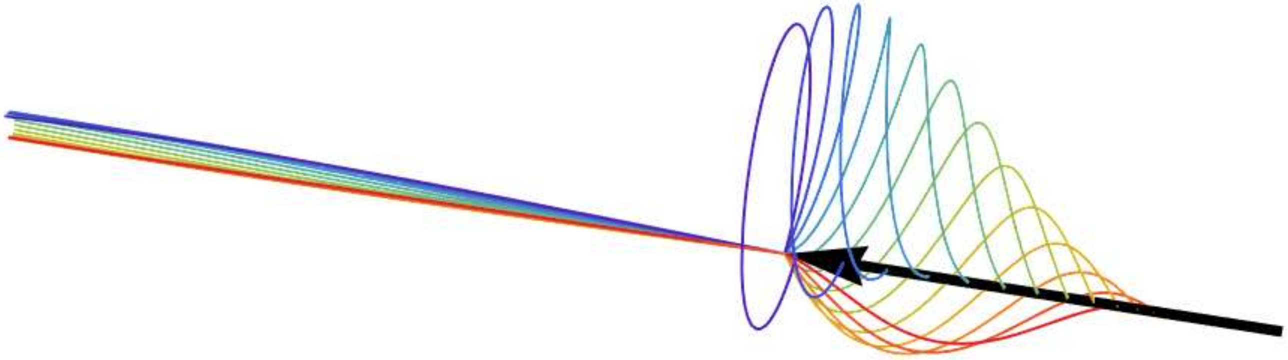


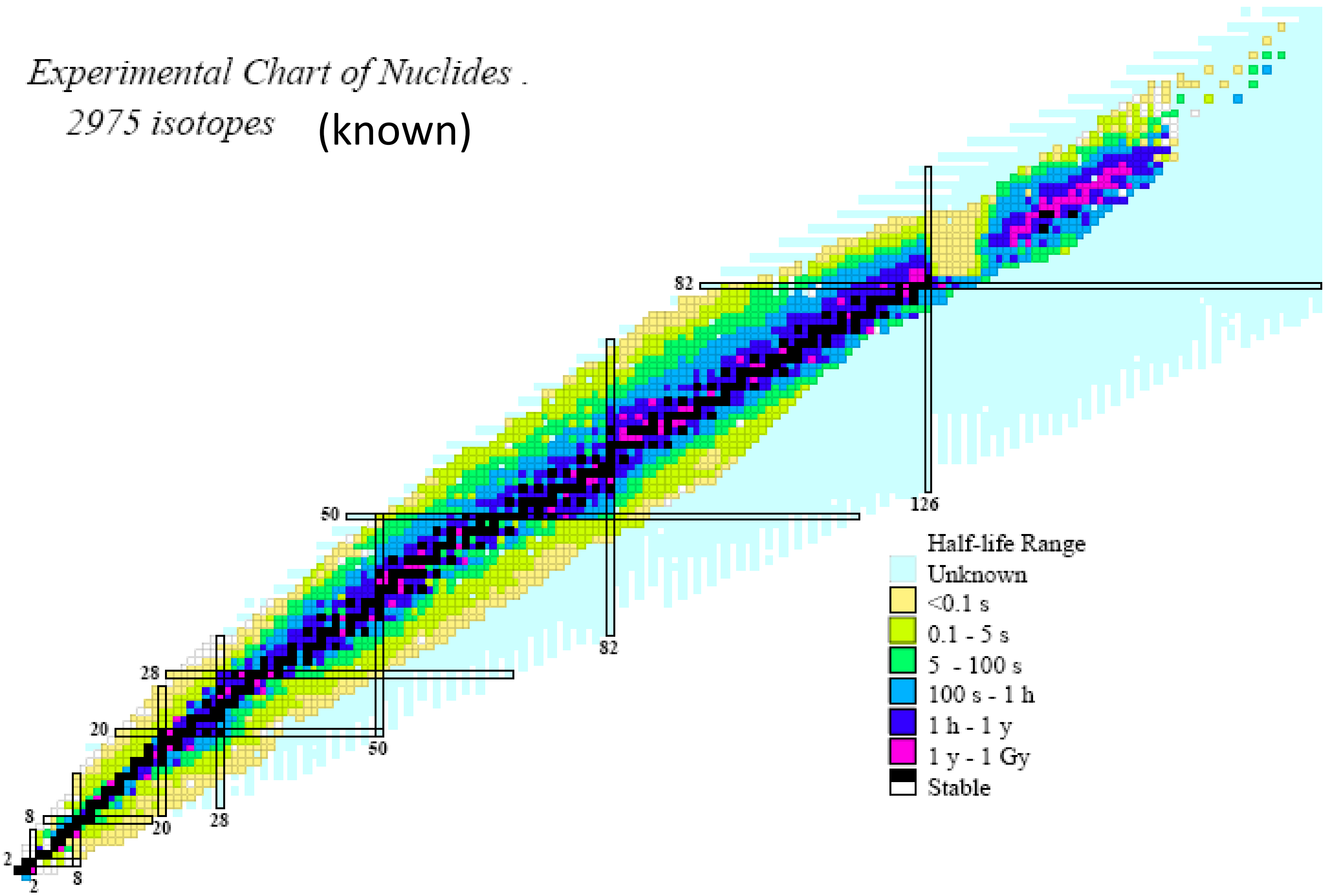
The Argonne HELIOS spectrometer & its scientific discoveries

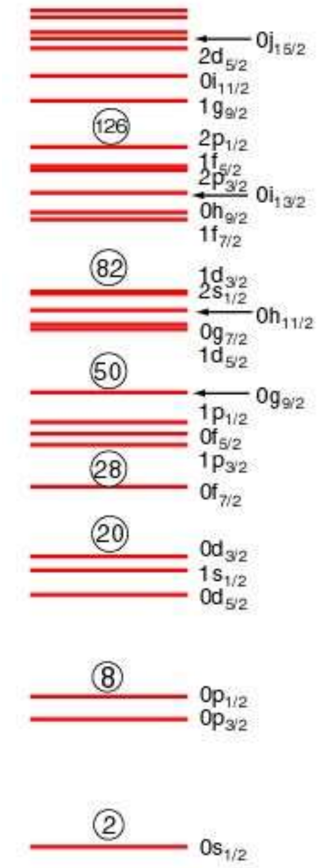
Tsz Leung (Ryan) TANG

Post-Doctoral Researcher

Experimental Chart of Nuclides .

2975 isotopes (known)





Shell Model of Nuclei

Because of spin-orbital coupling,
Magic number appears.

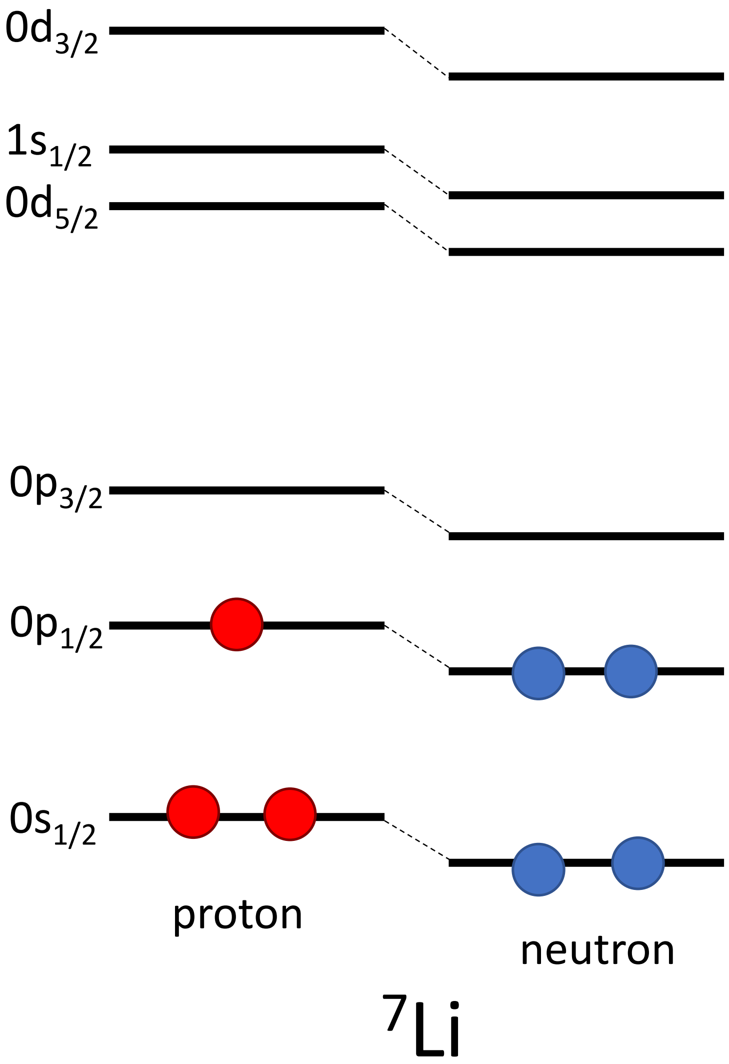
Nuclear structure

- Nucleons are moving in a *MEAN* field
- This mean field is created by the nucleons themselves

Hartree-Fock approach
(Independent Particle Model)

  - single particle energy/state
  - occupancy

1-body interaction



Nuclear structure

- Nucleons are moving in a *MEAN* field
- This mean field is created by the nucleons themselves

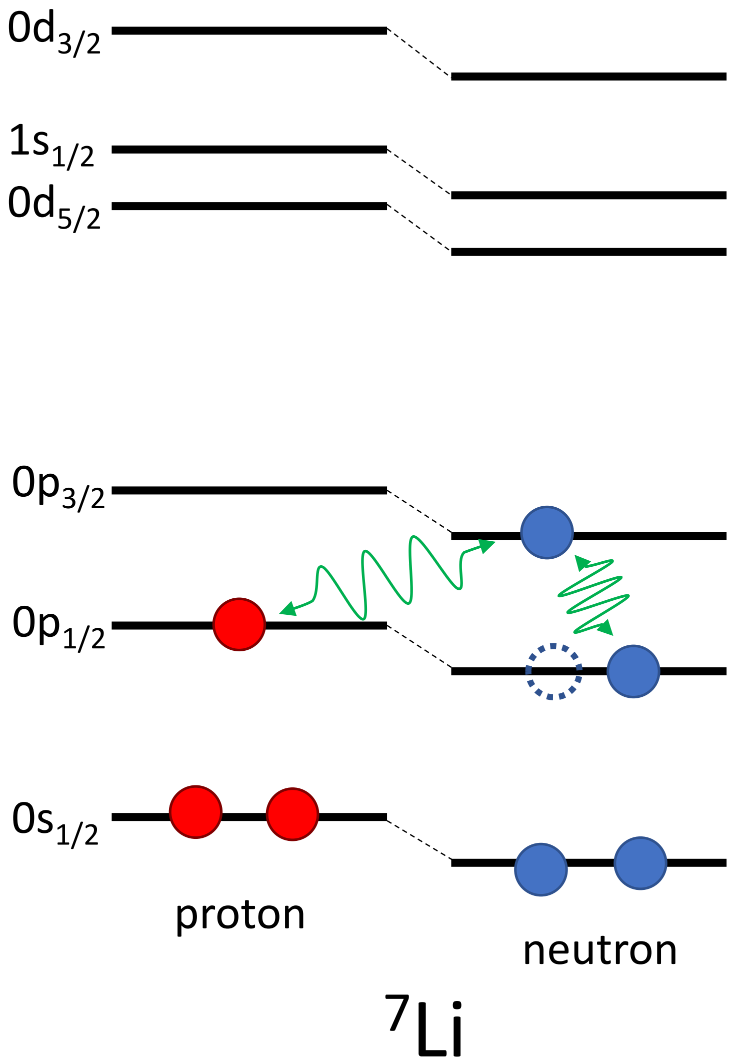
Hartree-Fock approach
(Independent Particle Model)

  - single particle energy/state
  - occupancy

1-body interaction

Many-body interaction
Mutual Interactions

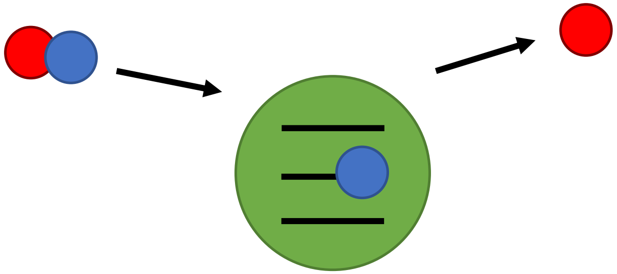
Perturbation of the single particle state



Transfer reaction – to study the single particle state

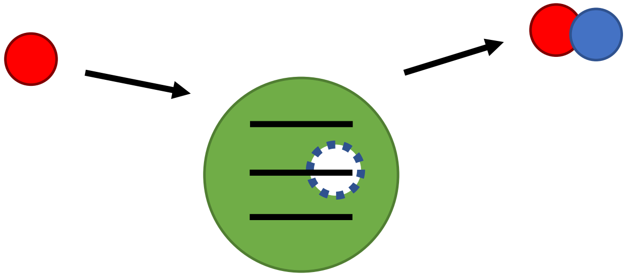
(d,p) neutron transfer

study the emptiness of orbital



(p,d) neutron pickup

study the fullness of orbital



Spin-isospin factor

assume full/empty orbital

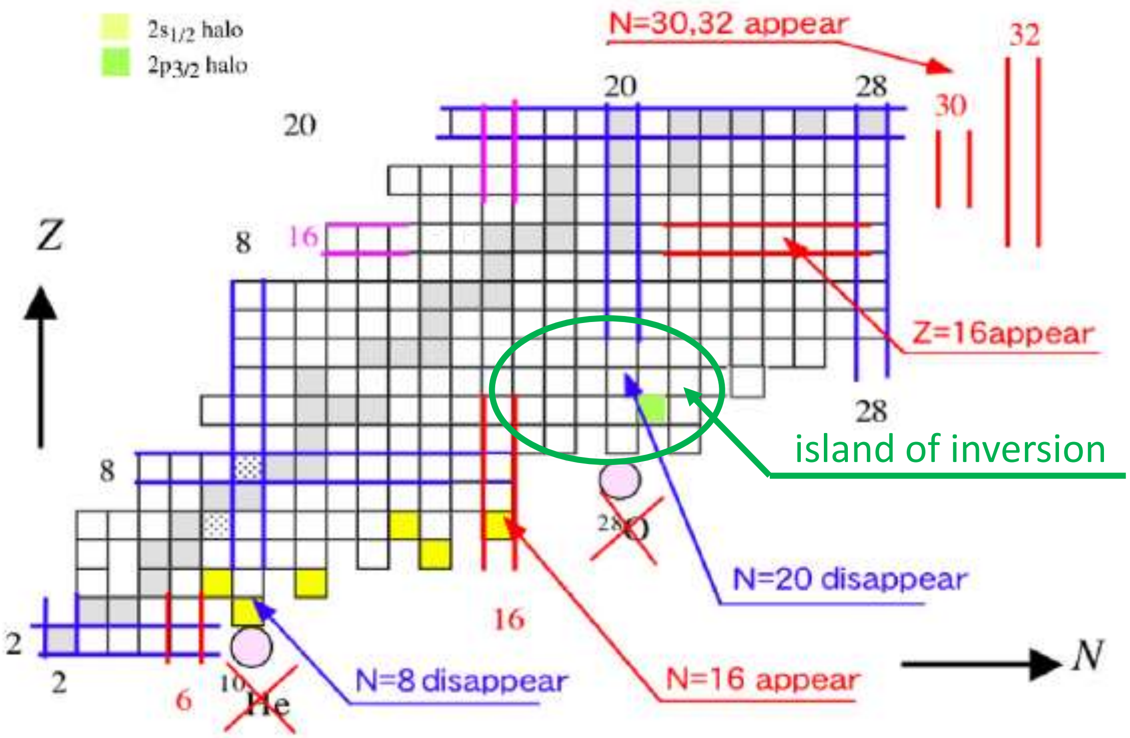
Experimental differential cross section:

$$\left.\frac{d\sigma}{d\Omega}\right|_{exp} = g_{lj} S_{lj} \left.\frac{d\sigma}{d\Omega}\right|_{theory}$$

spectroscopic factor ~ occupancy

Nuclear structure of *unstable* Nuclei

R. Kanungo, Phys. Scr. T152(2013) 014002

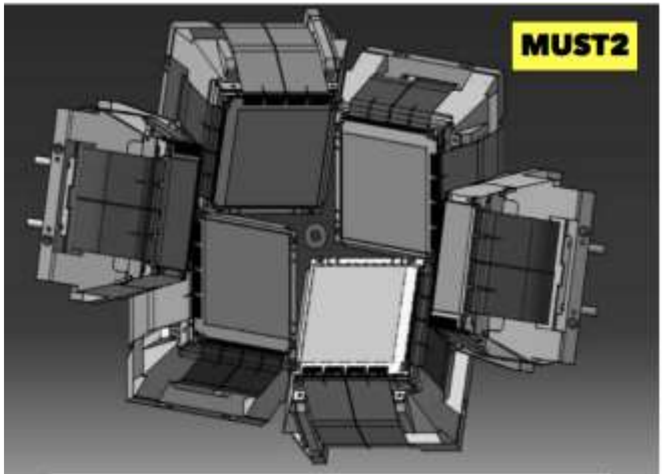


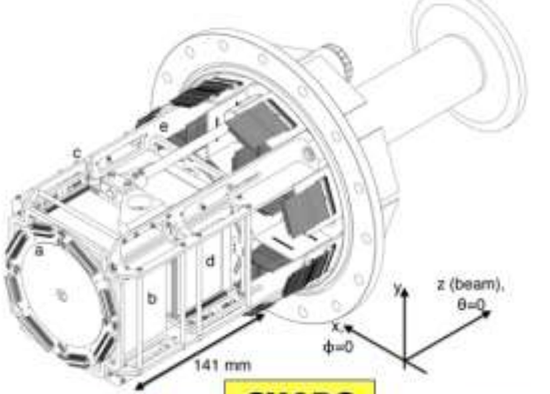
- New shell closure
- Neutron Halo
- Location of dripline
- Island of inversion

