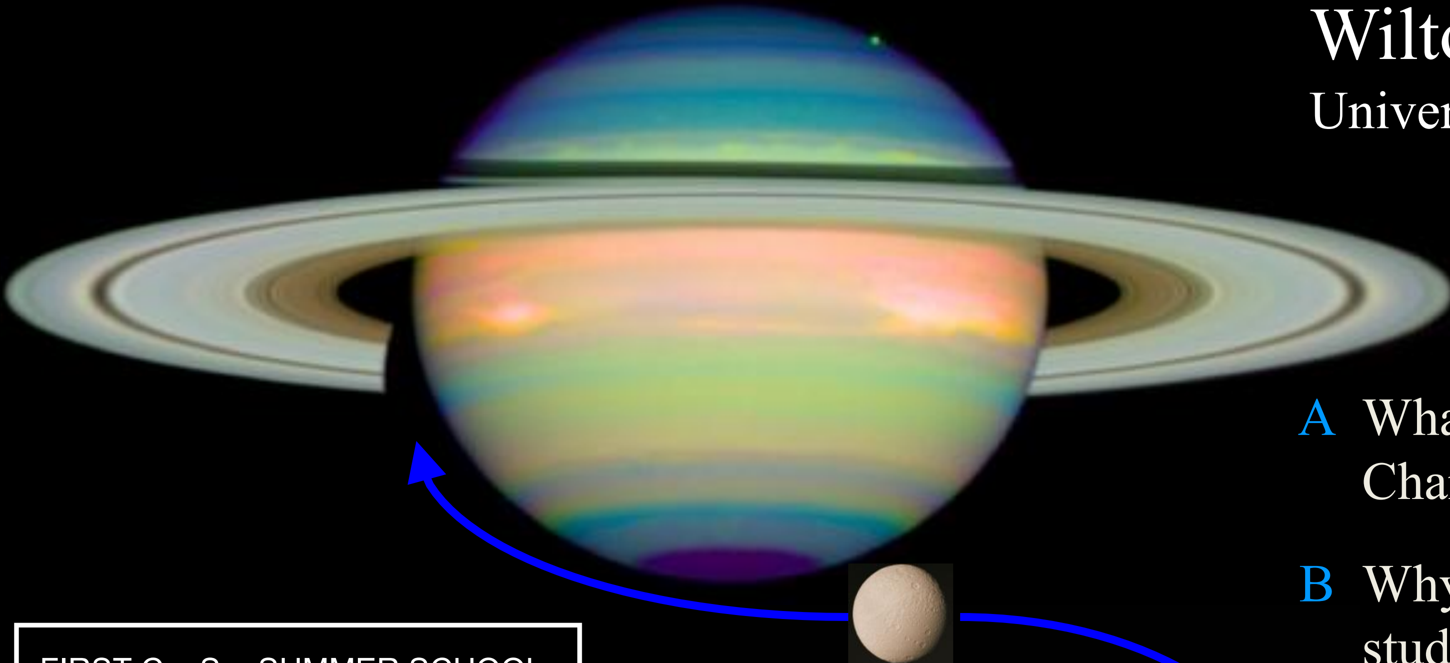
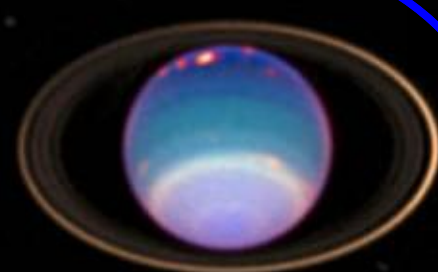
Exploring Unusual Nuclei with Nucleon Transfer Reactions

Wilton Catford
University of Surrey





A What can we learn?; Changing magic no.'s

B Why use transfer to study this physics?

C What can we measure in specific nuclei?

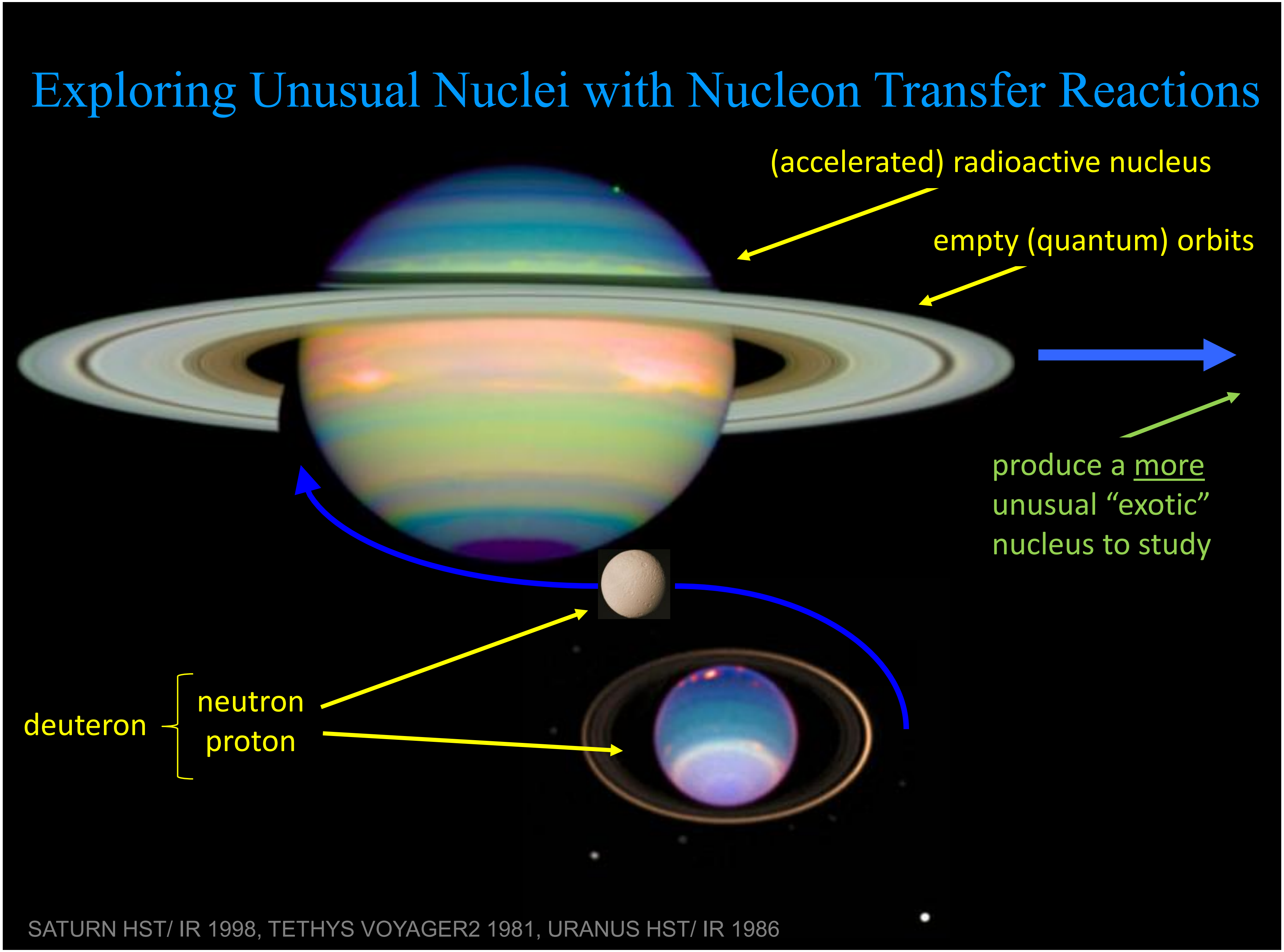
D Experimental setups

E Examples of data & Interpretation

FIRST CaeSar SUMMER SCHOOL

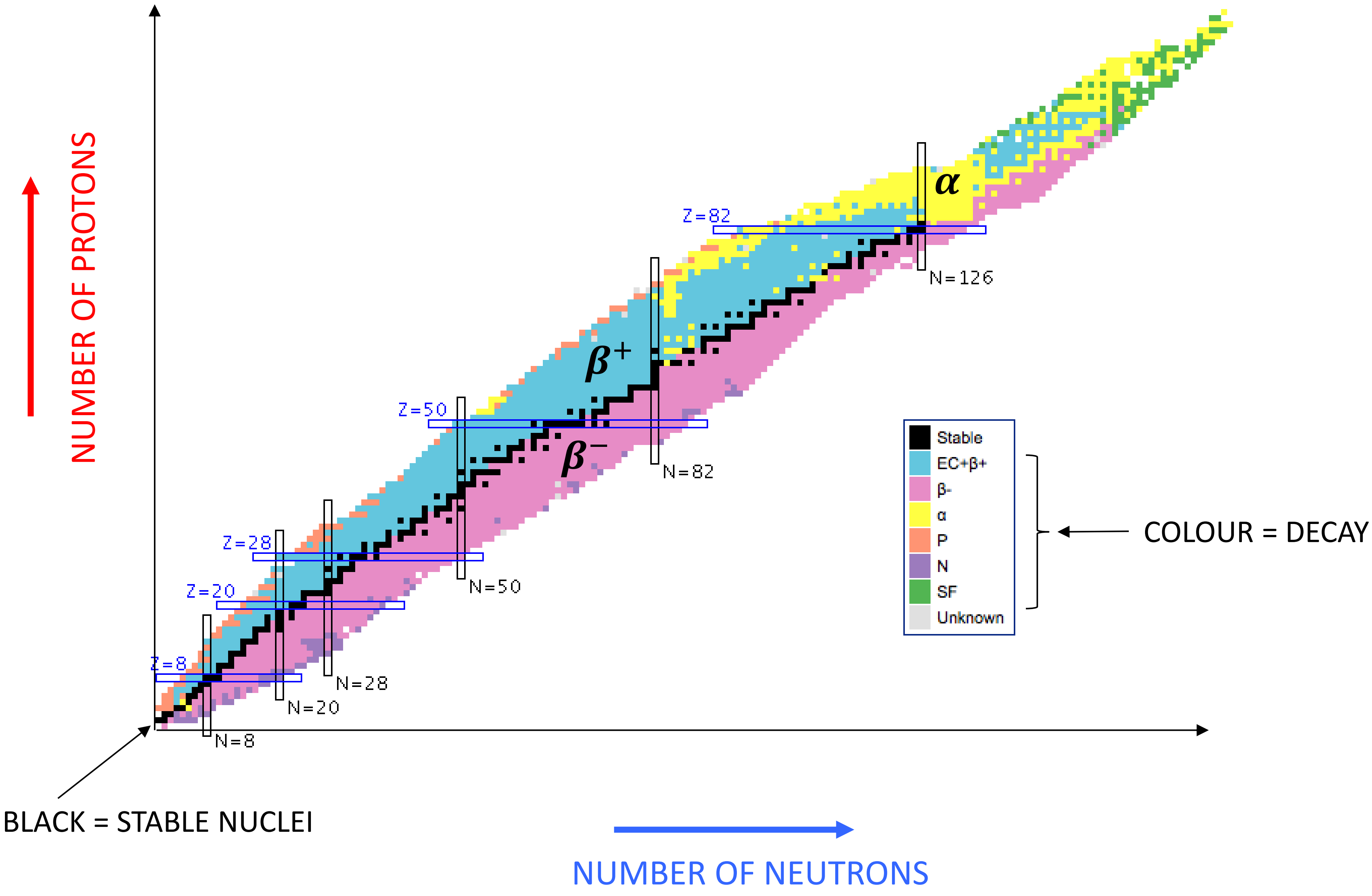
Pont L'Évêque**3-5 September 2025

SATURN HST/ IR 1998, TETHYS VOYAGER2 1981, URANUS HST/ IR 1986

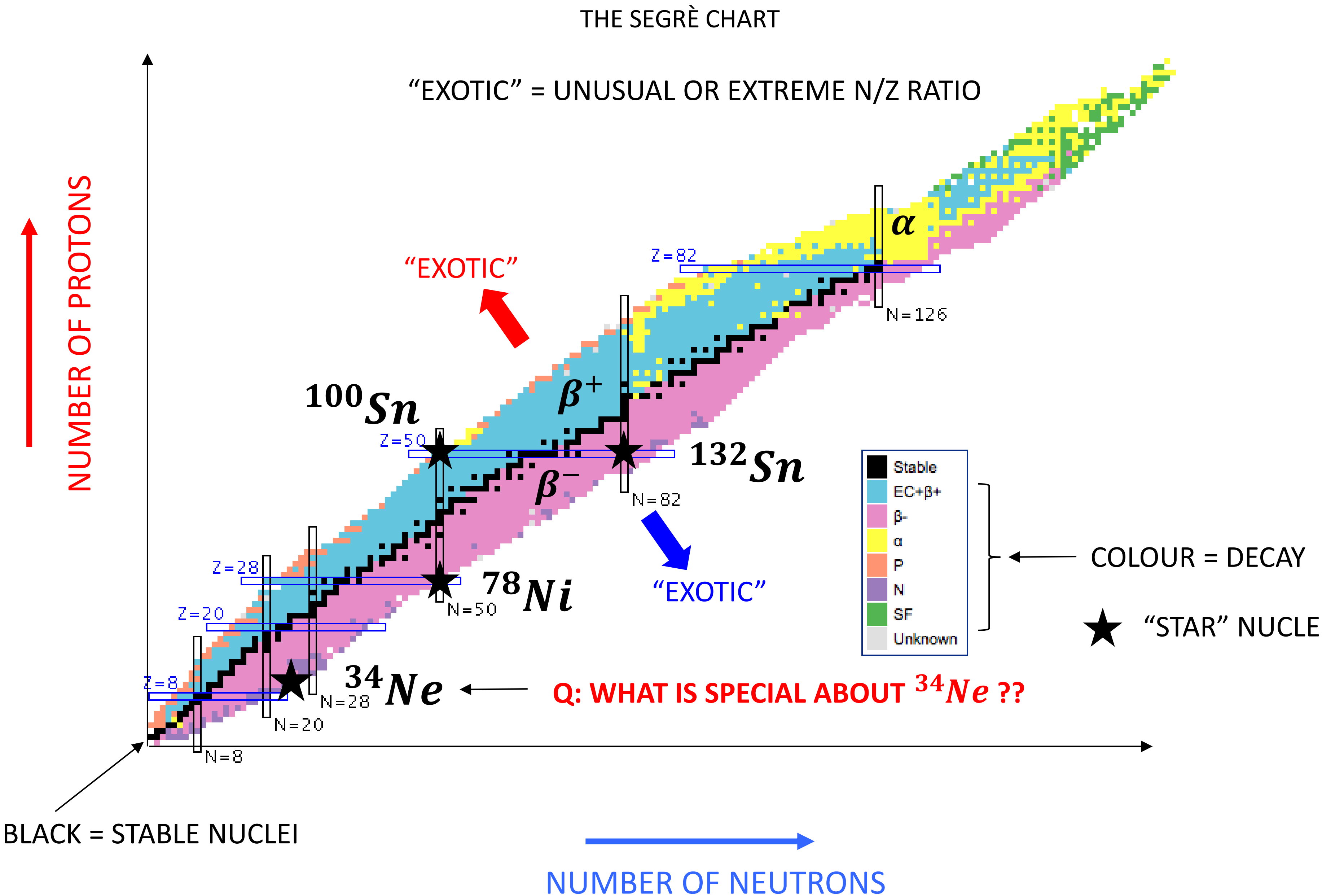

Exploring Unusual Nuclei with Nucleon Transfer Reactions
(accelerated) radioactive nucleus
empty (quantum) orbits
produce a more unusual "exotic" nucleus to study
deuteron
neutron
proton
SATURN HST/ IR 1998, TETHYS VOYAGER2 1981, URANUS HST/ IR 1986

MAP OF THE NUCLEI

THE SEGRÈ CHART



MAP OF THE NUCLEI



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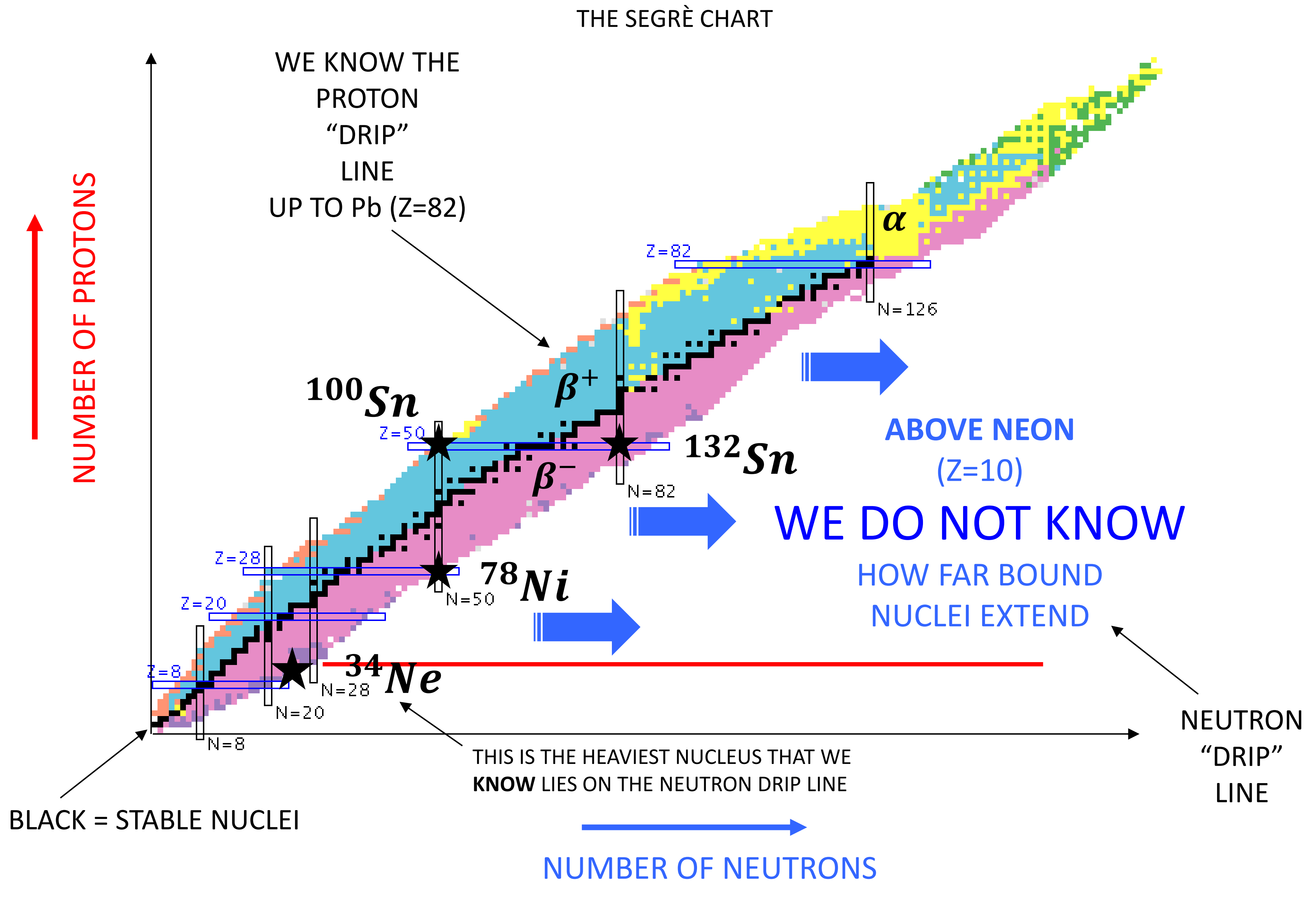
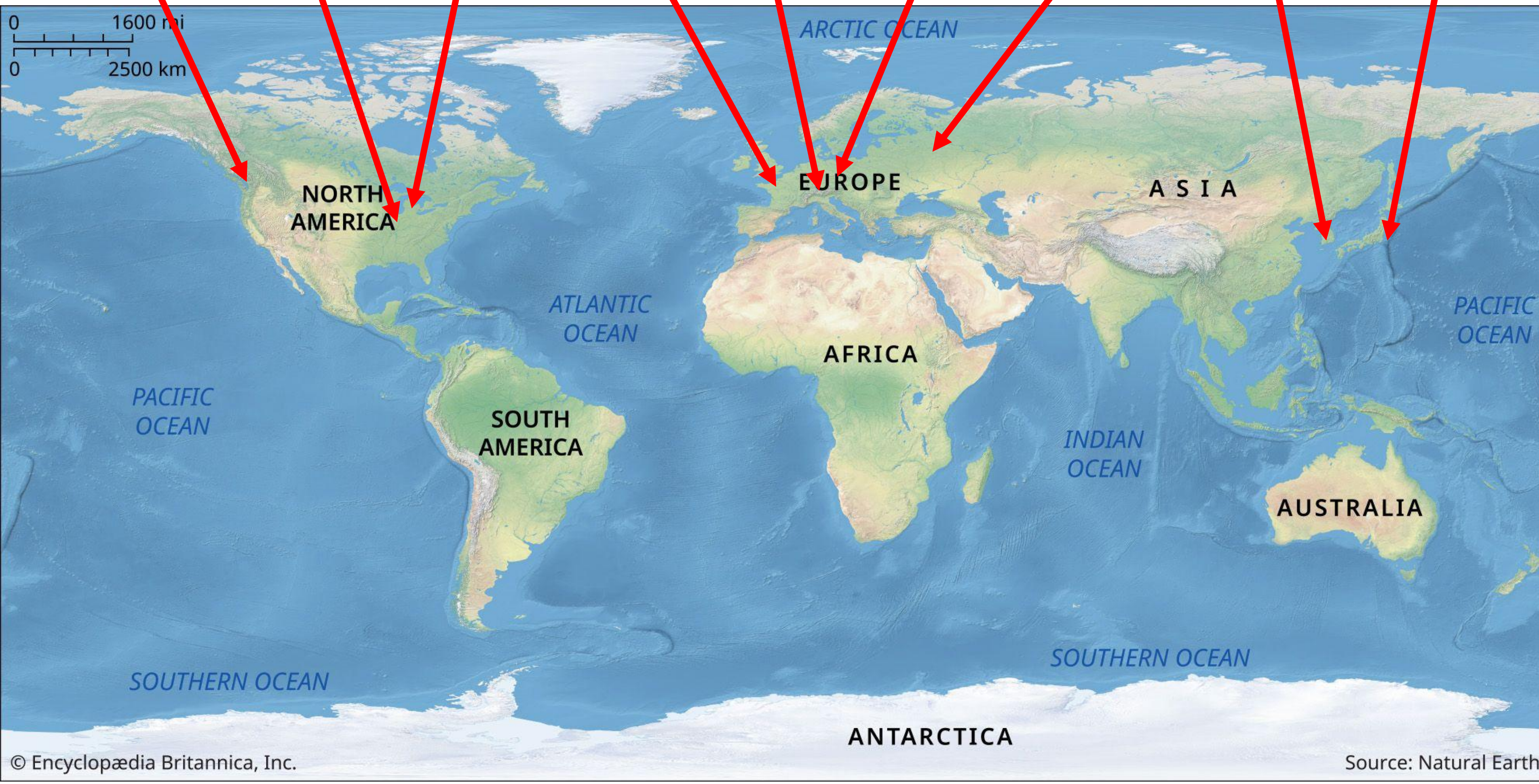


