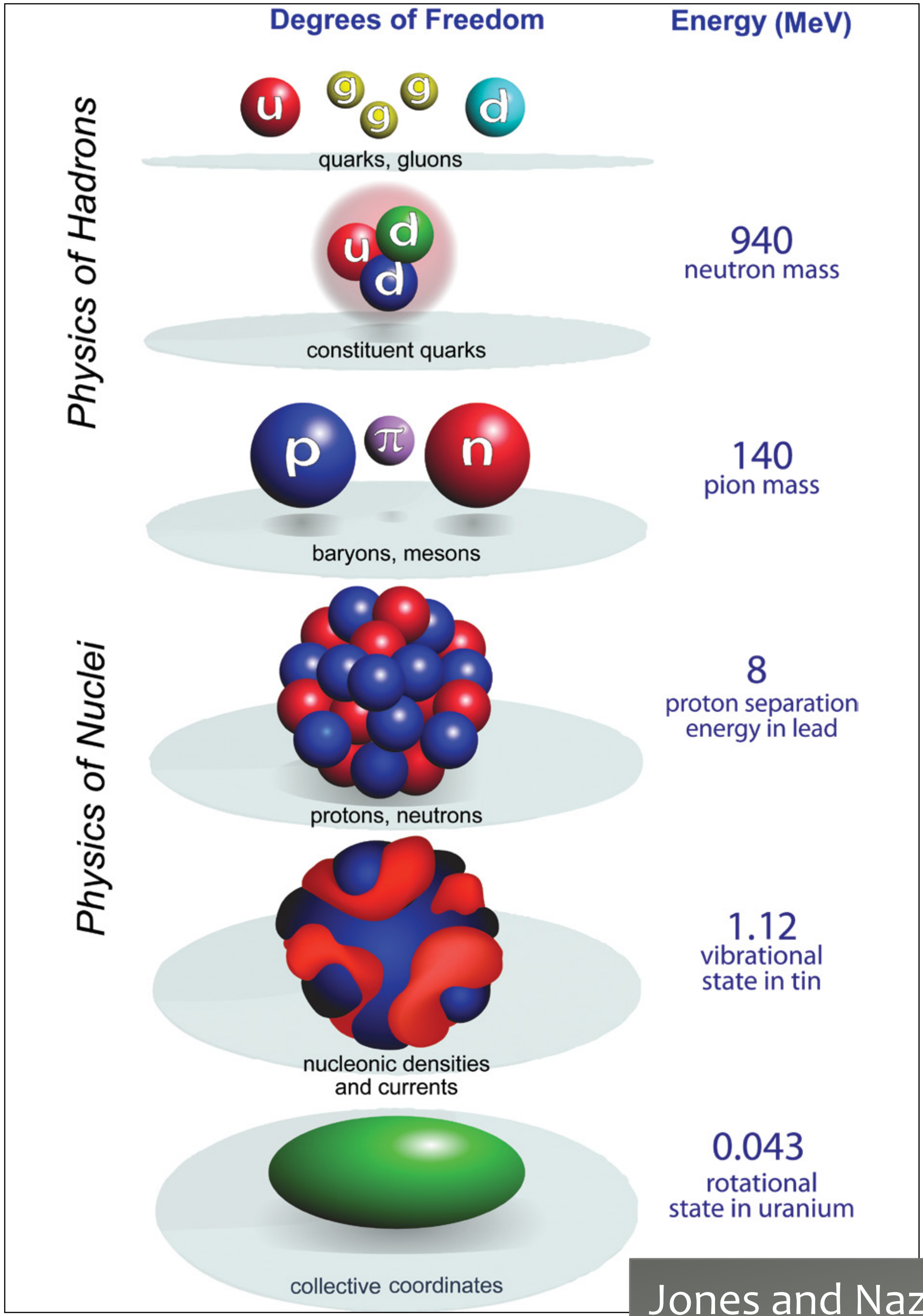
EXTRACTING STRUCTURE FROM REACTIONS

Kate Jones

University of Tennessee



Jones and Nazarewicz, The Physics Teacher, **48** (2010).

Warm-up questions

1. Which reactions are direct?
2. What defines a direct reaction?
3. What is meant by the Q-value of a reaction?
4. Does it depend on beam energy?

Warm-up questions

- Which reactions are direct?

Elastic scattering, transfer reactions, knockout, charge exchange etc. As opposed to compound nuclear reactions such as fusion evaporation.

- What defines a direct reaction?

The time scale. If the compound nucleus does **not** have time to equilibrate we define the reaction as direct.

- What is meant by the Q-value of a reaction?

Difference in mass energy between initial and final states.

$$Q = -\Delta Mc^2 = \left(M_A + M_a - M_B - M_b\right)c^2$$

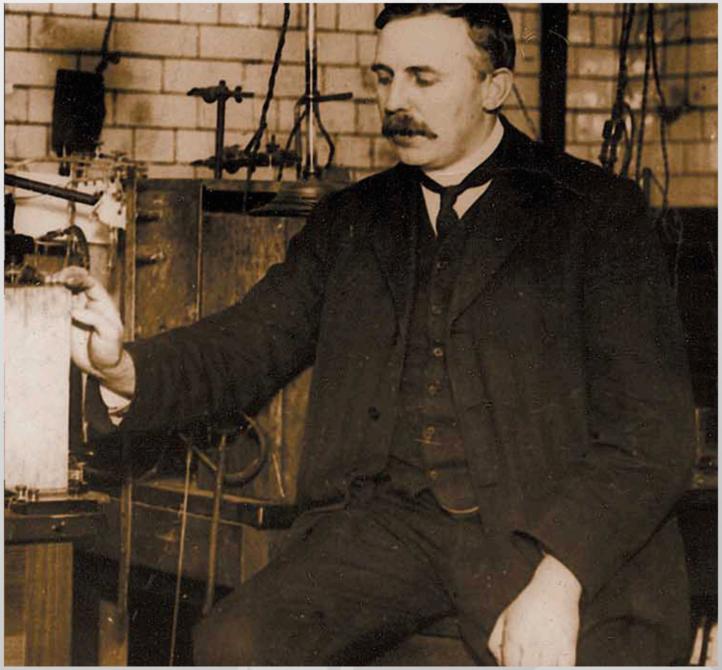
$$Q = \Delta T = T_B + T_b - T_A - T_a$$

- Does it depend on beam energy?

No

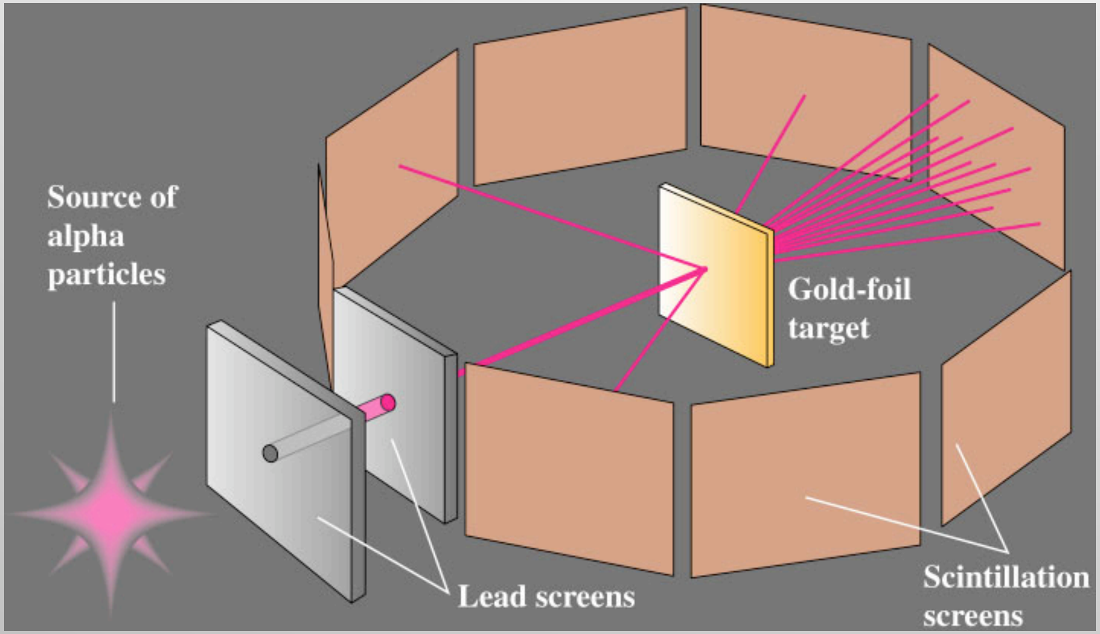
Let’s start from the very beginning

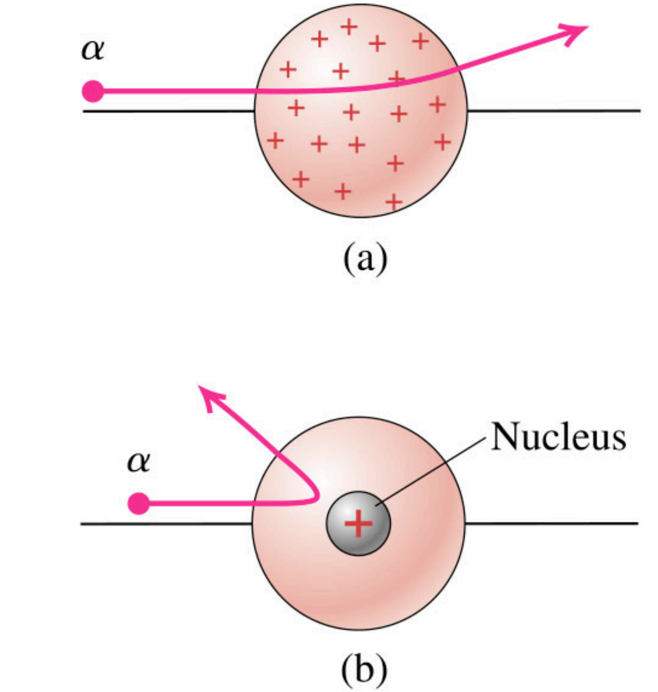
1) The original alpha male
2) Famous disproof of the pudding
3) Student of JJ Thomson

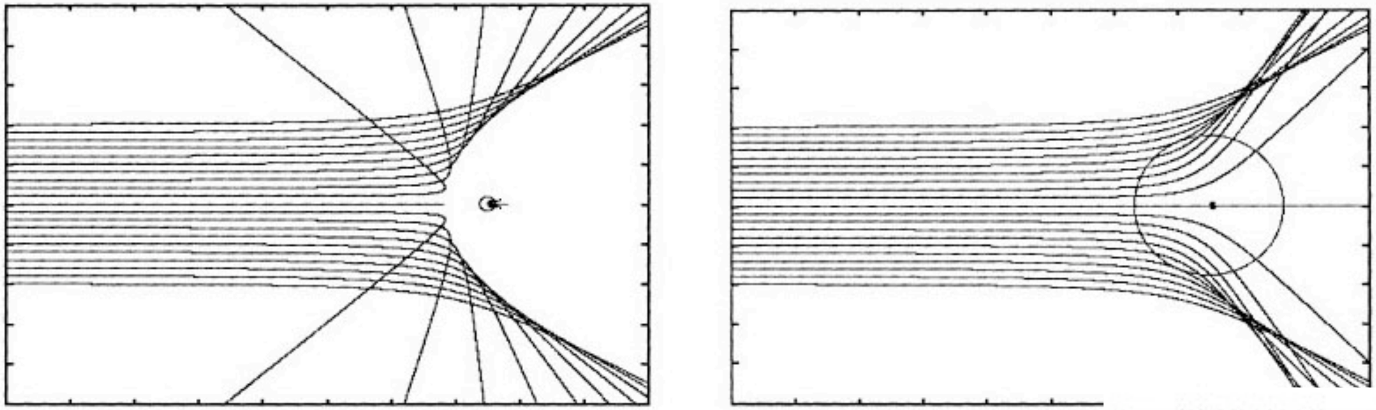


(from Michael Fowler, U. VA)

Direct reaction at the birth of nuclear physics



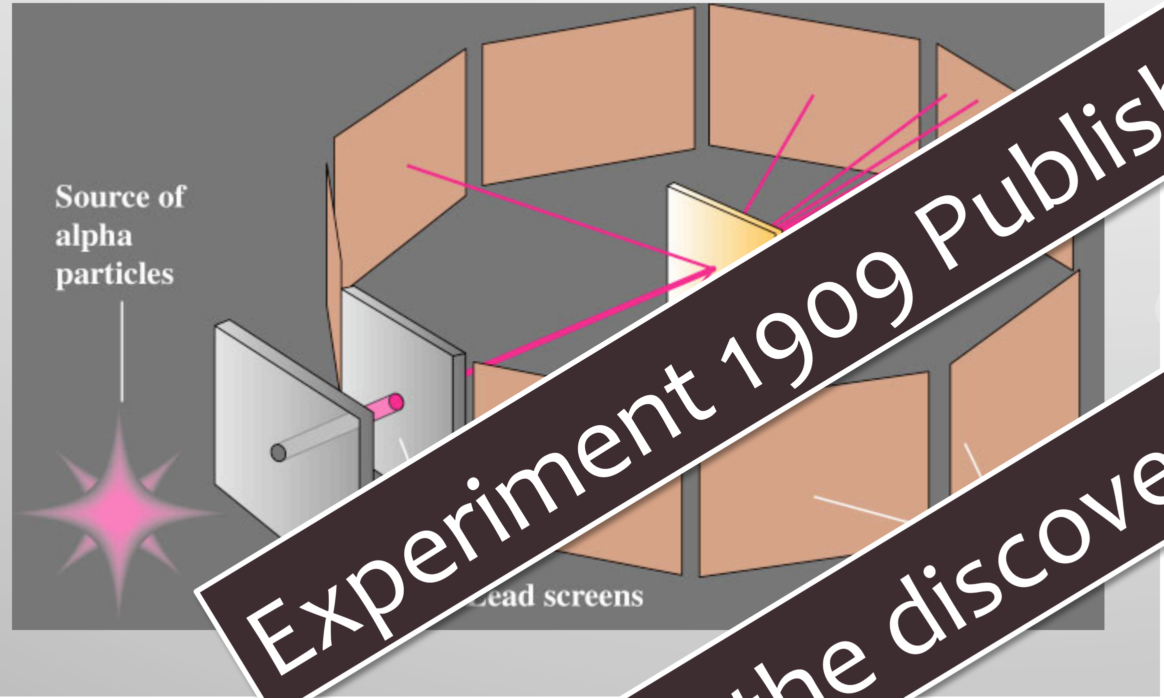


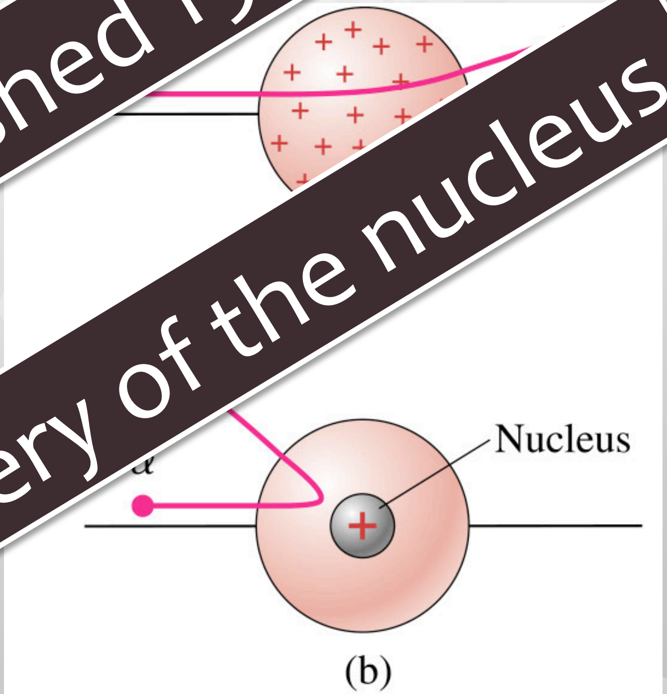

(a)

(b)

NOTE: from standard undergraduate physics book.