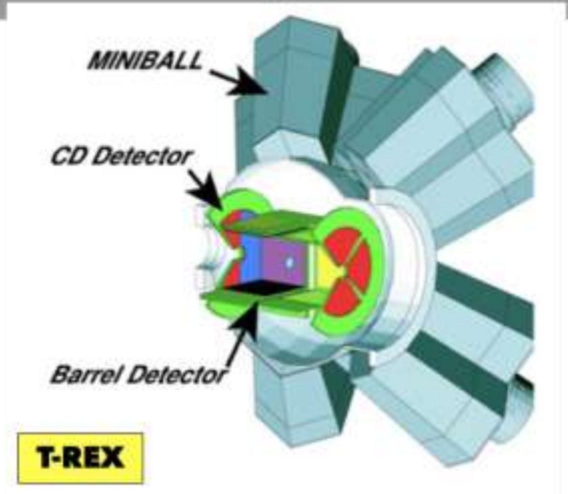
To study unstable nuclei → need *inverse kinematics*

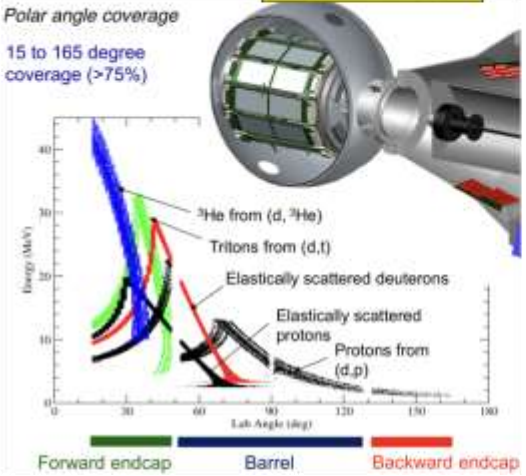
Convention experimental setups

Inverse Kinematics

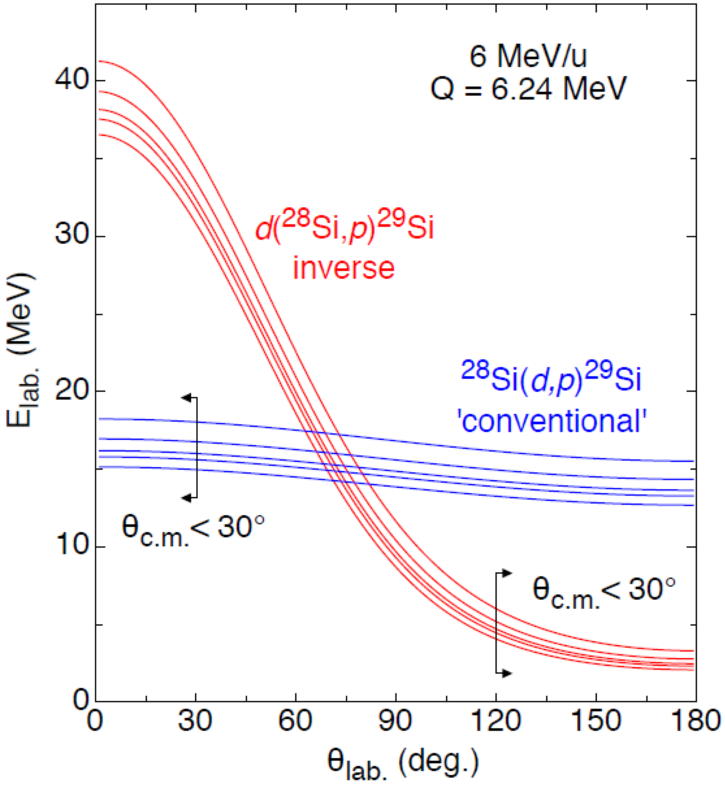




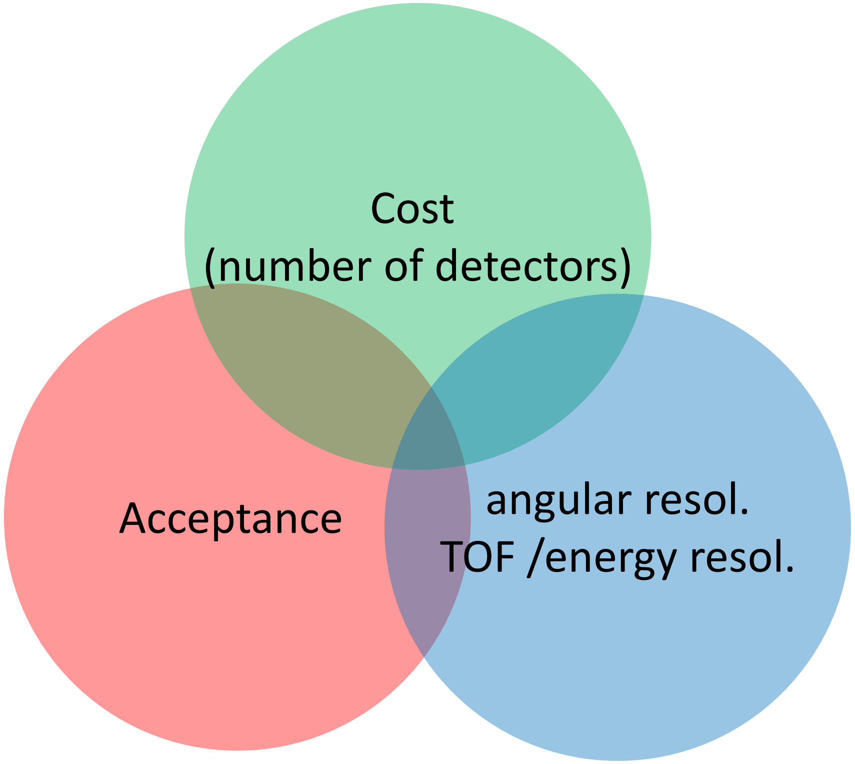




Difficulties (Unstable Beam)



Inverse kinematics → Energy compression
Unstable Beam → low beam intensity
→ large acceptance

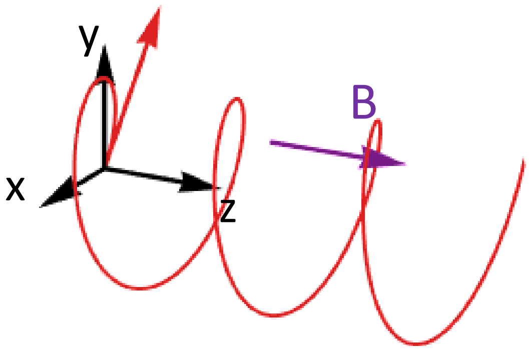


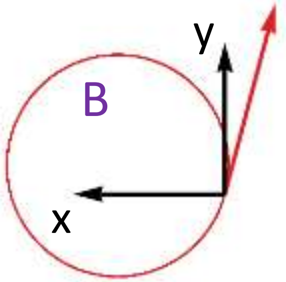
Cost
(number of detectors)

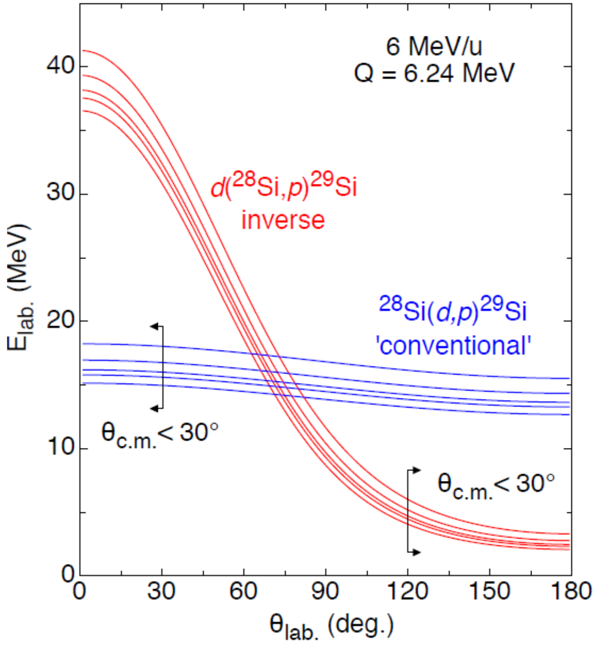
Acceptance

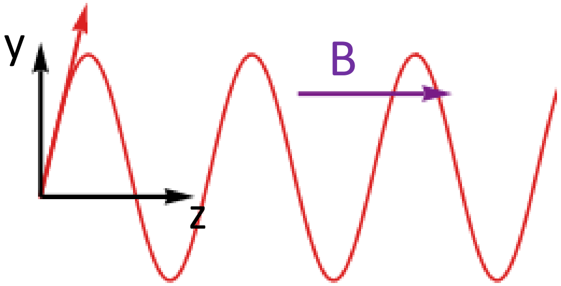
angular resol.
TOF /energy resol.

Idea of HELIOS









A charged particle moves in a helix orbit.
It will return to the beam axis!!

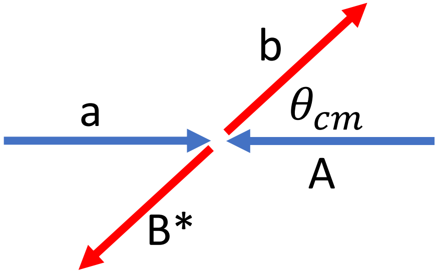
How about we placed a detector on the axis
in a uniform *MAGNETIC FIELD*?

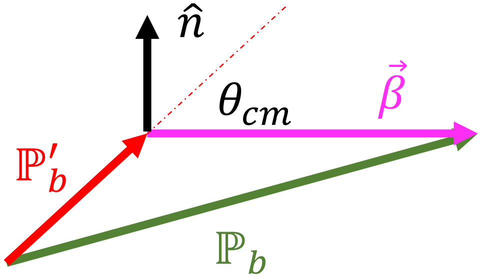
Can we measure

- Energy - OK!
- Scattering angle - ???

Transfer Reaction (II)

In the Center of Momentum frame….





Two degrees of freedom are

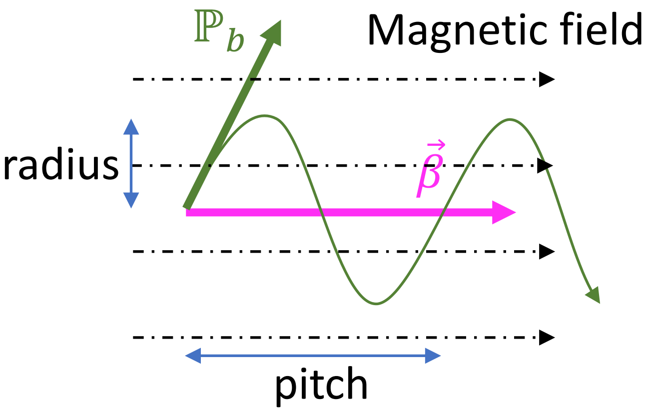
- scattering angle θ_{cm}
- excitation energy E_x

$$\mathbb{P}'_b = \begin{pmatrix} E' \\ \vec{p} \end{pmatrix}$$

$$\mathbb{P}_b = \begin{pmatrix} E \\ \vec{k} \end{pmatrix} = \begin{pmatrix} \gamma E' + \gamma\beta\left(\hat{\beta}\cdot\vec{p}\right) \\ \left(\gamma\beta E' + \gamma\left(\hat{\beta}\cdot\vec{p}\right)\right)\hat{\beta} + (\hat{n}\cdot\vec{p})\hat{n} \end{pmatrix}$$

Although transfer reaction usually non-relativistic,
for simplicity and generosity, lets do it in relativistic way.

In Magnetic field



$$\mathbb{P}_b = \begin{pmatrix} E \\ \vec{k} \end{pmatrix} = \begin{pmatrix} \gamma E' + \gamma\beta\left(\hat{\beta}\cdot\vec{p}\right) \\ \left(\gamma\beta E' + \gamma\left(\hat{\beta}\cdot\vec{p}\right)\right)\hat{\beta} + (\hat{n}\cdot\vec{p})\hat{n} \end{pmatrix}$$

The helix radius $\rho = \dfrac{\vec{k}\cdot\widehat{xy}}{cZB}$ $\quad c = 300$

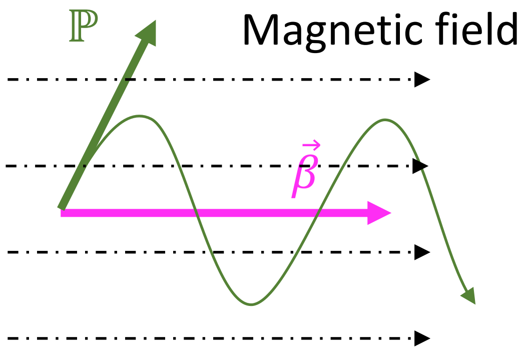
The helix period $T_{cyc} = \dfrac{2\pi\rho}{v_{xy}} = \dfrac{2\pi}{cZB}\dfrac{\vec{k}\cdot\widehat{xy}}{v_{xy}}$ $\quad \vec{k} = \vec{\beta}E \rightarrow \vec{k}\cdot\widehat{xy} = \dfrac{v_{xy}}{c}E$

$$T_{cyc} = \frac{2\pi}{c^2 ZB}E$$

The helix patch $z_{cyc} = v_z\, T_{cyc} = \dfrac{2\pi}{cZB}\left(\vec{k}\cdot\widehat{xy}\right)\dfrac{v_z}{v_{xy}}$ $\quad \dfrac{v_z}{v_{xy}} = \dfrac{\vec{k}\cdot\hat{z}}{\vec{k}\cdot\widehat{xy}}$

$$z_{cyc} = \frac{2\pi}{cZB}\left(\vec{k}\cdot\hat{z}\right)$$

In Magnetic field



$$\mathbb{P}_b = \begin{pmatrix} E \\ \vec{k} \end{pmatrix} = \begin{pmatrix} \gamma E' + \gamma\beta(\hat{\beta}\cdot\vec{p}) \\ \left(\gamma\beta E' + \gamma(\hat{\beta}\cdot\vec{p})\right)\hat{\beta} + (\hat{n}\cdot\vec{p})\hat{n} \end{pmatrix}$$

The helix patch

$$z_{cyc} = \frac{2\pi}{cZB}\,(\vec{k}\cdot\hat{z})$$

$$z_{cyc} = \frac{2\pi}{cZB}\left(\left(\gamma\beta E' + \gamma(\hat{\beta}\cdot\vec{p})\right)\overset{1}{(\hat{\beta}\cdot\hat{z})} + (\hat{n}\cdot\vec{p})\overset{0}{(\hat{n}\cdot\hat{z})}\right)$$

$$z_{cyc} = \frac{2\pi}{cZB}\left(\gamma\beta E' + \gamma(\hat{\beta}\cdot\vec{p})\right)$$

$$\beta p \cos\theta_{cm}$$

YEAH!!!

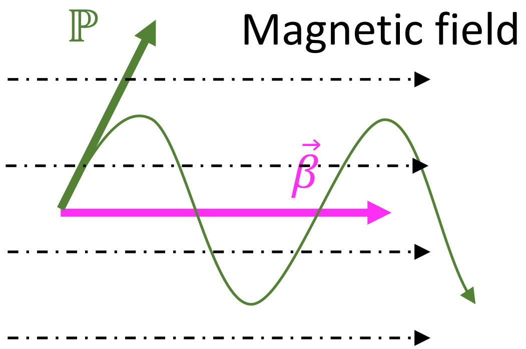
The $\cos\theta_{cm}$ is proportional to the z_{cyc} !!!

