Nuclear Structure Experiment I

I-Yang Lee

Lawrence Berkeley National Laboratory

Exotic Beam Summer School 2011
July 25 - 30

Outline

- Monday, July 25
  - Introduction
  - Shell evolution, nuclear forces, and shapes
  - Study weak binding by measuring lifetime
  - Nuclear wave functions from transfer and knock out reactions
- Wednesday, July 27
  - Study the evolution of collectivity between closed shells using Coulomb excitation
  - Study neutron/proton contributions to nuclear structure using magnetic moment measurements
  - Stability and properties of heavy element
  - Summary

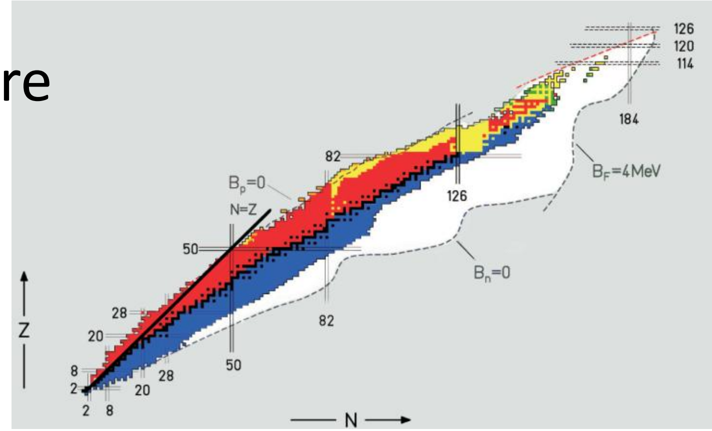
Introduction

Motivation

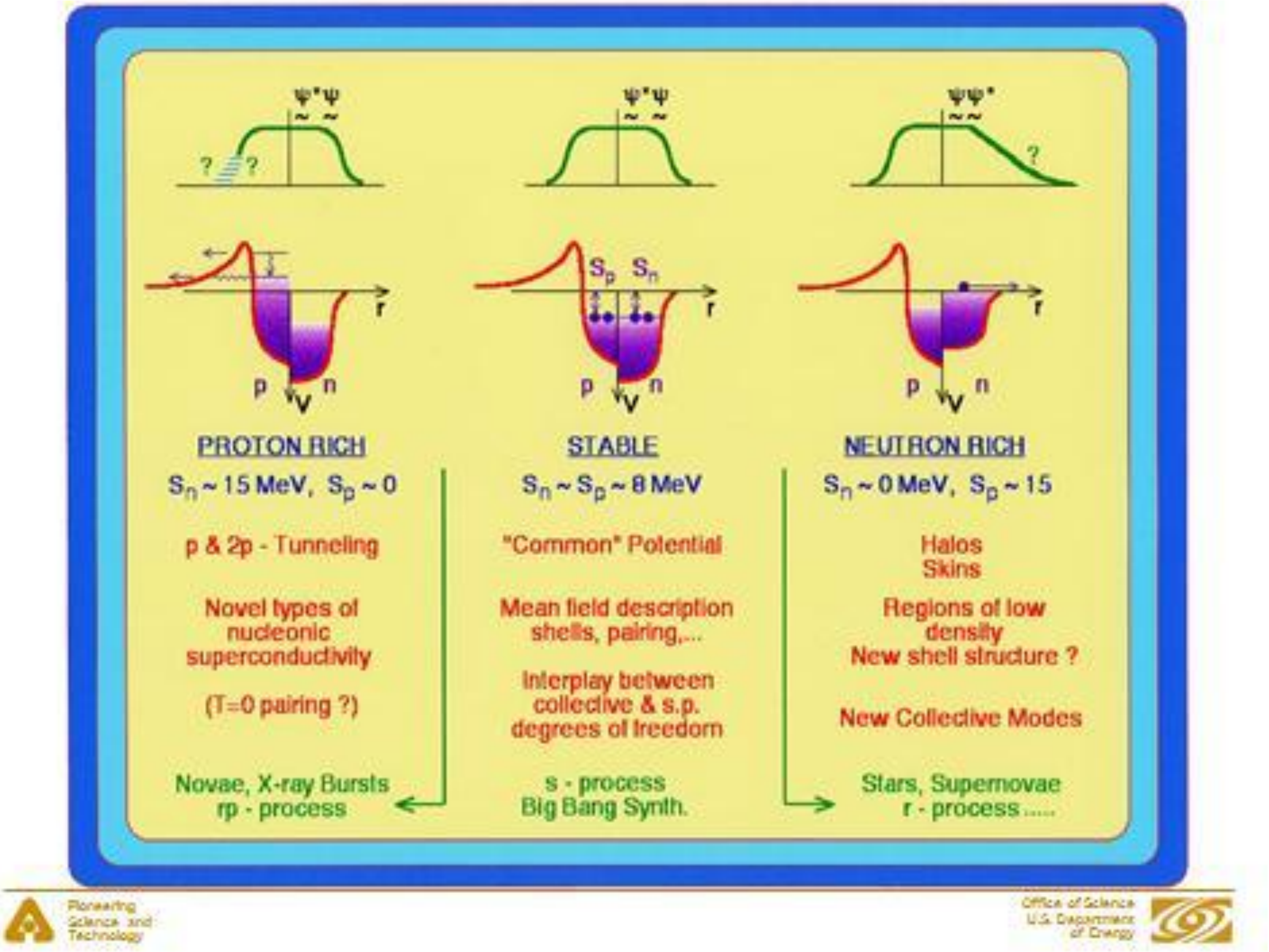
Why study nuclear structure using exotic beams?

To understand nuclei toward the edge of stability.

- Changes in the nuclear shell structure
- New modes of collectivity
- New phenomena
  - Delineation of the nucleon drip lines
  - Halo systems and nucleon skins
  - Exotic decay modes
  - Structure information for astrophysics



Nuclei at drip lines



PROTON RICH

$S_n \sim 15$ MeV, $S_p \sim 0$

p & 2p - Tunneling

Novel types of nucleonic superconductivity

(T=0 pairing ?)

Novae, X-ray Bursts
rp - process

STABLE

$S_n \sim S_p \sim 8$ MeV

"Common" Potential

Mean field description shells, pairing,...

Interplay between collective & s.p. degrees of freedom

s - process
Big Bang Synth.

NEUTRON RICH

$S_n \sim 0$ MeV, $S_p \sim 15$

Halos
Skins

Regions of low density
New shell structure ?

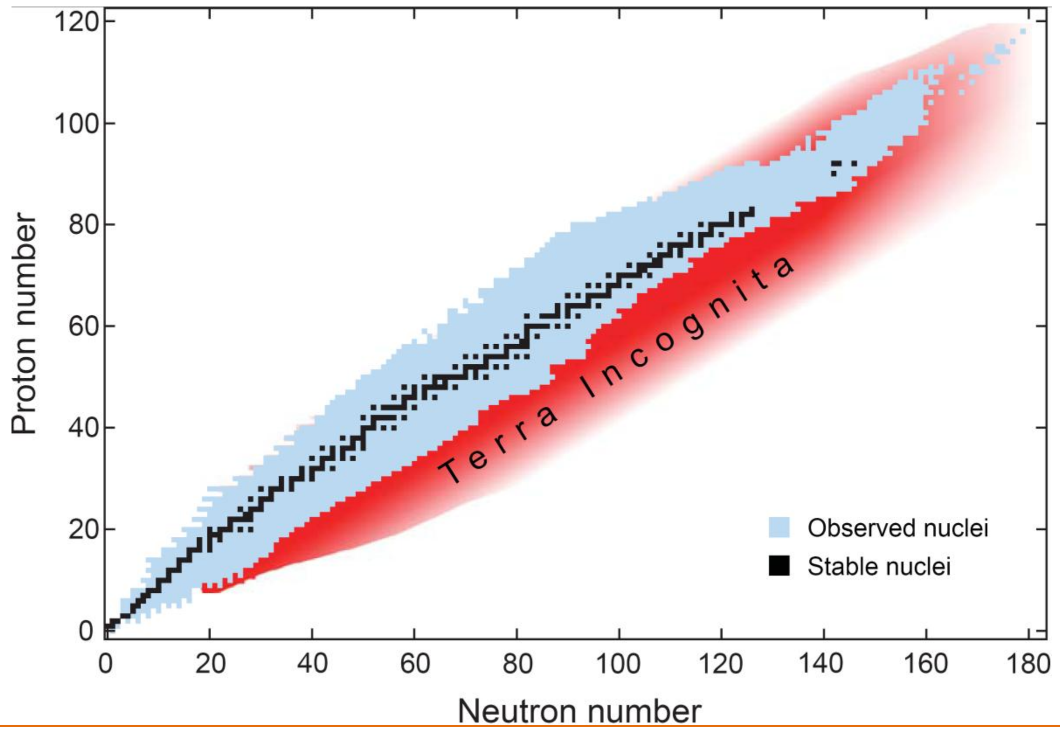
New Collective Modes

Stars, Supernovae
r - process .....

Pioneering Science and Technology

Office of Science
U.S. Department of Energy

New frontiers



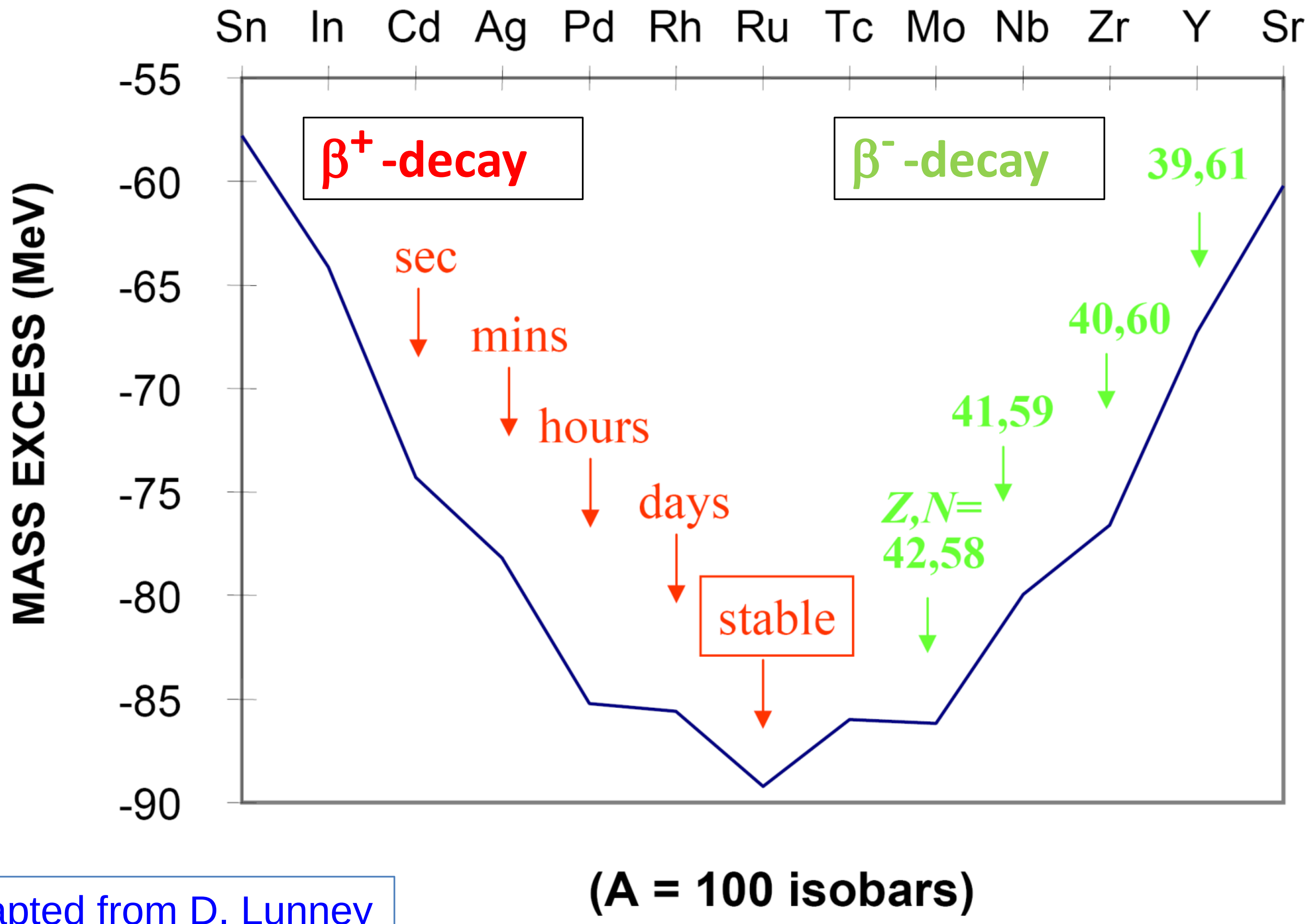
255 stable isotopes, 3100 observed isotopes

6000 - 8000 may be particle stable

neutron-rich

heavy

Decays toward stability



(A = 100 isobars)

Adapted from D. Lunney

Quiz

- How many stable nuclei has been observed per mass?
  - (a) 0 or 1
  - (b) 0, 1, or 2
  - (c) 0, 1, 2, or 3
  - (d) 0, 1, 2, 3, or 4
- What is the definition of stable nuclei?
  - (a) Decay has not been observed
  - (b) Decay is energetically forbidden
  - (c) Existed since primordial time

Opportunities and challenges

- Broader range in Z, N, and A
  - Varity of experimental methods → optimization
- Exotic beams
  - Low intensity
  - Beam impurity
  - High recoil velocity
    - Inverse reactions, fragmentation

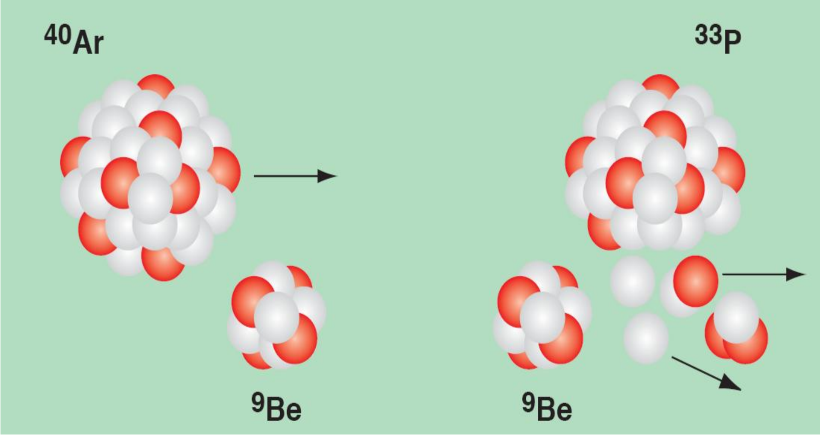
Requirements on instrument

Experimental conditions	Instrument capabilities
■ Large recoil velocity — Fragmentation — Inverse reaction	• High position resolution
■ Low beam intensity	• High efficiency
■ High background rate — Beam decay — Beam impurity	• High P/T • High counting rate • Background rejection

Produce excited states

- Reaction
  - Coulomb excitation at low and high energy
  - Inelastic scattering
  - Transfer reactions
  - Deep inelastic reactions
  - Fragmentation (single and two-step)
  - Nucleon knockout

- Decay
  - α-decay
  - β-decay
  - Spontaneous fission



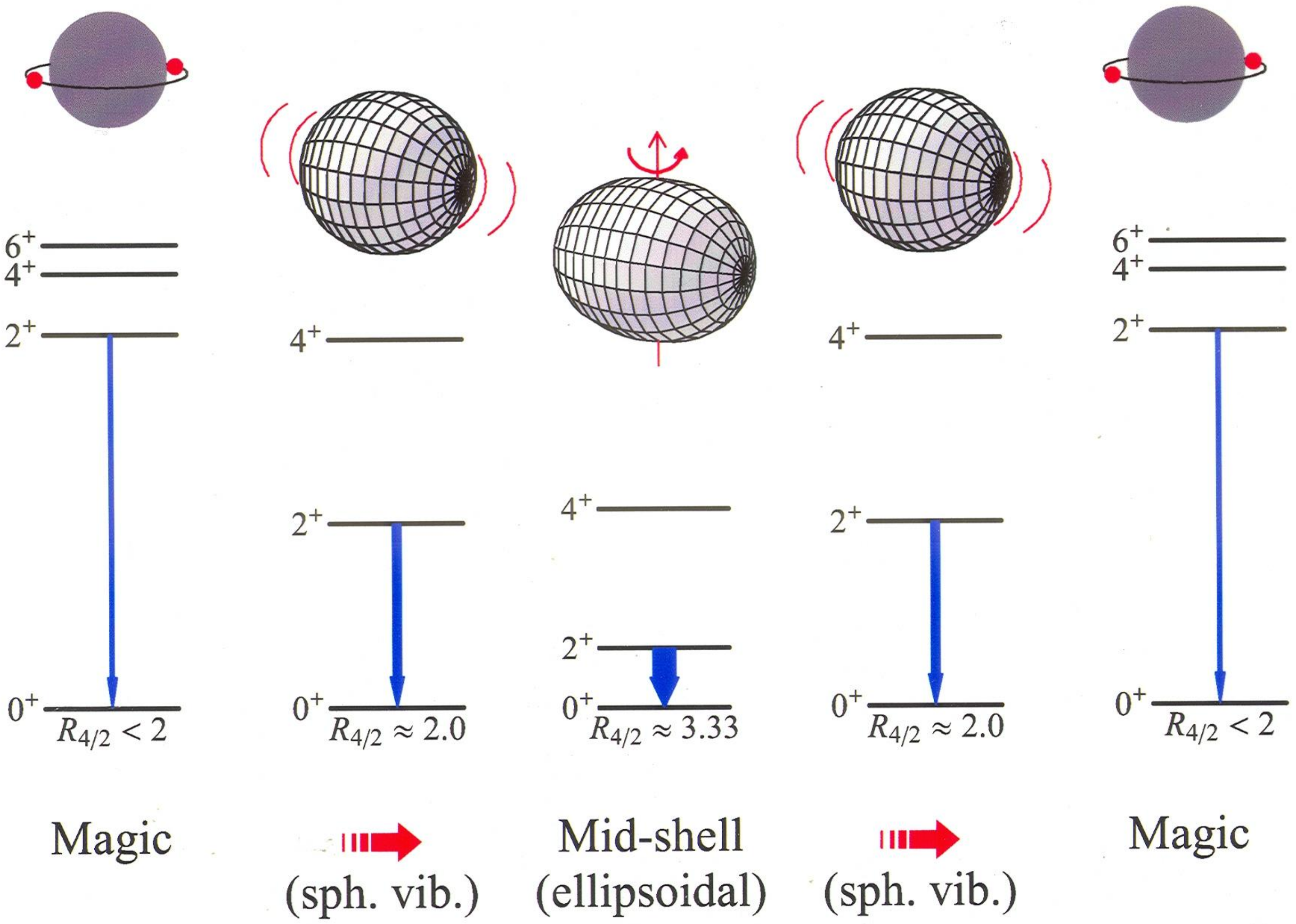
Nuclear properties

- Mass – binding energy
- Level energy
- Electromagnetic matrix elements
  - B(M1), B(E2), Q, lifetime, and *g*-factor
- Reaction cross sections (need reaction model)
  - Transfer reactions
  - Knockout reactions

Theory and model

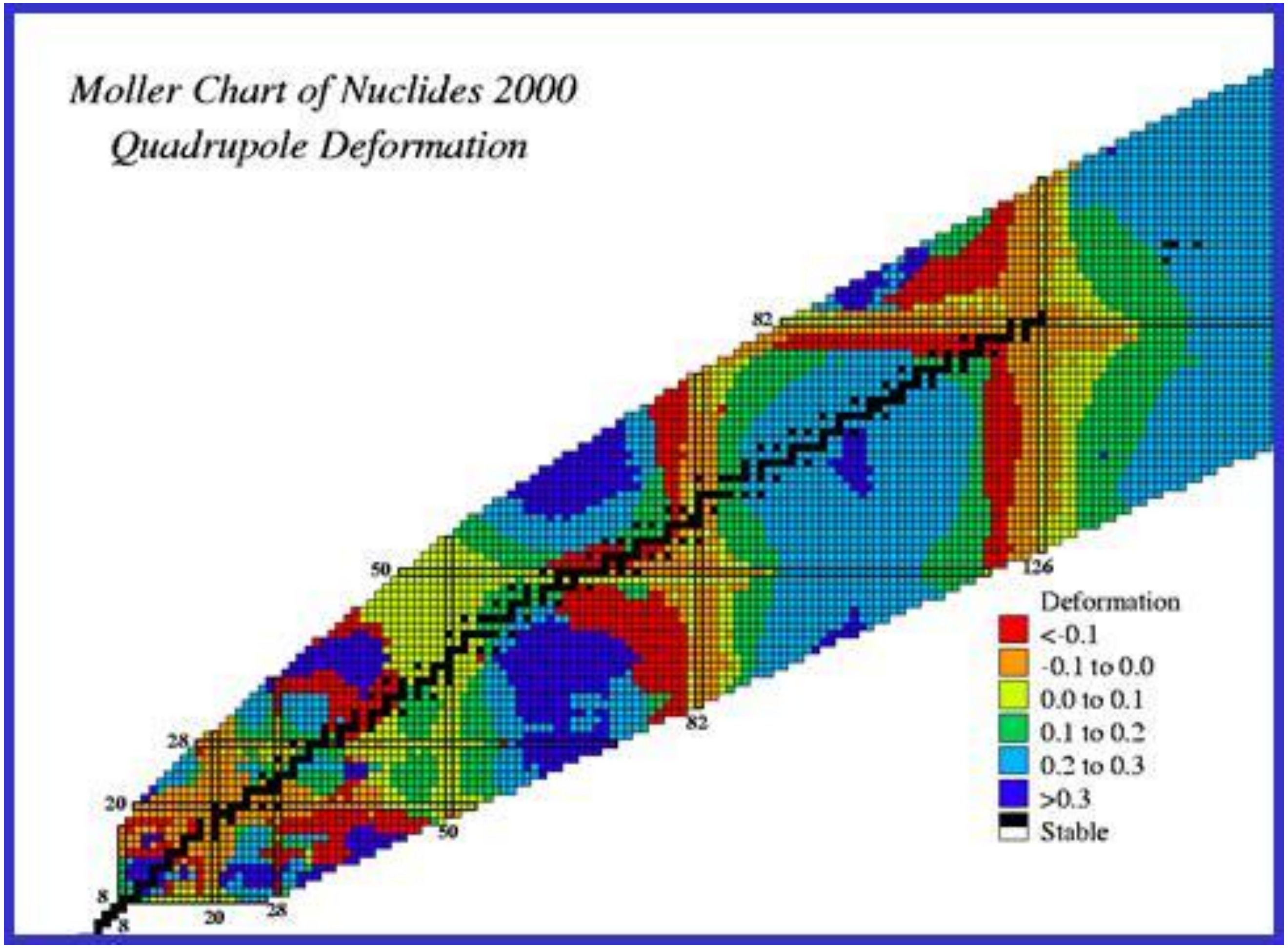
- Guidance on possible areas of interest
- Help on design of experiment
- Interpreting results

Evolution of level energy



Adapted from Rick Casten

Evolution of nuclear deformation



Shell evolution, nuclear forces, and shapes

Ti isotopes

28

30

32

34

Shell gaps at N=28, 32

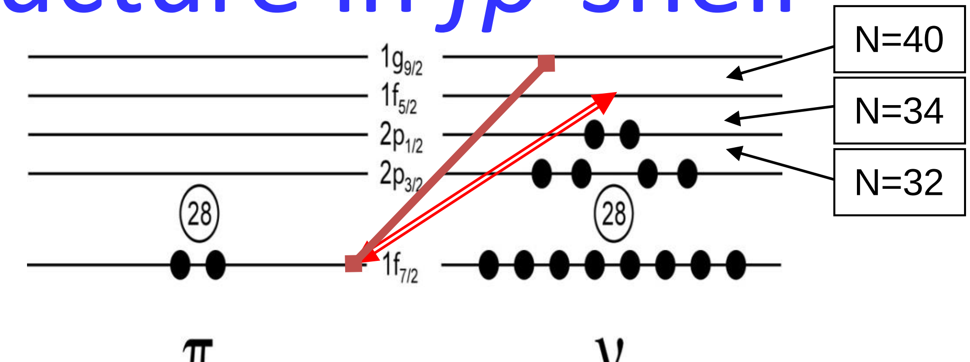
1129

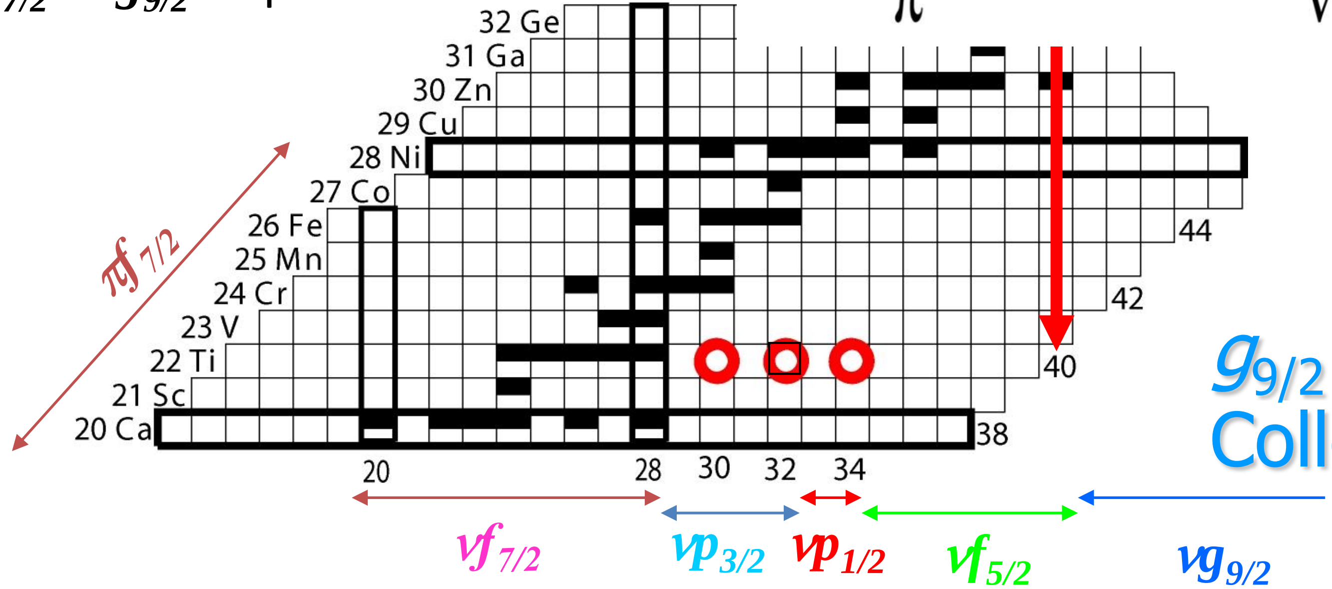
R.V.F. Janssens *et al.*, PLB 546, 22 (2002)
B. Fornal *et al.*, PRC 70, 064304 (2004)

(Sub)shell structure in *fp*-shell

As protons are removed from the $\pi f_{7/2}$ shell, the monopole interaction weakens:

- $\pi f_{7/2}$ – $\nu f_{5/2}$: attractive
- $\pi f_{7/2}$ – $\nu g_{9/2}$: repulsive





