Transfer Reactions on Argon Isotopes

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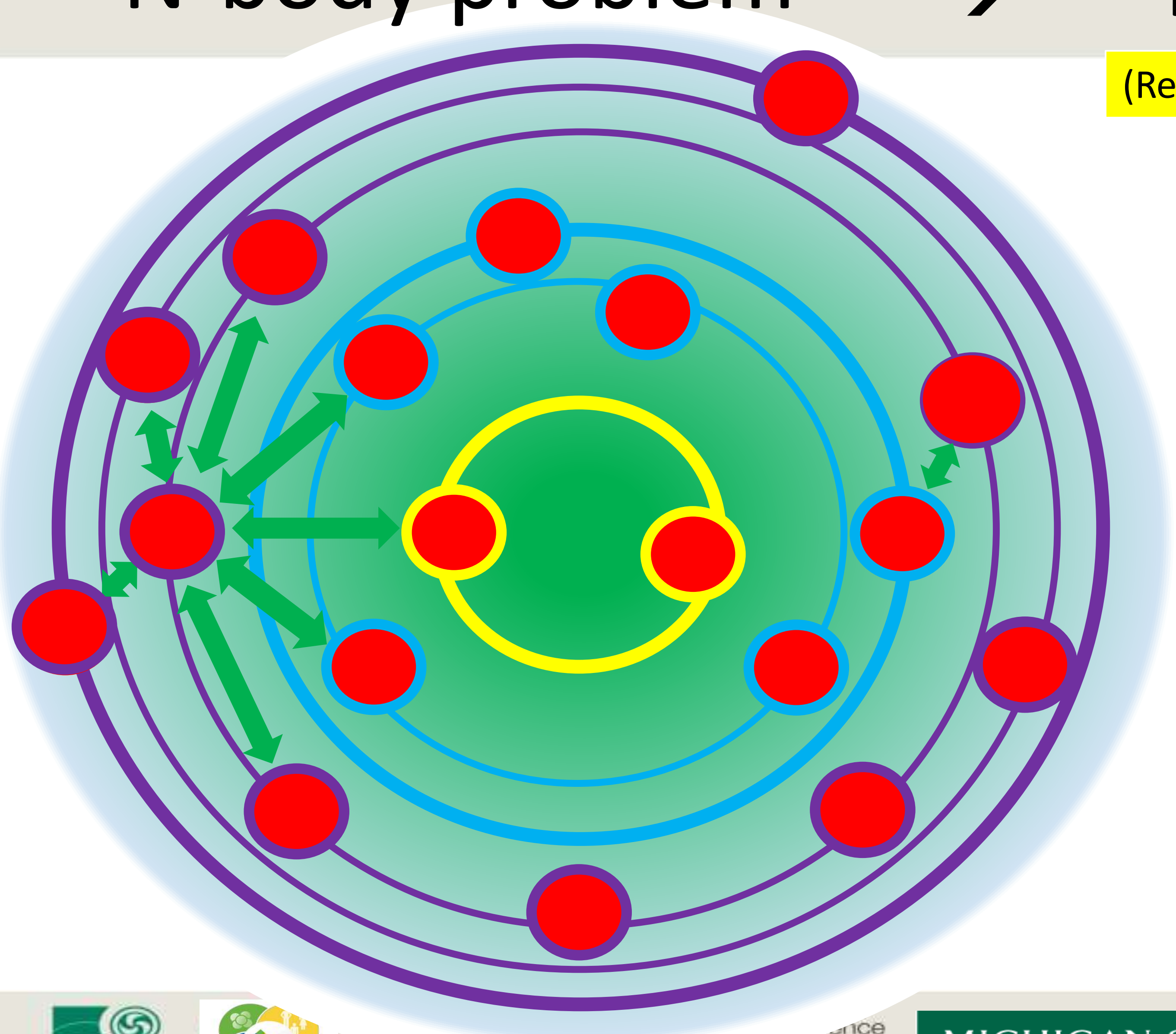
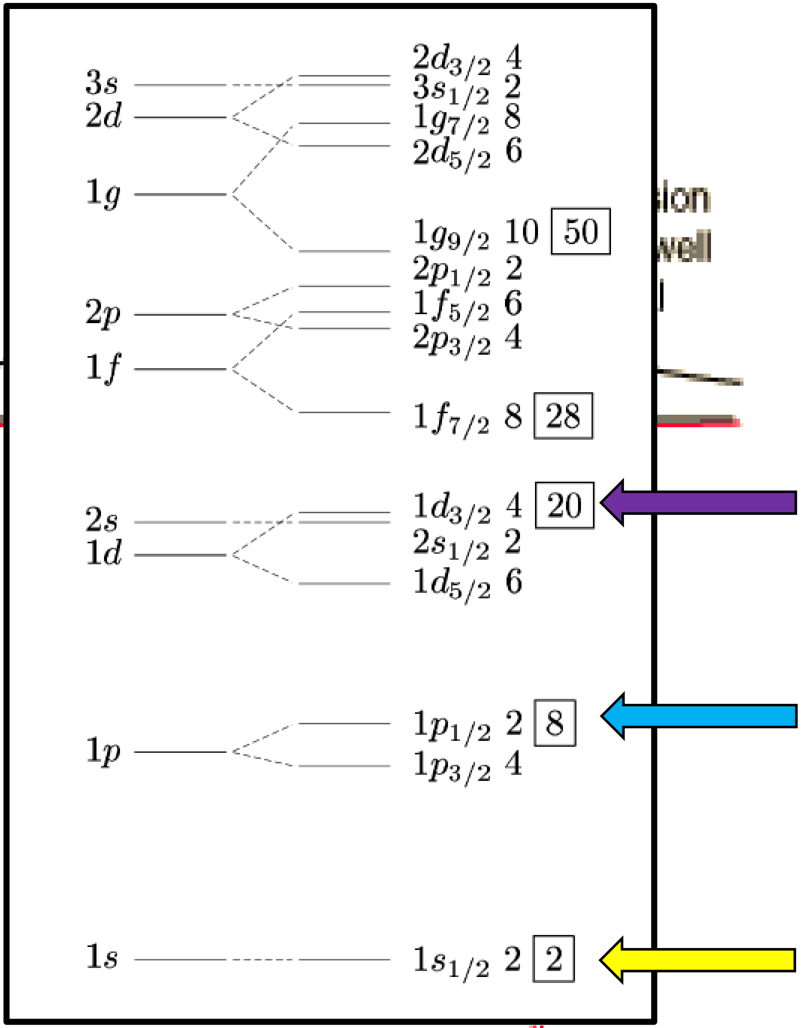
SSGF Annual Review

June 22, 2017

N-body problem → N 1-body problems

(Really <<N)





http://hyperphysics.phy-astr.gsu.edu/hbase/Nuclear/shell.html

How can we test this picture?

- One answer: **Spectroscopic Factors (SF)** $SF = \int d\vec{p}\, \left|\langle \Psi^{N-1} | a_{\vec{p}} | \Psi^{N} \rangle\right|^2$
  - SFs are a way to quantize the occupancy of a given single particle orbital

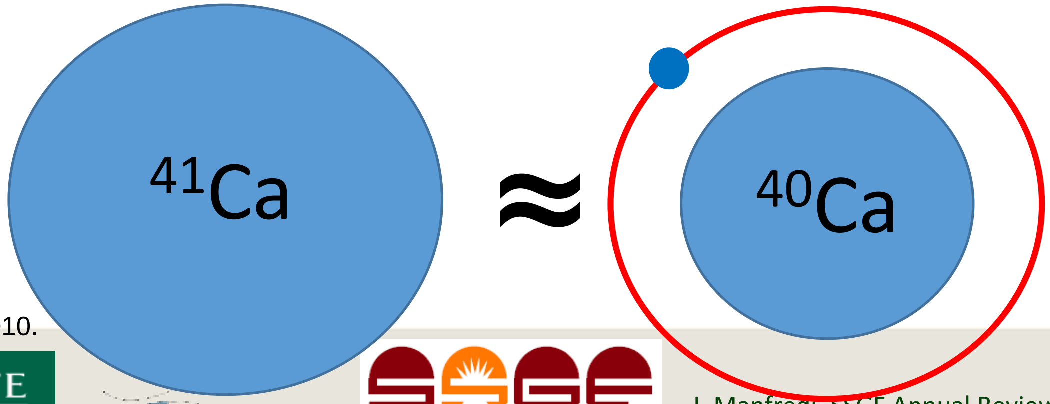
$$0 \leq SF \leq 2j + 1$$

Less single-particle like (strong influence of nucleon-nucleon correlations)

More single-particle like (mean field is a good approximation)

- Can be interpreted as **probability of finding core state N-1 within a composite state N when removing a nucleon in state p**

- Example: $SF(f_{7/2}\,,\ ^{41}Ca\ g.s.) = 1.01 \pm 0.06$

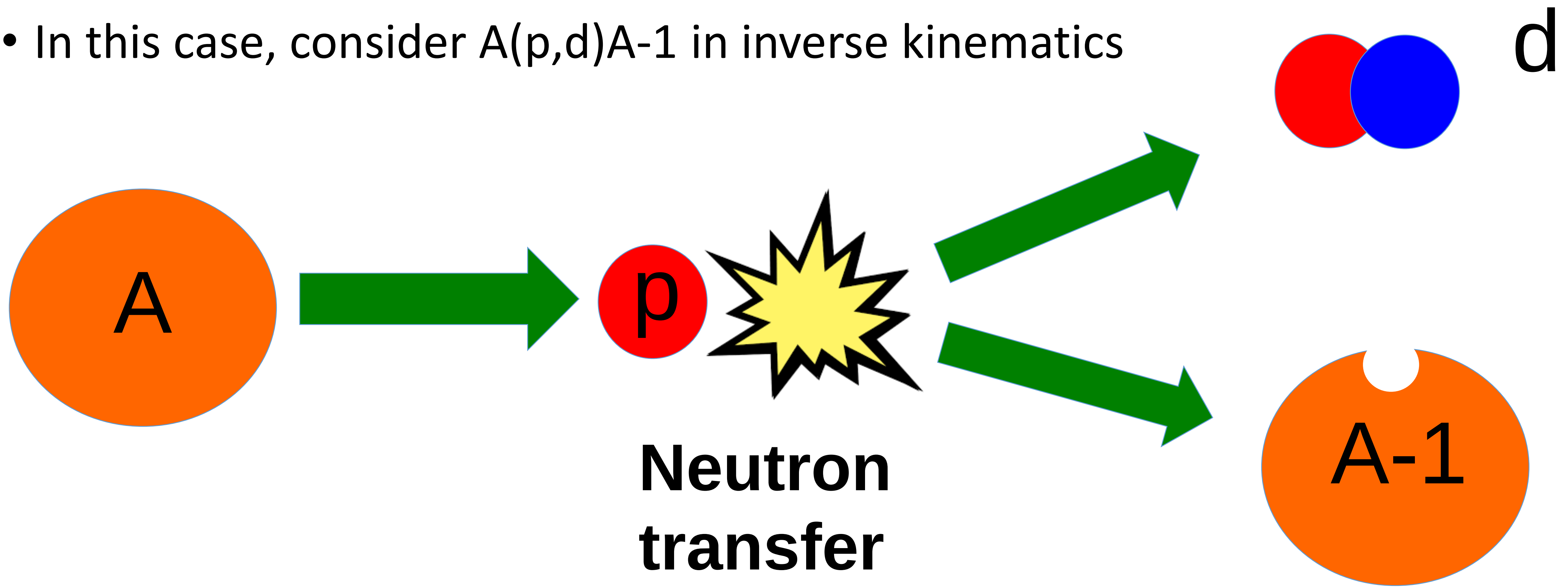


Lee, PhD Thesis, Michigan State University 2010.

Nuclear reactions can be used to extract *SF*'s

For example, consider a **transfer reaction**

- Nucleon(s) transferred to/from a projectile from/to a target
- In this case, consider A(p,d)A-1 in inverse kinematics

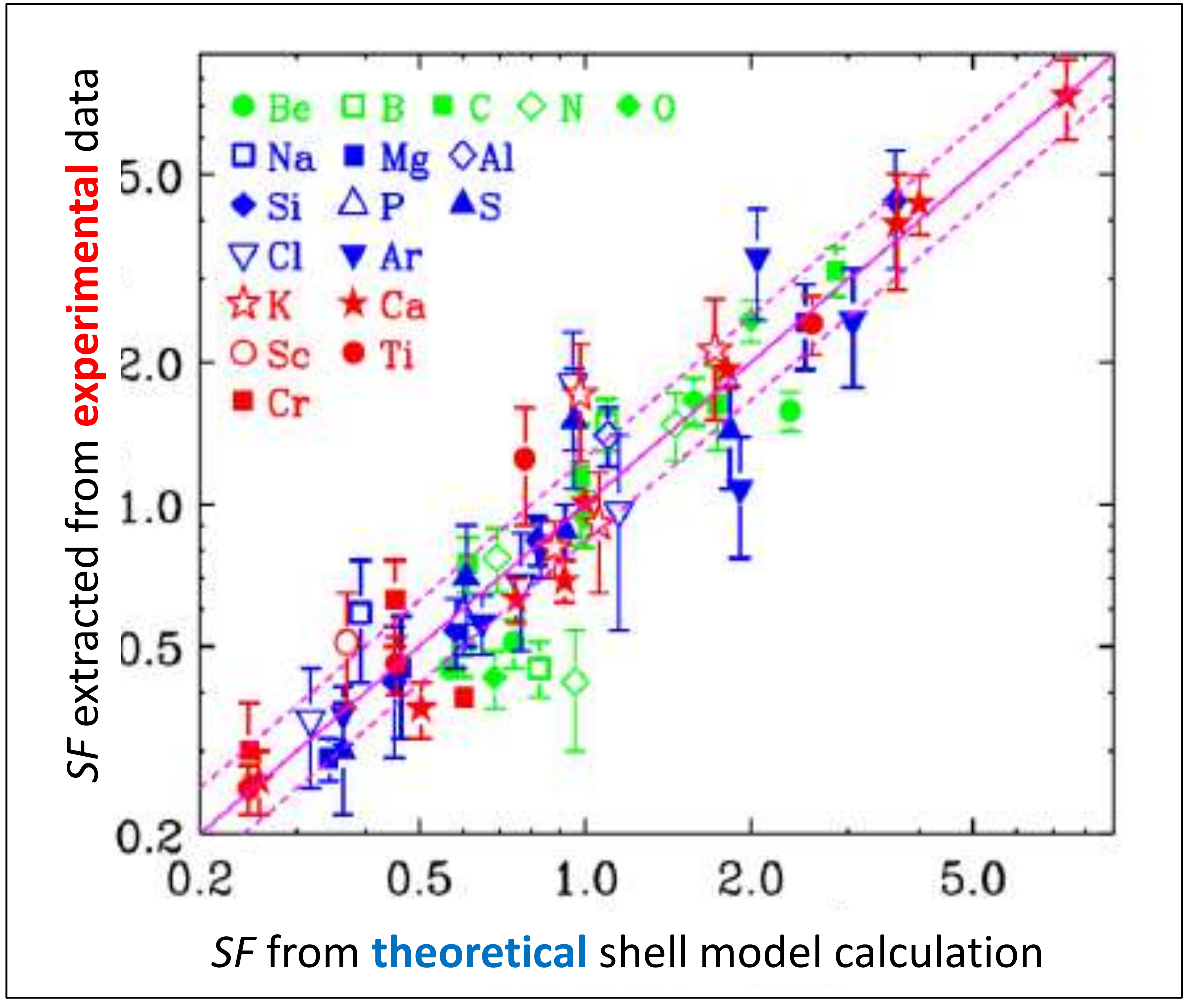


Lee, PhD Thesis, Michigan State University 2010.