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\phi d\cos\theta} = \frac{d\sigma}{d\phi\; dz_{cyc}}$$

Bonus!!

In Magnetic field

$$\mathbb{P}_b = \begin{pmatrix} E \\ \vec{k} \end{pmatrix} = \begin{pmatrix} \gamma E' + \gamma\beta\left(\hat{\beta}\cdot\vec{p}\right) \\ \left(\gamma\beta E' + \gamma\left(\hat{\beta}\cdot\vec{p}\right)\right)\hat{\beta} + (\hat{n}\cdot\vec{p})\hat{n} \end{pmatrix}$$



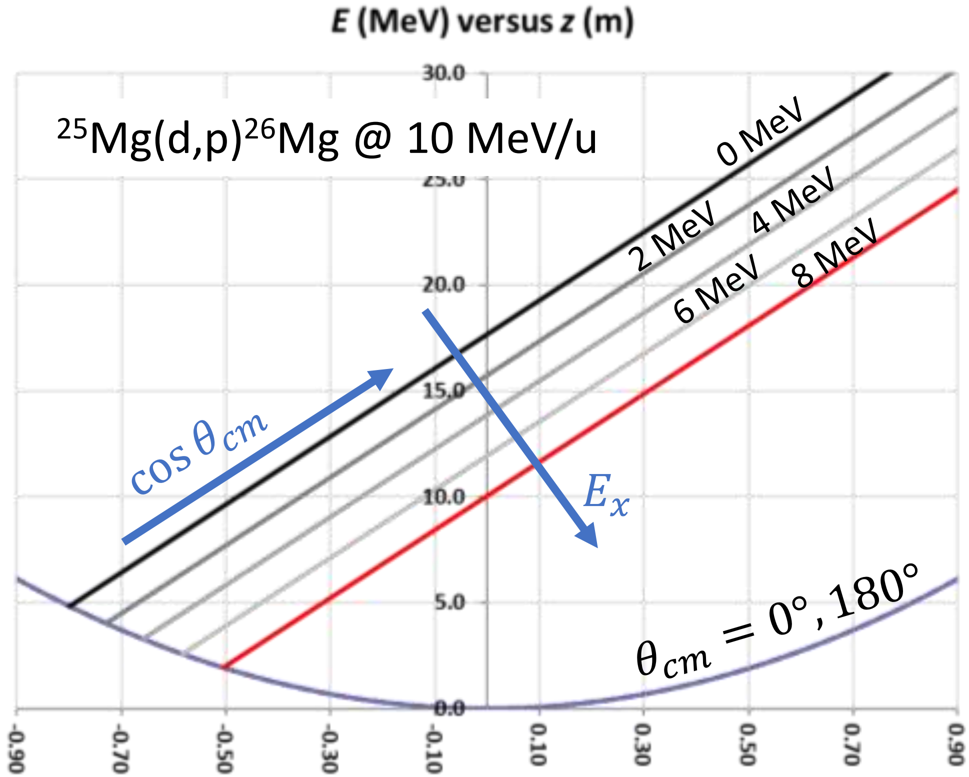
The helix patch

$$z_{cyc} = \frac{2\pi}{cZB}\left(\gamma\beta E' + \gamma\left(\hat{\beta}\cdot\vec{p}\right)\right)$$

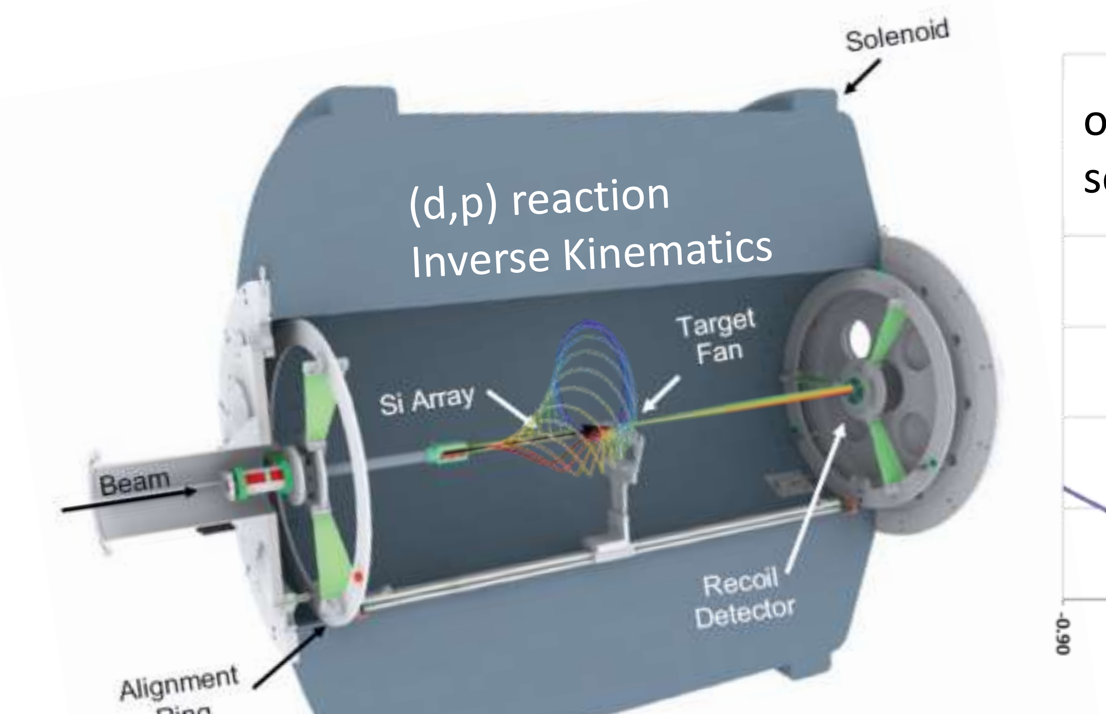
$$E = \gamma E' + \gamma\beta\left(\hat{\beta}\cdot\vec{p}\right)$$

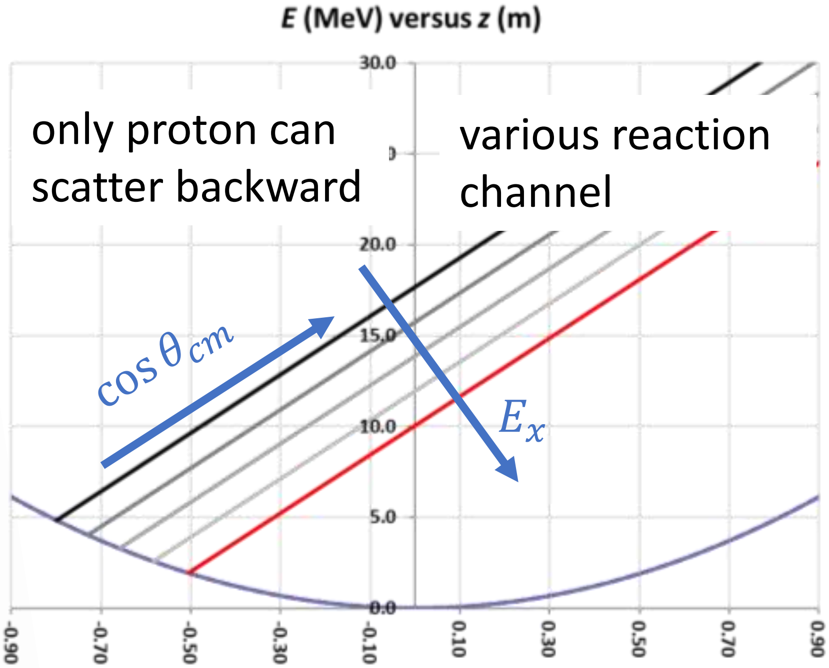
$$E = \frac{1}{\gamma}E' + \frac{cZB}{2\pi}\beta\, z_{cyc}$$

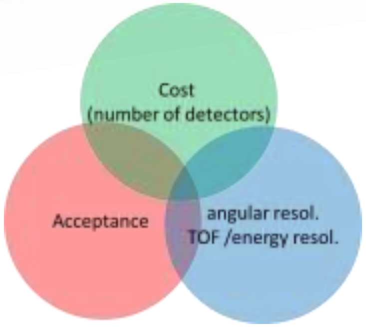
different charged particle
has different slope !



Simplicity of HELIOS







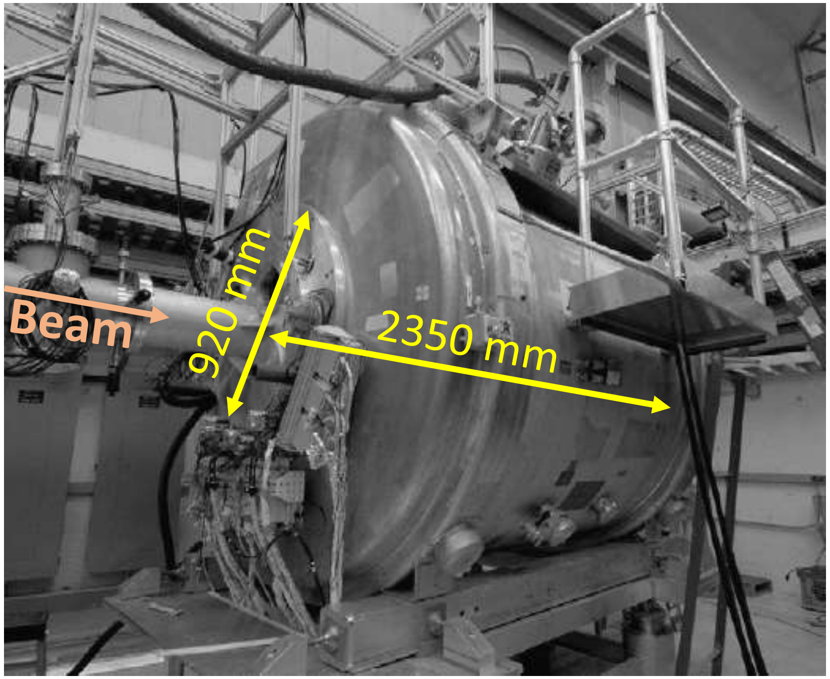
Large acceptance! → Good statistics

Good energy resolution (Silicon detectors)

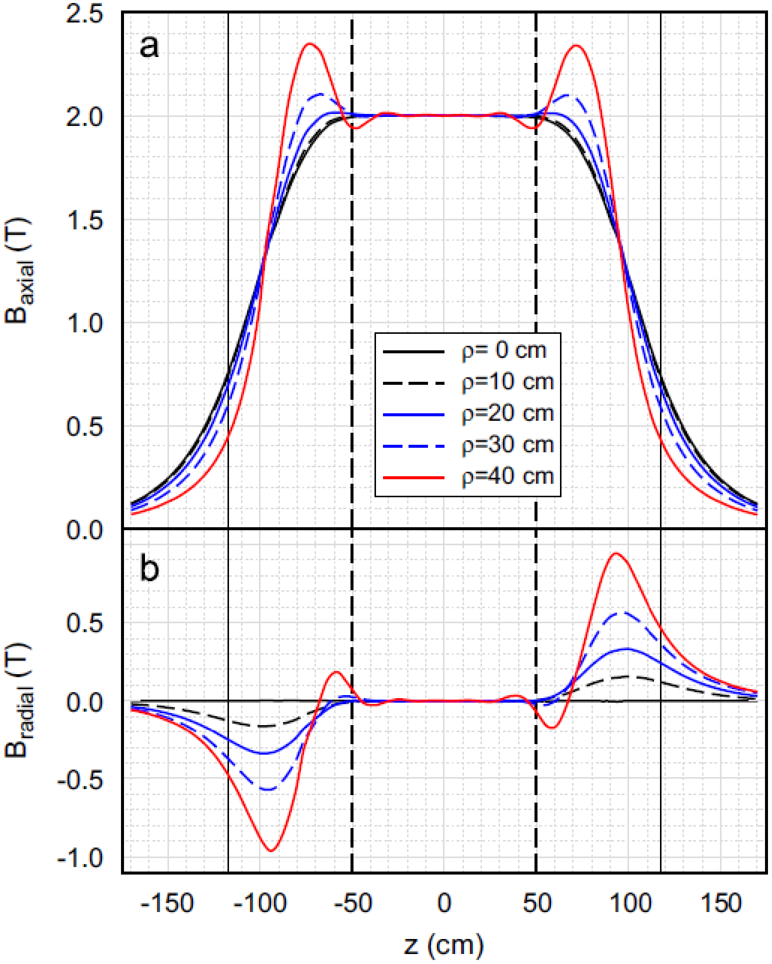
Relatively *cheap*! (for above cases)

