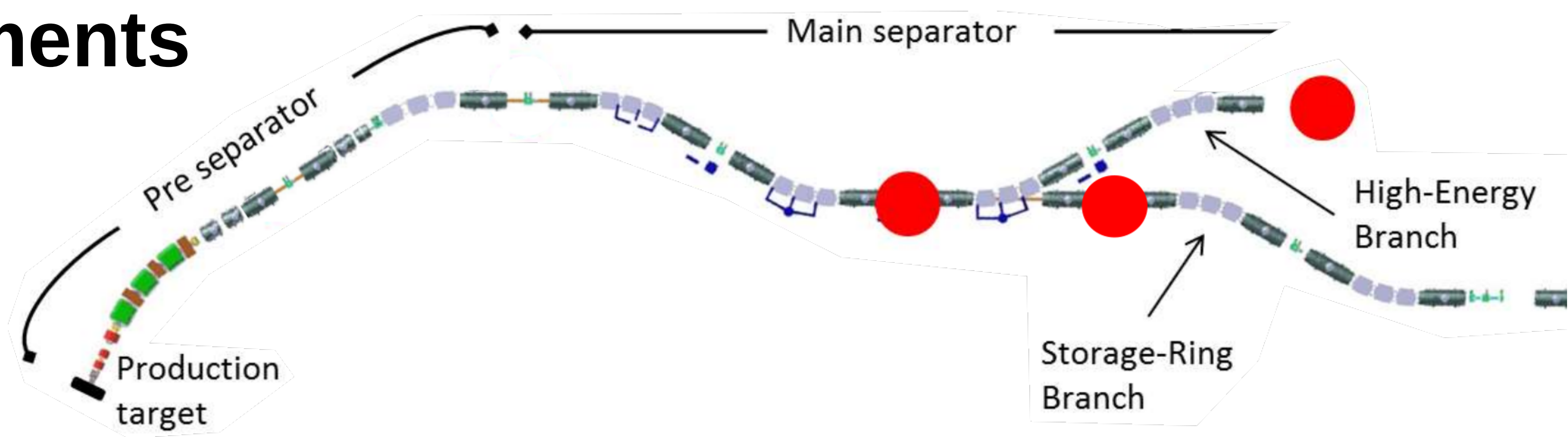
The EXPERT project at the Super-FRS fragment separator

Vratislav Chudoba

FLNR, JINR

NUclear STructure, Astrophysics and Reactions

SuperFRS Experiments



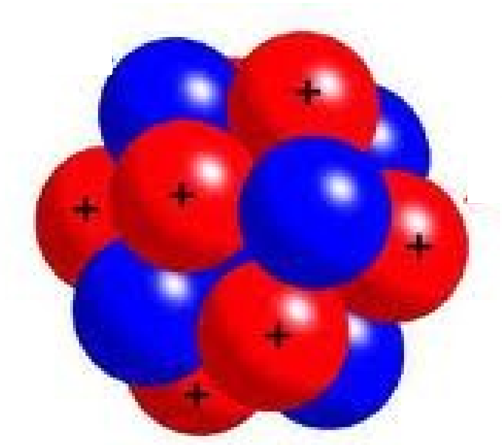
EXPERT (EXotic Particle Emission and Radioactivity by Tracking)

Physical case of EXPERT

- unknown exotic nuclear systems
- new types of radioactivity
- resonance decays
- beta-delayed decays
- exotic excitation modes

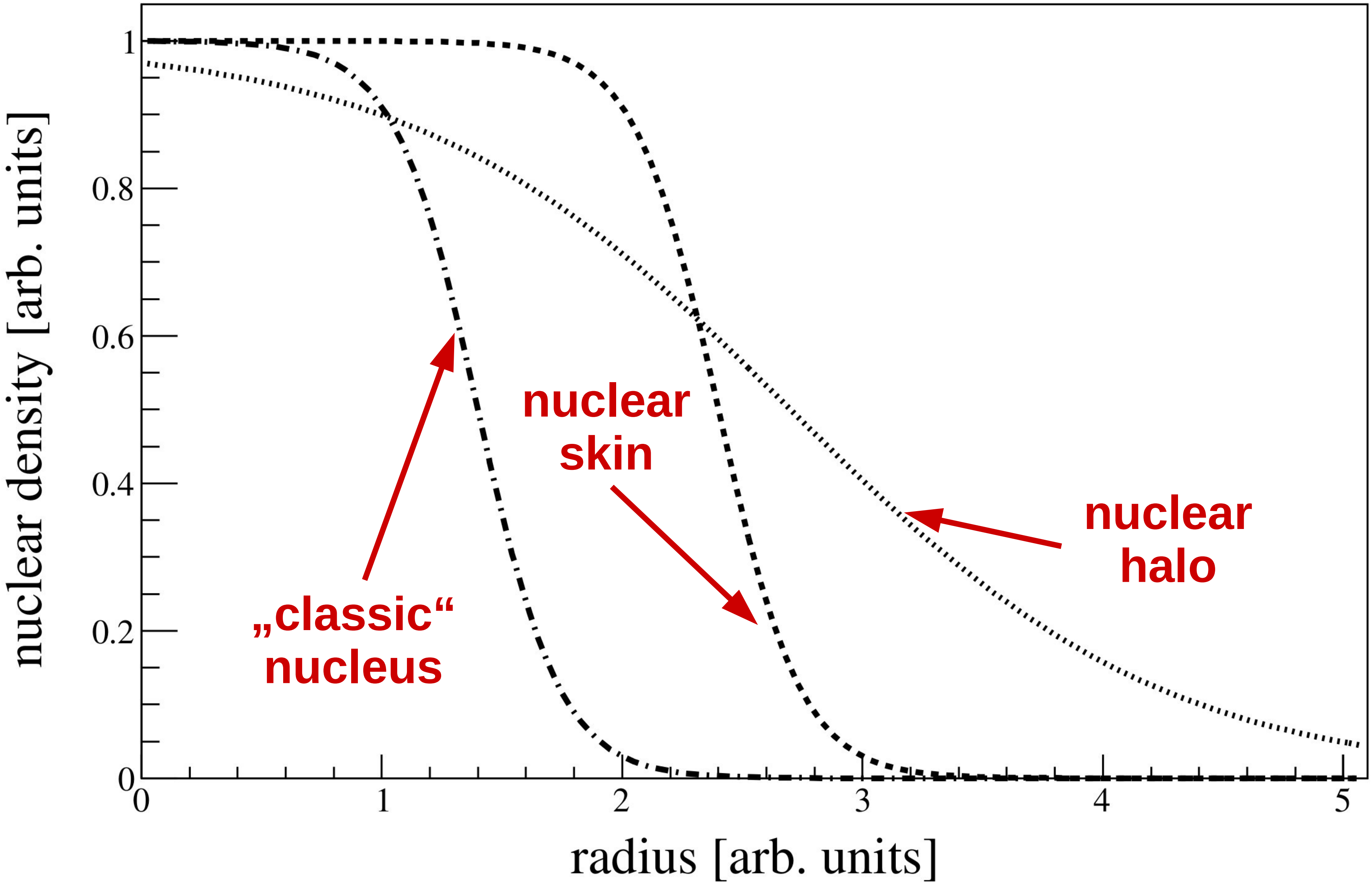
Why exotic?

- **far from stable nuclei**
- **complicatedly available**

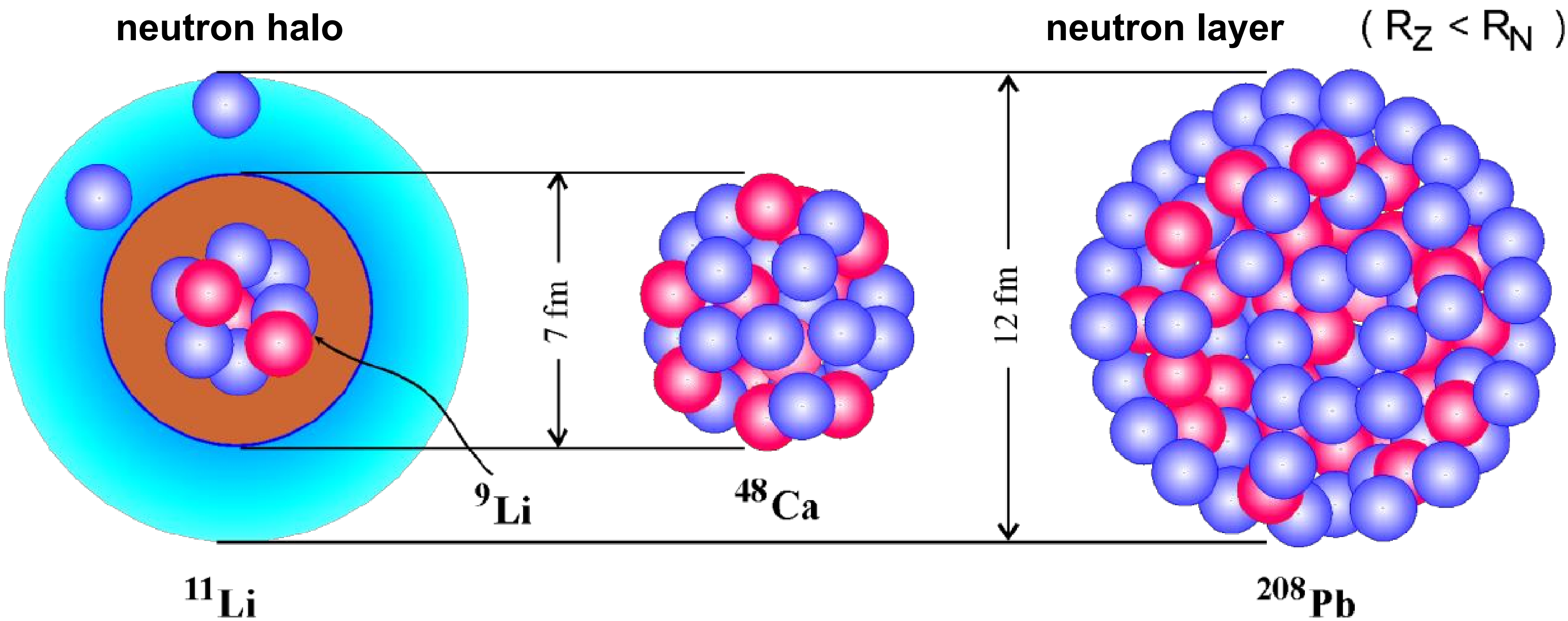


too heavy **or** **strange in other way**

Nuclear halo



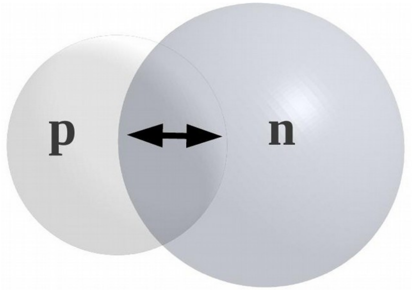
Nuclear halo



- **tunneling to the forbidden regions**
- **extended size of nucleus**

B. Jonson P.G. Hansen. The Neutron Halo of Extremely Neutron-Rich Nuclei. Europhys. Lett., 4(4):409–414, **1987**

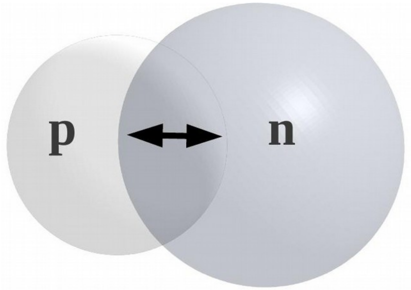
Soft dipole mode (SDM) of Giant dipole resonance (GDR)



GDR

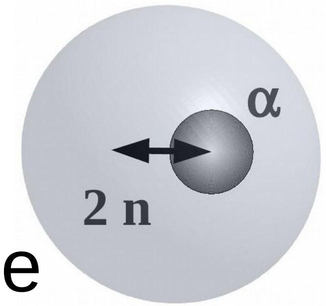
- protons vs. neutrons
- E_{GDR} ~ 14 – 24 MeV
- induced by EM excitation

Soft dipole mode (SDM) of Giant dipole resonance (GDR)



GDR

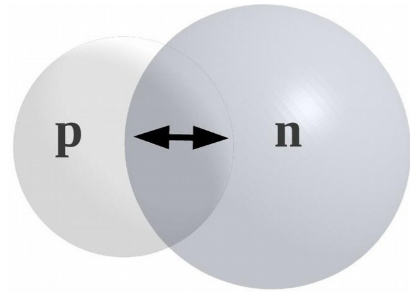
- protons vs. neutrons
- E_{GDR} ~ 14 – 24 MeV
- induced by EM excitation



SDM

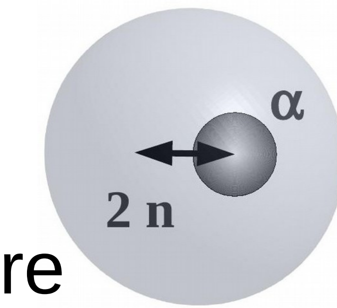
- halo vs. core
- E_{SDM} lower than E_{GDR}
- induced by EM excitation and charge-exchange reaction

Soft dipole mode (SDM) of Giant dipole resonance (GDR)



