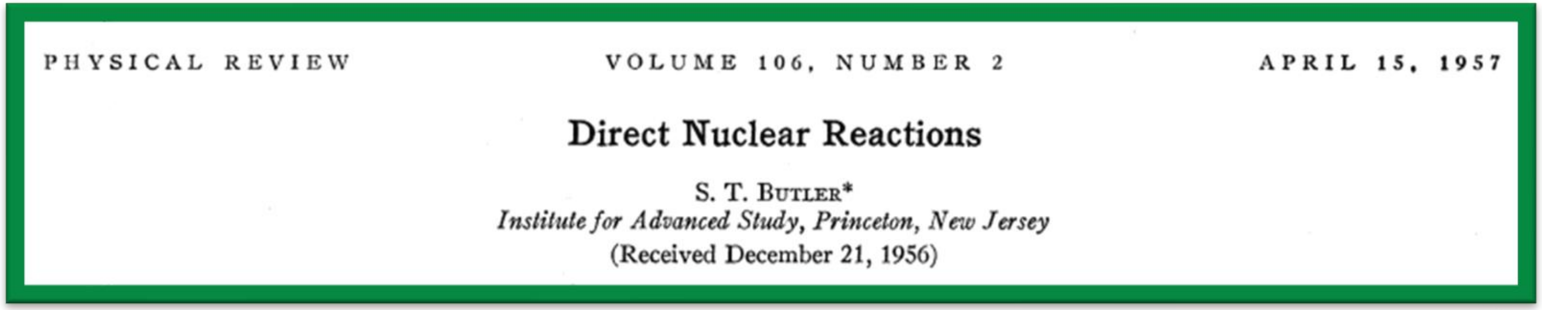
Single-particle spectroscopy of *exotic nuclei*:

The cases of ^{25}F and ^{207}Hg

Tsz Leung (Ryan) Tang

Argonne National Laboratory

Single-particle spectroscopy is a traditional probe. Used for more than 60 years.



PHYSICAL REVIEW VOLUME 106, NUMBER 2 APRIL 15, 1957

Direct Nuclear Reactions

S. T. Butler*
Institute for Advanced Study, Princeton, New Jersey
(Received December 21, 1956)

Stable beam

paradigm shift
in the past decades

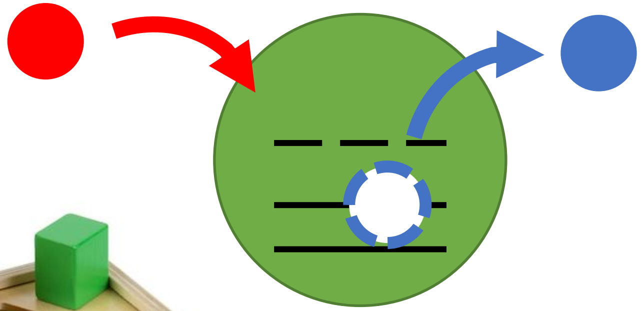
Radioactive beam

Inverse kinematics !!!

Single particle spectroscopy → **Fast Beam** $^{25}F(p,2p)^{24}O$ / **Slow Beam** $^{206}Hg(d,p)^{207}Hg$ → **Outlook**

Brief introduction to *Single-particle spectroscopy*

Single-particle spectroscopy



- **Direct reactions** that ADD/REMOVE a *single* nucleon.

  single step process

- Measure THREE things
  1. Energy level,
  2. Angular distribution,
  3. Yield / Cross section → Spectroscopic factor

- The power comes from the SHELL MODEL
  - The total wave function is constructed by ***single-particle wave function***

What is mean by single-particle?

The Hamiltonian of a nucleus A

$$H_A = \sum_i -\frac{\hbar^2}{2m_i}\nabla_i^2 + \sum_{i>j} V_{ij} + \cancel{\sum_{i>j>k} V_{ijk}} + \cdots$$

Mean Field Approximation

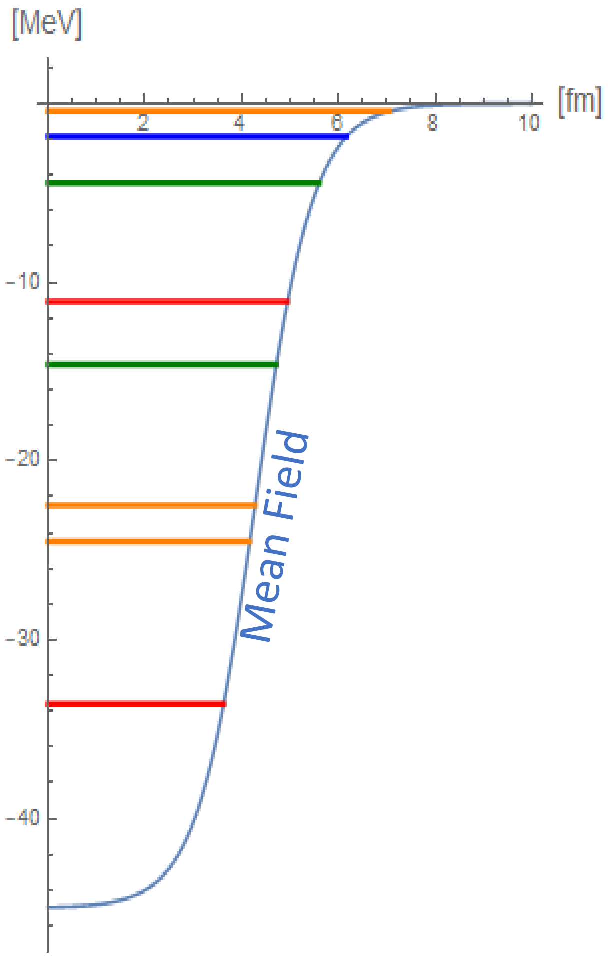
residual interaction

$$H_A = \left(\sum_i -\frac{\hbar^2}{2m_i}\nabla_i^2 + \boldsymbol{U}\right) + \left(\sum_{i>j} V_{ij} - \boldsymbol{U}\right) = \sum_i h_i + \sum_{i>j} R_{ij}$$

Single particle state

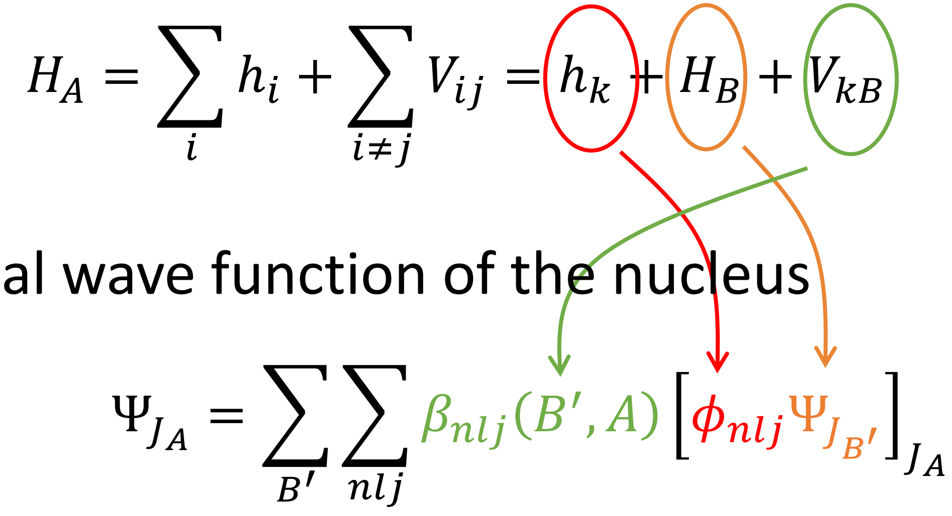
$$h_k \phi_{nlj} = \epsilon_{nlj}\phi_{nlj}$$

Single particle energy



Connection to single-particle spectroscopy

The Hamiltonian of a nucleus A = B + k



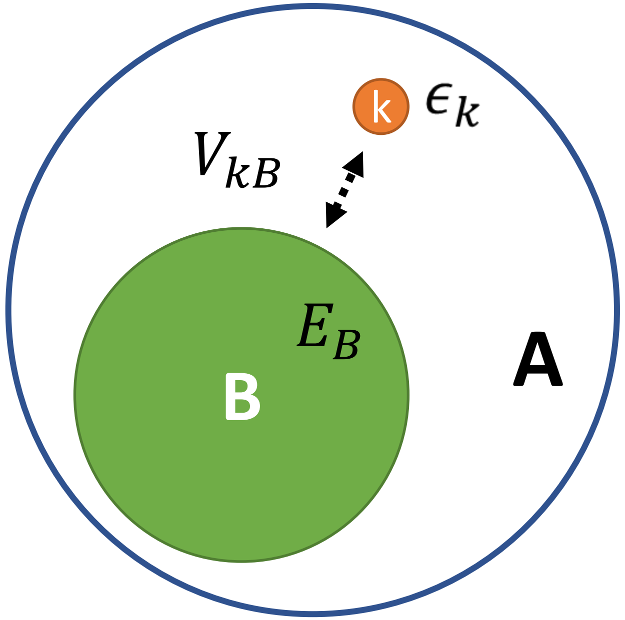
$$H_A = \sum_i h_i + \sum_{i\neq j} V_{ij} = h_k + H_B + V_{kB}$$

Total wave function of the nucleus

$$\Psi_{J_A} = \sum_{B'} \sum_{nlj} \beta_{nlj}(B', A) \left[\phi_{nlj} \Psi_{J_{B'}} \right]_{J_A}$$

$$h_k \phi_{nlj} = \epsilon_{nlj} \phi_{nlj}$$

$$H_B \Psi_{J_B} = E_{j_B} \Psi_{J_B}$$



Spectroscopic factor

$$S_{nlj}(B, A) = \left| \langle \Psi_B | a^+_{nlj} | \Psi_A \rangle \right|^2 = \left| \beta_{nlj}(B, A) \right|^2$$

$$\langle \Psi_B | \Psi_A \rangle = \beta_{nlj}(B, A) \phi_{nlj}$$

Effective Single particle energy

$$\epsilon_{nlj} = \frac{\sum_B E_j \left| \beta_{nlj}(B, A) \right|^2}{\sum_B \left| \beta_{nlj}(B, A) \right|^2}$$

$$h_k \phi_{nlj} = \epsilon_{nlj} \phi_{nlj}$$

$$H_A \Psi_{J_A} = E_{j_A} \Psi_{J_A}$$

Intuitive picture via Single-particle spectroscopy

Spectroscopic factor

$$\langle \Psi_B | \Psi_A \rangle = \beta_{nlj}(B,A)\phi_{nlj}$$

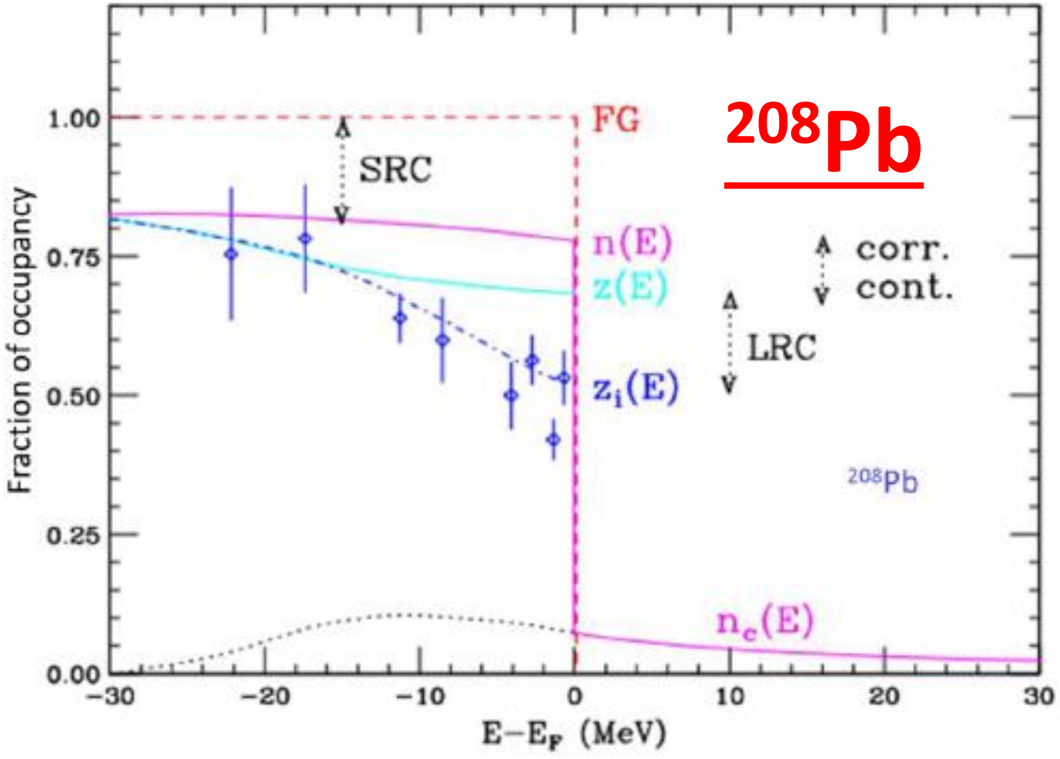
- Similarity between 2 nuclear systems
- fraction of occupancy

Effective single particle energy

$$\epsilon_{nlj} = \frac{\sum_B E_j \left|\beta_{nlj}(B,A)\right|^2}{\sum_B \left|\beta_{nlj}(B,A)\right|^2}$$

Weighted energy
→ average out the perturbation by the residual interaction.
→ monopole part of the Hamiltonian
→ mean field picture.
→ extract the spin-orbit splitting & more…

I. Sick, Quasi-free knockout reaction, QFS workshop at ECT, Trento, 2008.

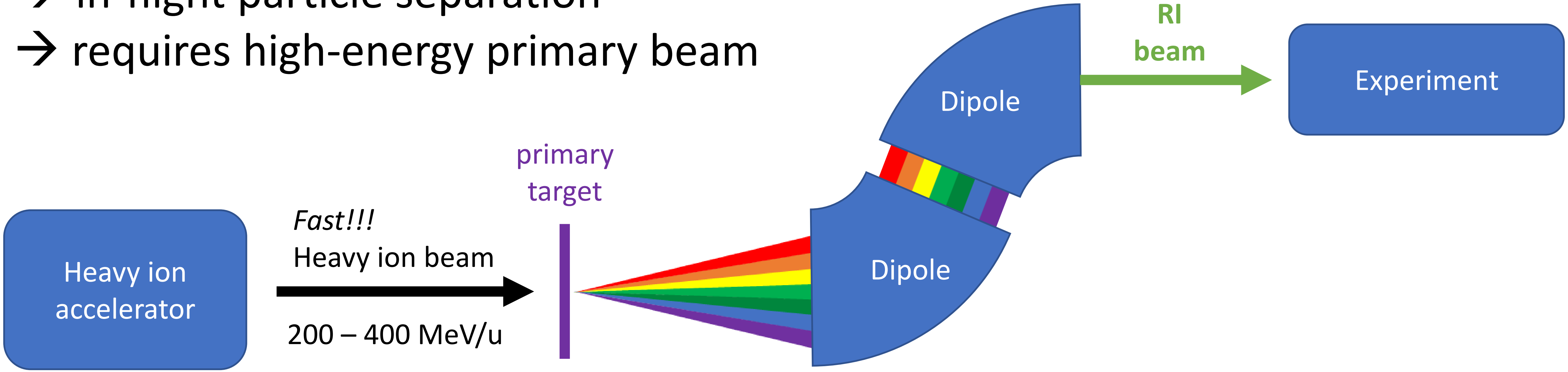


Fast beam case: $^{25}F(p,2p)^{24}O$

Similarity between ^{25}F and $^{24}O + p$

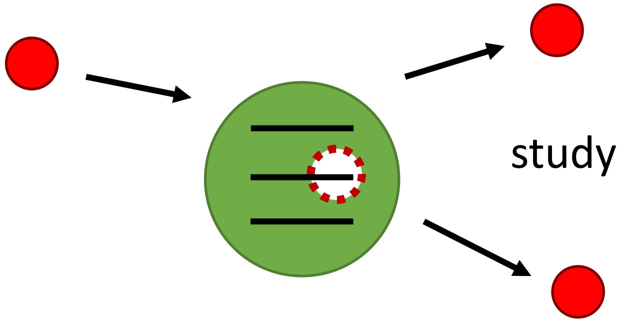
Fast beam production

Projectile fragmentation method
→ breaking up heavy nucleus into many light nuclei
→ in-flight particle separation
→ requires high-energy primary beam



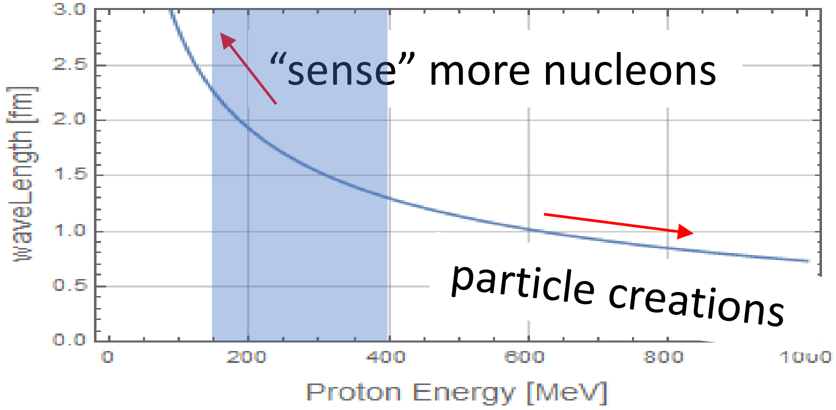
With fast beam, quasi-free (*p*,2*p*) is a natural choice.

The (*p*,2*p*) knockout Reaction



study the fullness of orbital

de Broglie wavelength

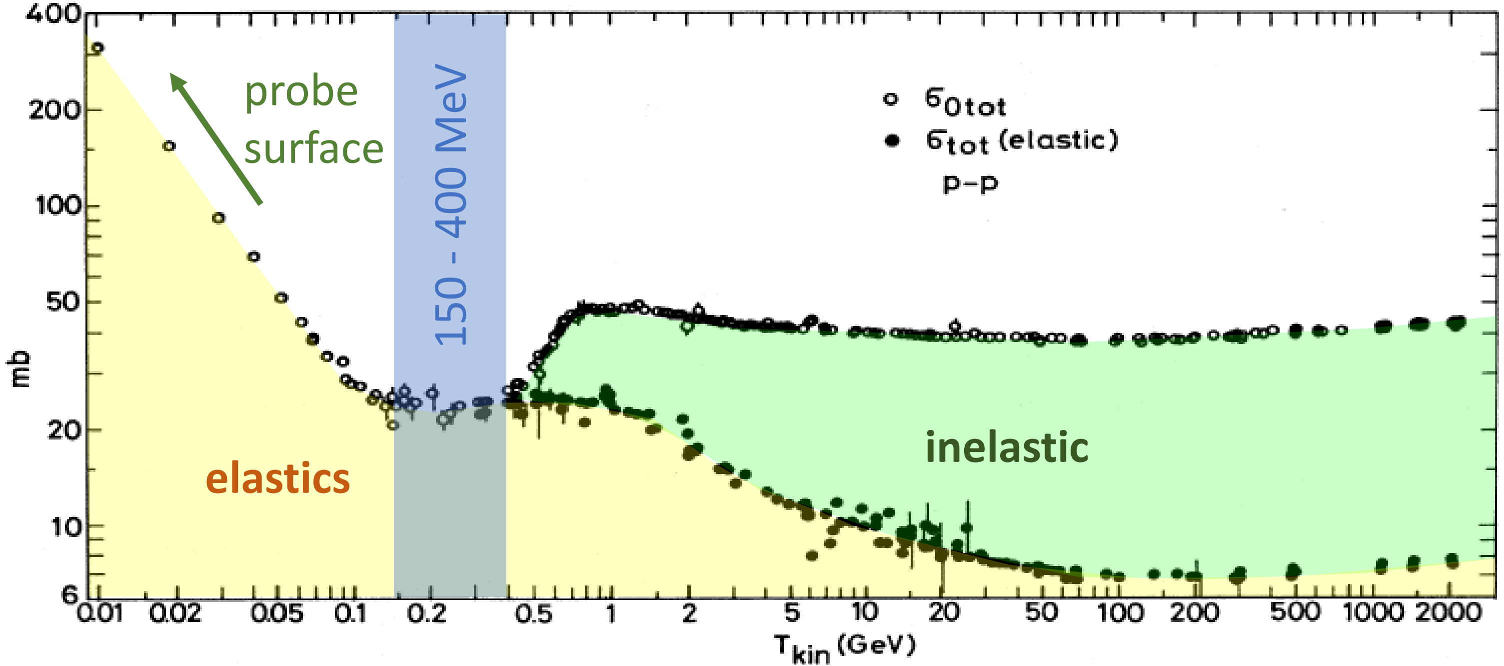


“sense” more nucleons

particle creations

Ideal energy is 150 – 400 MeV

- Nucleus to be mostly transparent
  Quasi-free!!
- Nucleon motion is **frozen**
- Able to probe deeply bound states
- The reaction is “**CLEAN**”



probe surface

150 - 400 MeV

elastics

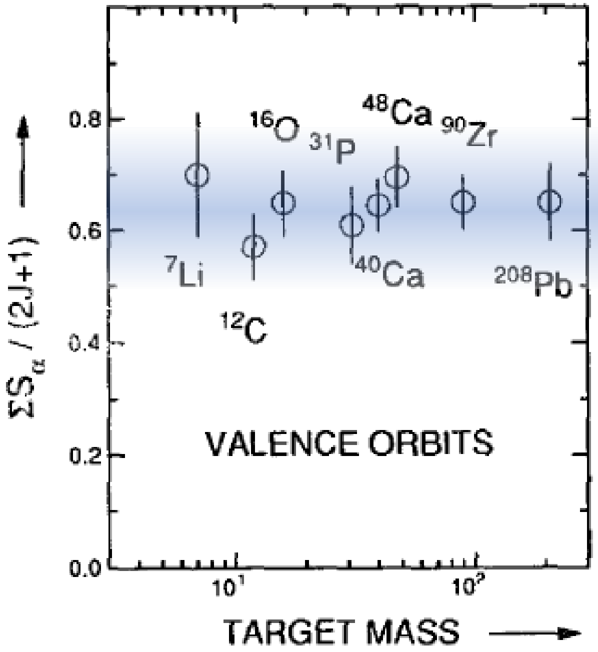
inelastic

Rev. Mod. Phys. **65**, 47 (1993)