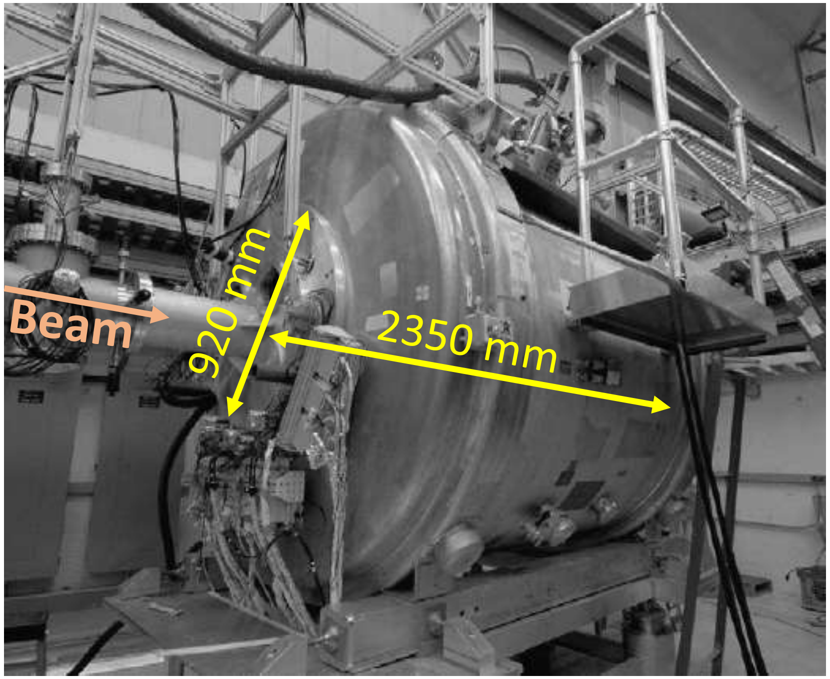
Building of HELIOS

Decommissioned Magnetic Resonance Imaging (MRI) device

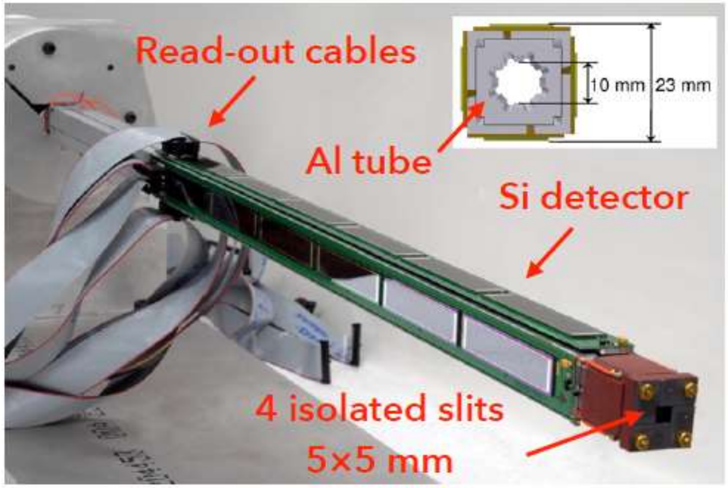


Magnetic field map

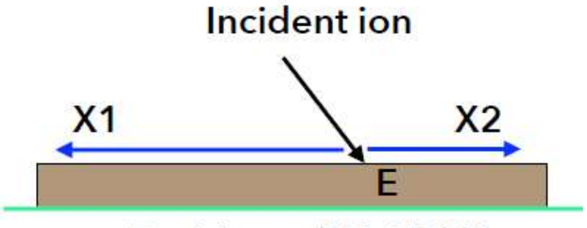




Position Sensitive Si detectors

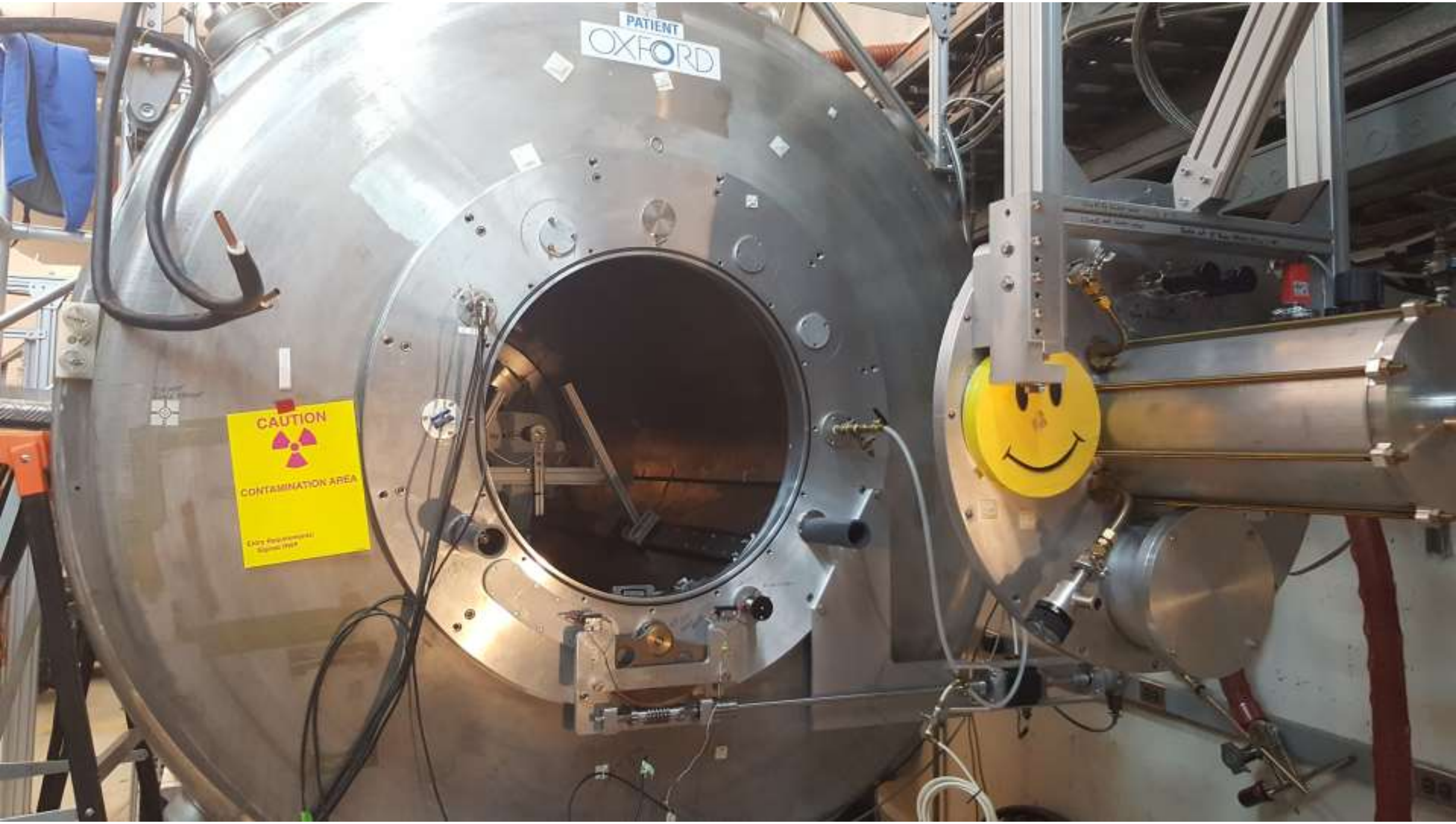


- 4 sides, 6 detectors long
- Detector size, 9×50 mm
- 700-μm thick (e.g. ~10 MeV protons)
- Φ coverage, 0.48 of 2π
- $\Omega_{detector}$ = 21 msr
- Ω_{array} = 493 msr

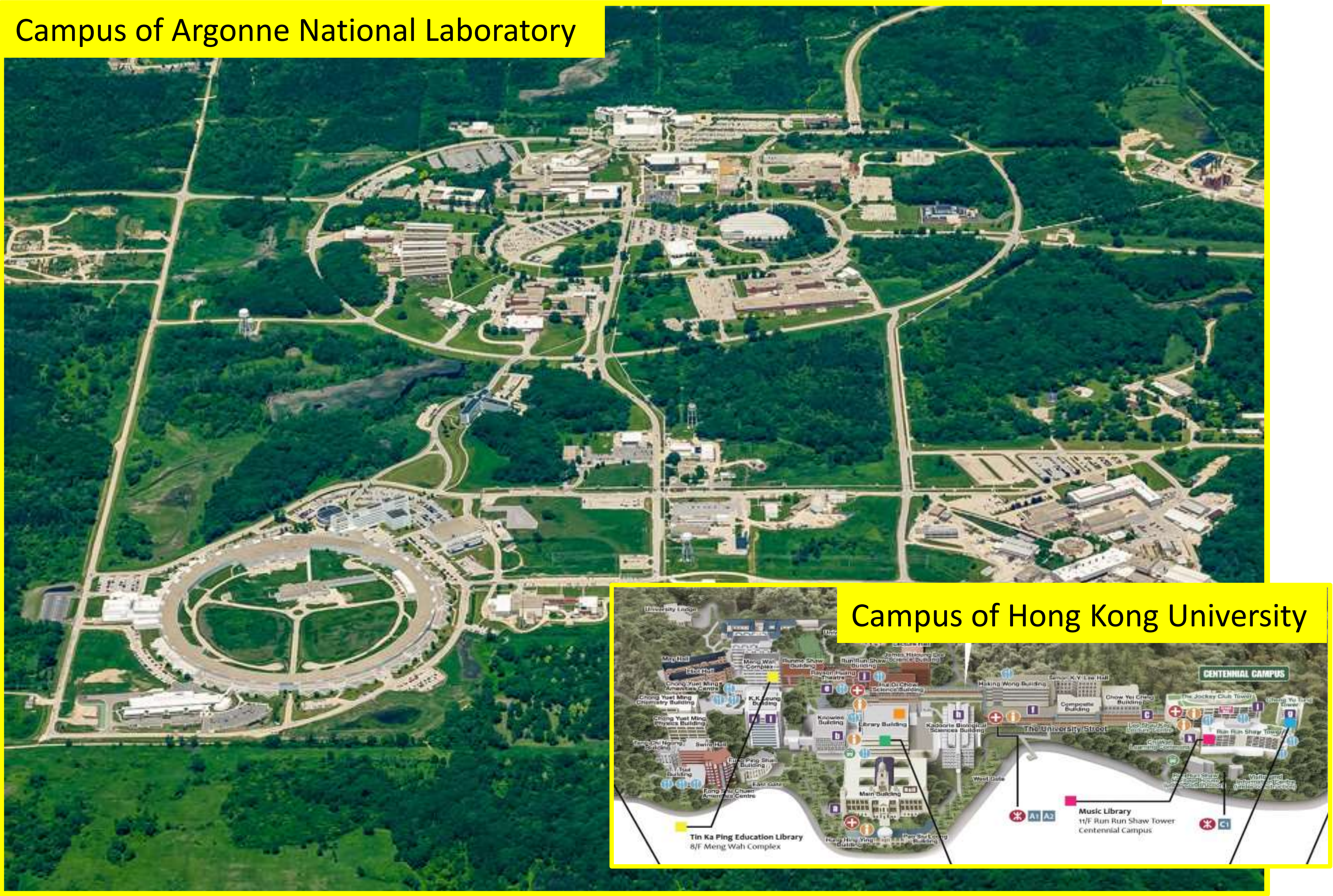


Position ≈ (X1-X2)/E

J. C. Lighthall et al., Nucl. Instrum. Methods Phys. A ***662****, 97 (****2010****)*


PATIENT
OXFORD
CAUTION
CONTAMINATION AREA

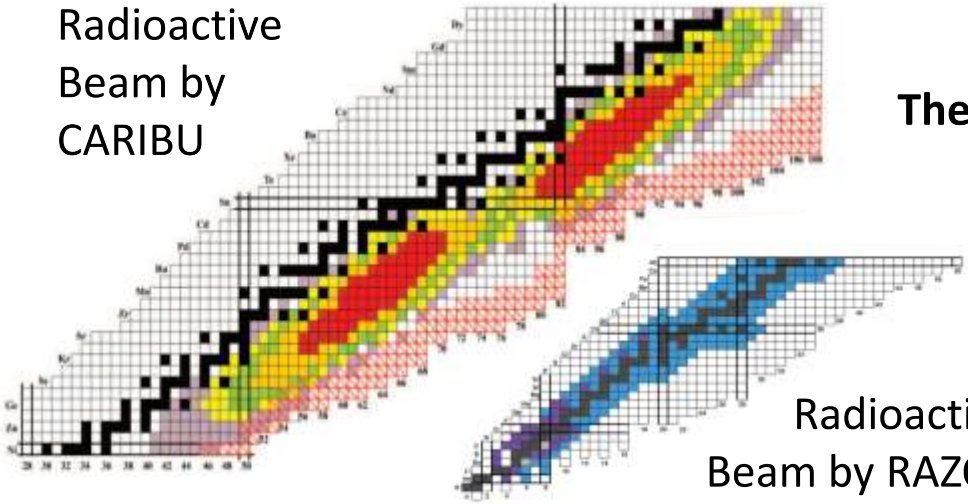
Campus of Argonne National Laboratory



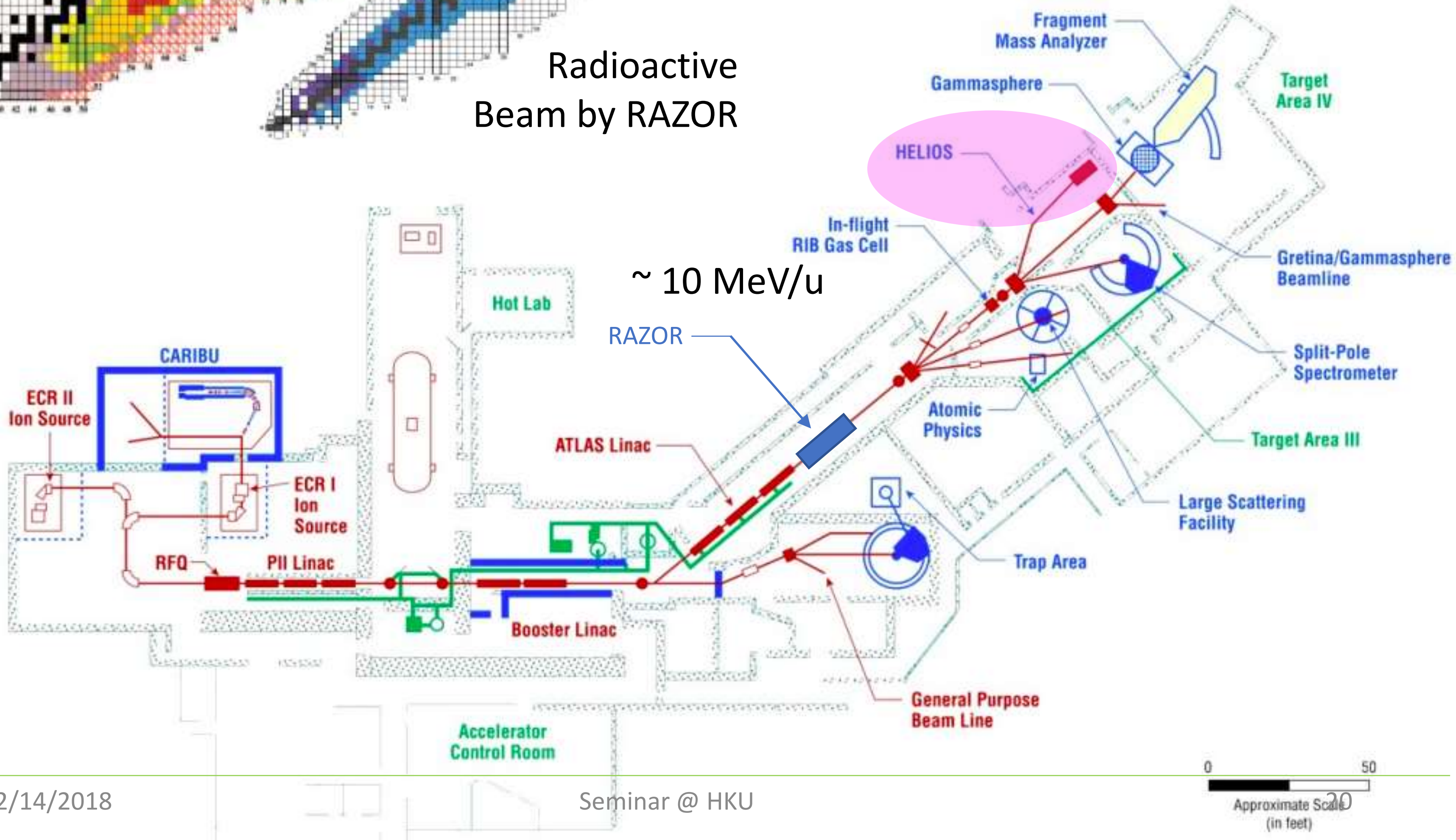
Campus of Hong Kong University

The Argonne Tandem Linac Accelerator System (ATLAS)

Radioactive Beam by CARIBU



Radioactive Beam by RAZOR



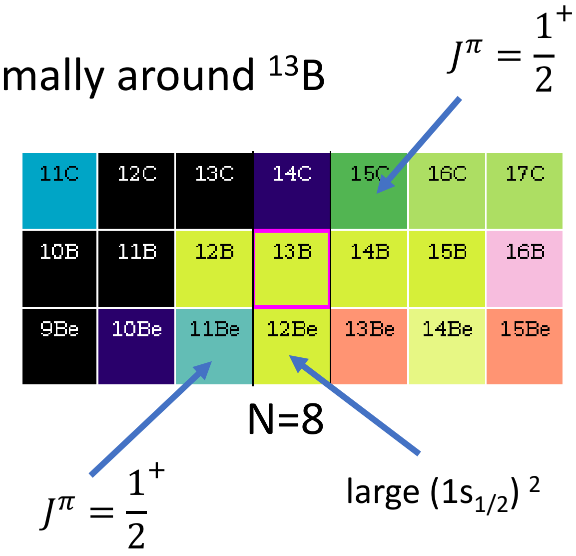
~ 10 MeV/u

The first experiment – Structure of ^{13}B

^{12}B(d,p)^{13}B @ 5.77 MeV/u, 10^5 pps

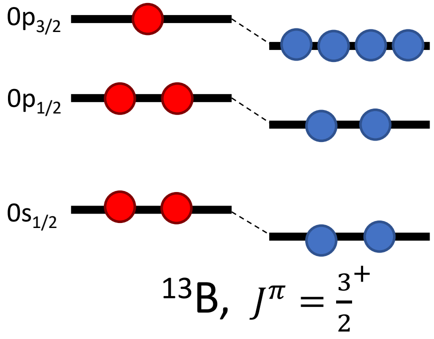
B.B. Back et al., PRL 104, 132501 (2010)

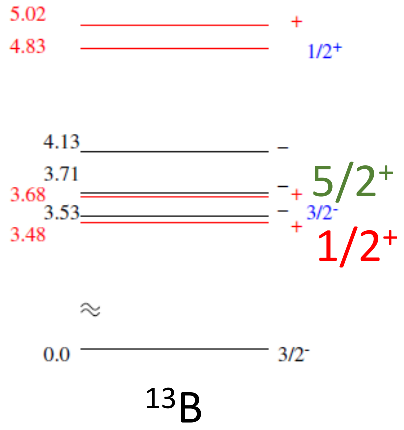
Abnormally around ^{13}B

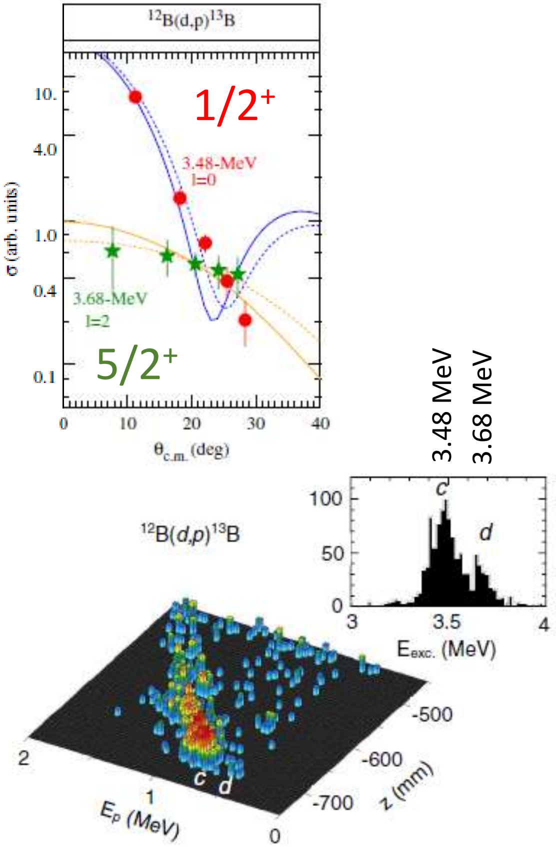


11C	12C	13C	14C	15C	16C	17C
10B	11B	12B	13B	14B	15B	16B
9Be	10Be	11Be	12Be	13Be	14Be	15Be

simple picture







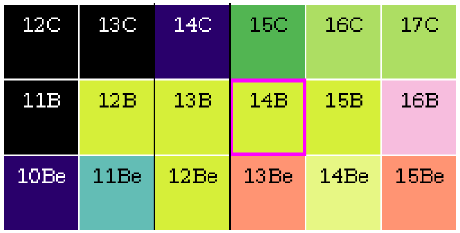
energy resolution : ~43 keV

- Many previous study using (t,p), (α,t) lack of energy resolutions.
- (d,p) reaction is relatively clean

