Nuclear reactions
Structure studies of nuclei far from stability with Knockout reactions

D. Bazin

Lecture 3

Heavy ion knockout reactions

- Sudden removal of one or two nucleons from a nucleus via nuclear interaction with a light target
  - Direct (one-step) reaction
  - Probability of finding A-1 or A-2 residual nucleus in a given quantum state
  - Composition of initial nucleus wave function
  - Spectroscopy of residual nucleus
- High sensitivity well adapted to radioactive beam intensities
  - Residual nucleus forward focused around 0° - 100% collection efficiency
  - Final state of residual nucleus identified via γ-ray detection
  - Use thick targets - high luminosity

Outline

- Spectroscopic factors
- One-nucleon knockout
- Eikonal theory - Demo!
- Experimental method
- Results
- Two-nucleon knockout
- Conclusion

Spectroscopic Factors

- Definition
  - Expansion of a A-nucleon initial state into the complete set of (A-1)-nucleon final states through overlap functions:

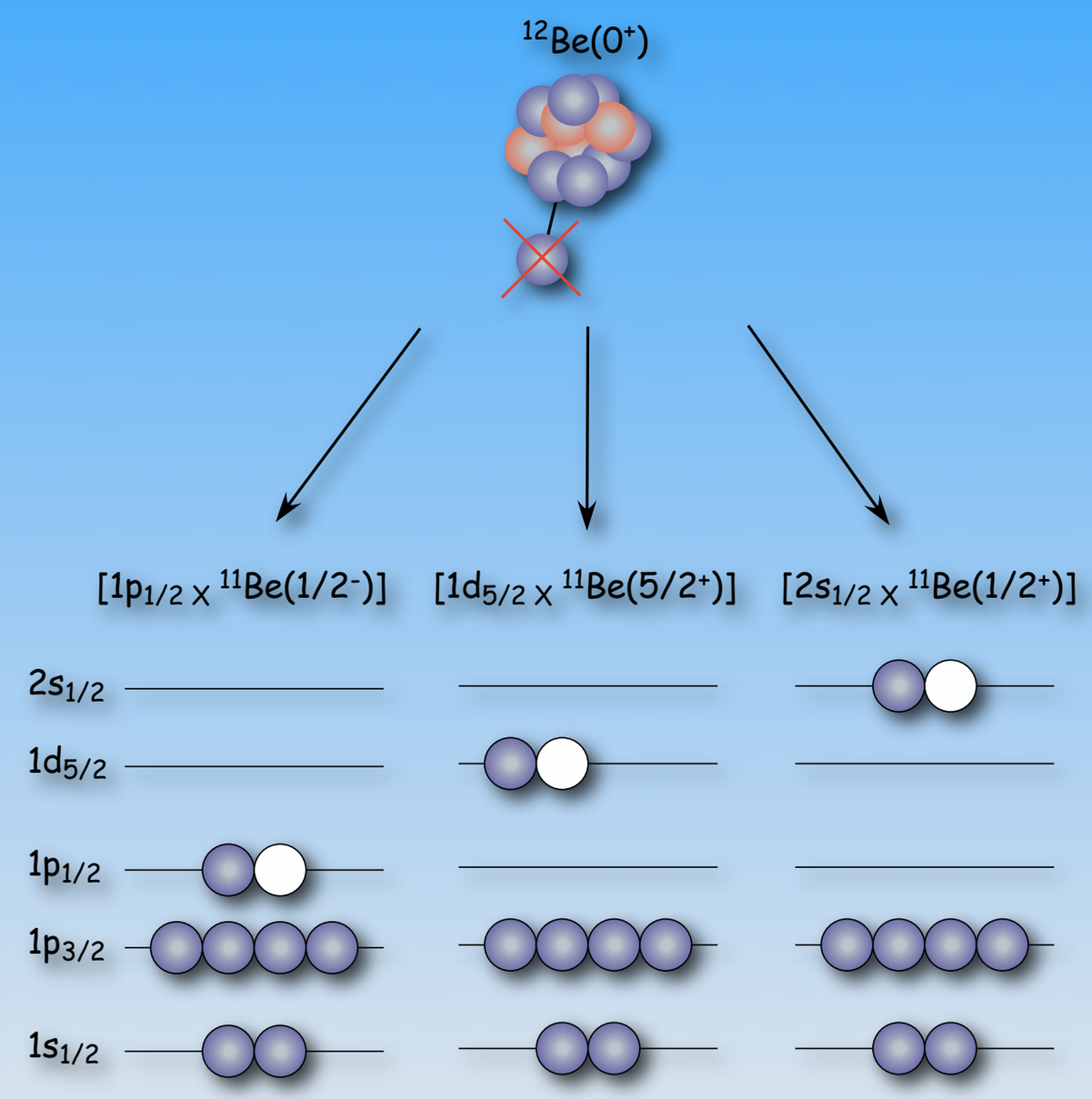
$$\left\langle \Psi_f^{A-1} \middle| \Psi_i^A \right\rangle = \sum_{|J_f - J_i| \leq j \leq J_f + J_i} c_j^{if} \psi_j \qquad S_j^{if} = \left| c_j^{if} \right|^2$$

- Interpretation
  - Parentage of initial state Ψ_i^A with respect to final state Ψ_f^{A-1} coupled to nucleons with quantum numbers (n, l, j)
  - Measure of configuration mixing within a given model space
  - For even-even nuclei (0^+): direct measure of spectroscopic factor

$$\sigma^{if} = \sum_{|J_f - J_i| \leq j \leq J_f + J_i} S_j^{if} \sigma_{sp}$$

Illustration

- What is the configuration of the ground state of ^{12}Be?
  - Consider 2 valence neutrons in $[1p_{1/2}]^2$, $[1d_{5/2}]^2$ or $[2s_{1/2}]^2$ configurations
  - Spectroscopic factors corresponding to different possible couplings of a neutron with ^{11}Be states
- Spectroscopic factors are related to single-particle occupancies



Applications

- Relative spectroscopic factors
  - Single-particle state occupancies
  - Composition of the nuclear wave function
  - Study of nuclear structure: shell gaps, intruder configurations
- Absolute spectroscopic factors
  - Based on accurate calculation of single-particle cross sections
  - Adequacy of nuclear structure models

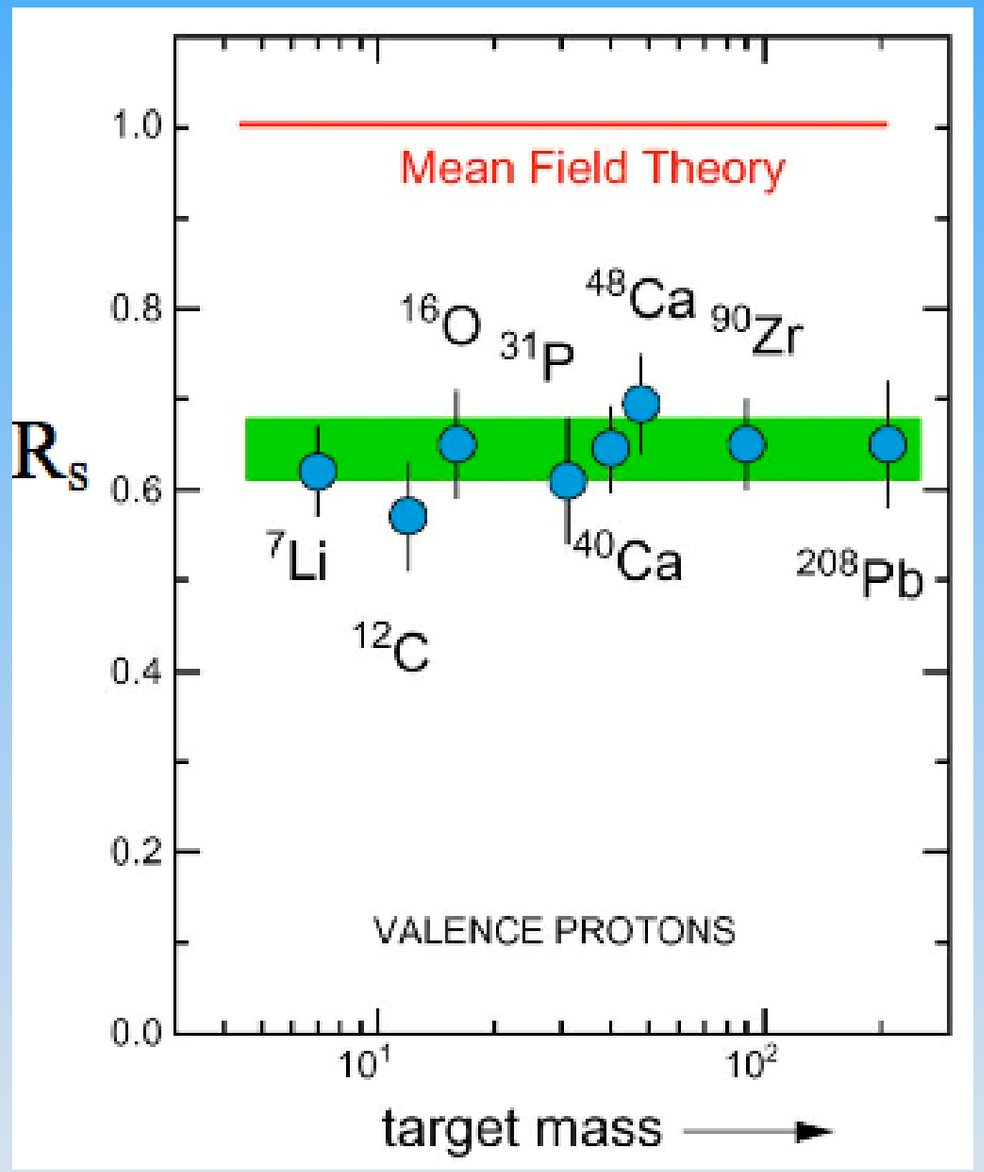
How to measure Spectroscopic Factors?

- Transfer reactions
  - Limited to stable or close to stable nuclei
  - Allow study of hole and particle states
- (e,e'p) knockout
  - Limited to stable nuclei and proton hole states
- Proton or neutron decay
  - Decay width directly related to Spectroscopic Factor
- Knockout reaction with radioactive projectiles
  - Study of nuclei far from stability
  - Proton and neutron hole states

Comparison with Shell Model

$$R_S = \frac{S_{exp}}{S_{theo}}$$

- Results from (e,e'p)
  - Reduction factor between experimental and theoretical Spectroscopic Factors
  - Average reduction 0.6 - 0.7 observed across variety of stable nuclei
  - Difference attributed to NN correlations not included in shell model, which spread strength to higher energy states
- Away from stable nuclei?
  - Same reduction?



V. R. Pandharipande et al., Rev. Mod. Phys. 69, 981 (1997)
W. Dickhoff and C. Barbieri, Prog. Nucl. Part. Sci. 52, 377 (2004)

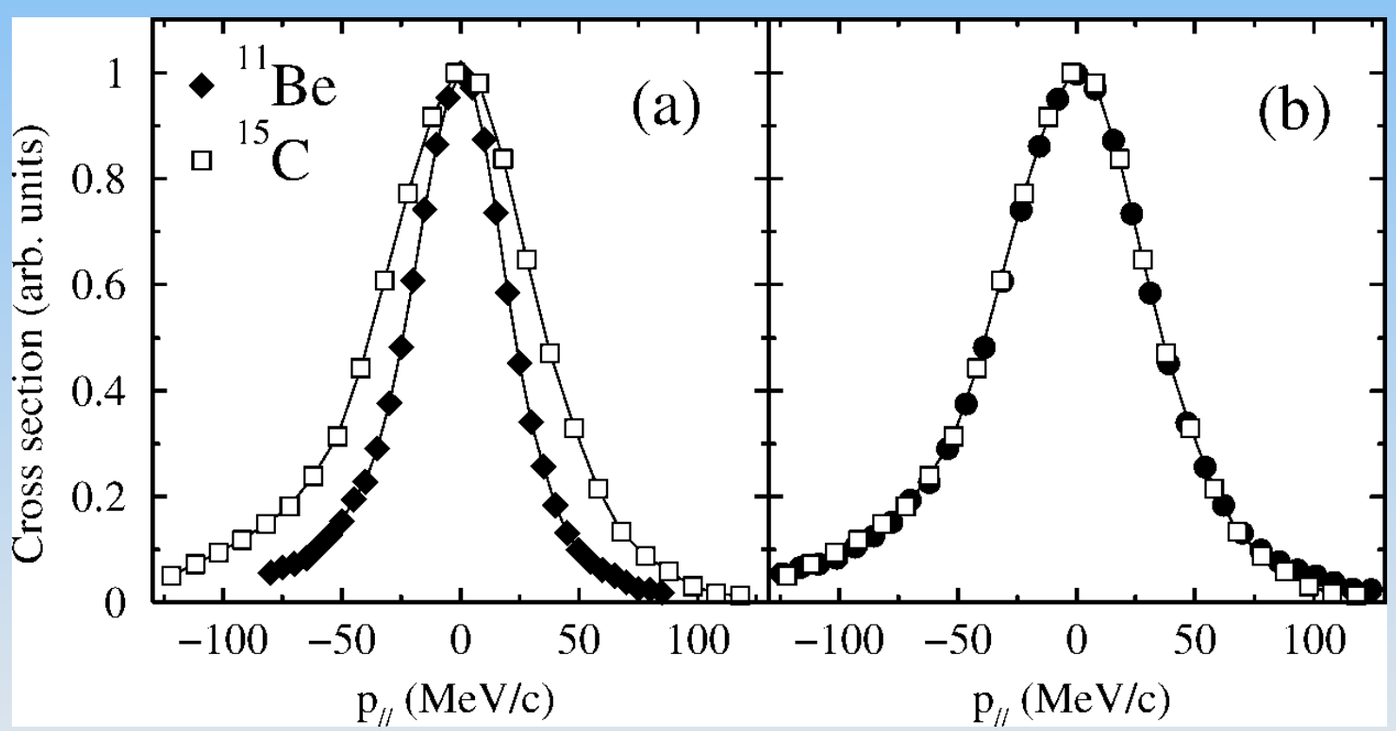
One-nucleon knockout on fast projectiles

- Surface dominated collision with a light target
  - Stripping or inelastic breakup: removed nucleon absorbed
  - Diffraction or elastic breakup: removed nucleon elastically scattered
  - Heavy residue detected at forward angles
  - Residue final state measured from in-flight γ-ray decay
- Fast projectile
  - Momentum of residue directly related to momentum of removed nucleon
  - Longitudinal momentum free of Coulomb deflection and diffractive scattering, directly related to angular momentum of removed nucleon
  - Direct reaction and eikonal theory

Recent review: P. G. Hansen & J. A. Tostevin, Annu. Rev. Nucl. Part. Sci. 53, 219-261 (2003)

Application to halo states

- Longitudinal momentum distributions of one-neutron knockout from ^{11}Be and ^{15}C
  - Both nuclei have valence neutron predominantly in s-state (Yukawa WF)
  - Separation energies 0.5 MeV and 1.2 MeV respectively
  - Momentum of ^{11}Be distribution scaled by ration √(1.2/0.5) in (b)
  - Shape directly related to spacial distribution of neutron



J. A. Tostevin et al., Phys. Rev. C 66, 024607 (2002)

Experimental assets

- Fast beams: high sensitivity
  - Thick targets; forward focusing of heavy residues
  - Angular momentum of removed nucleon identified from shape of residue longitudinal momentum distribution
  - Final state of residue identified from Doppler-corrected gamma-rays
  - Measurements can be performed with less than 1 atom/second
- Light absorptive target: ^{9}Be
  - Reaction dominated by strong interaction
  - Highly absorptive and surface localization due to short mean free path
- Input-output balance of γ-ray intensities
  - Necessary to deduce partial cross sections and extract Spectroscopic Factors
  - Well suited to drip-line nuclei with few bound states

Theoretical assets

$$\sigma_{th}^{if} = \sum_j S_j^{if} \sigma_{sp}(nlj)$$

- Single-particle cross section σ_{sp} for stripping and diffraction
  - Use eikonal approximation: straight line trajectories
  - Treatment reduced to a 3-body problem target-residue-nucleon
  - Wave functions calculated using Wood-Saxon potential
  - Densities and radii constrained from HF calculations using SKX parameter set
- Three-dimensional momentum distributions
  - Gaussian expansion method
  - Acceptance corrections