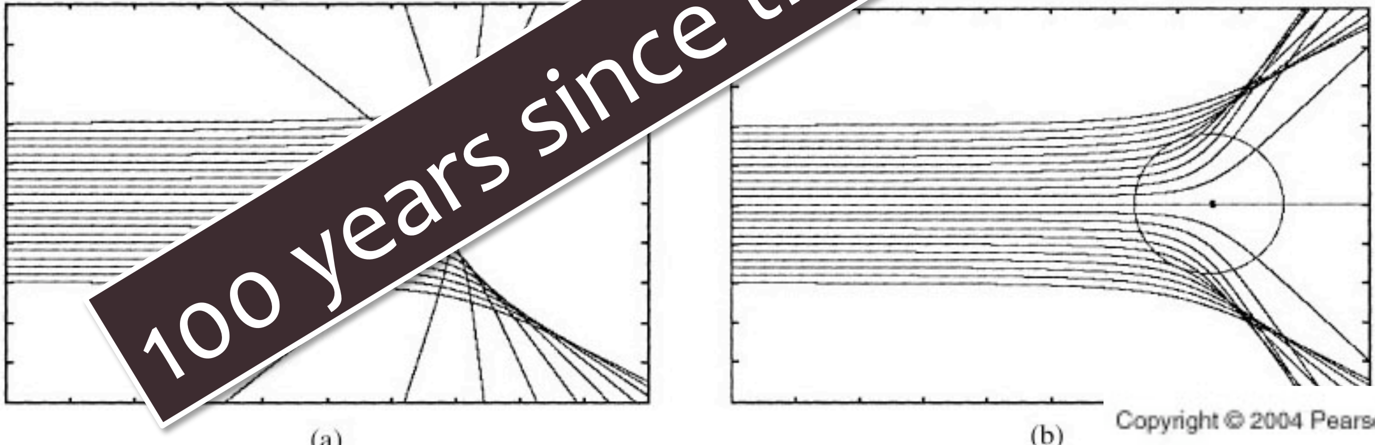
Direct reaction at the birth of nu ysics





Experiment 1909 Published 1911

100 years since the discovery of the nucleus



NOTE: from standard undergraduate physics book.

In his own words

I had observed the scattering of alpha-particles, and Dr. Geiger in my laboratory had examined it in detail. He found, in thin pieces of heavy metal, that the scattering was usually small, of the order of one degree. One day Geiger came to me and said, "Don't you think that young Marsden, whom I am training in radioactive methods, ought to begin a small research?" Now I had thought that, too, so I said, " Why not let him see if any alpha-particles can be scattered through a large angle?" **I may tell you in confidence that I did not believe that they would be**, since we knew the alpha-particle was a very fast, massive particle with a great deal of energy, and you could show that if the scattering was due to the accumulated effect of a number of small scatterings, the chance of an alpha-particle's being scattered backward was very small. Then I remember two or three days later Geiger coming to me in great excitement and saying "We have been able to get some of the alpha-particles coming backward … " **It was quite the most incredible event that ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.**"

Two types of elastic scattering

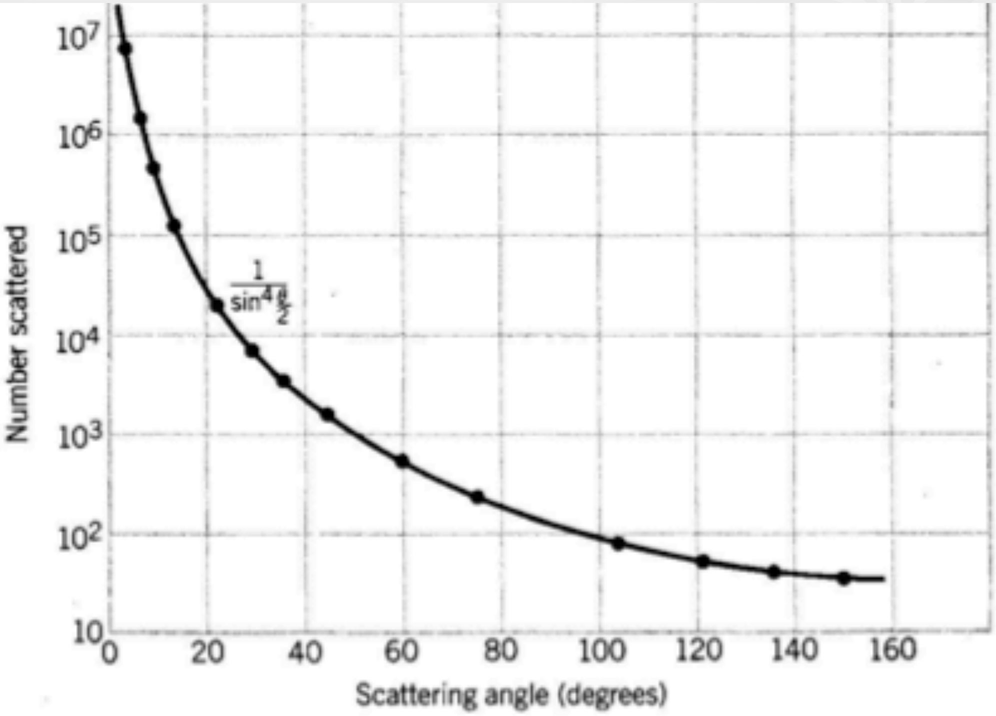
- **Rutherford, or Coulomb, scattering** due to the electrical potential of the nucleus.
  - Long-range force
  - Dominates at low energies and small c-o-m angles
  - Simple analytic form

$$\frac{d\sigma}{d\Omega}=\left(\frac{zZe^2}{4\pi\varepsilon_0}\right)\left(\frac{1}{4T_a}\right)^2\frac{1}{\sin^4\frac{\theta}{2}}$$

- **Nuclear scattering**
  - Sensitive to the nuclear potential
  - Short range
  - Optical potential often used to describe both nuclear and Coulomb parts of scattering
  - Useful to divide through by Rutherford cross-section in order to see details of elastic scattering.

Rutherford Scattering

Notice strong angular dependence. Need to divide this out to see nuclear scattering.



(d)

Figure 11.10 (*d*) The dependence of scattering rate on the scattering angle θ, using a gold foil. The $\sin^{-4}(\theta/2)$ dependence is exactly as predicted by the Rutherford formula.

from Krane (Wiley)

Light diffraction from circular hole

Sharp edges of the hole produce deep minima in the diffraction pattern.

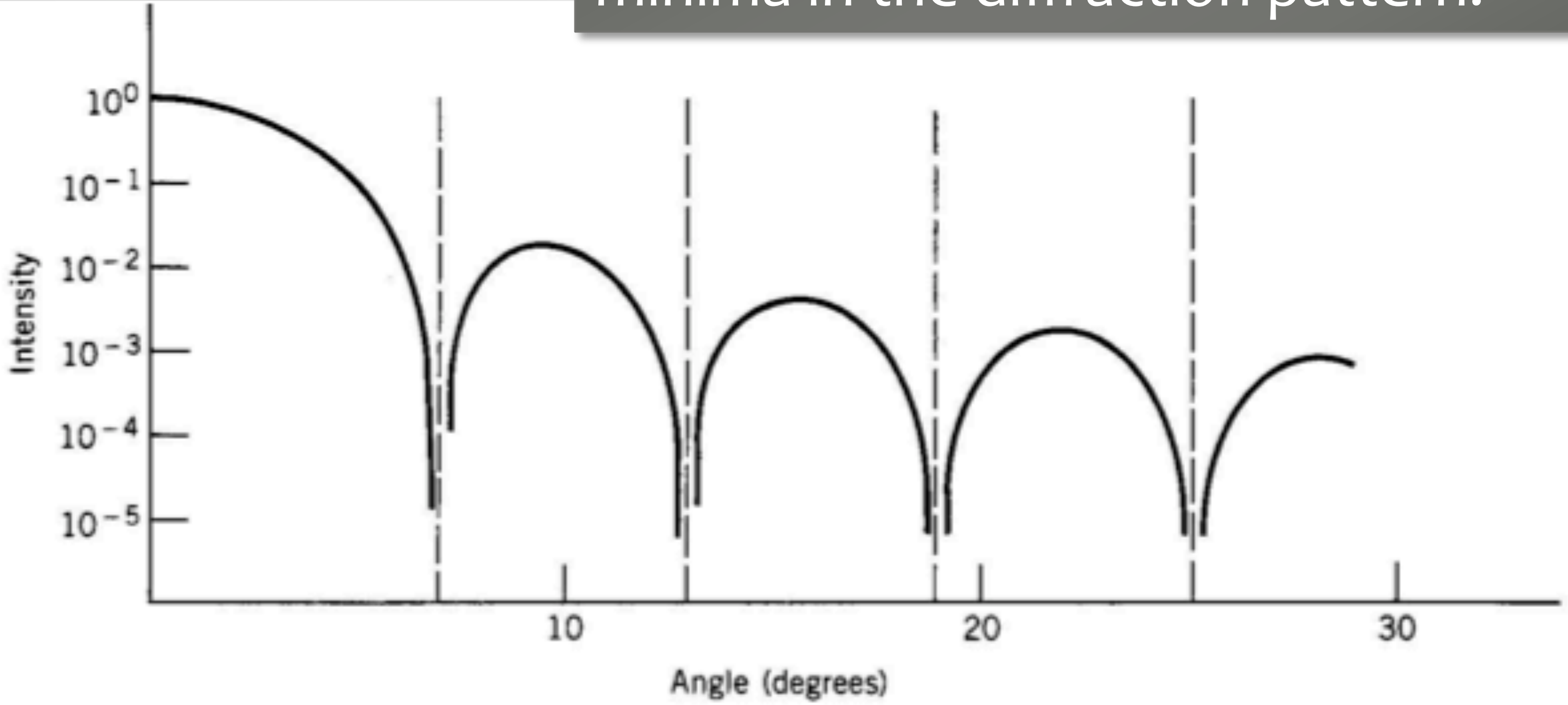


Figure 11.13 Diffraction pattern of light incident on a circular aperture; a circular disk gives a similar pattern. The minima have intensity of zero. The curve is drawn for a wavelength equal to ten times the diameter of the aperture or disk.

Elastic scattering of neutrons on Pb

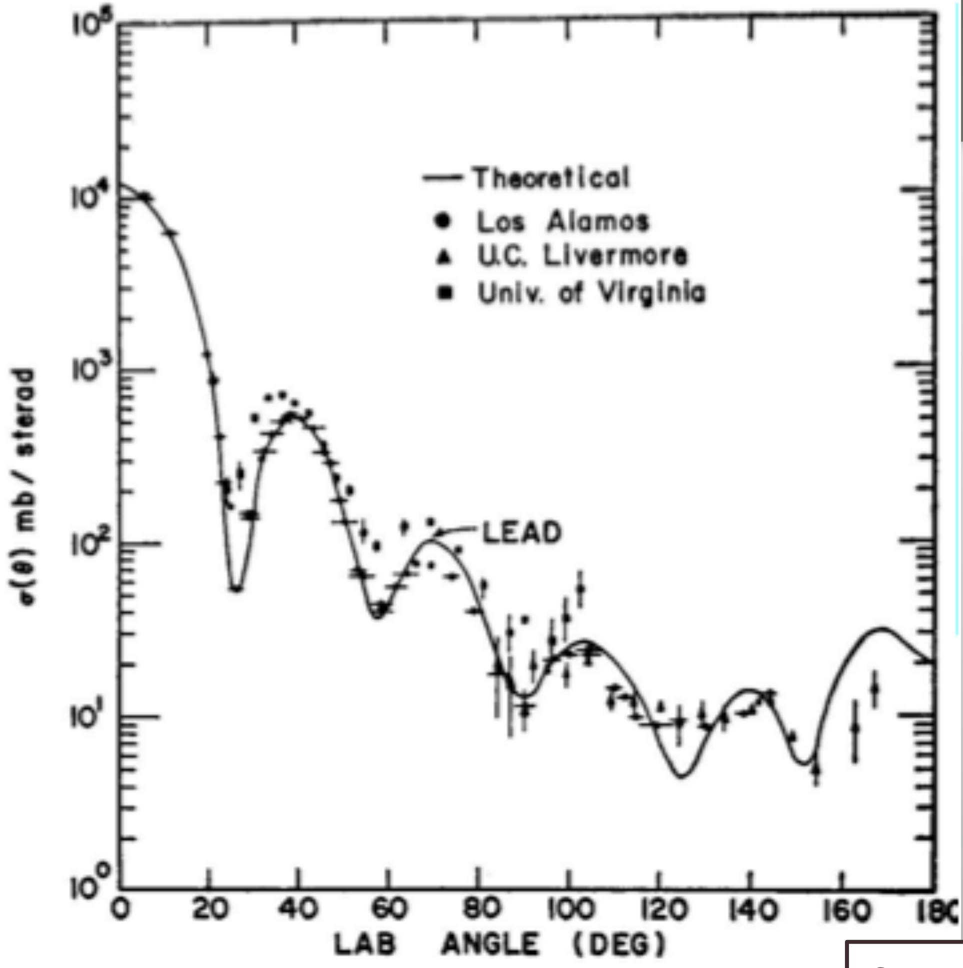


Figure 11.14 Elastic scattering of 14-MeV neutrons from Pb.

Why don't the troughs go to zero?

from S. Fernbach Rev. Mod Phys. **30**, 414 (1958)

Optical Potential

✧Fitting the details of elastic scattering data requires more than simple diffraction from an opaque disk.

✧The most common model in fitting scattering data entails a complex potential and is called the optical model.

✧The optical potential has the form: **U(r) = V(r) + iW(r)**.

✧The real part of the optical potential explains the scattering.

✧The imaginary part provides ***absorption*** ; the removal of particles from the elastic scattering channel via nuclear reactions.

Optical Potential

✧The radial dependence is rather flat throughout the inner region of the nucleus, falls off rapidly at the nuclear surface, but with some diffuseness such that interactions can occur for some distance beyond the surface.

✧The real part is usually taken as a **Woods-Saxon form**.

✧The **imaginary part is stronger at the surface**, i.e. the nucleus cannot capture into the full inner shells.

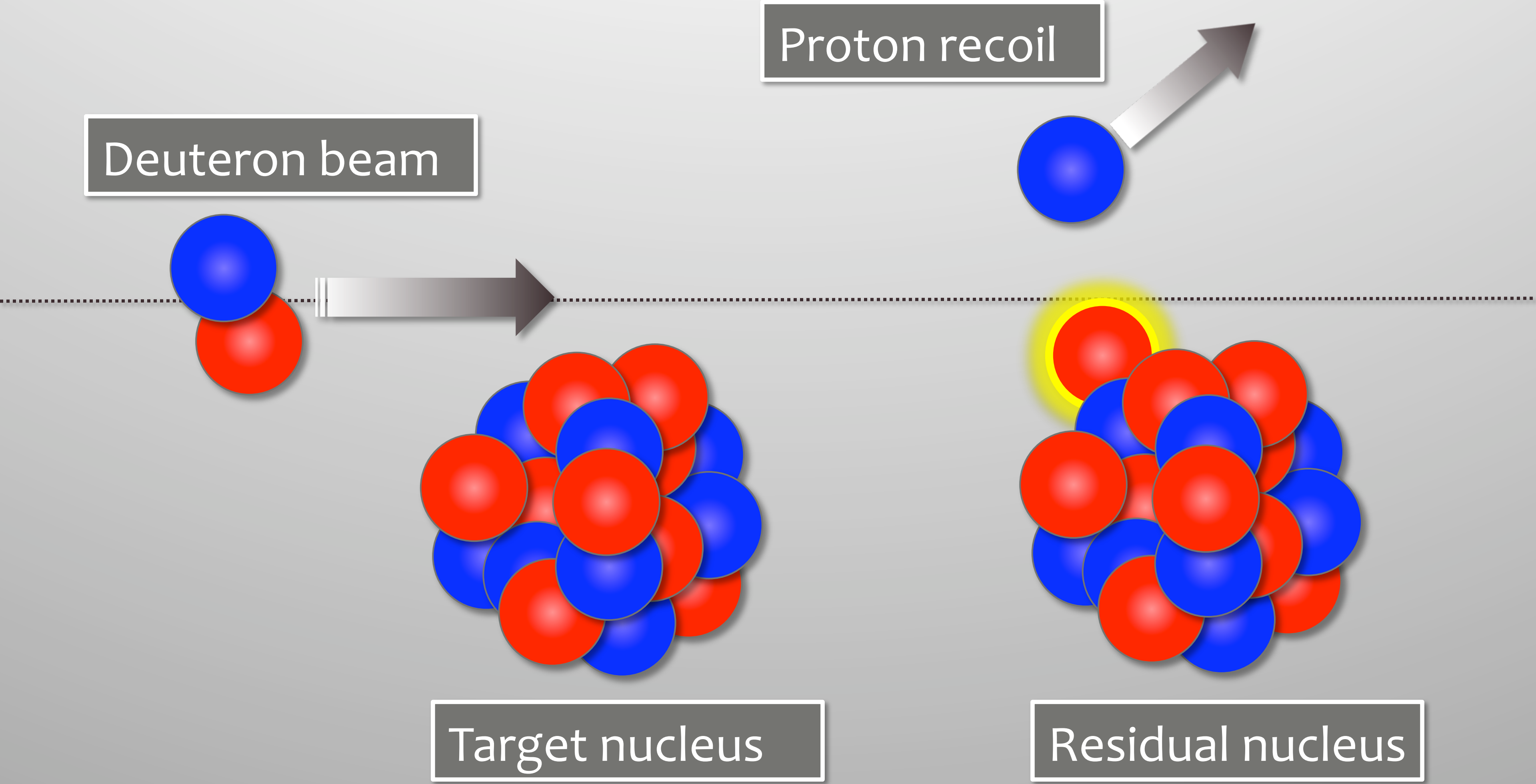
✧The form of W(r) therefore is often chosen (when at low energies) to be proportional to dV/dr.