Structure of ^{14}B

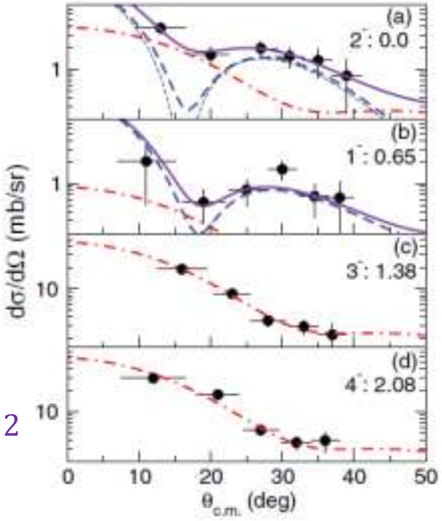
^{13}B(d,p)^{14}B @ 15.7 MeV/u, ~ 3 x 10^4 pps

S. Bedoor *et al.*, PRC 88, 011304 (2013)



12C	13C	14C	15C	16C	17C
11B	12B	13B	14B	15B	16B
10Be	11Be	12Be	13Be	14Be	15Be

N=9

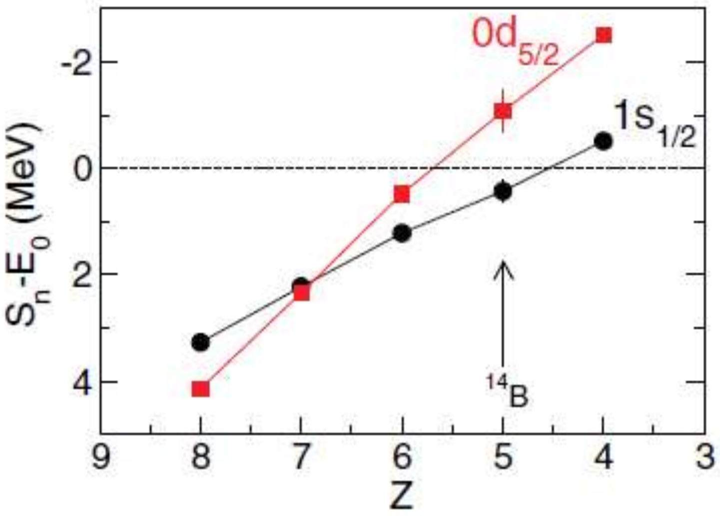


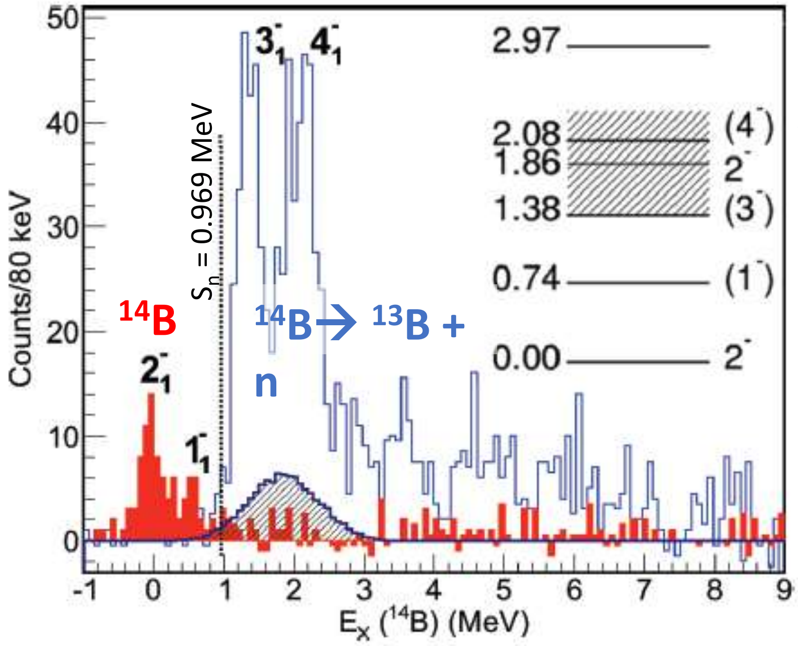
$l = 0$

$l = 2$

$l = 0 + 2$

- ^{14}B is the last N=9 isotone, S_n = 0.969 MeV
- Little knowledge about ^{14}B
- (d,p) reaction is one of the best tool.





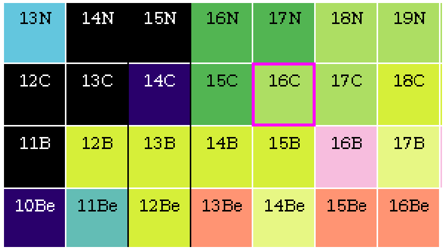
pure l=2

~ pure $1s_{1/2}$ (halo)

Structure of ^{16}C

^{15}C(d,p)^{16}C @ 8.2 MeV/u, 2 x 10^6 pps

A.H. Wuosmaa *et al.*, PRL 105, 132501 (2010)

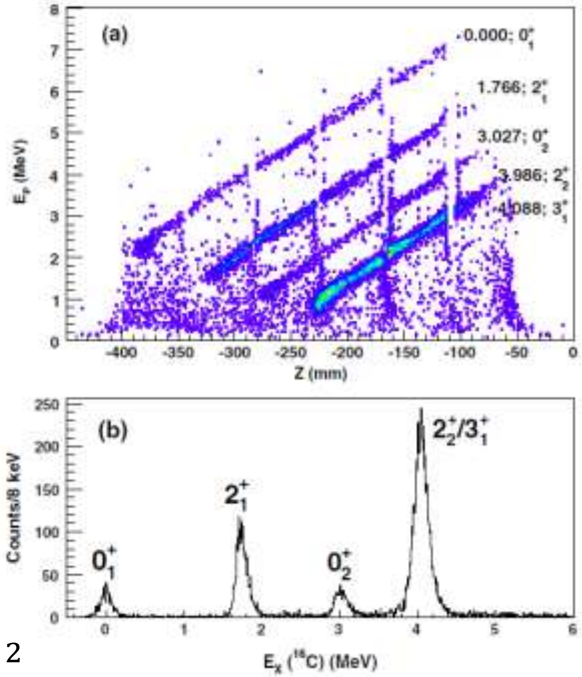


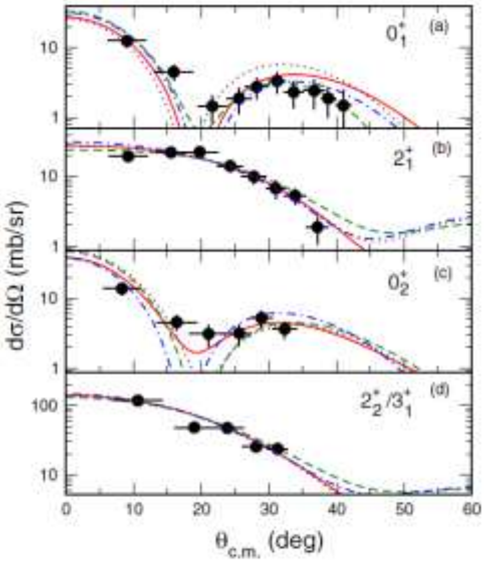
13N	14N	15N	16N	17N	18N	19N
12C	13C	14C	15C	16C	17C	18C
11B	12B	13B	14B	15B	16B	17B
10Be	11Be	12Be	13Be	14Be	15Be	16Be

N=10

Motivation:

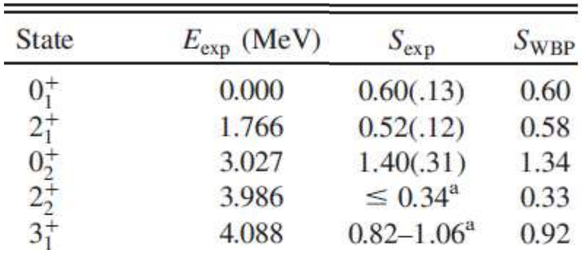
- B(E2) values were much smaller from stable nuclei
- Lifetime measurement for 2_1^+ state report much larger B(E2).





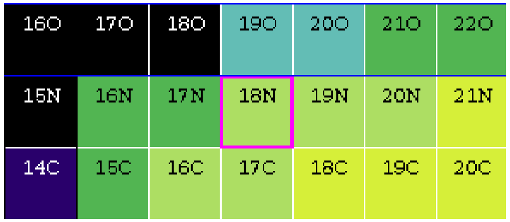
Conclusion:

- The spectroscopic factors are consistent with shell model calculation.
- $0_1^+ = \sqrt{0.3}\,(1s_{\frac{1}{2}})^2 + \sqrt{0.7}\,(0d_{\frac{5}{2}})^2$
- ^{16}C is well described by WBP → not very exotic nucleus.



State	E_{exp} (MeV)	S_{exp}	S_{WBP}
0_1^+	0.000	0.60(.13)	0.60
2_1^+	1.766	0.52(.12)	0.58
0_2^+	3.027	1.40(.31)	1.34
2_2^+	3.986	≤ 0.34[a]	0.33
3_1^+	4.088	0.82–1.06[a]	0.92

Structure of ^{18}N

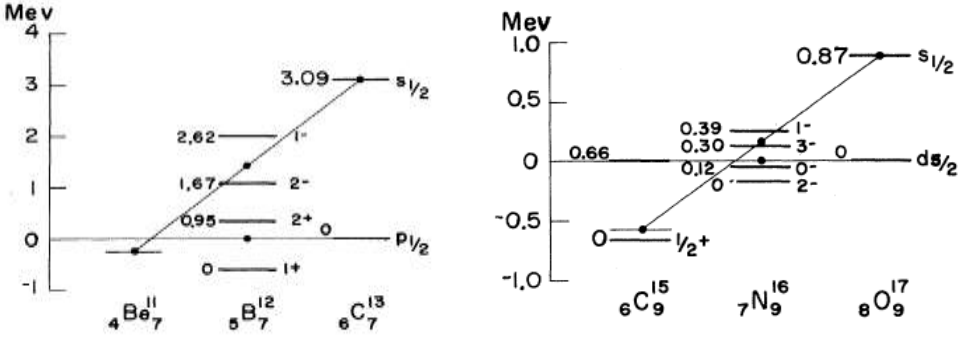


16O	17O	18O	19O	20O	21O	22O
15N	16N	17N	18N	19N	20N	21N
14C	15C	16C	17C	18C	19C	20C

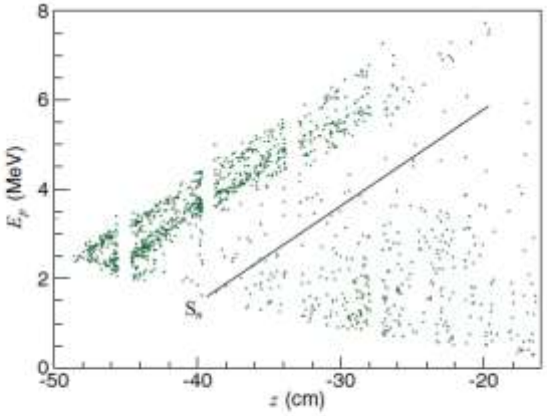
N=11

^{17}N(d,p)^{18}N @ 13.6 MeV/u, 2x10^4 pps, Purity = 25-75%

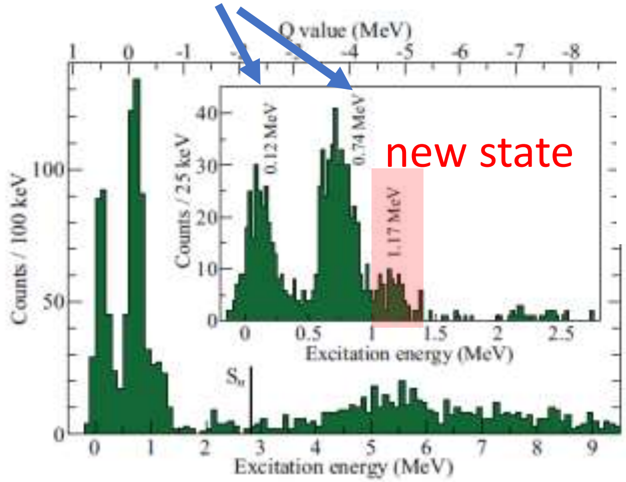
C.R. Hoffman *et al.*, PRC 88, 044317 (2013)



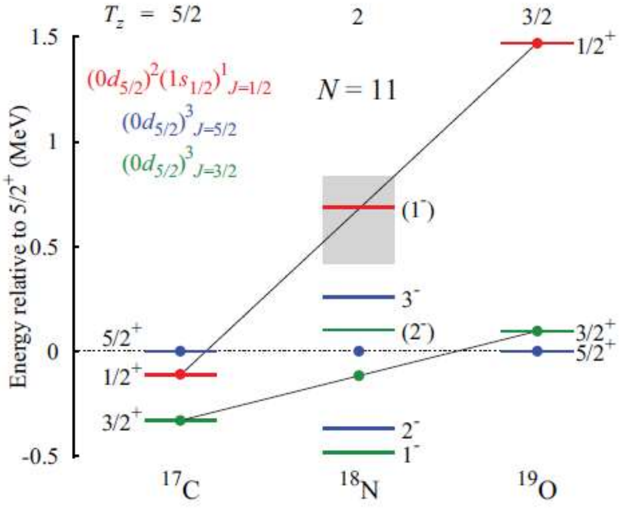
I. Talmi and I. Unna, PRL **4**, 469 (1960).



confirmed spin assignment



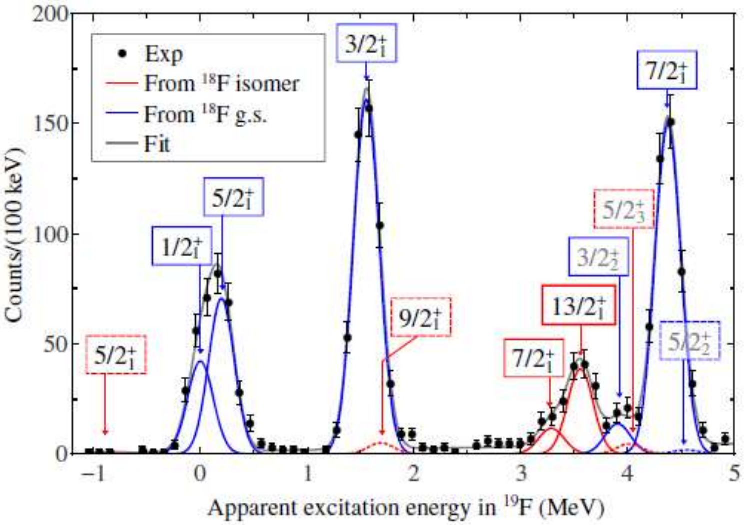
new state



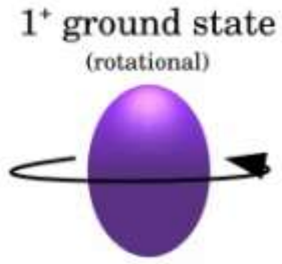
High spin state of ^{19}F

^{18m}F(d,p)^{19}F @ 14 MeV/u, ~ 5 x 10^5 pps, ^{18m}F ~ 36%

D. Santiago-Gonzalez *et al.*, PRL 120, 122503 (2018)



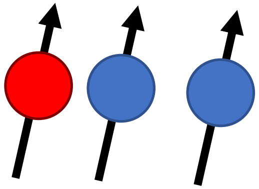
^{19}F is deformed,
has rotational band



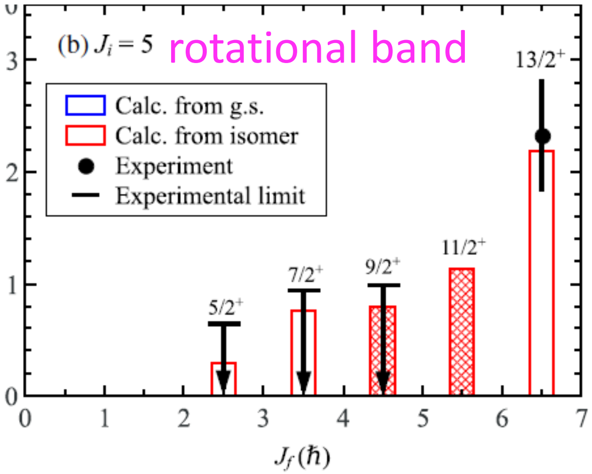
^{18m}F

It has 5^+ state

$\{(\pi 0d_{5/2})(\nu 0d_{5/2})\}_{5+}$



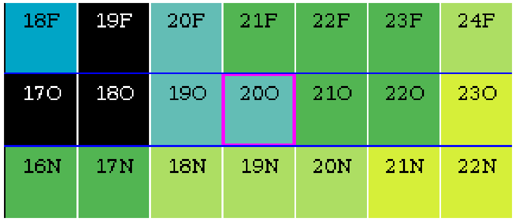
$$J^\pi = 5^+ + \frac{5^+}{2} = \frac{13^+}{2}$$