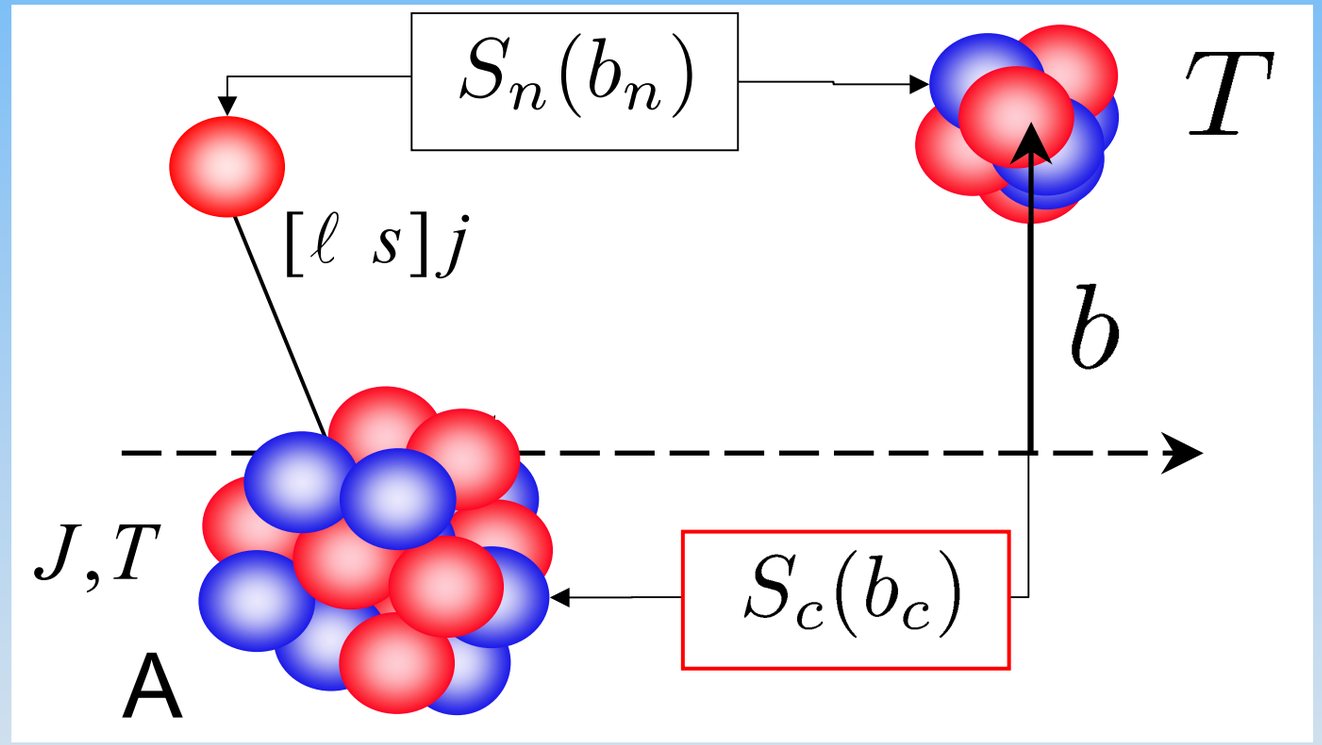
Single-particle cross sections

$$\sigma_{sp} = \sigma_{str} + \sigma_{dif} + \sigma_C$$

$$\sigma_{str} = \frac{1}{2j+1}\int d\vec{b}\sum_m \langle\psi_{jm}|(1-|S_n|^2)|S_c|^2|\psi_{jm}\rangle$$

$$\sigma_{dif} = \frac{1}{2j+1}\int d\vec{b}\,[\sum_m \langle\psi_{jm}||1-S_nS_c|^2|\psi_{jm}\rangle - \sum_{m,m'} |\langle\psi_{jm'}|(1-S_nS_c)|\psi_{jm}\rangle|^2]$$

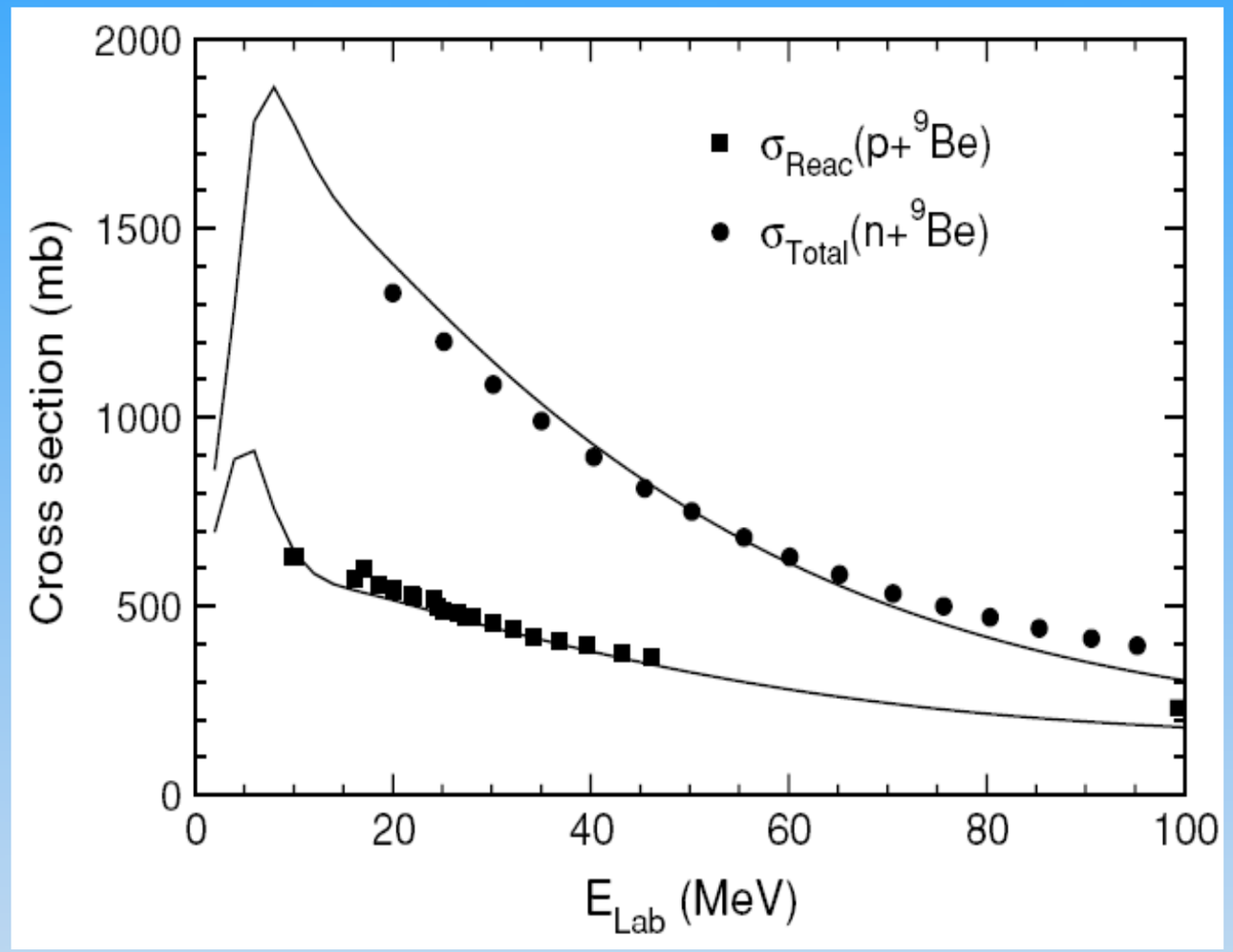
- S_n and S_c S-matrices for the scattering of the nucleon and the core respectively
- Calculated using Glauber theory, HF densities and effective NN interaction
- Stripping part only depends on absorptive part of the potential



J. A. Tostevin, Nucl. Phys. A682, 320c (2001)

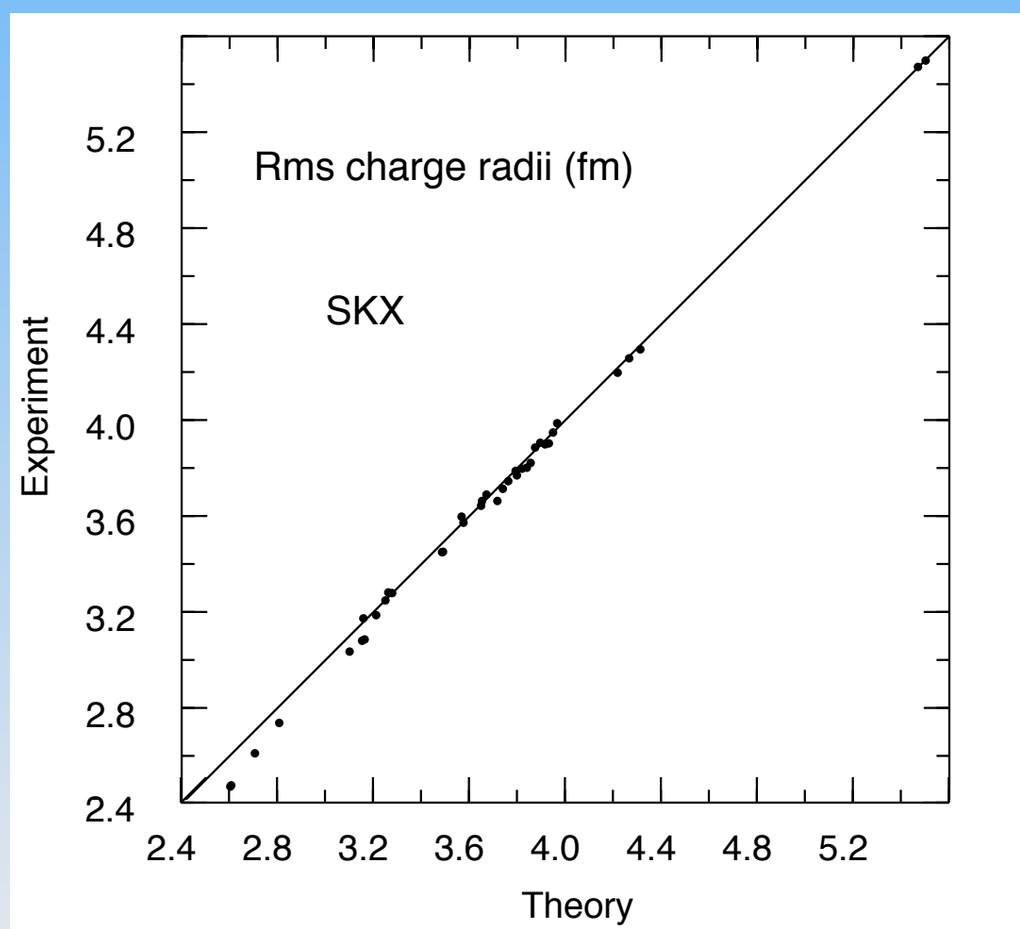
Nucleon-target interaction

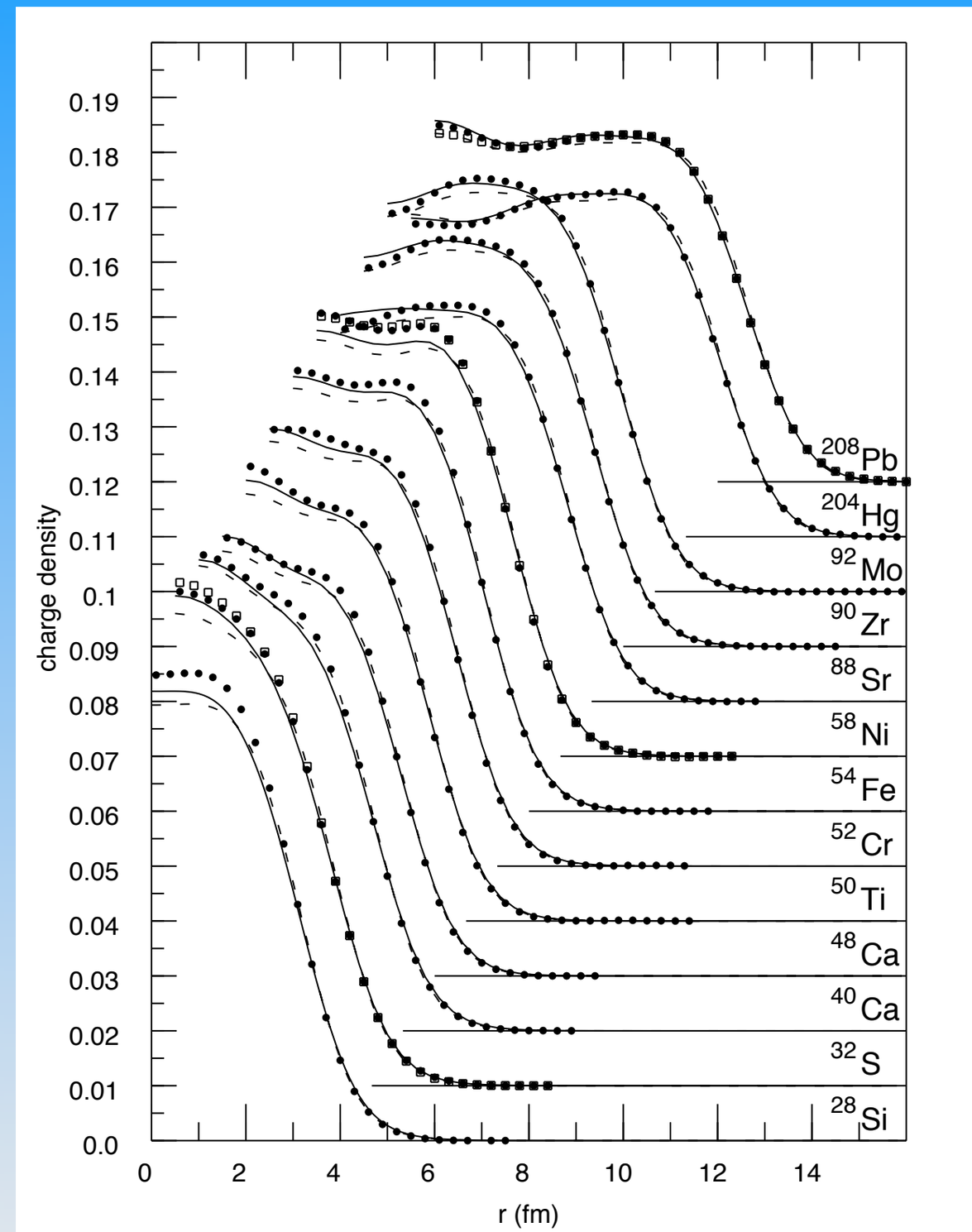
- Same target and limited range of energies used for all final states and systems
- S_n calculated using Gaussian density for the ^{9}Be target
- S_n highly constrained by cross section



Core-target interaction

- S_c calculated using HF densities
- SKX parameter set fit to stable and exotic spherical nuclei

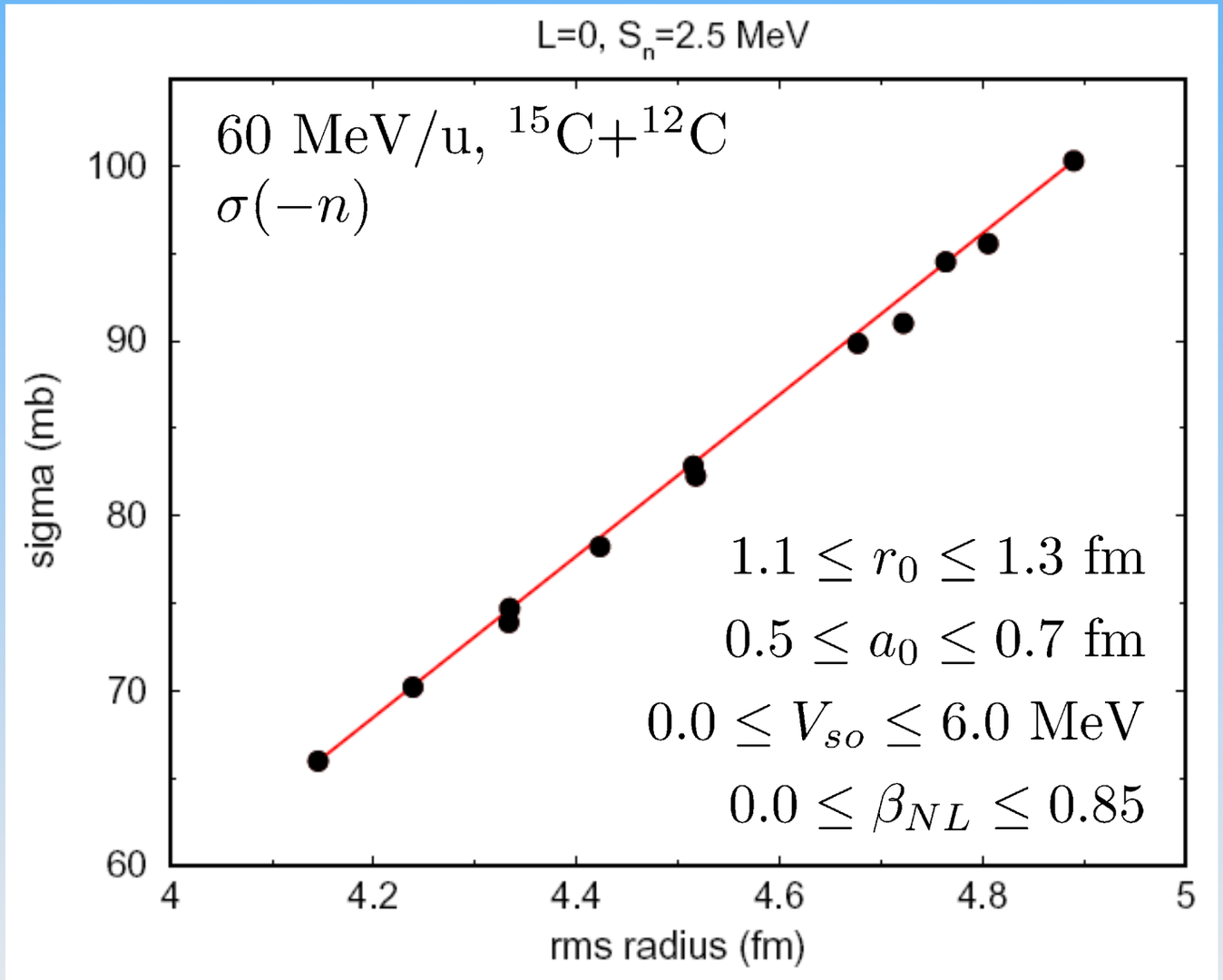




W. A. Richter and B. A. Brown, Phys. Rev. C 67, 034317 (2003)

Nucleon-core wave function

- Calculated using a Wood-Saxon potential
  - Depth of potential adjusted to reproduce binding energy of nucleon in state
  - Initially radius and diffuseness fixed to 1.25 fm and 0.7 fm
  - Now use HF rms radius in particular for deeply bound valence states



J. A. Tostevin,
Private communication

Demonstration of calculation

One-nucleon knockout cross section calculations

Reaction

Projectile		Channel	Core	Target	Energy	
Ne	28	-1n	Ne27	Be9	100	MeV/u

Options

Working Folder: /Users/lab/Docum.../Codes/tclknock — Browse — Exit

HF density | S-Matrix | Wave Function | Cross Sections | Mom. Dist.

Bound state calculation in a two-body potential
by J. A. Tostevin.
To fit the Wood-Saxon radius from HF, please first select an orbital in the HF page.

