Experimental research with exotic nuclei

Vratislav Chudoba

FLNR, JINR

Periodic table

период	ряд	группы элементов: а I б	а II б	а III б	а IV б	а V б	а VI б	а VII б	а VIII б		
1	I	Водород 1 H $1s^1$ 1,00794 Hydrogen							Гелий 2 He $1s^2$ 4,0026 Helium		
2	II	Литий 3 Li $2s^1$ 6,941 Lithium	Бериллий 4 Be $2s^2$ 9,012182 Beryllium	Бор 5 B $2p^1$ 10,811 Boron	Углерод 6 C $2p^2$ 12,011 Carbon	Азот 7 N $2p^3$ 14,00674 Nitrogen	Кислород 8 O $2p^4$ 15,9994 Oxygen	Фтор 9 F $2p^5$ 18,9984032 Fluorine	Неон 10 Ne $2p^6$ 20,1797 Neon		
3	III	Натрий 11 Na $3s^1$ 22,989768 Sodium	Магний 12 Mg $3s^2$ 24,3050 Magnesium	Алюминий 13 Al $3p^1$ 26,981539 Aluminum	Кремний 14 Si $3p^2$ 28,0855 Silicon	Фосфор 15 P $3p^3$ 30,973762 Phosphorus	Сера 16 S $3p^4$ 32,066 Sulfur	Хлор 17 Cl $3p^5$ 35,4527 Chlorine	Аргон 18 Ar $3p^6$ 39,948 Argon		
4	IV	Калий 19 K $4s^1$ 39,0983 Potassium	Кальций 20 Ca $4s^2$ 40,078 Calcium	21 $3d^14s^2$ Sc Скандий 44,955910 Scandium	22 $3d^24s^2$ Ti Титан 47,88 Titanium	23 $3d^34s^2$ V Ванадий 50,9415 Vanadium	24 $3d^54s^1$ Cr Хром 51,9961 Chromium	25 $3d^54s^2$ Mn Марганец 54,93805 Manganese	26 $3d^64s^2$ Fe Железо 55,847 Iron	27 $3d^74s^2$ Co Кобальт 58,93320 Cobalt	28 $3d^84s^2$ Ni Никель 58,6934 Nickel
	V	29 $3d^{10}4s^1$ Cu Медь 63,546 Copper	30 $3d^{10}4s^2$ Zn Цинк 65,39 Zinc	Галлий 31 Ga $4p^1$ 69,723 Gallium	Германий 32 Ge $4p^2$ 72,61 Germanium	Мышьяк 33 As $4p^3$ 74,92159 Arsenic	Селен 34 Se $4p^4$ 9,75238 78,96 Selenium	Бром 35 Br $4p^5$ 79,904 Bromine	Криптон 36 Kr $4p^6$ 83,80 Krypton		
5	VI	Рубидий 37 Rb $5s^1$ 85,4678 Rubidium	Стронций 38 Sr $5s^2$ 87,62 Strontium	39 $4d^15s^2$ Y Иттрий 88,90585 Yttrium	40 $4d^25s^2$ Zr Цирконий 91,224 Zirconium	41 $4d^45s^1$ Nb Ниобий 92,90638 Niobium	42 $4d^55s^1$ Mo Молибден 95,94 Molybdenum	43 $4d^55s^2$ Tc Технеций [98] Technetium	44 $4d^75s^1$ Ru Рутений 101,07 Ruthenium	45 $4d^85s^1$ Rh Родий 102,90550 Rhodium	46 $4d^{10}$ Pd Палладий 106,42 Palladium
	VII	47 $4d^{10}5s^1$ Ag Серебро 107,8682 Silver	48 $4d^{10}5s^2$ Cd Кадмий 112,411 Cadmium	Индий 49 In $5p^1$ 114,818 Indium	Олово 50 Sn $5p^2$ 118,710 Tin	Сурьма 51 Sb $5p^3$ 121,757 Antimony	Теллур 52 Te $5p^4$ 127,60 Tellurium	Иод 53 I $5p^5$ 126,90447 Iodine	Ксенон 54 Xe $5p^6$ 131,29 Xenon		
6	VIII	Цезий 55 Cs $6s^1$ 132,90543 Cesium	Барий 56 Ba $6s^2$ 137,327 Barium	57 $5d^16s^2$ La Лантан 138,9055 Lanthanum	72 $5d^26s^2$ Hf Гафний 178,49 Hafnium	73 $5d^36s^2$ Ta Тантал 180,9479 Tantalum	74 $5d^46s^2$ W Вольфрам 183,84 Tungsten	75 $5d^56s^2$ Re Рений 186,207 Rhenium	76 $5d^66s^2$ Os Осмий 190,23 Osmium	77 $5d^76s^2$ Ir Иридий 192,22 Iridium	78 $5d^96s^1$ Pt Платина 195,08 Platinum
	IX	79 $5d^{10}6s^1$ Au Золото 196,96654 Gold	80 $5d^{10}6s^2$ Hg Ртуть 200,59 Mercury	Таллий 81 Tl $6p^1$ 204,3833 Thallium	Свинец 82 Pb $6p^2$ 207,2 Lead	Висмут 83 Bi $6p^3$ 208,98037 Bismuth	Полоний 84 Po $6p^4$ [209] Polonium	Астат 85 At $6p^5$ [210] Astatine	Радон 86 Rn $6p^6$ [222] Radon		
7	X	Франций 87 Fr $7s^1$ 4,073 [223] Francium	Радий 88 Ra $7s^2$ 226,025 Radium	89 $6d^17s^2$ Ac Актиний [227] Actinium	104 Rf Резерфордий [261] Rutherfordium	105 Db Дубний [262] Dubnium	106 Sg Сиборгий [266] Seaborgium	107 Bh Борий [267] Bohrium	108 Hs Хассий [269] Hassium	109 Mt Мейтнерий [268] Meitnerium	110 Ds Дармштадтий [269] Darmstadtium
	XI	111 Rg Рентгений [272] Roentgenium	112 Cn Коперниций [285] Copernicium	113	Флеровий 114 Fl Flerovium	115	Ливерморий 116 Lv Livermorium	117	118		

Лантаноиды Lanthanides

Церий Ce $4f^15d^1$ 140,115 Cerium	Празеодим Pr $4f^3$ 140,90765 Praseodymium	Неодим Nd $4f^4$ 144,24 Neodymium	Прометий Pm $4f^5$ [145] Promethium	Самарий Sm $4f^6$ 150,36 Samarium	Европий Eu $4f^7$ 151,965 Europium	Гадолиний Gd $4f^75d^1$ 157,25 Gadolinium	Тербий Tb $4f^9$ 158,92534 Terbium	Диспрозий Dy $4f^{10}$ 162,50 Dysprosium	Гольмий Ho $4f^{11}$ 164,93032 Holmium	Эрбий Er $4f^{12}$ 167,26 Erbium	Тулий Tm $4f^{13}$ 168,93421 Thulium	Иттербий Yb $4f^{14}$ 173,04 Ytterbium	Лютеций Lu $4f^{14}5d^1$ 174,967 Lutetium

Актиноиды Actinides

Торий Th $7s^26d^2$ 232,0381 Thorium	Протактиний Pa $5f^26d^1$ 231,03588 Protactinium	Уран U $5f^36d^1$ 238,0289 Uranium	Нептуний Np $5f^46d^1$ [237] Neptunium	Плутоний Pu $5f^6$ [244] Plutonium	Америций Am $5f^7$ [243] Americium	Кюрий Cm $5f^76d^1$ [247] Curium	Берклий Bk $5f^9$ [247] Berkelium	Калифорний Cf $5f^{10}$ [251] Californium	Эйнштейний Es $5f^{11}$ [252] Einsteinium	Фермий Fm $5f^{12}$ [257] Fermium	Менделевий Md $5f^{13}$ [258] Mendelevium	Нобелий No $5f^{14}$ [259] Nobelium	Лоуренсий Lr $5f^{14}6d^1$ [262] Lawrencium

Водород 1 H $1s^1$ 1,00794 Hydrogen

символ / symbol

электронная конфигурация / electronic configuration

атомная масса / atomic mass

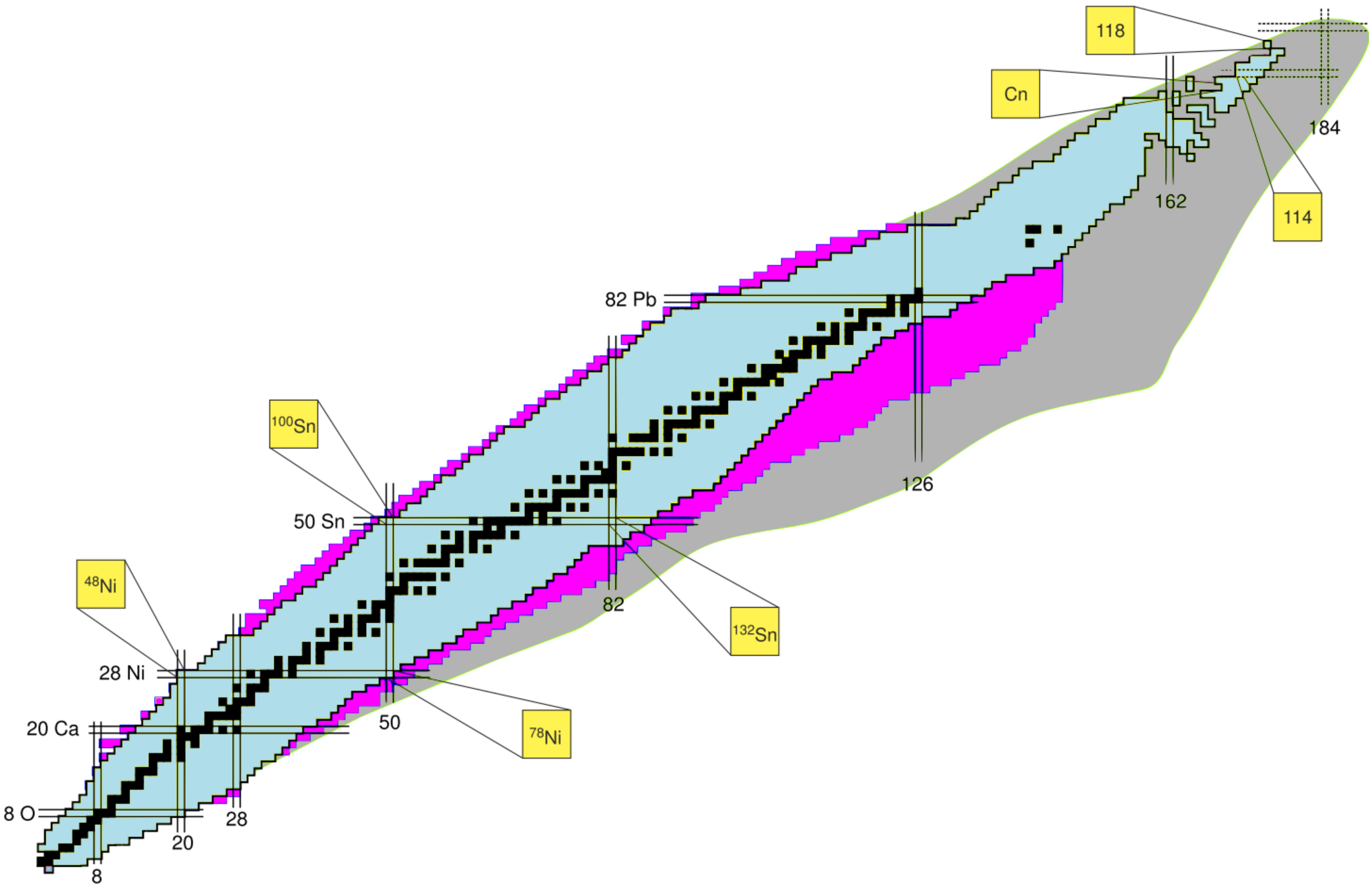
S-ЭЛЕМЕНТЫ/ELEMENTS

p-элементы

d-элементы

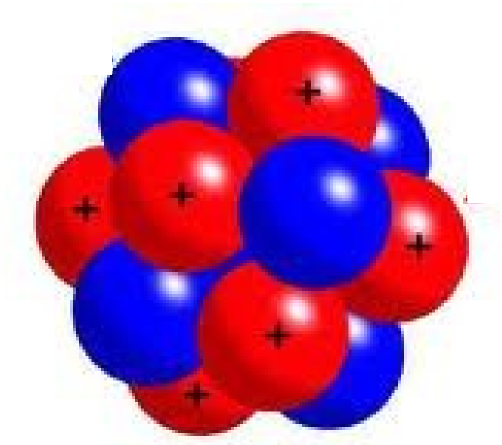
f-элементы

Nuclear landscape



Why exotic?

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

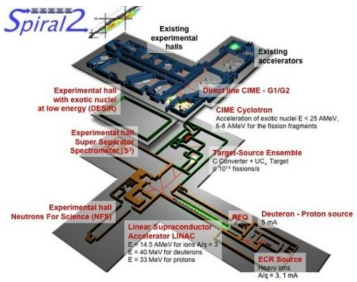


too heavy **or** **strange in other way**

What’s going on?

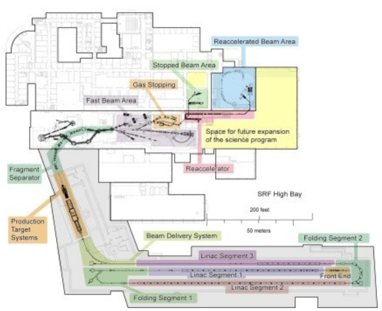
Modest vs. big, bigger, the biggest

Huge increase in the scale
of modern RIB facilities

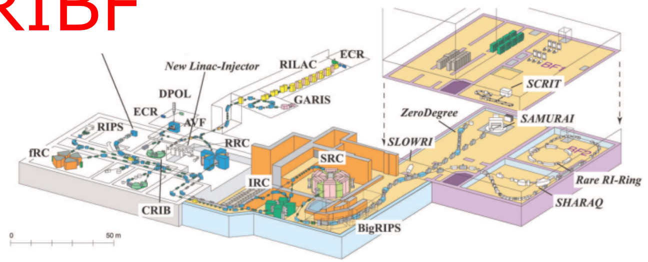


SPIRAL 2

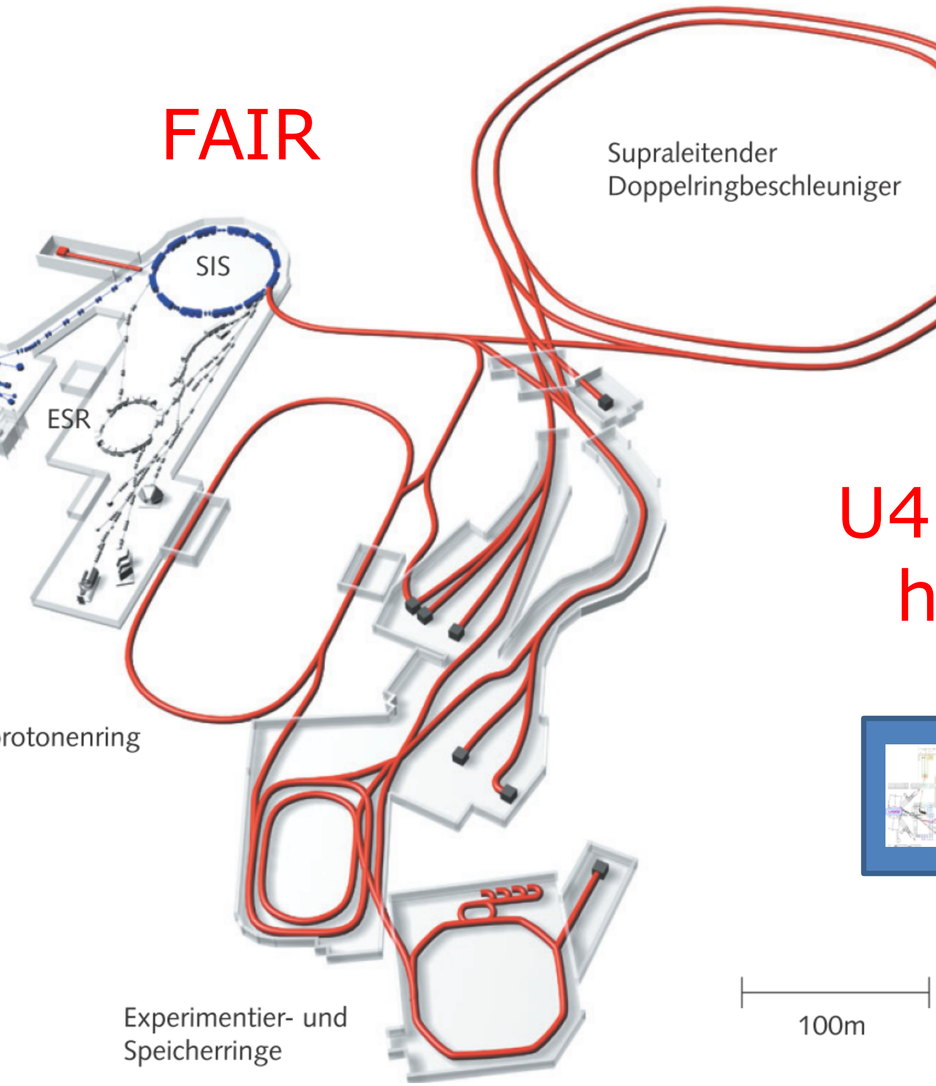
FRIB



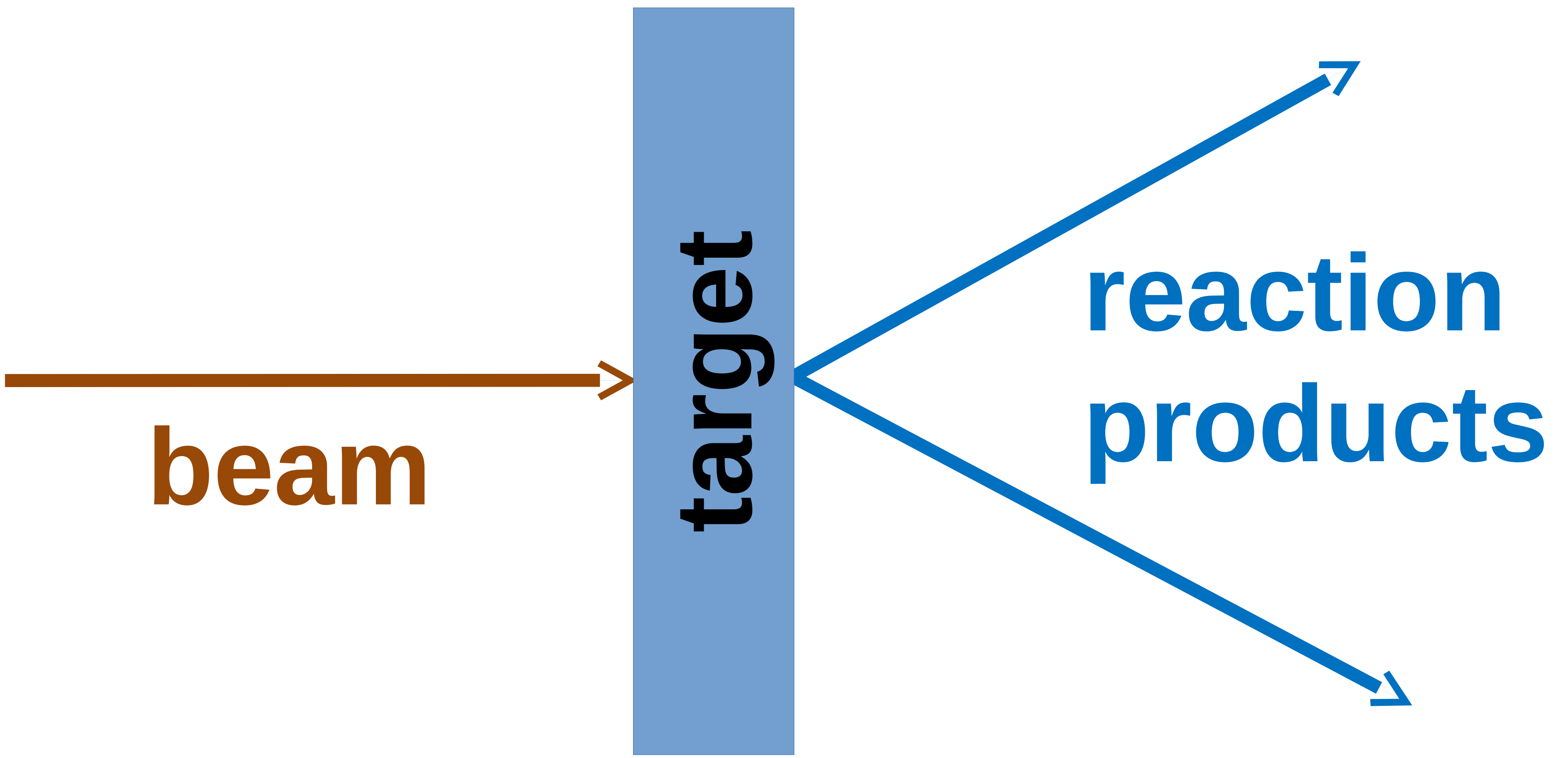
RIBF



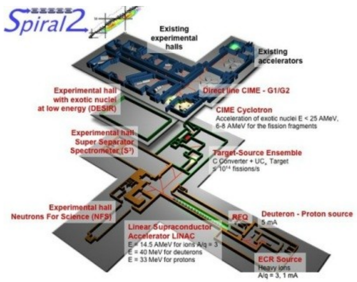
FAIR



U400M
hall

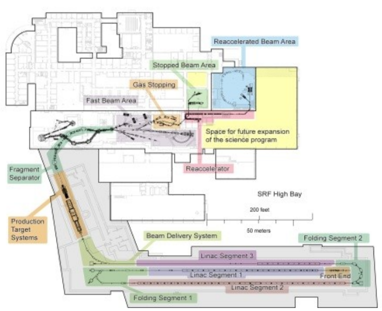

target
beam
reaction
products

Modest vs. big, bigger, the biggest

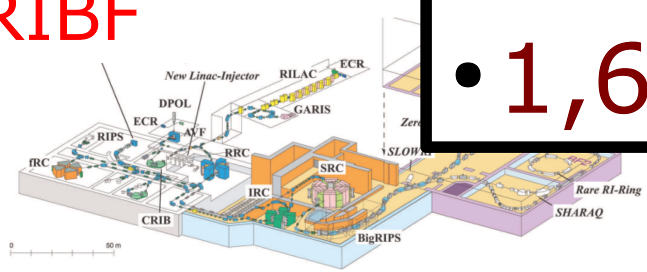


SPI

FRIB



RIBF



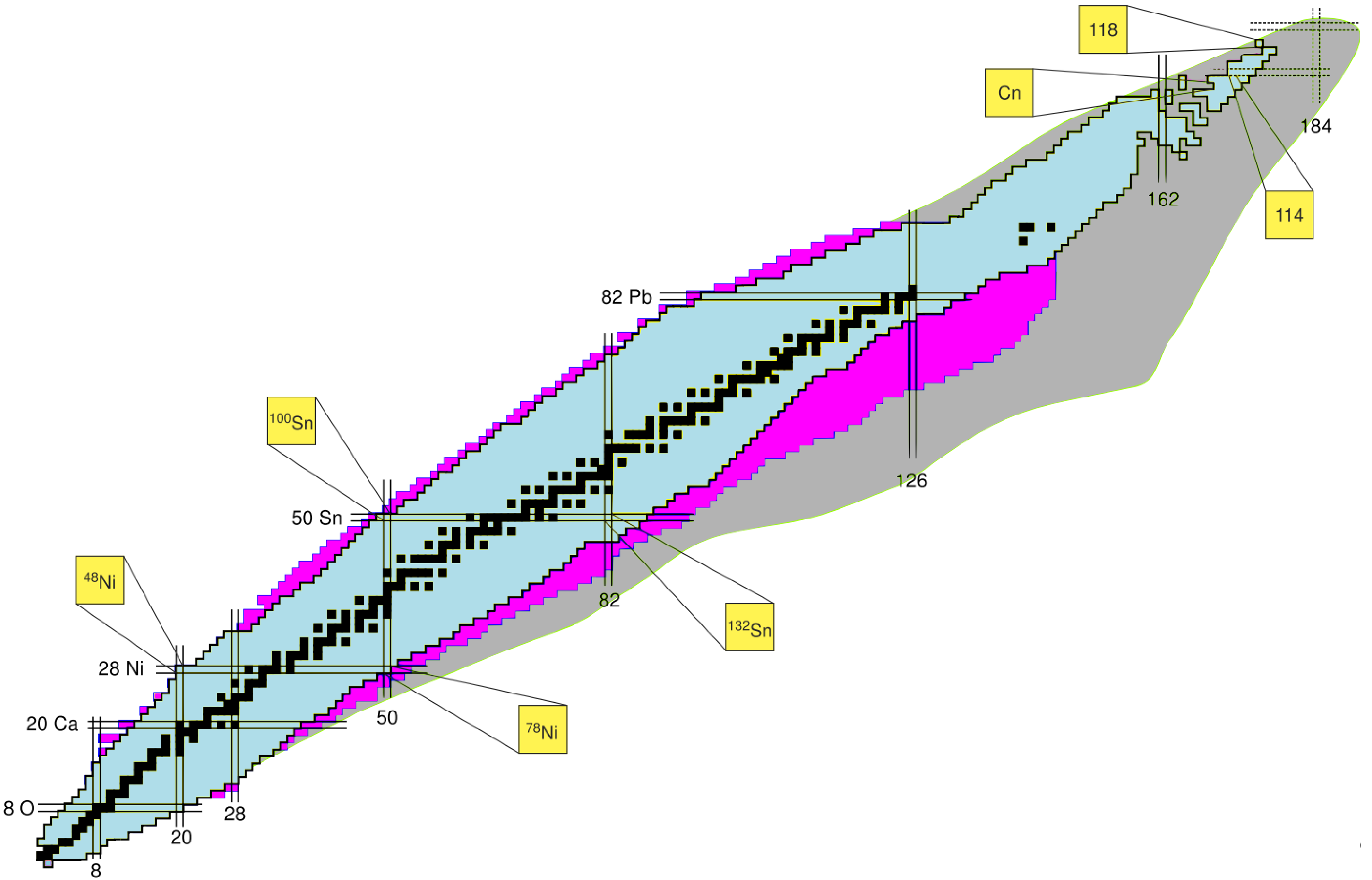
Facility for Antiproton and Ion Research:

- 10 member states
- scientists from more than 50 countries
- 20 years of construction
- 1,6 billions euro

Radioactive ion beams

acceleration of a primary beam ($I \sim 10^{12}$ pps)

Radioactive ion beams



Radioactive ion beams

acceleration of a primary beam (I~10^{12} pps)

ISOL technique

- reactions in a thick production target:
  (**fast** production – **slow** release)
- reaction products to be extracted, ionized and reaccelerated
- secondary beam: (I<10^{8} pps)

Radioactive ion beams

acceleration of a primary beam (I~10^{12} pps)

ISOL technique

- reactions in a thick production target: (**fast** production – **slow** release)
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- secondary beam: (I<10^8 pps)

reactions on a physical target

Radioactive ion beams

acceleration of a primary beam (I~10^{12} pps)

ISOL technique

- reactions in a thick production target: (**fast** production – **slow** release)
- reaction products to be extracted, ionized and reaccelerated
- secondary beam: (I<10^{8} pps)

In-Flight Production

- reactions on a thin production target
- secondary beam: fragment-separator (I<10^{6} pps)

reactions on a physical target

Examples of RIB facilities

- In flight
  - GANIL (France), RIKEN (Japan), GSI (Germany), MSU (USA)
- ISOL
  - REX-ISOLDE (CERN), SPIRAL (France), TRIUMF (Canada)
- Other
  - Sao Paolo (Brazil), Orsay (France), Catania (Italy), Oak Ridge (USA), Jyvaskyla (Finland), Dubna

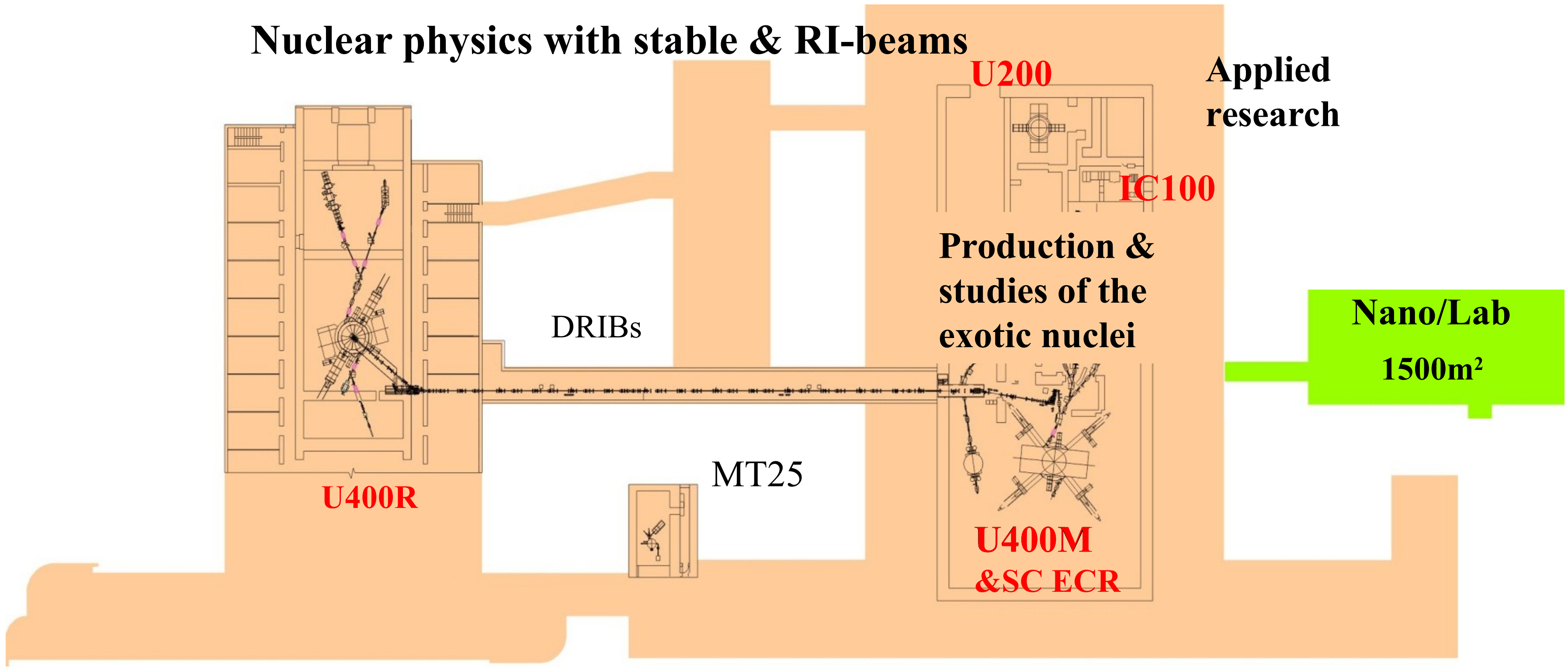
FLNR itself

Nuclear physics in FLNR

- **Heavy and superheavy elements**
  - synthesis of superheavy nuclei
  - nuclear spectroscopy
  - mass spectrometry
- **Light exotic nuclei**
  - properties and structure of light exotic nuclei
  - reactions with exotic nuclei