First experimental proof of ***DUAL*** description!!!

single particle picture and **collective picture**

Structure of ^{20}O



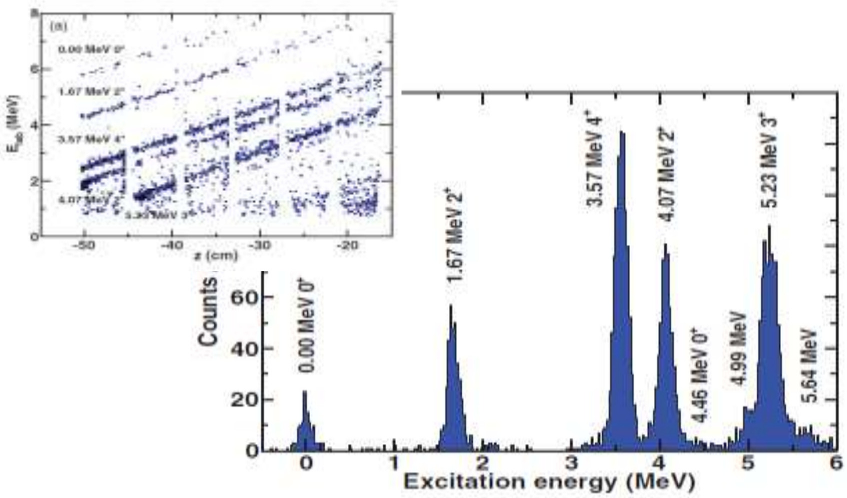
18F	19F	20F	21F	22F	23F	24F
17O	18O	19O	20O	21O	22O	23O
16N	17N	18N	19N	20N	21N	22N

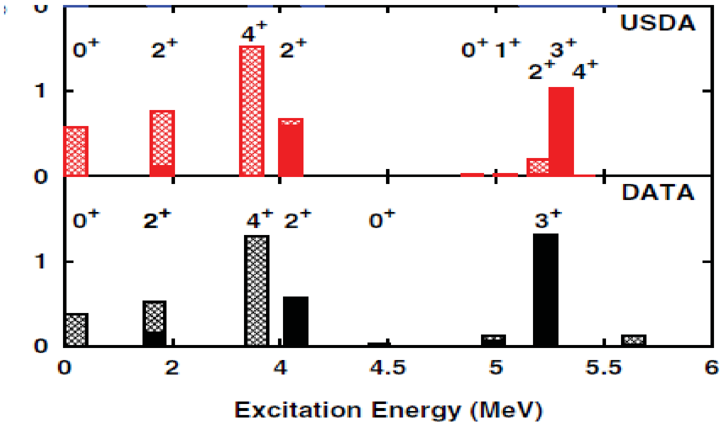
N=12

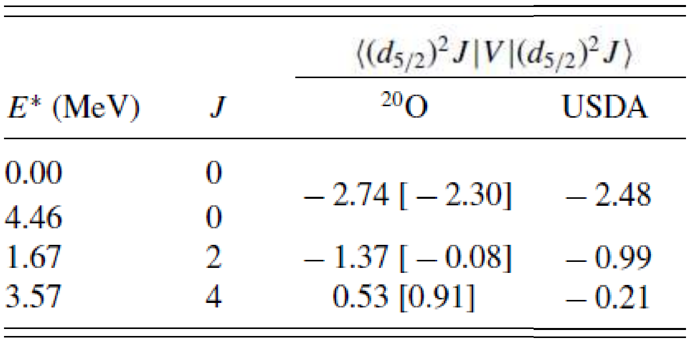
^{19}O(d,p)^{20}O @ 6.61 MeV/u

C.R. Hoffman *et al.*, PRC 85, 054318 (2012)

There are only (t,p) or beta decay study.
→ Hard to study the single particle states.







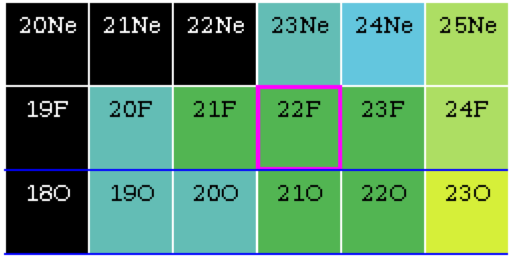
		$\langle (d_{5/2})^2 J \| V \| (d_{5/2})^2 J \rangle$	
E^* (MeV)	J	^{20}O	USDA
0.00	0	– 2.74 [– 2.30]	– 2.48
4.46	0		
1.67	2	– 1.37 [– 0.08]	– 0.99
3.57	4	0.53 [0.91]	– 0.21

- Only need to use $0d_{5/2}$ and $1s_{1/2}$ to describe the result. *Consistent with N = 14 shell closure*
- The USD Single particle energies are agreed with the result.

Structure of ^{22}F

^{21}F(d,p)^{22}F @ 10 MeV/u, ~3x10^{4} pps

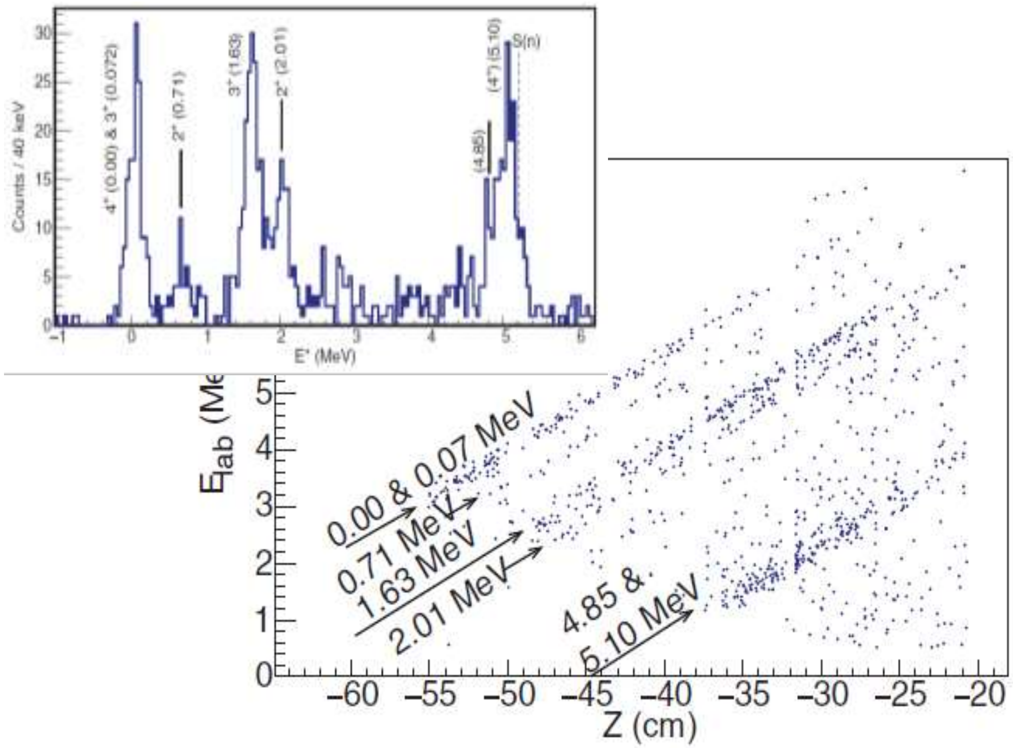
J. Chen *et al.*, PRC 98, 014325 (2018)

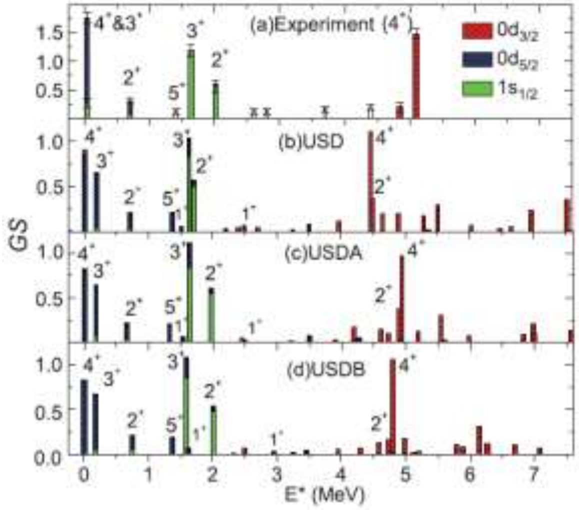


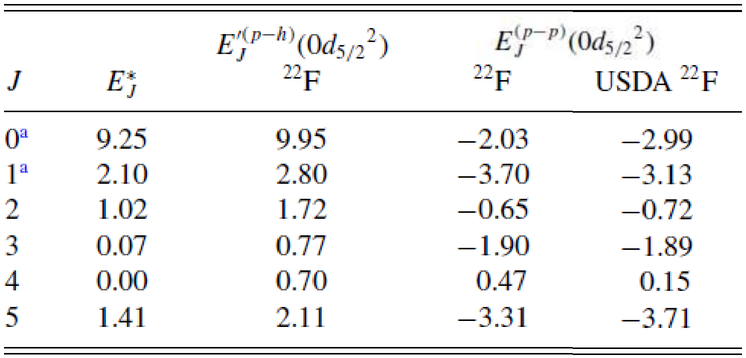
20Ne	21Ne	22Ne	23Ne	24Ne	25Ne
19F	20F	21F	22F	23F	24F
18O	19O	20O	21O	22O	23O

N=13

- There are many doubly magic oxygen
- Study the TBMEs between $\pi 0d_{5/2}$ to sd-shell neutrons







J	E_J^*	$E_J^{\prime(p-h)}(0d_{5/2}{}^2)$ ^{22}F	$E_J^{(p-p)}(0d_{5/2}{}^2)$ ^{22}F	USDA ^{22}F
0[a]	9.25	9.95	−2.03	−2.99
1[a]	2.10	2.80	−3.70	−3.13
2	1.02	1.72	−0.65	−0.72
3	0.07	0.77	−1.90	−1.89
4	0.00	0.70	0.47	0.15
5	1.41	2.11	−3.31	−3.71

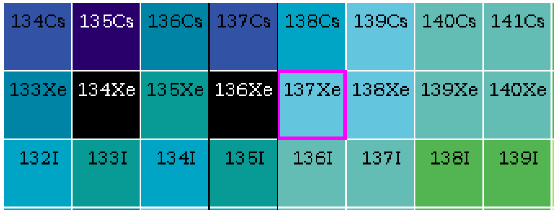
Structure of ^{137}Xe

^{136}Xe(d,p)^{137}Xe @ 10 MeV/u

B.P. Kay *et al.*, PRC 84, 024325 (2011)

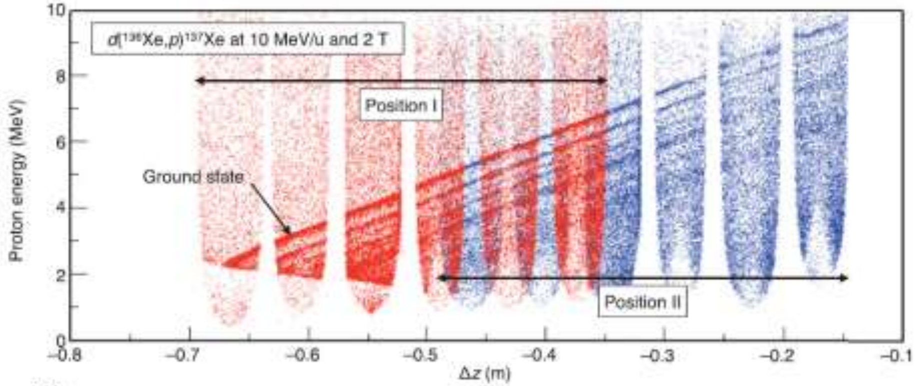
- Testing capability to do heavy ion reaction
- Determine the energy centroid of $h_{9/2}$ and $i_{13/2}$

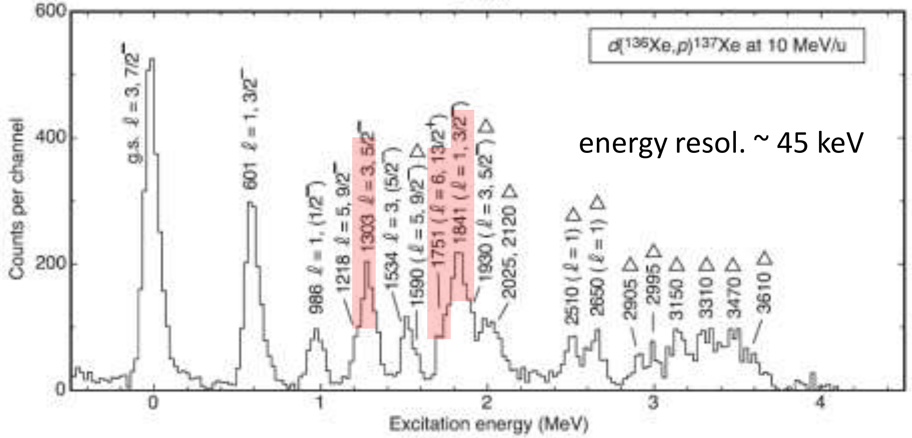
$l = 5$ $l = 6$



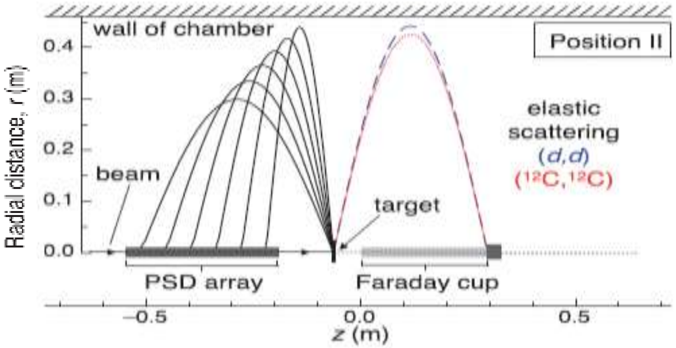
134Cs	135Cs	136Cs	137Cs	138Cs	139Cs	140Cs	141Cs
133Xe	134Xe	135Xe	136Xe	137Xe	138Xe	139Xe	140Xe
132I	133I	134I	135I	136I	137I	138I	139I

