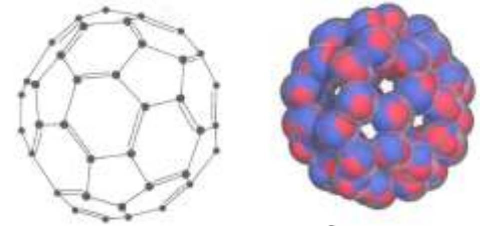
Экспериментальные исследования малонуклонных систем

Сергей Сидорчук

Школа FBS
Хабаровск, 29 сентября - 4 октября 2024

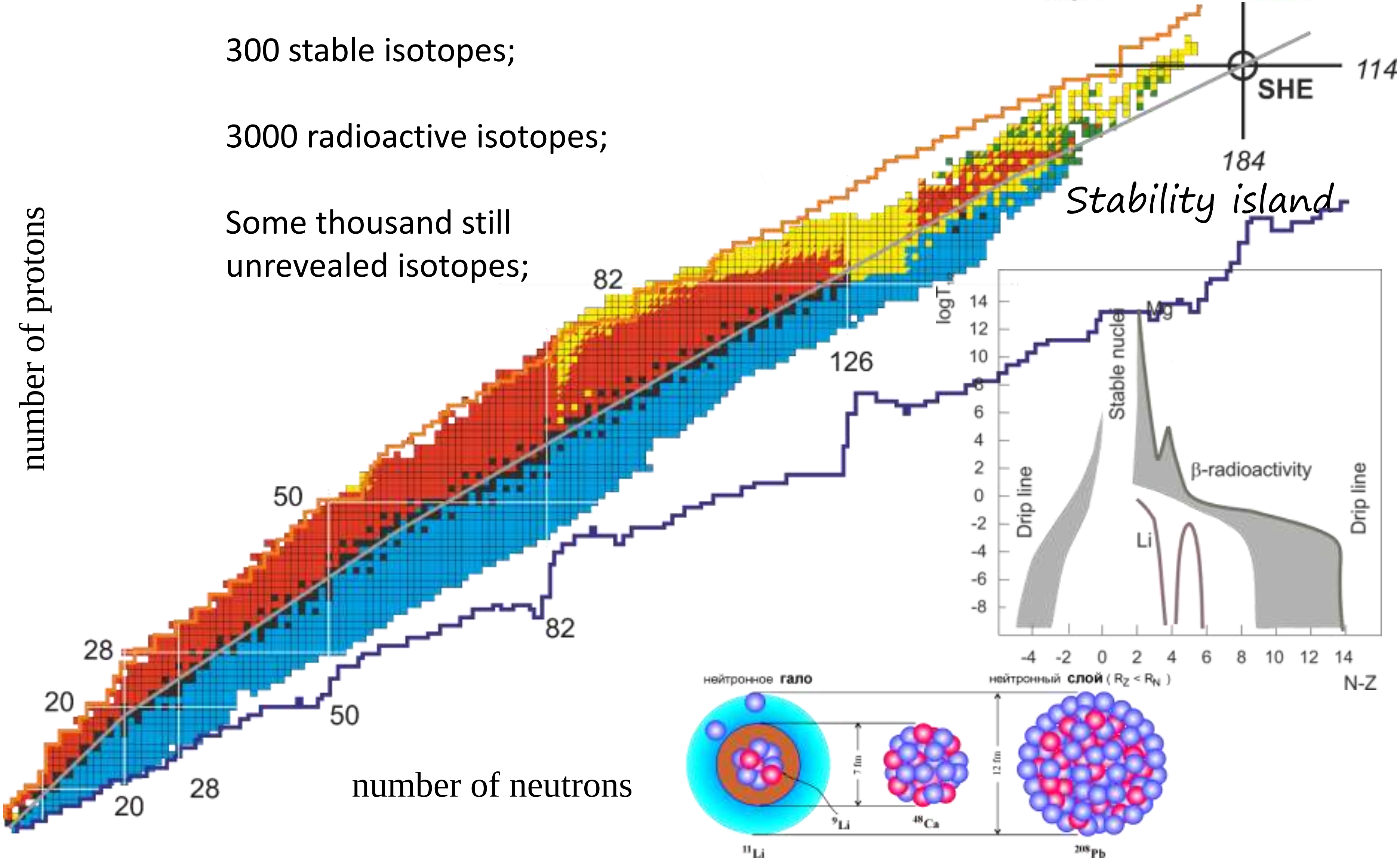
Isotope Chart



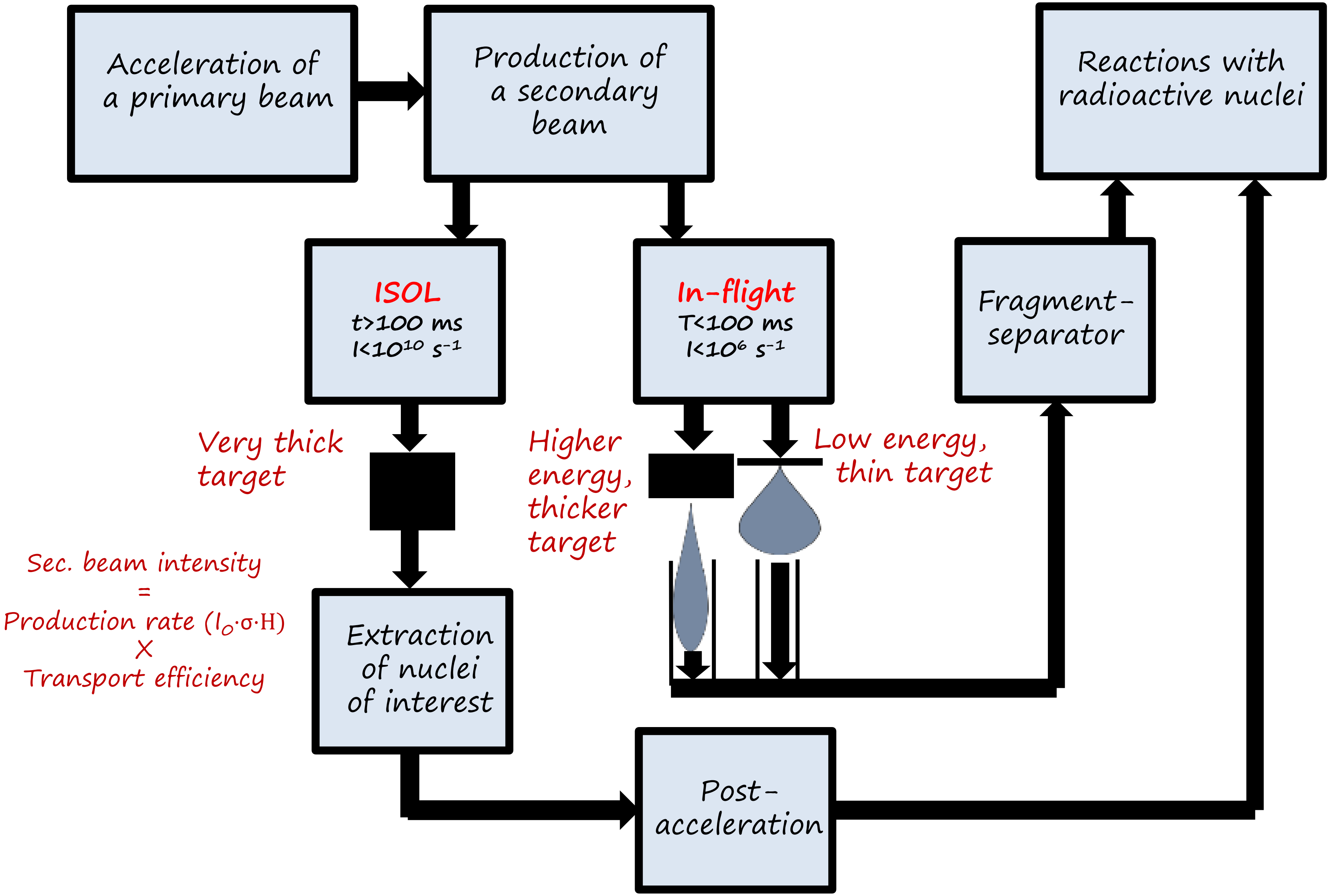
300 stable isotopes;

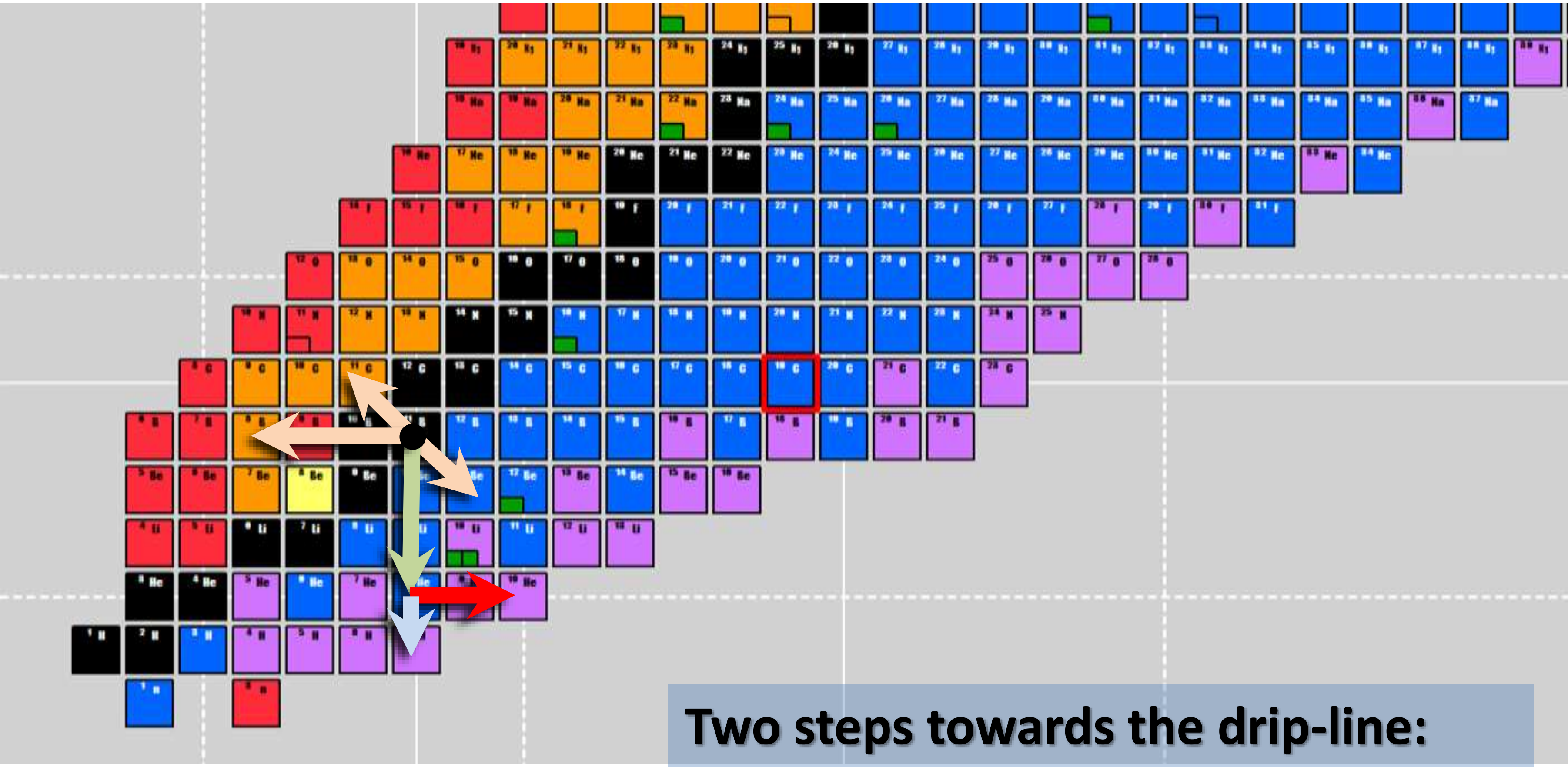
3000 radioactive isotopes;