Fit Wood-Saxon radius from HF — Calculate WF

Parameters

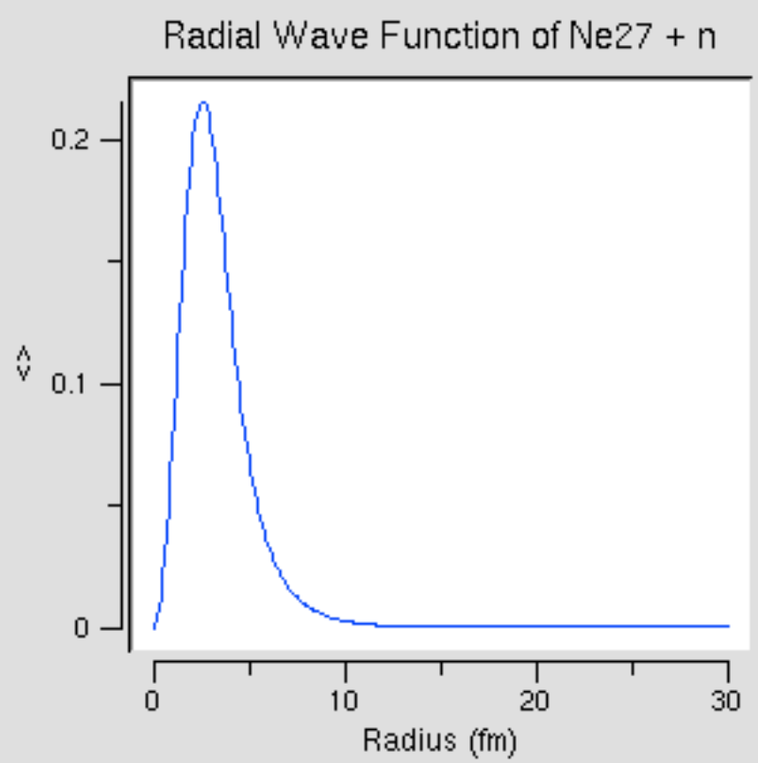
Binding energy (MeV):	3.9	Orbital:	1d3/2
Radius (fm):	1.237	Diffuseness (fm):	0.7
Spin-Orbit (MeV):	6		

Potential type

- Wood-Saxon
- Gaussian
- Yukawa
- Hulthen
- Cosh

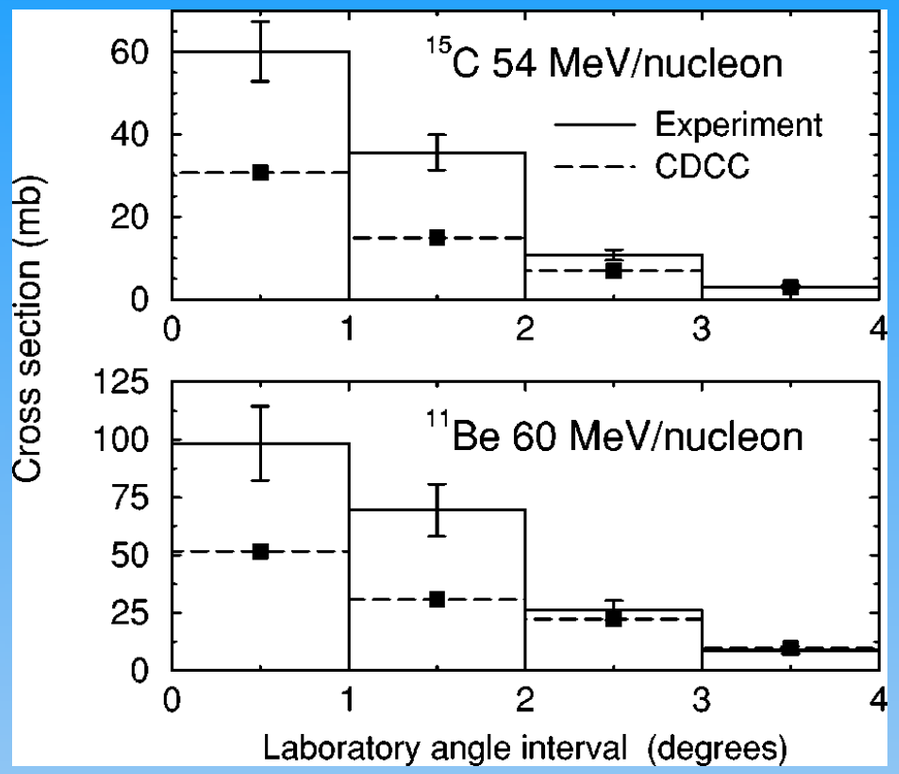
Results

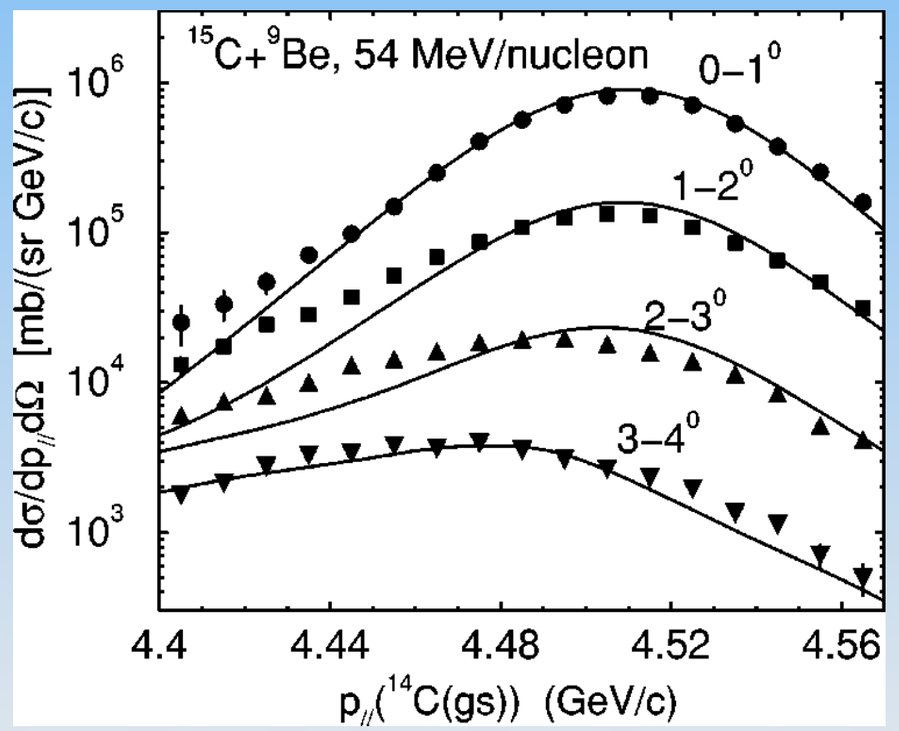
Normalization: 1.00000 Radius: 3.788
Depth: 46.916 r0: 1.237



Deviation from eikonal theory

- High - low momentum asymmetry
  - Not reproduced by eikonal calculation
  - Studied in two cases where diffraction component large and large statistics: ^{11}Be and ^{15}C
  - Diffractive breakup calculated using Continuum Discretized Coupled Channel calculation
  - Stripping still calculated with eikonal theory
  - Asymmetry well accounted for by CDCC calculation in elastic breakup
  - Asymmetry remains to some degree in stripping: due to dissipative reaction mechanism(s)?
- Exclusive experiments
  - Complete kinematics study of one-proton knockout on ^{9}C where ^{8}B residue and proton detected in coincidence (S800 + HiRA)





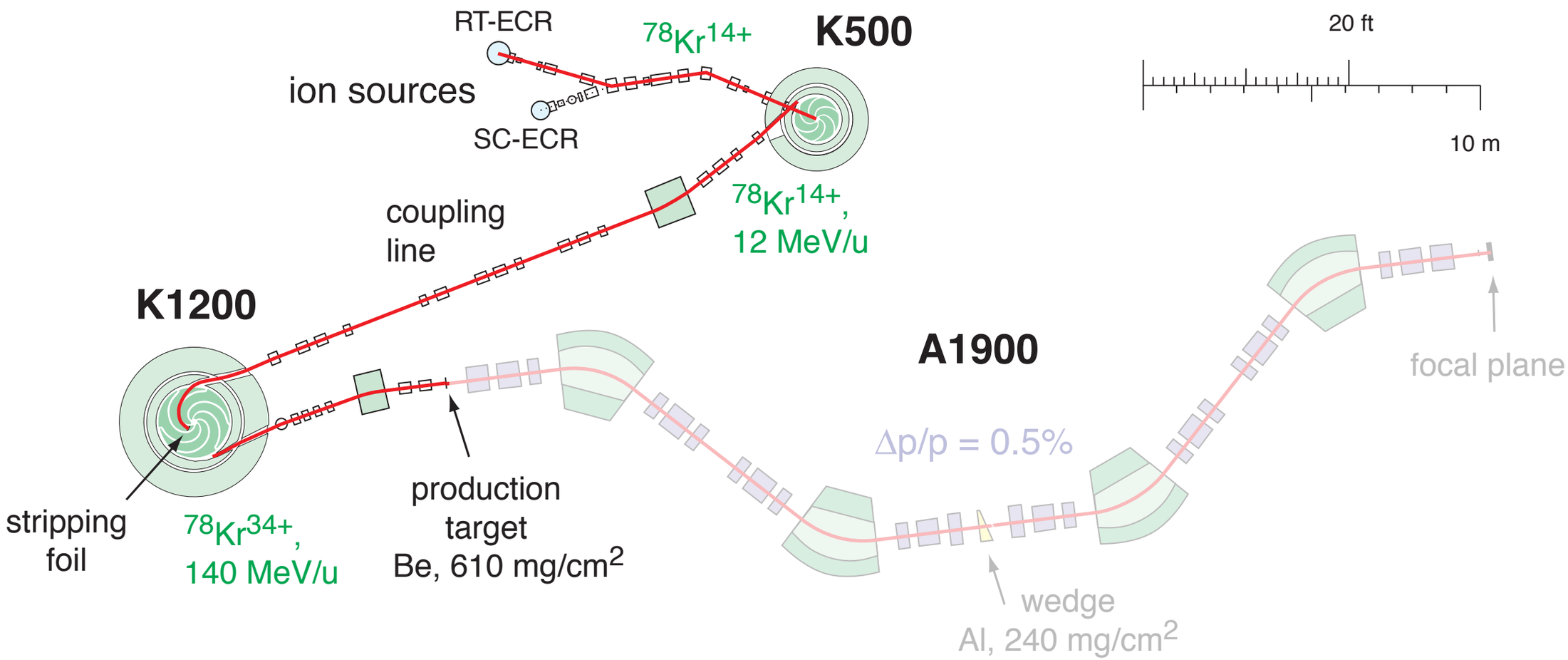
J. A. Tostevin et al., Phys. Rev. C 66, 024607 (2002)

Knockout reactions at the NSCL

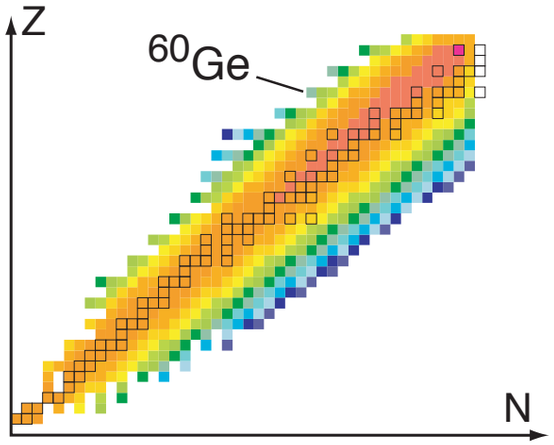
- Radioactive beams produced in A1900 fragment separator
  - Depending on mass region, single or cocktail beams available
- Residues collected in S800 spectrograph
  - Large acceptances (5% momentum - 20 msr solid angle)
  - Identification of residues from TOF & energy-loss measurements
  - Full momentum vector reconstruction of residue
- In-flight decay of residue detected by γ detector array
  - Segmentation allows Doppler correction
  - For low rate - low density use APEX NaI array (good efficiency - poor resolution)
  - For high rate - high density use SeGA Ge array (less efficiency - good resolution)

To S800 Spectrograph
K500 Cyclotron
A1900 Fragment Separator
Production target
K1200 Cyclotron