J. P. Schiffer et al., Phys. Rev. 164, 1274 (1967).

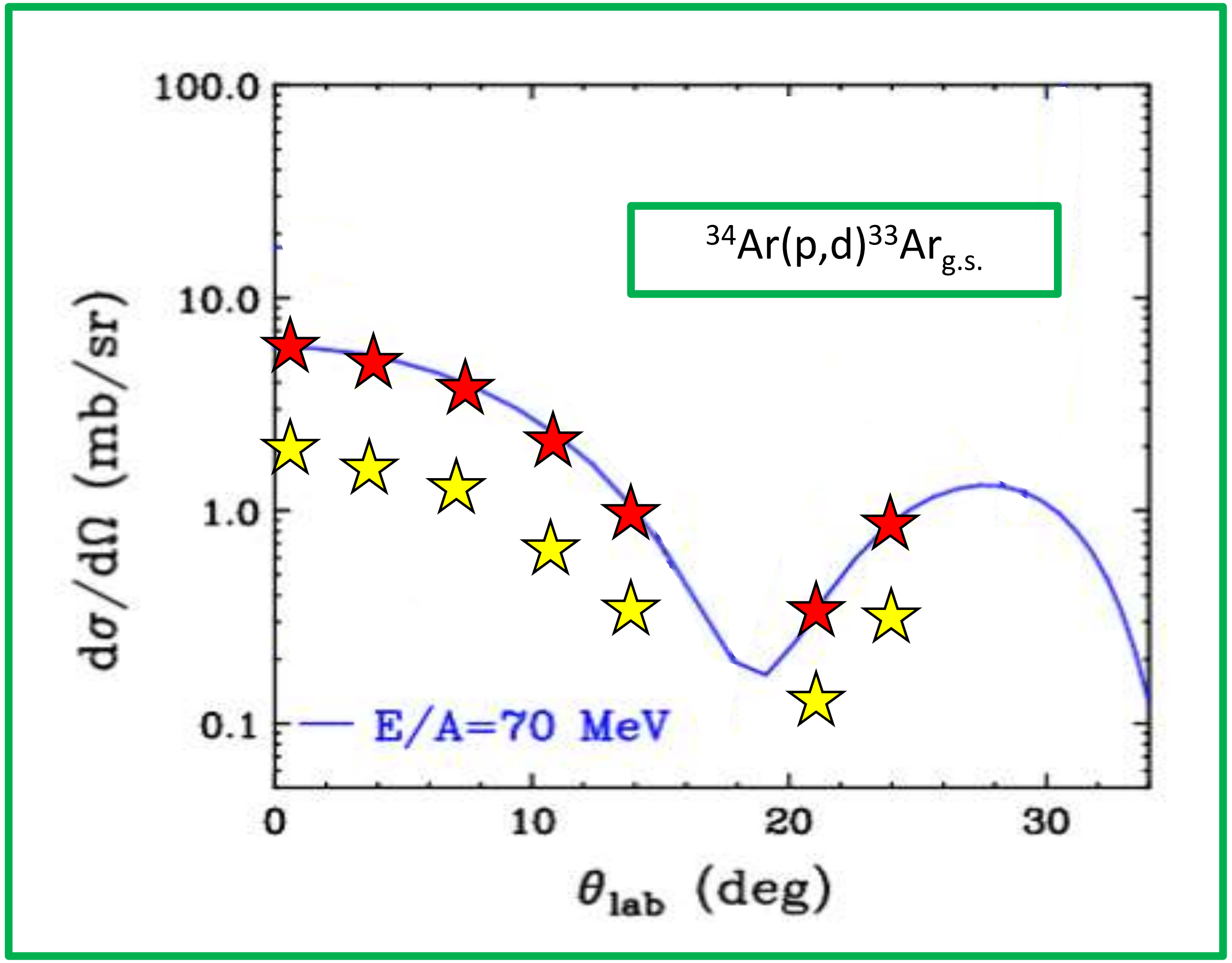
Transfer Reactions To Study Nuclear Structure

- SF's are NOT observables…but can be *extracted* from experimental data via comparison to theory
- Transfer reactions have been successfully used to extract SF's for decades
  - Advent of radioactive ion beams opens up new sections of nuclear chart for exploration



Extracting SFs

- Calculations tell us shape of angular distribution for transfer reaction to a given state with SF = 1

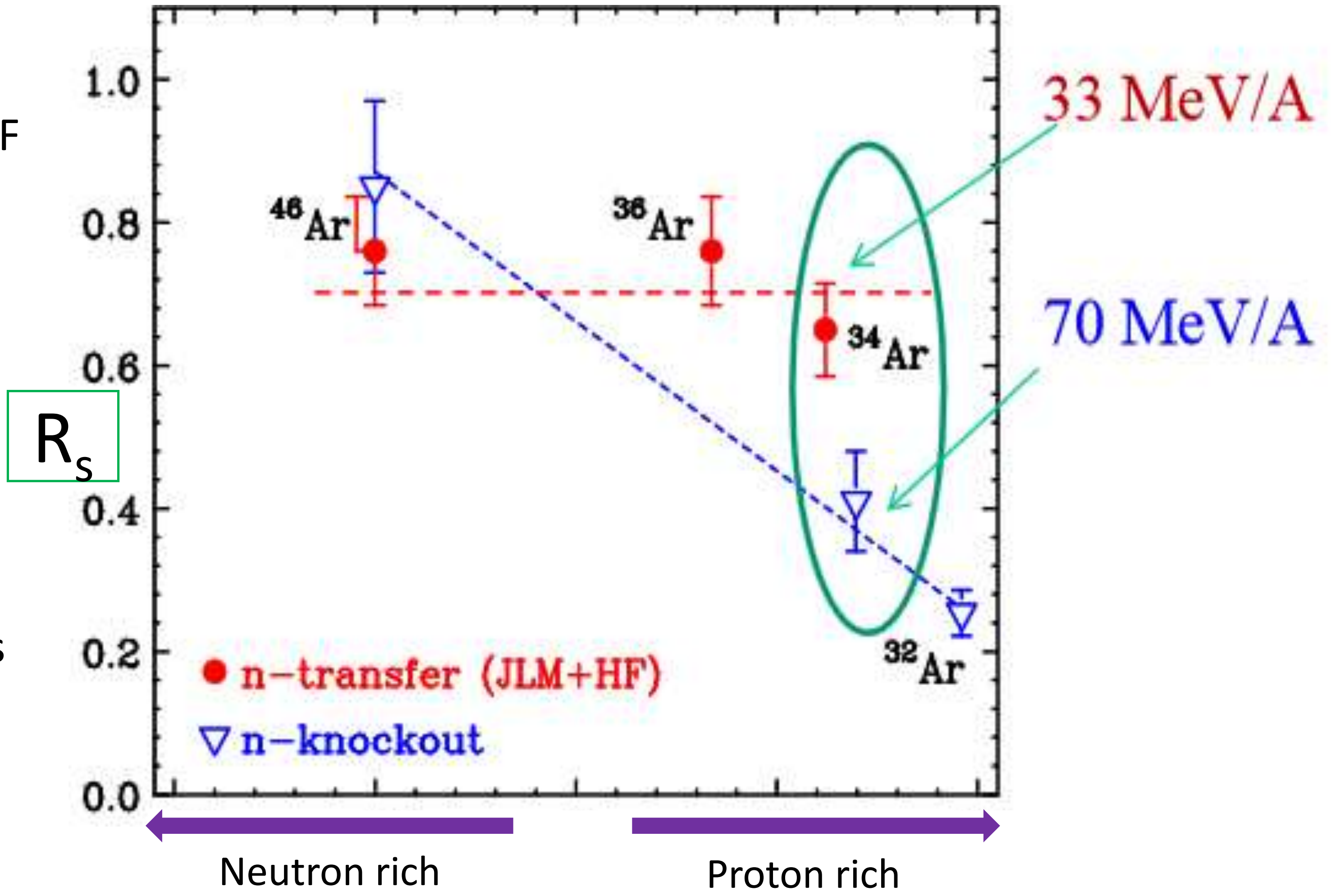


Transfer vs. Knockout

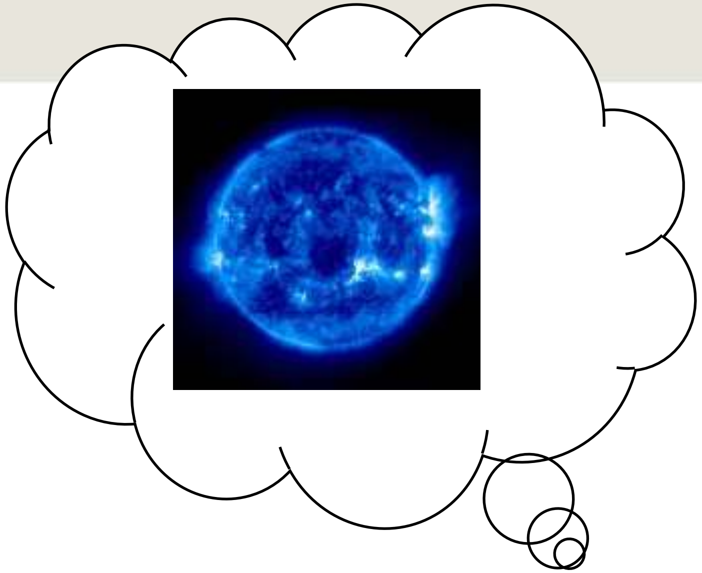
- Different reaction probes of SF *should* be consistent (nuclear structure is invariant)
- **Reduction factor**: compares experimental SF with shell model prediction

$$R_s = \frac{SF_{EXP}}{SF_{SM}}$$

- Energy dependence of optical potential? Reaction mechanism energy dependent? Techniques/approximations unreliable at extremes of asymmetry, beam energy, cross section? Many body effects?



Lee, PhD Thesis, Michigan State University 2010. Jensen, Phys. Rev. Lett. 107, 032501 2011.Gade, Phys. Rev. C 77, 044306 2008.



?

Transfer vs. Knockout

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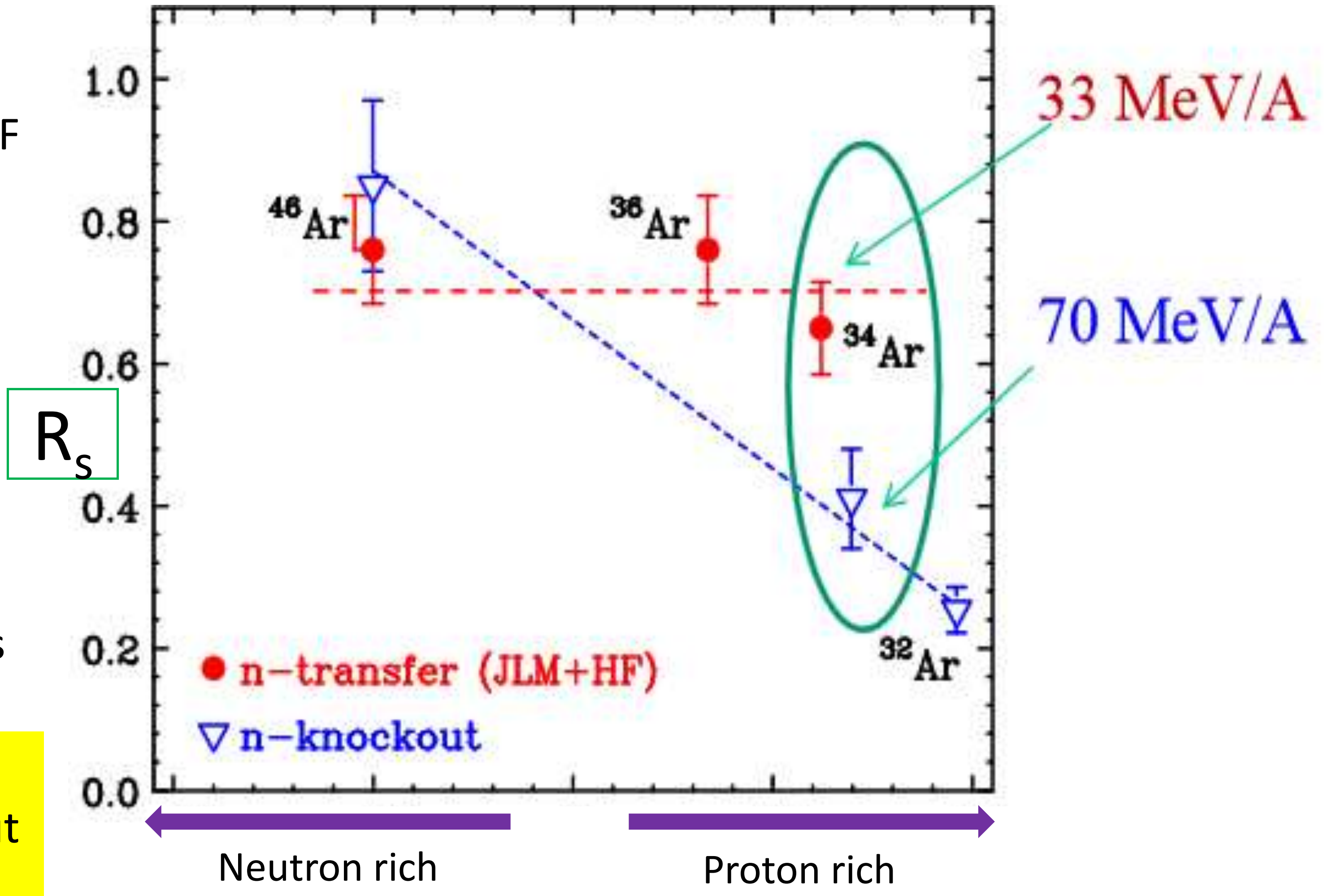
- **Reduction factor**: compares experimental SF with shell model prediction

$$R_s = \frac{SF_{EXP}}{SF_{SM}}$$

- Energy dependence of optical potential? Reaction mechanism energy dependent? Techniques/approximations unreliable at extremes of asymmetry, beam energy, cross section? Many body effects?
- Repeat transfer measurement, but matching the beam energy for the knockout measurement



Lee, PhD Thesis, Michigan State University 2010. Jensen, Phys. Rev. Lett. 107, 032501 2011.Gade, Phys. Rev. C 77, 044306 2008.

National Superconducting Cyclotron Laboratory (NSCL)

- Coupled Cyclotron Facility at the NSCL (on the campus of Michigan State University)
  - K500 and K1200 cyclotrons accelerate stable isotopes (from ^{16}O to ^{238}U) up to half the speed of light
  - Smash stable beam into Be target: fragmentation produces a wide variety of nuclei, some of which are exotic
  - A1900 Fragment Separator selects particular isotopes of interest, which are delivered to experimental areas

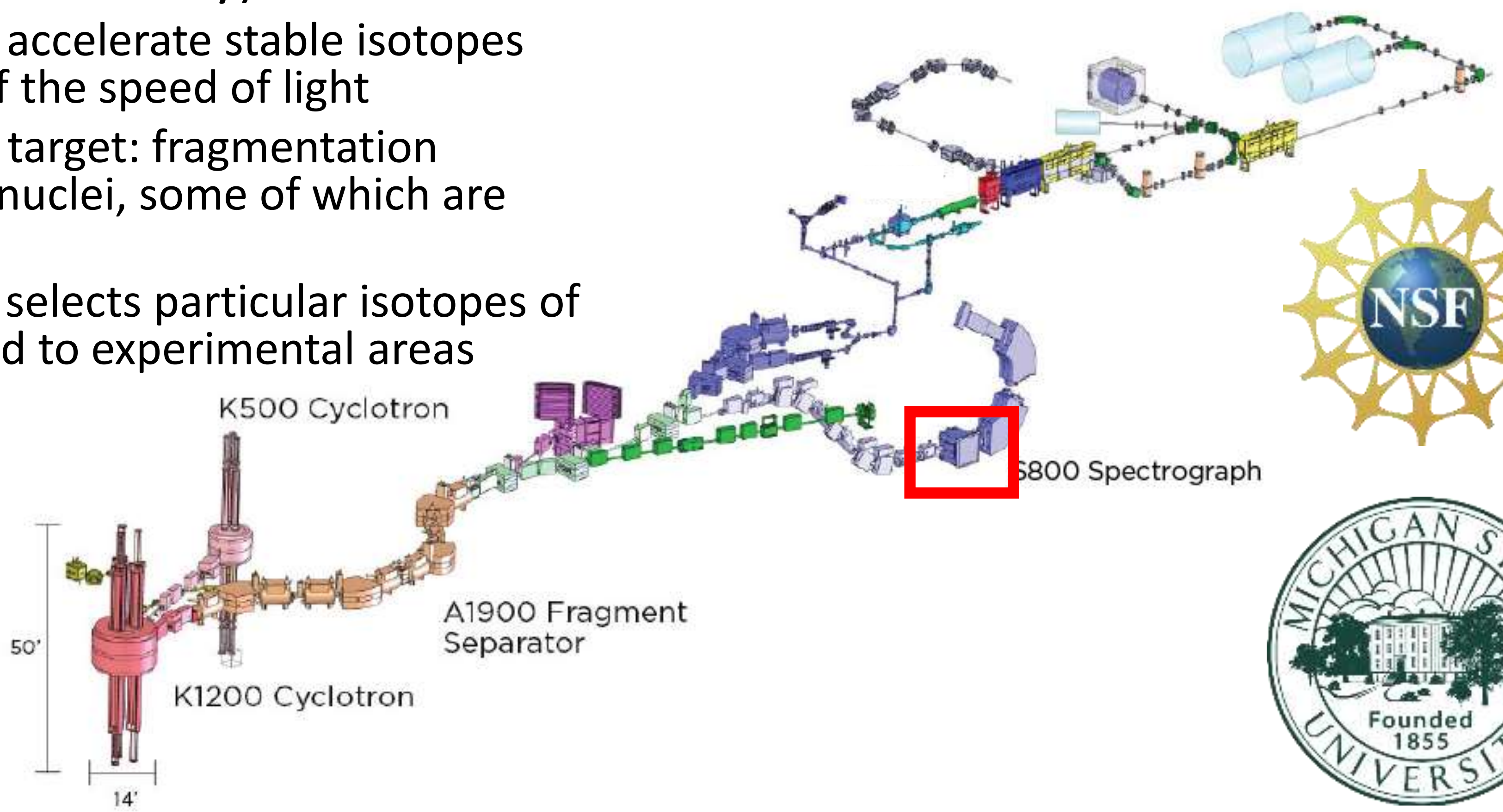
For this experiment

Primary beams:

^{36}Ar, ^{48}Ca

Secondary beams:

^{34}Ar, ^{46}Ar

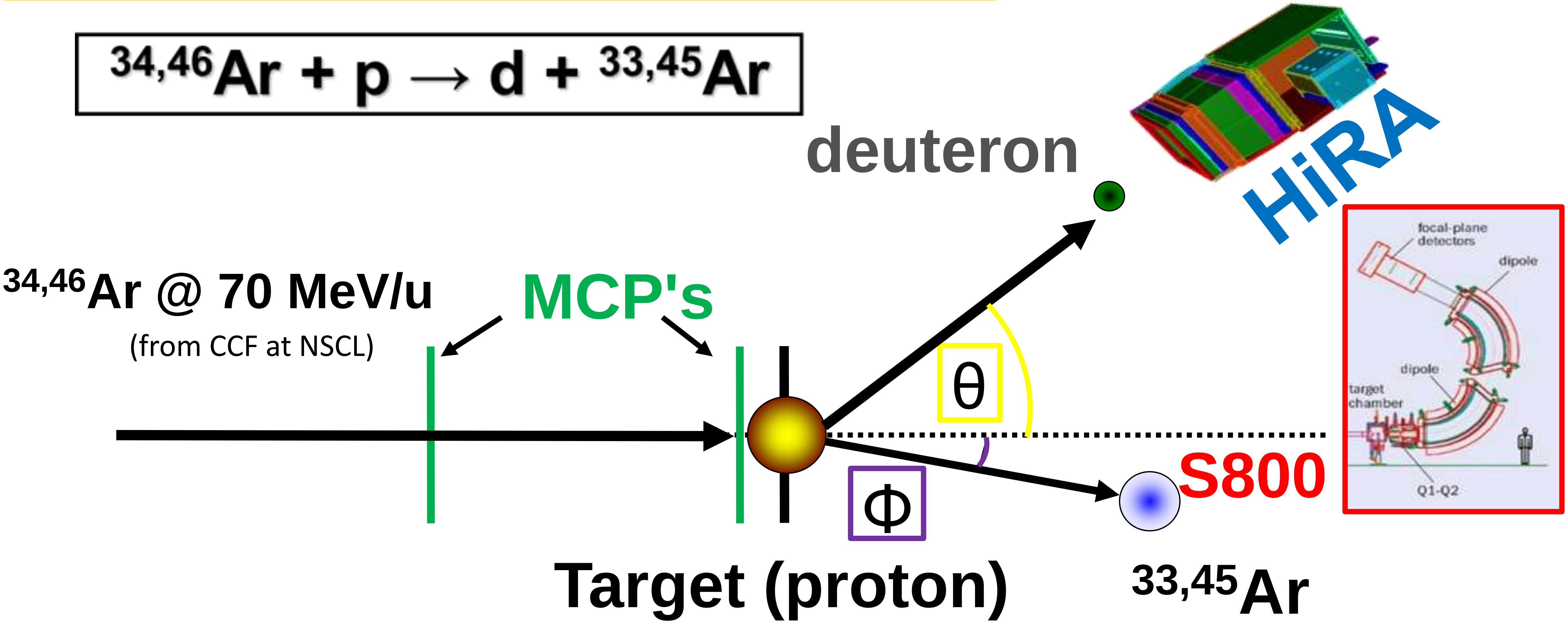


http://www.nscl.msu.edu/public/science/isotope.html

Experimental Setup

Measuring complete kinematics of ^{34,46}Ar(p,d) at 70 MeV/u

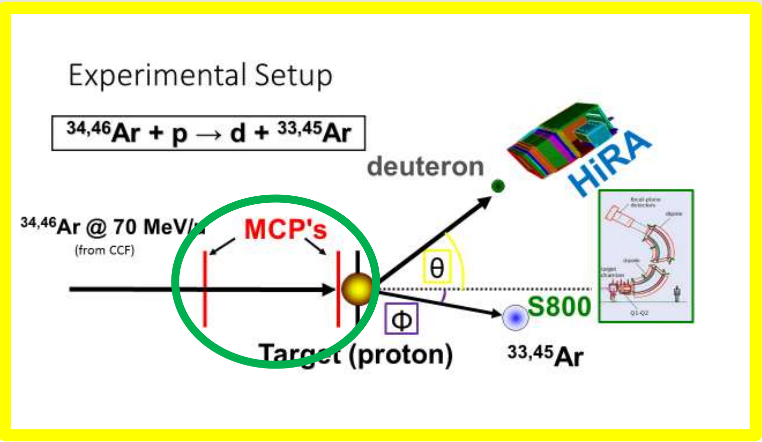
$$^{34,46}\mathrm{Ar} + p \rightarrow d + {}^{33,45}\mathrm{Ar}$$

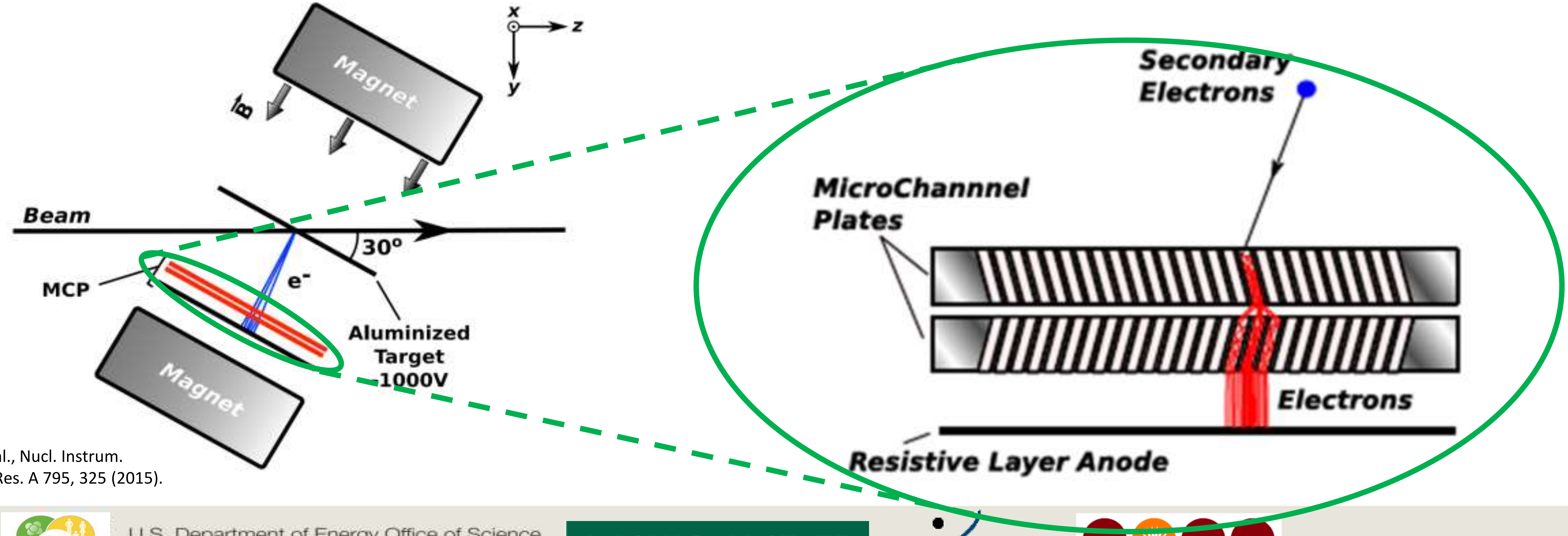


Based on figure courtesy of Jenny Lee

Microchannel plates: MCPs

- Needed to calculate absolute cross section
- Allows for reactions to be localized on target (i.e. better angular resolution)

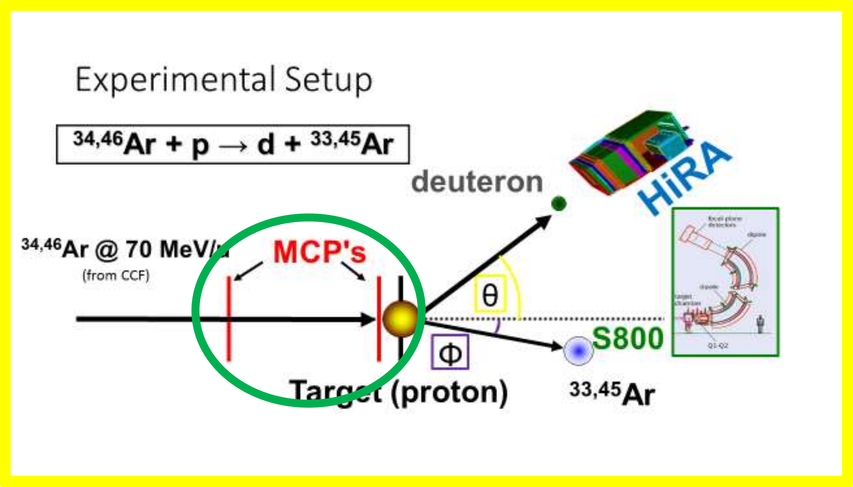


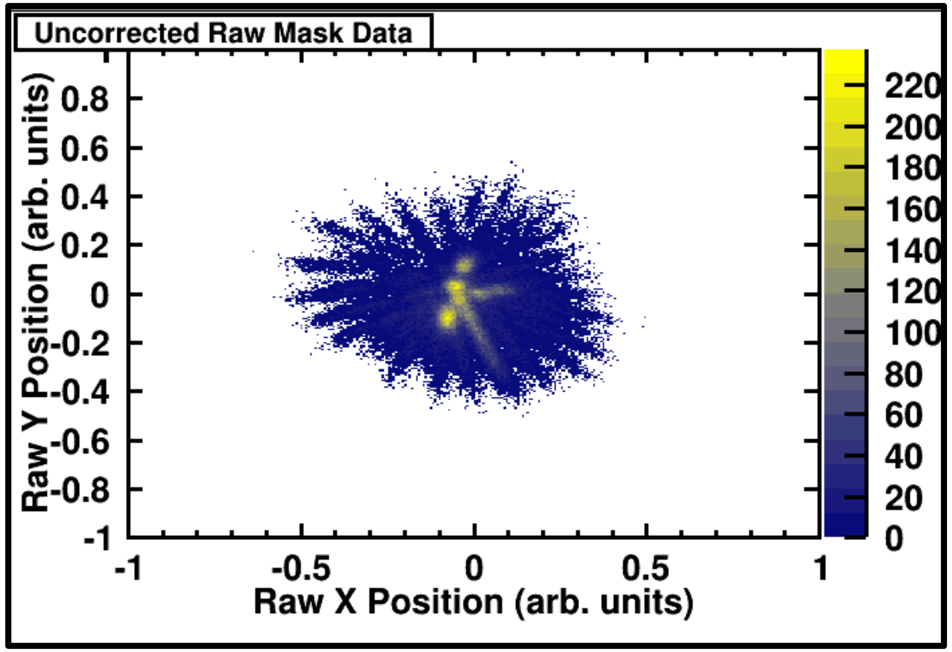


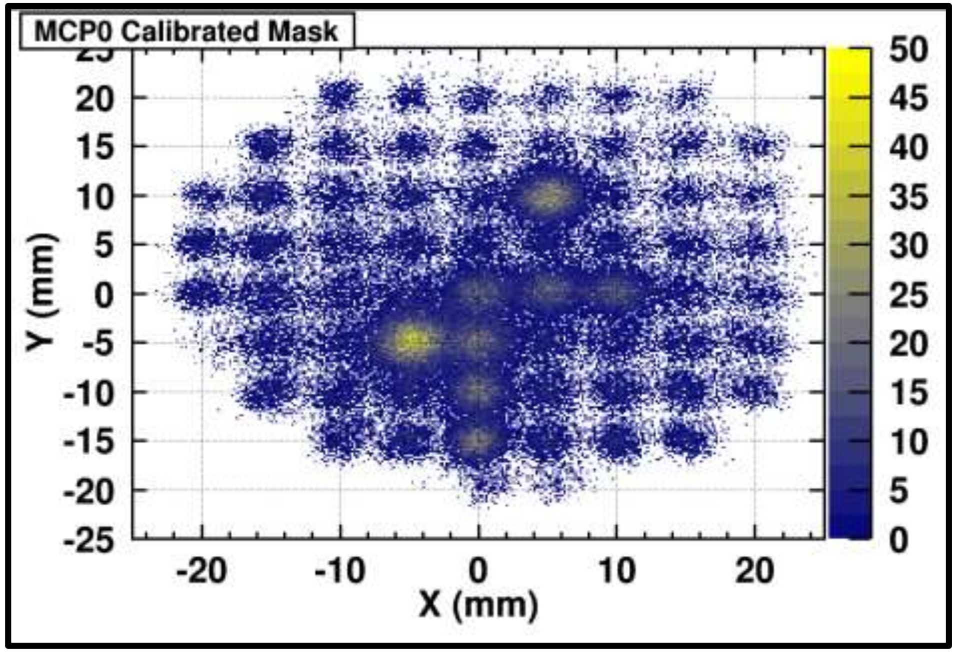
A.M. Rogers et al., Nucl. Instrum. Methods Phys. Res. A 795, 325 (2015).