MAP OF THE WORLD

EVERY MAJOR LABORATORY PRODUCING INTENSE BEAMS OF SHORT-LIVED RADIOACTIVE NUCLEI

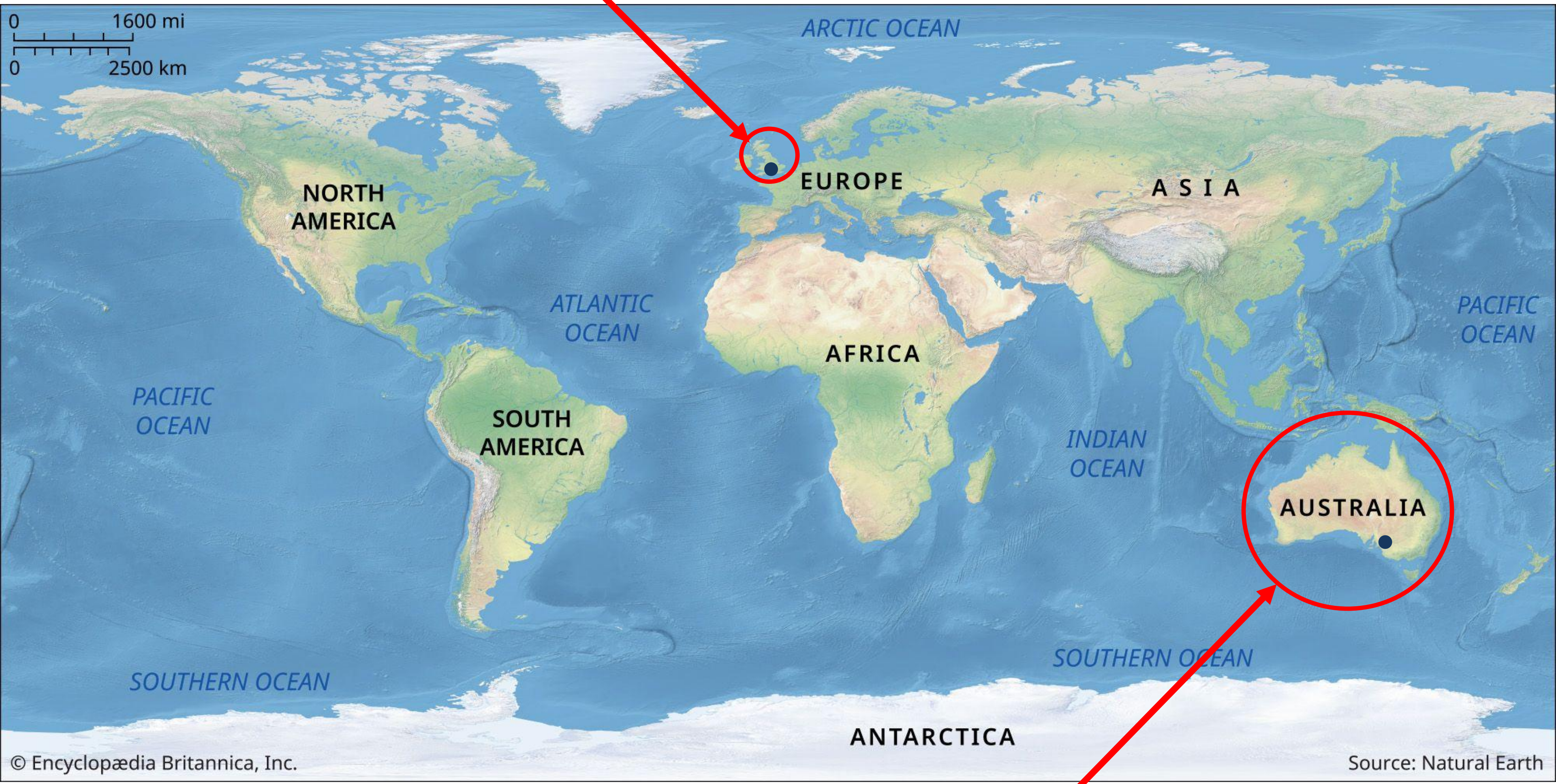
VANCOUVER	CHICAGO	MICHIGAN	CAEN	GENEVA	DARMSTADT	DUBNA	DAEJEON	TOKYO
TRIUMF	ARGONNE	FRIB	GANIL	CERN/ISOLDE	GSI/FAIR	JINR	IBS/CENS	RIKEN



MAP OF THE WORLD

AN IRRELEVANT ASIDE

This is where I live



This is where I am from

SO HOW DO WE MAKE A BEAM OF RADIOACTIVE NUCLEI?

Q: WHY DO I TALK JUST ABOUT RADIOACTIVE <u>BEAMS</u> ??

(AND NOT ABOUT <u>TARGETS</u> MADE OF THESE RADIOACTIVE NUCLEI ??)

SO HOW DO WE MAKE A BEAM OF RADIOACTIVE NUCLEI?

(a) "ISOL"

<u>Smash up</u> a big nucleus and <u>reaccelerate</u> the fragments

Isotope Separation On-line

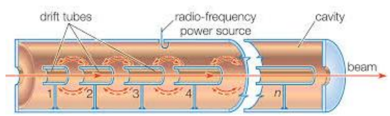
driver beam

production target

ion extraction

$\beta = {}^{v}/_{c} \approx 0$

accelerator



experiment

target

radioactive ion beam

(b) "IN FLIGHT"

<u>Tear pieces out</u> of a big nucleus and <u>filter</u> the "good guys" magnetically

Fragmentation Facility

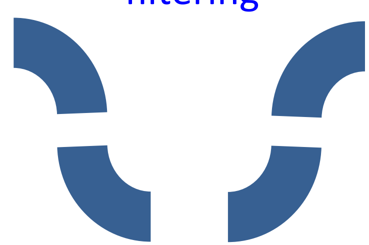
driver beam

production target

fragments continue

$\beta = {}^{v}/_{c} \gtrsim 0.3$

magnetic filtering



experiment

target

radioactive ion beam

- Motivation: nuclear structure reasons for transfer
- What quantities we actually measure
- What reactions/energies can we choose to use?
- Inverse Kinematics
- Implications for Experimental approaches
- Why do people make the choices that they do?
- Example experiments and results

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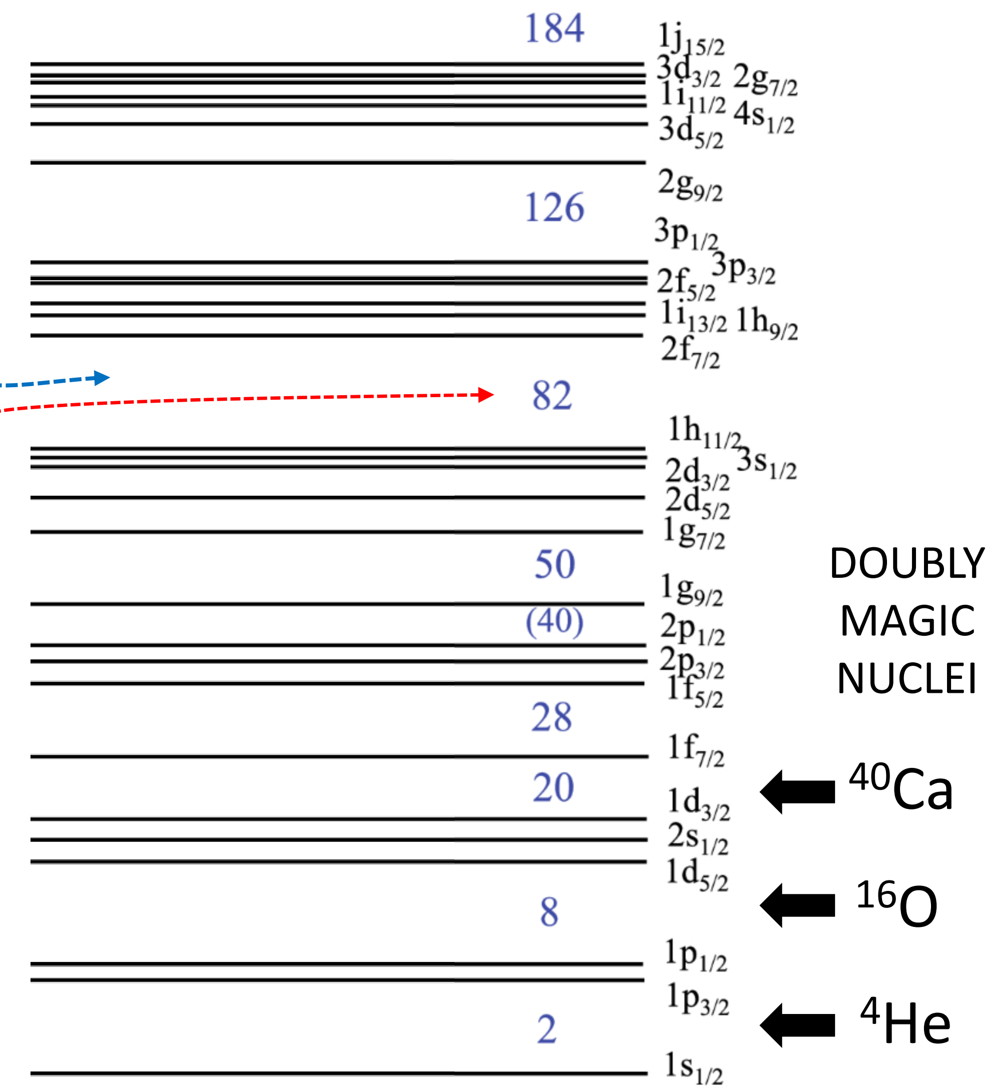
LE LAC DE PONT-L'ÉVÊQUE

SINGLE PARTICLE STATES in the nuclear shell model…

1. Mean Field Approximation
2. Woods-Saxon Potential
3. Spin-Orbit Interaction
4. ENERGY GAPS = SHELLS
5. Magic numbers



6. Fill with protons & neutrons
7. Two quantum fluids
8. Pauli Exclusion Principle

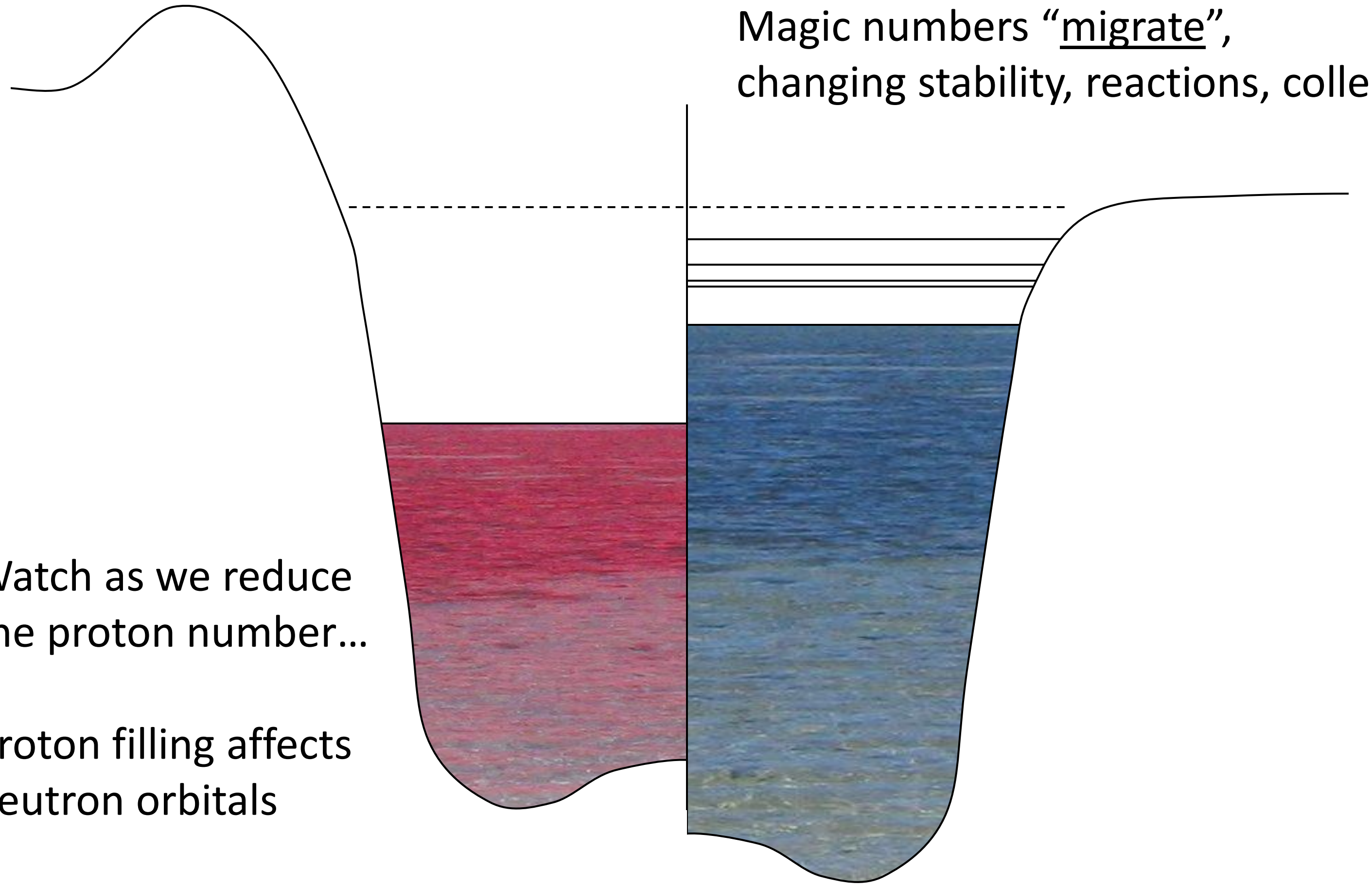
9. Simple Shell Model
   Pretend that adding particles doesn't change the orbitals
10. Large-scale Shell Model:
    Perturbation theory,
    Matrix diagonalisation

SINGLE PARTICLE STATES

Changes – tensor force, p-n

Residual interactions <u>move</u> the mean field levels

Magic numbers "<u>migrate</u>", changing stability, reactions, collectivity…



Watch as we reduce the proton number…

proton filling affects neutron orbitals

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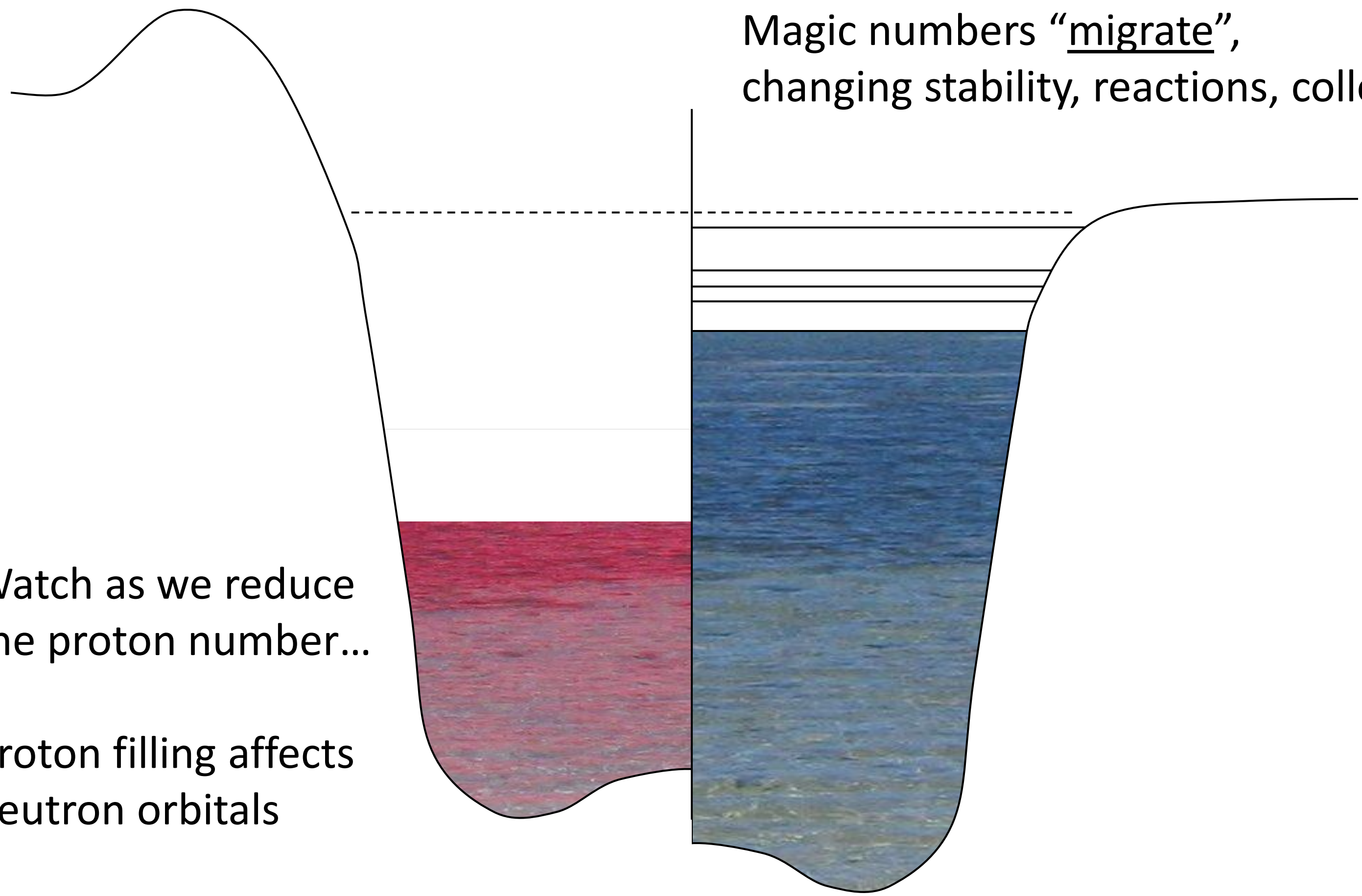