FLNR accelerator complex

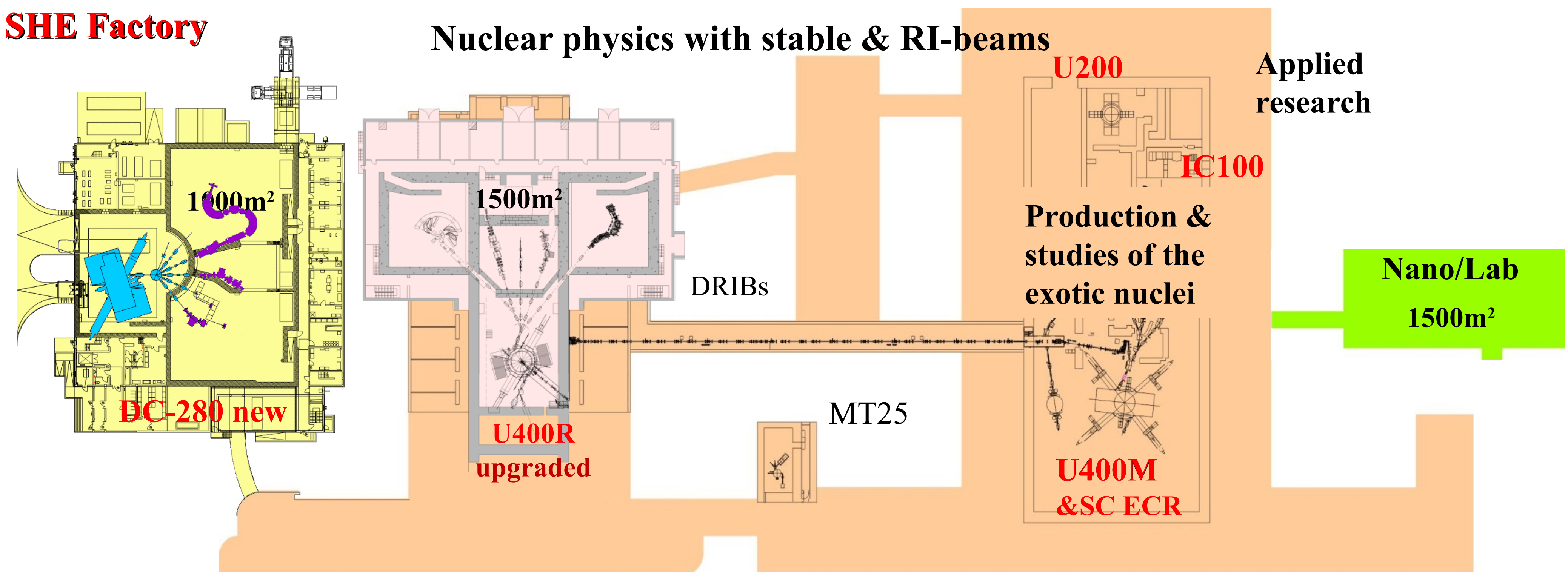
Current state of FLNR



FLNR accelerator complex

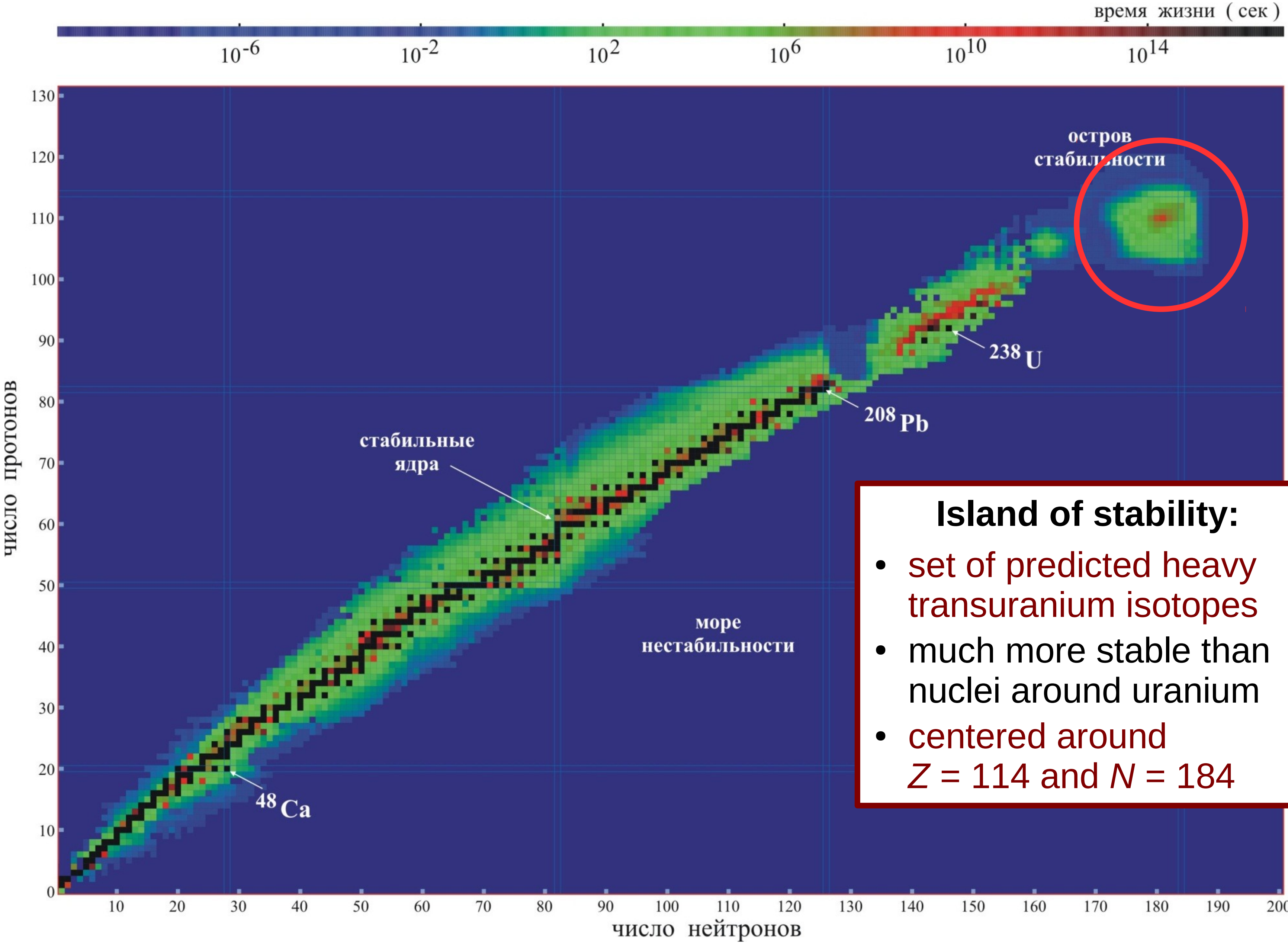
Full-scale realization of the DRIBs-III

Dubna Radioactive Beams



Superheavy elements factory

SHE: 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

SHE: to the Island of Stability

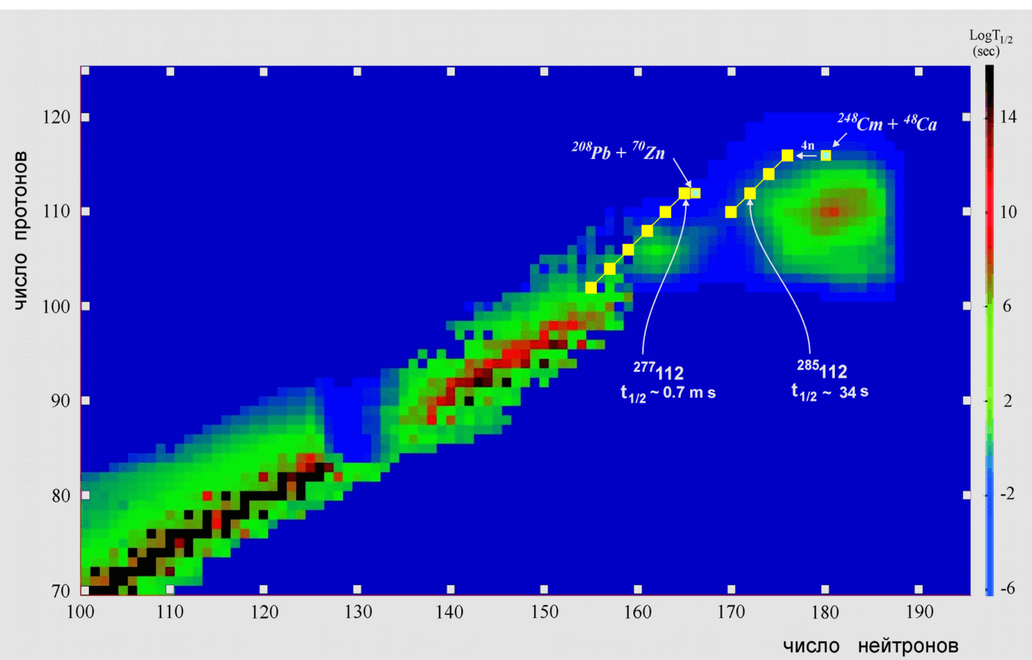
synthesis of superheavies

$$Z_1 + Z_2 = Z$$

$$N_1 + N_2 = N + (2 - 4)n$$

"cold" fusion: Pb + heavy ion

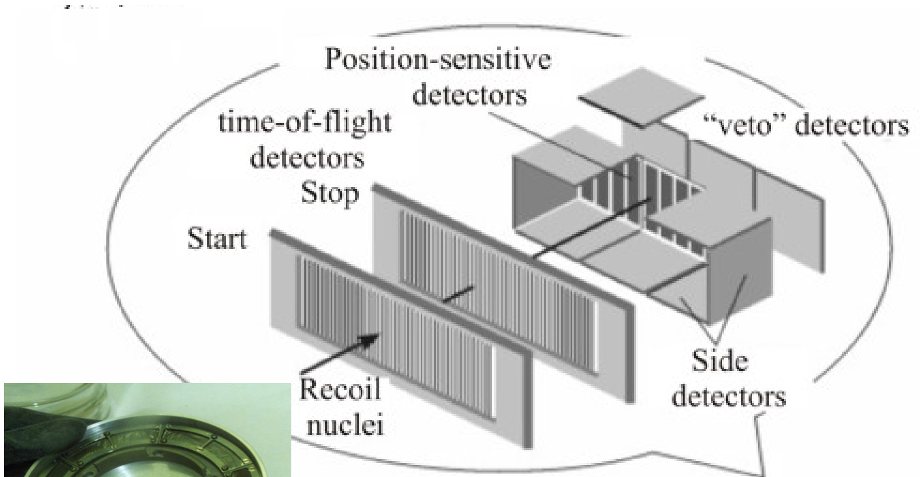
"hot" fusion: light beam + heavy target

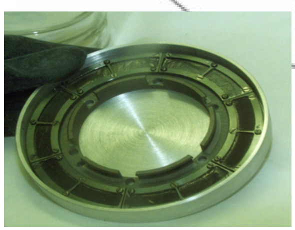


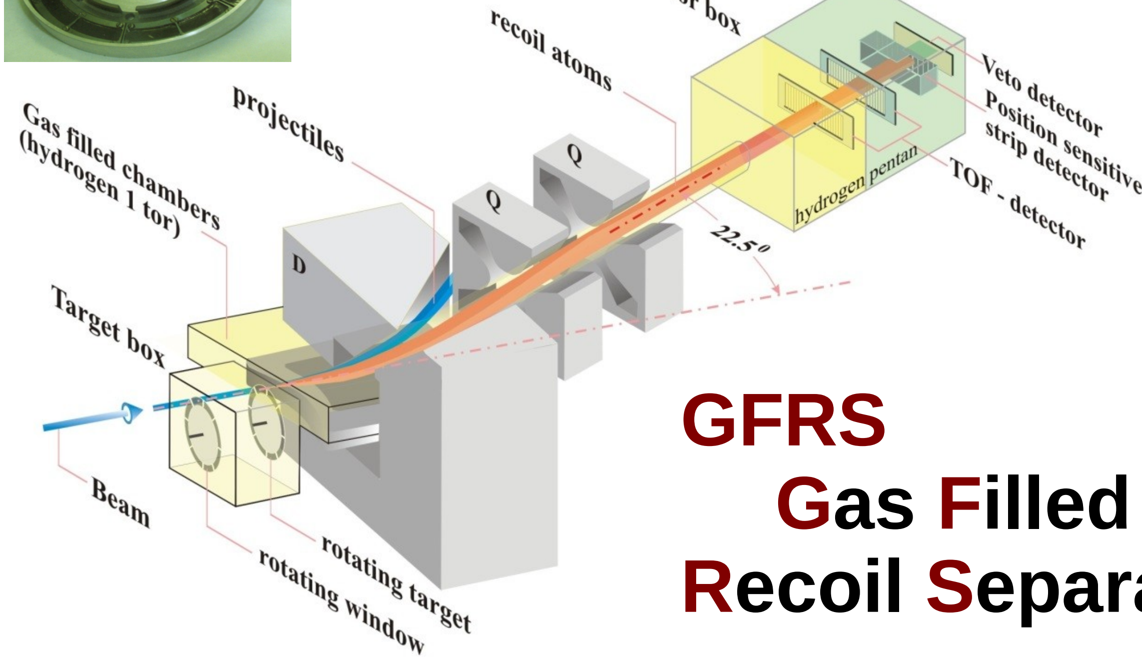
- low-energy physics
- compound nucleus
- combination of light and heavy nuclei gives higher cross sections

SHE: synthesis of superheavies

in collaboration with LLNL (USA)





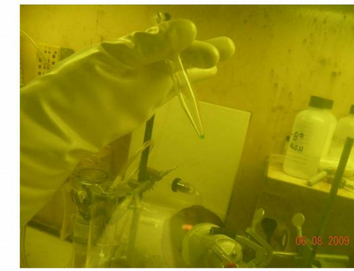


GFRS

Gas Filled Recoil Separator

beam

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



$Bk(NO_3)_3$Product

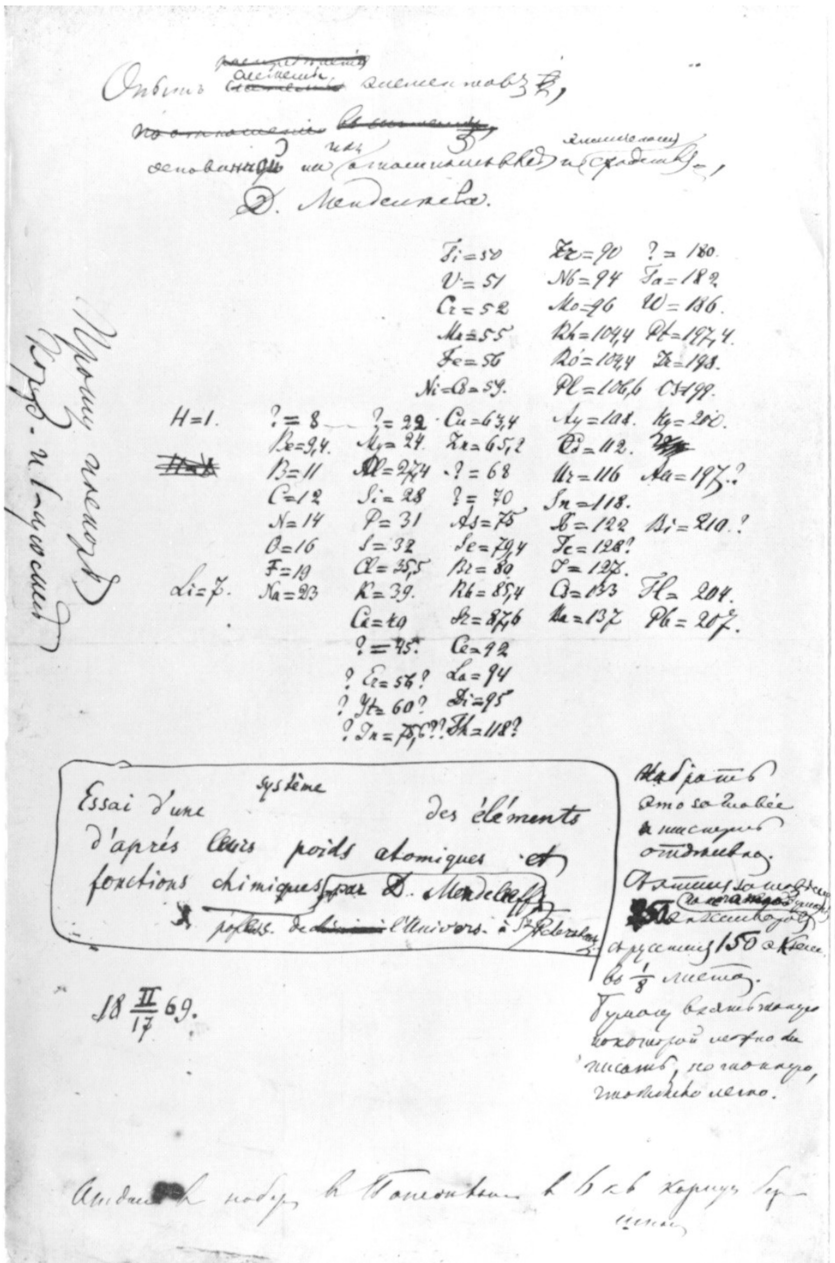
targets

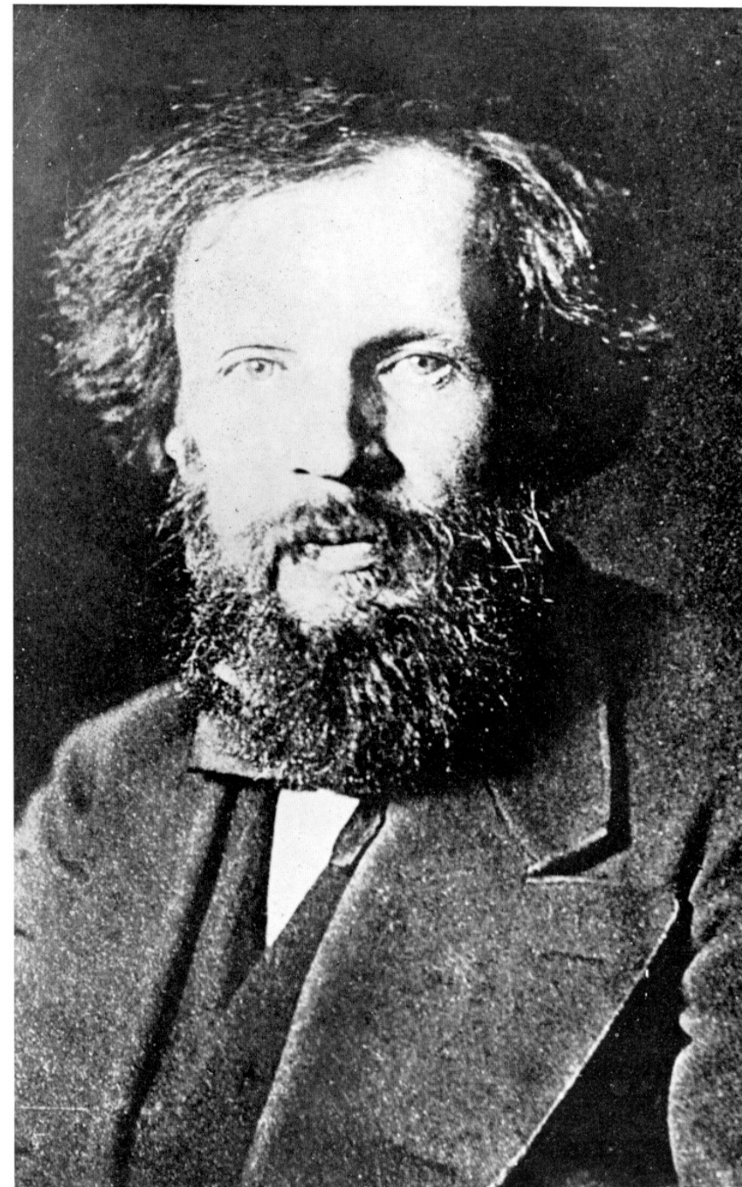
- ^{249}Bk (117), ^{251}Cf (118)
  - $T_{1/2}$ = 330 d, 900 y
- much more expensive than beam
  - delivered by LLNL

recently synthesized

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

Periodic table (~150 years ago)

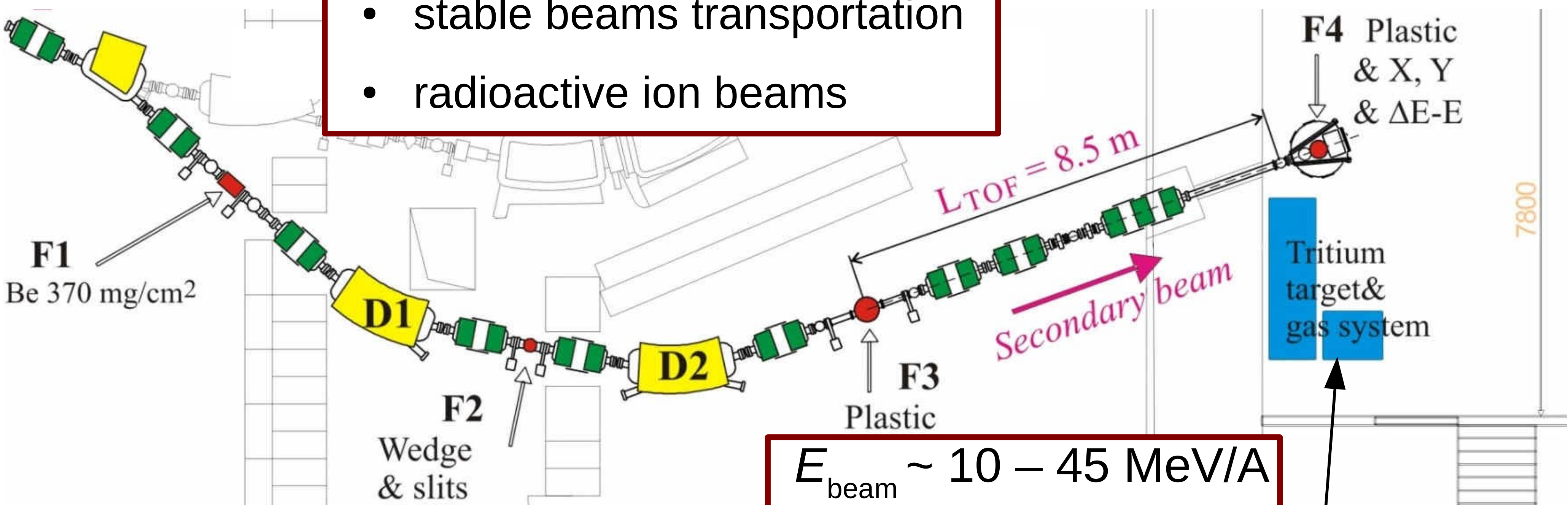




Periodic table today

ACCULINNA

- stable beams transportation
- radioactive ion beams



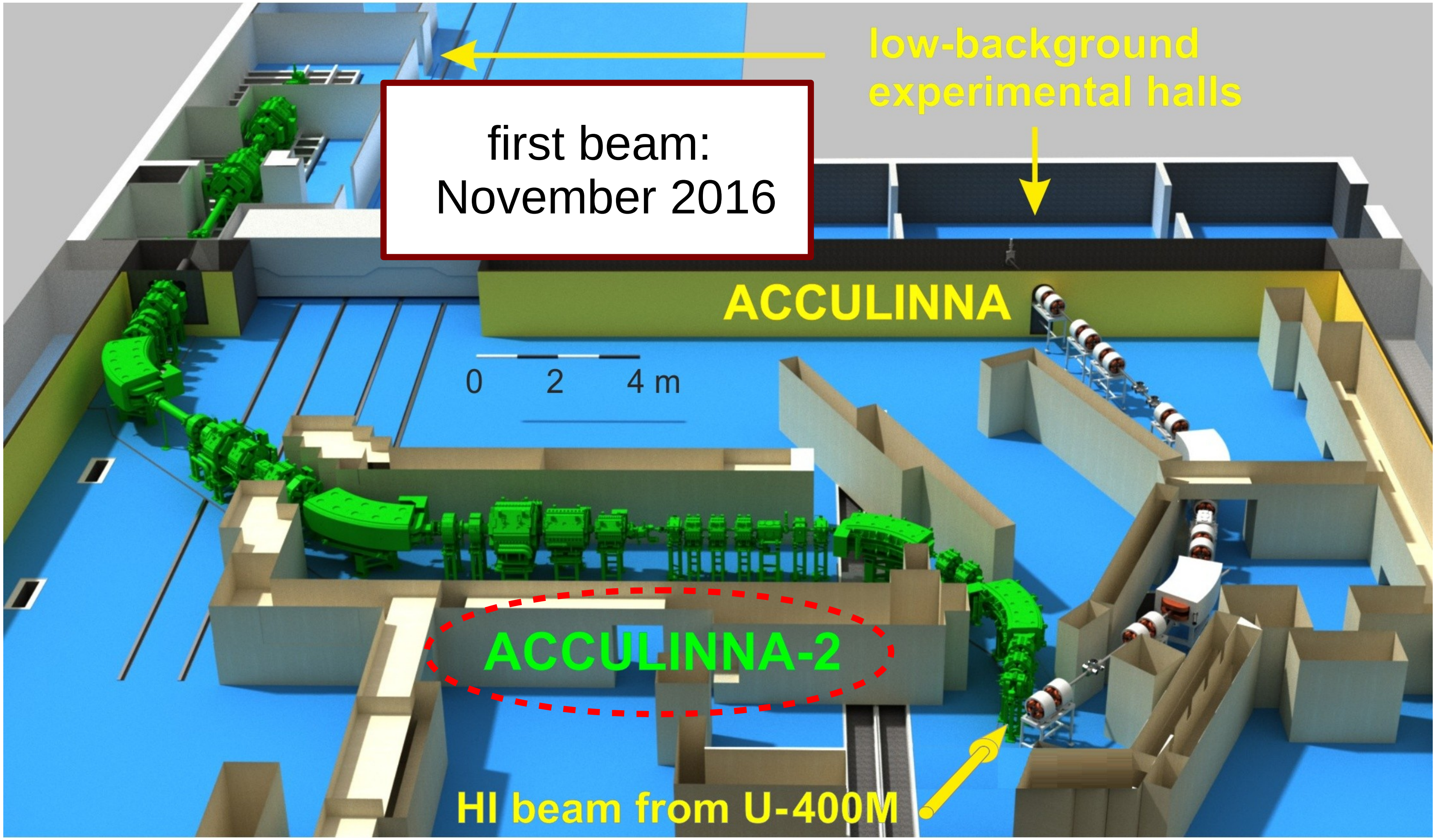
E_{beam} ~ 10 – 45 MeV/A

I_{beam} ~ 10^3 – 10^6 pps

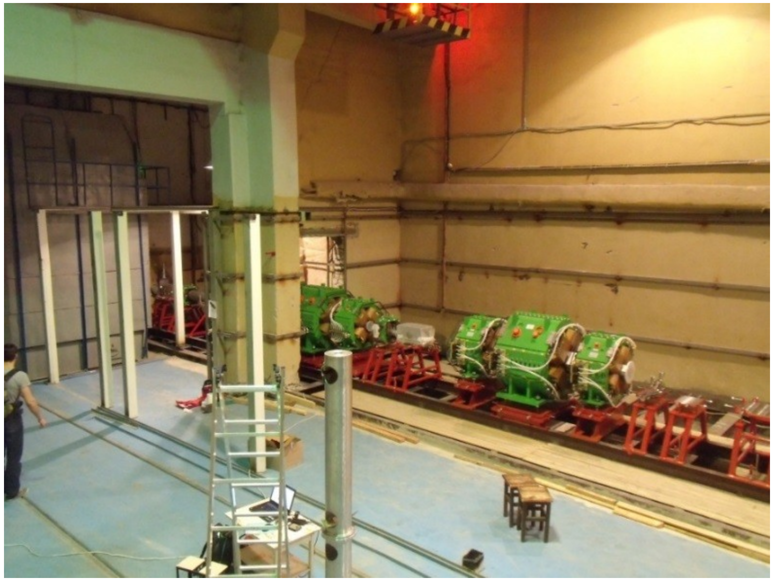
unique combination of tritium beam and target

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

ACCULINNA-2



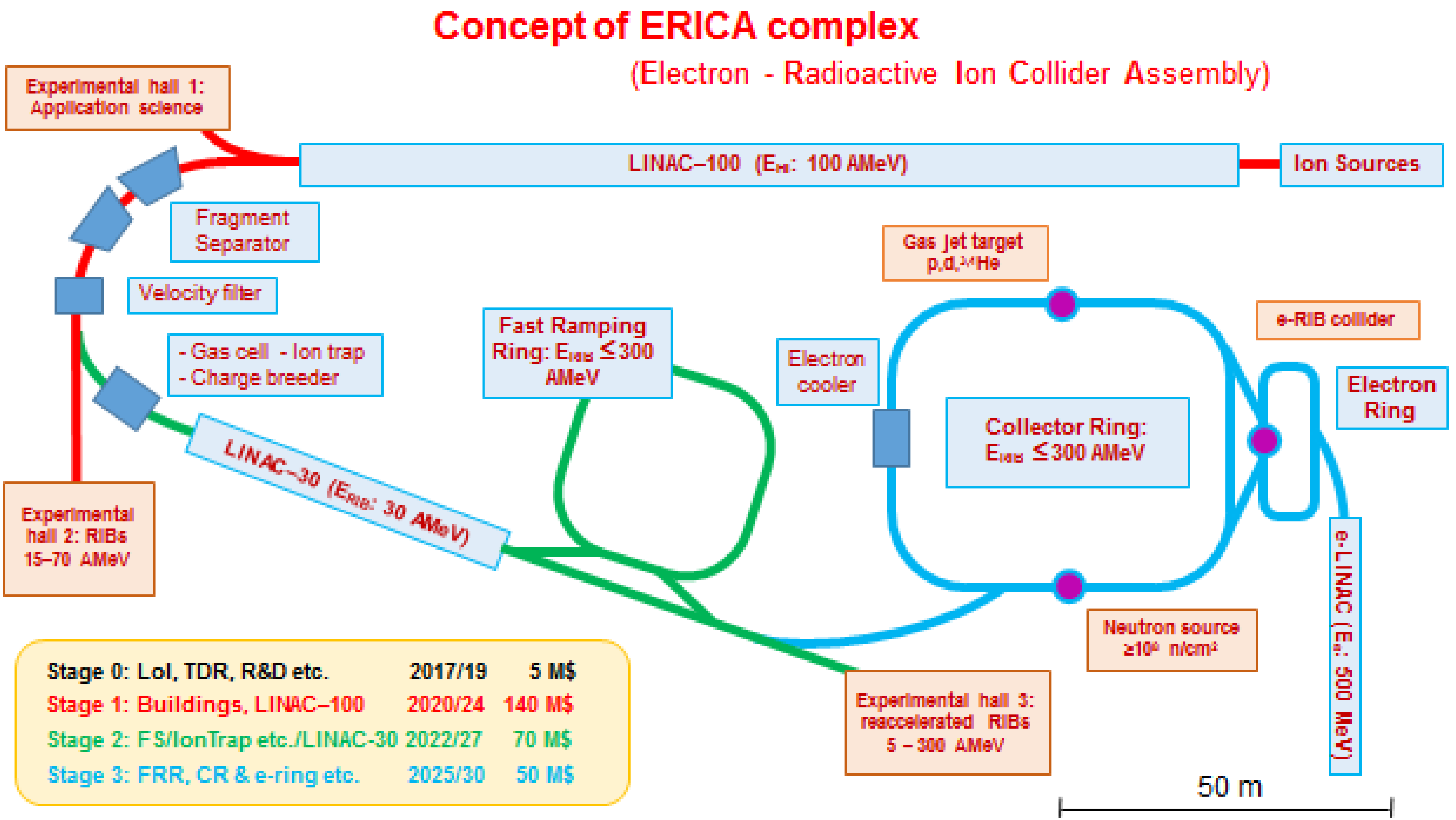
- energy range 6 – 60 MeV/A
- beam intensities higher in 2 orders
- Z_{RIB} ~ 1 – 36




BQ4
BQ3

New megascience project

New megascience project



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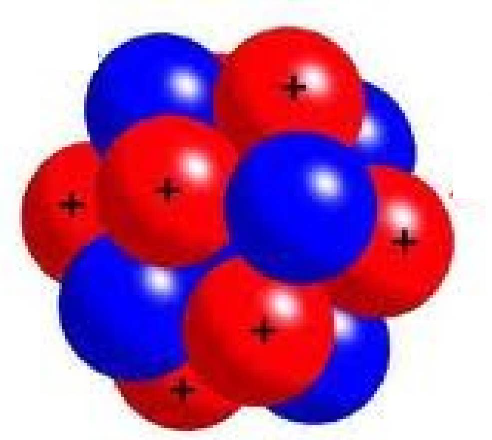
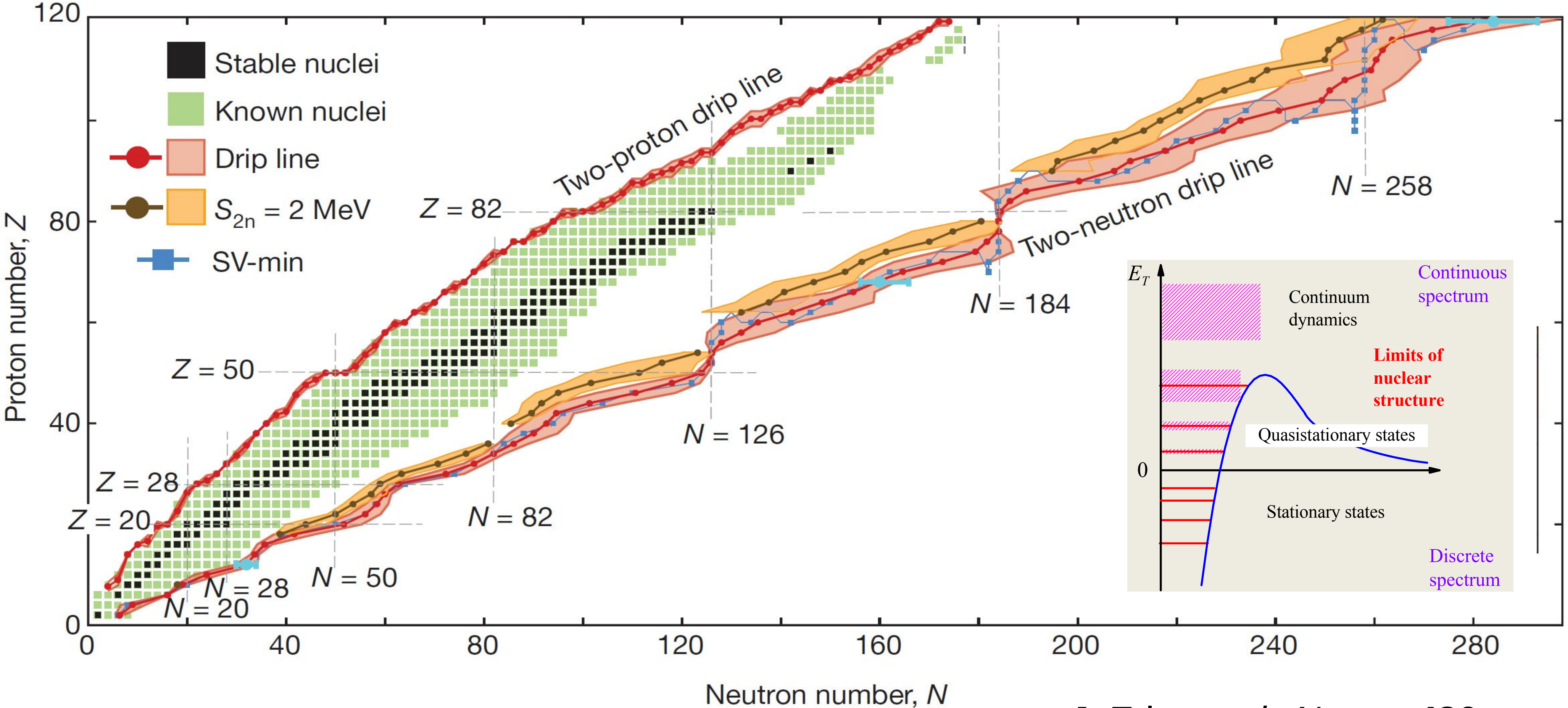


too heavy **or** **strange in other way**

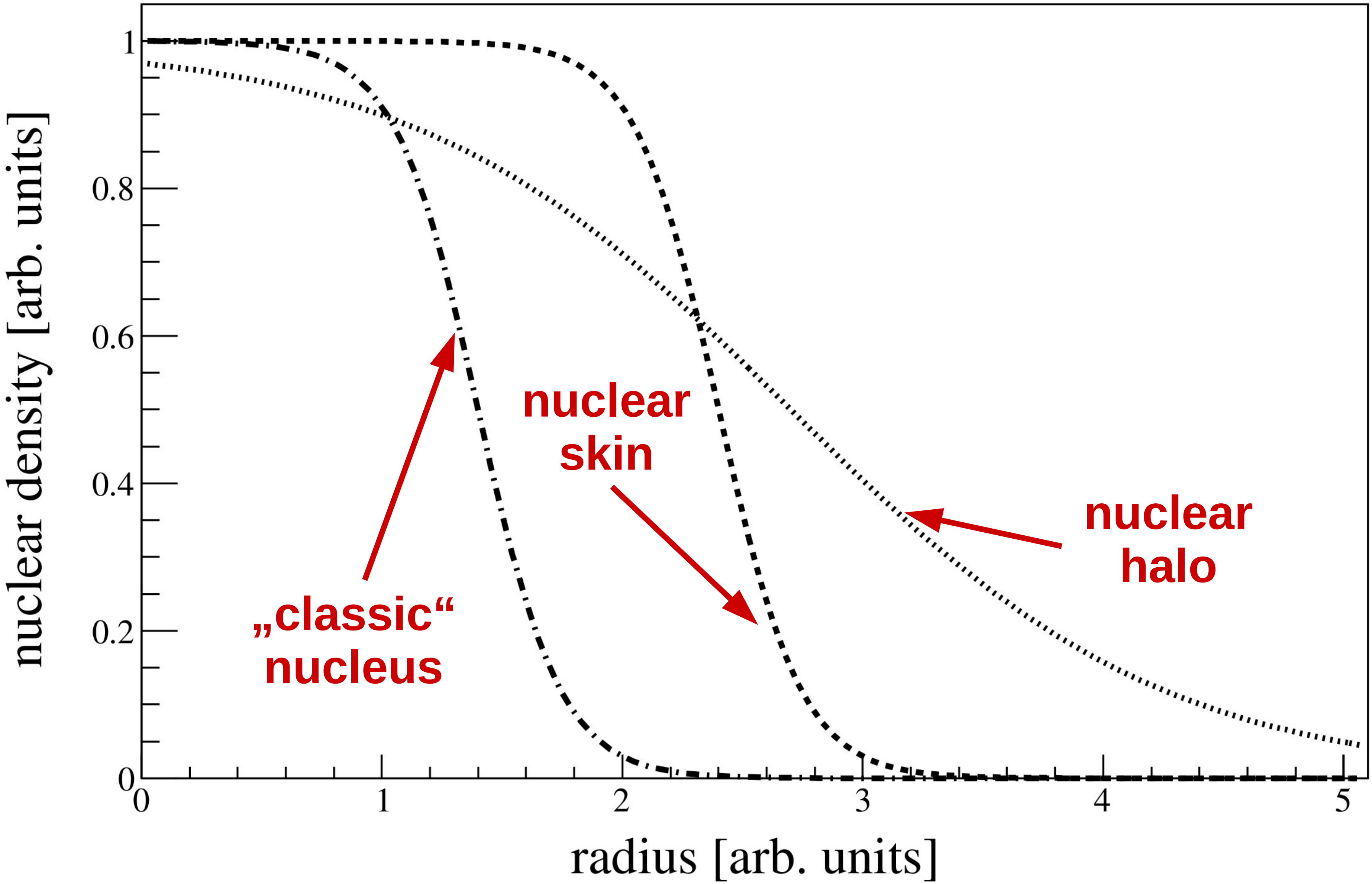
Drip-line



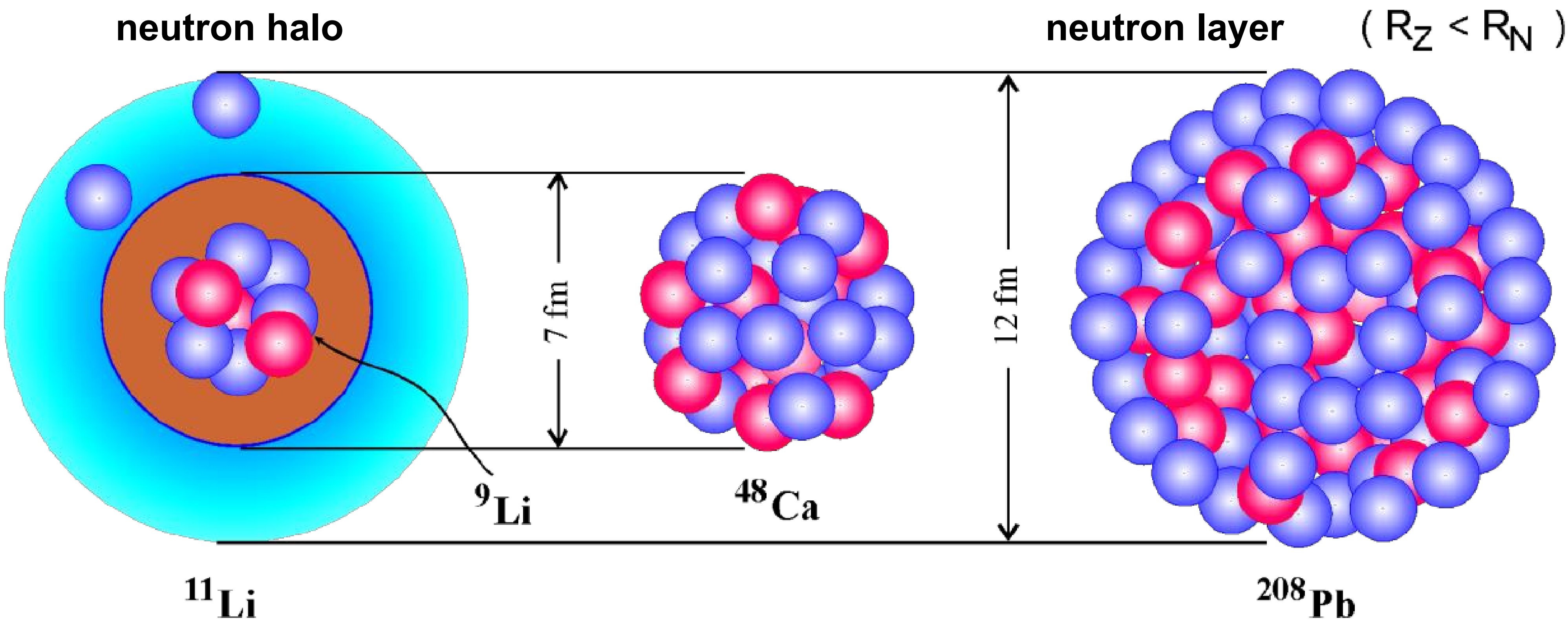
J. Erler *et al.*, Nature **486** (2012) 509

moving away from the nuclear stability → transition from discrete spectrum to continuum → immediate emission of nucleon