Some thousand still unrevealed isotopes;



Production of secondary beams





Two steps towards the drip-line:

1. **Radioactive beam production**

   Charge exchange; One nucleon removal/pickup;

   $\mathbf{A_Z \rightarrow A_{Z\pm1}}$, $\mathbf{A_Z \rightarrow A\pm1_{Z\pm1}}$

   Fragmentation; Multinucleon removal;

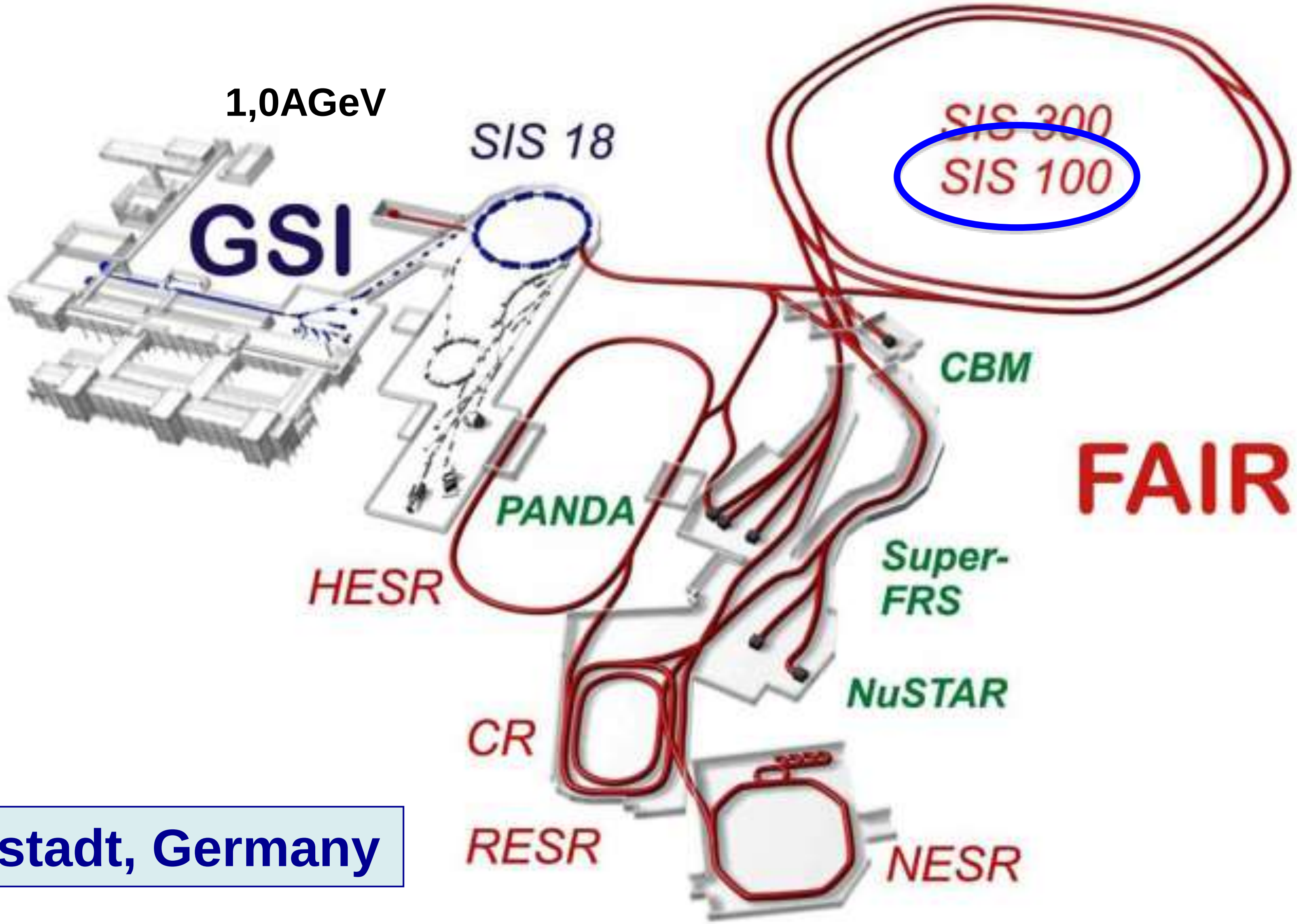
   $\mathbf{A_Z \rightarrow A\text{-}n_{Z\text{-}m}}$