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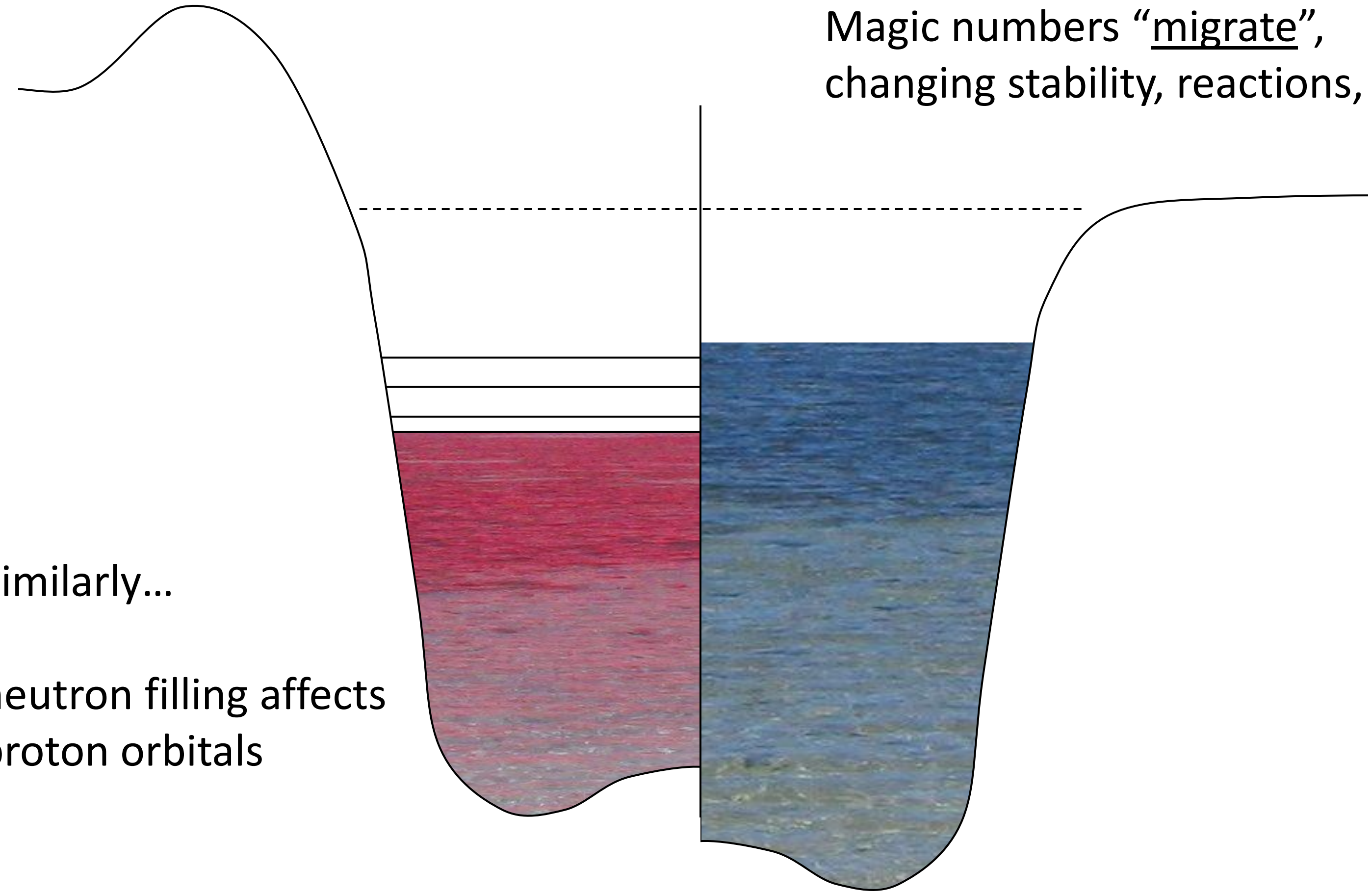

Similarly…

neutron filling affects proton orbitals

SINGLE PARTICLE STATES

Changes – tensor force, p-n

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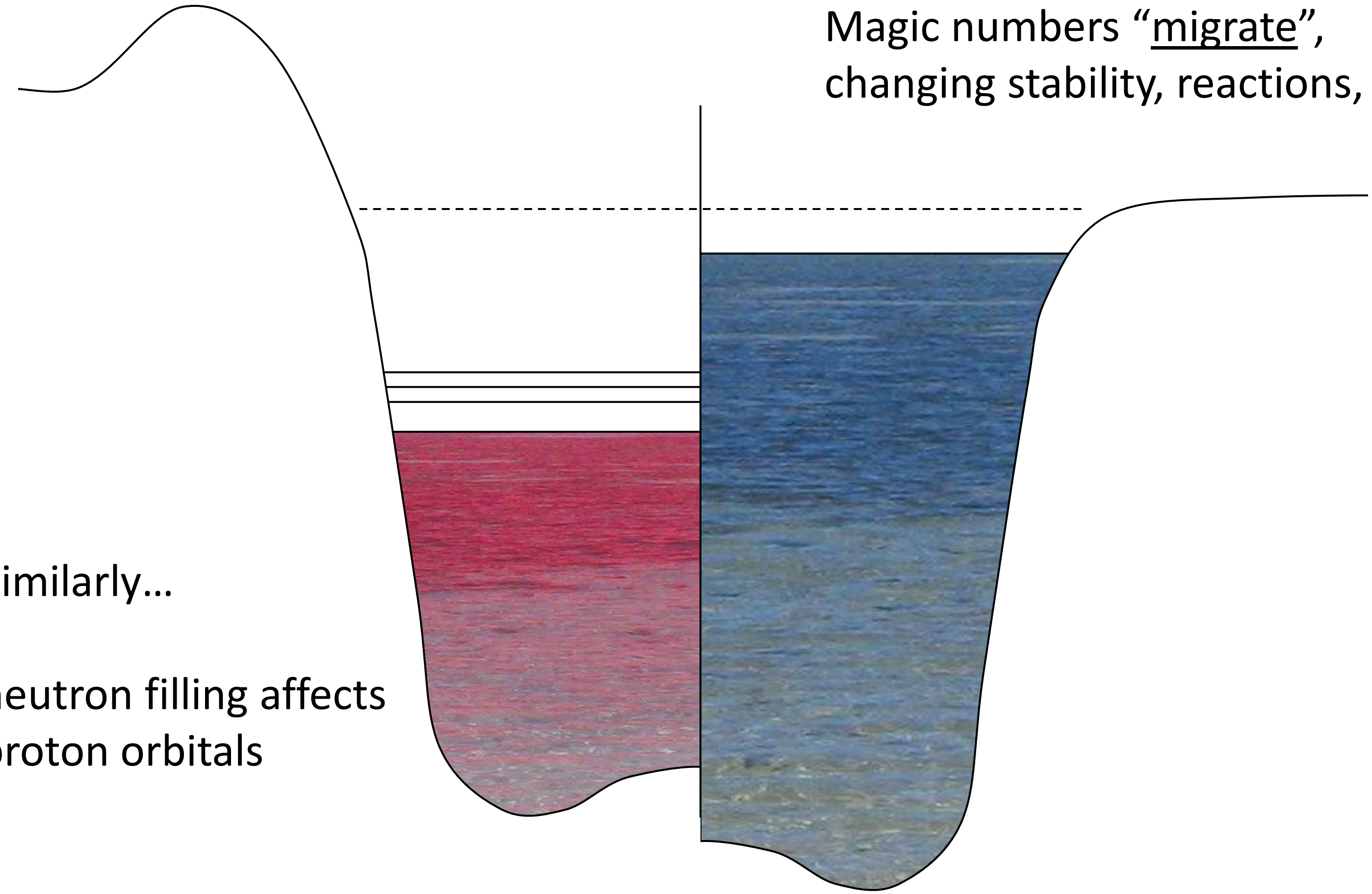


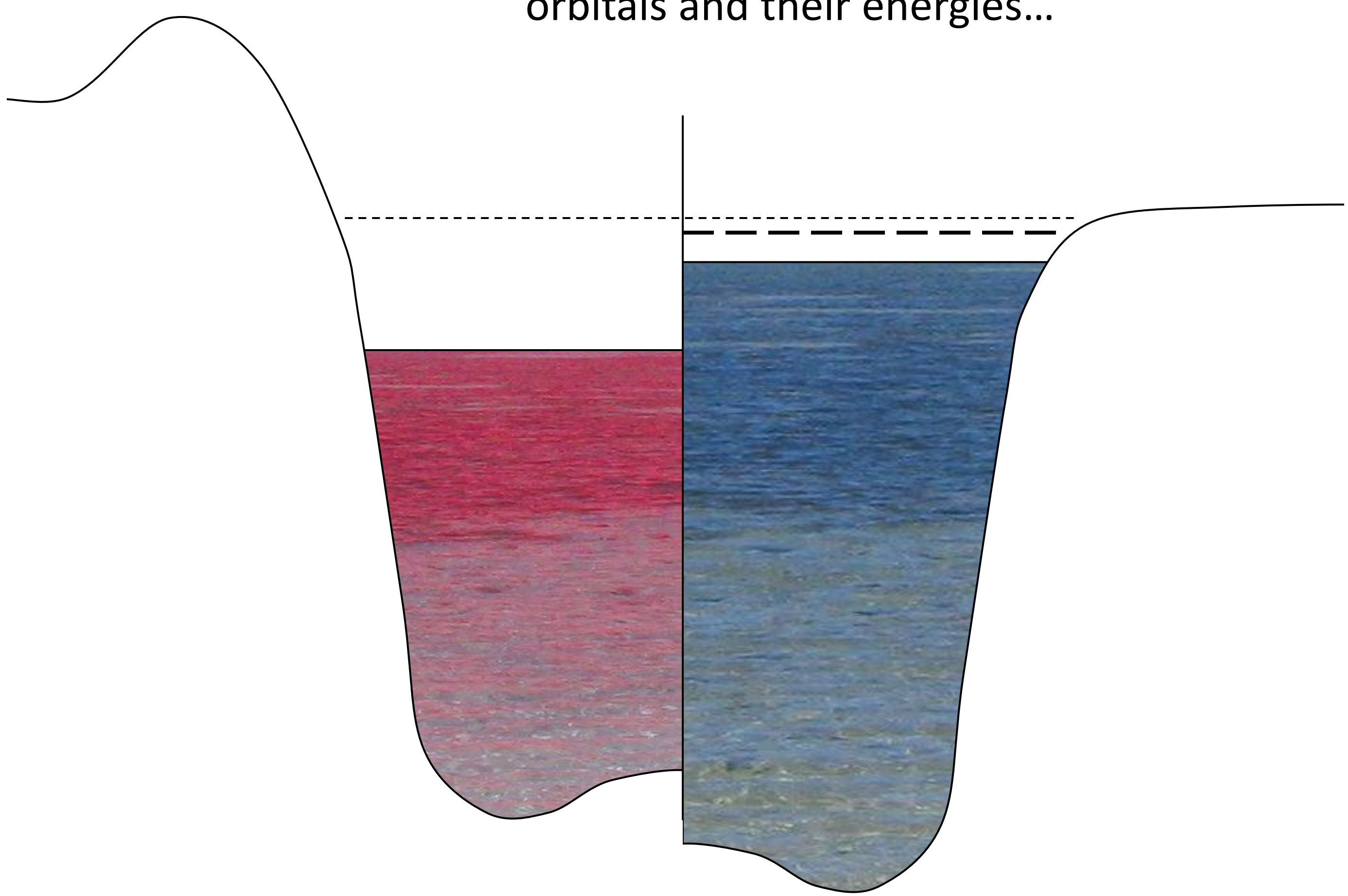
Similarly…

neutron filling affects proton orbitals

SINGLE PARTICLE STATES

(d, p)

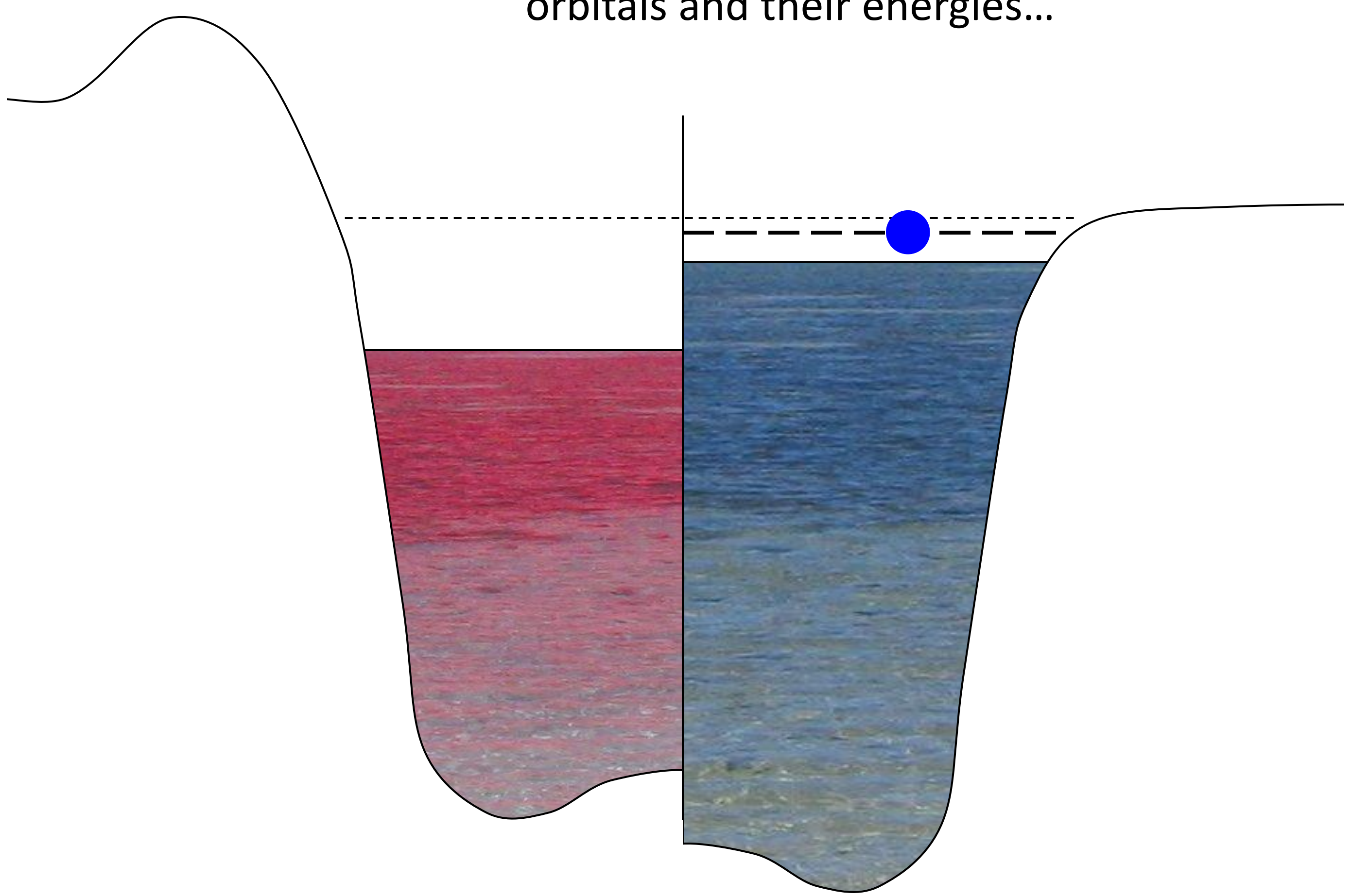
Probing the changed orbitals and their energies…



SINGLE PARTICLE STATES

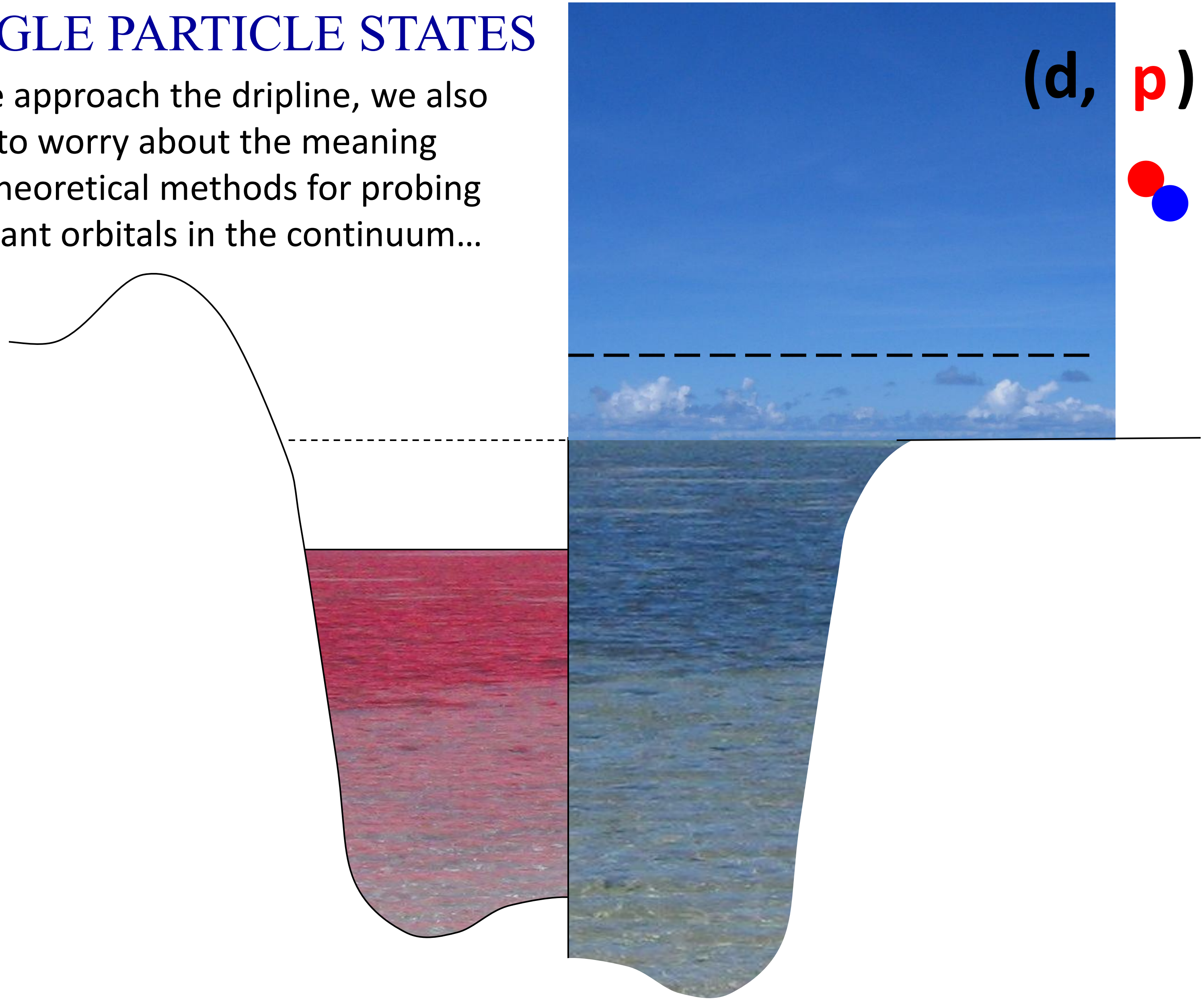
(d, p)

Probing the changed orbitals and their energies…



SINGLE PARTICLE STATES

As we approach the dripline, we also have to worry about the meaning and theoretical methods for probing resonant orbitals in the continuum…