$g_{9/2}$ orbital: Collectivity

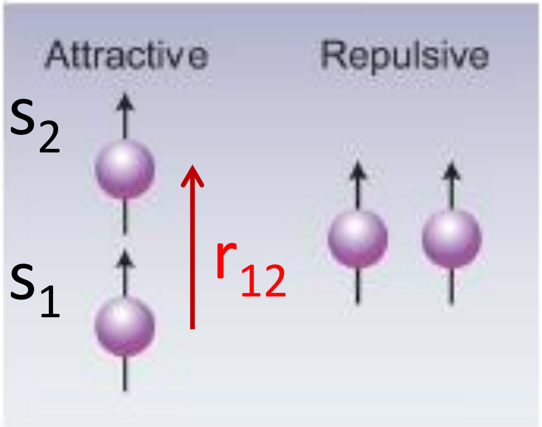
T. Otsuka *et al.*, Phys. Rev. Lett. 87 (2001) 082502
T. Otsuka *et al.*, Phys. Rev. Lett. 97 (2005) 162501
T. Otsuka *et al.*, Phys. Rev. Lett. 104 (2010) 012501

Tensor force

$$V_T = S_{12} V(r_{12})$$

$$S_{12} = 3(\vec{s}_1 \cdot \hat{r}_{12})(\vec{s}_2 \cdot \hat{r}_{12}) - (\vec{s}_1 \cdot \vec{s}_2)$$

$$S_{12} = 3[\vec{s}_1 \times \vec{s}_2]^{(2)} \cdot [\hat{r}_{12} \times \hat{r}_{12}]^{(2)}$$



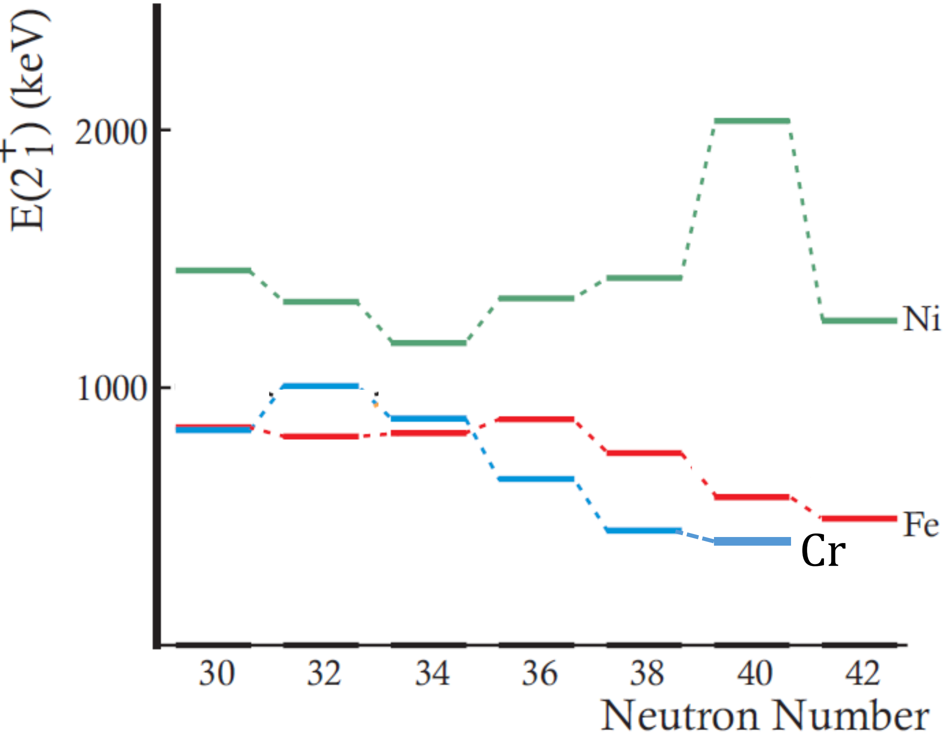
S_{12}= 0.5 S_{12}= - 0.25

Quiz

- What is the tensor force between (π $p_{3/2}$) and (ν $g_{9/2}$)
  - (a) Attractive
  - (b) Repulsive
  - (c) Zero

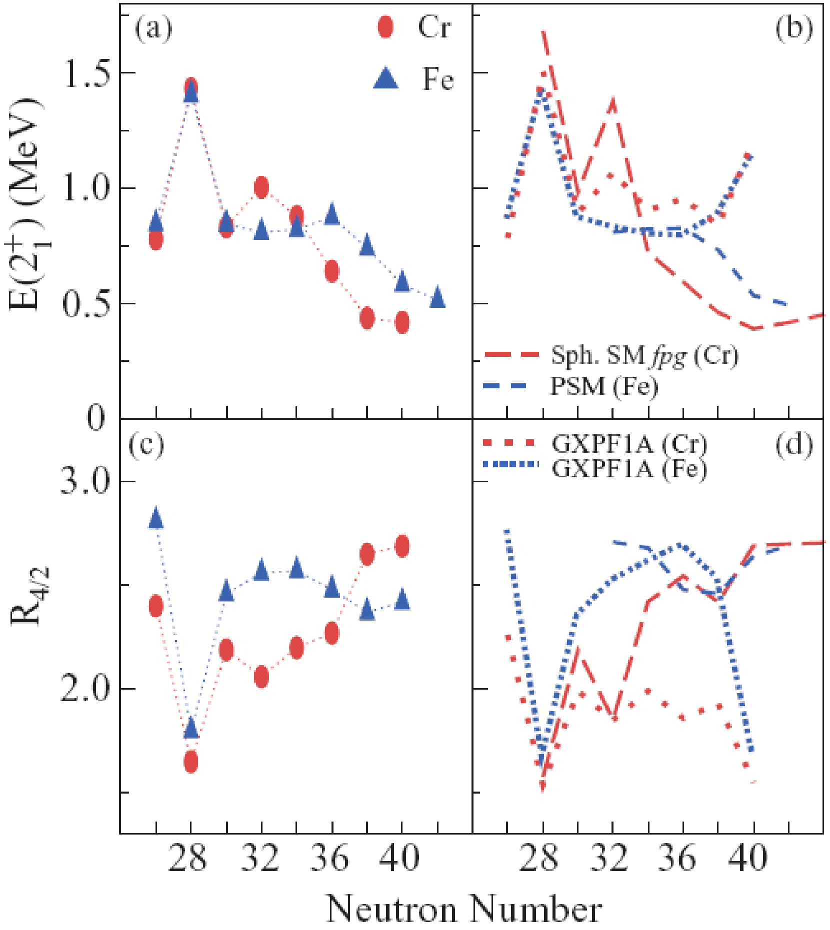
N=40 Magic Number

- Sub-shell closure at *N*=40 observed for the Ni isotopes
- Addition or removal of protons washes out the effect of the sub-shell gap
- Evidence of collectivity is seen in Fe and Cr isotopes – decreasing E(2^+) through *N*=40



Broda, R., *et al*., Phys. Rev. Lett. **74**, 868 (1995).
Hannawald, M., *et al*., Phys. Rev. Lett. **82**, 1391 (1999).
Adrich, P., *et al*., Phys. Rev. C **77**, 05436 (2008).

Levels of Neutron-Rich Fe and Cr Isotopes



GXPF1A:
high E(2^+) and low $R_{4/2}$

Cr *fpg* space:
low E(2^+) and high $R_{4/2}$

Fe PSM:
low E(2^+) and high $R_{4/2}$

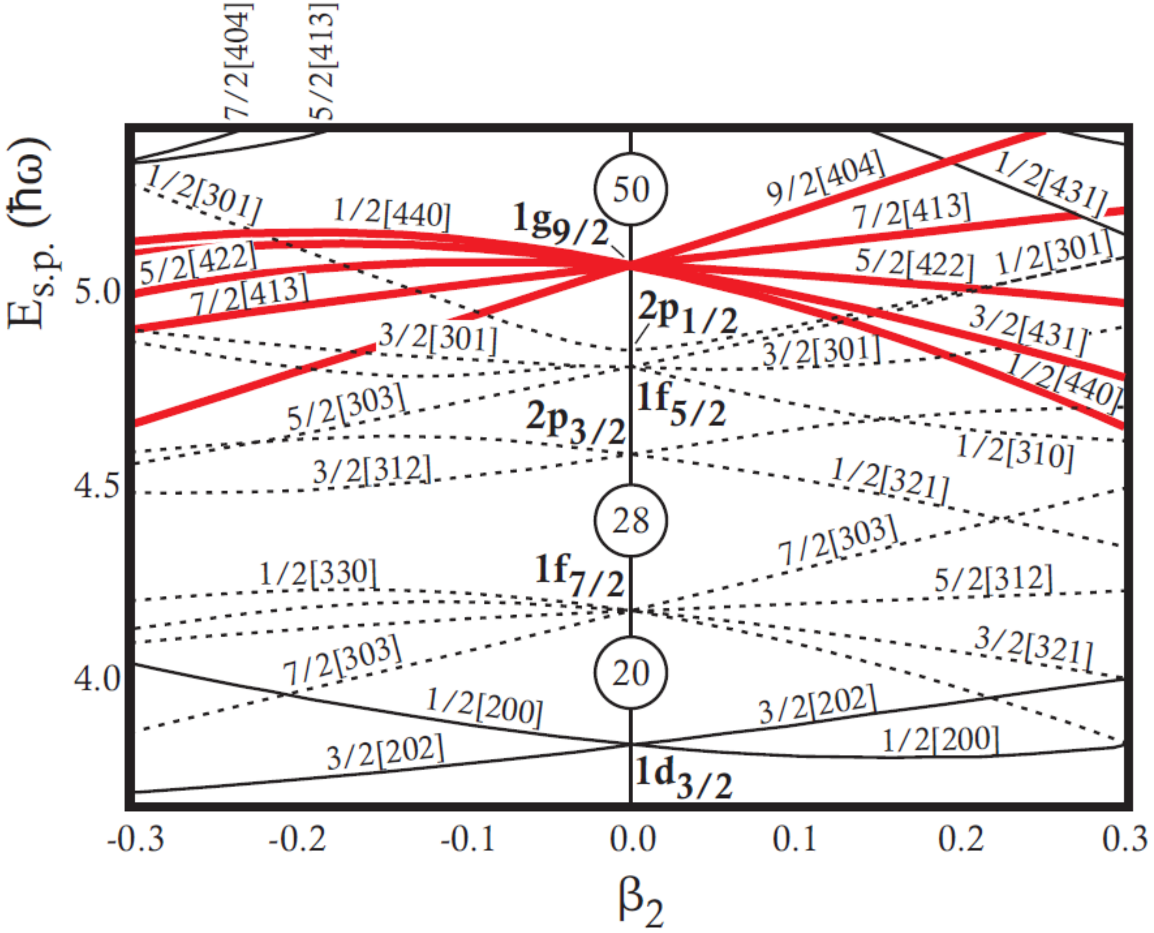
Most Recent Calculations:

S. Lenzi *et al.*, Phys. Rev. *C* **82** (2010) 054301

Stress need to include not only $g_{9/2}$ but $d_{5/2}$ to model space.

A. Gade *et al.*, Phys. Rev. C, 81 (2010) 051304(R) and ref. therein.

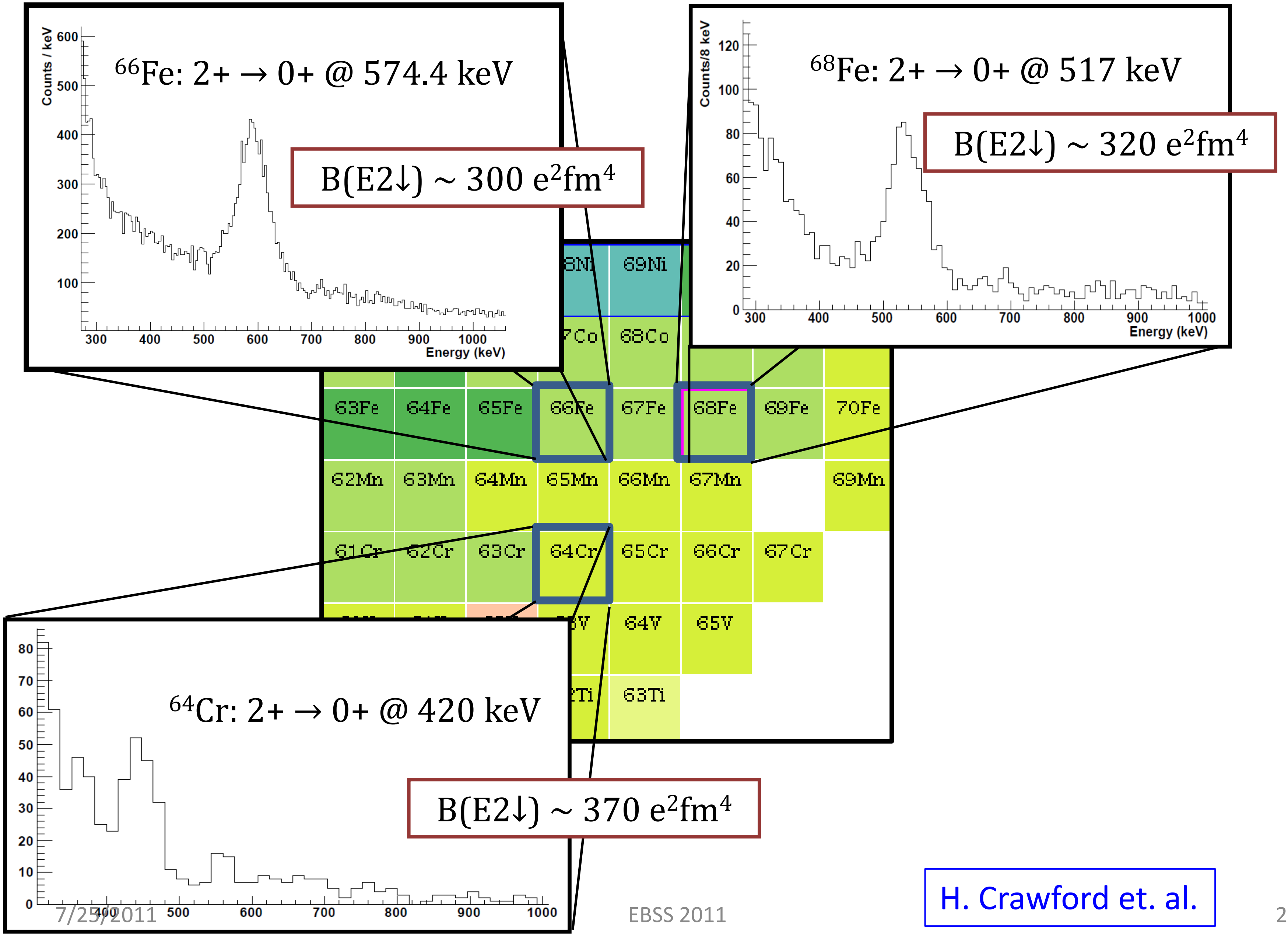
Driving Deformation near N=40



- proton-neutron interactions between $1f_{7/2}$ proton holes and $1g_{9/2}$ neutrons results in a lowering of the $1g_{9/2}$ neutron orbital
- first two Nilsson substates of $1g_{9/2}$ orbital are steeply downsloping with increasing deformation

Hannawald, M., *et al.*, Phys. Rev. Lett. **82**, 1391 (1999).
Deacon, A.N., *et al.*, Phys. Lett. B **622**, 151 (2005).

New Coulomb excitation results



^{66}Fe: 2+ → 0+ @ 574.4 keV

B(E2↓) ~ 300 e^2fm^4

^{68}Fe: 2+ → 0+ @ 517 keV

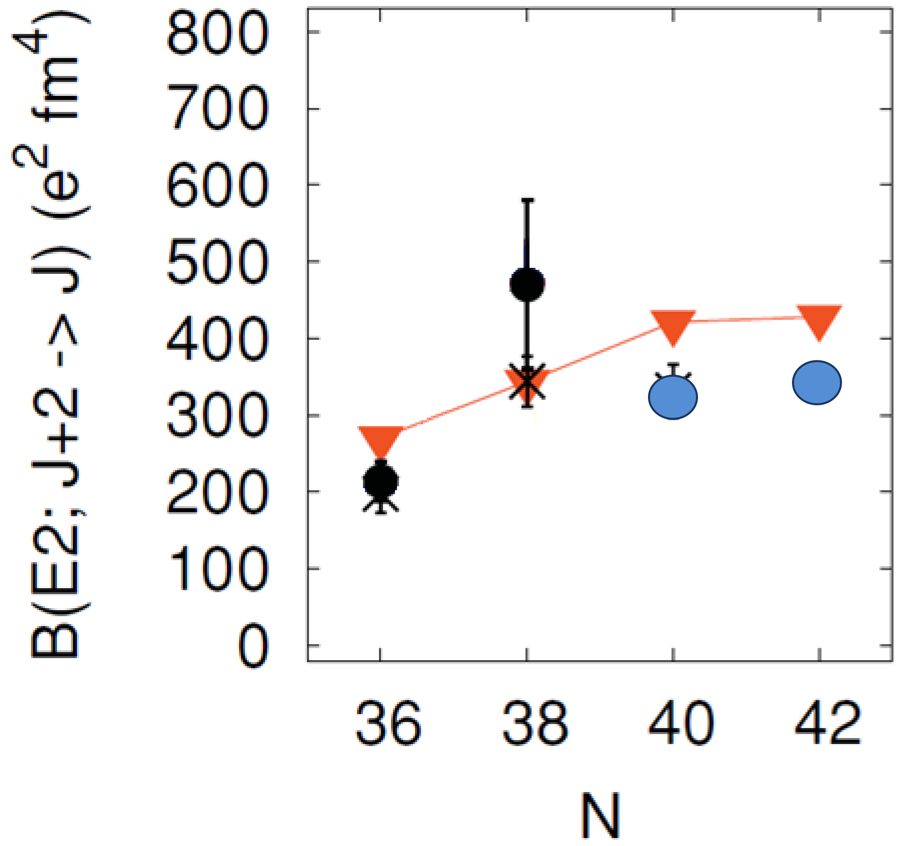
B(E2↓) ~ 320 e^2fm^4

^{64}Cr: 2+ → 0+ @ 420 keV

B(E2↓) ~ 370 e^2fm^4

H. Crawford et. al.

Recent Results – $_{26}$Fe

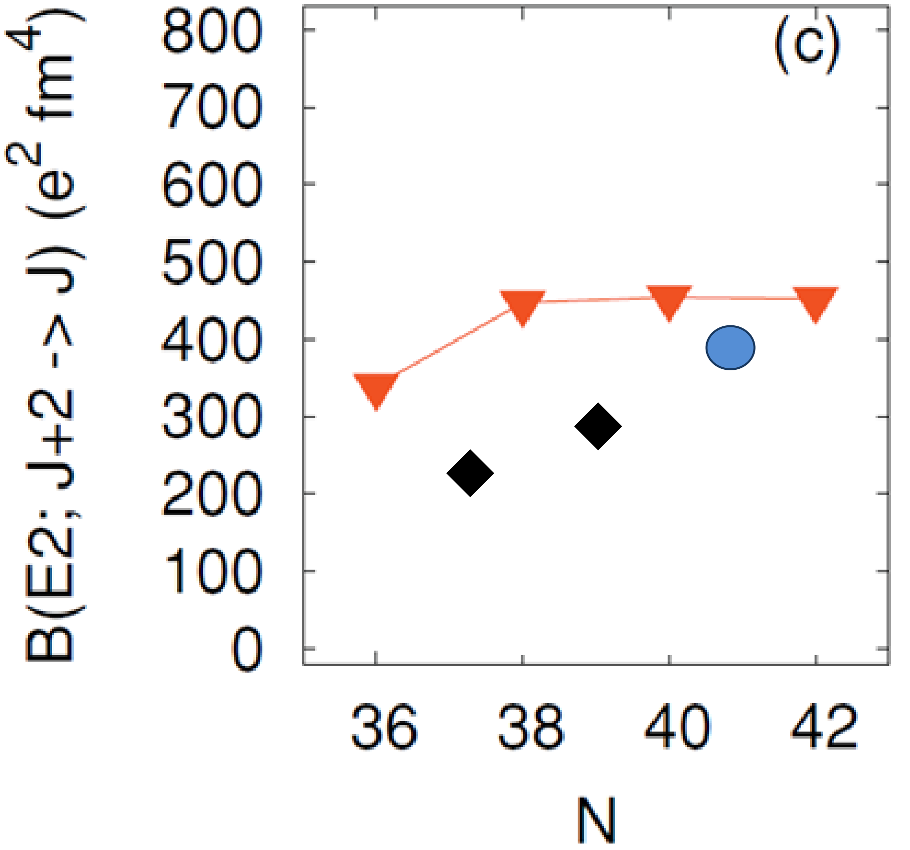


- New results for the ^{66,68}Fe isotopes suggest B(E2) values of ~ 300 e^{2}fm^4 and ~320 e^{2}fm^4 respectively
- Measurement agrees with previous Recoil Distance lifetime measurement in ^{66}Fe
- Results fall below shell-model calculations, but adjustment of effective charges can improve agreement

Lenzi *et al.*, Phys. Rev. C **82**, 054301 (2010)
H. Crawford *et al.*,.

Recent Results – $_{64}$Cr

- Preliminary results suggest a B(E2↓) in ^{64}Cr of ~ 370 e^2fm^4
- Same ss for the Fe isotopes, experimental result falls below the shell-model prediction – effective charges?

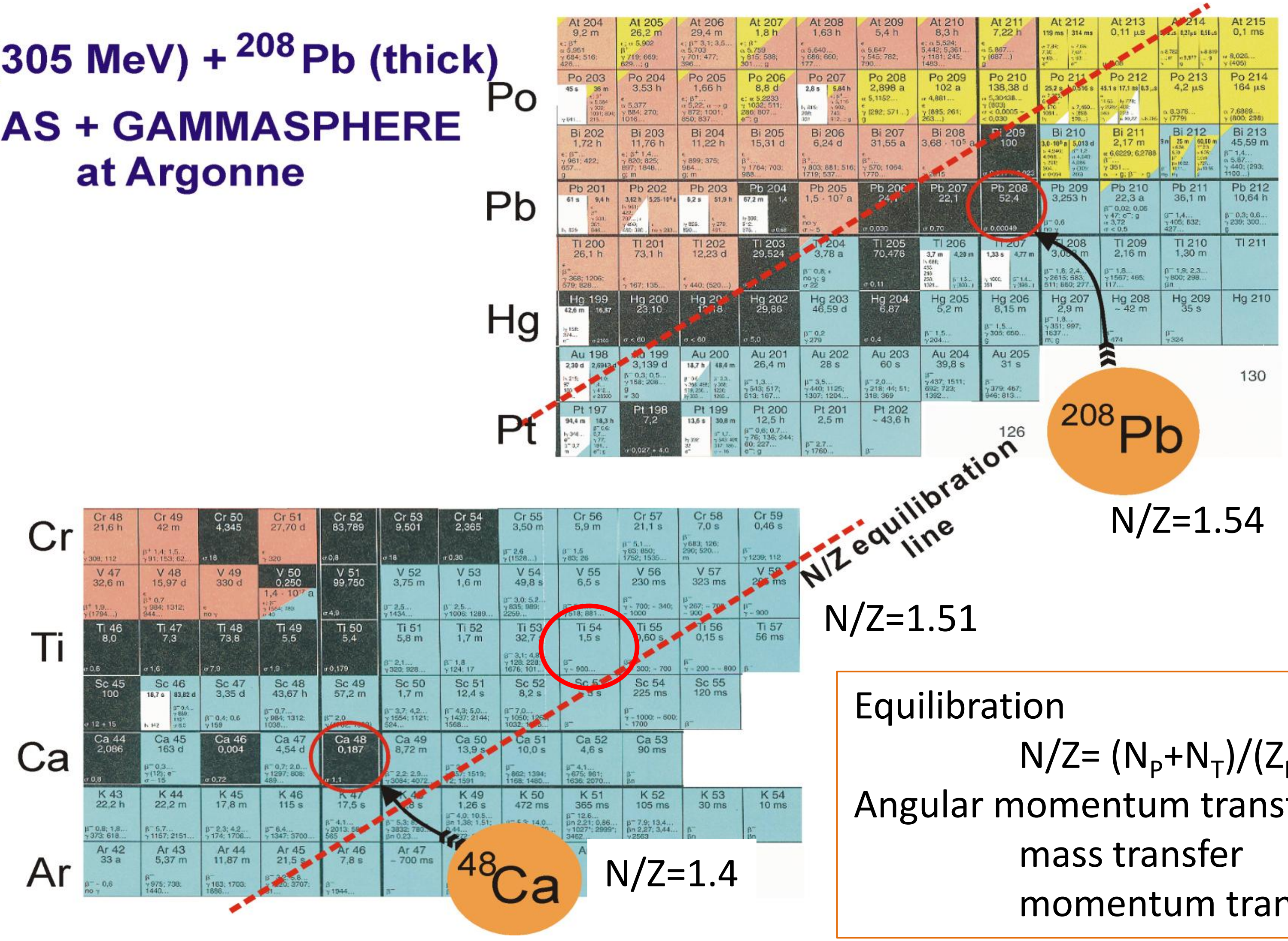


Lenzi *et al.*, Phys. Rev. C **82**, 054301 (2010).
Aoi *et al.*, Phys. Rev. Lett. **102**, 012502 (2009).
H. Crawford et al.,

Higher spin states from deep-inelastic Reaction

^{48}Ca (305 MeV) + ^{208}Pb (thick)