2. **Reactions with secondary beams**

   Neutron transfer; $\mathbf{A_Z \rightarrow A+2_Z}$

   Proton knockout; $\mathbf{A_Z \rightarrow A\text{-}1_{Z\text{-}1}}$

Complex ***FAIR***

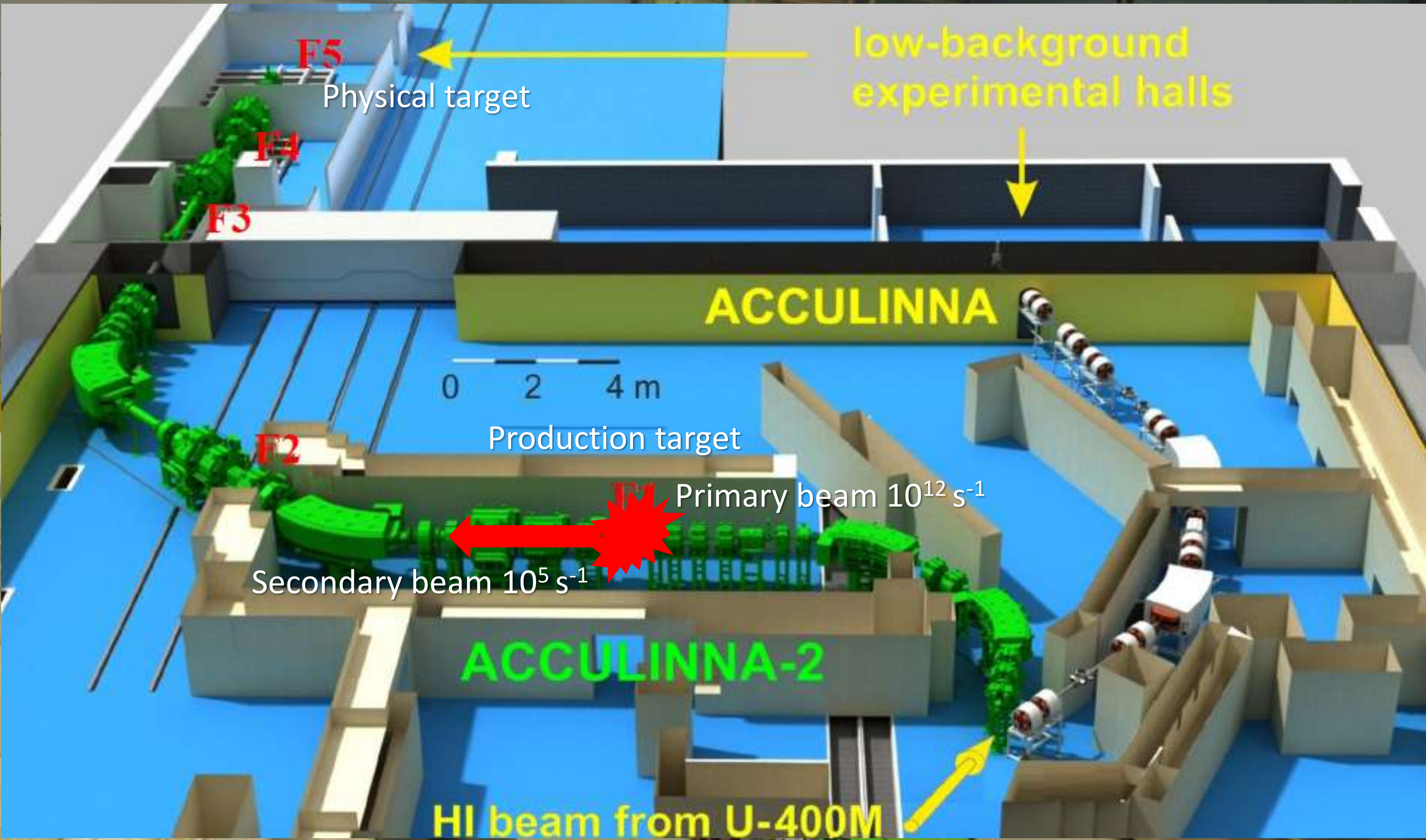


Darmstadt, Germany

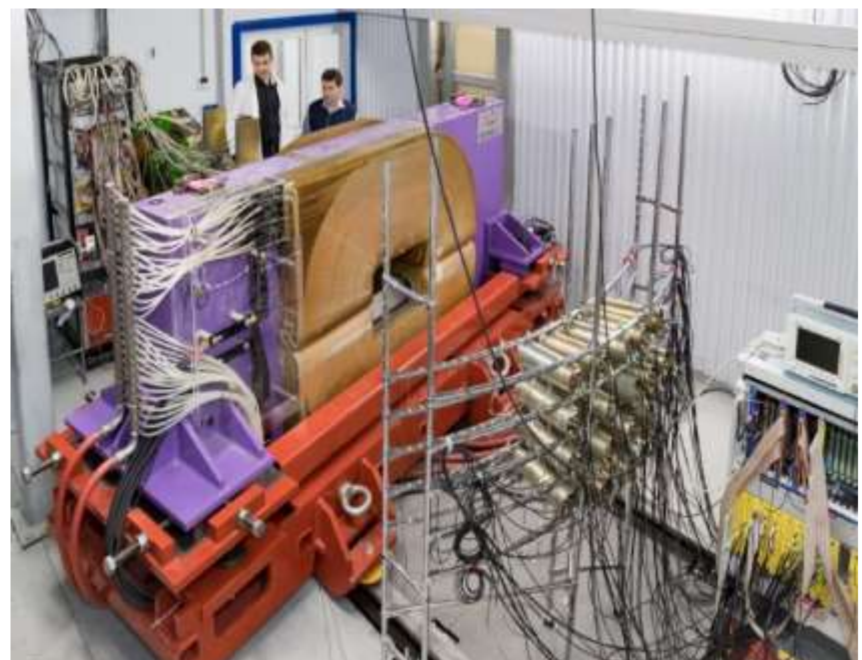

MT25
U400M
DC280
DC140
U400

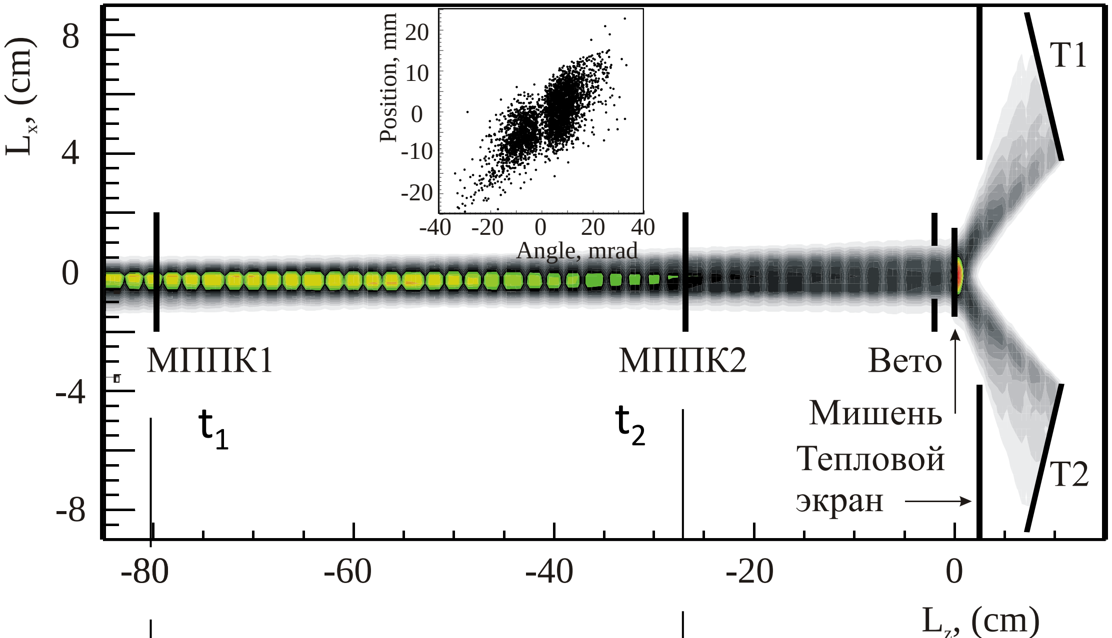
Primary Beams: U400M cyclotron

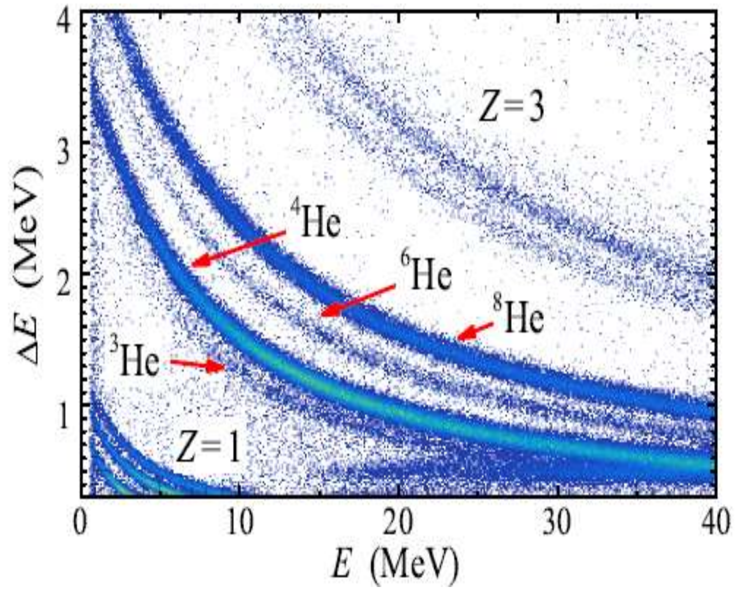
In-flight separation of secondary beams



RIB*	Intensity, pps (at 1 pμA)	Energy, MeV/A
^{6}He	$4x10^{7}$	22
^{6}He	$1x10^{7}$	13
^{8}He	$8x10^{4}$	23
^{11}Li	$7x10^{3}$	33
^{14}Be	$2x10^{3}$	35
^{15}B	$4x10^{5}$	32

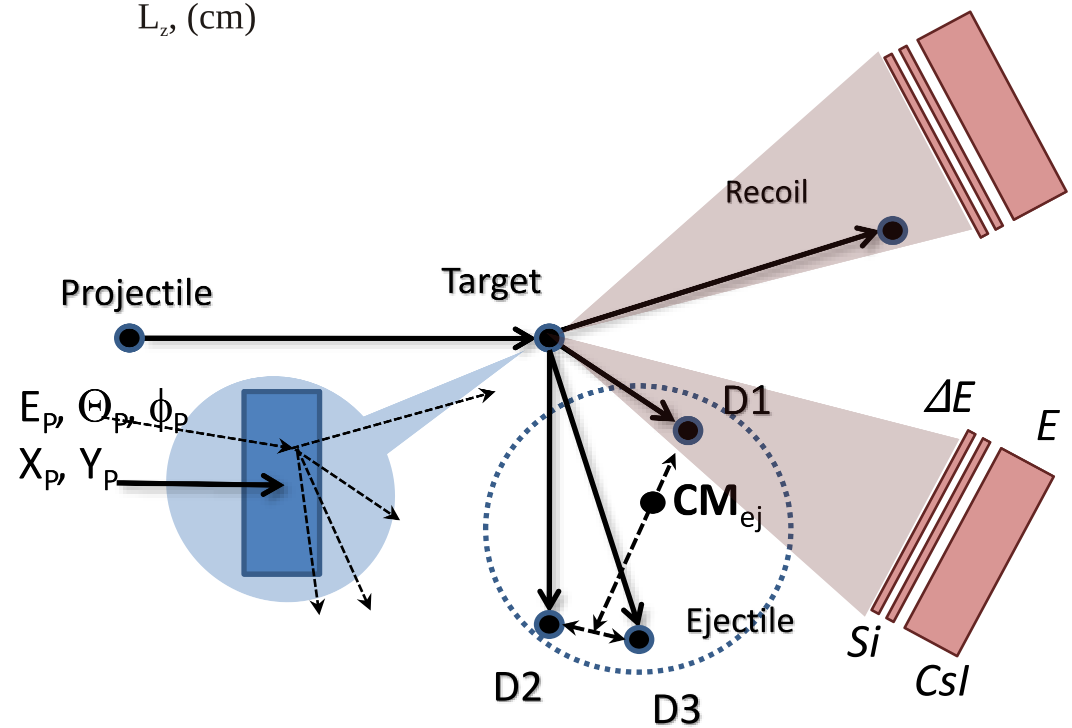






Time of flight

TOF vs ΔE → identification → energy



<u>Missing mass:</u>

$\mathbf{P}_{ej} = \mathbf{P}_{pr} - \mathbf{P}_{rec}$

$T_{ej} = \mathbf{P}_{ej}^2 / 2M_{ej}$

$E_{ej}^* = T_{pr} - T_{rec} - T_{ej} + Q$; Resolution ~ 1 MeV

<u>Invariant mass:</u>

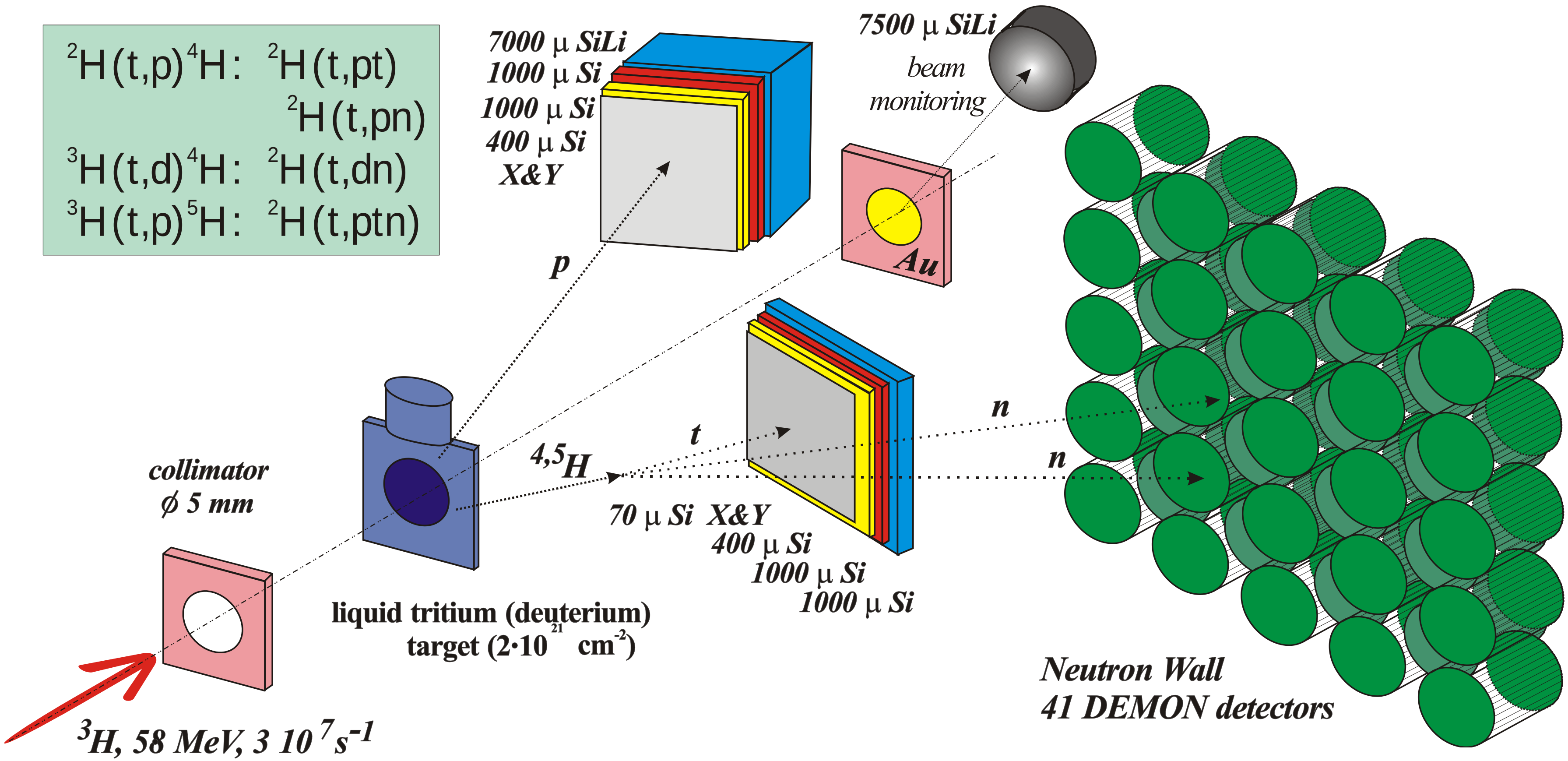
$(E_{ej}^* + \Sigma_i M_{Di})^2 = (\Sigma_i T_{Di} + \Sigma_i M_{Di})^2 - \mathbf{P}^2$

Resolution ~ 0.1 MeV

^{4}H

Beyond the drip-line.
Simple example: ^{2}H(t,p)^{4}H

^{2}H(t,p)^{4}H:	^{2}H(t,pt)
	^{2}H(t,pn)
^{3}H(t,d)^{4}H:	^{2}H(t,dn)
^{3}H(t,p)^{5}H:	^{2}H(t,ptn)

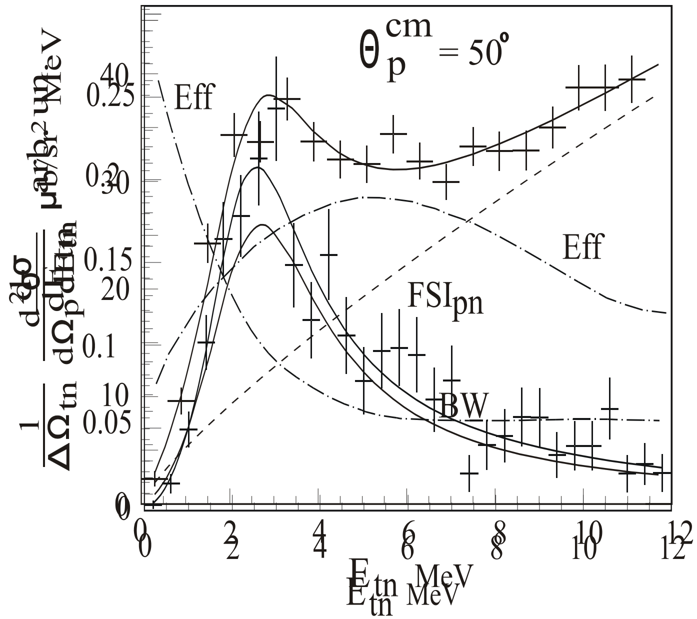


Система регистрации в экспериментах по изучению ^{4,5}H.

