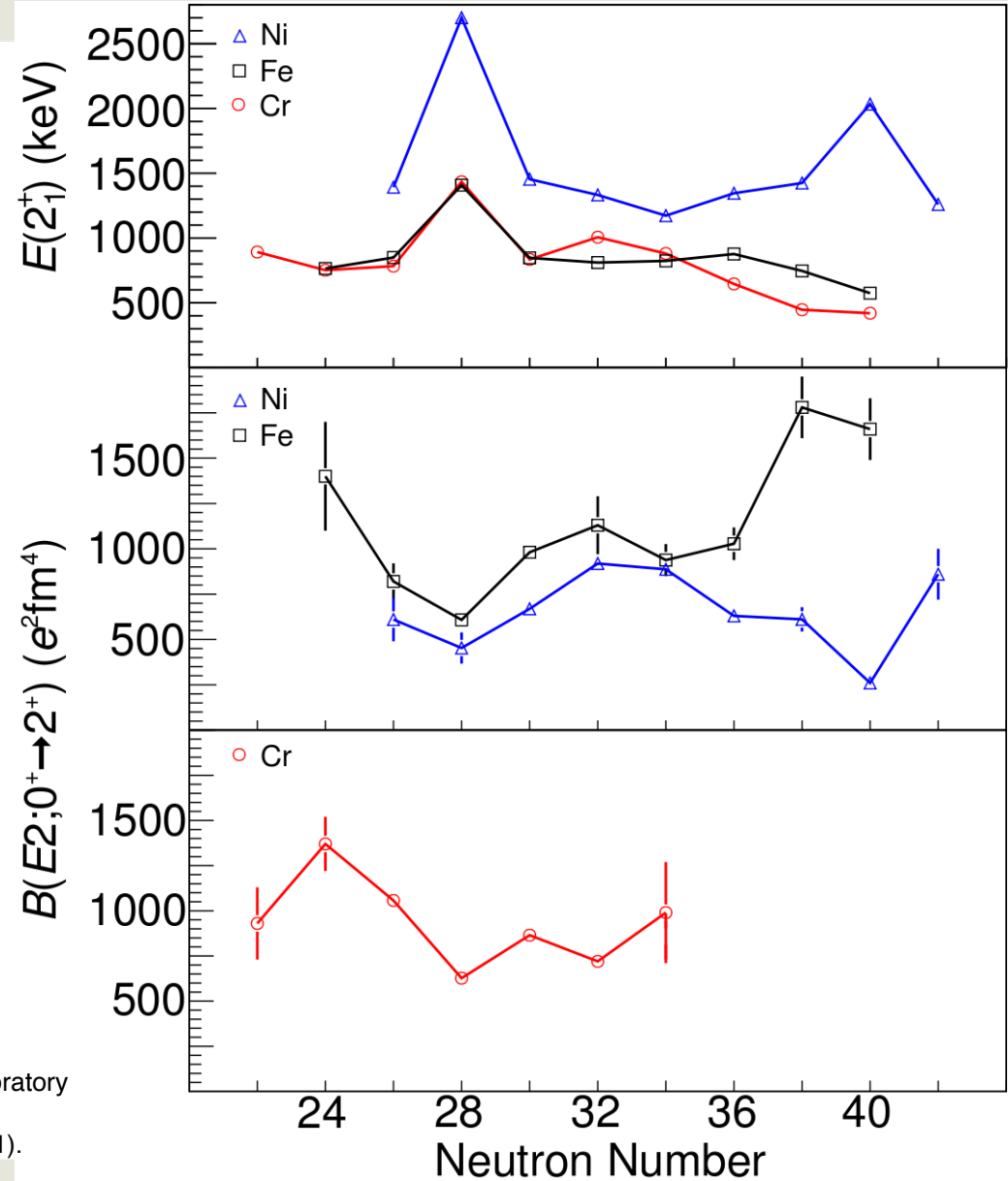
Coulomb excitation of Cr isotopes approaching *N*=40

Travis Baugher
NS2012
August 13, 2012

Collectivity in the *pf*-shell

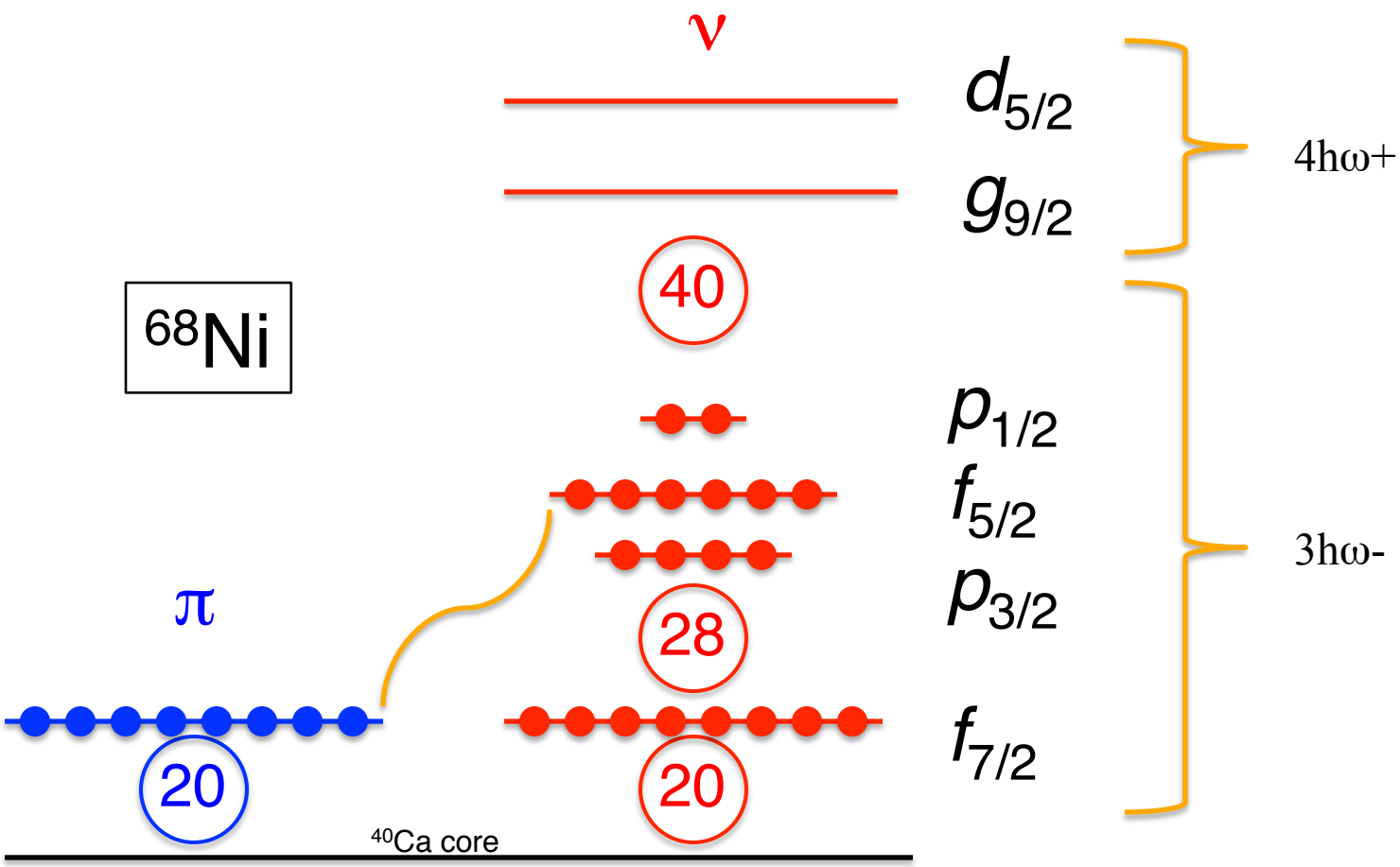
^{60}Ni	^{61}Ni	^{62}Ni	^{63}Ni	^{64}Ni	^{65}Ni	^{66}Ni	^{67}Ni	^{68}Ni
^{59}Co	^{60}Co	^{61}Co	^{62}Co	^{63}Co	^{64}Co	^{65}Co	^{66}Co	^{67}Co
^{58}Fe	^{59}Fe	^{60}Fe	^{61}Fe	^{62}Fe	^{63}Fe	^{64}Fe	^{65}Fe	^{66}Fe
^{57}Mn	^{58}Mn	^{59}Mn	^{60}Mn	^{61}Mn	^{62}Mn	^{63}Mn	^{64}Mn	^{65}Mn
^{56}Cr	^{57}Cr	^{58}Cr	^{59}Cr	^{60}Cr	^{61}Cr	^{62}Cr	^{63}Cr	^{64}Cr



Motivation:
- What are the driving forces?
- What happens in Cr?

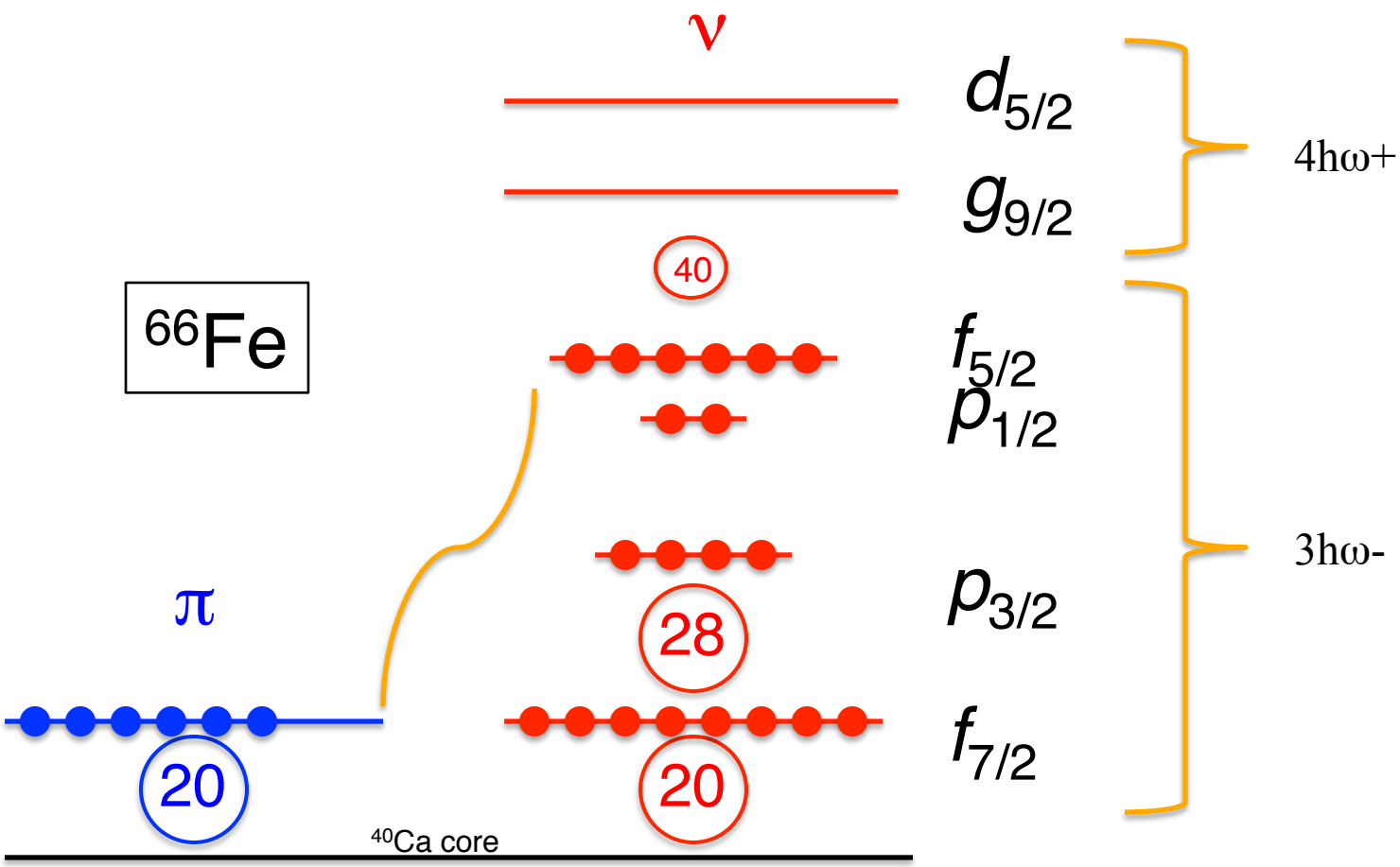
-B. Pritychenko et al., Brookhaven National Laboratory Report BNL-94720-2011-JA, 2011.
-M. Seidlitz et al., Phys. Rev. C 84, 034318 (2011).