ATLAS + GAMMASPHERE
at Argonne



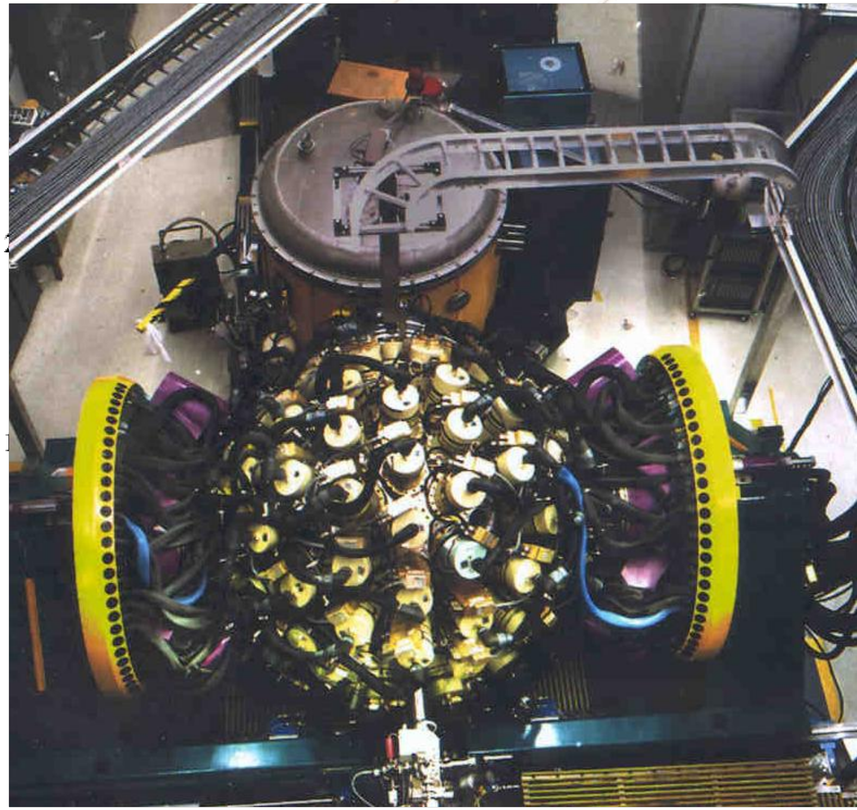
Equilibration

$N/Z = (N_P+N_T)/(Z_P+Z_T)$

Angular momentum transfer
mass transfer
momentum transfer

Gammasphere

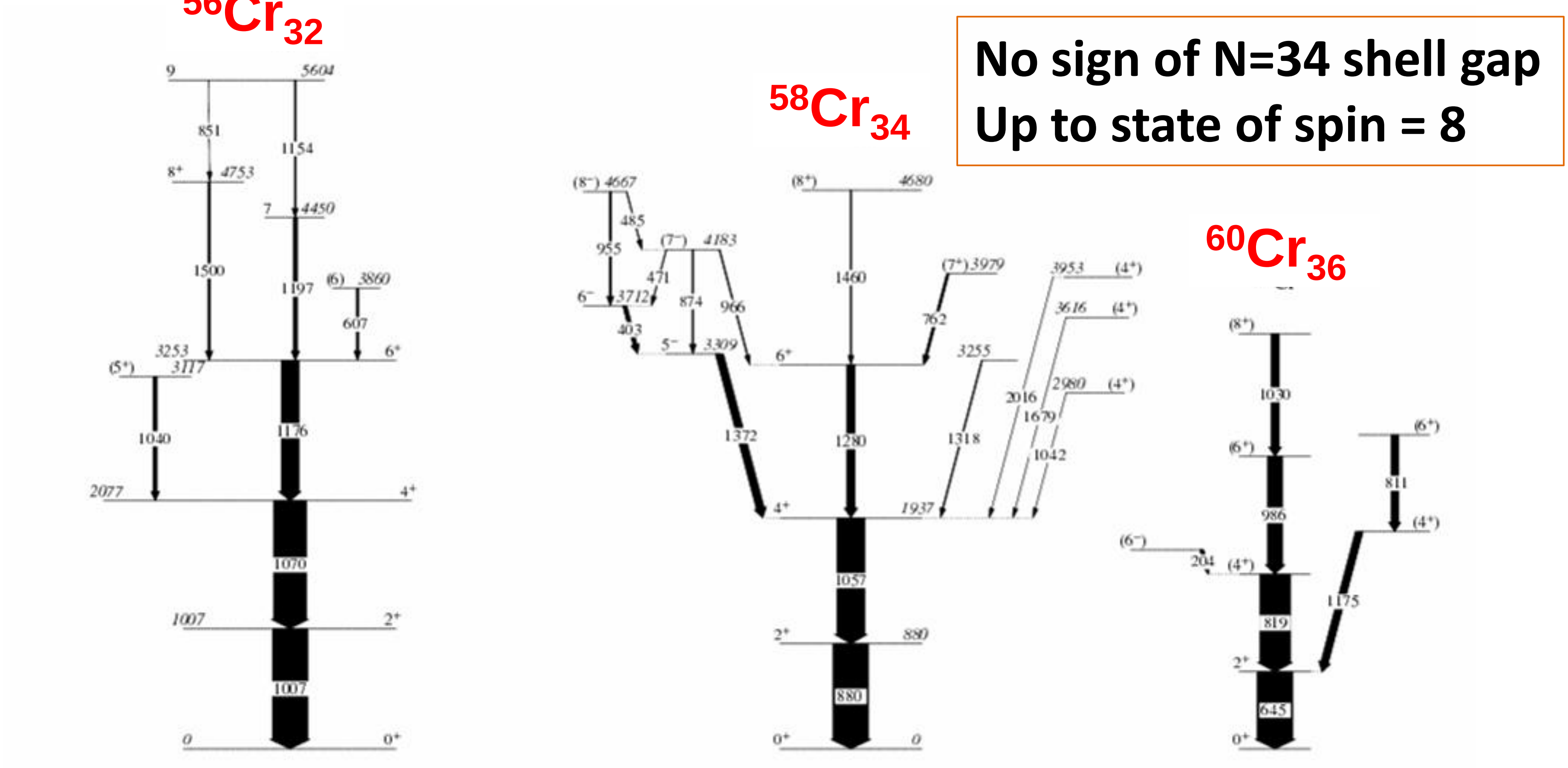
- Gammasphere can accommodate up to 110 Compton Suppressed Ge detectors.
- The relative efficiency of each Ge detector is 70-75%.
- The device began operations in the spring of 1993 with ~30 detectors (Early Implementation Phase).
- The device has operated at the 88-inch Cyclotron at LBNL and at ATLAS at ANL.



Cr isotopes energy levels systematics

No sign of N=34 shell gap

Up to state of spin = 8

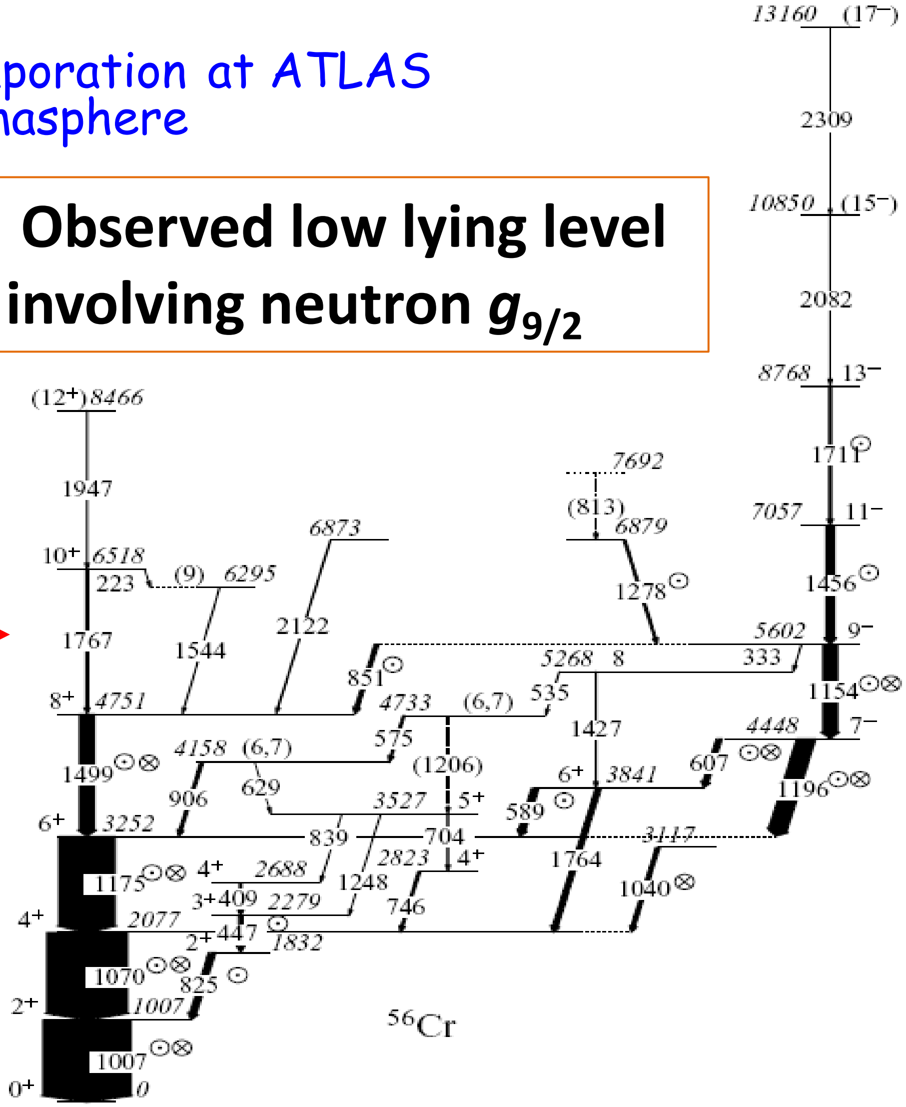


S. Zhu *et al.*, Phys. Rev. C **74** (2006) 064351

Higher spin properties

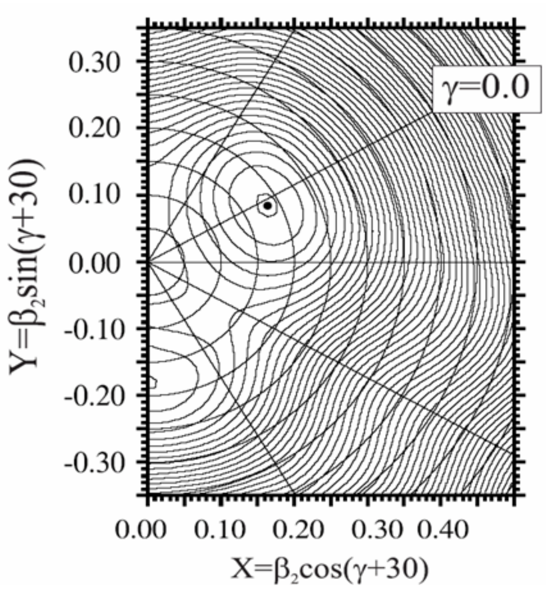
Fusion Evaporation at ATLAS
with Gammasphere

- **Observed low lying level involving neutron $g_{9/2}$**



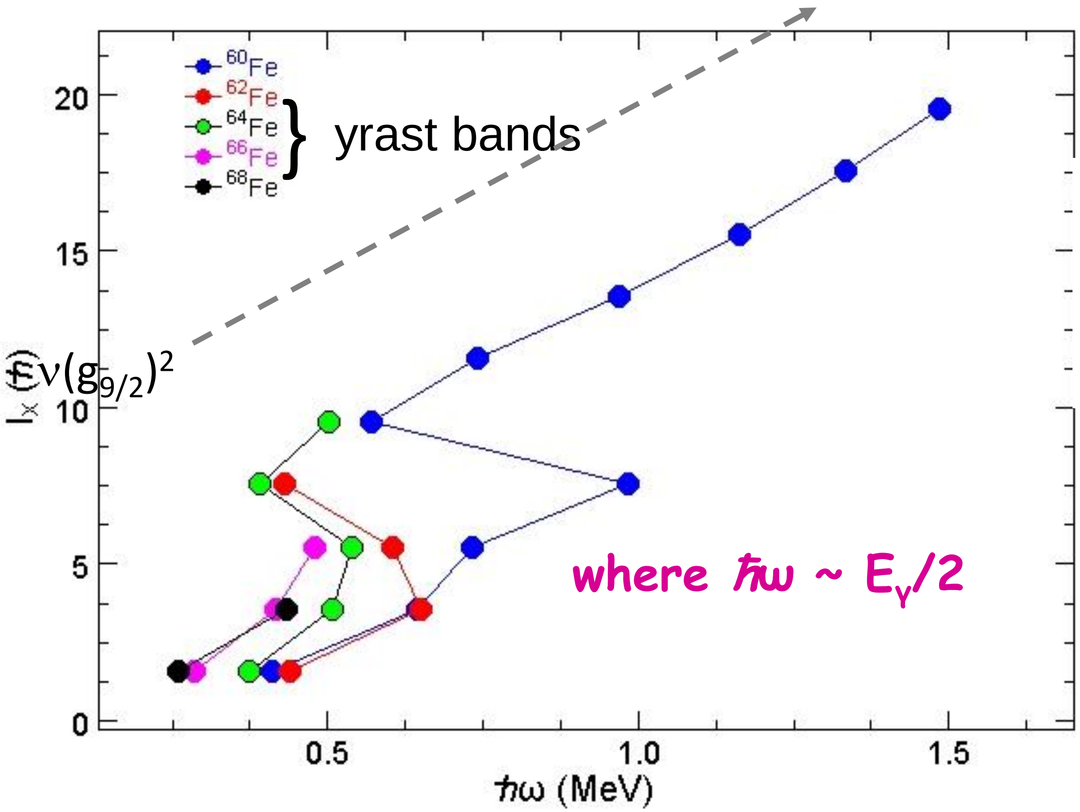
DIC limit

$\nu(g_{9/2} x f_{5/2})$



S. Zhu *et al.*, Phys. Rev. C **74** (2006) 064351

What Is the Nature of the Collectivty at N=40 in Fe and Cr?

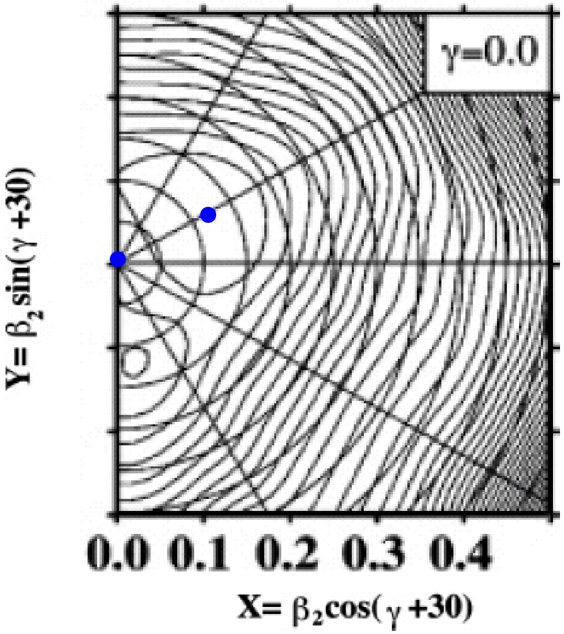


} yrast bands

$\nu(g_{9/2})^2$

where ħω ~ $E_\gamma/2$

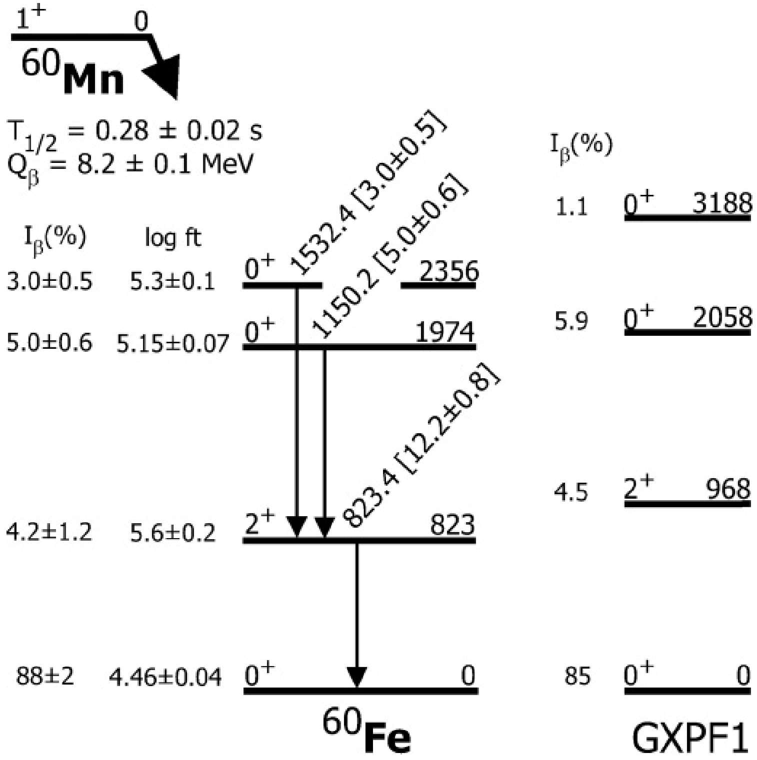
^{60}Cr



F.R. Xu, Peking University

- All yrast bands are approaching $(g_{9/2})^2$ aligned structure at 8^+
- 8+ levels in Fe isotopes decrease in energy ^{60}Fe (5.3 MeV), ^{62}Fe (4.25 MeV), and ^{64}Fe (3.6MeV)

Co-existence of spherical and deformed shapes



S. Liddick *et al*., PRC **73**, 044322 (2006)

- Decay from low-spin ground state in ^{60}Mn from data taken at NSCL has identified excited 0^+ states in ^{60}Fe.
- GXPF1 results can only account for one of the excited 0^+ states. (no $g_{9/2}$ orbital)
- The 2356 keV level is a very good candidate for the intruder 0^+ in ^{60}Fe.

Summary

- A rich variety of phenomena have been observed in the *fp*-shell
  - Subshell closure, deformation, and shape coexistence
- The underlying physics involve
  - Residual interaction, and deformation driving force of high-*j* orbitals.
- Many complementary experimental methods were used
  - Gamma-ray spectroscopy using Fusion reaction, β-decay, deep inelastic reactions, and Coulomb excitation

Study weak binding by measuring lifetime

Evolution of single particle levels

- In a well bound nucleus
  - steady evolution of energy levels in a 1 body potential
  - modified by 2-body NN interaction (σ.τ, Tensor)
- A second distinct effect is due to weakly bound levels
  - low *l* levels (*s, p*) → extended wavefunctions (“halos”)
  - Valence nucleons can become decoupled from the core
  - Coupling to continuum states

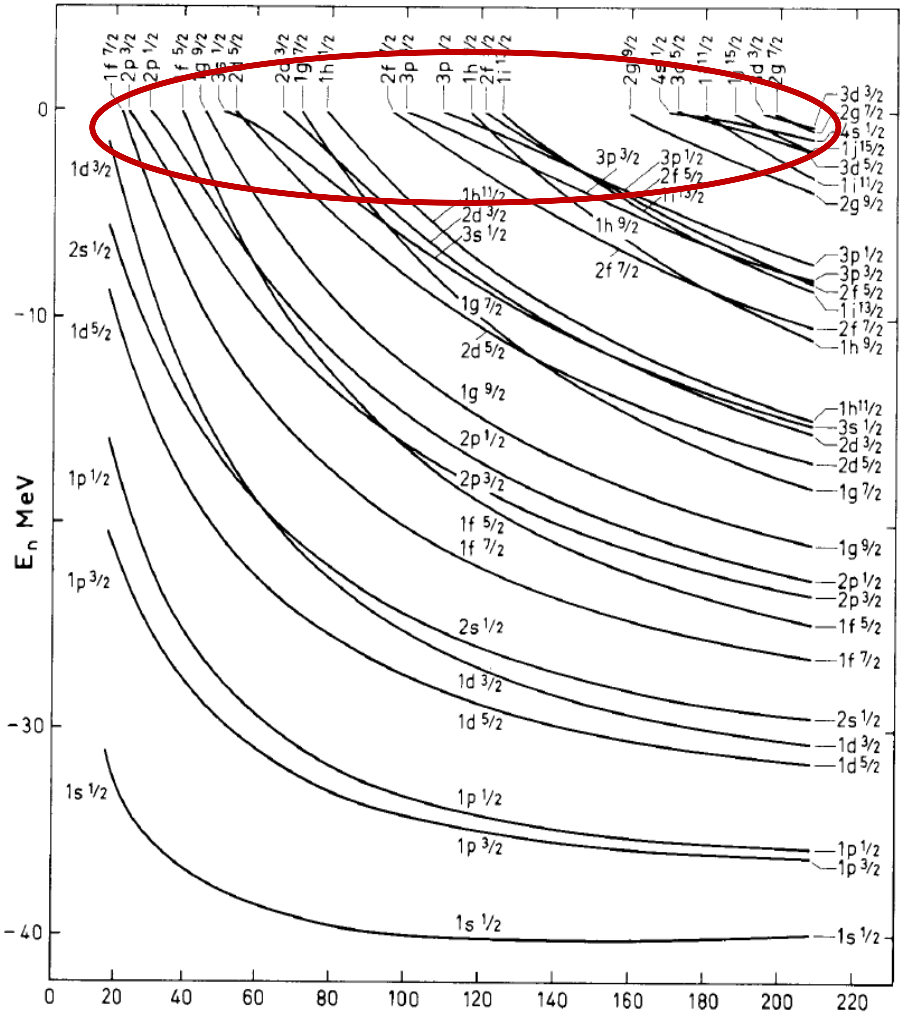
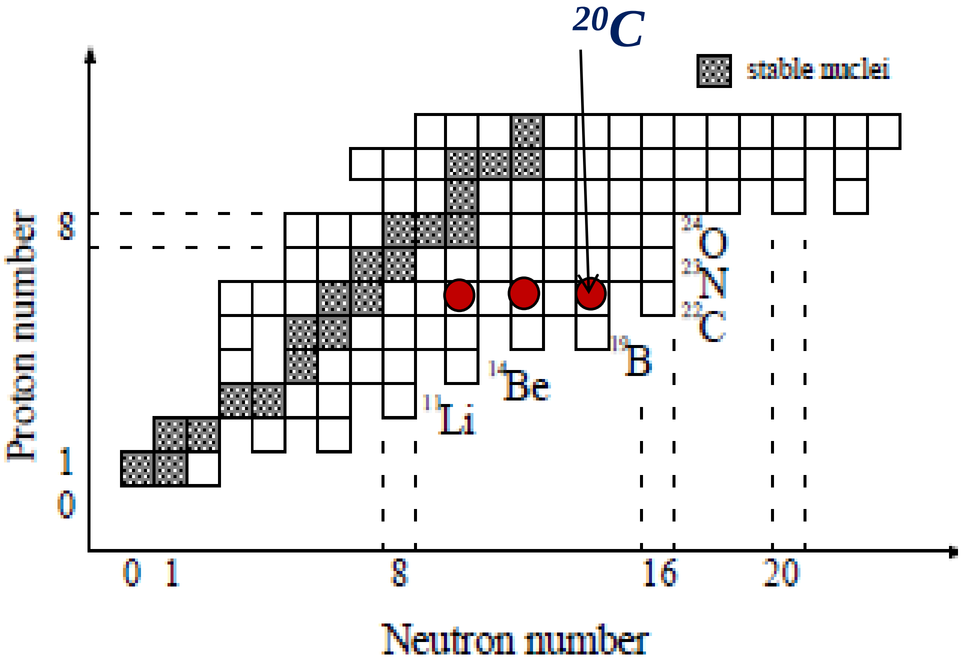


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

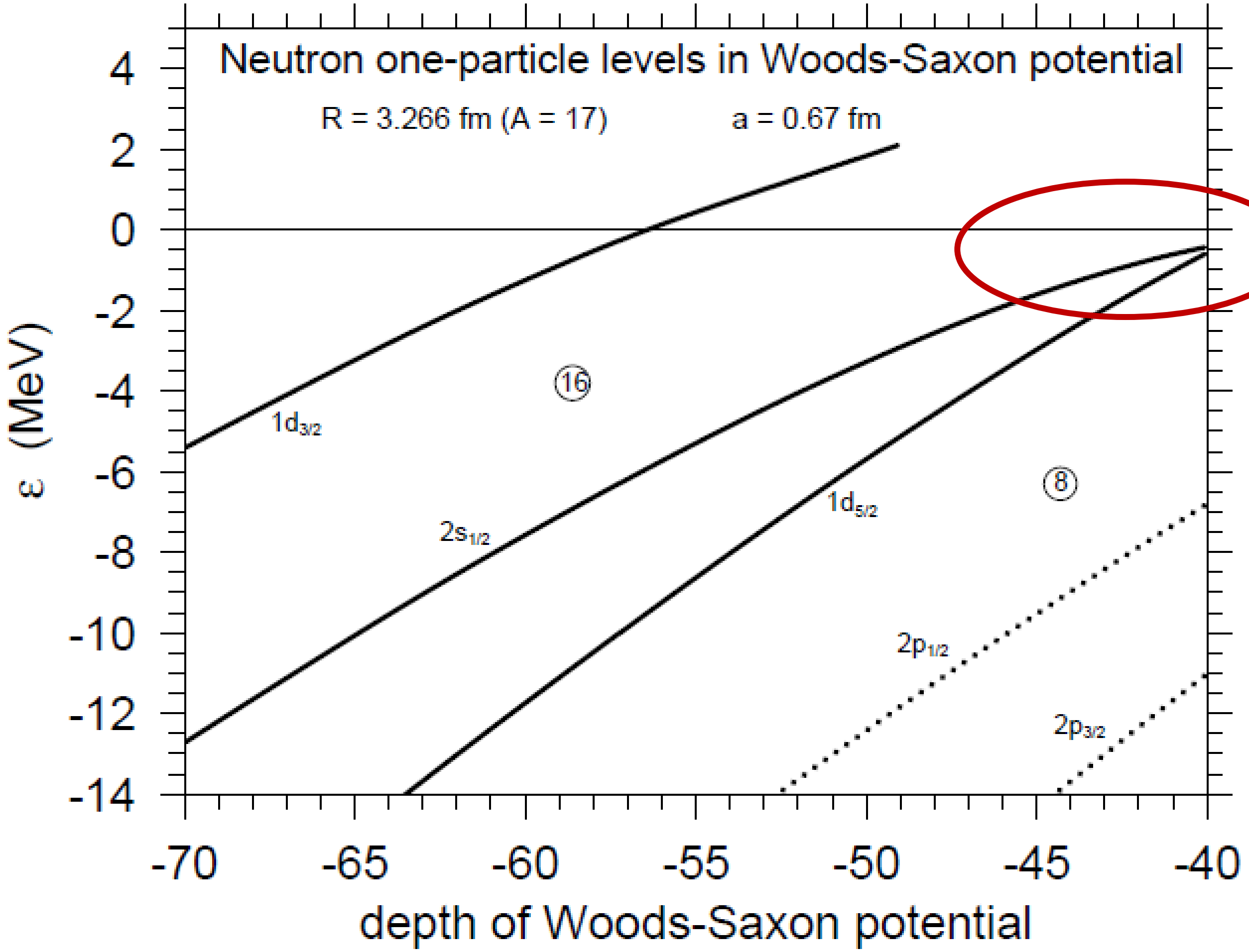
A.Bohr and B.R. Mottelson, vol. 1

Study the effects of weak binding

- B(E2) is sensitive to the coupling of valence neutron to the core.
- Determine B(E2, $0^+ \rightarrow 2^+$) of ^{16,18,20}C
- ^{20}C has a neutron binding energy of 3.3 MeV
- Life time measured using Recoil Distance Method with fast beams from NSCL