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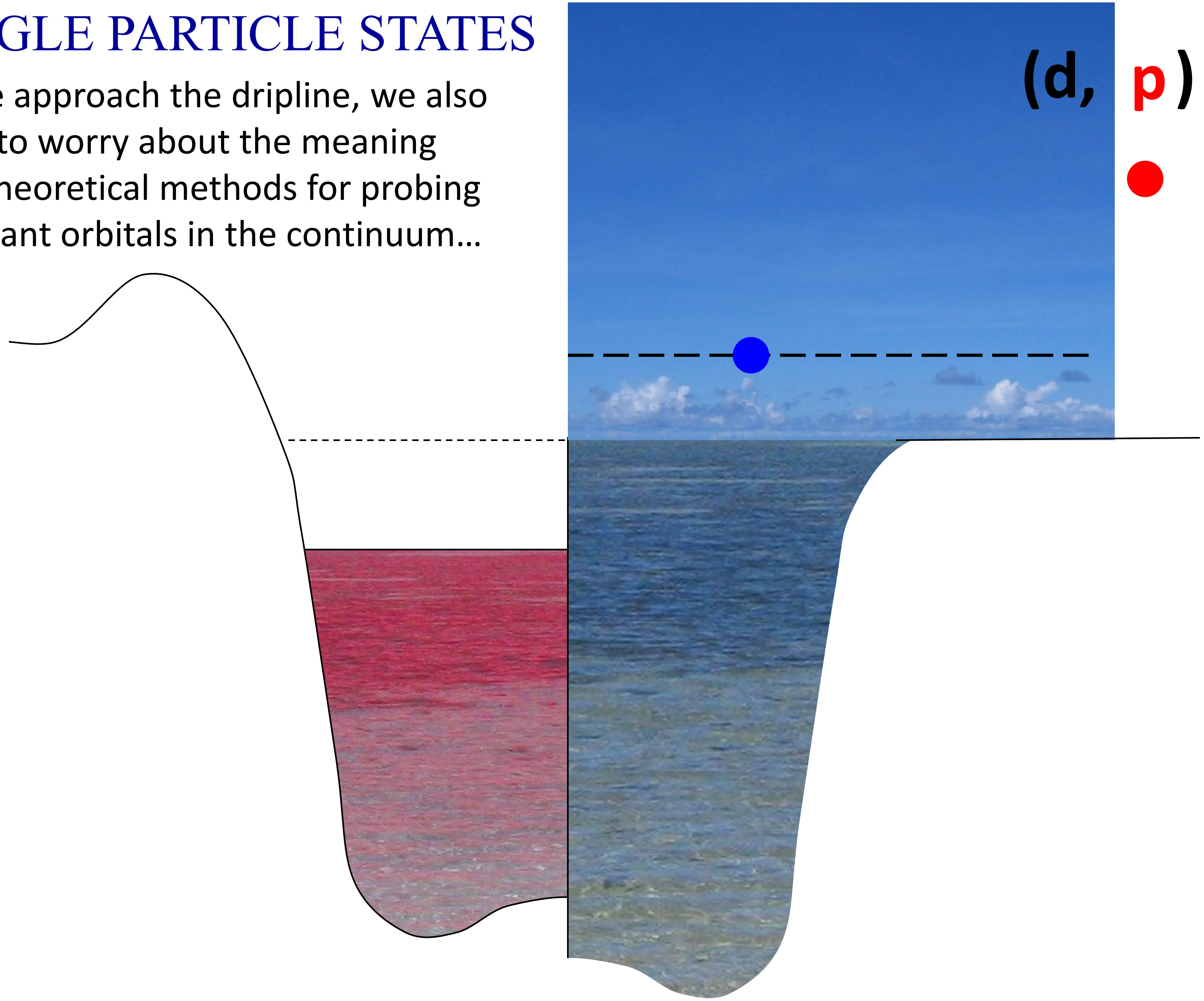
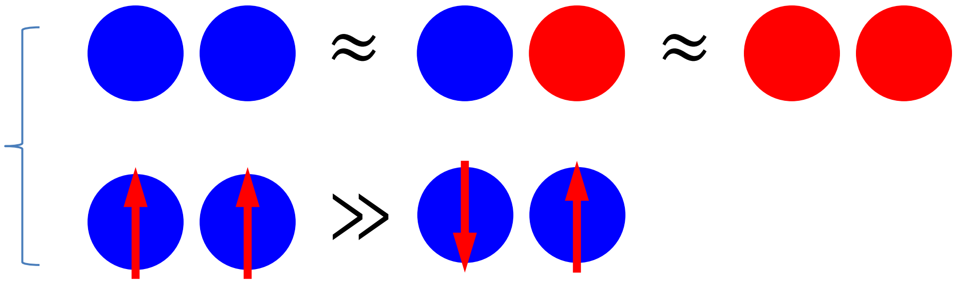
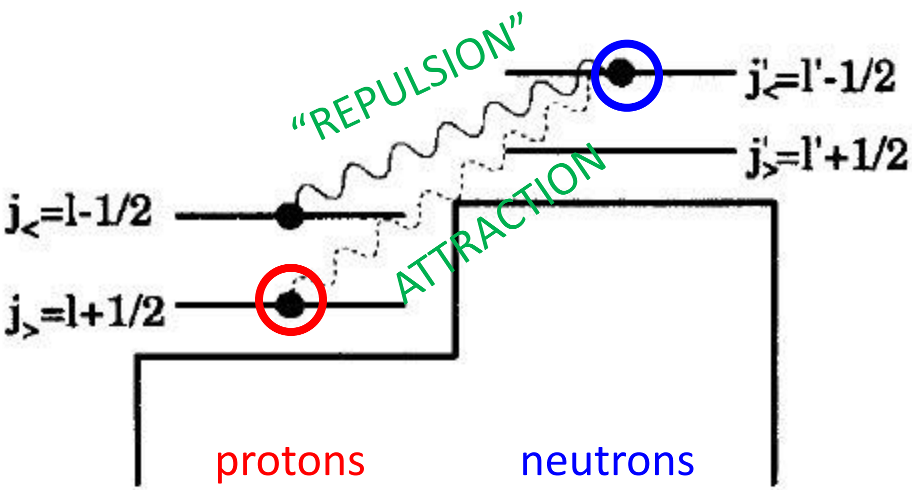
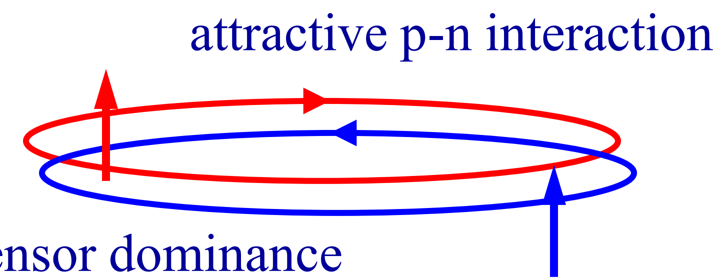


Nucleon-Nucleon Interaction:



Changing Magic Numbers:





T. Otsuka *et al.*, Phys. Rev. Lett. **97**, 162501 (2006).

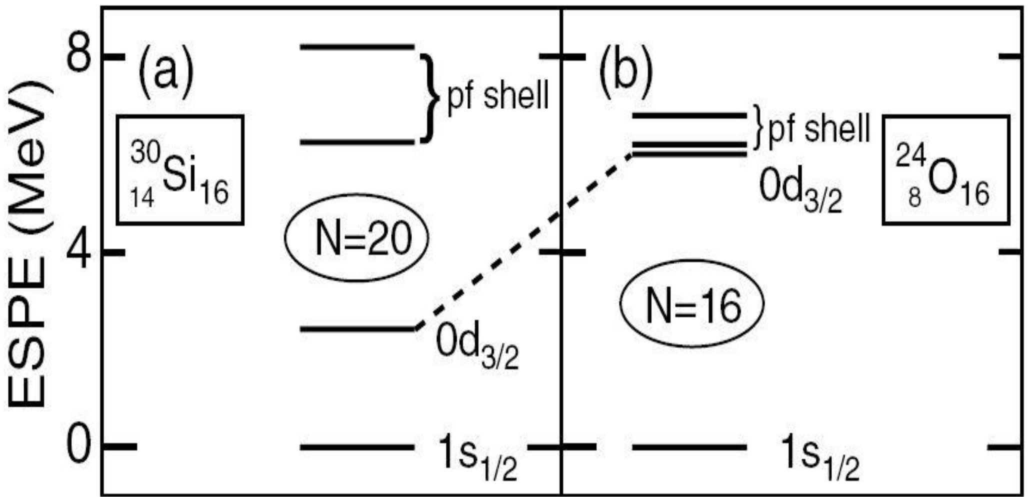
T. Otsuka *et al.*, Phys. Rev. Lett. **87**, 082502 (2001).

Nuclei are quantum fluids comprising
two distinguishable particle types…
They separately fill their quantum wells…
Shell structure emerges…
Valence nucleons interact…
This can perturb the orbital energies…

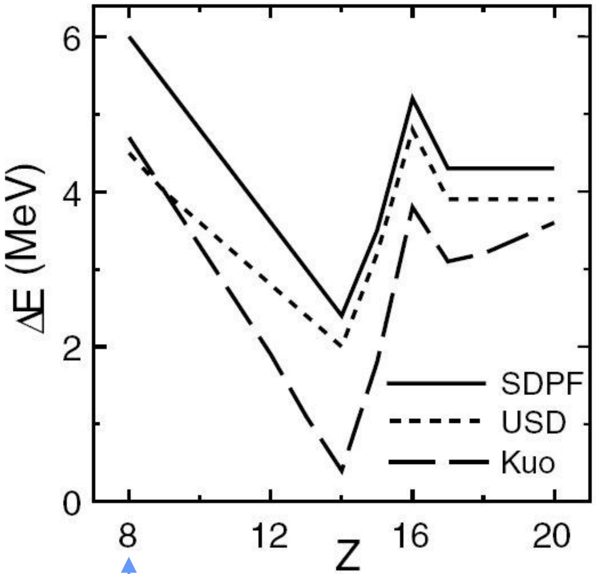
The shell magic numbers for p(n) depend on the level of filling for the n(p)

Changing Magic Numbers

energies of shell model orbitals



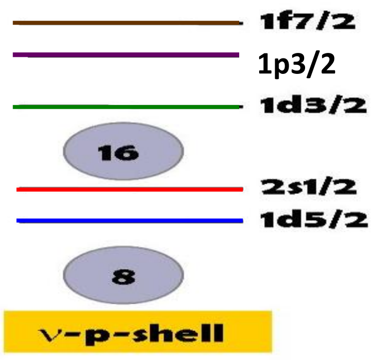
gap between $1s_{1/2}$ and $0d_{5/2}$



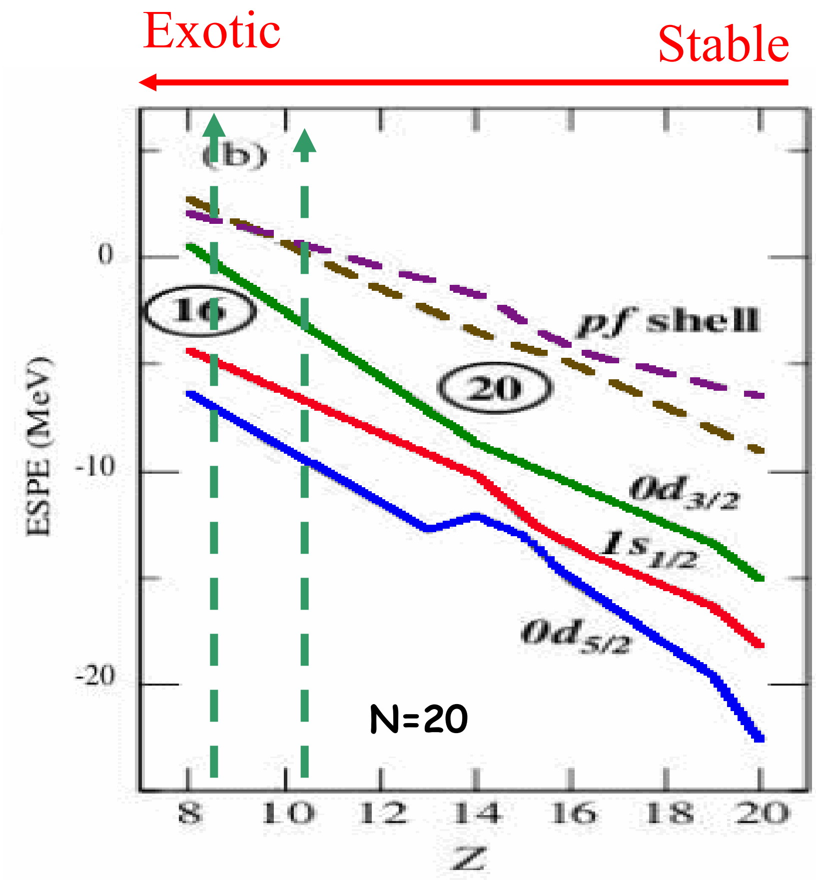
As the occupancy of the $j_>$ orbit $d_{5/2}$ is reduced in going from (a) ^{30}Si to (b) ^{24}O, then the attractive force on $j_<$ $d_{3/2}$ neutrons is reduced, and the orbital rises relatively in energy. This is shown in the final panel by the $s_{1/2}$ to $d_{3/2}$ gap, calculated using various interactions within the Monte-Carlo shell model.

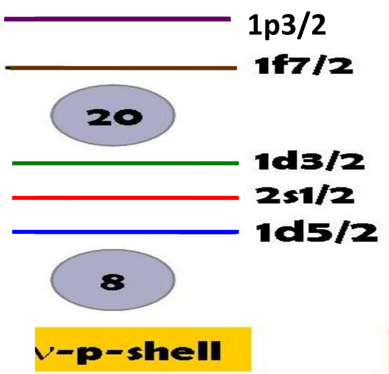
The trend varies for different orbitals in nuclei, as we go more exotic…

Utsuno et al., PRC,60,054315(1999)
Monte-Carlo Shell Model (SDPF-M)



Exotic





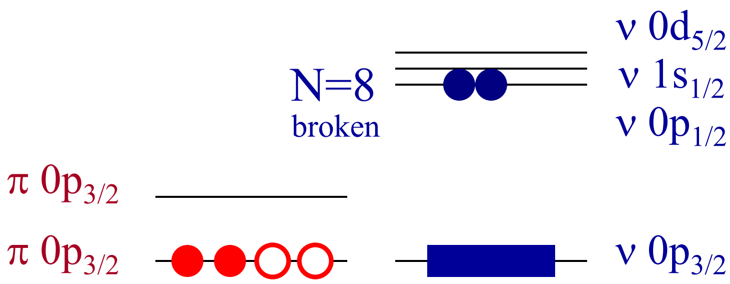
Stable

Removing d5/2 protons (Si →O)

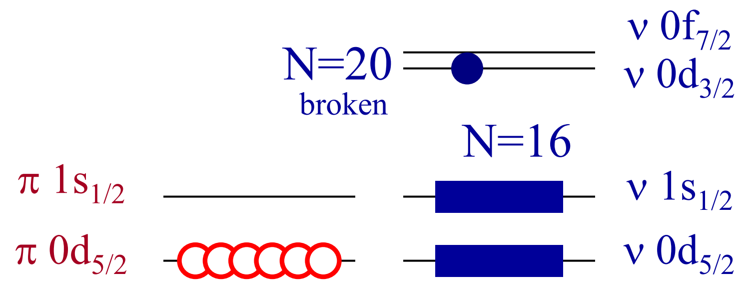
gives relative rise in ν(d3/2)

Note:
This changes collectivity, also…

Changing Magic Numbers: proton-deficient examples



^{12}Be

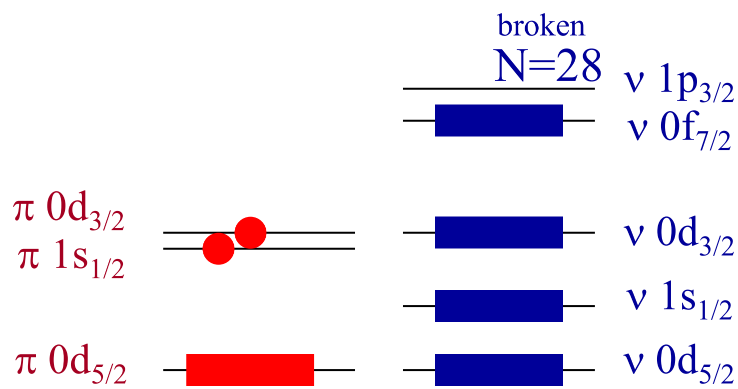


^{24}O

In the lighter nuclei (A<50) a good place to look is near closed proton shells, since a closed shell is followed in energy by a $j_>$ orbital. For example, compared to ^{14}C the nuclei ^{12}Be and ^{11}Li (just above Z=2) have a reduced π ($0p_{3/2}$) occupancy, so the N=8 magic number is lost.

Similarly, compared to ^{30}Si, the empty π ($0d_{5/2}$) in ^{24}O (Z=8) leads to the breaking of the N=20 magic number.

Another possible extreme is when a particular neutron orbital is much more complete than normal.



^{44}S

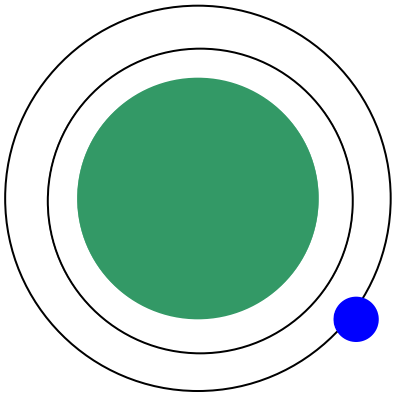
Nuclear states are not in general pure SP states, of course

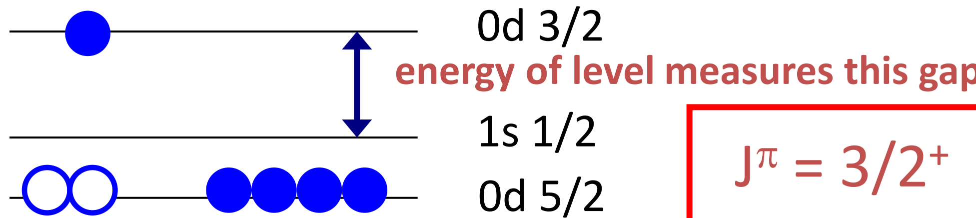
For nuclear states, we measure the **spin** and **energy**
and
the magnitude of the single-particle component for that state
(the **spectroscopic factor**)

Next slide example: low-lying $3/2^+$ states in ^{21}O

Single-particle States MIXING with states with other structures

Example of population of single particle state: ^{21}O



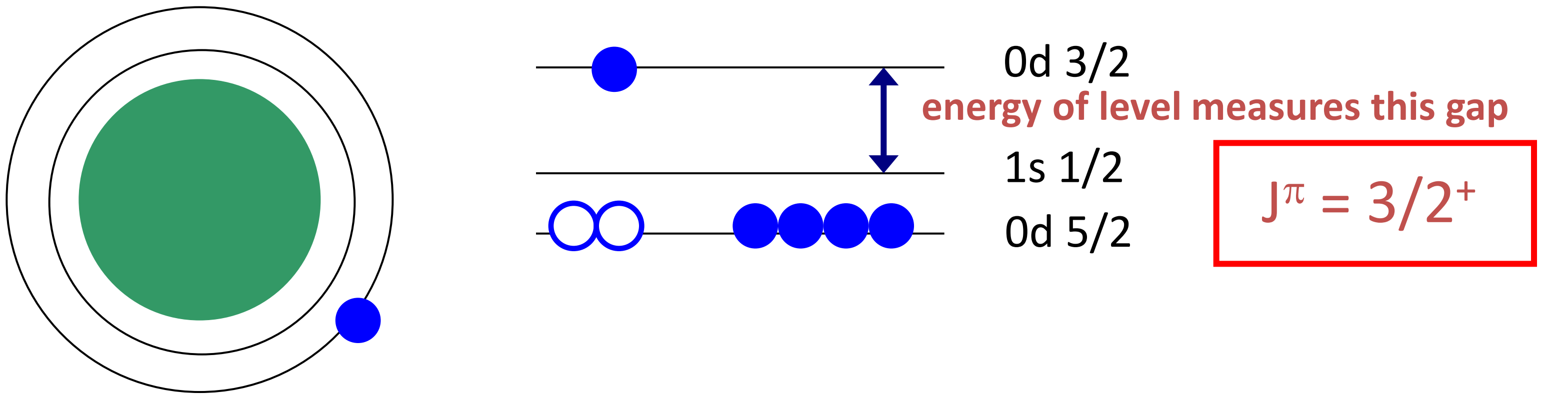


$J^{\pi} = 3/2^{+}$

The mean field has orbitals, many of which are filled.
We probe the energies of the orbitals by transferring a nucleon
This nucleon enters a vacant orbital
In principle, we know the orbital wavefunction and the reaction theory