Quasi-free *(p,2p)* is as “clean” as *(e,e’p)*

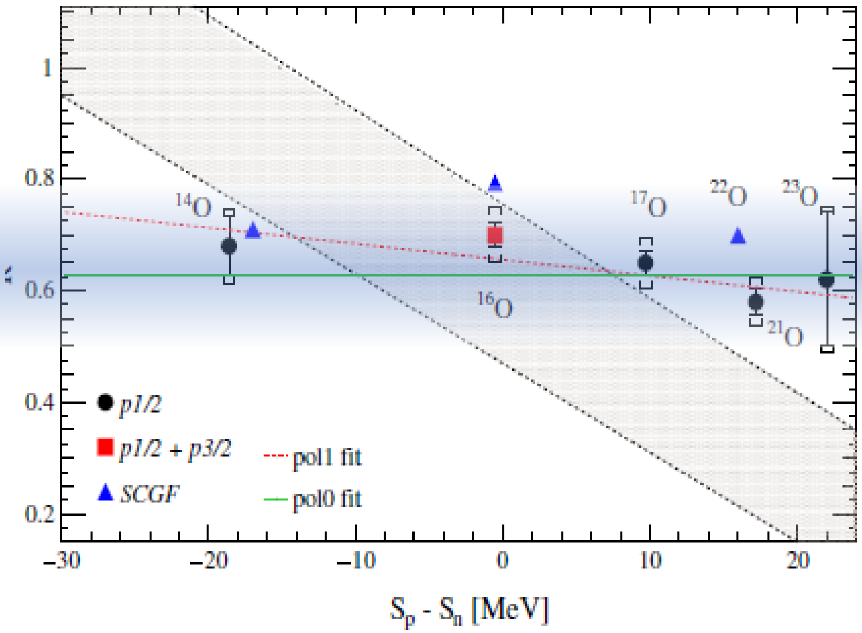
L. Lapikas, NPA **553**, 297 (1993)

(e,e’p)



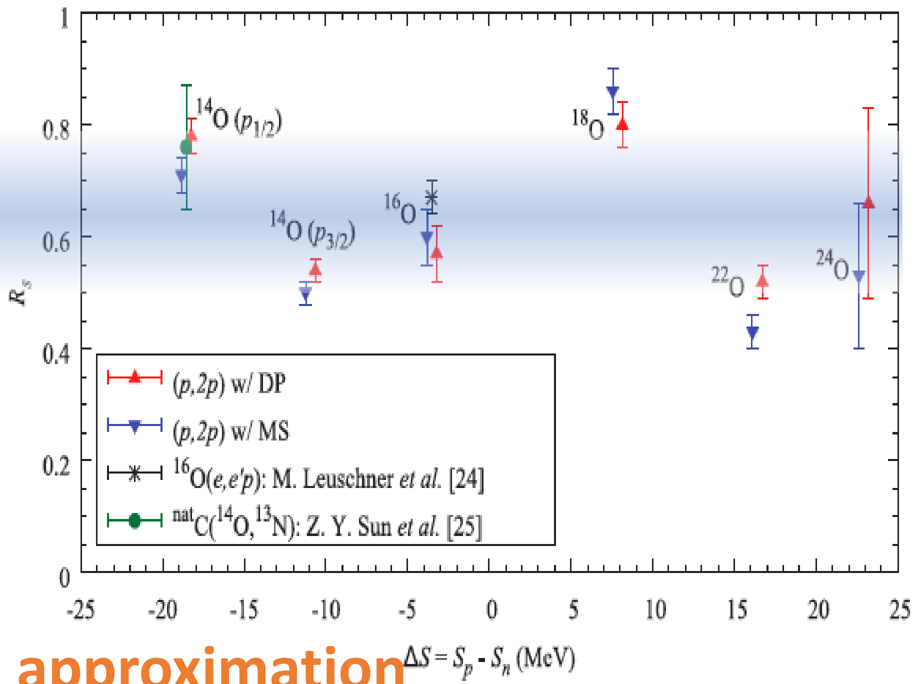
L. Atar *et al.*, PRL **120**, 052501 (2018)

GSI, ***(p,2p)*** @ 300 – 450 MeV/u



S. Kawase *et al.*, PTEP 021D01 (2018)

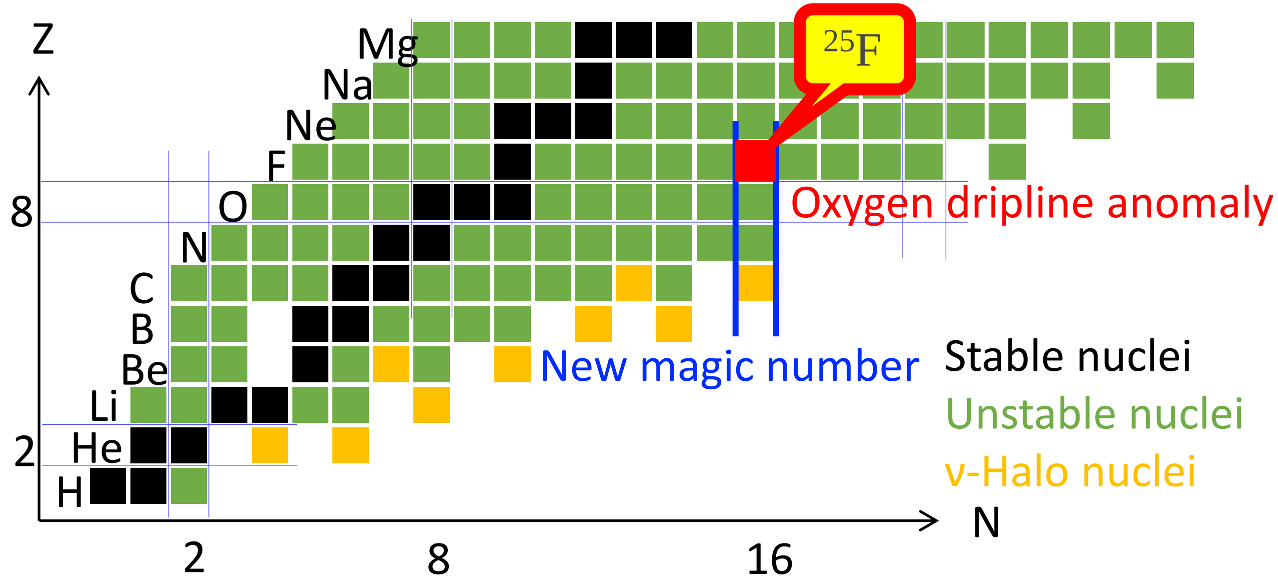
RCNP/RIKEN, ***(p,2p)*** @ 200 - 250 MeV/u



(e,e’p) **: Coulomb interaction is well known.**

(p,2p) **:**
- **Impulse approximation**
- **delta interaction**
- **frozen nucleon motion**

^{25}F(p,2p)^{24}O: Oxygen dripline anomaly



Fluorine : 1-proton in sd shell.

→ support neutrons up to the p-f shell!

→ something interesting from that proton.

^{25}F(p,2p)

- ^{24}O is a doubly magic
  → the proton configuration mixing should be minimum.
- Knockout of the proton
  → study the neutron shell

$$S_{nlj}(O,F) = \left|\langle\Psi_O|a_{nlj}\,|\Psi_F\rangle\right|^2$$

$$= \left|\beta_{nlj}(O,F)\right|^2$$

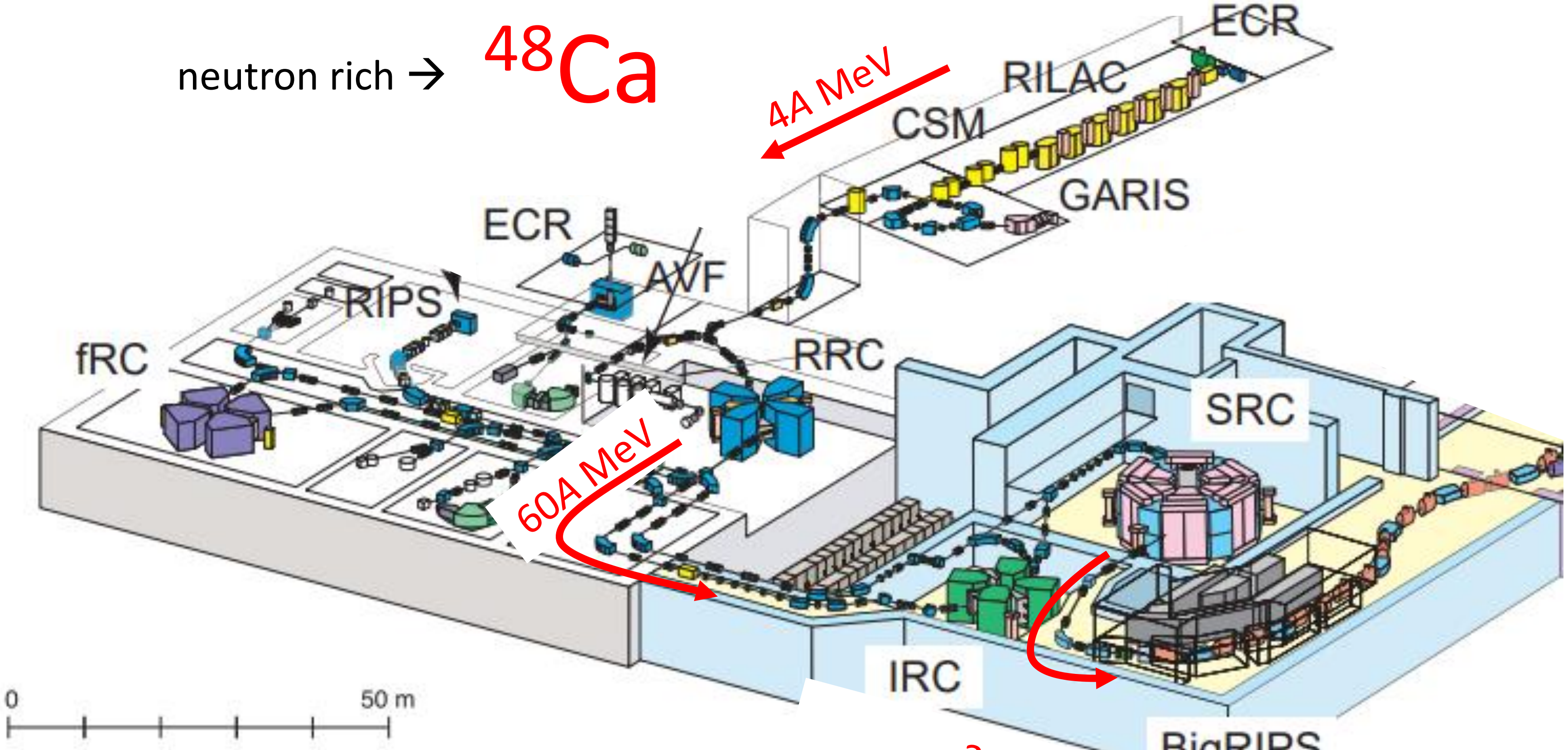
$$= \left|\langle\pi_O|a_{nlj}\,|\pi_F\rangle\right|^2 \left|\langle\nu_O|\nu_F\rangle\right|^2$$

proton shell neutron shell

^{25}F beam production (I)

Radioactive Ion Beam Factory (RIBF), RIKEN

neutron rich → ^{48}Ca



4A MeV

60A MeV

345A MeV,
200 pnA = 1.25 x 10^{12} pps

東京大学 THE UNIVERSITY OF TOKYO

RIKEN NiSHiNA CENTER

^{25}F beam production (II)

Radioactive Ion Beam Factory (RIBF), RIKEN

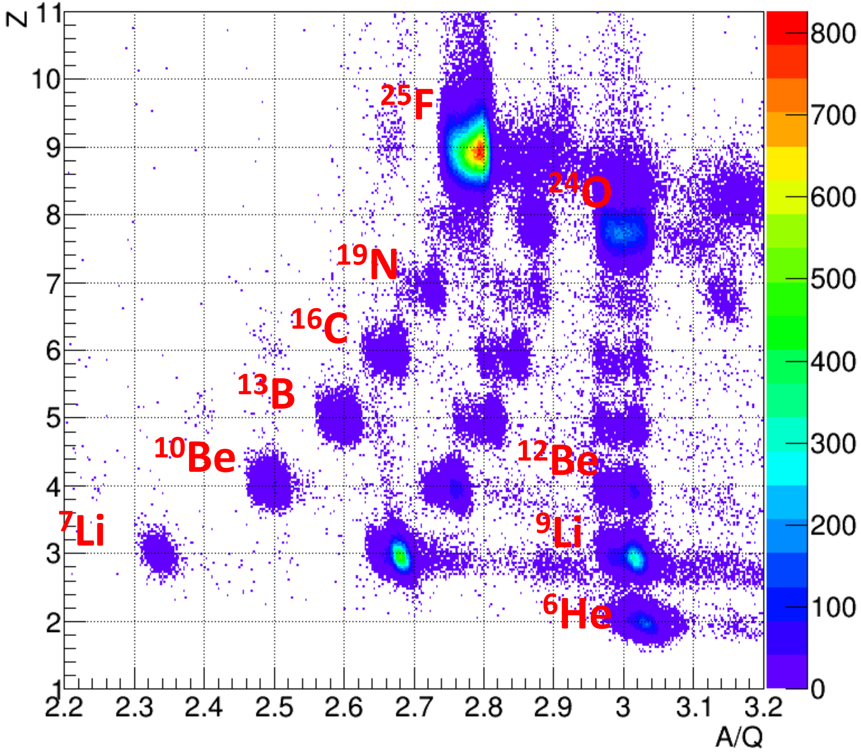
^{48}Ca

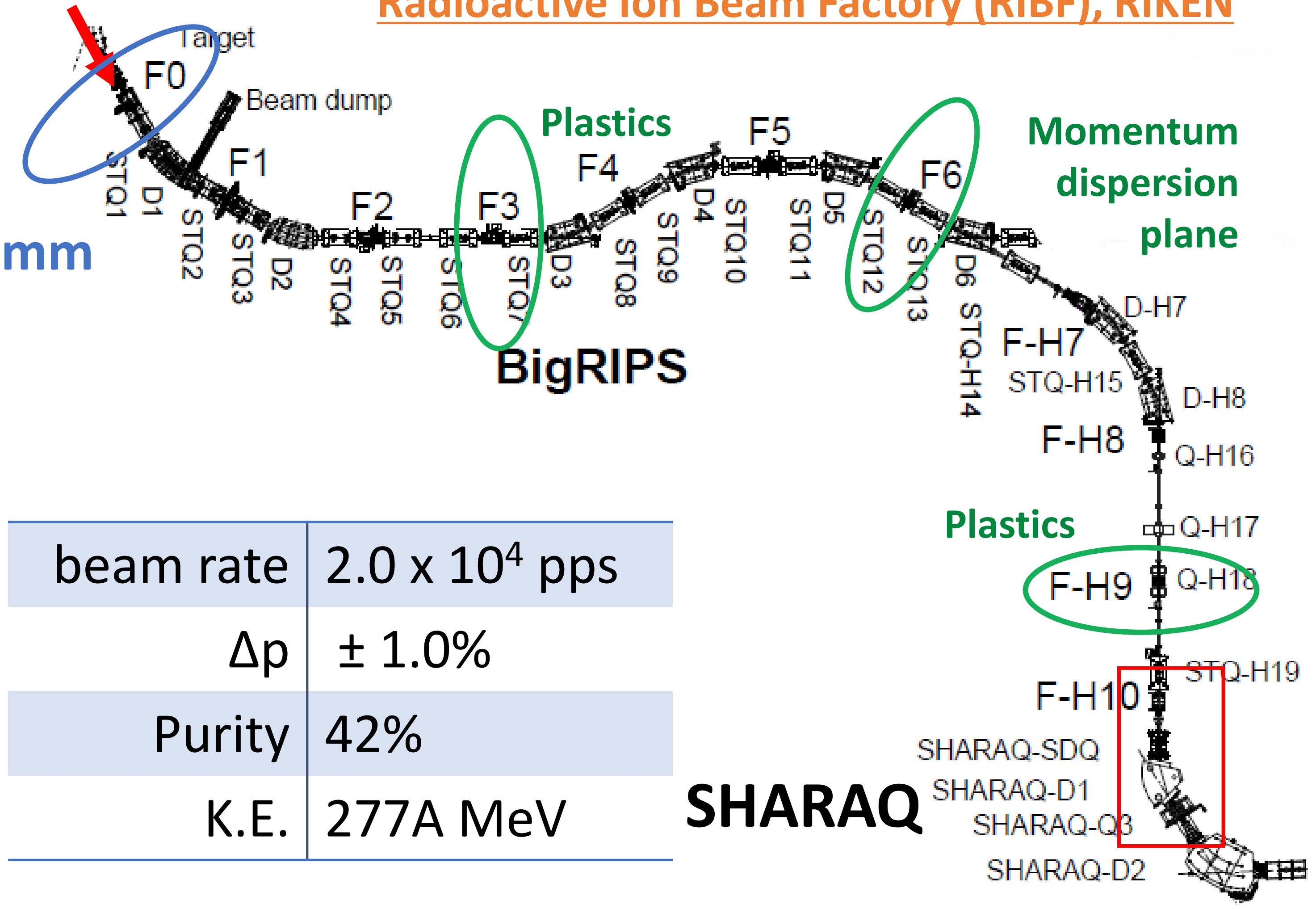
345*A* MeV

200pnA

^{9}Be 30mm

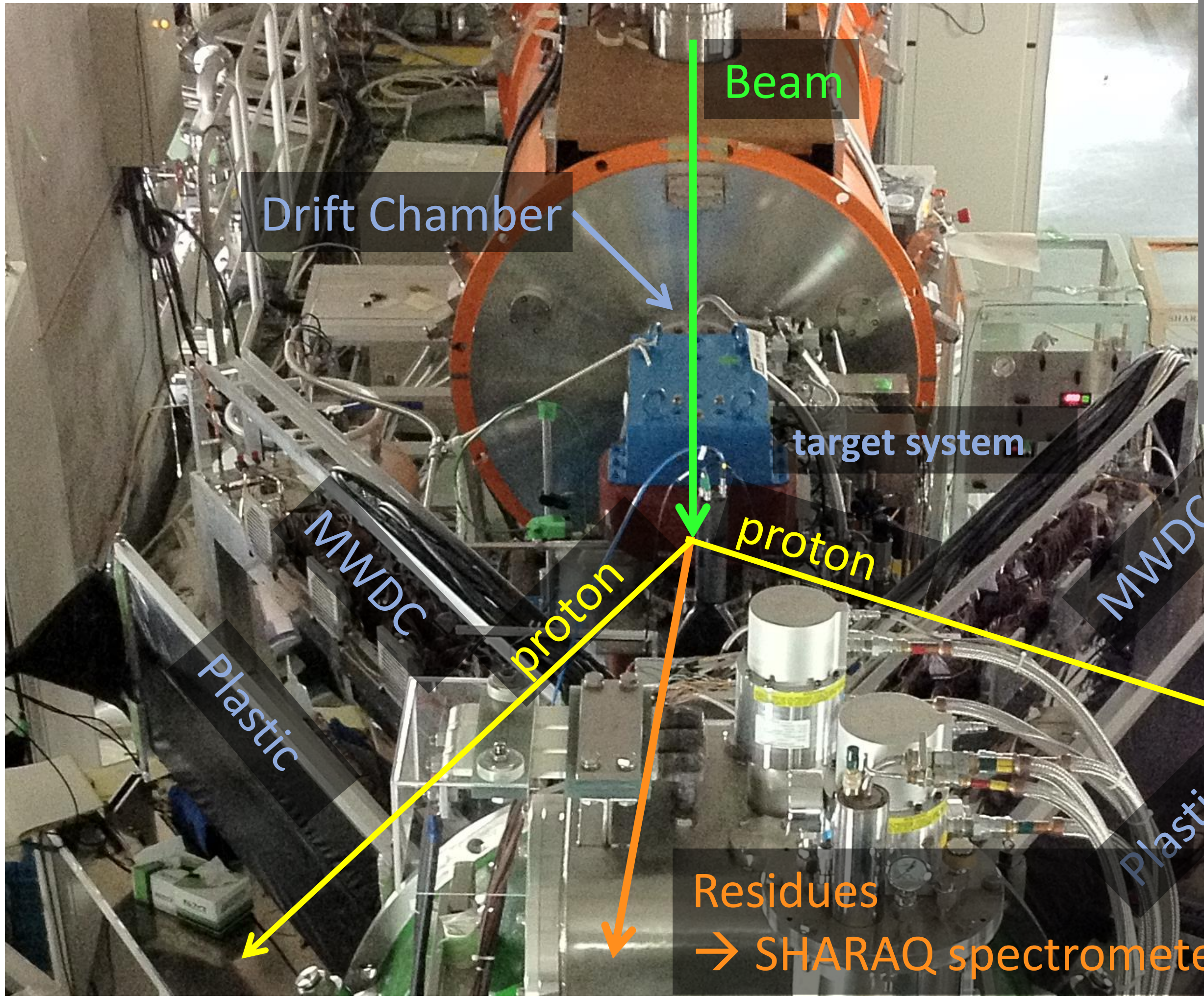
ΔE – TOF – Bρ method

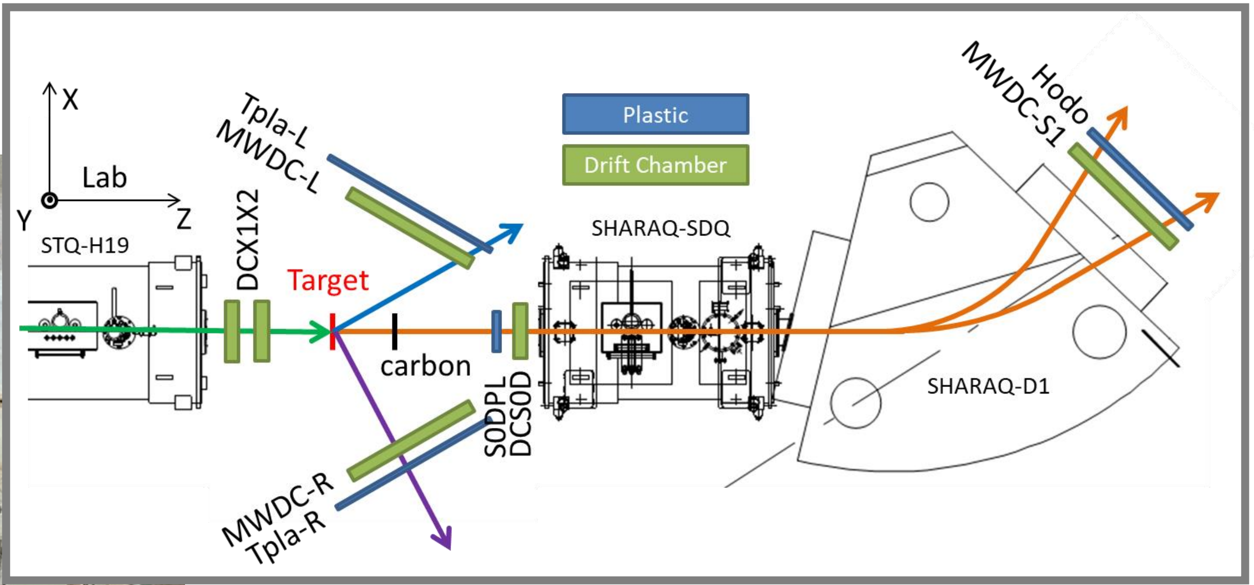




beam rate	2.0 x 10^{4} pps
Δp	± 1.0%
Purity	42%
K.E.	277A MeV

Experimental Setup





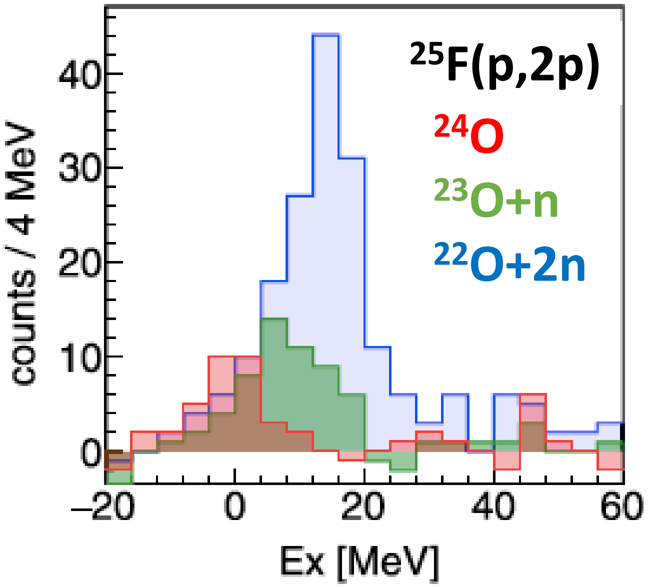
$$S_p = m_O + m_2 - m_F$$

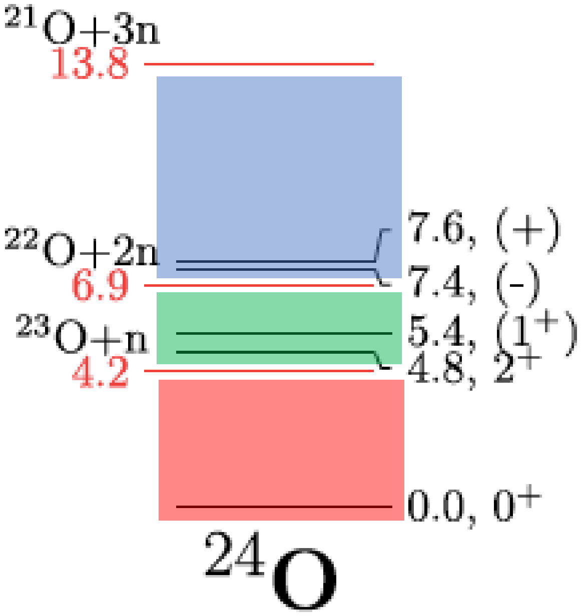
$$m_O = m\left(\mathbb{P}_F + \mathbb{P}_p - \mathbb{P}_1 - \mathbb{P}_2\right)$$