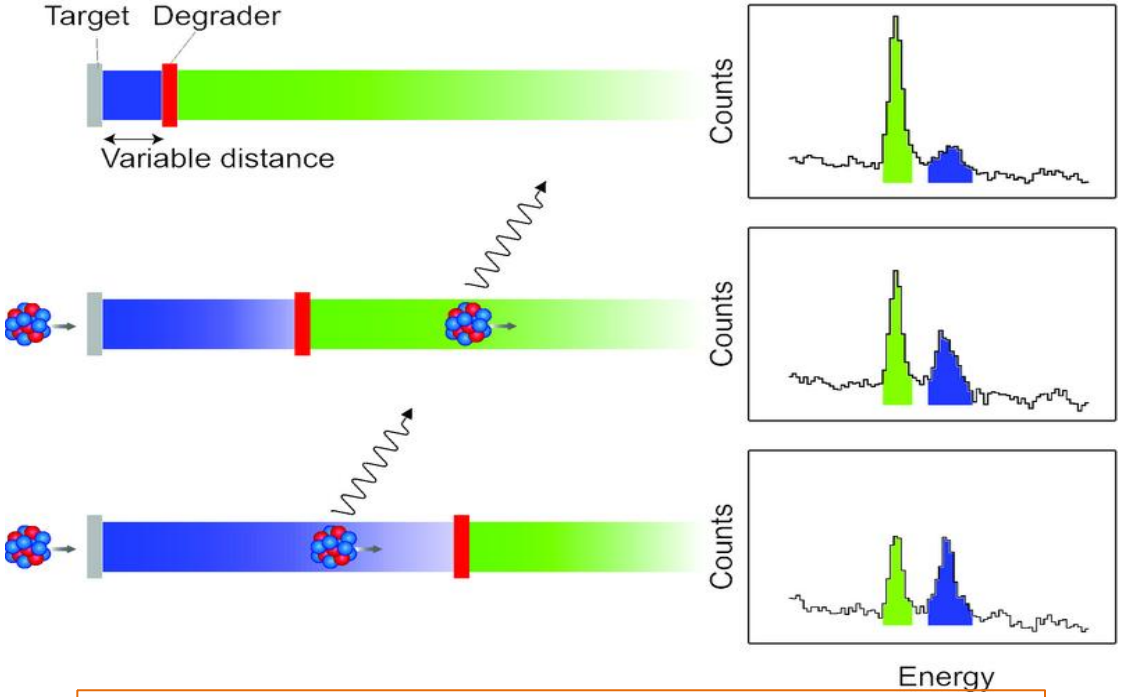


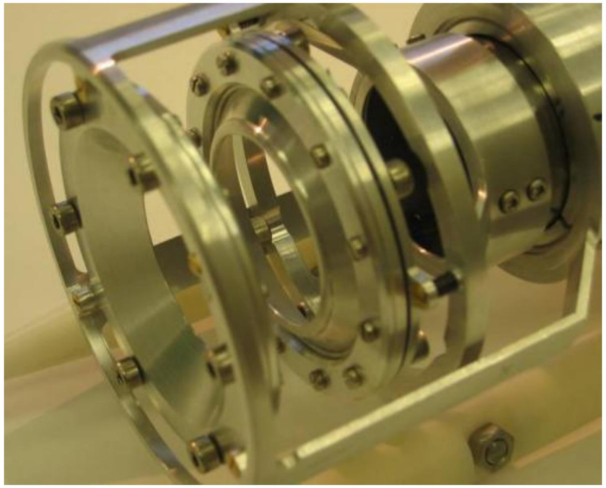
Nilsson diagrams for light neutron-rich nuclei with weakly-bound neutrons



Ikuko Hamamoto Phy. Rev. C **76**, 054319 (2007)

Recoil distance (plunger) method





Koln/NSCL plunger

Target-Degrader Distance:

0.1 - 10mm (precision 1μm)

Flight time:

0.17 – 17 psec (v/c=0.5)

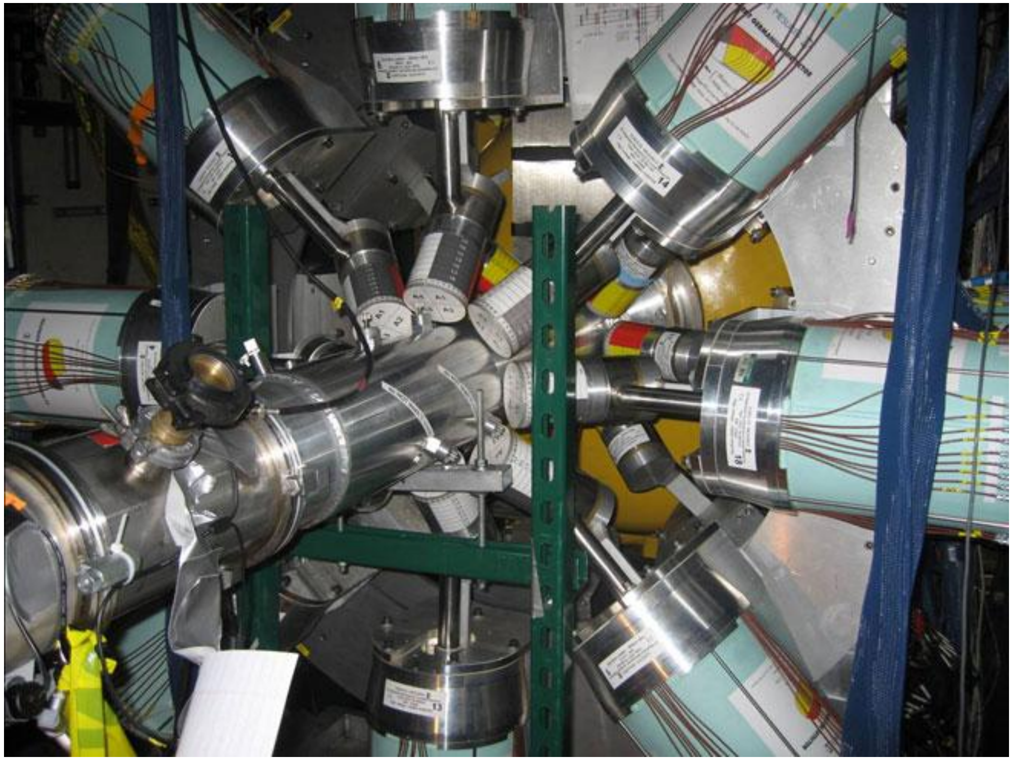
quiz

- What is the optimal target- degrade distance if we take only one distance.

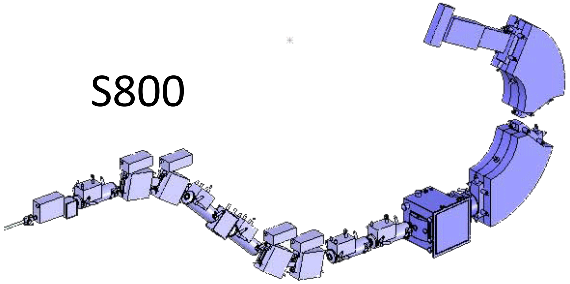
$$e^{-t/\tau} = 0.5^{-t/T_{1/2}}$$

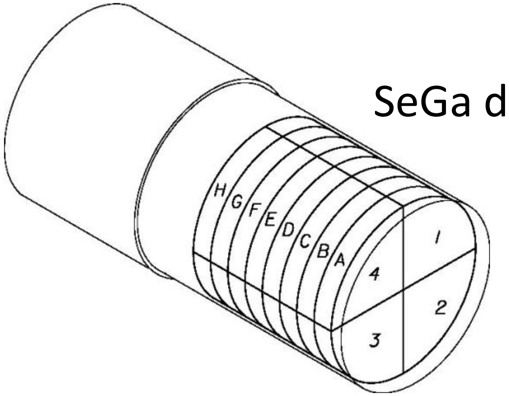
  - (a) d= $v \times \tau$
  - (b) d= $v \times T_{1/2}$
  - (c) d= $2\,v \times T_{1/2}$
  - (d) d= $v \times \tau / e$

Setup at NSCL

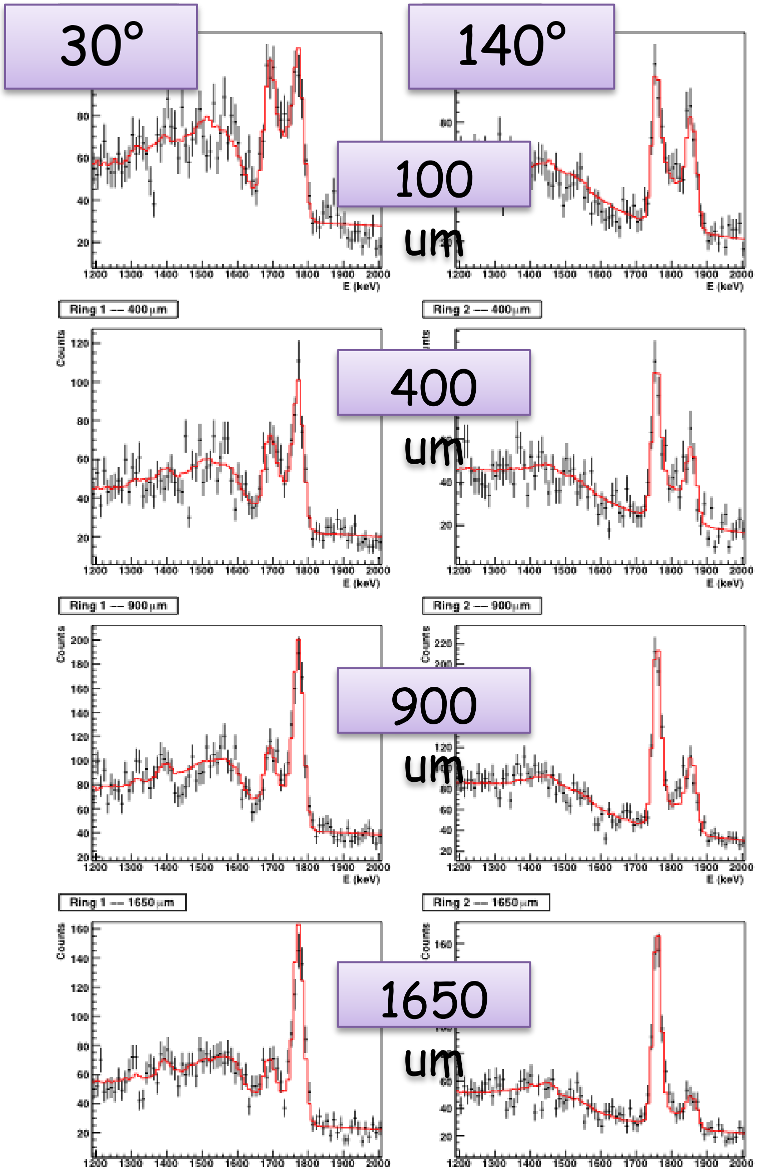


- **Koln/NSCL plunger**
- **S800**
- **SeGA- 4 × 8 Segmented Ge detector Array**
  - **7 detectors at forward angles (30°)**
  - **8 detectors at backward angles (140°)**

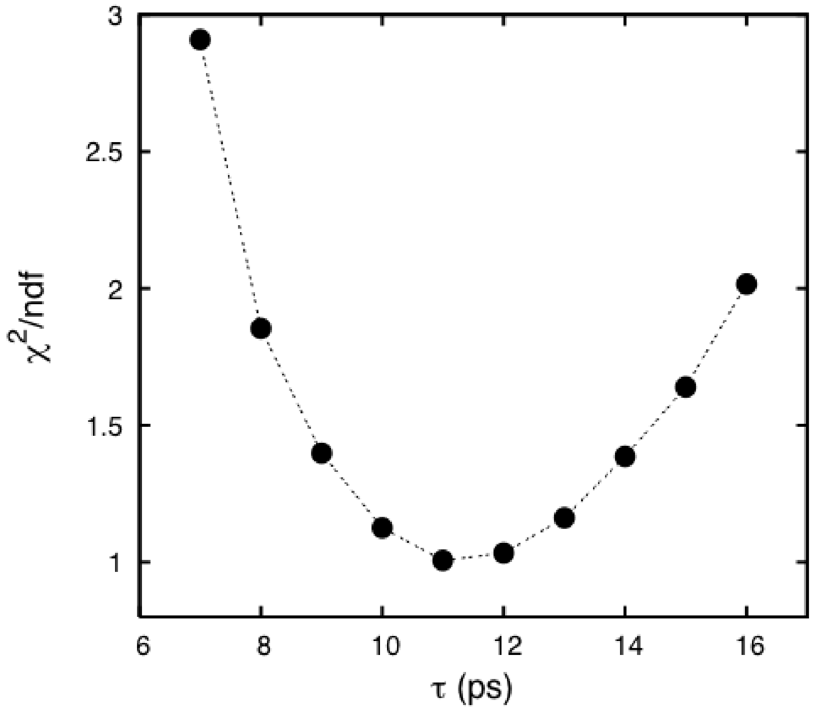




^{16}C Lifetime



τ = 11.4 ± 0.3 (stat) ± 0.8 (syst) ps



Marina Petri *et al.,* and

Previous measurements

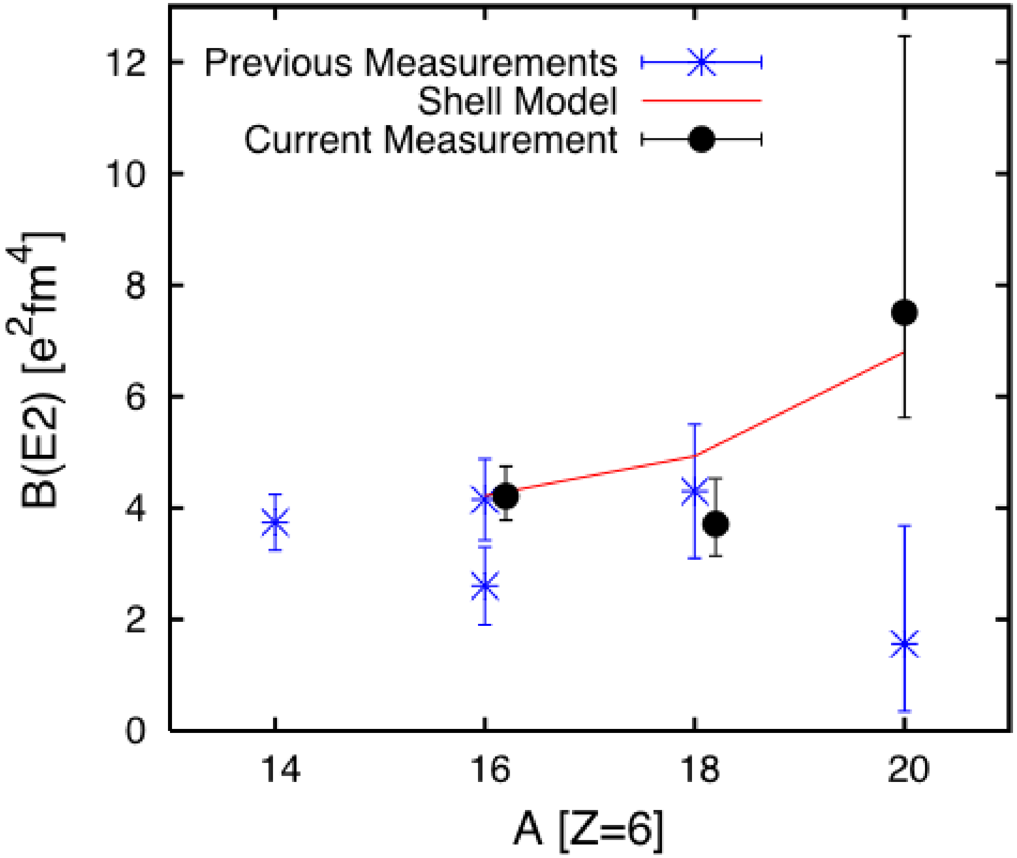
[1] M. Wiedeking et al., PRL 100, 152501 (2008)

[2] H. J. Ong et al., PRC 78, 014308 (2008)

Carbon Isotopes B(E2) Systematics

$B(E2)=1/(2J_i+1)\ |M_n e_n^* + M_p e_p^*|^2$

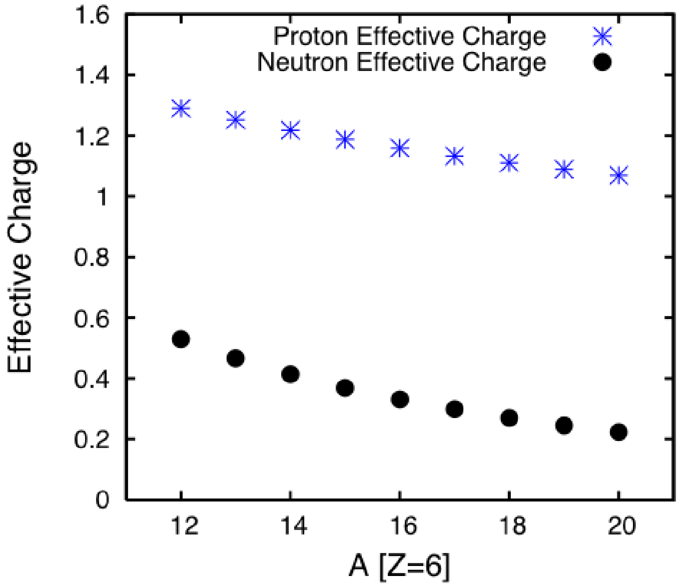
Using isospin-dependent polarization charges
that follow a smooth 1/A trend



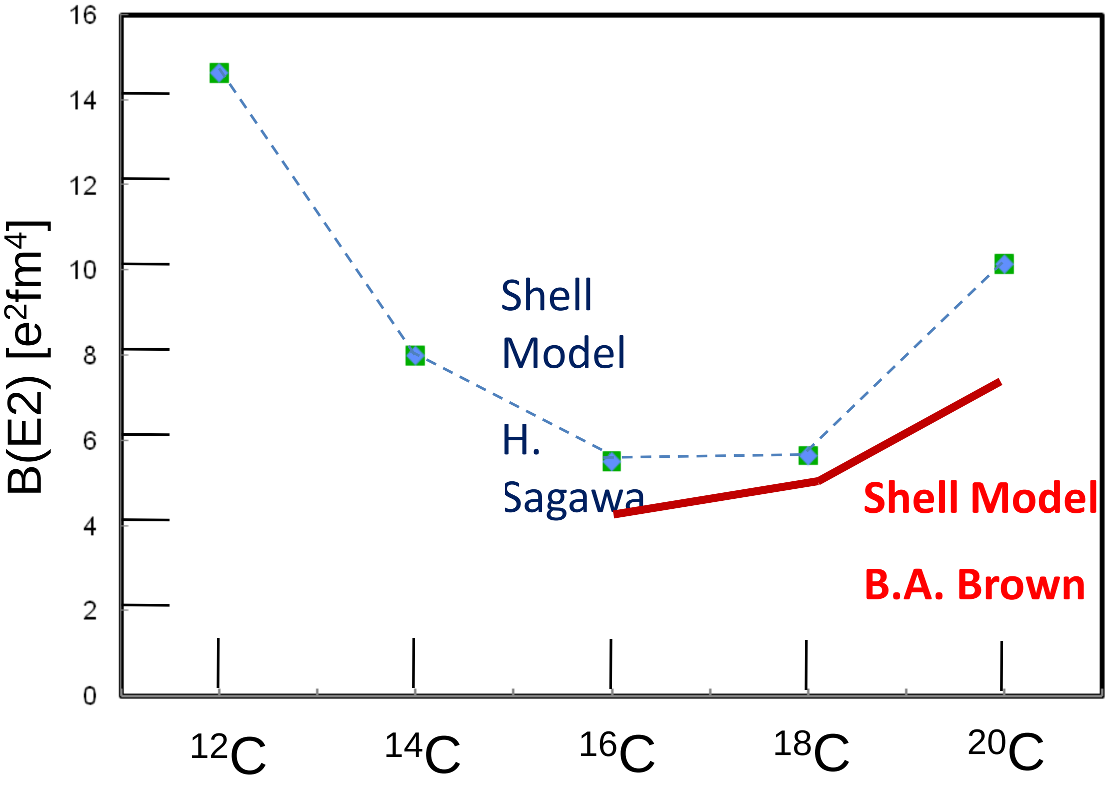
Shell Model WBT interaction (B.A.Brown)

	M_p	M_n
^{16}C	1.28	9.39
^{18}C	1.76	11.16
^{20}C	**3.06**	11.48

***Sagawa et al.*, PRC 70, 054316 (2004)**



Shell Model B(E2) Systematics



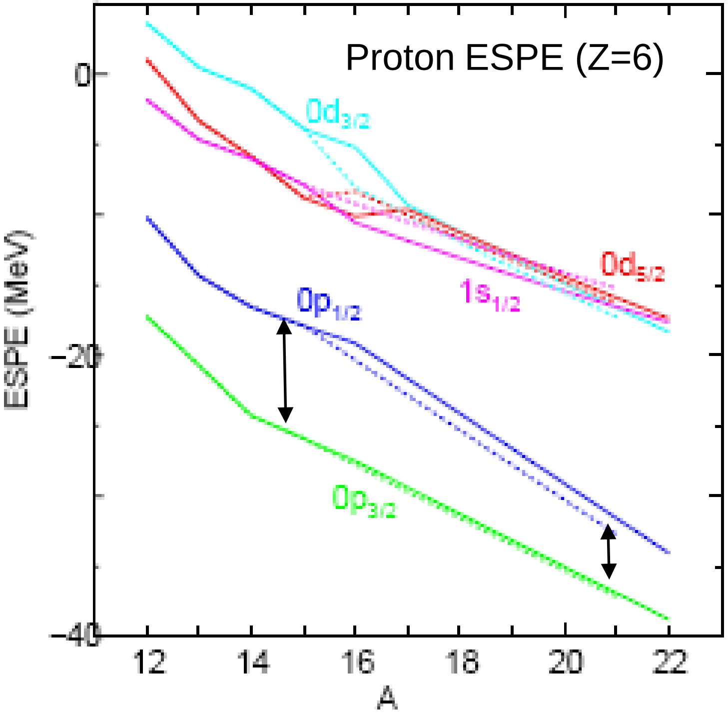
"↑ proton"

"neutron"

"↑ proton"

2^+ state dominant component

R.Fujimoto. PhD Thesis (U.Tokyo 2002)



- Reduced $p_{3/2}$-$p_{1/2}$ gap

Vpn
$\pi p_{1/2}$ – $\nu d_{5/2}$ attractive
$\pi p_{3/2}$ – $\nu d_{5/2}$ repulsive

Summary

- Change of nuclear structure such as decoupling neutron from the core will change the collective (B(E2) thus lifetime).
- In ^{20}C the increase of proton contribution cause a increase of B(E2), structure changed compared with ^{18}C.

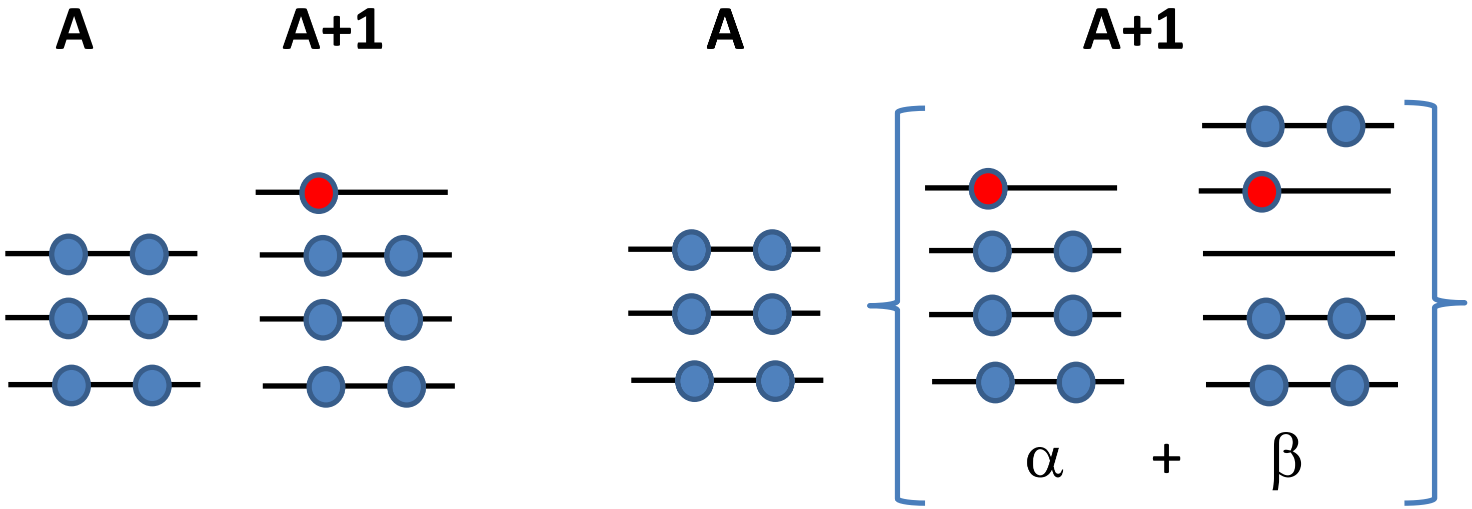
Nuclear wave functions from transfer and knock out reactions

Transfer reactions

- Cross section (spectroscopic factor) → similarity of target and product structure
- Angular distribution → ℓ-transfer → spin

Transfer cross section

A (d,p) A+1



$$\Psi^{A+1} = \Psi_0^A \times \varphi_j$$

$$\Psi^{A+1} = \left\{\alpha\, \Psi_0^A + \beta\, \Psi_i^A\right\} \times \varphi_j$$

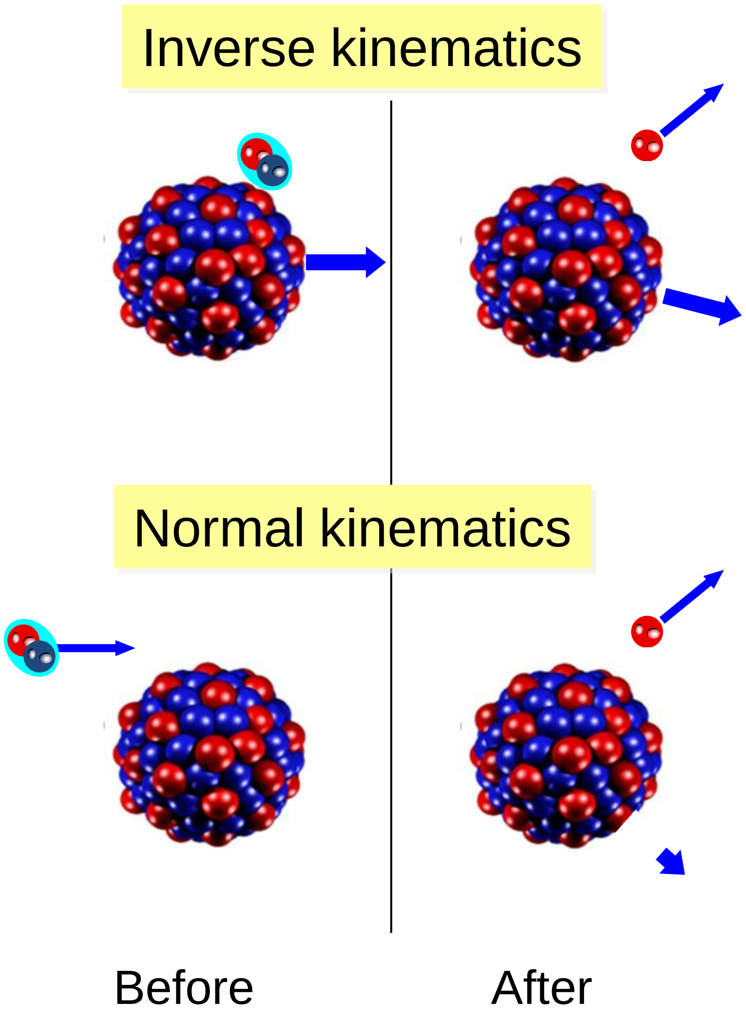
Cross section ~ 1

Cross section ~ α

- The ratio of the measured cross section to the calculated cross section with assumed wave functions