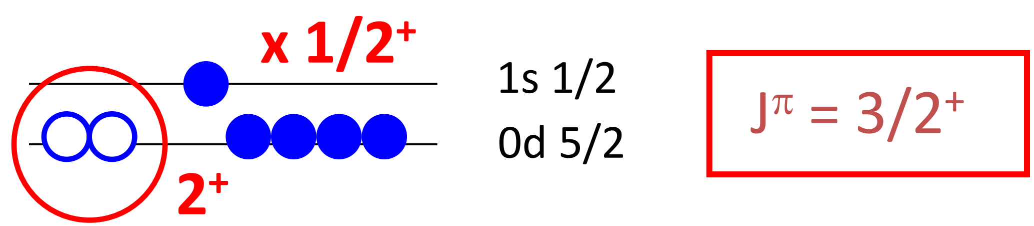
Single-particle States MIXING with states with other structures

Example of population of single particle state: ^{21}O



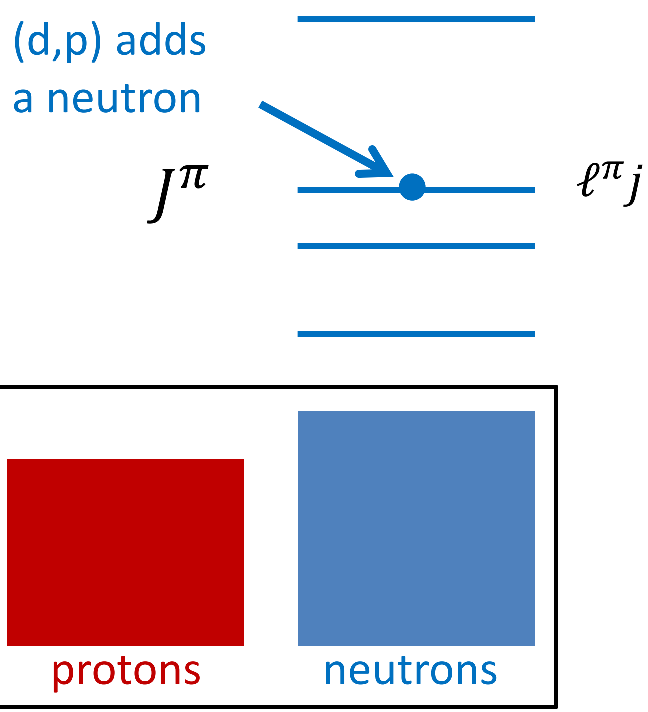
The mean field has orbitals, many of which are filled.
We probe the energies of the orbitals by transferring a nucleon
This nucleon enters a vacant orbital
In principle, we know the orbital wavefunction and the reaction theory

But not all nuclear excited states are single particle states…



We measure how the two $3/2^{+}$ states share the SP strength when they mix

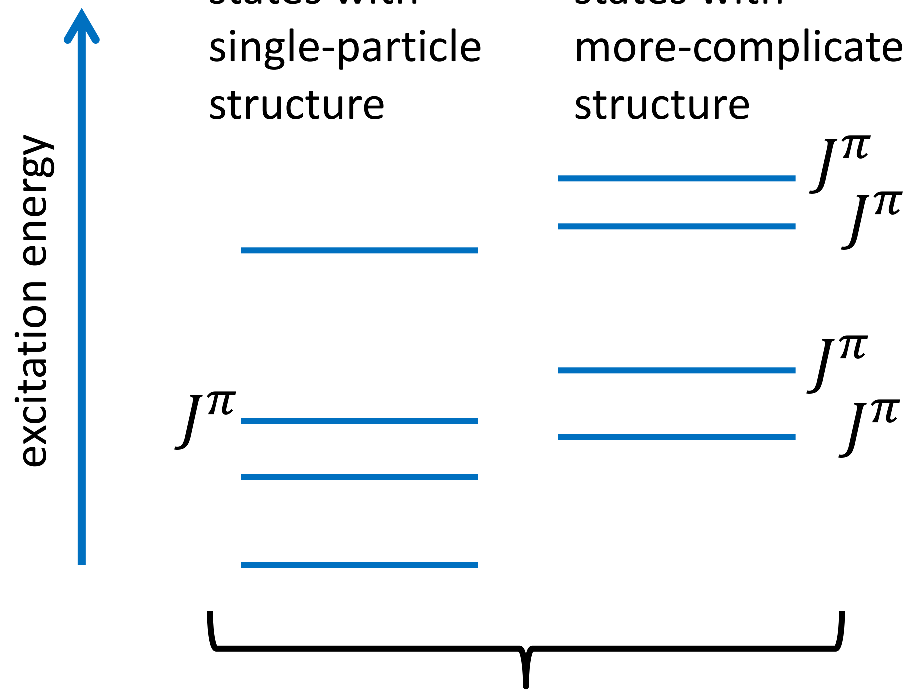
Single-particle States MIXING



single-particle state,
unperturbed core
(idealized situation)

states with single-particle structure

states with more-complicated structure



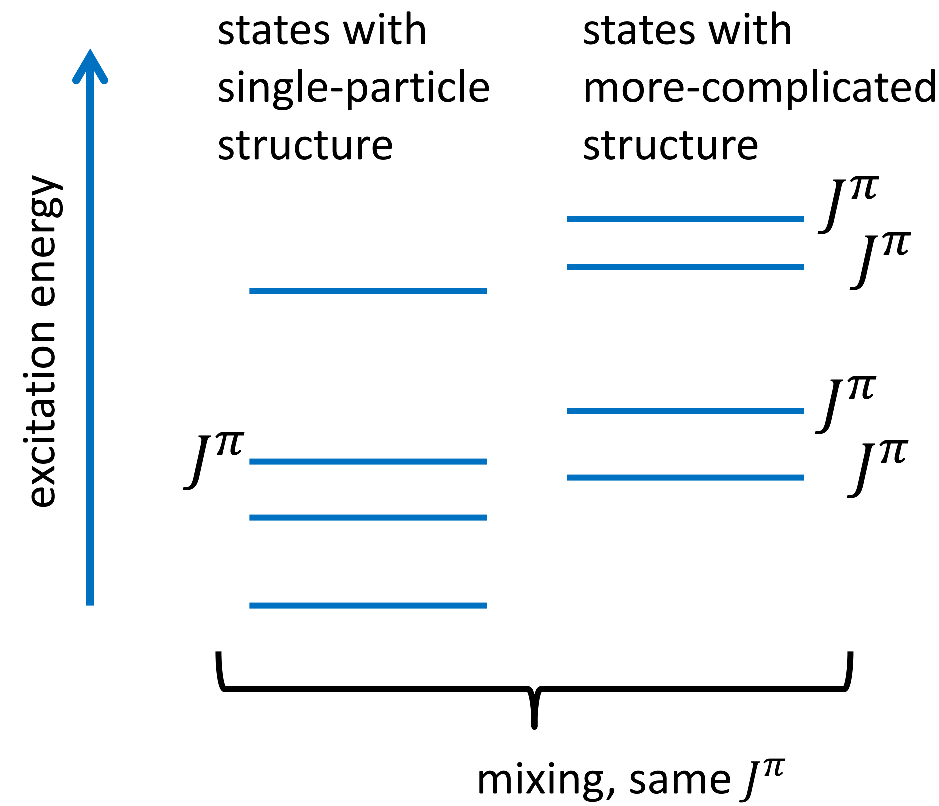
mixing, same J^π

$$| \; J_i^\pi > \; = \sqrt{S} \; |J_{SP}^\pi > + \sum_k \alpha_k \; |J_k^\pi >$$

$$S = | \, \langle J_{SP}^\pi \mid J_i^\pi \rangle |^2$$

spectroscopic factor
= overlap with pure SP state

Single-particle States MIXING



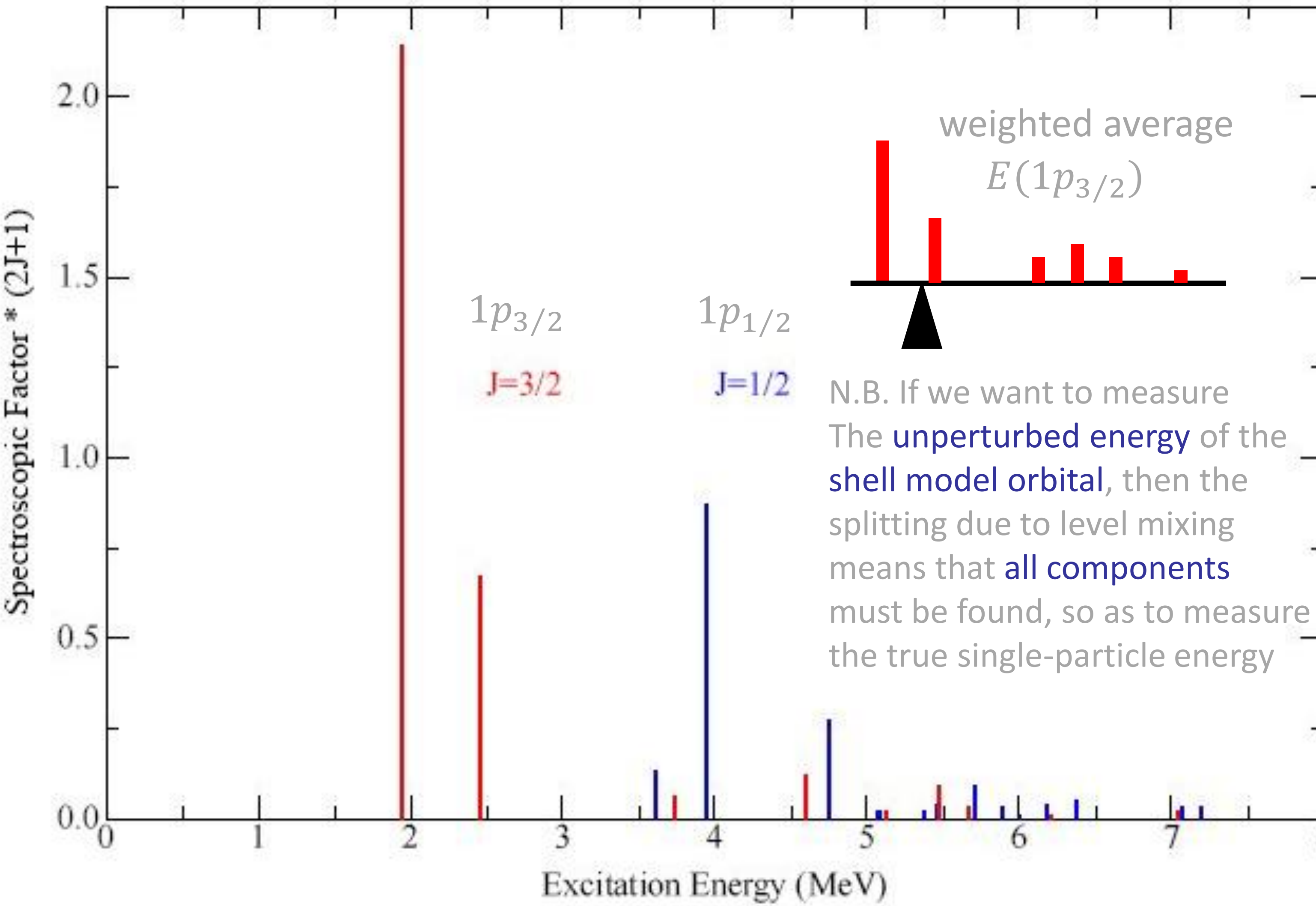
$$| \; J_i^\pi > \; = \sqrt{S} \; |J_{SP}^\pi > + \sum_k \alpha_k \; |J_k^\pi >$$

- we measure transferred ℓ_n from ${}^{d\sigma}/_{d\Omega}$
- we measure gamma-decays
- we aim to identify J and π
- we model the transfer yield for S=1
- we deduce S from the observed yield

$$S = | \, \langle J_{SP}^\pi \mid J_i^\pi \rangle |^2$$

spectroscopic factor
= overlap with pure SP state

Single-particle States – SPLITTING of strength due to MIXING

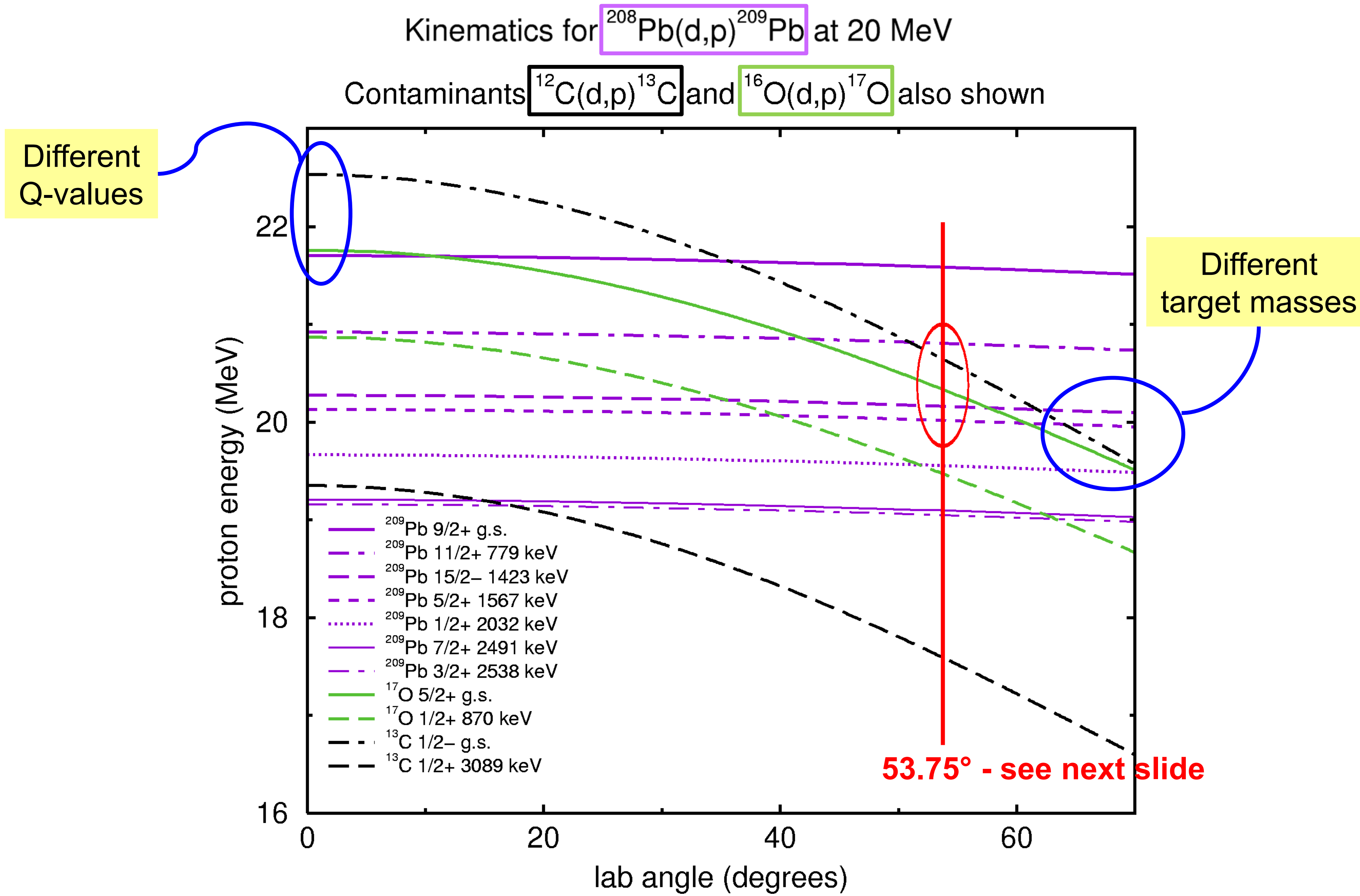


N.B. If we want to measure
The **unperturbed energy** of the
shell model orbital, then the
splitting due to level mixing
means that **all components**
must be found, so as to measure
the true single-particle energy

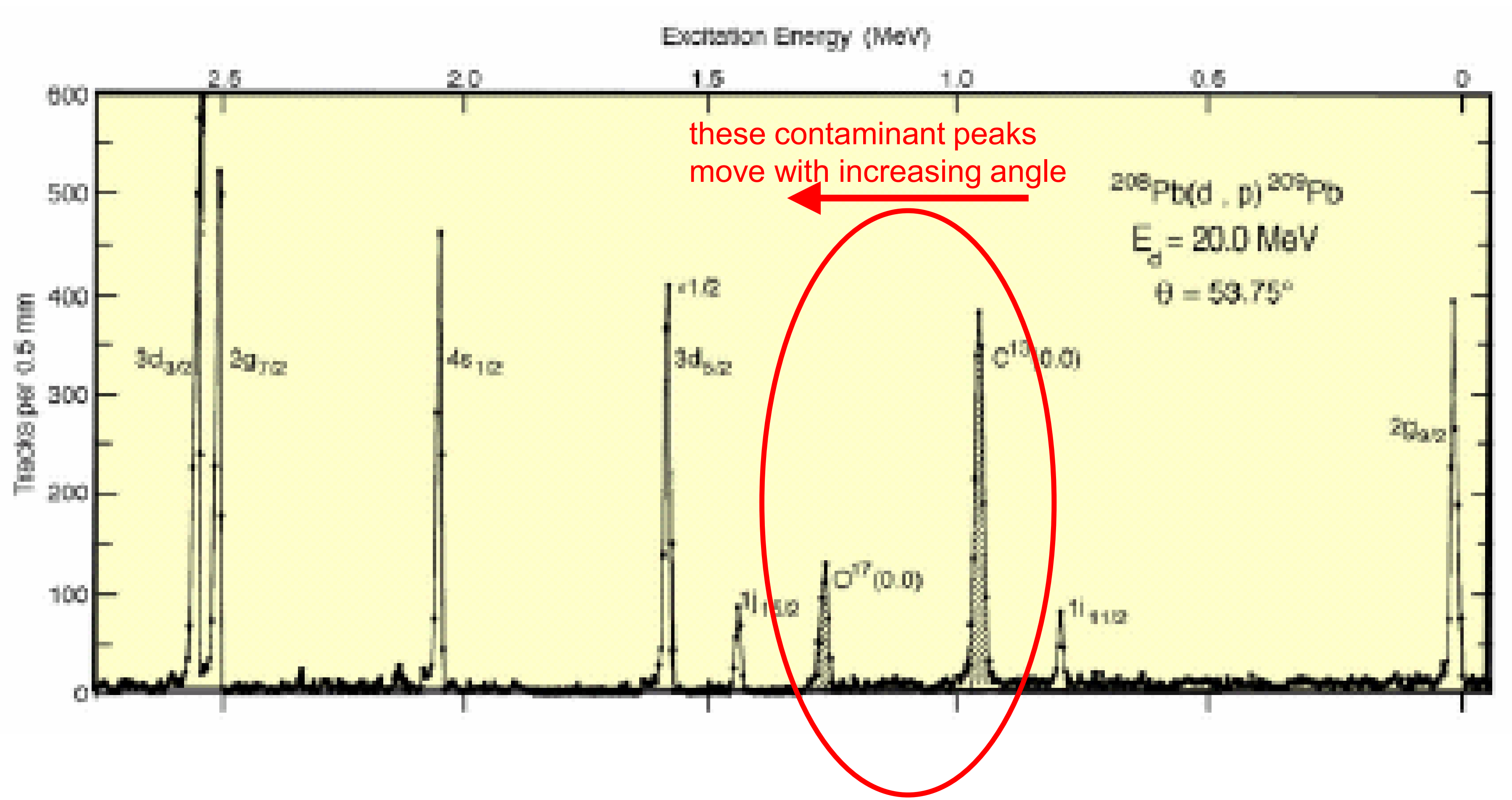
All p-wave ($\ell = 1$) spectroscopic strengths in $^{40}Ca(d,p)^{41}Ca$