known

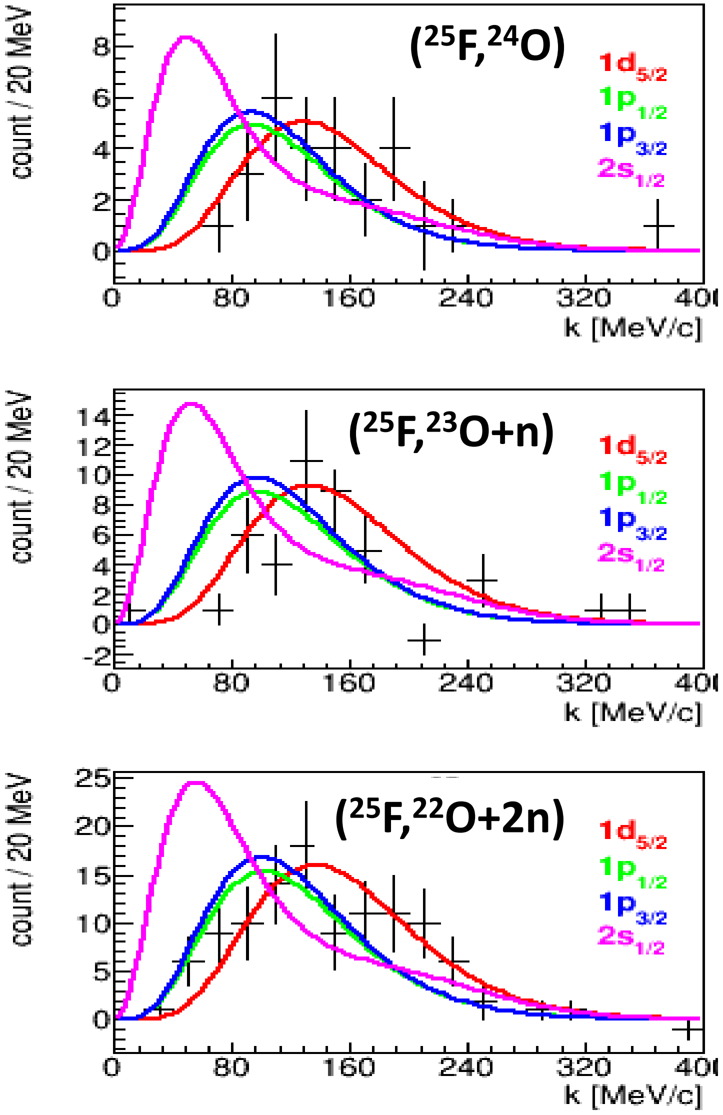
measure

Experimental Result





Momentum distribution



- **$(^{25}F,^{24}O)$** is a single peak from $1d_{5/2}$ orbital.
- **$(^{25}F,^{23}O+n)$** is from sd-orbit → no s-orbital → $1d_{5/2}$ orbtial

- Mean energy of **$(^{25}F,^{22}O+2n)$** is ~ 13 MeV
- shell gap between sd and p-shells = 12.7 MeV
  - p-orbital should dominate.

Spectroscopic factor and wave function of ^{25}F

$$\text{Spectroscopic factor} = \frac{\text{Exp. Cross Section}}{\text{DWIA Cross Section}}$$

(PIKOE, K. Ogata *et al.*, Osaka University, Japan)

Optical potential :
Microscopic folding potential
(Melbourne G-matrix interaction)

Bound state:
Woods-Saxon potential
$r = 1.27A^{1/3}$ fm,
$a = 0.67$ fm

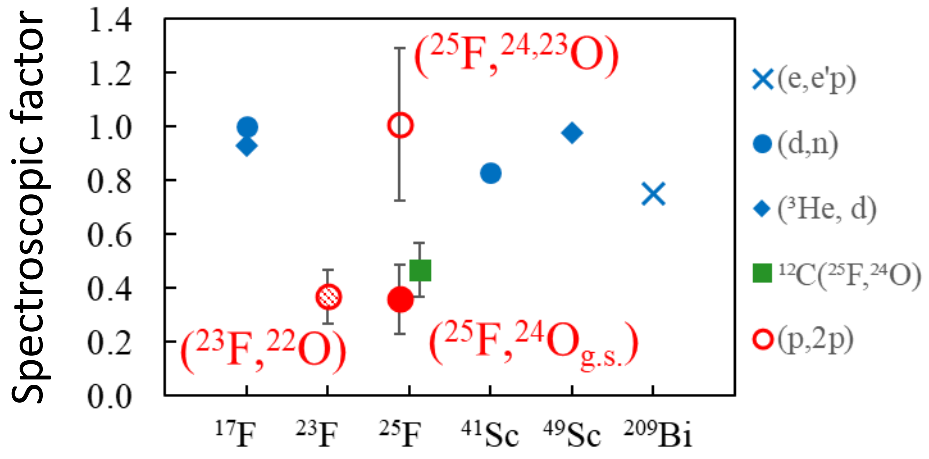
	Residue	Orbital	SF
^{25}F(p,2p)	^{24}O	$1d_{5/2}$	0.36 ± 0.13
	^{23}O + n		0.65 ± 0.25

Double magic
↓

Wave function of ^{25}F = $|^{25}\mathrm{F}\rangle \approx |\pi 1d_{5/2}\rangle \otimes \left(\sqrt{0.36}\,|^{24}\mathrm{O}_{\mathrm{g.s.}}\rangle + \sqrt{0.65}\,|^{24}\mathrm{O}^{*}\rangle + \cdots\right)$

Core of ^{25}F = **~35%** $^{24}\mathrm{O}_{\mathrm{g.s.}}$ and **~65%** ^{24}O excited states.

Why the G.S. spectroscopic factor is so small?



- In double magic + p nuclei,
  the quenching is small.

1. The proton in ^{25}F is almost stay in $d_{5/2}$ shell.
   → it seems that proton is in SPS
2. There are 65% excited ^{24}O in ^{25}F core.
   → something on the neutron side.

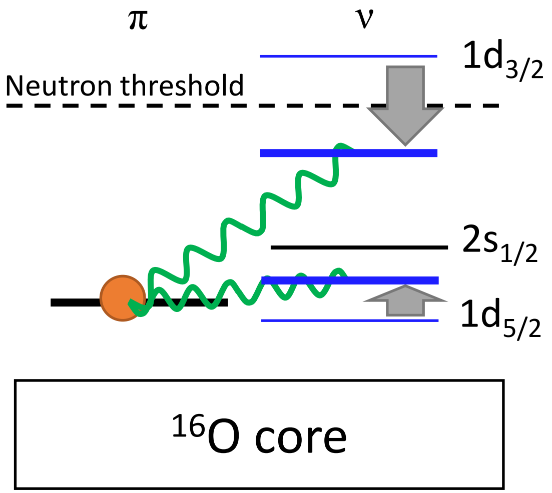
Possible Mechanism:

Type-I shell evolution driven by **tensor force**

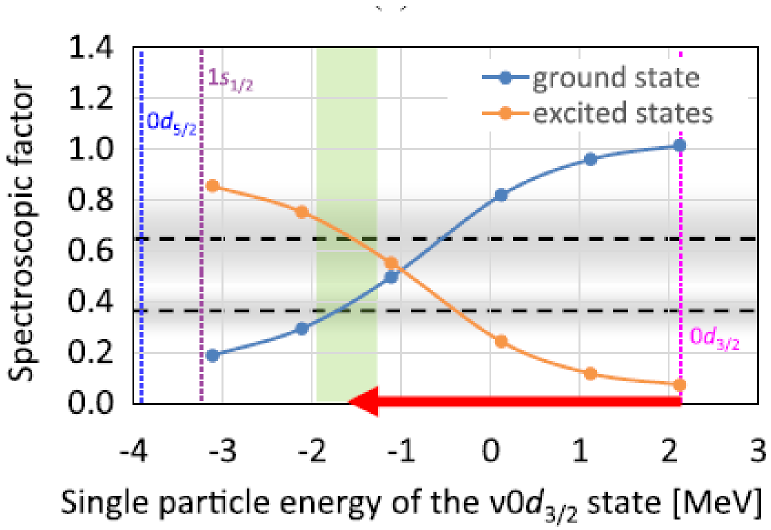
T. Otuska *et al.*, J. Phys. G: Nucl. Part. Phys. **43** (2016) 024009

Consequence are:

- Increase neutron configuration mixing
- Disappear of *N = 16* magicity.
- Long Fluorine neutron dripline



Fluorine



Can shell model calculations explain the result?

	Residue	Orbit	SF_{exp}	SF(SFO)	SF(USDB)	SF(SDPF-MU)
^{25}F(p,2p)	^{24}O	$1d_{5/2}$	0.36 ± 0.13	0.9	1.01	0.95
	^{23}O + n		0.65 ± 0.25	0.1	-	-
			Model space	p-sd	sd	sd-pf
			Reference	T. Suzuki *et al.*, PRC **67** (2003) 044302	B. A. Brown *et al.*, PRC **74** (2006) 034315	Y. Utsno *et al.*, RPC **86** (2012) 051301

with 0, 1, 2 $\hbar\omega$

1. **Give almost unity of ground state**
2. **Produce no/little fragmentation.**

May be…
- The tensor force is not strong enough?
- Real 3N force is needed?
- Strong deformation of ^{25}F?

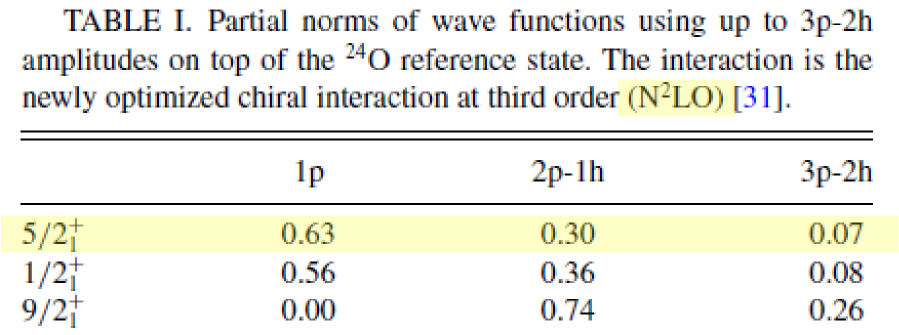
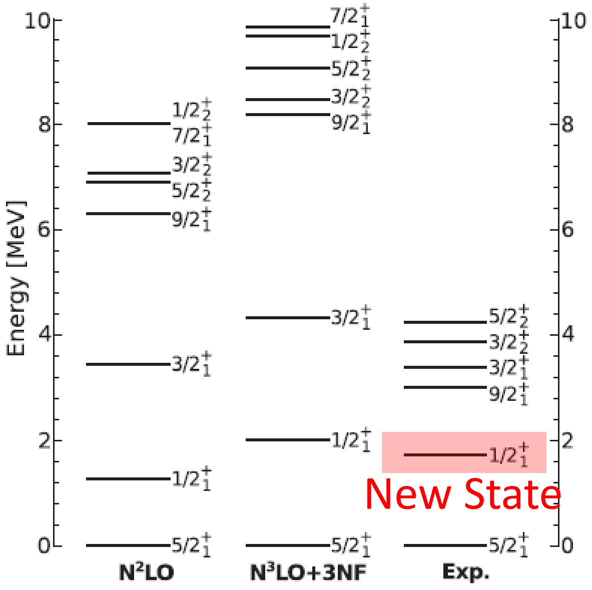


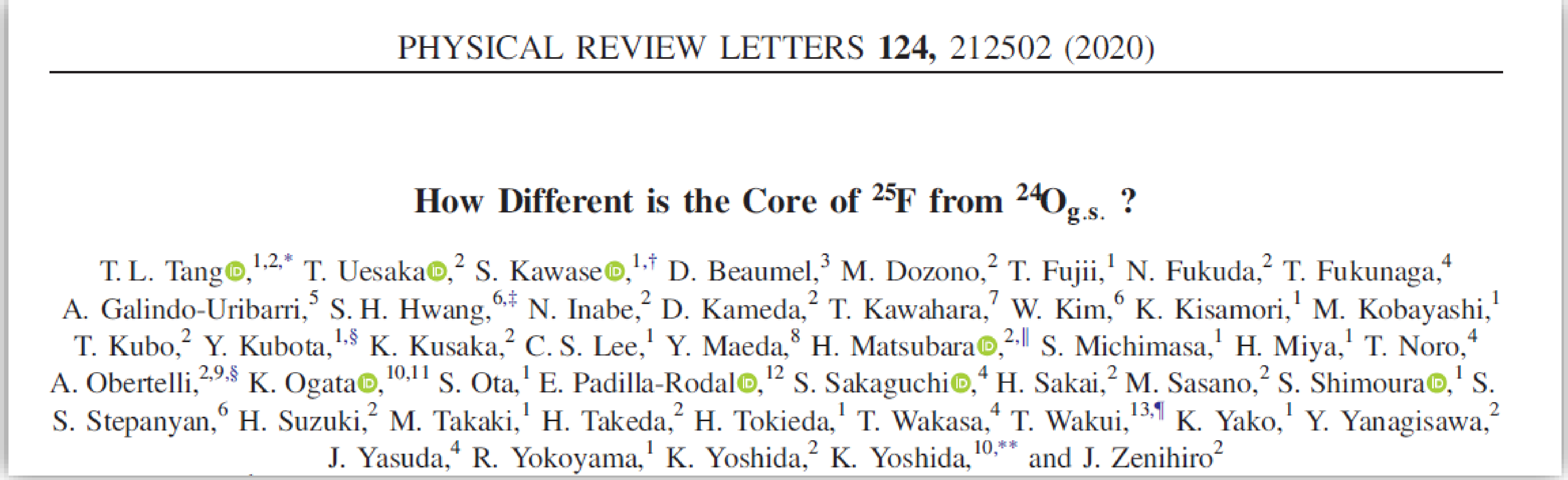
TABLE I. Partial norms of wave functions using up to 3p-2h amplitudes on top of the ^{24}O reference state. The interaction is the newly optimized chiral interaction at third order (N^{2}LO) [31].

	1p	2p-1h	3p-2h
$5/2_1^+$	0.63	0.30	0.07
$1/2_1^+$	0.56	0.36	0.08
$9/2_1^+$	0.00	0.74	0.26

in-beam γ -ray spectroscopy



Zs. Vajta *et al.*, PRC **89**, 054323 (2014)



PHYSICAL REVIEW LETTERS **124**, 212502 (2020)

How Different is the Core of ^{25}F from $^{24}\mathrm{O}_{\mathrm{g.s.}}$?

T. L. Tang,[1,2,*] T. Uesaka,[2] S. Kawase,[1,†] D. Beaumel,[3] M. Dozono,[2] T. Fujii,[1] N. Fukuda,[2] T. Fukunaga,[4] A. Galindo-Uribarri,[5] S. H. Hwang,[6,‡] N. Inabe,[2] D. Kameda,[2] T. Kawahara,[7] W. Kim,[6] K. Kisamori,[1] M. Kobayashi,[1] T. Kubo,[2] Y. Kubota,[1,§] K. Kusaka,[2] C. S. Lee,[1] Y. Maeda,[8] H. Matsubara,[2,∥] S. Michimasa,[1] H. Miya,[1] T. Noro,[4] A. Obertelli,[2,9,§] K. Ogata,[10,11] S. Ota,[1] E. Padilla-Rodal,[12] S. Sakaguchi,[4] H. Sakai,[2] M. Sasano,[2] S. Shimoura,[1] S. Stepanyan,[6] H. Suzuki,[2] M. Takaki,[1] H. Takeda,[2] H. Tokieda,[1] T. Wakasa,[4] T. Wakui,[13,¶] K. Yako,[1] Y. Yanagisawa,[2] J. Yasuda,[4] R. Yokoyama,[1] K. Yoshida,[2] K. Yoshida,[10,**] and J. Zenihiro[2]