Disappearance of the *N*=40 sub-shell gap – ^{68}Ni



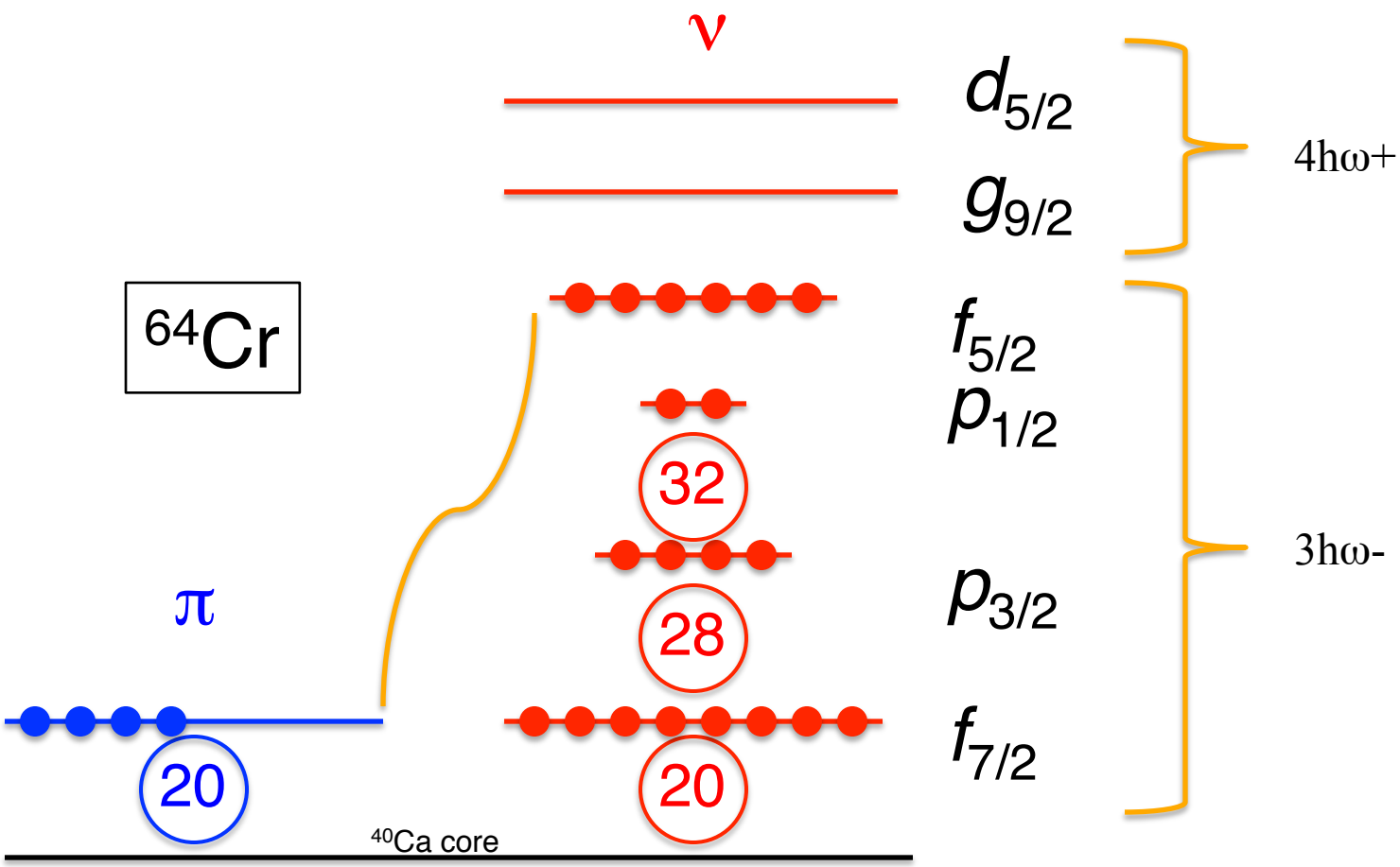
Takaharu Otsuka, *et al.*, PRL 95, 232502 (2005)

Disappearance of the *N*=40 sub-shell gap – ^{66}Fe



Takaharu Otsuka, *et al.*, PRL 95, 232502 (2005)

Disappearance of the *N*=40 sub-shell gap – ^{64}Cr

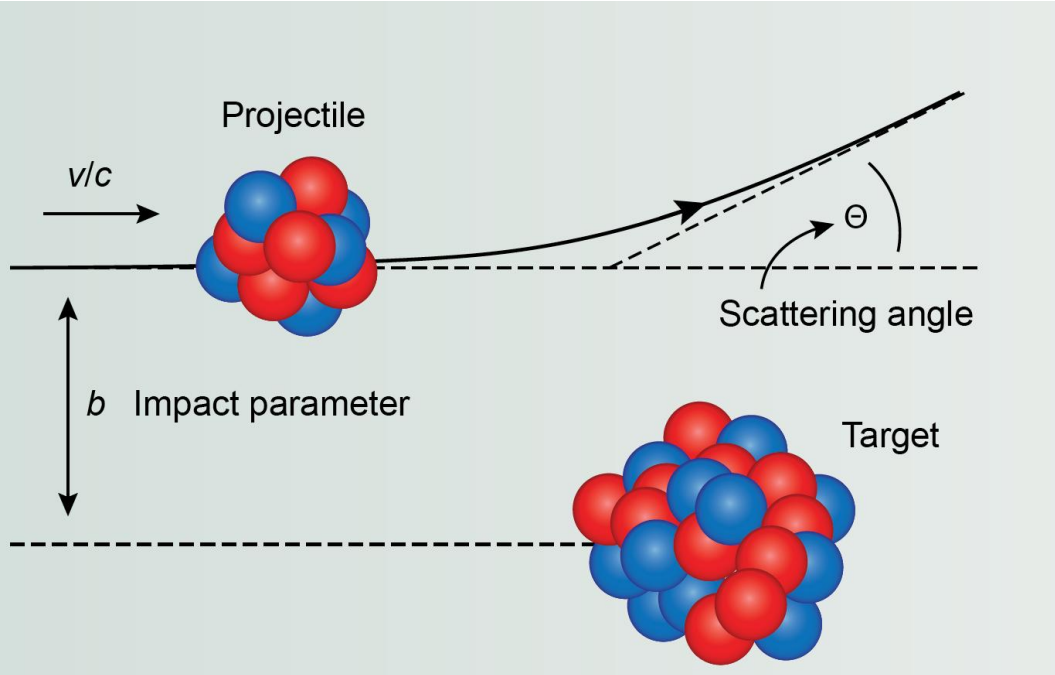


Takaharu Otsuka, *et al.*, PRL 95, 232502 (2005)

Intermediate-energy Coulomb excitation

$$B(\pi\lambda; I_i \rightarrow I_f) = \frac{|\langle J_f || M(\pi\lambda) || J_i \rangle|^2}{2J_i + 1}$$

$$\sigma = \frac{N_\gamma}{N_{\text{beam}} N_{\text{target}} \epsilon}$$



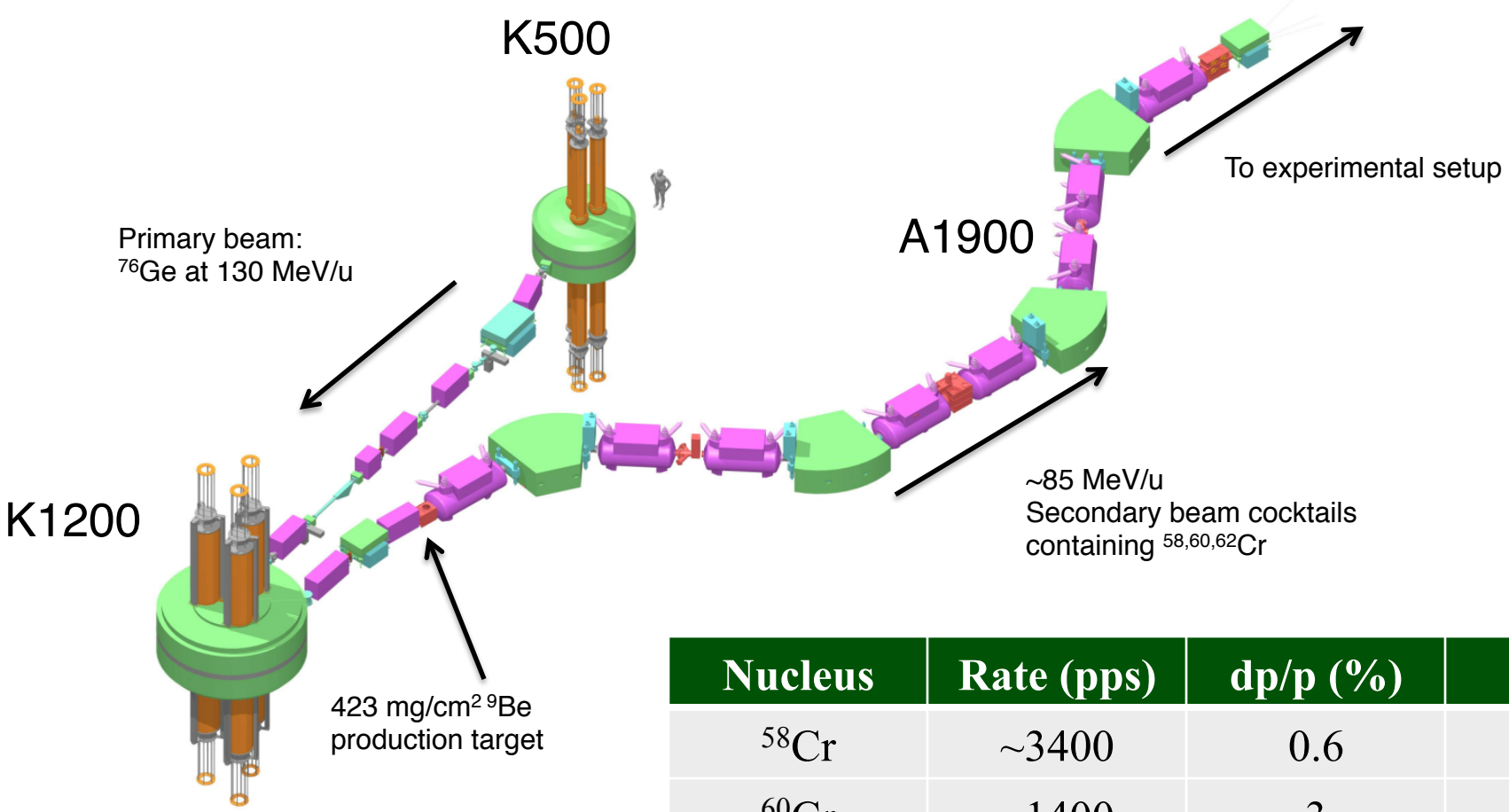
Need to measure:

- Excitation cross section
  - Number of γ rays
  - Number of target particles
  - Number of beam particles
  - Efficiency
- Scattering angle
  - Constrains impact parameter

$$\sigma_{\text{coulex}} \propto Z^2 B(E2)$$

A. Winther and K. Alder, Nucl. Phys. A319, 518 (1979)

Beam production at NSCL CCF

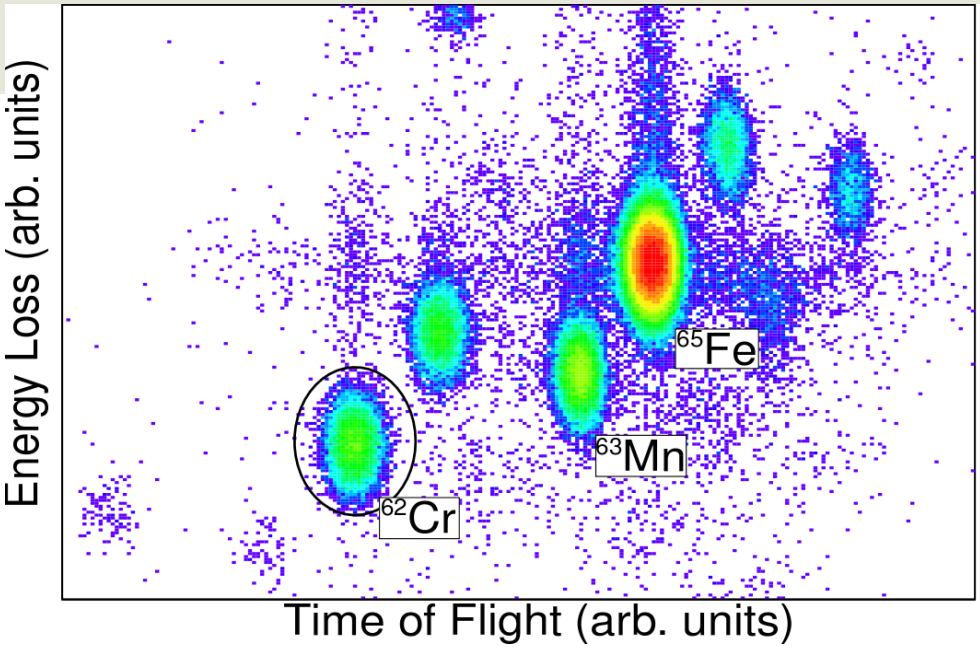


Nucleus	Rate (pps)	dp/p (%)	Purity
^{58}Cr	~3400	0.6	~80%
^{60}Cr	~1400	3	~50%
^{62}Cr	~66	3	~10%

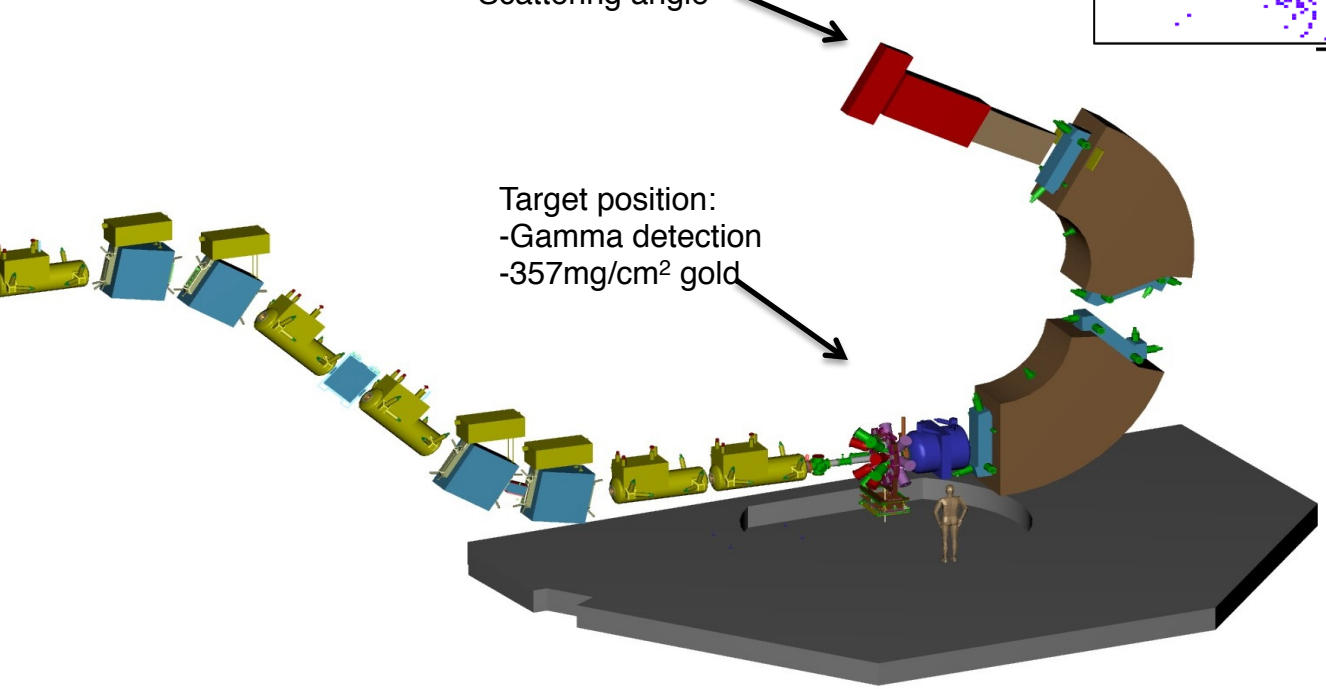
D. J. Morrissey et al., Nucl. Instrum. Methods Phys. Res., Sect.B 204, 90 (2003).