✧A spin-orbit term is also often included which also peaks near the surface. The spin density in the interior of the nucleus tends to zero.

✧For a charged projectile a Coulomb term is also necessary.

✧The optical potential can be fit to elastic scattering data and then used for more complex reactions.

Transfer Reactions (normal kinematics)



Proton recoil

Deuteron beam

Target nucleus

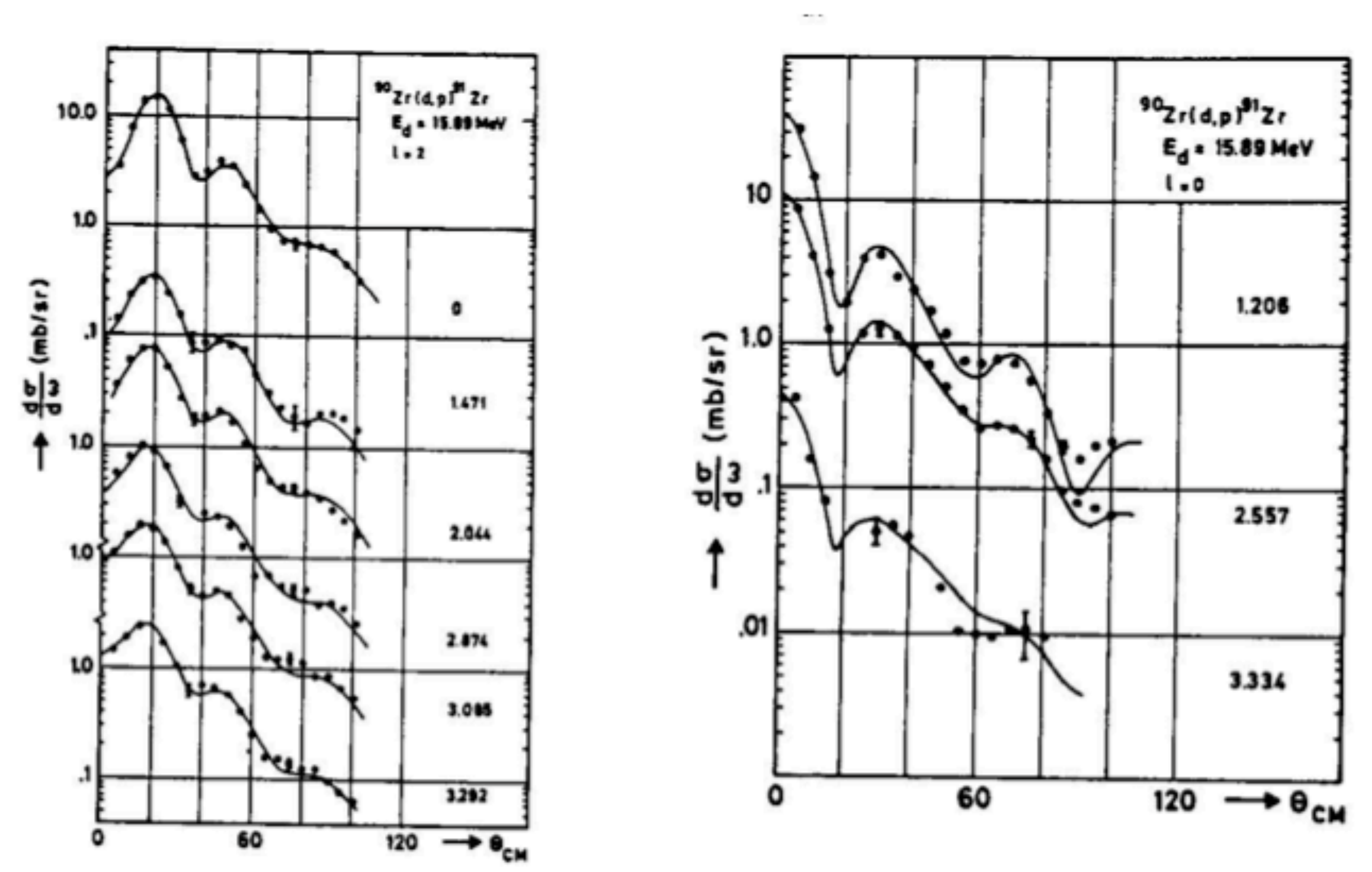
Residual nucleus

What we can learn from transfer reactions?

- Q-value
  - mass.
  - excitation energies.
- Angular distributions of recoils
  - ℓ-value of transferred nucleon.
  - combined with calculations extract spectroscopic factor.

Transfer:

^{90}Zr(d,p) E_d = 16 MeV for $\ell = 2$ and $\ell = 0$

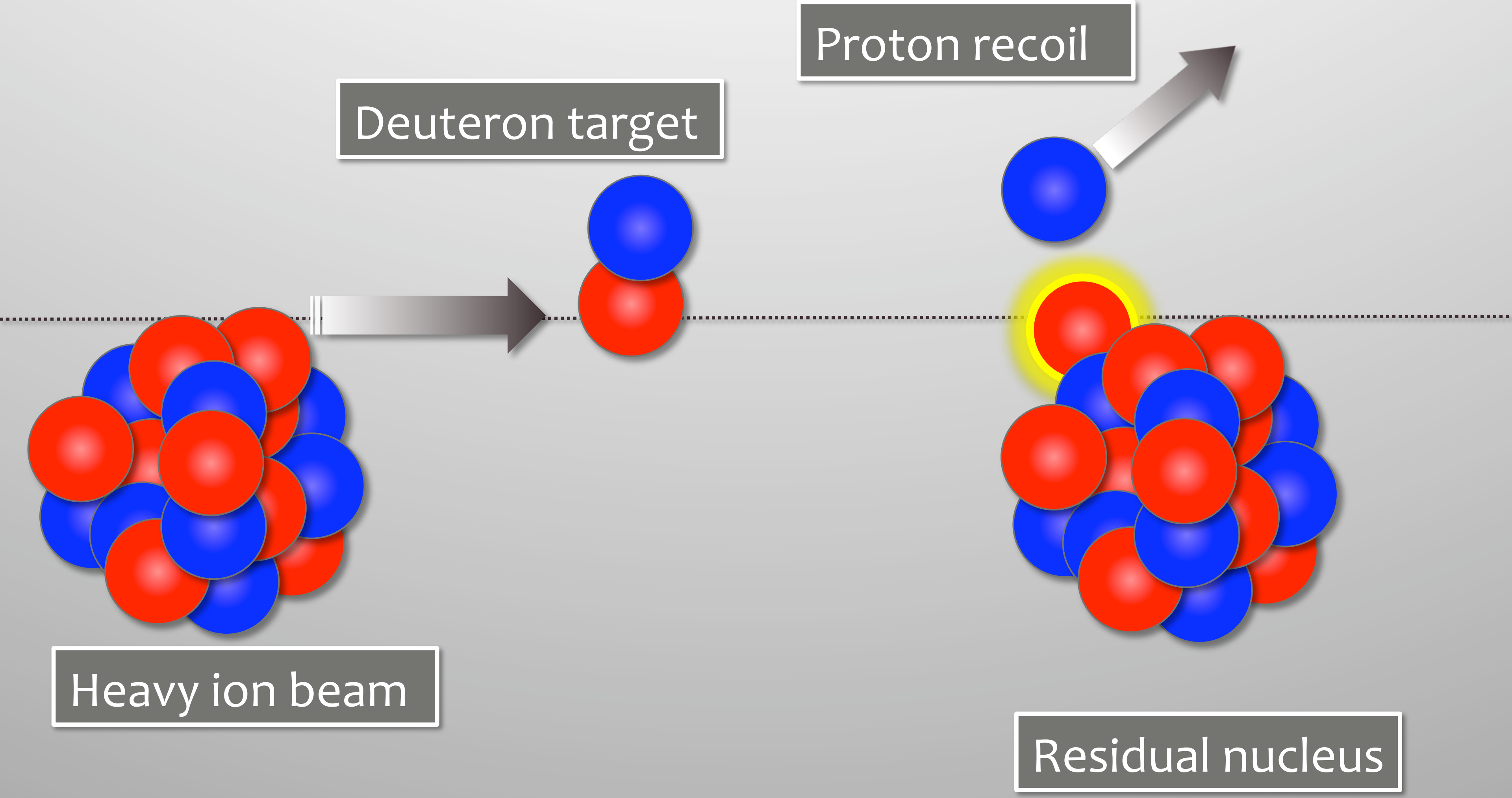


from H.P. Blok
Nucl. Phys. A. **273**, 142 (1976)

That’s where things were in the 1970’s

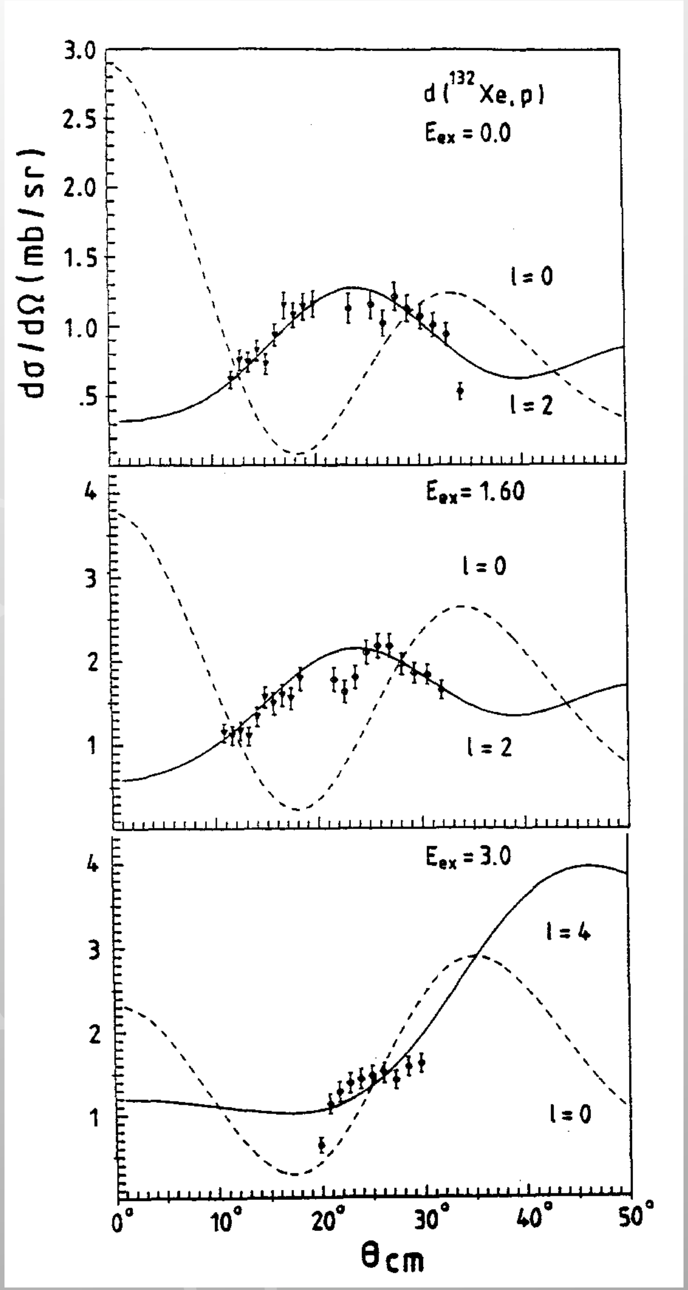
- Could explain elastic scattering and transfer using optical potentials.
- Could measure direct reactions with anything that could be made into a target.
- **Normal kinematics.**
- Gradually everything of interest that could be measured was measured and then transfer reactions slowly died away … .

Transfer Reactions (inverse kinematics)



Test of inverse kinematics

- First experiment using (d,p) reactions in **inverse kinematics.**
- ^{132}Xe(d,p) at 5.9 MeV/nucleon.
- WORKS BEAUTIFULLY.
- Tools in place.
- Slowly move toward transfer reactions with radioactive ion beams.



G. Kraus (Masters Thesis)
Z. Phys. A. **340**, 339 (1991)

What is a Spectroscopic Factor?

- It’s the norm of the overlap function between the initial state and the final state.
- Example for (d,p)
  - “How much does my recoiling nucleus look like my target nucleus plus a neutron in a given single particle state?”

What is a Spectroscopic Factor?

- Specific Illustration

$$\left|{}^{11}\mathrm{Be(g.s.)}\right\rangle = A_{2s_{1/2}}\left|{}^{10}\mathrm{Be(g.s.)}\otimes 2s_{1/2}\right\rangle + A_{1d_{5/2}}\left|{}^{10}\mathrm{Be}(2^{+})\otimes 1d_{5/2}\right\rangle + \ldots$$

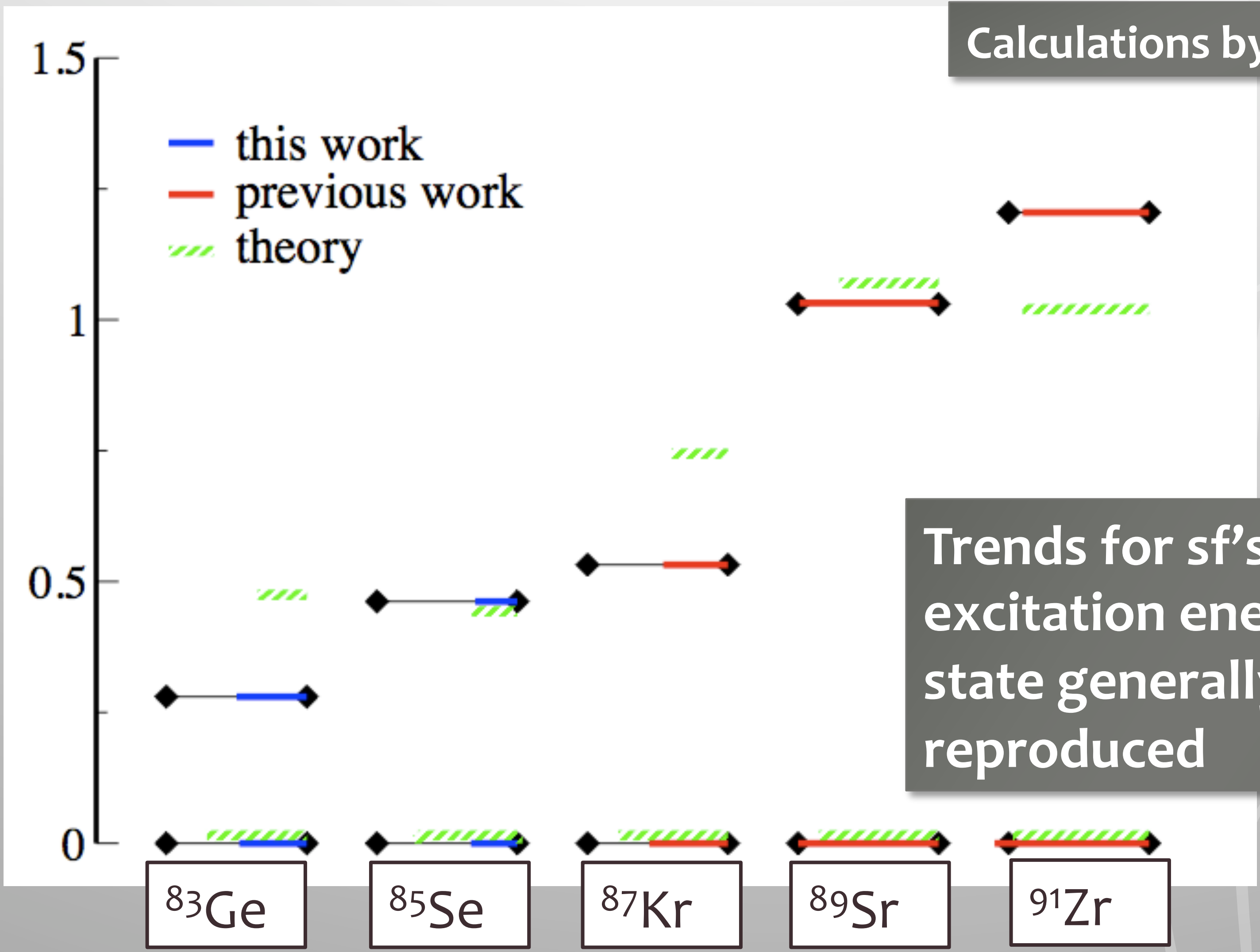
- Nuclear Reaction Theory

$$S_{\ell sj} = \left|A_{\ell sj}\right|^{2} \qquad \text{where} \qquad u_{\ell sj}(r) = A_{\ell sj}\, v_{\ell sj}(r)$$