Nuclear halo



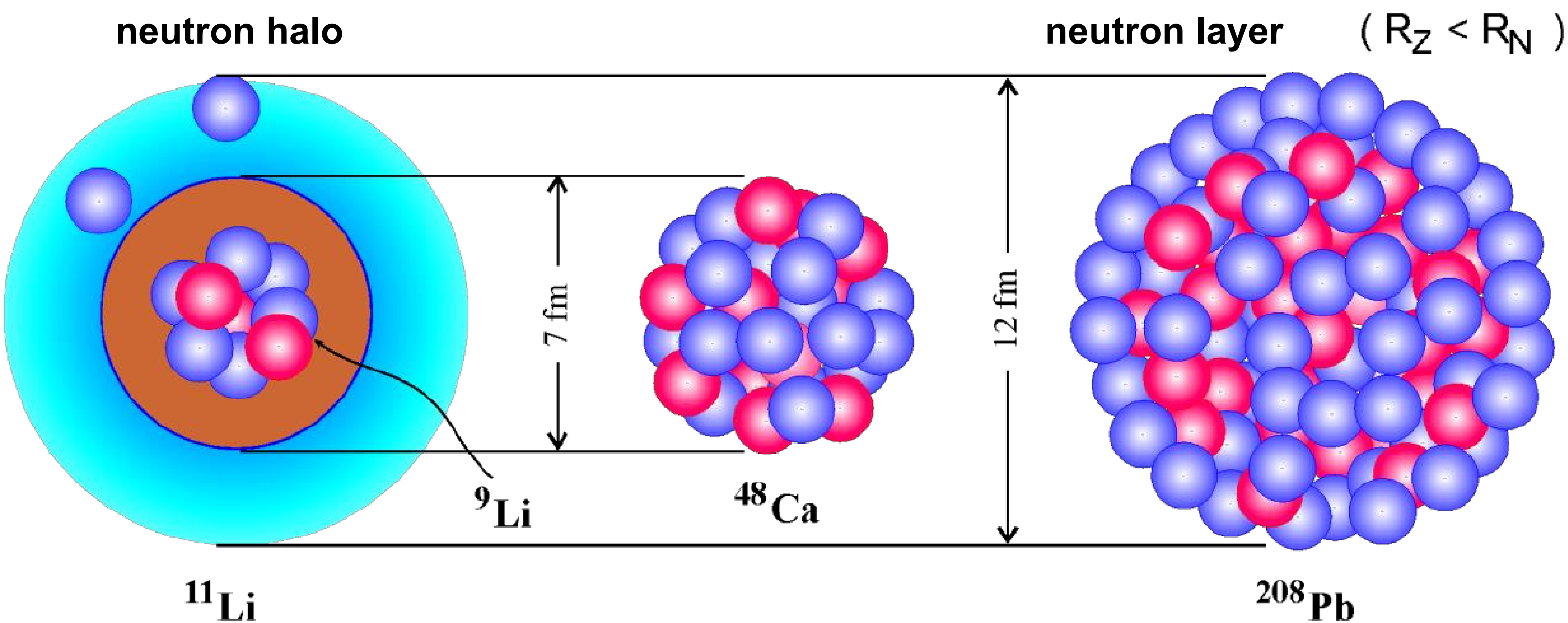
Nuclear halo



- **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**

Nuclear halo



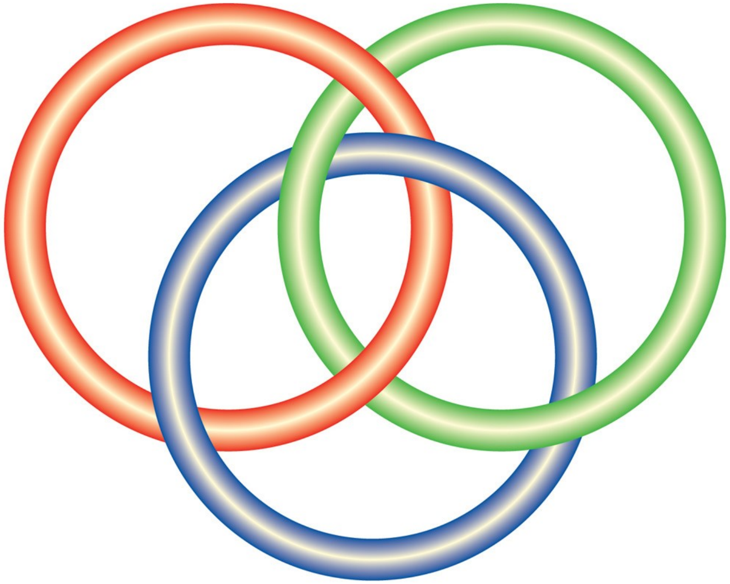
First observation of ^{6}He

T. Bjerge. Radio-Helium. NATURE, 137, 865, 138:400–400, **1936**!!!

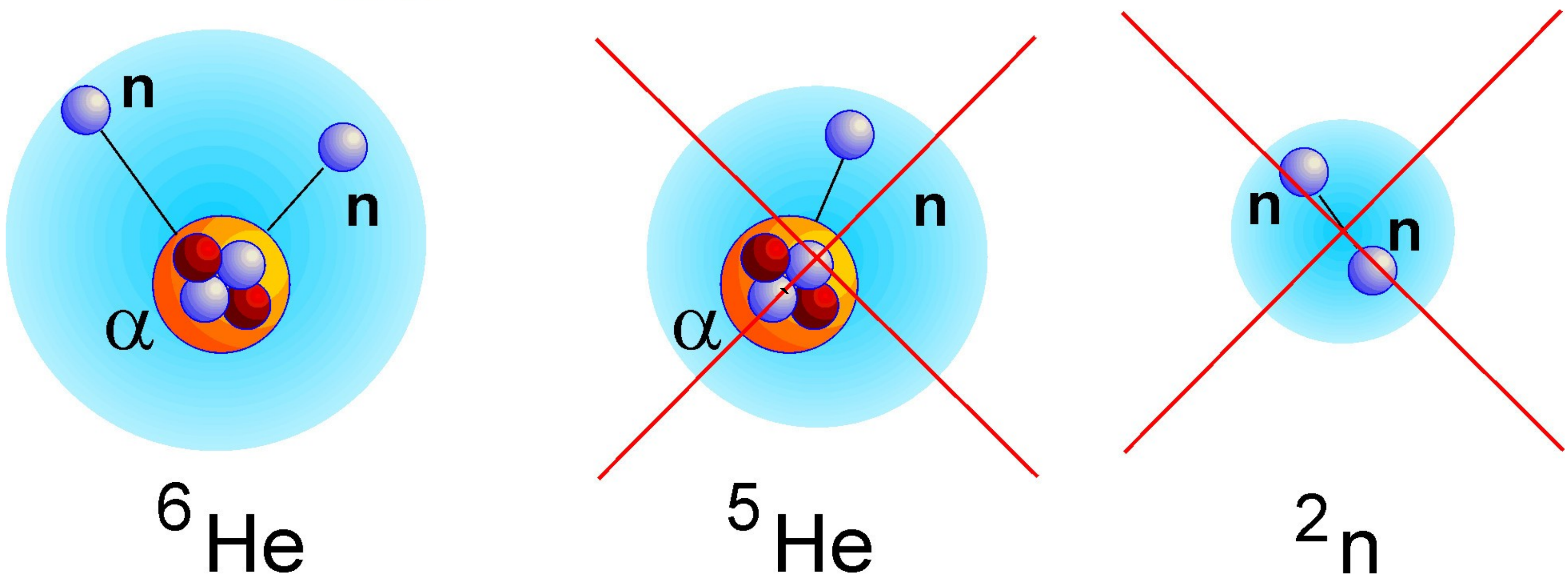
Observation of large ^{6}He radius

I. Tanihata et al., Physics Letters B, 160(6):380–384, 1985.

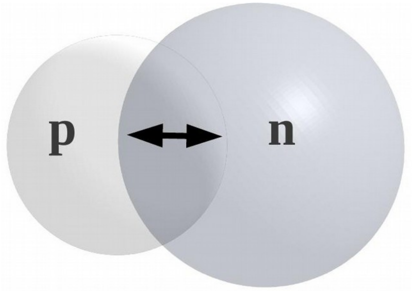
Borromean nuclei



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



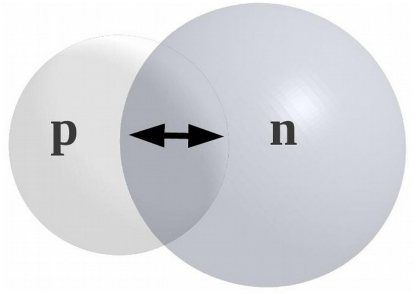
Soft dipole mode (SDM) of Giant dipole resonance (GDR)



GDR

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

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



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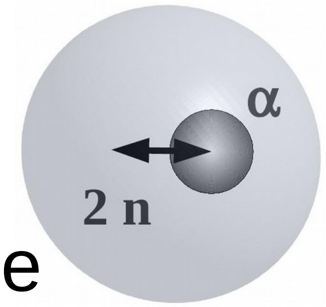
SDM



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

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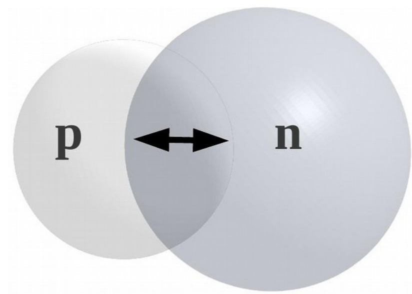

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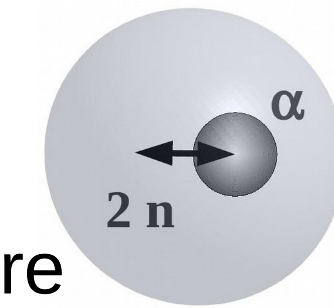

SDM

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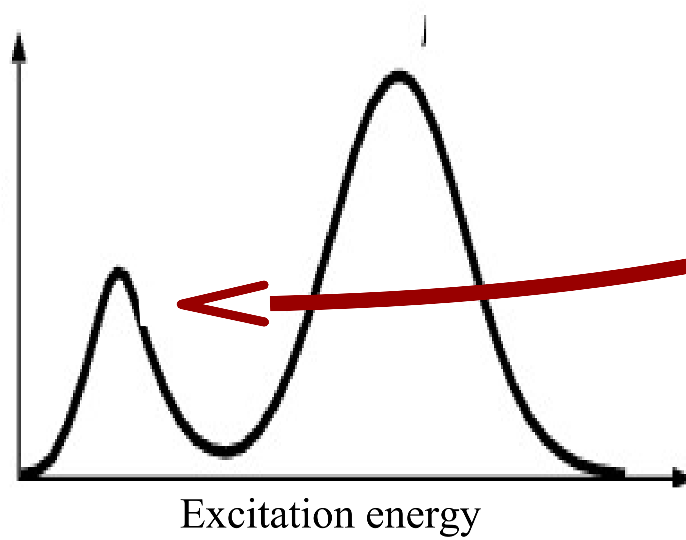
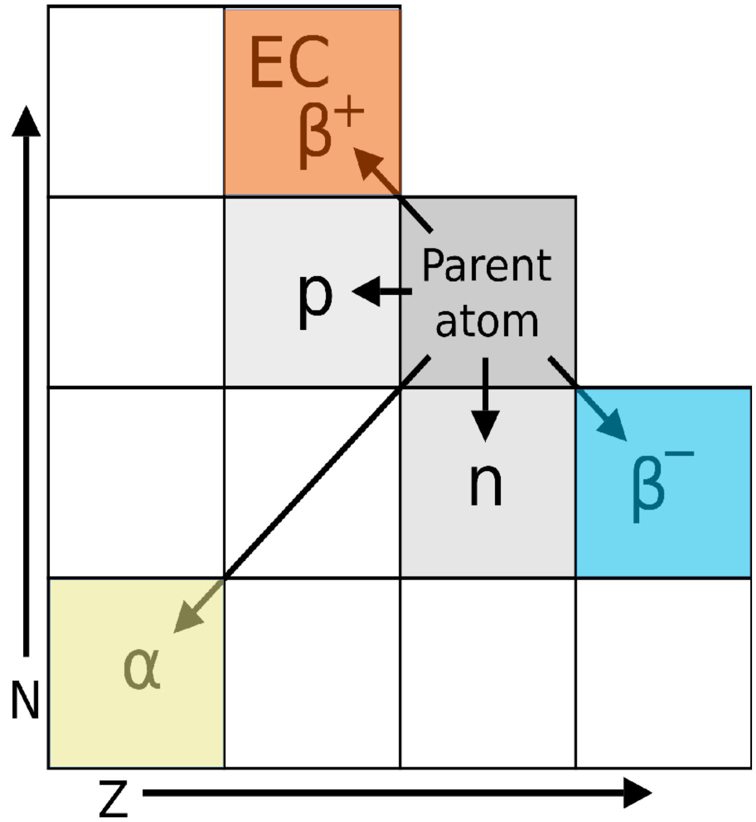
- E_{SDM} lower than E_{GDR}
- induced by EM excitation and charge-exchange reaction



Radioactivity and decays



α decay
E. Rutherford, 1899

β⁻ decay
H. Becquerel, 1886

β⁺ decay
F. and I. Joliot-Curie, 1932

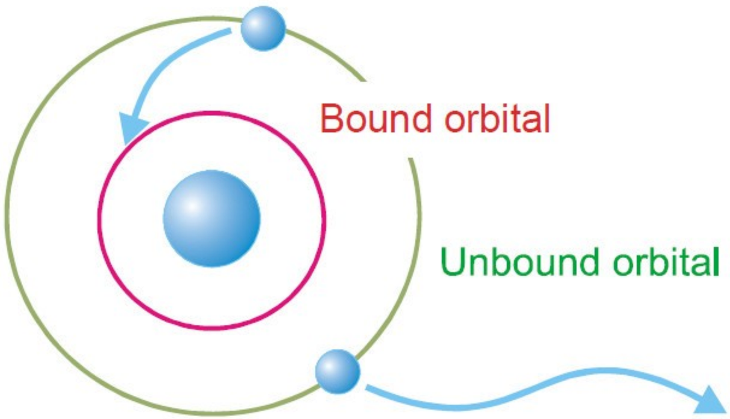
p rad.
S. Hoffman, 1982

2p rad.
M. Pfützner, B. Blank, 2002

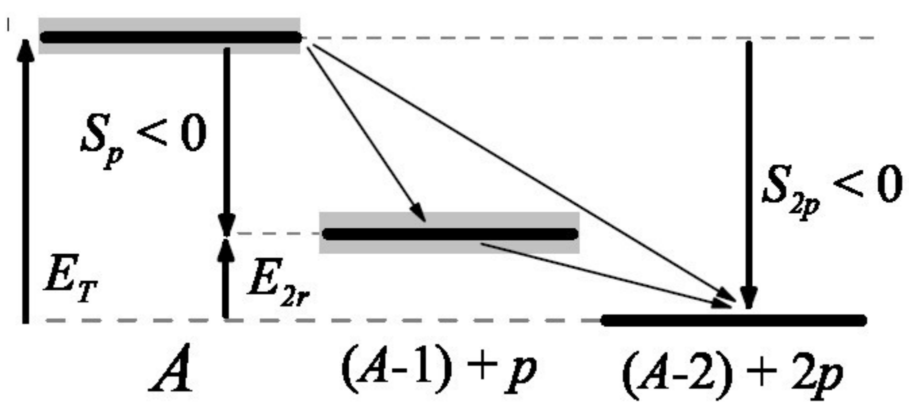
cluster emission
H. Rose, 1984

(multi)-n radioactivity
still waiting

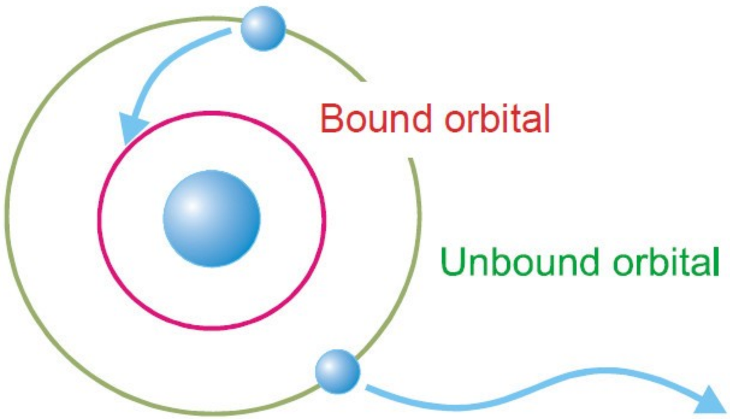
Proton radioactivity

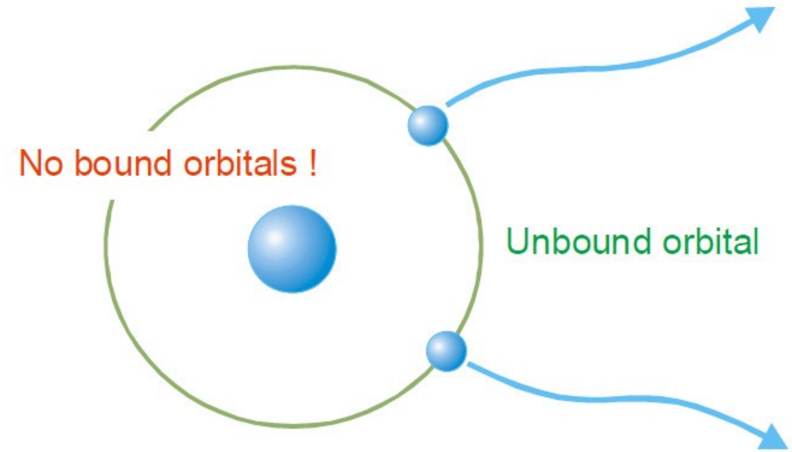


p-radioactivity
natural generalization
of α-radioactivity



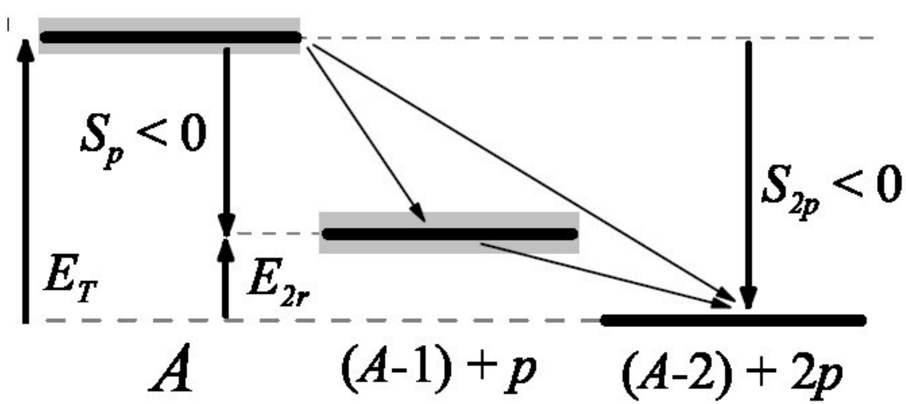
Proton radioactivity

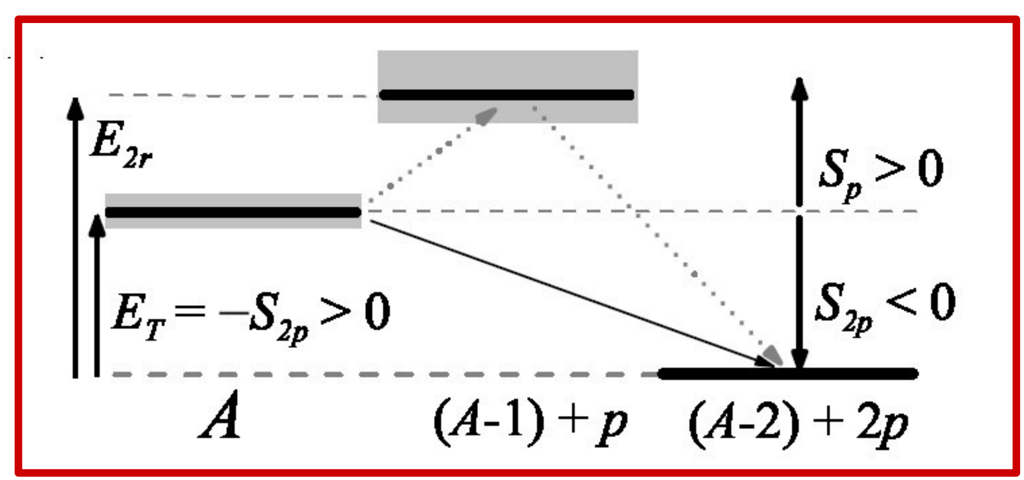




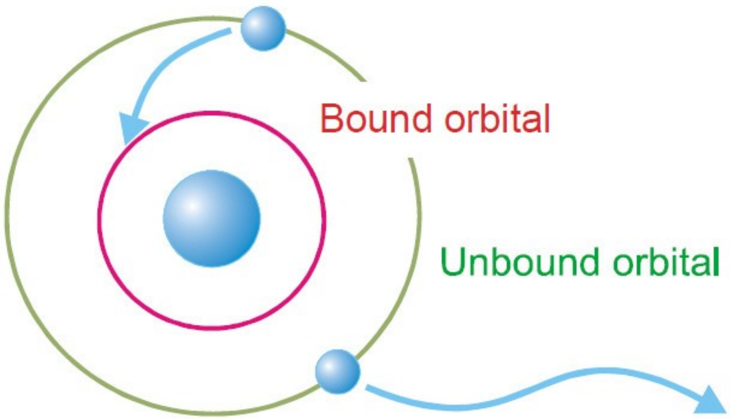
p-radioactivity
natural generalization
of α-radiactivity

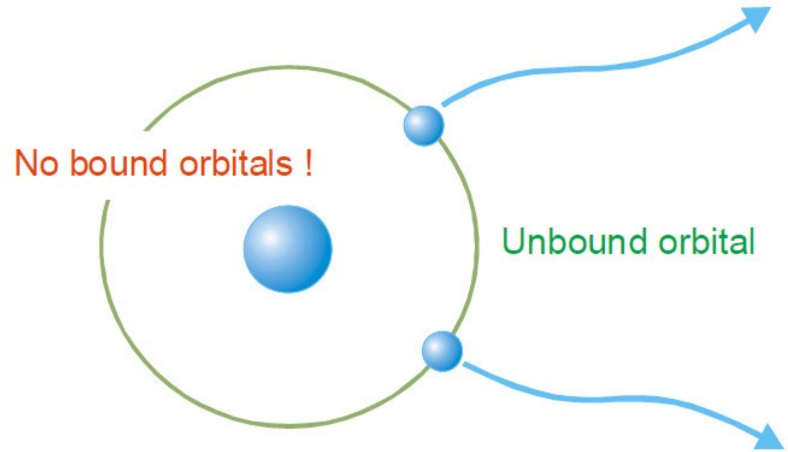
2p-radioactivity
no analogue in
classical mechanics





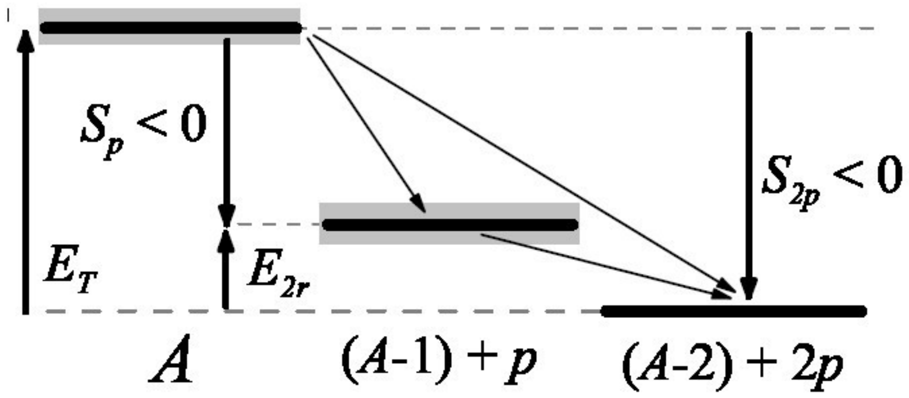
Proton radioactivity





p-radioactivity
natural generalization
of α-radiactivity

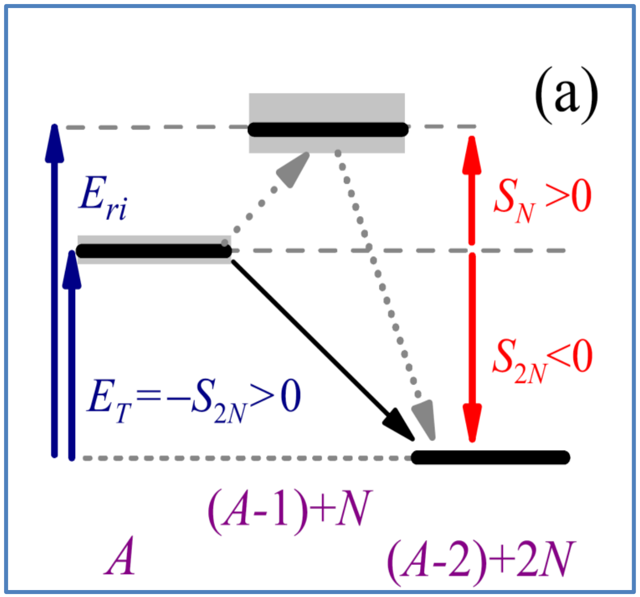
2p-radioactivity
no analogue in
classical mechanics



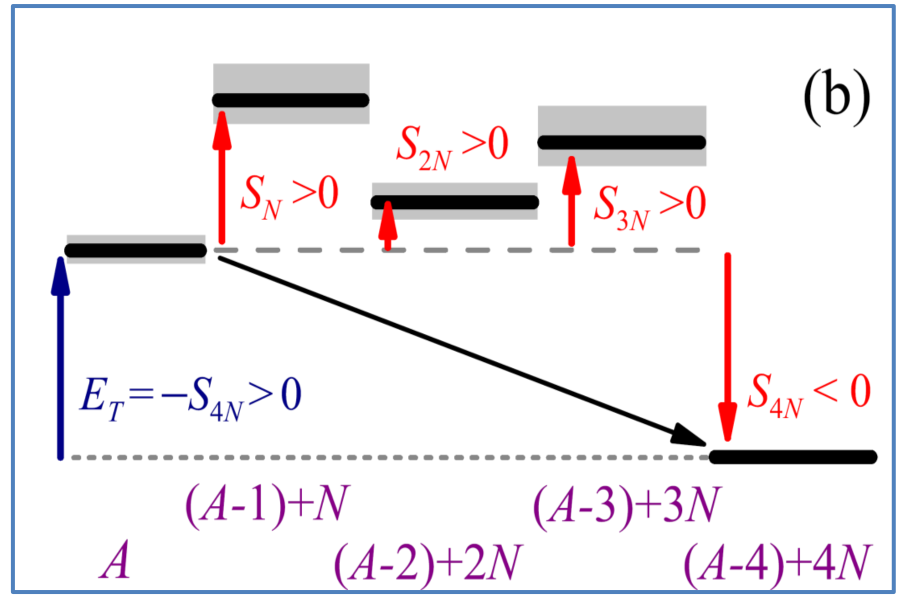
^{45}Fe, ^{19}Mg, ^{54}Zn,
^{48}Ni, ^{67}Kr, ^{94m}Ag

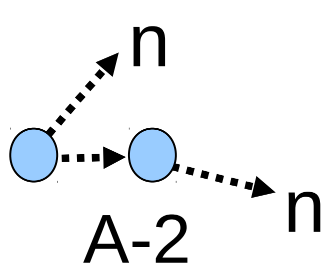
Neutron radioactivity

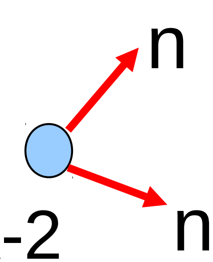
2n decays

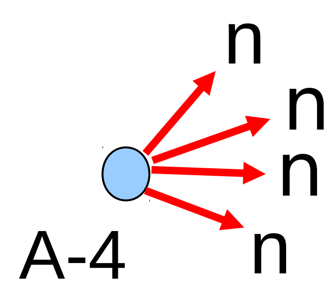


4n decays



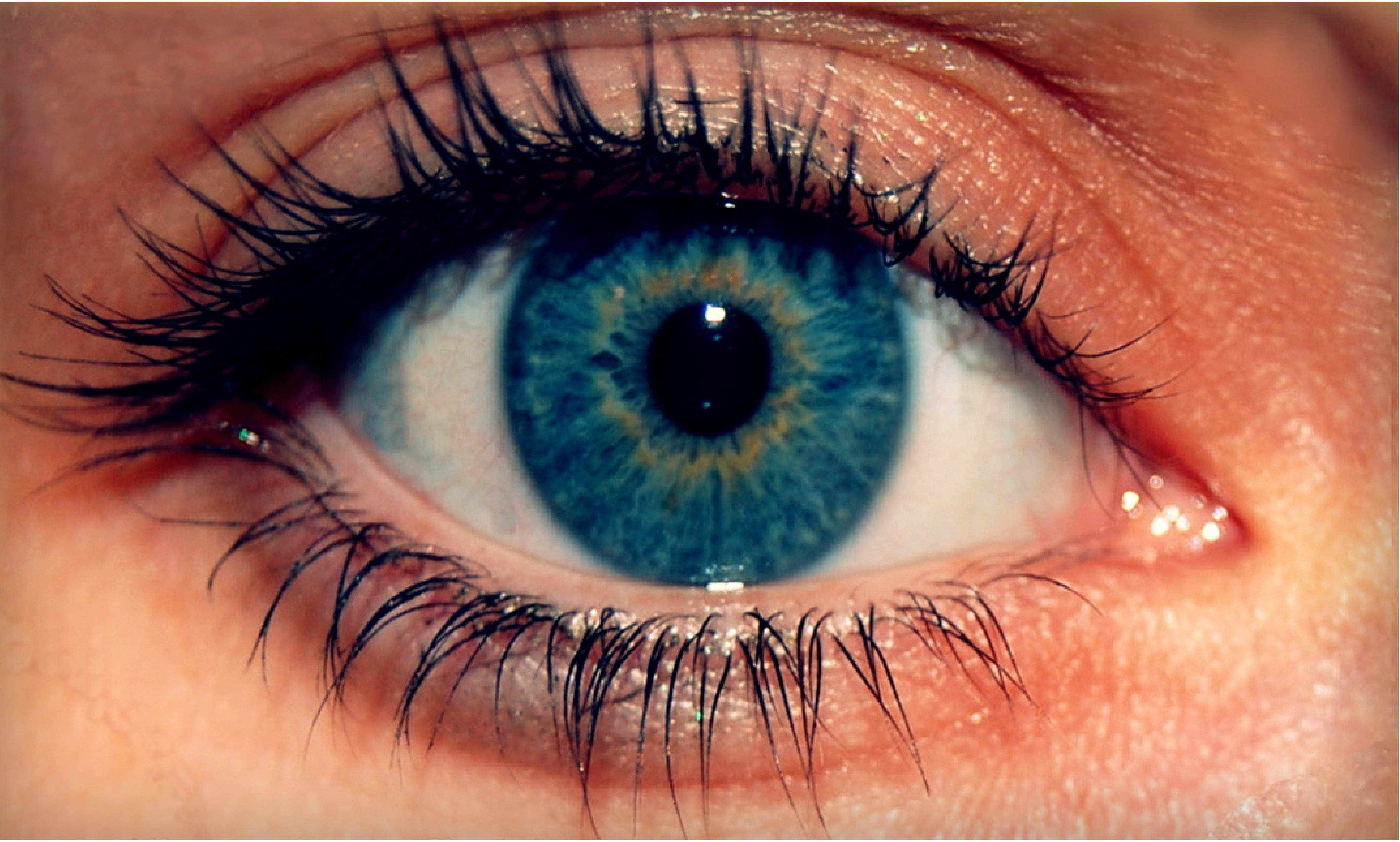


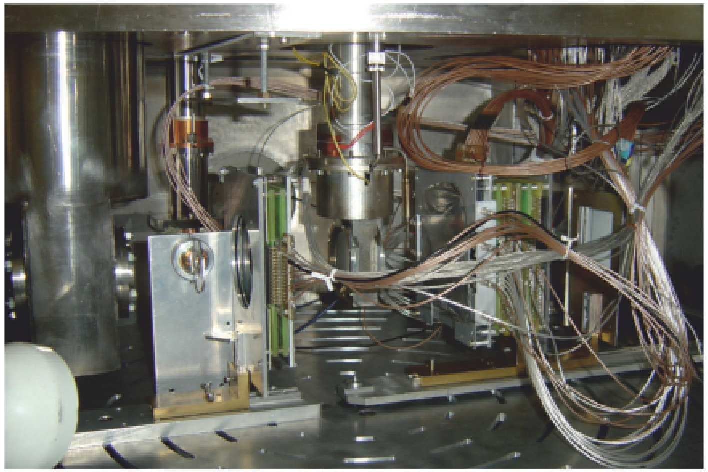
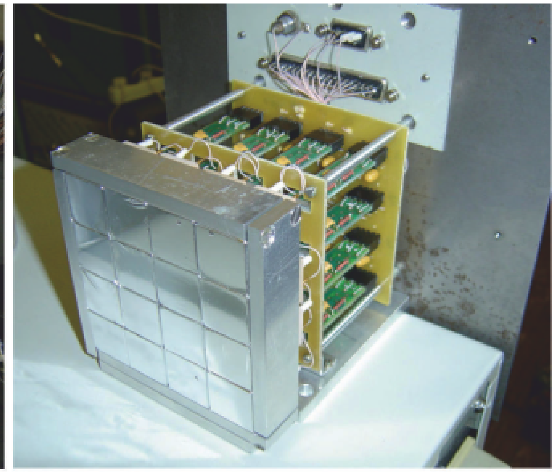
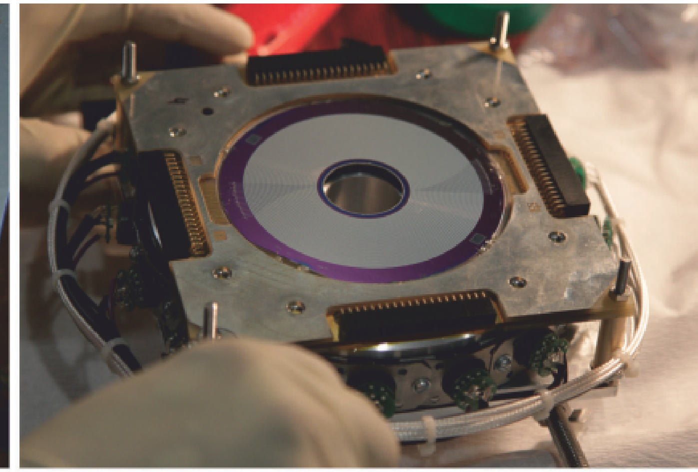
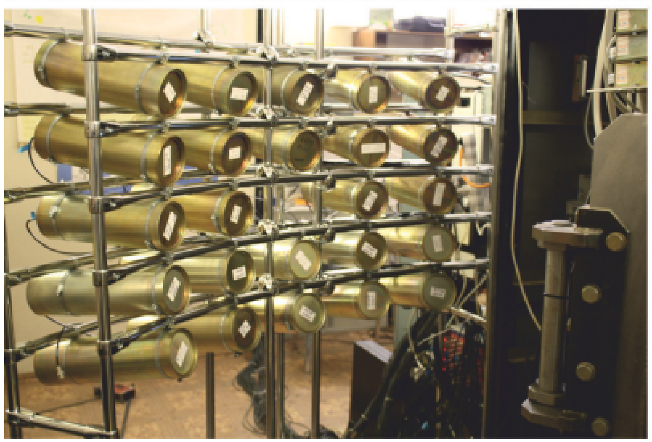
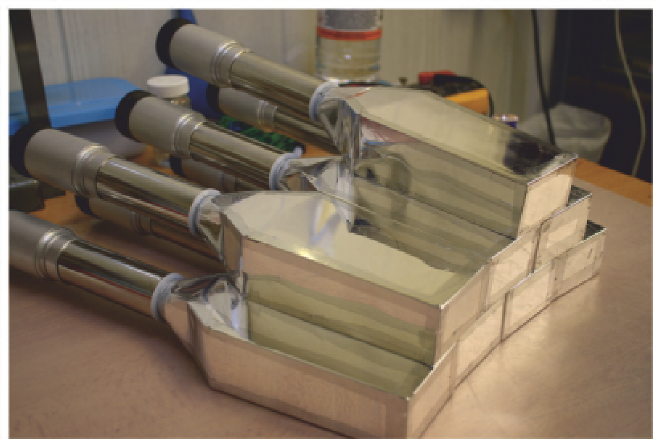
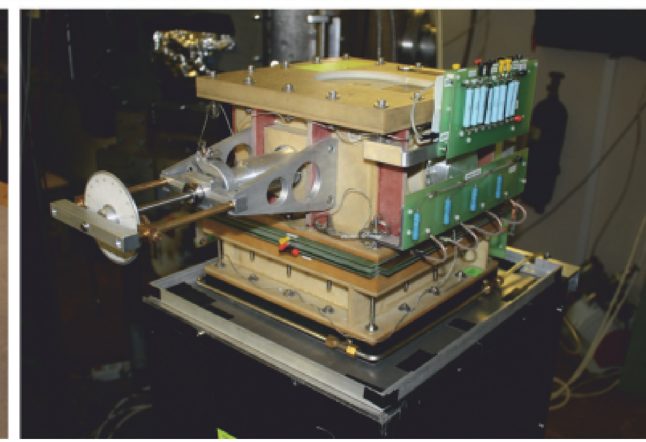