Microchannel plates: MCPs

- MCPs are each calibrated using brass mask
- With calibrations, we can get beam position at each MCP, and therefore beam position at target

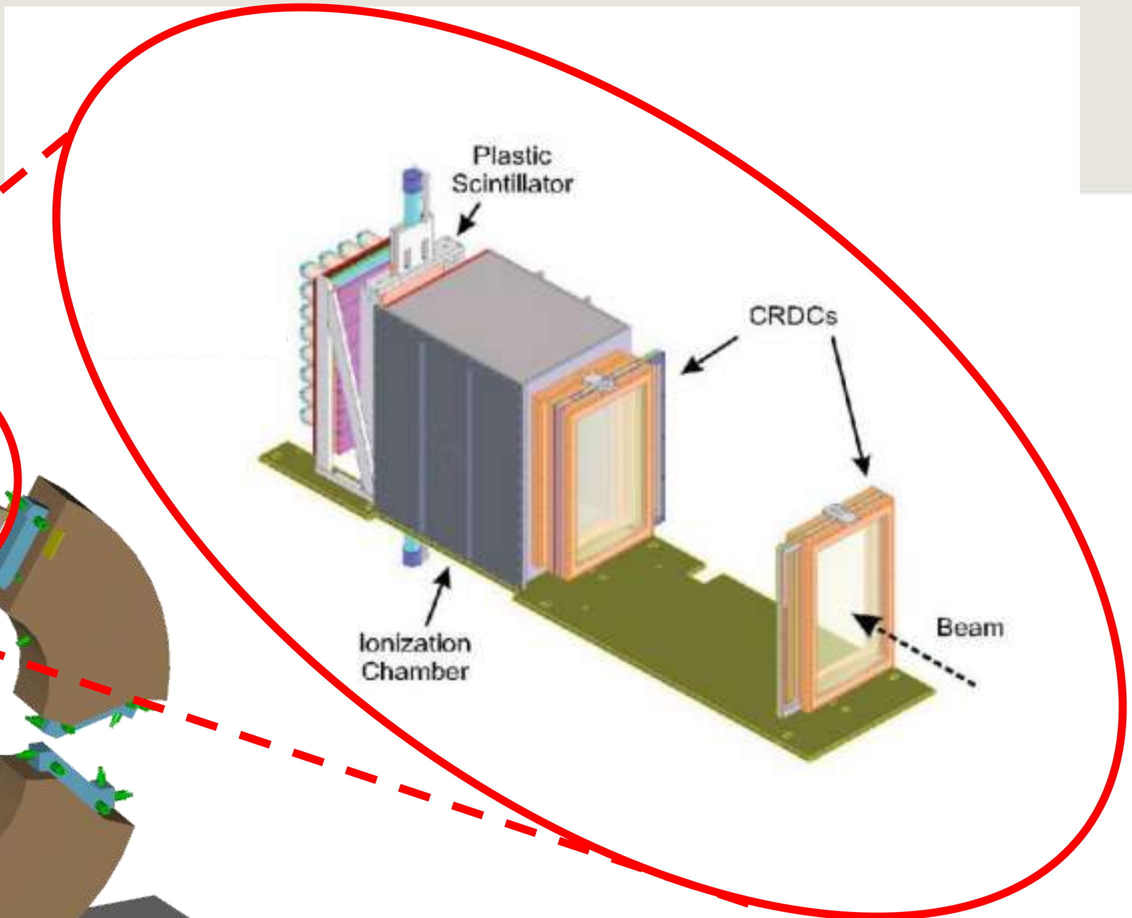


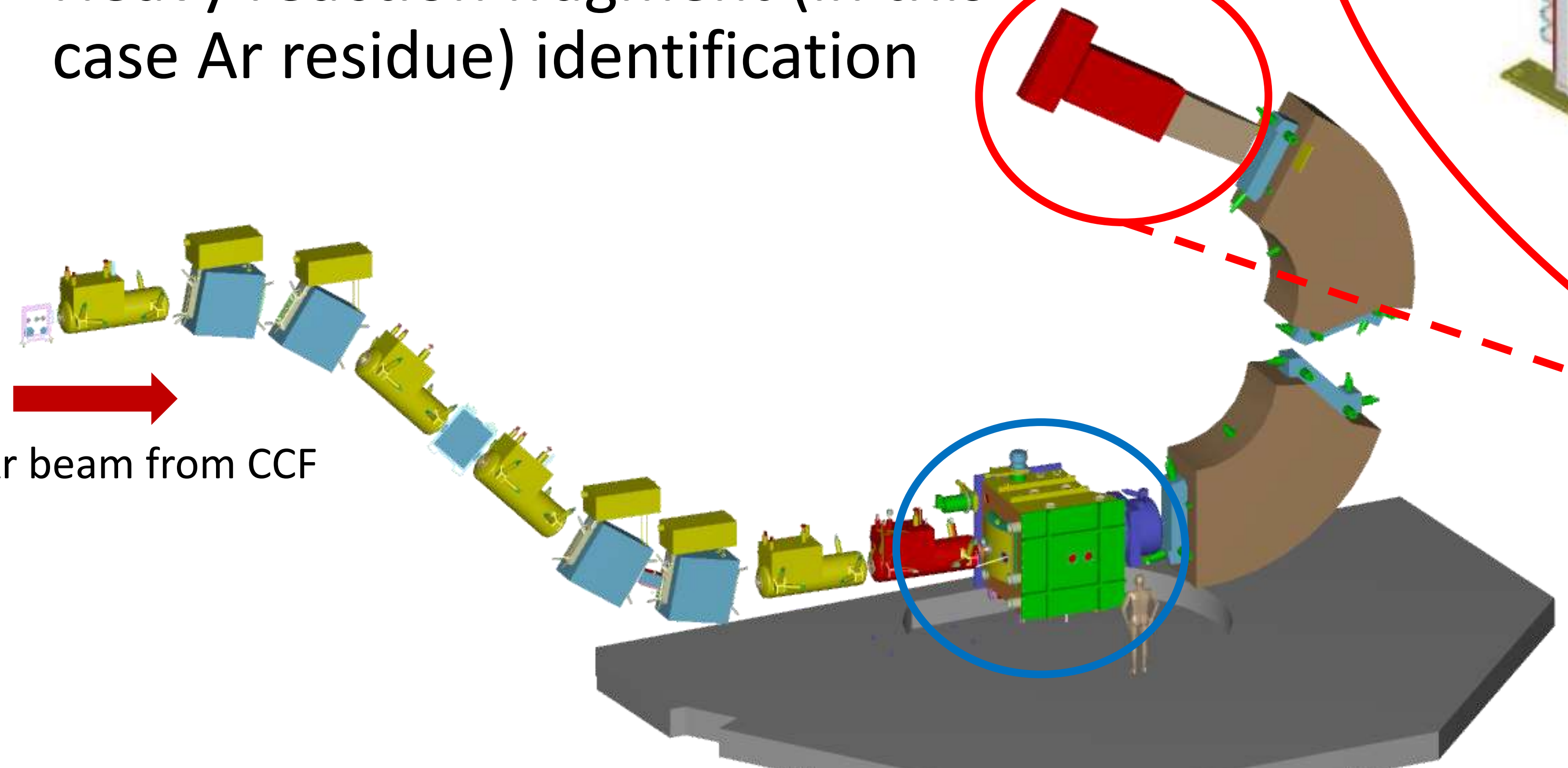


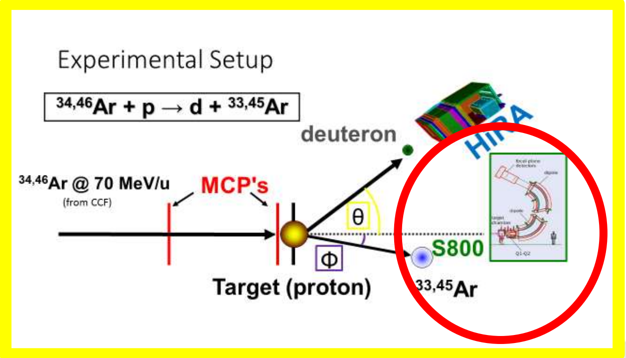


S800 Spectrometer

- TOF, ΔE, Φ, P
- Heavy reaction fragment (in this case Ar residue) identification



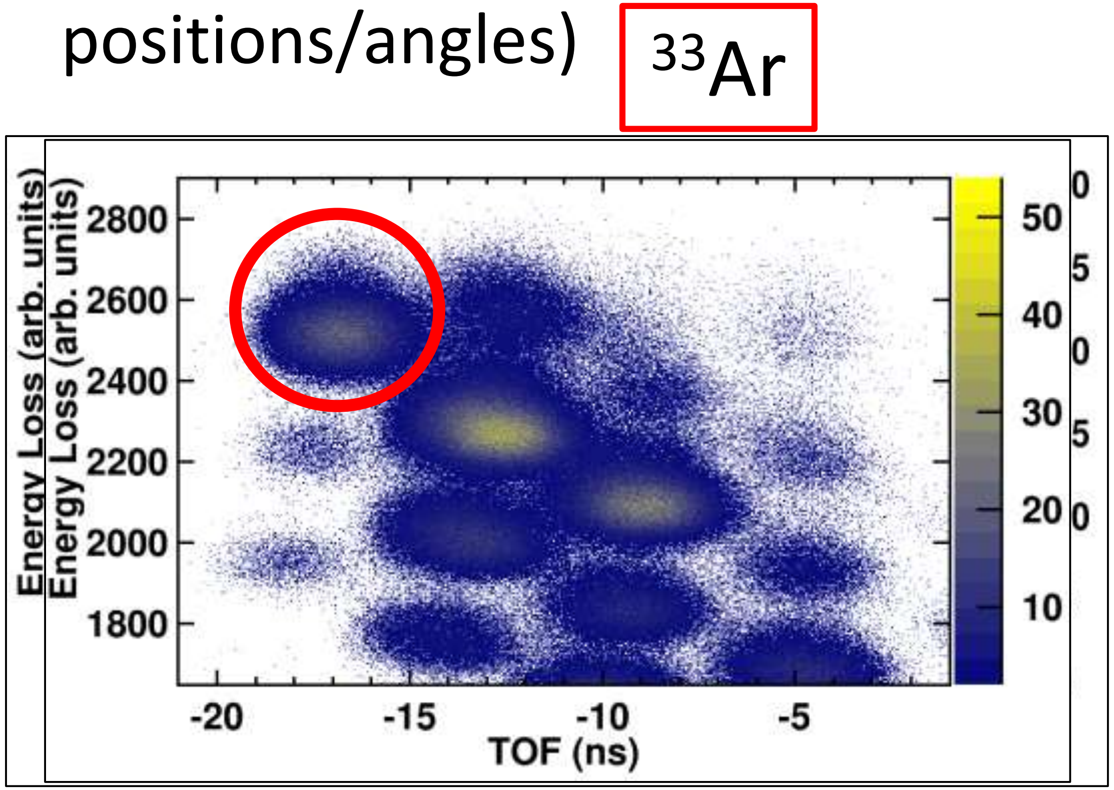


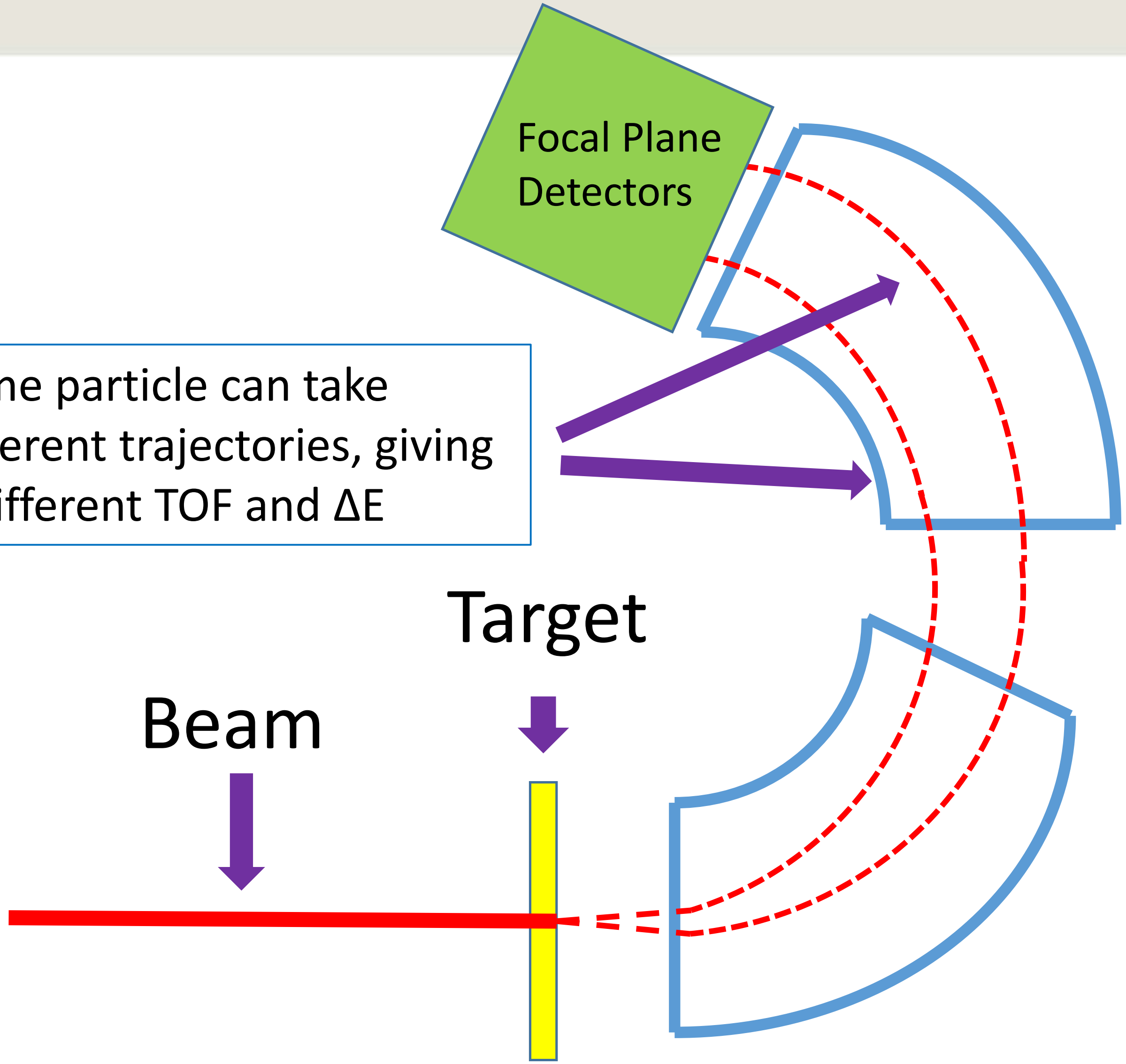


D. Bazin et al., Nucl. Instrum. Methods Phys. Res. B 204, 629 (2003).
J. Yurkon et al., Nucl. Instrum. Methods Phys. Res. A 422, 291 (1999).

S800 Spectrometer

- To calibrate, account for dependence of TOF and ΔE on focal plane coordinates (CRDC positions/angles)

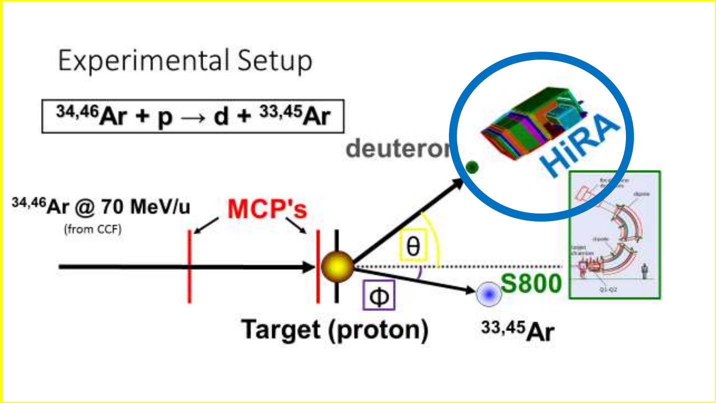


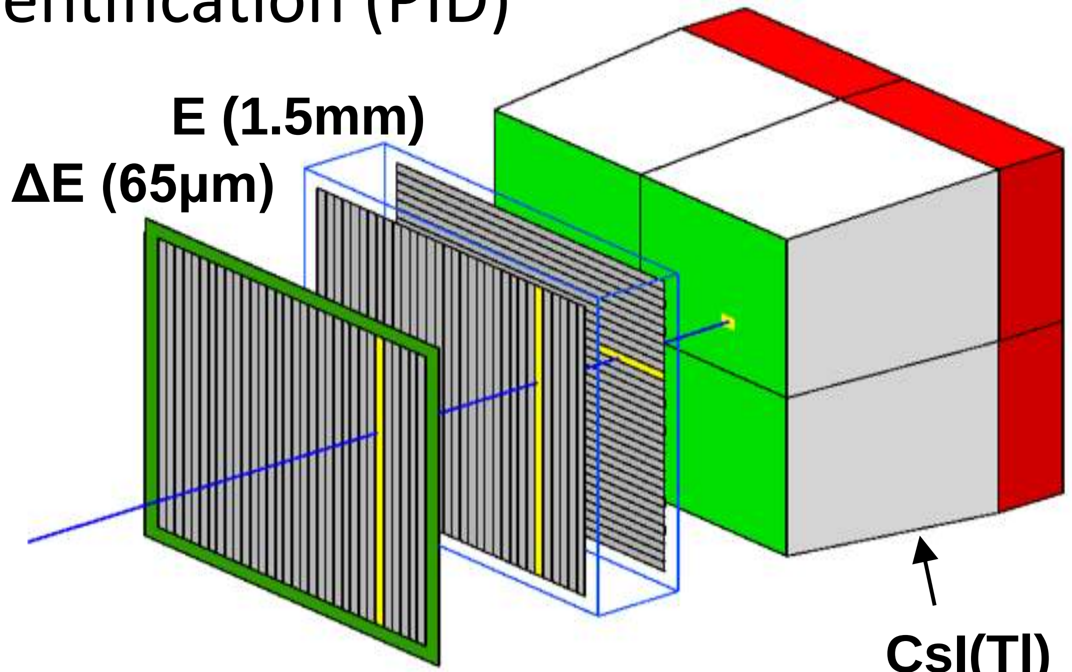


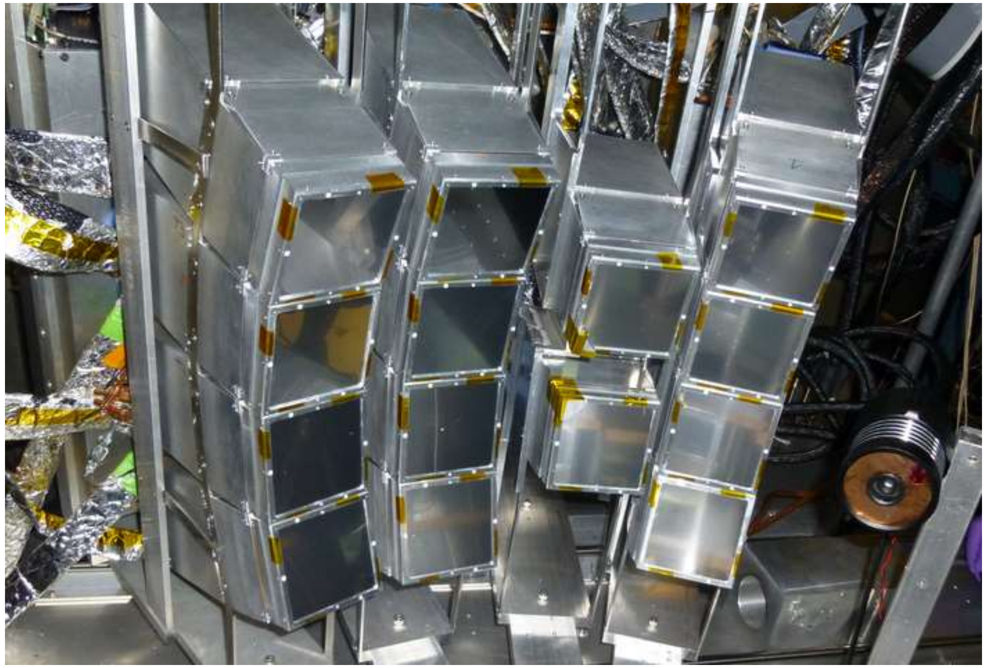
- Same particle can take different trajectories, giving a different TOF and ΔE