Slow beam case: $^{206}\mathrm{Hg}(d,p)^{207}\mathrm{Hg}$

Transfer reaction

Solenoidal spectrometer

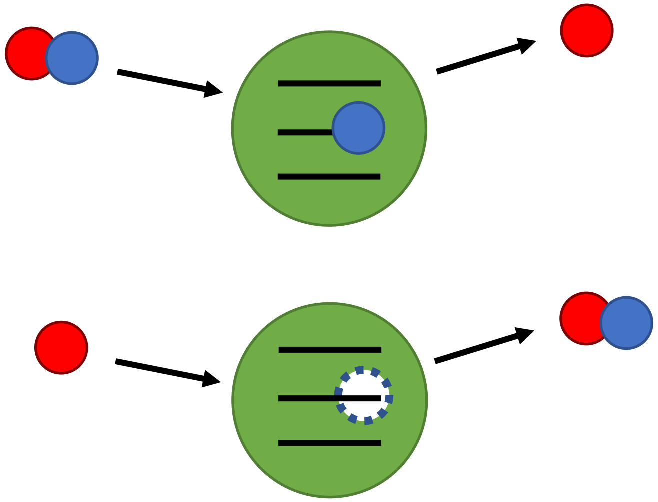
Transfer reaction

(*d,p*) neutron ***removal***

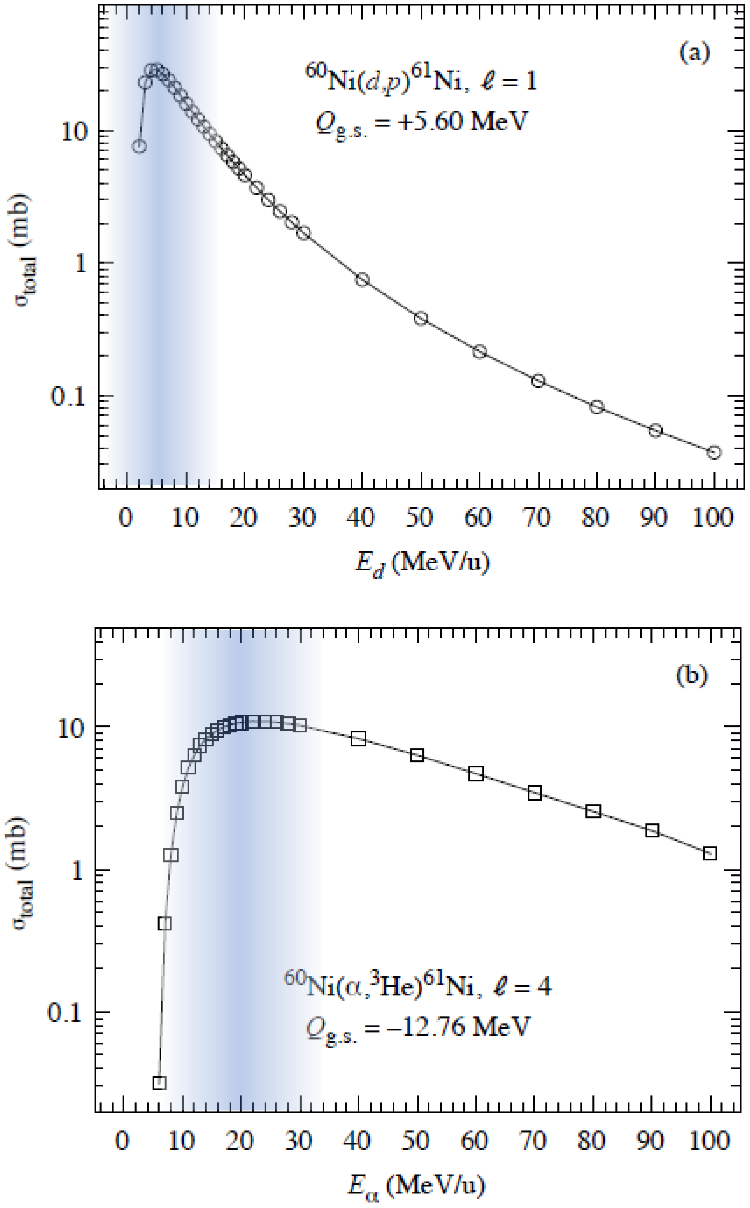
study the emptiness of orbital

(*p,d*) neutron ***adding***

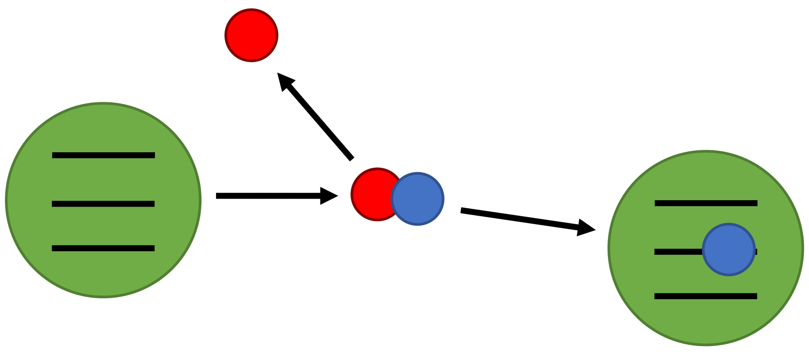
study the fullness of orbital

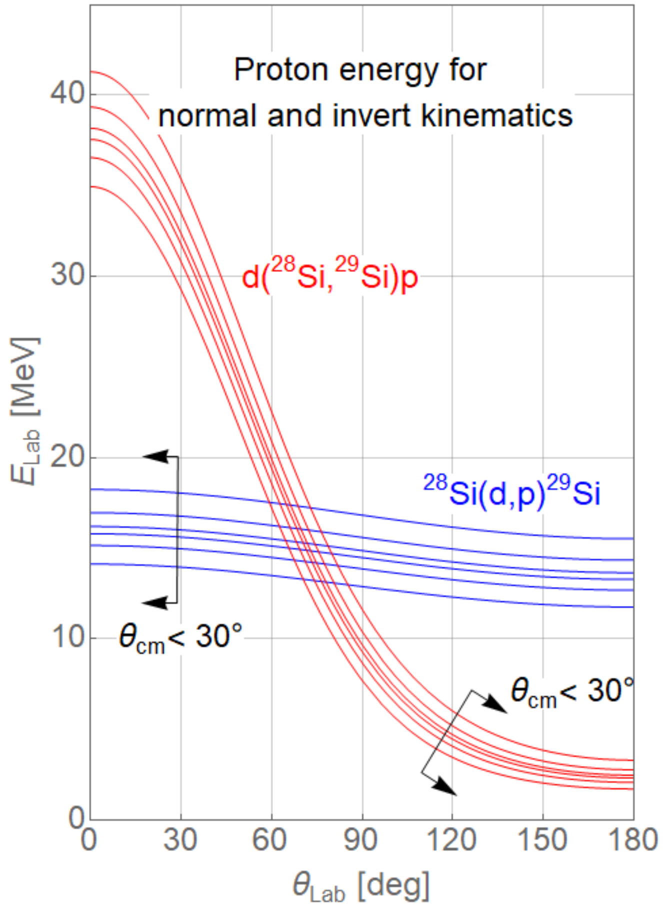


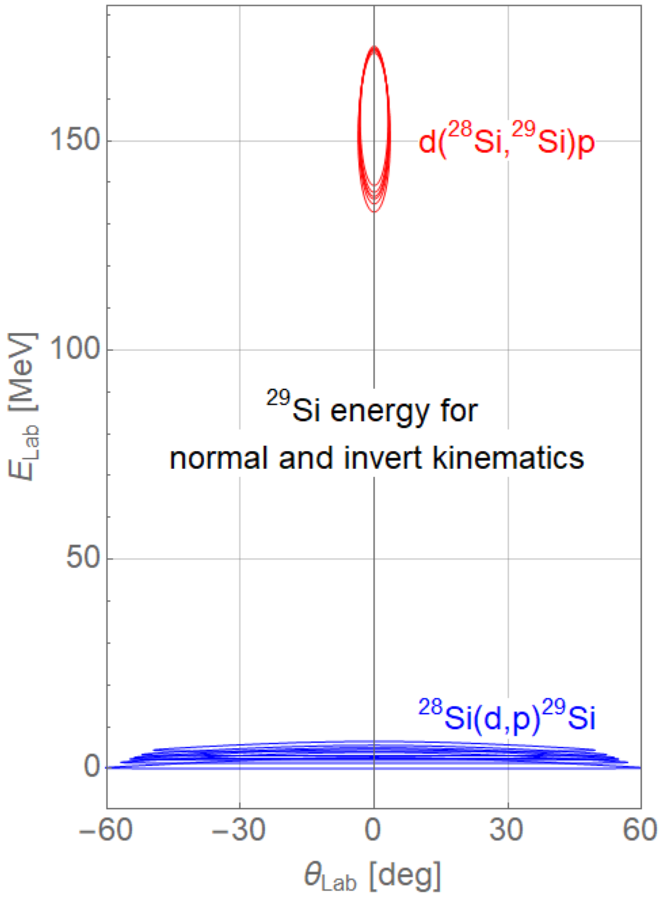
- Momentum matching
  - Slow beam
  - ➢ 5 ~ 20 MeV/u for maximum cross section
- Reaction on surface.
- Only 2 degree of freedoms: θ_{cm} and E_x



Inverse Kinematics for transfer reaction



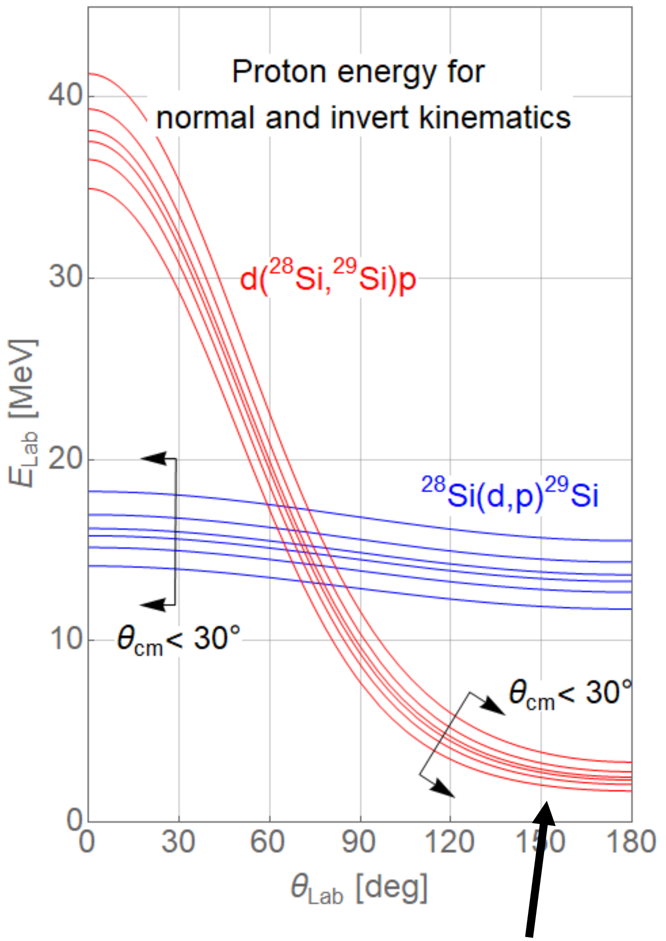




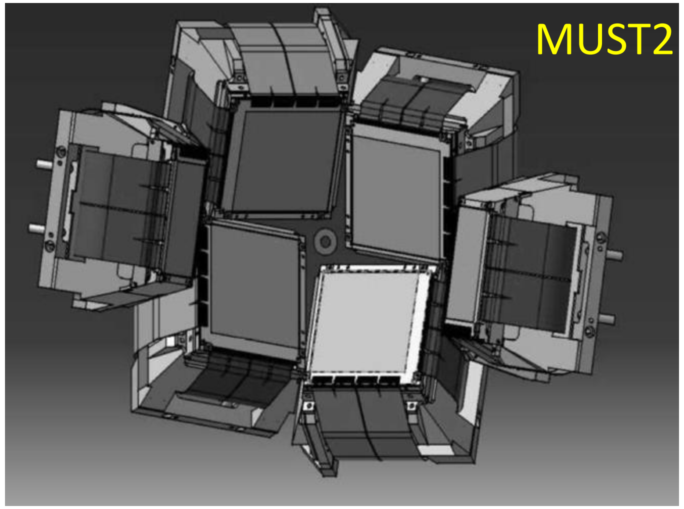
Advantage of inverse kinematics:

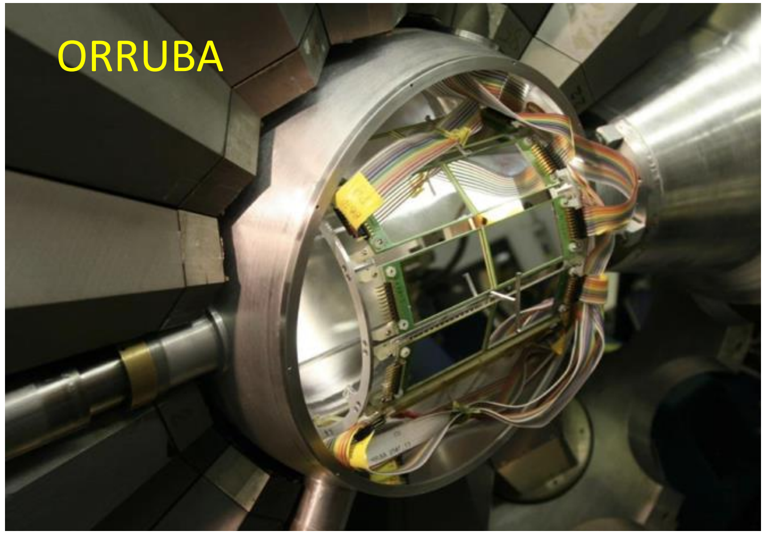
- Detection of the residual nucleus
- Smaller KE for the light particle
- Larger spread of θ_{Lab} for $\theta_{cm} \in (0°, \sim 30°)$

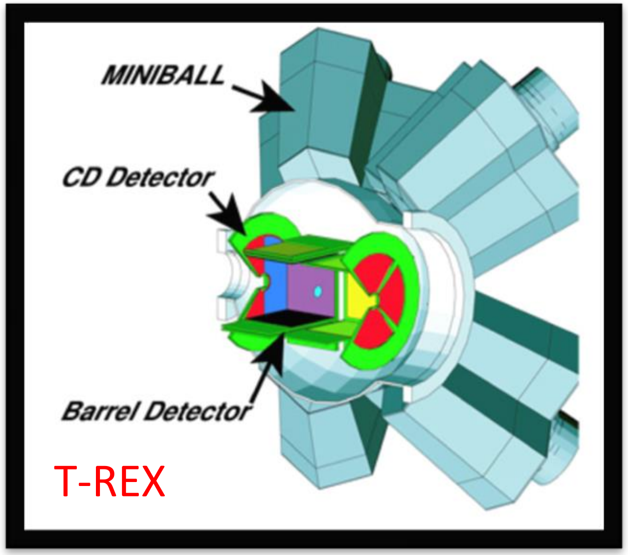
Some detectors systems

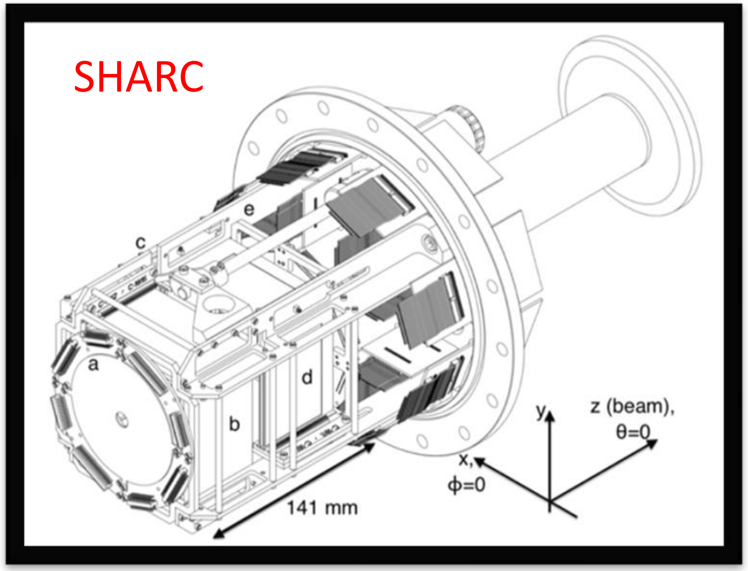


Cross section concentrates on $\theta_{cm} < 30°$



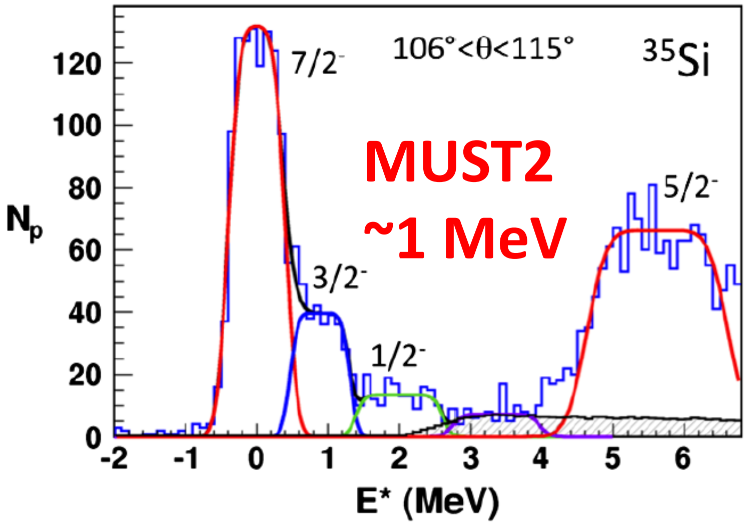




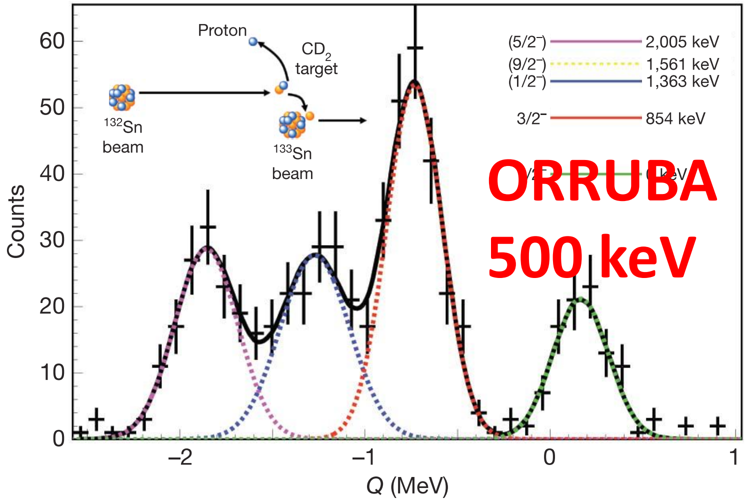


Energy resolution is challenging…

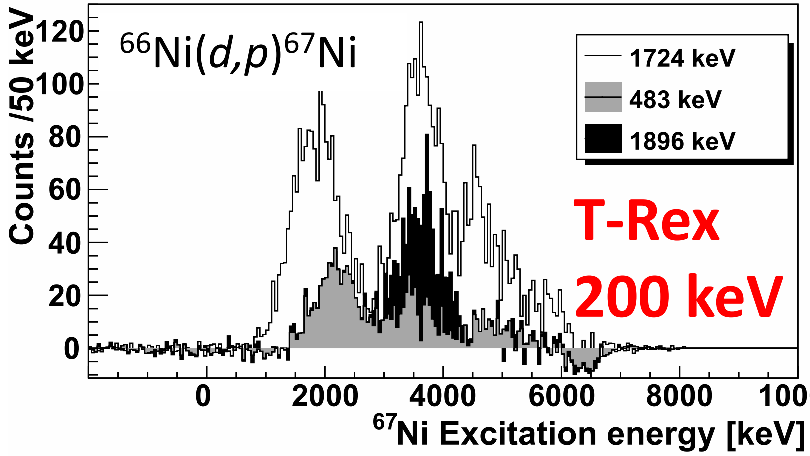
G. Burgunder et al., PRL **112**, 042502 (2014)

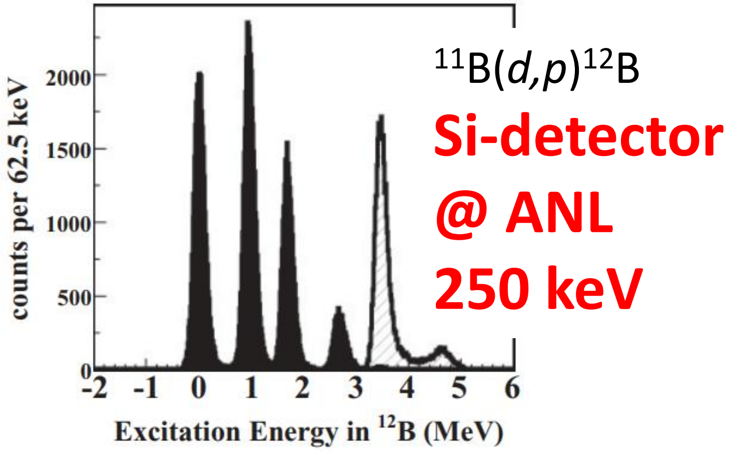


K. L. Jones *et al.*, Nature **465**, 454 (2010)



J. Diriken *et al.*, Phys. Rev. C **91**, 054321 (2015)





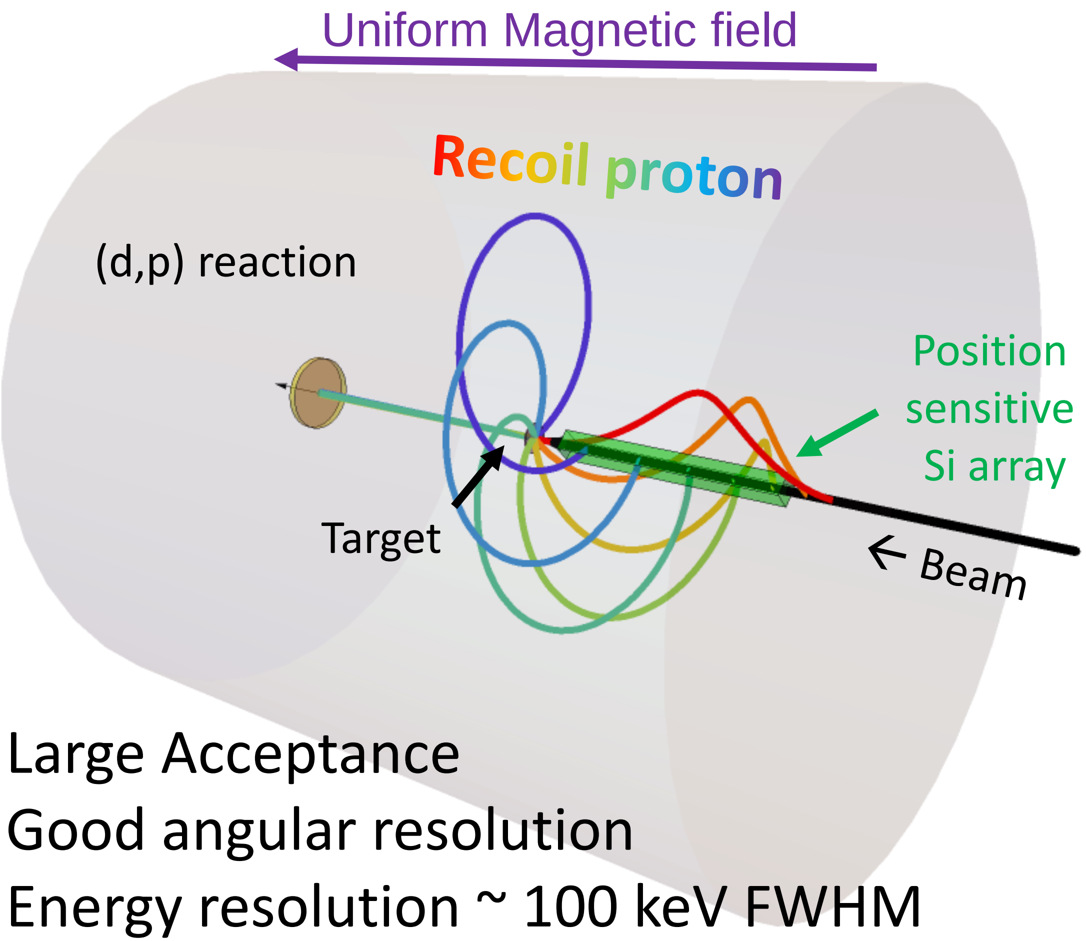
H. Y. Lee *et al.*, PRC 81, 015802 (2010)

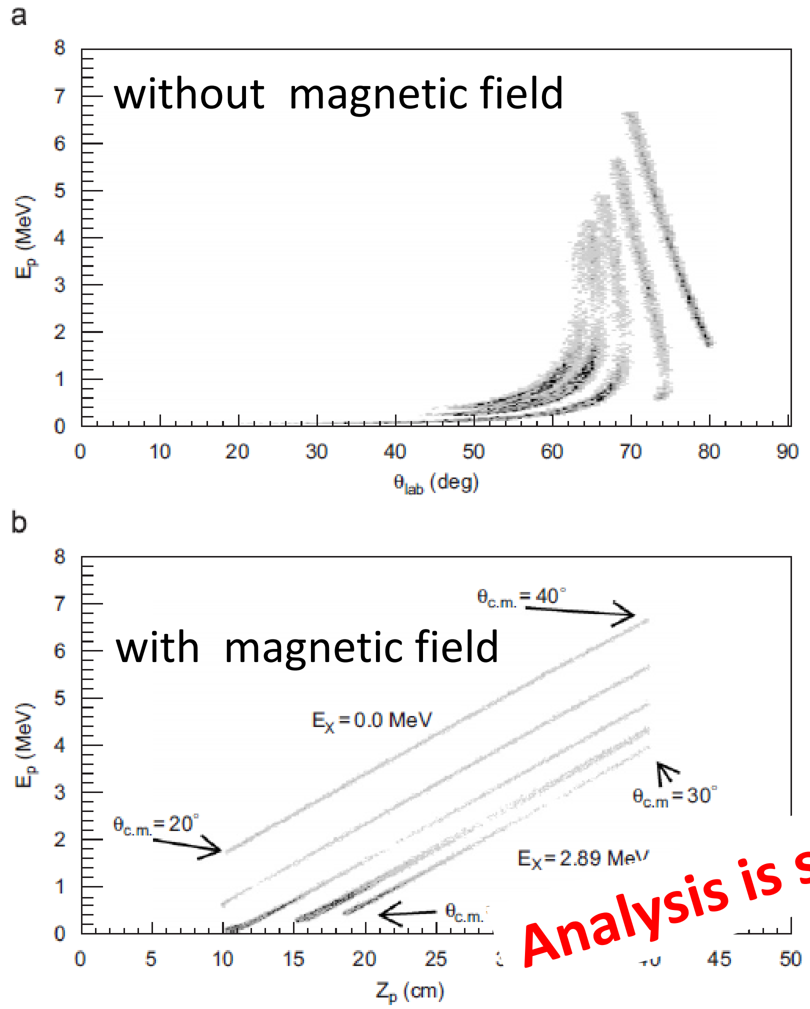
- Resolution typically around ~ 200 – 500 keV FWHM
- They are near the target
  → angular resolution is limited.