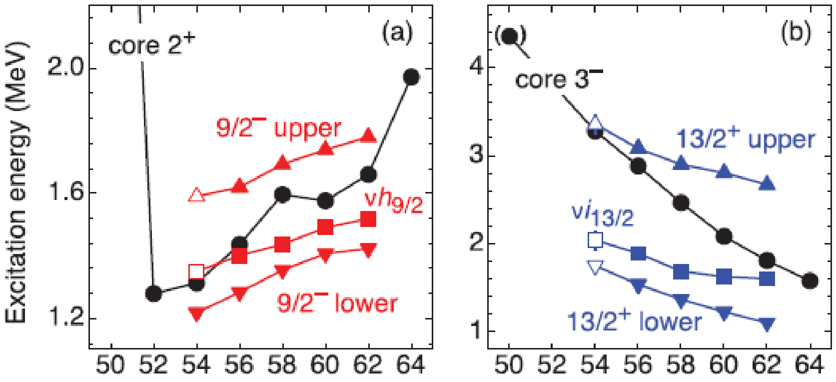
N=83



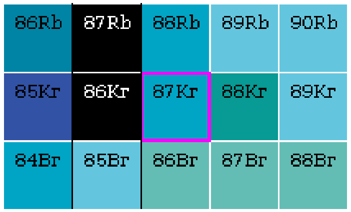


energy resol. ~ 45 keV





Structure of ^{86}Kr



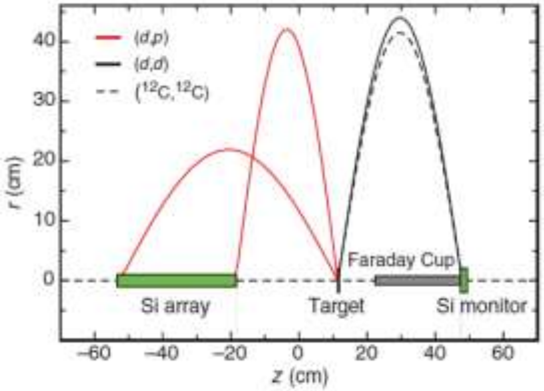
Z=36

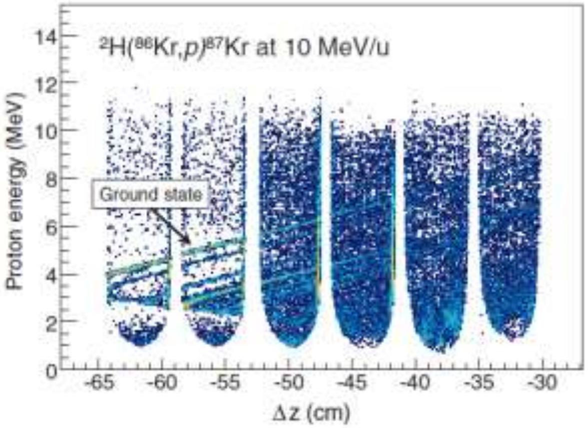
86Rb	87Rb	88Rb	89Rb	90Rb
85Kr	86Kr	87Kr	88Kr	89Kr
84Br	85Br	86Br	87Br	88Br

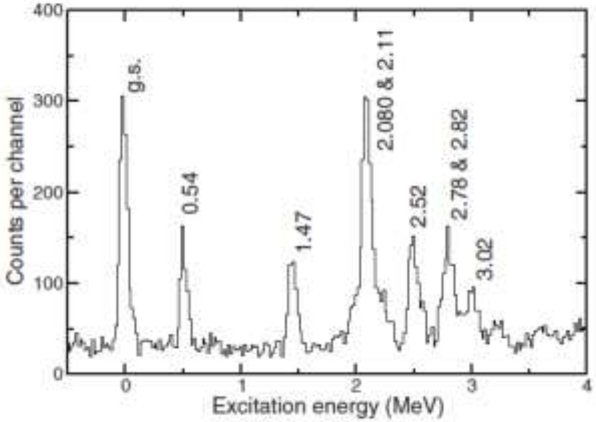
N=51

^{86}Kr(d,p)^{87}Kr @ 10 MeV/u, 5 x 10^7 pps

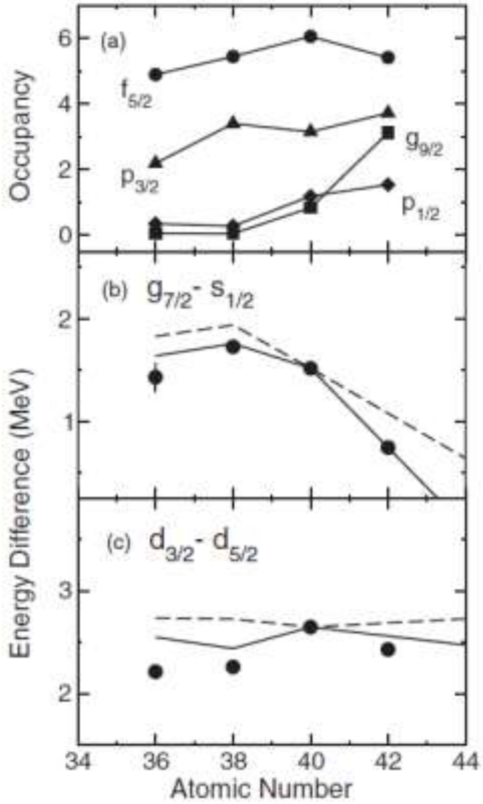
D.K. Sharp *et al.*, PRC 87, 014312 (2013)



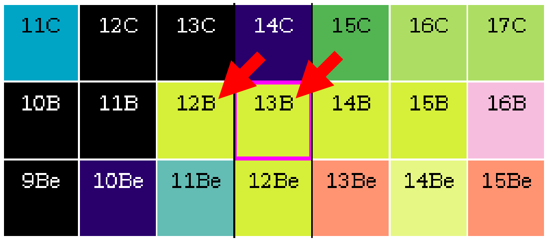




N= 51 isotone



Structure of $^{12,13}\mathrm{B}$



11C	12C	13C	14C	15C	16C	17C
10B	11B	12B	13B	14B	15B	16B
9Be	10Be	11Be	12Be	13Be	14Be	15Be

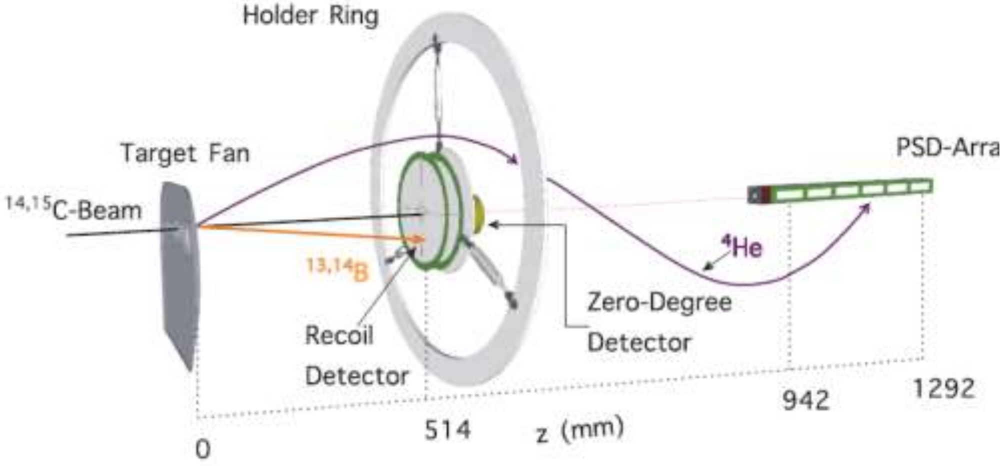
N=8

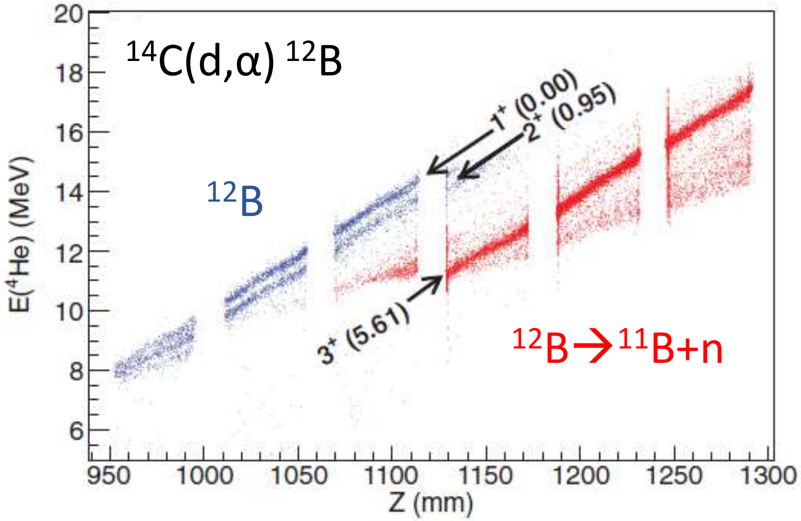
$^{14}\mathrm{C}(d,\alpha)^{12}\mathrm{B}$ @ 17.1 MeV/u, $10^{7\text{-}8}$ pps

$^{15}\mathrm{C}(d,\alpha)^{13}\mathrm{B}$ @ 15.7 MeV/u, 5×10^{5} pps

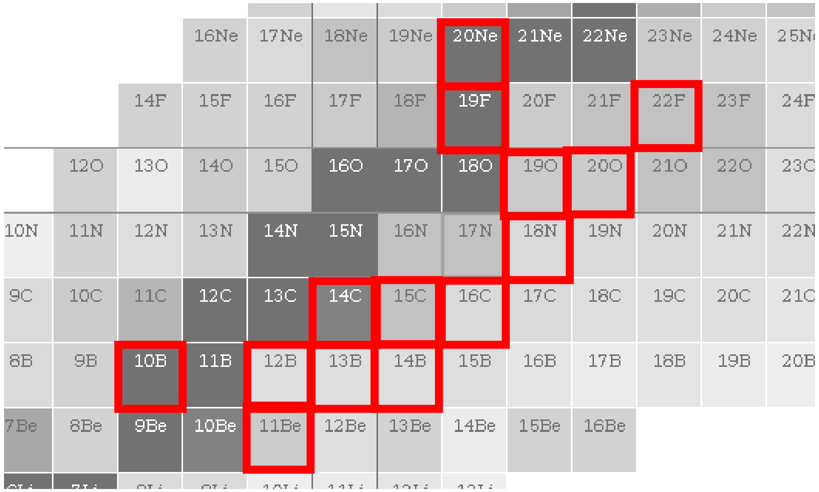
A. H. Wuosmaa *et al.*, PRC 90, 061301 (2014)

- (d,α) reaction is highly selective,
  - the neutron + proton has to be aligned.
- Populate inaccessible states (T=0) by single-particle transfer

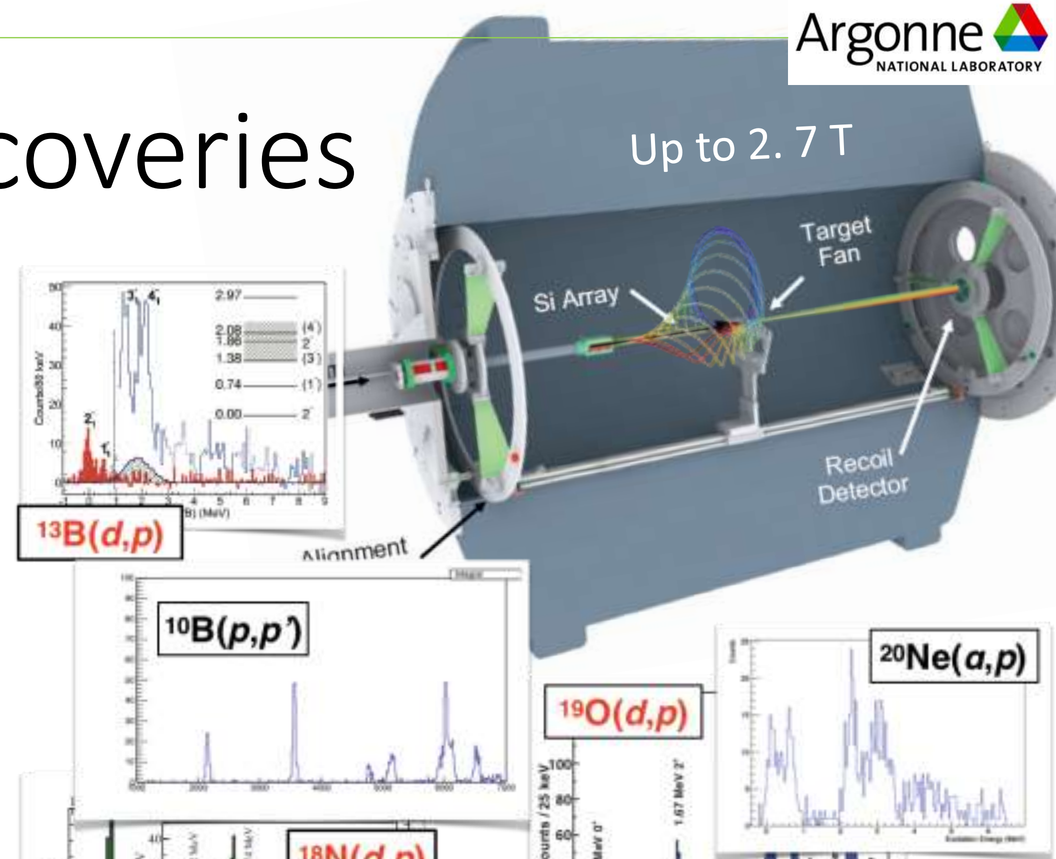


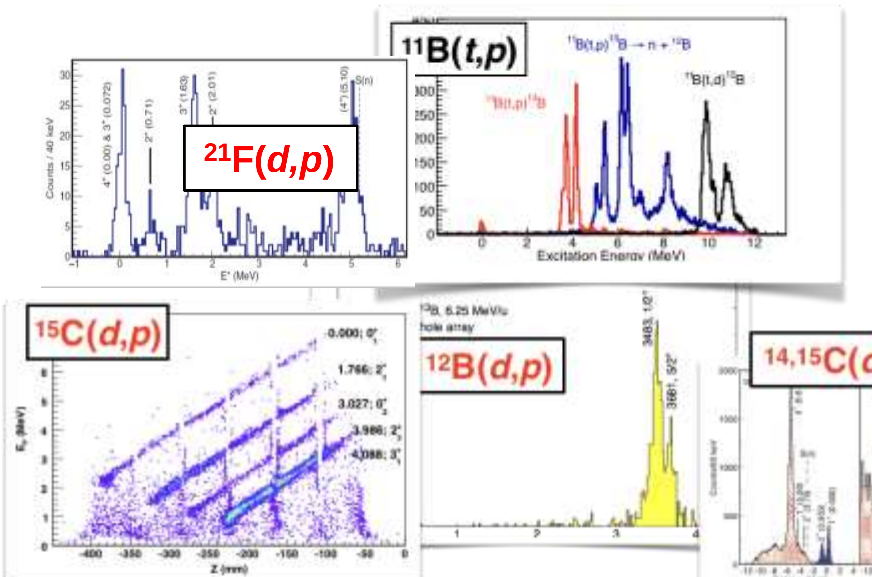


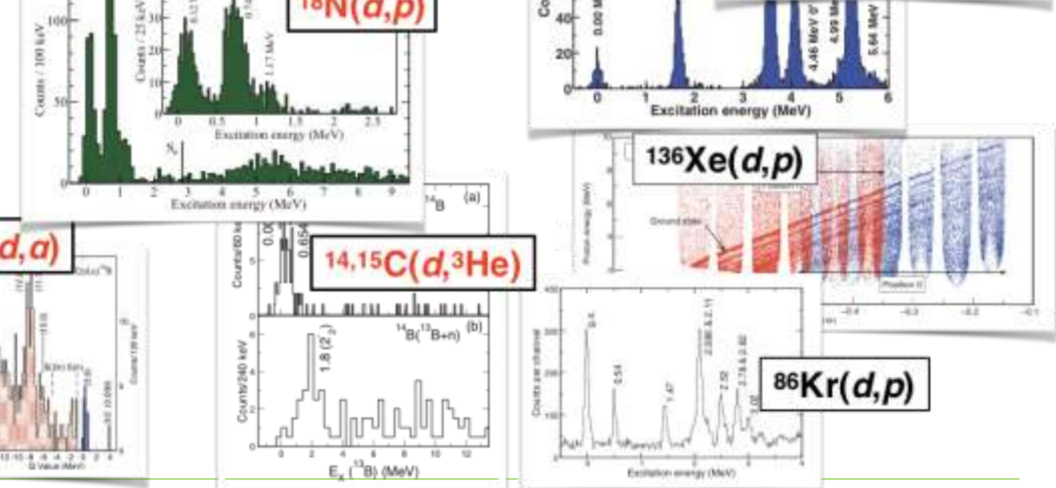
A decade of discoveries



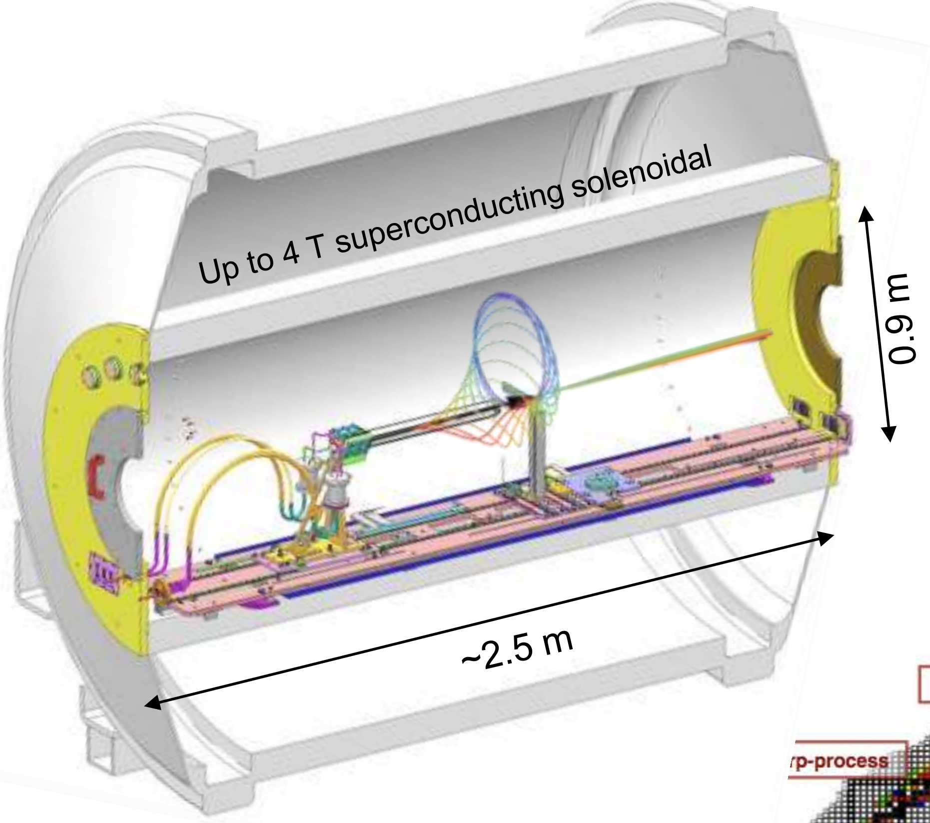
			16Ne	17Ne	18Ne	19Ne	20Ne	21Ne	22Ne	23Ne	24Ne	25N
		14F	15F	16F	17F	18F	19F	20F	21F	22F	23F	24F
	12O	13O	14O	15O	16O	17O	18O	19O	20O	21O	22O	23O
10N	11N	12N	13N	14N	15N	16N	17N	18N	19N	20N	21N	22N
9C	10C	11C	12C	13C	14C	15C	16C	17C	18C	19C	20C	21C
8B	9B	10B	11B	12B	13B	14B	15B	16B	17B	18B	19B	20B
7Be	8Be	9Be	10Be	11Be	12Be	13Be	14Be	15Be	16Be			