Experimental Setup at the NSCL

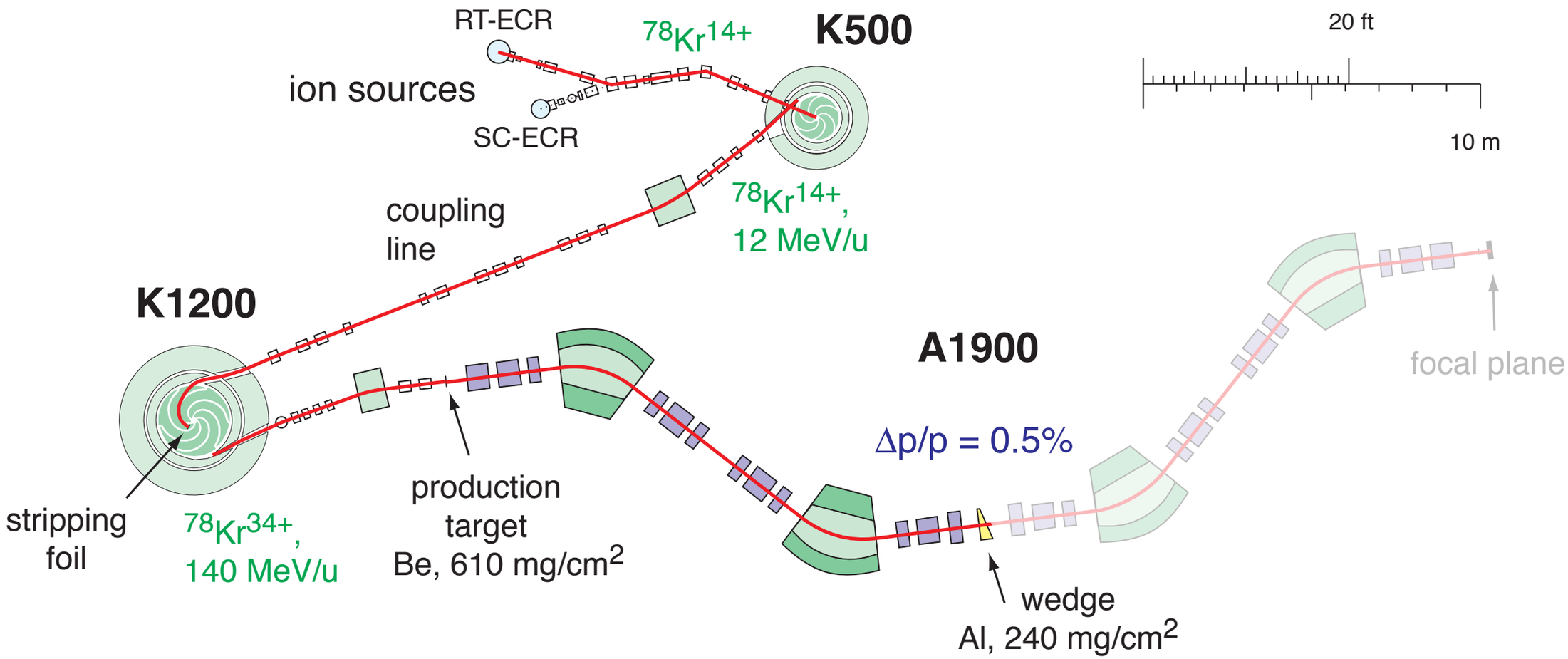


fragment yield after target

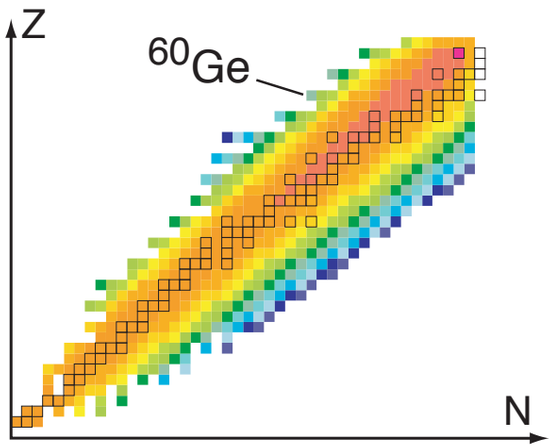


stolz@nscl.msu.edu 2005-01

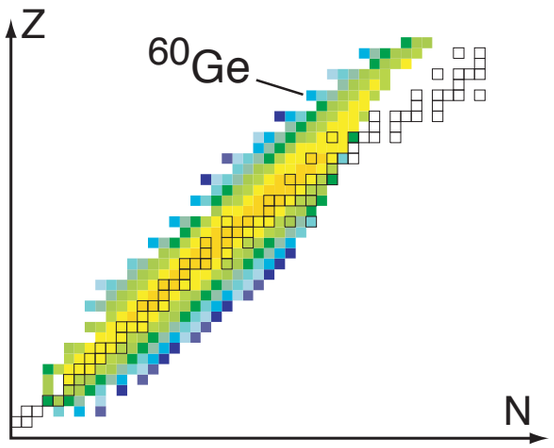
Experimental Setup at the NSCL



fragment yield after target



fragment yield after wedge



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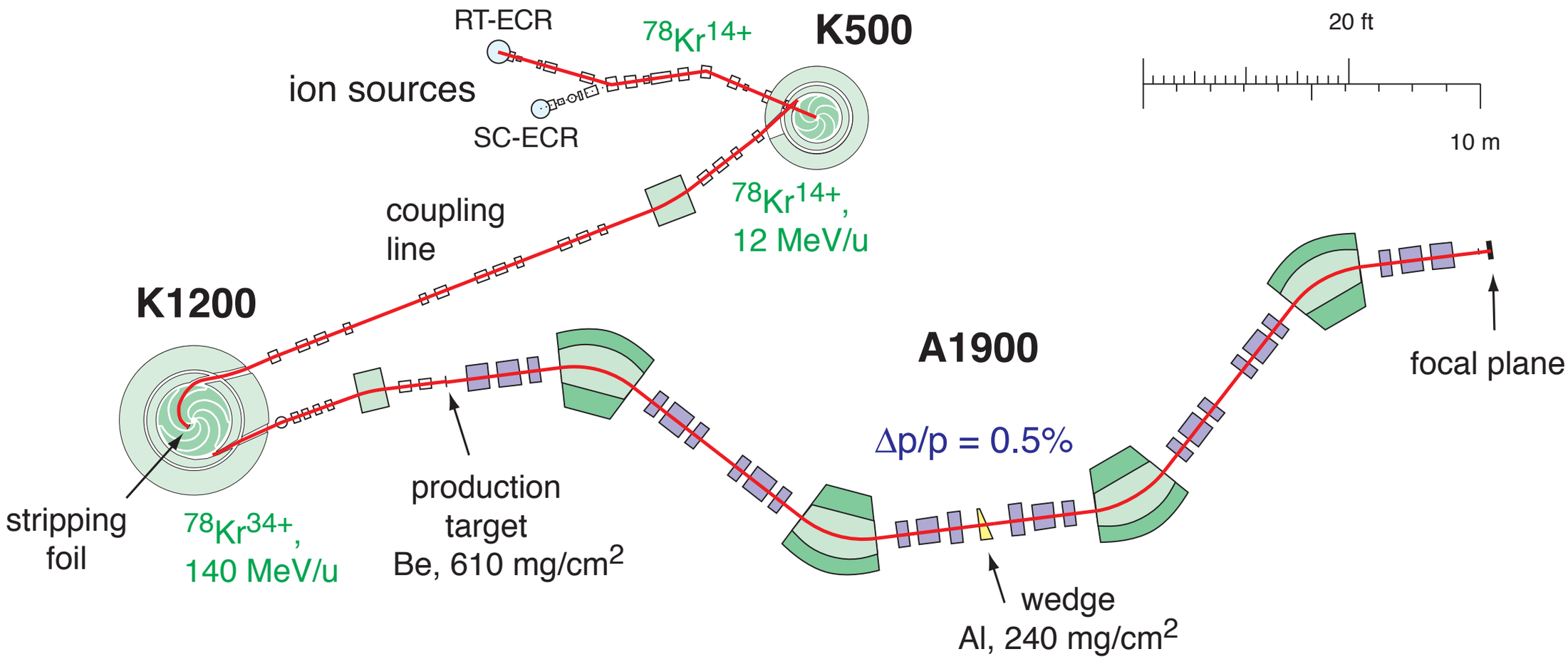
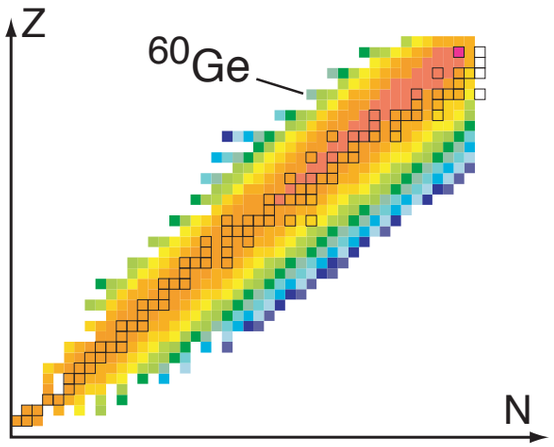
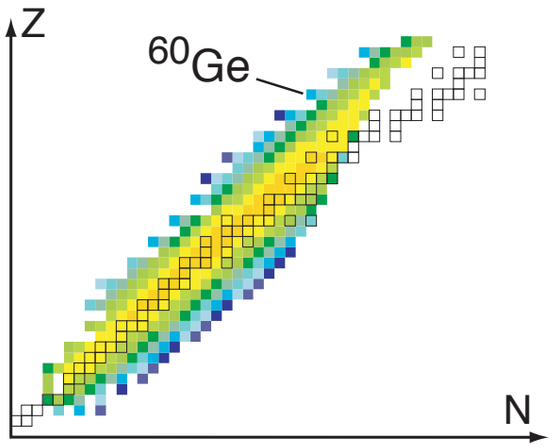
Experimental Setup at the NSCL



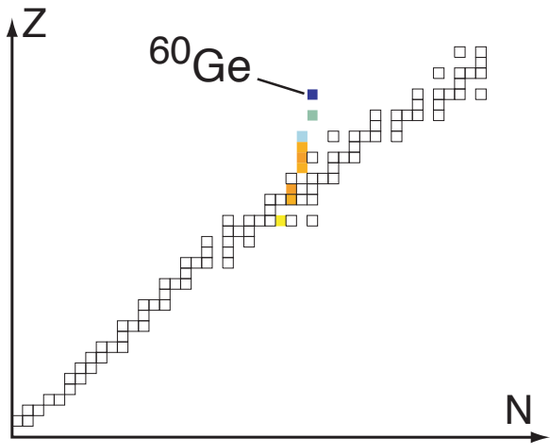
fragment yield after target



fragment yield after wedge



fragment yield at focal plane



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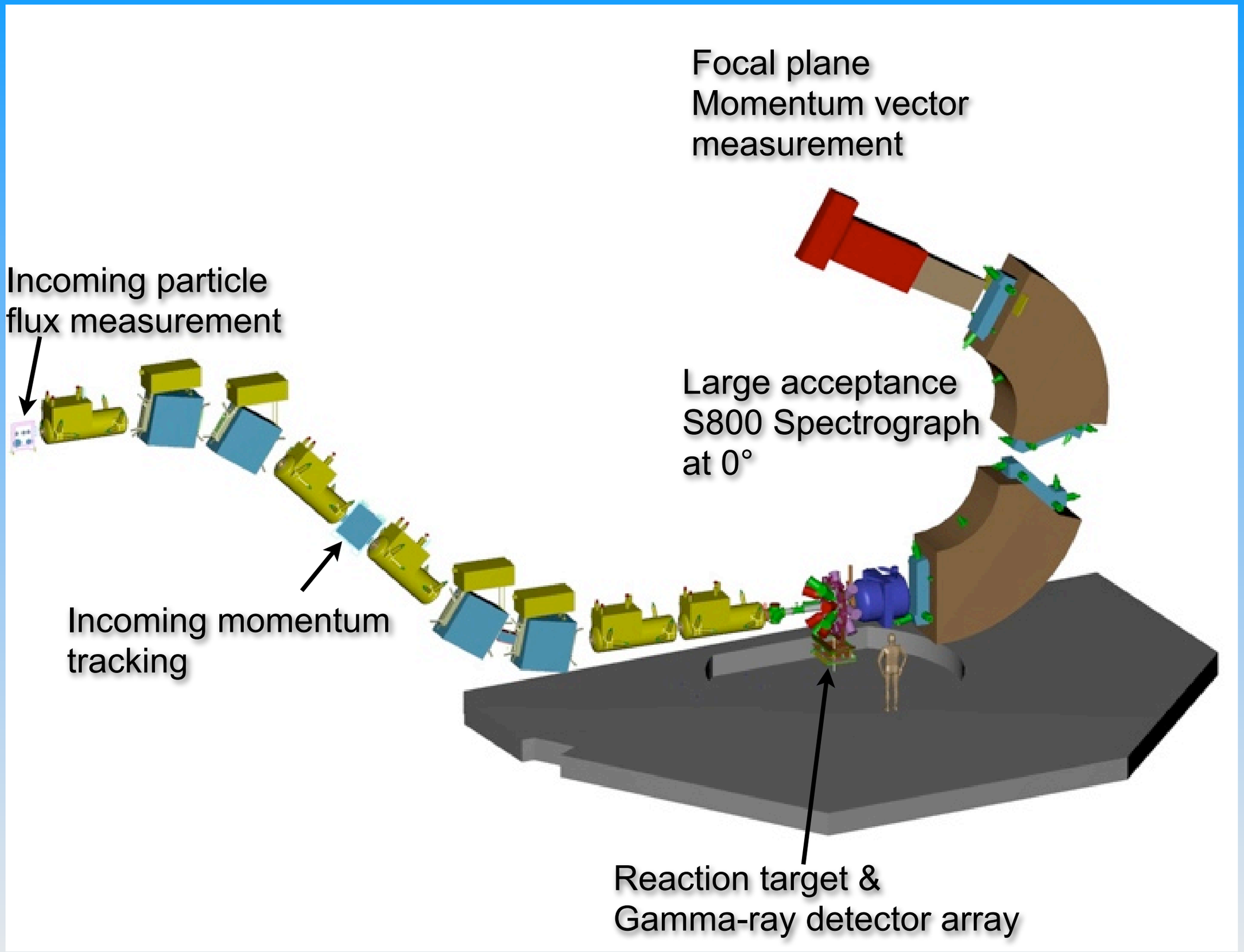
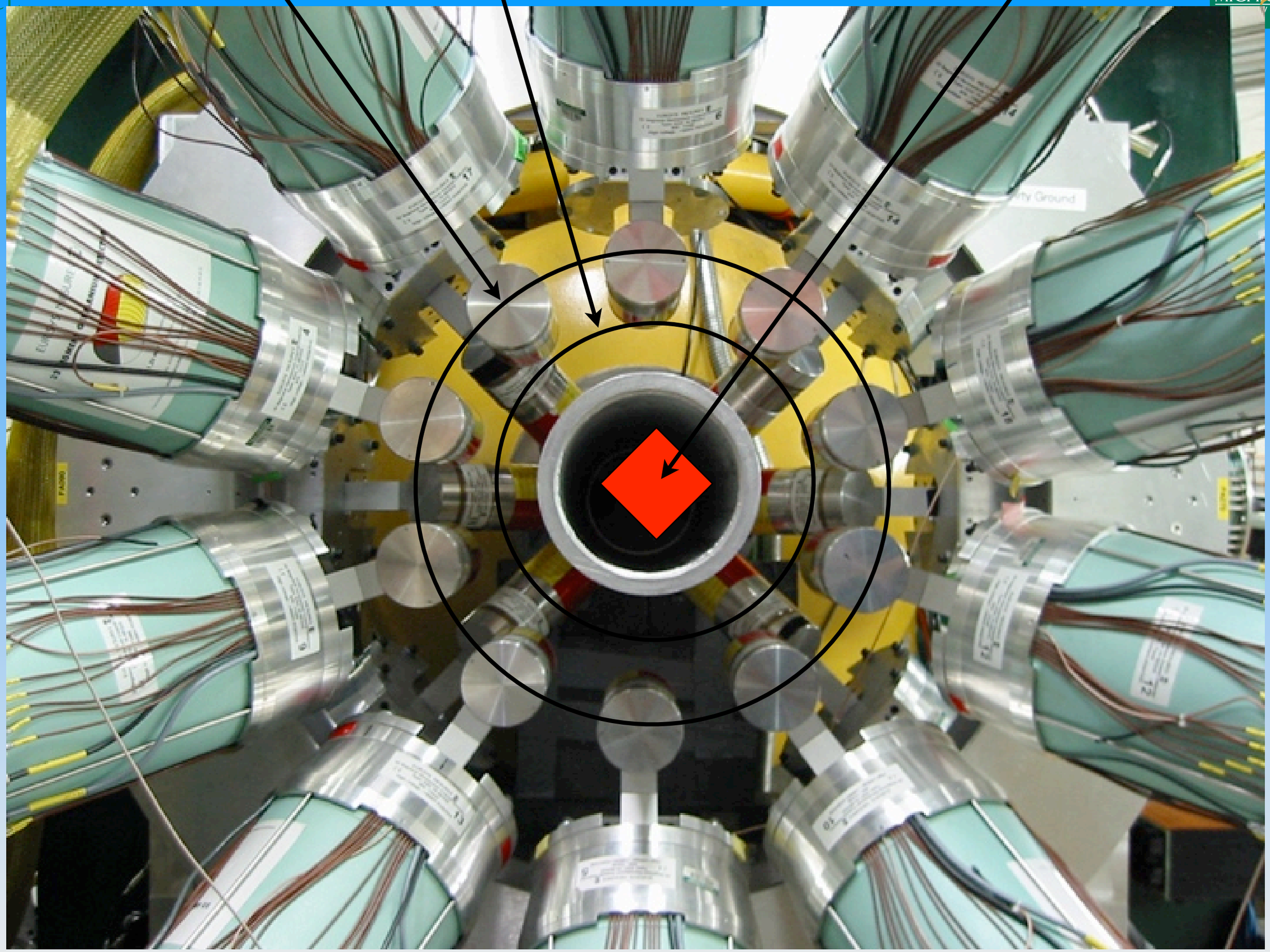
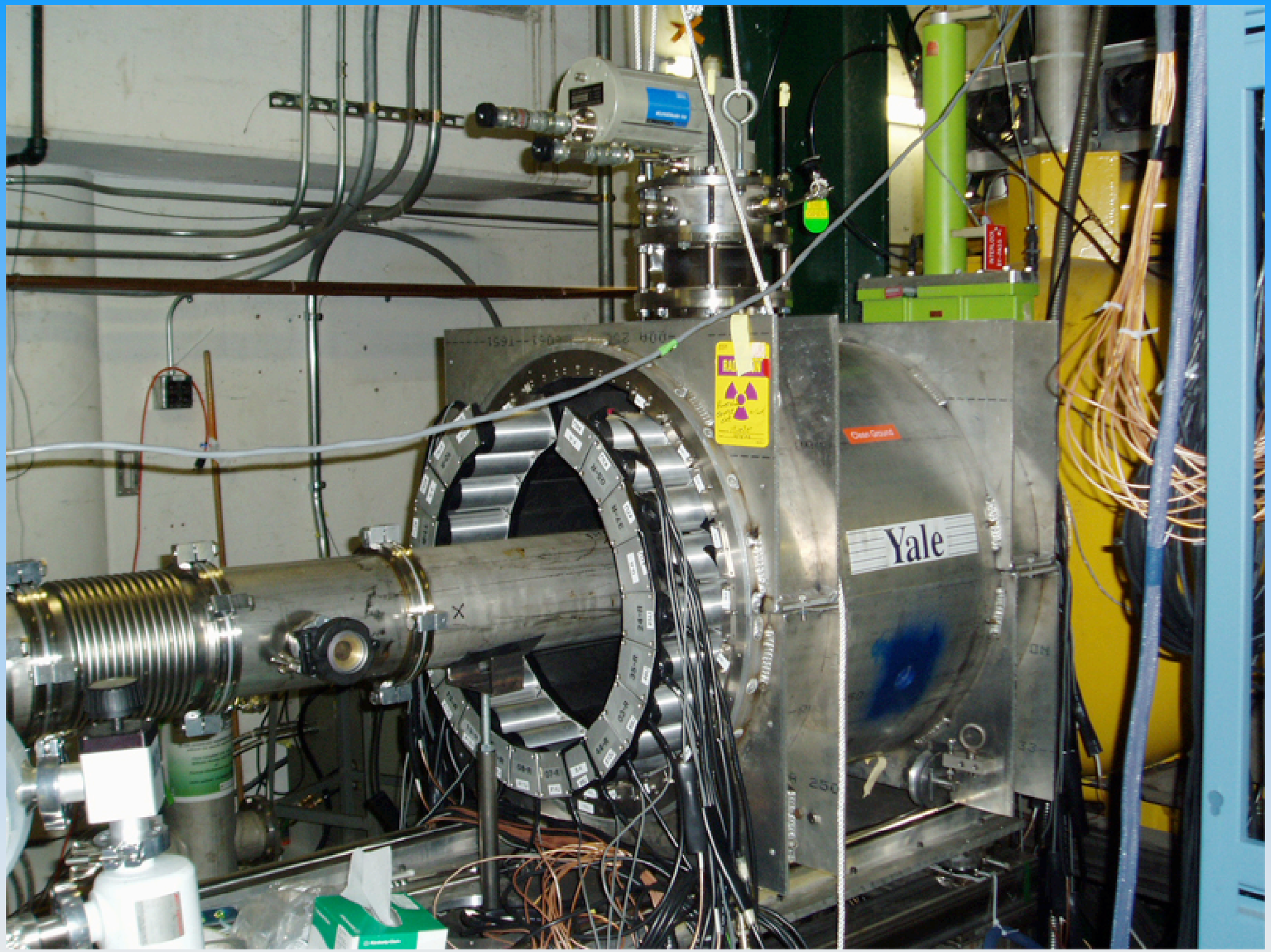

Focal plane
Momentum vector
measurement
Incoming particle
flux measurement
Large acceptance
S800 Spectrograph
at 0°
Incoming momentum
tracking
Reaction target &
Gamma-ray detector array