It is better to have resolution ~ 100 keV FWHM.

The Idea of Solenoidal Spectrometer

A.H. Wuosmaa, J.P. Schiffer, B.B. Back, C.J. Lister, K.E. Rehm, NIM A **580** (2007) 1290





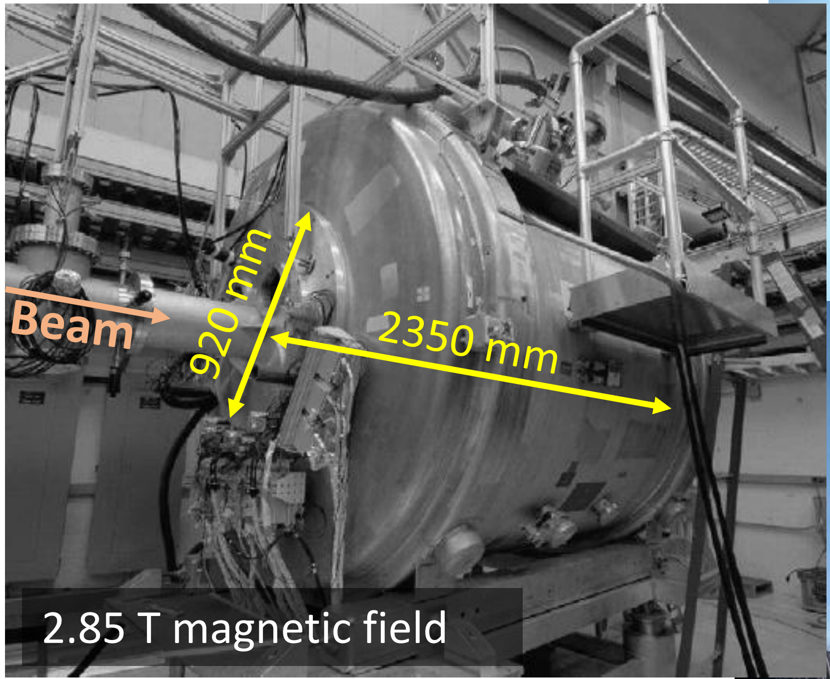
Analysis is simple!!

- Large Acceptance
- Good angular resolution
- Energy resolution ~ 100 keV FWHM

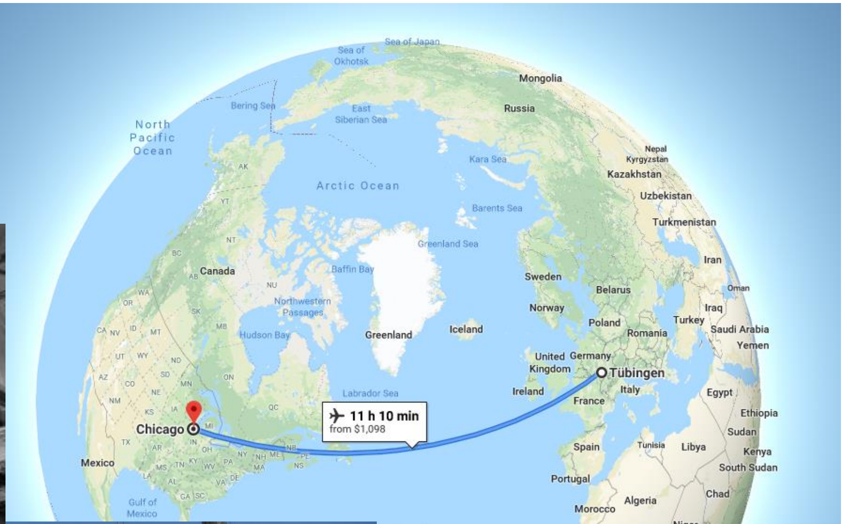
Argonne NATIONAL LABORATORY

HELIOS in ANL

Decommissioned
Magnetic Resonance Imaging device



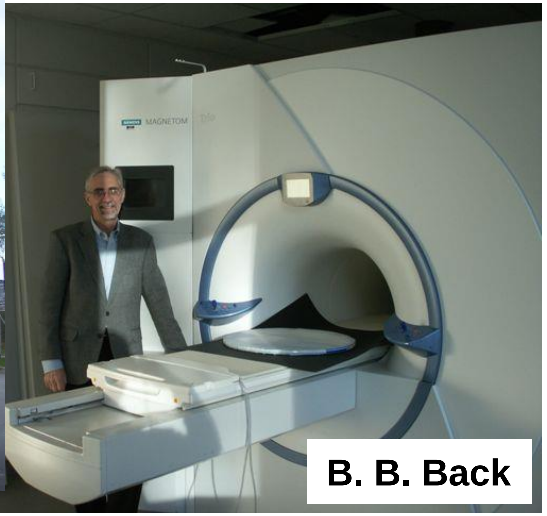
2.85 T magnetic field



Tübingen, Monday, Nov 6, 2006

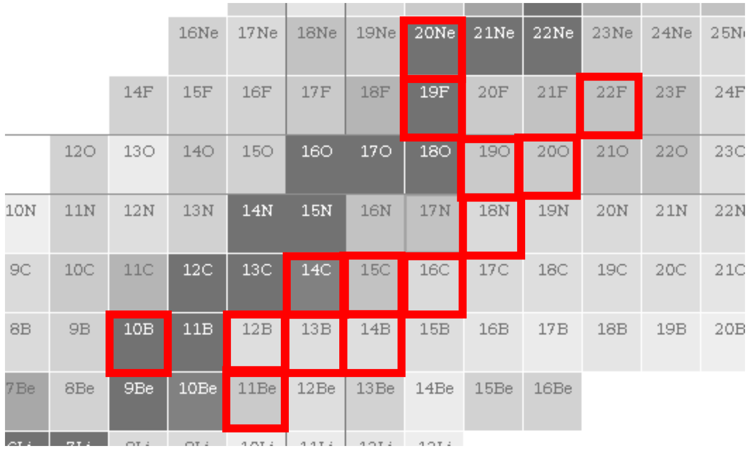
K. E. Rehm

December 8, 2006

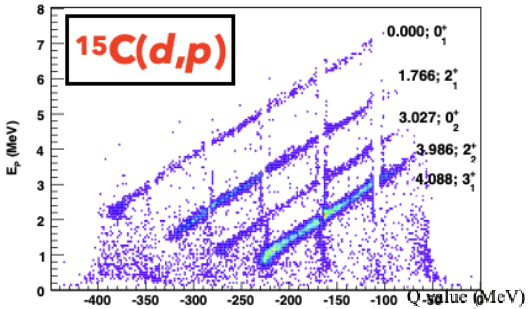


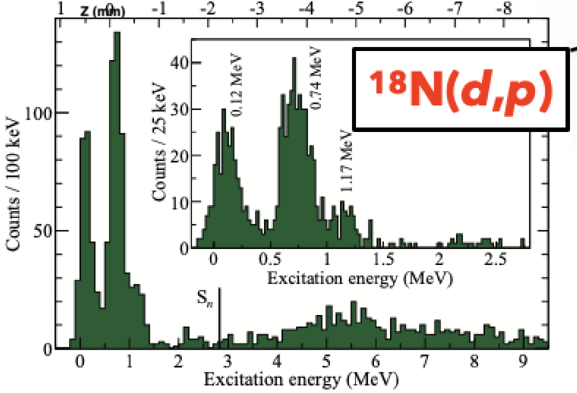
B. B. Back

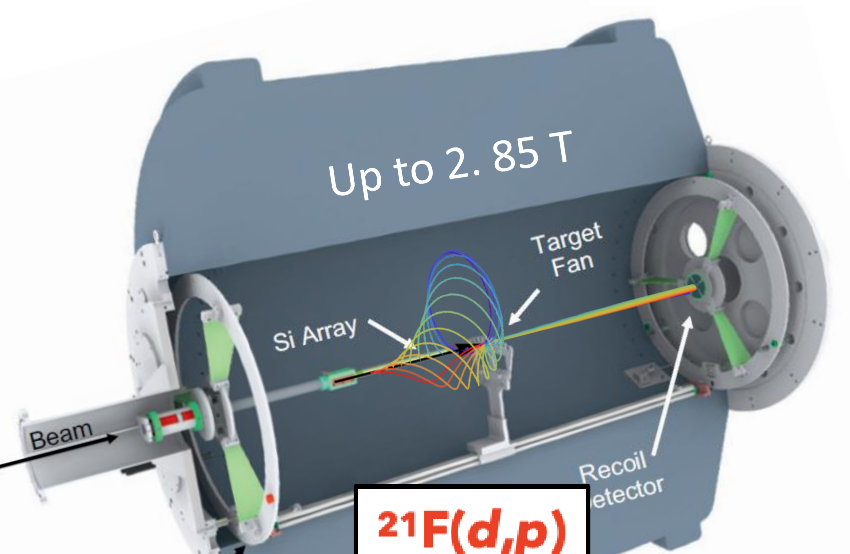
The (*d*,*p*) reactions with HELIOS

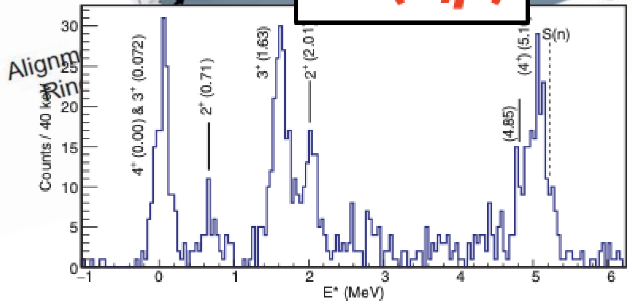


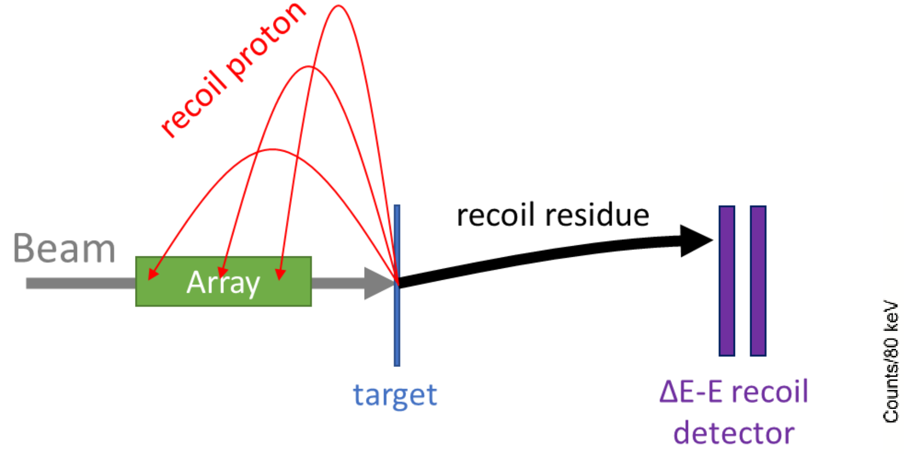
			16Ne	17Ne	18Ne	19Ne	20Ne	21Ne	22Ne	23Ne	24Ne	25Ne
		14F	15F	16F	17F	18F	19F	20F	21F	22F	23F	24F
	12O	13O	14O	15O	16O	17O	18O	19O	20O	21O	22O	23O
10N	11N	12N	13N	14N	15N	16N	17N	18N	19N	20N	21N	22N
9C	10C	11C	12C	13C	14C	15C	16C	17C	18C	19C	20C	21C
8B	9B	10B	11B	12B	13B	14B	15B	16B	17B	18B	19B	20B
7Be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



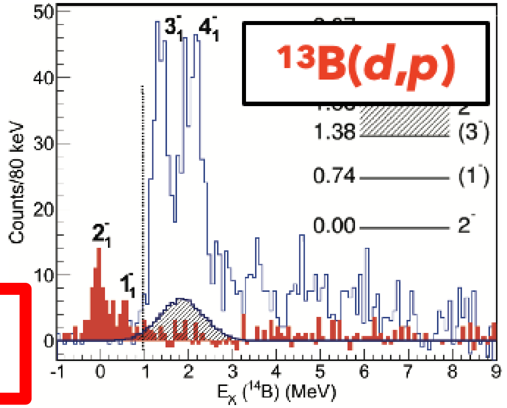


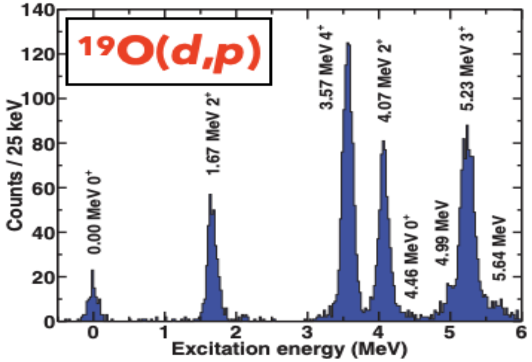


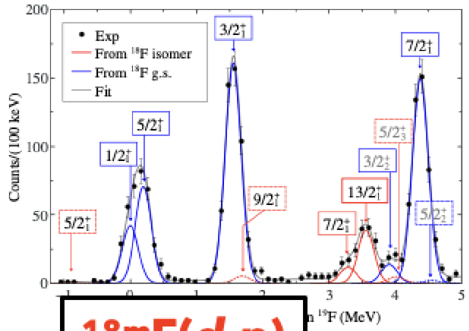




Resolution ~ 100 keV FWHM

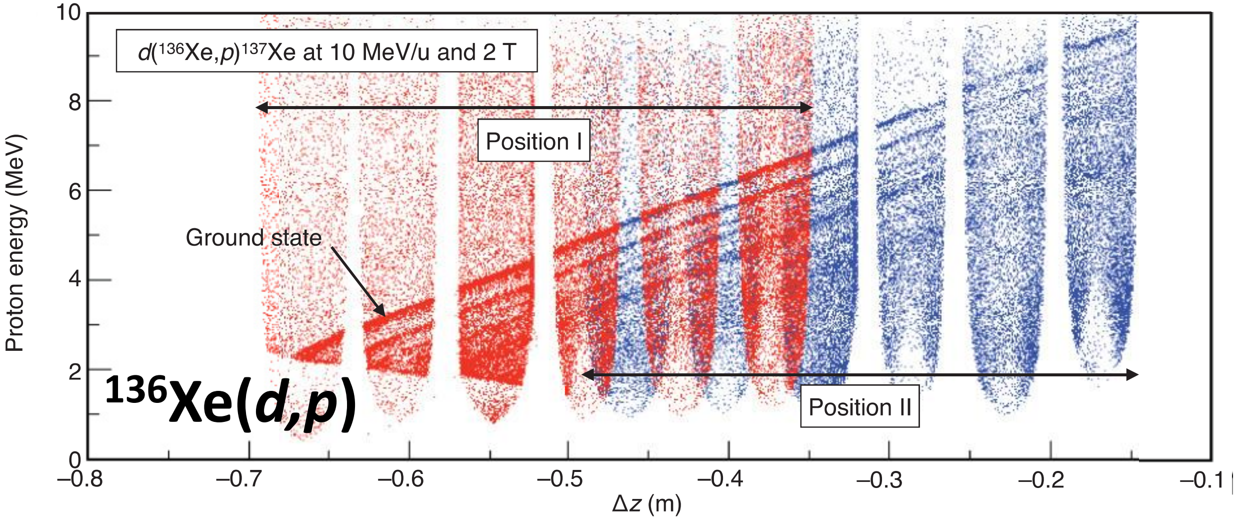


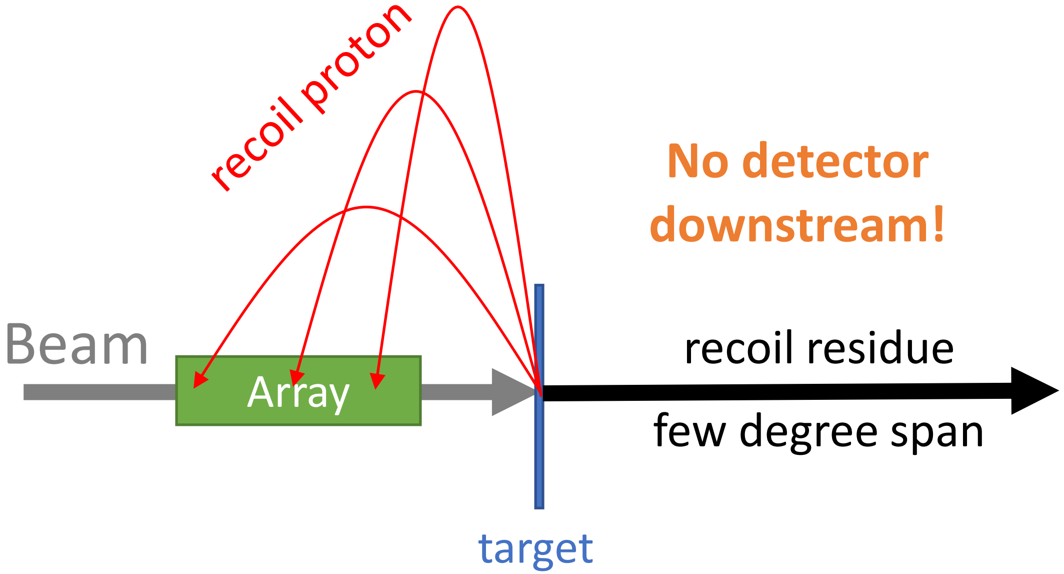


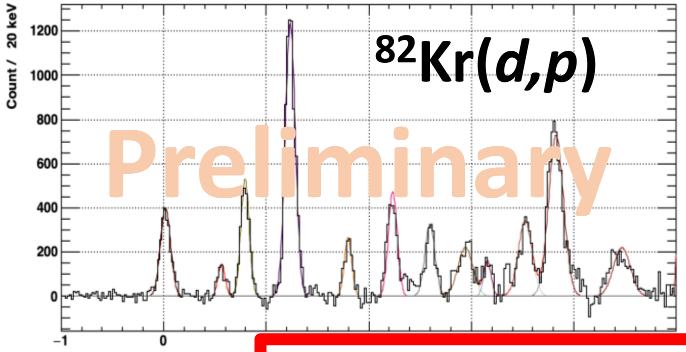


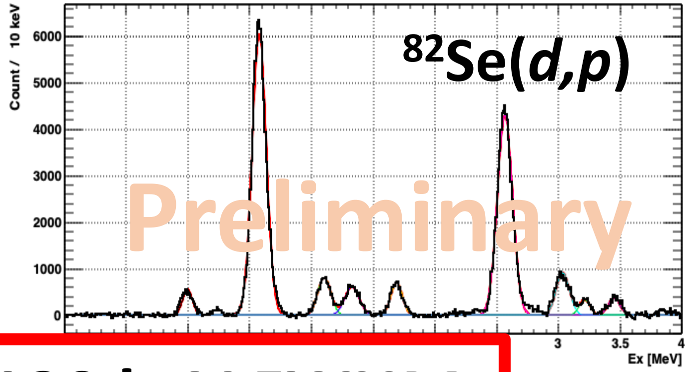
Medium Mass Nucleus with HELIOS

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









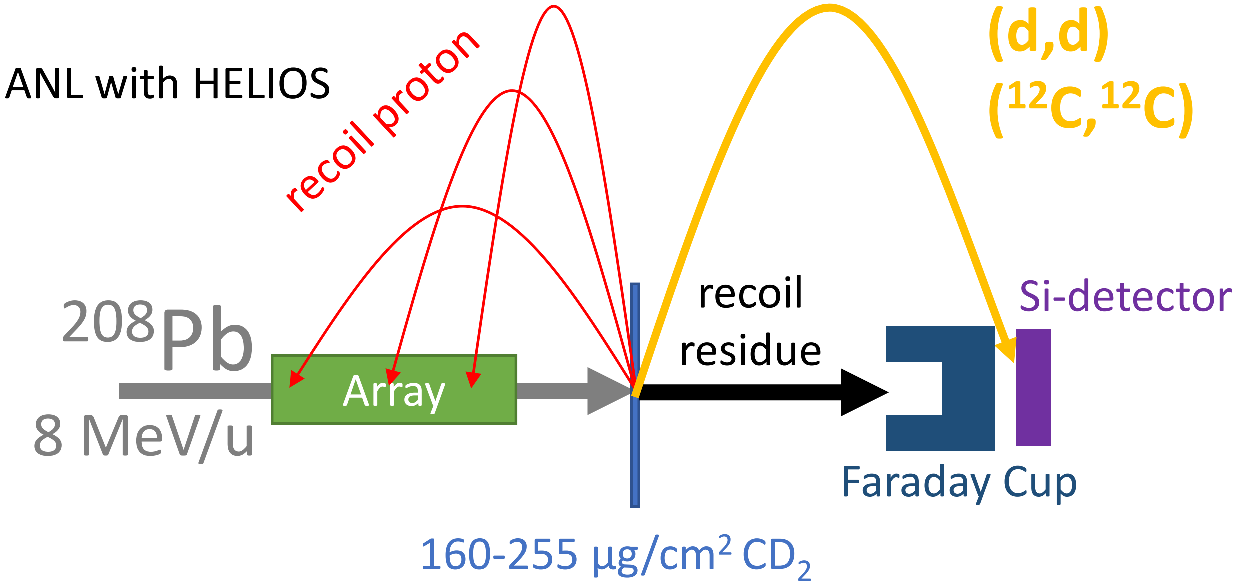
Resolution ~ 130 keV FWHM

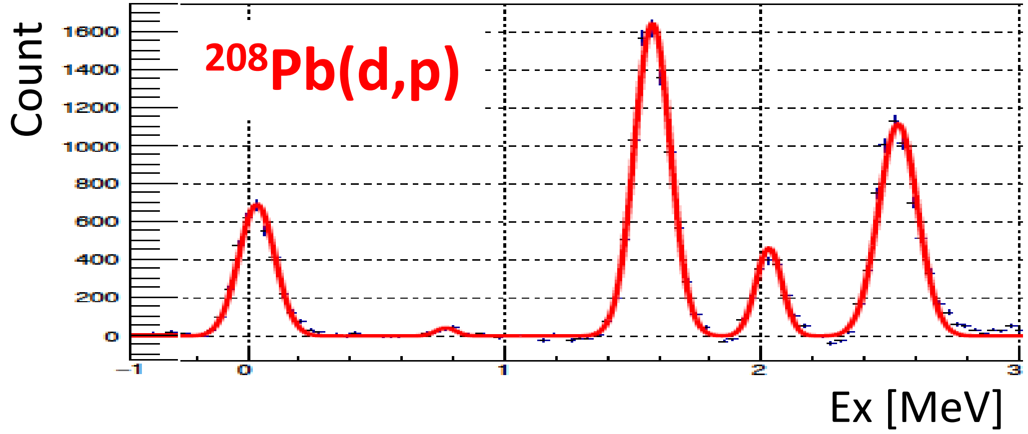
Medium mass nuclei are OK!!!