Future of HELIOS
- ISOLDE Solenoidal Spectrometer



CERN
HIE-ISOLDE
HIGH INTENSITY AND ENERGY UPGRADE

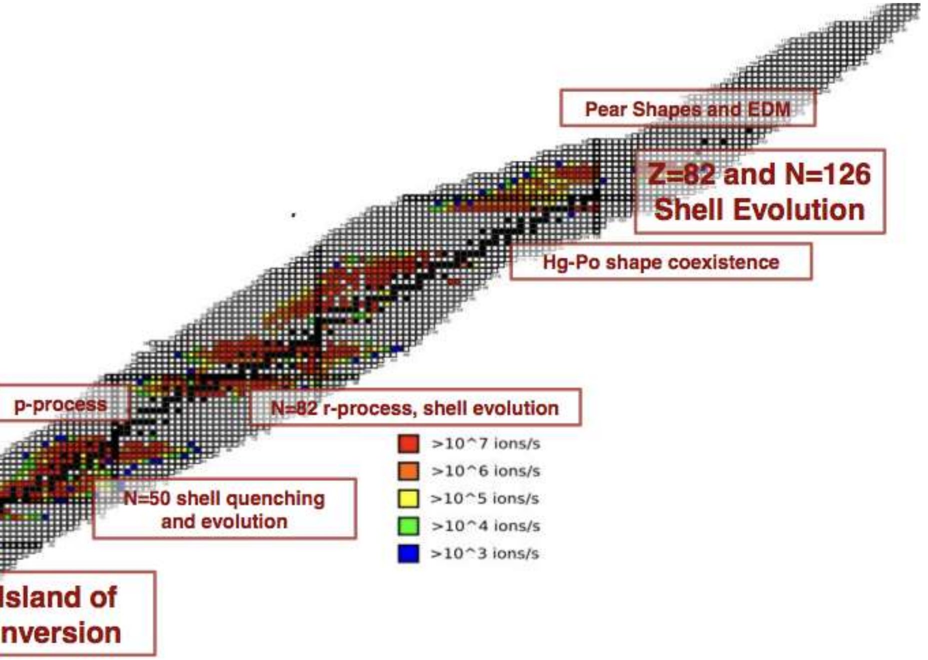
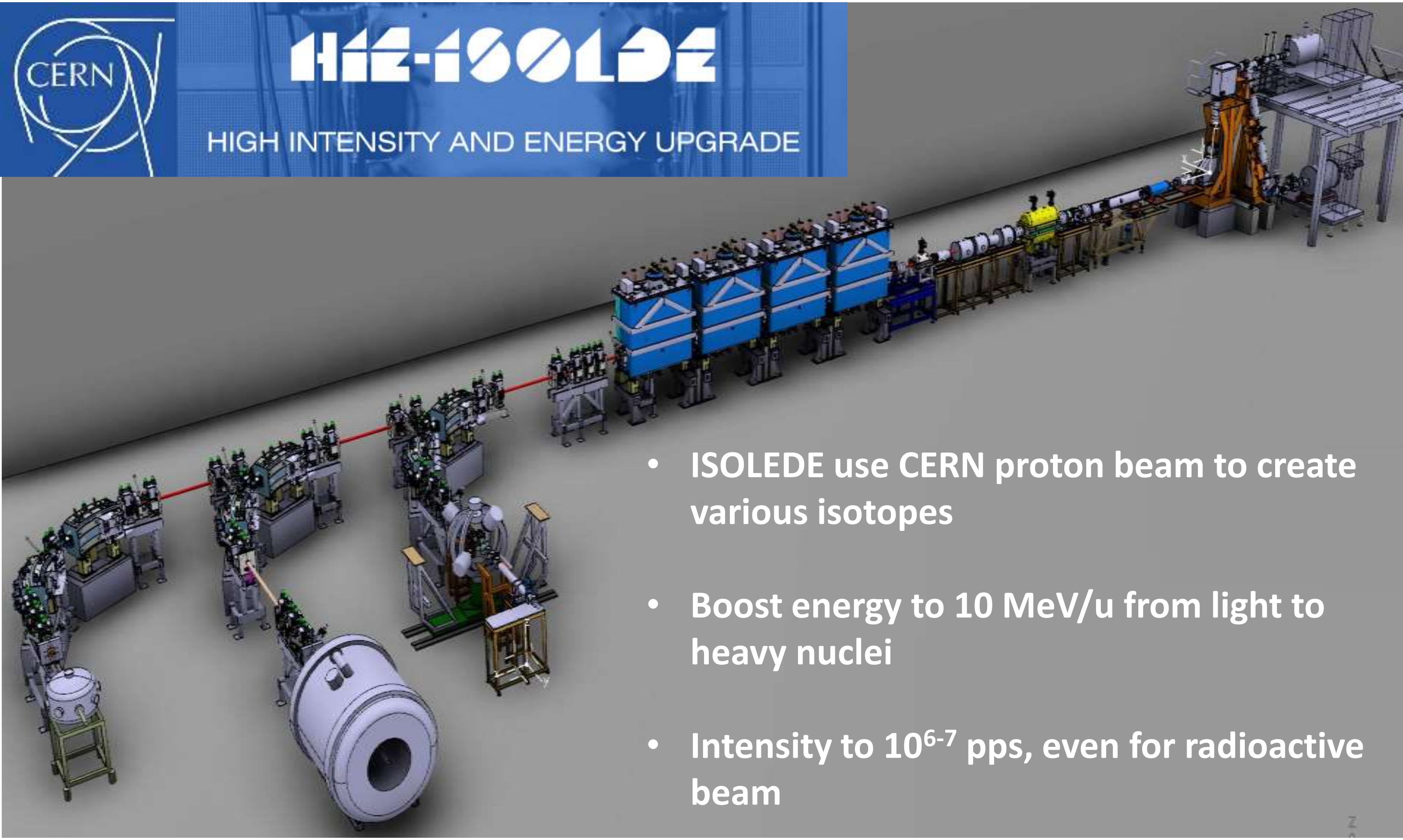


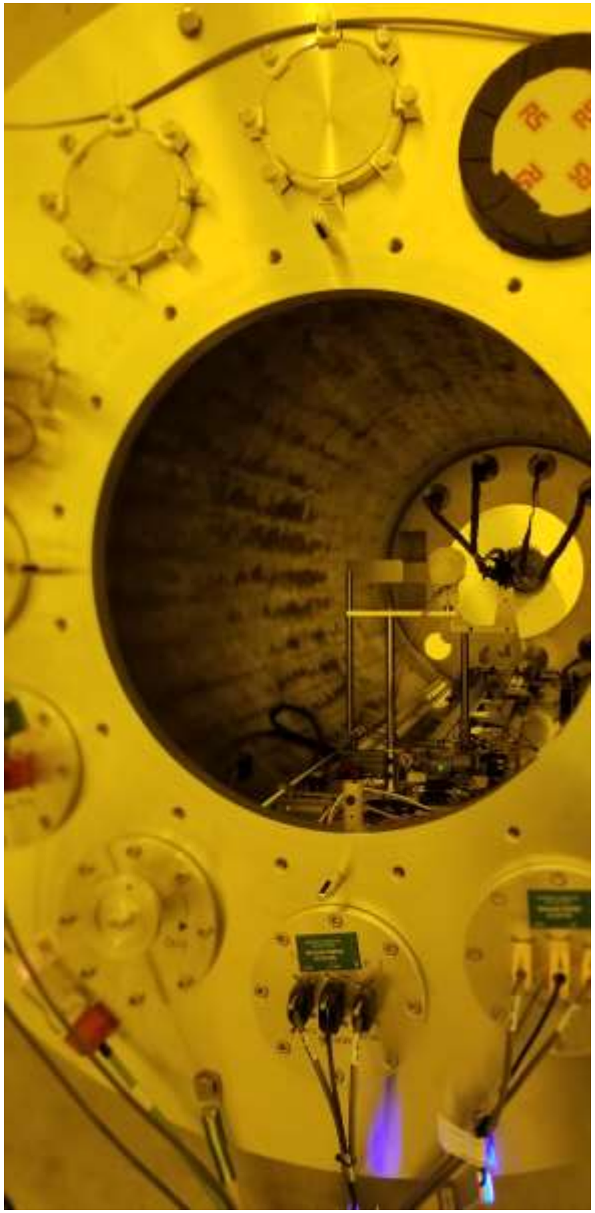
Chart of Nuclides plot courtesy of Liam Gaffney



HIE-ISOLDE

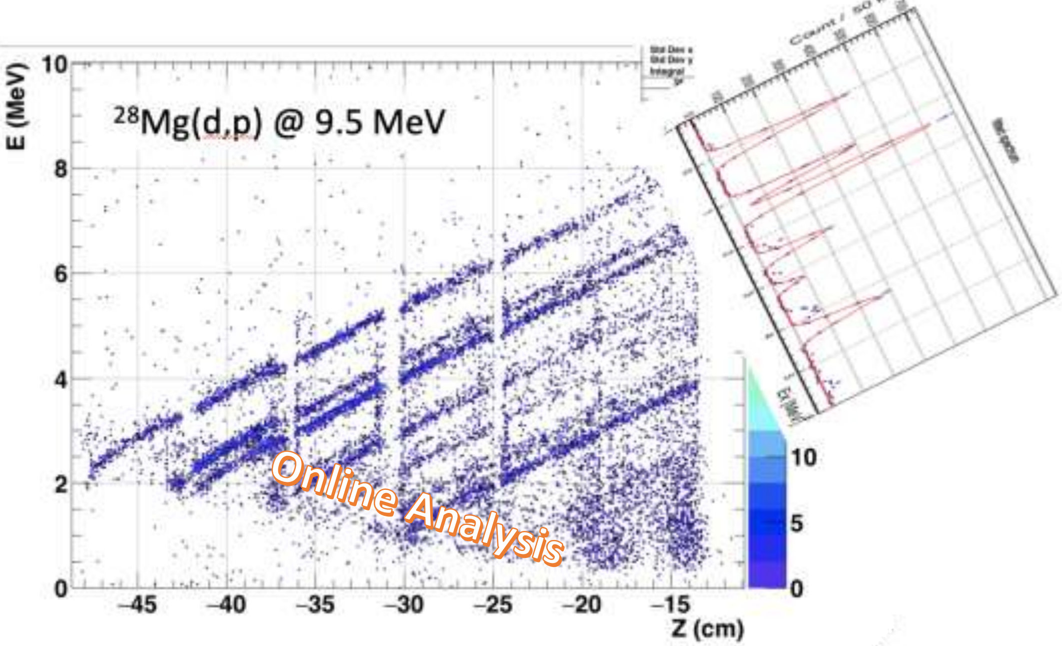
HIGH INTENSITY AND ENERGY UPGRADE

- ISOLEDE use CERN proton beam to create various isotopes
- Boost energy to 10 MeV/u from light to heavy nuclei
- Intensity to 10^{6-7} pps, even for radioactive beam

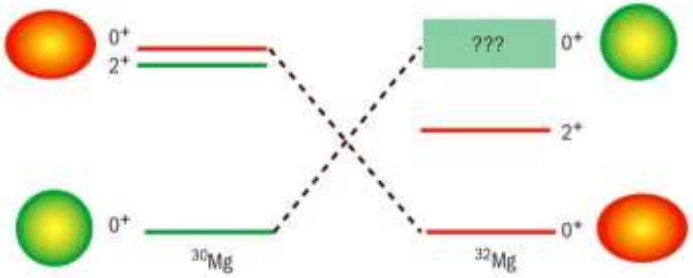



Active Shield

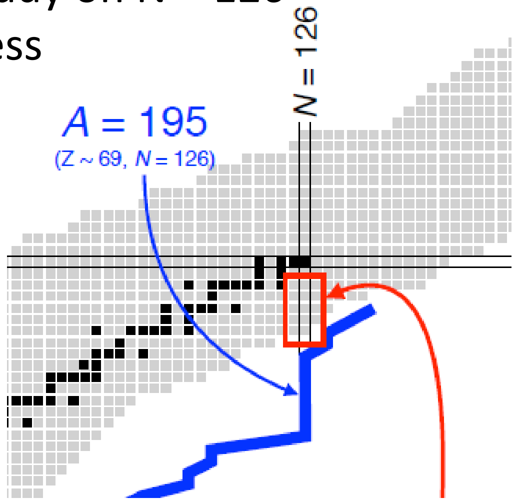

DANGER
MAGNETIC FIELD
Active Shield

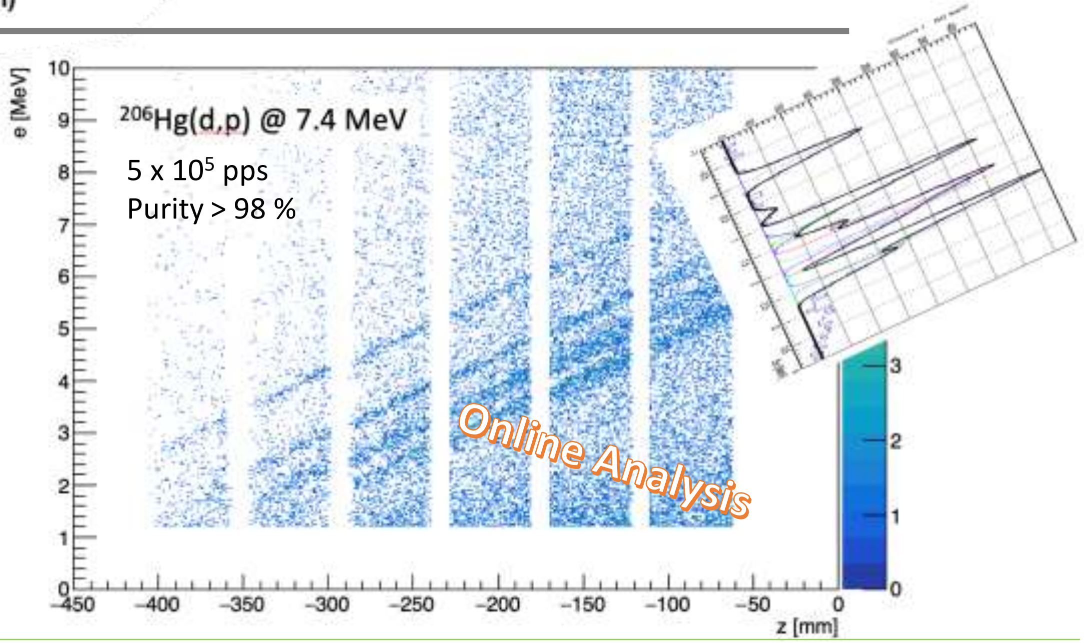


- The island of inversion
- Deformation



- First study on N > 126
- r-process





Summary

- HELIOS is a *large* acceptance, *small* energy resolution spectrometer.
- The measurement and data analysis is relatively simple and easy.
- It made a lot discoveries in the past decade.(will be more!!)