Experimental setup – S800

- Particle ID
- Scattering angle

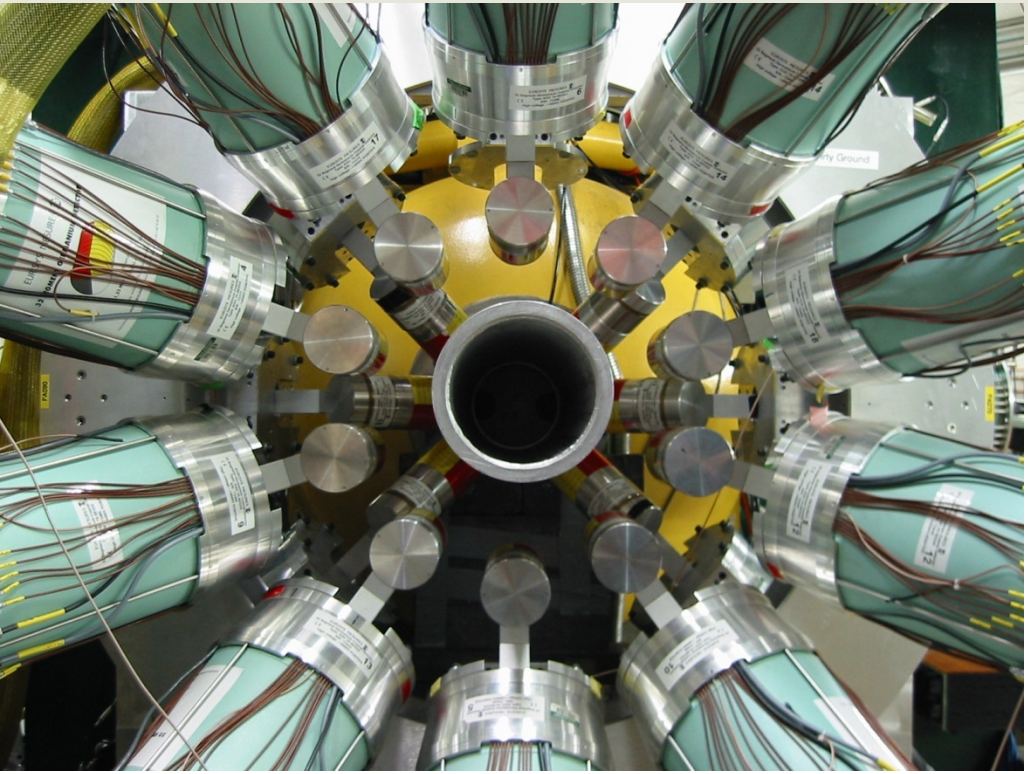


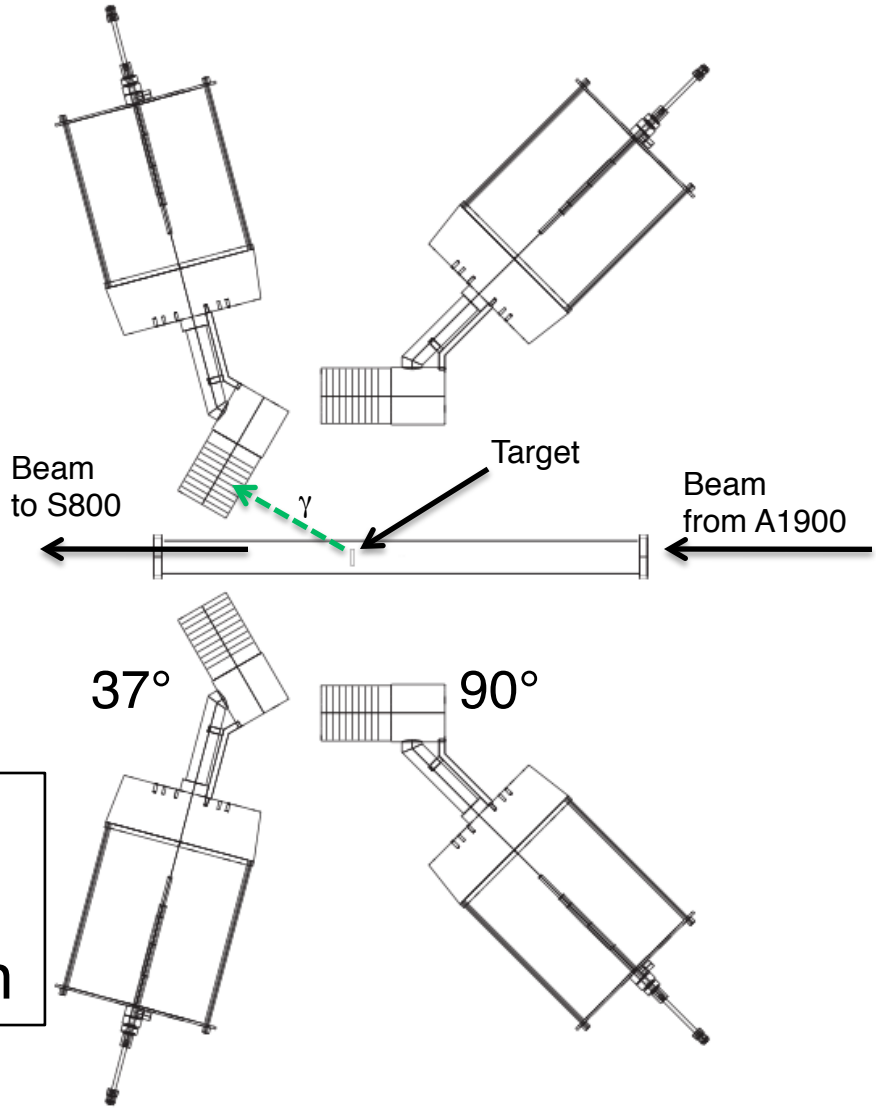
T. Baugher et al., Phys. Rev. C 86, 011305(R) (2012)



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

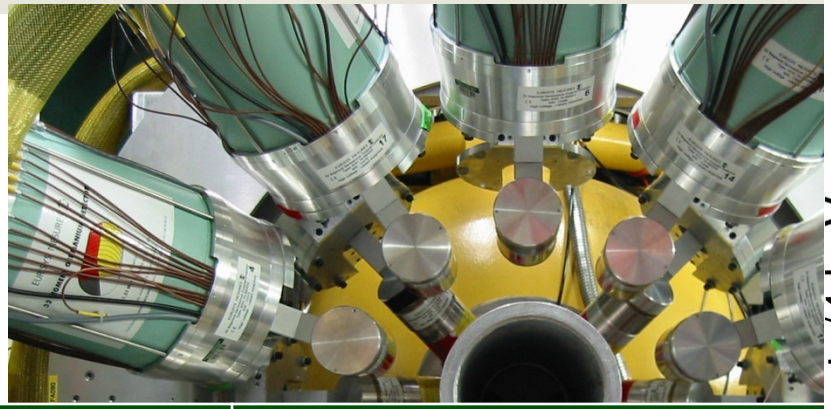
Experimental setup - SeGA





-γ rays tag the inelastic process
-v/c ~ 0.4
-event-by-event Doppler reconstruction

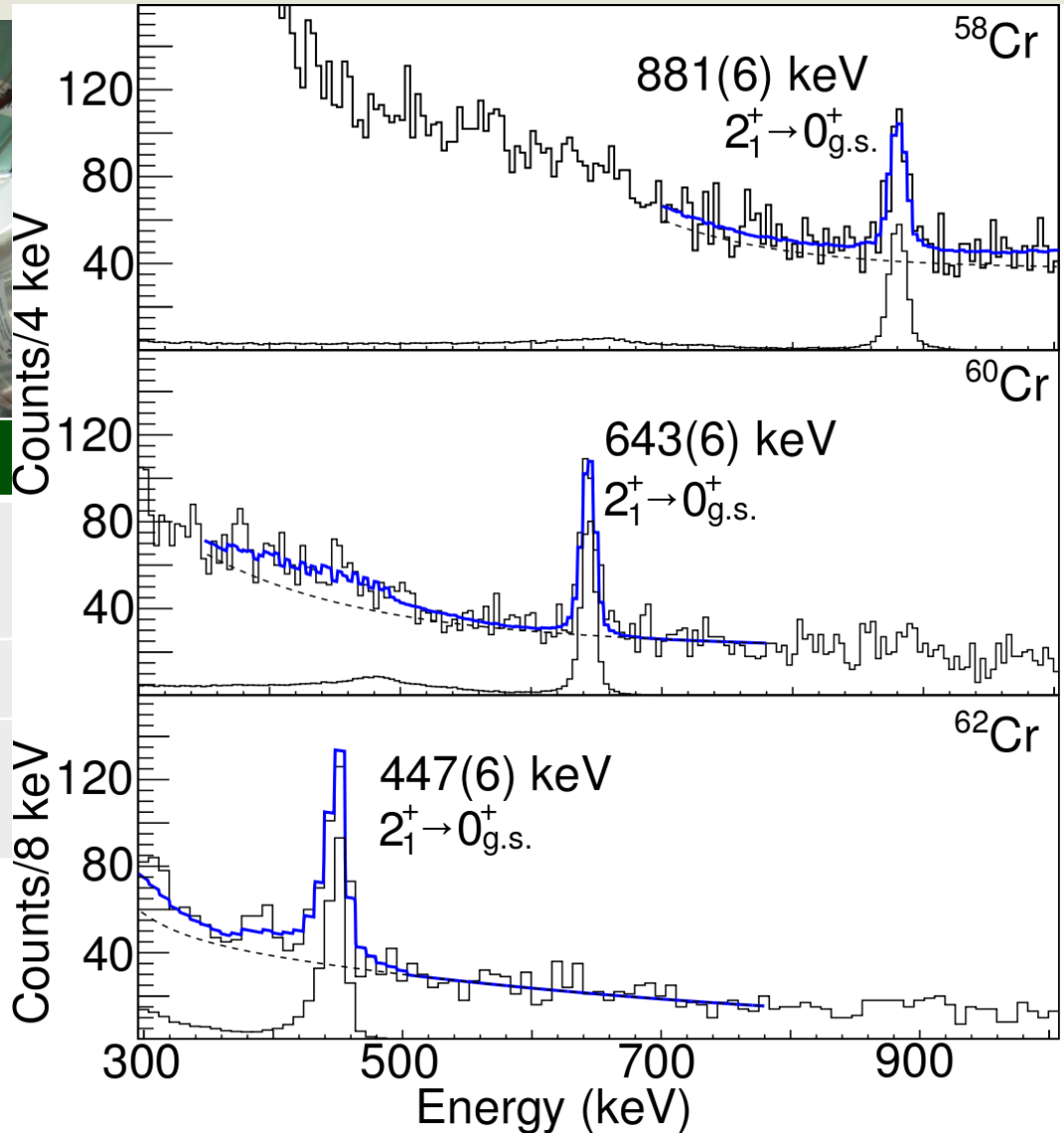
Experimental setup - SeGA



Nucleus	$B(E2\uparrow)$ (e^2fm^4)
^{58}Cr	860(125), 990(280)*
^{60}Cr	1105(145)
^{62}Cr	1625(220) 1605(+302 -246)**