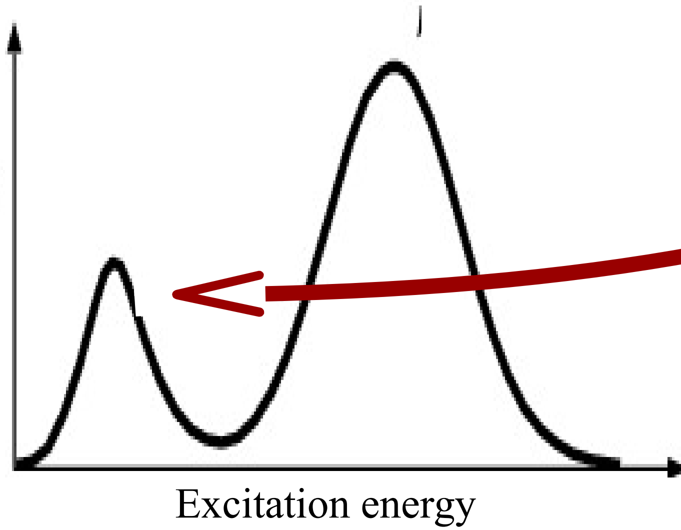
GDR

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

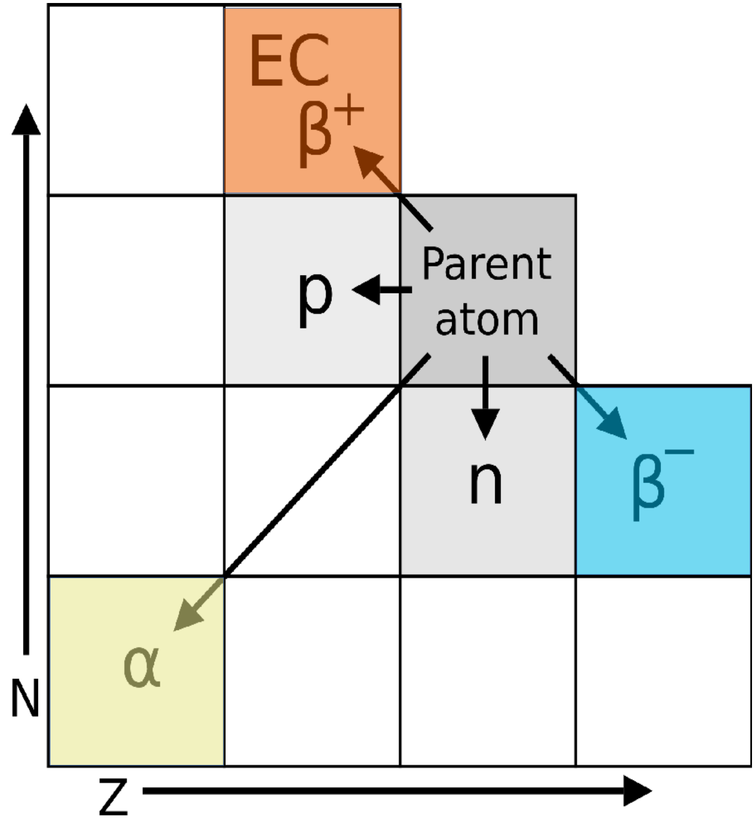


SDM

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



Radioactivity and decays



α decay
E. Rutherford, 1899

β^- decay
H. Becquerel, 1886

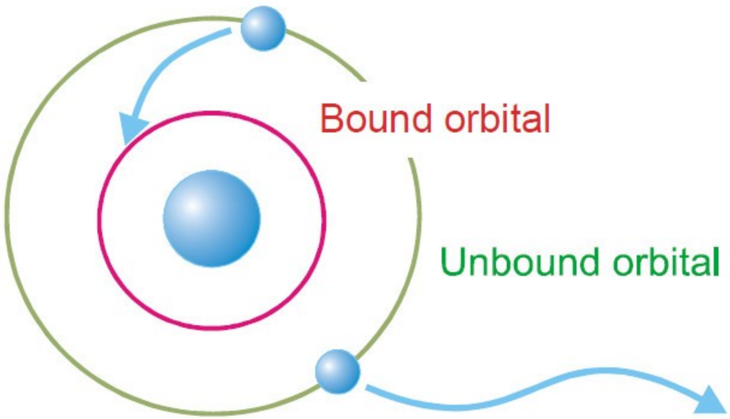
β^+ decay
F. and I. Joliot-Curie, 1932

p radioactivity
S. Hoffman, 1982

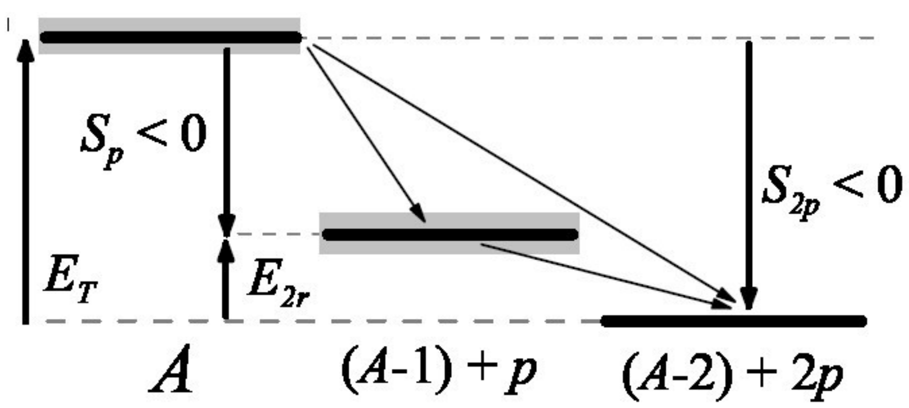
2p radioactivity
M. Pfützner, 2002

n radioactivity
still waiting

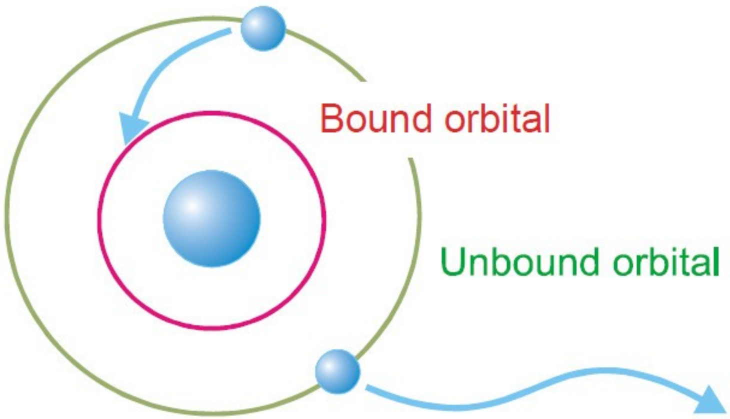
Proton radioactivity

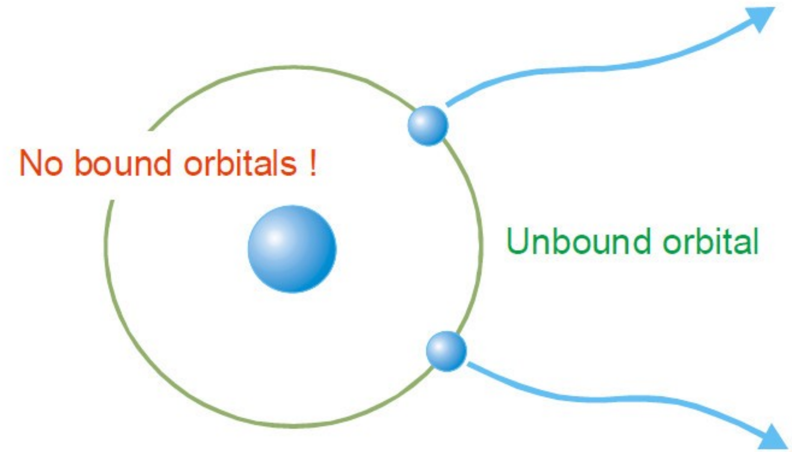


p-radioactivity
natural generalization
of α-radioactivity



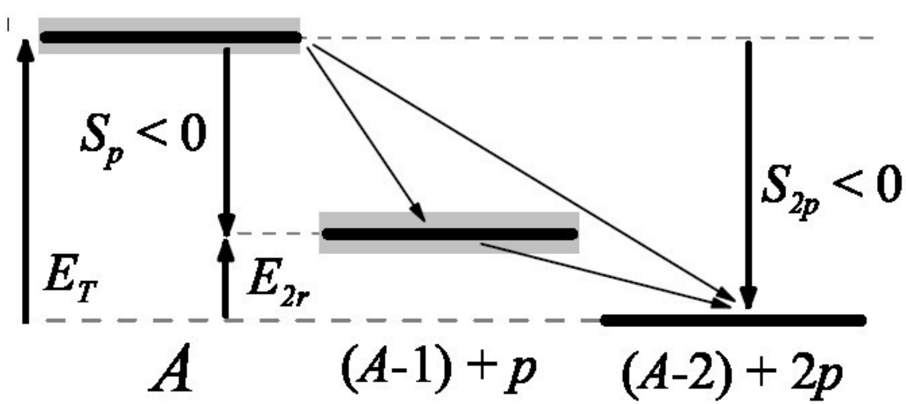
Proton radioactivity

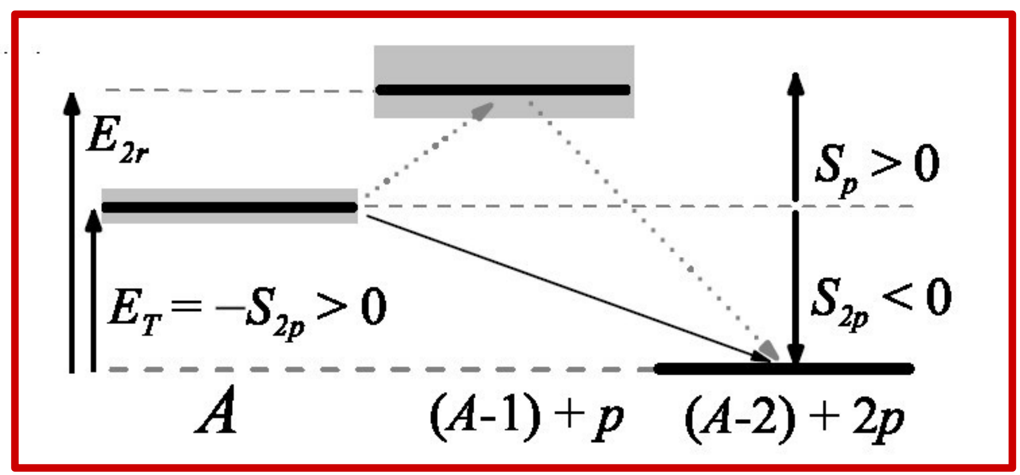




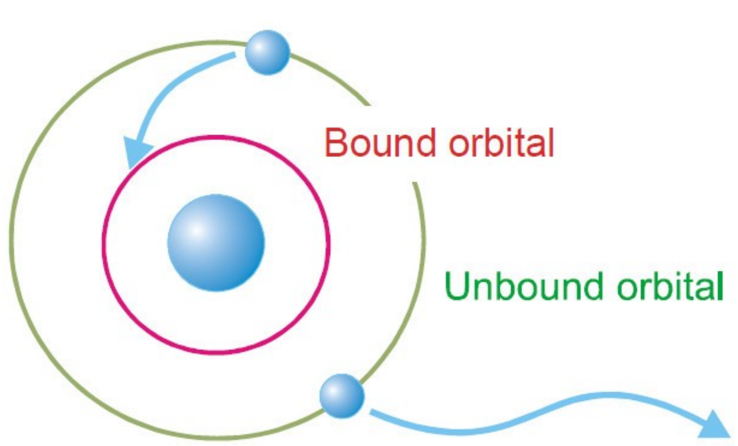
p-radioactivity
natural generalization of α-radiactivity

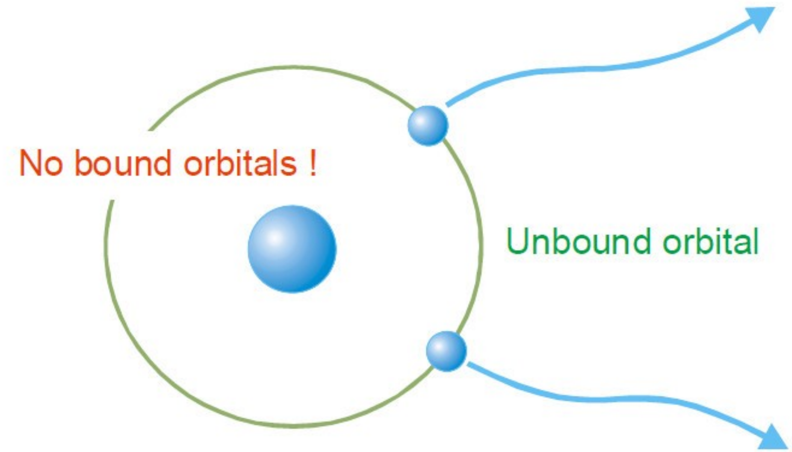
2p-radioactivity
genuine quantum mechanical phenomenon





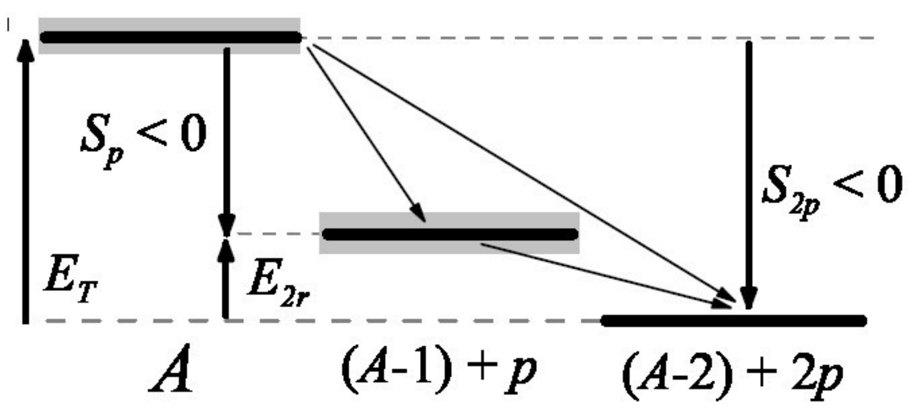
Proton radioactivity





p-radioactivity
natural generalization of α-radiactivity

2p-radioactivity
genuine quantum mechanical phenomenon

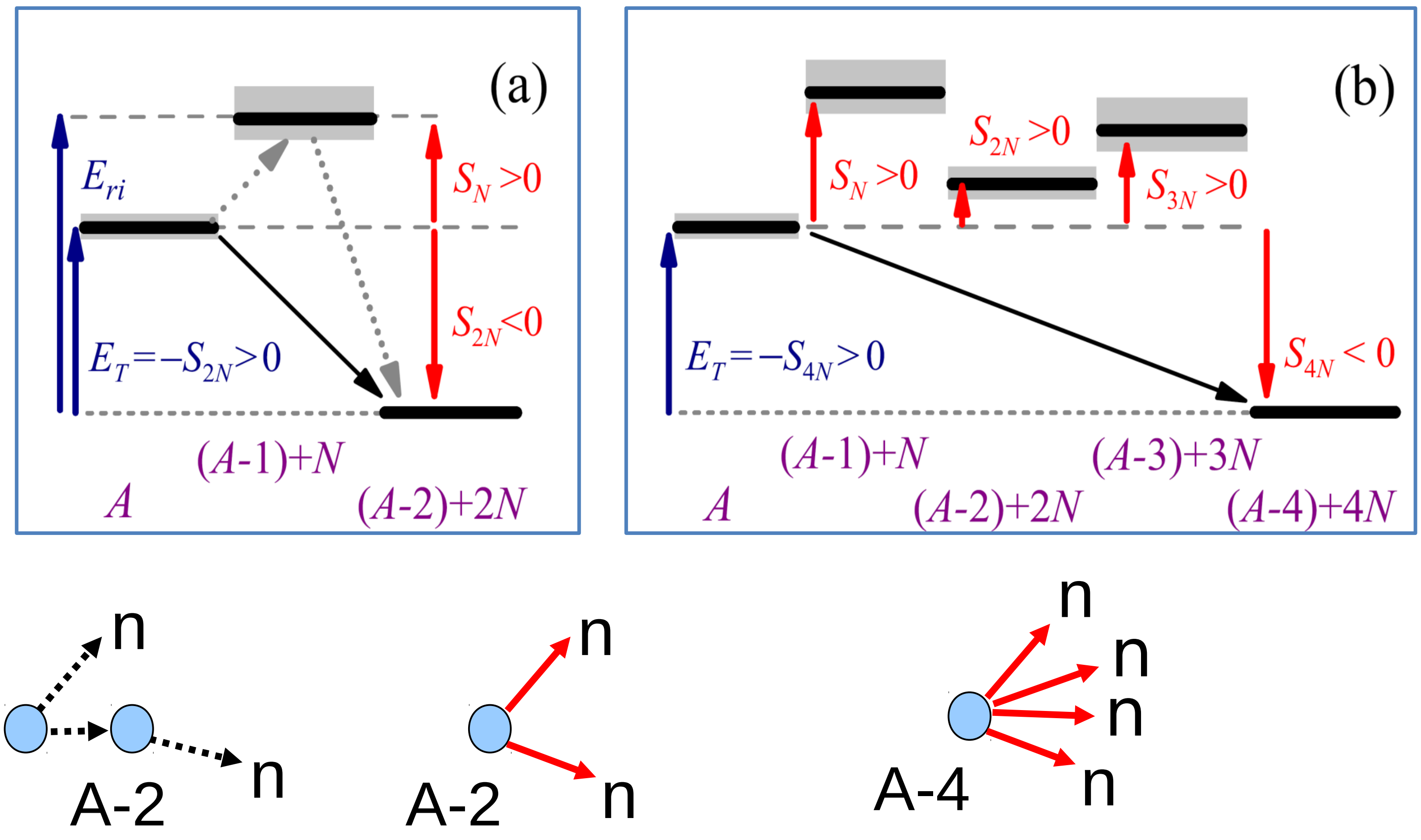


^{45}Fe, ^{19}Mg, ^{54}Zn, ^{48}Ni, ^{67}Kr, ^{94m}Ag

Neutron radioactivity

2n decays

4n decays



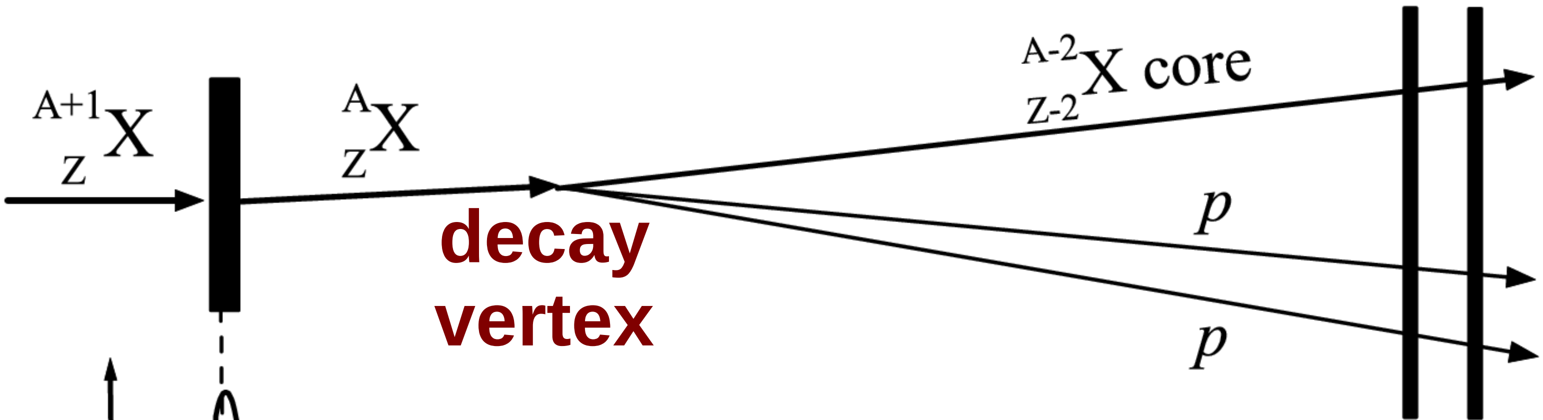
^{5}H, ^{10}He, ^{26}O, …

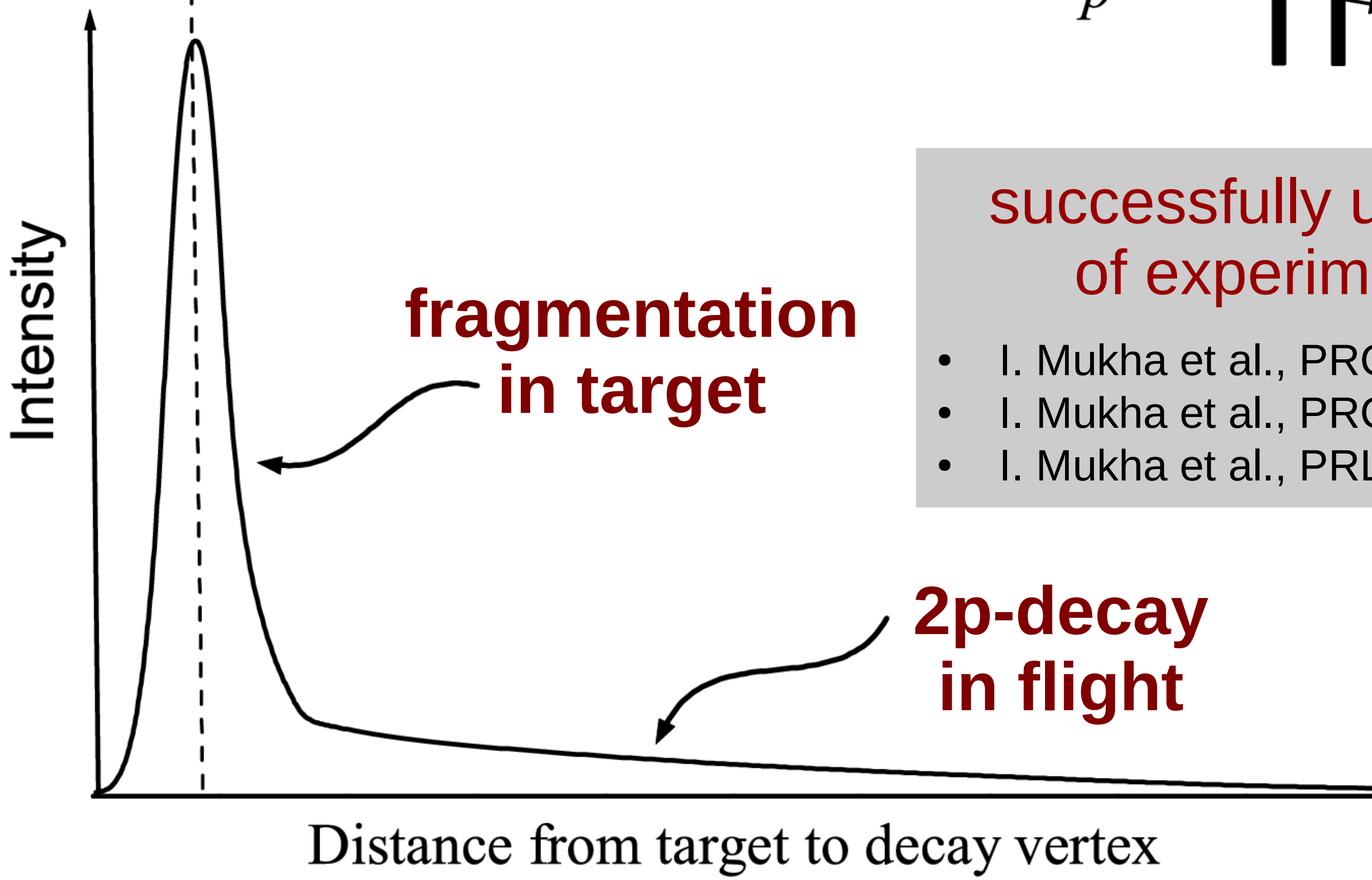
^{7}H, ^{18}Be, ^{28}O, ...