High Resolution Array: HiRA

- Modular array of Si + CsI charged particle detectors
- Measures energy, position information
- Energy loss in a "thin" detector vs. a "thick detector" yields particle identification (PID)

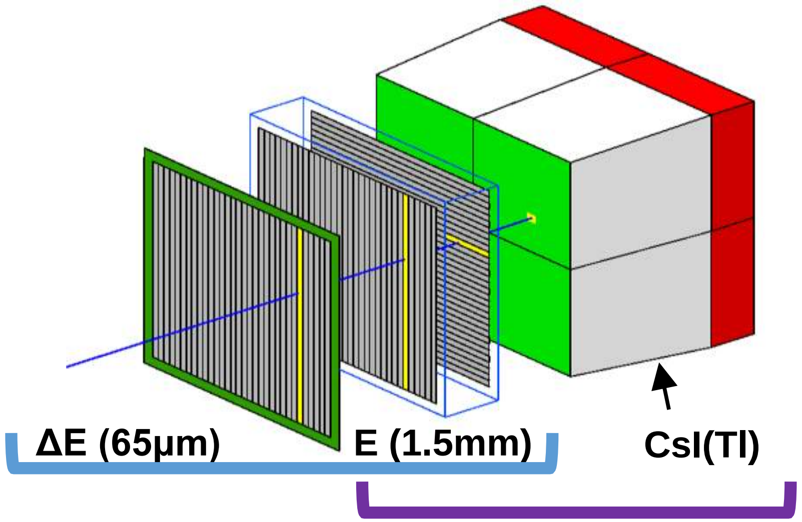


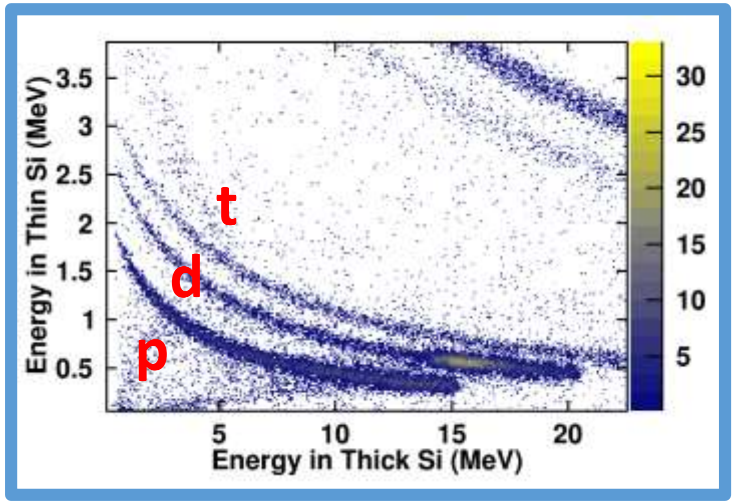


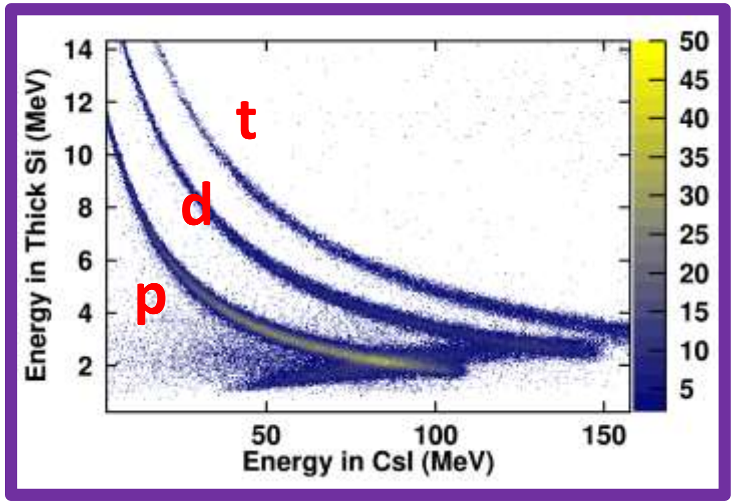


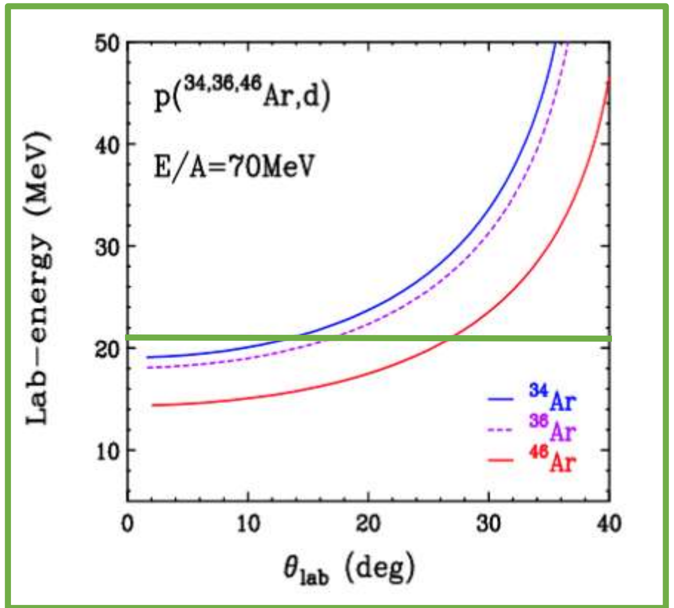
Wallace, et al., NIM A 583, 302-312, 2007.

High Resolution Array: HiRA





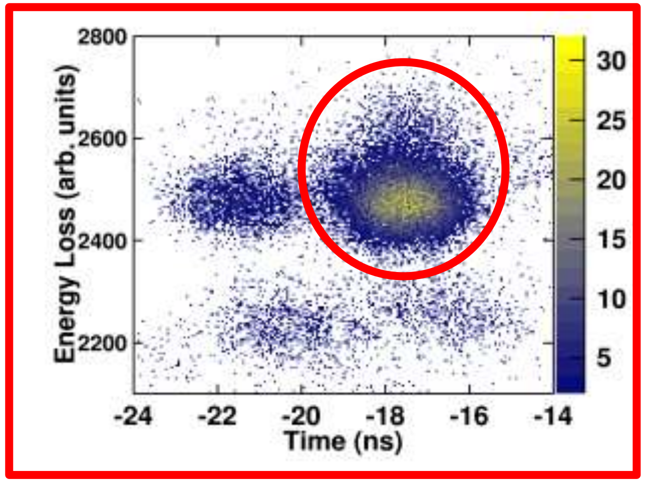




- Need two stages of PID (due to kinematics)

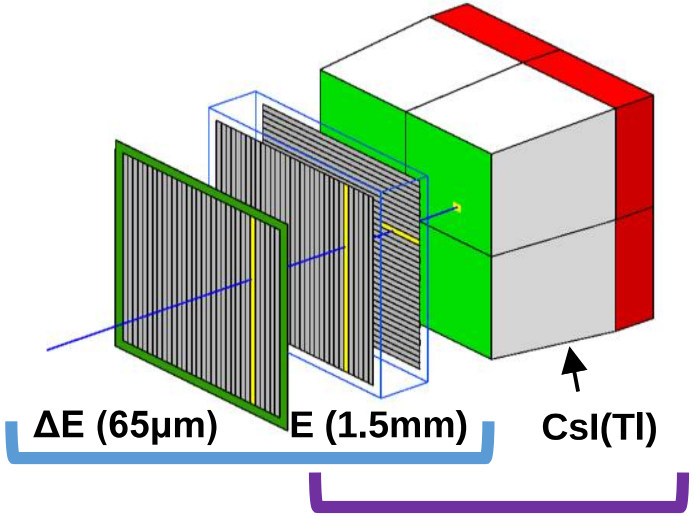
Wallace, et al., NIM A 583, 302-312, 2007.

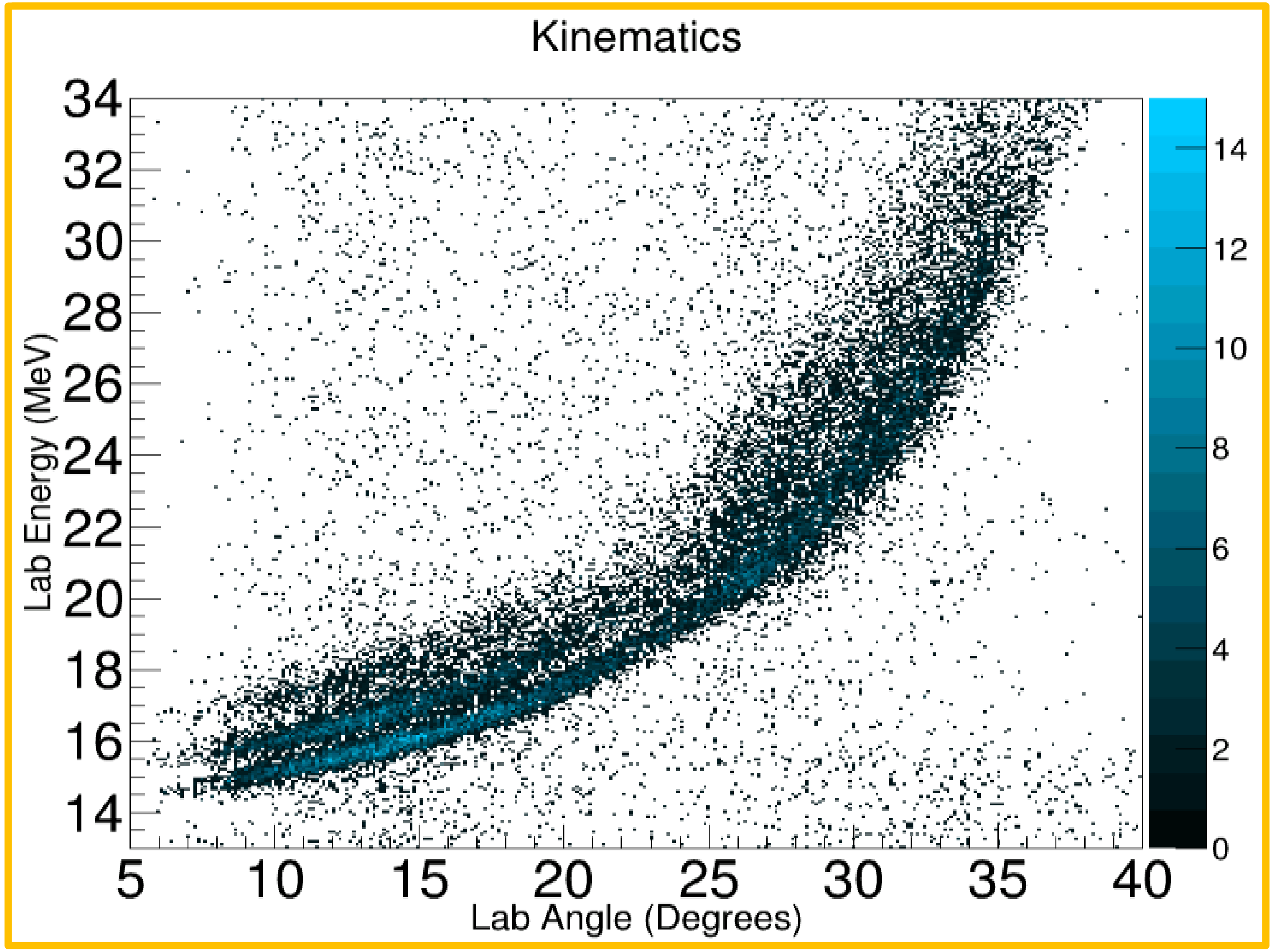
Kinematics for $^{46}Ar(p,d)^{45}Ar$ Gated on S800