*A. Bürger *et al.*, Phys.Lett. B 622, 29 (2005)
** Deduced from the lifetime determined in the line-shape analysis

$$B(E2) \propto \sigma \propto \frac{N_\gamma}{N_{\text{beam}}}$$



T. Baugher et al., Phys. Rev. C 86, 011305(R) (2012)

^{62}Cr line-shape analysis

Provides an independent measure of the *B*(*E*2) value

$$B(E2) \propto \frac{1}{E_\gamma^5 \tau}$$

Nucleus	$B(E2\uparrow)$ (e^2fm^4)
^{58}Cr	860(125), 990(280)*
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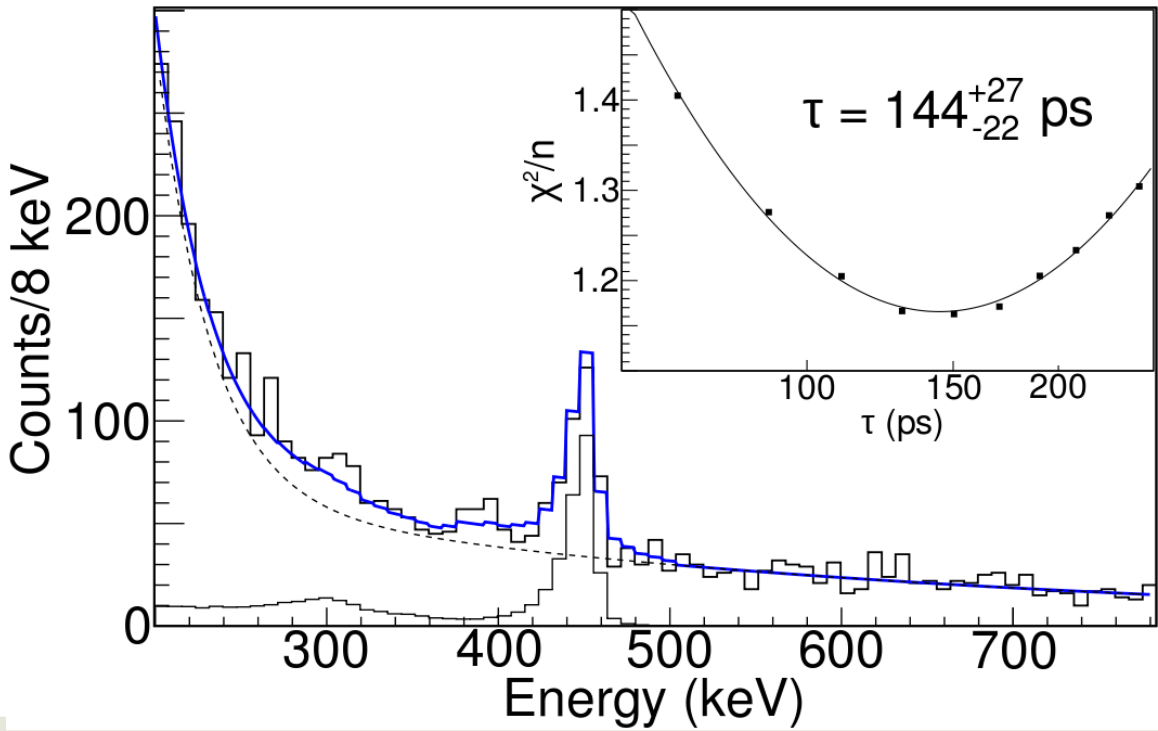
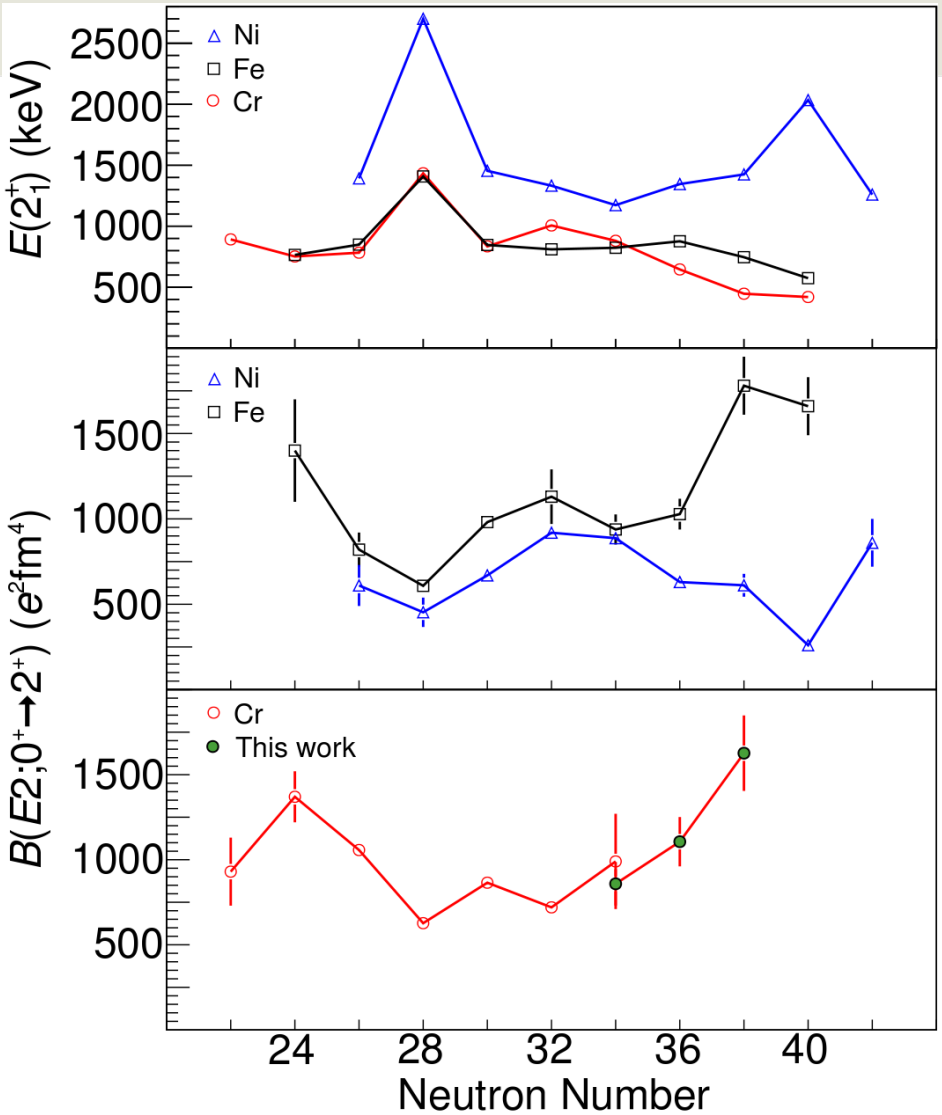


Results



-B. Pritychenko et al., Brookhaven National Laboratory Report BNL-94720-2011-JA, 2011.
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Results indicate trend of increasing *B*(*E*2) values similar to Fe isotopes

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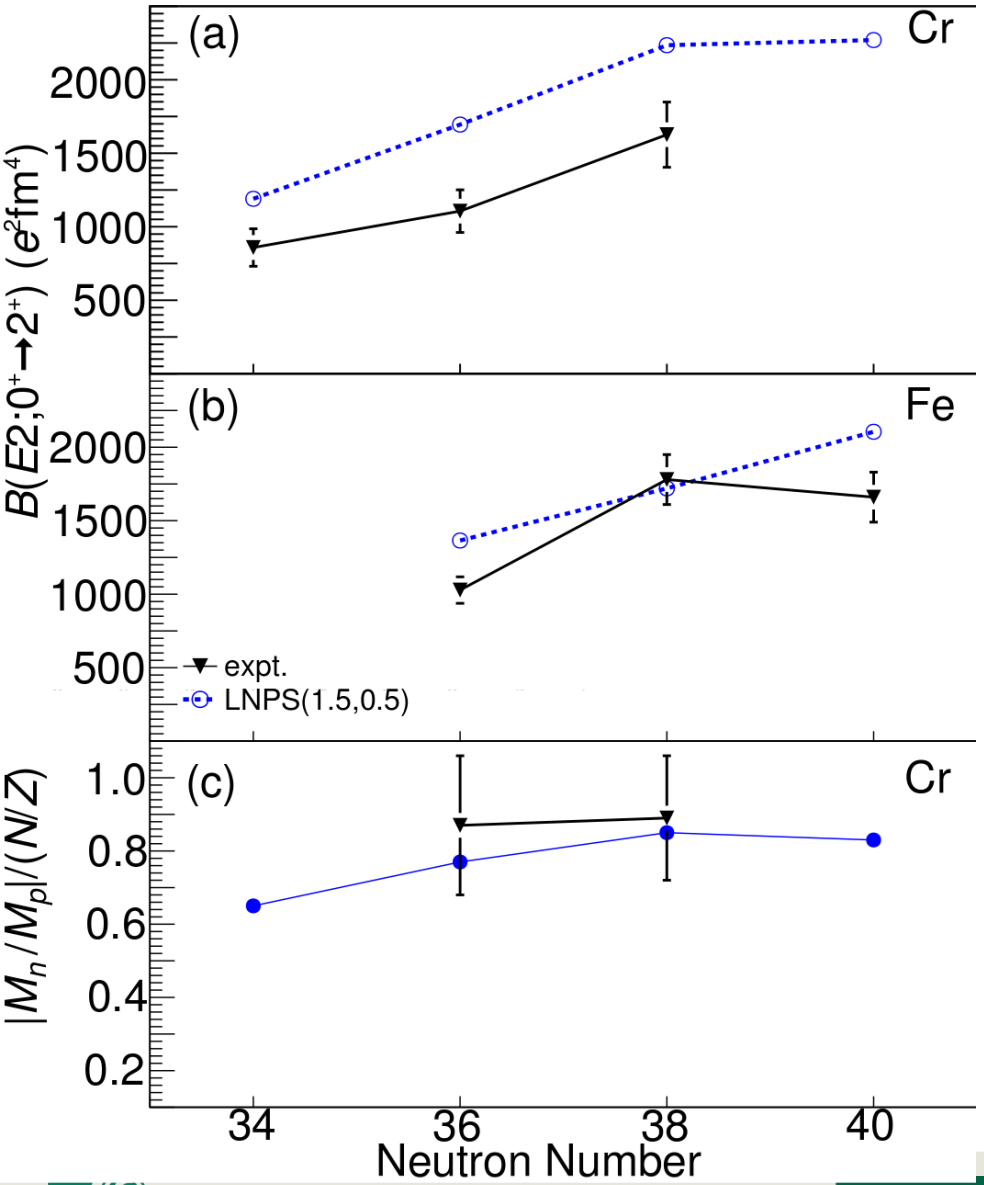
Comparison with shell model:
constant effective charge



LNPS interaction*
pf-shell for protons
$1p_{3/2}$, $1p_{1/2}$, $0f_{5/2}$, $\mathbf{0g_{9/2}}$, $\mathbf{1d_{5/2}}$ for neutrons

$$M_n = e_p A_n + e_n A_p$$

$$M_p = e_p A_p + e_n A_n$$

$$B(E2) = M_p^2$$

M_n/M_p calculated from deformation lengths from proton scattering (Aoi) and $B(E2)$ values from the current work

N. Aoi et al., Phys. Rev. Lett. 102, 012502 (2009).

LNPS Interaction:
***S. M. Lenzi F. Nowacki, A. Poves, and K. Sieja, PRC 82, 054301 (2010)**

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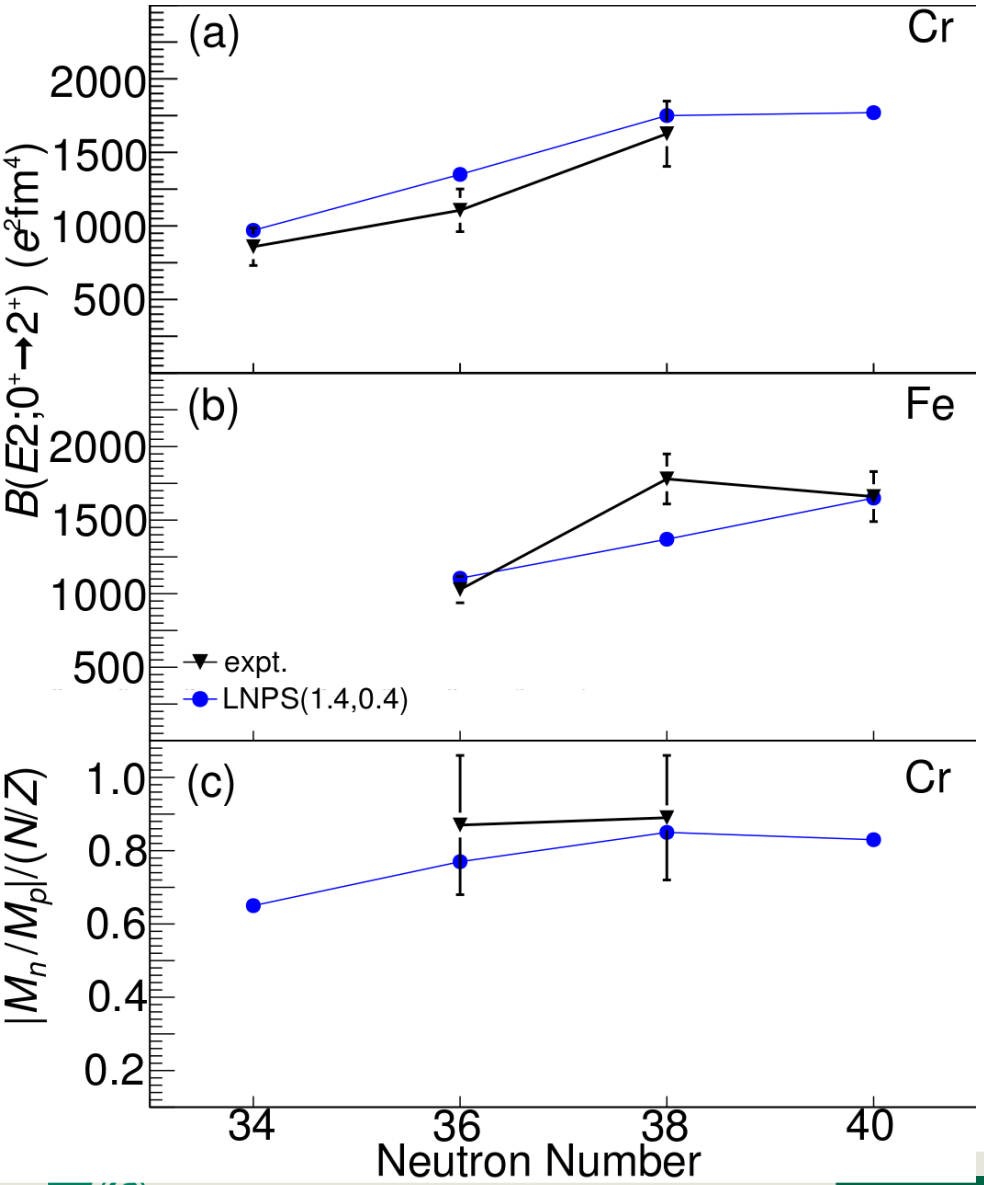