Available experimental methods

- ion-implantation method
- decay-in-flight by tracking technique
  - information on life-time accessible
  - identification of 2p-decay channels by correlations

Decay-in-flight by tracking



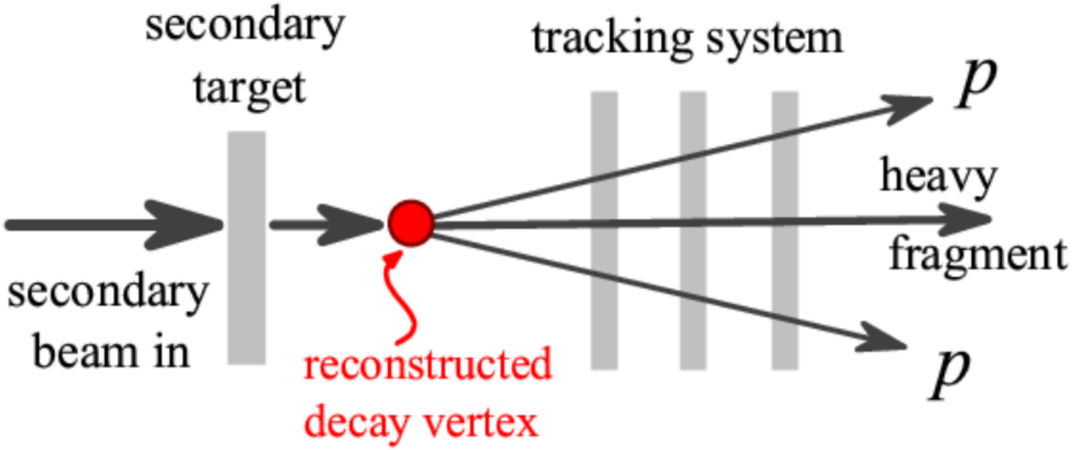


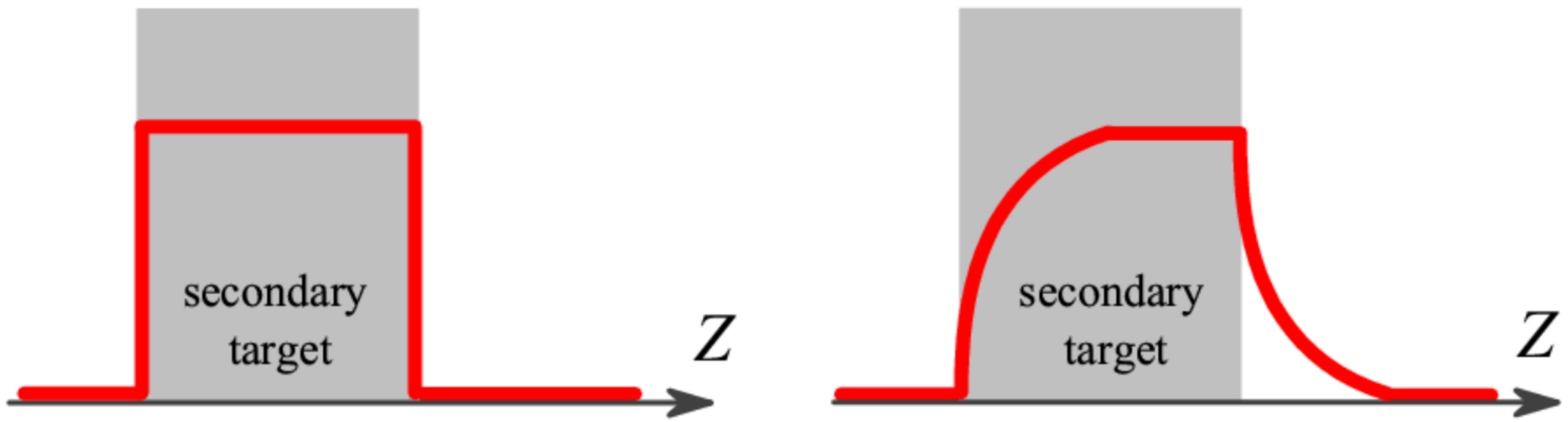
successfully used in series of experiments (*e.g.*)

- I. Mukha et al., PRC 77 (2008) 061303
- I. Mukha et al., PRC 82 (2010) 054315
- I. Mukha et al., PRL 115 (2015) 202501

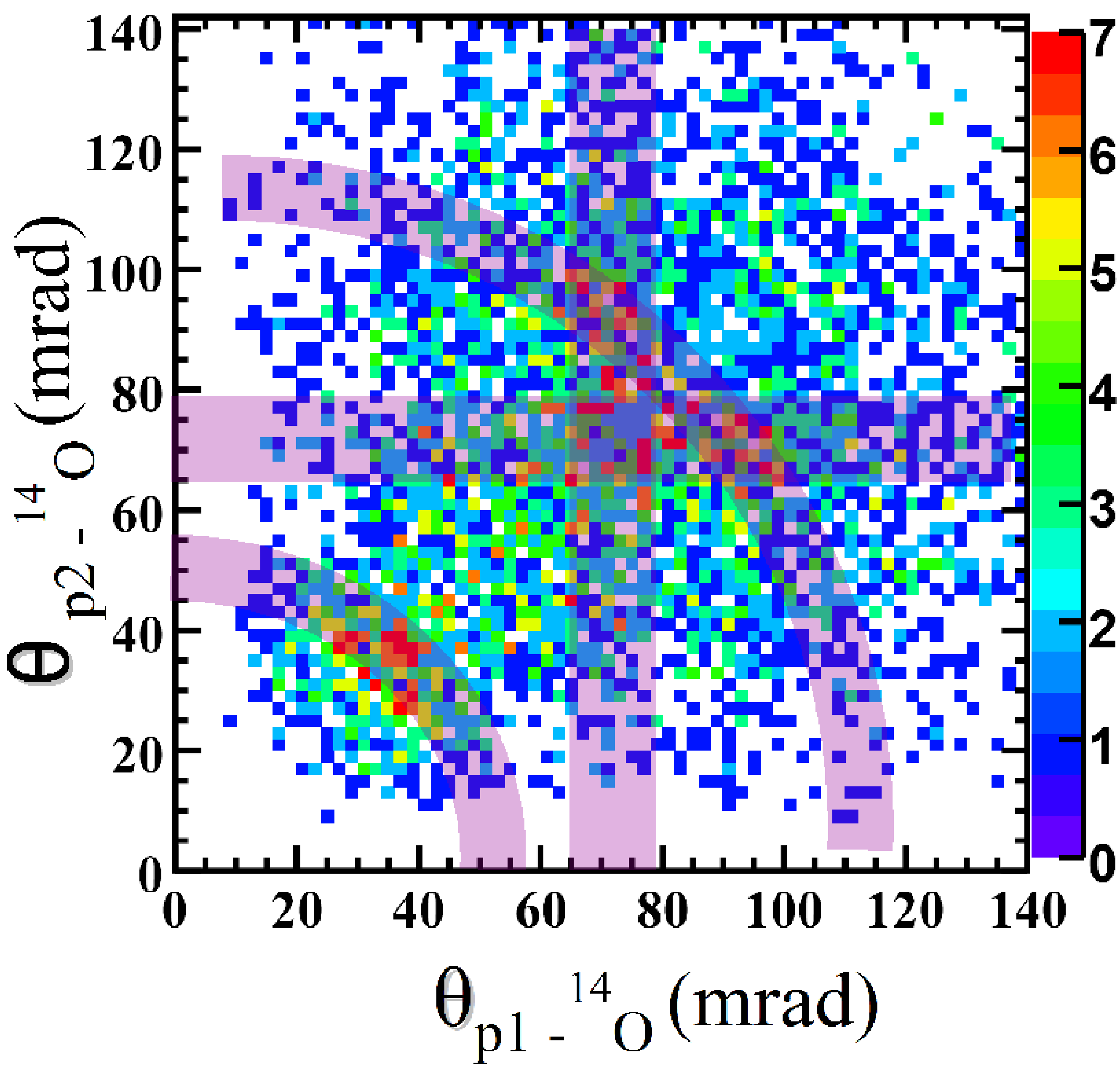
Life-time measurement by tracking

- characteristic shape of vertices distribution
- suitable for lifetimes 10^{-7} – 10^{-12} s

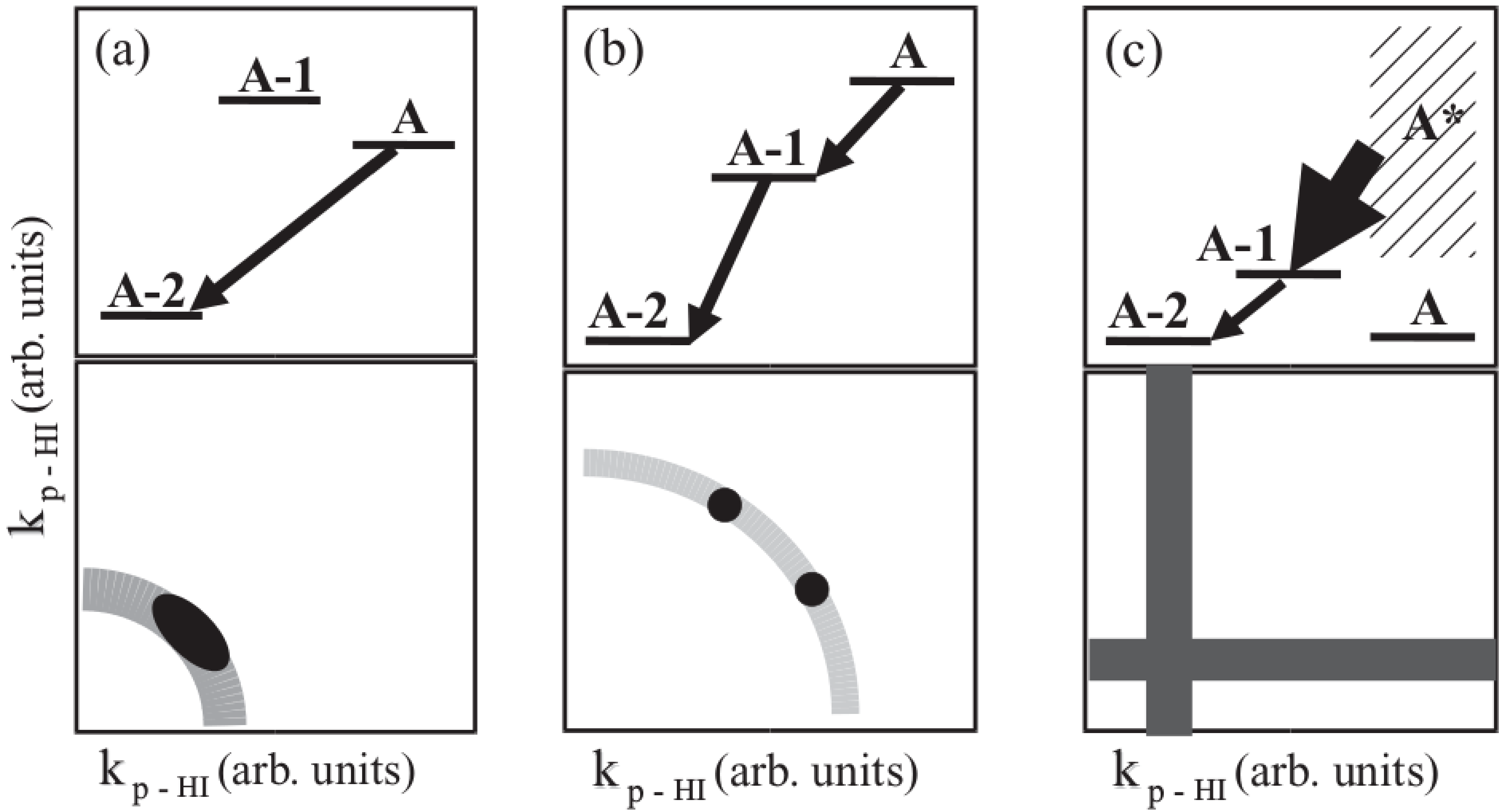




Identification of 2p-decay channels



Identification of 2p-decay channels

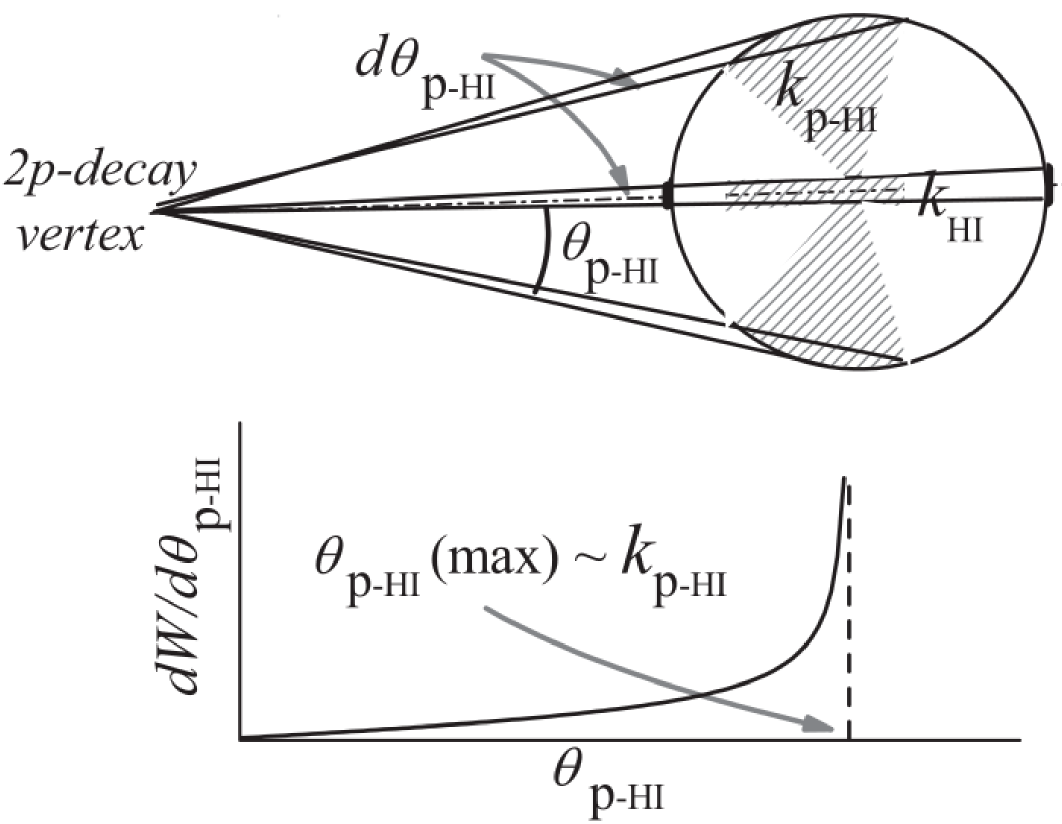


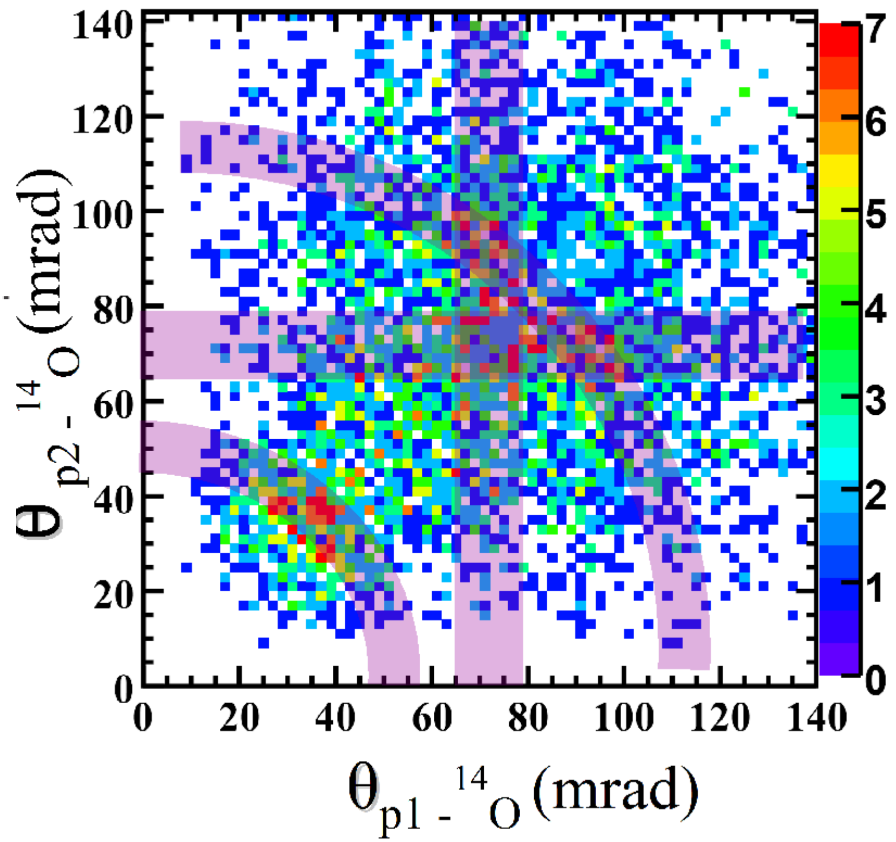
Identification of 2p-decay channels

- transition $k_{p\text{-}HI} \rightarrow \theta_{p\text{-}HI}$
- without measurement of proton energies