90° ring
37° ring
^{9}Be reaction target

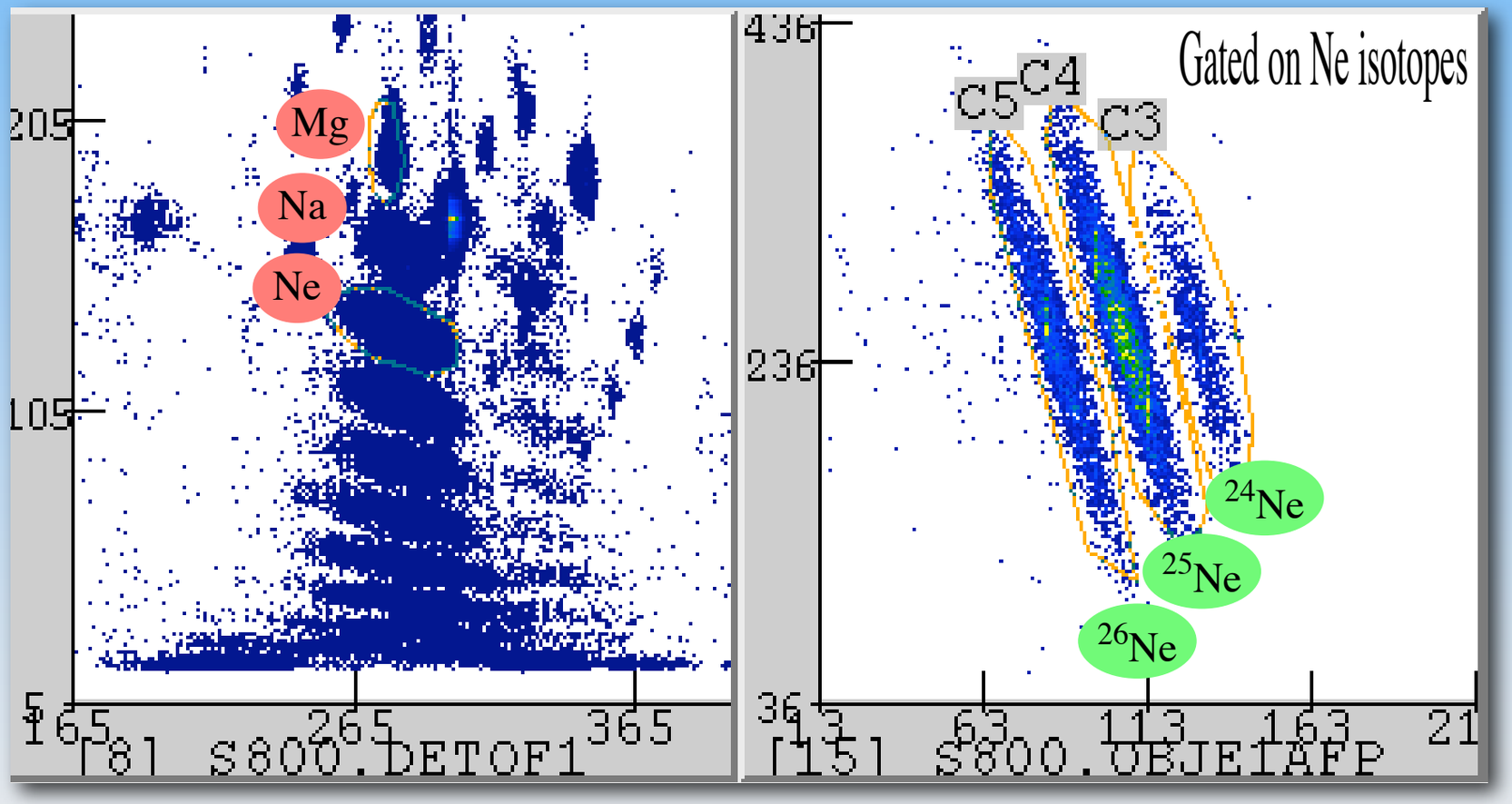

Yale

Observables

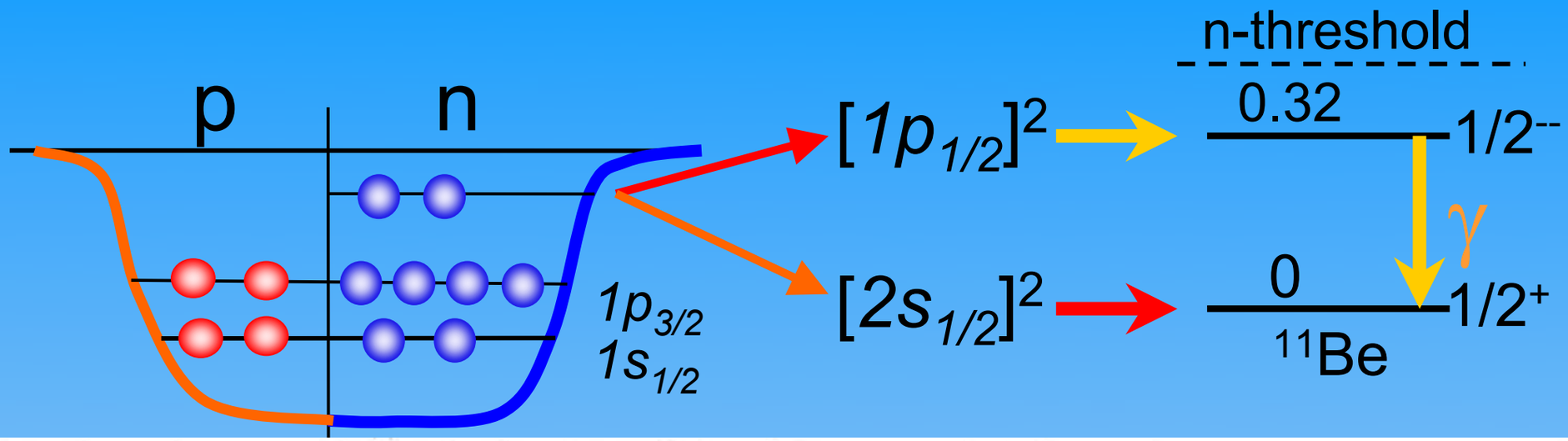
- Inclusive one-nucleon removal cross section
  - Obtained from integrated incident flux and PID of residue
  - In case of cocktail beam incoming particle selected from TOF measurement
- Final state of residue
  - Gamma-rays detected in coincidence with residue
  - In-beam spectroscopy of residue
- Partial cross sections to individual states
  - Deduced using photo-peak efficiencies
  - Require input-output balance in case of feeding from higher states
  - Ground state partial cross section by difference with inclusive
- Angular momentum of removed nucleon
  - Obtained from shape of momentum distribution in coincidence with gamma-ray
  - Shape corresponding to ground state feeding by subtraction with inclusive

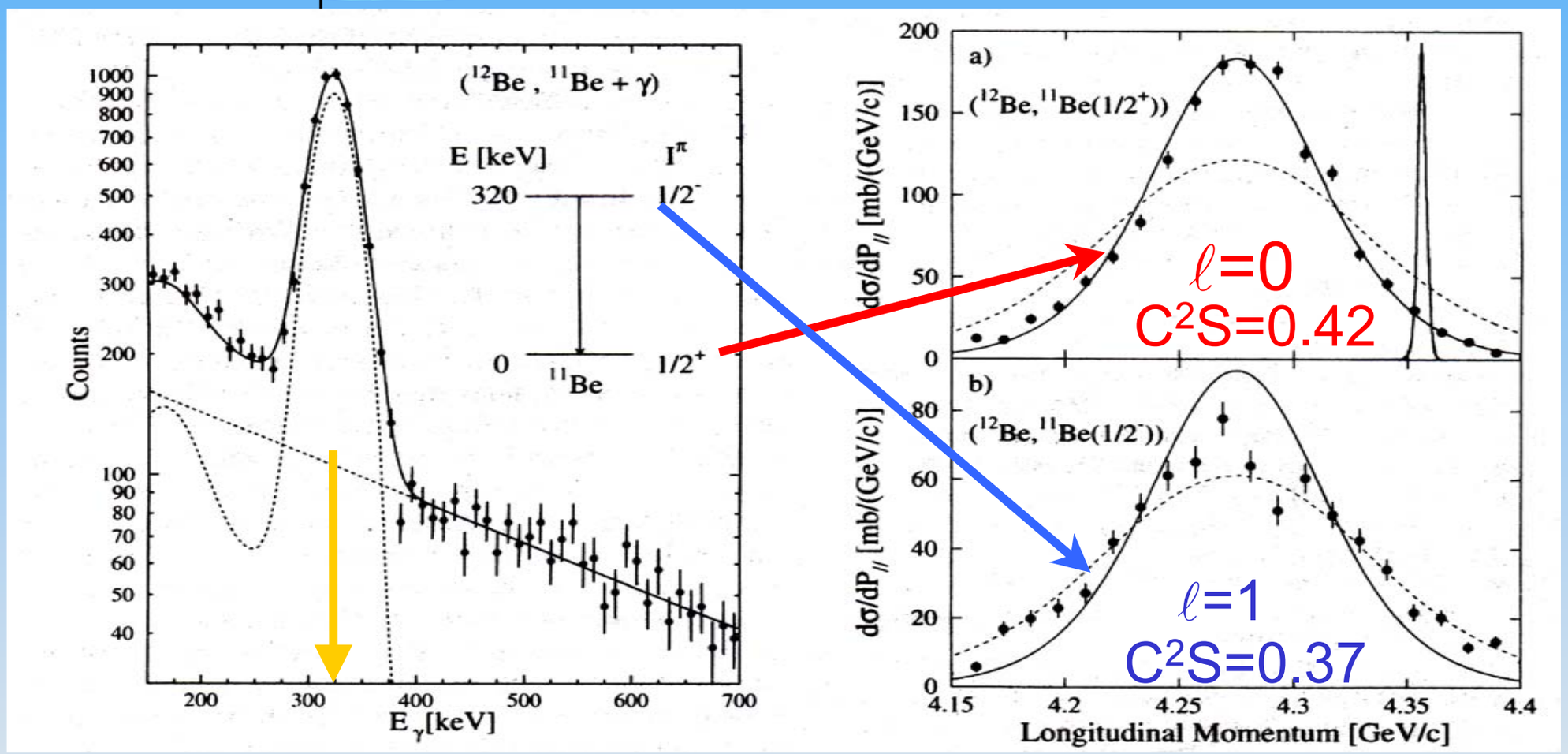
Identification of residue

- Incoming beam and residue atomic number Z
  - Histogram on left shows TOF vs energy-loss
- Mass of residue
  - Histogram on right shows TOF as a function of dispersive angle in focal plane, which is directly related to length of flight path in spectrograph



Break down of N=8 in ^{12}Be

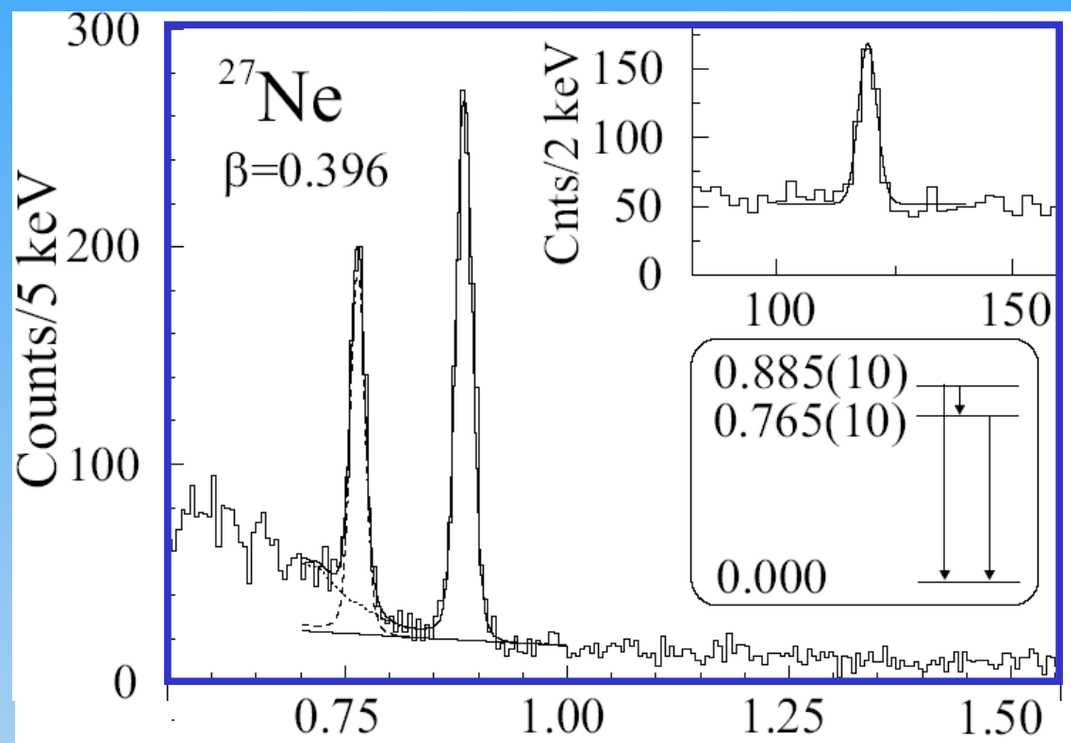


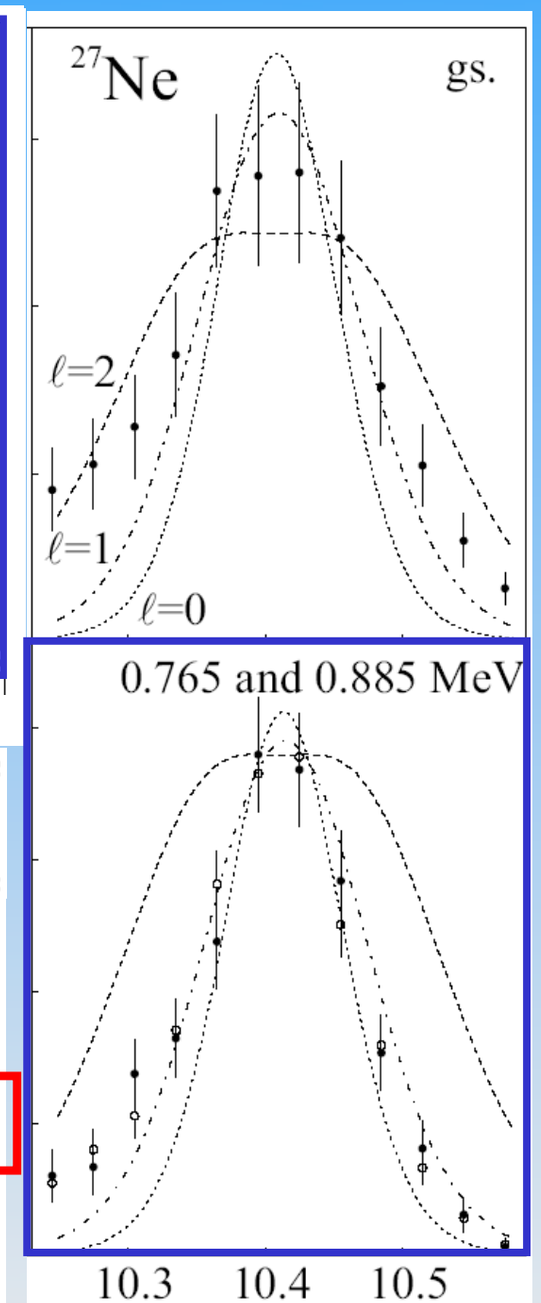


A. Navin et al., Phys. Rev. Lett. 85, 266 (2000)

Intruder configuration in ^{28}Ne

- Feeding to 765 keV state in ^{27}Ne
  - Not predicted by USD
  - Corresponds to l=0,1
  - Predicted by Monte-Carlo shell model from $2p_{3/2}$ orbital



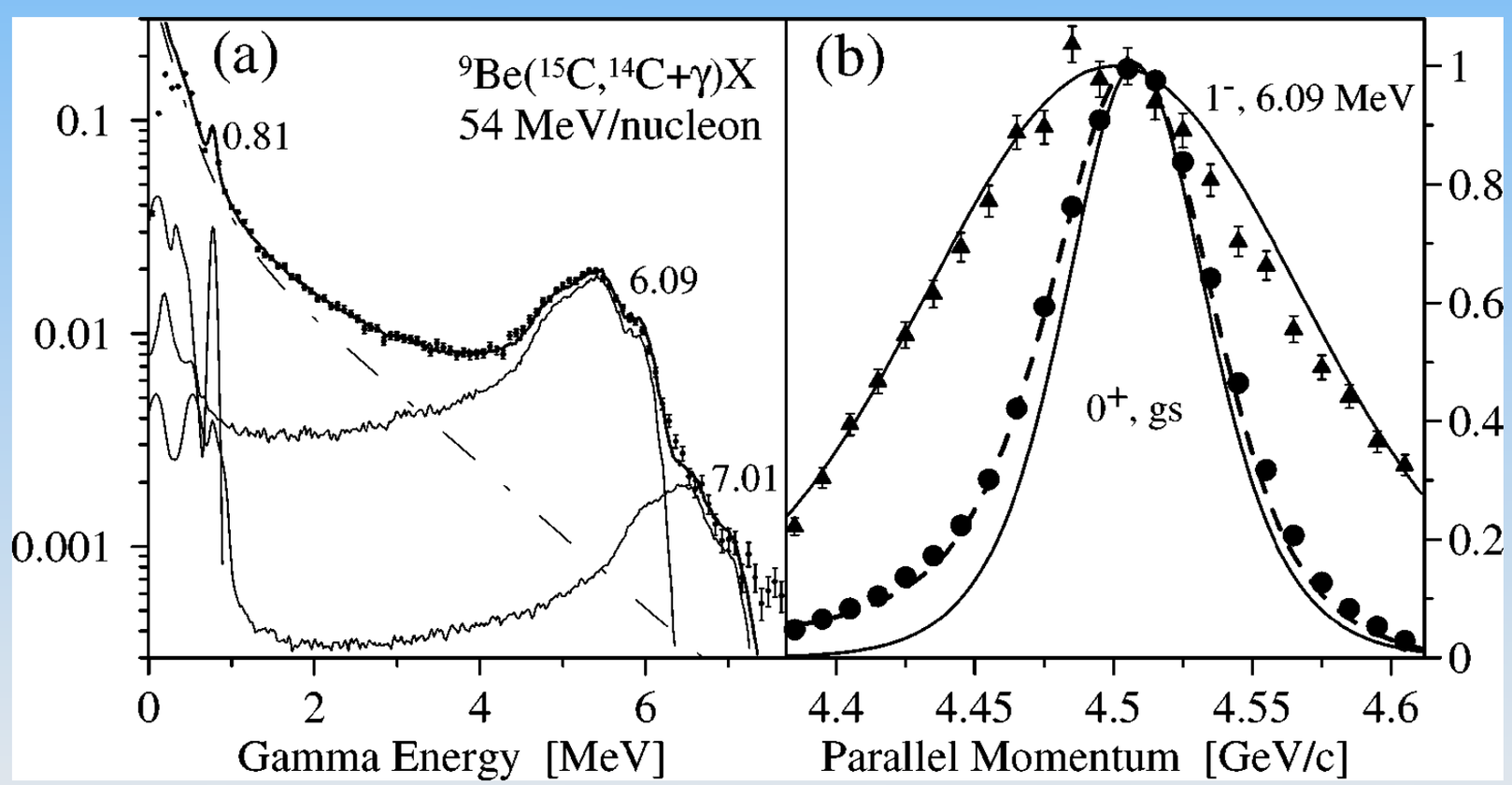


E_{level}	J^{π}	l	b [%]	σ_{obs}	σ_{sp}	C^2S_{obs}	C^2S	$\langle n \rangle$
^{9}Be(^{28}Ne,^{27}Ne)X							$\sigma_{inc} = 66(3)\ mb$	
0.000			31.3(19)	20.6(17)				
0.765	$3/2^{-}$ $	(0,1)	15.6(16)	10.3(12)	32.5	0.317(36)	—	0.244
0.885	$1/2^{+}$ $	(0,1)	53.1(23)	35.0(24)	32.5	1.077(73)	1.612	1.865