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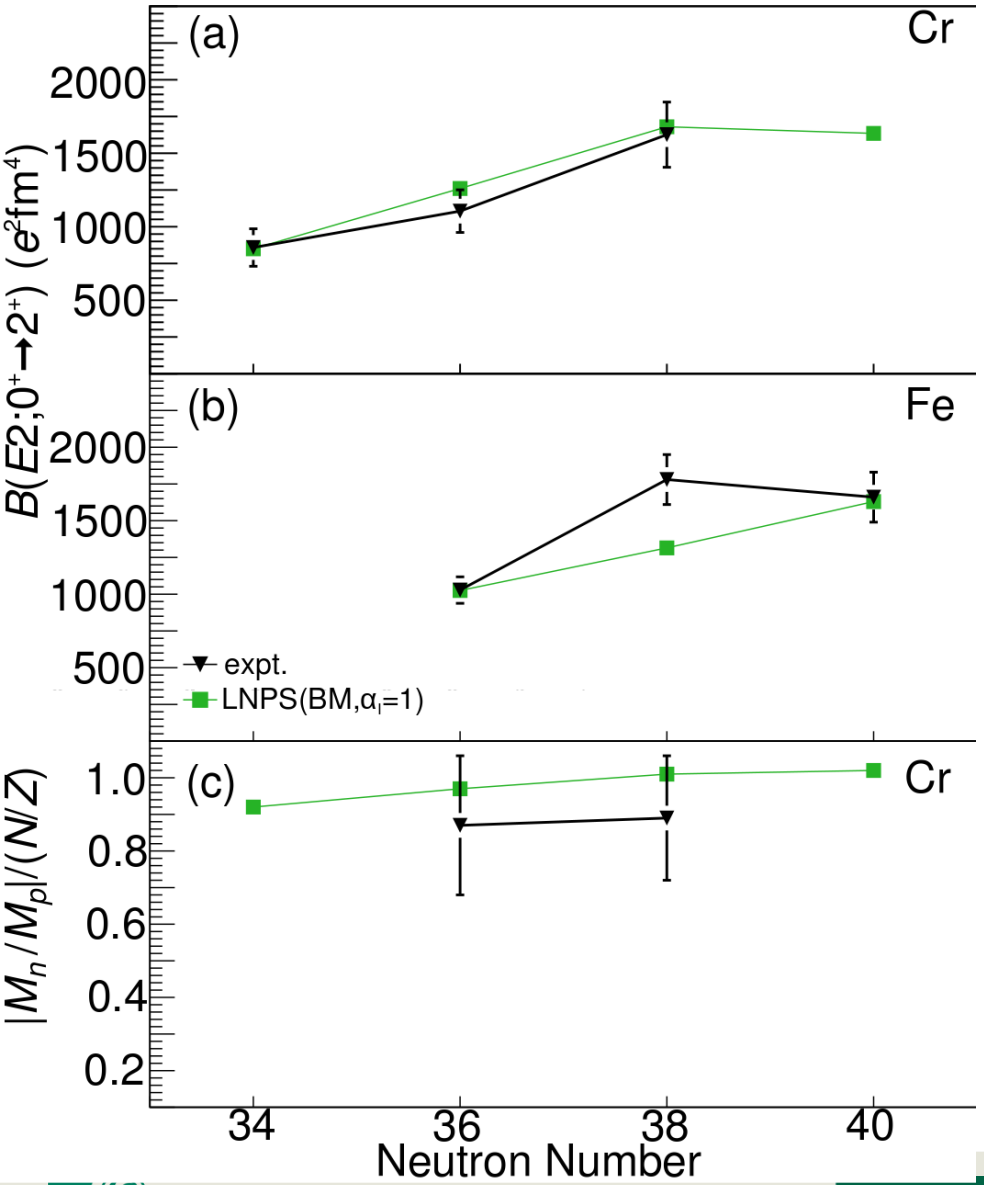
Comparison with shell model:
N- and *Z*-dependent effective charges



$$M_p = A_p(1+\delta e_p) + A_n \delta e_n$$

$$M_n = A_n(1+\delta e'_n) + A_p \delta e'_p$$

$$\delta e_{p/n} = a\frac{Z}{A} \pm c + \alpha_I[b\frac{N-Z}{A} \pm d\frac{Z}{A}\frac{N-Z}{A}]$$

$$\delta e'_{p/n} = a\frac{N}{A} \pm c - \alpha_I[b\frac{N-Z}{A} \pm d\frac{N}{A}\frac{N-Z}{A}]$$

$$a = 1,\ b = -0.32,\ c = 0.32 \text{ and } d = -0.65$$

H. Sagawa, T. Suzuki, and K. Hagino, Nucl. Phys. A 722, c183 (2003).

A. Bohr and B. R. Mottelson, Nuclear Structure, Vol. 2 (Benjamin, New York, 1975).

T. Baugher et al., Phys. Rev. C 86, 011305(R) (2012)

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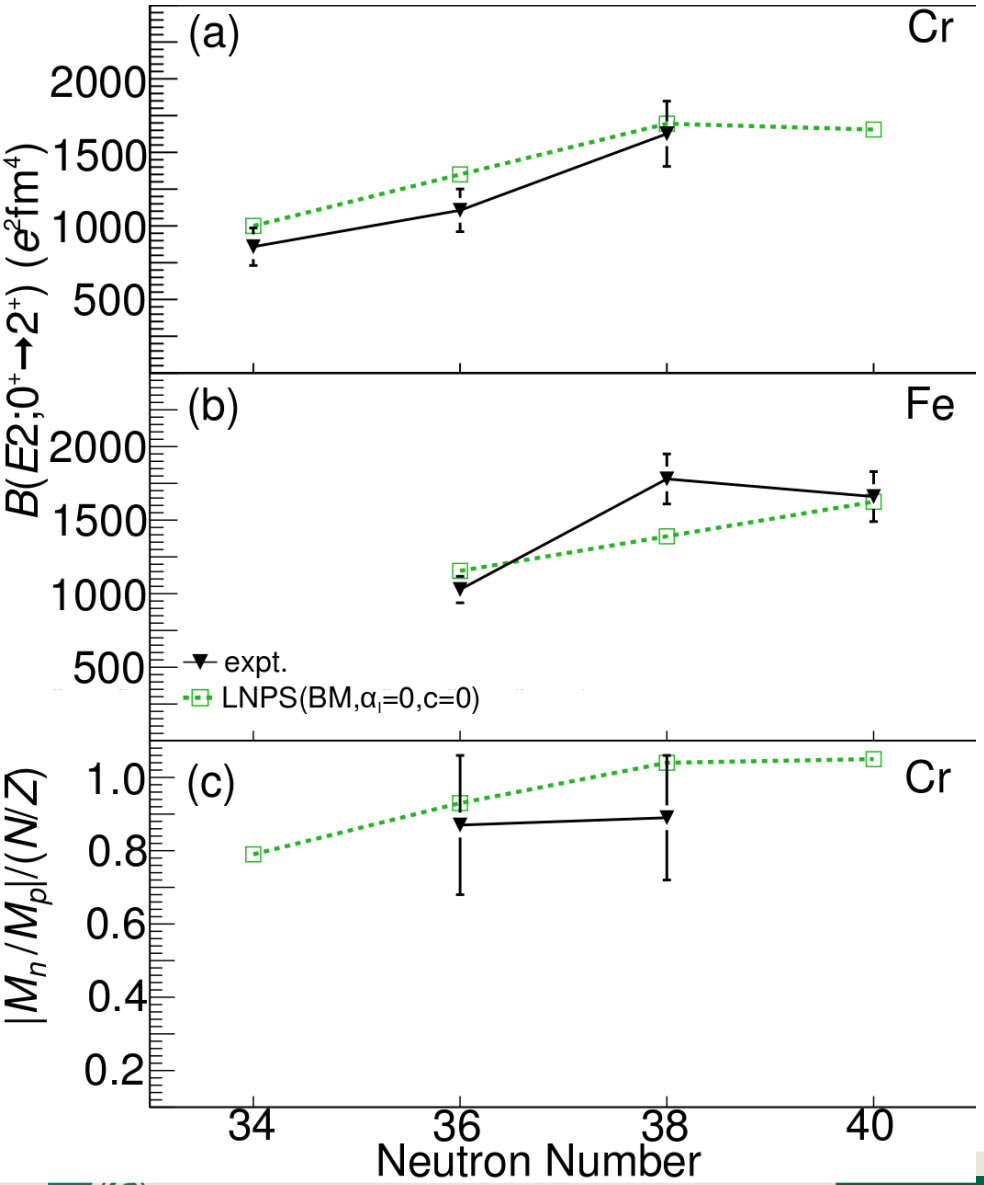

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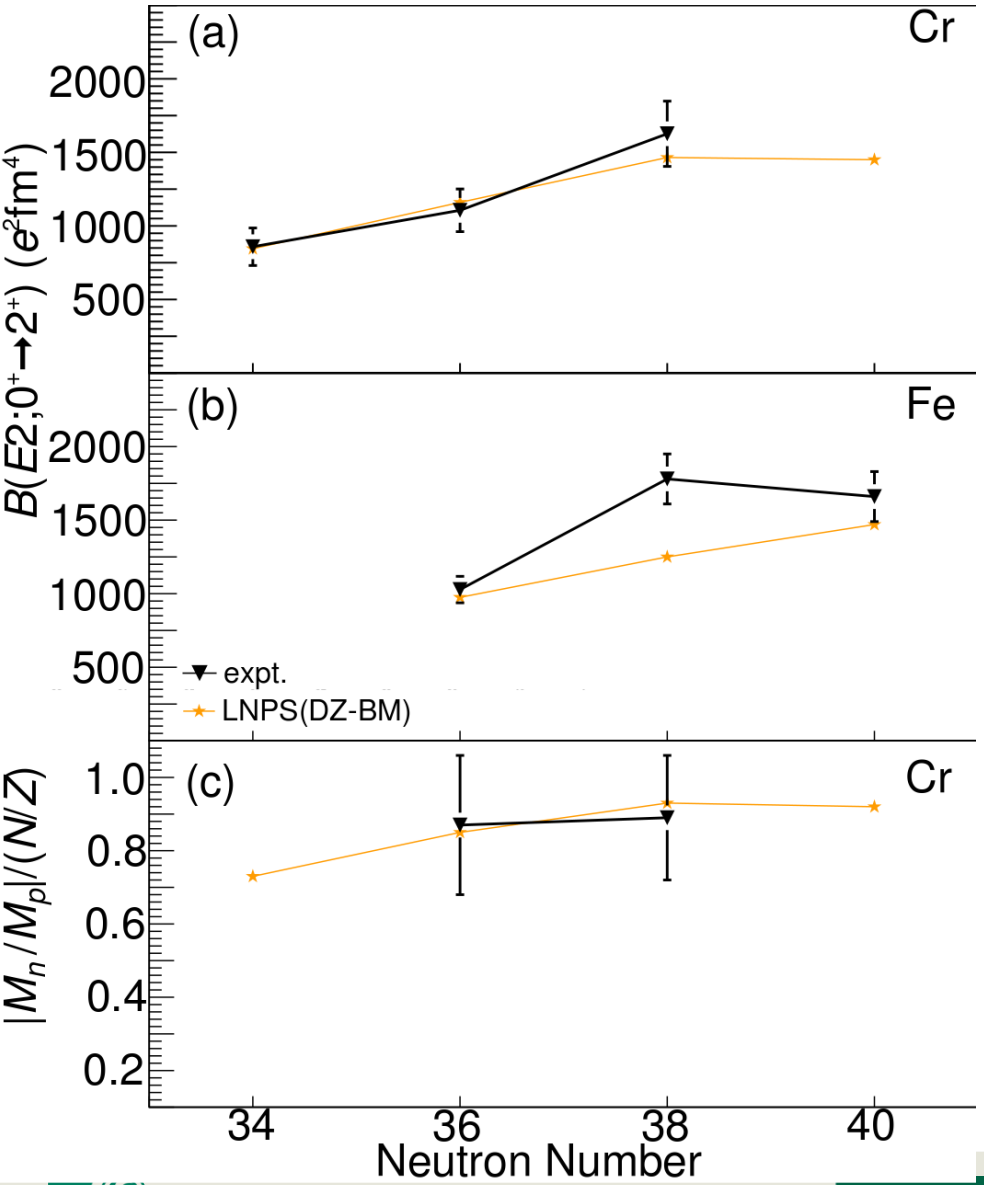

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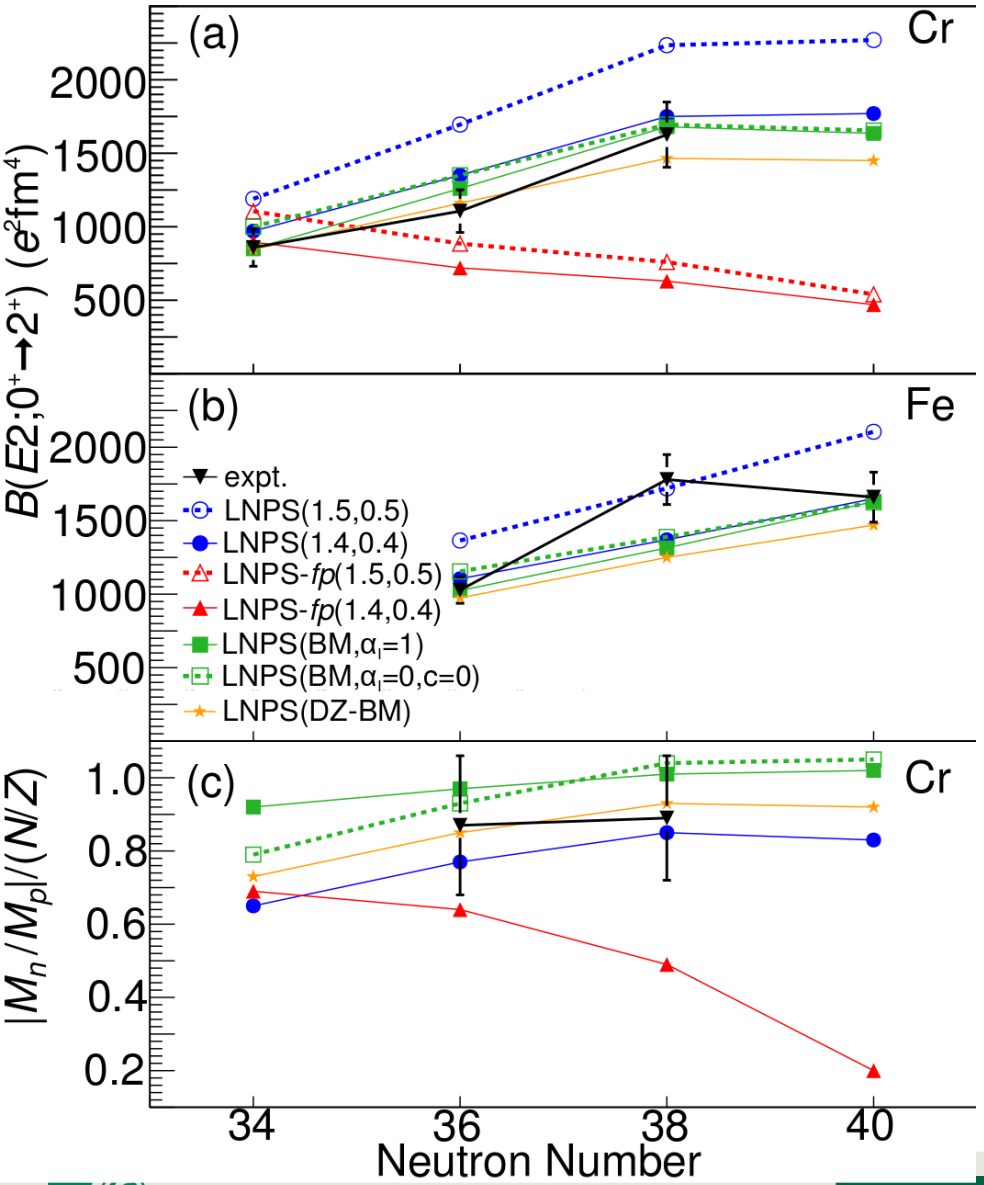
M. Dufour and A. P. Zuker, Phys. Rev. C 54, 1641 (1996).