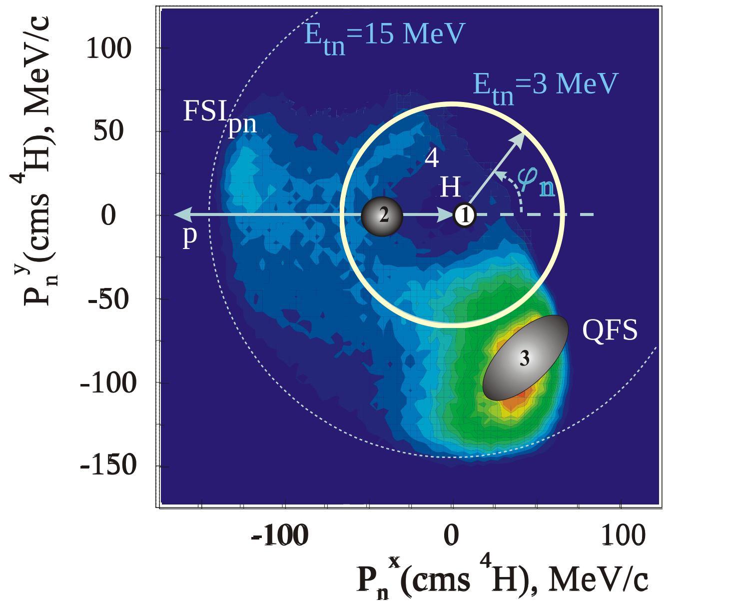
^4H

Beyond the drip-line.
Simple example: $^2H(t,p)^4H$

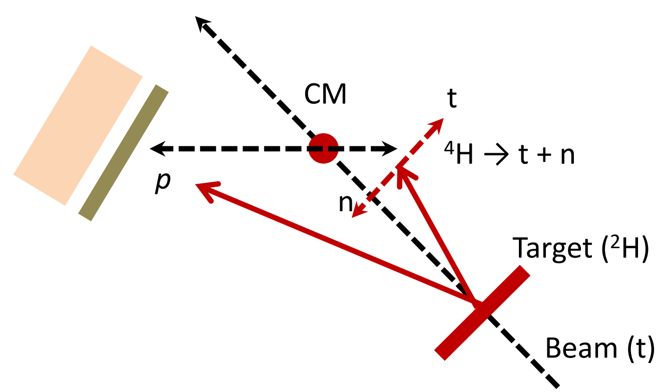
^{4}H Missing Mass Spectrum



Neutron Momentum Distribution in the ^{4}H cms



- Not everything we observe is what we are looking for;
- A process at one edge of phase space also contributes at the opposite edge;
- Observed spectra are distorted, because detection system acceptance is limited.



^5H

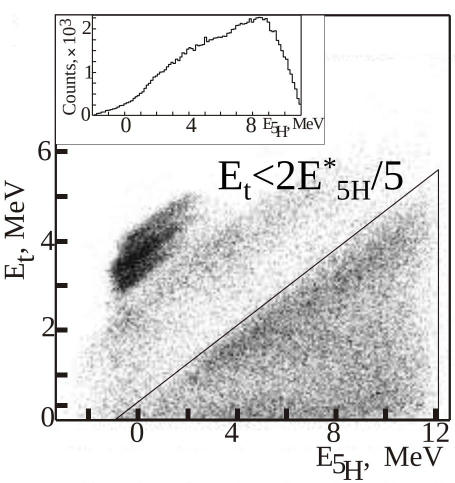
Beyond the drip-line.
More complex case – one neutron more: $^3H(t,p)^5H$

- 1 kCi T_2;
- Liquid (T~25 K): h=0.4 mm;
  Gas: h=4 mm;
- Three stages of radiation protection;
- Radiation safety control;
- Automatic control and parameter setting;
- The cell can also be filled with H_2, D_2, ^3He, ^4He.

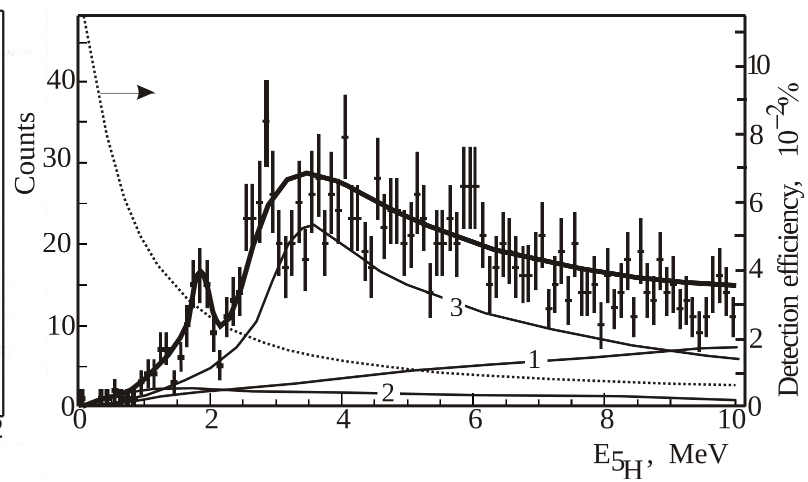
Why tritium?

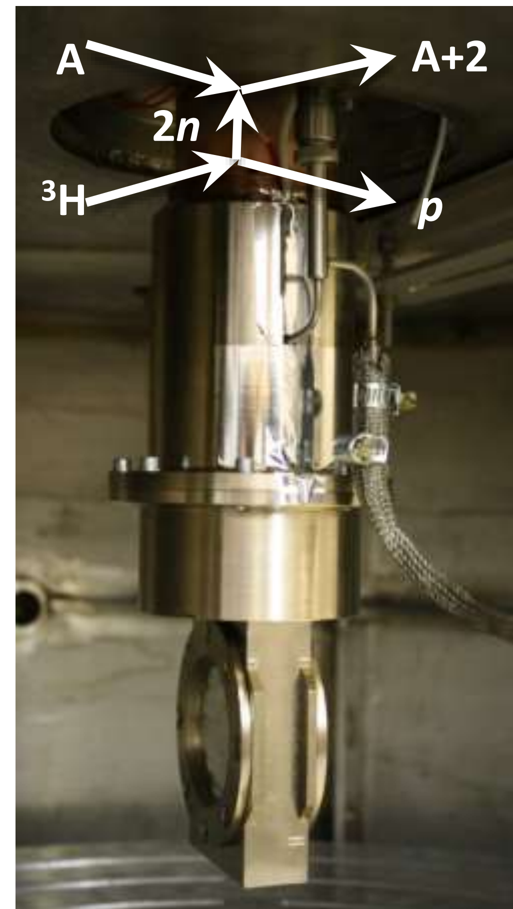
- Required excess of neutrons – 2 neutrons can be transferred ;
- Energy of separation of two neutrons from triton (~ 8.4 MeV) is the minimum possible;
- Recoil is a proton which can be detected in a low-background kinematic range where it is emitted in the angular range close to 180° in respect to the beam direction.