Heavy nuclei should be OK too!!

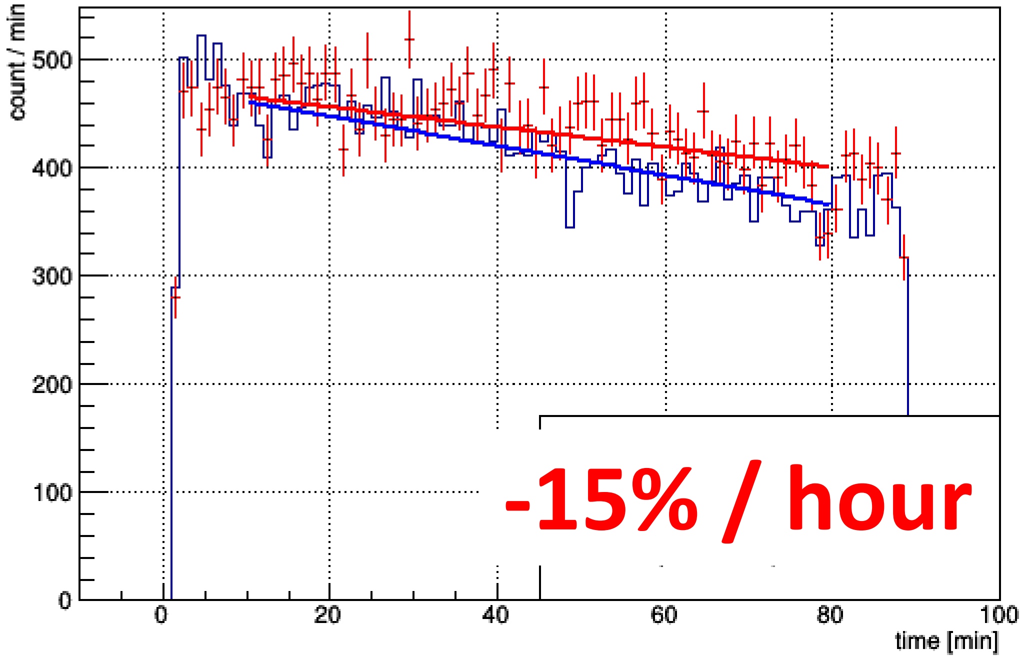
Target degradation with heavy beam

At ANL with HELIOS





Approximation: $e^{-\alpha t} \approx 1 - \alpha t$



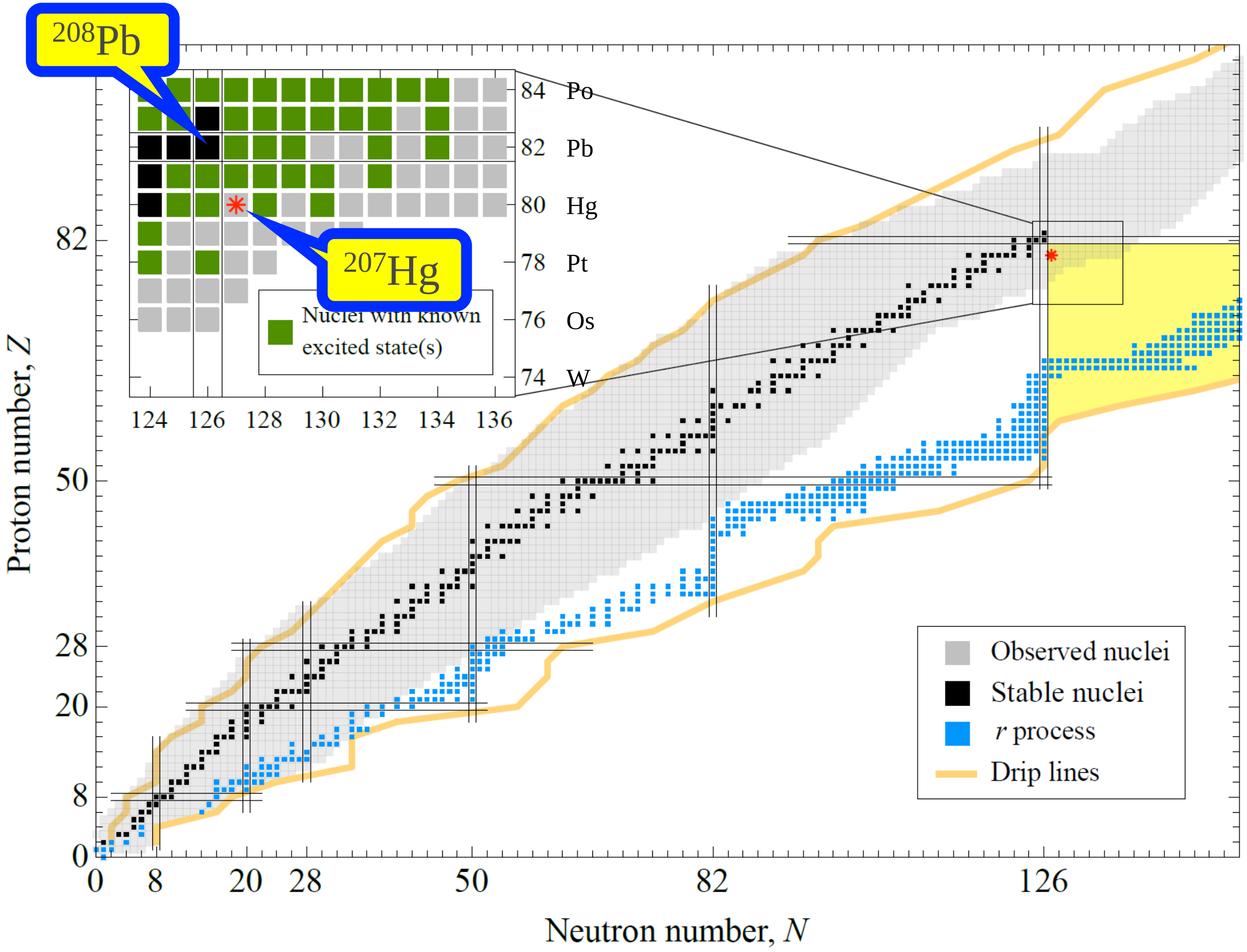
-15% / hour

167 μg/cm^2

Beam rate : 8.37×10^6 pps

Total particle: 6.0×10^{10}

Into Terra Incognita…..

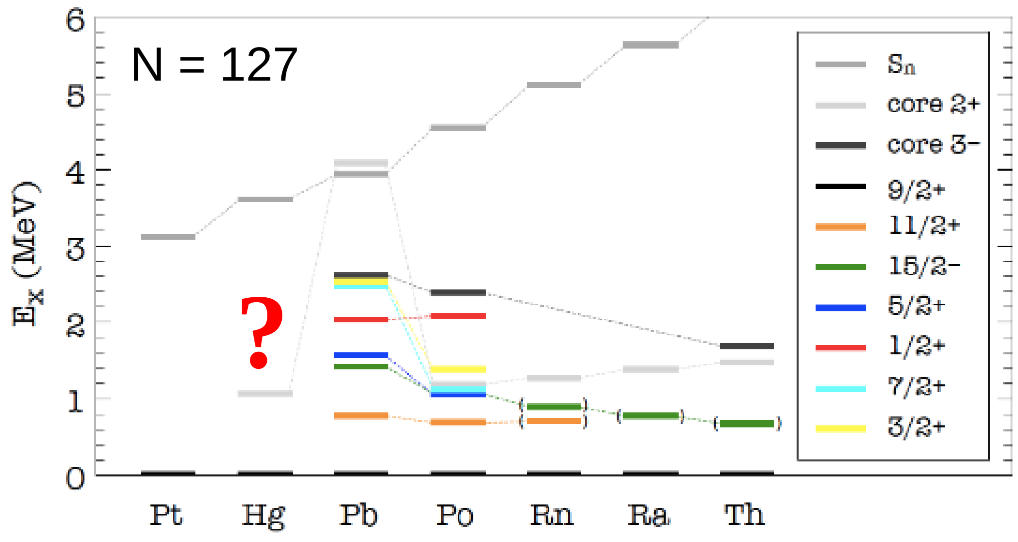


^{208}Pb is a cornerstone to our understanding of the **single-particle structure** of heavy nuclei.

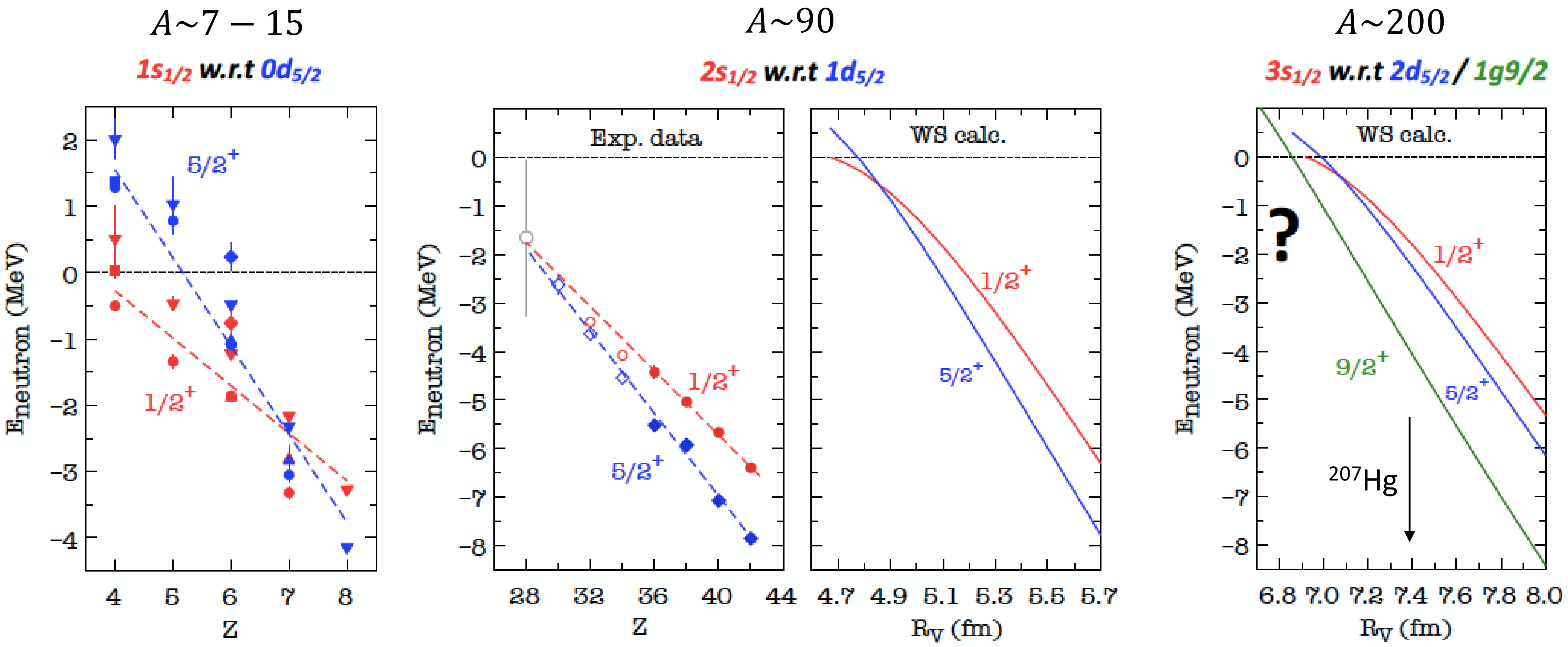
Study of ^{207}Hg

- Toward **r-process** for heavy elements
- Evolution of shell-structure along N=127
- NO spectroscopy study of isotones below Pb

→ **First measurement** on the single-particle state of **^{207}Hg**!!!



Weak binding and nuclear structure

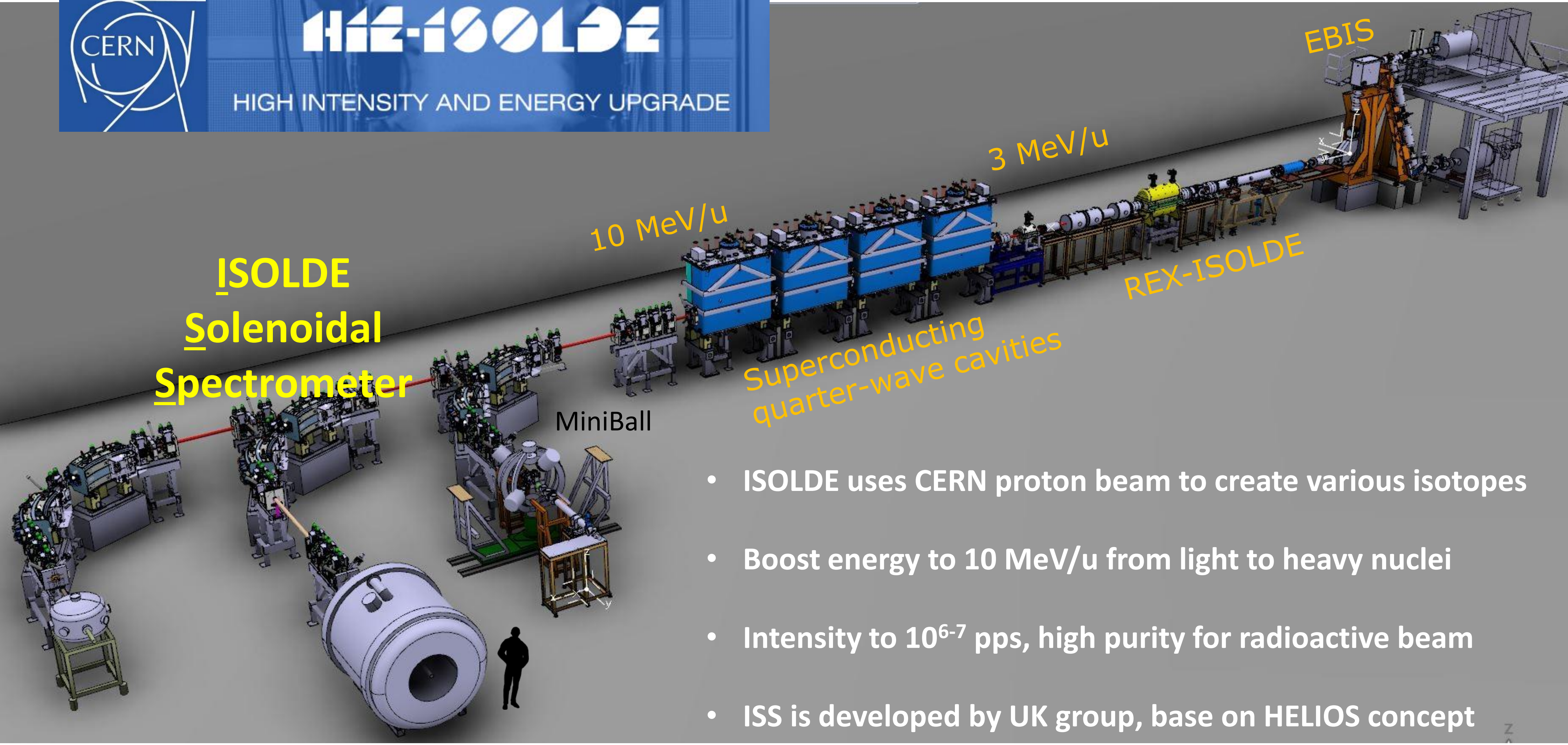


C. R. Hoffman et al., PRC89(2014)061305

Is it a universal behavior?

HIE-ISOLDE

HIGH INTENSITY AND ENERGY UPGRADE



- **ISOLDE uses CERN proton beam to create various isotopes**
- **Boost energy to 10 MeV/u from light to heavy nuclei**
- **Intensity to $10^{6\text{-}7}$ pps, high purity for radioactive beam**
- **ISS is developed by UK group, base on HELIOS concept**

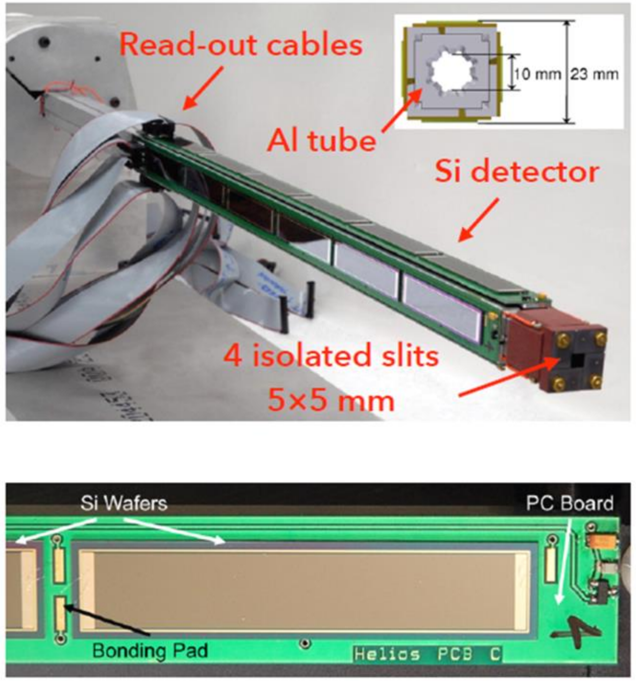
ISOLDE Solenoidal Spectrometer

First commission on Sept 2018

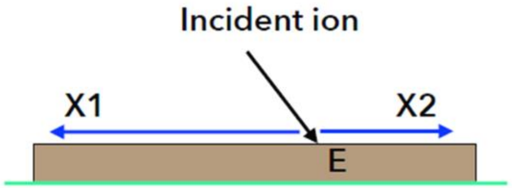
Setup at the time of commission

heavy beam is used,
radiation damage is large
→ target degradation,
→ A dedicated 8 × 8 type-writer target ladder is used.

Both the DAQ and the detector are borrowed from ANL.



- 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

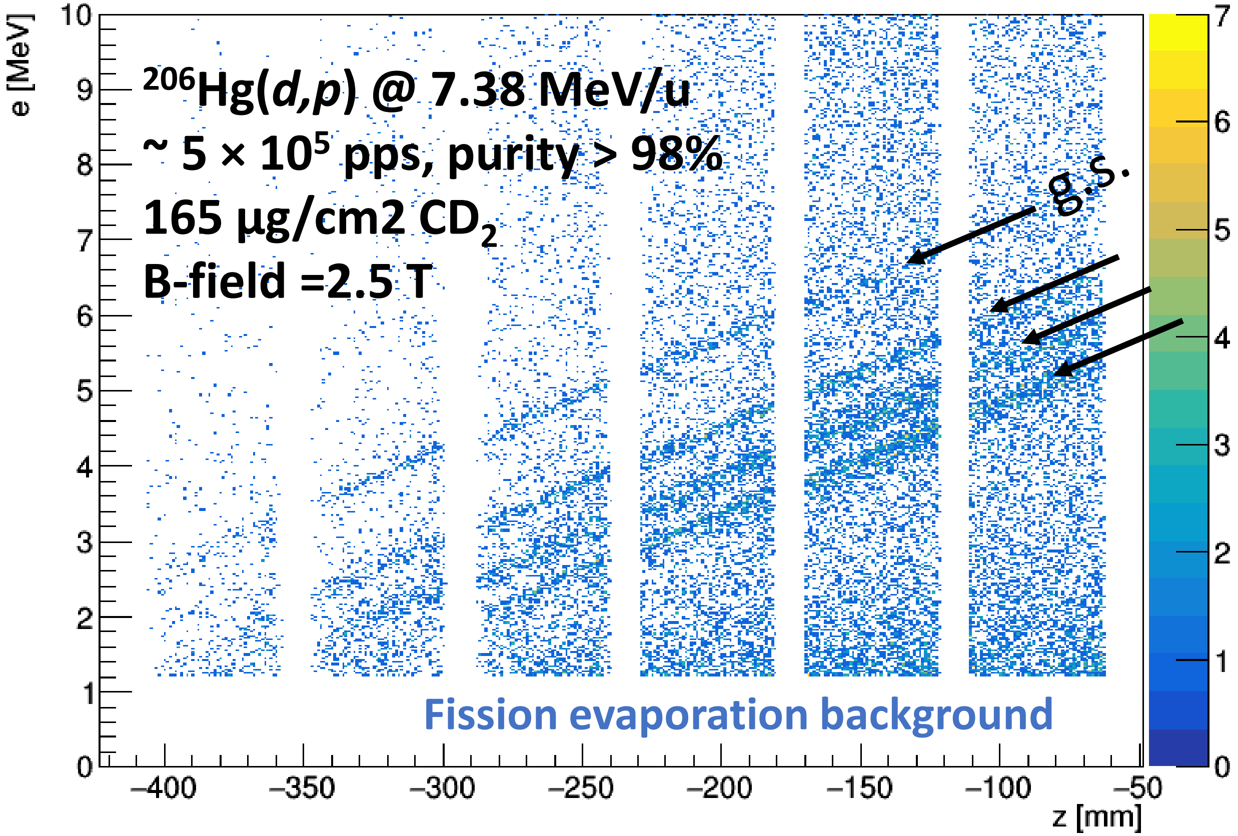


Position ≈ (X1-X2)/E

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

Target ladder Mechanical: Russell A. Knaack
Targets: Matthew D. Gott

Experimental Result


^{206}Hg(*d*,*p*) @ 7.38 MeV/u

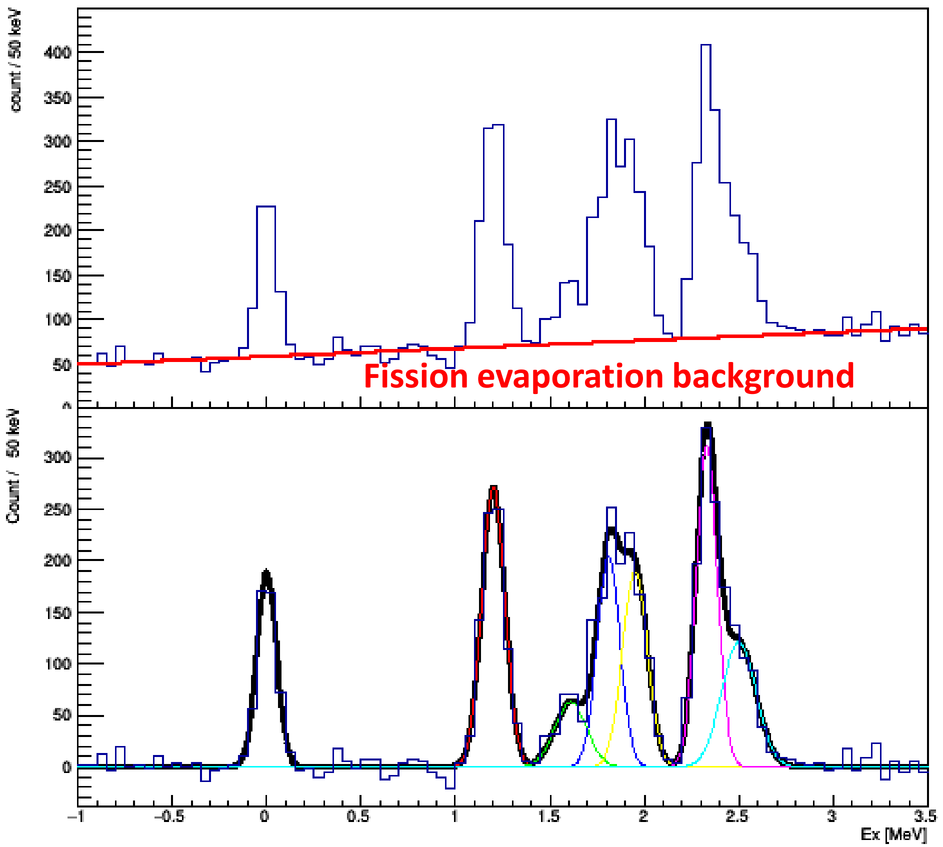
~ 5 × 10^5 pps, purity > 98%

165 μg/cm2 CD_2

B-field =2.5 T

g.s.