- Nuclear Reaction Experimentalist

$$S^{\exp} = \frac{d\sigma_{\exp}/d\Omega}{d\sigma_{DWBA}/d\Omega}$$

Example: N = 51 isotones



Calculations by D. Dean

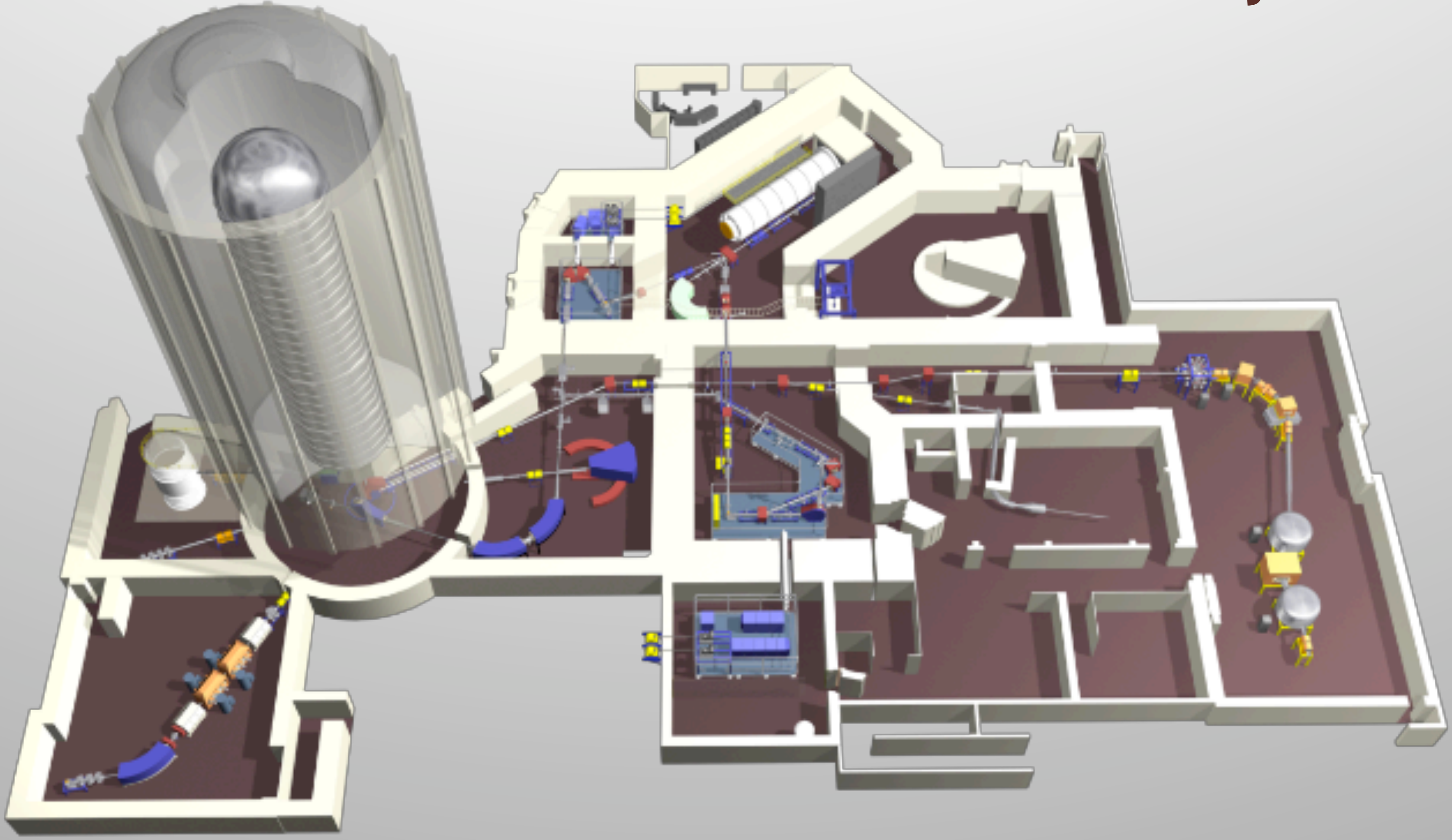
Trends for sf's and falling excitation energy of $1/2^+$ state generally well reproduced

J. Thomas et al., Phys. Rev. C 76, 044302 (2007).

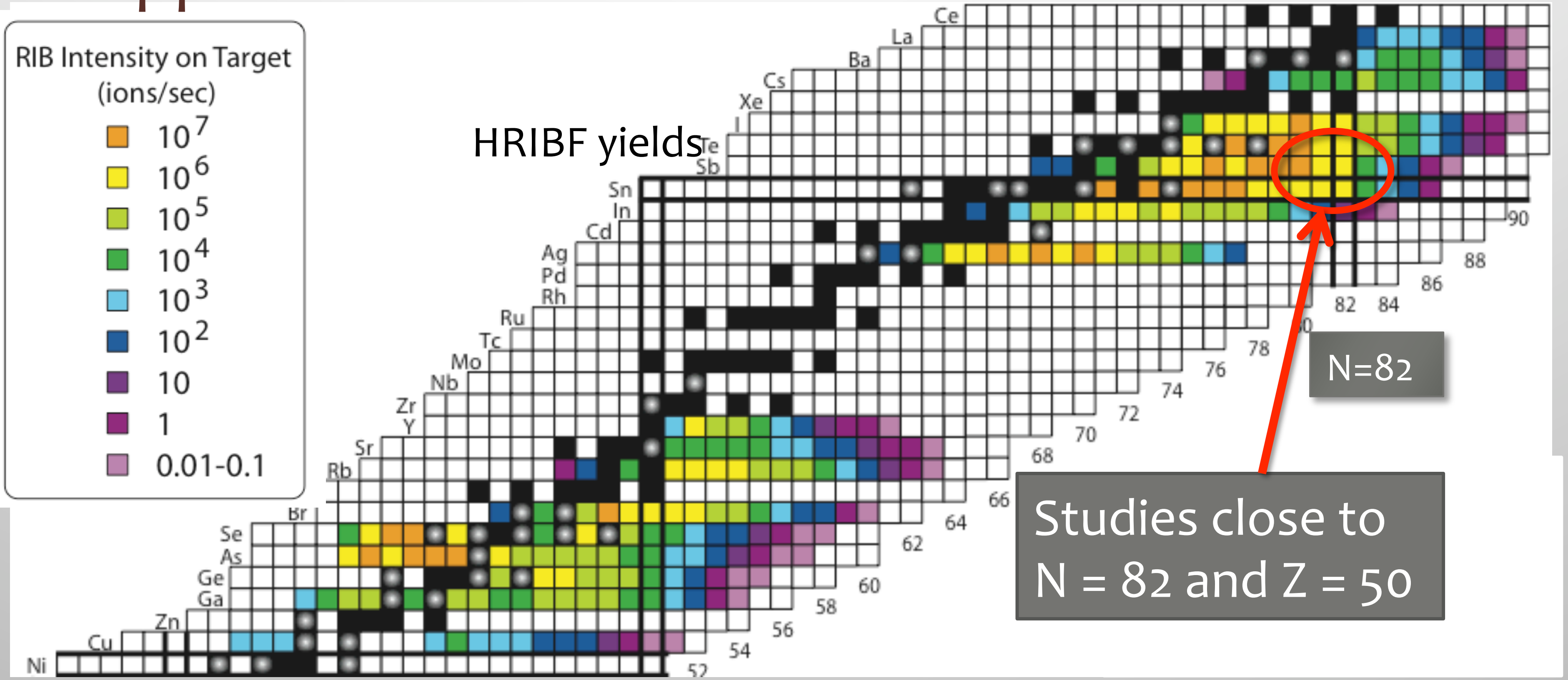
Transfer reactions in inverse kinematics

^{132}Sn(d,p)^{133}Sn

Holifield Radioactive Ion Beam Facility



Opportunities at the HRIBF



N=82

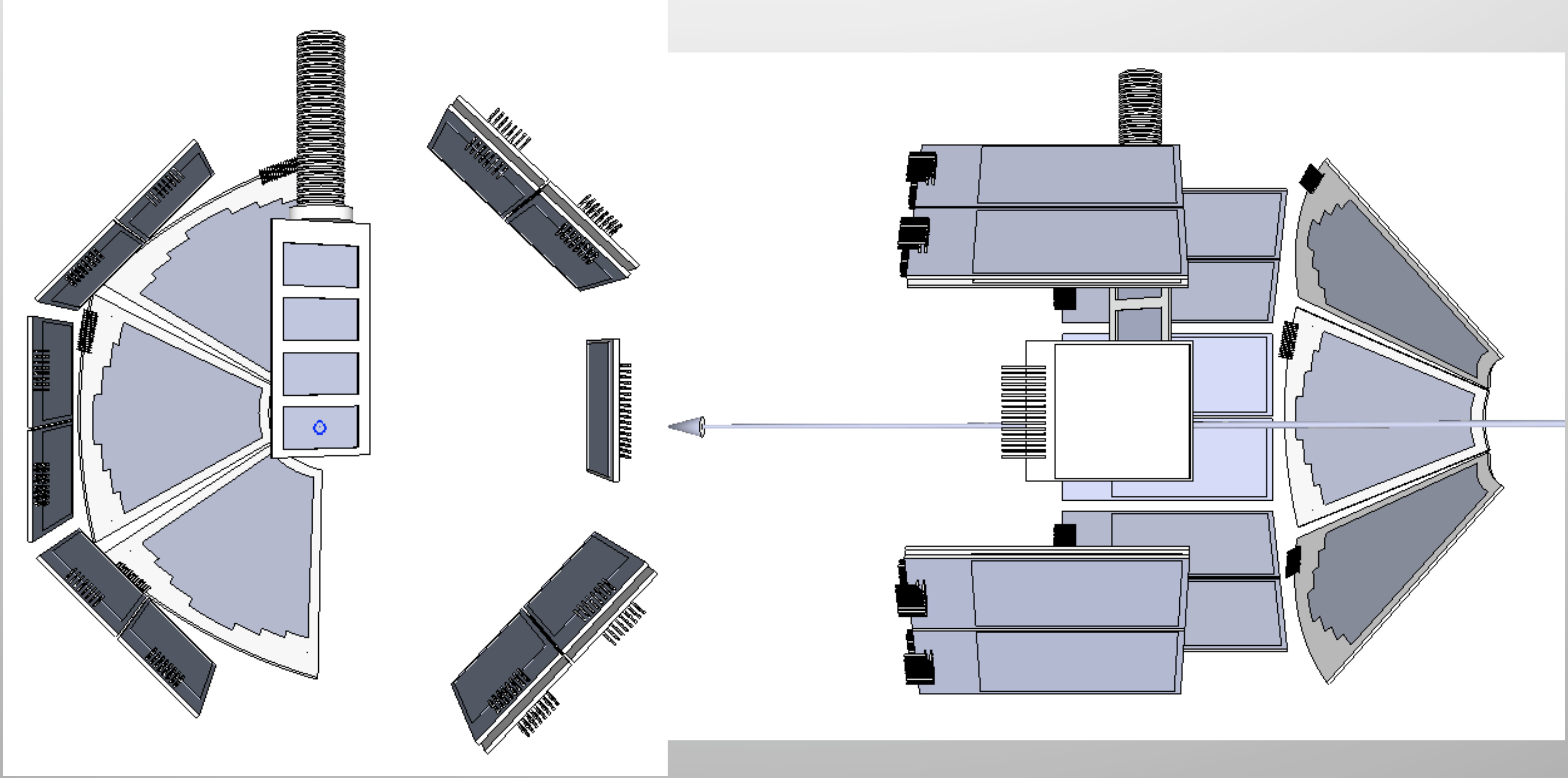
Studies close to N = 82 and Z = 50

N=50

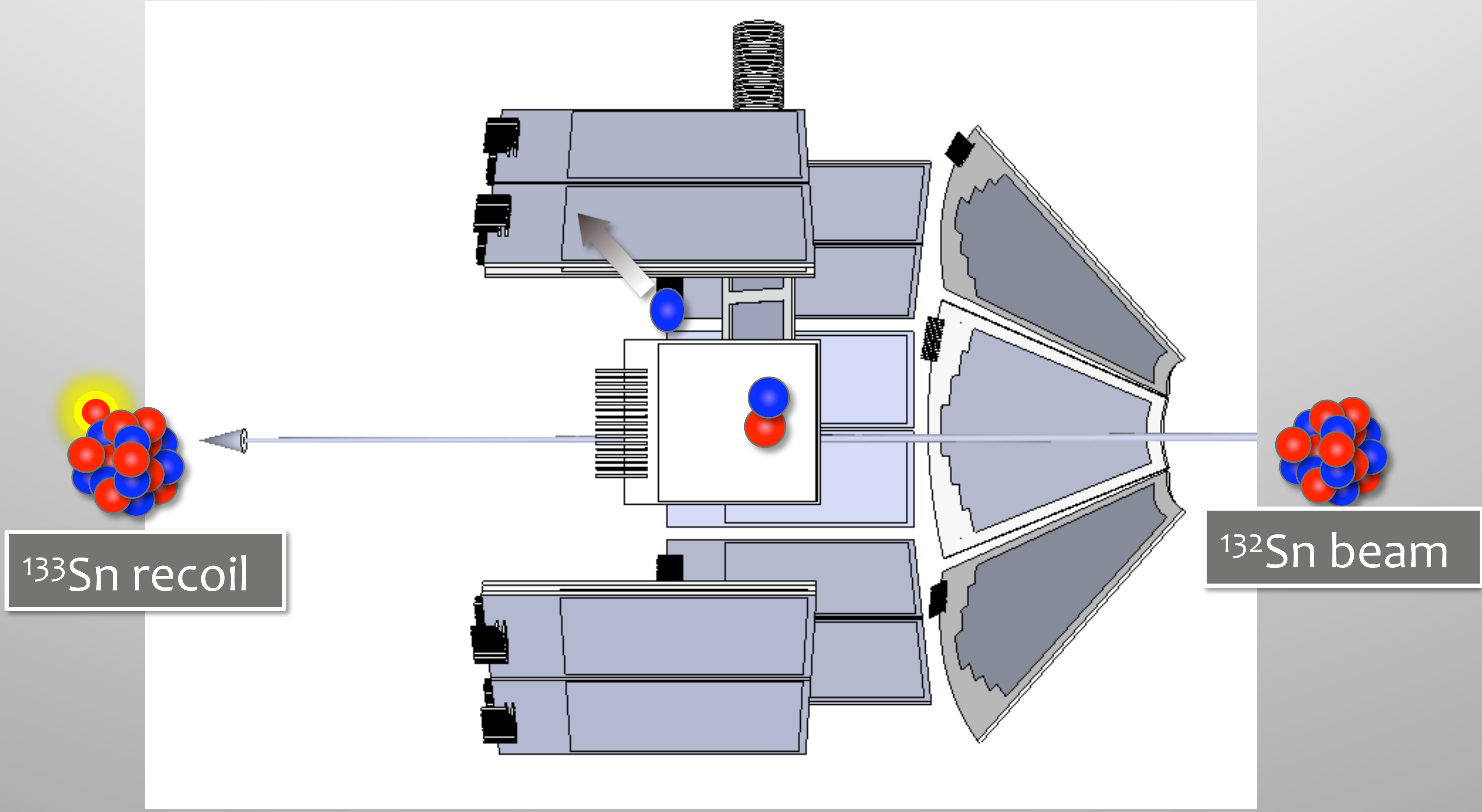
Fission fragment beams

Production via p-induced fission on U gives access to n-rich nuclei close to N=50,82