I. Mukha et al. Phys. Rev. C 82 (2010) 054315

^{16}**Ne**



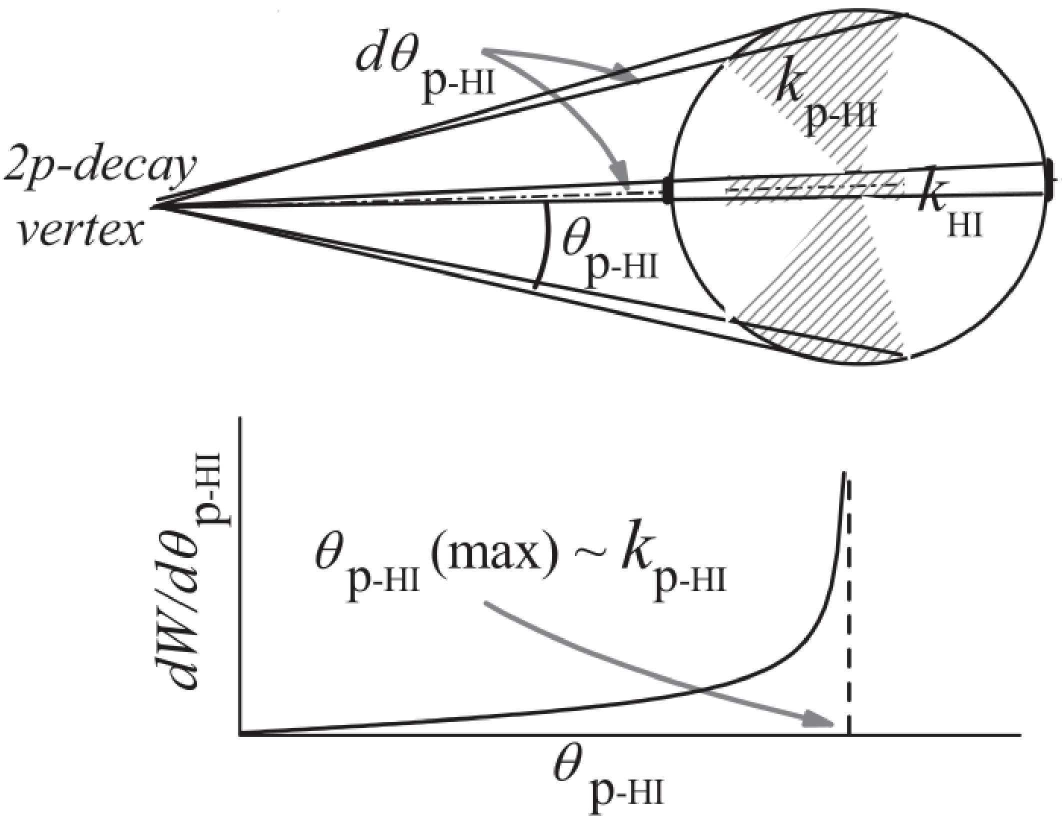


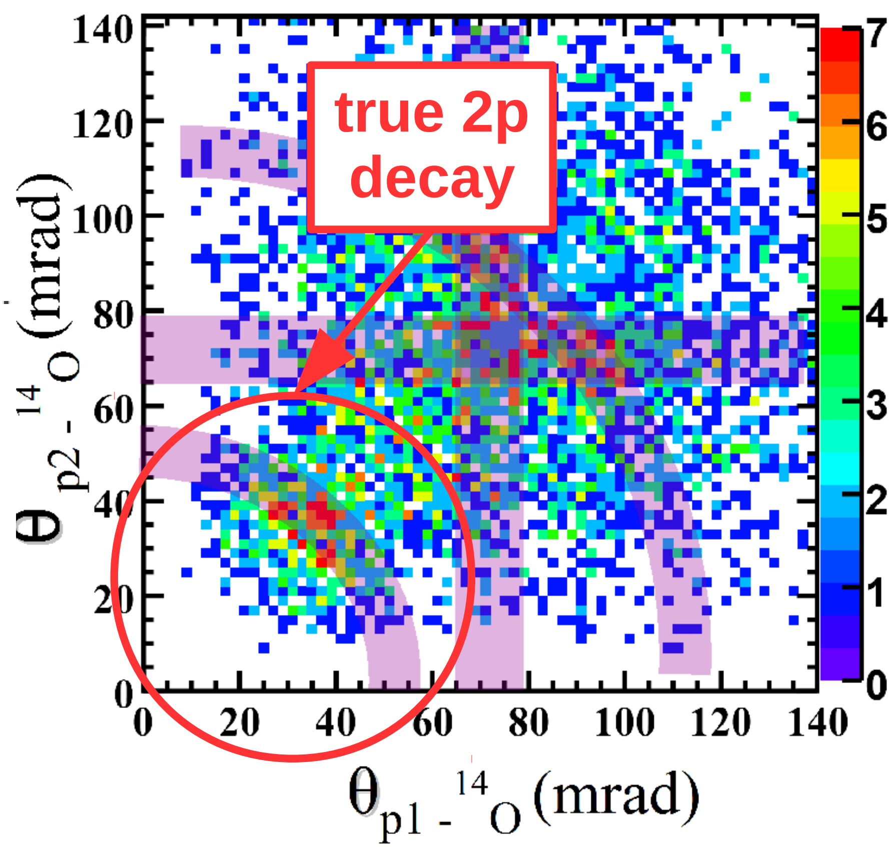
Identification of 2p-decay channels

- transition $k_{p\text{-}HI} \rightarrow \theta_{p\text{-}HI}$
- without measurement of proton energies