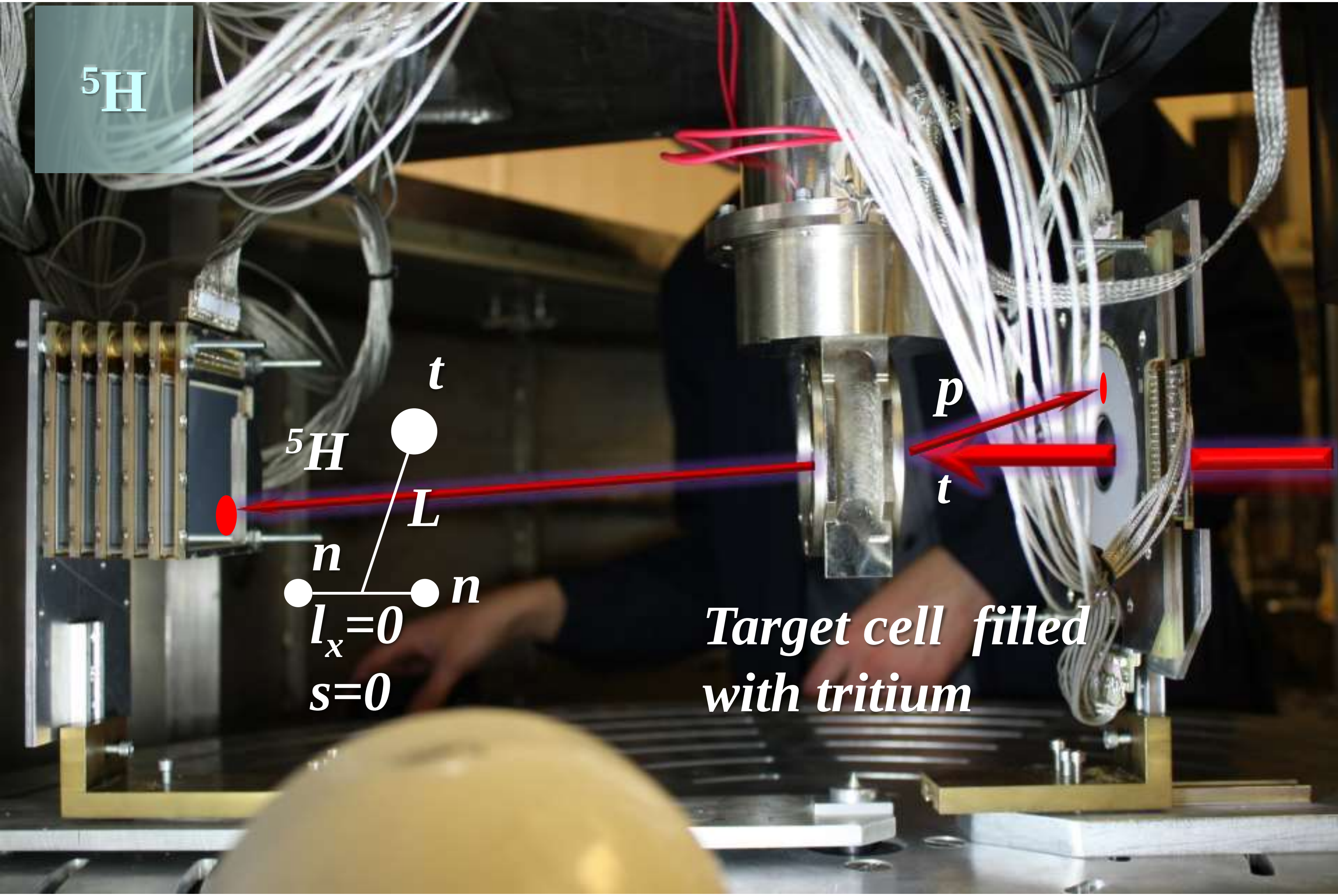
p-t coincidences



p-t-n coincidences

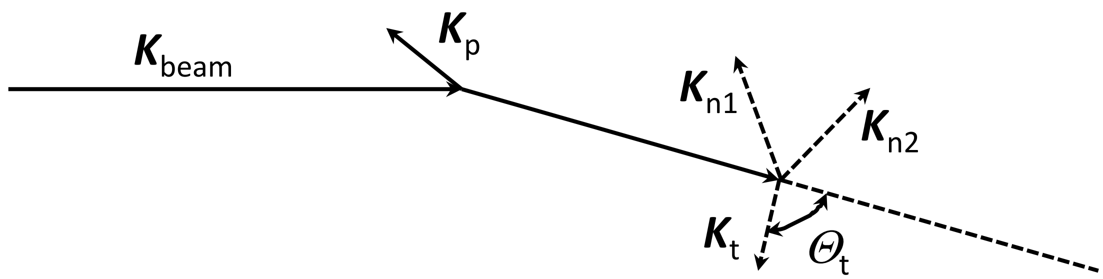


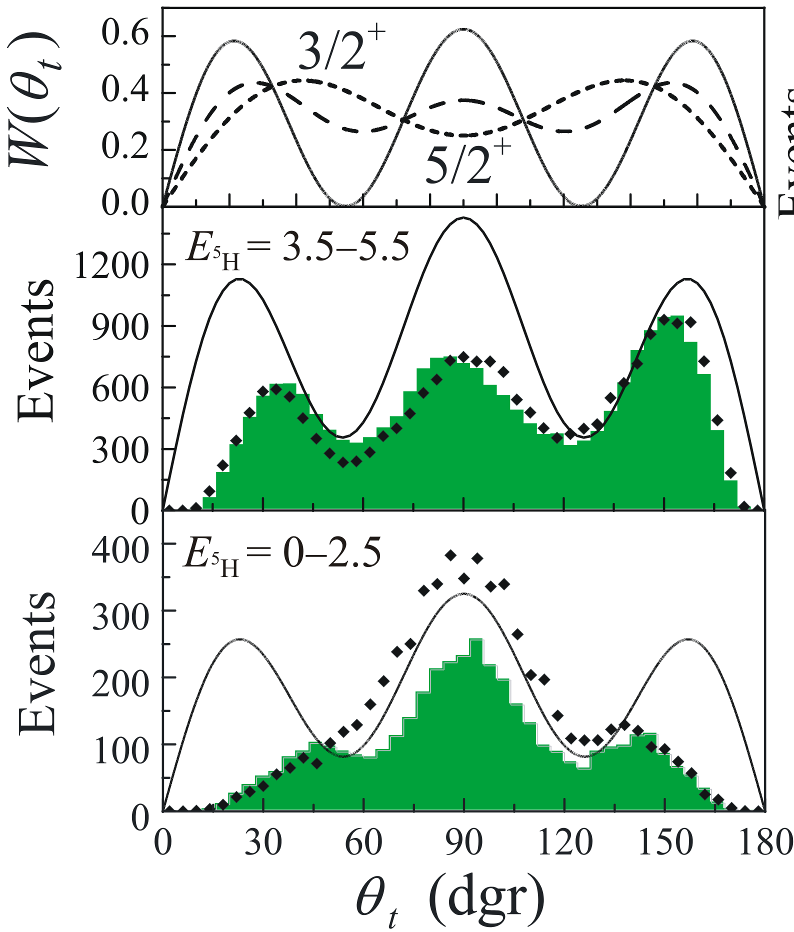


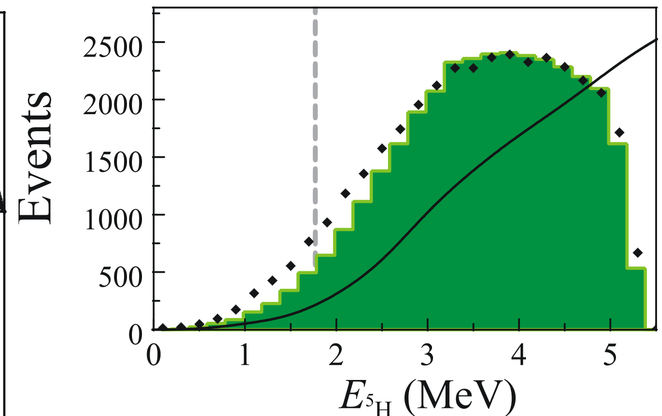


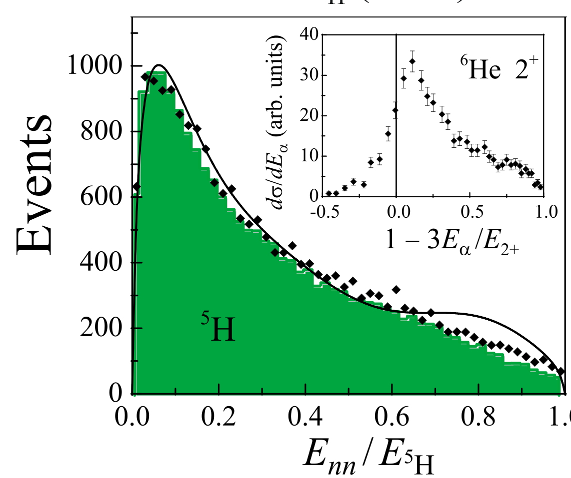
^{5}H
t
^5H
L
n
n
l_x=0
s=0
p
t
Target cell filled
with tritium

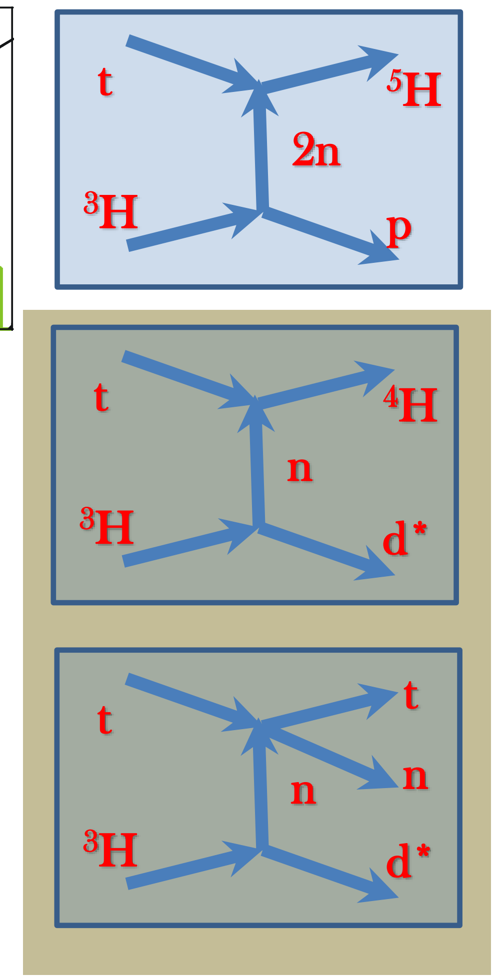
^{5}H


K beam
K p
K n1
K n2
K t
Θ t

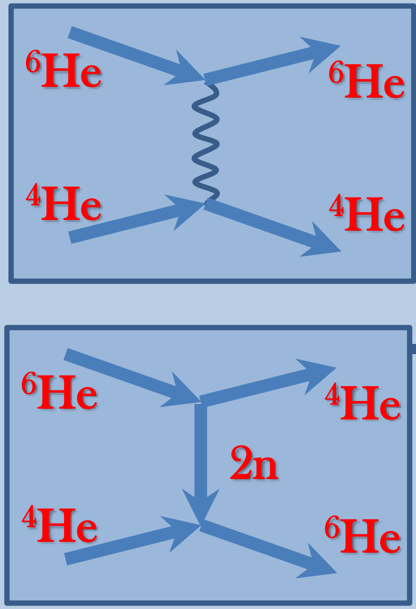

W(θt)
0.6
0.4
0.2
0.0
3/2+
5/2+
E5H = 3.5–5.5
Events
1200
900
600
300
0
E5H = 0–2.5
Events
400
300
200
100
0
0
30
60
90
120
150
180
θt (dgr)

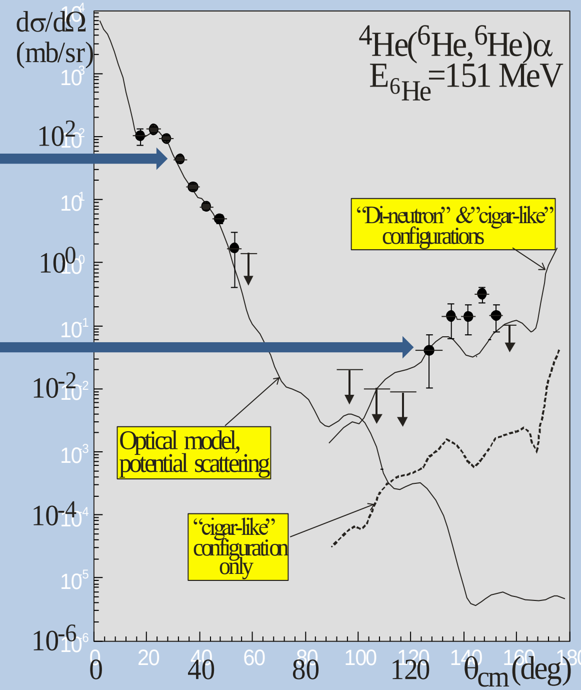

Events
2500
2000
1500
1000
500
0
0
1
2
3
4
5
E5H (MeV)

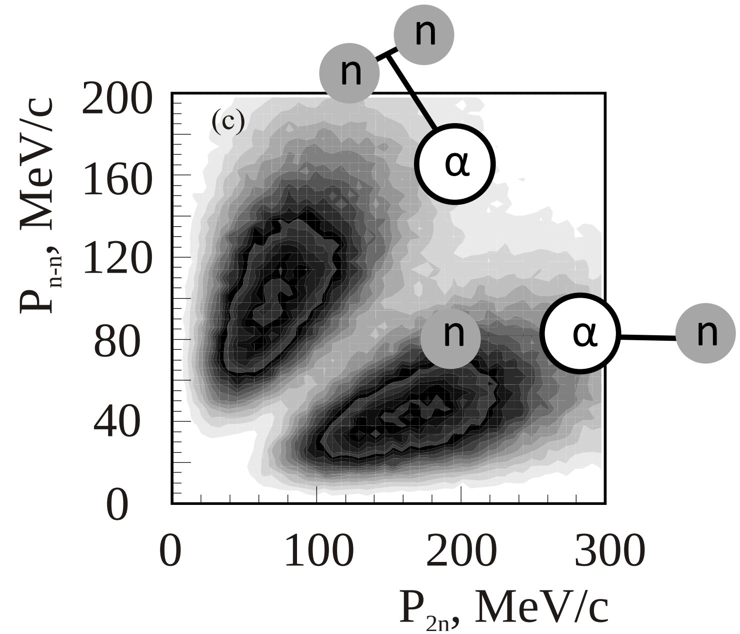

Events
1000
800
600
400
200
0
0.0
0.2
0.4
0.6
0.8
1.0
Enn / E5H
5H
dσ/dEα (arb. units)
40
30
20
10
0
-0.5
0.0
0.5
1.0
6He 2+
1 – 3Eα/E2+