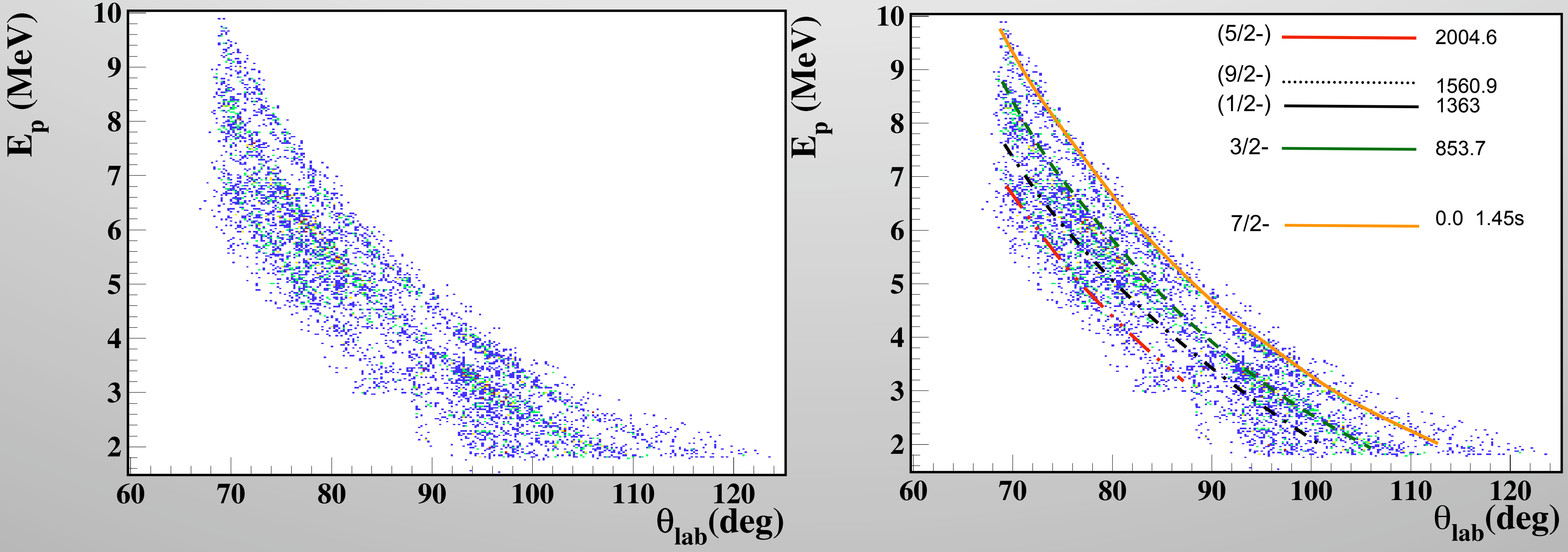
^{132}Sn(d,p)setup



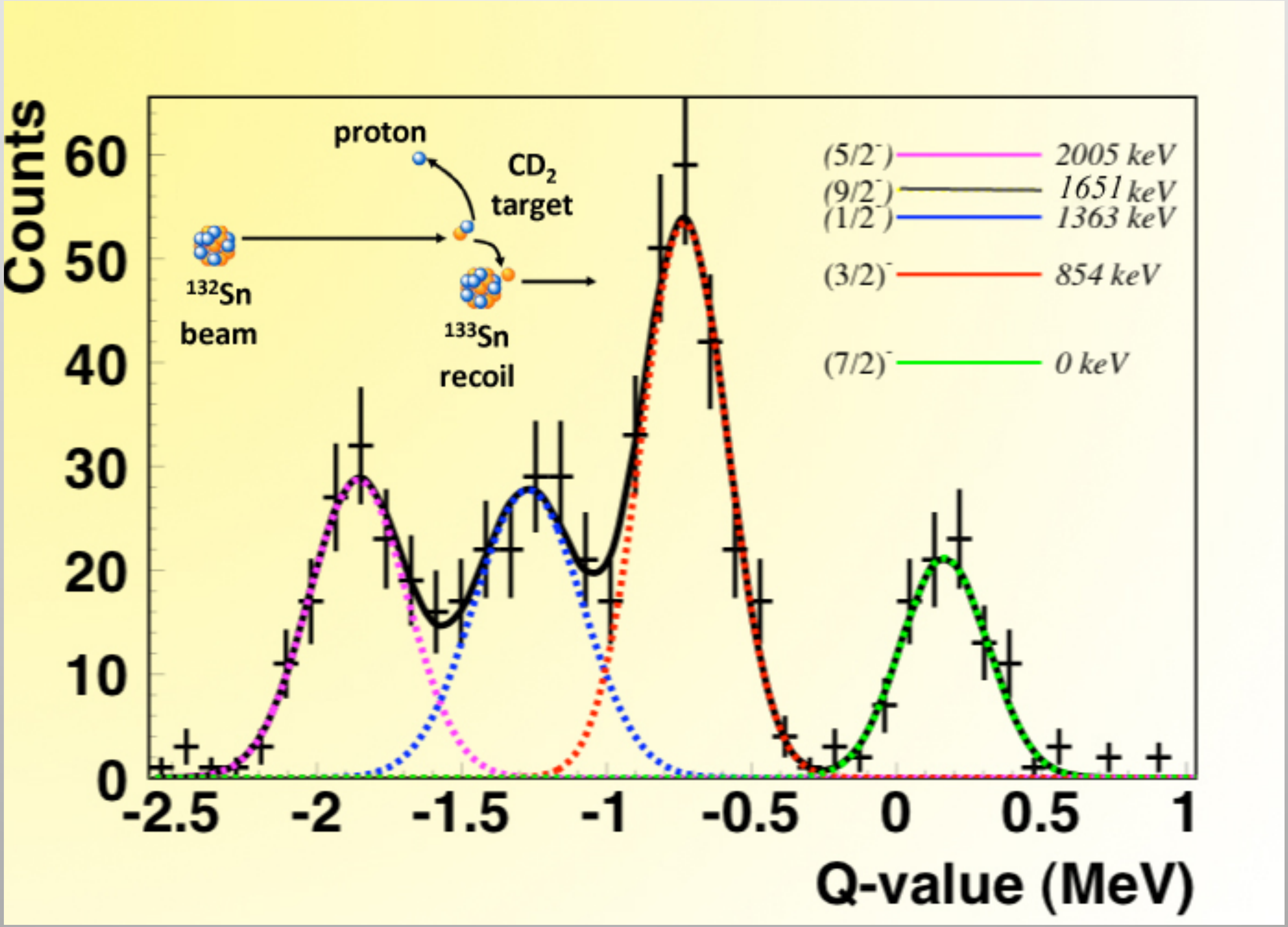
^{132}Sn(d,p) experiment



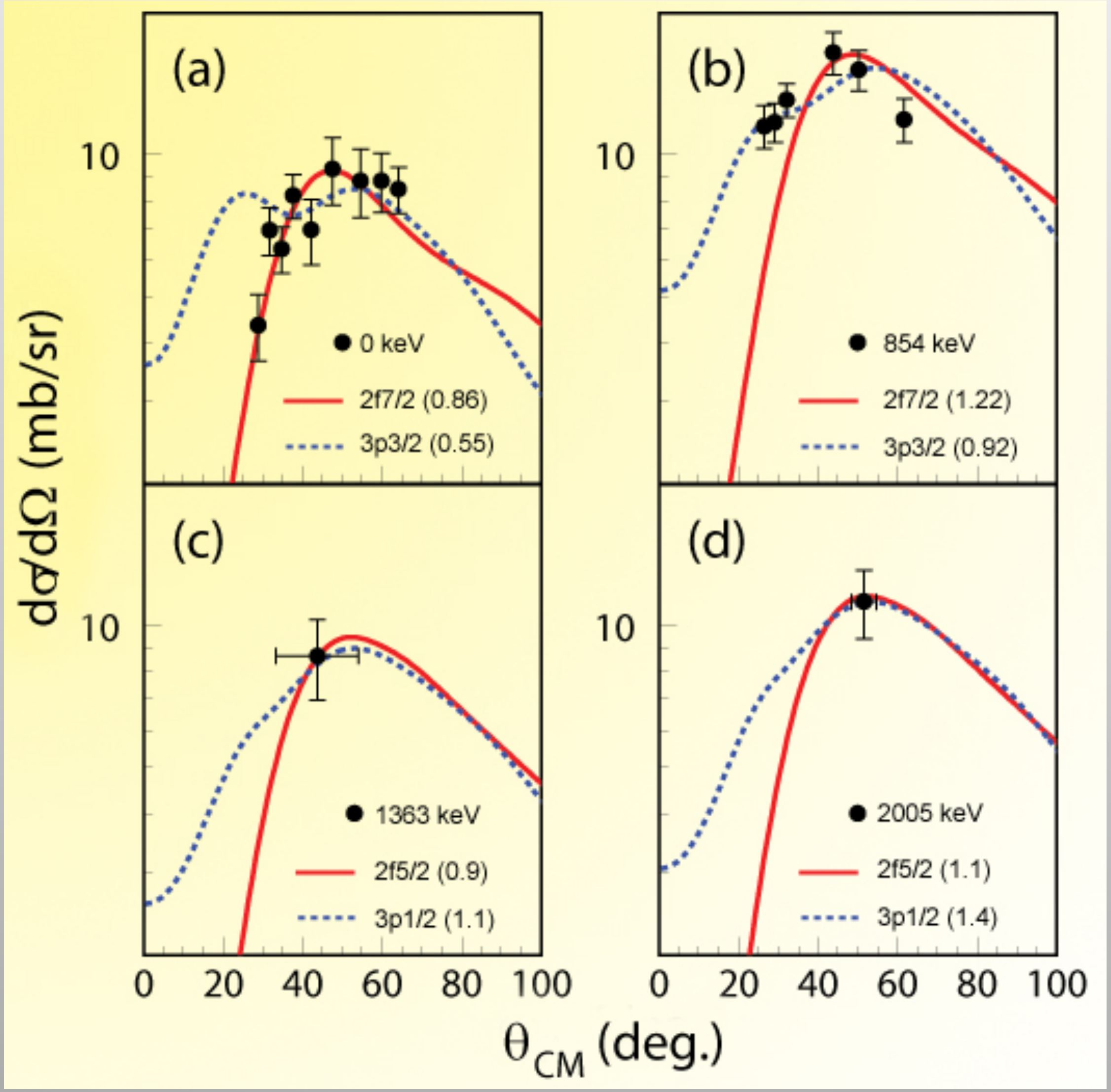
^{132}Sn(d,p) data



^{133}Sn Q-value spectrum



^{133}Sn Angular Distributions

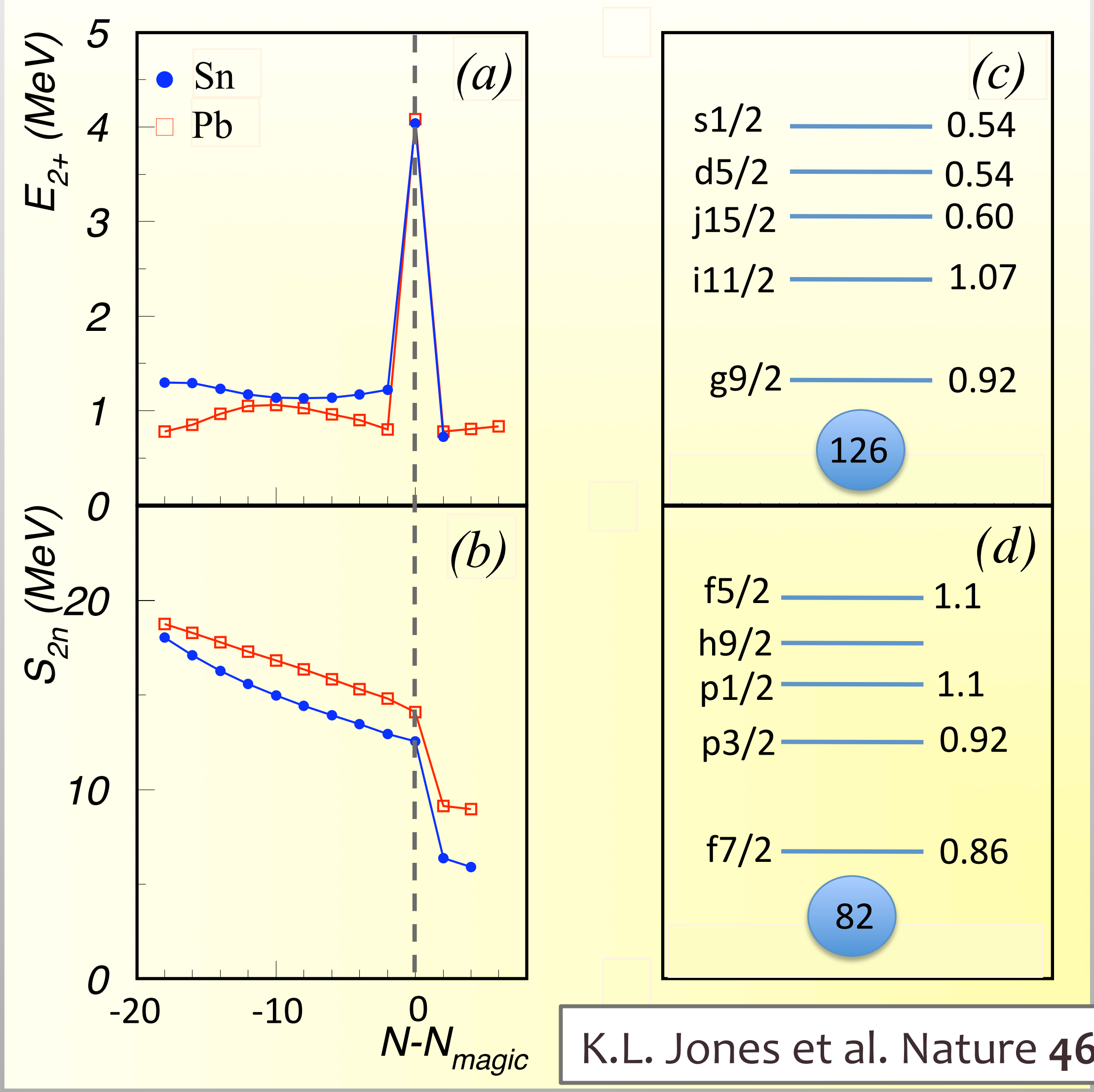


Theory from Filomena Nunes (NSCL)

Spectroscopic factors for ^{133}Sn from DWBA

Ex (keV)	J^π	Configuration	SF	C^2 (fm^{-1})
0	$7/2^-$	$^{132}Sn_{gs} \otimes \nu_{f7/2}$	0.86 ± 0.16	0.64 ± 0.10
854	$3/2^-$	$^{132}Sn_{gs} \otimes \nu_{p3/2}$	0.92 ± 0.18	5.61 ± 0.86
1363±31	$(1/2)^-$	$^{132}Sn_{gs} \otimes \nu_{p1/2}$	1.1 ± 0.3	2.63 ± 0.43
2005	$(5/2)^-$	$^{132}Sn_{gs} \otimes \nu_{f5/2}$	1.1 ± 0.2	$(9 \pm 2)\times10^{-4}$

Magicity of ^{132}Sn



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

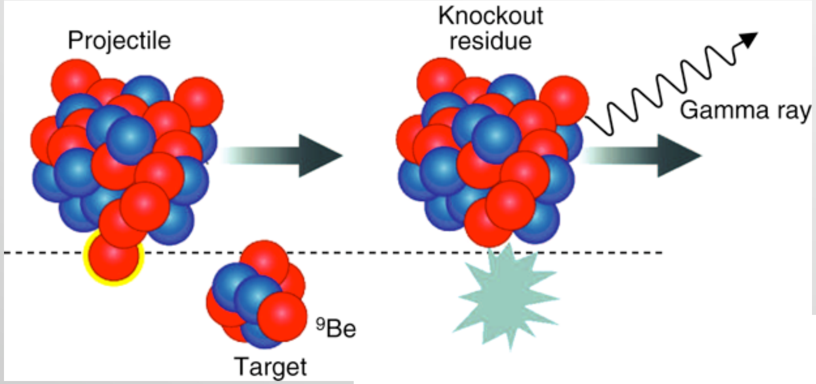
^{132}Sn is a great doubly-magic nucleus

- All the spectroscopic factors are around 1.
- Pure single particle states.
- Even better than ^{208}Pb.
- Everything’s fine and dandy …. right?