I. Mukha et al. Phys. Rev. C 82 (2010) 054315

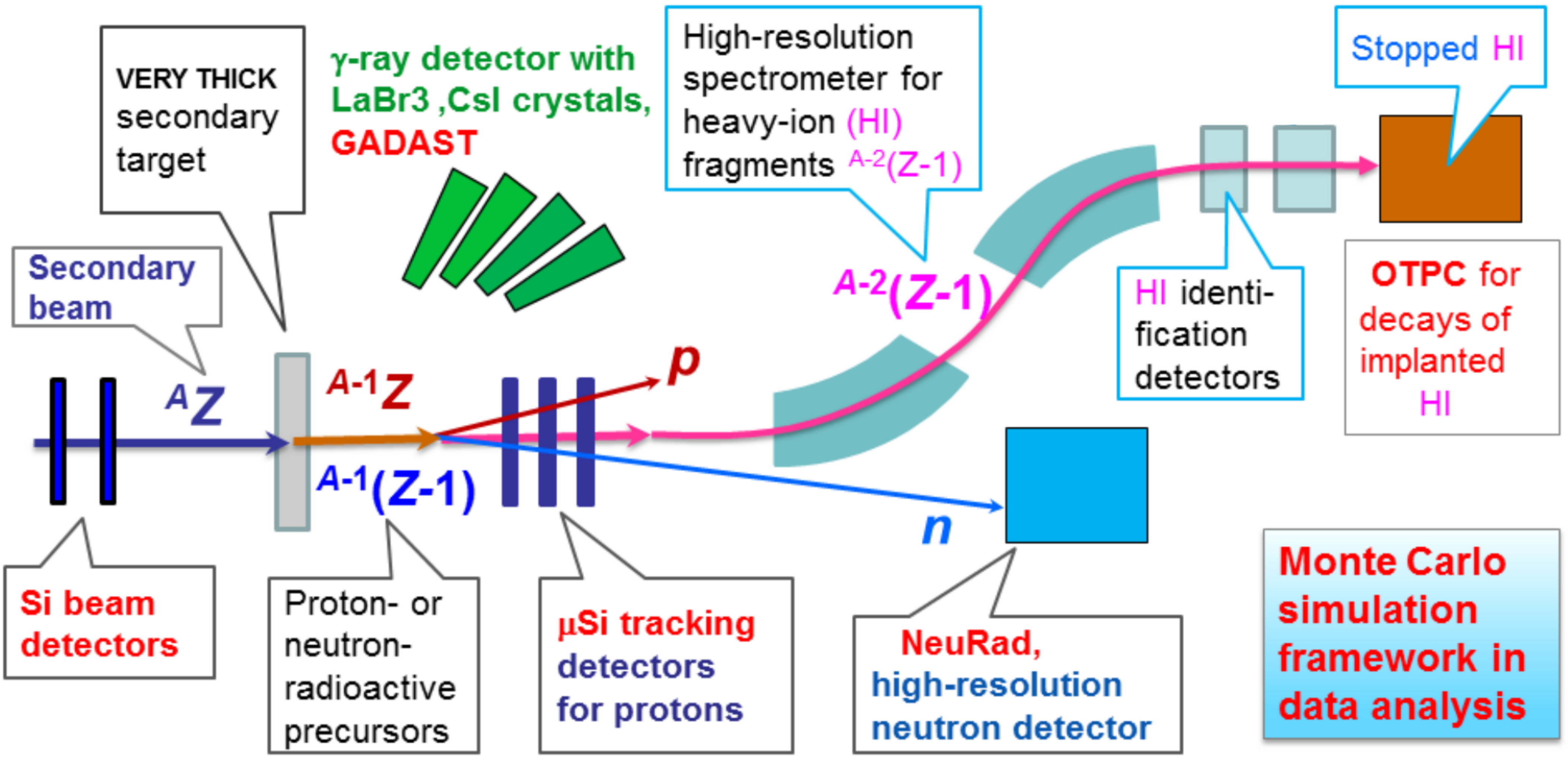
^{16}Ne



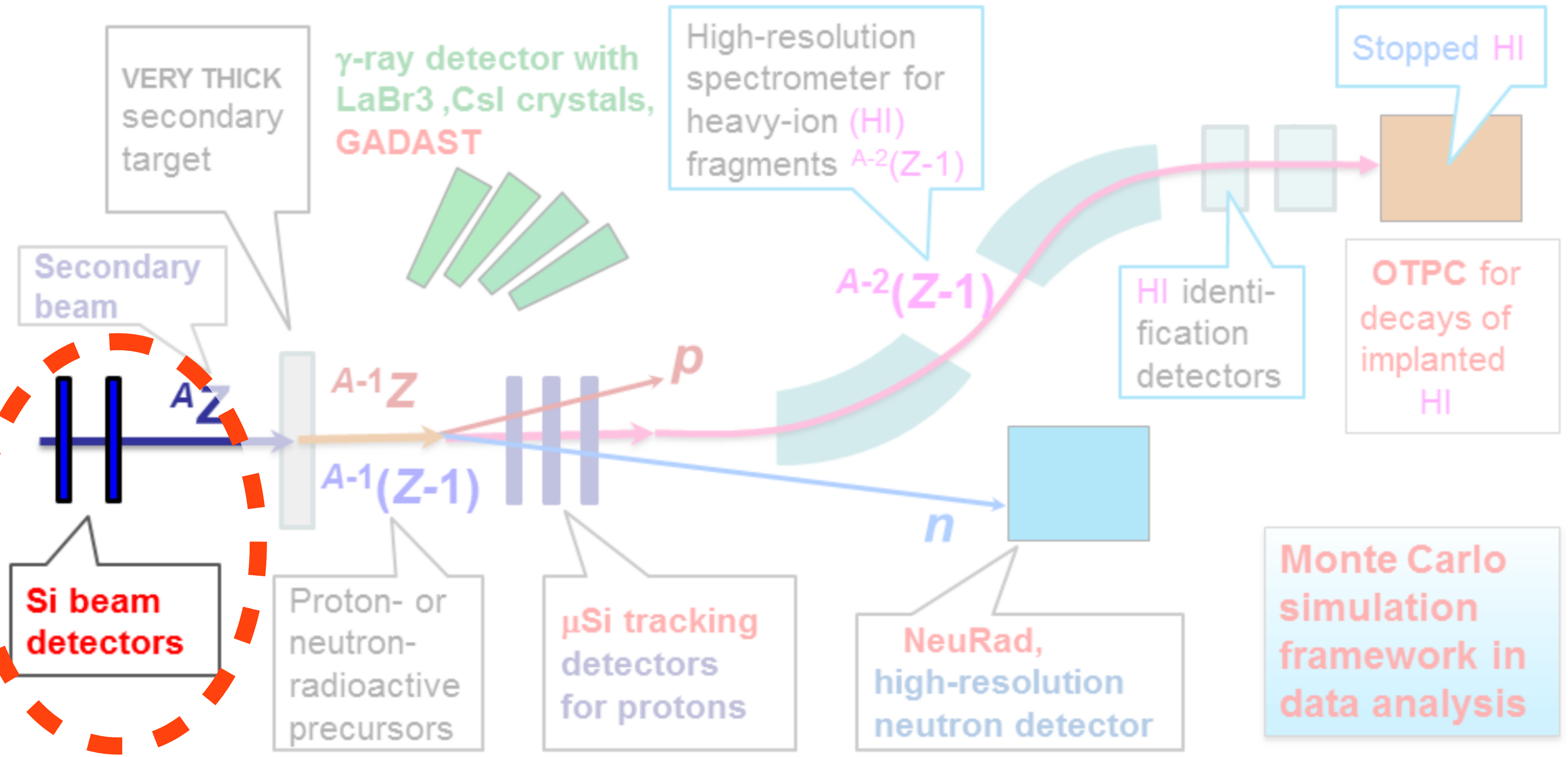


Hardware

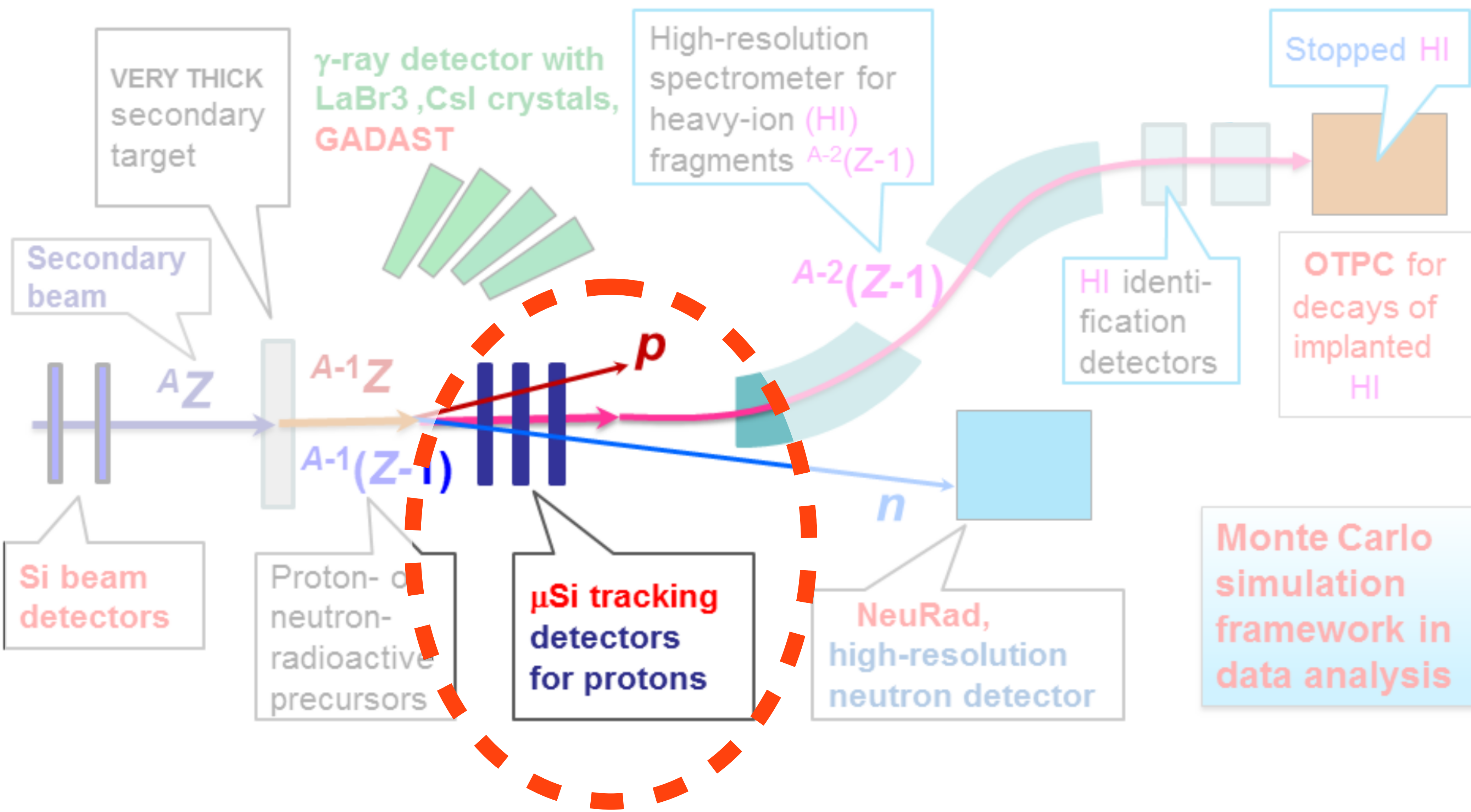
EXPERT: Experimental setup



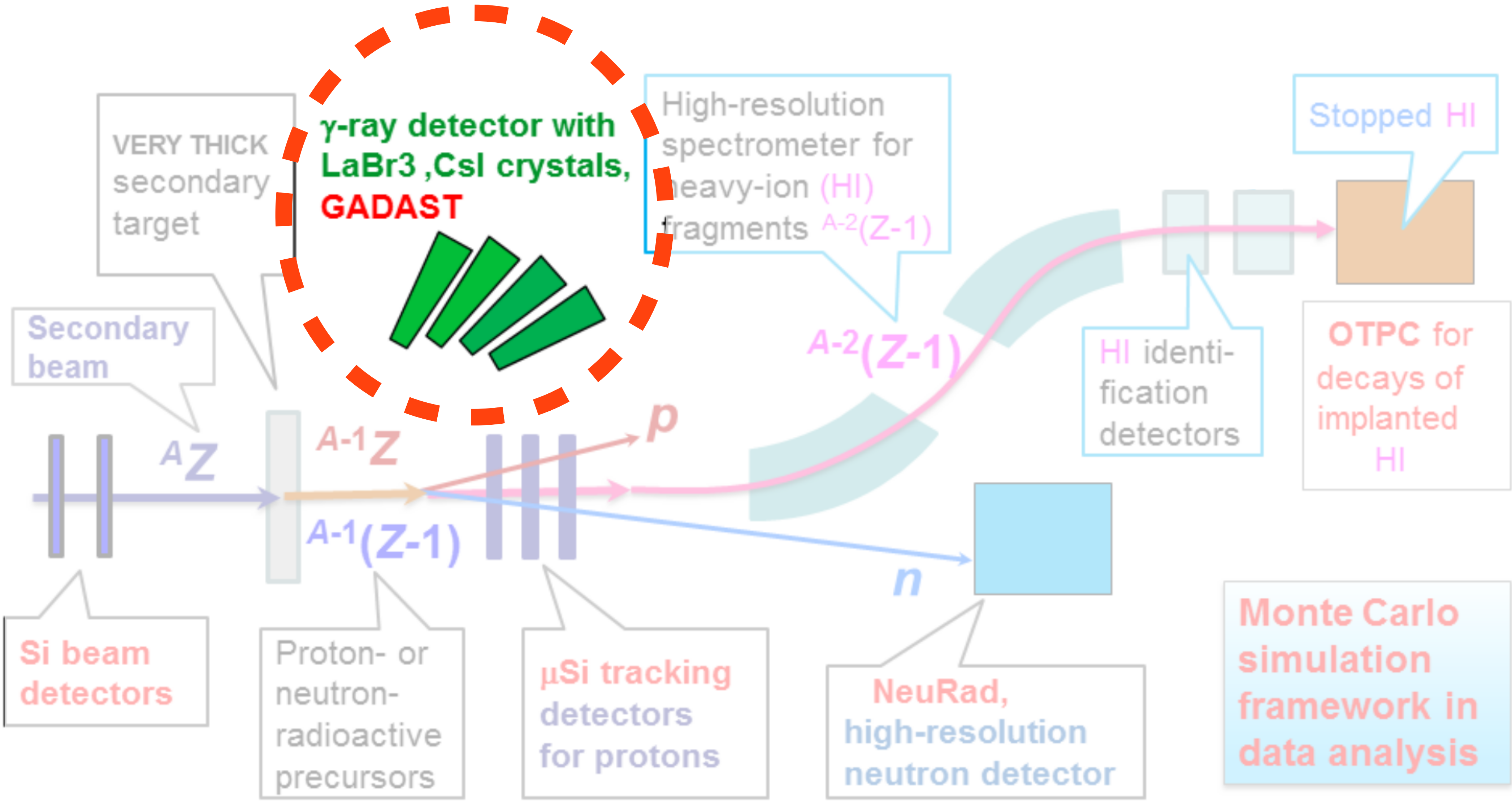
EXPERT: Experimental setup



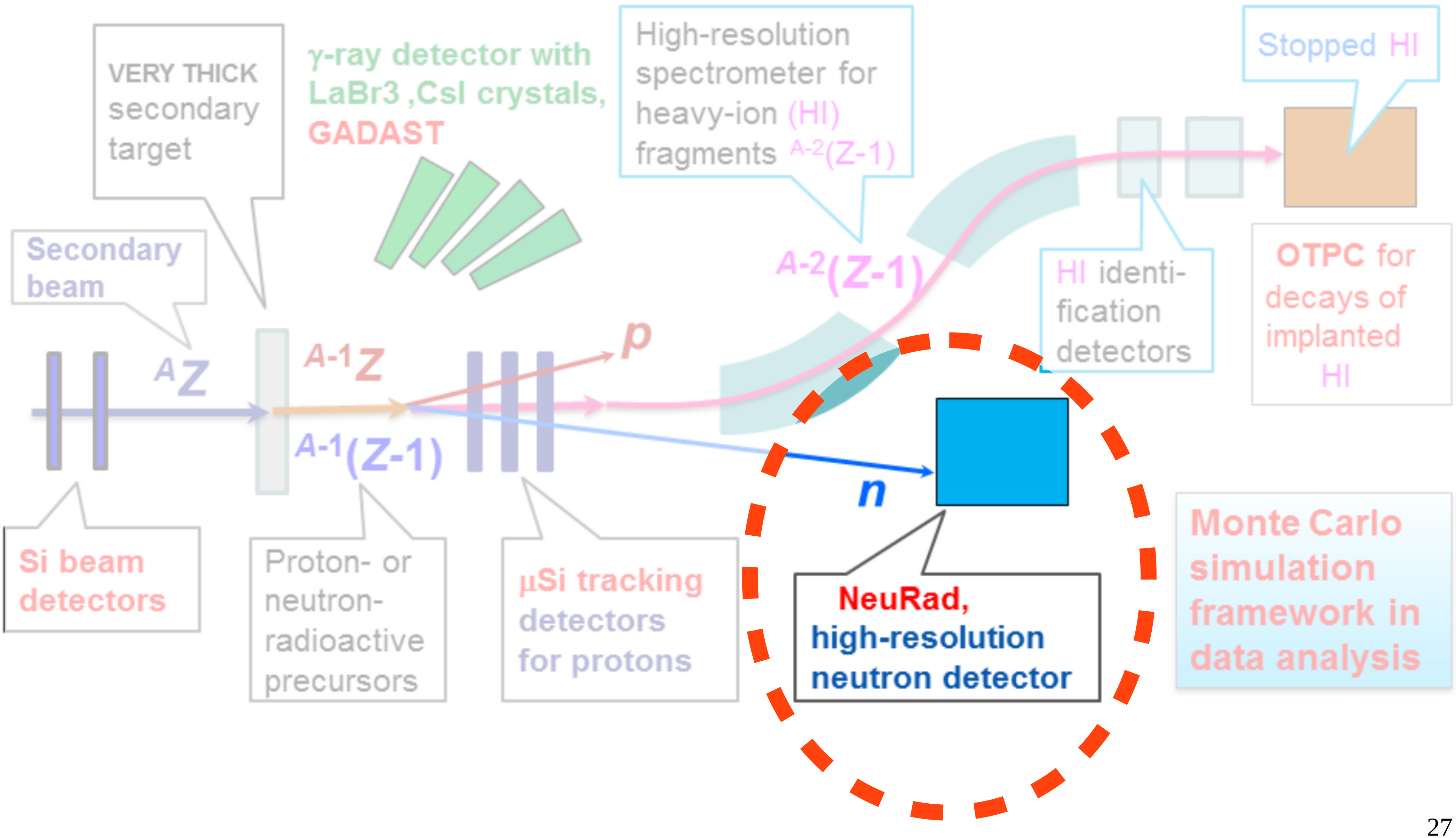
EXPERT: Experimental setup



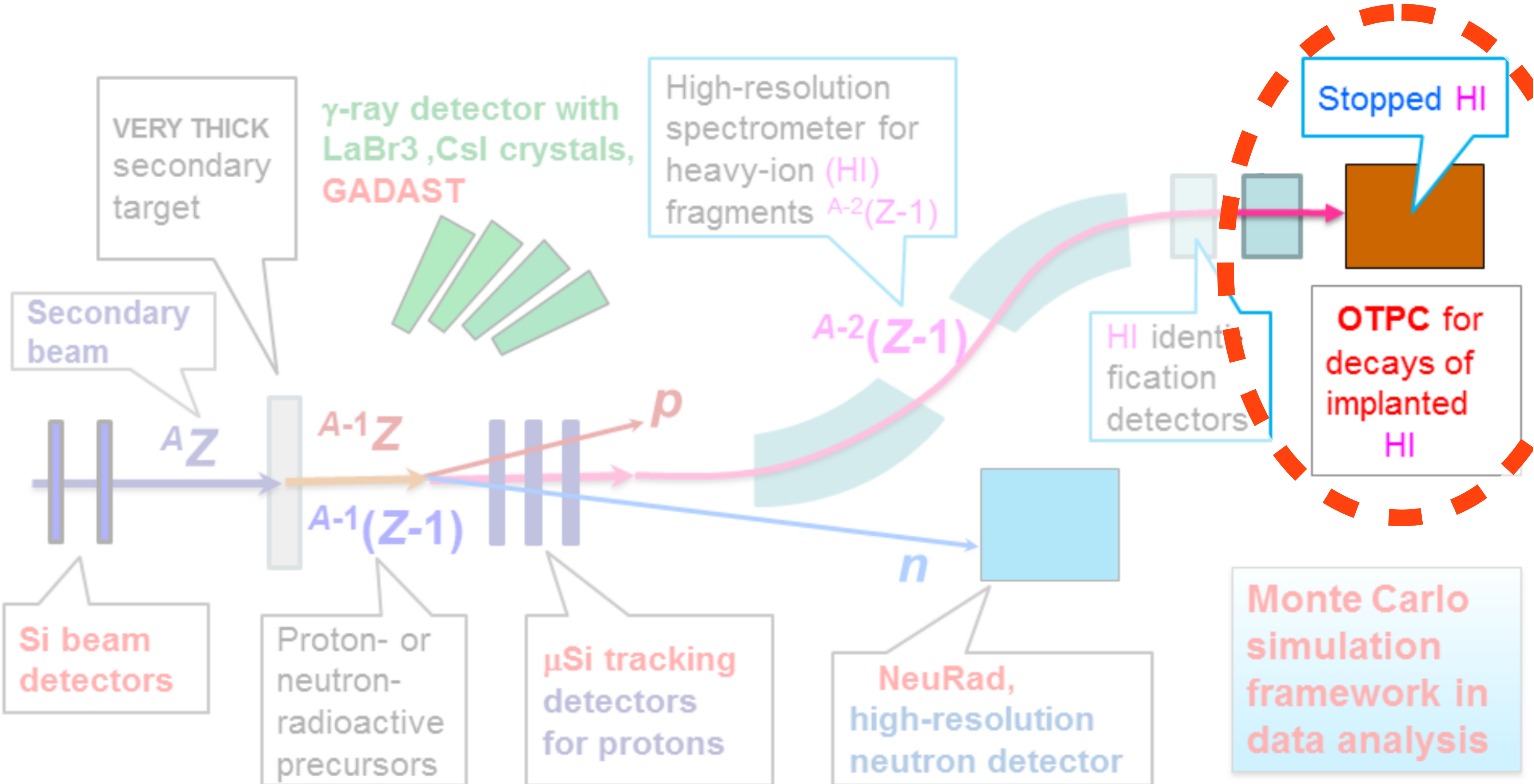
EXPERT: Experimental setup



EXPERT: Experimental setup



EXPERT: Experimental setup

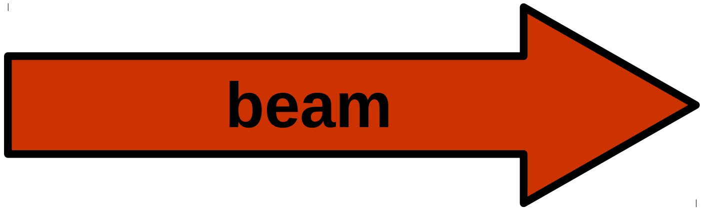


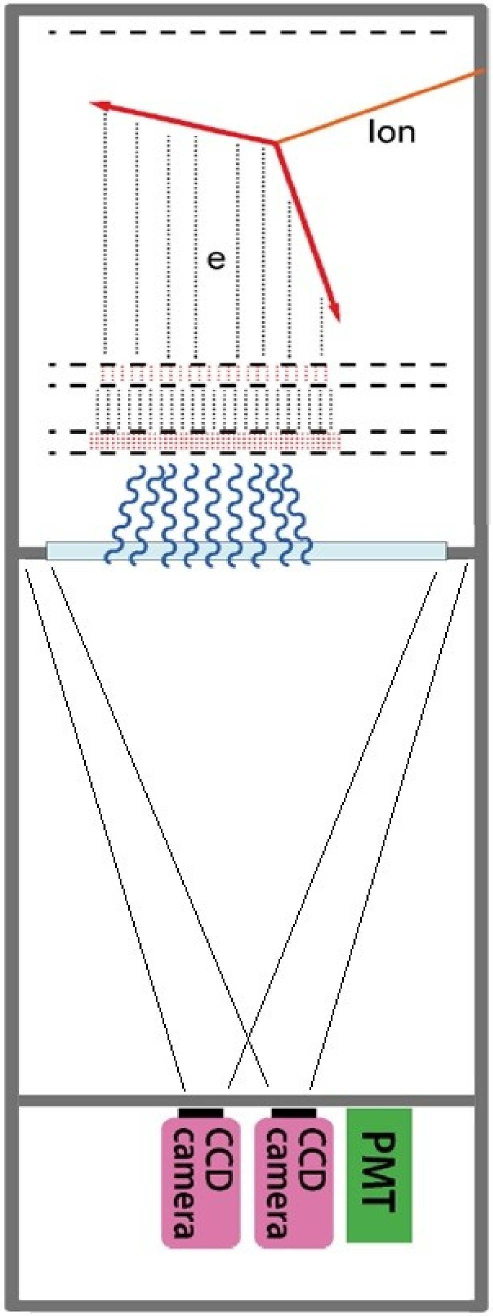
OTPC

Optical Time Projection Chamber

lifetime range:

100 ns – 1 s



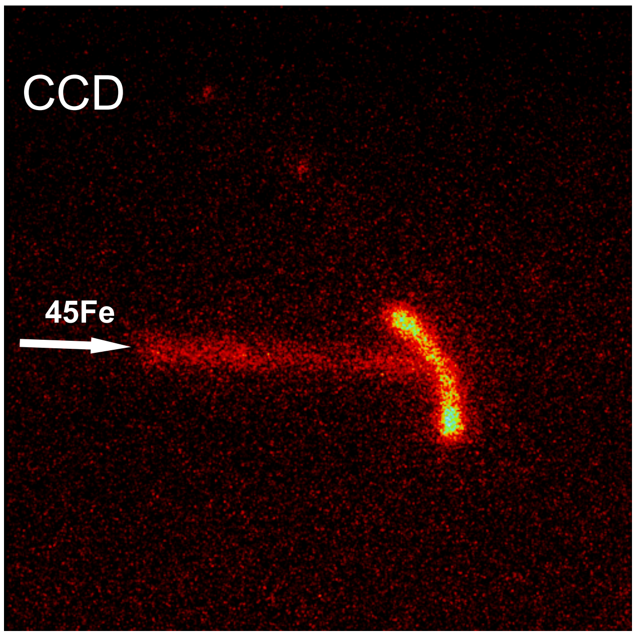


Optical Time Projection Chamber

lifetime range:

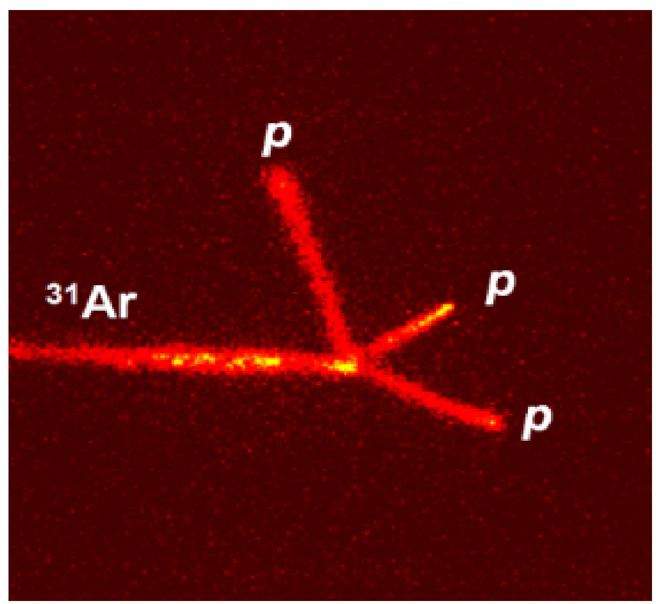
100 ns – 1 s

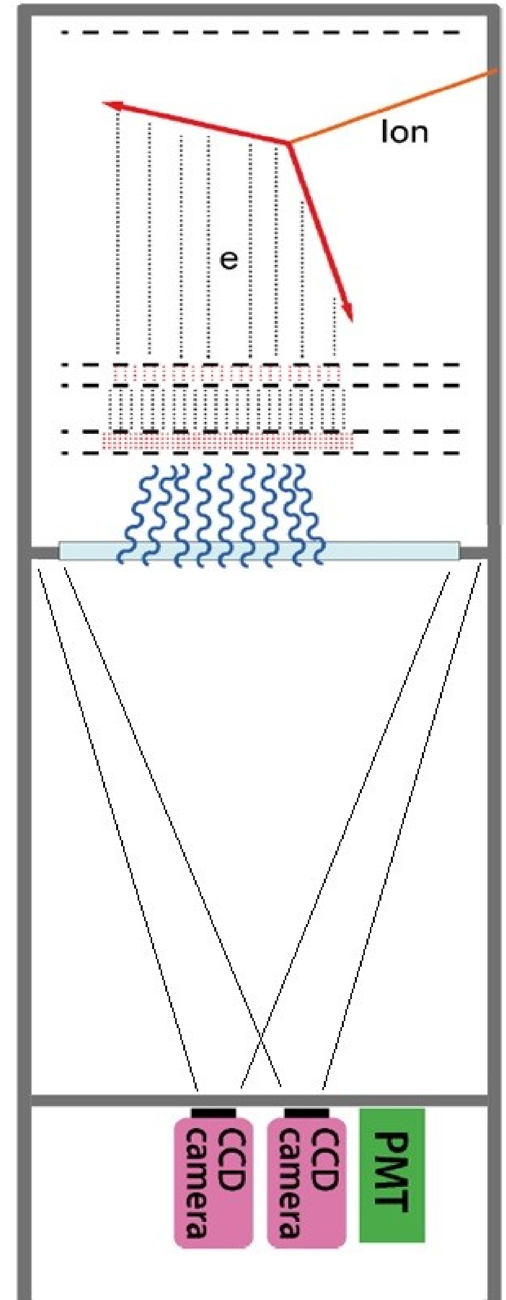
beam



M. Pfützner et al., Eur.Phys.J. A, 14(3), 2002

A.A. Lis et al., Phys. Rev. C91 (2015) 064309





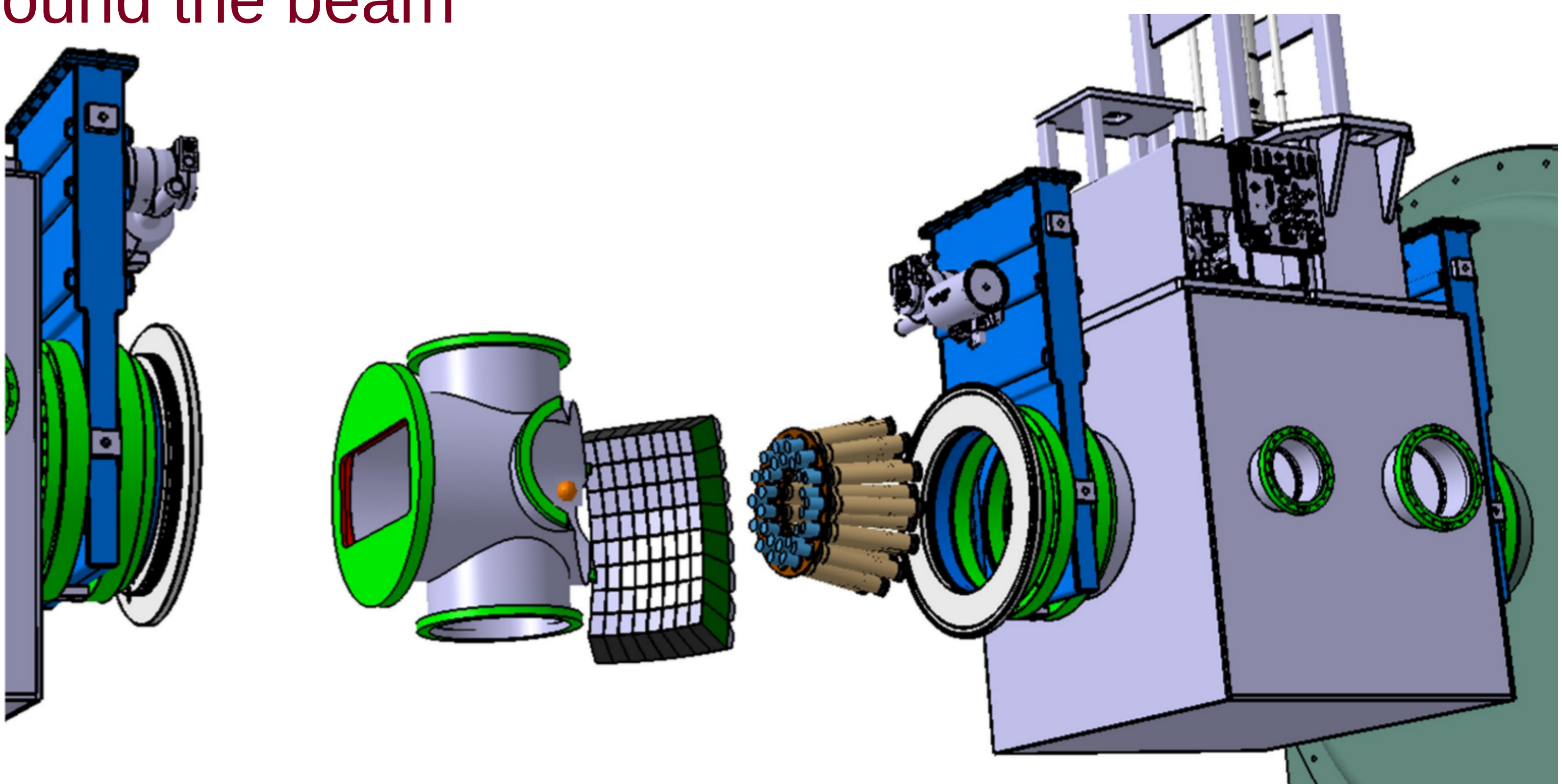
GADAST

GADAST

- tagging of gammas from 2p-radioactivity
- E_g ~ 100 keV – 2 MeV
- CsI(Tl) crystals
  more than 15° in LAB
- $LaBr_3$(Ce) crystals
  around the beam

in the middle of SuperFRS in FMF2

128 CsI(Tl) modules
32 $LaBr_3$(Ce) modules

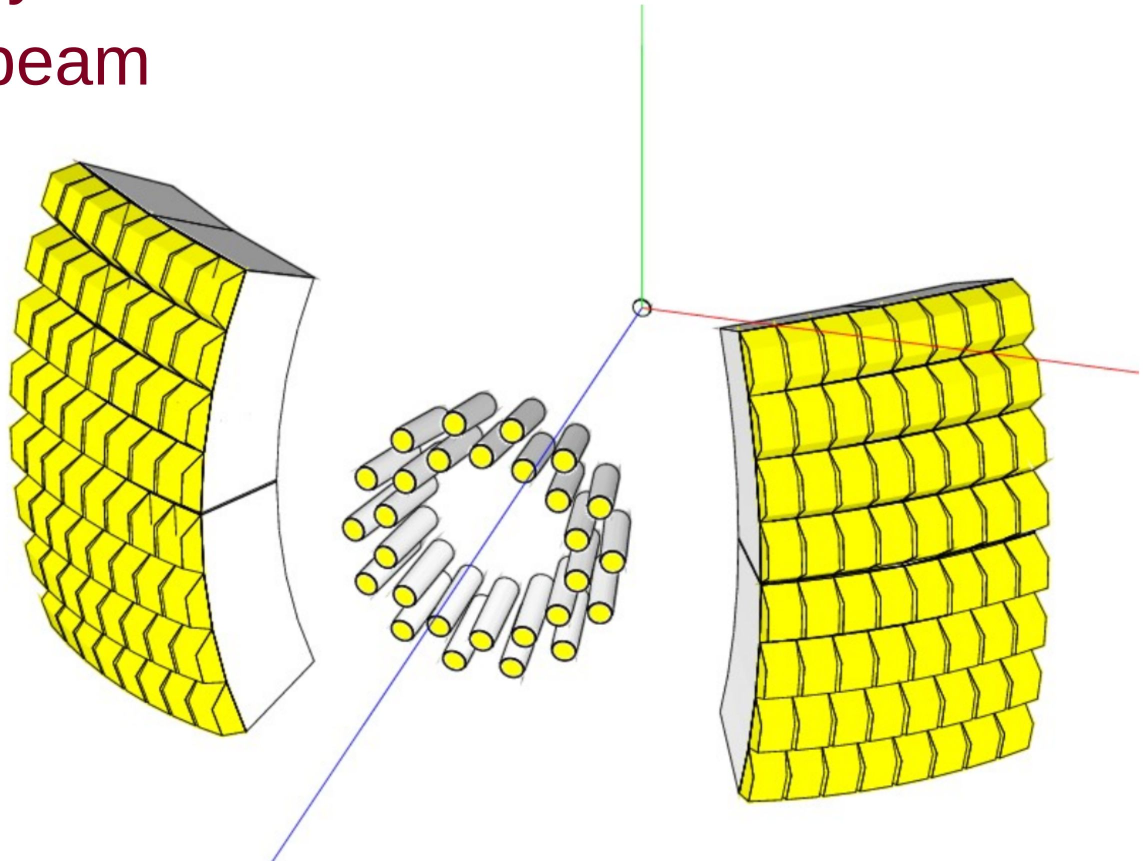


GADAST

- tagging of gammas from 2p-radioactivity
- E_g ~ 100 keV – 2 MeV
- CsI(Tl) crystals more than 15° in LAB
- $LaBr_3$(Ce) crystals around the beam

in the middle of SuperFRS in FMF2

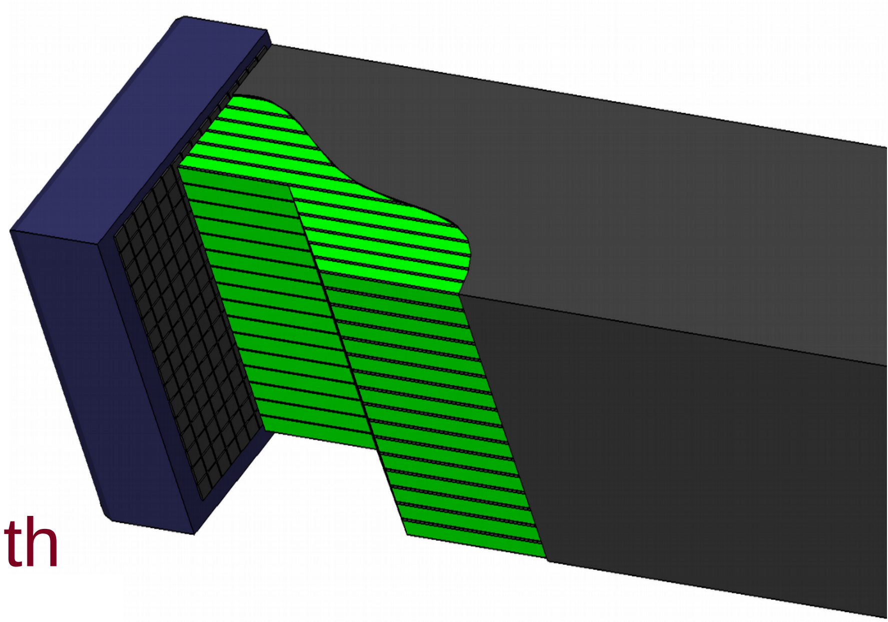
128 CsI(Tl) modules
32 $LaBr_3$(Ce) modules

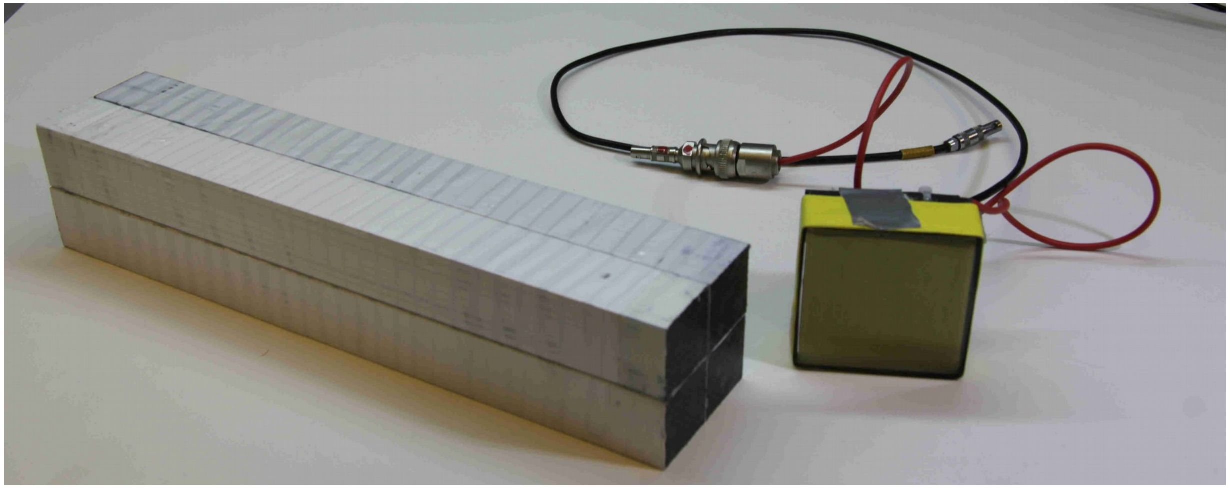


NeuRad

NeuRad

- neutron radioactivity studies
- E_n ~ 200 – 800 MeV in LAB
- low transverse momenta
  0.1 – 100 keV
- precise information on angular correlations of decay neutrons with a charged fragment
- angular resolution ~0.1 – 0.2 mrad





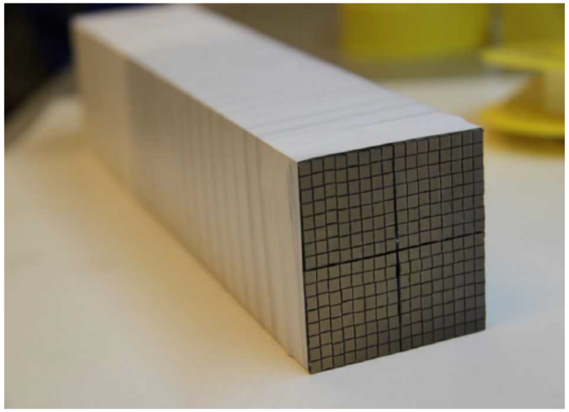
28 m from the target in FMF2

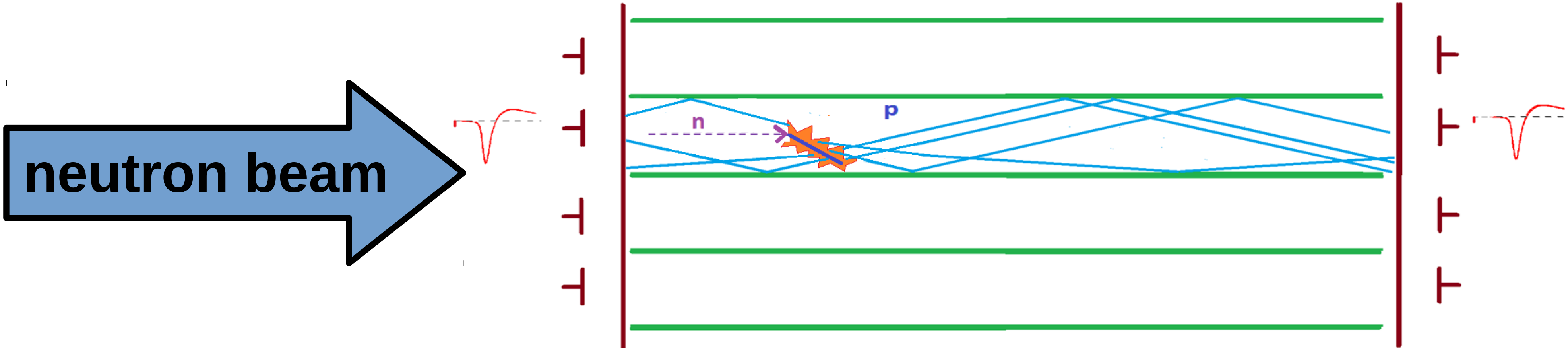
at least 36 modules
30 x 30 x 100 cm^3

NeuRad

bundles

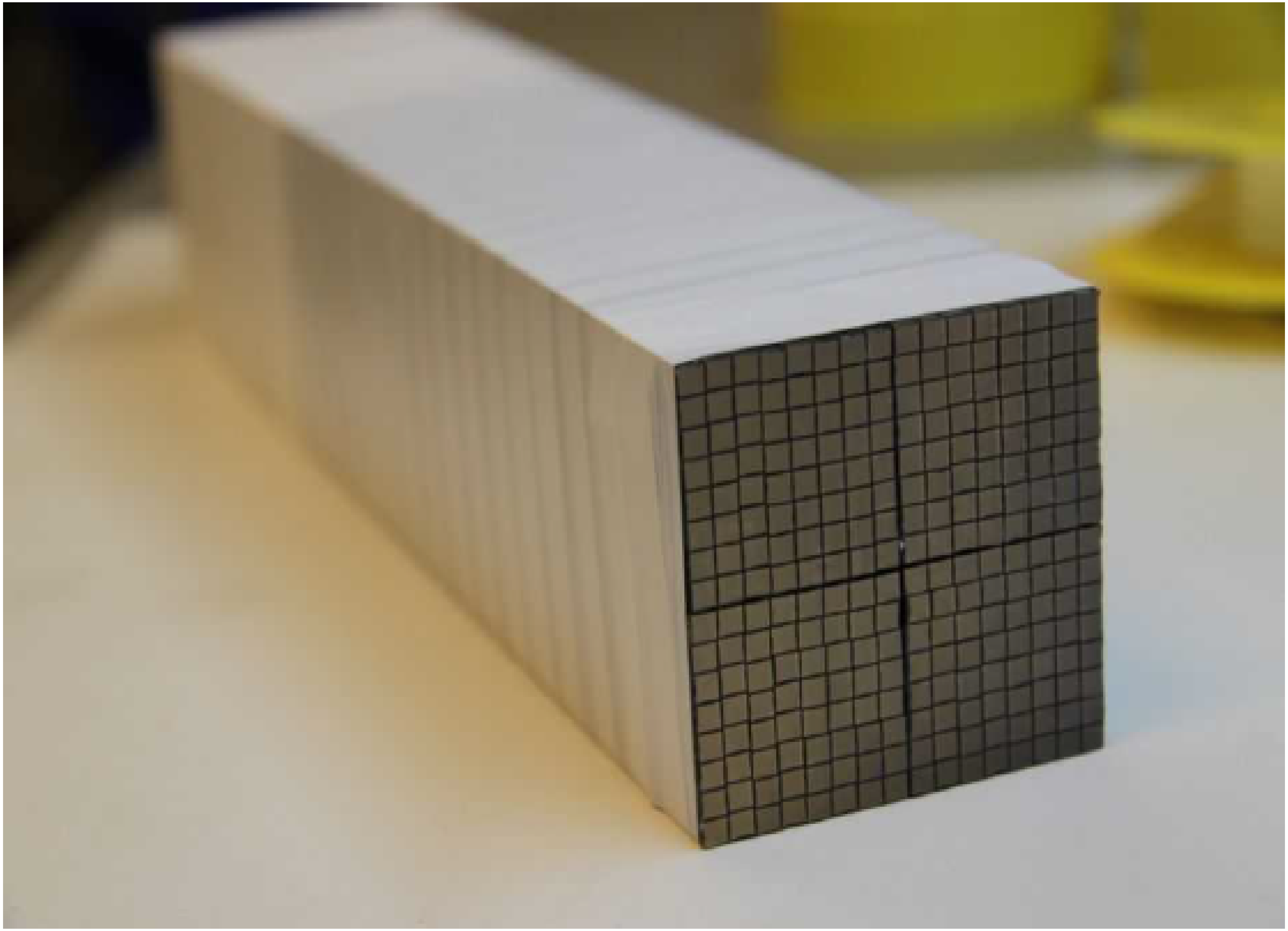
- 3 x 3 mm scintillation fibers BCF12
- 48 x 48 x 1000 mm
- 2 MAPMT from both sides