J. R. Terry, in preparation

Weakly bound valence state

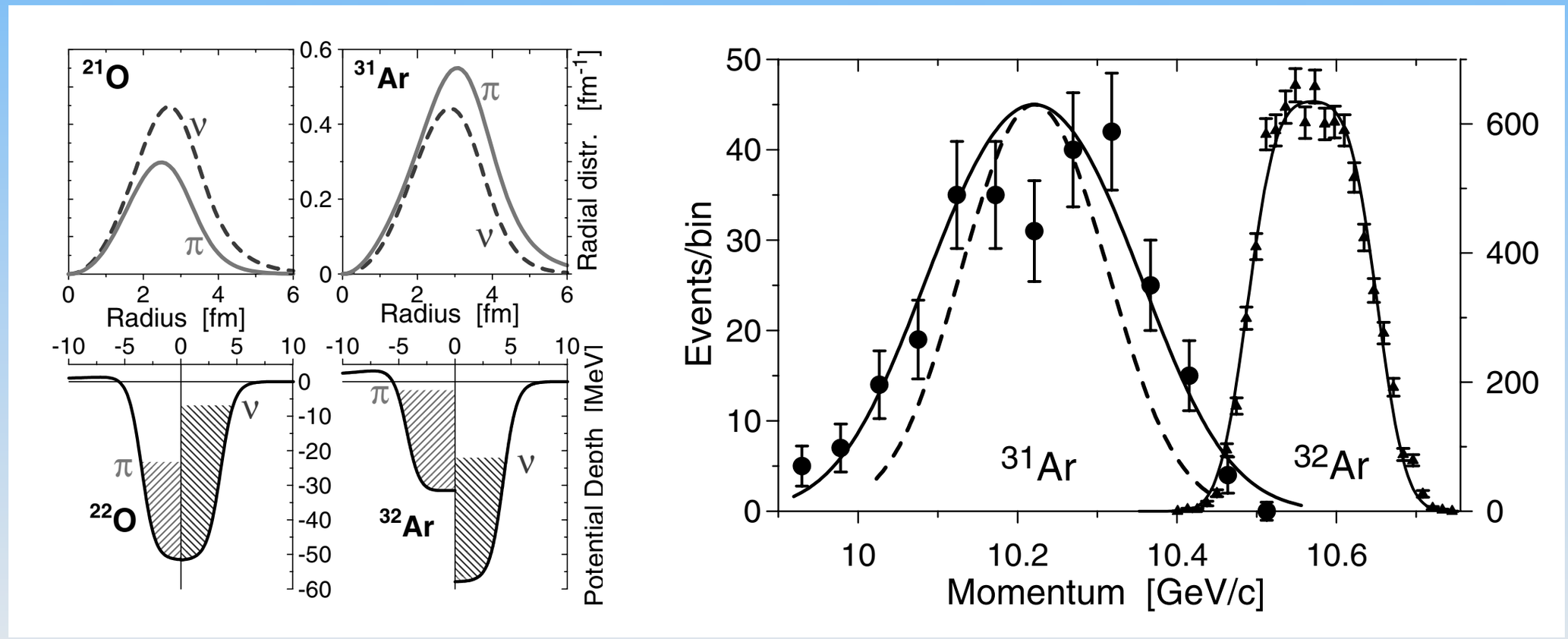
- ^{15}C valence neutron bound by 1.2 MeV
  - Most of the cross section goes to $^{14}C(0^+)$ with l=0
  - Some l=1 component observed in coincidence with $^{14}C(1^-)$
- Reduction factor R_s=0.9(4)(5) for $S[2s_{1/2} \times {}^{14}C(0^+)]$
  - Less effect of correlations on halo state?



J. R. Terry et al., PRC 69, 054306 (2004)

Deeply bound valence state

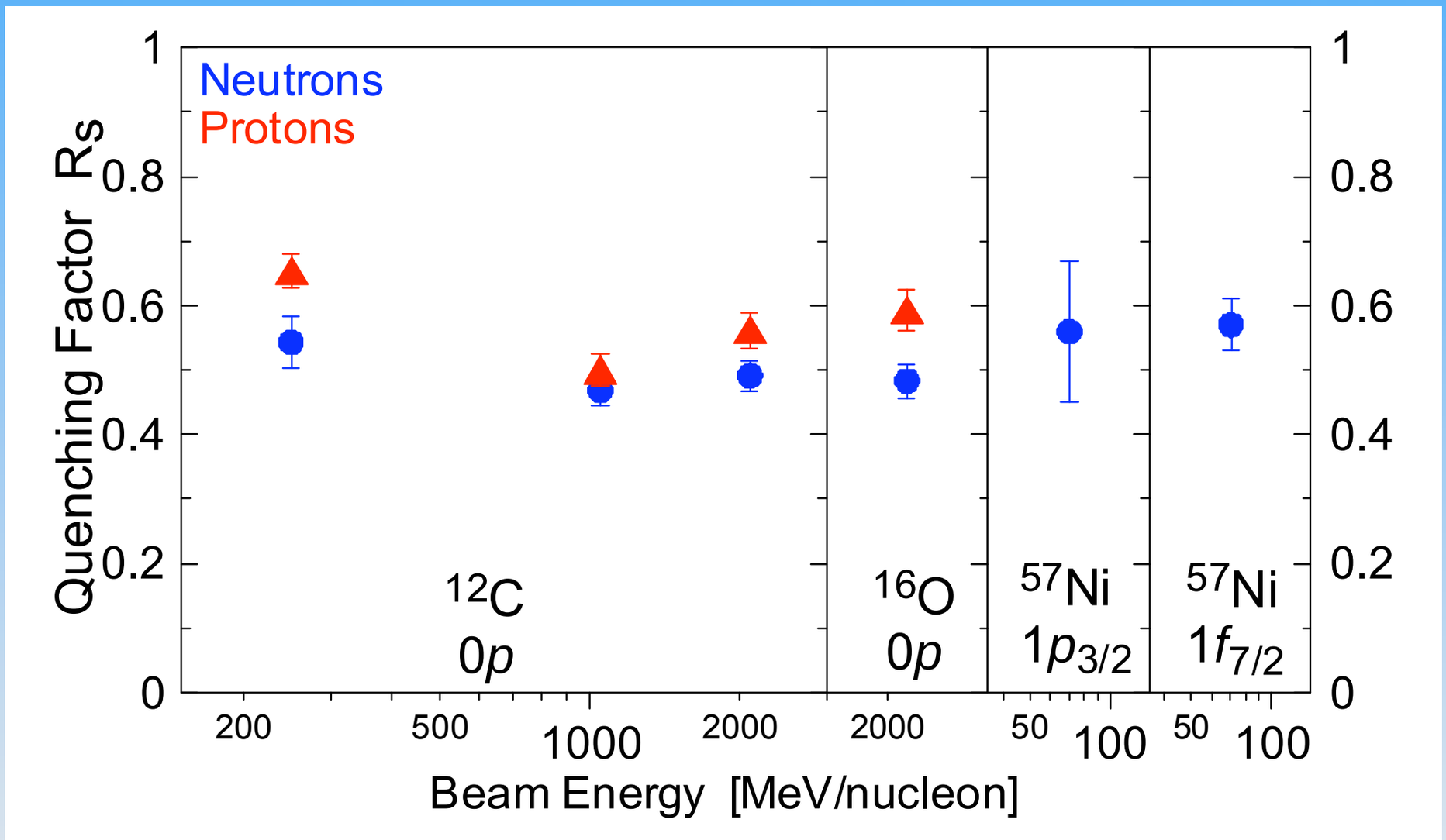
- ^{32}Ar valence neutron bound by 22 MeV
  - Residue ^{31}Ar has no bound excited states
  - Removed neutron has l=2 (solid line)
- Reduction factor R_s=0.24(3) for S[$1d_{5/2}$ x ^{31}Ar($5/2^+$)]
  - In contrast, ^{22}O has R_s=0.7(6) with neutron separation energy 6.8 MeV



A. Gade et al., PRL 93, 042501 (2004)

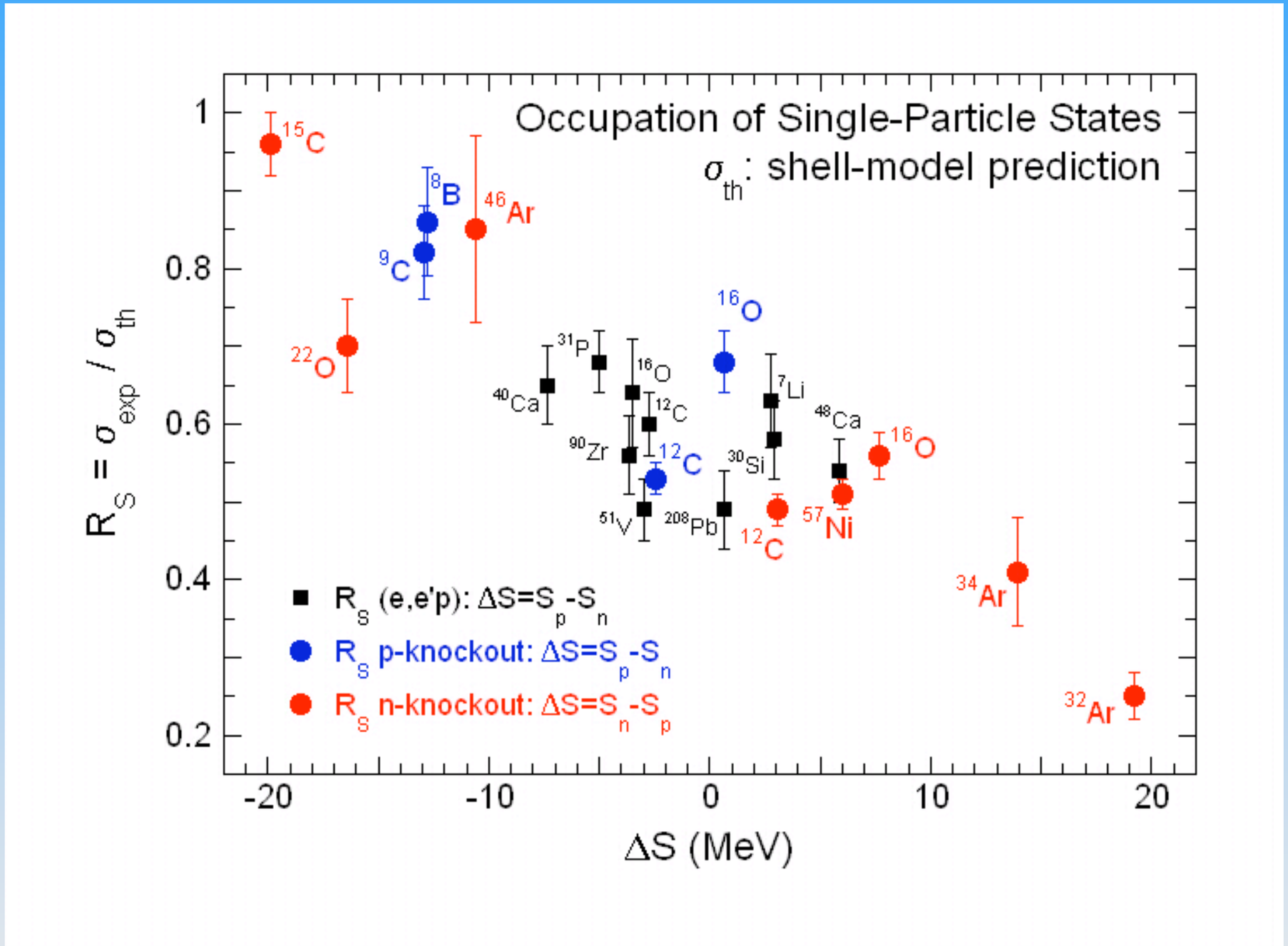
Stable nuclei

- Reduction factor consistent with (e,e'p) results
- Neutron reduction factor consistent with proton



Global picture

- Trend observed in stable nuclei not conserved when going towards drip lines



Comparison with ab initio theory in p-shell nuclei

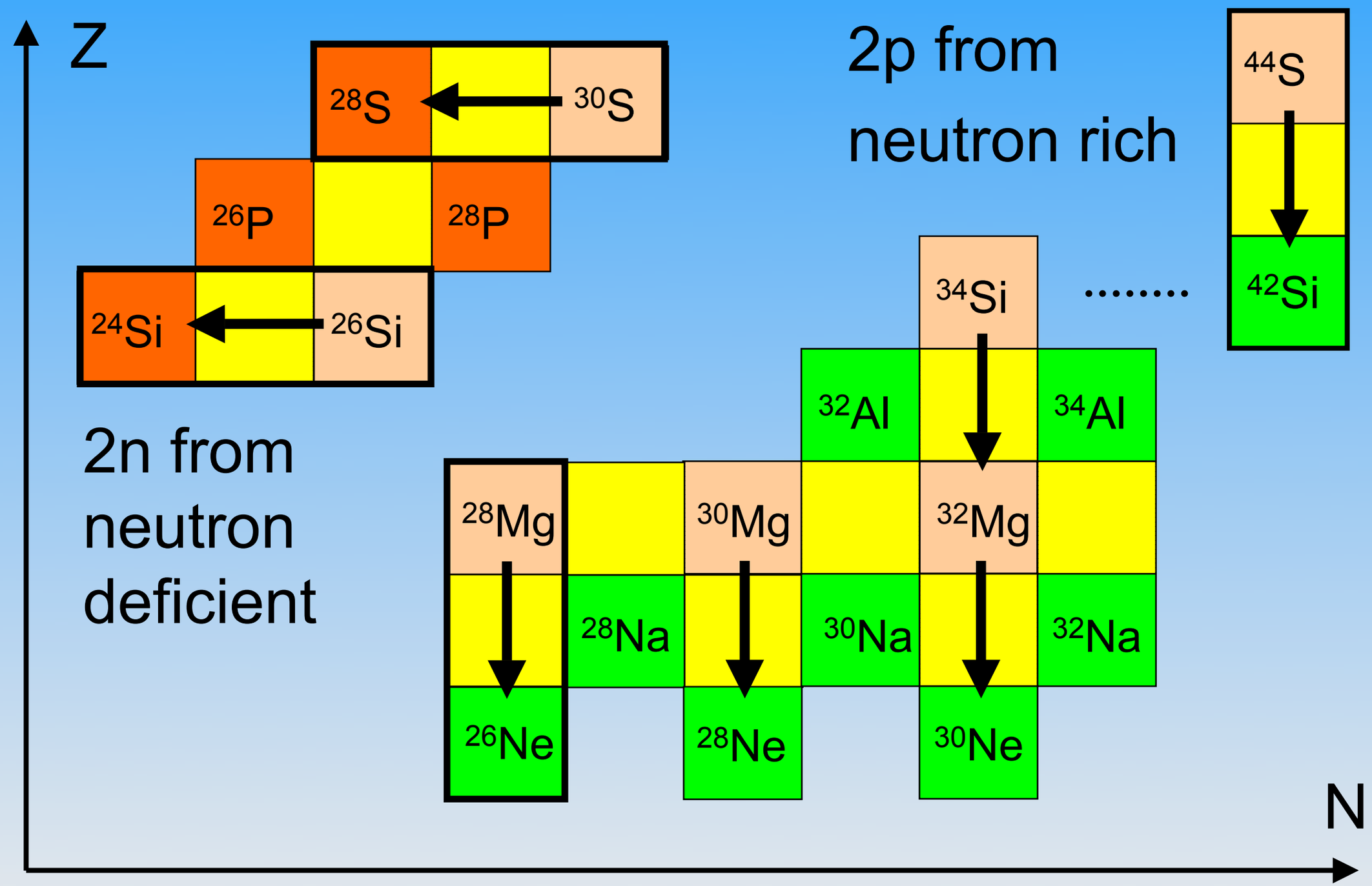
- Unstable nuclei accessible via knockout reactions
  - Experiment performed to study the reactions ^{10}Be-1n, ^{10}C-1n, ^{10}Be-1p, ^{9}Li-1n
  - Data under analysis

Initial state	Final state	S_n or S_p (MeV)	Spectroscopic Factor				
			PJT[b)]	VMC[a)]	Exp.	Method	Ref.
^{7}Li (3/2$^-$)	^{6}He(0$^+$,2$^+$)	10.0	1.15	0.55	0.58(3)	(e,e'p)	c)
^{8}B(2$^+$)	^{7}Be(3/2$^-$,1/2$^-$)	0.14	1.44	1.27	1.23(6)	Knockout	d)
^{9}C(3/2$^-$)	^{8}B(2$^+$)	1.3	1.03	1.11	0.85(6)	Knockout	d)
^{10}Be(0$^+$)	^{9}Be(3/2$^-$)	6.8	2.36	1.93	-	Knockout	
^{10}C(0$^+$)	^{9}C(3/2$^-$)	21.3	1.74	1.09	-	Knockout	
^{10}Be(0$^+$)	^{9}Li(3/2$^-$)	19.6	1.74	1.09	-	Knockout	
^{9}Li(3/2$^-$)	^{8}Li(2$^+$)	4.1	0.9	1.11	-	Knockout	

a) S.C. Pieper and R.B Wiringa, Annu. Rev. Nucl. Part. Sci. 51, 53 (2001)
b) B.A. Brown, Prog. Part. Nucl. Phys. 47, 517 (2001)
c) L. Lapikás, J. Wesseling and R.B. Wiringa, Phys. Rev. Lett. 82, 4404 (1999)
d) B.A. Brown et al., Phys. Rev. C 65, 061601 (2002); J.Enders et al., Phys. Rev. C 67, 064301 (2003).