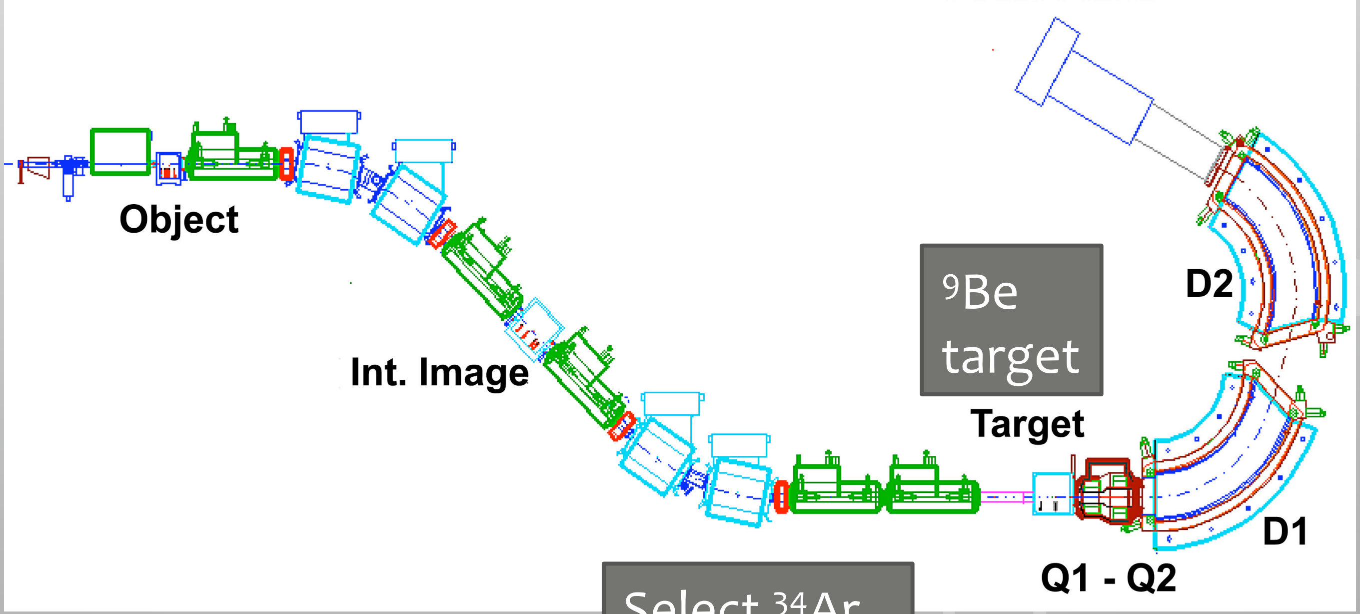
Knockout reactions

REDUCTION FACTORS

Knockout reactions e.g. at the NSCL



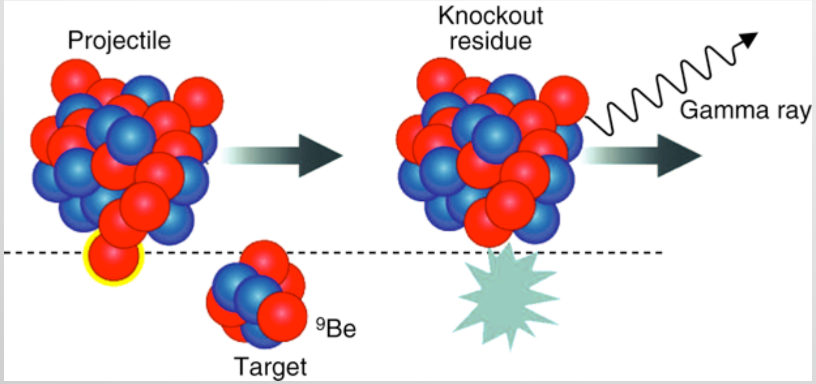
Select ^{33}Ar at the focal plane of the S800