^{5}H, ^{10}He, ^{26}O, …

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

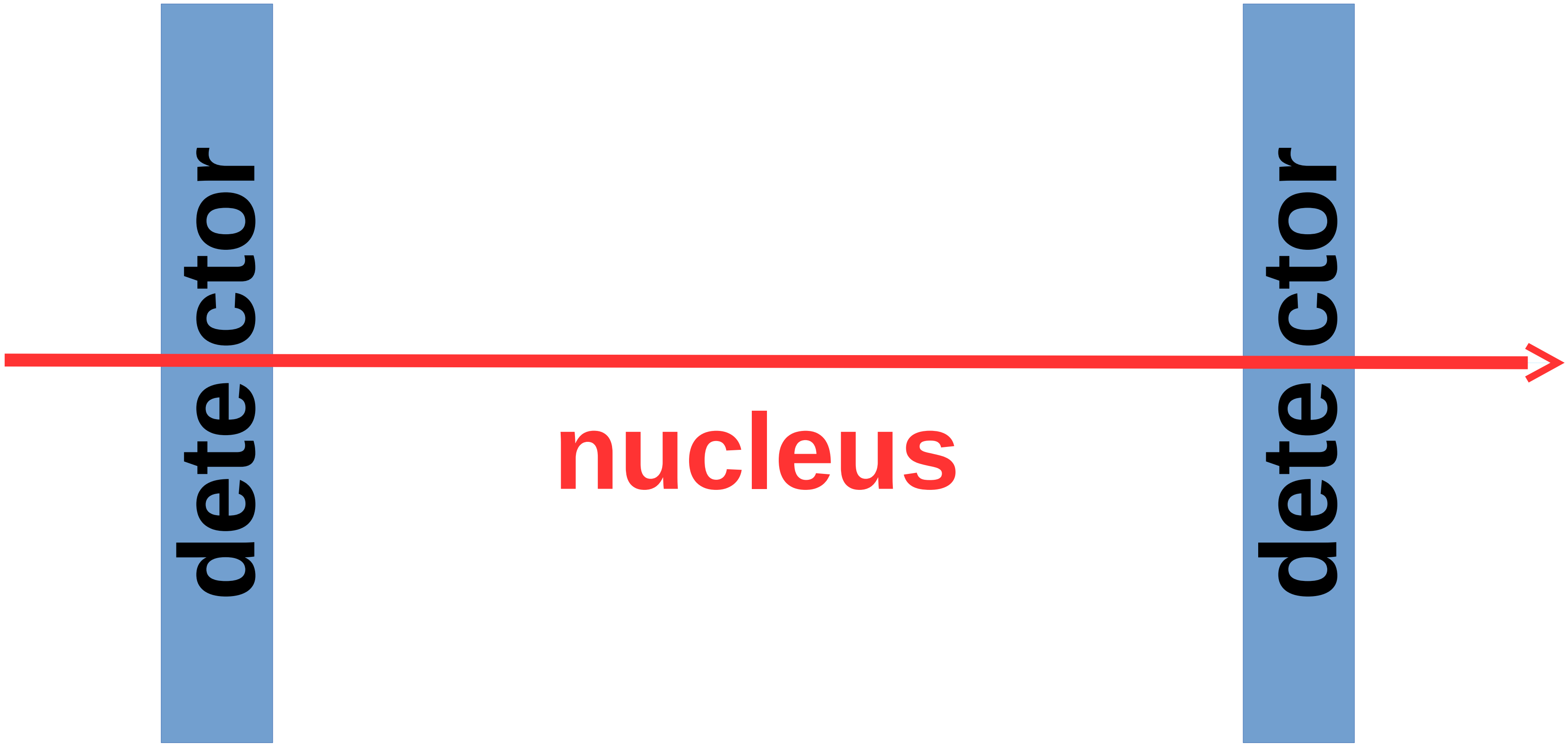


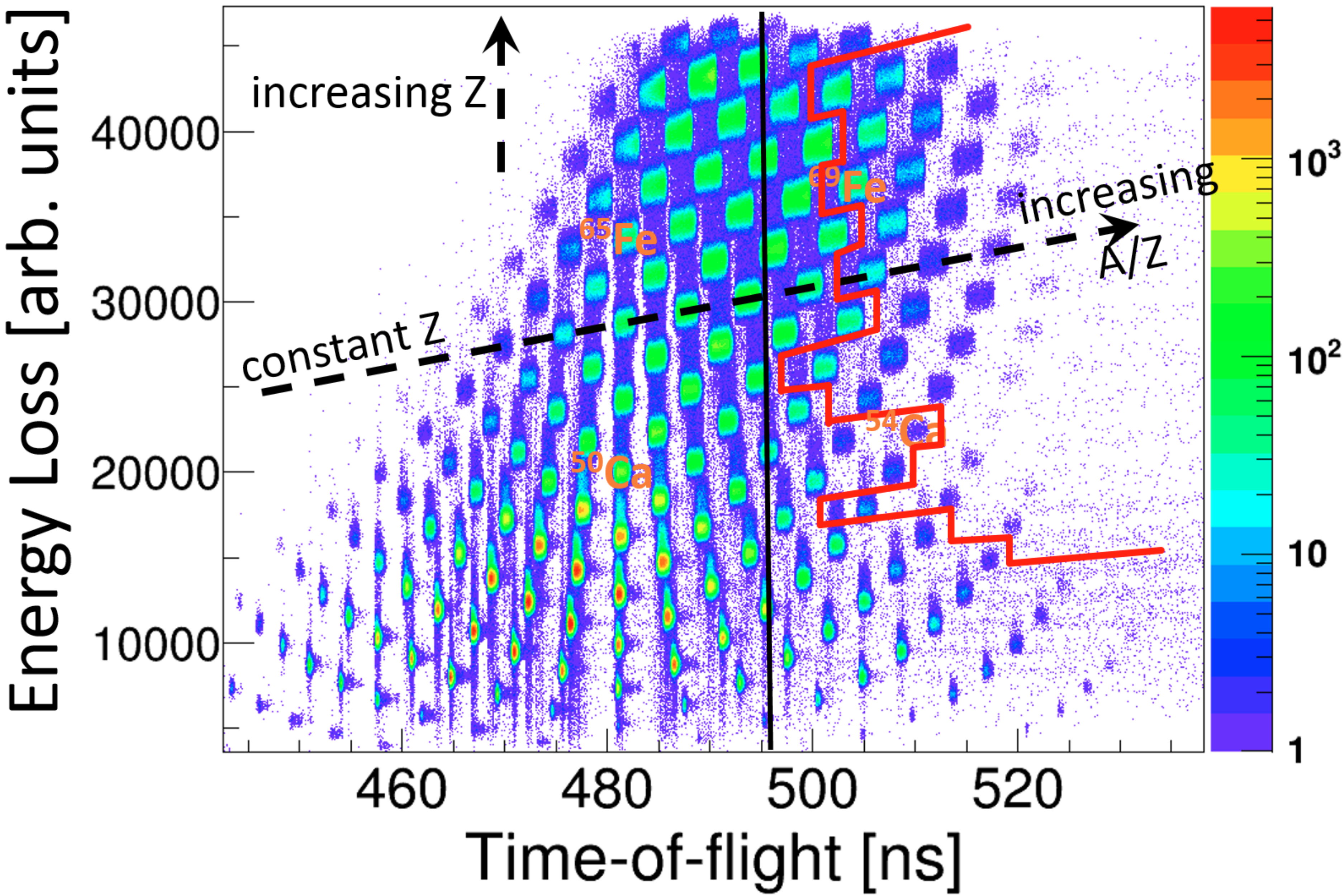
General tasks

1) existence of the isotope
2) mass of the isotope
3) decays
4) eventually J^{π} identification

Ion identification

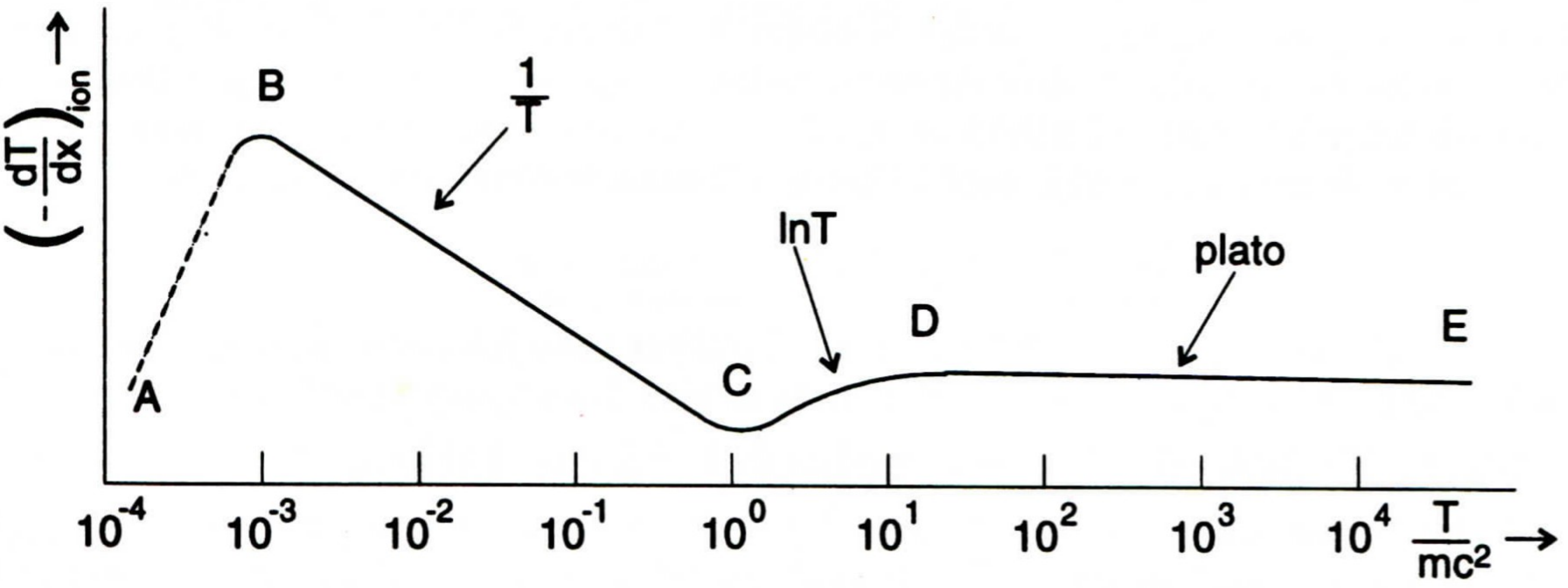


Ion identification

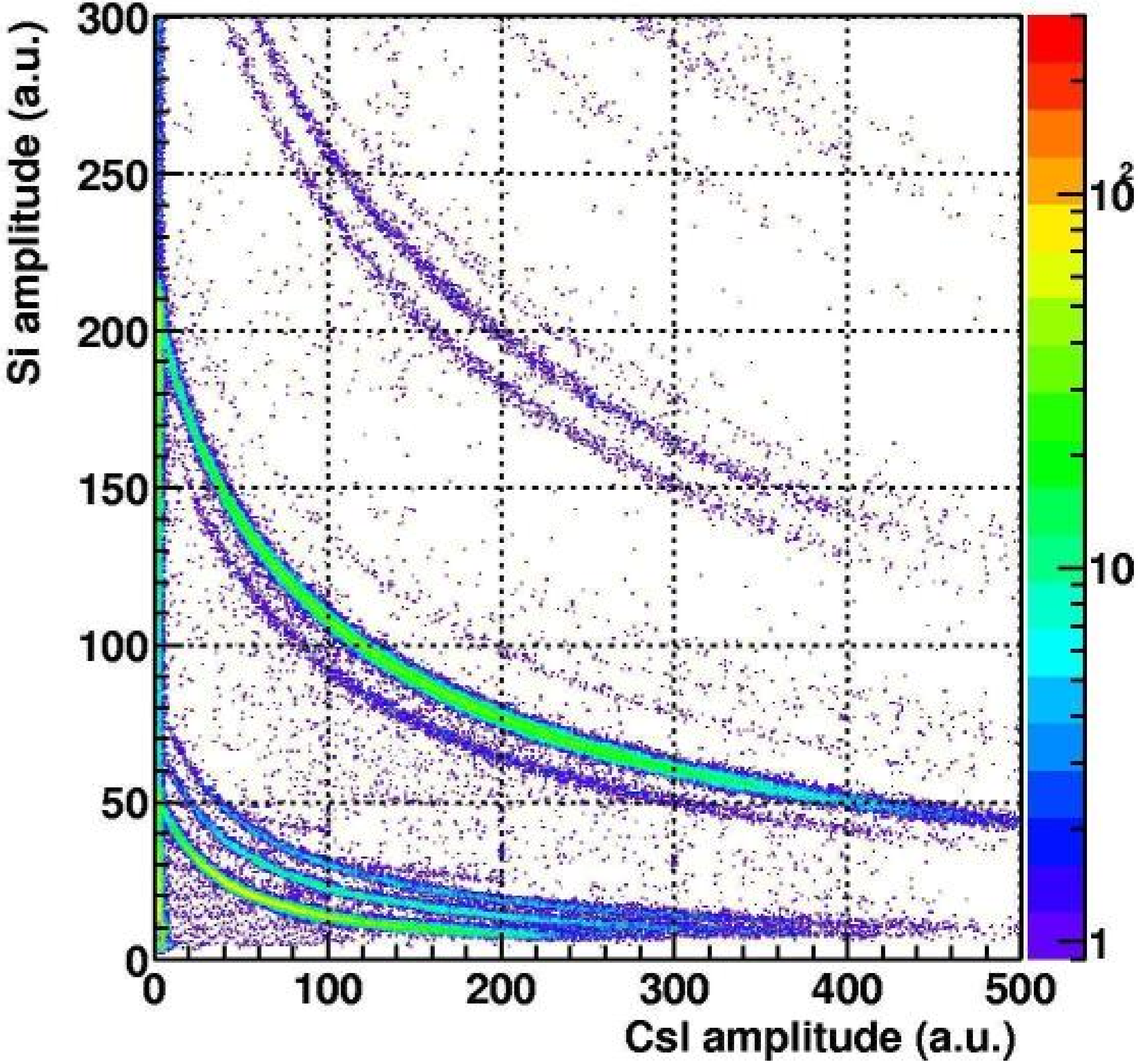


Ion identification

mean energy loss



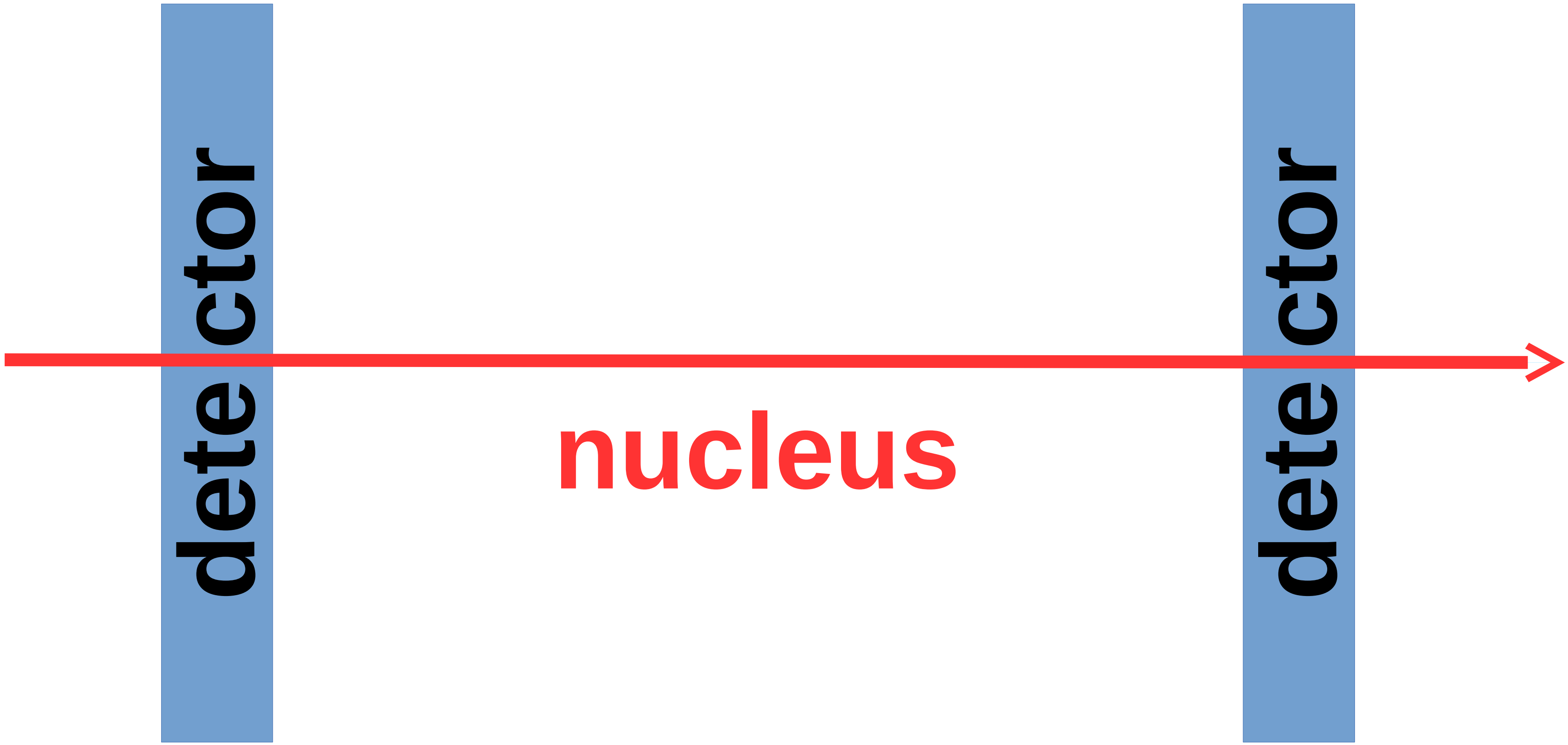
Ion identification



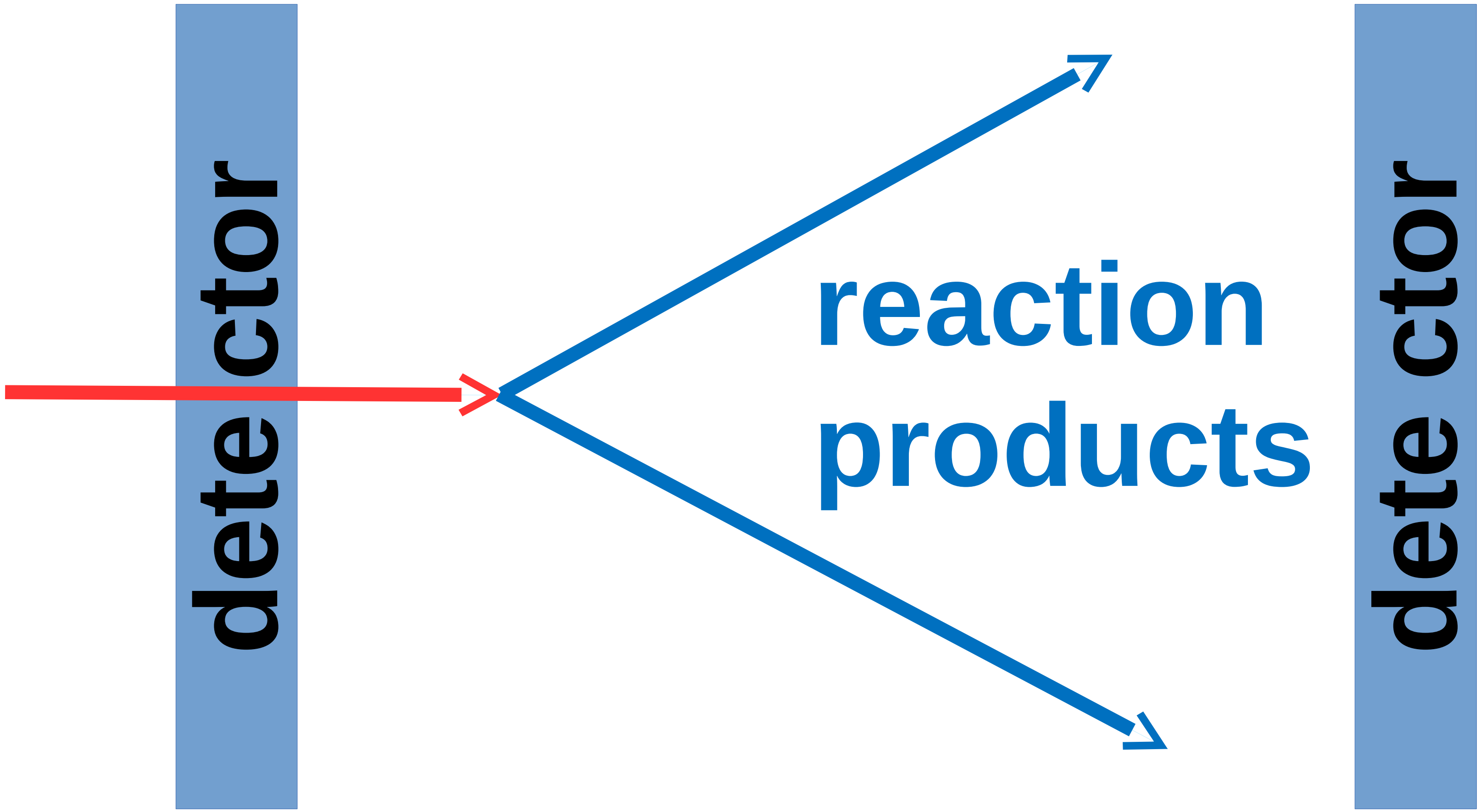
Mass measurement

- mass spectrometers
- calculations from decay kinematics

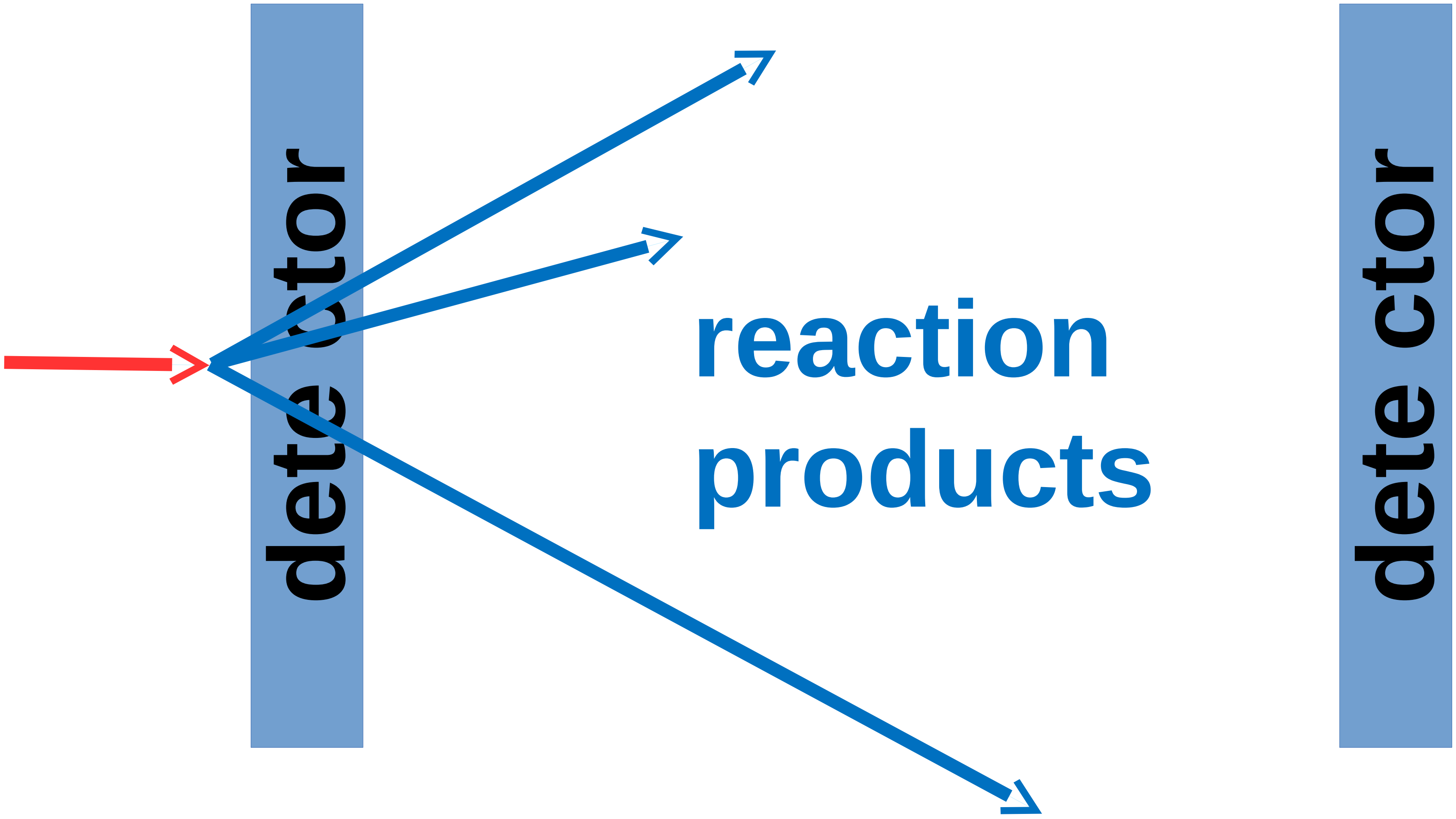
Decays



Decays



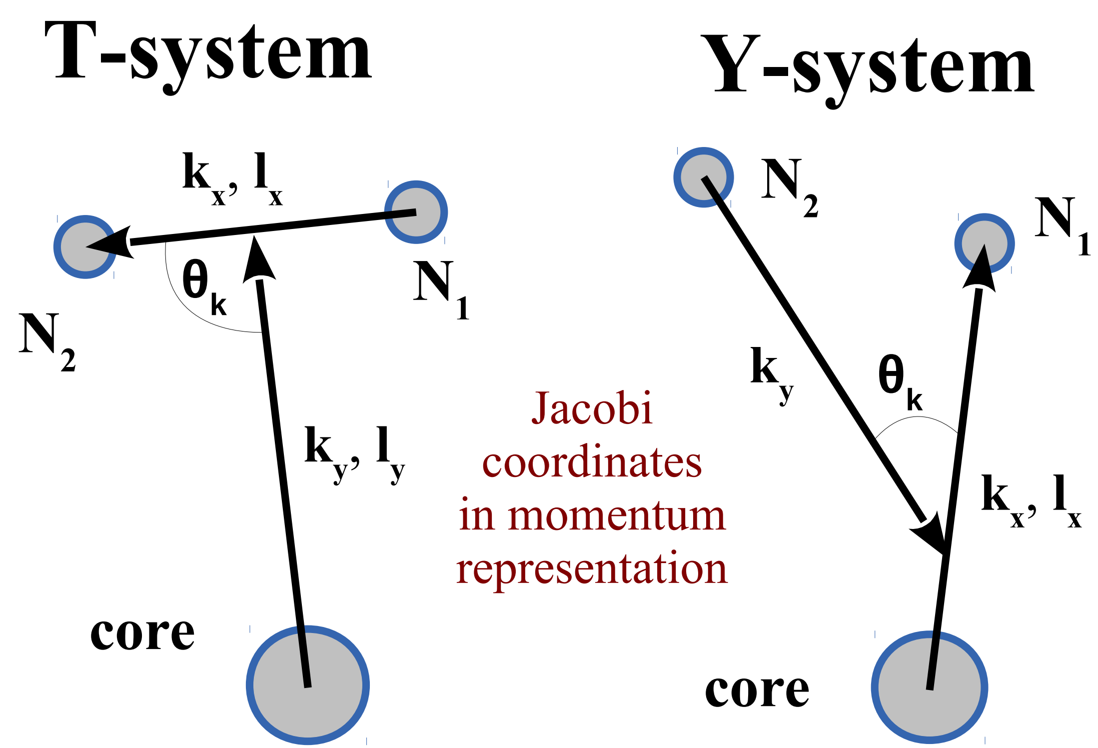
Decays



3-body decays

2-body vs. 3-body decay

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

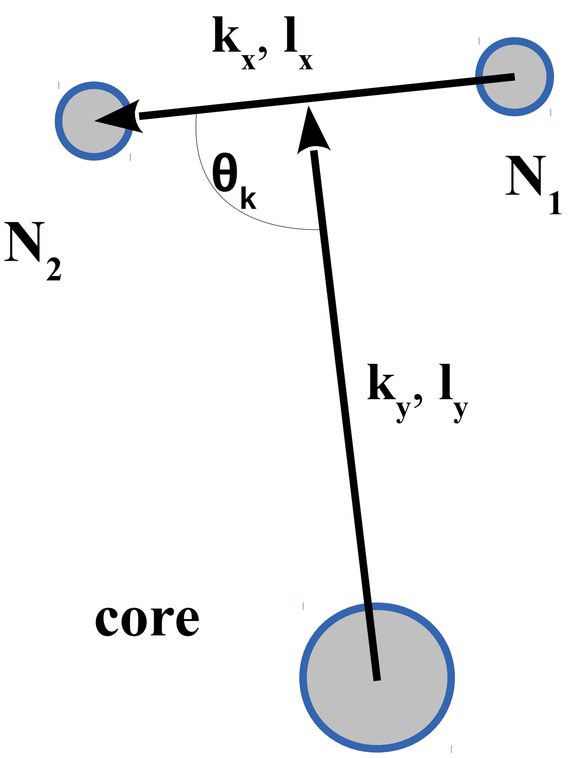


Correlations

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

$$\varepsilon = \frac{E_x}{E_x + E_y}$$

$$\cos\theta_k = \frac{\mathbf{k}_x \cdot \mathbf{k}_y}{k_x k_y}$$



- external correlations:
  3-body system
  orientation

Correlations

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

$$\varepsilon = \frac{E_x}{E_x + E_y}$$

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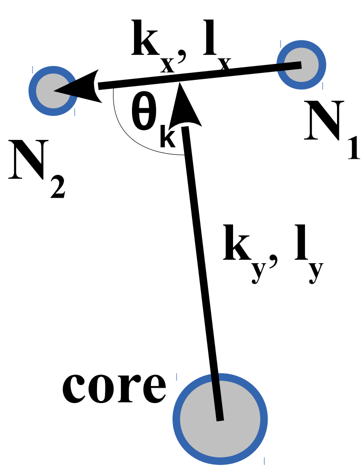
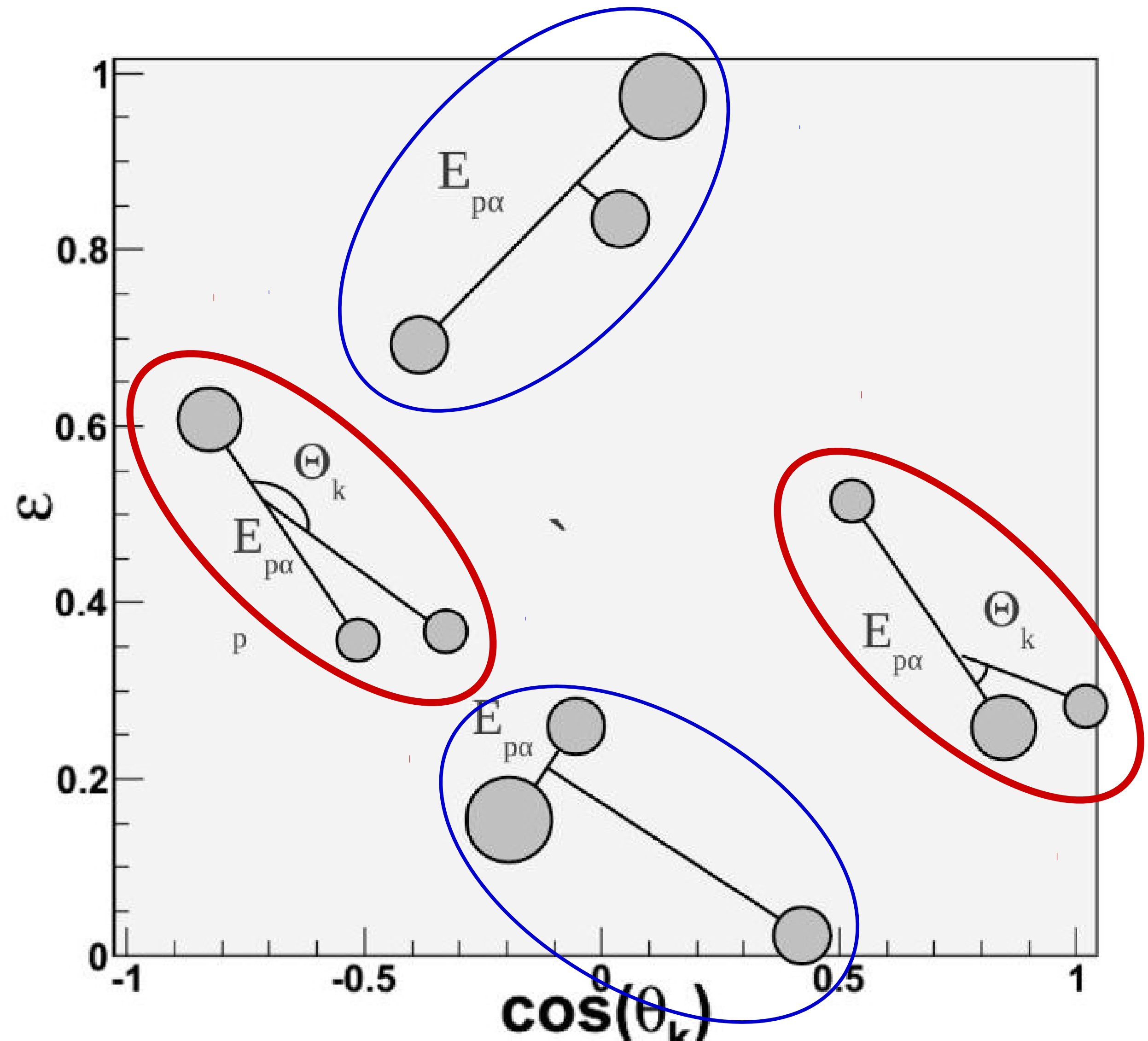
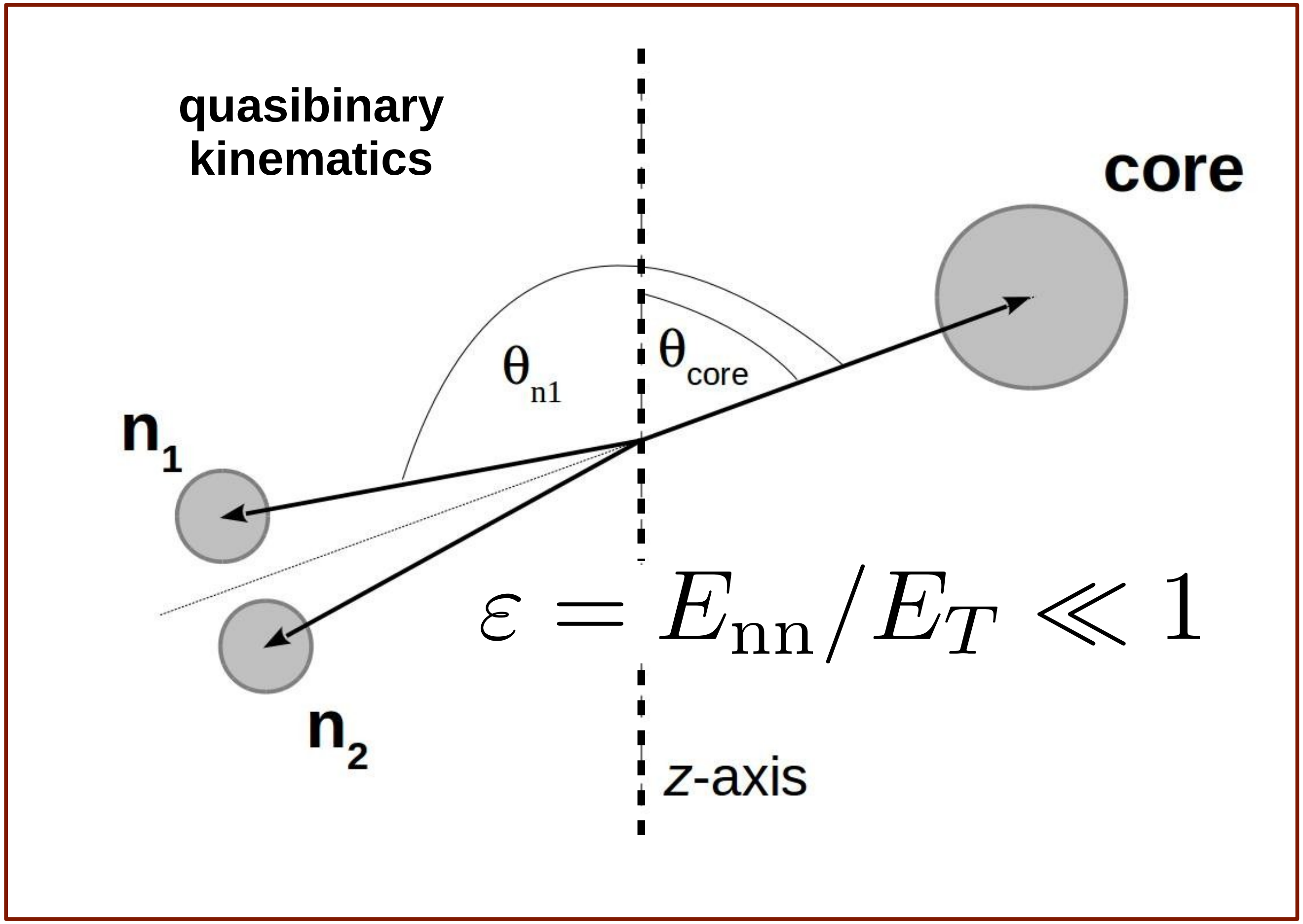