→ Spectroscopic Factor

Inverse kinematics problems



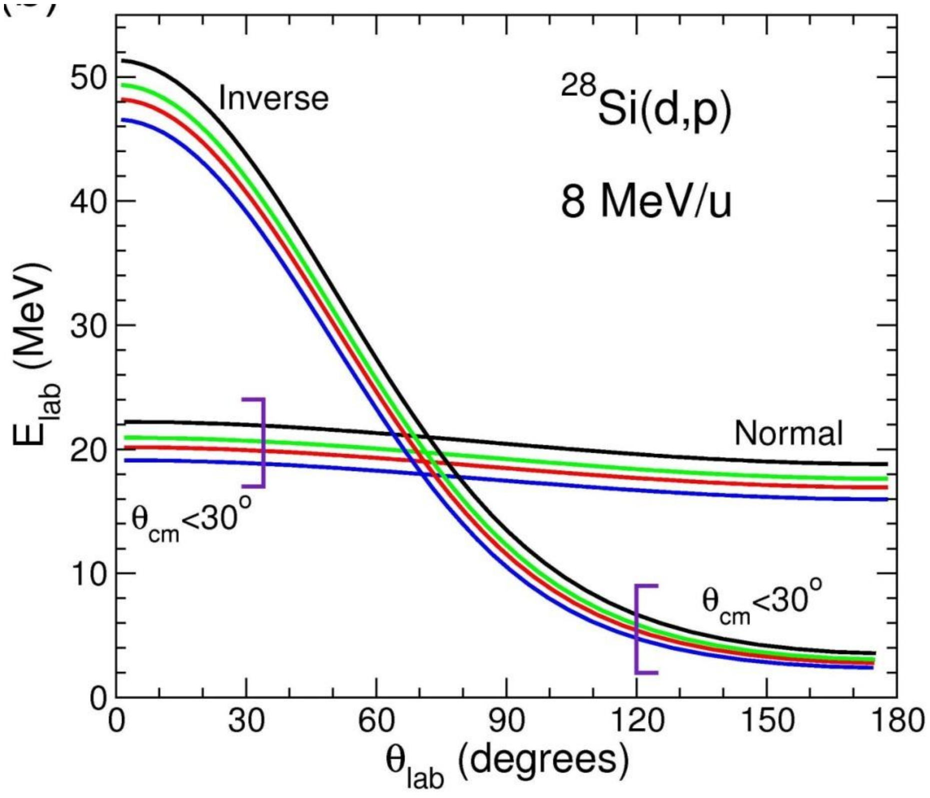
Inverse kinematics

Normal kinematics

Before

After

1. Low energy – ΔE-E identification
2. Kinematic compression- resolution
3. Strong angle dependence- broadening



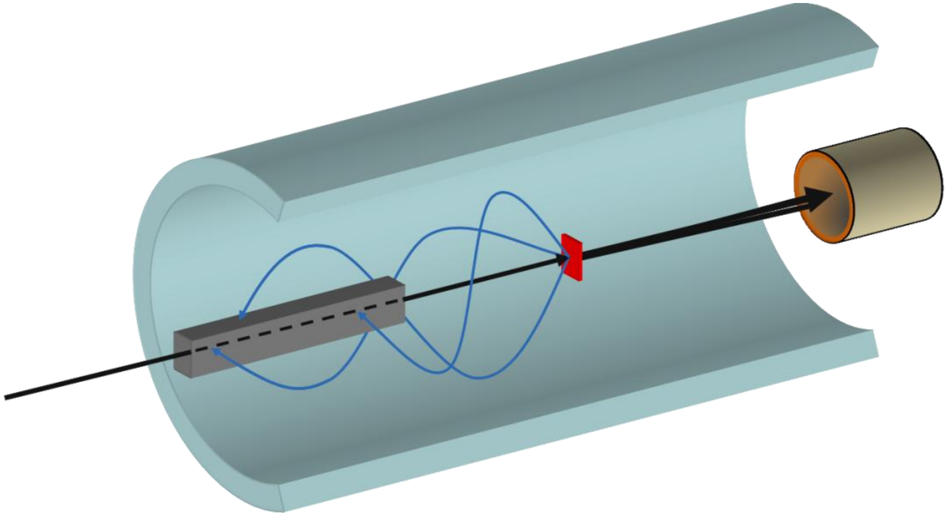
HELIOS (**HELI**cal **O**rbit **S**pectrometer)

<u>Measured quantities</u>

Flight time:	$T_{flight}=T_{cyc}$
Position:	z
Energy:	E_{lab}

<u>Derived quantities</u>

Part. ID:	m/q
Energy:	E_{cm}
Angle:	θ_{cm}



B=2T

Particle	T_{cyc} (ns)
p	**34.2**
^{3}He^{2+}	**51.4**
d, α	**68.5**
t	**102.7**

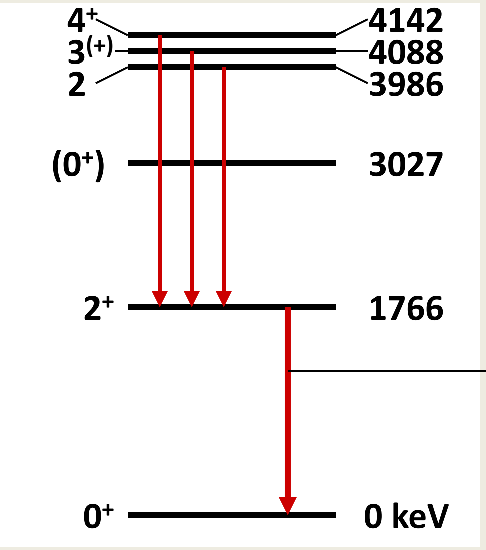
$$\frac{m}{q} = \frac{eB}{2\pi}\times T_{flight}$$

$$E_{cm} = E_{lab} + \tfrac{1}{2}mV_{cm}^2 - \frac{V_{cm}qeB}{2\pi}z$$

$$\theta_{cm} = \arccos\left(\frac{1}{2\pi}\frac{qeBz - 2\pi mV_{cm}}{\sqrt{2mE_{lab} + m^2V_{cm}^2 - mV_{cm}qeBz/\pi}}\right)$$

^{15}C(d, p) ^{16}C spectroscopic factor

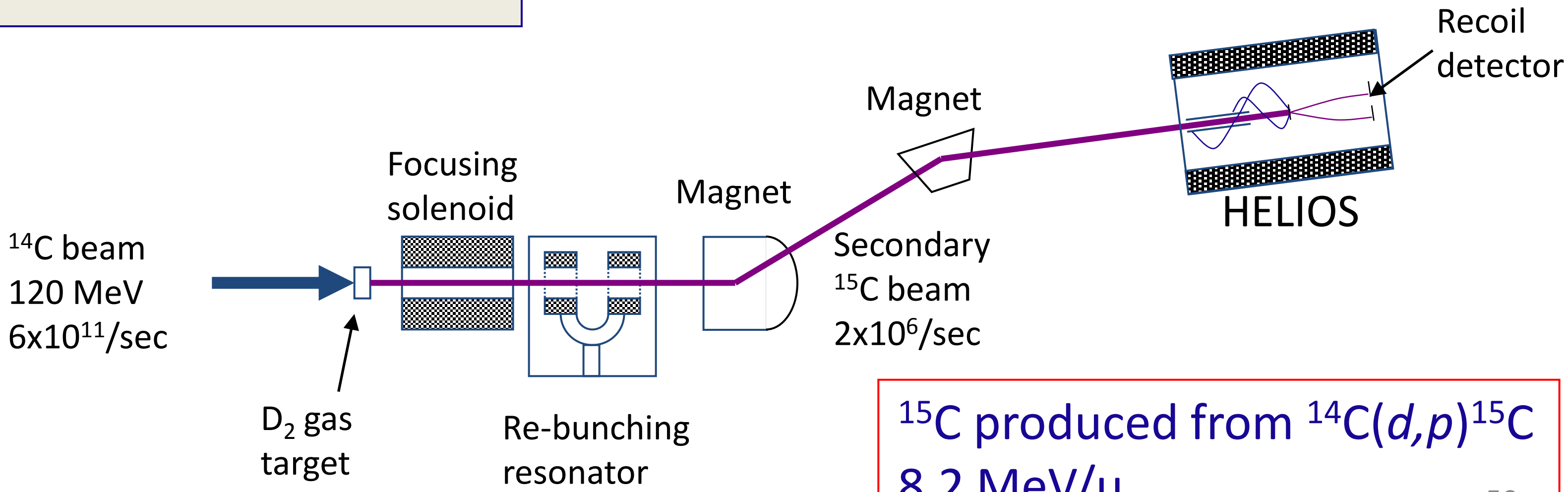
^{16}C level scheme



- **Are the motions of the protons and neutrons decoupled in ^{16}C?**

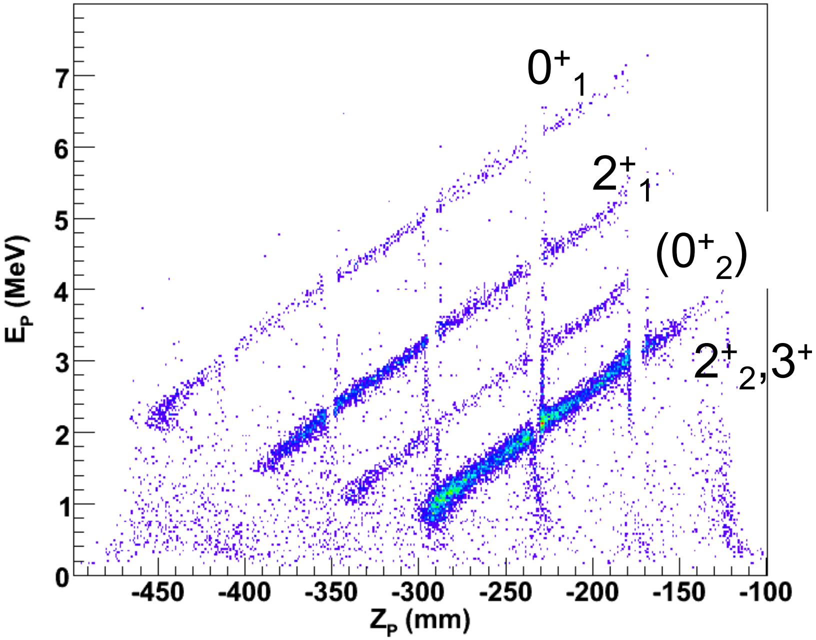
Wuosmaa *et al.*
Western Michigan University
Argonne National Laboratory
University of Manchester, UK
Lawrence Berkeley National Laboratory

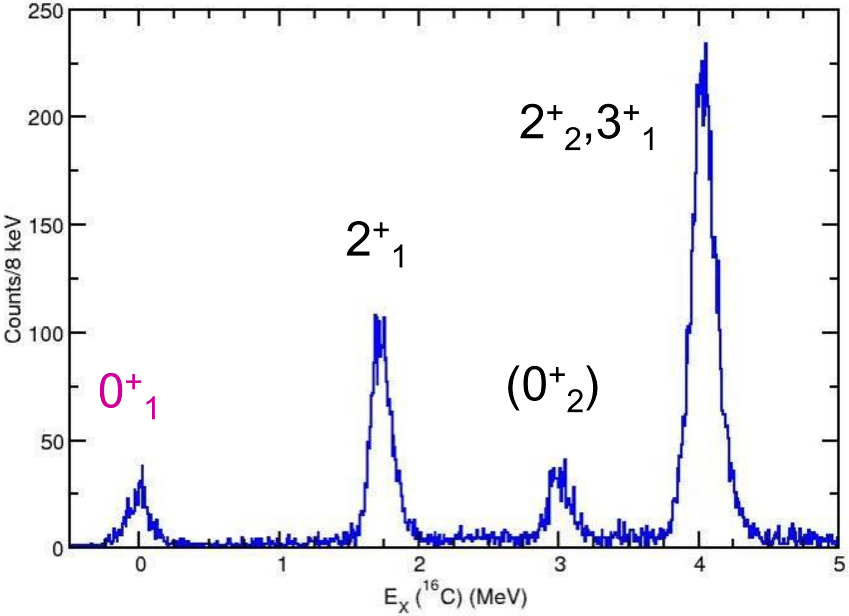
B(E2) W.U.
0.26 Imai *et al*. PRL 92, 62501 (2004) ^{16}C scattering
0.28 Elekes et al., PLB 586, 34 (2004) ^{16}C scattering
1.73 Wiedeking *et al*, PRL 100, 152501 (2008) Fusion-evap



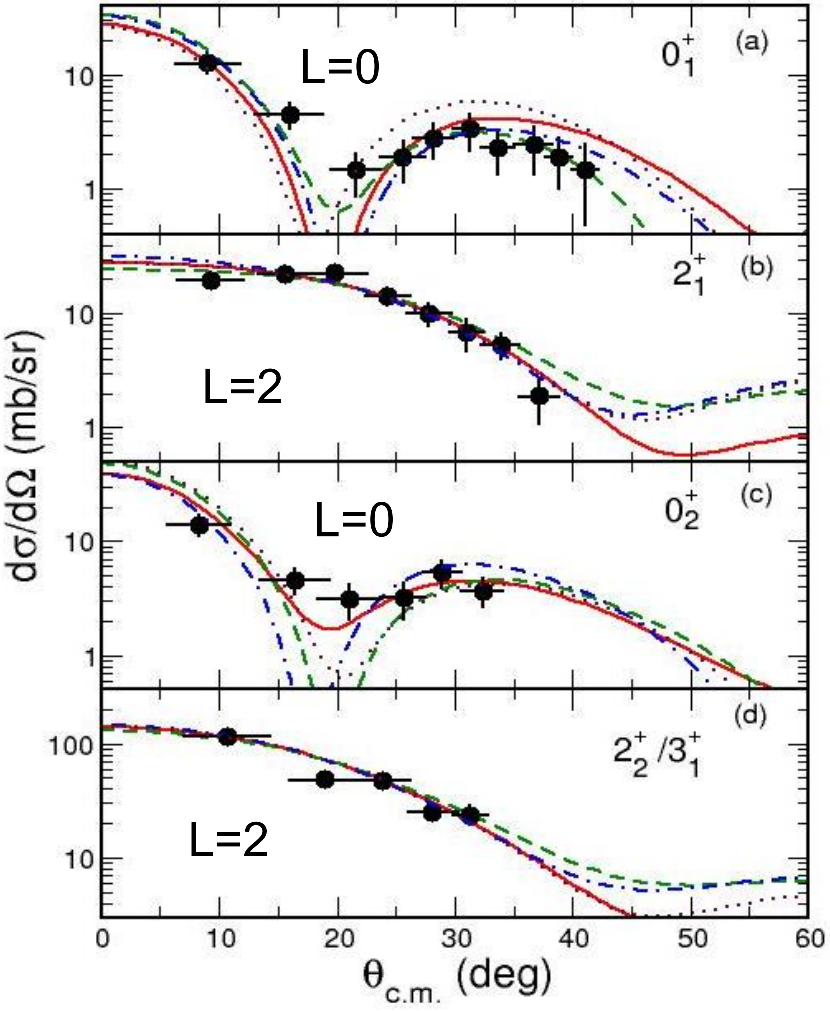
^{15}C produced from ^{14}C(*d,p*)^{15}C
8.2 MeV/u

HELIOS data for $^{15}C(d,p)^{16}C$



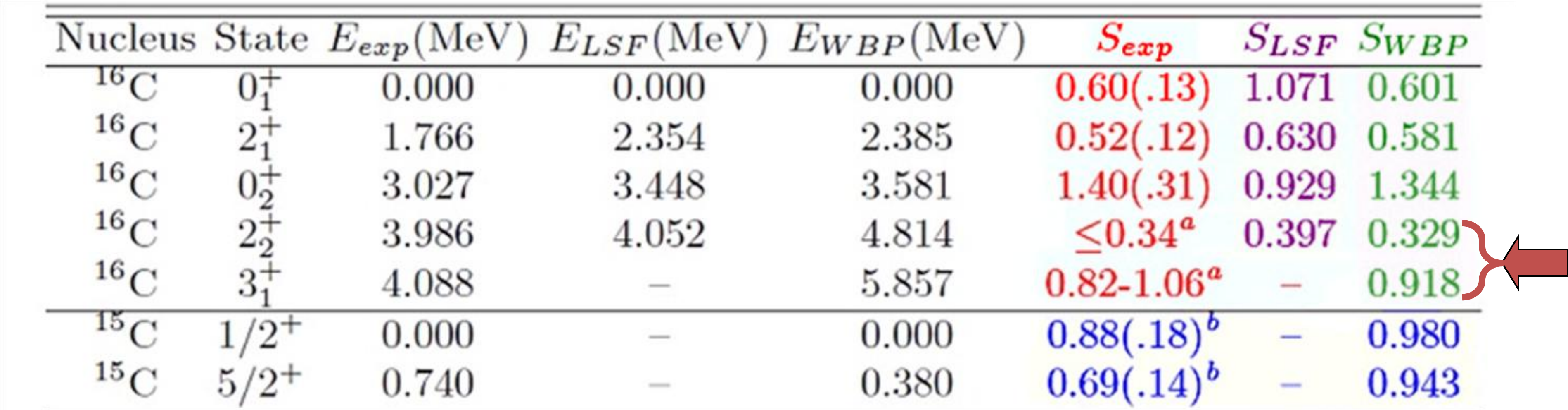


$^{15}C(d,p)$ angular distributions



- **Curves are DWBA calculations with various optical-model potentials.**
- **Spectroscopic factors obtained from the average over four sets of OMP.**
- **Relative uncertainties in SF dominated by OMP variations.**
- **Absolute uncertainty (~30%) from beam-integration uncertainty.**

Measured spectroscopic factors



Nucleus	State	E_{exp}(MeV)	E_{LSF}(MeV)	E_{WBP}(MeV)	S_{exp}	S_{LSF}	S_{WBP}
^{16}C	0_1^+	0.000	0.000	0.000	0.60(.13)	1.071	0.601
^{16}C	2_1^+	1.766	2.354	2.385	0.52(.12)	0.630	0.581
^{16}C	0_2^+	3.027	3.448	3.581	1.40(.31)	0.929	1.344
^{16}C	2_2^+	3.986	4.052	4.814	$\leq 0.34^a$	0.397	0.329
^{16}C	3_1^+	4.088	–	5.857	$0.82\text{-}1.06^a$	–	0.918
^{15}C	$1/2^+$	0.000	–	0.000	$0.88(.18)^b$	–	0.980
^{15}C	$5/2^+$	0.740	–	0.380	$0.69(.14)^b$	–	0.943

[b] ^{14}C(*d*,*p*) Goss et al, PRC **12** 1730 (1975).

Data normalization: $\Sigma S(0^+) = 2.0$

LSF: empirical interaction only from ^{18}O

WBP: Warburton-Brown from fit to broader range of nuclei, PRC **46**, 923 (1992).

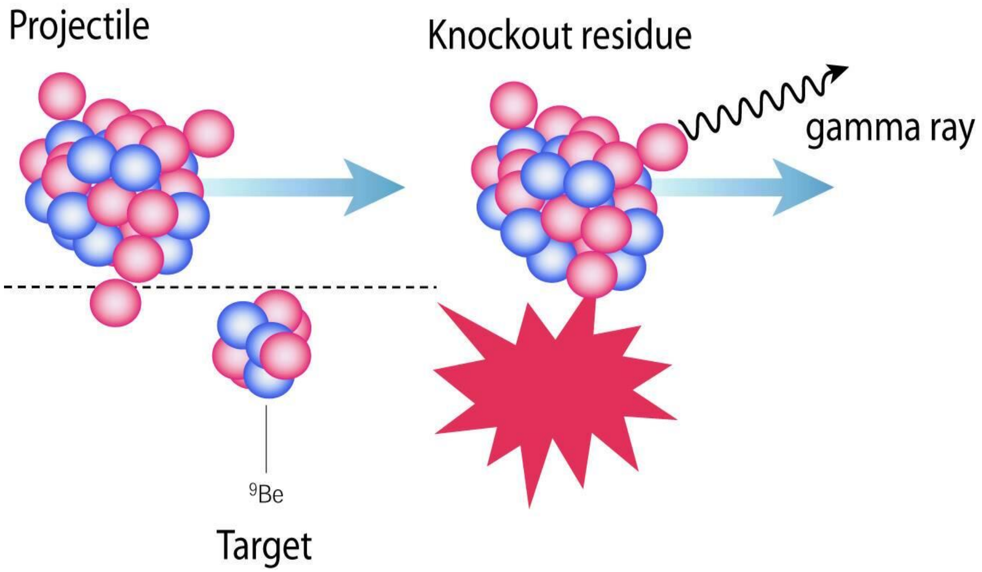
- Relative spectroscopic factors agree with SM calculations – strongly mixed 0^+ and 2^+ states
- Consistent The B(E2) measured by the LBL group.

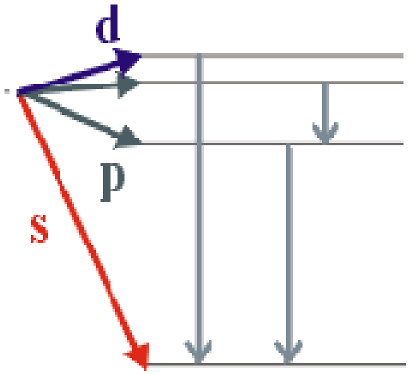
A. H. Wuosmaa *et al*.,Phys. Rev. Lett. **105**, 132501(2010)

One-nucleon knockout reaction

- **more than 50 MeV/nucleon:**

sudden approximation+eikonal approach (J.A. Tostevin, Surrey)





residue moment distribution

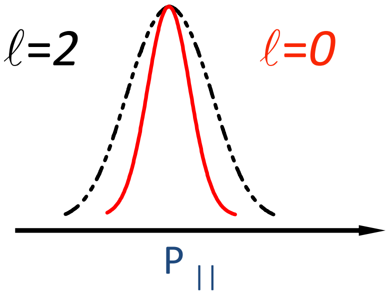
→ ℓ-value of knocked-out n

P.G. Hansen, PRL 77, 1016 (1996)

$$\sigma(nl^{\pi}) = \sum_{j} c^{2}S(j,nl^{\pi})\,\sigma_{sp}(j,S_{n})$$

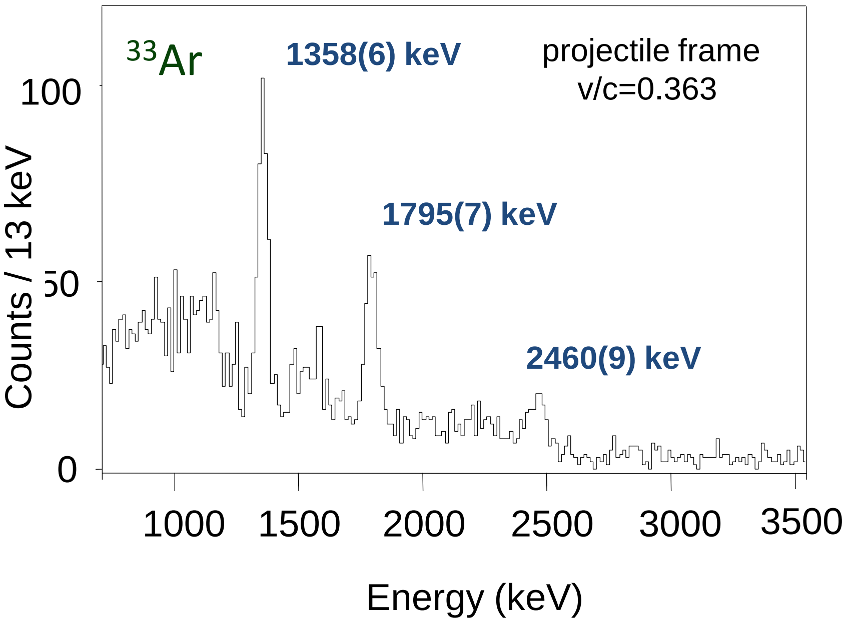
nuclear structure information

reaction process

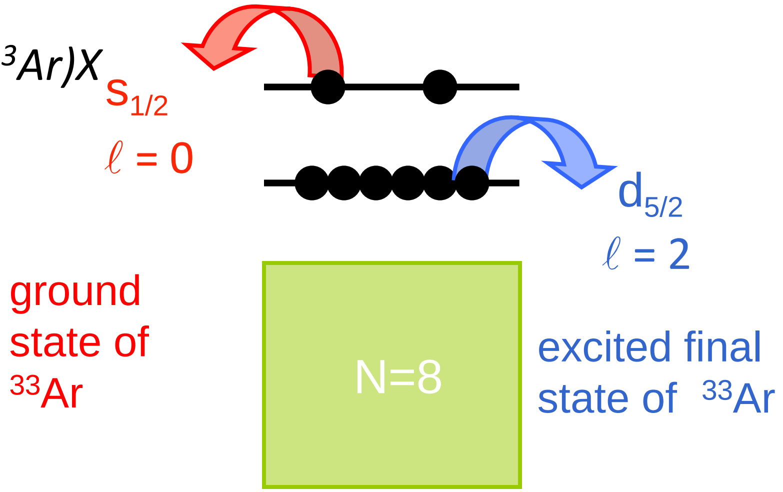


P.G. Hansen and B.M. Sherrill, NPA 693 ,133 (2001).
P.G. Hansen and J. A. Tostevin, Annu. Rev. of Nucl. and Part. Sci. 53, 219 (2003).

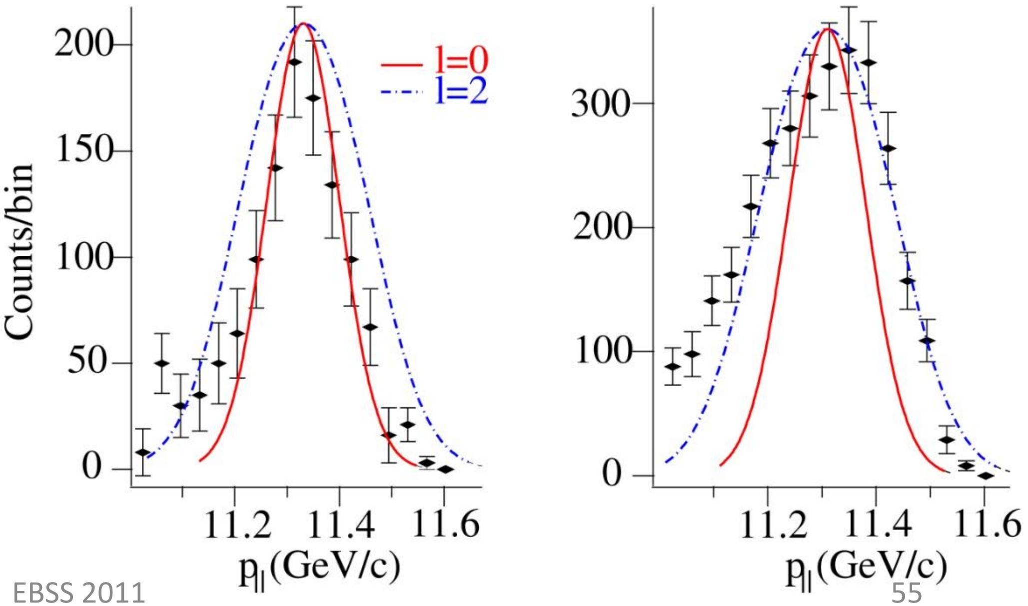
Spectroscopy in one-nucleon knockout



$^{9}Be(^{34}Ar,^{33}Ar)X$



	BR (%)	σ_{exp} (mb)	C^2S_{exp}
$1/2^+$	30.2(46)	4.7(9)	0.38(6)
$3/2^+$	20.2(44)	3.2(8)	0.36(9)
$5/2^+$	31.7(31)	4.9(7)	0.56(8)
$(5/2^+)$	17.9(30)	2.8(6)	>0.34(7)



A. Gade *et al.*, PRC 69 034311 (2004).

Summary

- Transfer and knock out reactions can provide information on difference of nuclear wave function between the target and the product.
  - Fragmentation of wave functions observed in (^{15}C,^{16}C) and (^{34}Ar, ^{33}Ar)
- For inverse kinematic reaction new instrument has provide improved resolution.