^{45}Ar

d



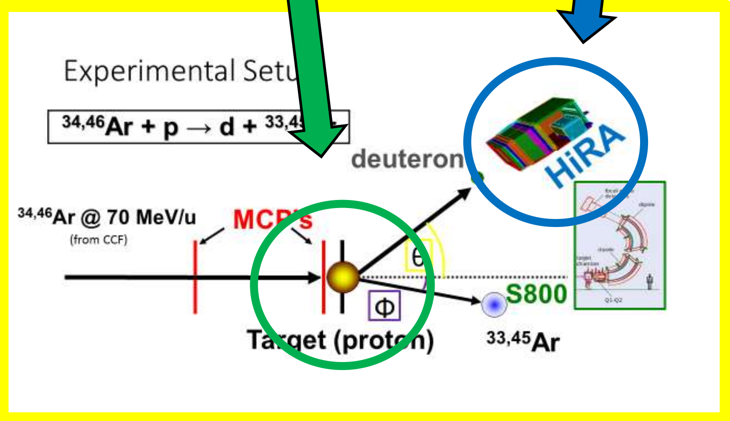


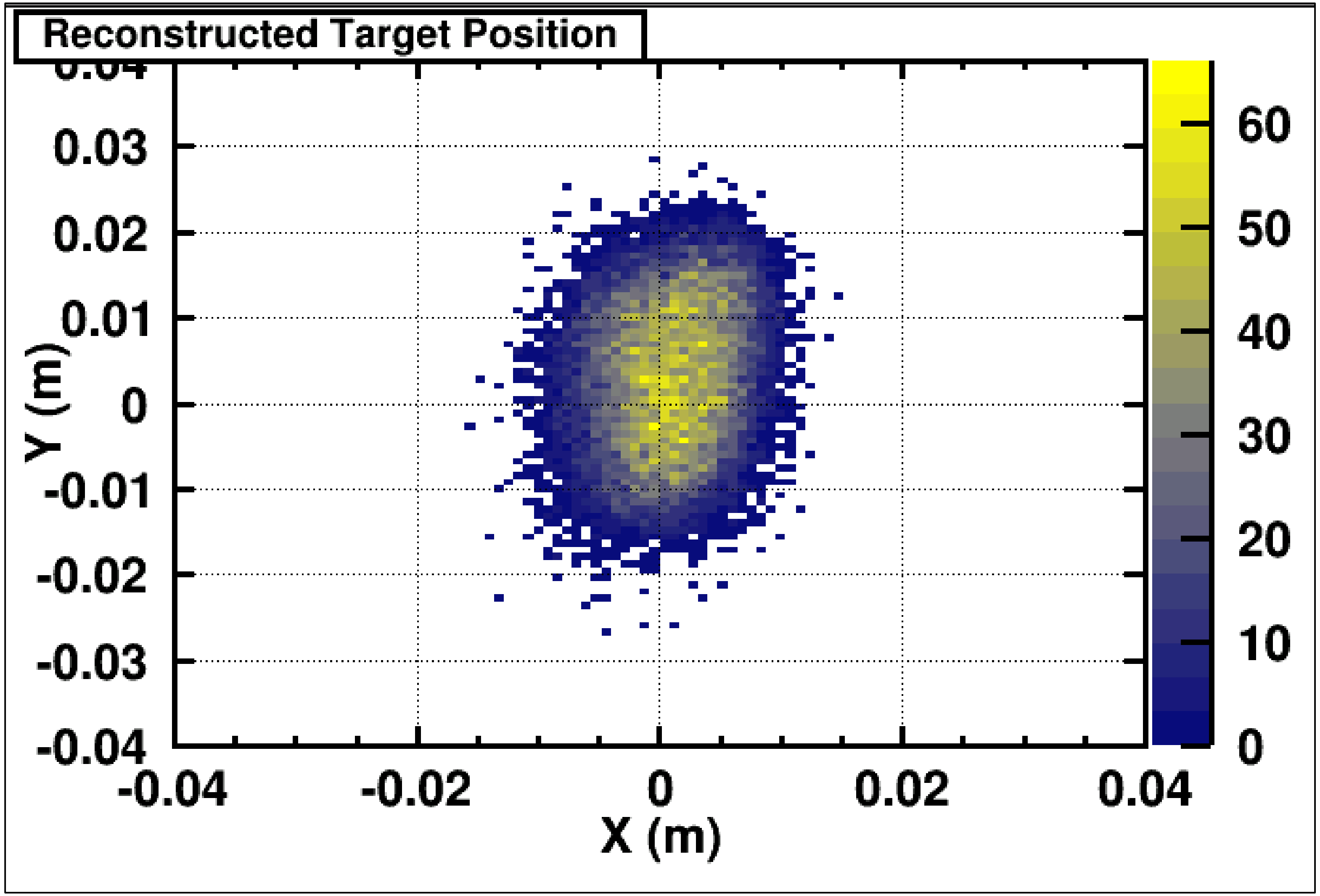
Beam Spot Reconstruction for $^{46}Ar(p,d)^{45}Ar$

- Beam spot large at target position

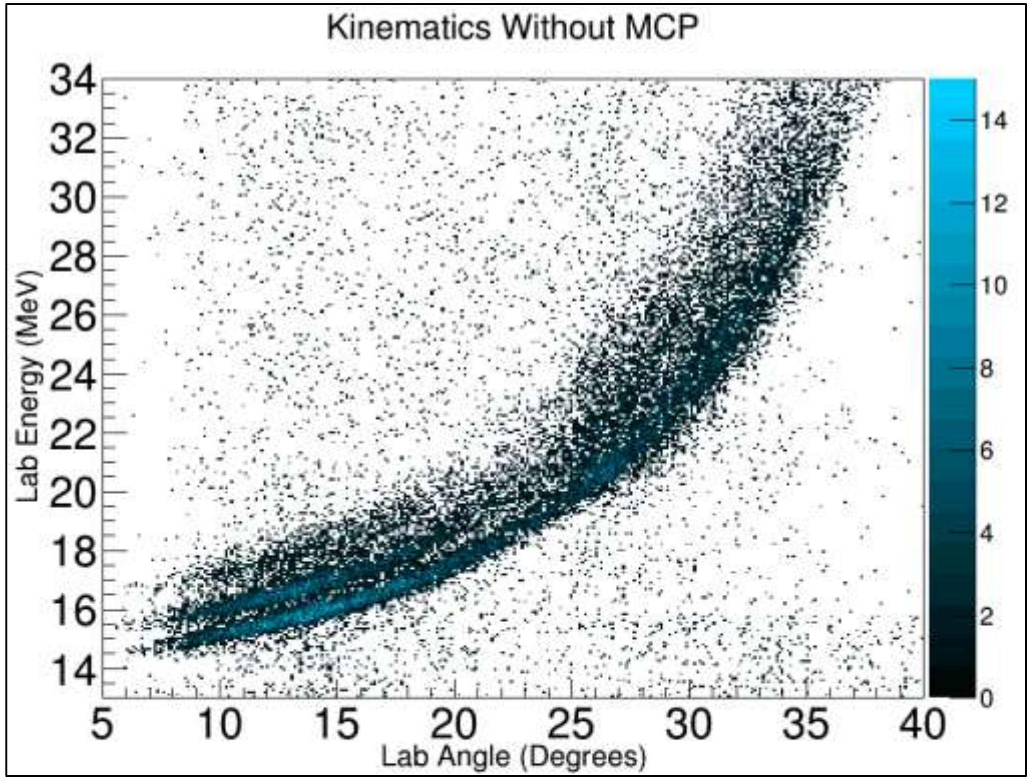
~300 mm^2 beam spot

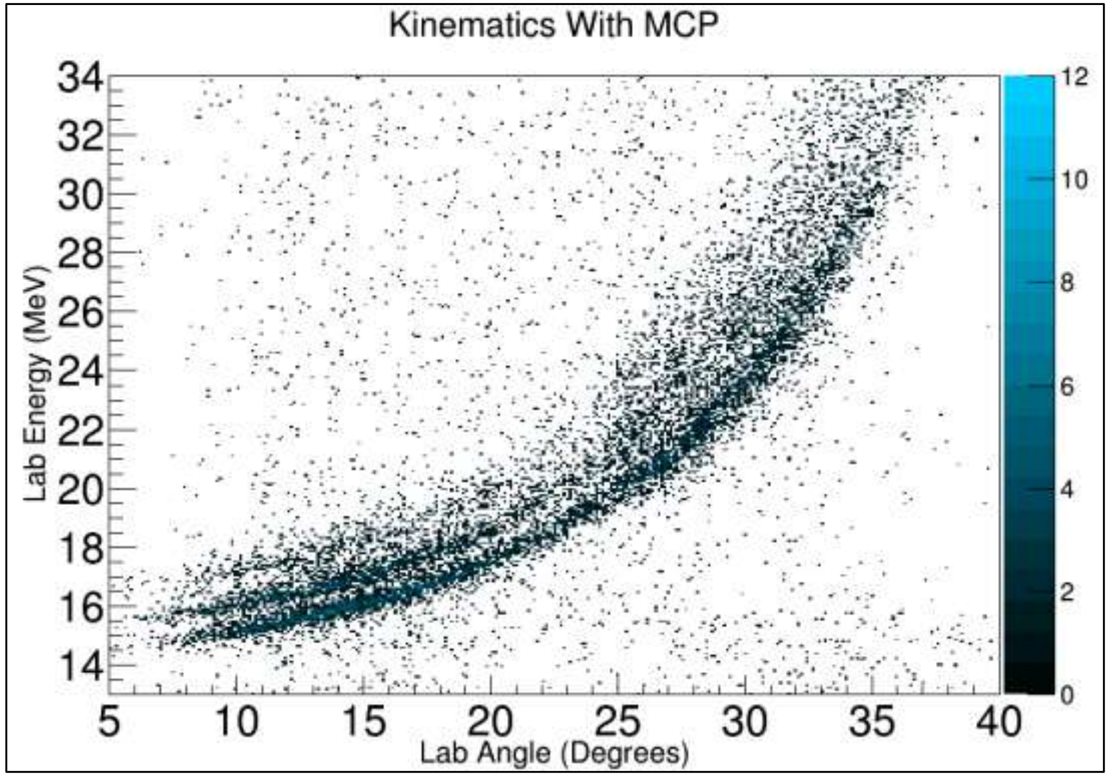
4 mm^2 per pixel





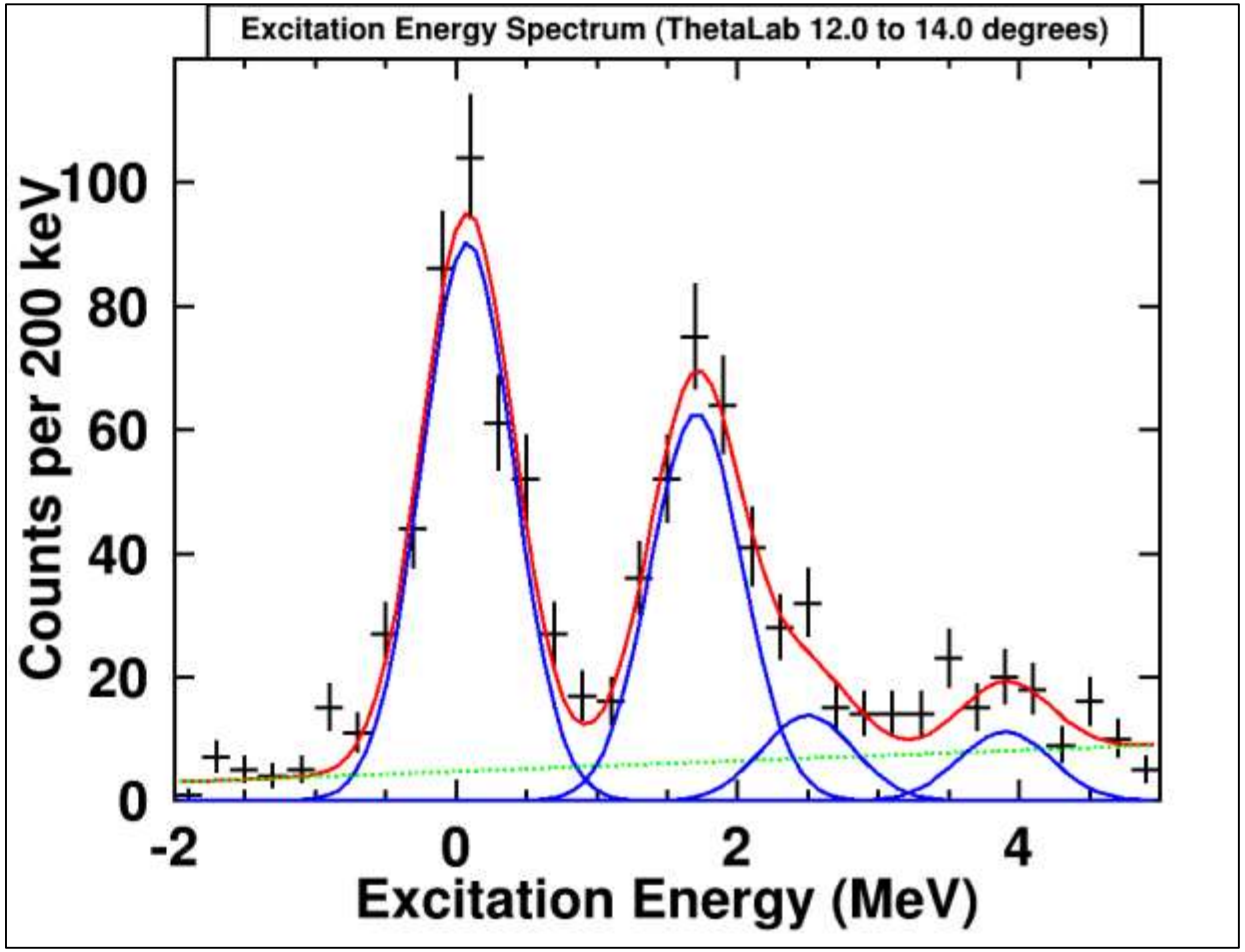
Kinematics Comparison





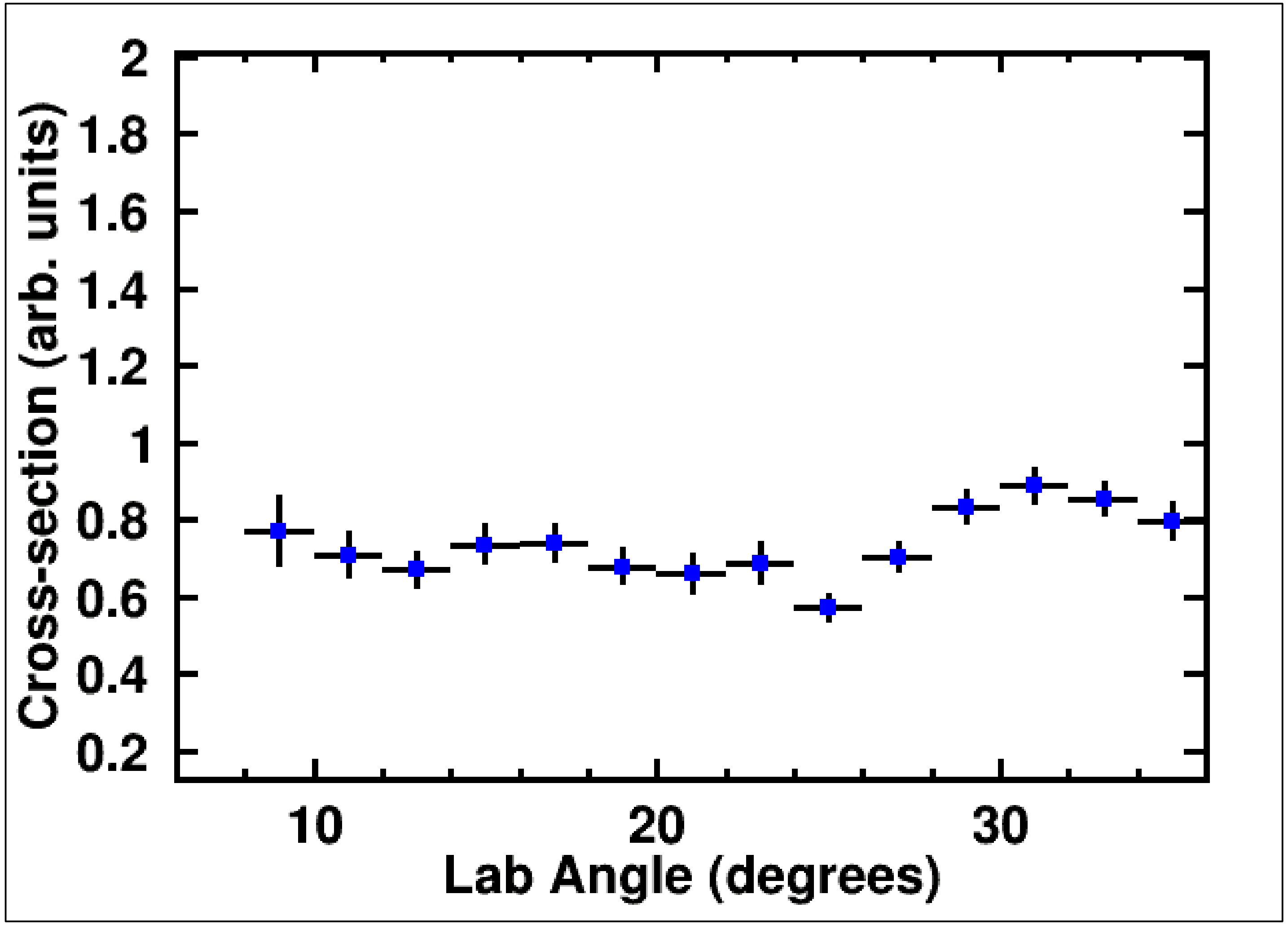
Example Excitation Energy Spectrum

- In the center-of-mass frame:
  - Deuteron energy
    - → Q-value
    - → Excitation Energy of ^{45}Ar
- Use the number of counts in a given angular range to get cross section



Example Angular Distribution

- Correct for geometrical efficiency
- $^{46}Ar(p,d)^{45}Ar_{g.s.}$



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Conclusions

- Spectroscopic factors are an important tool in studying nuclear structure
- Nuclear reactions can be used to probe nuclear structure via extraction of spectroscopic factors
  - Discrepancy between transfer and knockout reactions
- High energy transfer reactions on proton-rich (^{34}Ar) and neutron-rich (^{46}Ar) argon isotopes were measured at the NSCL
- Next step: perform theoretical calculations, compare to data, and extract spectroscopic factors