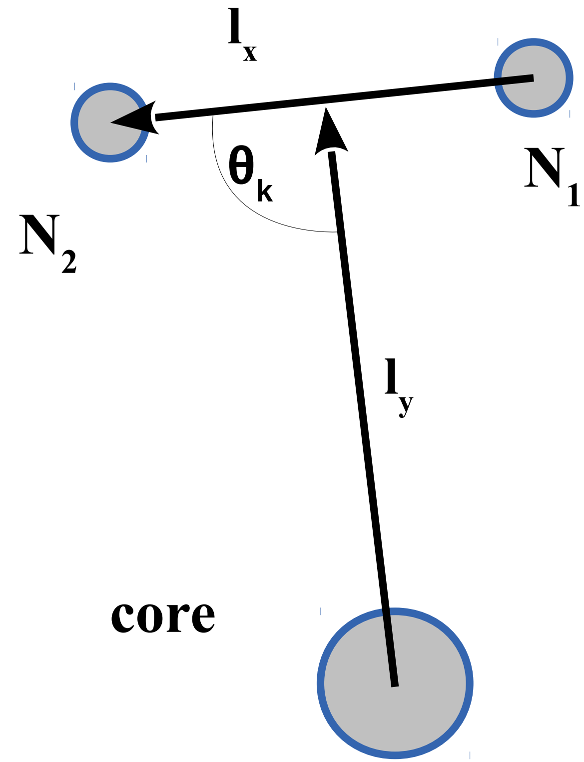


- external correlations: 3-body system orientation

External correlations



$$\varepsilon = E_{\mathrm{nn}}/E_T \ll 1$$



- useful when a few overlapping states present
- total angular momentum is determined by emission angle of the core

Legendre polynomials can be visible

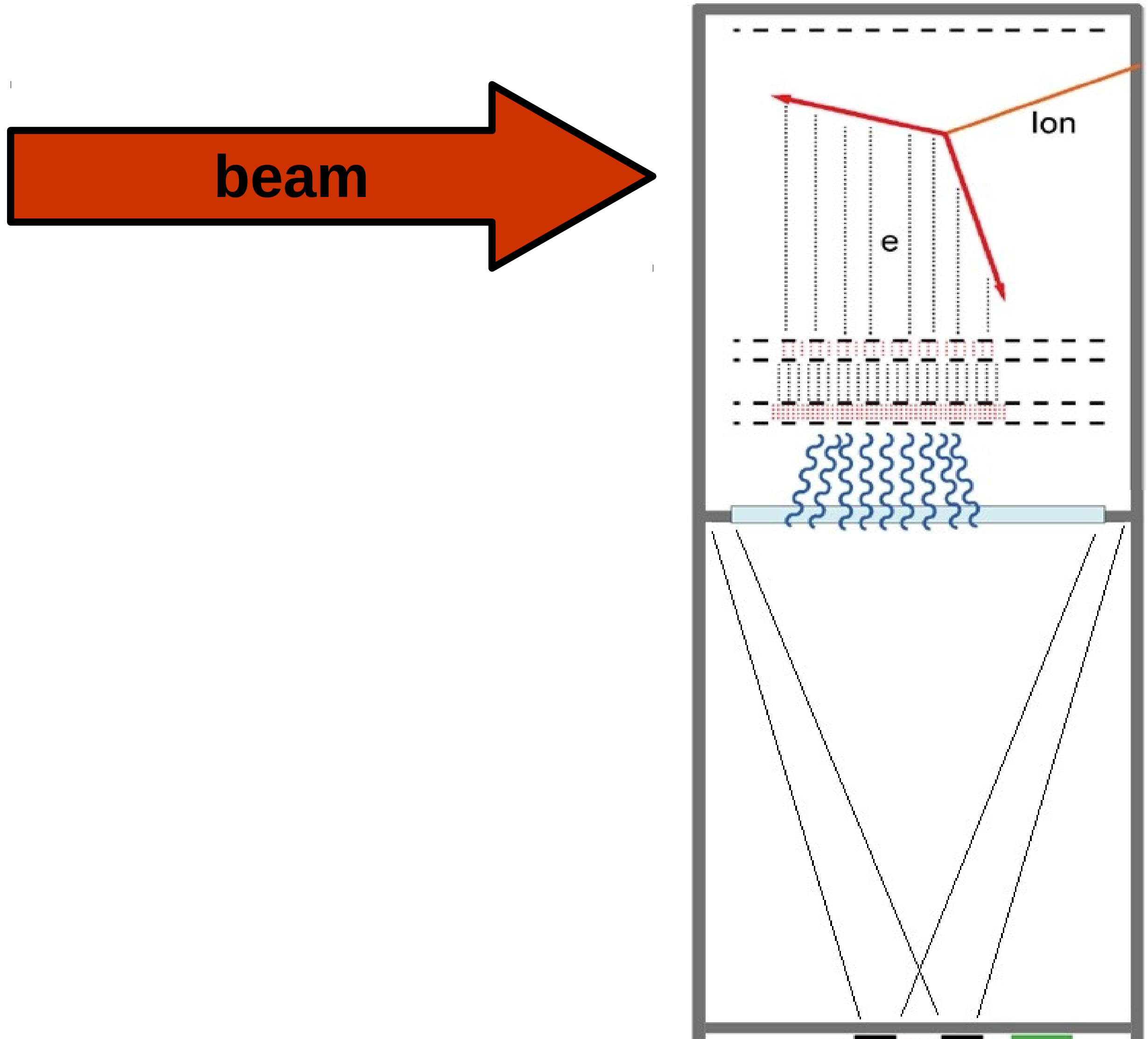
Available experimental methods

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

Optical Time Projection Chamber

lifetime range:

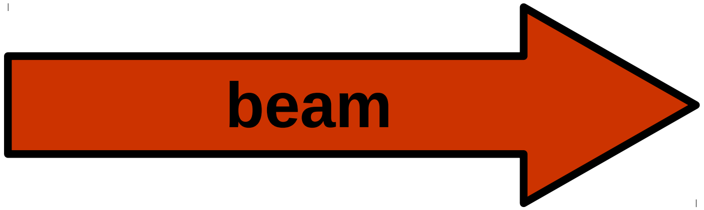
100 ns – 1 s

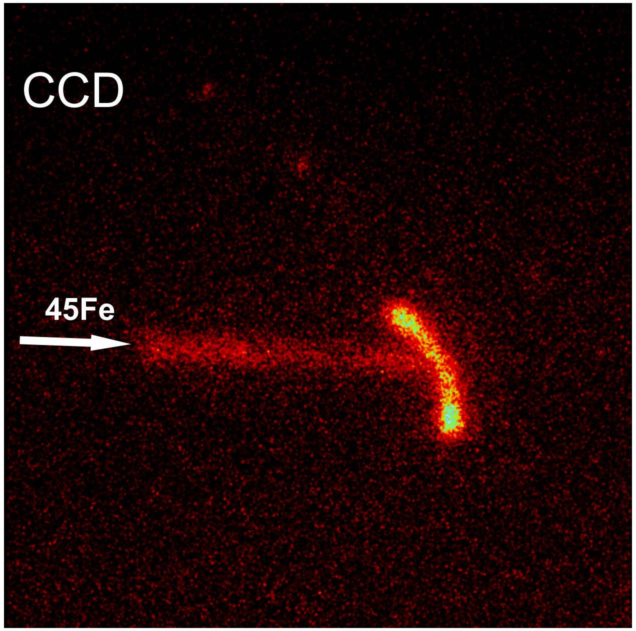


Optical Time Projection Chamber

lifetime range:

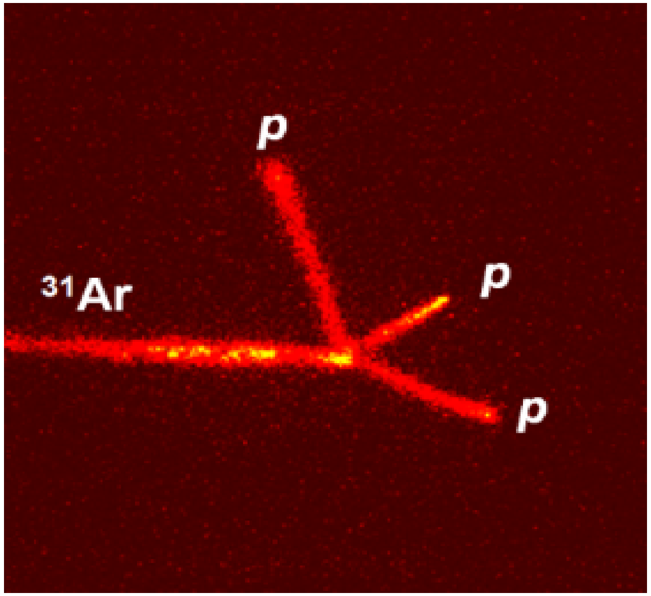
100 ns – 1 s

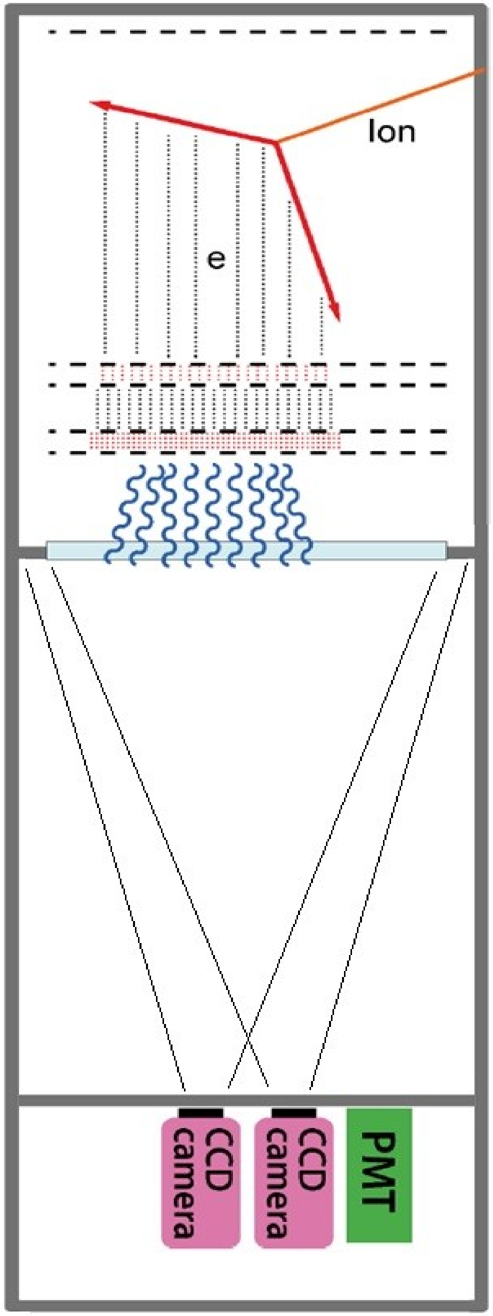




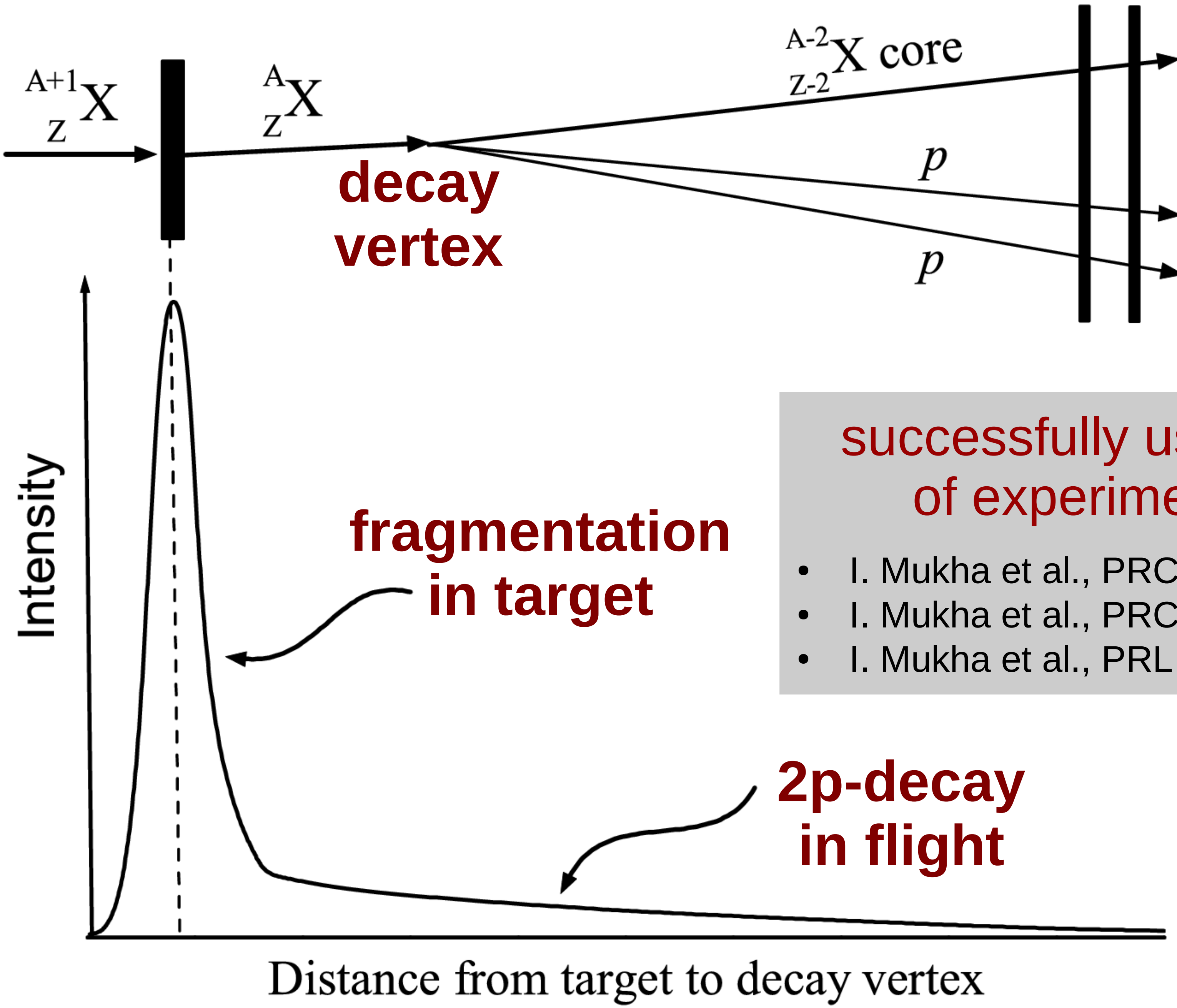
M. Pfützner et al., Eur.Phys.J. A, 14(3), 2002

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





Decay-in-flight by tracking

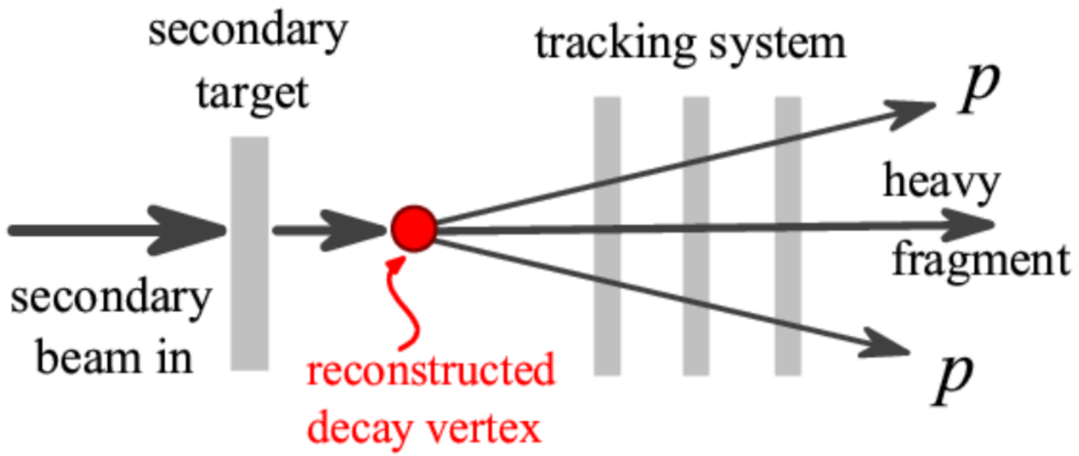


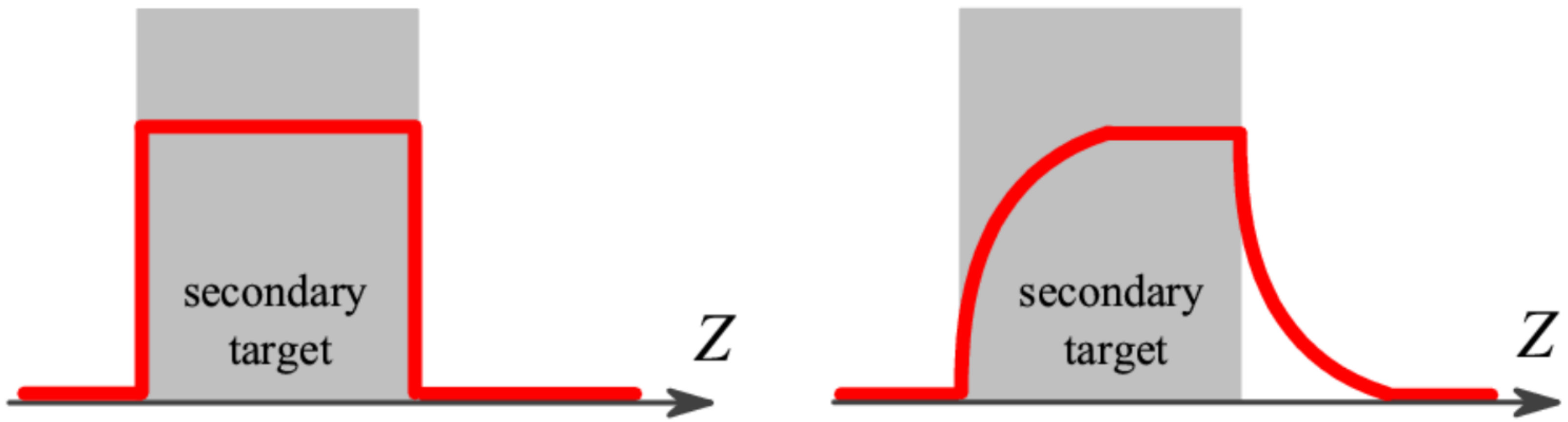
successfully used in series of experiments (*e.g.*)

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

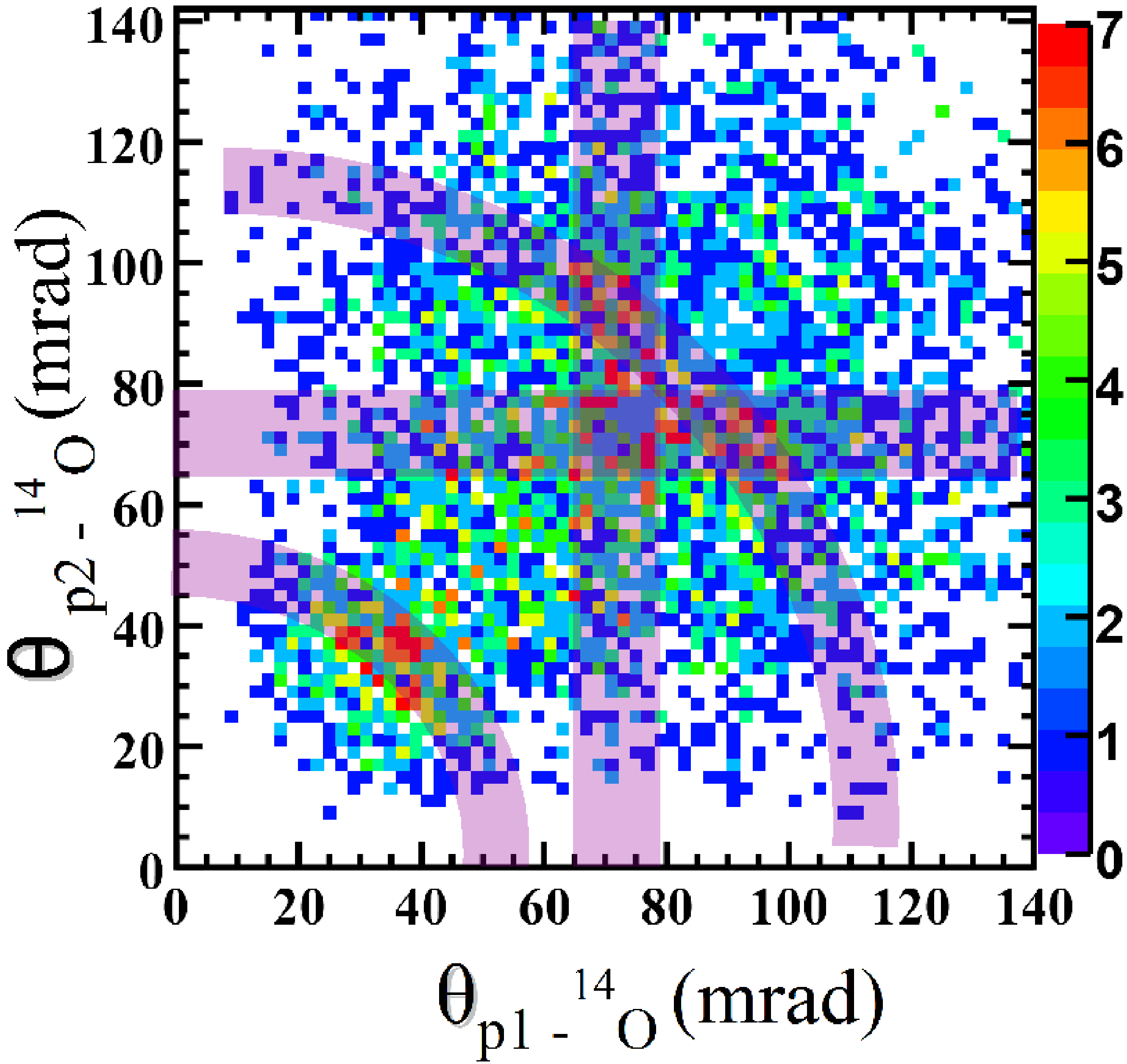
Life-time measurement by tracking

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





Identification of 2p-decay channels



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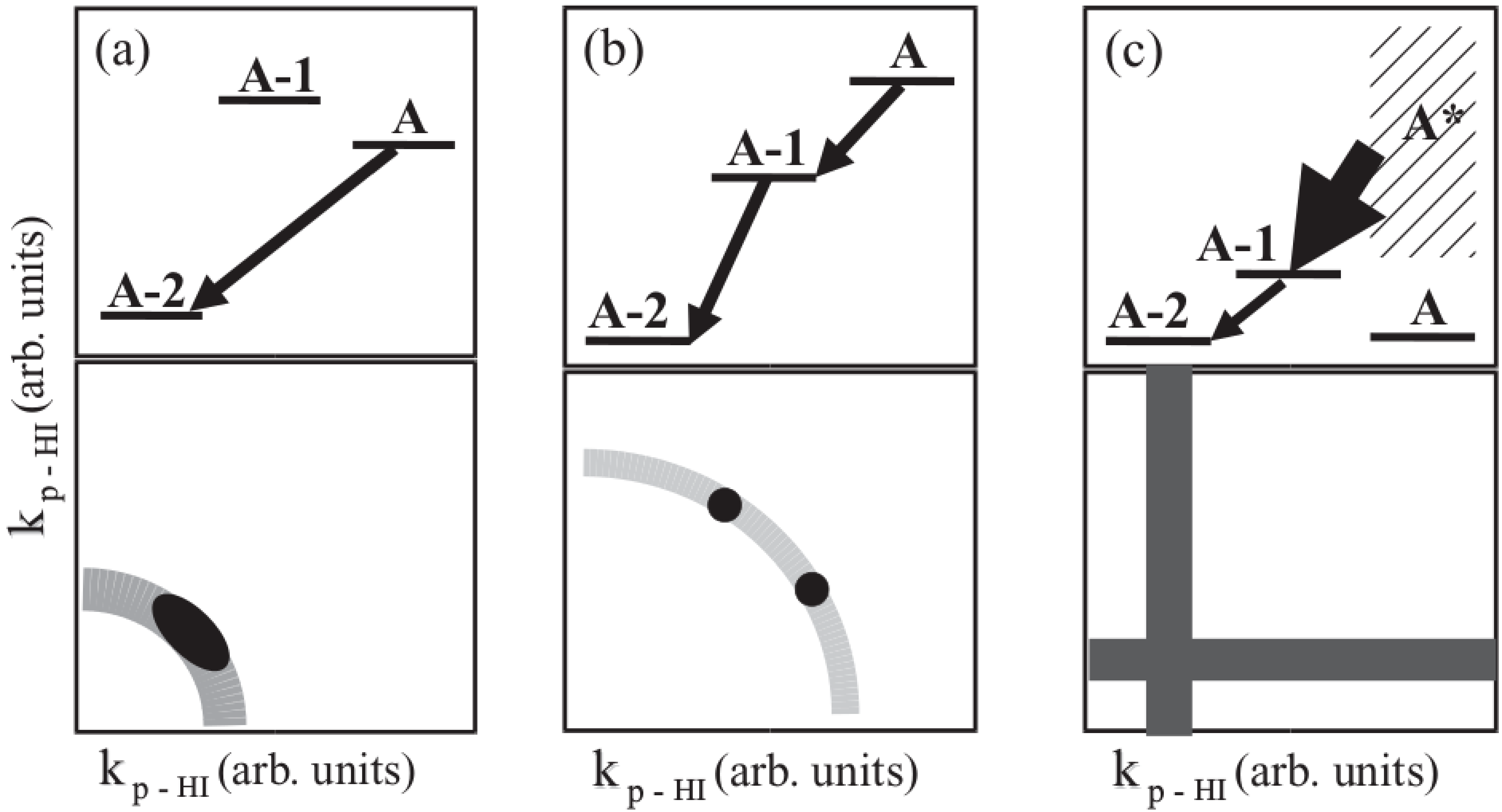
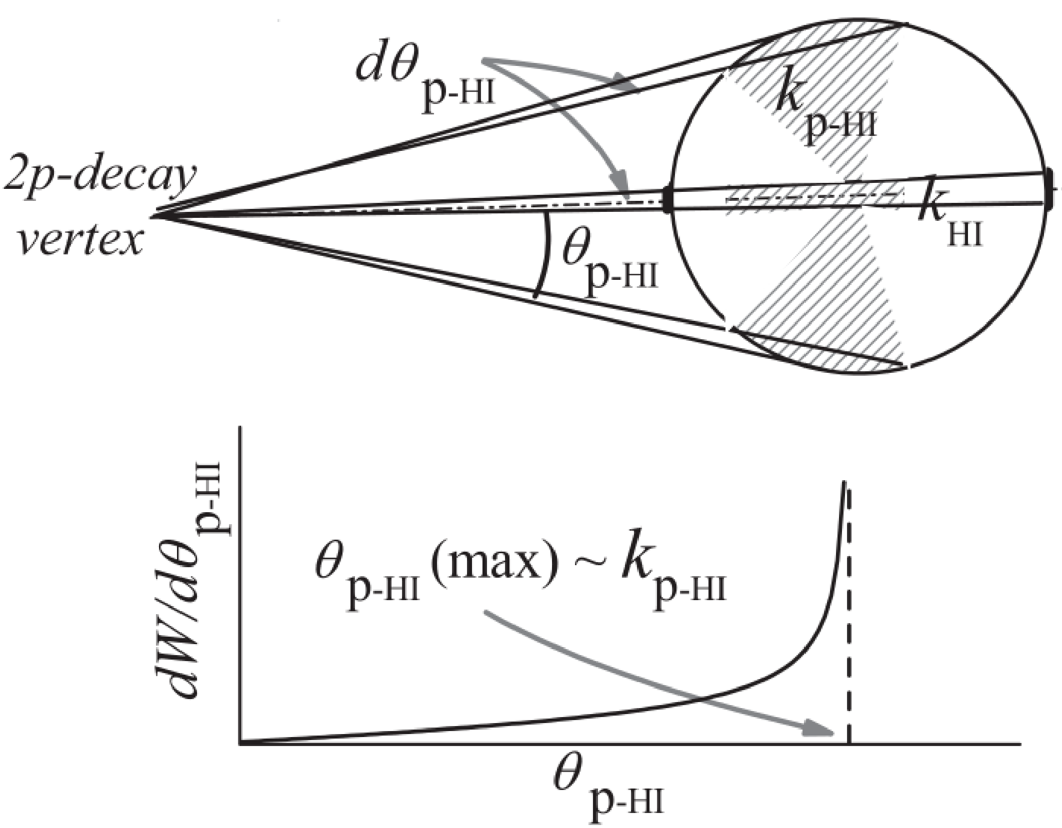