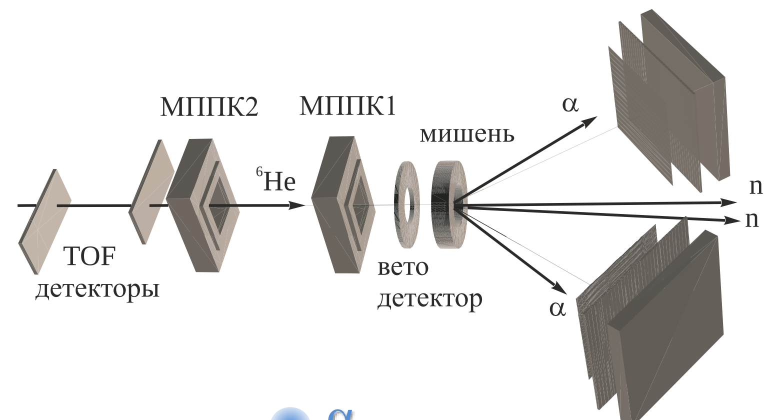

t
5H
2n
3H
p
t
4H
n
3H
d*
t
t
n
n
3H
d*

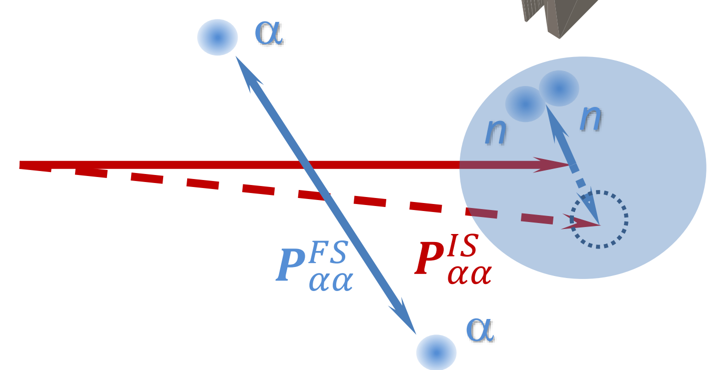
^{6}He+^{4}He. Elastic scattering



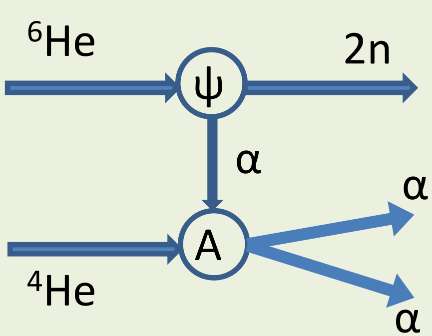


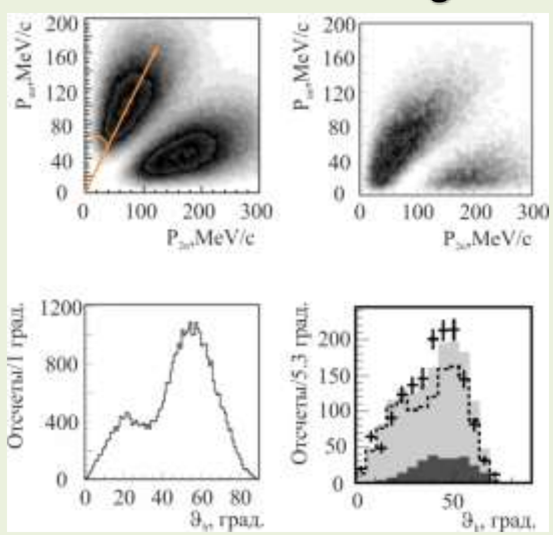




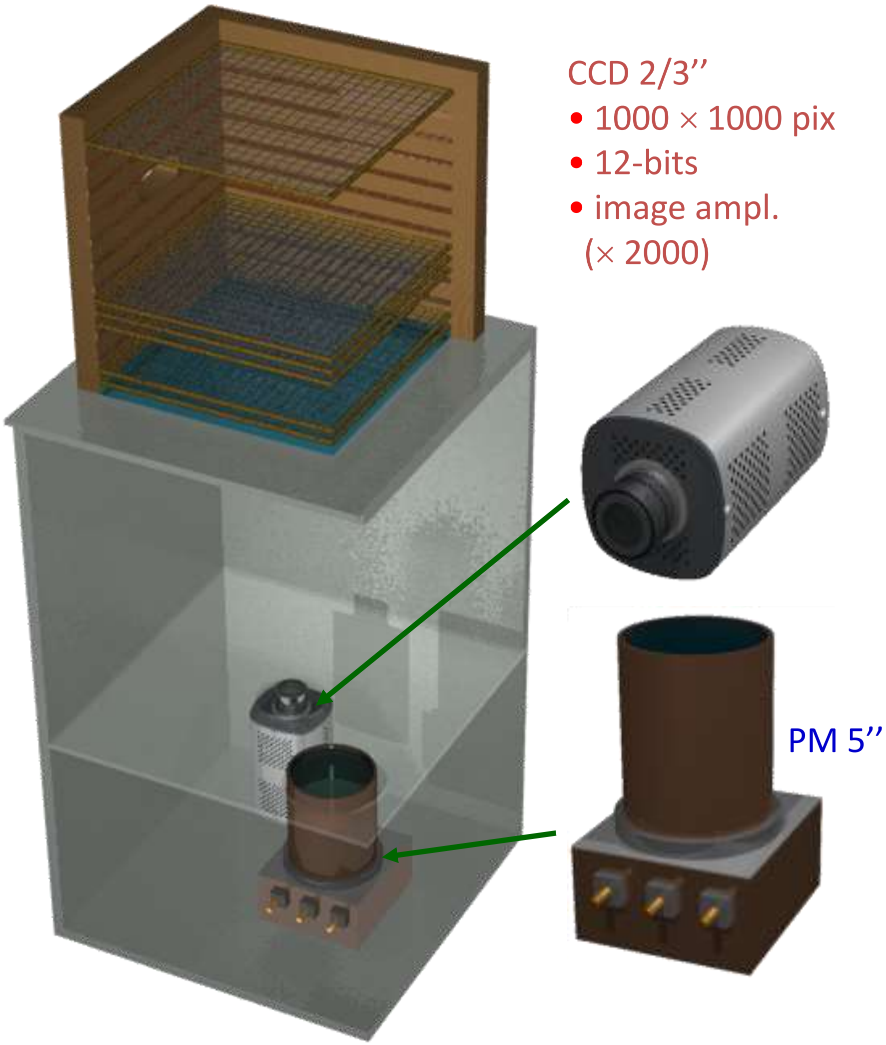


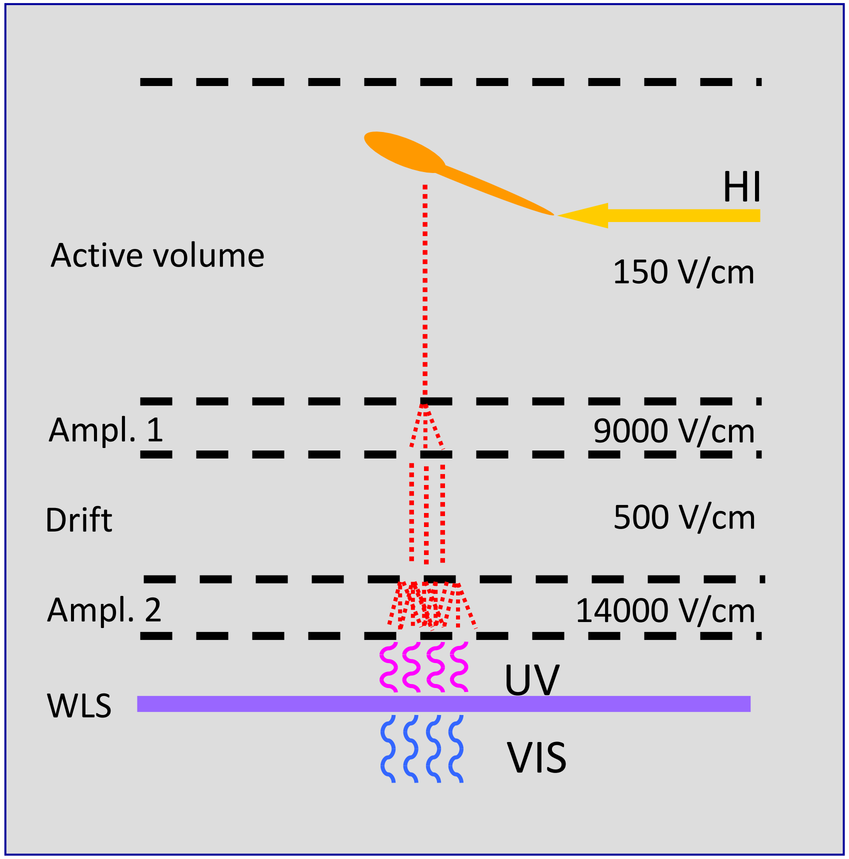
^{6}He+^{4}He. Quasi-free elastic scattering





Optical Time Projection Chamber





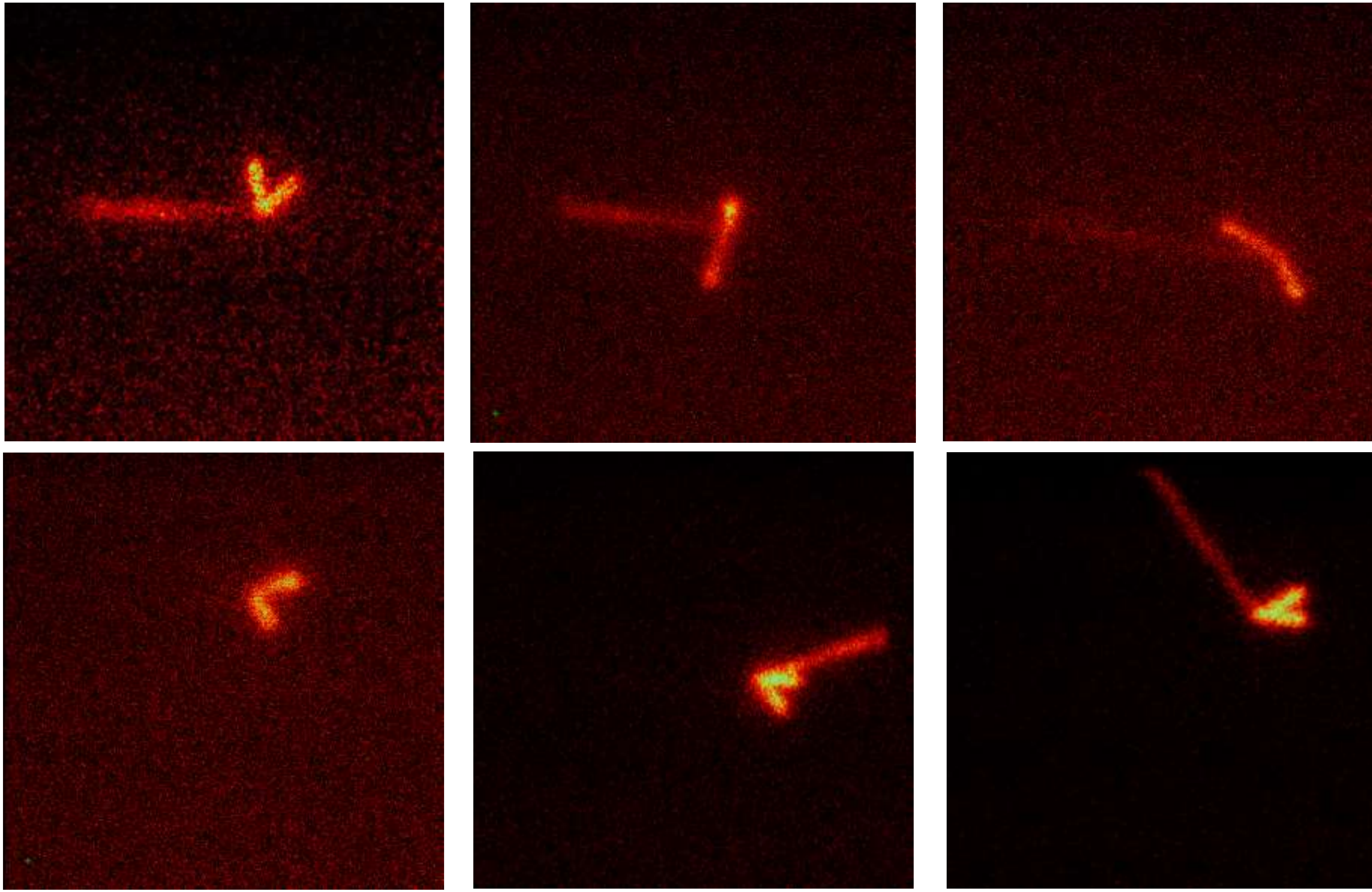
Gas (1 atm) : 49% He + 49% Ar + 1% N_2 + 1% CH_4

Active volume: 20×20×15 cm^3; drift velocity: ≈ 1 cm/μs

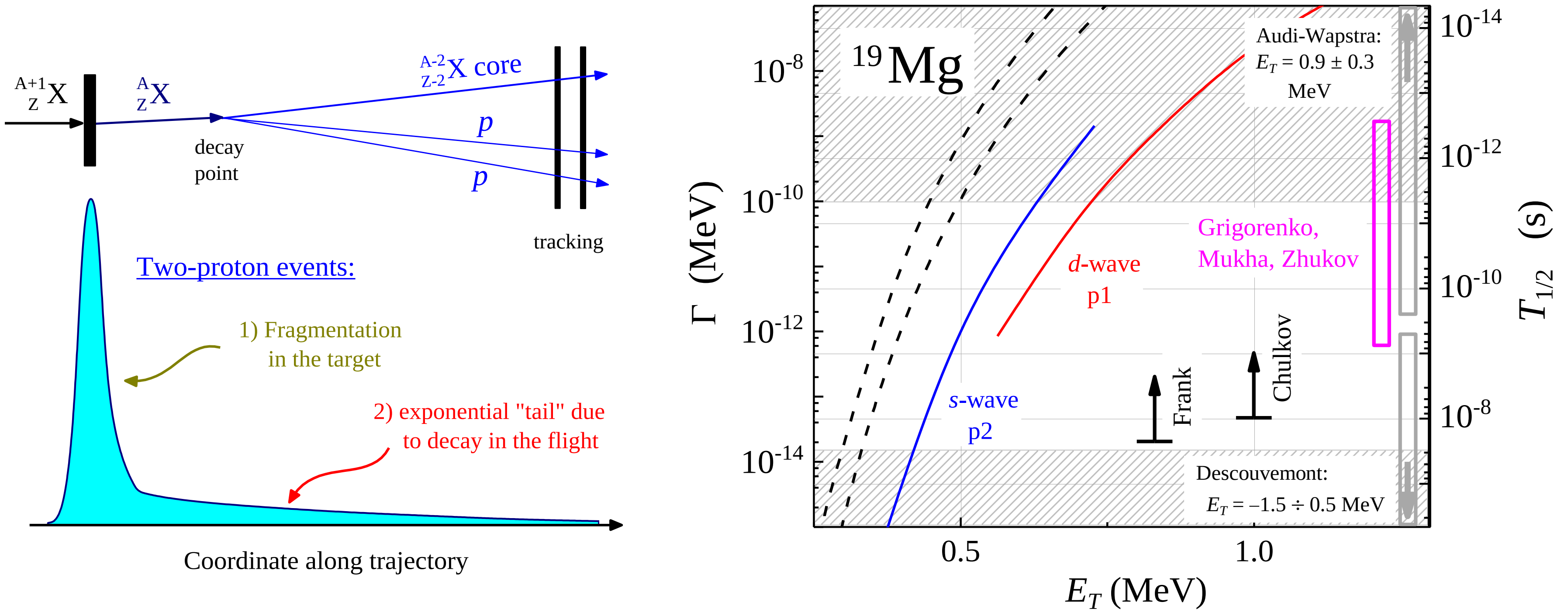
M. Ćwiok et al., IEEE TNS, 52 (2005) 2895