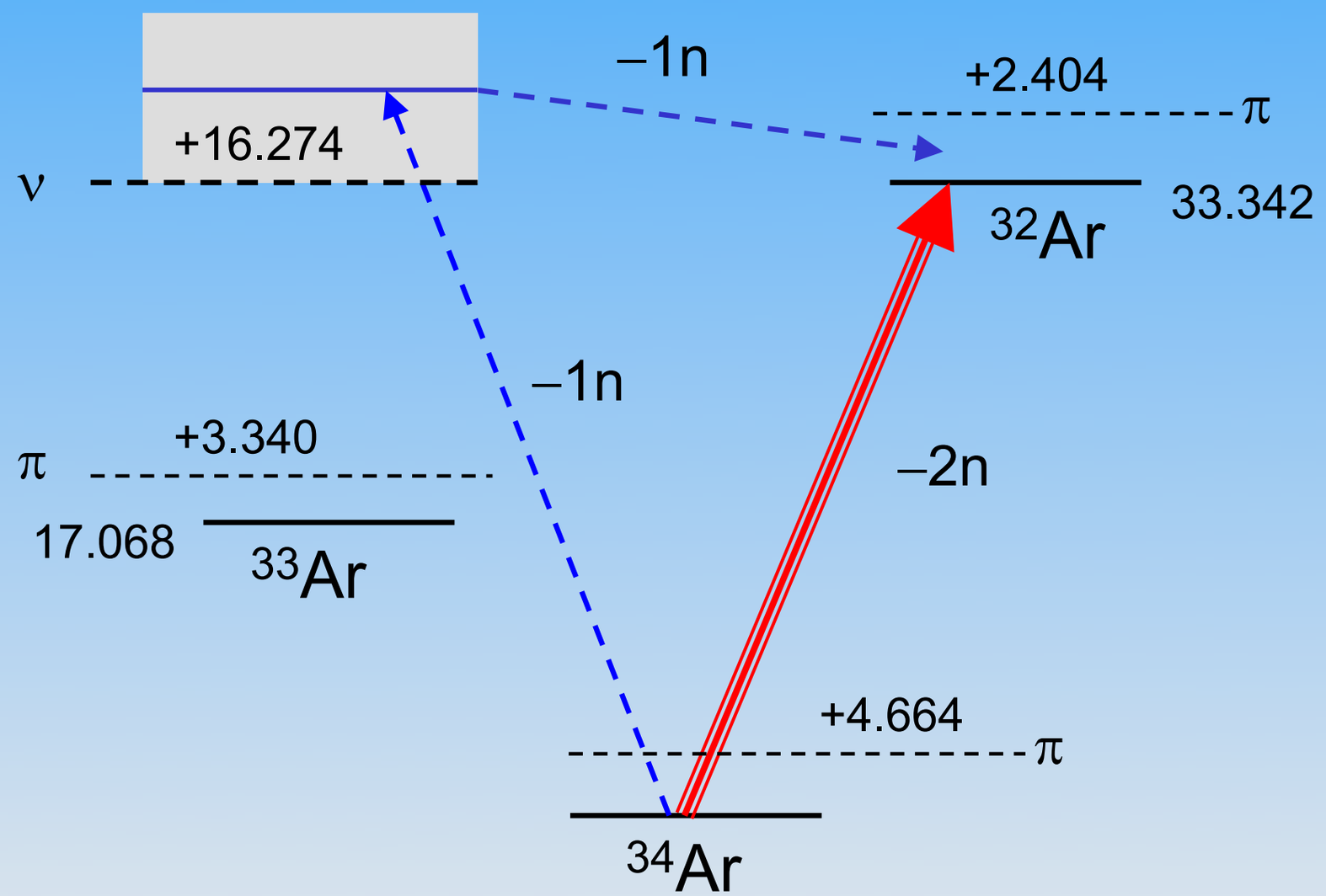
Two-nucleon knockout reactions

- Direct reaction depending on isospin



Direct reaction

- Two-step process suppressed
  - In neutron-deficient nuclei for instance, proton evaporation channel open much lower than neutron threshold



Eikonal theory

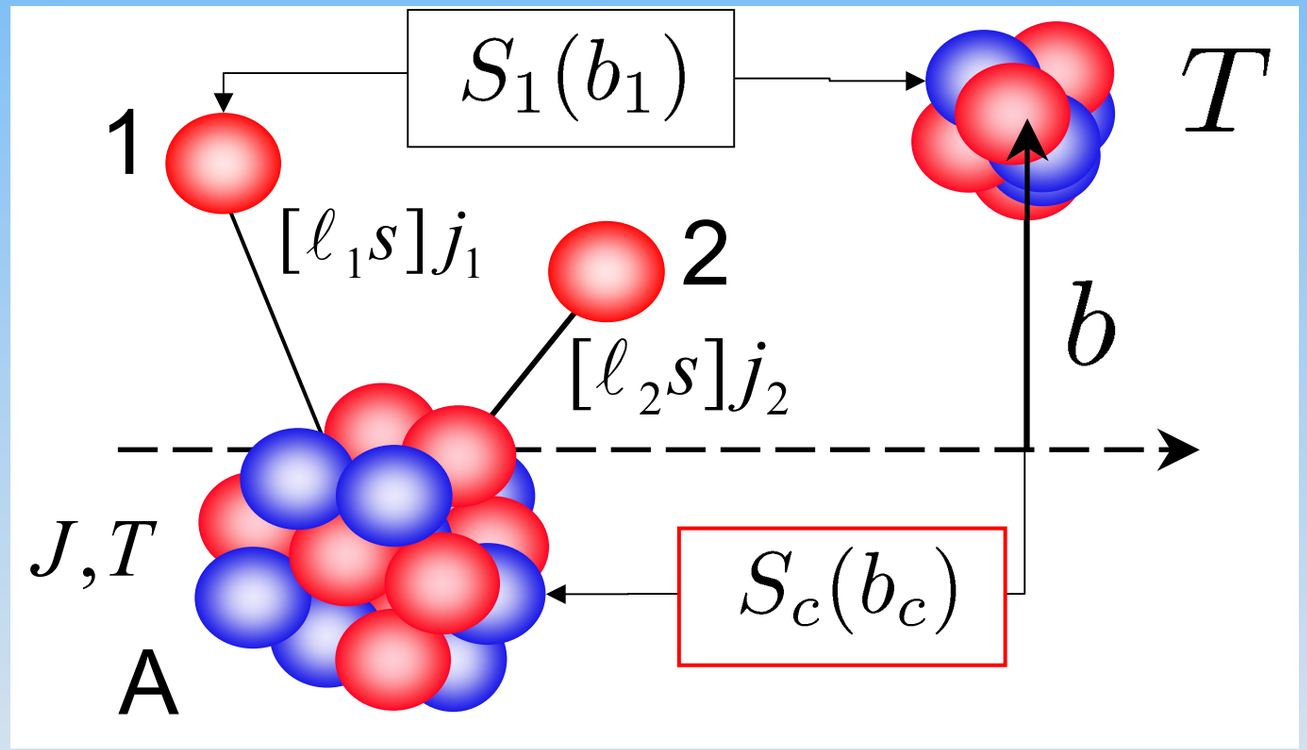
- Three possible mechanisms
  - Dominant channel is 2N stripping: both nucleons absorbed

$$|S_c|^2(1-|S_1|^2)(1-|S_2|^2)$$

  - 1N stripping / 1N diffraction: one nucleon absorbed, the other scattered

$$|S_c|^2|S_1|^2(1-|S_2|^2) \qquad |S_c|^2(1-|S_1|^2)|S_2|^2$$

  - 2N diffraction: both nucleons scattered
    - Estimated as square of single-nucleon diffraction ~5%



J. A. Tostevin et al., Phys. Rev. C 70, 064602 (2004),
J. A. Tostevin, in preparation

Two-nucleon amplitudes

- Two-nucleon overlap functions in projectile ground state

$$\Psi_{JM} = \sum_{\alpha I} C_{\alpha}^{JIc} [\overline{[\phi_{j_1\ell_1}(1) \otimes \phi_{j_2\ell_2}(2)]_I} \otimes \phi_c]_{JM}, \alpha \equiv (j_1\ell_1, j_2\ell_2)$$

  - Sum of all possible two-particle configurations relative to the residue final state
  - Use shell model amplitudes calculated from a set of active single-particle orbits

- No factorization between S.F. and σ_{sp}
  - Spectroscopic information based on cross section comparison

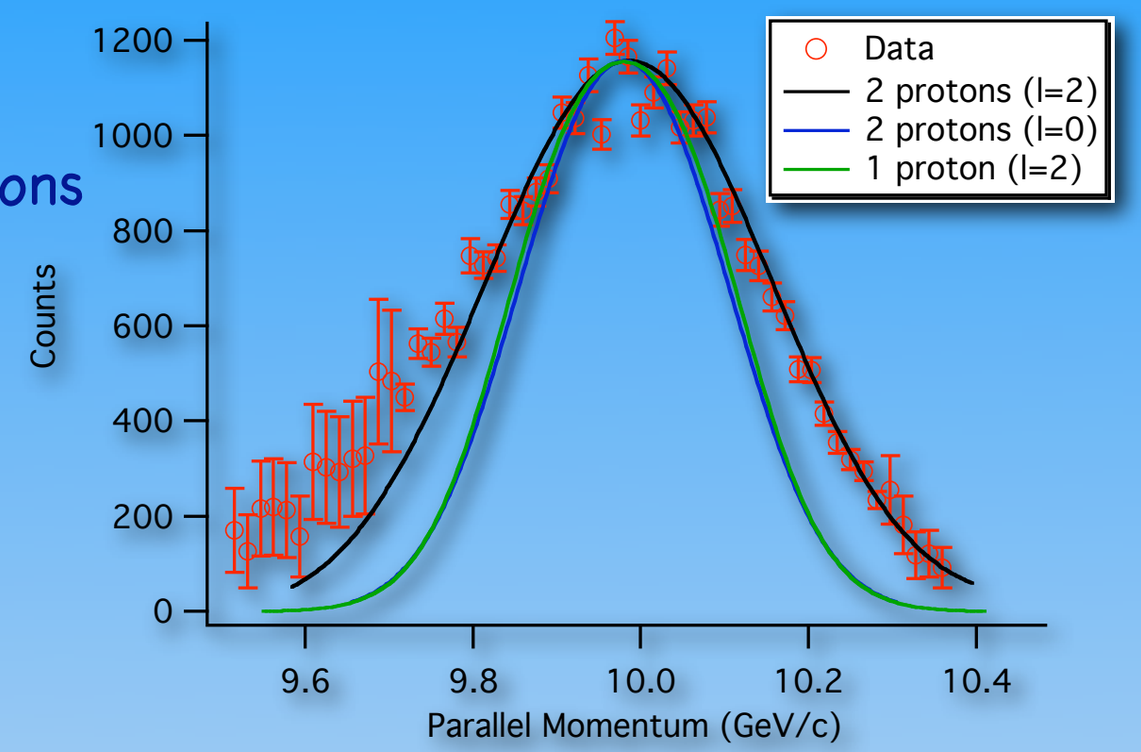
TABLE II. The *sd*-shell model two-nucleon spectroscopic amplitudes $C_{\alpha}^{J_iJ_fI}(\equiv C_{\alpha}^{0J_fJ_f})$ for the required ^{28}Mg$(0^+) \rightarrow {}^{26}Ne(J_f^{\pi})$ two-proton removal transitions. The assumed phase conventions are discussed in the text.

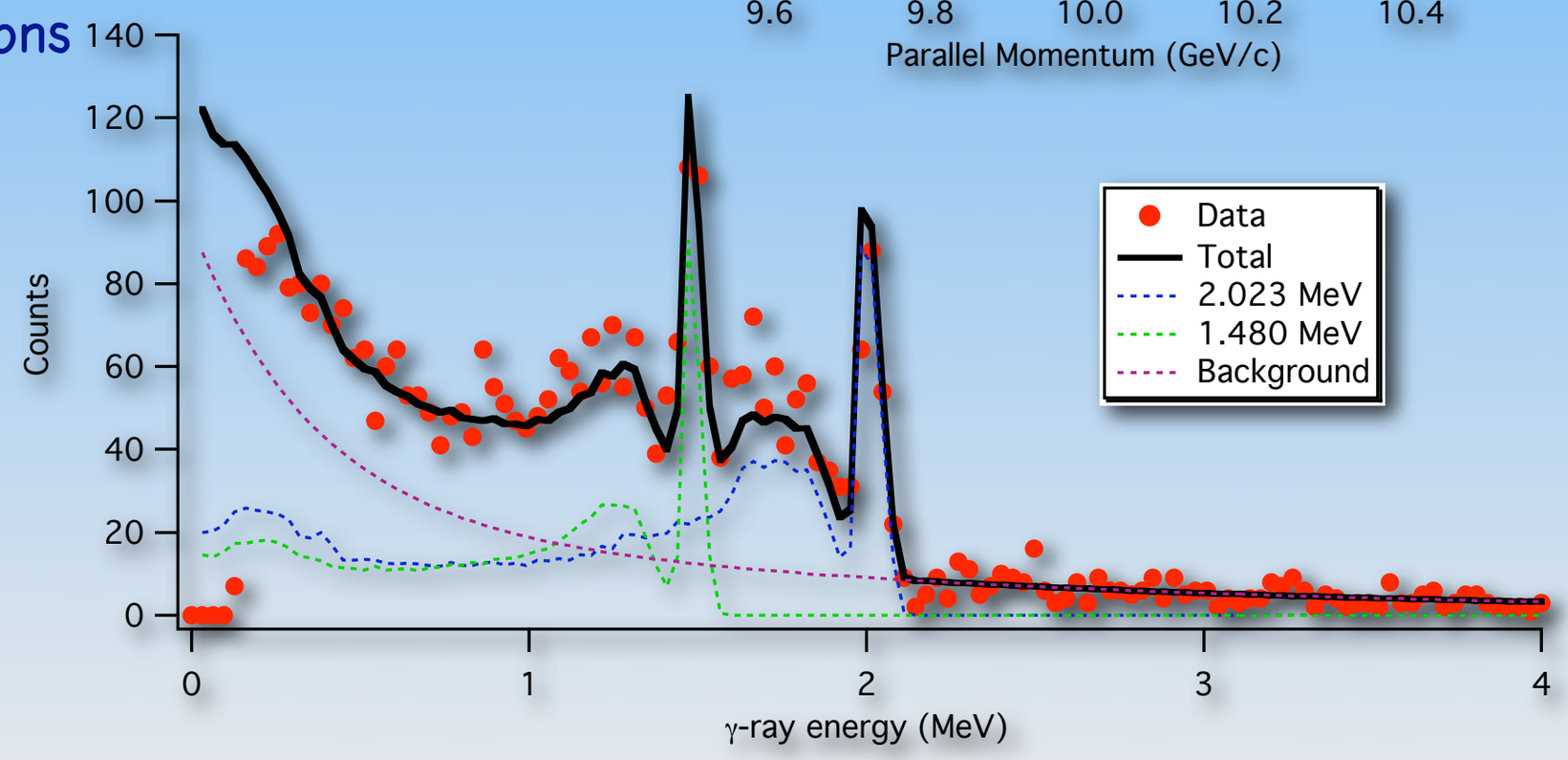
J_f^{π}	E^* (MeV)	$[0d_{3/2}]^2$	$[0d_{3/2}0d_{5/2}]$	$[0d_{5/2}]^2$	$[1s_{1/2}0d_{3/2}]$	$[1s_{1/2}0d_{5/2}]$	$[1s_{1/2}]^2$
0_1^+	0.0	–0.30146	—	–1.04685	—	—	–0.30496
2_1^+	2.02	–0.05030	0.37358	–0.63652	–0.06084	–0.13916	—
4_1^+	3.50	—	0.33134	1.59639	—	—	—
2_2^+	3.70	0.04721	–0.07248	0.85297	0.16158	0.17590	—

J. A. Tostevin et al., Phys. Rev. C 70, 064602 (2004)

Two-proton knockout from ^{28}Mg

- Momentum distribution
  - Calculated for two uncorrelated protons
  - Shape matches removal from $1d_{5/2}$
- Coincident gamma-rays
  - Feeding of ^{26}Ne(2^+) and ^{26}Ne(4^+)
  - Partial cross sections





D. Bazin et al., PRL 91, 012501 (2003)

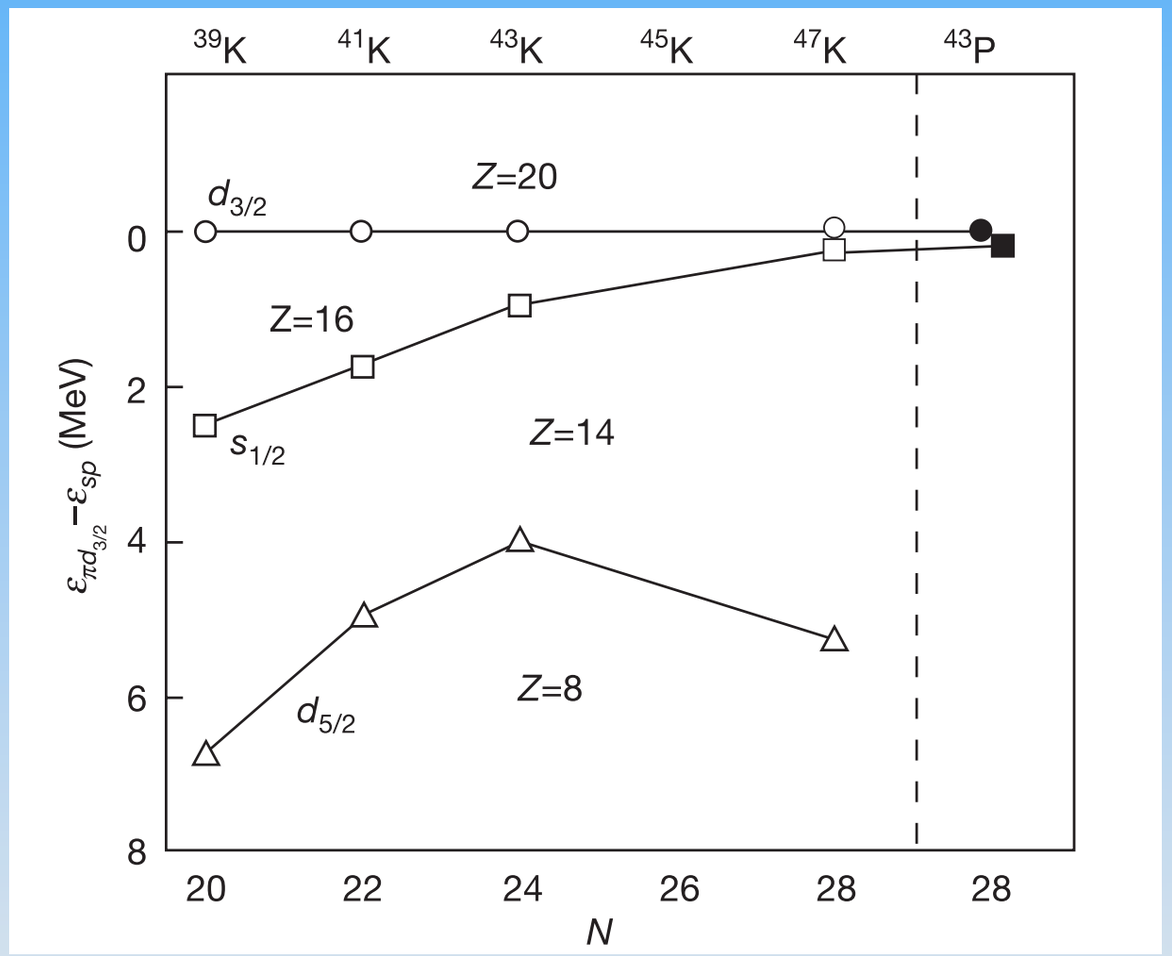
Comparison with theory

- Partial and inclusive cross sections
  - Uncorrelated cross sections unable to follow experimental data
  - Observed depletion of 2+ state accounted for (interference effects in W.F.)
  - Inclusive Reduction factor $R_S(2N) = 1.50(10) / 2.514 = 0.60(4)$
- Diffractive components
  - Account for 42% of the cross section
  - 2N diffraction small fraction (6 %)