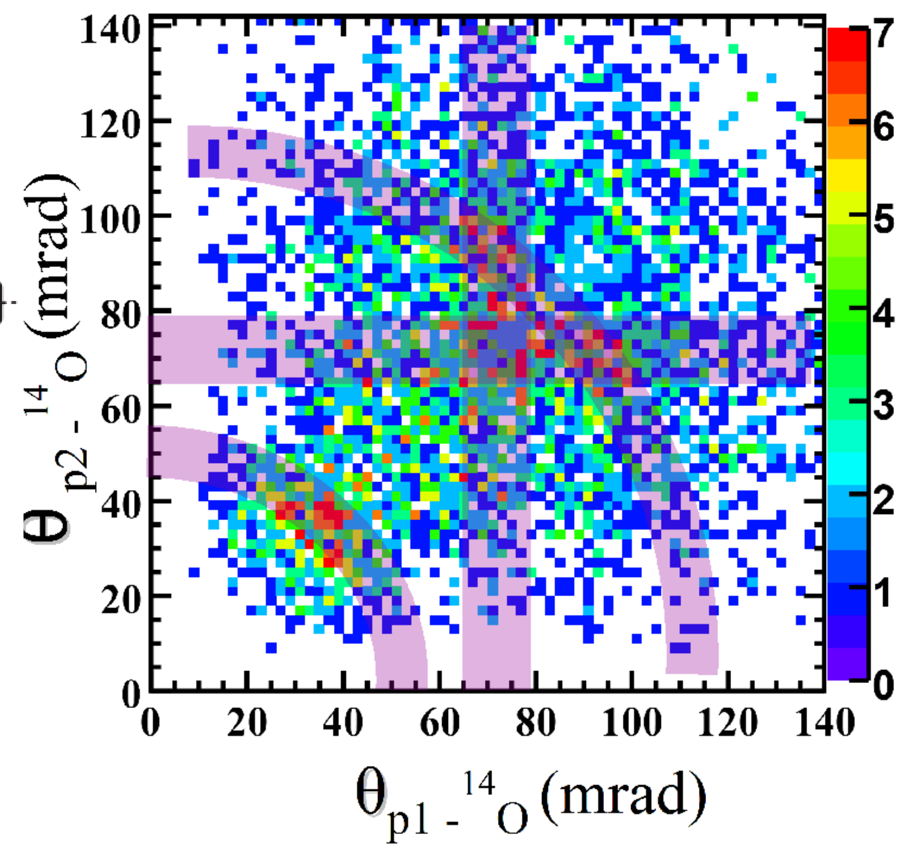
Identification of 2p-decay channels

- 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

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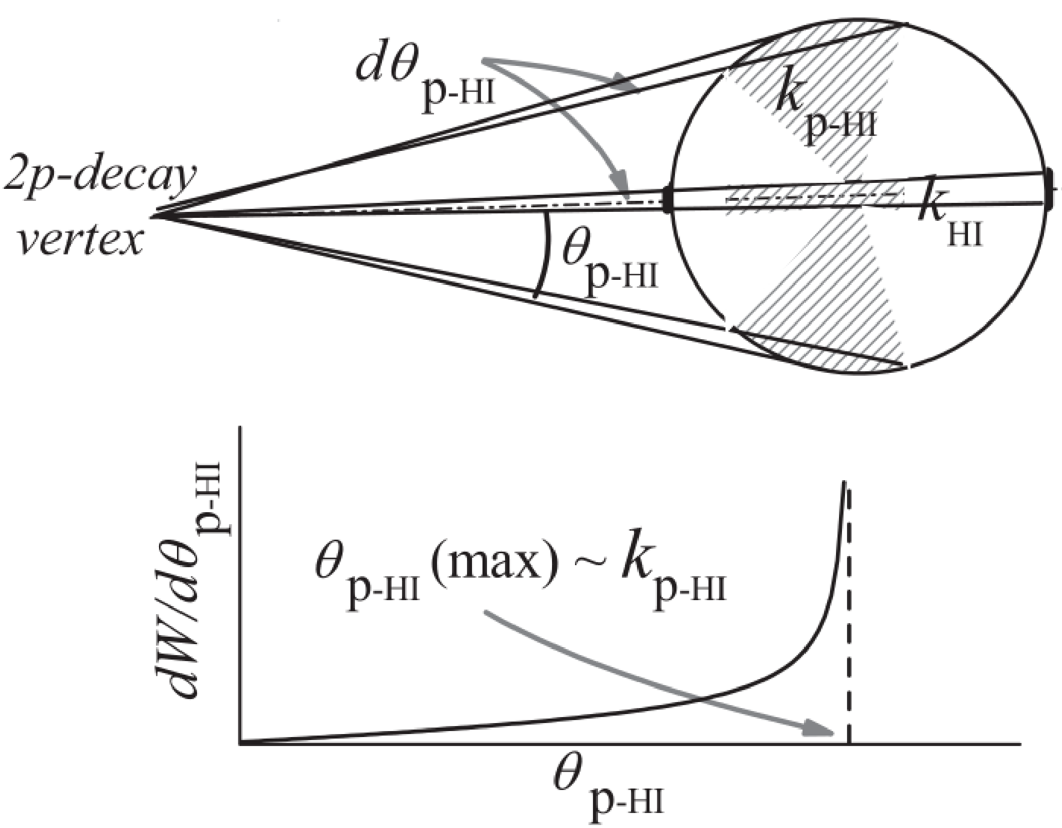
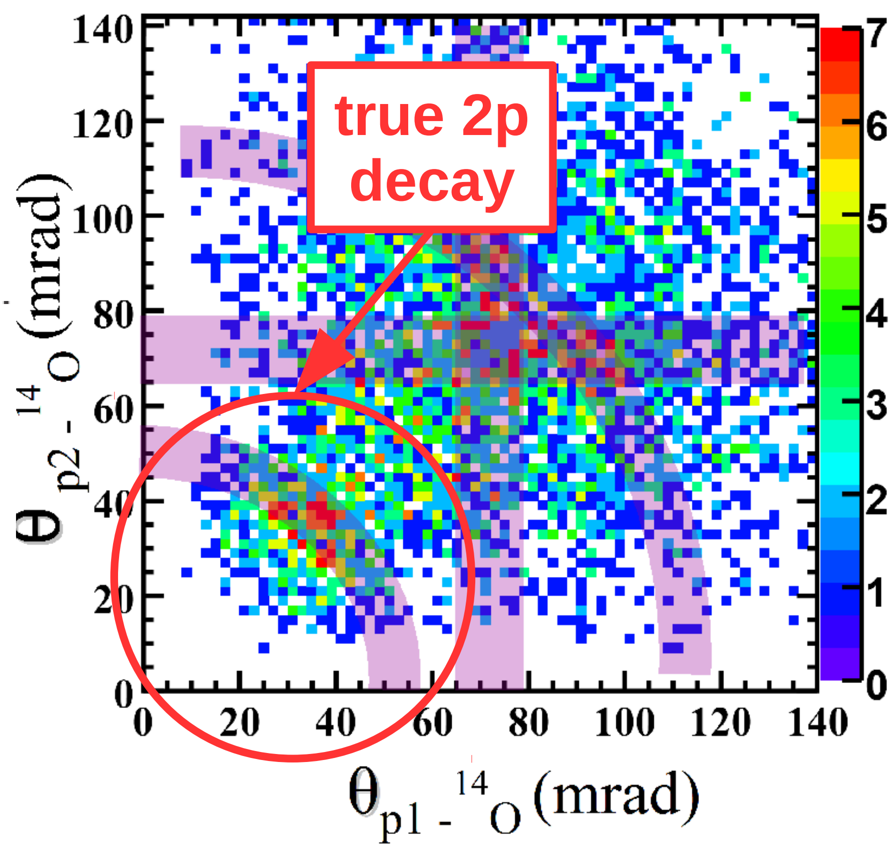
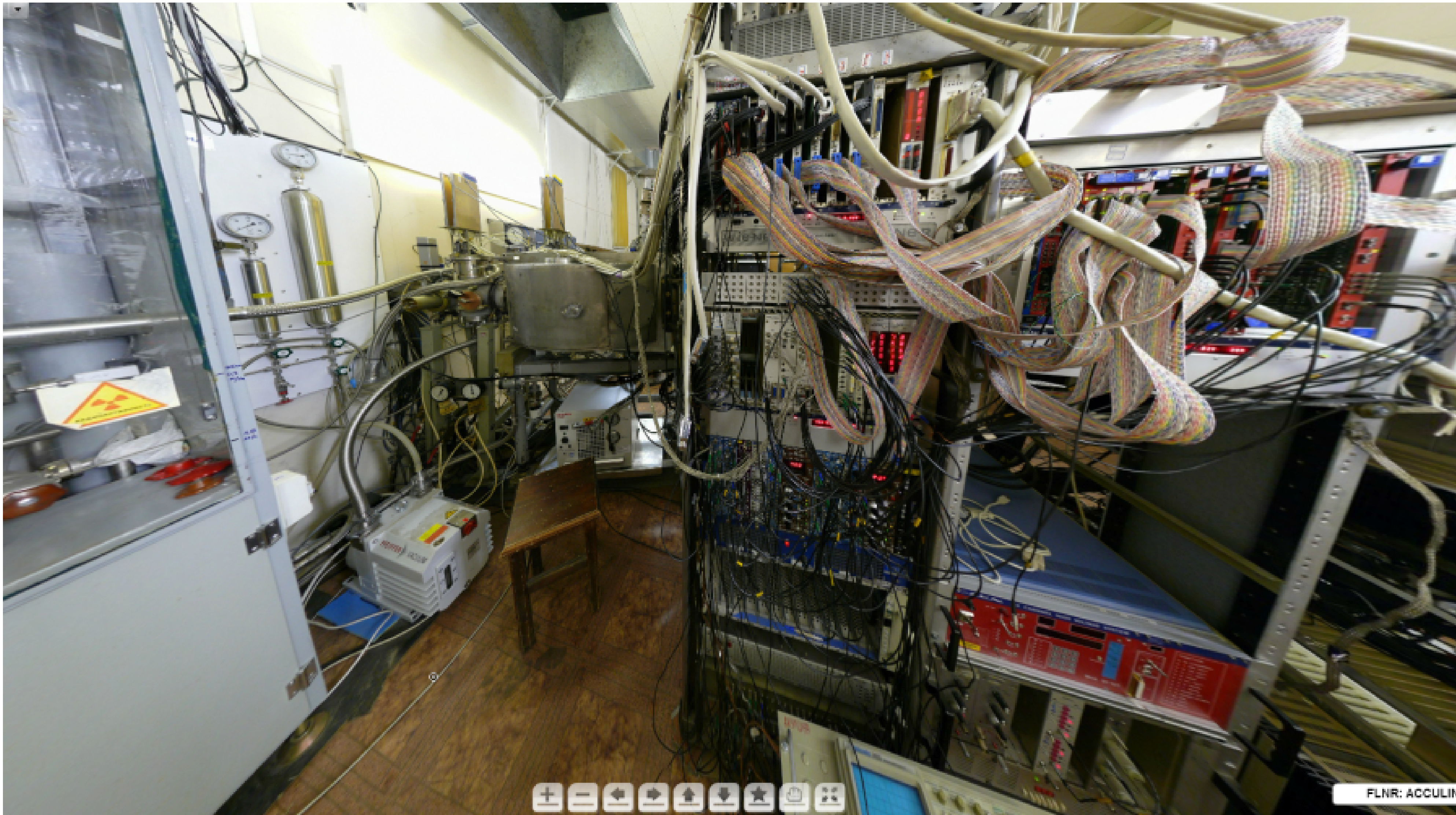
I. Mukha et al. Phys. Rev. C 82 (2010) 054315

^{16}Ne

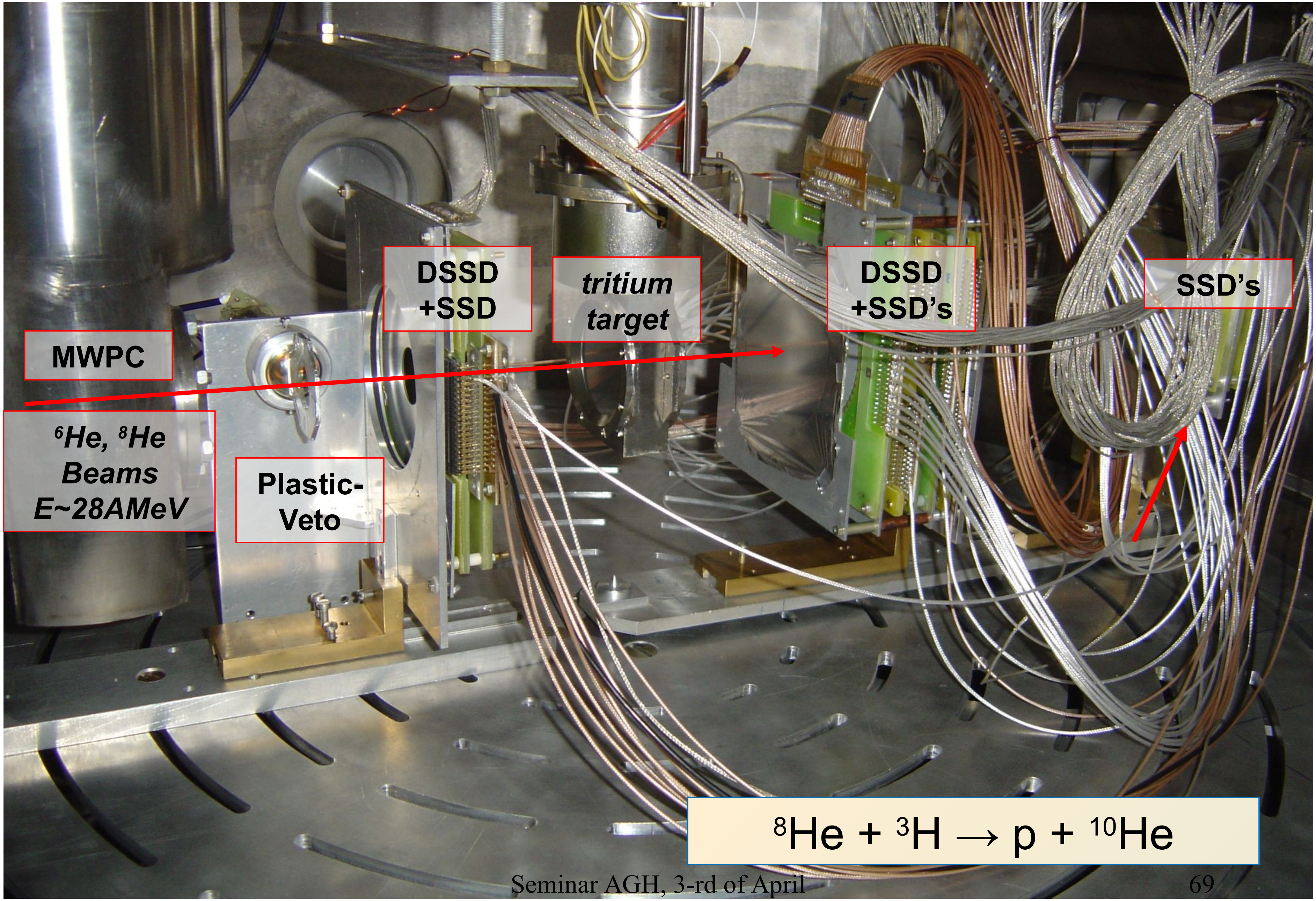




ACCULINNA experiment



ACCULINNA experiment

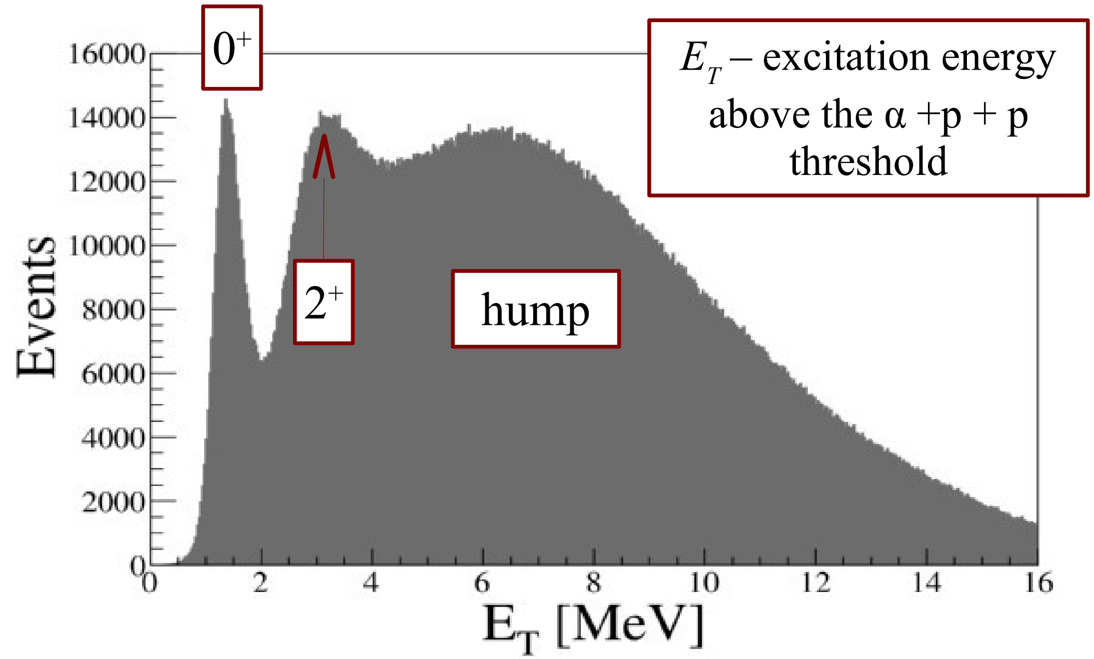


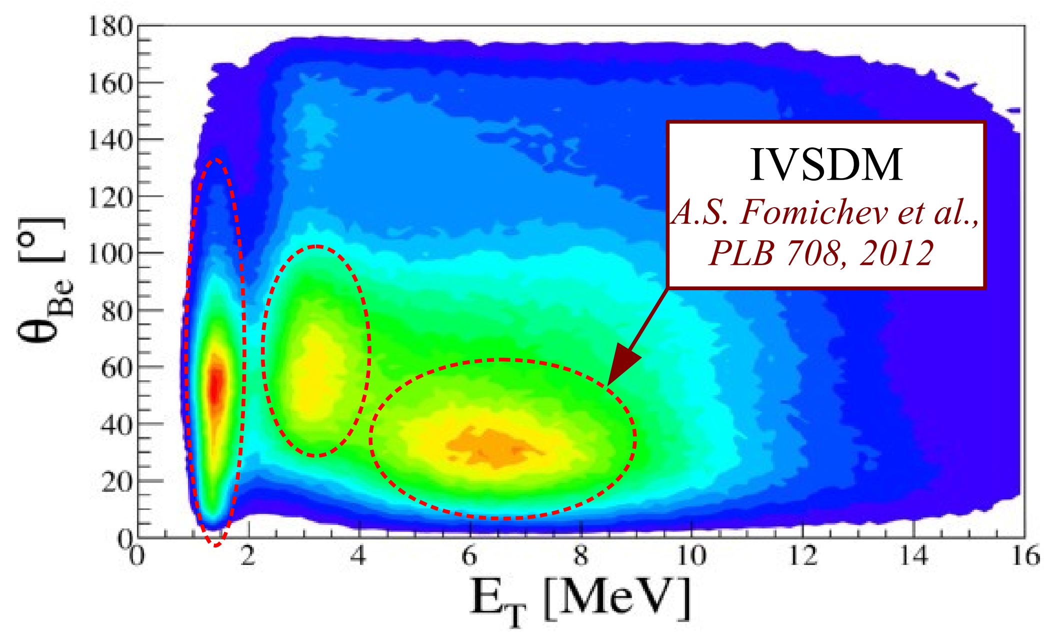
$^{8}He + ^{3}H \rightarrow p + ^{10}He$

^{6}Be: Invariant mass spectrum

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

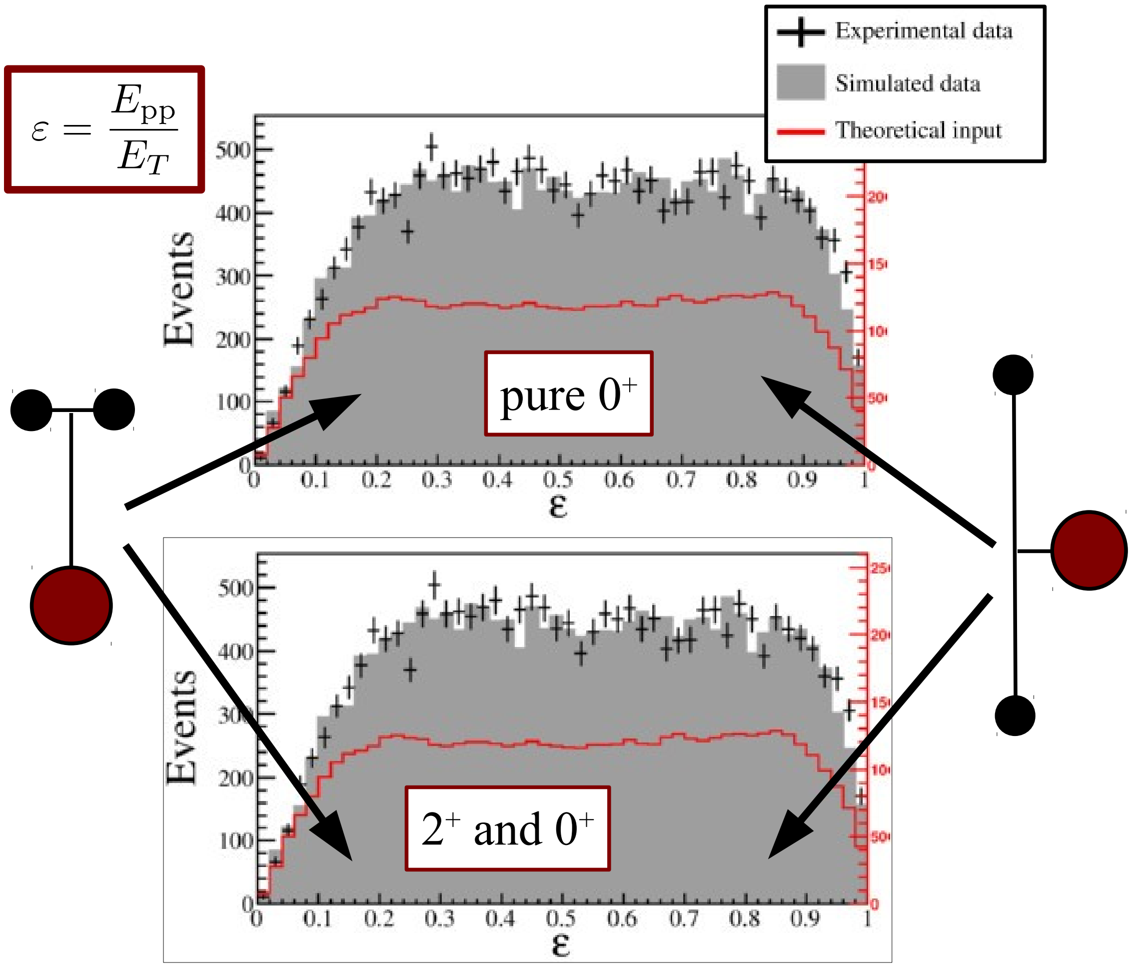
- 0^+, 2^+ states
- broad hump at $E_T > E_T(2^+)$





^{6}Be: Internal correlations

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



Theoretical model

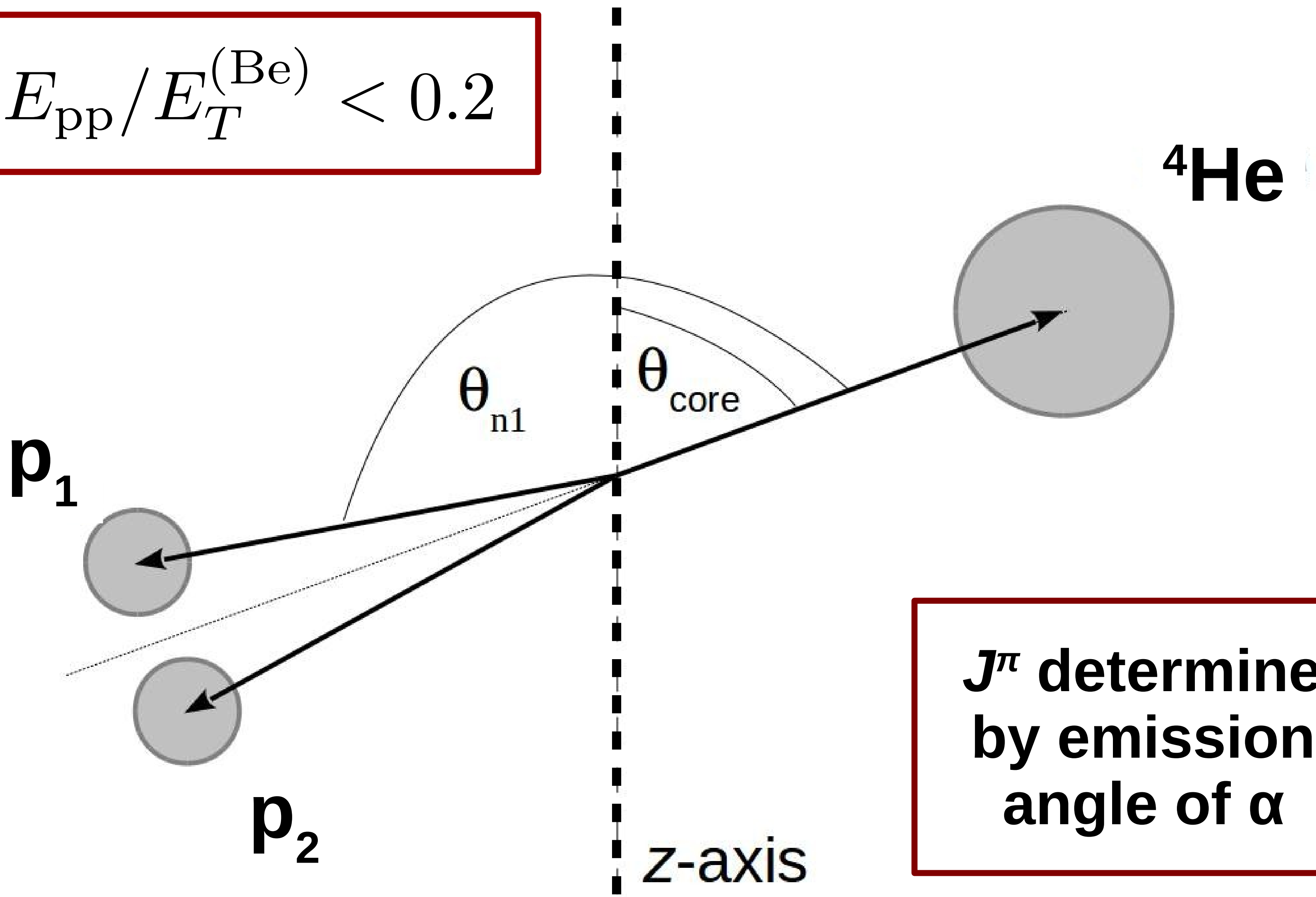
PWIA in combination with 3-body model

- test on 0^+ ground state (no free parameters)
- overlapping states 0^+ and 2^+
  - 2^+ alignment
  - Interference of 0^+ and 2^+

low sensitivity of internal correlations to model parameters

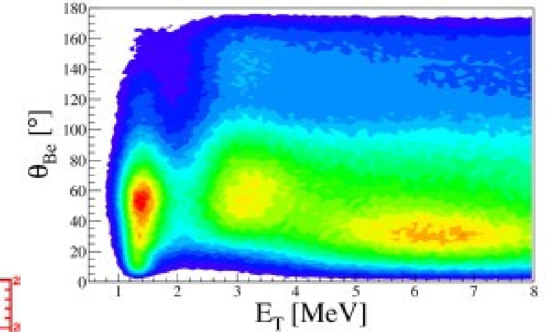
^{6}Be: Quasibinary kinematics

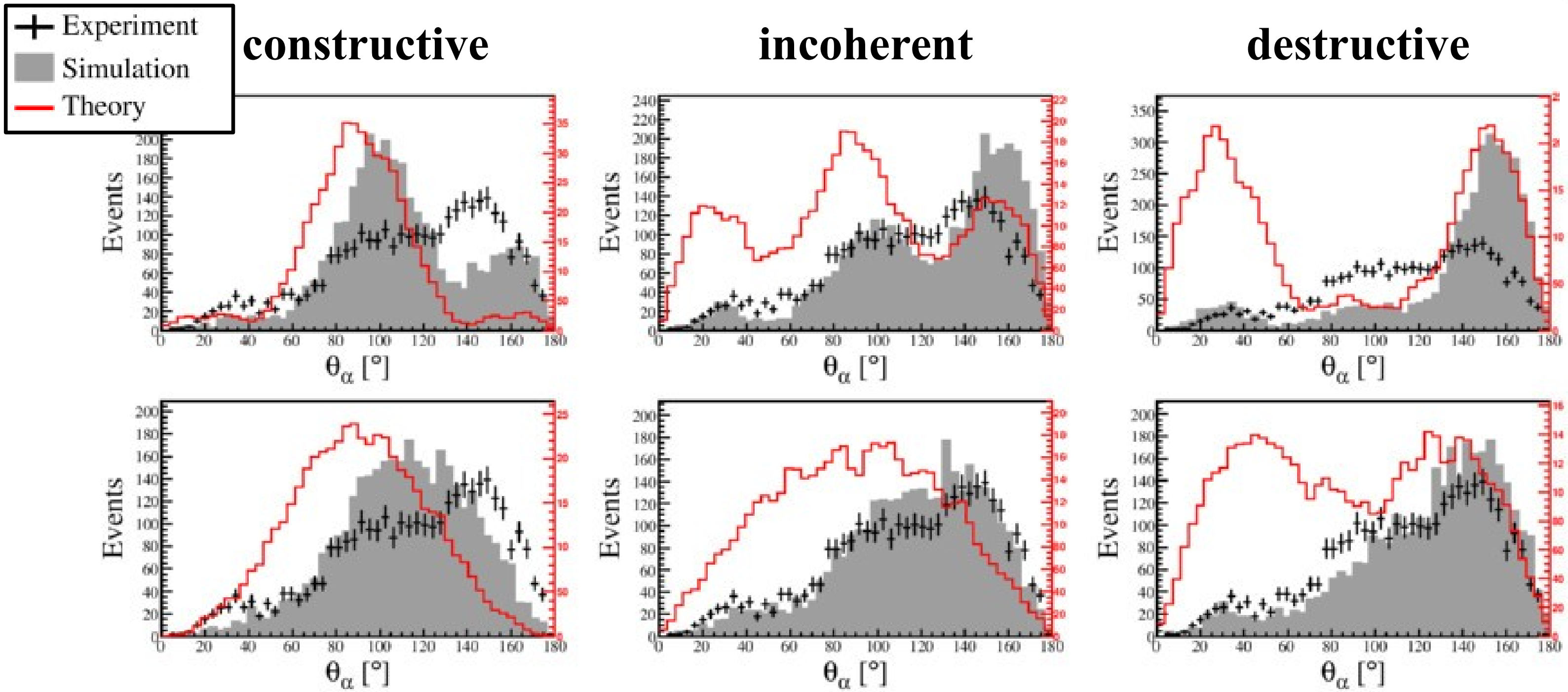
$$\varepsilon = E_{\mathrm{pp}}/E_T^{(\mathrm{Be})} < 0.2$$



J^π determined by emission angle of α

^{6}Be: External correlations





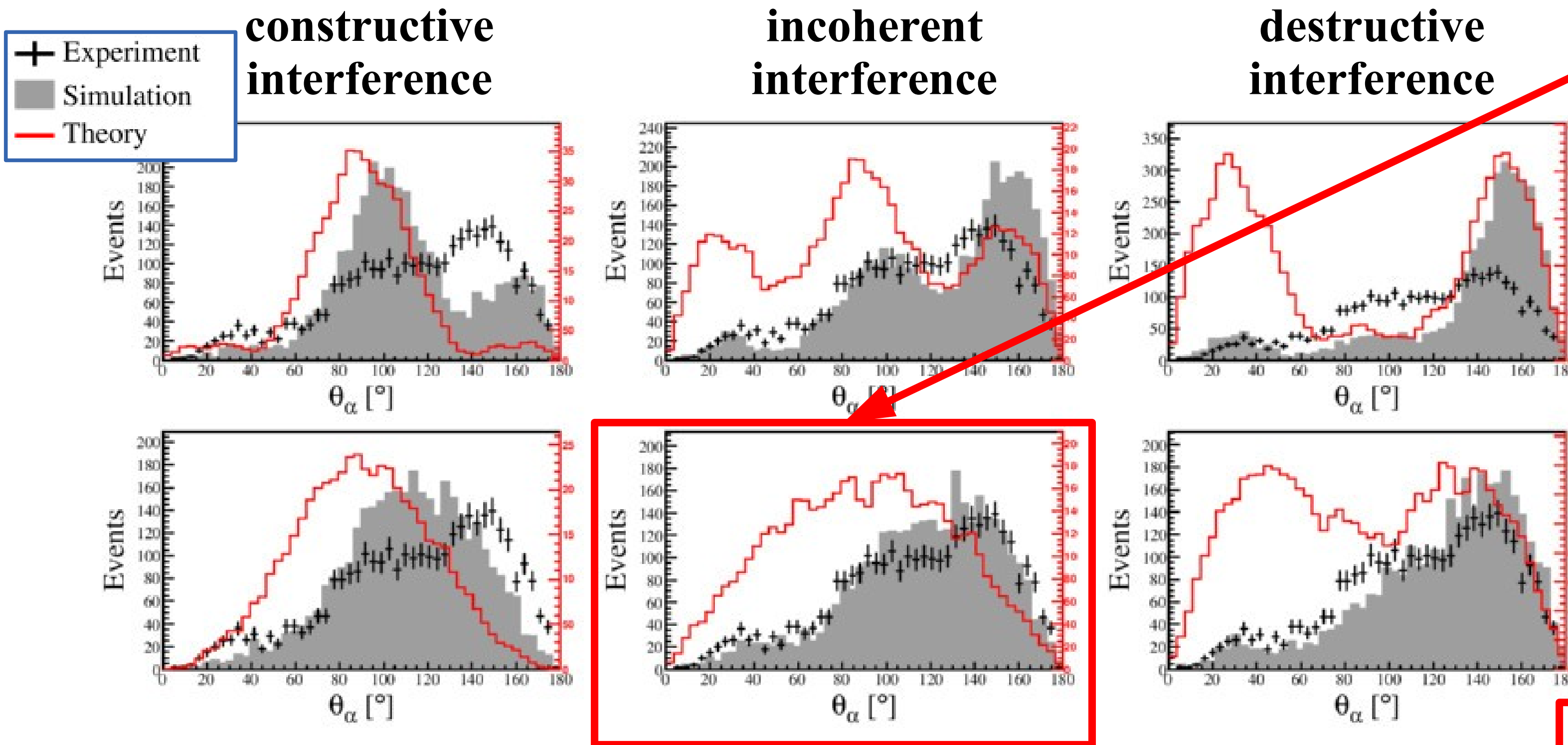
aligned

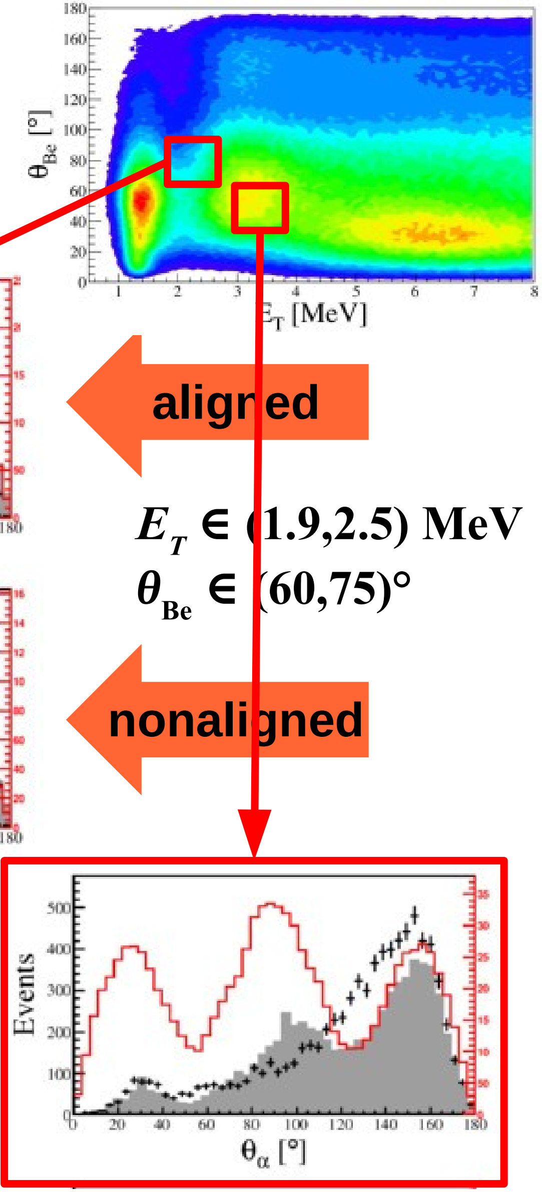
$E_T \in (1.9, 2.5)$ **MeV**
$\theta_{Be} \in (60, 75)°$

nonaligned

- 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



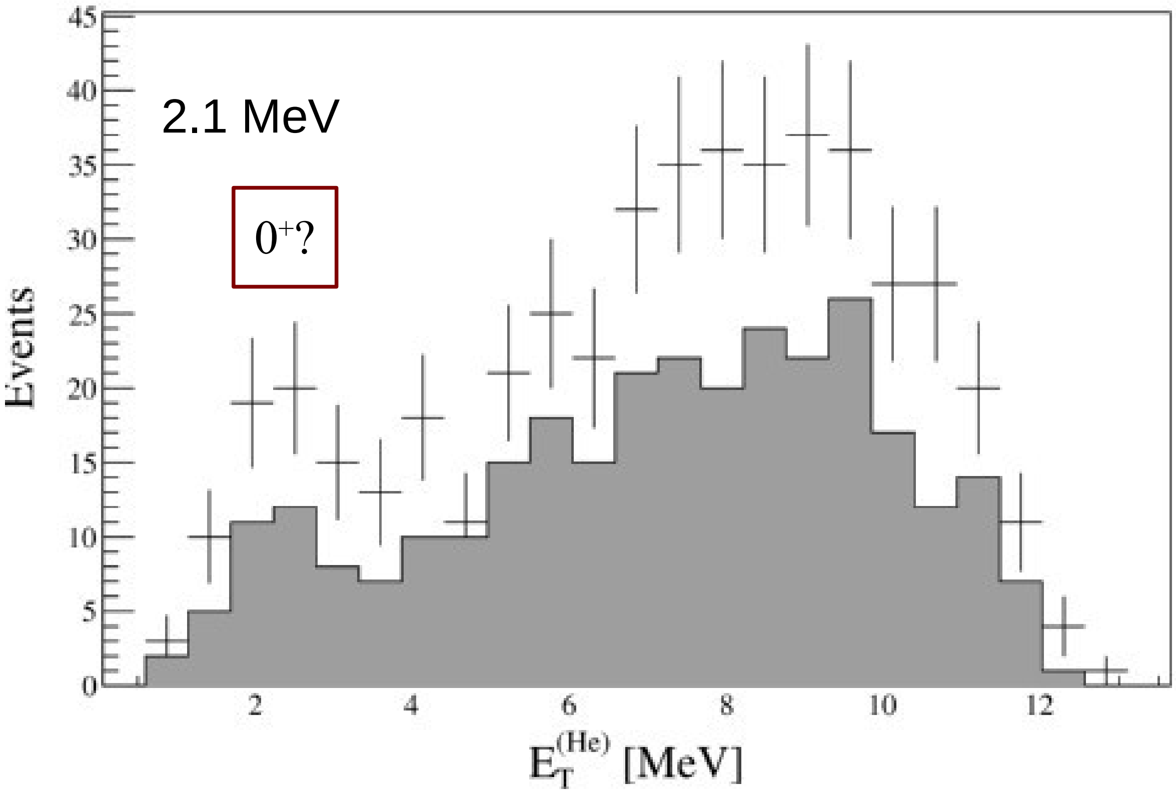


experimental sensibility to J^π orientation and interference between 0^+ and 2^+

- 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: Missing mass spectrum



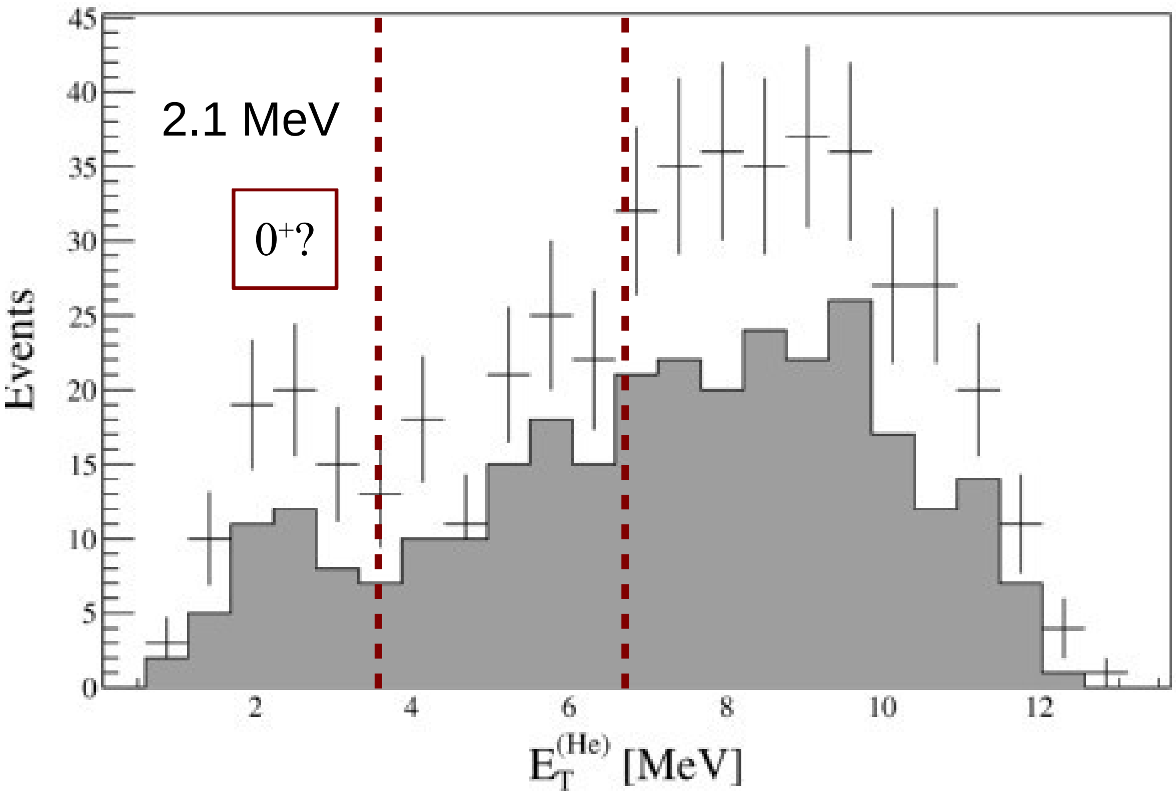
$$^3\mathrm{H} + ^8\mathrm{He} \rightarrow ^{10}\mathrm{He} + \mathrm{p}$$
$$^{10}\mathrm{He} \rightarrow ^8\mathrm{He} + \mathrm{n} + \mathrm{n}$$