Plot: John Schiffer

An Experiment to Study Neutron Orbitals Above Doubly Magic ^{208}Pb…

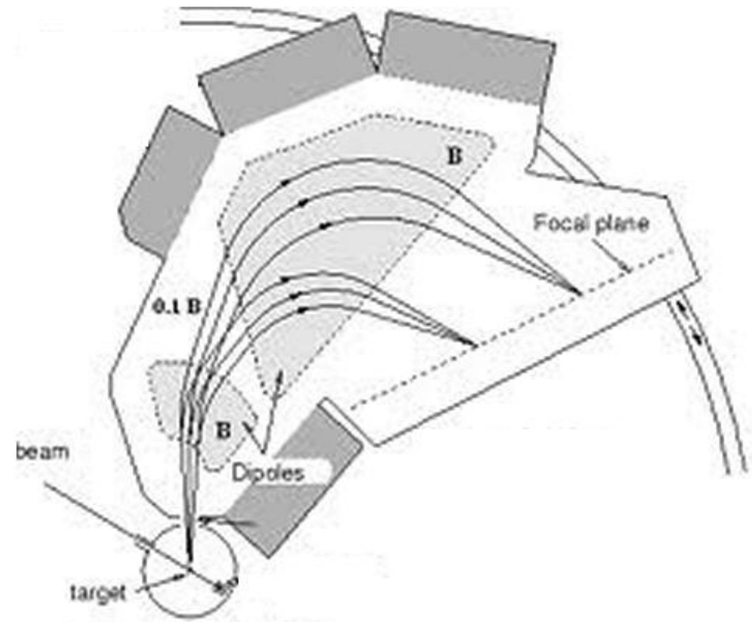


An Experiment to Study Neutron Orbitals Above Doubly Magic ^{208}Pb…

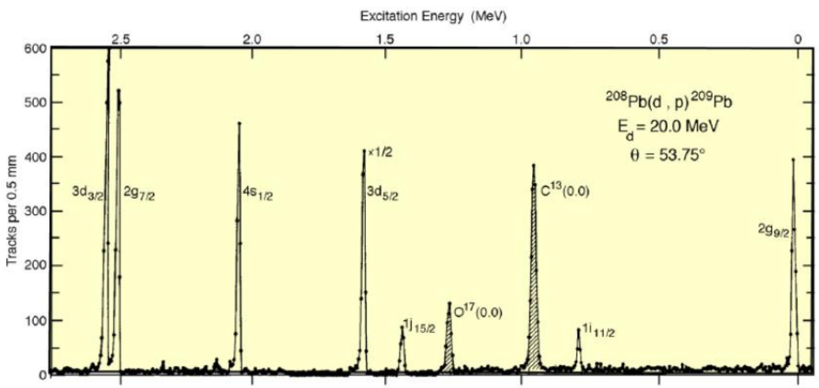


Adapted from: John Schiffer, Argonne

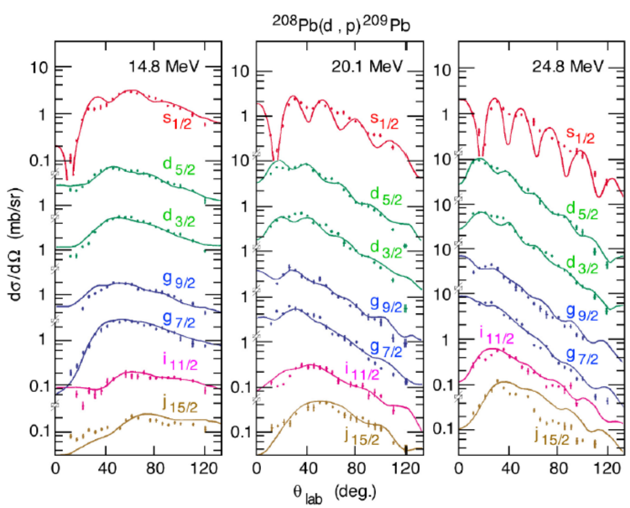
1950’s
1960’s



1967 ^{208}Pb(d,p)^{209}Pb



Deuteron beam + target
Tandem + spectrometer
$>10^{10}$ pps (stable) beam
Helpful graduate students



Muehllener et al.
Phys. Rev. 159, 1043 (1967)

1950's
1960's

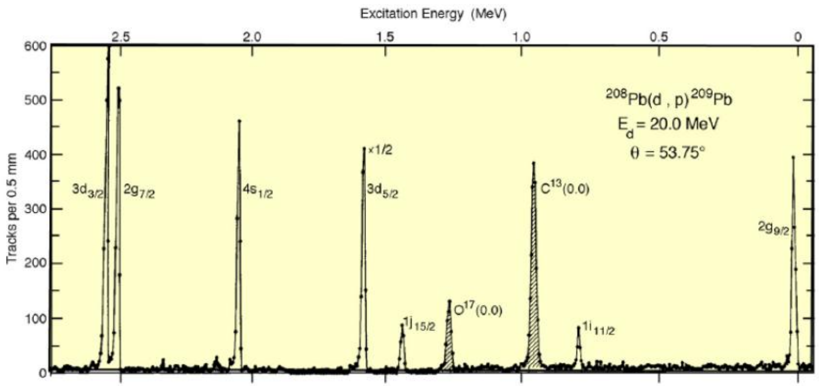
STABLE NUCLEI

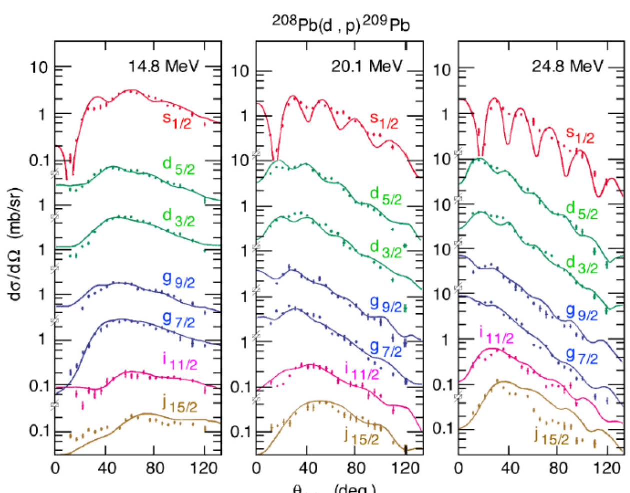
RADIOACTIVE

1990's
2000's, 2010's, 2020's ……..

radioactive ion beam

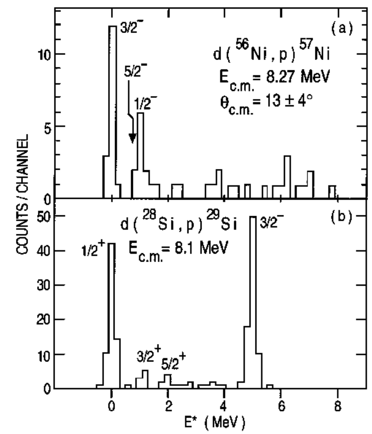
1967 $^{208}Pb(d,p)^{209}Pb$



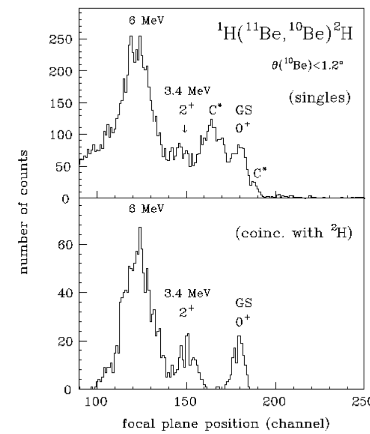


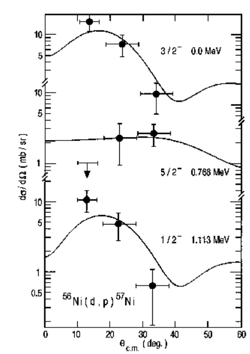
Muehllener et al.
Phys. Rev. 159, 1043 (1967)

1998 $d(^{56}Ni,p)^{57}Ni$
Rehm ARGONNE



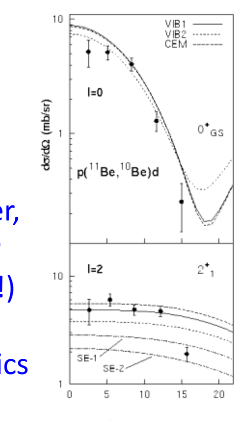
1999 $p(^{11}Be,d)^{10}Be$
Fortier/Catford GANIL



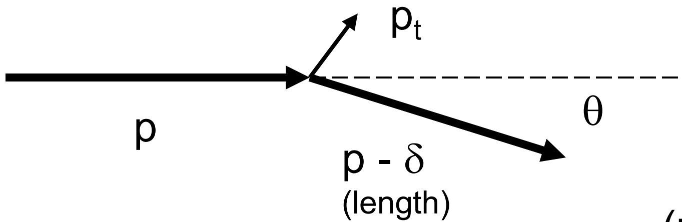


Beam 10^6 weaker,
experiments 10^6
more difficult (?!)

i.e. fewer statistics



Measuring Spin, or at least…
Angular Momentum Transfer



Cosine rule, 2nd order: $$\theta^2 = \frac{(p_t/p)^2 - (\delta/p)^2}{1 - (\delta/p)}$$

But $p_t \times R \geq \sqrt{\ell(\ell+1)}\ \hbar$ (R = max radius)

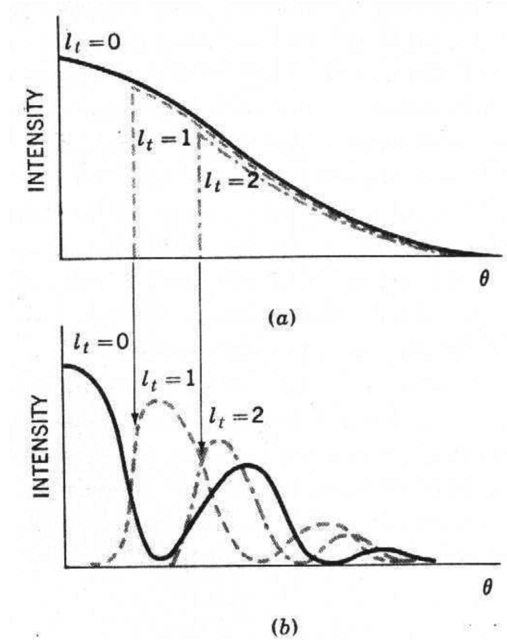
So $$\theta^2 \geq \frac{\ell(\ell+1)\,\hbar^2 / p^2R^2 \;-\; (\delta/p)^2}{1 - (\delta/p)}$$

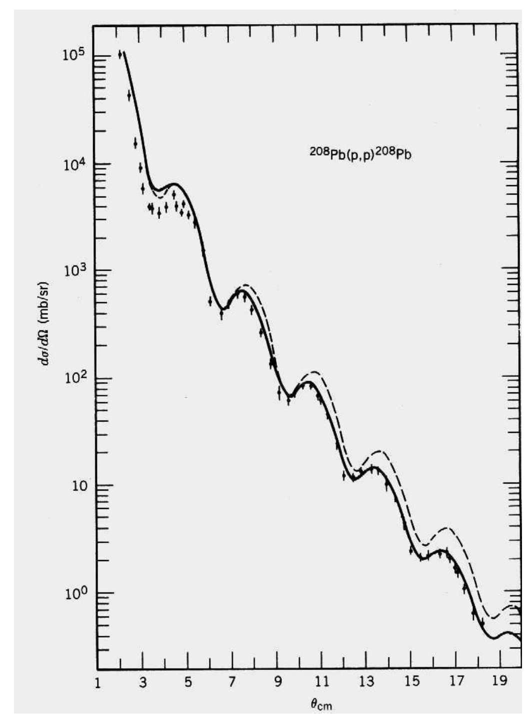
or $\theta \geq \text{const} \times \sqrt{\ell(\ell+1)}$ neglecting (δ/p)

$$\boxed{\theta_{min} \approx \text{const} \times \ell}$$

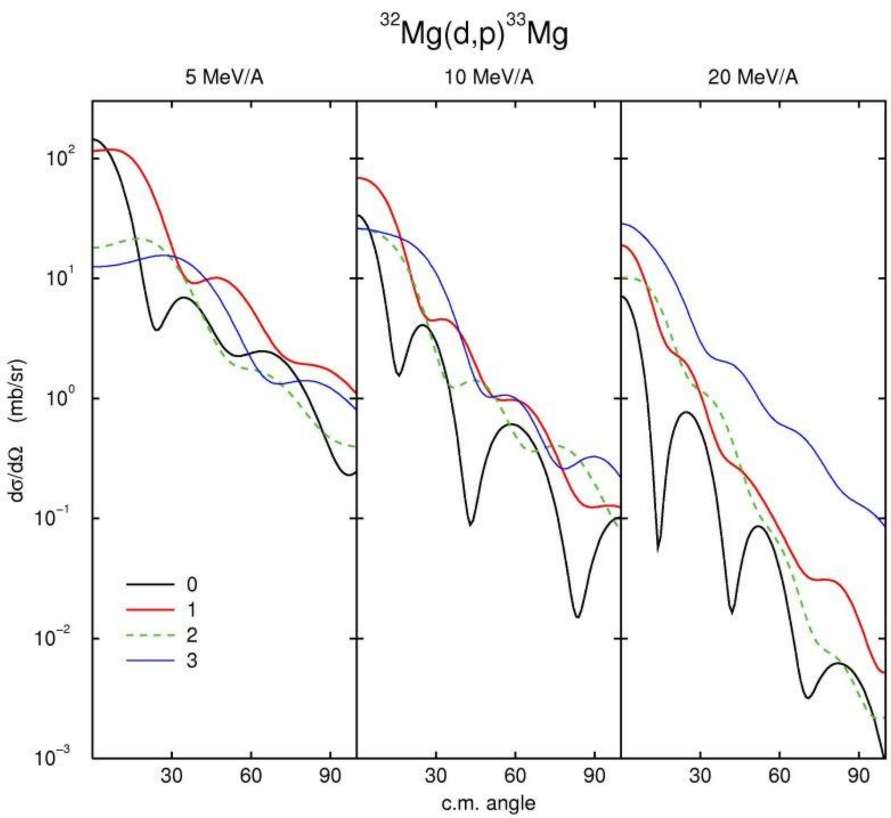
<u>Diffraction structure</u> also expected (cf. Elastics)

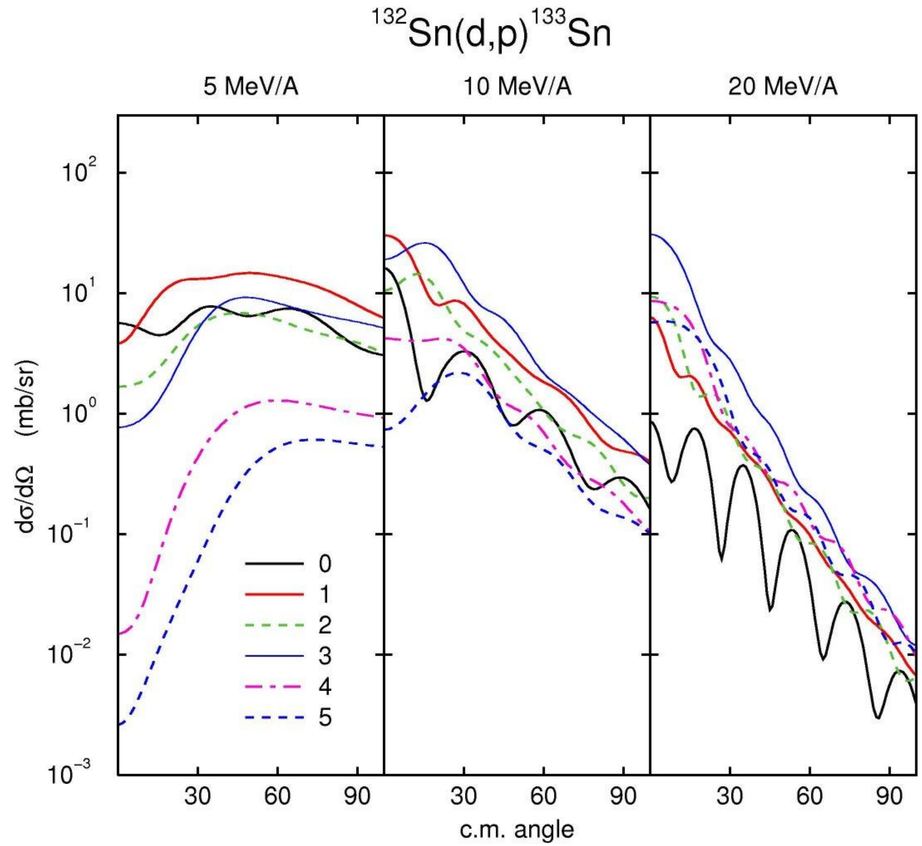
<u>PWBA</u> ⇒ spherical Bessel function, $\theta_{peak} \approx 1.4\ \sqrt{\ell(\ell+1)}$



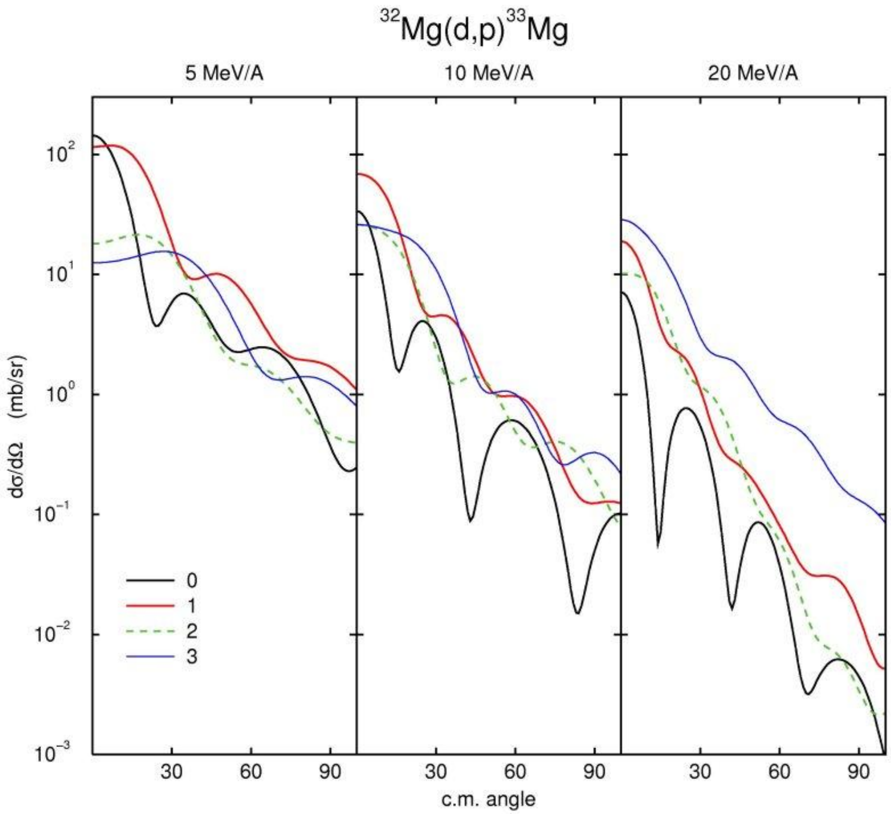


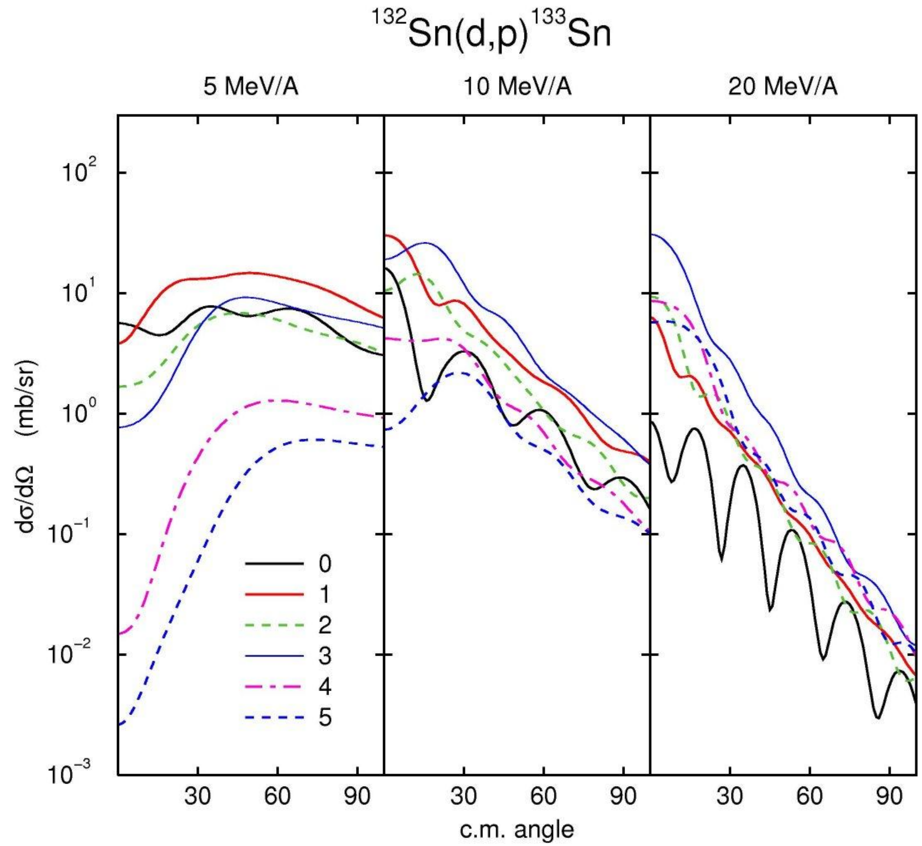
How does the differential cross section vary with beam energy ?