W. A. Richter, S. Mkhize, and B. A. Brown, Phys. Rev. C 78, 064302 (2008).

T. Baugher et al., Phys. Rev. C 86, 011305(R) (2012)

LNPS interaction:
S. M. Lenzi F. Nowacki, A. Poves, and K. Sieja, PRC 82, 054301 (2010)

Comparison with shell model:
summary



- Unable to reproduce ^{66}Fe

- $B(E2)$ for ^{64}Cr (*H. Crawford*) always predicted to be the same as ^{62}Cr

- M_n/M_p possibly useful in discriminating between effective charge formulations

T. Baugher et al., Phys. Rev. C 86, 011305(R) (2012)

Summary and acknowledgments

- $B(E2)$ values for ^{60,62}Cr measured for the first time, $B(E2)$ value for ^{58}Cr confirmed

- Results indicate trend of increasing collectivity toward $N = 40$

- Shell-model calculations including $g_{9/2}$ and $d_{5/2}$ neutron orbitals can reproduce the $B(E2)$ values and M_n/M_p ratios

- M_n/M_p ratios provide possibility to discriminate between effective charge approaches

- Many different approaches to effective charge fail to reproduce ^{66}Fe

- A. Gade
- R. V. F. Janssens
- S. M. Lenzi
- D. Bazin
- B. A. Brown
- M. P. Carpenter
- A. N. Deacon
- S. J. Freeman
- T. Glasmacher
- G. F. Grinyer
- F. G. Kondev
- S. McDaniel
- A. Poves
- A. Ratkiewicz
- E. A. McCutchan
- D. K. Sharp
- I. Stefanescu
- K. A. Walsh
- D. Weisshaar
- S. Zhu

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LNPS Interaction

- S. M. Lenzi F. Nowacki, A. Poves, and K. Sieja, PRC 82, 054301 (2010)
- ^{48}Ca core
- KB3gr interaction for the *pf*-shell
- Renormalized G-Matrix (M. Hjorth-Jensen, T. Kuo, and E. Osnes, Phys. Rep. 261, 125 (1995)) with monopole corrections from (F. Nowacki, Ph.D. thesis, IReS Strasbourg, 1996) for $1p_{3/2}$, $1p_{1/2}$, $0f_{5/2}$, $0g_{9/2}$
- G matrix based on Kahana-Lee-Scott for d5/2
- Z=28 gap fixed to reproduce B(E2) in 80Zr
- Neutron dependency of N=50 gap modeled after behavior of Zr isotopes (reproduces 1p-1h excitations in 82Ge)
- QQ strength between g9/2-d5/2 orbitals reduced by 20%.

Experimental Mn/Mp

- Computed a la L. A. Riley et al., Phys. Rev. C 72, 024311 (2005), using the prescription of
- A. M. Bernstein, V. R. Brown, and V. A. Madsen, Phys. Lett. B103, 255 (1981) and
- A. M. Bernstein, V. R. Brown, and V. A. Madsen, CommentsNucl. Part. Phys. 11, 203 (1983).
- Deformation lengths from (p, p') measurements N. Aoi et al., Phys. Rev. Lett. 102, 012502 (2009).

$$\frac{M_n}{M_p} = \frac{b_p}{b_n}\left[\frac{\delta_{(p,p')}}{\delta_p}\left(1 + \frac{b_n}{b_p}\frac{N}{Z}\right) - 1\right]$$

deformation lengths

^{60}Cr	^{62}Cr
0.23(3)	0.27(3)

"DZ-BM" effective charge

- Use pol. Charges from dedicated shell-model studies as starting points at N=Z and evolve them as function of N-Z using BM.
- DZ: (ep, en) = (1.31, 0.46), USD: (1.36(5), 0.45(5))
- Replace first term of BM by constant s.t. $\delta e_p = \delta e_n' = 0.31$ and $\delta e_n = \delta e_p' = 0.46$ at N=Z
- Alpha = 0.8 gave best description of data

$$M_p = A_p(1+\delta e_p) + A_n \delta e_n$$

$$M_n = A_n(1+\delta e_n') + A_p \delta e_p'$$

$$\delta e_{p/n} = a\frac{Z}{A} \pm c + \alpha_I[b\frac{N-Z}{A} \pm d\frac{Z}{A}\frac{N-Z}{A}]$$

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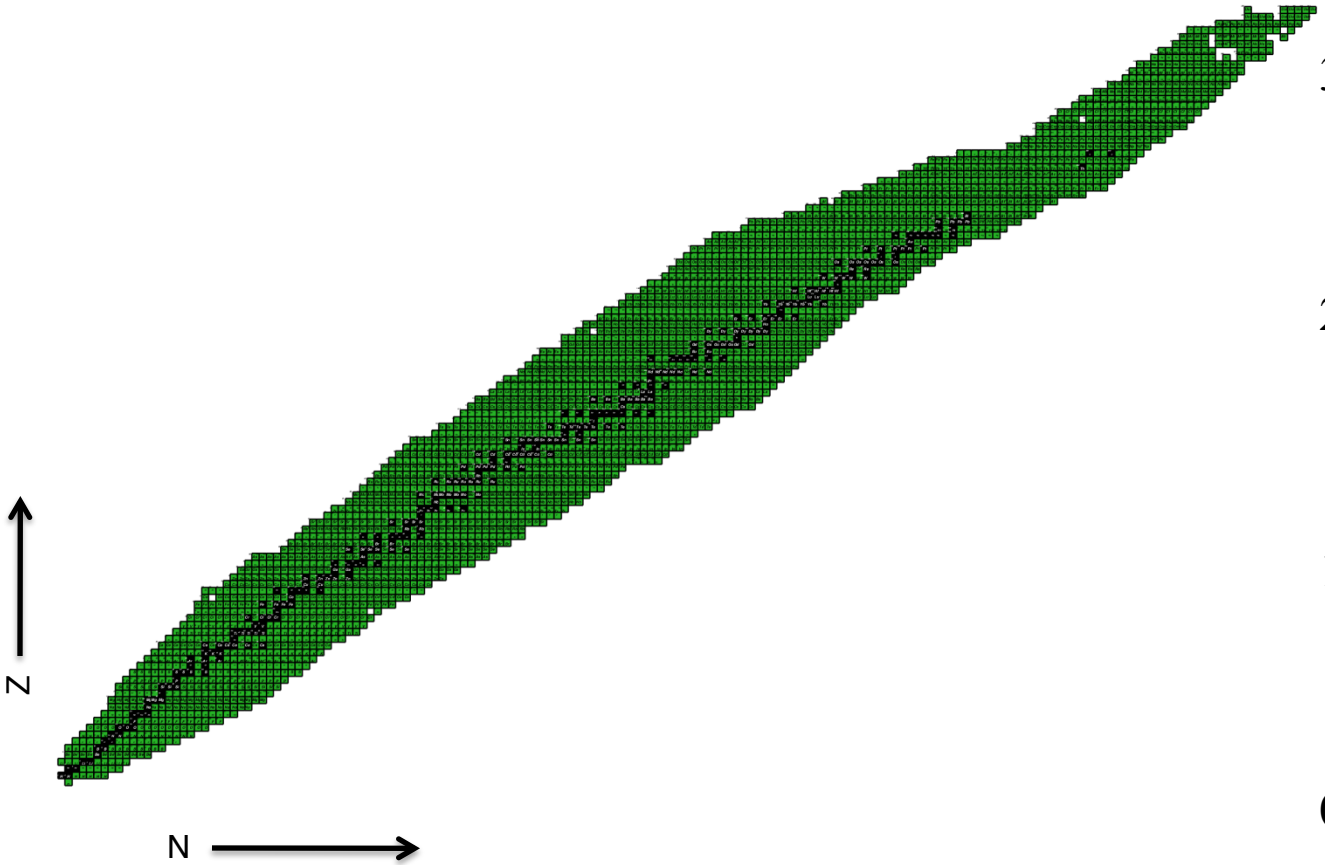
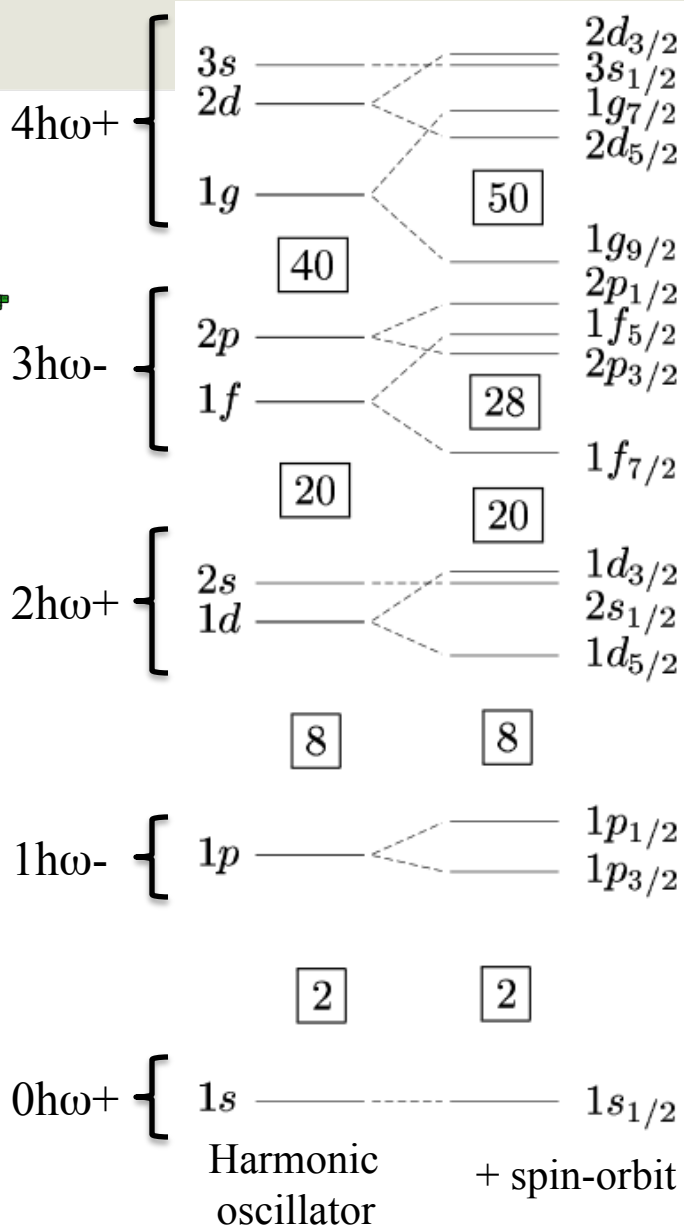
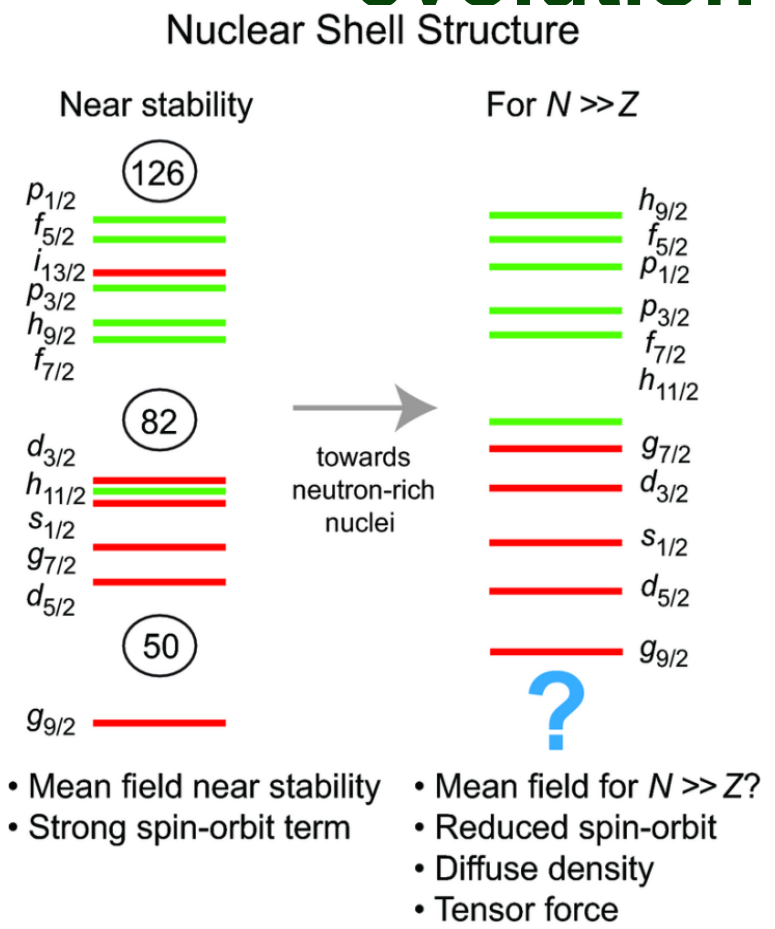
Introduction