Fission evaporation background


Fission evaporation background

Resol. ~ 140 keV (FWHM)

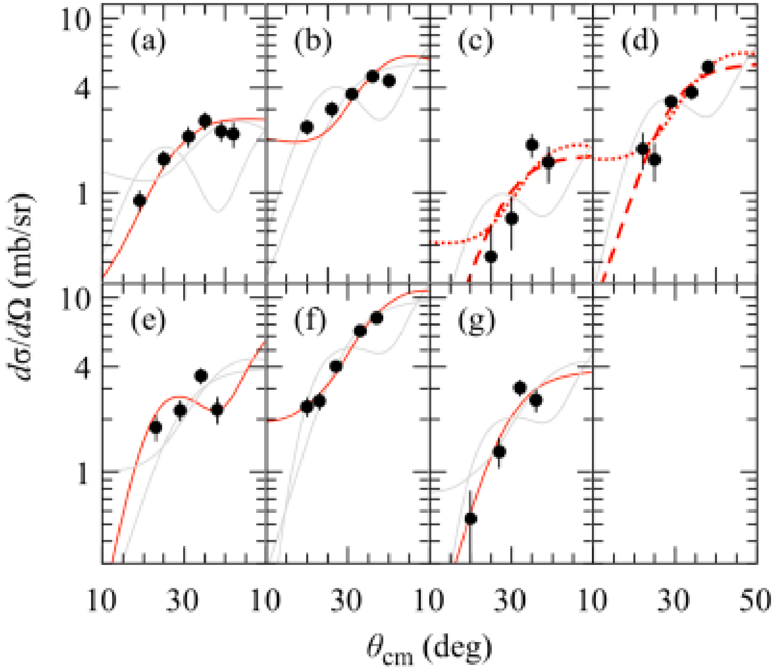
Angular Distributions & Spectroscopic Factors

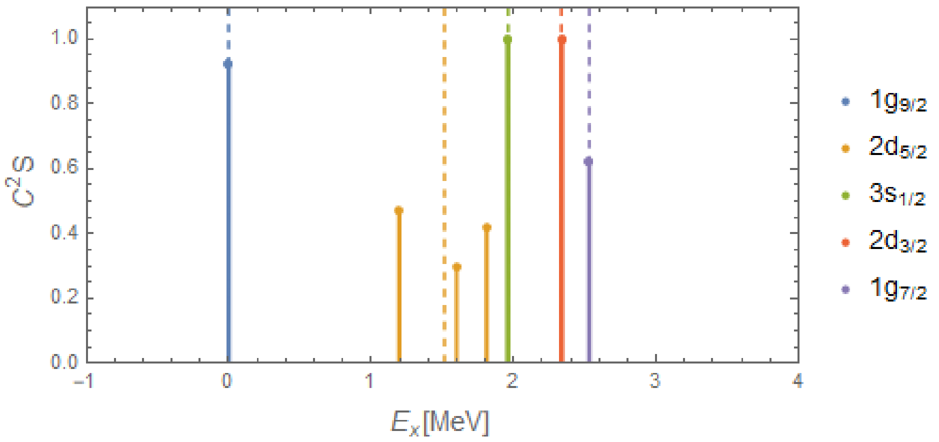
DWBA calculation: Ptolemy
d-channel : A. J. Koning and J. P. Delaroche, Nucl. Phys. A**713**, 231 (2003)
p-channel : H. An and C. Cai, PRC **73**, 054605 (2006)
Bound state: Woods-Saxon, $r_0 = 1.28$ fm, $a_0 = 0.65$ fm

Spin-parity assignment and Spectroscopic factors

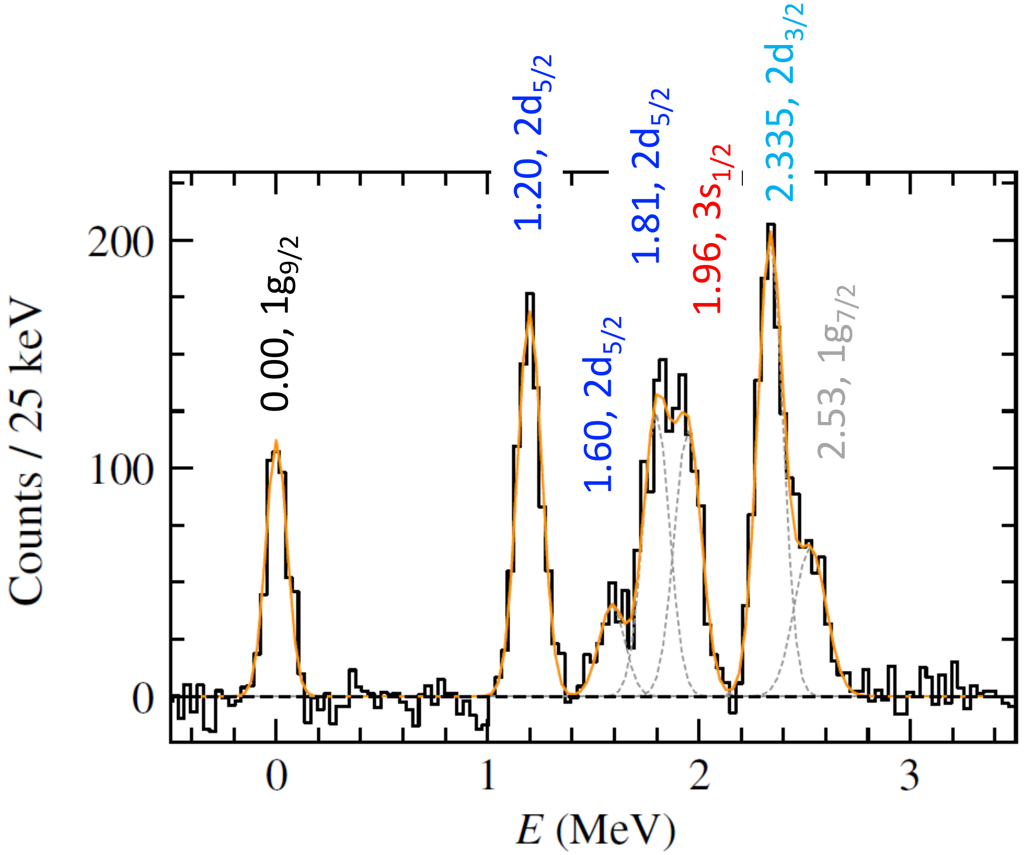
E (keV)	ℓ	j^π	$n\ell s$	S	χ^2/dof
0	4	$9/2^+$	$1g_{9/2}$	0.82(5)	1.3(8)
1197(5)	2	$5/2^+$	$2d_{5/2}$	0.47(6)	2.9(1.1)
1600(45)	~~4~~	~~$9/2^+$~~	~~$1g_{9/2}$~~	~~0.30(4)~~	~~1.5(2)~~
	2	$5/2^+$	$2d_{5/2}$	0.13(1)	1.4(3)
1810(20)	~~4~~	~~$9/2^+$~~	~~$1g_{9/2}$~~	~~0.93(12)~~	~~1.1(1)~~
	2	$5/2^+$	$2d_{5/2}$	0.42(3)	1.3(3)
1960(30)	0	$1/2^+$	$3s_{1/2}$	1.00(13)	4.4(2.7)
2335(6)	2	$3/2^+$	$2d_{3/2}$	1.00(7)	1.1(9)
2530(20)	4	$7/2^+$	$1g_{7/2}$	0.62(6)	1.4(2)

* Normalized to $3s_{1/2}$ state.

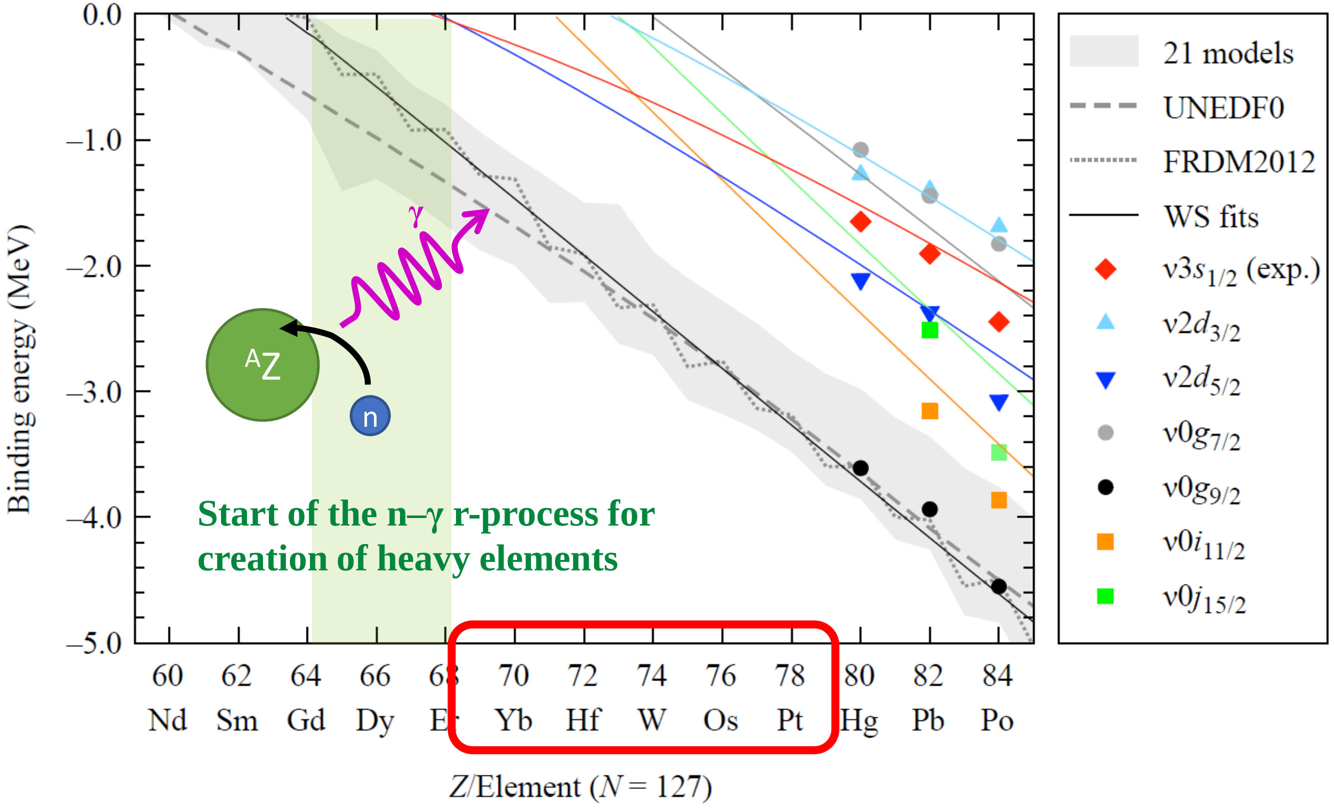




Connection to r-process

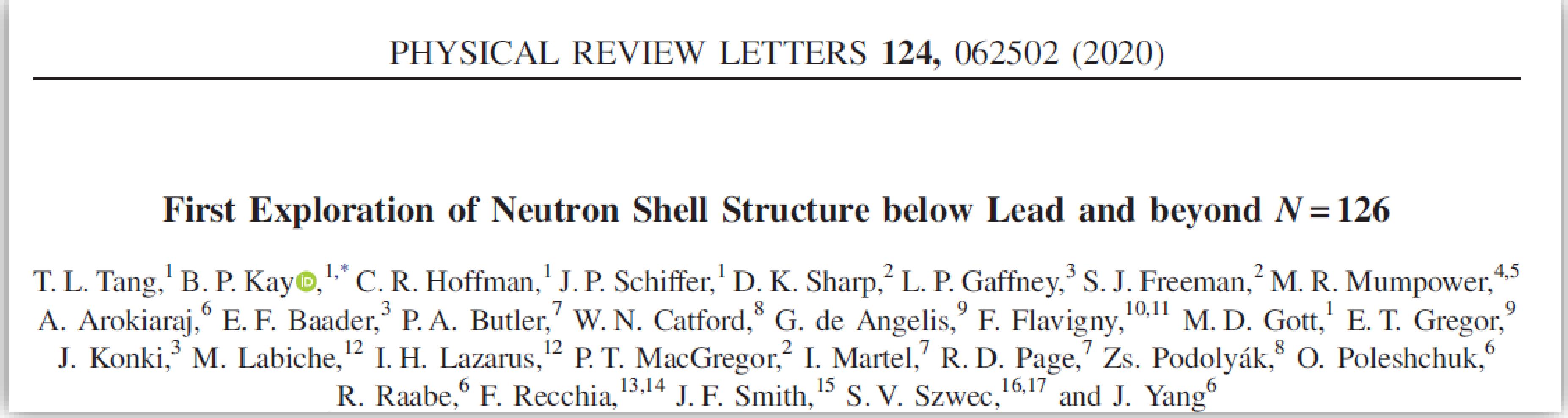


Woods-Saxon calculations fitted to experimental binding energies of the neutron orbitals at N = 127 (^{207}Hg, ^{209}Pb, and ^{211}Po).



Start of the n–γ r-process for creation of heavy elements

Those isotope could be produced in FRIB era.



PHYSICAL REVIEW LETTERS **124**, 062502 (2020)

First Exploration of Neutron Shell Structure below Lead and beyond $N = 126$

T. L. Tang,[1] B. P. Kay,[1,*] C. R. Hoffman,[1] J. P. Schiffer,[1] D. K. Sharp,[2] L. P. Gaffney,[3] S. J. Freeman,[2] M. R. Mumpower,[4,5] A. Arokiaraj,[6] E. F. Baader,[3] P. A. Butler,[7] W. N. Catford,[8] G. de Angelis,[9] F. Flavigny,[10,11] M. D. Gott,[1] E. T. Gregor,[9] J. Konki,[3] M. Labiche,[12] I. H. Lazarus,[12] P. T. MacGregor,[2] I. Martel,[7] R. D. Page,[7] Zs. Podolyák,[8] O. Poleshchuk,[6] R. Raabe,[6] F. Recchia,[13,14] J. F. Smith,[15] S. V. Szwec,[16,17] and J. Yang[6]

CERN

UNIVERSITY OF LIVERPOOL

Argonne NATIONAL LABORATORY

MANCHESTER 1824
The University of Manchester

Los Alamos NATIONAL LABORATORY EST. 1943

KU LEUVEN

UNIVERSITY OF THE WEST of SCOTLAND UWS

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

UNIVERSITY OF SURREY

UNIVERSITÀ DEGLI STUDI DI PADOVA

UNIVERSITY OF HELSINKI

UNIVERSITY OF JYVÄSKYLÄ

lpc caen laboratoire de physique corpusculaire

INFN

UKRI Science and Technology Facilities Council

Outlook

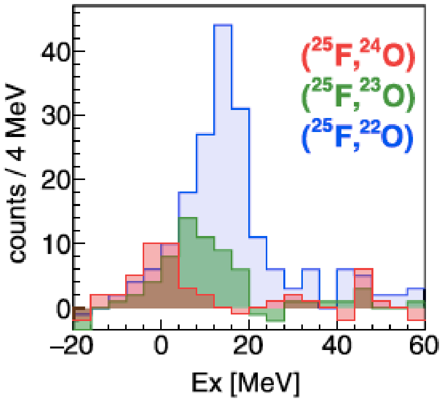
The future of :

- Single-particle spectroscopy
- Solenoidal spectrometer**s**

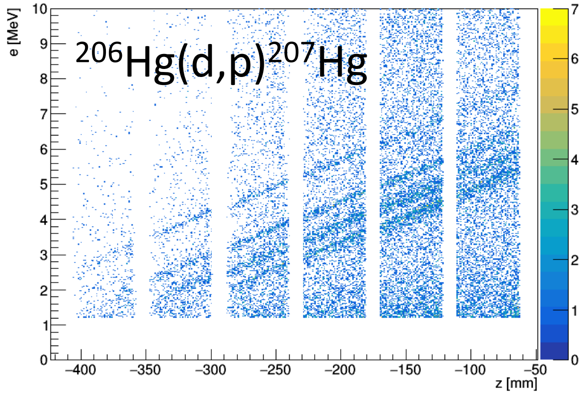
More Applications

There are new *tricks* for single-particle spectroscopy.

T.L.Tang et al., PRL **124**, 212502 (2020)

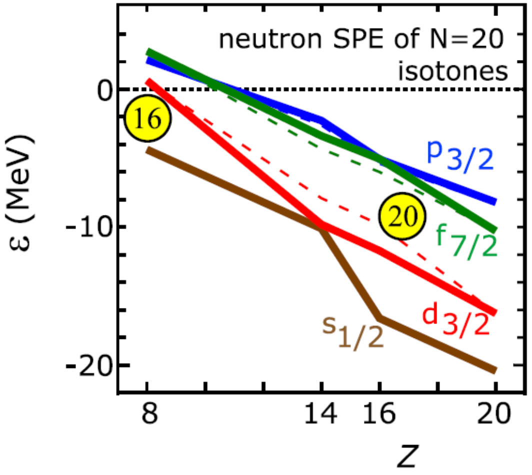


T.L.Tang et al., PRL **124**, 062502 (2020)



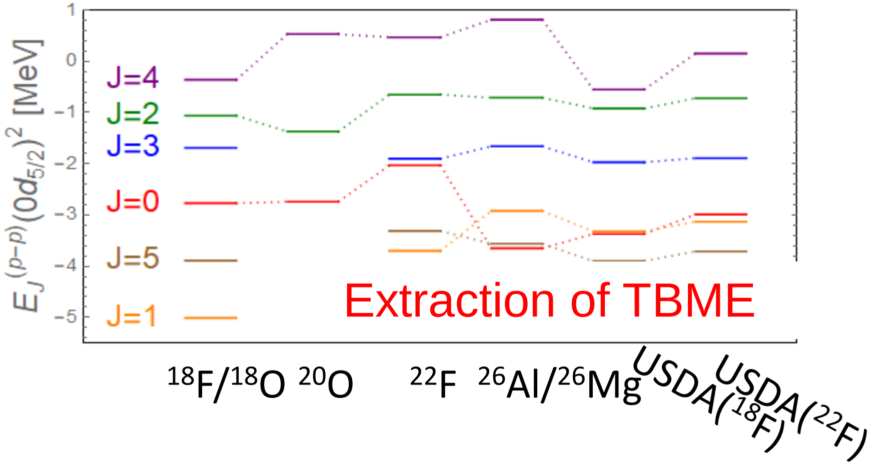
^{206}Hg(d,p)^{207}Hg

T. Otsuka, Phys. Scr. **T152** (2013) 014007



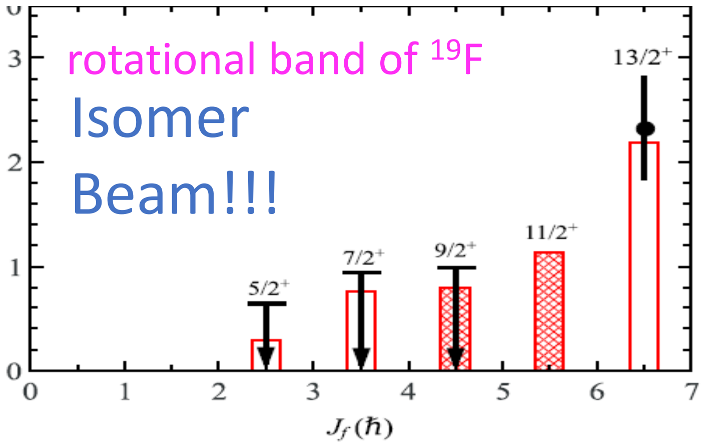
Study of ESPE and shell evolution

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



Extraction of TBME

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



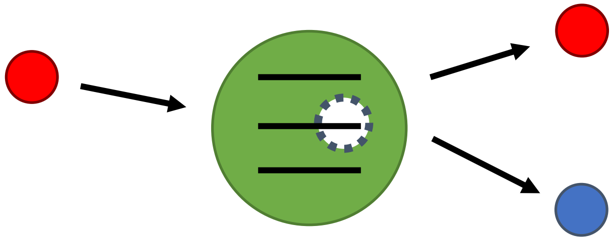
Isomer Beam!!!

Connection between single-particle and collective motion.

Above are only few applications, a lot MORE !!!