^{26}Ne (J^π)	Stripping^2	Diff/Strip	Diffraction^2	Sum	Exp	Uncorr
0^+	0.543	0.389	0.070	1.002	0.70(15)	0.386
2^+	0.159	0.093	0.014	0.266	0.09(15)	0.484
4^+	0.524	0.296	0.042	0.862	0.58(9)	0.870
2_2^+	0.229	0.135	0.020	0.384	0.15(9)	-
Inclusive	1.455	0.913	0.145	2.514	1.50(10)	1.74

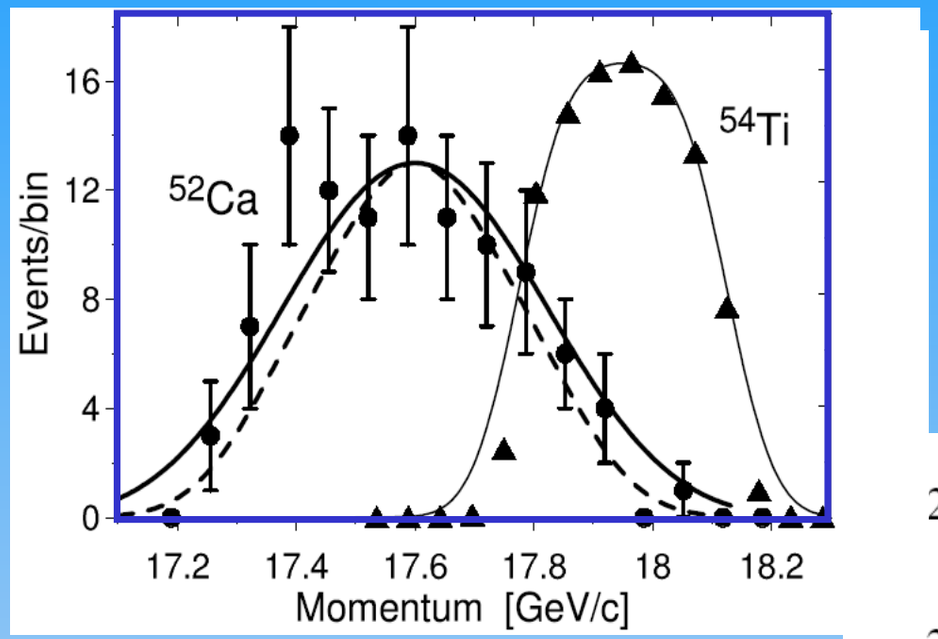
The structure of ^{42}Si

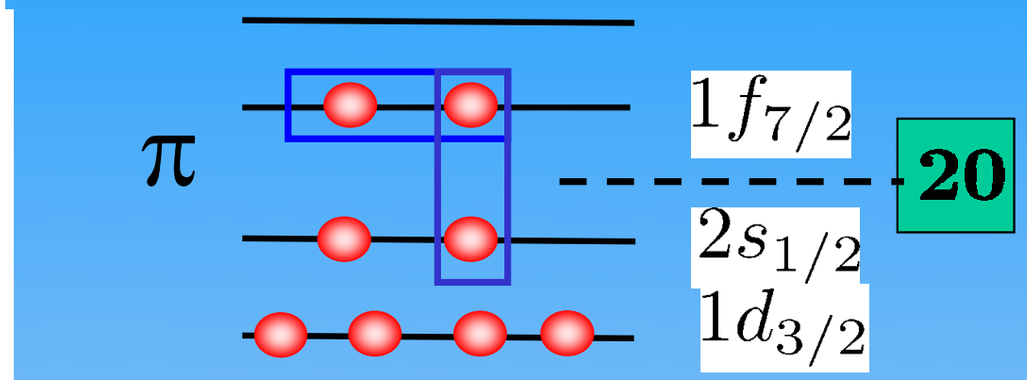
- One-proton knockout ^{9}Be(^{44}S, ^{43}P)X
  - Near degeneracy between proton orbits $1d_{3/2}$ and $2s_{1/2}$
  - Gap to the filled $1d_{5/2}$ at Z=14 is large
- Two-proton knockout ^{9}Be(^{44}S, ^{42}Si)X
  - No gamma-ray observed in ^{42}Si
  - Very small inclusive cross section: 0.12(2) mb
  - Calculated stripping with 70% $[1d_{5/2}]^2$ configuration: 0.17 mb
- Sub-shell closure at Z=14 in ^{42}Si

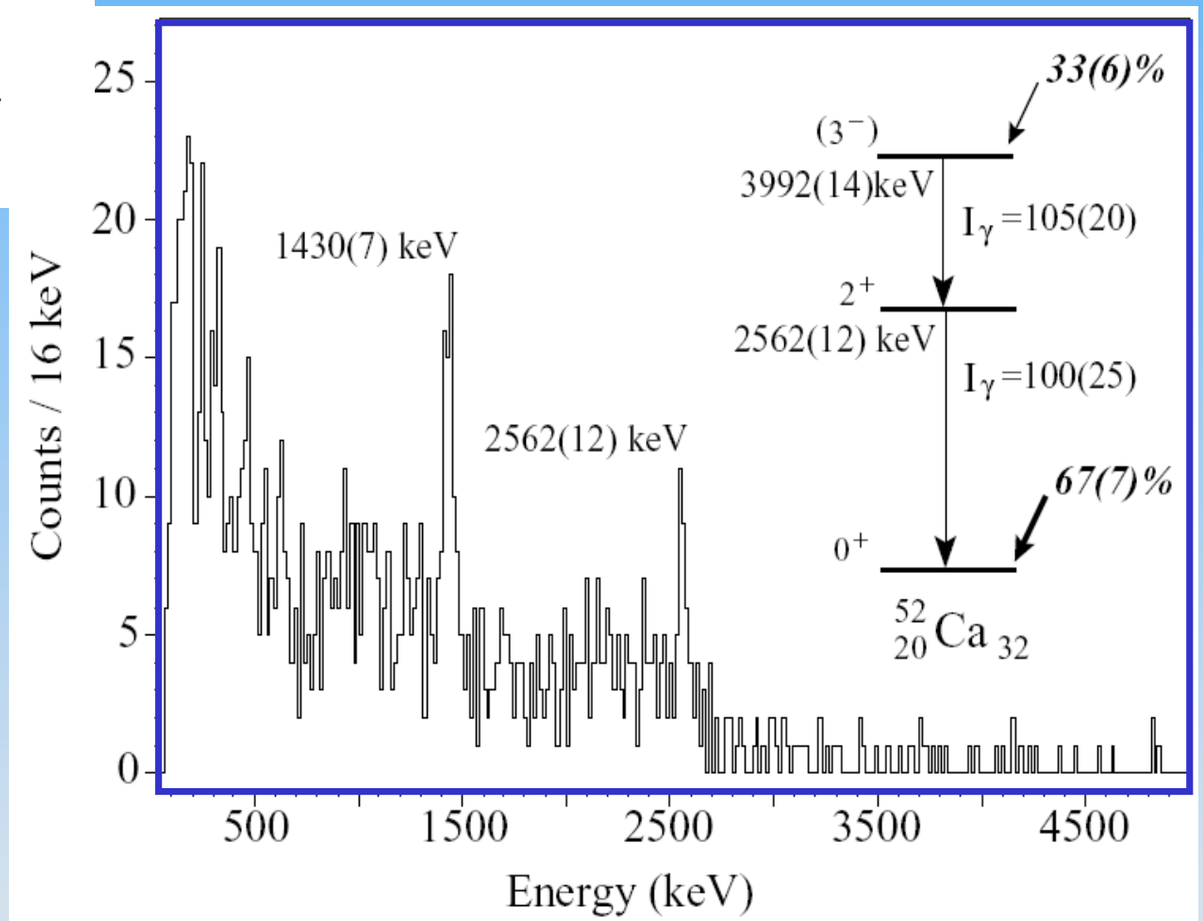


J. Fridmann et al., Nature 435, 922 (2005)

Two-proton removal from ^{54}Ti







Experiment:

Inclusive 0.32(4) mb

Theory: "Preliminary"

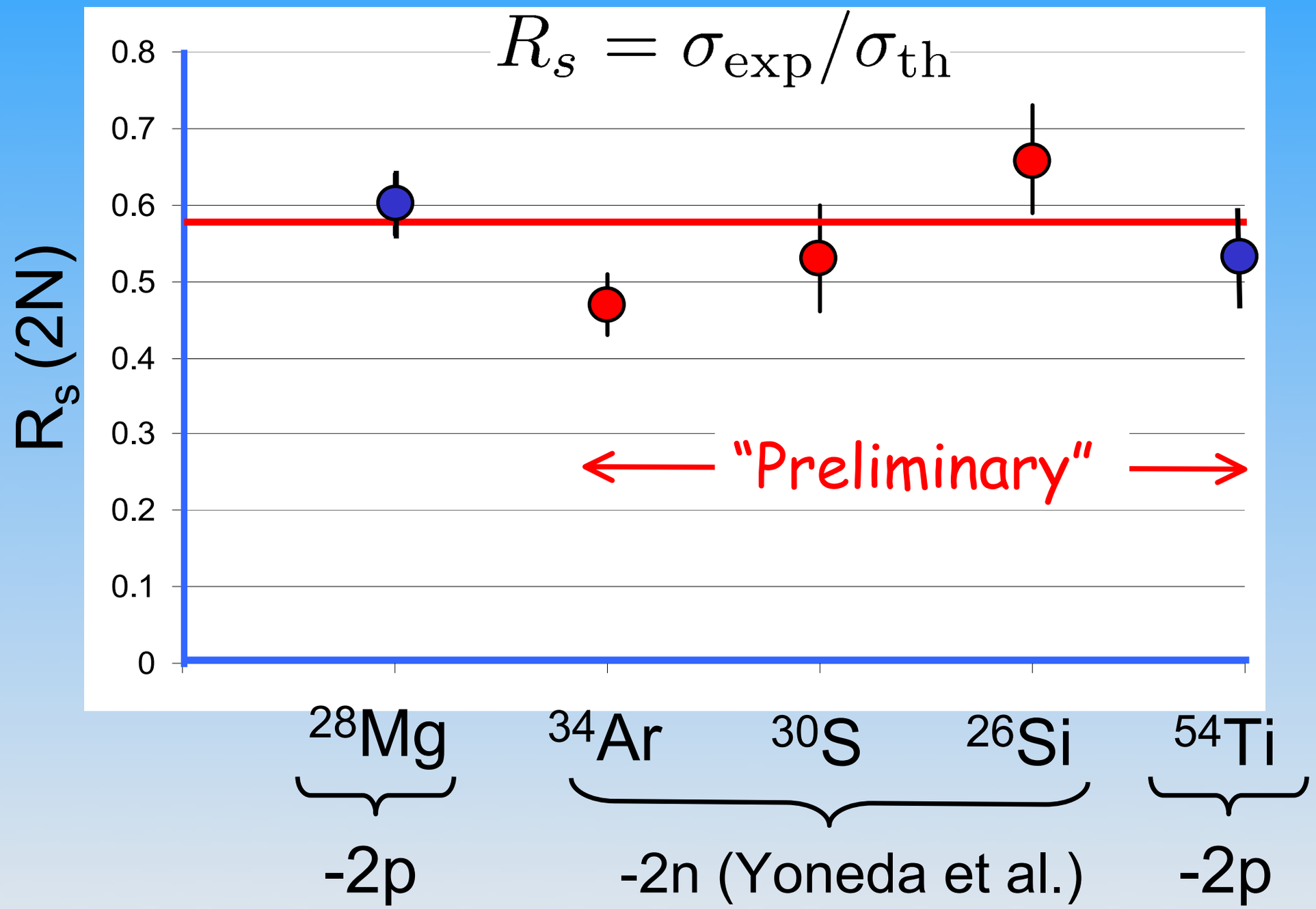
(3^-): 50%[$s_{1/2}$]+50%[$d_{3/2}$]

Inclusive 0.60 mb

0^+ 63%, 3^- 37%, 2^+ 0%

A. Gade et al., ~~in preparation 2005~~
in press in PRC

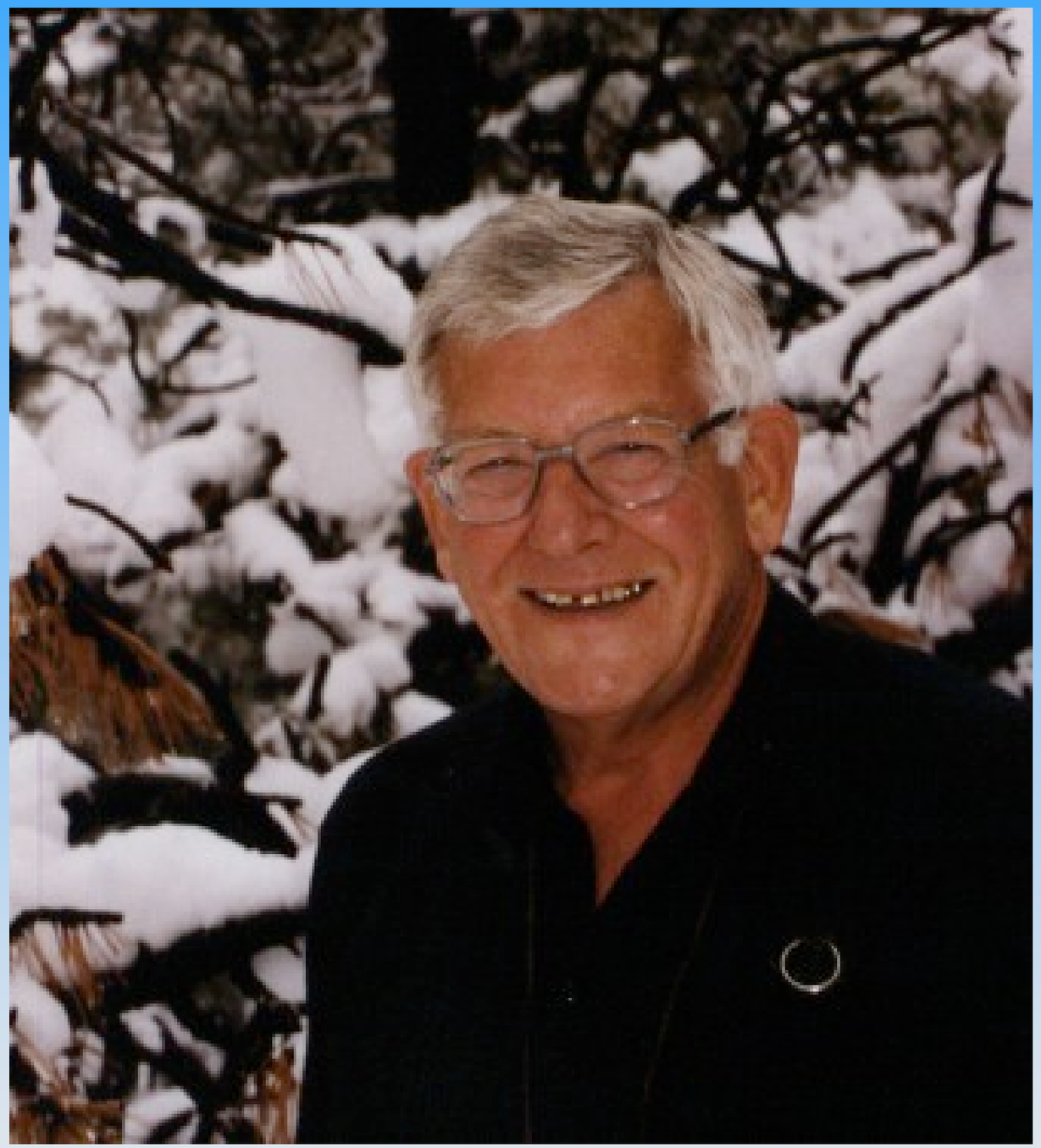
Reduction factor in two-nucleon removal



Conclusion

- One-nucleon knockout reactions
  - Powerful tool to study wave function of nuclei far from stability
  - Use of simple and well constrained eikonal theory
  - Extract absolute spectroscopic factors to compare with structure theory
  - Wide variation of single-particle strength reduction observed near drip lines
- Two-nucleon knockout reactions
  - Direct reaction depending on isospin
  - Leads to extremely rare nuclei
  - Eikonal theory in final stages of completion
  - Reduction factor also smaller than unity
  - Possibility to study NN correlations

Dedication



- Gregers Hansen pioneered the field of knockout reactions with fast radioactive beams
- At the NSCL, we are continuing his quest for the understanding of the nucleus using knockout reactions