Acknowledgements

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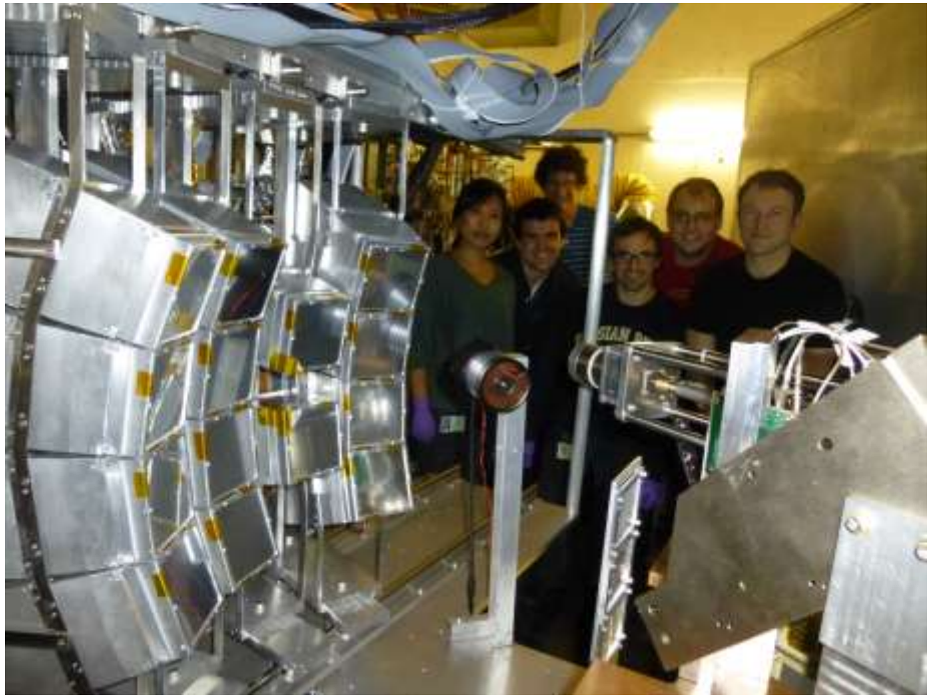

NSCL

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Backup Slides

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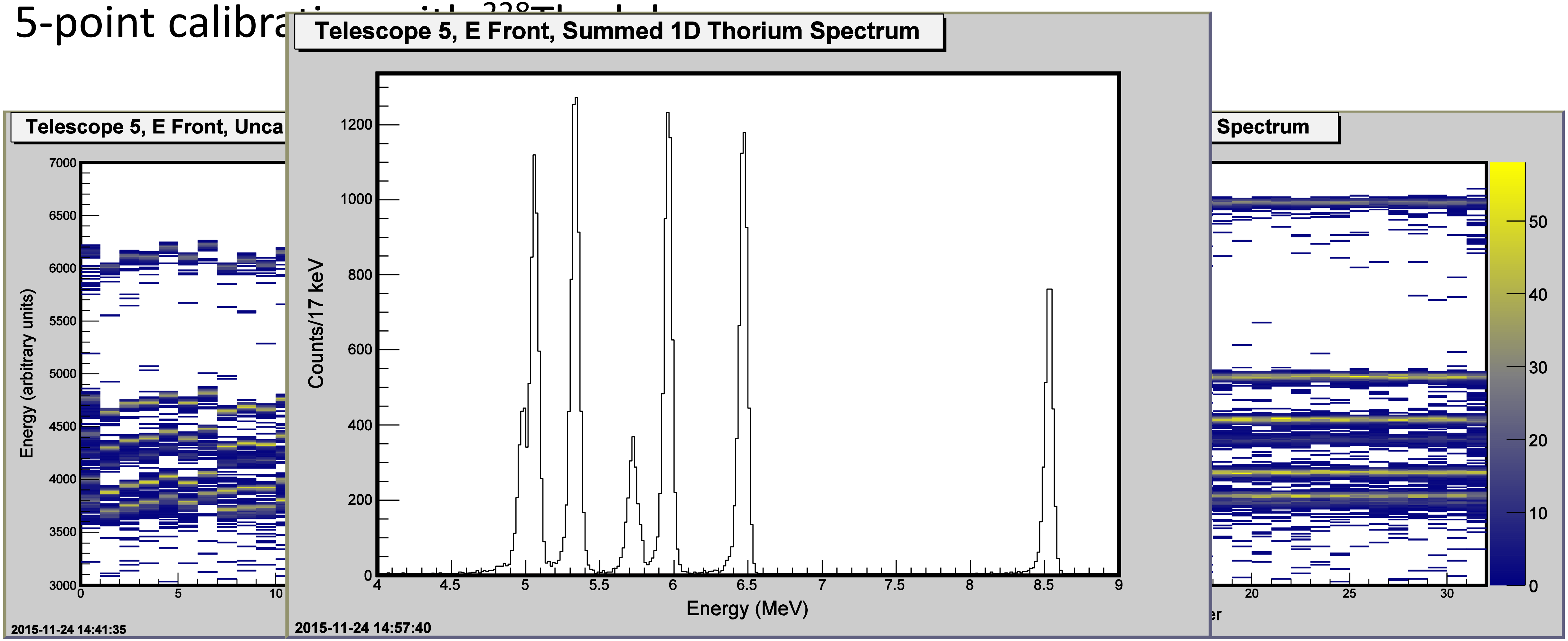
Analysis Progress: HiRA Si Calibration

- 5-point calibra



HiRA Efficiency

Bethe Bloch Equation

$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

$$\beta\gamma = \frac{p}{E}\frac{E}{m} = \frac{p}{m}$$

A : atomic mass of absorber

$\frac{K}{A} = 4\pi N_A r_e^2 m_e c^2 / A = 0.307075 \text{ MeV g}^{-1}\text{cm}^2, \text{ for A} = 1\text{g mol}^{-1}$

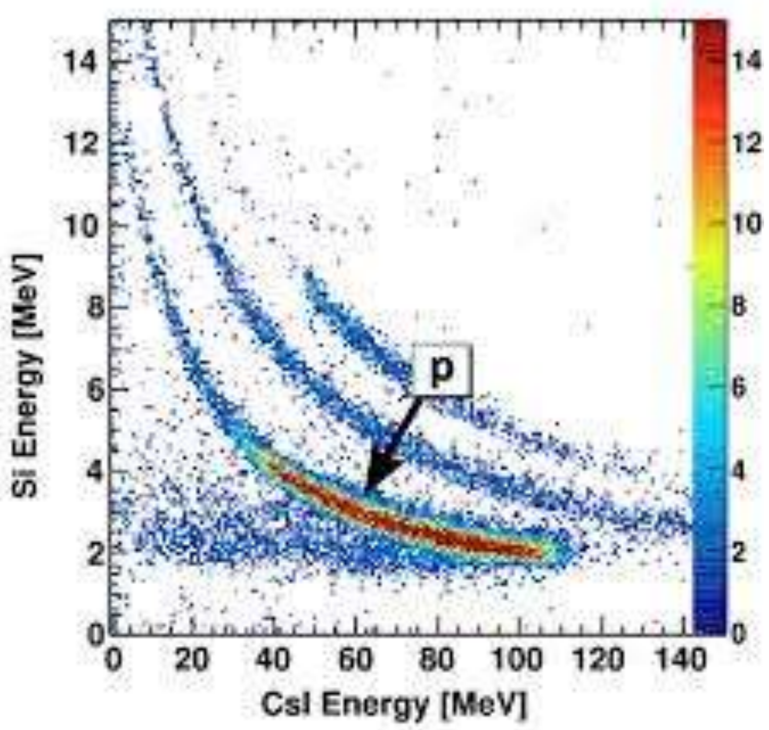
z: atomic number of incident particle

Z: atomic number of absorber

I : characteristic ionization constant, material dependent

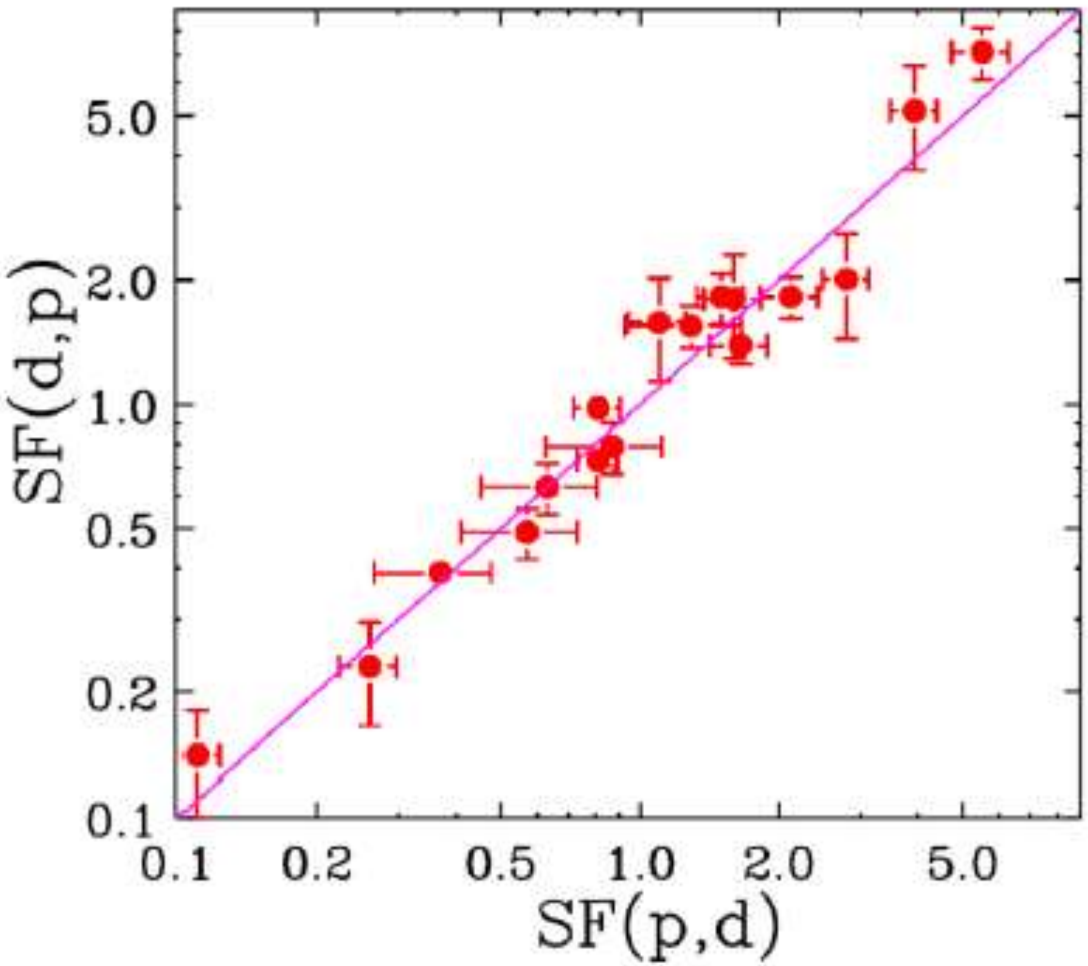
T^{max}: max. energy transfer (see previous slide)

δ ($\beta\gamma$): density effect correction to ionization energy loss



(p,d) vs. (d,p)

- Masses with both measurements range from 11 to 53
- Good check for consistency of transfer



Deriving SF relation

- Fermi's golden rule
- DWBA Approximations:

$$\frac{d\sigma}{d\Omega} = \frac{(2I_b+1)(2I_B+1)}{2\pi^2\hbar^4}\mu_i\mu_f\frac{k_f}{k_i}|T_{if}|^2$$

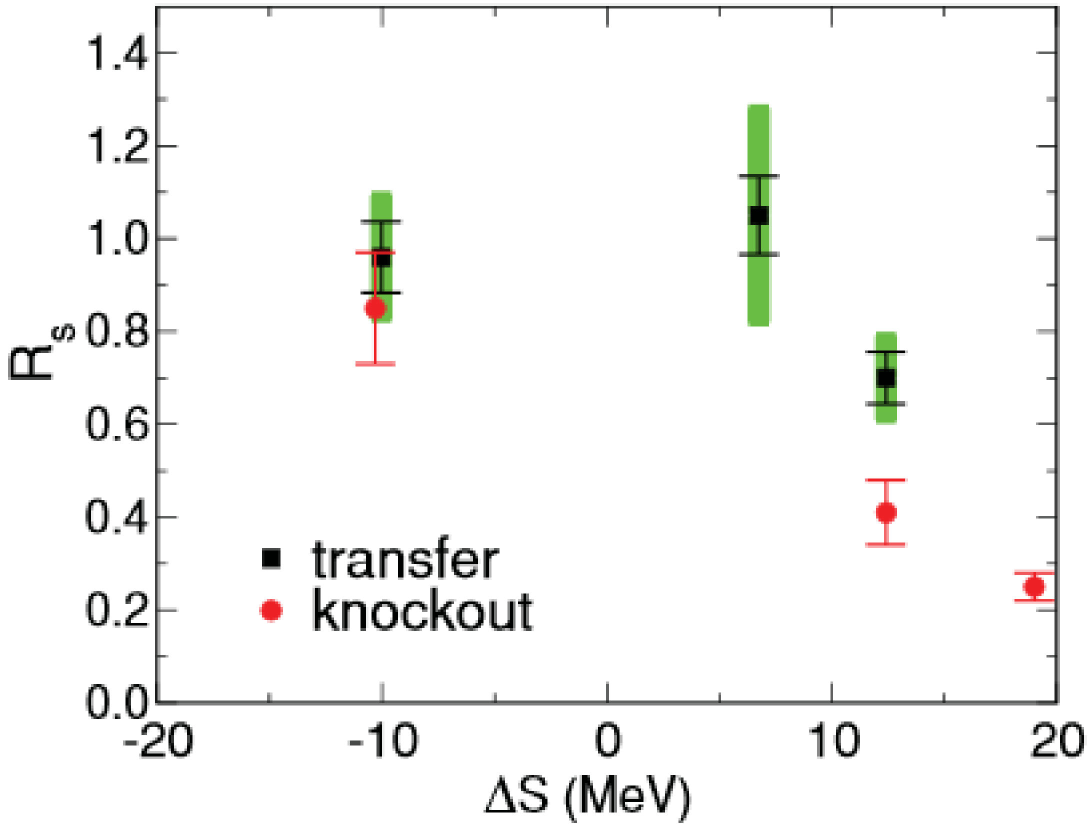
Approximations: one step direct process, reaction weak enough to use 1st order perturbation theory, adiabatic approximation (deuteron breakup), distorted waves

- Assuming single particle states…

$$\left(\frac{d\sigma}{d\Omega}\right)^{\ell j}_{\mathrm{exp}} = S_{\ell j}\left(\frac{d\sigma}{d\Omega}\right)^{\ell j}_{\mathrm{DWBA}}.$$

Evaluation of transfer theory

- Nunes, et al claim transfer data corroborates knockout data
- Quantified errors in reaction theory from optical potential by performing exact three-body Faddeev calculation
- But…large (20%) divergence between Faddeev and ADWA results
- PRC 83, 034610