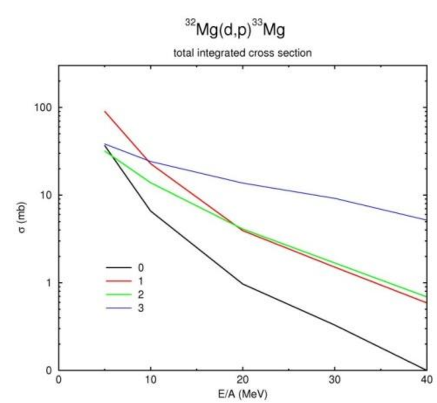


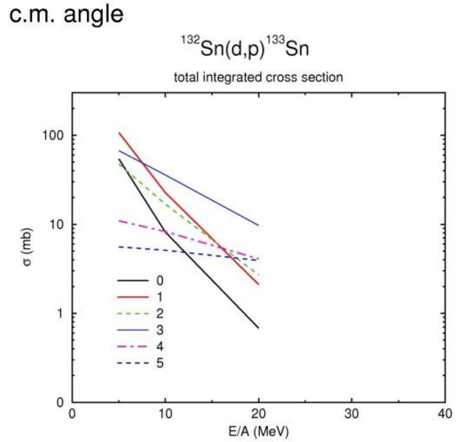
How does the differential cross section vary with beam energy ?





and the total cross section ?





Distorted Wave Born Approximation – Outline (1 of 3)

e.g. (d,p) with a deuteron beam (following H.A.Enge Chap.13 with ref. also to N. Austern book)

$H_{tot} = \Sigma\, T + \Sigma\, V$ ... in either entrance/exit ch

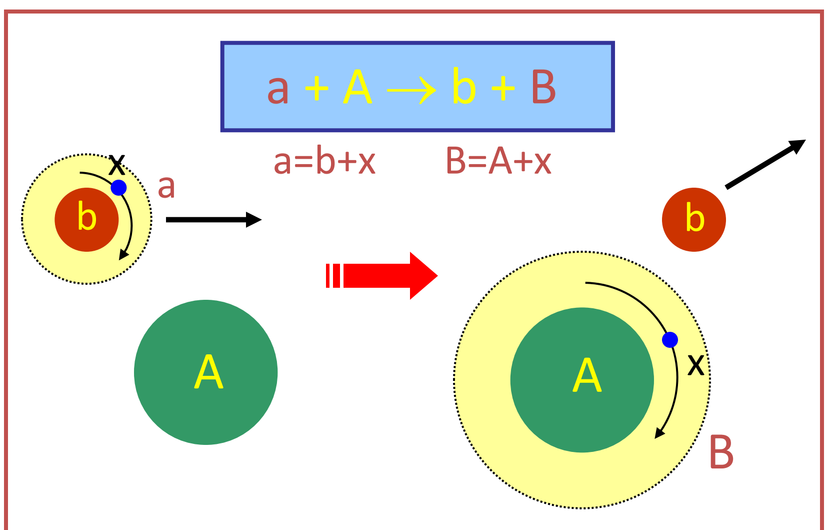
Entrance: $H_{tot} = T_{aA} + T_{xb} + V_{xb} + V_{xA} + V_{bA}$

Exit: $H_{tot} = T_{bB} + T_{xA} + V_{xb} + V_{xA} + V_{bA}$

Same in each case

But the final scattering state can be written approximately as an outgoing DW using the optical potential for the exit channel:

$$|\psi_f\rangle \approx \underbrace{|\phi_b\rangle\ |\phi_B\rangle}_{\text{Internal wave functions}}\ \underbrace{\chi^{-}_{bB}}_{\text{outgoing distorted wave}}$$



Distorted Wave Born Approximation – Outline (2 of 3)

e.g. (d,p) with a deuteron beam (following H.A.Enge Chap.13 with ref. also to N. Austern book)

$H_{tot} = \Sigma\, T + \Sigma\, V$ ... in either entrance/exit ch

Entrance: $H_{tot} = T_{aA} + T_{xb} + V_{xb} + V_{xA} + V_{bA}$

Exit: $H_{tot} = T_{bB} + T_{xA} + V_{xb} + V_{xA} + V_{bA}$

Same in each case

But the final scattering state can be written approximately as an outgoing DW using the optical potential for the exit channel:

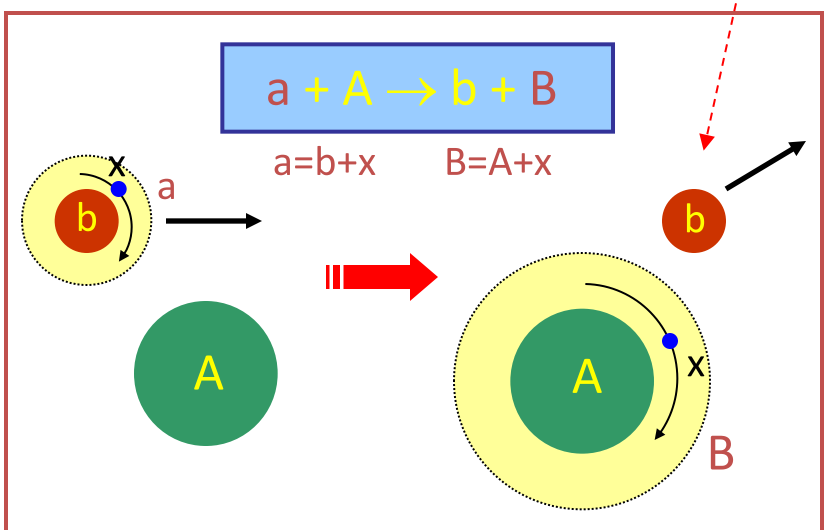
$$|\psi_f\rangle \approx \underbrace{|\phi_b\rangle\ |\phi_B\rangle}_{\text{Internal wave functions}}\ \underbrace{\chi^{-}_{bB}}_{\text{outgoing distorted wave}}$$

In the optical model picture, $V_{xb} + V_{bA} \approx U_{bB}$ ($= V^{opt}_{bB} + i\, W^{opt}_{bB}$), the optical potential)

And the final state, we have said, can be approximated by an eigenstate of U_{bB}

The transition -inducing interaction is $V_{int} = H_{entrance} - H_{exit} = V_{xb} + \cancel{V_{xA}} + V_{bA} - (\underbrace{V_{xb} + V_{bA}}_{\approx U_{bB}}) - \cancel{V_{xA}}$

$$= V_{xb} + \underbrace{V_{bA} - U_{bB}}_{\text{Remnant term} \approx 0 \text{ if } x << A}$$



i.e. $V_{int} \approx V_{xb}$ which we can estimate reasonably well

$$\boxed{T_{f,i}^{\ DWBA} = \langle\, \phi_b\, \phi_B\, \chi_{bB}^{-}\, |\ V_{xb}\ |\, \chi_{aA}^{+}\, \phi_a\, \phi_A\,\rangle}$$

$\phi_B = \phi_x\, \phi_A\, \psi_{rel,Ax}$ $\qquad$ $\phi_a = \phi_x\, \phi_b\, \psi_{rel,bx}$

$$\text{so}\ \ T_{i,f}^{\ DWBA} = \langle\, \underbrace{\psi_{rel,Ax}}_{}\ \chi_{bB}^{-}\, |\ V_{xb}\ |\, \chi_{aA}^{+}\ \underbrace{\psi_{rel,bx}}_{}\,\rangle$$

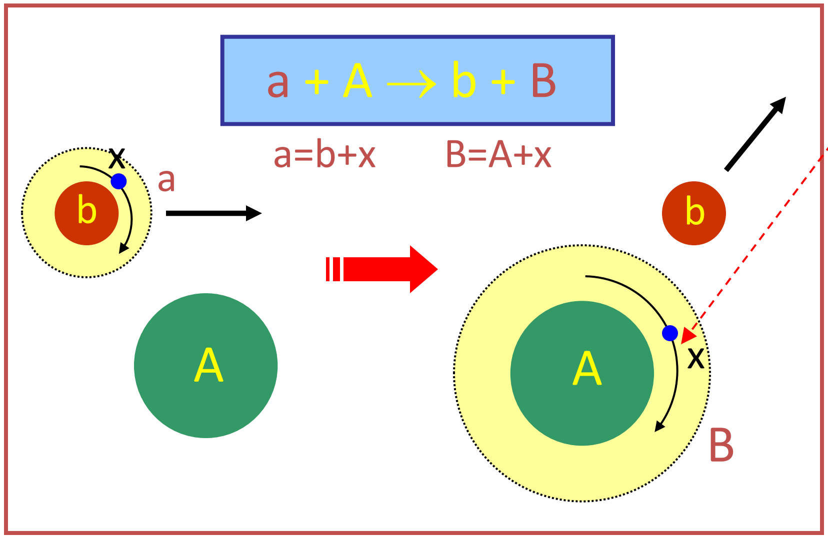
known as *radial form factor* for the transferred nucleon

often simple, e.g. if a = d

Distorted Wave Born Approximation – Outline (3 of 3)

$$\text{so } T_{f,i}^{\,DWBA} = \langle \underbrace{\psi_{rel,Ax}}\, \overbrace{\chi_{bB}^{-} \mid V_{xb} \mid \chi_{aA}^{+}\, \psi_{rel,bx}}^{\text{known from previous}} \rangle$$

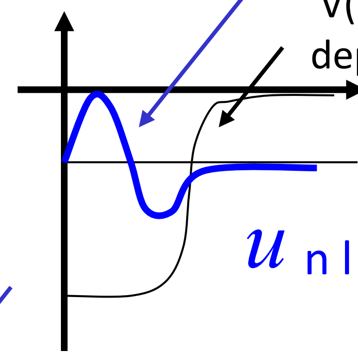
(compare Enge eq. 13-60)



The wave function of the transferred **nucleon x, orbiting A, inside of B :**

radial wave function u(r) given by $\psi(r) = u(r)/r$

V(r) given by Woods-Saxon; depth determined by known binding energy



$$u_{n\,l\,j} * \underbrace{S^{1/2}_{n\,l\,j}}$$

Woods-Saxon:

$$V(r) = \frac{-V_0}{1 + e^{(r - r_0 A^{1/3})/a}}$$

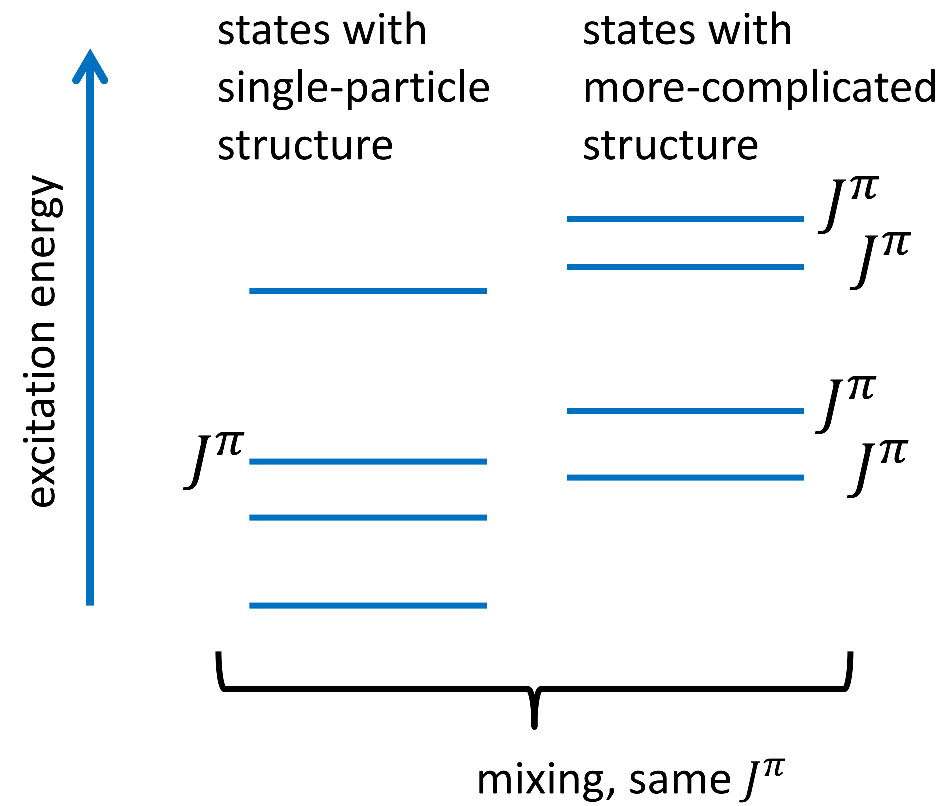
The radial wave function
In the Woods-Saxon potential
represents the shell orbital

S measures the occupancy of the shell model orbital… the ***spectroscopic factor***

$S = (S^{1/2})^2$ is a factor that scales the predicted DWBA cross section for a pure single-particle state and is determined by comparison between DWBA and experiment

So, in summary:

$$\left(\frac{d\sigma}{d\Omega}\right)_{experiment} = S \times \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$



$$|\, J_i^\pi > \; = \sqrt{S}\; |J_{SP}^\pi > \; + \sum_k \alpha_k \,|J_k^\pi >$$

- we measure transferred ℓ_n from $d\sigma/d\Omega$
- we measure gamma-decays
- we aim to identify J and π
- we model the transfer yield for S=1
- we deduce S from the observed yield

$$S = |\,\langle J_{SP}^\pi \,|\, J_i^\pi \,\rangle|^2$$

spectroscopic factor
= overlap with pure SP state

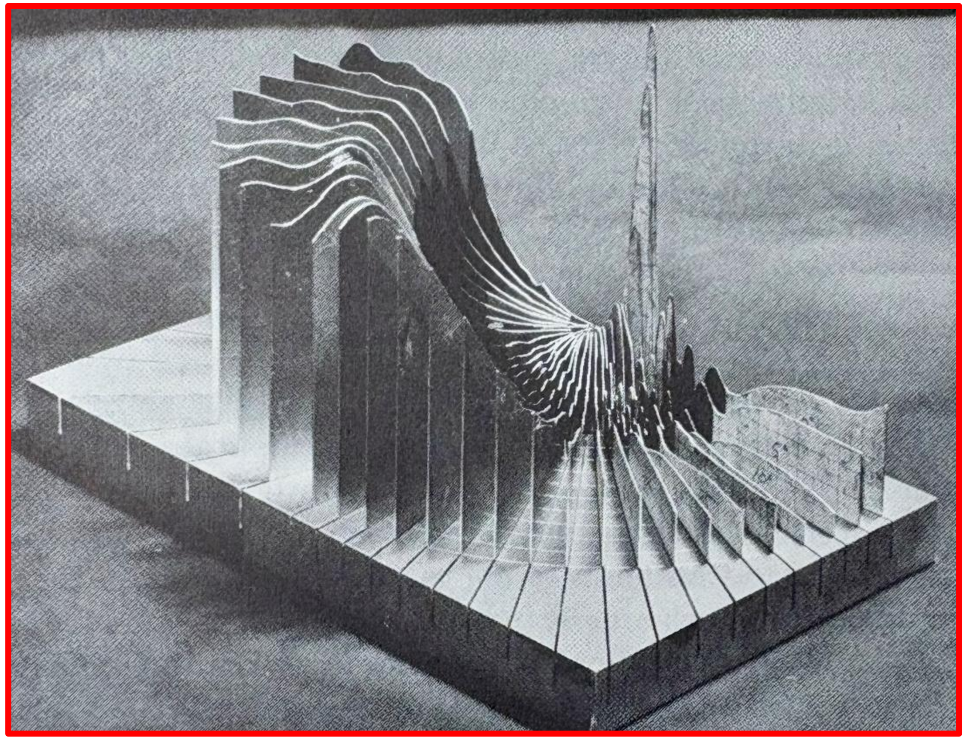
Photographs of Distorted Waves

From: N. Austern

Direct Nuclear Reaction Theories

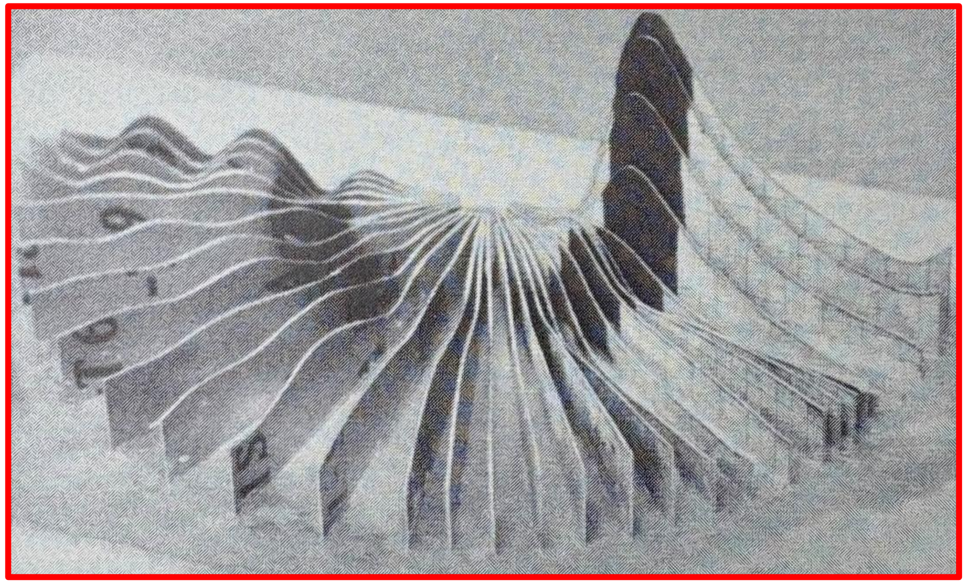
Beam of α's on ^{40}Ca

18 MeV from left



Beam of p's on ^{40}Ca

40 MeV from left



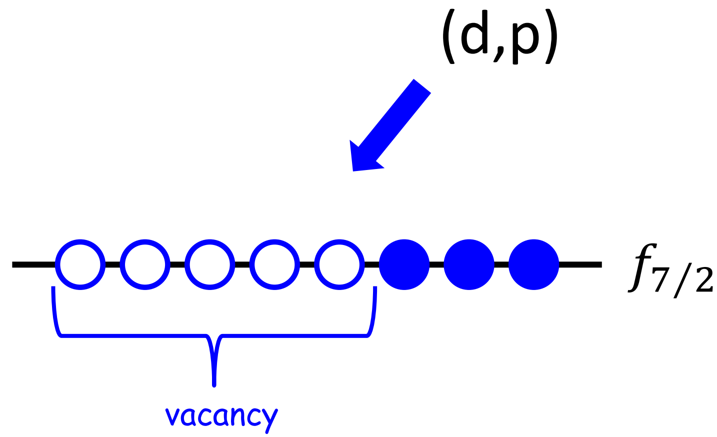
What's plotted: modulus $\left|\chi^{(+)}\right|$ of the incoming optical model wavefunction

Dark zone: 10%-90% region of the potential

SUM RULES for Single-Nucleon Transfer

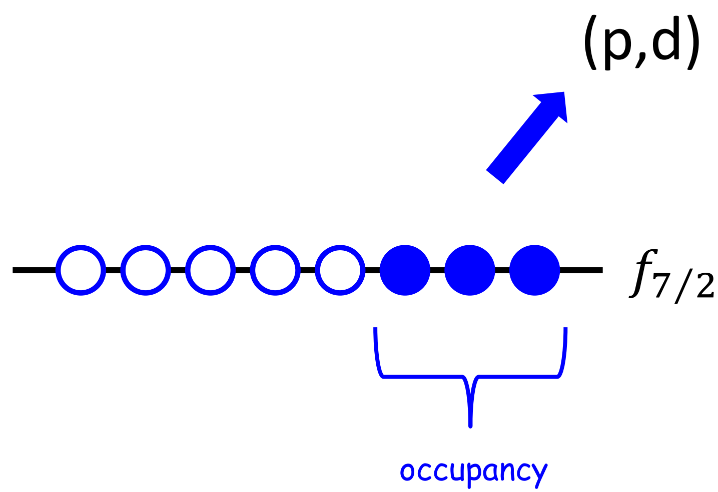
For adding a nucleon to a given j-shell the sum rule gives the vacancy in the shell

$$Number\ of\ Holes = \sum_i \left(\frac{2T_f^i+1}{2T_0+1}\right)\left(\frac{2J_f^i+1}{2J_0+1}\right) S_i$$



for removing a nucleon from a given j-shell it gives the occupancy of the shell, with the sum running over all final states *i*.

$$Number\ of\ Particles = \sum_i \left(\frac{2T_f^i+1}{2T_0+1}\right) S_i$$



Note that only one value of isospin $T_f(=T_0+1/2)$ is allowed for neutron adding or proton removing reactions, and two values $T_f(=T_0 \pm 1/2)$ for neutron removal or proton adding.