- **longitudinal coordinate** of the n interaction along the fiber
- **determination the very first hit**
- avoid **neutron cross-talk**

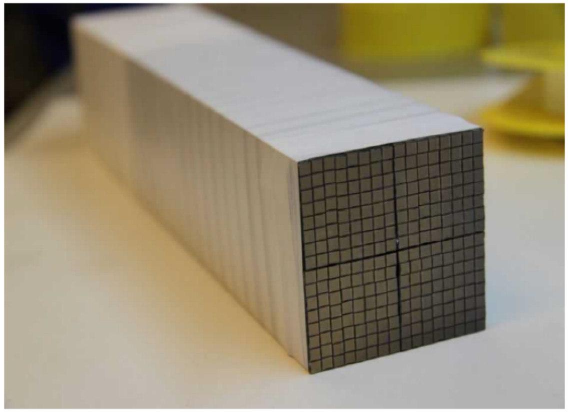
NeuRad

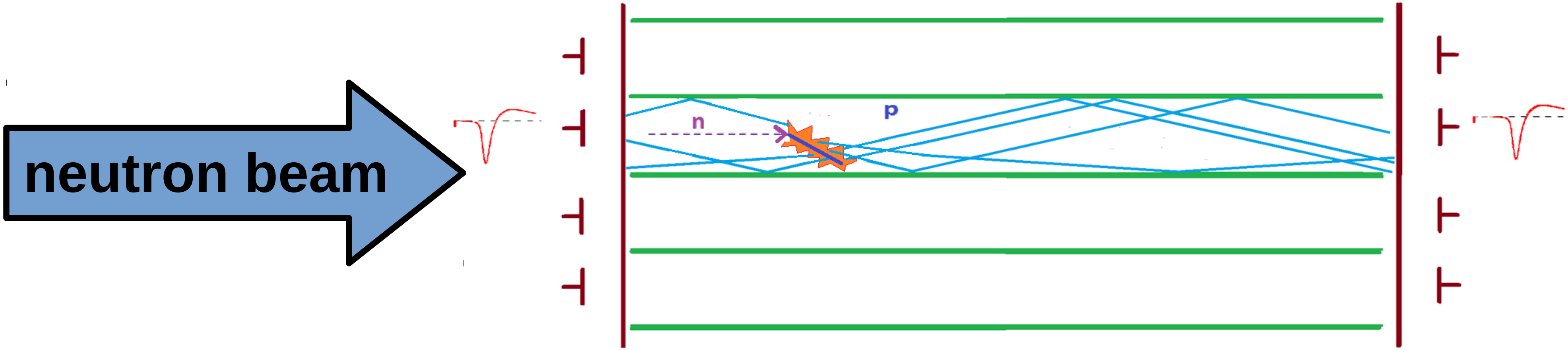


NeuRad

bundles

- 3 x 3 mm scintillation fibers BCF12
- 48 x 48 x 1000 mm
- 2 MAPMT from both sides





- **longitudinal coordinate** of the n interaction along the fiber
- **determination the very first hit**
- avoid **neutron cross-talk**

EXPERT software

- **MC generator of events**
  - decay and reaction mechanism
- **ExpertRoot**
  - simulation of experiment
  - data analysis

http://er.jinr.ru

Outlook

- **two experimental proposals for FAIR phase-0**
- **4 of 5 detectors will be commissioned in 2018**
- **looking forward to SuperFRS**

Appendix: Nuclear halo

Stable nuclei

$$< r_n^2 >^{1/2} - < r_p^2 >^{1/2} \approx 0.1 fm$$

Exotic nuclei

$$< r_n^2 >^{1/2} - < r_p^2 >^{1/2} \gtrsim 1.5 fm$$

neutron halo

one neutron: **^{11}Be, ^{19}C**

two neutron: **^{6}He, ^{11}Li, ^{17}B, ^{19}B, ^{22}C**

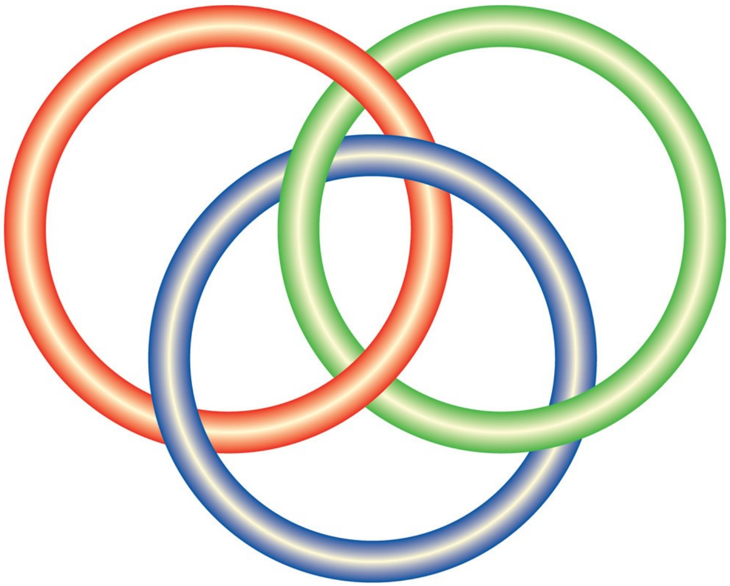
neutron skin: **^{8}He and ^{14}Be**

proton halo

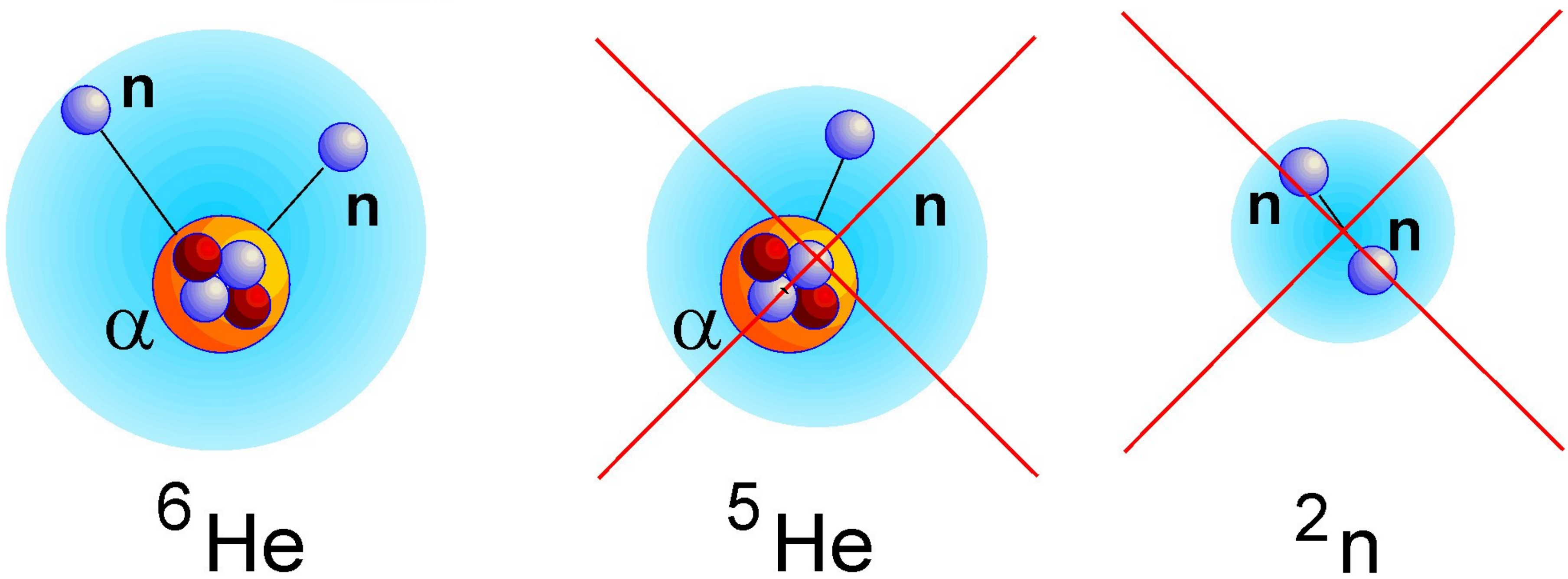
g.s. of **^{8}B, ^{13}N, ^{17}Ne, ^{26}P, ^{27}S**

the first e.s. of **^{17}F**

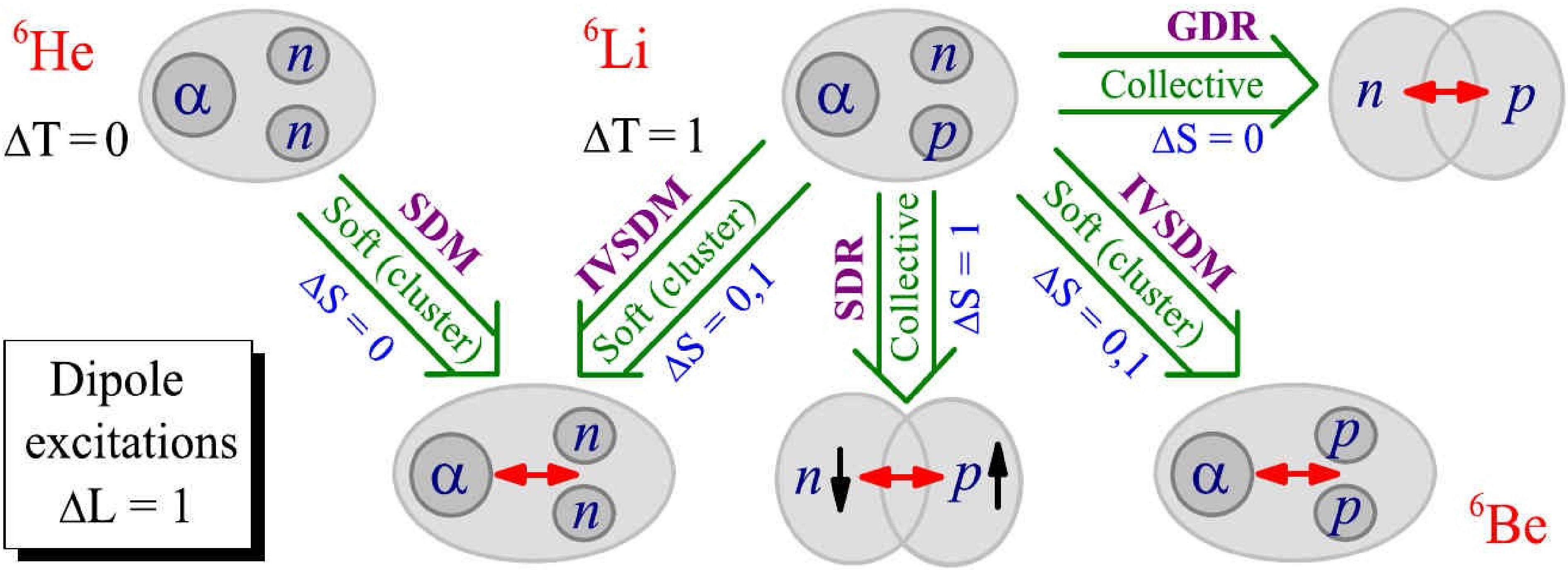
Appendix: Borromean nuclei



M.V. Zhukov et al., Bound state properties of Borromean halo nuclei: ^{6}He and ^{11}Li. Physics Reports, 231(4):151–199, 1993

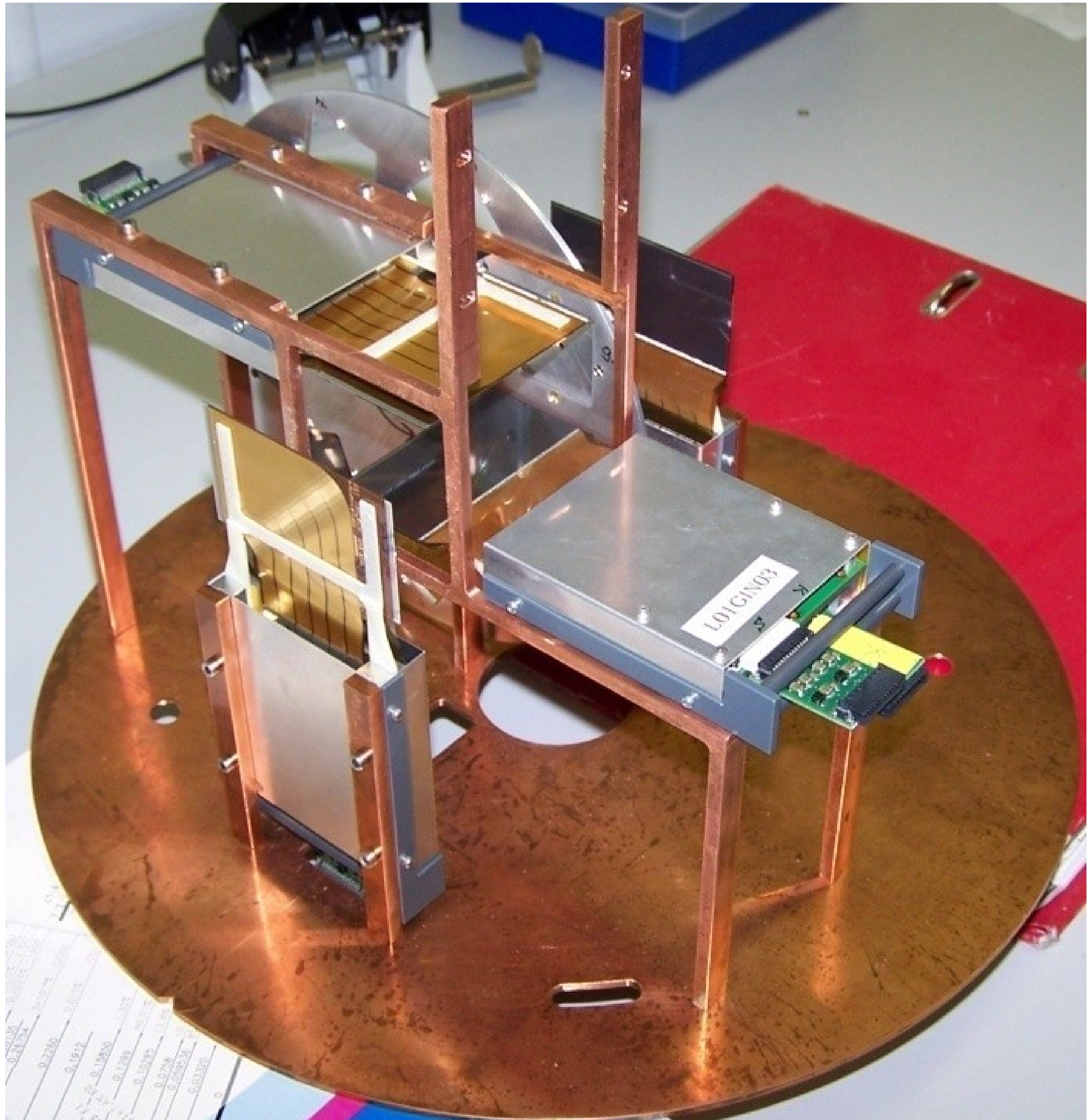


Appendix: Dipole modes

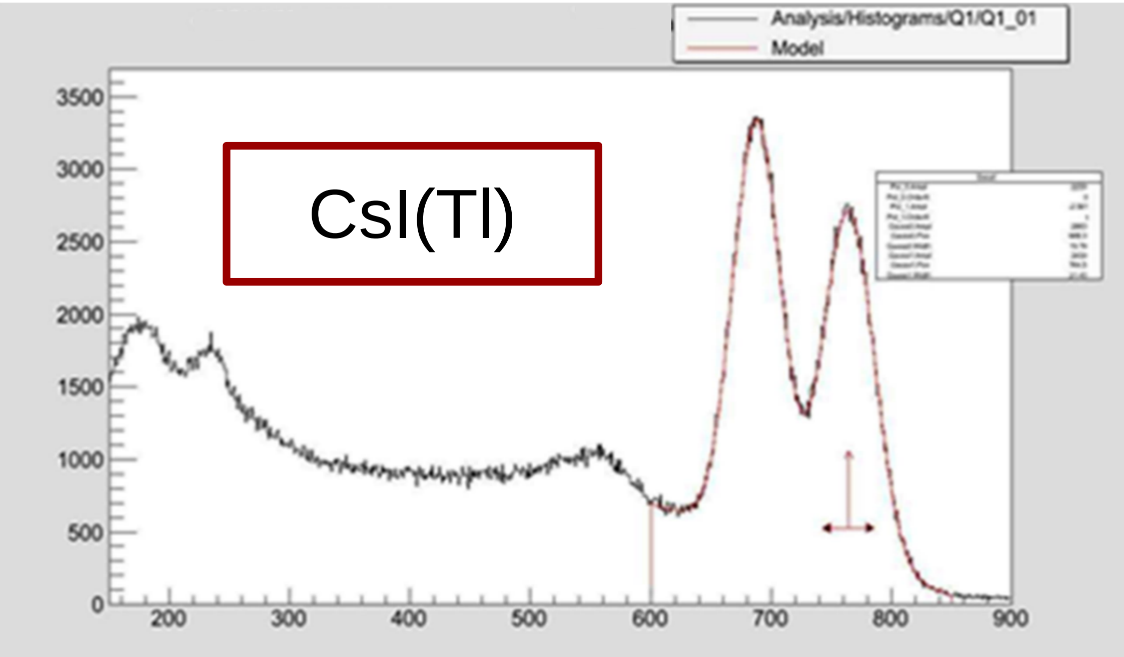


resonance	vs.	mode
• property of particular nucleus • its population does not depend on reaction mechanism		• characteristic for specific reaction • its population is given by reaction mechanism