Nuclear Structure Experiment II

I-Yang Lee

Lawrence Berkeley National Laboratory

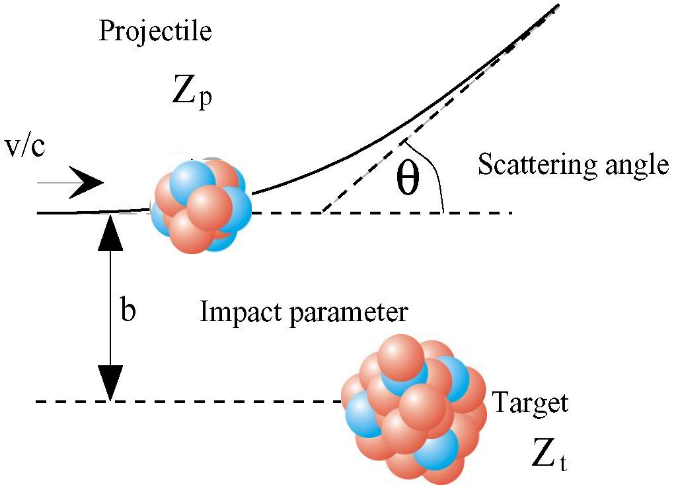
Exotic Beam Summer School 2011
July 25 - 30

Outline

- Monday, July 25
  - Introduction
  - Shell evolution, nuclear forces, and shapes
  - Study weak binding by measuring lifetime
  - Nuclear wave functions from transfer and knock out reactions
- Wednesday, July 27
  - Study the evolution of collectivity between closed shells using Coulomb excitation
  - Study neutron/proton contributions to nuclear structure using magnetic moment measurements
  - Stability and properties of heavy elements
  - Summary

Study the evolution of collectivity between closed shells using Coulomb excitation

Coulomb Excitation



- Nuclei excited by electromagnetic interaction only, no nuclear interaction
  - Distance of closest approach > $r_p + r_T$
  - $E_{beam} < E_B$ (Coulomb barrier), all scattering angles are safe
  - $E_{beam} > E_B$, only $\theta < \theta_{grazing}$ are save

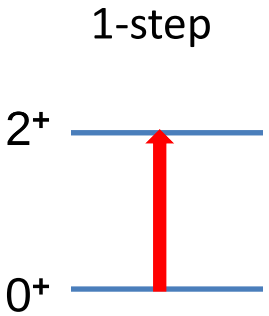
Grazing angle (in CM):

$$\theta g = 2\ \sin^{-1}\left(\frac{1}{\frac{2\,E}{E_B} - 1}\right)$$

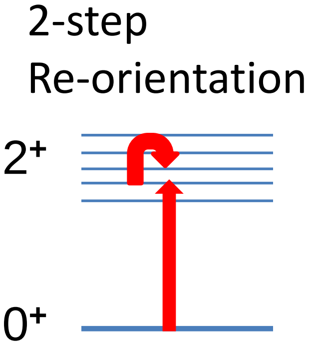
E/E_B	θg
1.0	180°
1.2	91°
1.5	60°
3.0	23°
10	6°

Coulomb Excitation

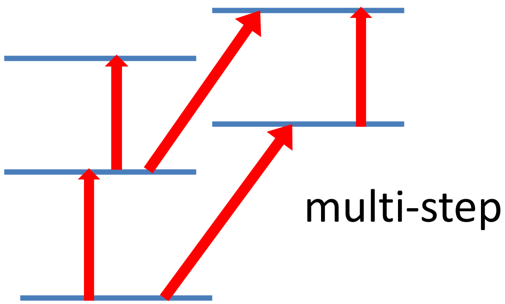
- Reaction mechanism is well defined, the cross section is determined by
  - Charge of the projectile
  - Electromagnetic matrix elements of the target
  - Adiabaticity of the excitation $\xi = \frac{Z_p Z_t e^2}{hv} \frac{\Delta E}{2E}$



$\sigma \sim \langle 0^+ \| M(E2) \| 2^+ \rangle^2$
$\sim B(E2, 0^+ \rightarrow 2^+)$



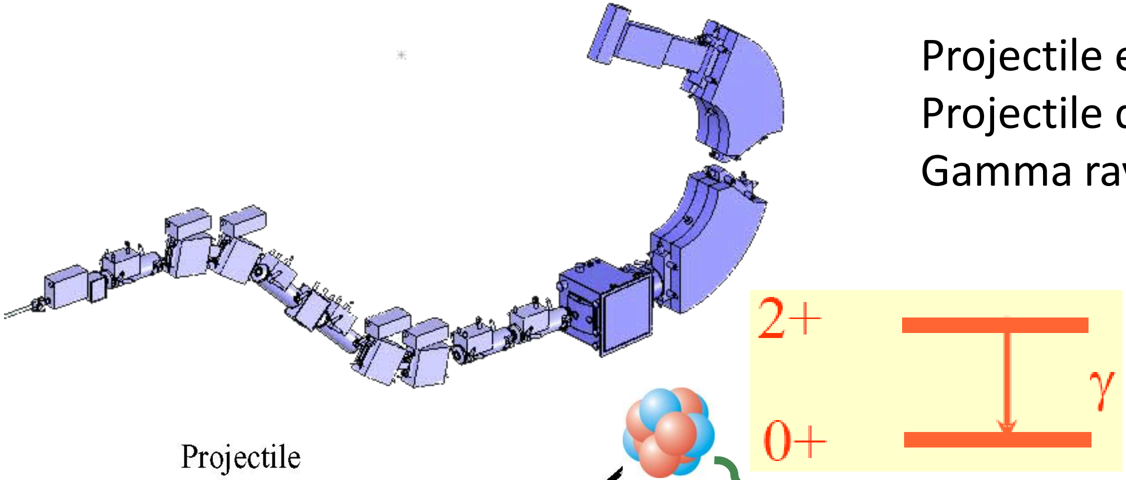
$\sigma \sim \langle 0^+ \| M(E2) \| 2^+ \rangle^2 (1 + C \, \langle 2^+ \| M(E2) \| 2^+ \rangle)$
$\sim B(E2)(1 + C \, Q(2^+))$

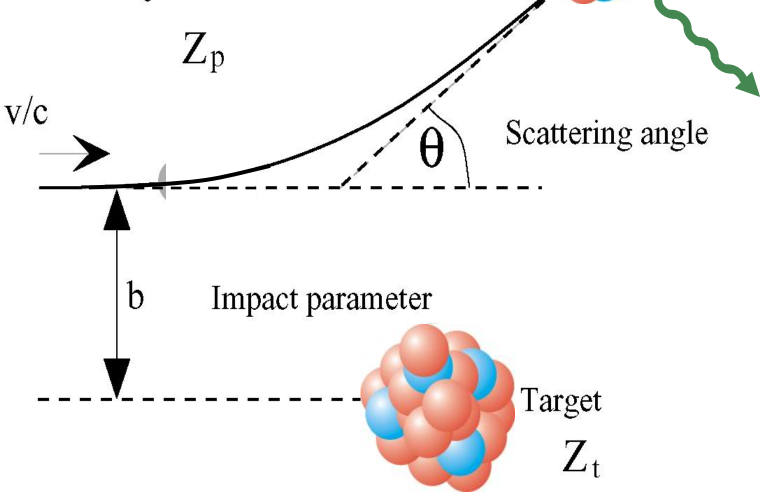


Coupled-channels

Coulomb excitation setup at NSCL

Projectile excitation
Projectile detected in S800 spectrograph
Gamma rays detected in Ge array SeGA



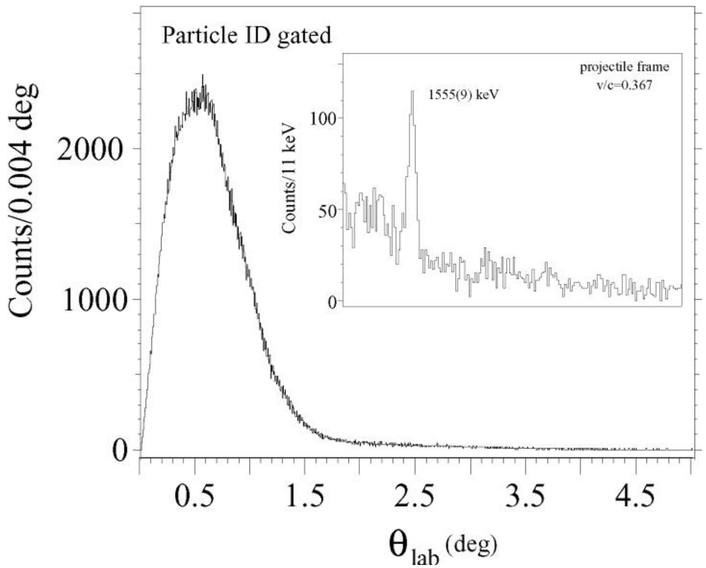


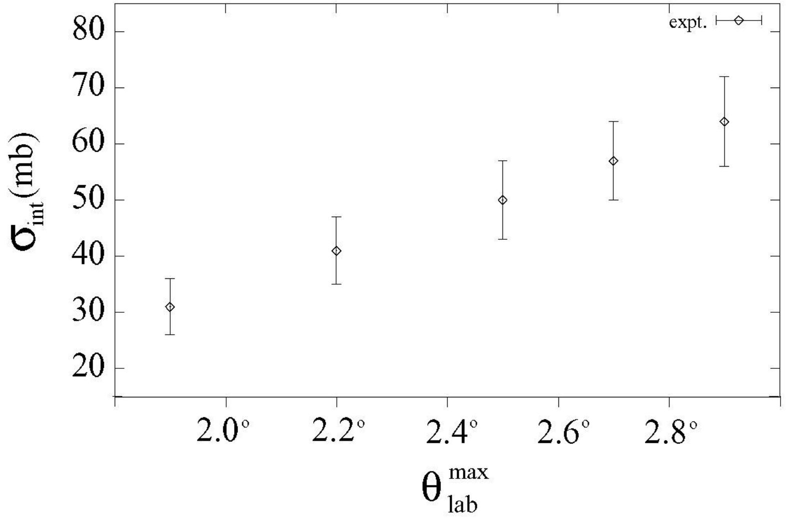
Intermediate-energy Coulomb excitation

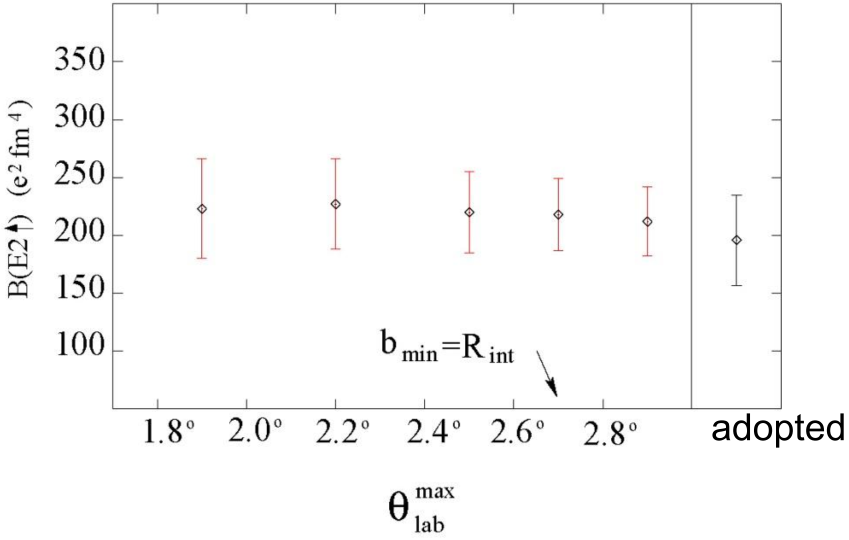
A. Winther and K. Alder, NPA 319, 518 (1979)

^{46}Ar + ^{197}Au
Measured B(E2) values are
constant at $\theta < \theta_g$

A. Gade *et al.*, PRC **68**, 014302 (2003)

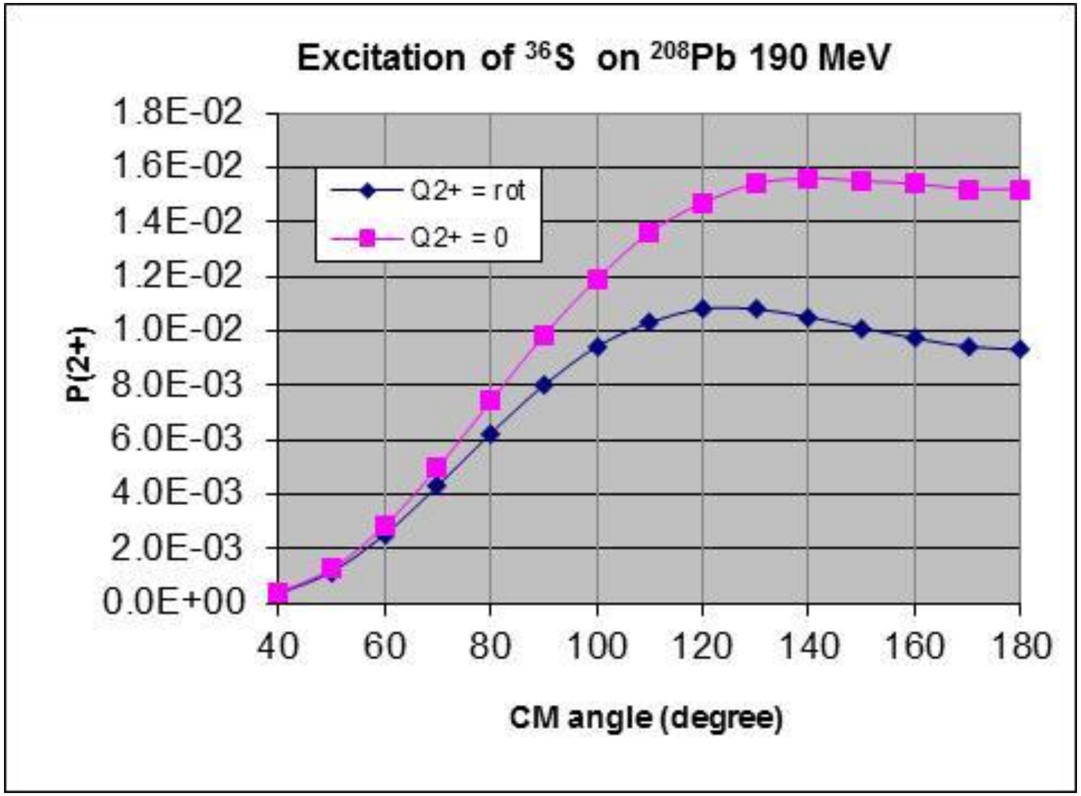




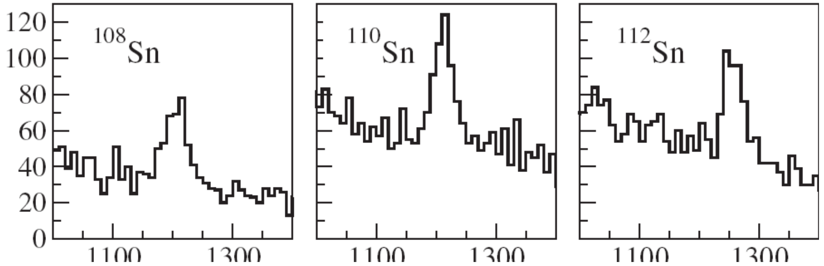


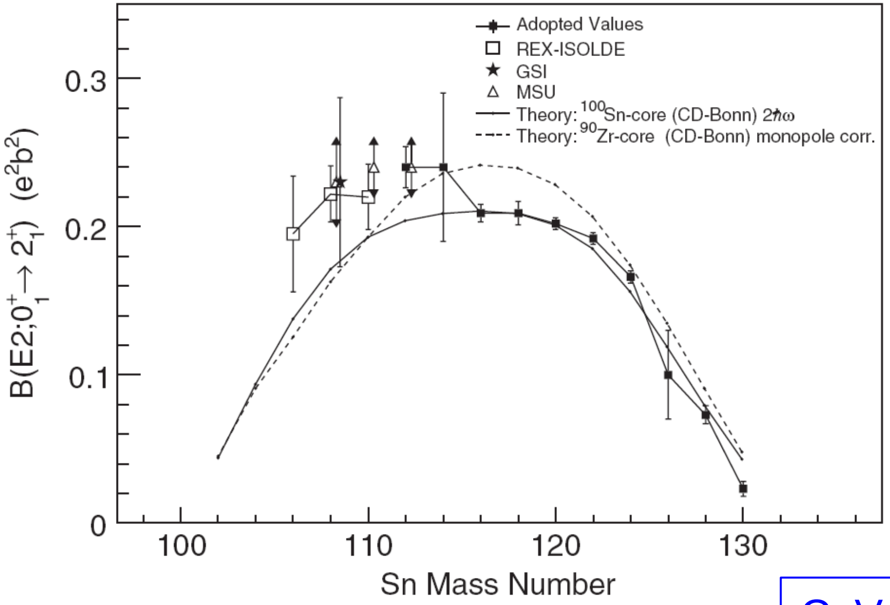
Coulomb excitation probability

- Excitation probability is higher at back angle
- Sensitivity to Q2$^+$ at back angles
- One-step (no re-orientation) excitation at forward angle

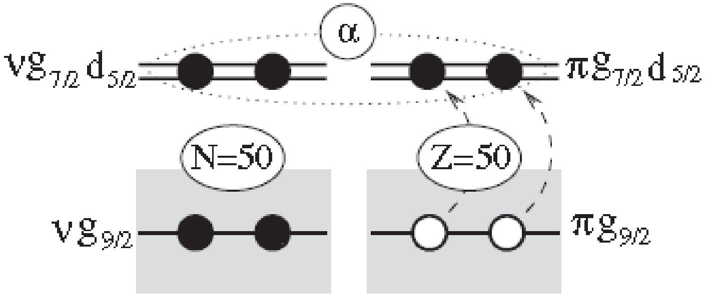


B(E2) values of Tin isotopes





- Measured values are larger than theory prediction for A < 112
- Could be due to contributions of the protons from within the *Z* =50 shell



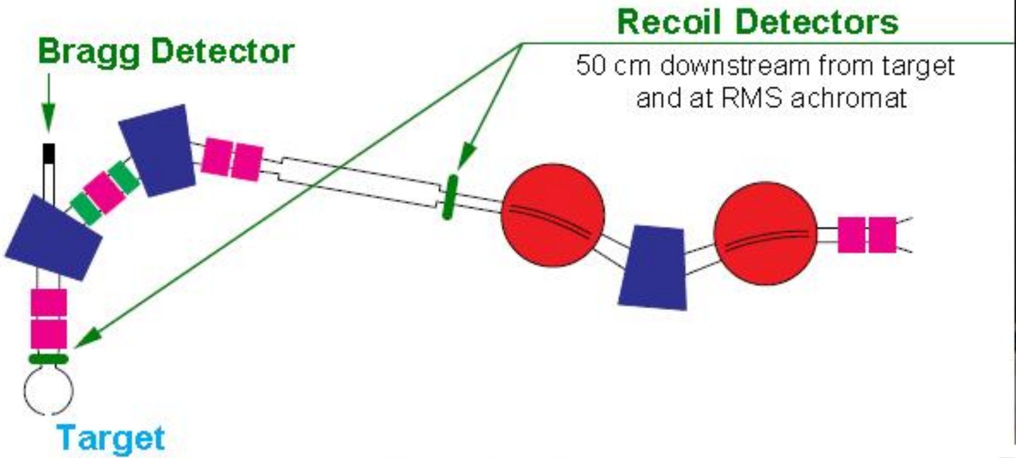
C. Vaman et al., PRL 99, 162501 (2007)
A. Ekstrom et al., PRL 101, 012502 (2008)
E. Padilla-Rodal et al., PRL 94, 122501 (2005)

Coulomb Excitation of N-rich Tin Isotopes

Experiments at HRIBF facility

- $^{124\text{-}134}$Sn beams on C, Al and Ti targets.
- Stable ^{124}Sn included for comparison with high-precision adopted values, to verify experimental procedures
- γ-rays detected in CLARION, particles in HyBall
- ^{132}Sn measurements were carried using BaF_2 array for γ-rays
- Able to extract both B(E2) values and static quadrupole moments by reorientation effect

Coulomb excitation setup at HRIBF

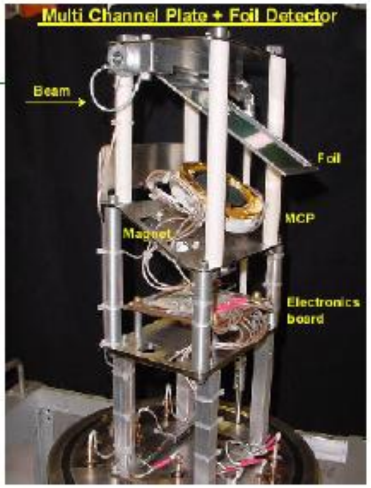


Bragg Detector

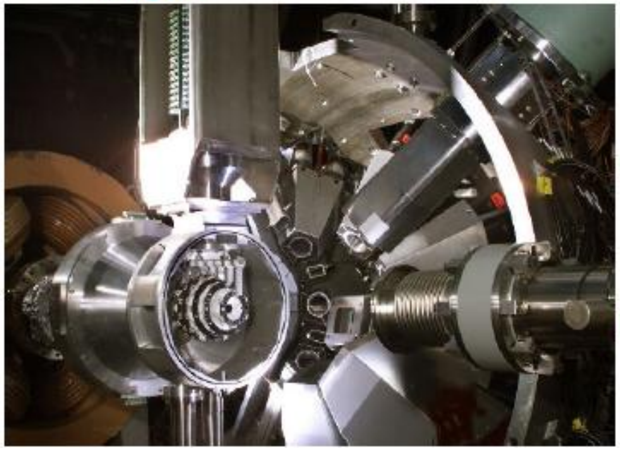
Recoil Detectors

50 cm downstream from target
and at RMS achromat

Target



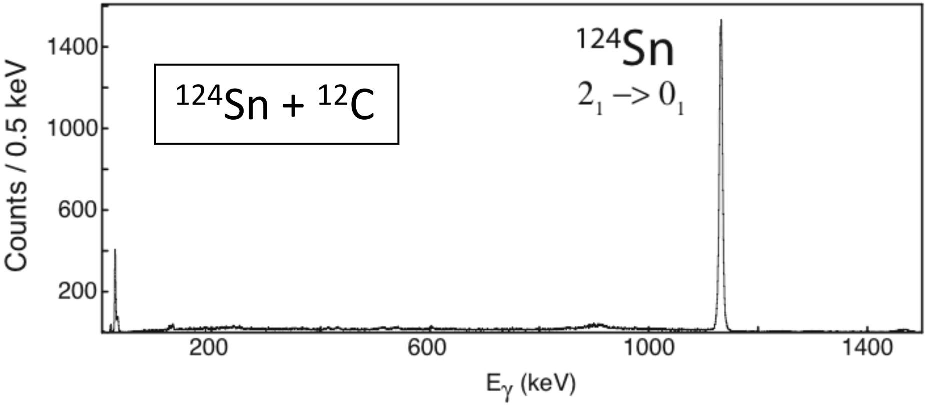
Foil plus multichannel plate

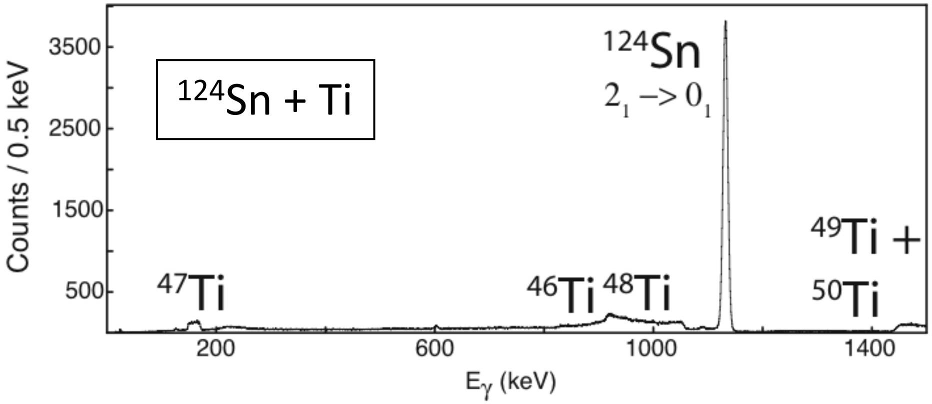


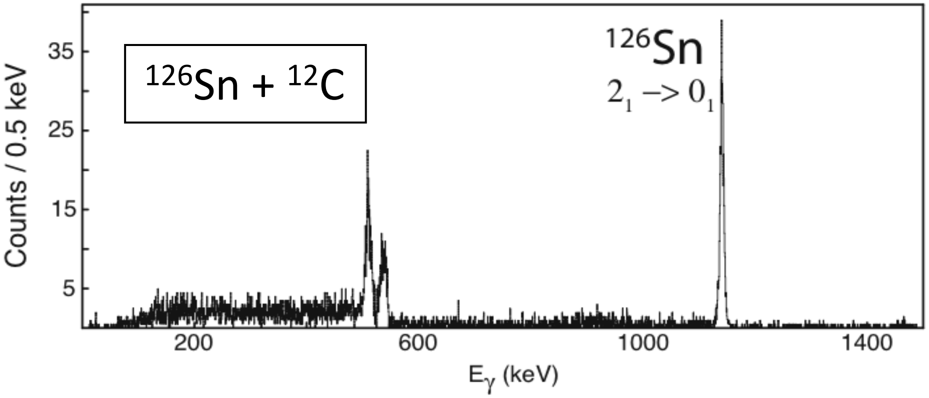
CLARION
11 segmented clover Ge detectors

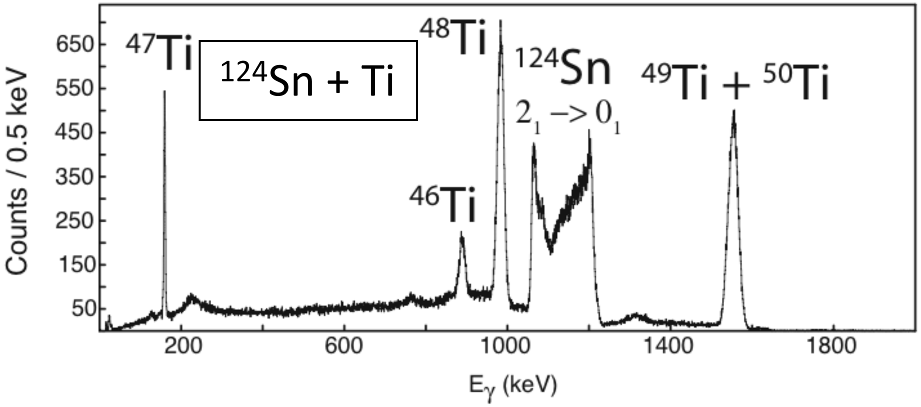
HyBall
95 CsI detectors with photodiodes