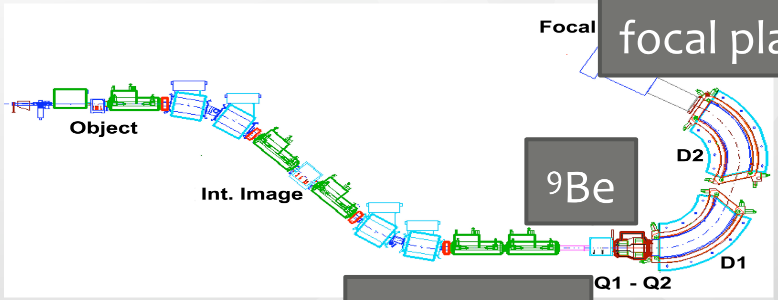


^{9}Be target

Select ^{34}Ar in the Beam

Knockout reactions

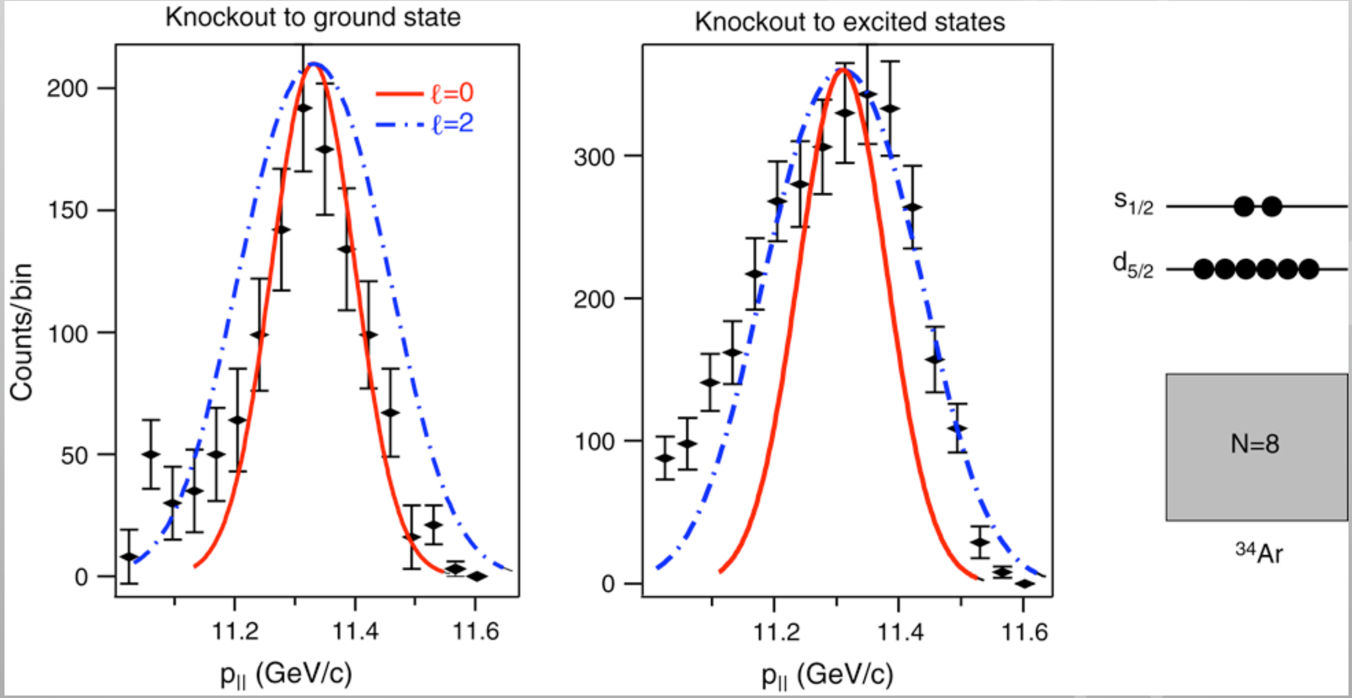




^{33}Ar in focal plane

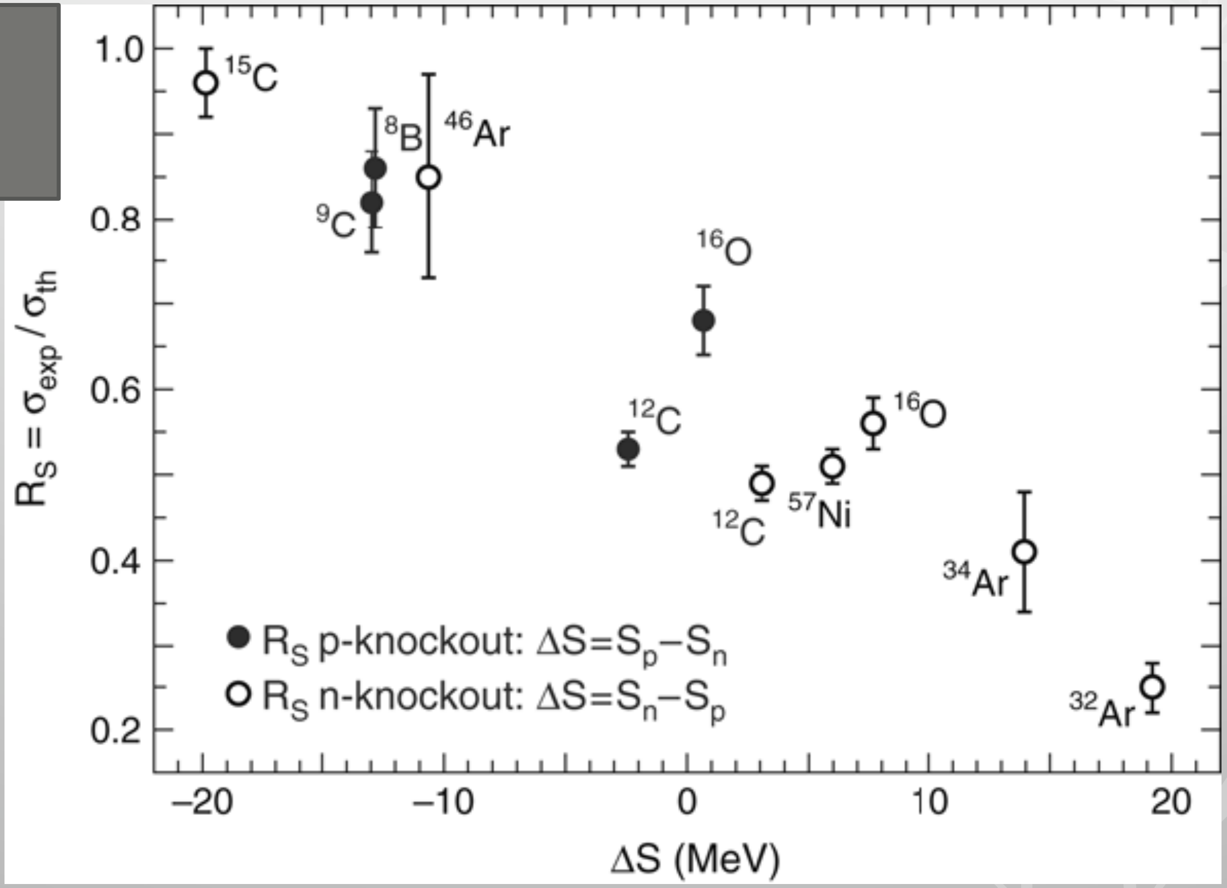
^{9}Be

^{34}Ar Beam



Reduction Factors from Knockout

Weakly-bound nucleons

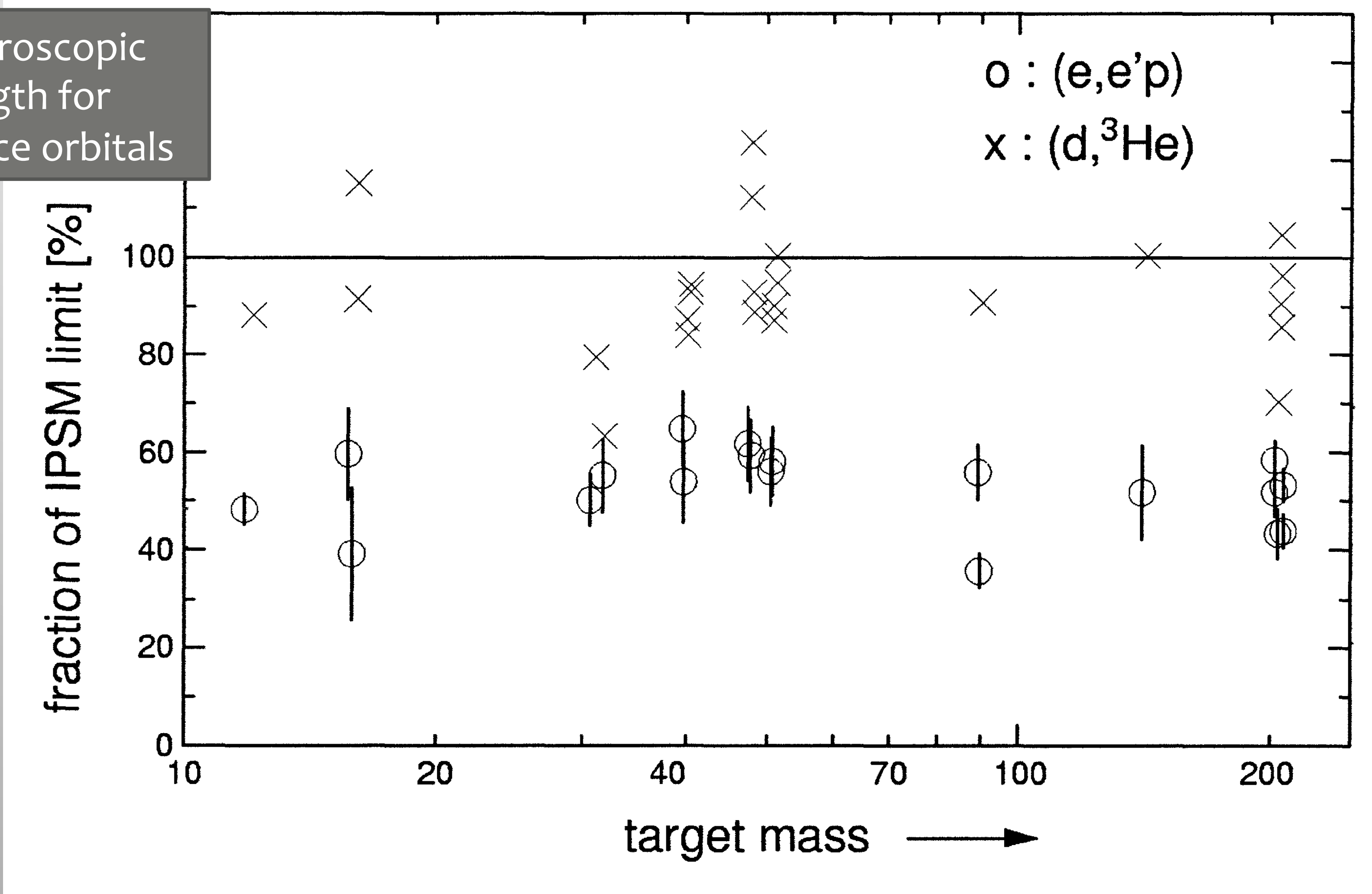


Deeply-bound nucleons

A. Gade and T. Glasmacher, Prog. Part. Nucl. Phys. 60 (2008) 161.

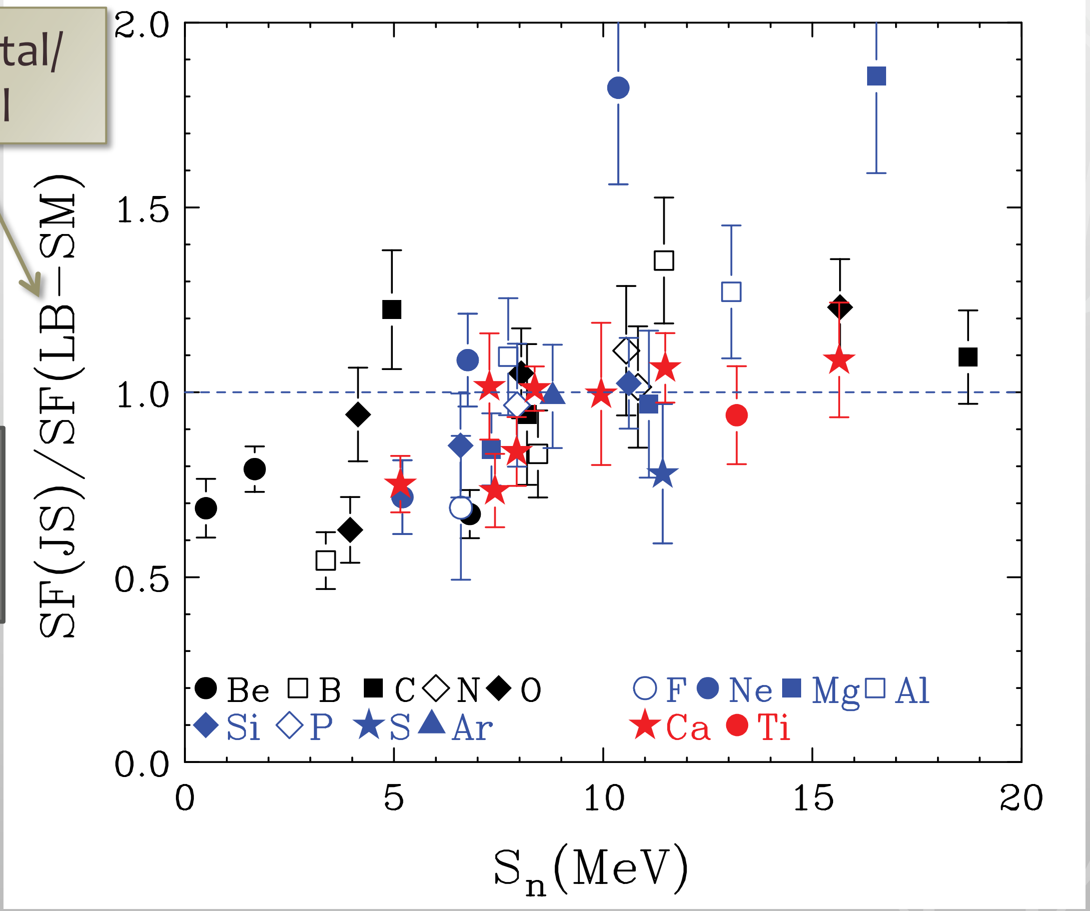
Reduction Factors from (e,e'p)

Spectroscopic strength for valence orbitals



G.J Kramer et al Nucl. Phys. A 679 (2001) 267.

Reduction Factors? from Transfer



Experimental/
shell model

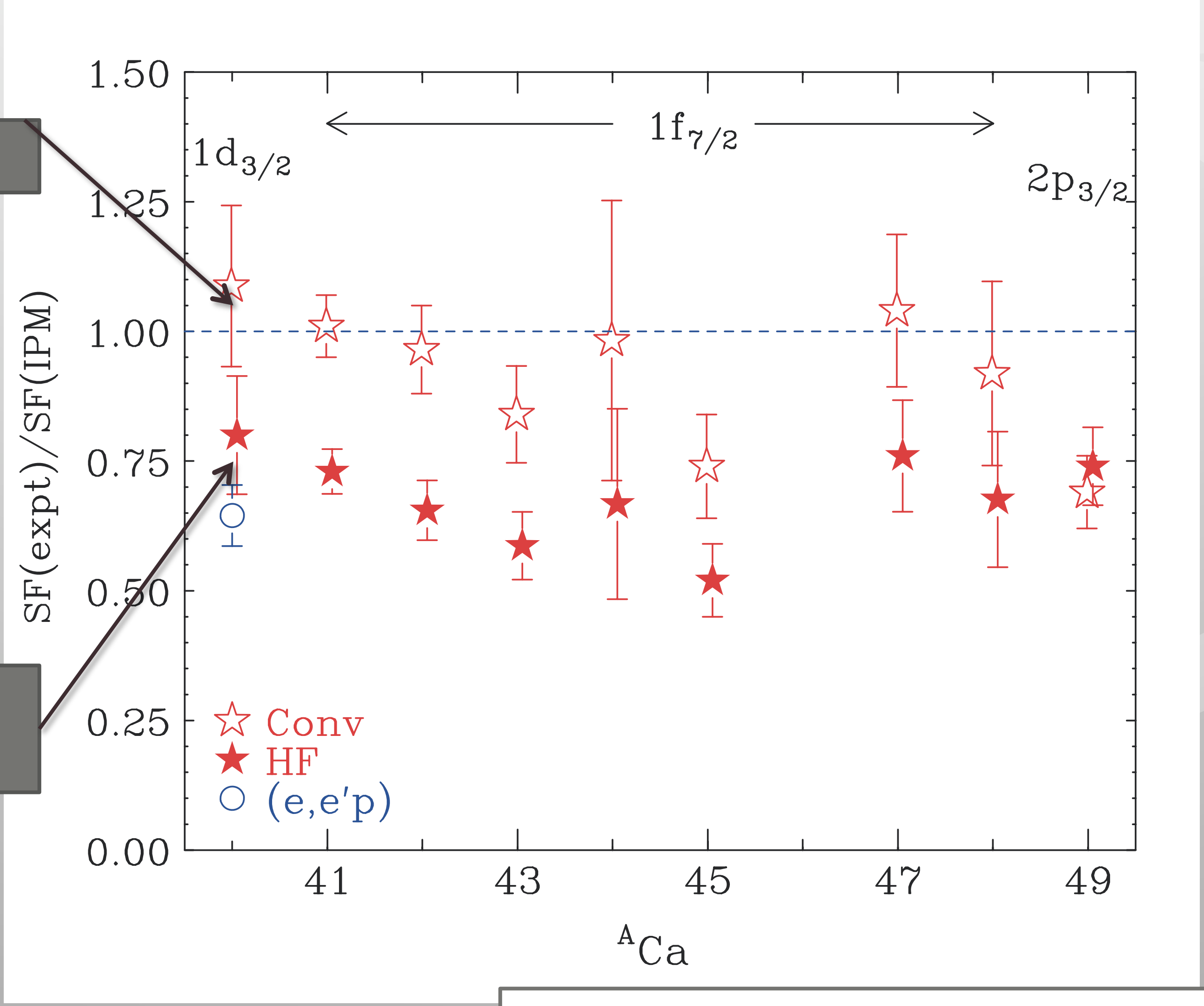
Weakly-
bound
nucleons

Deeply-
bound
nucleons

Johnson-Soper, Chapel-Hill 89, r = 1.25 fm, a = 0.65 fm TWOFNR with Local Energy Approximation, Reid soft-core deuteron.

J. Lee et al., Phys. Rev. C 75, 064320 (2007).

More Spectroscopic Factors from Transfer



Fixed geometry

HF constrained geometry

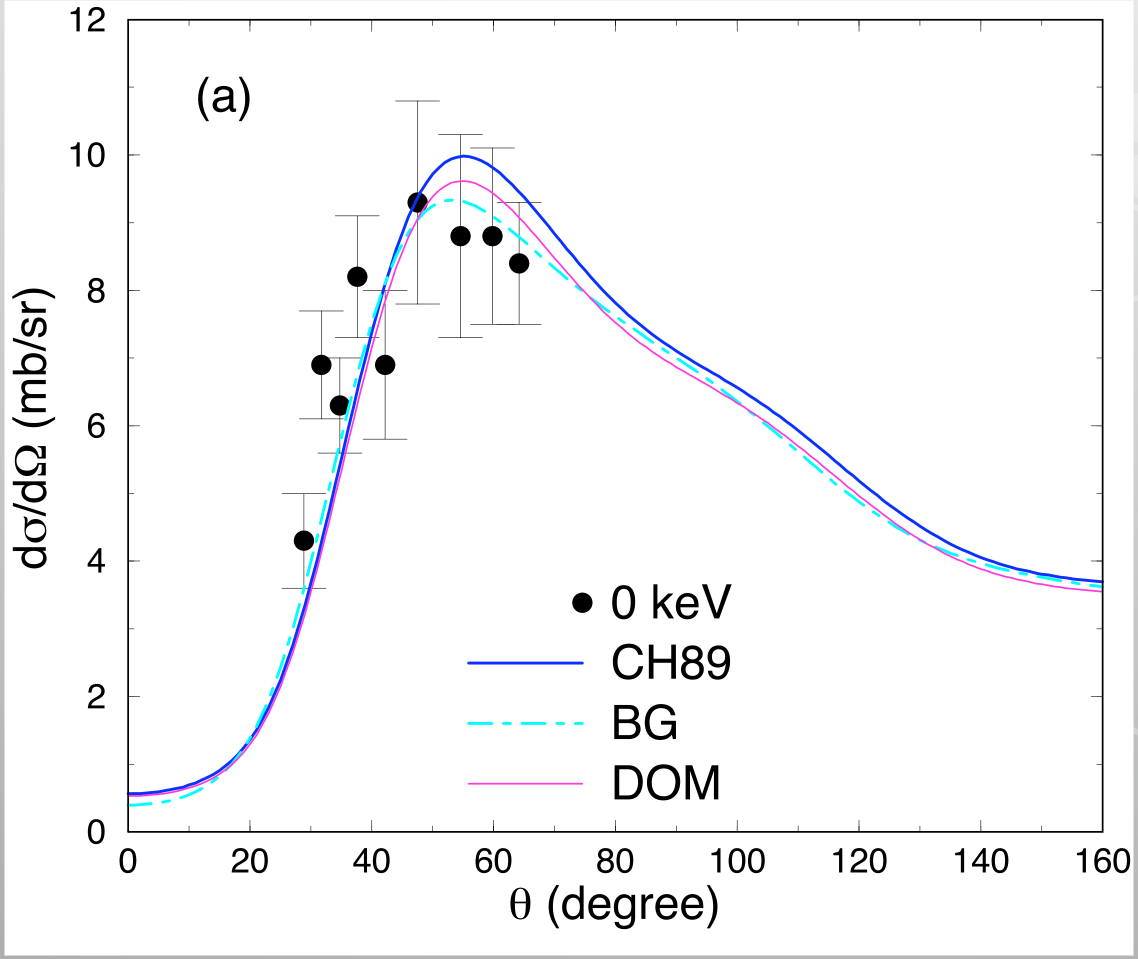
J. Lee et al., Phys. Rev. C 73, 044608 (2006).

Reduction factors

- From (d,p)
  - when analyzed the same way and use standard geometry, reasonably consistently around 1.
  - when use HF to constrain geometry, reasonably consistent with maximum of 0.75.
- From knockout
  - depends on how tightly bound the nucleon is.
- From (e,e'p)
  - reasonably consistent around 0.5
  - only stable nuclei, so $\Delta S \approx 0$.

More ^{132}Sn: Dispersive Optical Model

- **PRELIMINARY! From NSCL/WashU theory groups**



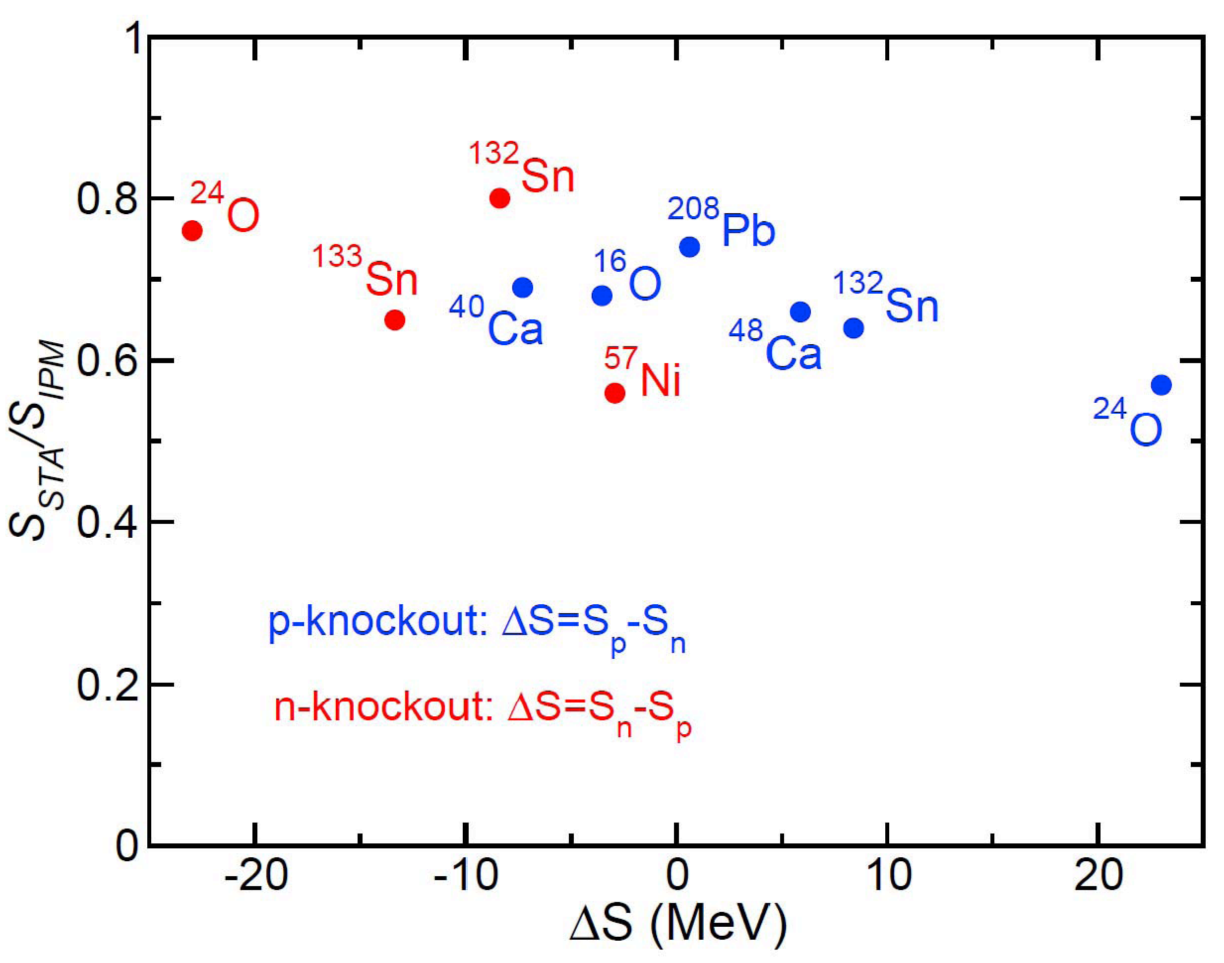
With standard geometry
Spectroscopic Factor = 1.0

When DOM is used to generate the overlap function
Spectroscopic Factor = 0.72

Open Questions on Spectroscopic Factors

- Problem with analysis of transfer data?
  - Constraining geometry gives different results of having r = 1.25 fm and a = 0.65 fm for all nuclei.
  - note this is not the radius and diffuseness of the nucleus, rather those of the potential binding the last nucleon.
- Should Magic nuclei lead to SF = 1?
  - what does that really mean?
  - loss of correlation between the core and the last nucleon?
  - how is it bound?
- Is there something missing in the shell model?