K. Miernik et al., NIM A581 (2007) 194

Gallery of 2p events



^{19}Mg: decay in flight experiment

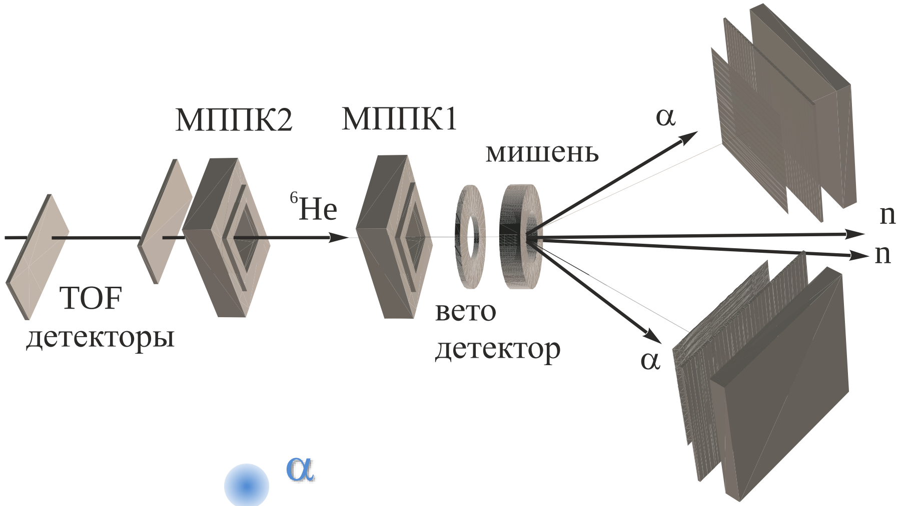


- Idea of decay-in-flight experiment (GSI S271):
  I. Mukha and G. Schrieder, NPA 690 (2001) 280c.
- Structure and decays of ^{19}Mg:
  L. Grigorenko, I. Mukha, M. Zhukov, NPA 713 (2003) 372.
- Dependence of the predicted lifetime on the structure.
- “Belt” of posible lifetimes defined by calculations with pure configuration

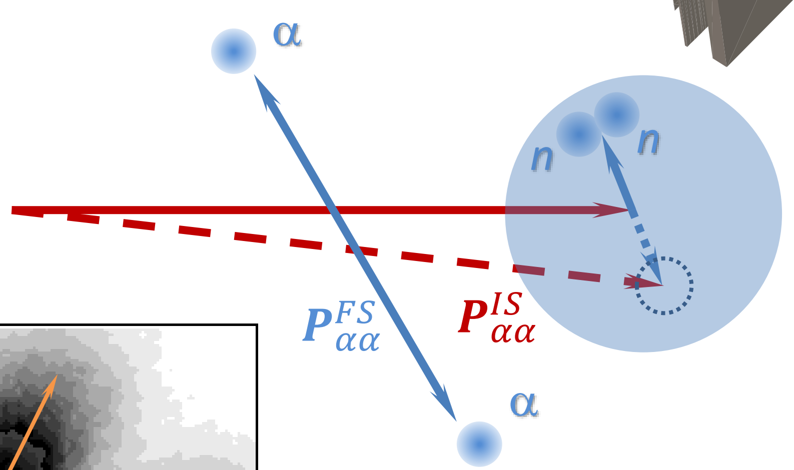
Спасибо!

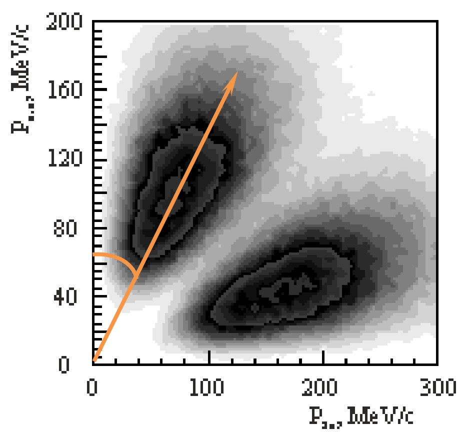
Рассеяние на связанной α-частице в реакции ^{4}He(^{6}He,2α)2n

Идентификация КСР по 7 независимым кинематическим и структурным параметрам:

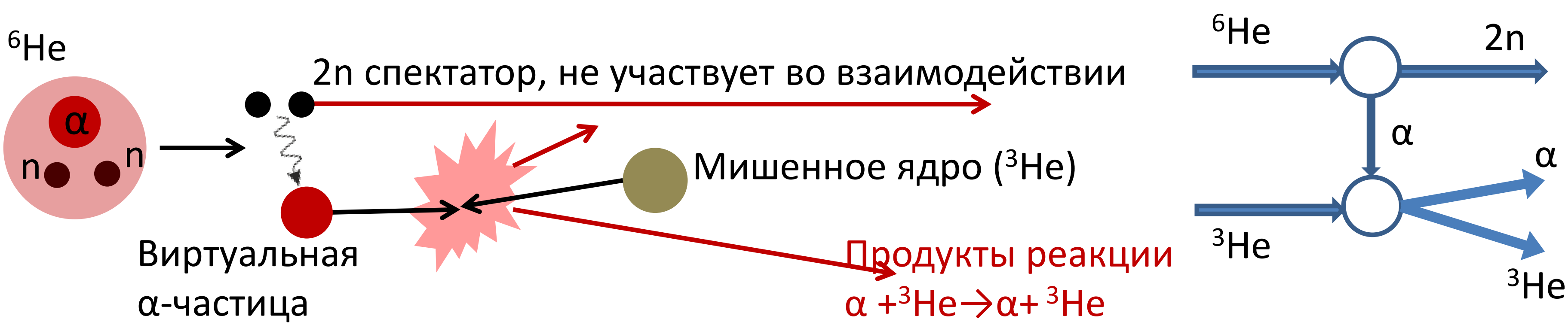


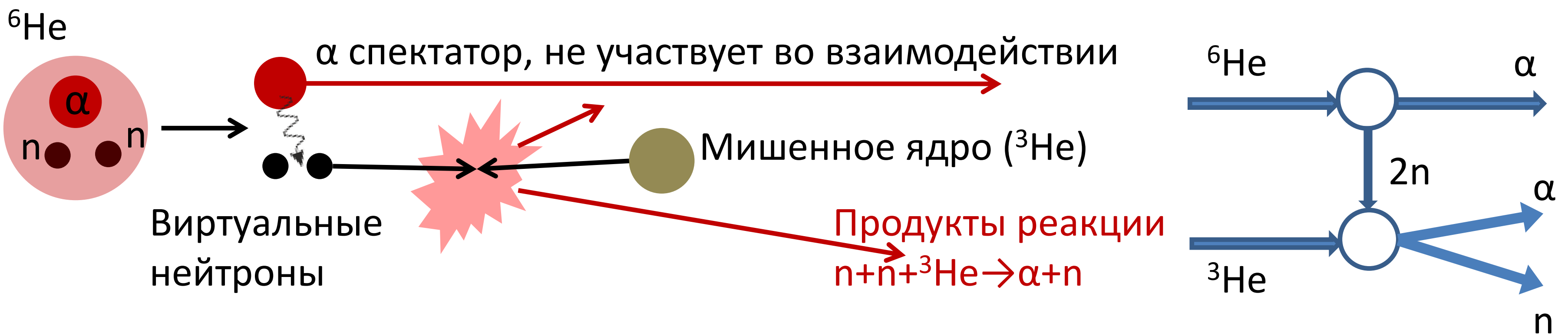
- Продольный и поперечный импульсы спектатора;
- Относительные энергии двух α-частиц и двух нейтронов;
- Угол α-α рассеяния $\cos\vartheta_{\alpha\alpha} = \frac{(\boldsymbol{P}_{\alpha\alpha}^{IS}\boldsymbol{P}_{\alpha\alpha}^{FS})}{|\boldsymbol{P}_{\alpha\alpha}^{IS}||\boldsymbol{P}_{\alpha\alpha}^{FS}|}$;
- Угол Треймана-Янга $\cos\vartheta_{TY} = \frac{([\boldsymbol{P}_{\alpha1}\boldsymbol{P}_{\alpha2}][\boldsymbol{P}_{6He}\boldsymbol{P}_{2n}])}{|[\boldsymbol{P}_{\alpha1}\boldsymbol{P}_{\alpha2}]||[\boldsymbol{P}_{6He}\boldsymbol{P}_{2n}]|}$;
- Гипер-угол $\tan\vartheta_h = \sqrt{E_{nn}/\tilde{E}_{2n-\alpha}}$.





«Квазисвободные» реакции на виртуальных частицах можно использовать для изучения трехтельных взаимодействий





Industrial age of Nuclear Physics.

Industrial scale of the production of rare isotope s;

Search for new phenomena untypical for stable nuclei

«Сверхтяжелые» атомы водорода и нейтронная материя

Beams: ^{3}H, ^{6}He, ^{8}He

Targets: ^{1}H, ^{2}H, $\mathbf{^{3}H}$

$$^{3}H + {}^{3}H \rightarrow p + {}^{5}H \quad ({}^{5}H \rightarrow {}^{2}n + t)$$