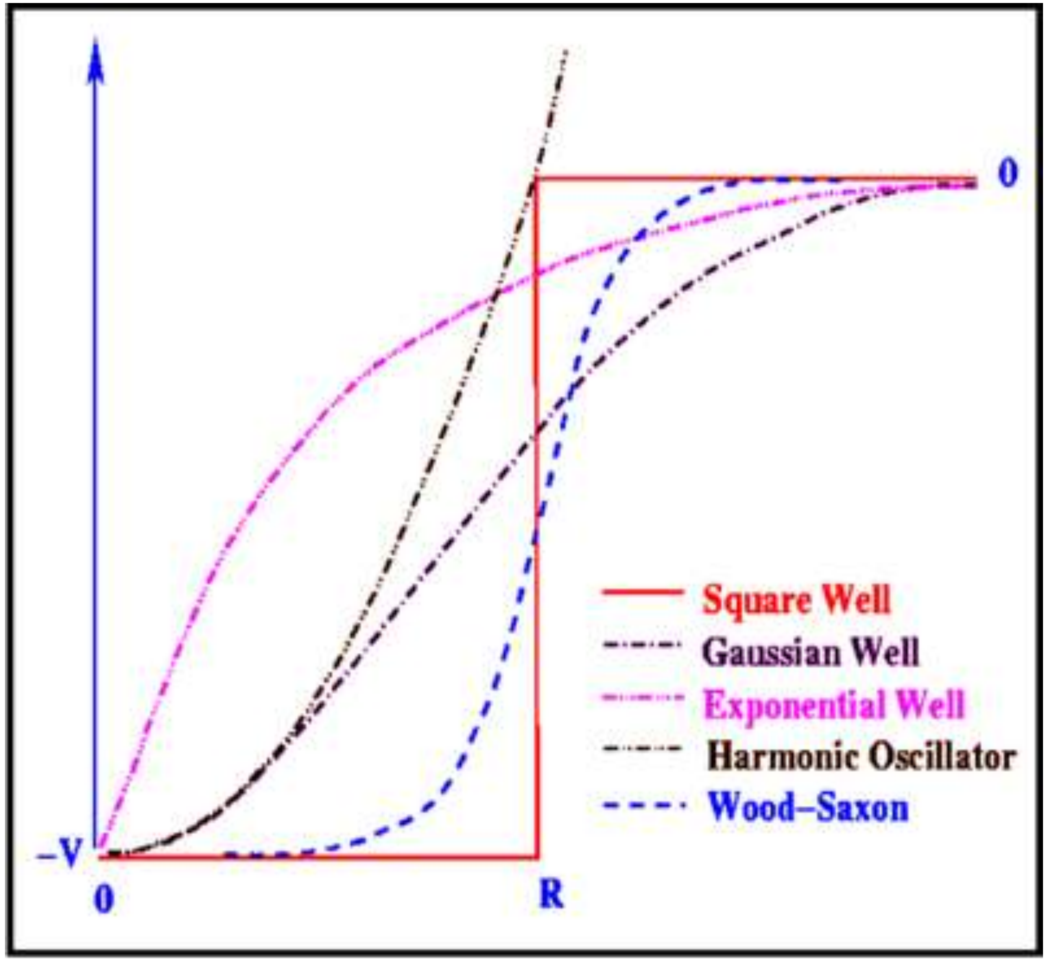


Woods-Saxon Potential

$$V = -\frac{V_0}{1 + exp\left(\frac{r-R}{a}\right)}$$

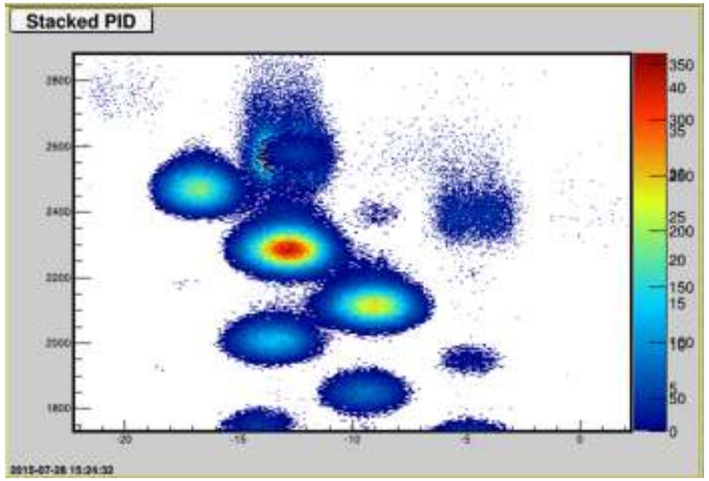
- Plus spin orbit:

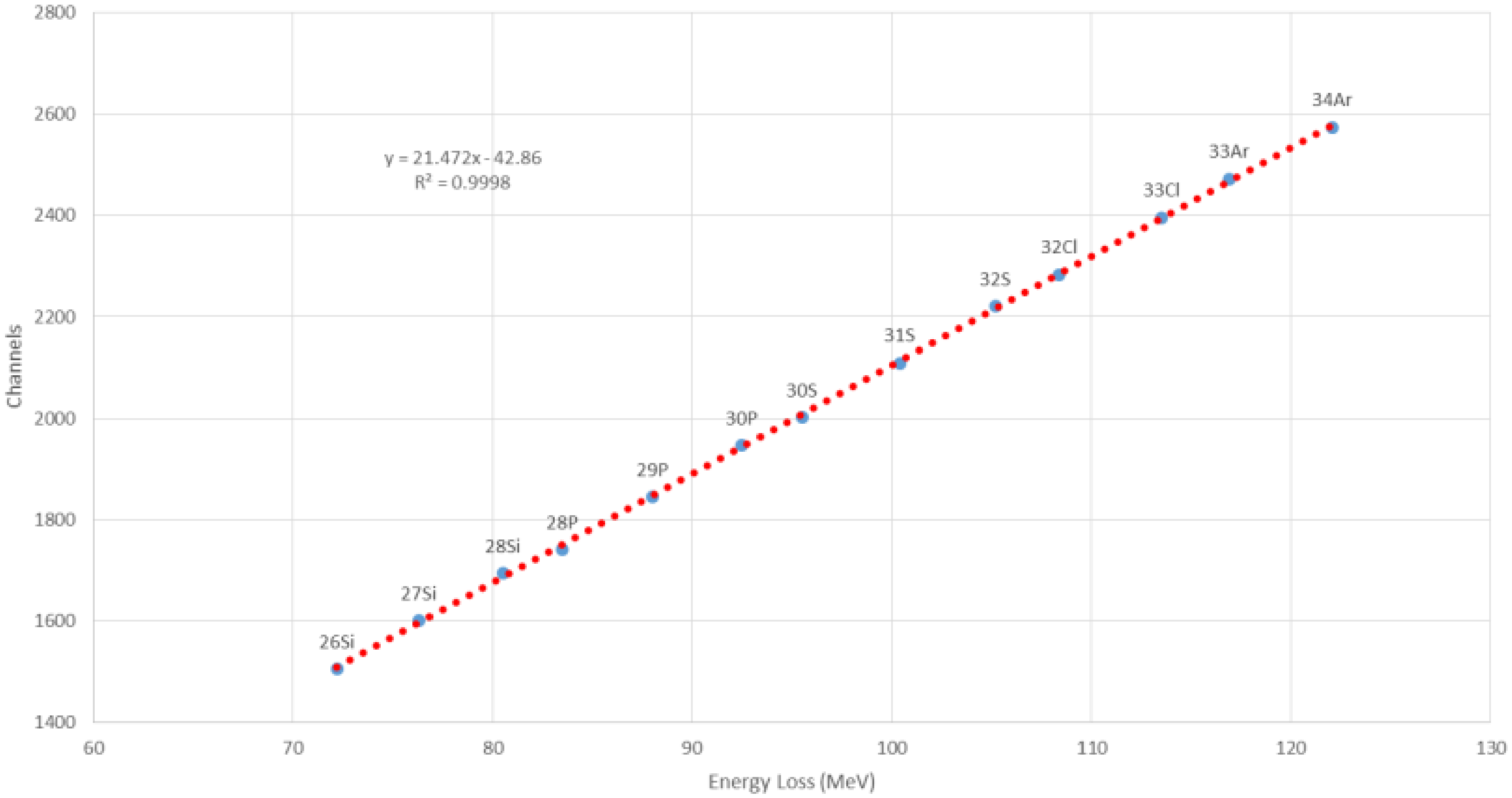
$$V = V(r) - f(r)\vec{l}\,.\,\vec{s}$$



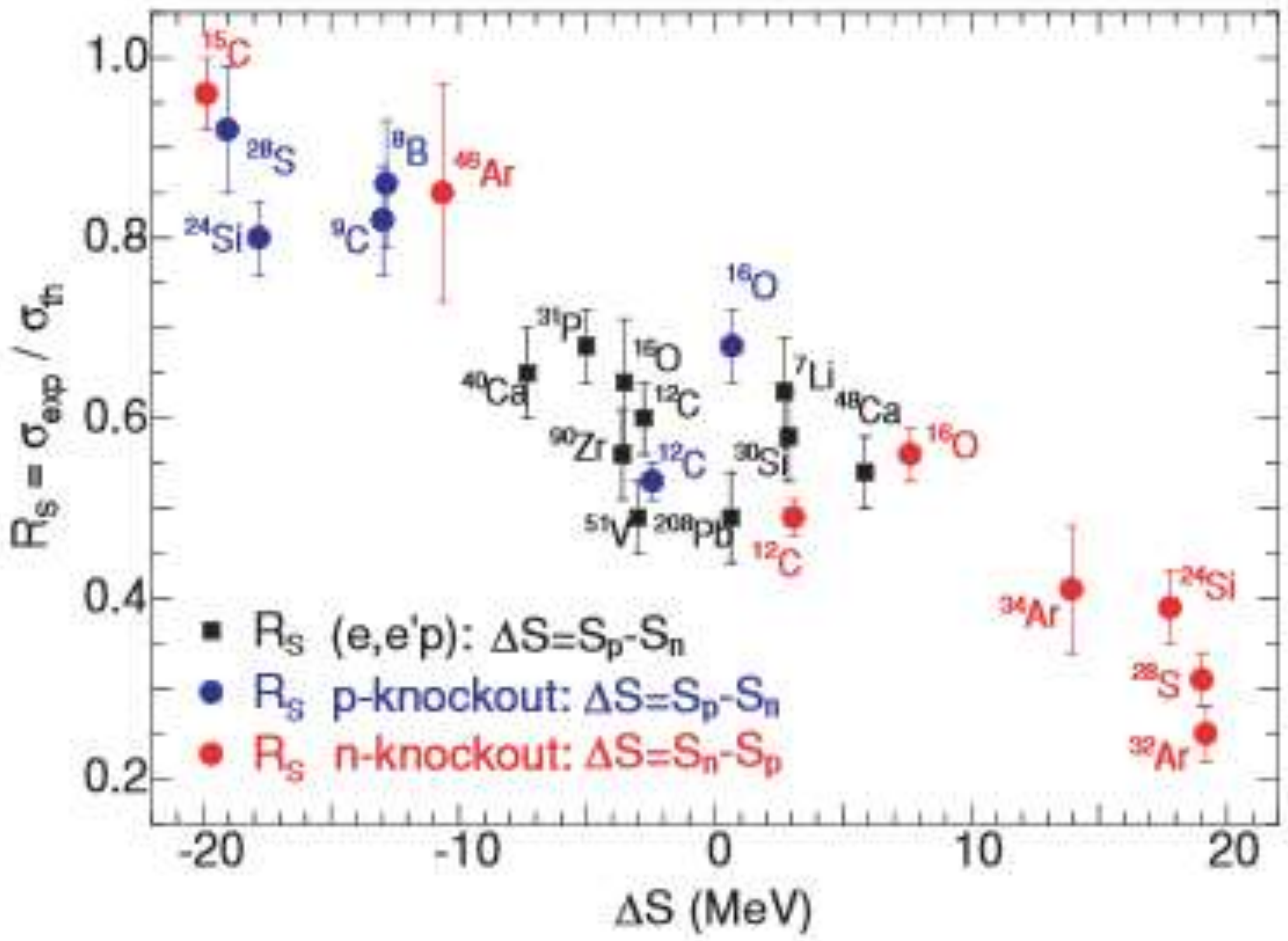
Ion Chamber Energy check

- Energy loss calculations performed with LISE++





Knockout vs (e, e' p)



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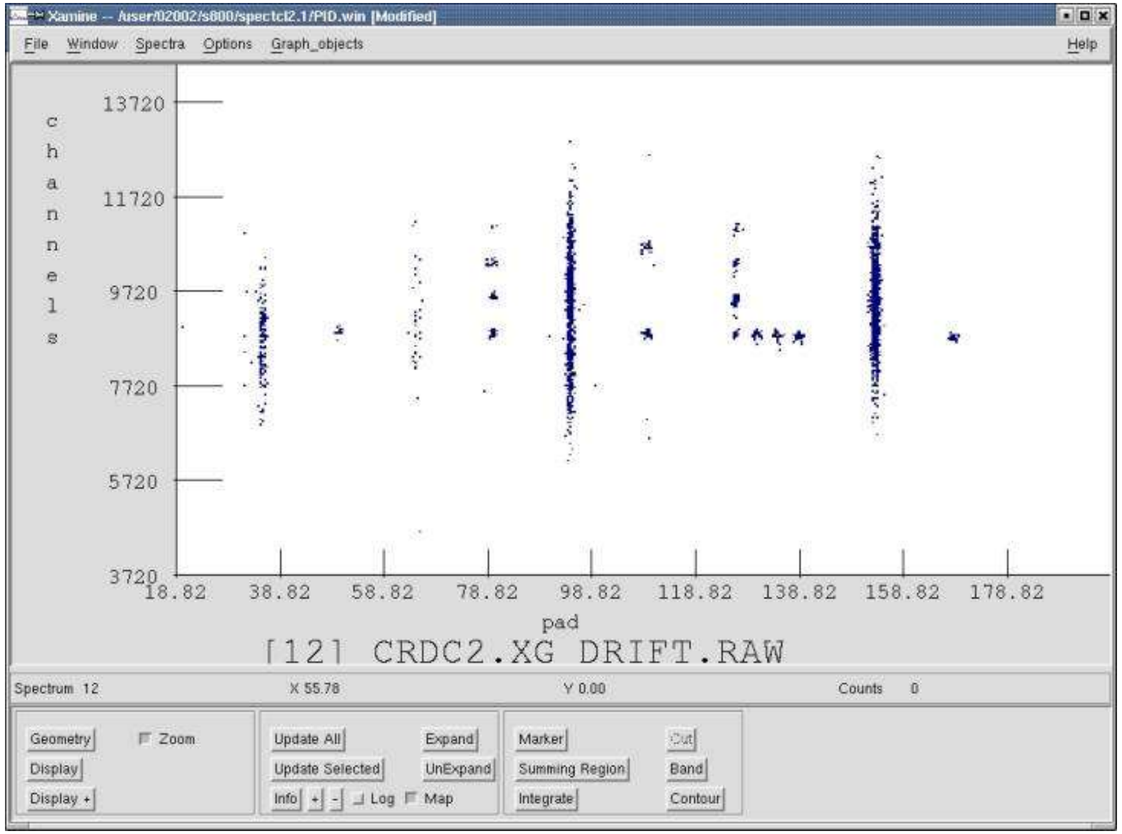
CRDCs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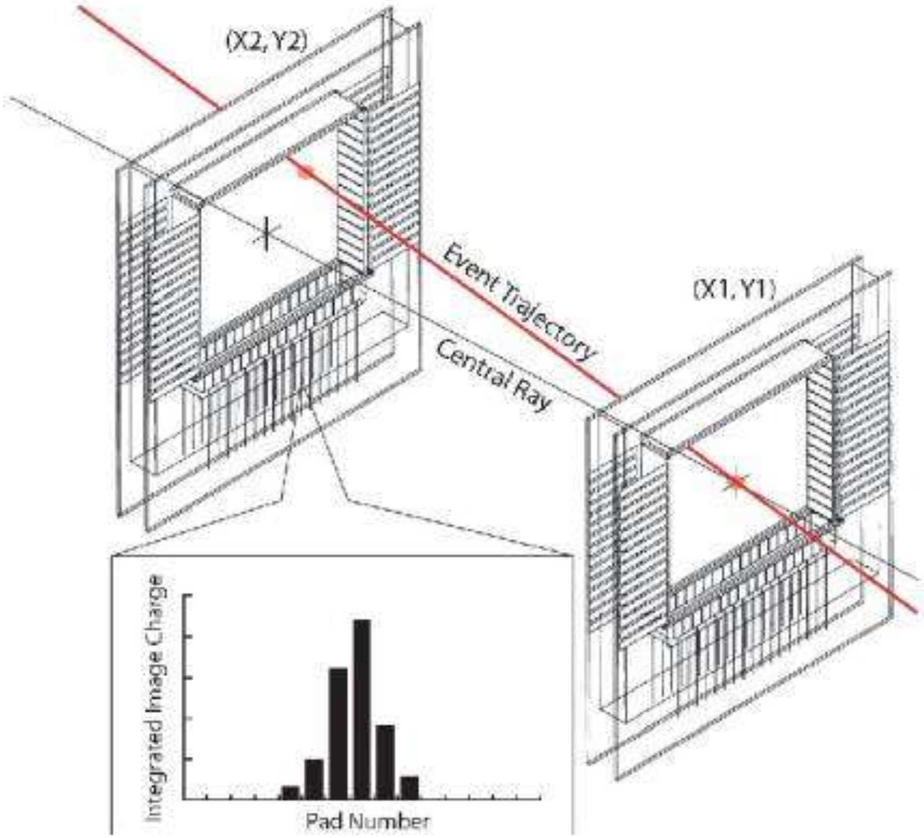
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