- missing mass spectrum from protons measured in coincidence with ^{8}He
- 479 events found

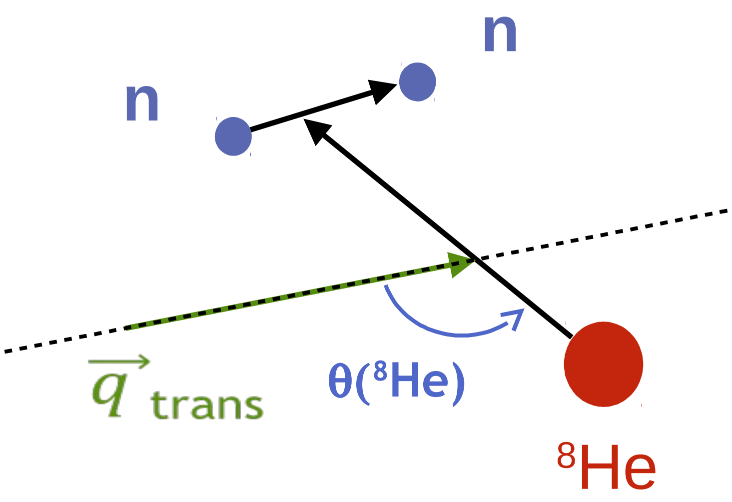
S.I. Sidorchuk et al.
Phys. Rev. Lett. 108
202502 (2012)

- population of 0+ ground state with maximum at E_T~2.1 MeV
- structureless spectrum for E_T>4 MeV

^{10}He: Correlations



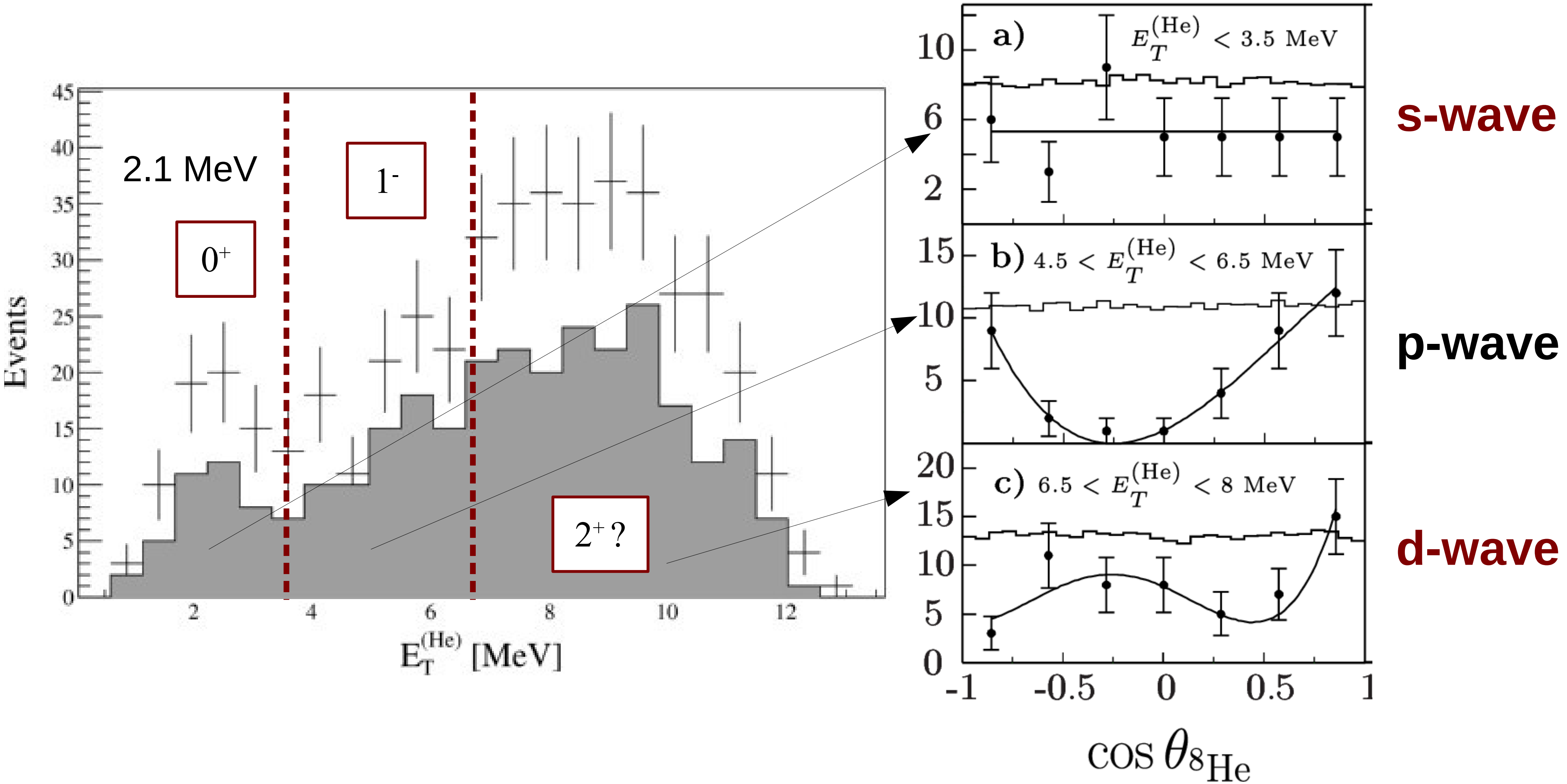
quasibinary kinematics



- J^{π} is fully determined by L of ^{8}He

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

^{10}He: Correlations



- 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

Conclusion and outlook

- extensive field for pioneering research
- 3000 isotopes known, 3000 to be discovered
- new RIB factories constructed worldaround
- new facility in Dubna, new plans for the future (ERICA)
- new research methods

Thank for attention

End

Spin-parity identification

Standard methods:

- Elastic resonance scattering
- Direct reactions

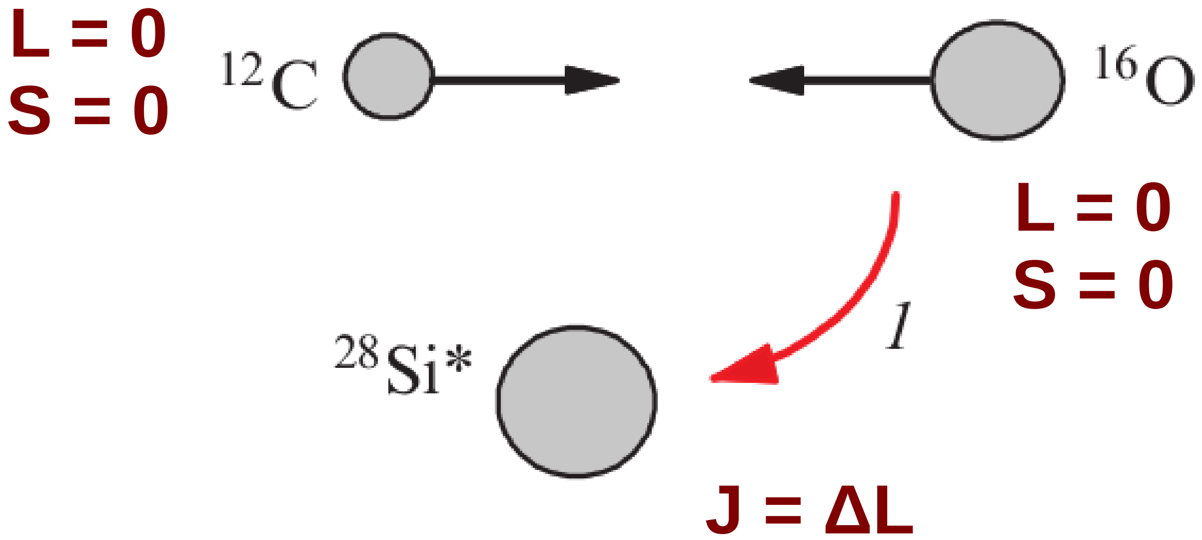
Elastic resonance scattering

- fit to R-matrix
- unambiguous J^{π} identification
- constrains:
  - width of resonance
  - existing beams

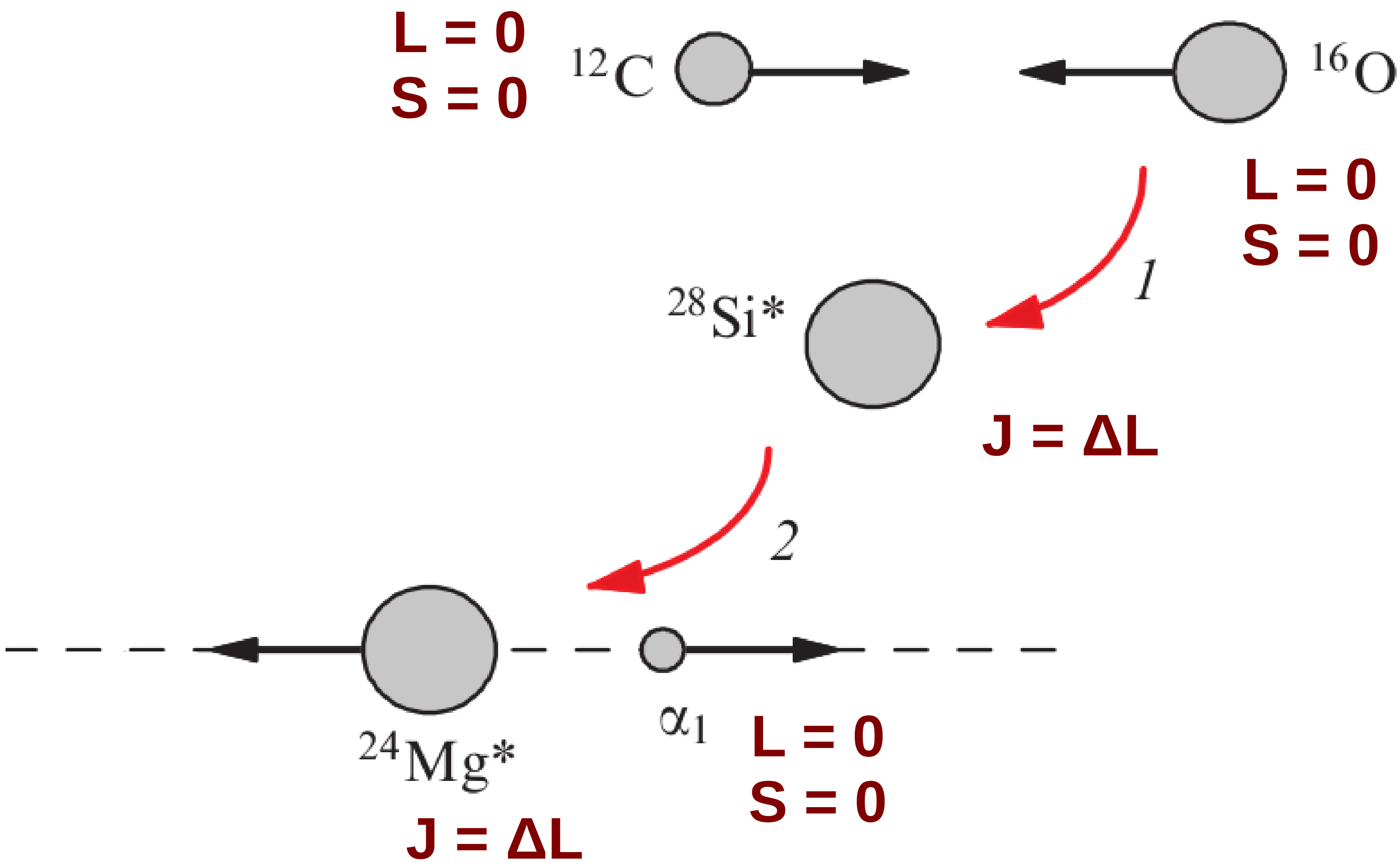
Direct reactions

- angular distribution of products
  - using (*e.g.* DWBA) ΔL may be determined
- “zero geometry“ approach

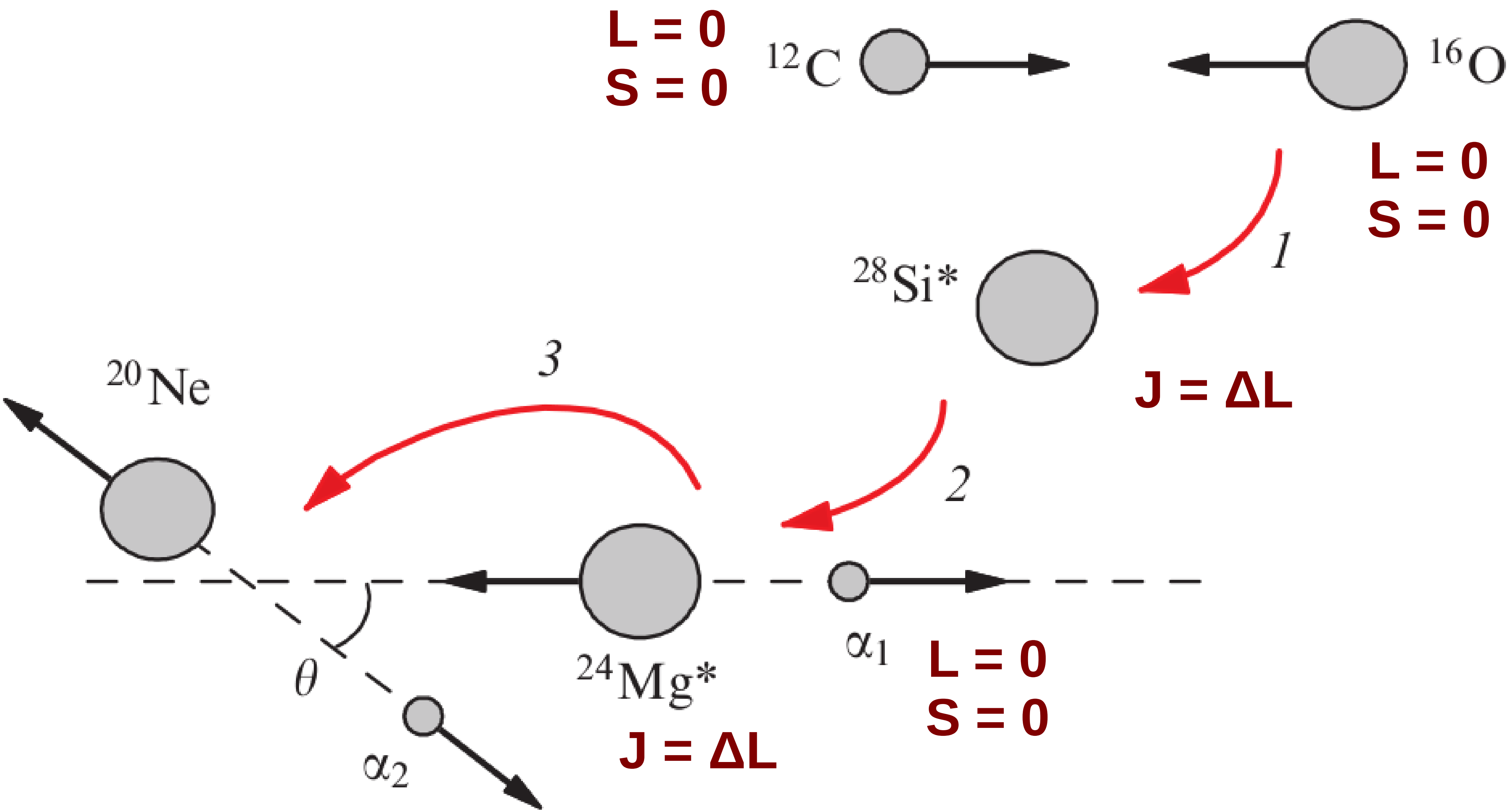
Zero geometry approach



Zero geometry approach



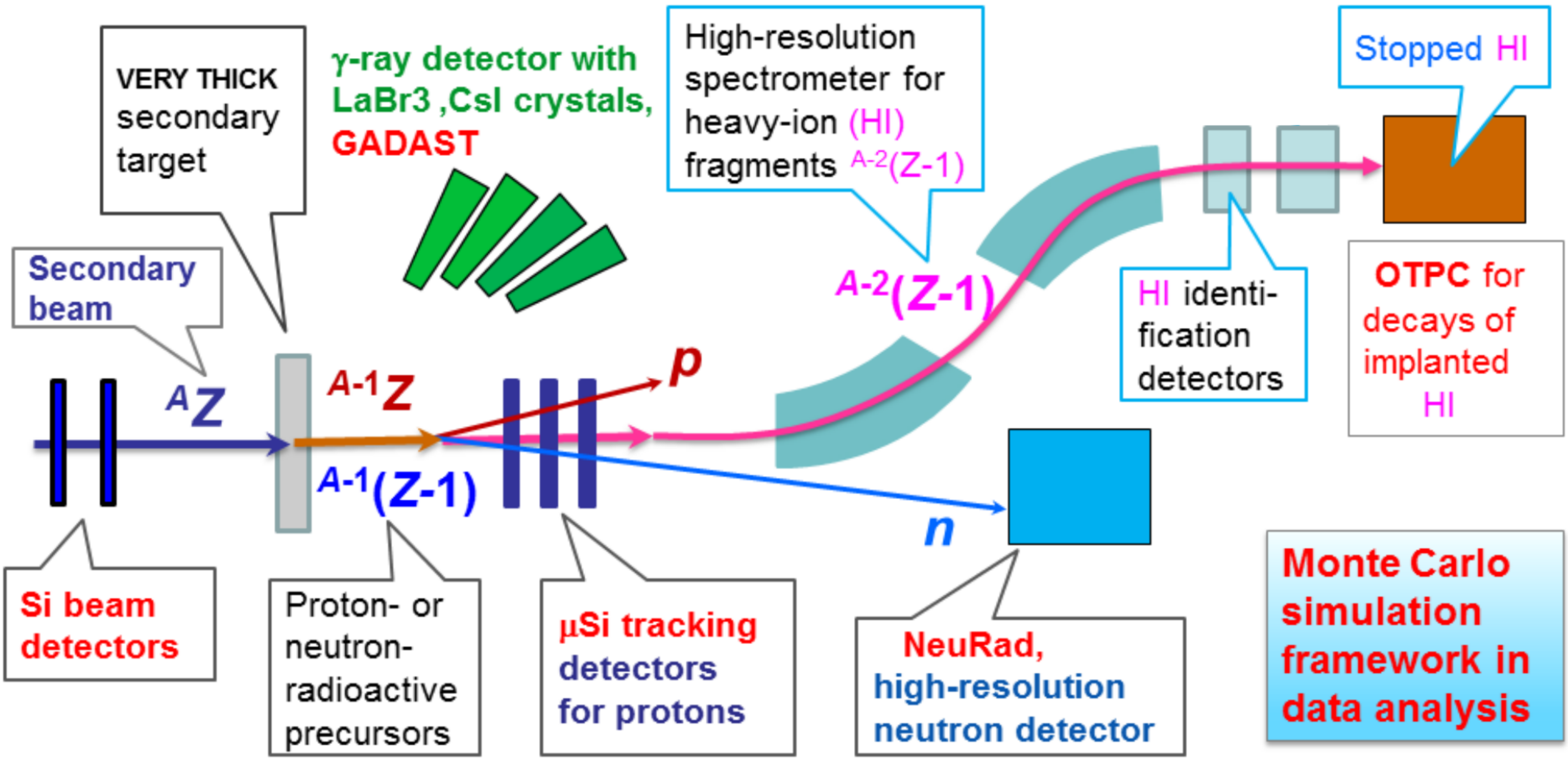
Zero geometry approach



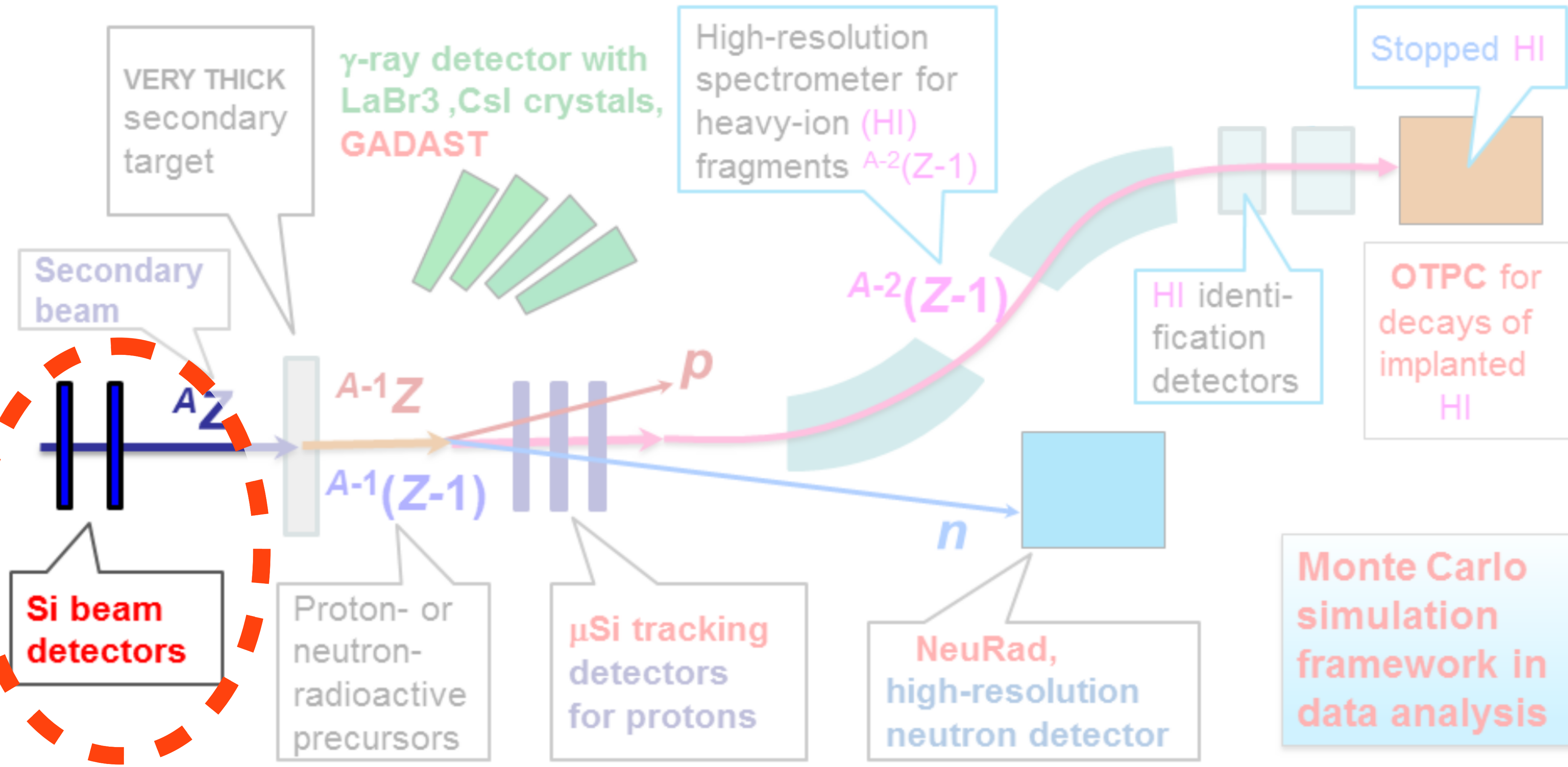
Zero geometry approach

- constrains:
  - spinless reaction participants
  - high reaction cross section needed
- it can be easily generalized
  → correlation patterns