$$^{6}He + {}^{3}H \rightarrow {}^{8}He(nlj) + p$$

$$\rightarrow {}^{7}He(nlj) + d$$

$$\rightarrow {}^{4}He + {}^{5}H \quad ({}^{5}H \rightarrow {}^{2}n + t)$$

$$\rightarrow {}^{2}n + {}^{7}Li$$

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

$$\rightarrow {}^{9}He(nlj) + d$$

$$\rightarrow {}^{4}He + {}^{7}H \quad ({}^{7}H \rightarrow {}^{4}n + t)$$

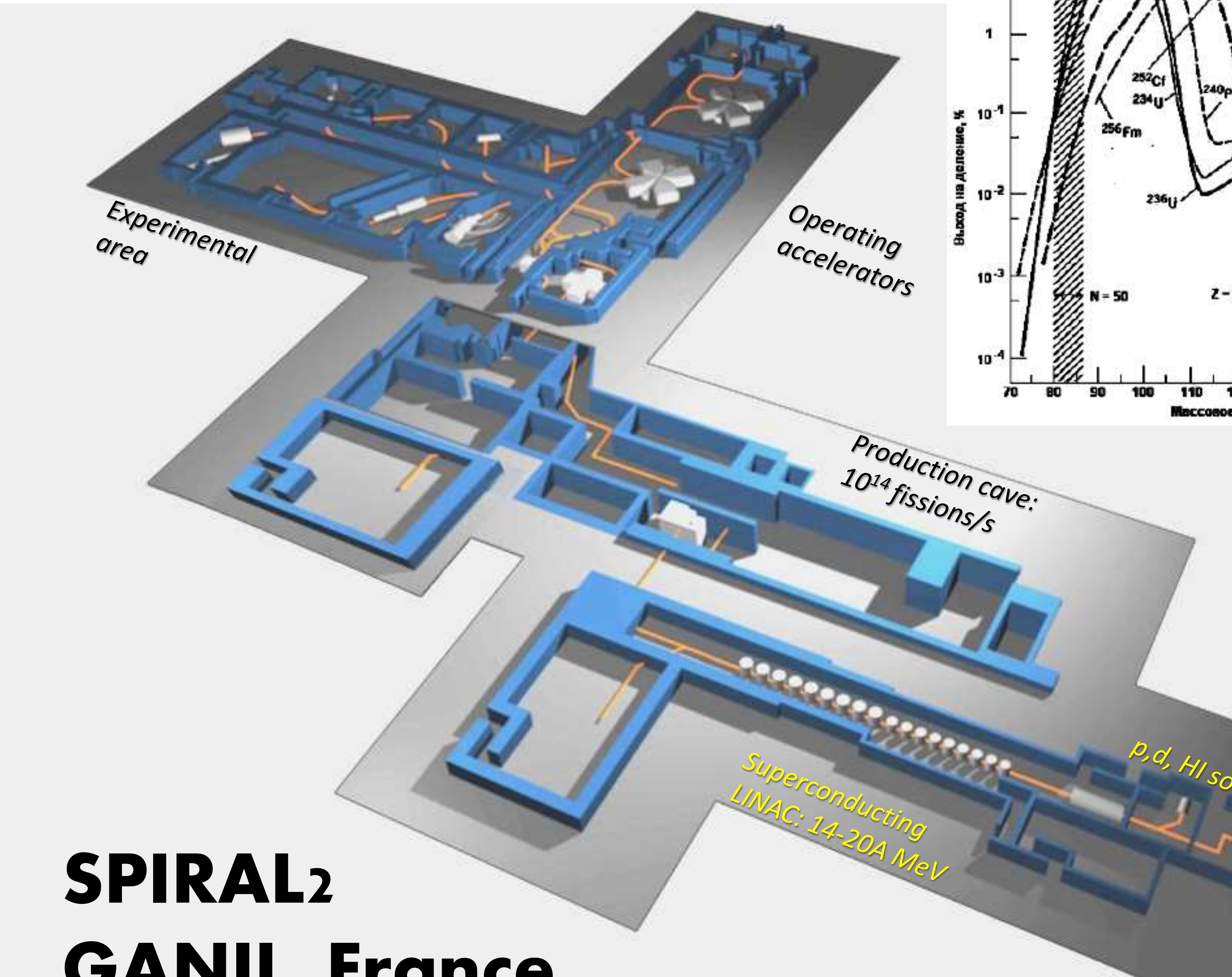
$$\rightarrow {}^{4}n + {}^{7}Li$$

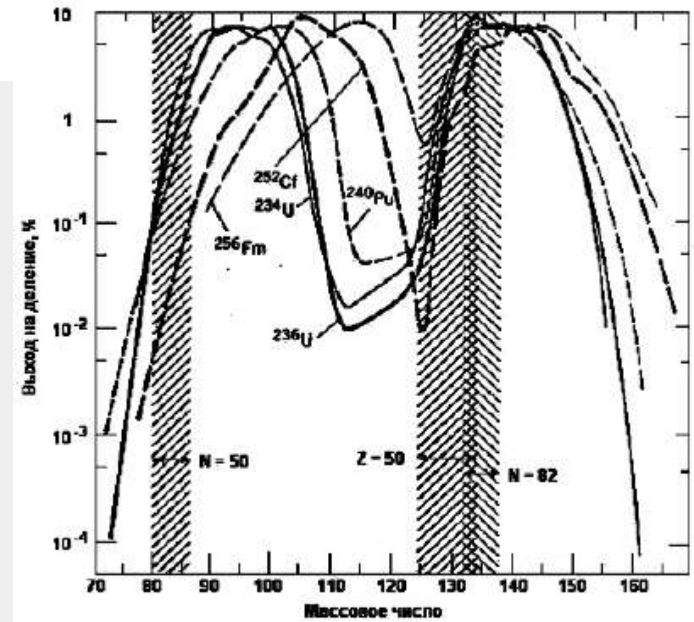
Multi-neutron states

$$^{6}He + {}^{3}H \rightarrow {}^{2}n + {}^{7}Li$$

$$^{8}He + {}^{3}H \rightarrow {}^{4}n + {}^{7}Li$$

$$^{8}He + {}^{3}H \rightarrow {}^{6}n + {}^{5}Li$$



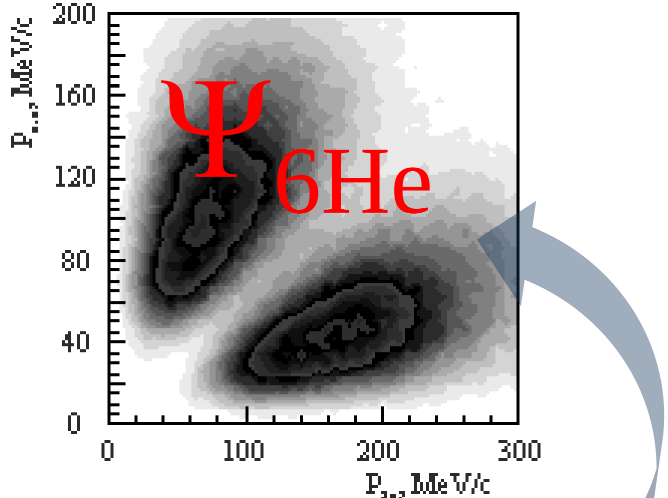


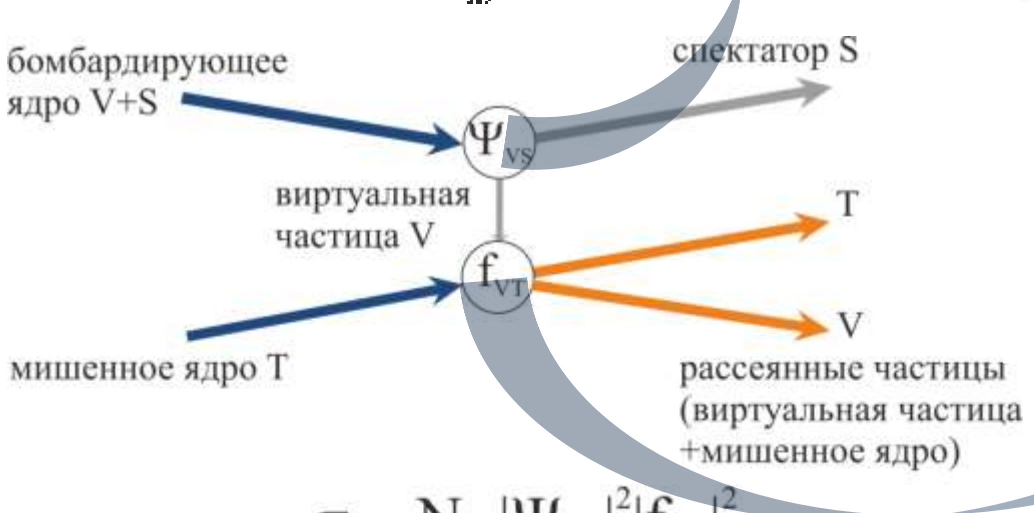
SPIRAL2
GANIL, France

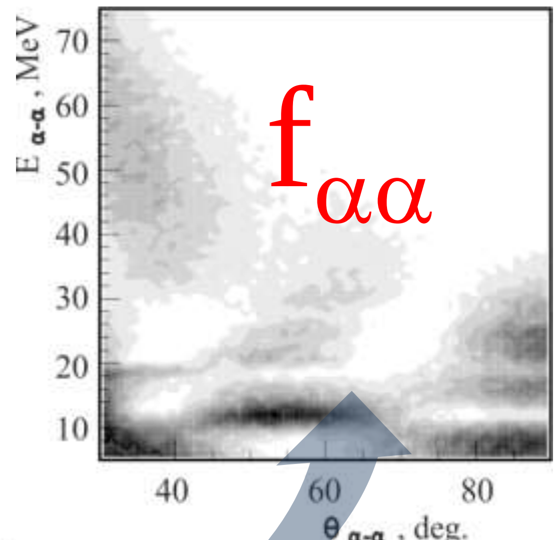
Квазисвободные реакции. Приближение плоских волн

$^{4}He(^{6}He,2\alpha)2n$

1. Механизм реакции устанавливается экспериментально;
2. Трехтельная волновая начального состояния (^{6}He) известна;
3. Амплитуда α-α рассеяния известна;
4. Волновая функция конечного состояния (*n*-*n*) известна.

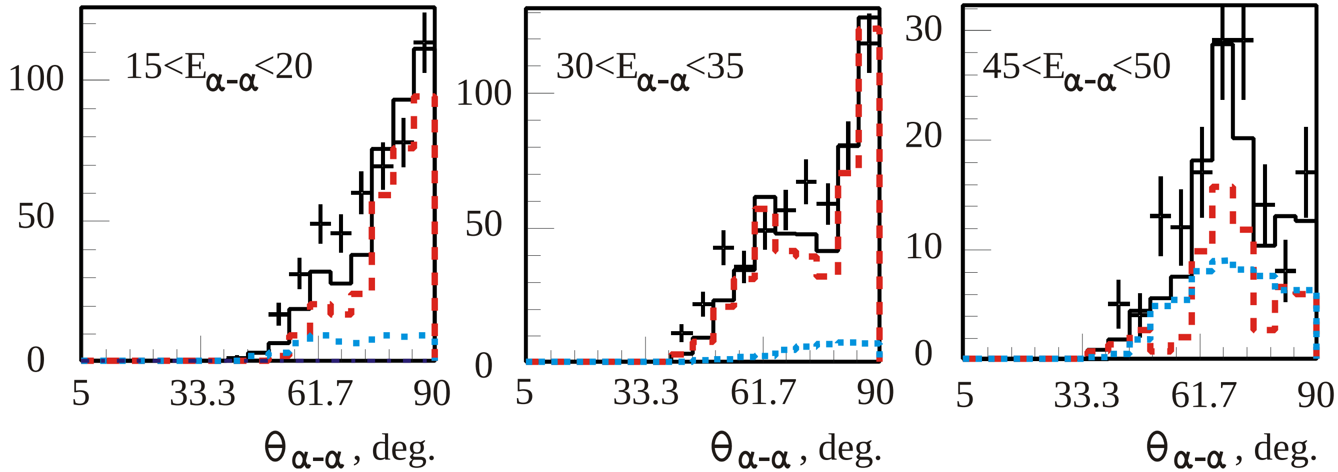






$$\sigma \sim N_{eff}|\Psi_{VS}|^2|f_{VT}|^2$$

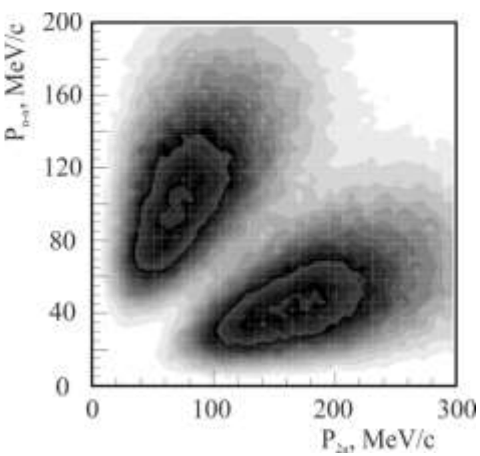
Форма углового распределения совпадает с модельным представлением



Волновая функция должна быть модифицирована

$$\Psi_{6He} \rightarrow S(p_{nn}, p_{2n})$$

$$S(\vec{p}_{n-n}, \vec{p}_{2n}) = \int d\vec{r}_{n-n} d\vec{r}_{2n} \psi^{*}_{n-n}(\vec{r}_{n-n}, \vec{p}_{n-n}) e^{-i\vec{p}_{2n}\vec{r}_{2n}} \psi_{6He}(\vec{r}_{n-n}, \vec{r}_{2n})$$



$$\sigma \sim N_{eff} |S|^2 |f_{\alpha\alpha}|^2$$

$$\sigma \approx 18 \text{ мб}$$

$$N_{eff} \approx 0.03$$