Appendix: microStrip detectors

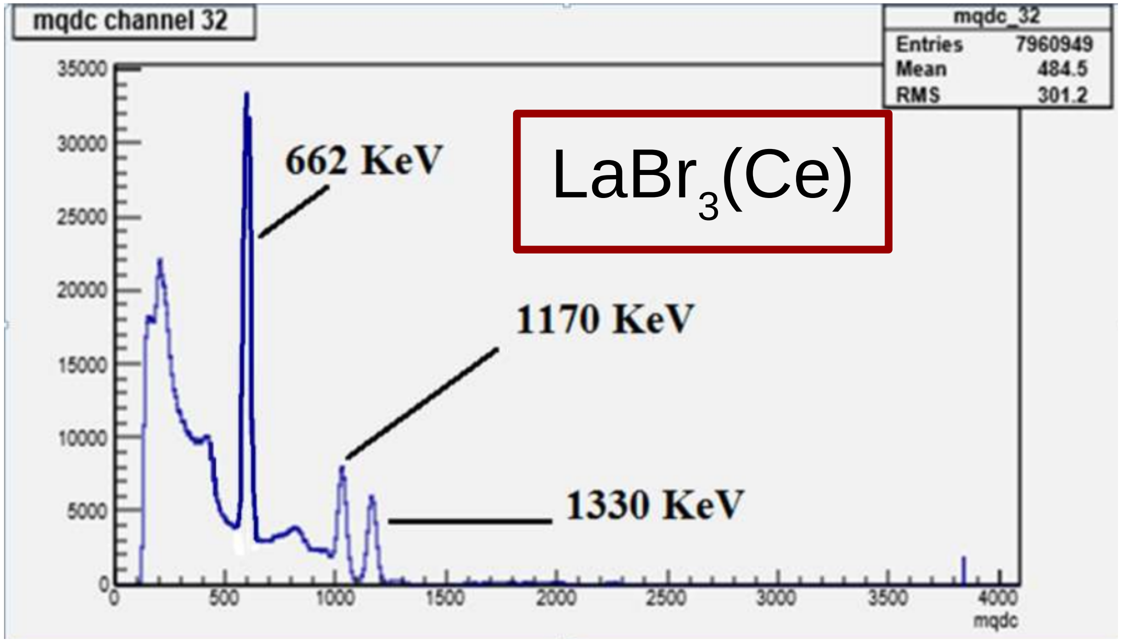


Appendix: GADAST



^{60}Co

ΔE/E =7.5%
at E_γ=1.17 MeV

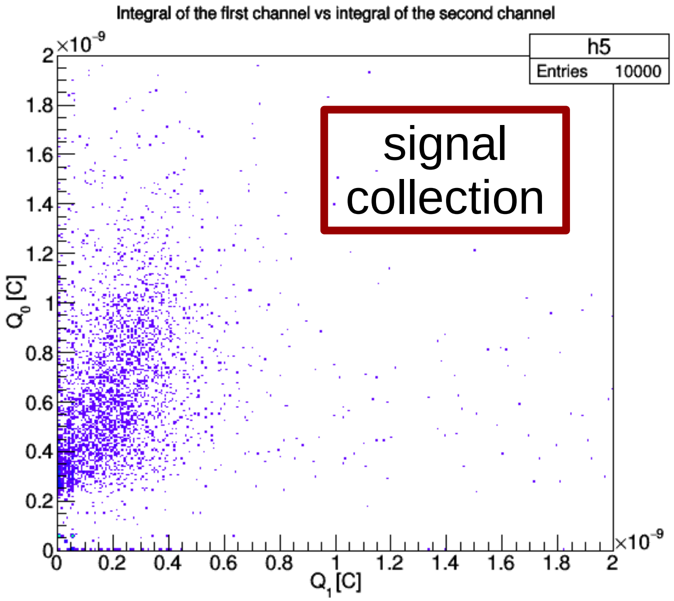


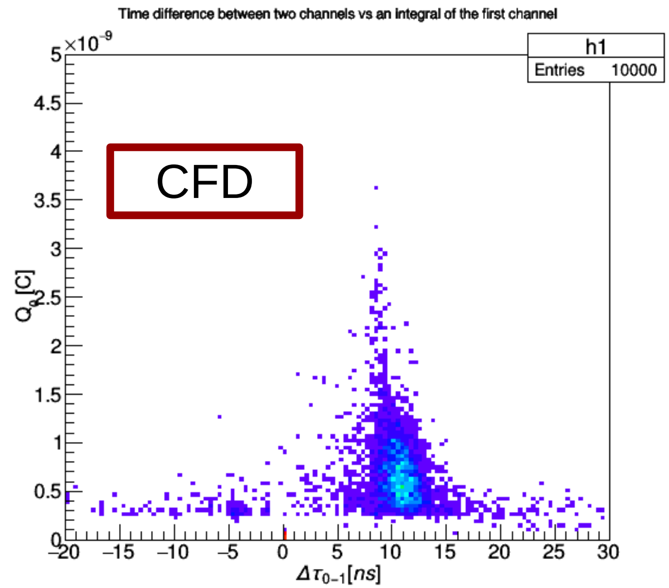
^{137}Cs + ^{60}Co

ΔE/E =4.0%
at E_γ=662 keV;

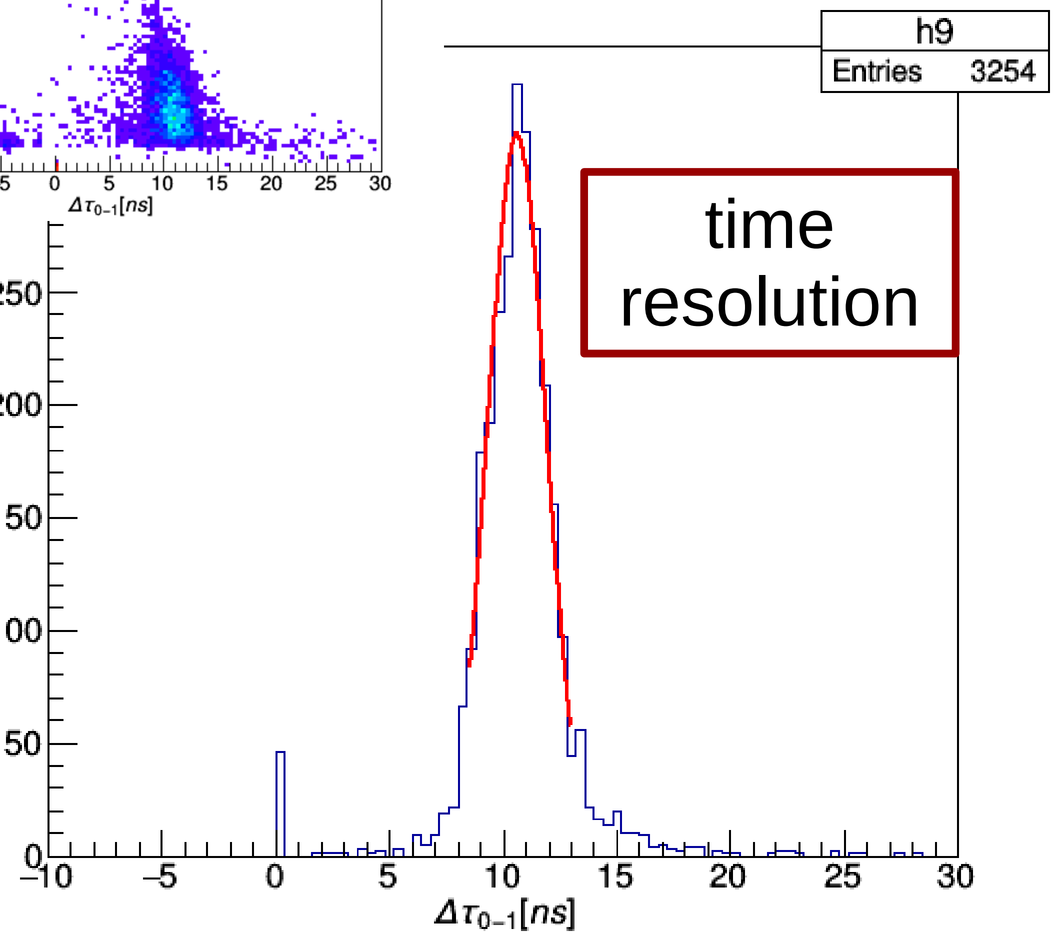
ΔE/E =2.9%
at E_γ=1.33 MeV

Appendix: NeuRad status



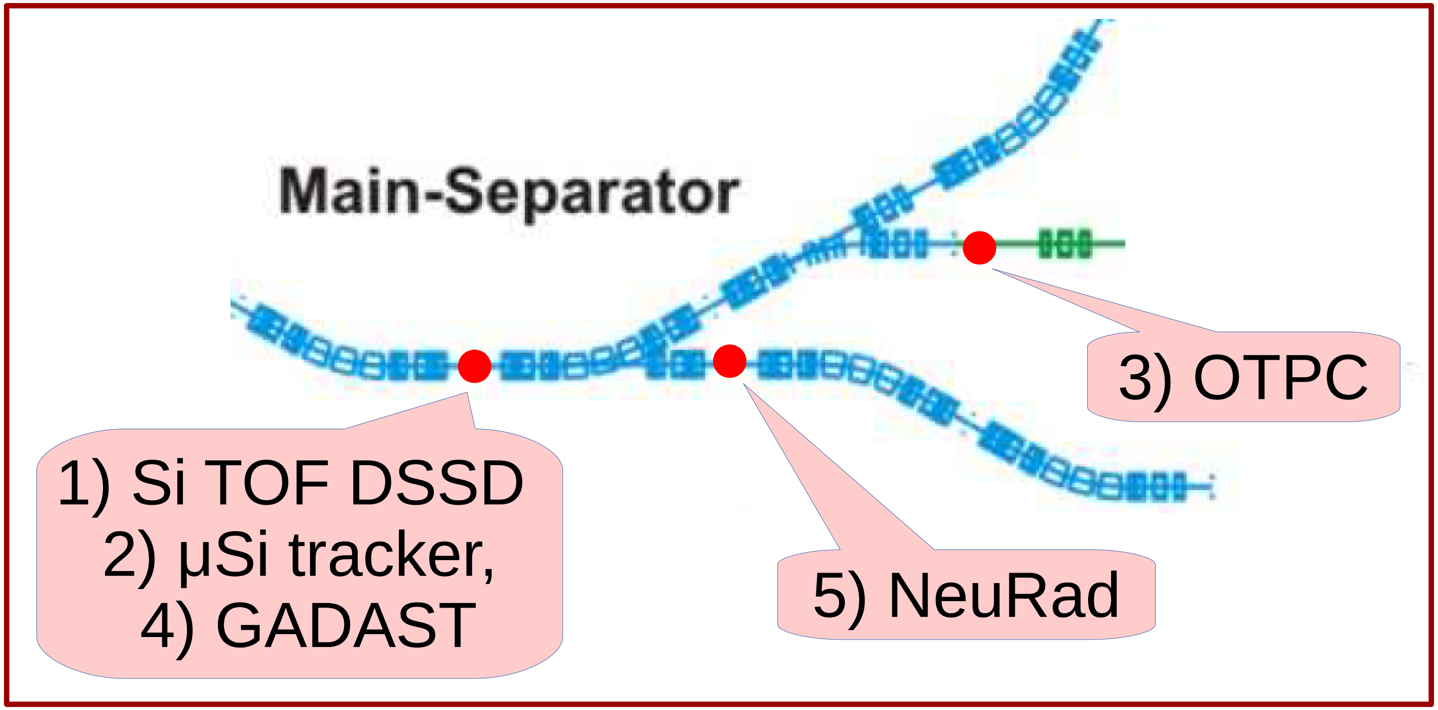


Very preliminary results!!!



- collimated beam - ^{60}Co
- only one fiber of the bundle selected
- Time resolution: 2.9 ns
- comparison with simulations needed

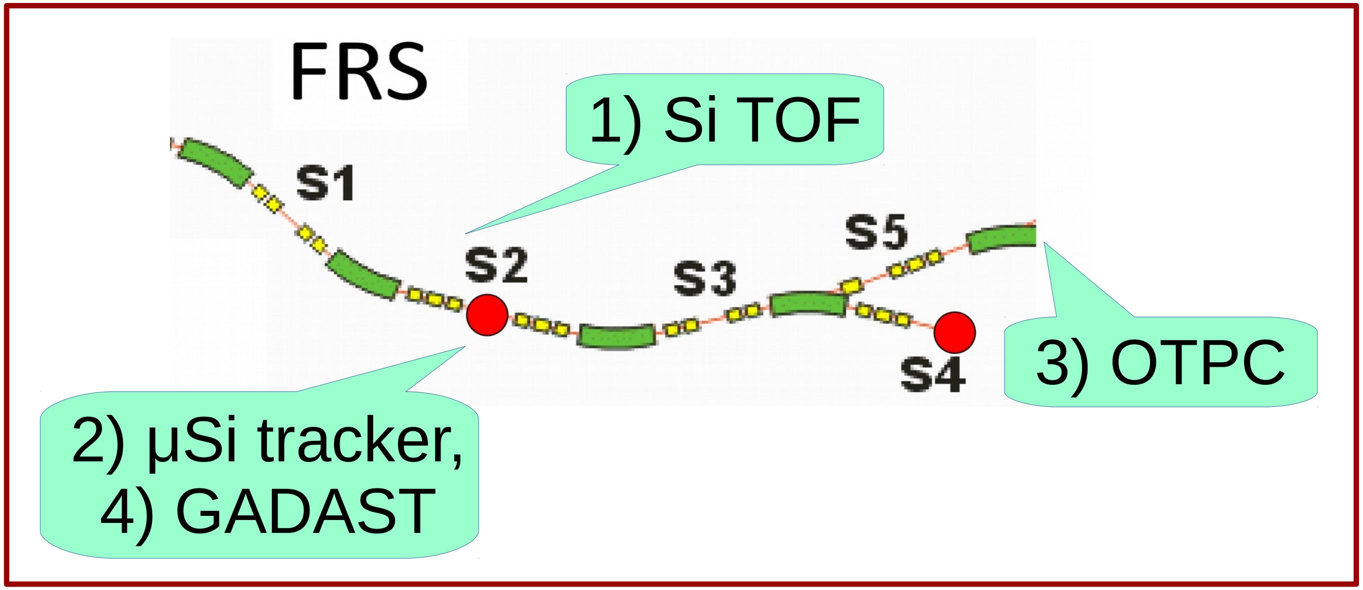
Appendix: Proposed experiments



+ simulation and data analysis framework

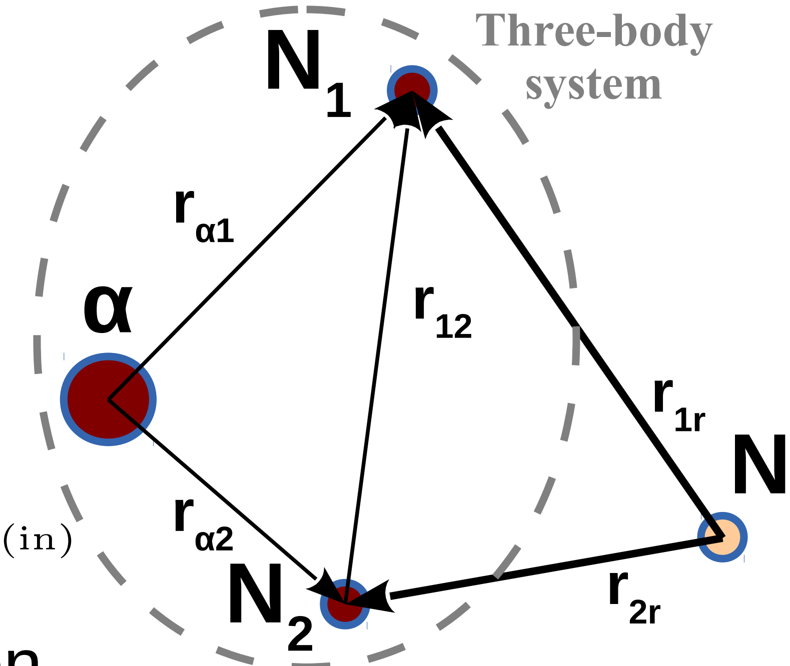
ExpertRoot

(http://er.jinr.ru)



Appendix: Theoretical model

- PWIA in combination with 3-body problem
- task reduced to solving of Schroedinger equation with source



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

- transition operator contains information about population of ^{6}Be from ^{6}Li

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

- Transition operator takes a "simple" analytical form thanks to the choice of the N-N potential used in PWIA

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

NUSTAR

NUclear STructure, Astrophysics and Reactions

- HISPEC/DESPEC (High-Resolution Spectroscopy/Decay Spectroscopy)
- R3B (Reactions with Relativistic Radioactive Beams)
- MATS (Precision Measurements of very short-lived nuclei with Advanced Trapping System)
- LaSpec (Laser Spectroscopy)
- ILIMA (Isomeric Beams, Lifetimes and Masses)
- ELISe (Electron-Ion Scattering in a Storage Ring)
- EXL (Exotic nuclei studied in light-ion induced reactions at the NESR storage ring)
- **Super-FRS Experiments**
- SHE (Super-Heavy Element Research)

SuperFRS Experiments

- **Mass and charge resolution**
  - Search for new isotopes and ground-state properties
  - Atomic collisions
- **Unique experiments at Super-FRS as high-energy high-resolution spectrometer**
  - Spectroscopy of meson-nucleus bound system
  - Exotic hypernuclei and their properties
  - Importance of tensor forces in nuclear structure
  - Delta resonances probing nuclear structure
- **Experiments taking advantages of multi-stages and high-resolution of the Super-FRS**
  - Nuclear radii and momentum distributions
  - EXPERT (**EX**otic **P**article **E**mission and **R**adioactivity by **T**racking)
  - Low-q experiments with an active target
  - Nuclear reaction studies and synthesis of isotopes with low-energy RIBs