Driving forces for shell evolution in neutron-rich nuclei



- Mean field near stability
- Strong spin-orbit term

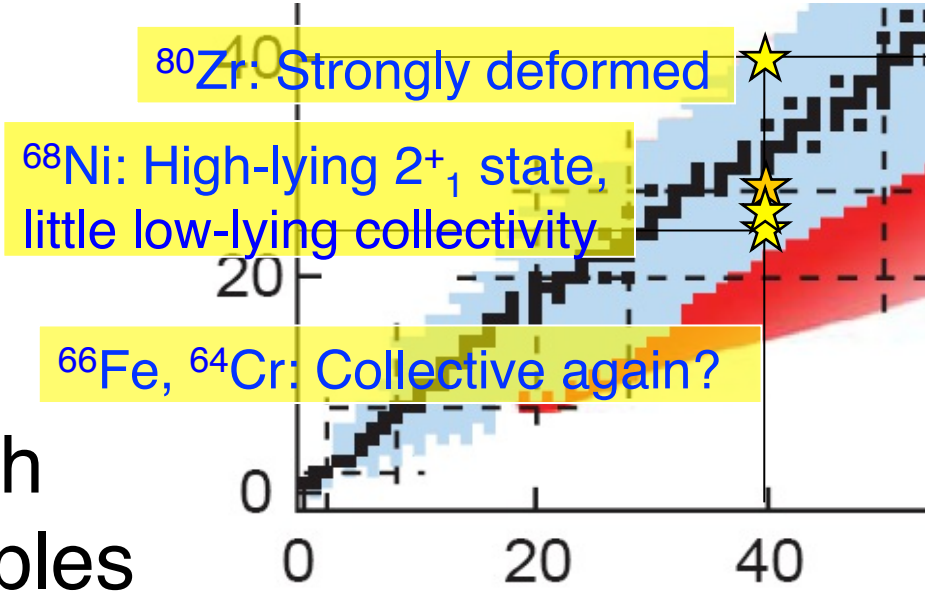
- Mean field for $N >> Z$?
- Reduced spin-orbit
- Diffuse density
- Tensor force

- One important driving force: Spin-isospin parts of the NN interaction

  T. Otsuka et al., PRL 87, 082502 (2001)

  - Particularly the proton-neutron monopole parts of the tensor force

    T. Otsuka et al., PRL 95, 232502 (2005)



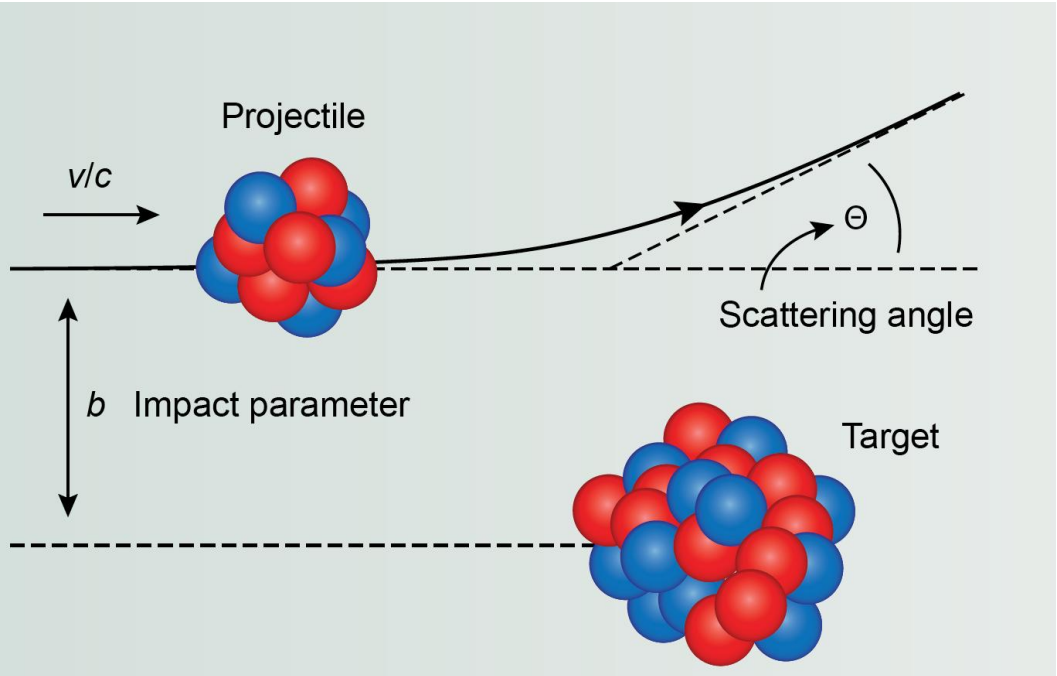
Neutron-rich nuclei with N=40: Excellent examples

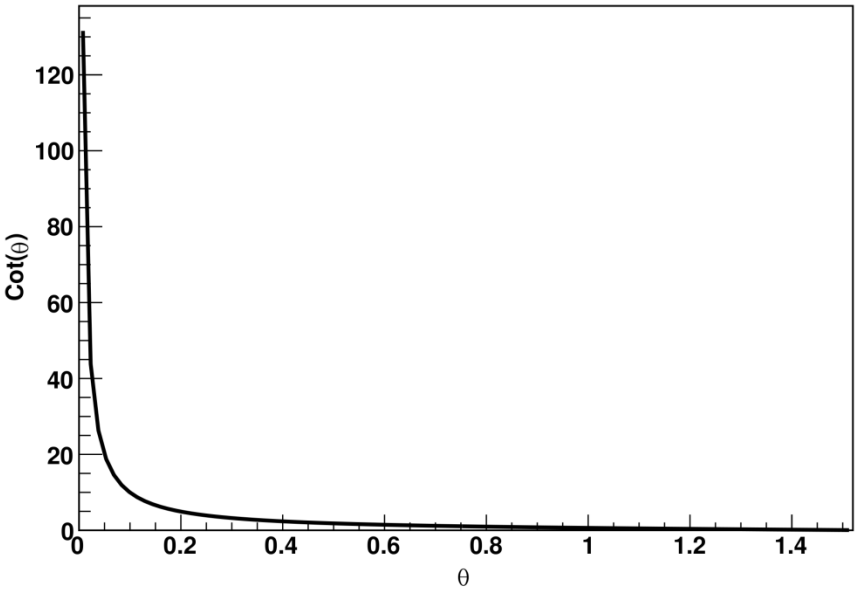
Slide courtesy of A. Gade

Intermediate-energy Coulomb Excitation

Caveat: at NSCL, beam energies are above the Coulomb barrier.

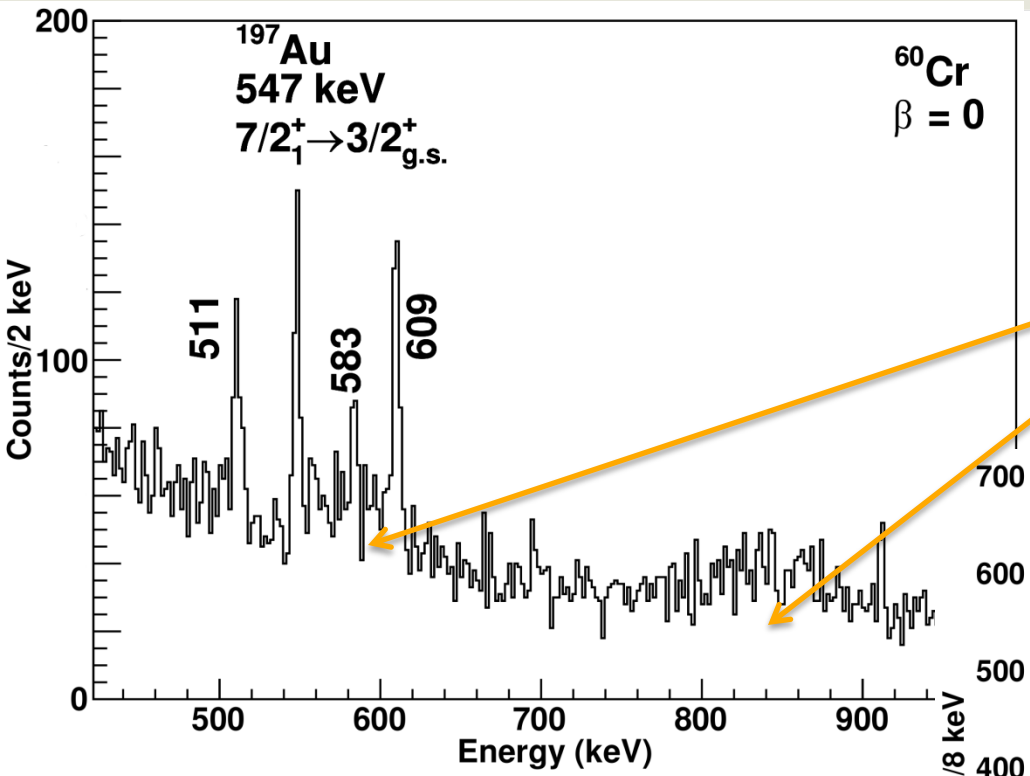
$$b_{\min} = (1.2\text{fm})(A_p^{1/3} + A_t^{1/3}) + 2\text{fm} = \frac{a_0}{\gamma}\cot(\theta_{\max}^{\text{cm}}/2)$$

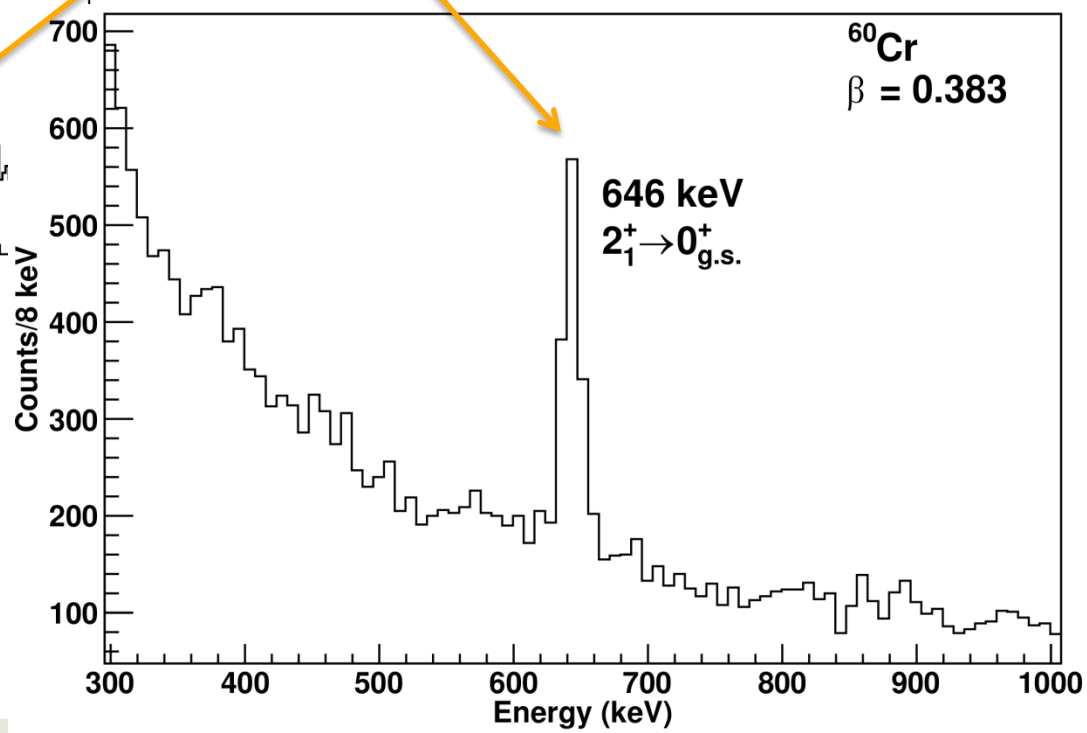




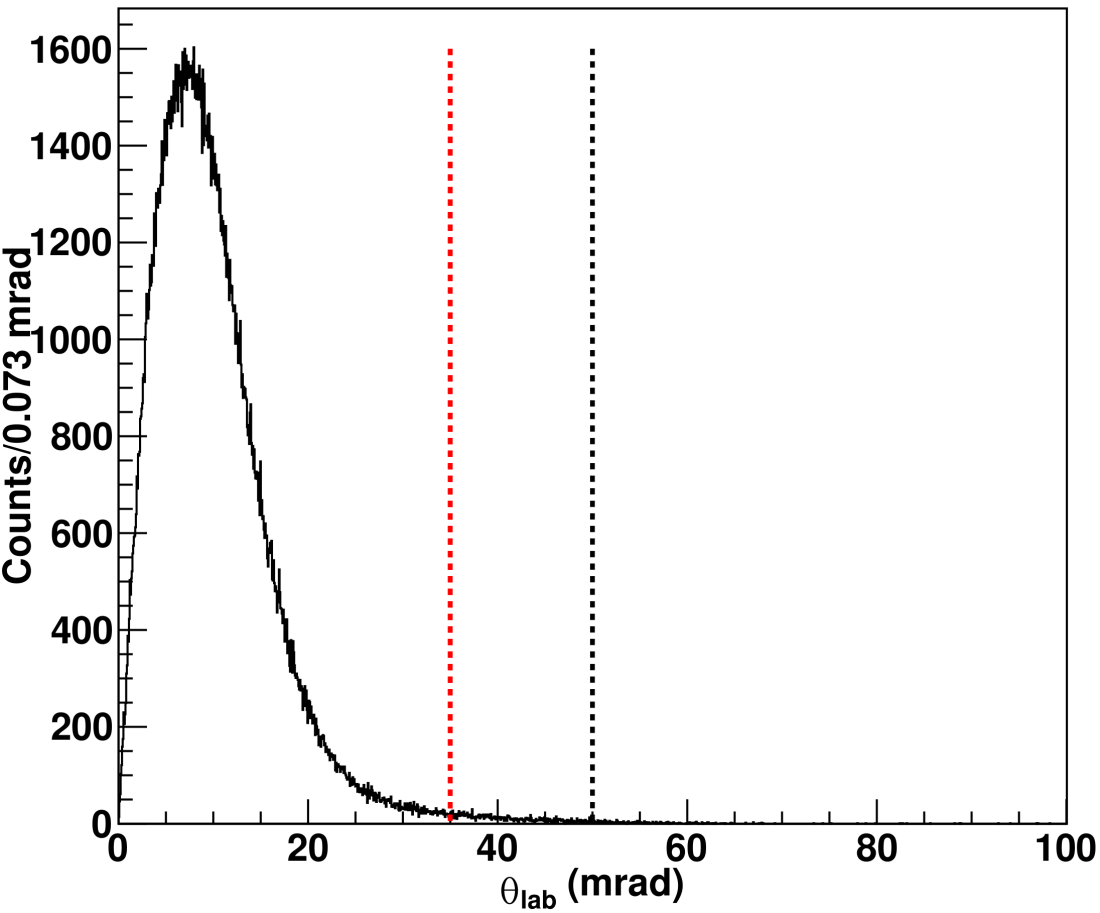
A. Winther and K. Alder, Nucl. Phys. A319, 518 (1979)