Doppler-Corrected Gamma-ray Spectra



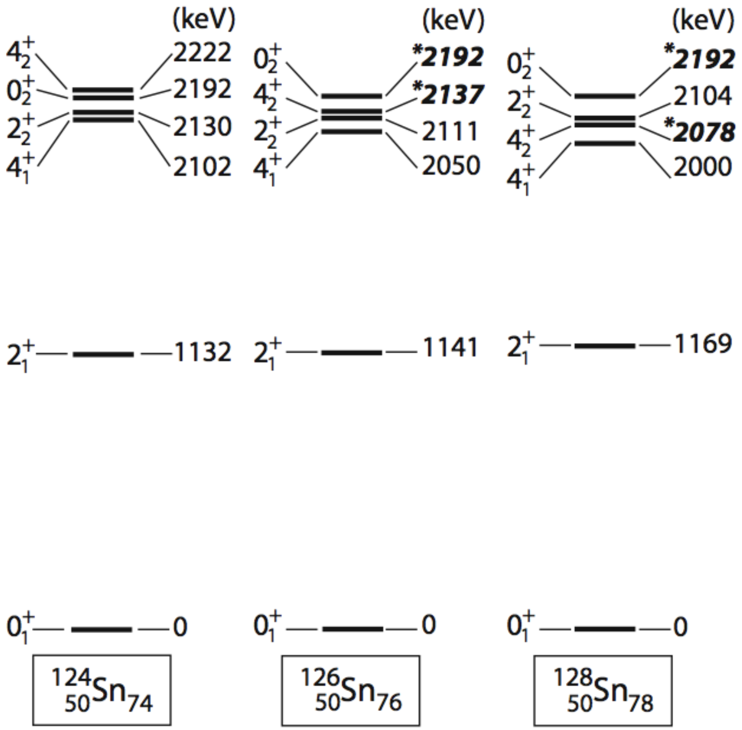


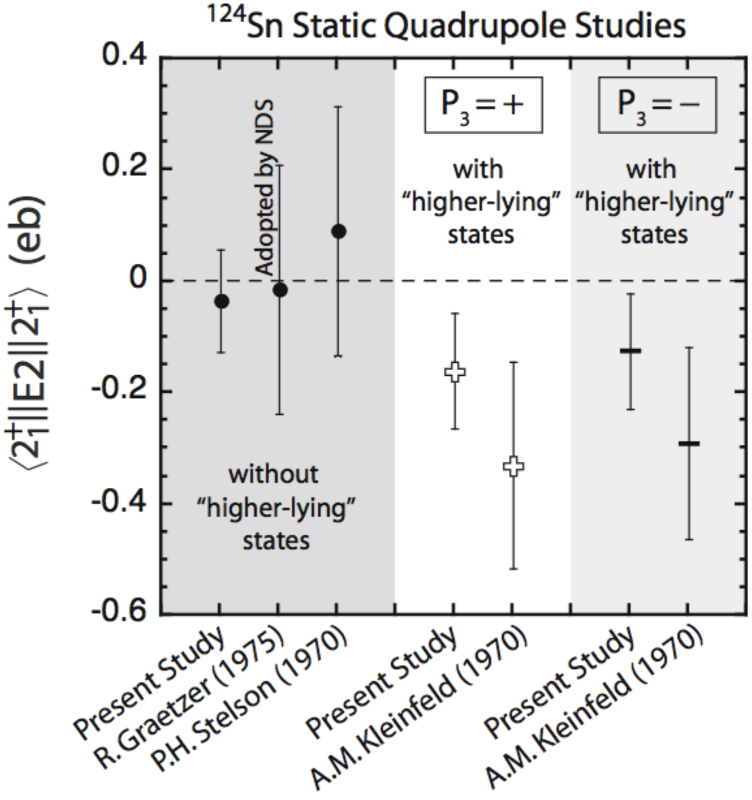




Static Quadrupole Moments

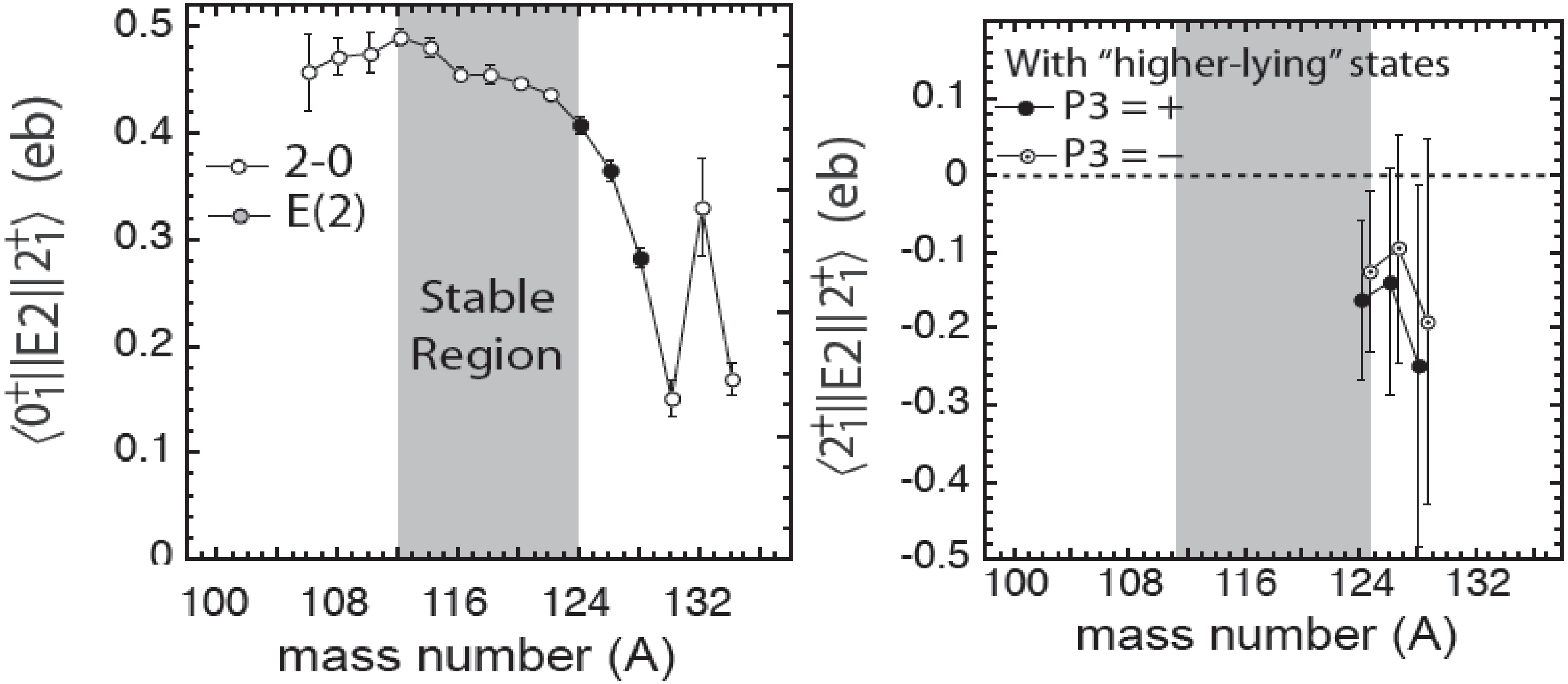
- Analyze both C and Ti data together to extract $Q(2_1)$
- Results indicate *weak prolate deformation,* when the higher-lying states are included in the Coulex analysis (ignored in most previous studies)
- Suggests that we should perhaps remeasure other stable Sn isotopes
- Extracted $Q(2_1)$ is relatively insensitive to the sign of the interference term





B(E2) and Static Quadrupole Moments

- ^{130,134}Sn has small (1.2, 1.4 s.p.) B(E2) value, and ^{132}Sn has larger B(E2)
- This trend was reproduced by QRPA calculations.
- ^{124,126,128}Sn shows small prolate deformation from their static quadrupole moment.



D. C. Radford *et al.*, Nucl. Phys. **A752**, 264c (2005).

quiz

- The Coulomb excitation cross section of the first 2^+ state in ^{132}Sn is smaller than that of ^{130}Sn because
  - (a) smaller $B(E2, 0^+ \rightarrow 2^+)$
  - (b) smaller $Q(2^+)$
  - (c) smaller adiabaticity
  - (d) larger adiabaticity

Summary

- The studies of the collectivity of tin isotopes shown several interesting observations
  - Enhanced B(E2) at lower mass, rotational-like behaviors at higher mass, ^{132}Sn has higher B(E2) than ^{130,134}Sn.
- Coulomb excitation can give model independent determination of EM moments (e.g. B(E2) and Q(2^+)). However, needs to pay attention to possible multi-step excitations.
- The study a broad range of isotopes needs multiple accelerator facilities and equipment.

Study neutron/proton contributions to nuclear structure using magnetic moment measurements

Nuclear magnetic moment

- Single particle state (Schmidt limits)

$$\mu = \frac{1}{j+1} < j, m = j | \vec{\mu} \cdot \vec{j} | j, m = j >$$

$$= g_l \langle l_z \rangle + g_s \langle s_z \rangle$$

$$= j\left(g_l \; \pm \; (g_s - g_l)\frac{1}{2l+1}\right) \;, \quad j = l \pm {}^1\!/_2$$

g_l : orbital *g*-factor

g_s : spin *g*-factor

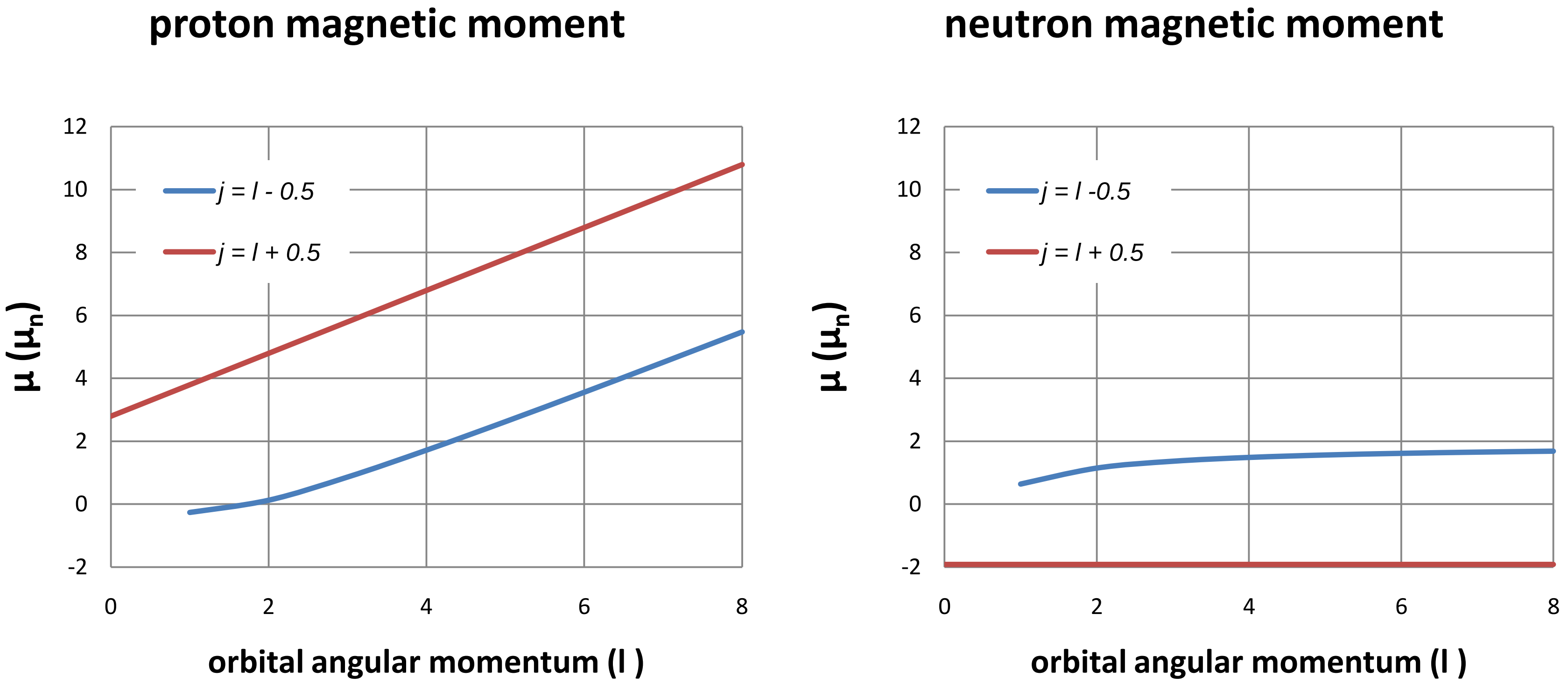
μ_n= eħ /2m$_p$ = 5.05 10^{-27} J/T

g-factor	g_l	g_s
	(μ_n)	
Proton	1	5.5858
neutron	0	-3.8263

Quiz

- What determines the proton and neutron g_s values?
  - (a) proton-neutron tensor interaction
  - (b) quark structure of proton and neutron
  - (c) relativistic effects
  - (d) higher order QED effects

Single particle magnetic moment



For *j= l + ½* , proton has large positive values
neutron has negative values

Collective model

- Deformed rotating nuclei

$$g = \frac{\mu}{I} = \frac{K}{I+1}(g_k - g_R) + g_R$$

$$g_K = g_l + \frac{g_s - g_l}{K}\langle K|s_z|K\rangle$$

$$g_R = \frac{Z}{A}$$

For K=0

Both rotational and vibrational states have

$g = Z/A$

Measurement of magnetic moment

- Produce nucleus with spin alignment
  - Coulomb excitation, transfer reaction, fission etc.
- Precession in magnet field (B) : Larmor frequency

$$\omega = \frac{\mu\, B}{I} \qquad \text{define} \quad g = \frac{\mu/\mu_n}{I/\hbar}$$

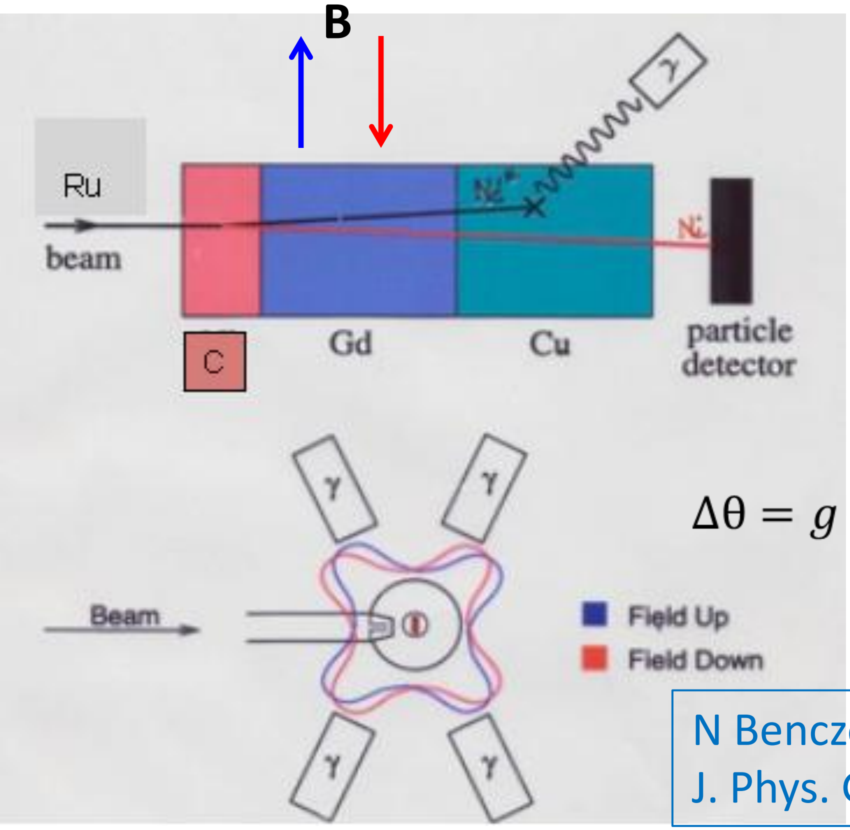
$$= g\, B \frac{\mu_n}{\hbar}$$

- Measure angular distribution (e.g. gamma ray)
  - $W(\theta, t) = 1 + \sum_k A_k P_k(\cos(\theta + \omega t))$
  - State with shorter lifetime τ needs faster ω (stronger B field) to produce measureable precession angle

$g = 1$	$\omega\tau$=10°
τ	B
1 μsec	0.0036 T
1 nsec	3.6 T
1 psec	3644 T

Transient field method

- Nucleus moves through magnetized material (e.g. Fe, Gd)
- Précesses in transient magnetic field B (≈100 Z T)
- Measure angular distribution of decay gamma ray



$$\Delta\theta = g\,\frac{\mu_n}{\hbar}\int_0^T B\, e^{-t/\tau}\,dt$$

Setup at ANU
H. Crawford et., al.

N Benczer-Koller and G J Kumbartzki
J. Phys. G: Nucl. Part. Phys. 34 (2007) R321–R358

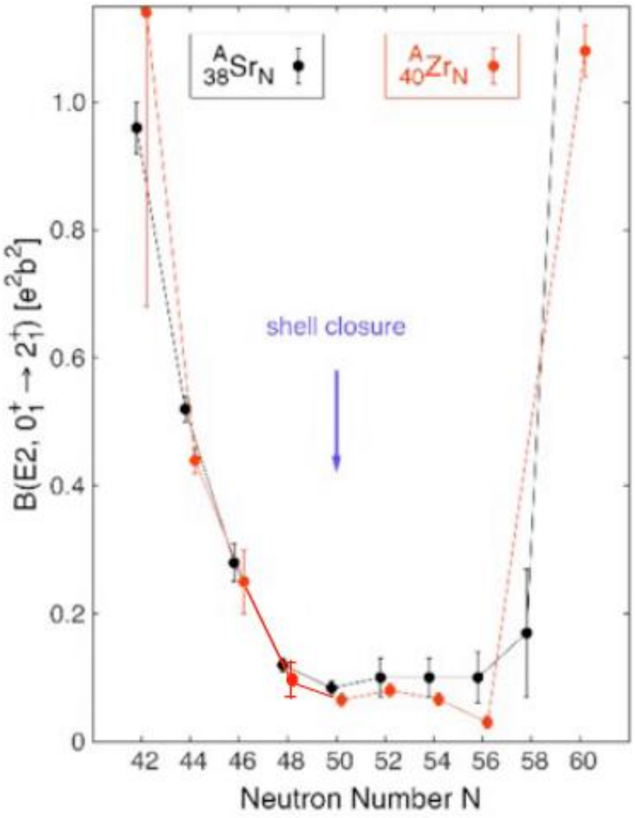
Quiz

Given $W(\theta) = 1 + \sum_k A_k P_k(\cos\theta)$

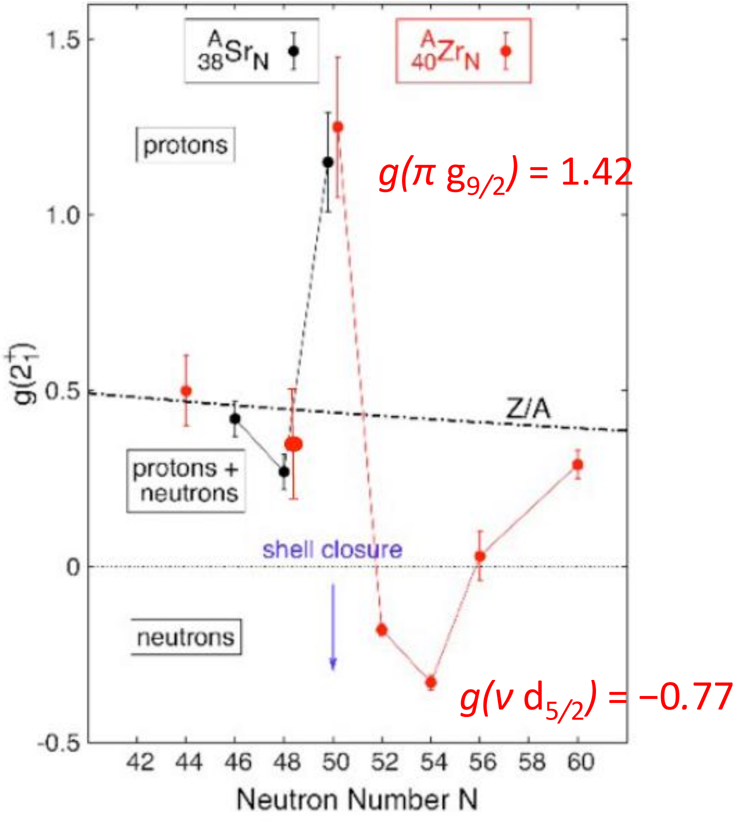
- Where to place detectors to maximize the sensitivity of TF magnetic moment measurements?
  - (a) maximum of $W(\theta)$
  - (b) maximum of $\frac{d\,W(\theta)}{d\,\theta}$
  - (c) maximum of $\left|\frac{d\,W(\theta)}{d\,\theta}\right|$
  - (d) maximum of $\left|\frac{1}{W(\theta)}\frac{d\,W(\theta)}{d\,\theta}\right|$

N=50 neutron closed shell

B(E2) values give collectivity



g-factor give the n/p contribution



$g(\pi\ g_{9/2}) = 1.42$

$g(\nu\ d_{5/2}) = -0.77$

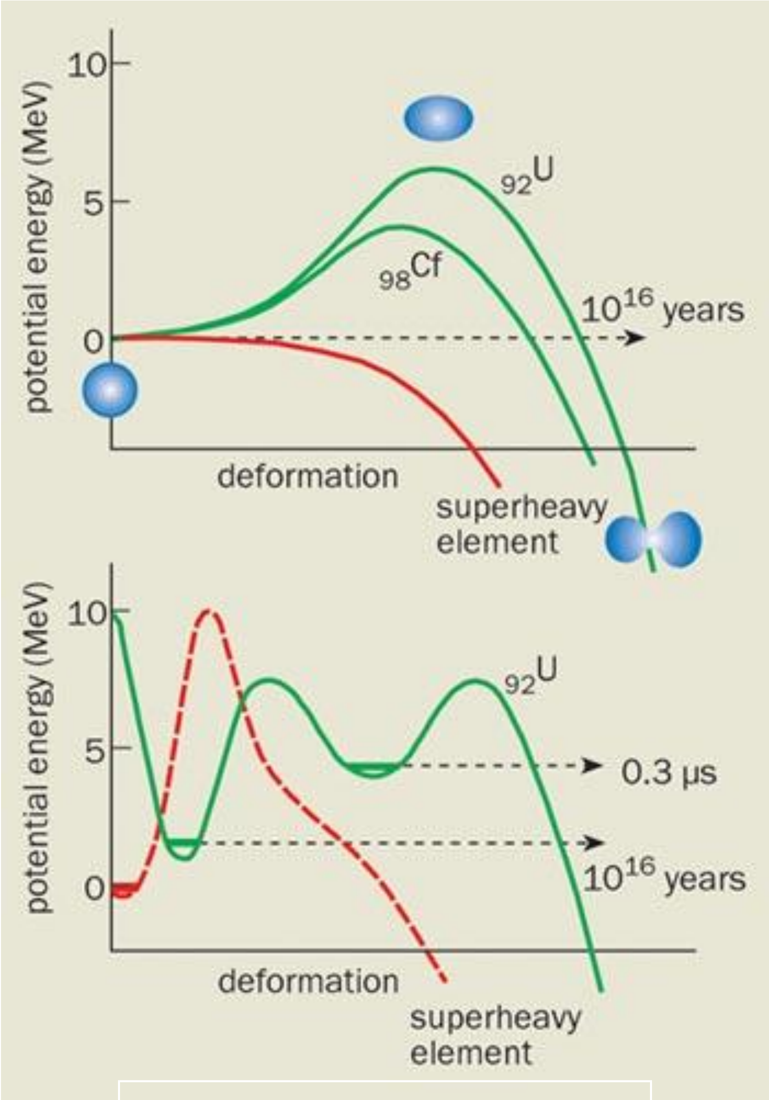
G. Jakob G, N. Benczer-Koller , et al., Phys. Lett. B 468 (1999) 13

Summary

- Magnetic moment is an effect quantity for distinguishing neutron and proton contribution to nuclear states.
- Nuclear properties, such as collective, can vary smoothly while the underlying neutron/proton contributions could have large variations.

Stability and properties of heavy element

Why Do Heavy Nuclei Exist?

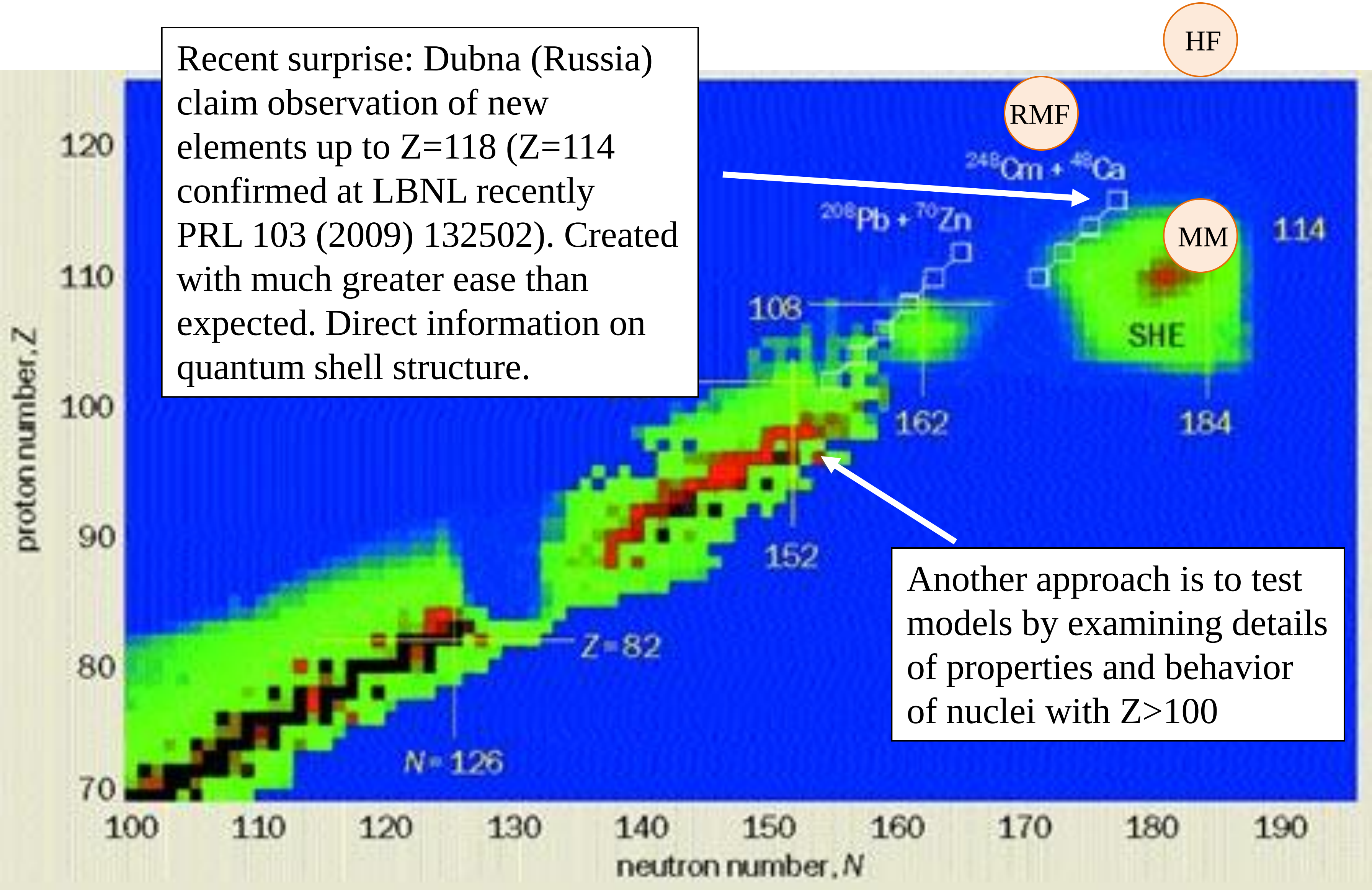


Physics World, July 2004

From a macroscopic viewpoint (as developed initially by Bohr and Wheeler) of the nucleus as a liquid drop, the stability of nuclei is governed by interplay of Coulomb repulsion and surface tension. Nuclei with Z>100 should immediately fall apart since there is no “barrier” to their decay (the red line).