Source Term Approximation



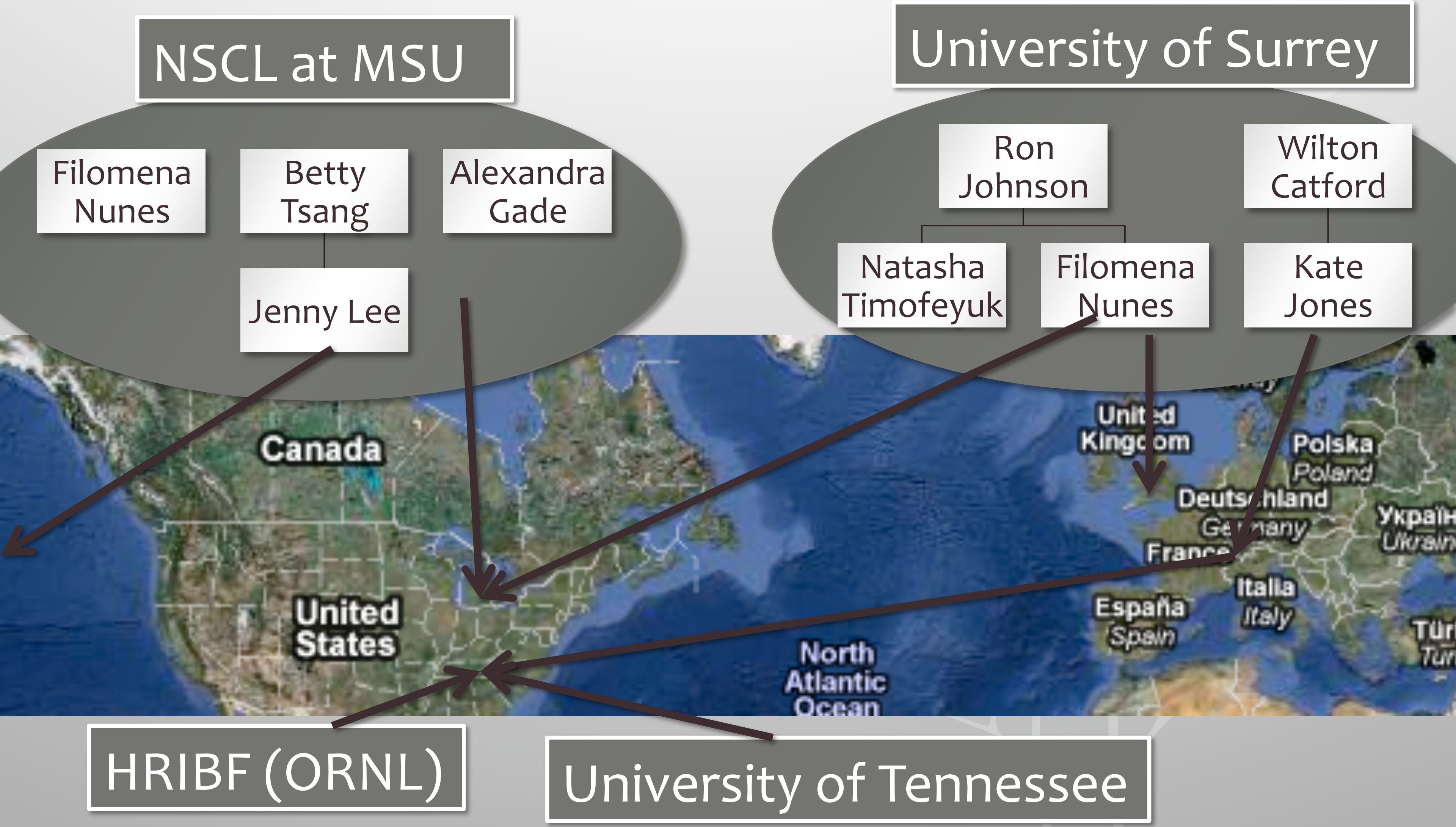
Natasha Timofeyuk, private communication

Also see Natasha Timofeyuk, PRL **103**, 242501 (2009) and PRC **81**, 064306 (2010)

Summary

- Direct reactions present a selection of powerful spectroscopic tools.
- Only brushed the surface of the subject.
- Currently hot topic in nuclear physics – how to interpret spectroscopic factors from different types of measurements.
- Lots of work by a few people over the last couple of decades.
  - more structure in reaction calculations.
  - better reaction calculations.
  - a lot of ongoing work
- The lines between structure theory and reaction theory are becoming blurred – good thing!
- At the same time, more measurements on exotic nuclei.

Statement of bias (some people mentioned in talk)



NSCL at MSU

- Filomena Nunes
- Betty Tsang
  - Jenny Lee
- Alexandra Gade

University of Surrey

- Ron Johnson
  - Natasha Timofeyuk
  - Filomena Nunes
- Wilton Catford
  - Kate Jones

HRIBF (ORNL)

University of Tennessee

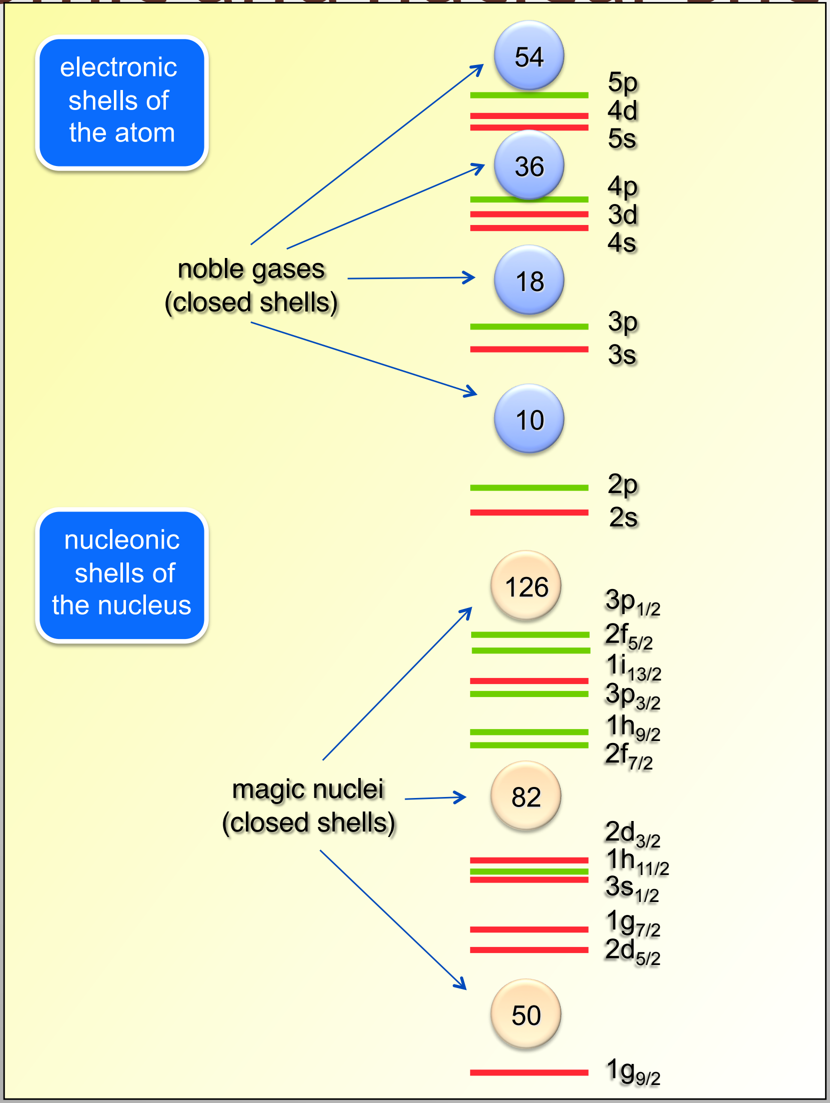
AND THANKS!!!!!

Three quotes from Natasha Timofeyuk

- Source Term Approximation (STA) “can reconcile reduction of spectroscopic strength in double closed shell nuclei with double magic nature of these nuclei”.
- “STA employs IPM wave function but gets reduced spectroscopic factors if NN interaction is chosen correctly.”
- “SFs are the measure of strength of the interaction of the removed nucleon rather than the measure of the shell occupancies.”

Also see Natasha Timofeyuk, PRL **103,** 242501 (2009) and PRC **81,** 064306 (2010)

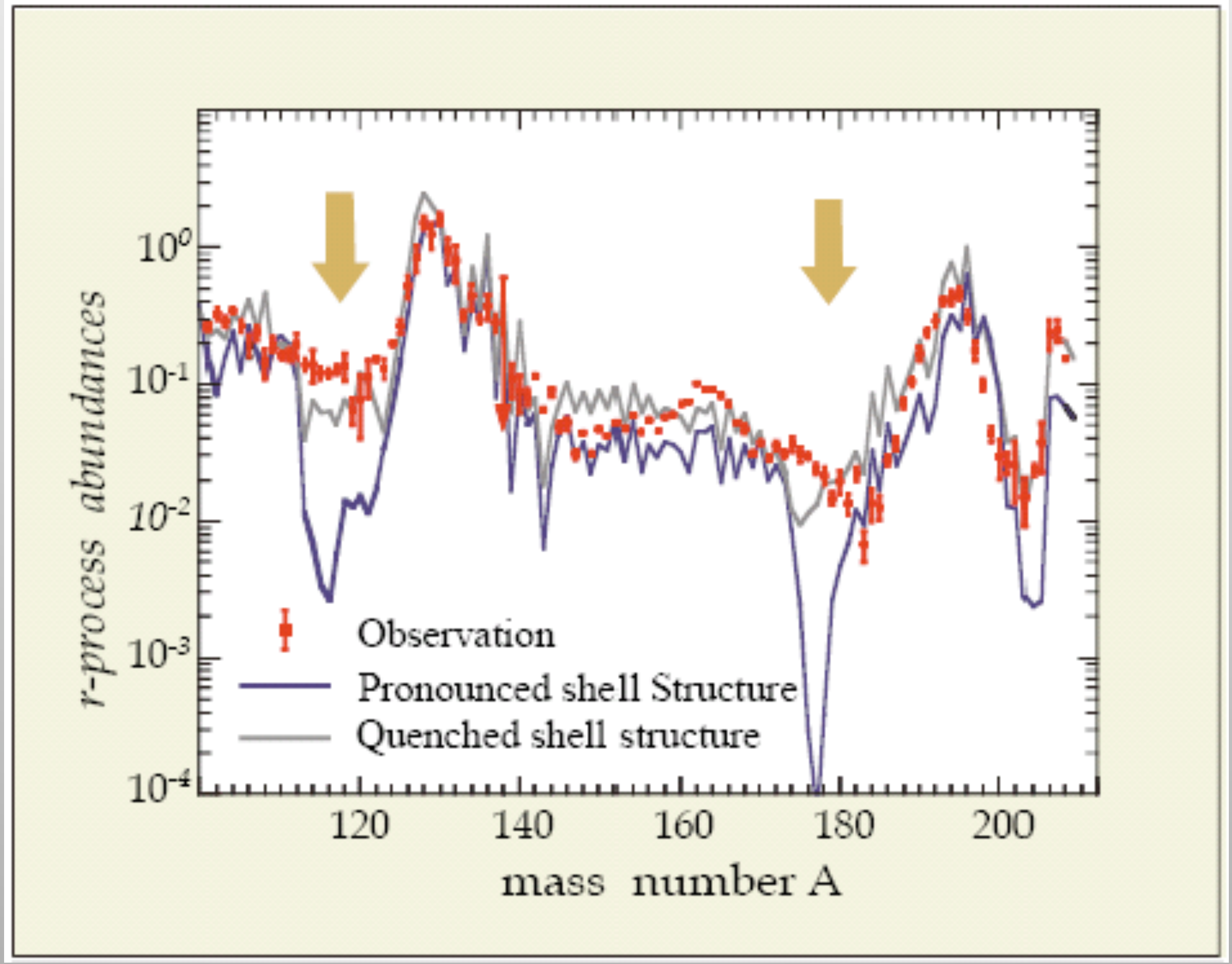
Atomic and nuclear shells



Nuclei are comprised of two types of particles, neutrons and protons. If both the number of neutrons and the number of protons is magic then we have a doubly magic nucleus.

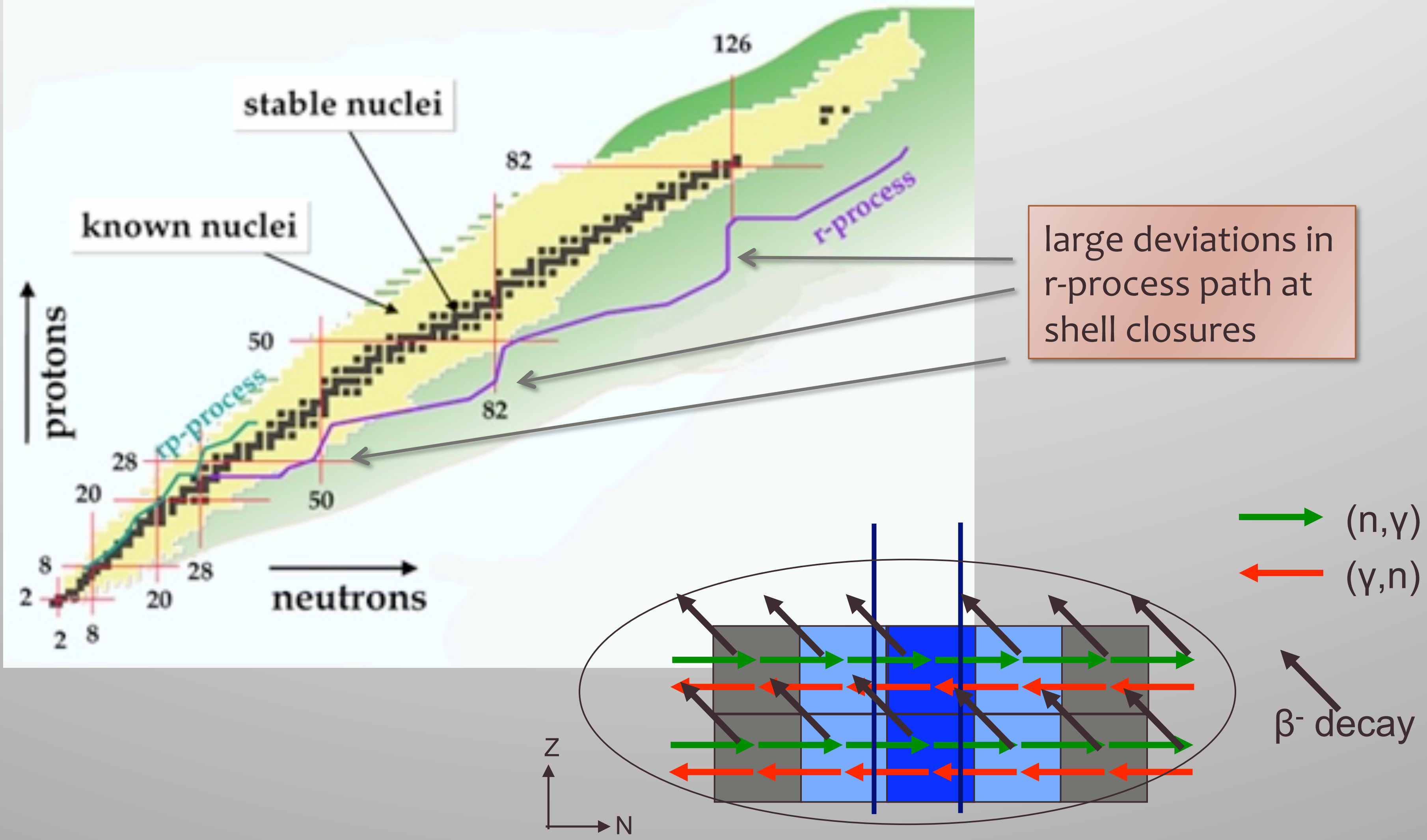
Jones and Nazarewicz, The Physics Teacher, **48** (2010).

Shell model fingerprints on the galaxy



Pfeiffer, Kratz, Thielemann and Walters, Nuc. Phys. A **693** 282 (2001)

The rapid neutron capture (r-)process



large deviations in r-process path at shell closures