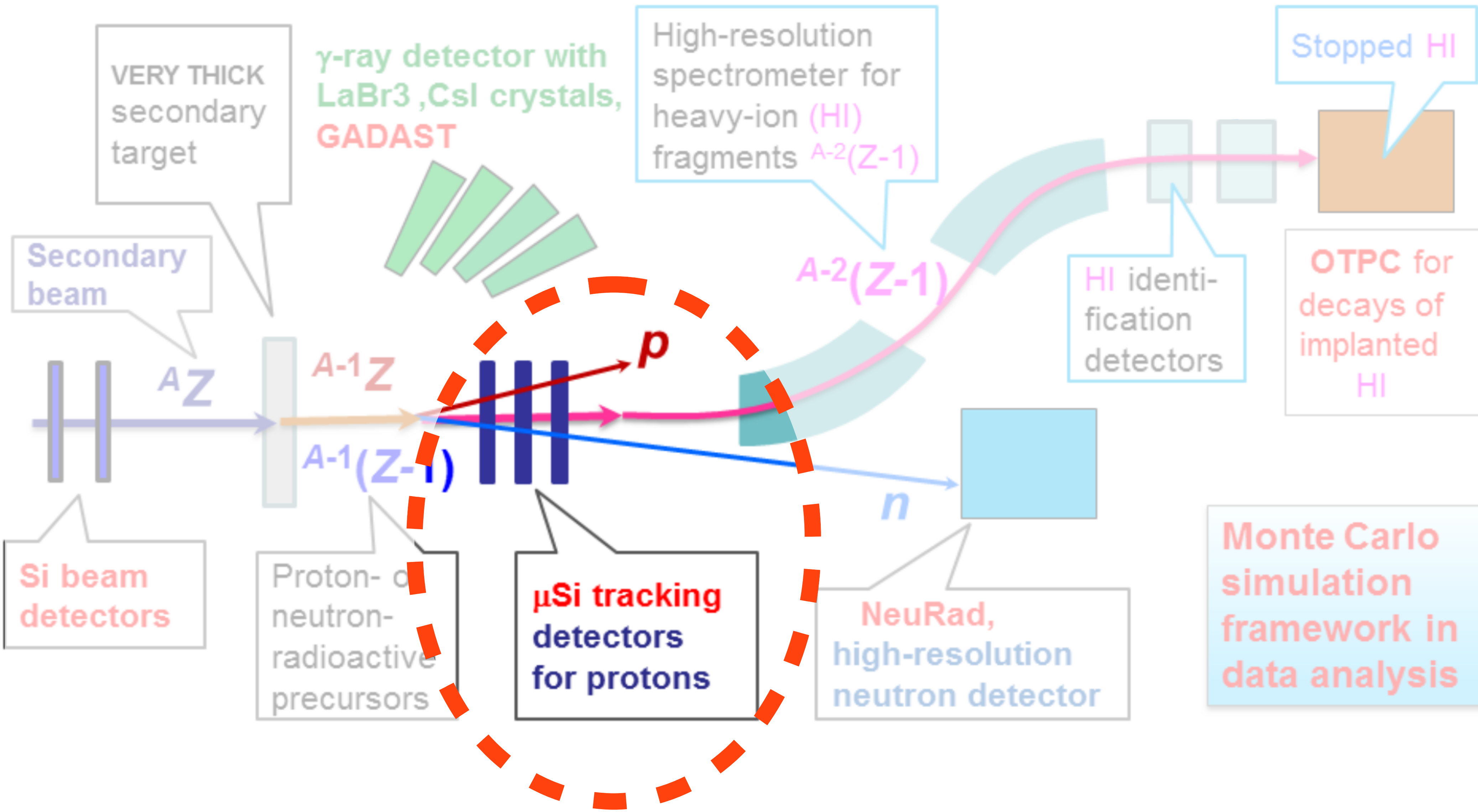
EXPERT: Experimental setup



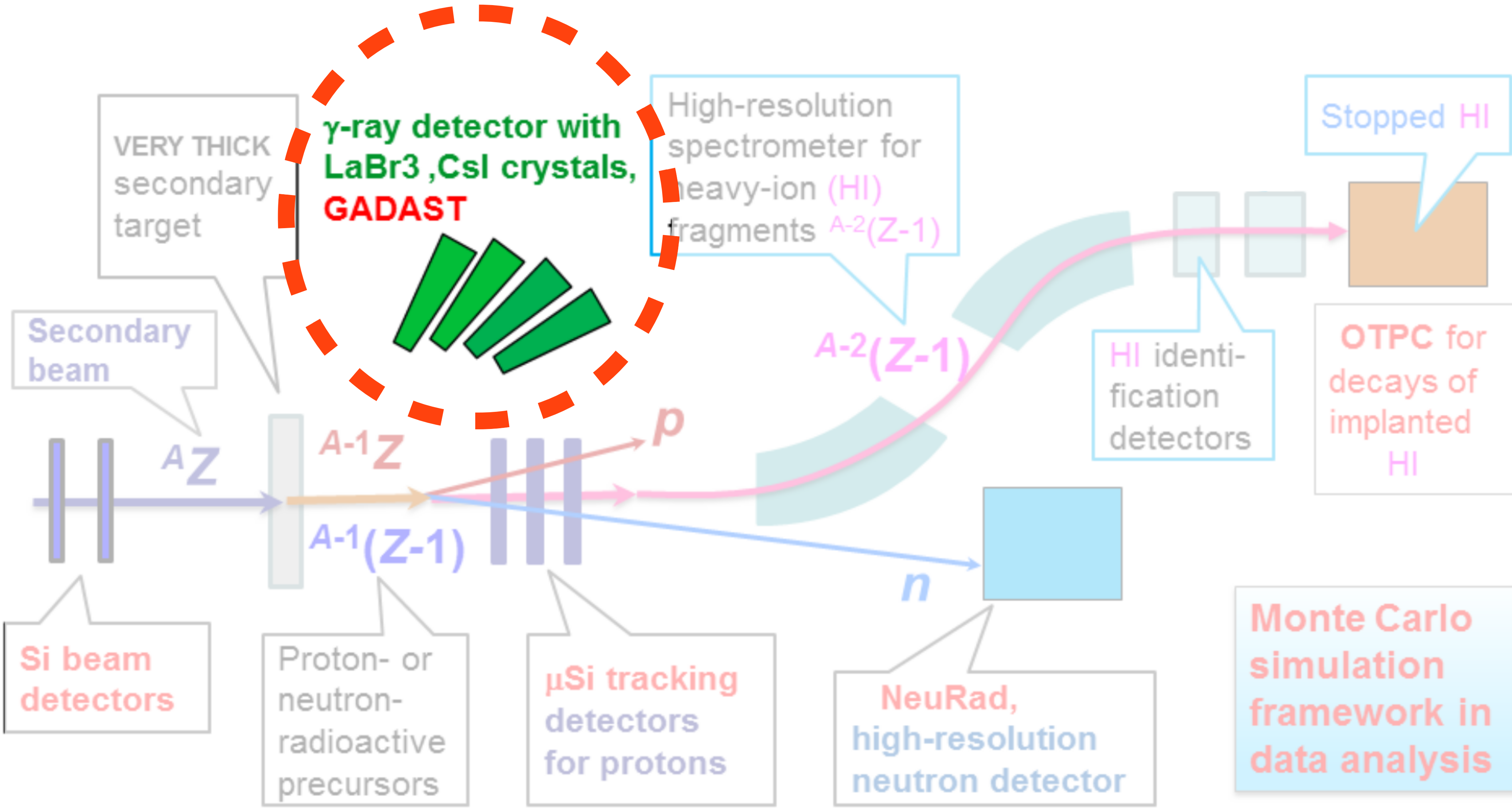
EXPERT: Experimental setup



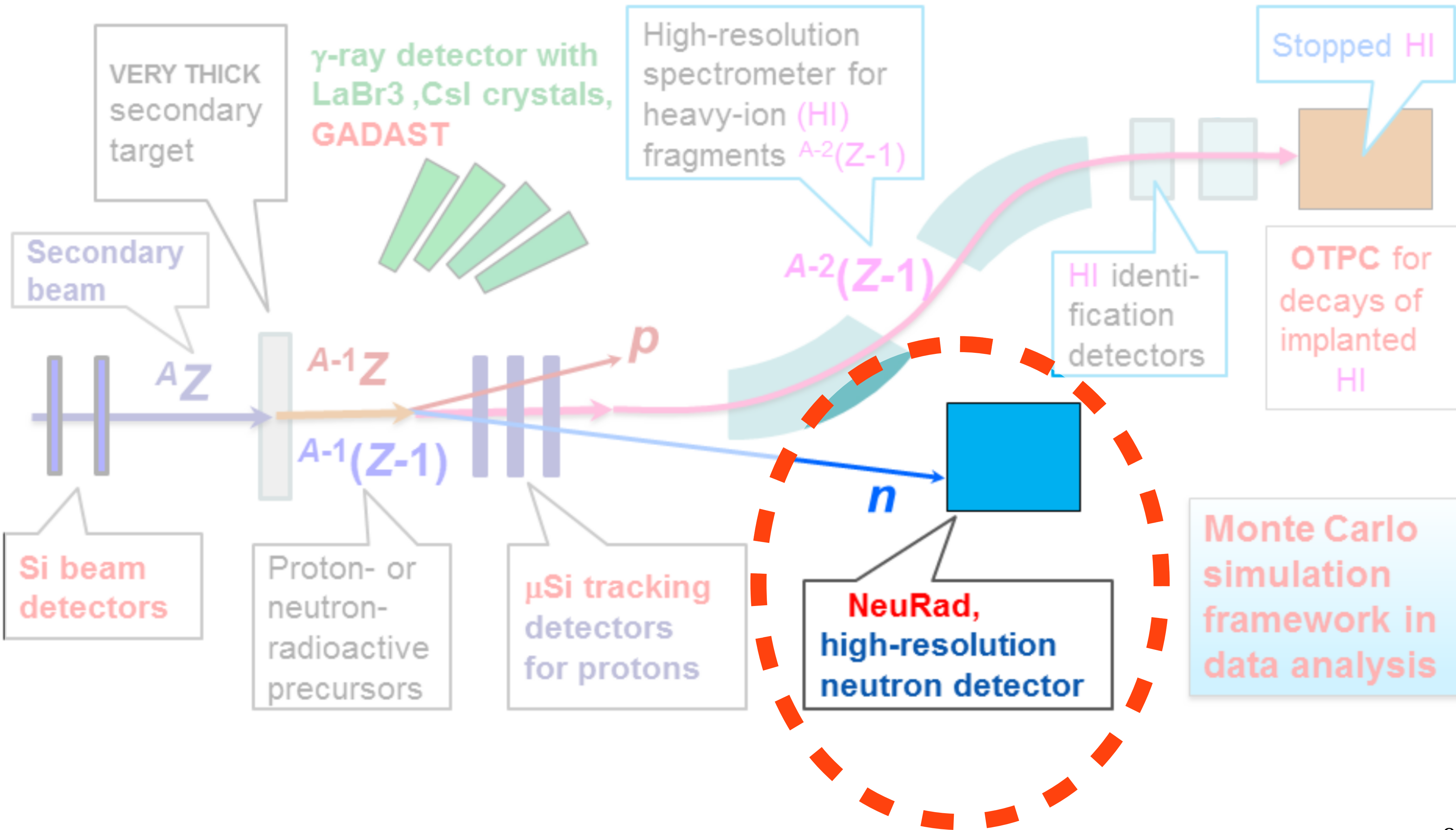
EXPERT: Experimental setup



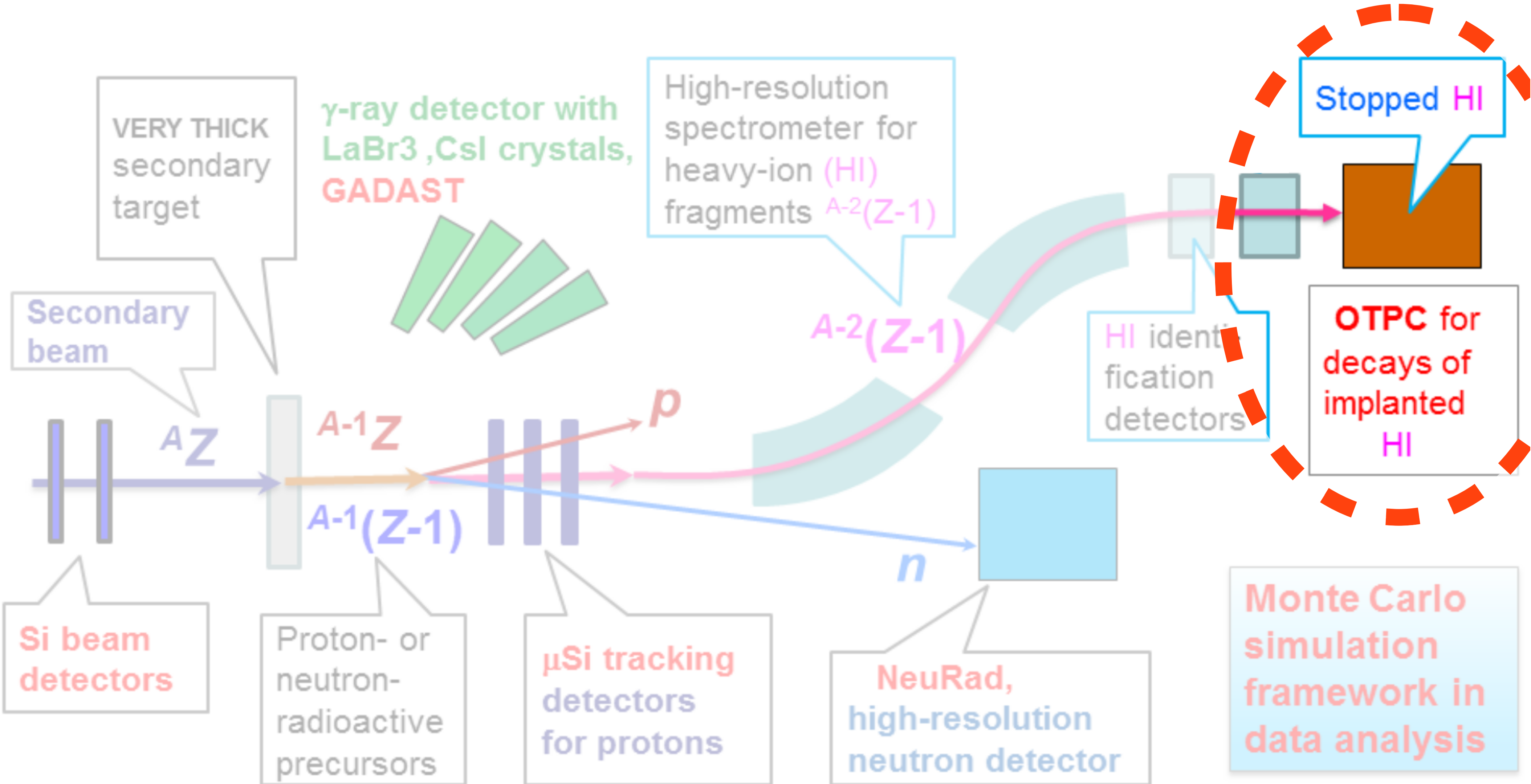
EXPERT: Experimental setup



EXPERT: Experimental setup



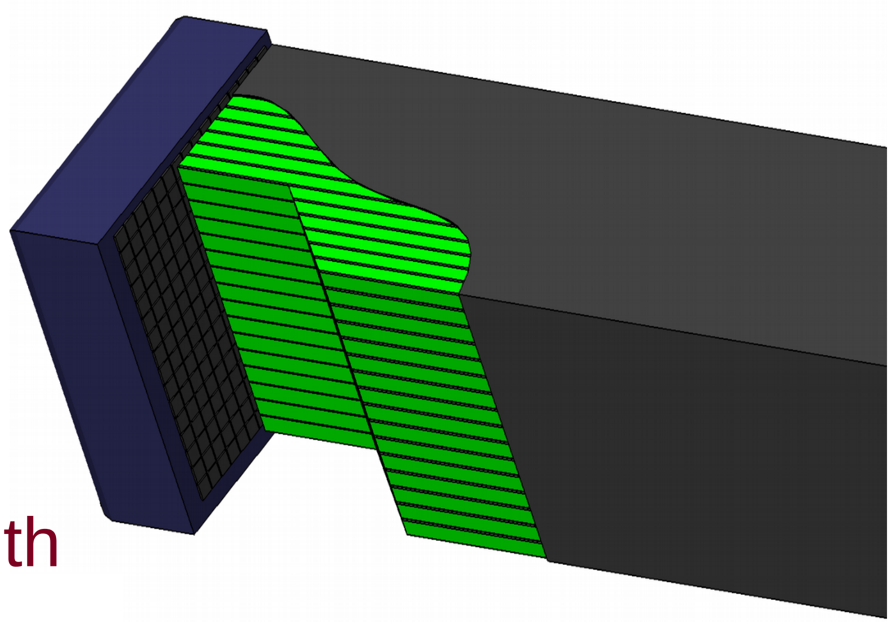
EXPERT: Experimental setup



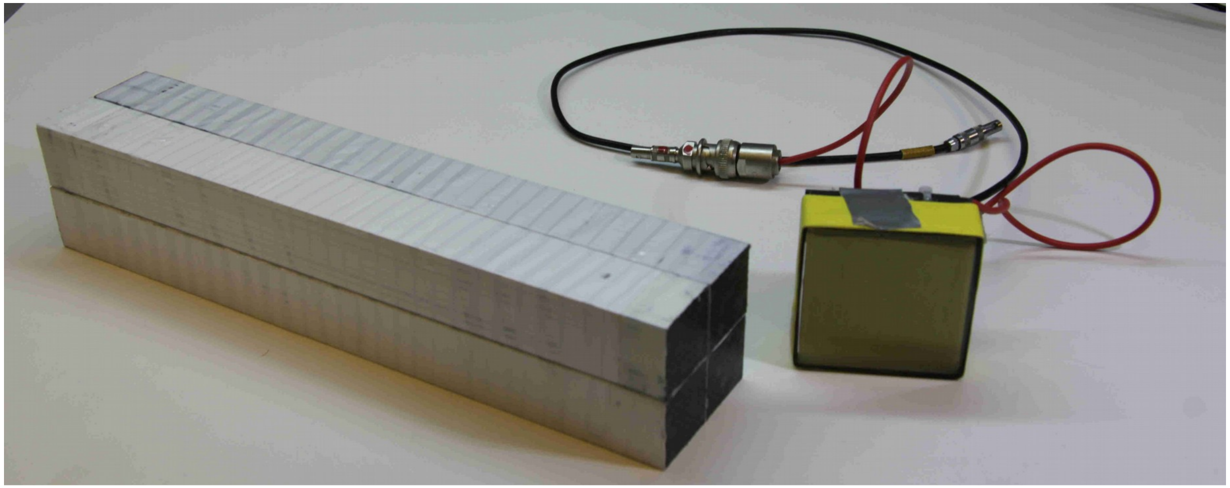
OTPC

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



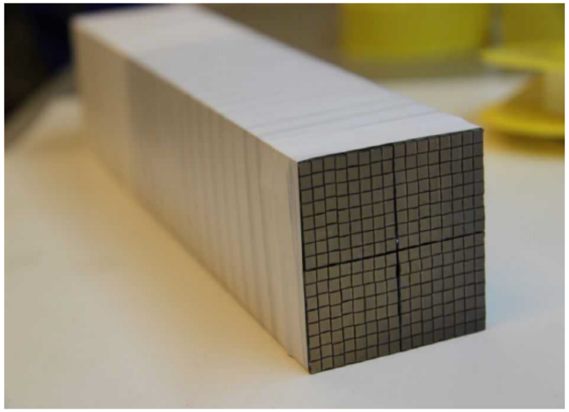
28 m from the target in FMF2

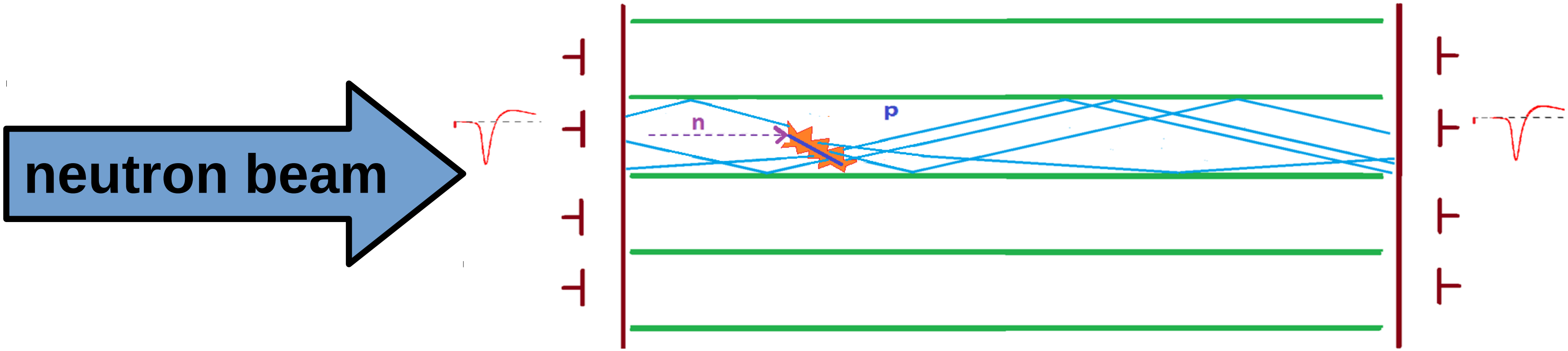
at least 36 modules
30 x 30 x 100 cm^3

NeuRad

bundles

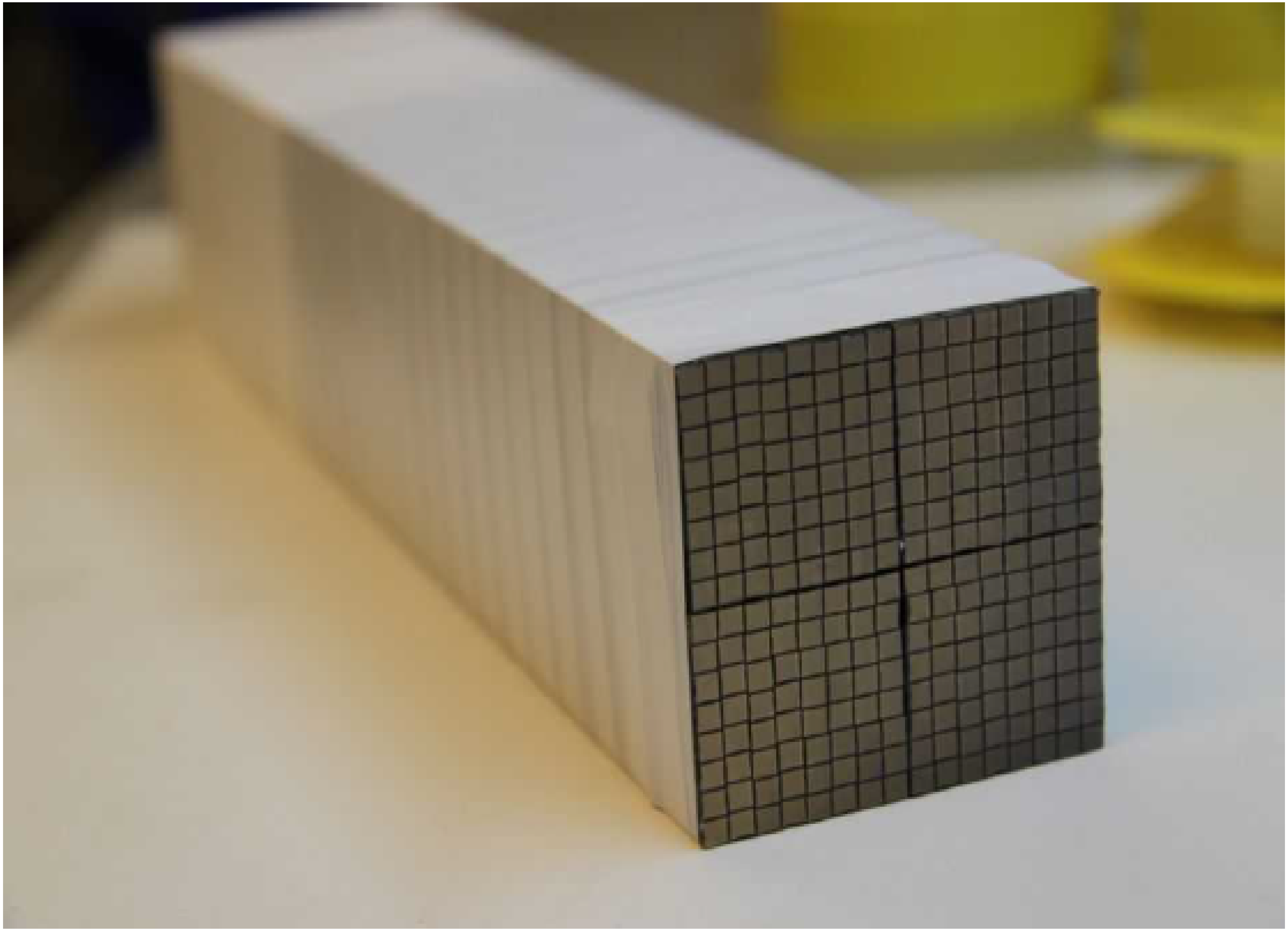
- 3 x 3 mm scintillation fibers BCF12
- 48 x 48 x 1000 mm
- 2 MAPMT from both sides





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

NeuRad



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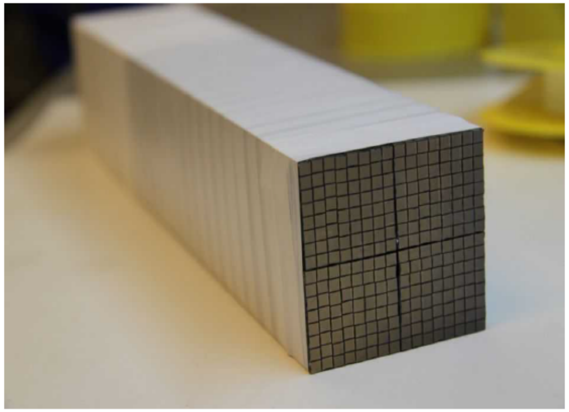

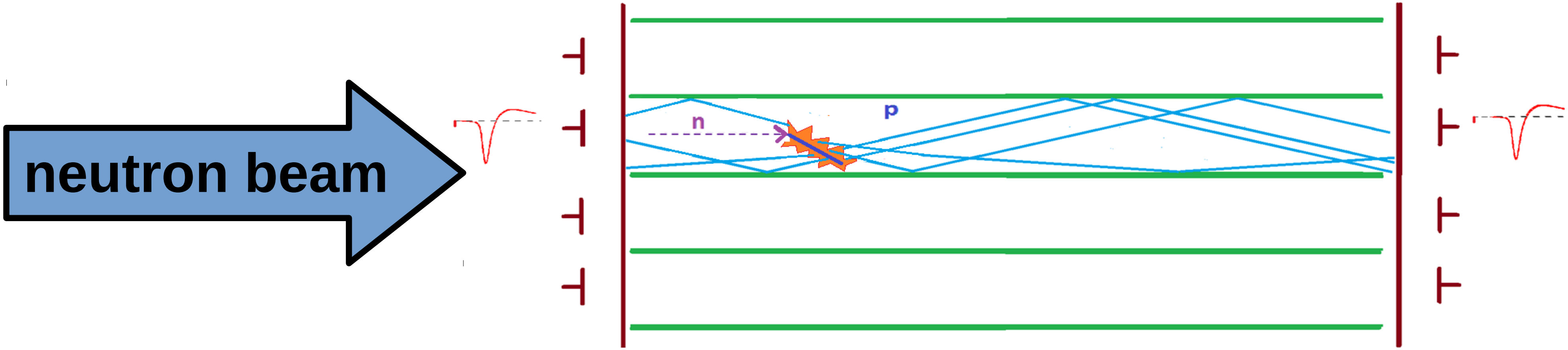

- **longitudinal coordinate** of the n interaction along the fiber
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Appendix: Nuclear halo

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**

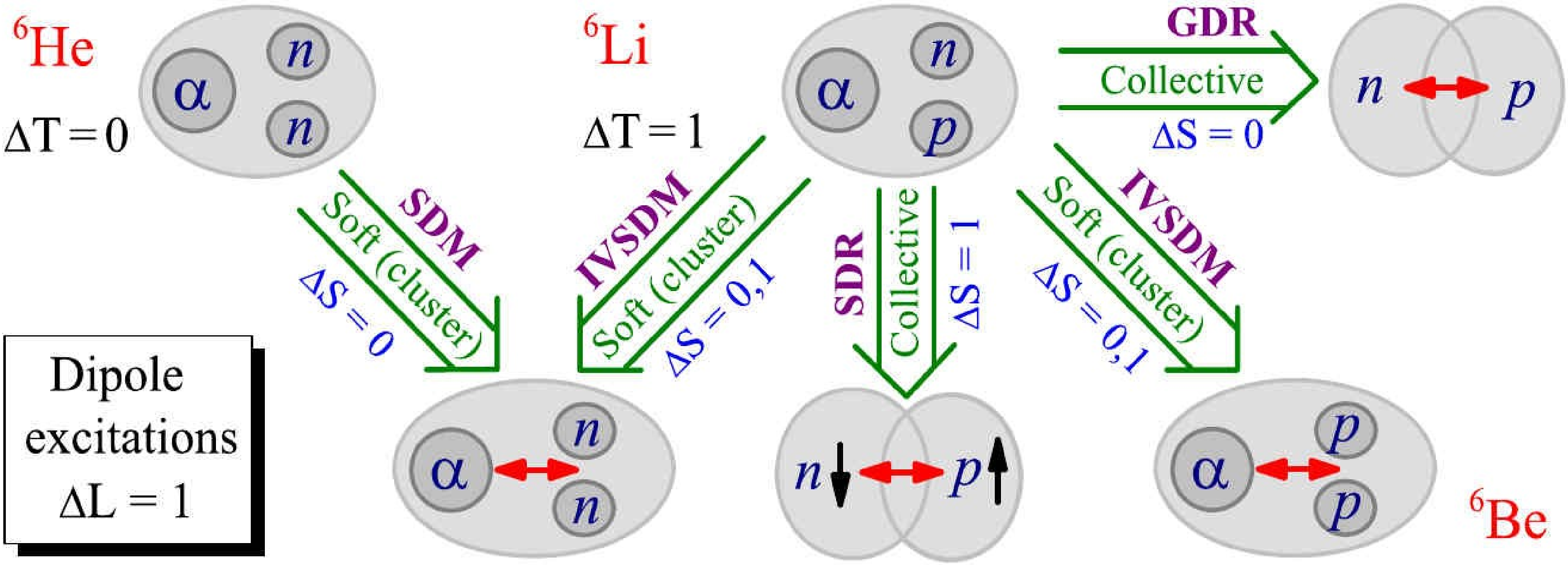
neutron skin: **^{8}He and ^{14}Be**

proton halo

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

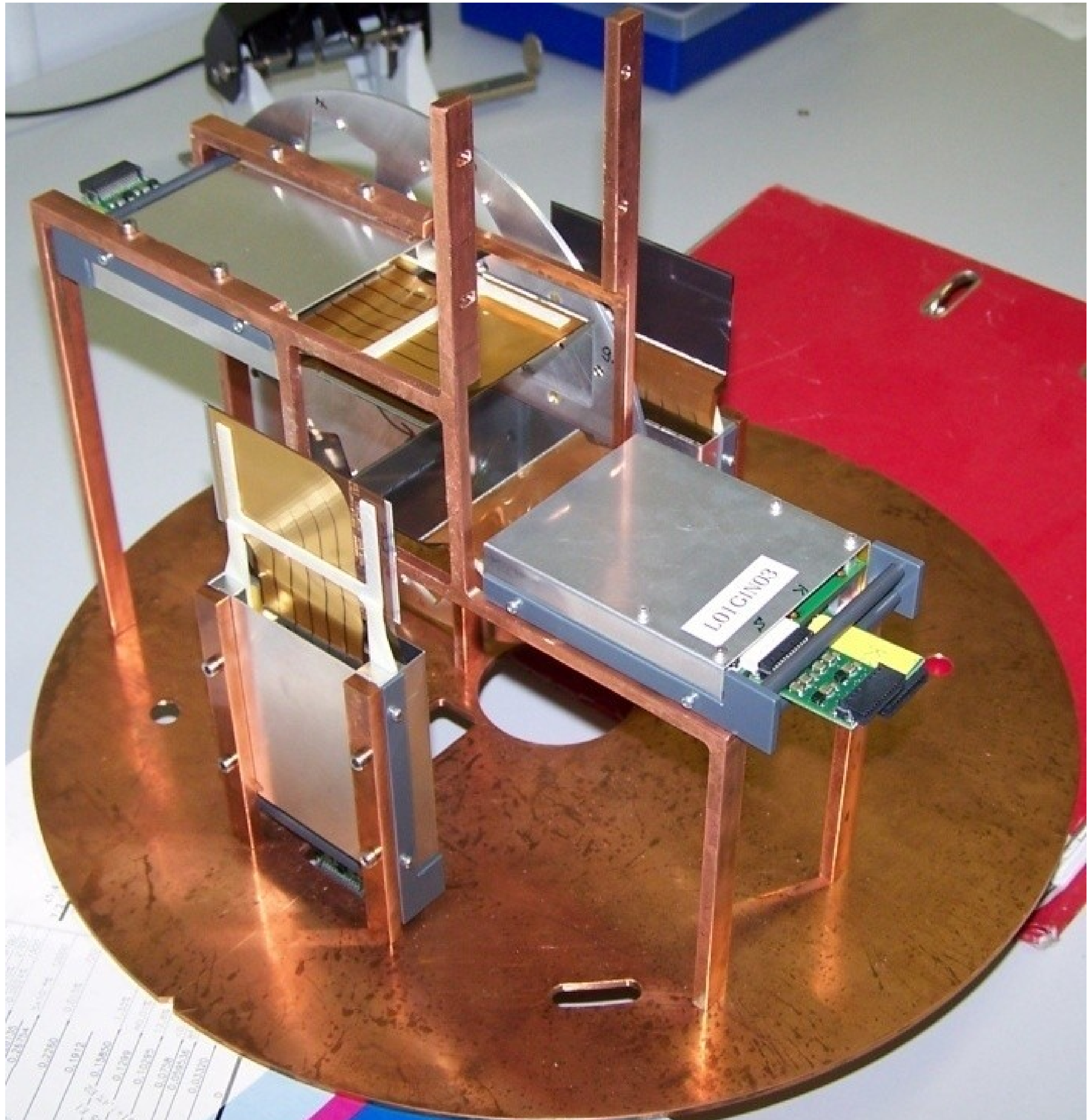
the first e.s. of **^{17}F**

Appendix: 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



Hardware

NeuRad

NeuRad

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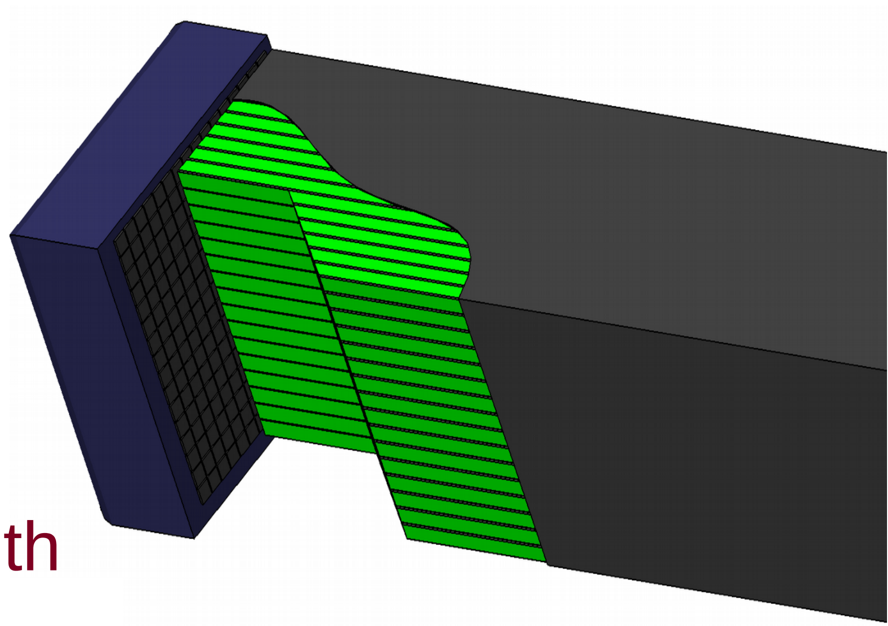
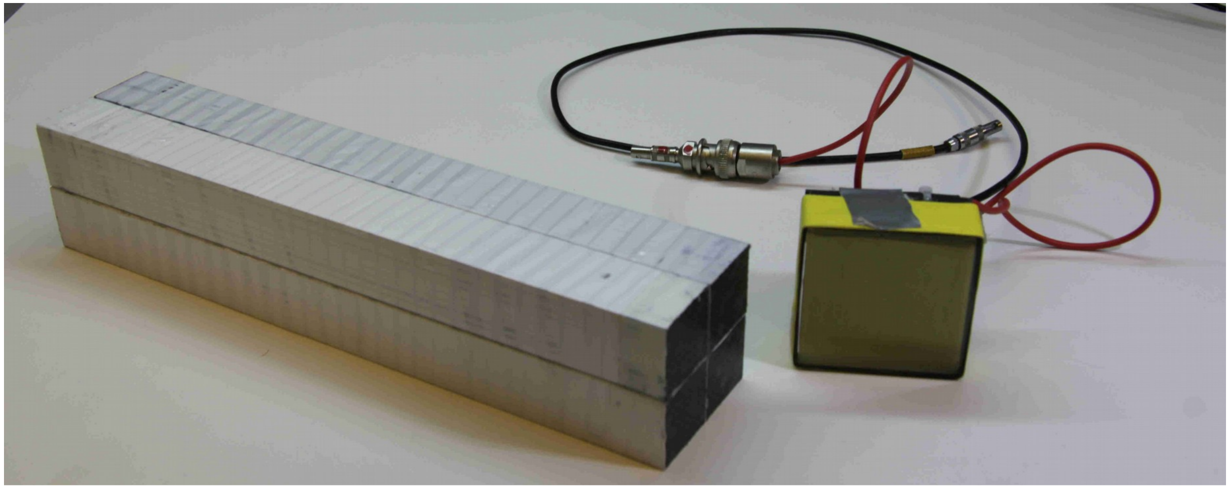
- low transverse momenta 0.1 – 100 keV
- precise information on angular correlations of decay neutrons with a charged fragment
- angular resolution ~0.1 – 0.2 mrad





28 m from the target in FMF2

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$30 \times 30 \times 100$ cm^3

NeuRad

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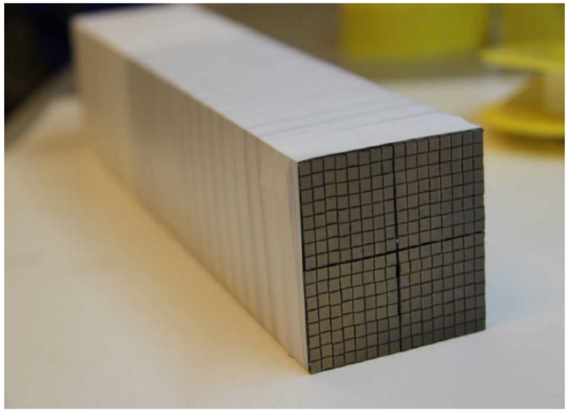

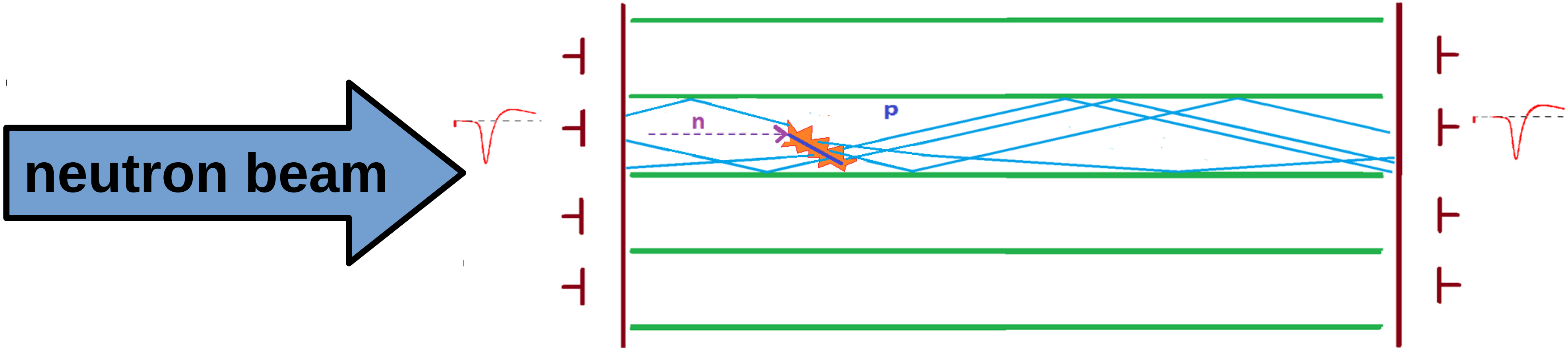

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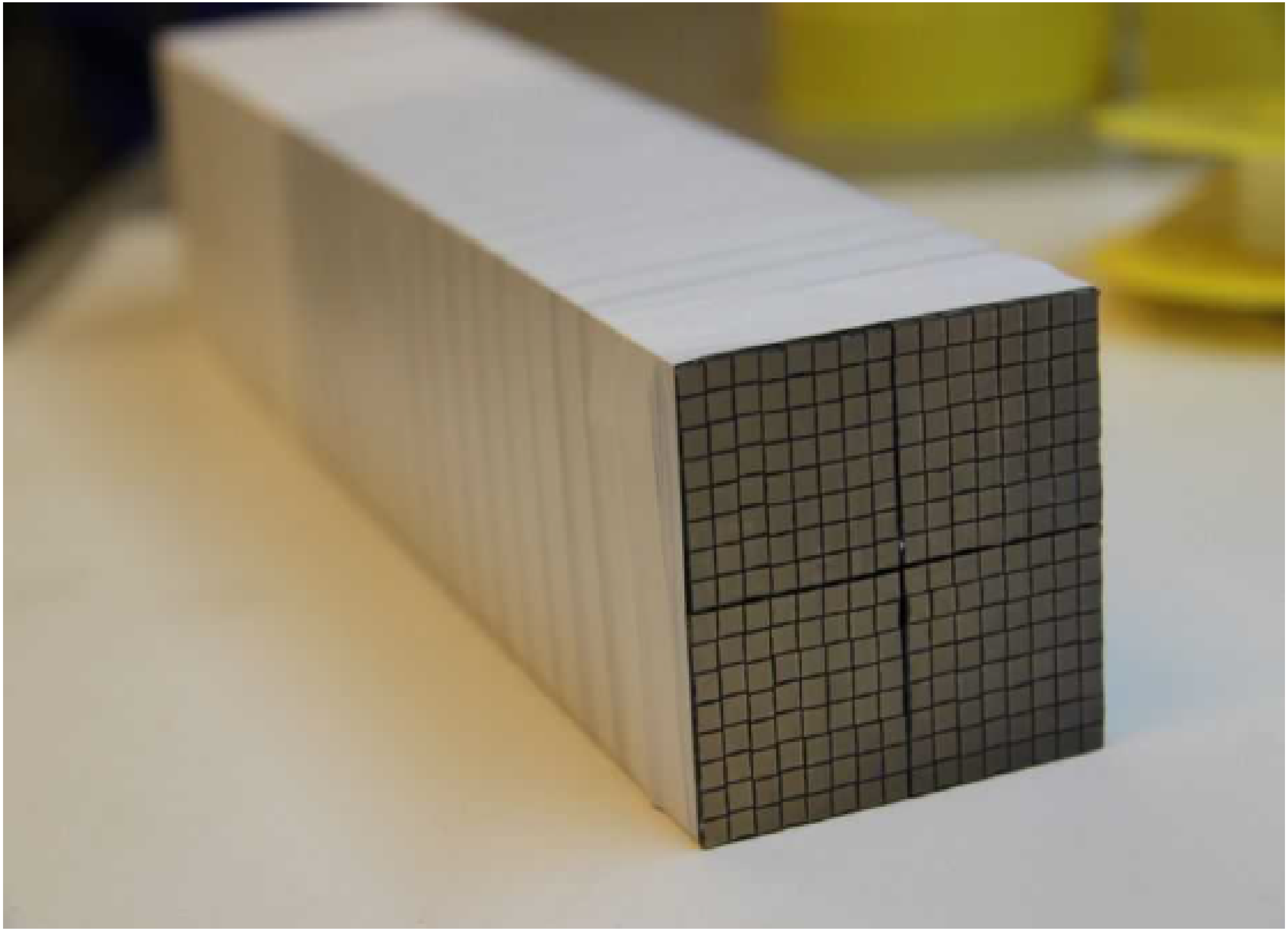
NeuRad



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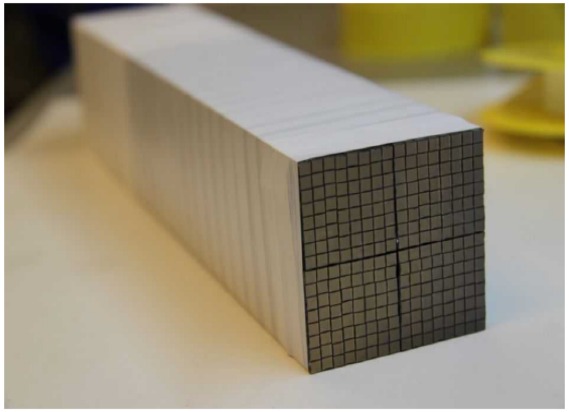

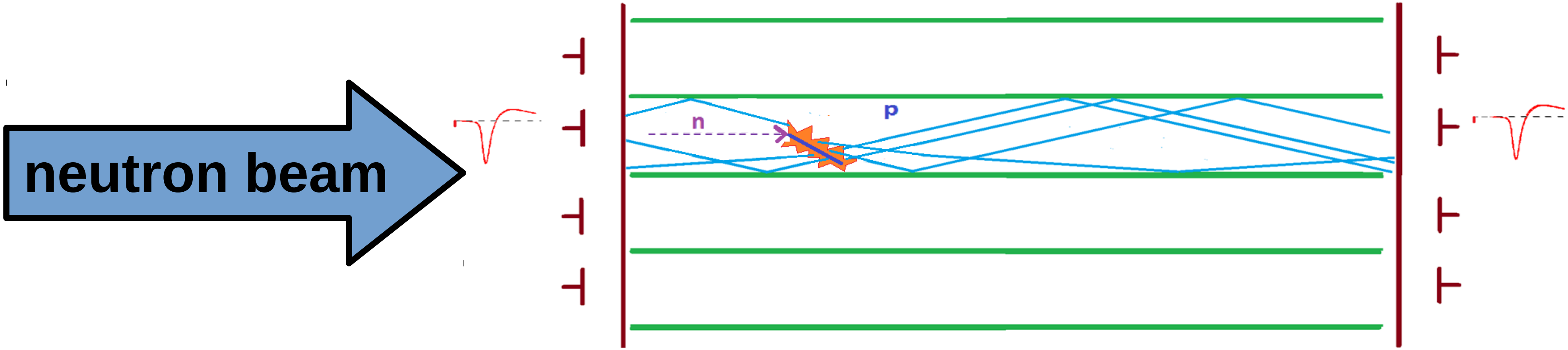

- **longitudinal coordinate** of the n interaction along the fiber
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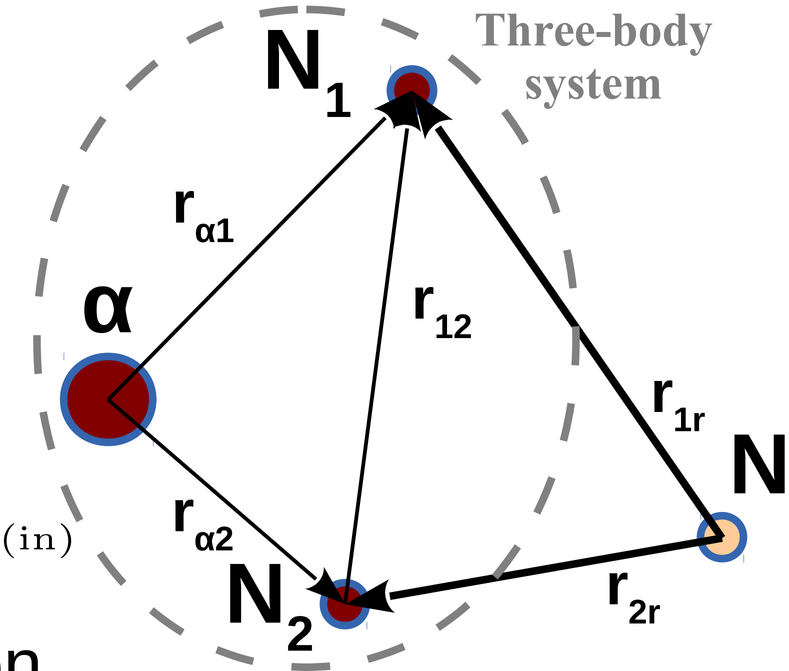
Appendix: Theoretical model



- 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

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

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

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

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