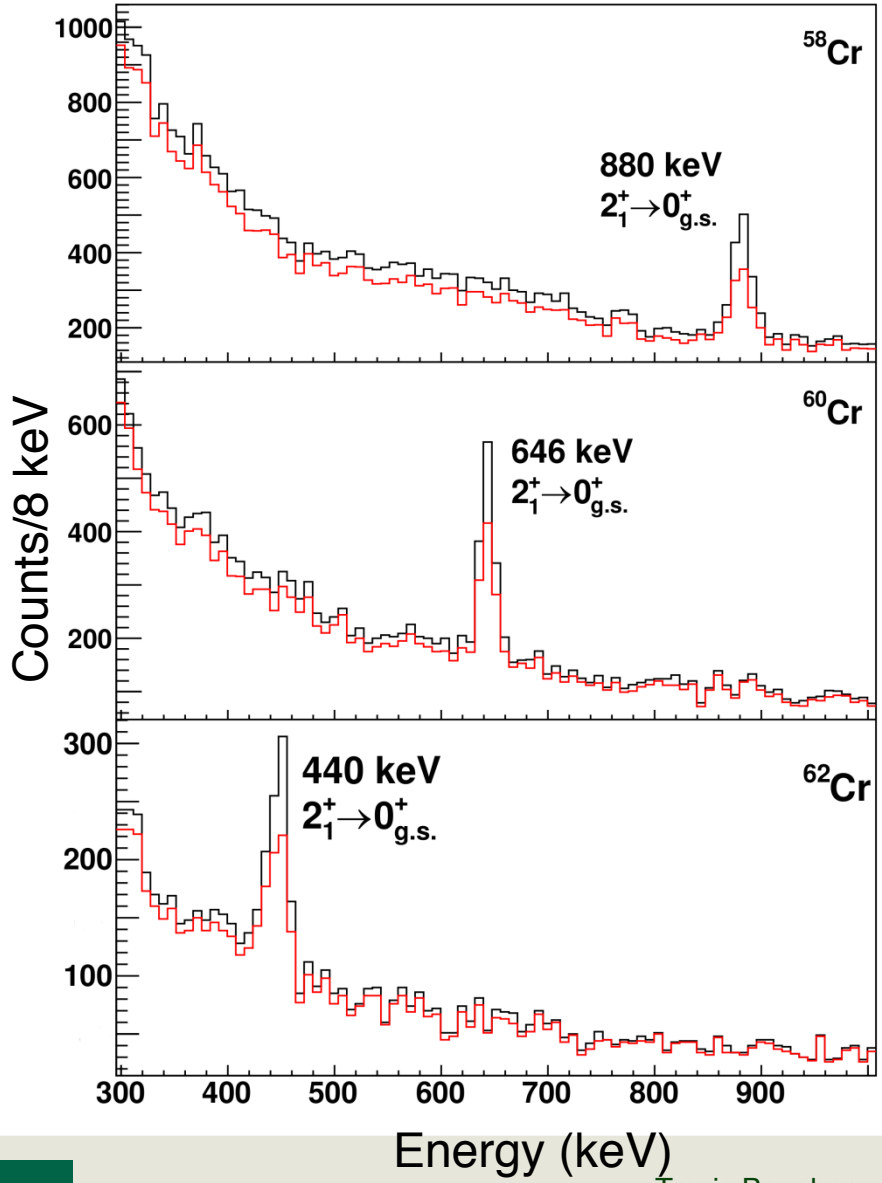
Doppler Reconstruction



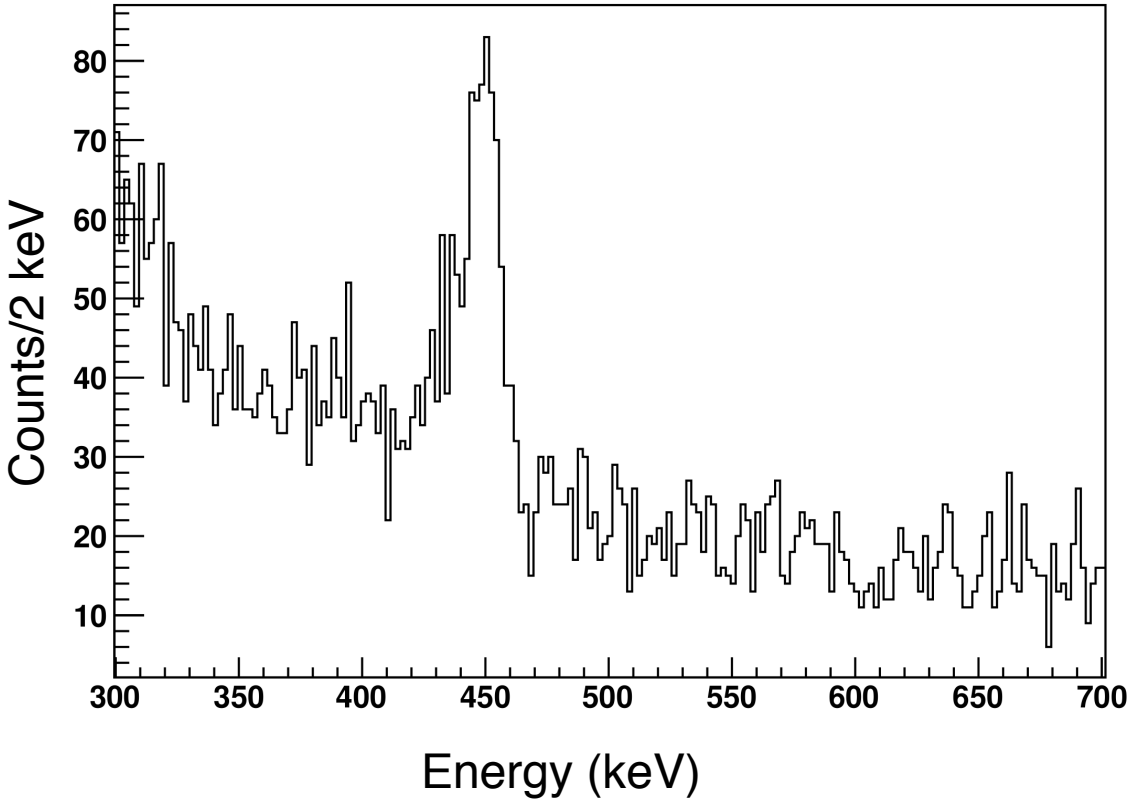


Scattering Angle and γ spectra

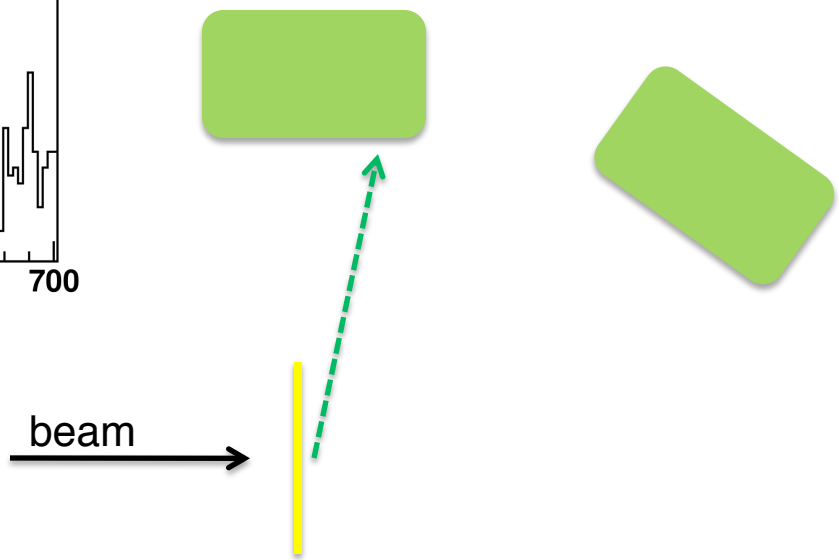




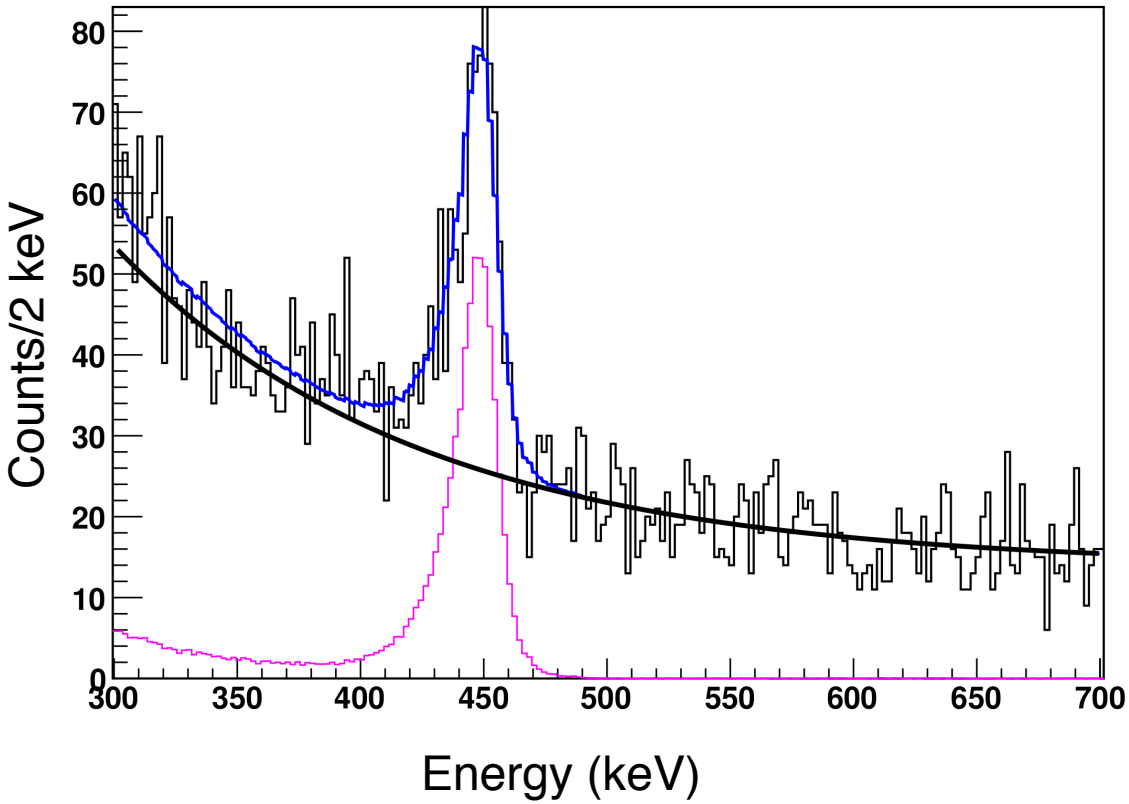
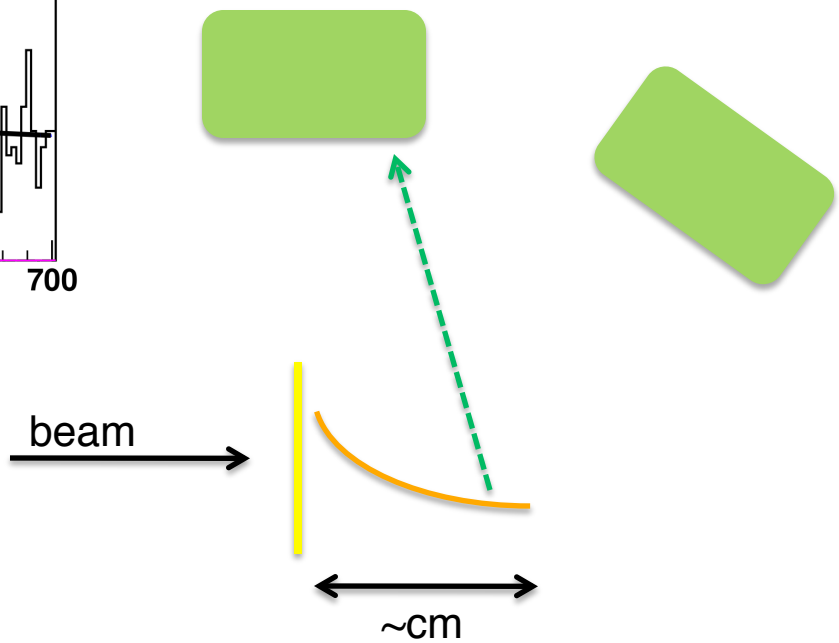
^{62}Cr Lineshape



$$B(E2) \propto \frac{1}{E_\gamma^5 \tau}$$



^{62}Cr Lineshape



$$B(E2) \propto \frac{1}{E_\gamma^5 \tau}$$