S = spectroscopic factor
J = spin
T = isospin
i = sum over all states

Adapted from: John Schiffer, Argonne

Some Physics that Complicates Transfer Interpretation

We do not compare like-with-like when we compare theory and experiment

Left: chalk; Right: cheese – they are not the same

Spectroscopic Factor

Shell Model: overlap of **$|\psi$ (N+1) $\rangle$ with $|\psi$ (N) $\rangle_{core} \otimes$ n (ℓ j)**

Reaction: the observed yield is not just proportional to this S, because in T the **overlap integral** has a radial-dependent weighting or sampling

Many-body theory of $d + A(N, Z) \rightarrow B(N+1, Z) + p$

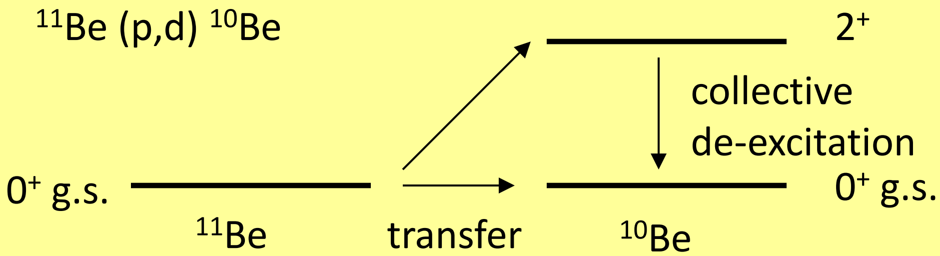
overlap integral $$\phi_n^{BA}(\vec{r}_n) = \sqrt{N+1} \int d\xi_A \phi_B^*(\xi_A, \vec{r}_n) \phi_A(\xi_A)$$

spectroscopic factor $$S^{AB} = \int d\vec{r}_n \mid \phi_n^{AB}(\vec{r}_n) \mid^2$$

$$T_{d,p} = \langle \chi_p^{(-)} \phi_n^{BA} \mid V_{np} \mid \Psi_{\vec{K}_d} \rangle$$

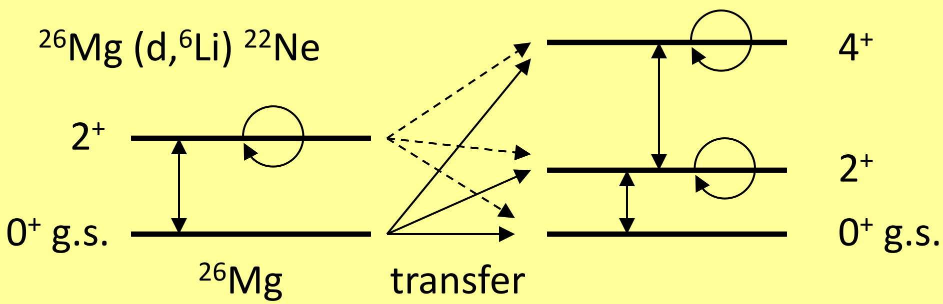
Hence the yield, and hence deduced spectroscopic factor, depends on the radial wave function and thus the geometry of the assumed potential well for the transferred nucleon, or details of some other structure model

Some Other Physics that can Complicate Transfer Calculations

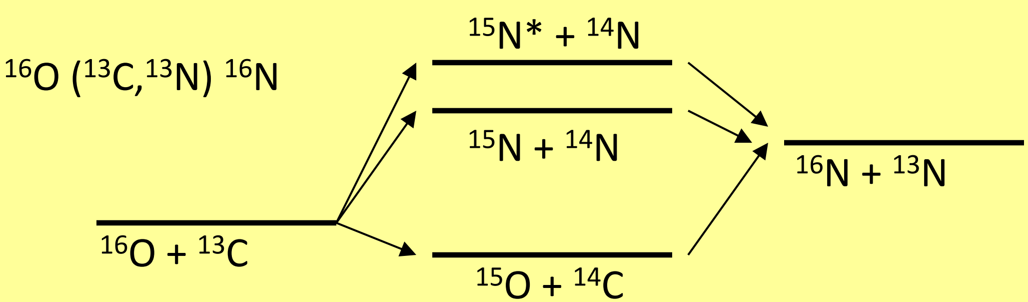


Example of **two-step**

the two paths will interfere



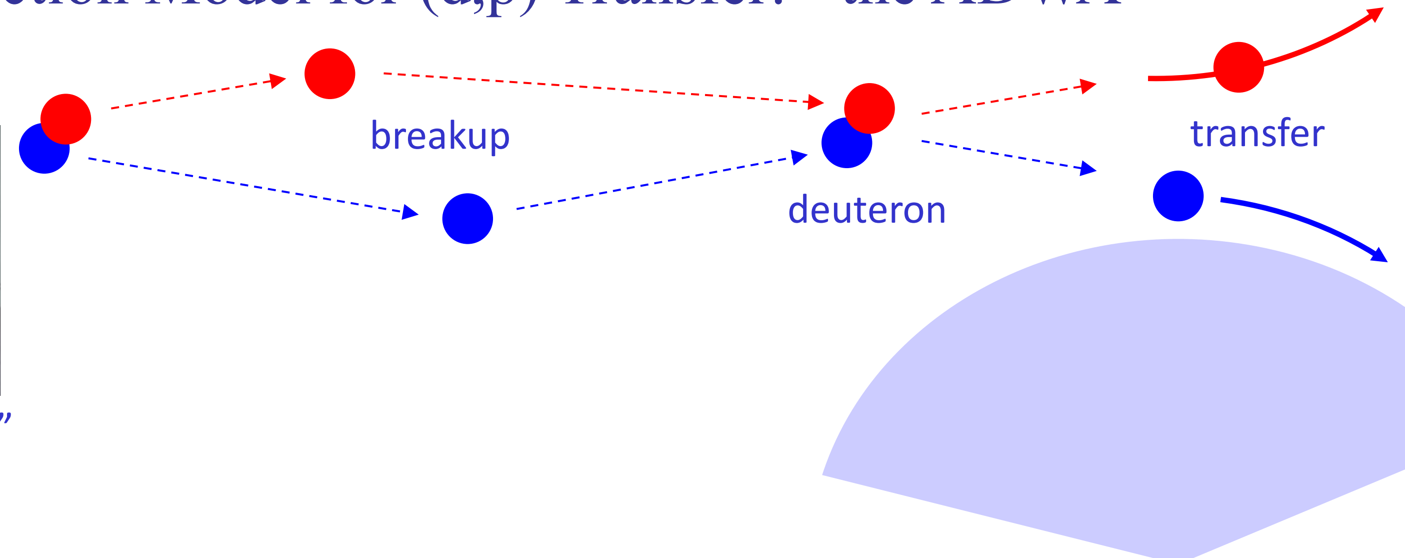
Example of **coupled channels**



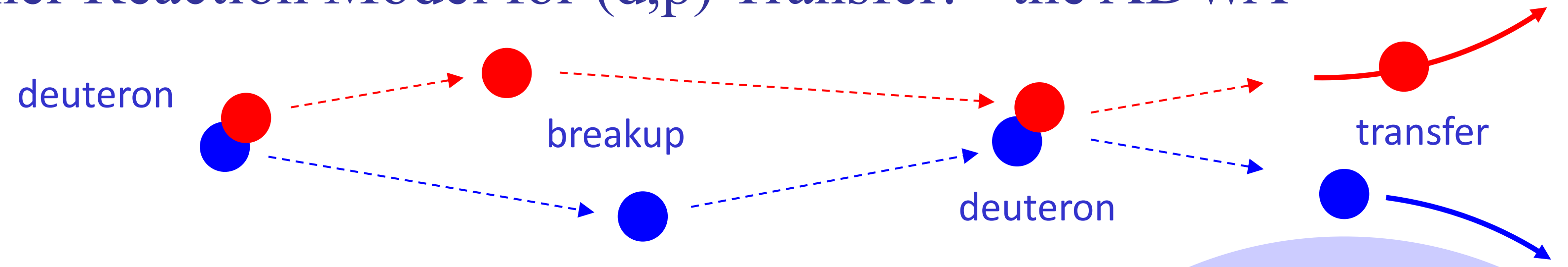
Example of
coupled reaction channels

Another Reaction Model for (d,p) Transfer: - the ADWA

“Due to Ron Johnson”
Deuteron Johnson



Another Reaction Model for (d,p) Transfer: - the ADWA



ADIABATIC DISTORTED WAVE APPROXIMATION (~~BORN~~)

Johnson-Soper Model: an **alternative to DWBA** that gives a simple prescription for taking into account coherent *entangled* **effects of deuteron break-up** on (d,p) reactions [1,2]

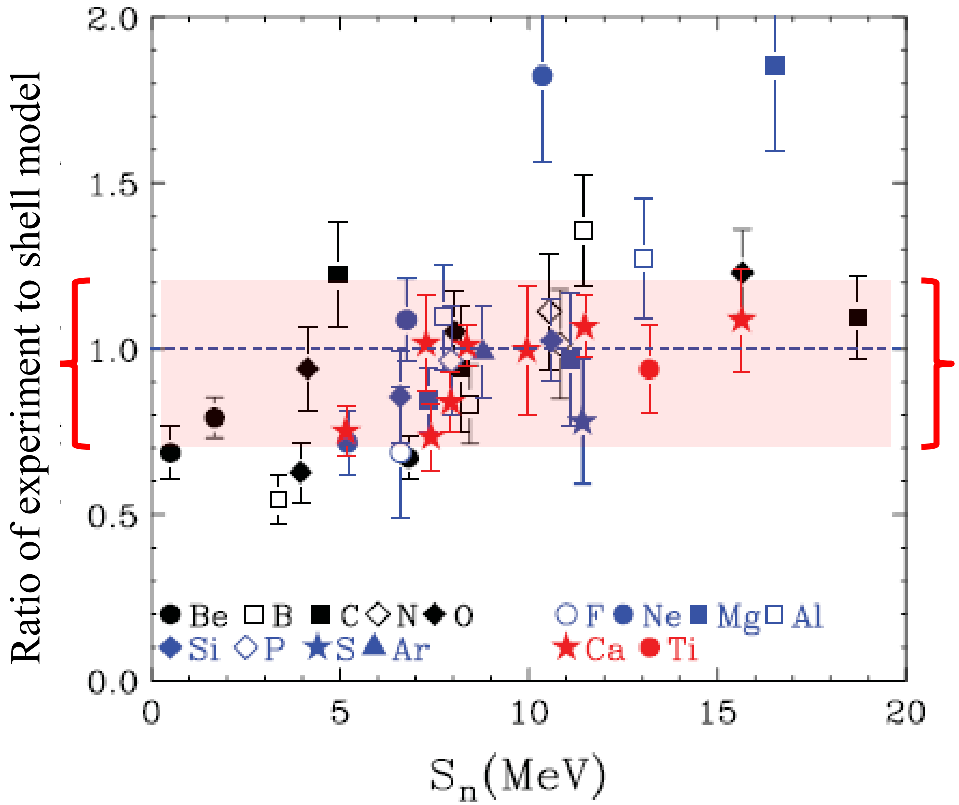
- does not use deuteron optical potential – uses ***nucleon-nucleus optical potentials*** only
- formulated in terms of adiabatic approximation, which is sufficient but not necessary [3]
- uses parameters (overlap functions, **spectroscopic factors**, ANC's) just as in DWBA

[1] Johnson and Soper, PRC 1 (1970) 976
[2] Harvey and Johnson, PRC 3 (1971) 636; Wales and Johnson, NPA 274 (1976) 168
[3] Johnson and Tandy NPA 235 (1974) 56; Laid, Tostevin and Johnson, PRC 48 (1993) 1307

Another Reaction Model for (d,p) Transfer: - the ADWA

A **CONSISTENT** application of ADWA gives 20% agreement with large basis SM for well-understood (near-stability) nuclei

$\pm 20\%$ consistency



80 spectroscopic factors
Z = 3 to 24
Jenny Lee et al.

Tsang et al
PRL 95 (2005) 222501

Lee et al
PRC 75 (2007) 064320

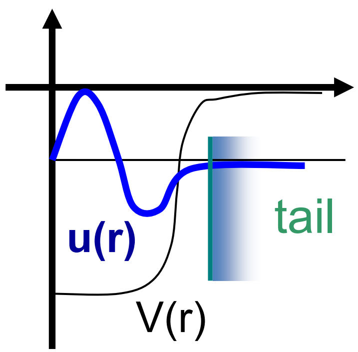
Delaunay at al
PRC 72 (2005) 014610

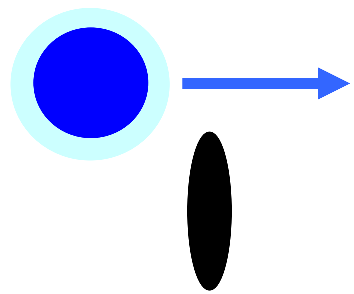
… so we can compare experiment and theory in a reliable fashion

A Different Type of Reaction to Study Similar Things

Q: Given what we have seen, **is transfer the BEST way** to isolate and study <u>single particle structure</u> and its <u>evolution</u> in exotic nuclei?

- TRANSFER – decades of (positive) experience, makes nuclei more exotic
- KNOCKOUT* – high cross section, requires orbitals to be occupied





REMOVES nucleons
…to be validated with (d,t)

- (e,e'p) – ambitious for general RIB application, requires occupied orbitals
- (p,p'p) – more practical than (e,e'p) for RIB, requires occupied orbitals

*KNOCKOUT is also called REMOVAL

A: **YES !**

and don't forget:
heavy ion transfer (^{9}Be),
^{3,4}He-induced reactions

Summary of single-particle studies via transfer and knockout

Each of these processes can probe single-particle structure:

- measure the occupancy of single-particle (shell model) orbitals *(spectroscopic factors)*
- identify the angular momentum of the relevant nucleon.

We can therefore identify the distribution of single-particle strength across nuclear states and this allows detailed comparisons with the predictions of our best nuclear structure model: the nuclear shell model.

Summary of single-particle studies via transfer and knockout

Each of these processes can probe single-particle structure:
- measure the occupancy of single-particle (shell model) orbitals *(spectroscopic factors)*
- identify the angular momentum of the relevant nucleon.

With knockout we can probe:
- occupancy of single-particle (shell model) orbitals in the **projectile** ground state
- identify the angular momentum of the **removed** nucleon
- hence, identify the s.p. level energies in odd-A nuclei produced from even-even projectiles

and the **projectile-like particle** is detected essentially at zero degrees

With transfer we can probe:
- occupancy of single-particle (shell model) orbitals in the original nucleus A ground state
  or distribution of s.p. strength in **all final states** of A–1 or A+1 nucleus
  that is, **can add a nucleon** to the original nucleus, e.g. by (d,p)
- identify the angular momentum of the transferred nucleon
- hence, identify the s.p. level energies in A–1 or A+1 nuclei produced from even-even nuclei
- identify the s.p. purity of coupled states in A–1 or A+1 nuclei produced from odd nuclei

and the **scattered particle** is detected, with most yield being at small centre-of-mass angles

Energy Regimes Best Matched to Transfer and Knockout

5-10 MeV/A	GANIL/ISOLDE	
10-50 MeV/A	GANIL/FRIB	
>100 MeV/A	FAIR/FRIB/RIKEN	

example world-leading facility for this energy

transfer
- Lenske & Schrieder Eur. J. Phys. A2(1998)41
- Winfield et al Nucl. Phys. A683(2001)48

knockout
- Sauvan et al Phys. Lett. B175(2000)1
- Hansen & Sherrill Nucl. Phys. A693(2001)133

example early papers in these energy regimes

Intensity Regimes Best Matched to Transfer and Knockout

knockout
- > 1 pps near drip-lines; $>10^3$ pps for more-bound projectiles
- ~ 100 mb near drip-lines, closer to 1 mb for more-bound

transfer
- $>10^4$ pps is essentially the minimum possible
- ~ 1 mb cross sections typical

Some additional comments about transfer reactions in general…

The nucleon having to "stick" places **kinematic restrictions** on the population of states:

- the reaction Q-value is important (for Q large and negative, higher ℓ values are favoured)
- the degree (ℓ-dependent) to which the kinematics favour a transfer is known as ***matching***

Various **types of transfer** are employed typically, and using different mass probe-particles:

- **light-ion transfer reactions**: (probe$\leq \alpha$ say) … (d,p) (p,d) (d,t) (d,^{3}He) also (^{3}He,α) etc.
- **heavy-ion transfer reactions**: e.g. (^{13}C,^{12}C) (^{13}C,^{14}C) (^{17}O,^{16}O) (^{9}Be,^{8}Be)
- **two-nucleon transfer**: e.g. (p,t) (t,p) (^{9}Be,^{7}Be) (^{12}C,^{14}C) (d,α)
- **alpha-particle transfer** (or α-transfer): e.g. (^{6}Li,d), (^{7}Li,t), (d,^{6}Li), (^{12}C,^{8}Be)

Some additional comments specifically about light-ion transfer…

$p, d, t, {}^{3}He, \alpha$

… induced by radioactive ion beams…

… where the light ion is the target

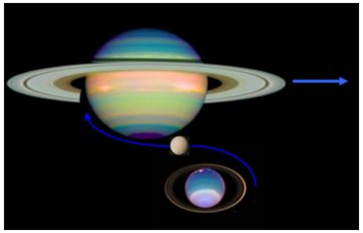
Light-ion induced reactions give the clearest measure of the transferred ℓ ,
and have a long history of application in experiment and a highly refined theory.

Thus, they are attractive to employ as an essentially reliable tool, now that radioactive beams of sufficient intensity have become available.

To the **theorist**, there are some new aspects to address, near the drip lines.

To the **experimentalist**, the transformation of reference frames is a much bigger problem!

The new experiments need hydrogen (or He) nuclei as targets & the beam is much heavier.
This is inverse kinematics, and the energy-angle systematics are completely different.



A PLAN for how to study nuclear STRUCTURE :

- Use **transfer reactions** to identify strong single-particle states, measuring their spins and strengths
- Use the **energies** of these states to compare with theory
- **Refine** the structure (e.g. shell model, ab initio) theory
- Improve the extrapolation to very exotic nuclei
- **Hence learn the structure of very exotic nuclei**

N.B. The **shell model** is arguably the best theoretical approach for us to confront with our results, but it's **not the only one**. The experiments are needed, no matter which theory we use.

N.B. Transfer (as opposed to knockout) allows us to study orbitals that are empty, so **we don't need** quite **such exotic beams**.


Coffee time!!