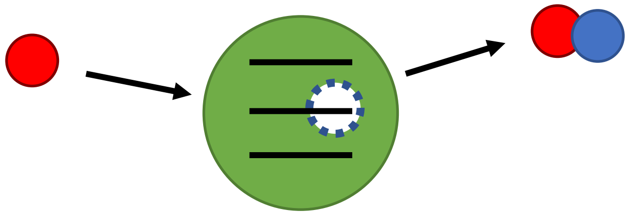
The needs of ***Fast*** and ***Slow*** beams reactions

$(p,2p)$, (p,pn)



Study the fullness of orbital

(p,d), (d,t), $(d,{}^{3}\mathrm{He})$



Fast beam knockout

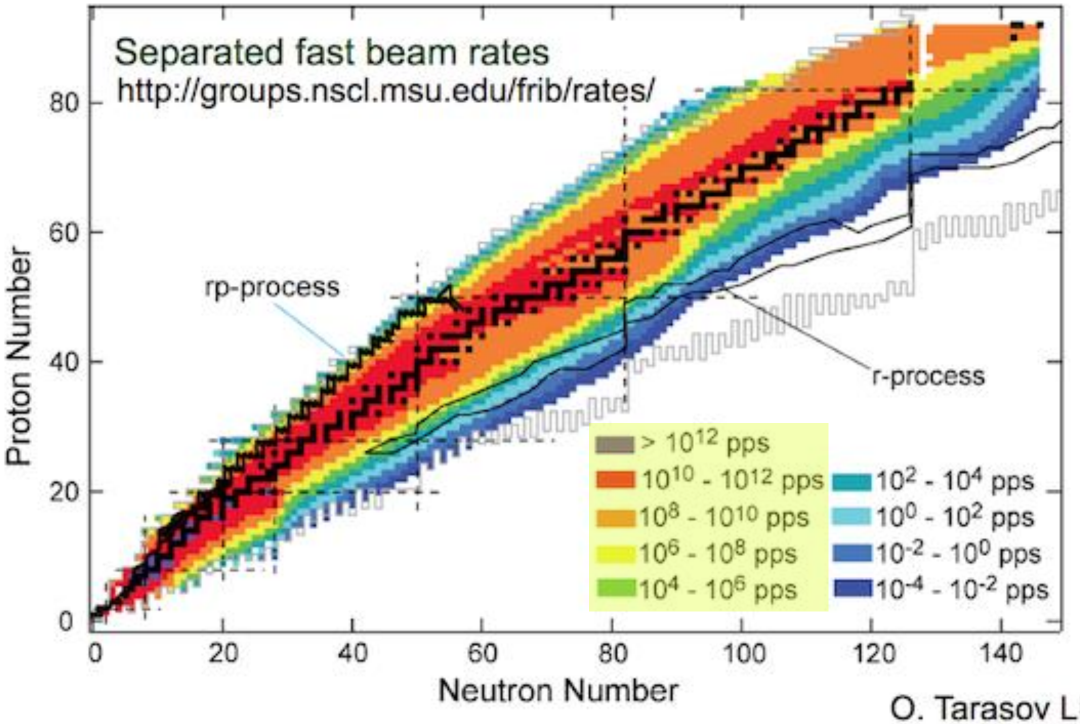
- Deep inelastic scattering.
- No Q-value limitation.
- Simpler reaction mechanism (Impulse approximation)
- High energy → less energy loss
  - Solid polarized proton target
  - Thick target technique
  - Beam event-by-event PID & tracking
  - Not everything in vacuum

Slow beam removal

- On nuclear surface
- Sometimes limited by Q-value.
  → Beam energy > - Q-value
- Easy for neutron removal
- Reaction mechanic is well-understood

Both can extend to *Quasi-particle* spectroscopy!!!

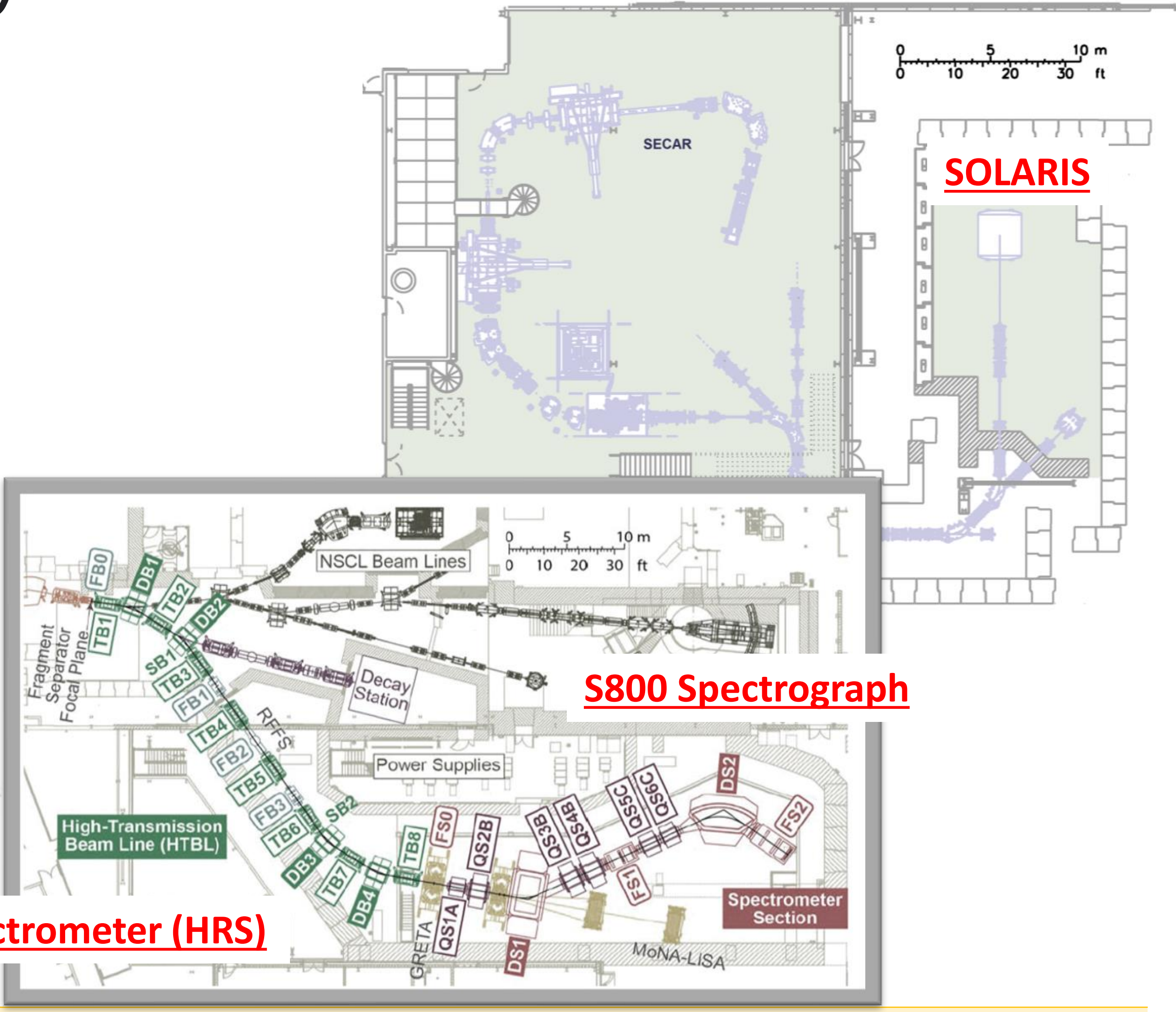
Single-particle spectroscopy in FRIB



O. Tarasov LISE++

Reaccelerated Beams <6 MeV/u for A/Q=2

Reaccelerated Beams <12 MeV/u for A/Q=2

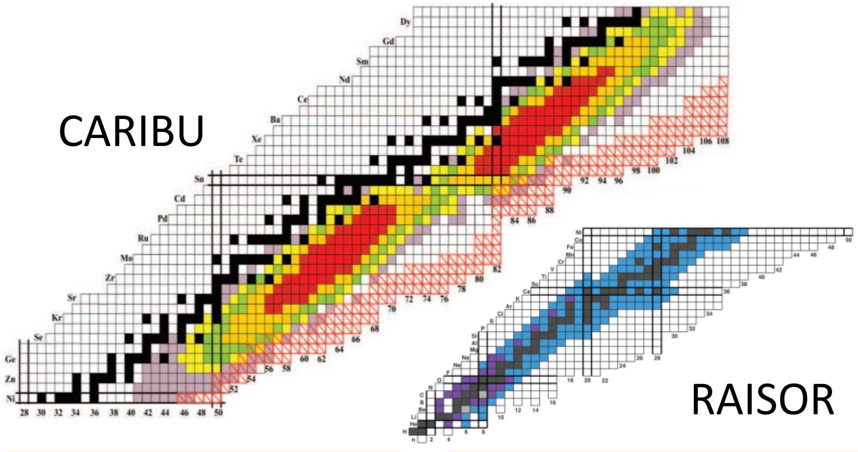


SOLARIS

S800 Spectrograph

High Rigidity Spectrometer (HRS)

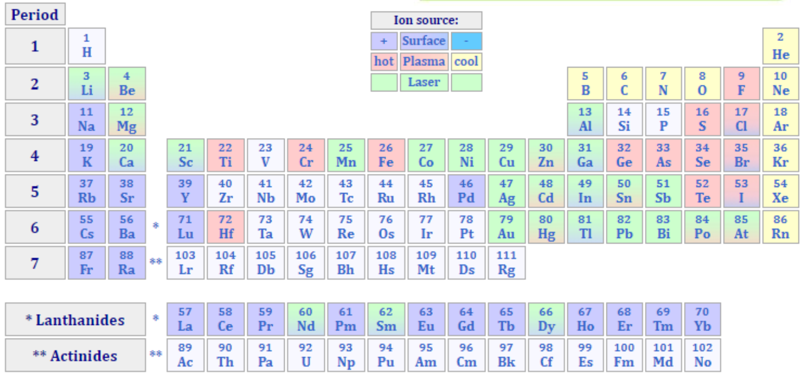
Future of the Solenoidal Spectrometers



CARIBU

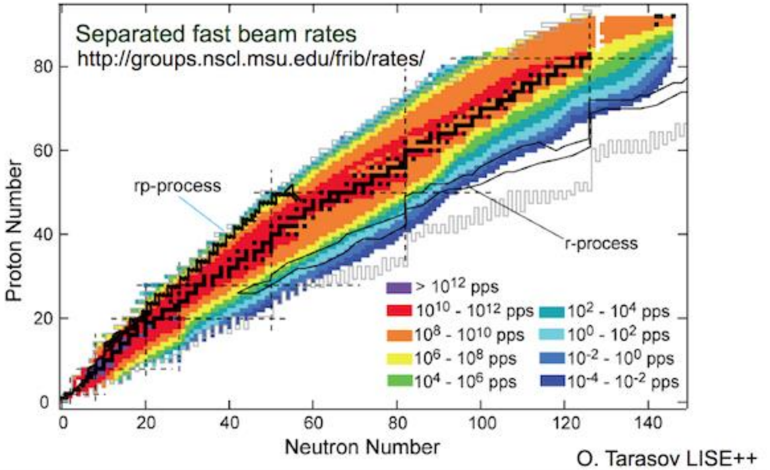
RAISOR

ISOLDE



Ion source:		
+	Surface	-
hot	Plasma	cool
	Laser	

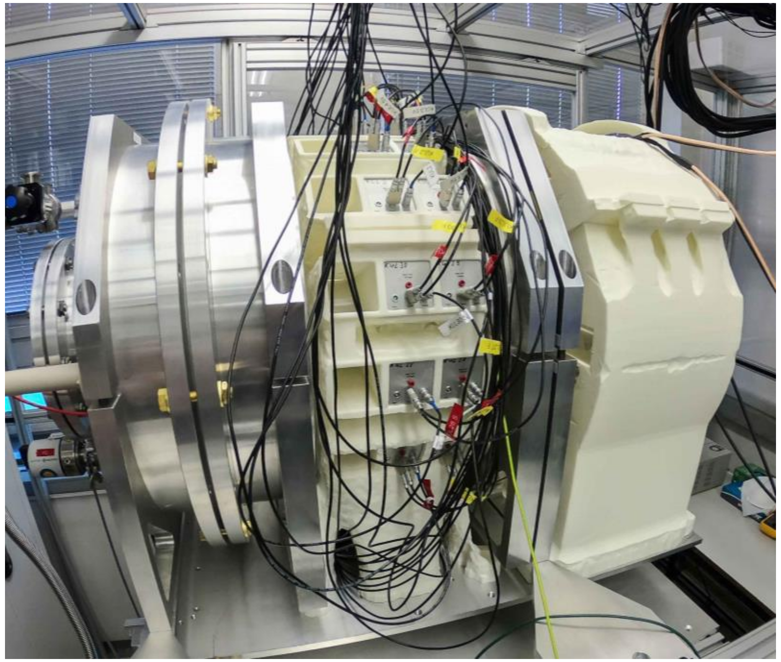
Period																				
1	1 H																			2 He
2	3 Li	4 Be														5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg														13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							
* Lanthanides			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
** Actinides			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		



O. Tarasov LISE++

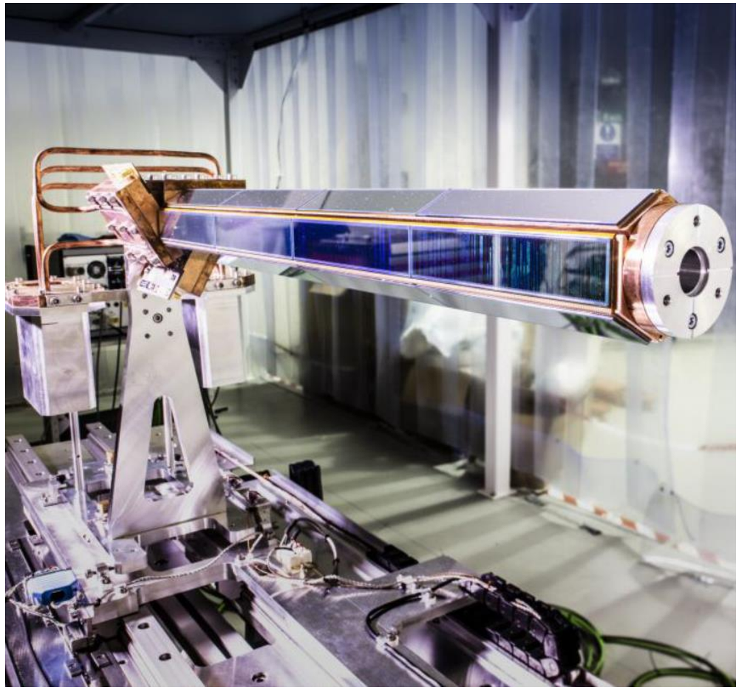
New Devices for Solenoidal Spectrometers

ISOLDE Solenoidal Spectrometer



SpecMat : Charged particle
+ Gamma-ray detector
Lead by **Oleksii Poleshchuk**, KU Leuven

X-Y Sensitive Si-detector
Lead by **Robert Page**,
University of Liverpool

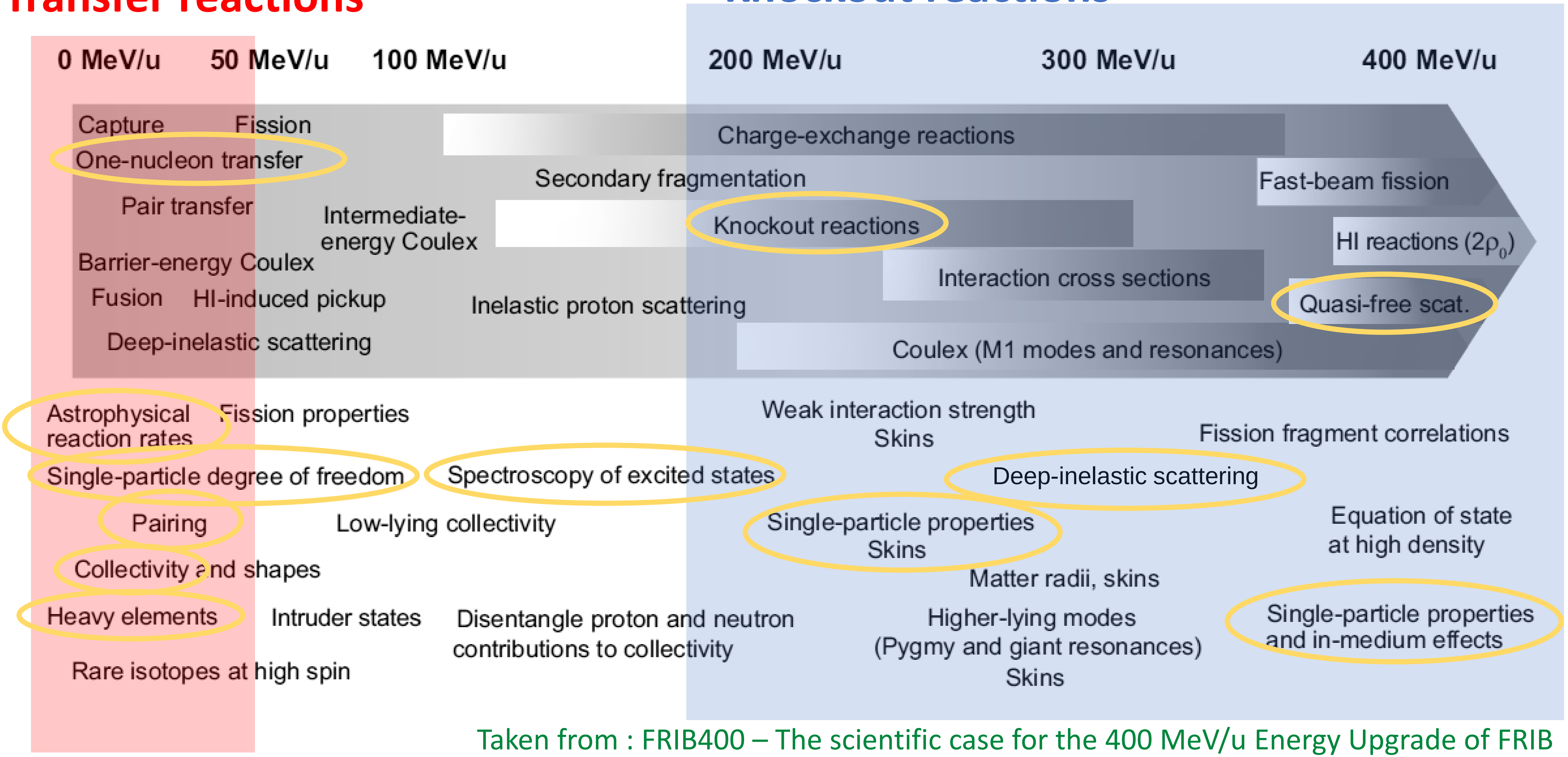


SOLARIS

AT-TPC, Lead by **Daniel Bazin**, NSCL

Transfer reactions

Knockout reactions



0 MeV/u 50 MeV/u 100 MeV/u 200 MeV/u 300 MeV/u 400 MeV/u

Capture

Fission

One-nucleon transfer

Pair transfer

Barrier-energy Coulex

Fusion

HI-induced pickup

Deep-inelastic scattering

Intermediate-energy Coulex

Secondary fragmentation

Inelastic proton scattering

Charge-exchange reactions

Knockout reactions

Interaction cross sections

Coulex (M1 modes and resonances)

Fast-beam fission

HI reactions ($2\rho_0$)

Quasi-free scat.

Astrophysical reaction rates

Fission properties

Single-particle degree of freedom

Spectroscopy of excited states

Pairing

Low-lying collectivity

Collectivity and shapes

Heavy elements

Intruder states

Disentangle proton and neutron contributions to collectivity

Rare isotopes at high spin

Weak interaction strength
Skins

Fission fragment correlations

Deep-inelastic scattering

Single-particle properties
Skins

Equation of state at high density

Matter radii, skins

Higher-lying modes
(Pygmy and giant resonances)
Skins

Single-particle properties and in-medium effects

Taken from : FRIB400 – The scientific case for the 400 MeV/u Energy Upgrade of FRIB

Summary

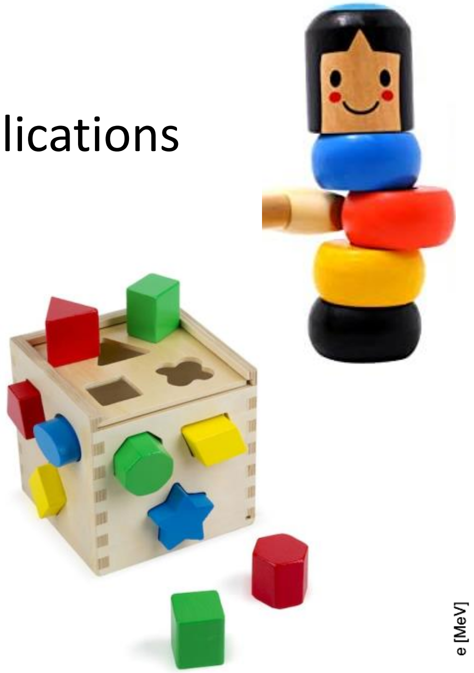
Single-particle spectroscopy is an active tool with many applications

- most intuitive picture of how nucleon assembly.

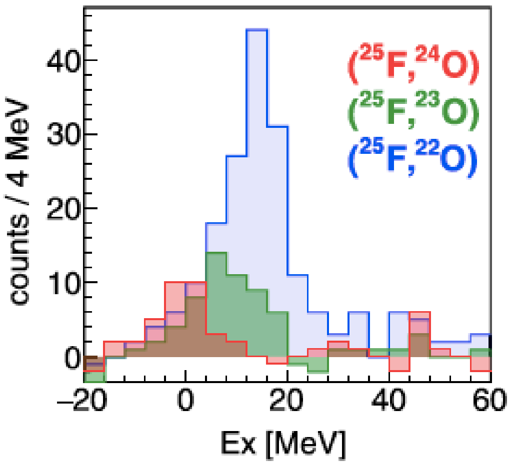
But still many new frontiers, 2 examples:

- Fast beam (*p,2p*) : study neutron shell of ^{25}F
- Slow beam (*d,p*) : single-neutron spectroscopy of ^{207}Hg

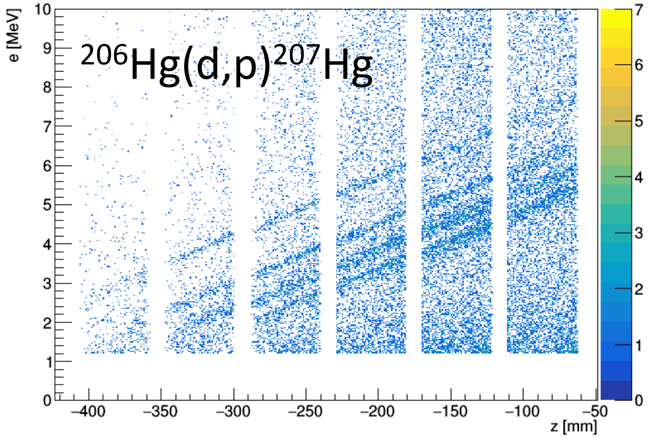
There are more applications!
Solenoidal spectrometers are around the world!



T.L.Tang et al., PRL **124**, 212502 (2020)



T.L.Tang et al., PRL **124**, 062502 (2020)



Thank you for your attention!!!