There is also a microscopic contribution to the stability arising from the quantum structure. Regions of very low level density, quantum shell gaps, enhance the stability and heavy nuclei can develop a large “barrier” to decay (the red line).

Different Theories, Different Shell Gaps

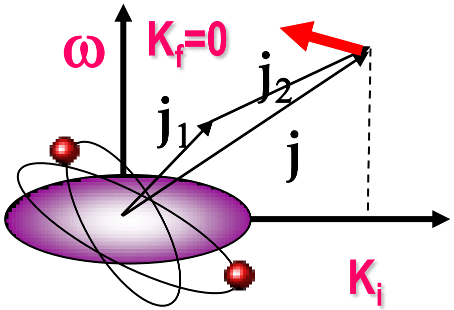


Recent surprise: Dubna (Russia) claim observation of new elements up to Z=118 (Z=114 confirmed at LBNL recently PRL 103 (2009) 132502). Created with much greater ease than expected. Direct information on quantum shell structure.

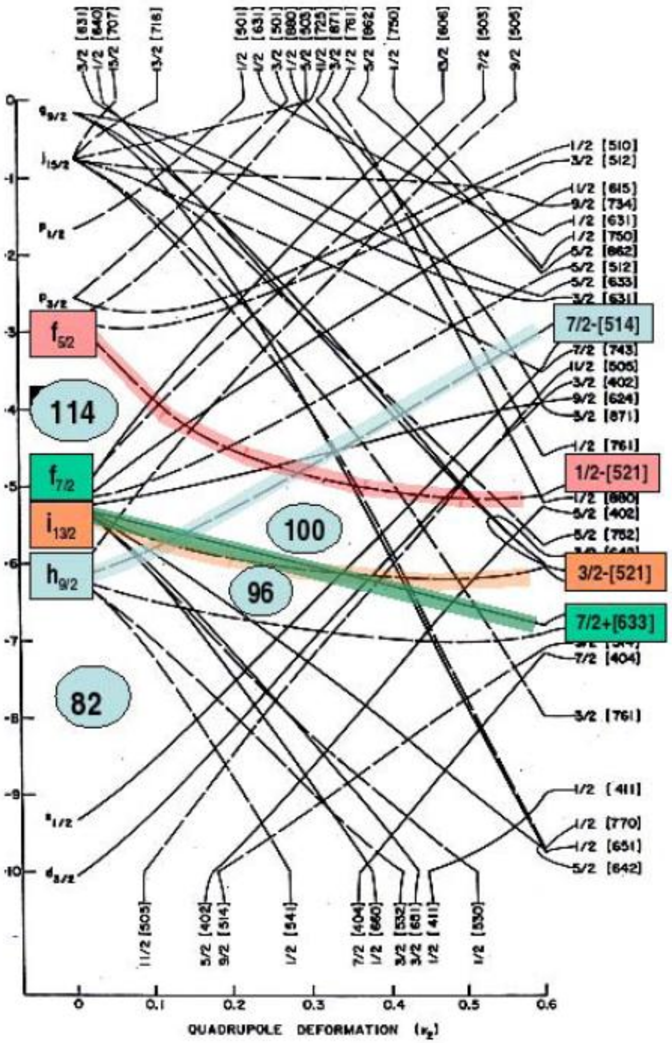
Another approach is to test models by examining details of properties and behavior of nuclei with Z>100

Shapes and Shells

- Single-particle levels → shell structure
  - Next major spherical gaps
  - Deformed gaps
- Deformation and collectivity
  - K-isomerism



  - Rotational structures
  - Low-lying vibrations
- Pairing properties
  - Multi-quasiparticle states
  - Rotation, α-decay, fission

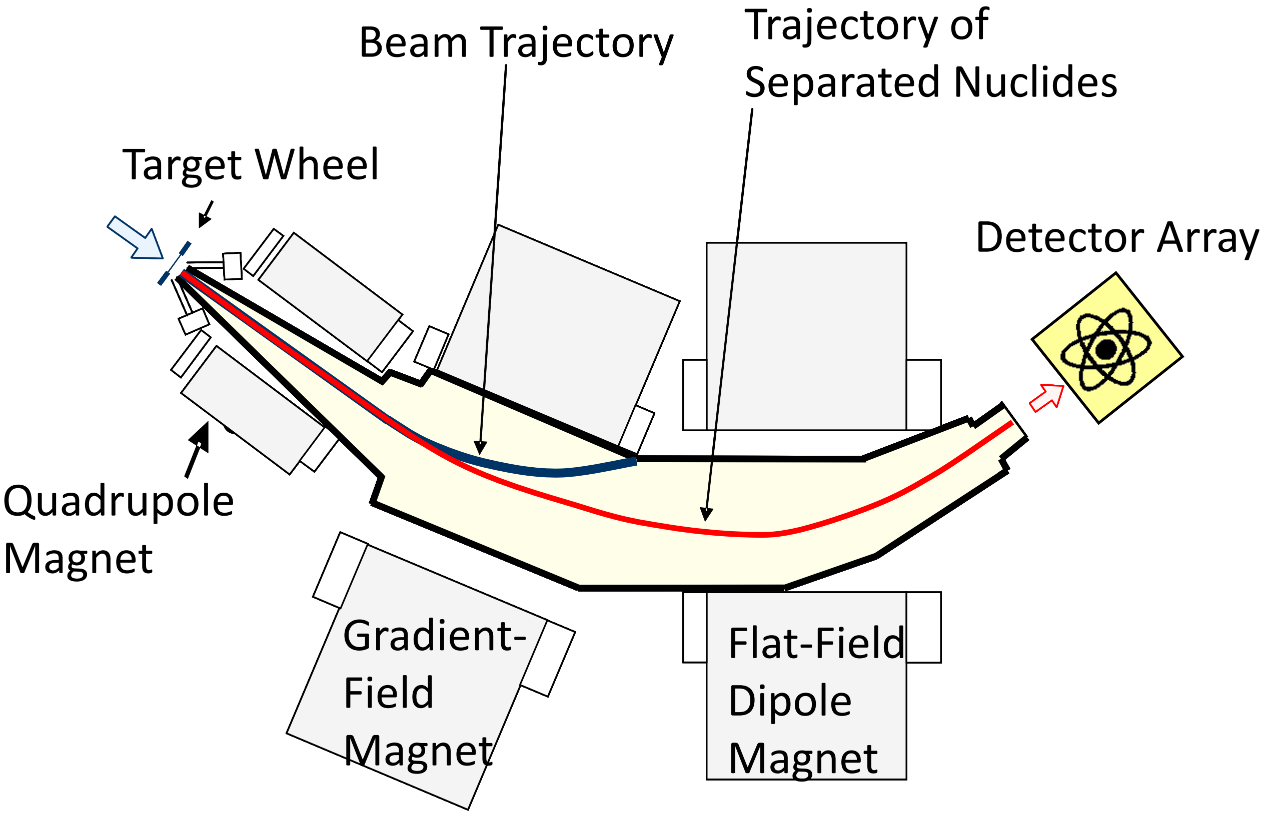


R. R. Chasman et al.,
Rev. Mod. Phys. 49 833 (1977)

Isomer in $Z \approx 100$ nuclei

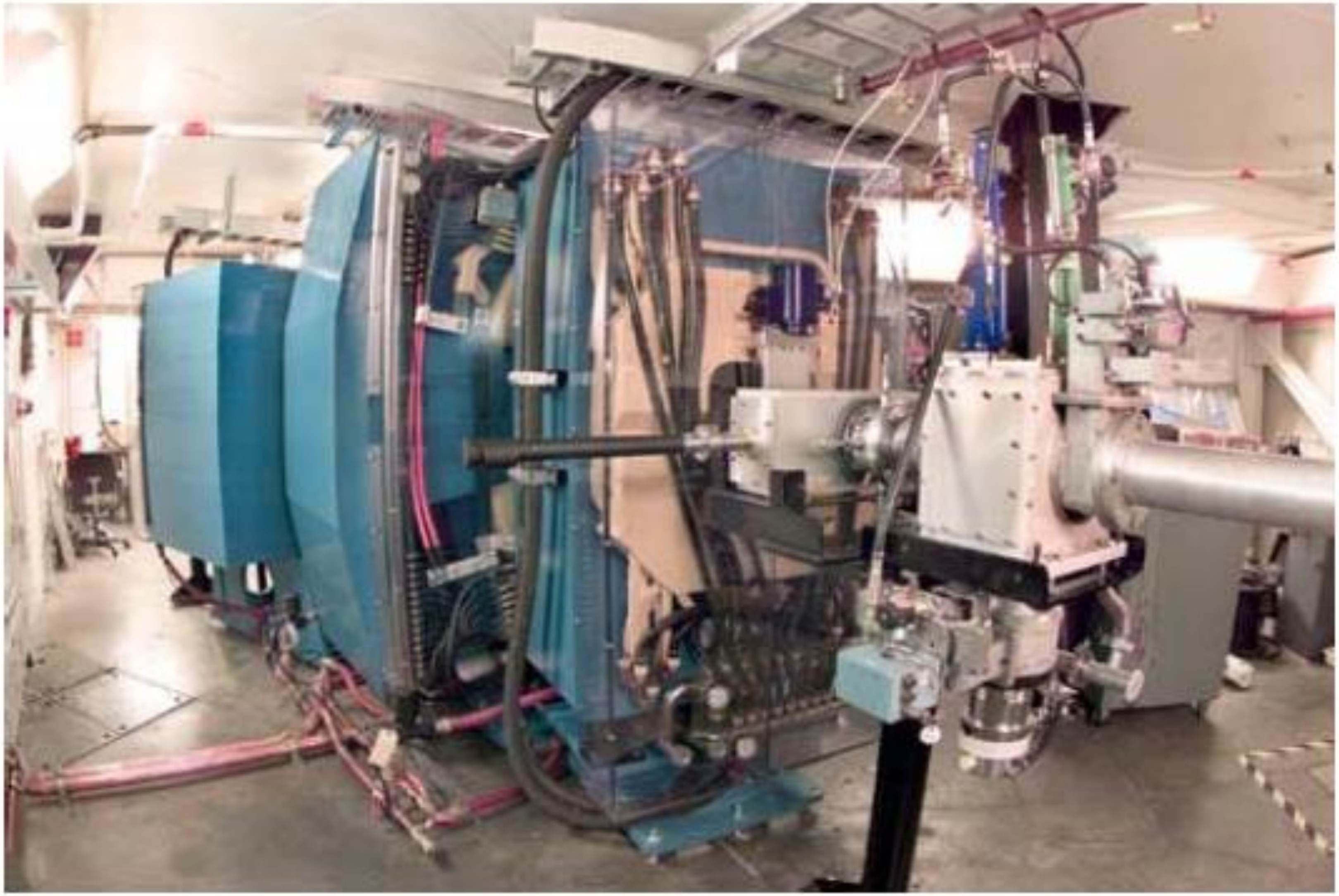
- Identify the position of single particle levels
- Determine the shape of the nuclei
- Validate theory
- Predication properties of $Z \approx 110$ nuclei
  - Shell closure
  - Binding energy
  - Deformation

Berkeley Gas-filled Separator

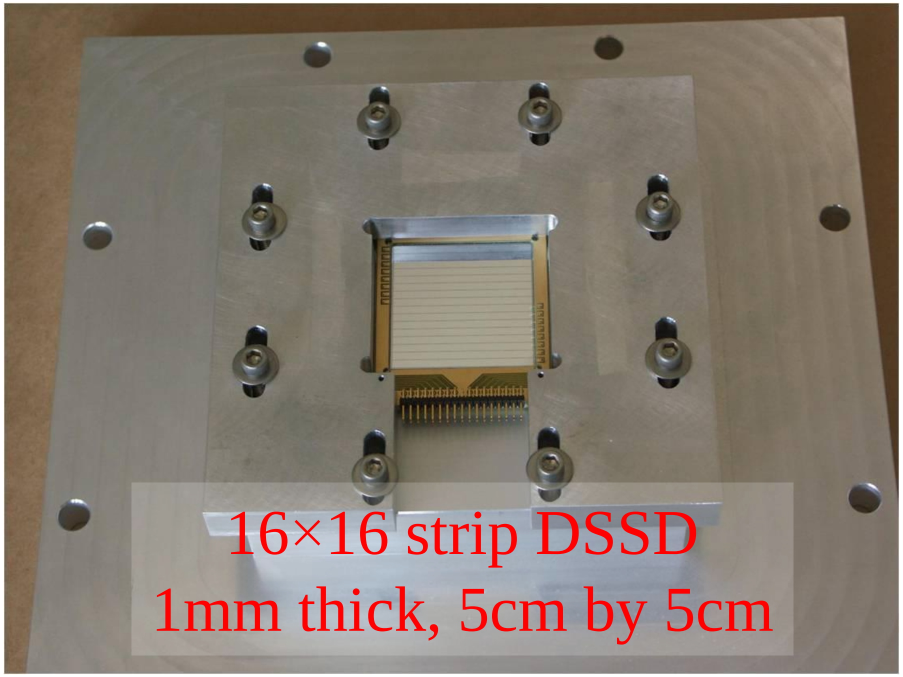


- Large acceptance: 45 msr (± 9° vertical, ±4.5° horizontal)
  - → Highest transmission (Ni+Pb: 70%, Ca+Pb: 60%, Mg+U: 18%)
- Large bend angle: 70°
  - → Lowest background rates (40Hz/pμA, 20Hz/pμA, 100Hz/pμA)

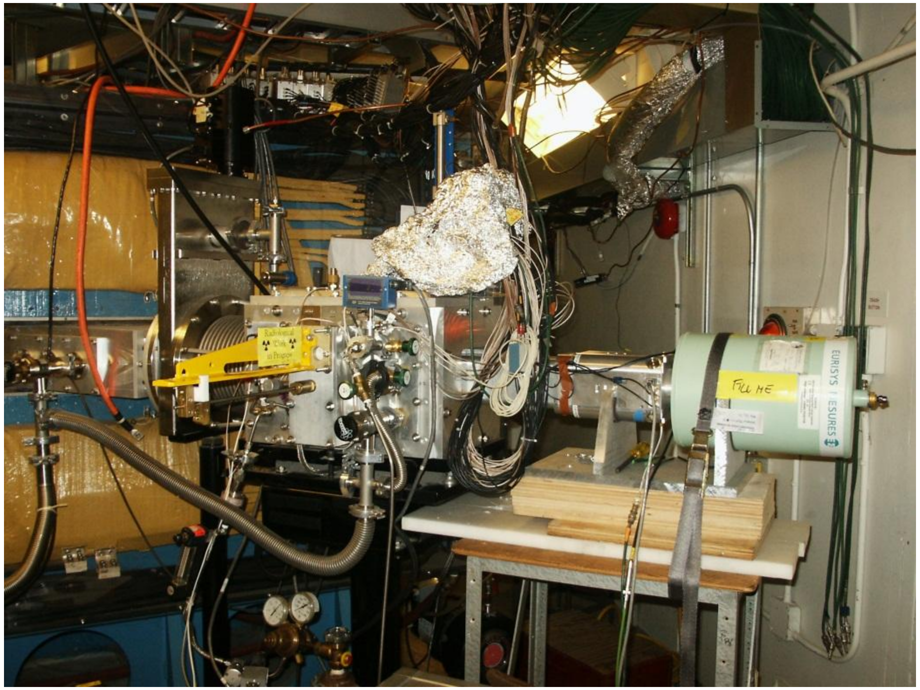
Berkeley Gas-filled Separator



Focal Plane Detectors



16×16 strip DSSD
1mm thick, 5cm by 5cm

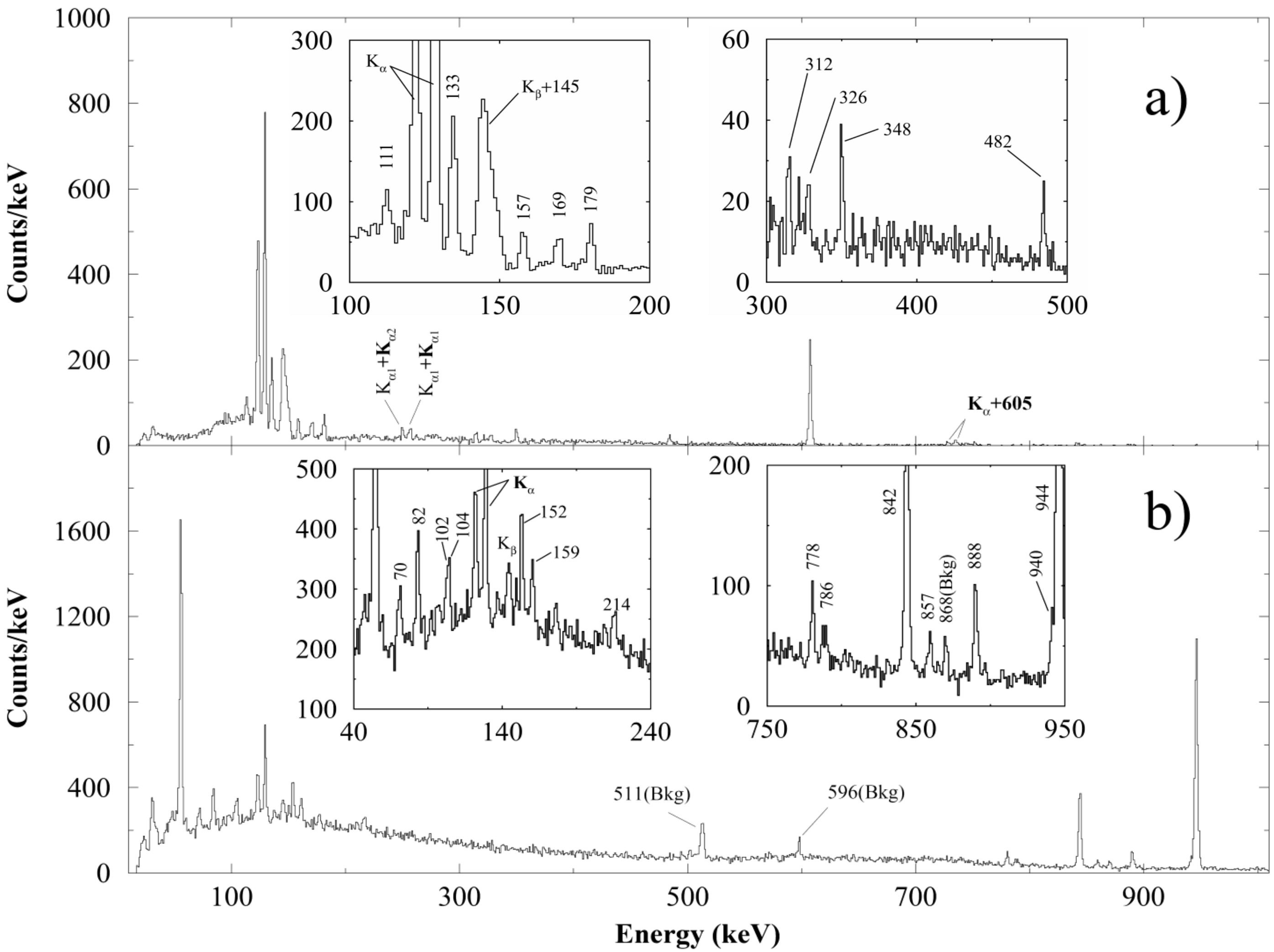


1) Recoil implanted in pixel of DSSD
2) Burst of conversion electrons in same pixel from isomer decay
3) Gamma-rays in coincidence with electron burst
4) Recoil decays in same pixel by alpha/fission

Key idea was to tag on isomer by searching for burst of conversion electrons and using a single pixel as a calorimeter.

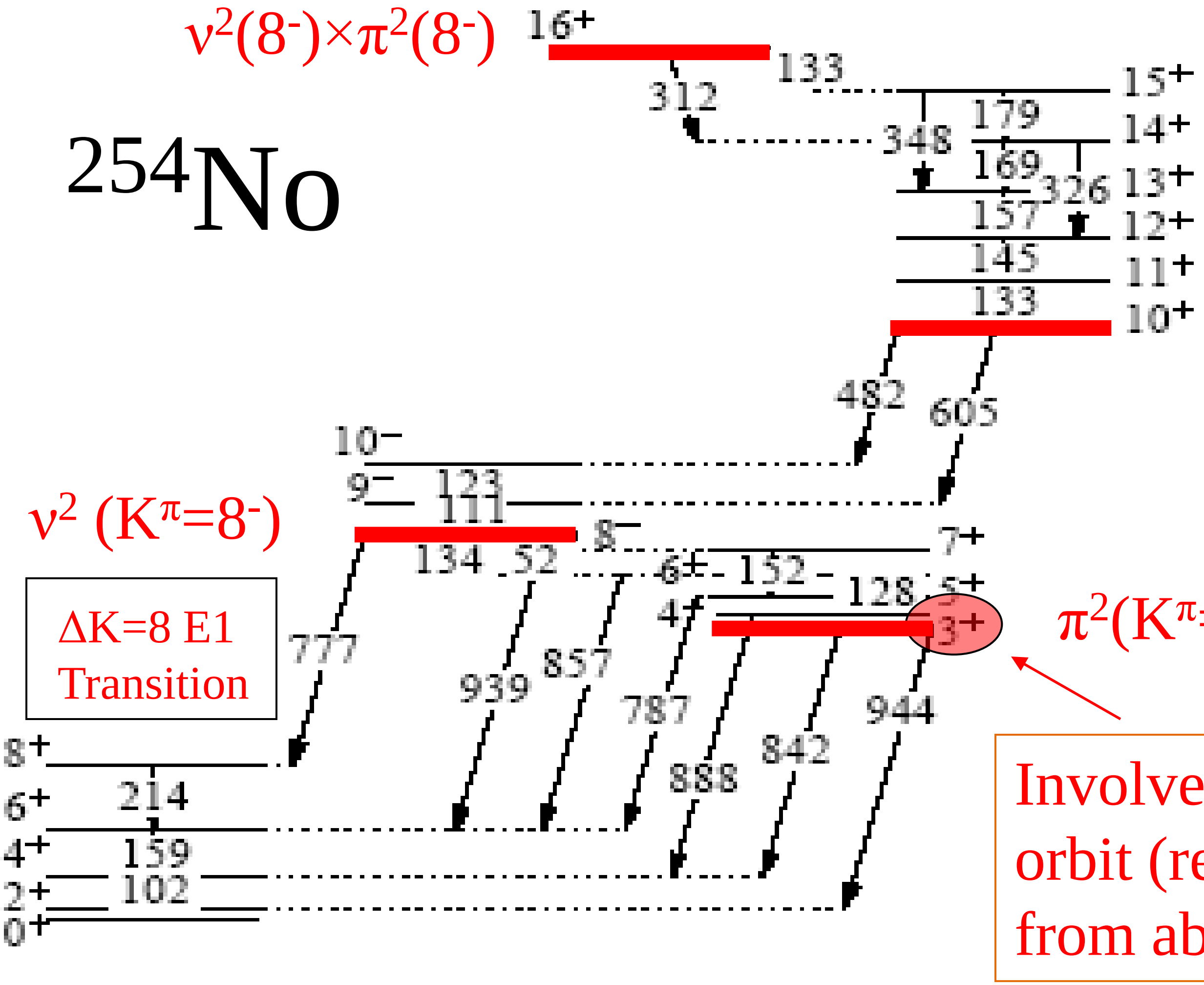
G.D. Jones (Liverpool), NIM A 488 471 (2002).

New Results on ^{254}No (Z =102)



R.M.Clark et al., PLB 690 19 (2010)

New Results on ^{254}No



^{254}No

$\nu^2(8^-)\times\pi^2(8^-)$

ν^2 ($K^\pi=10^+$)

ν^2 ($K^\pi=8^-$)

$\pi^2(K^\pi=3^+)$

Rotational sequences:

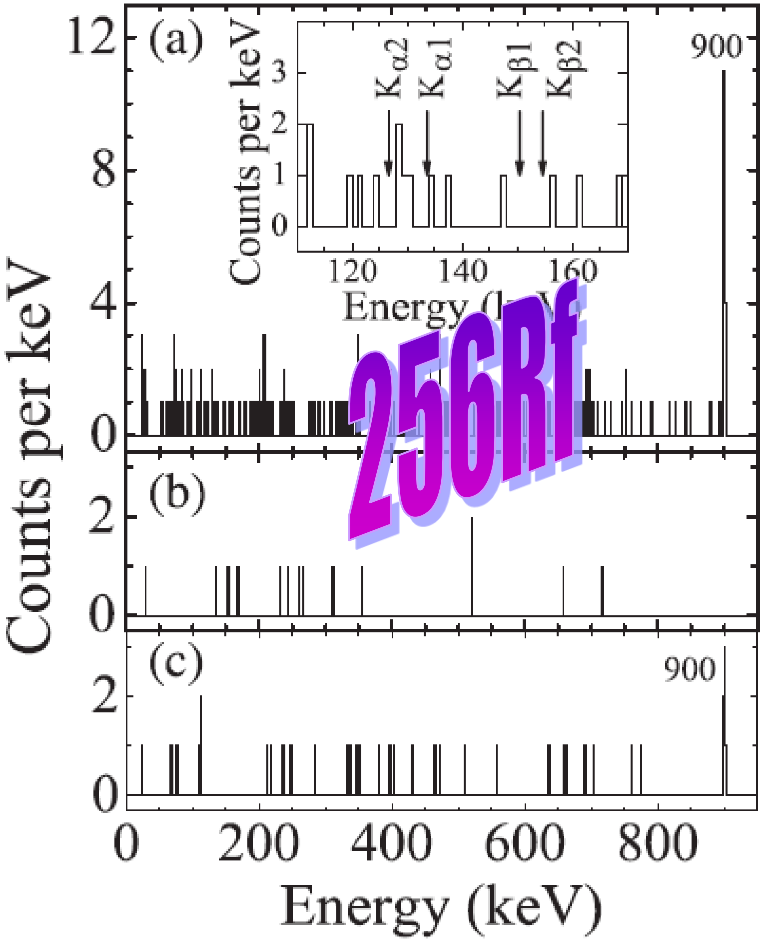
$$E_{rot}=\frac{\hbar^2}{2\Im}\left[I(I+1)\right]+E_K$$

ΔK=8 E1 Transition

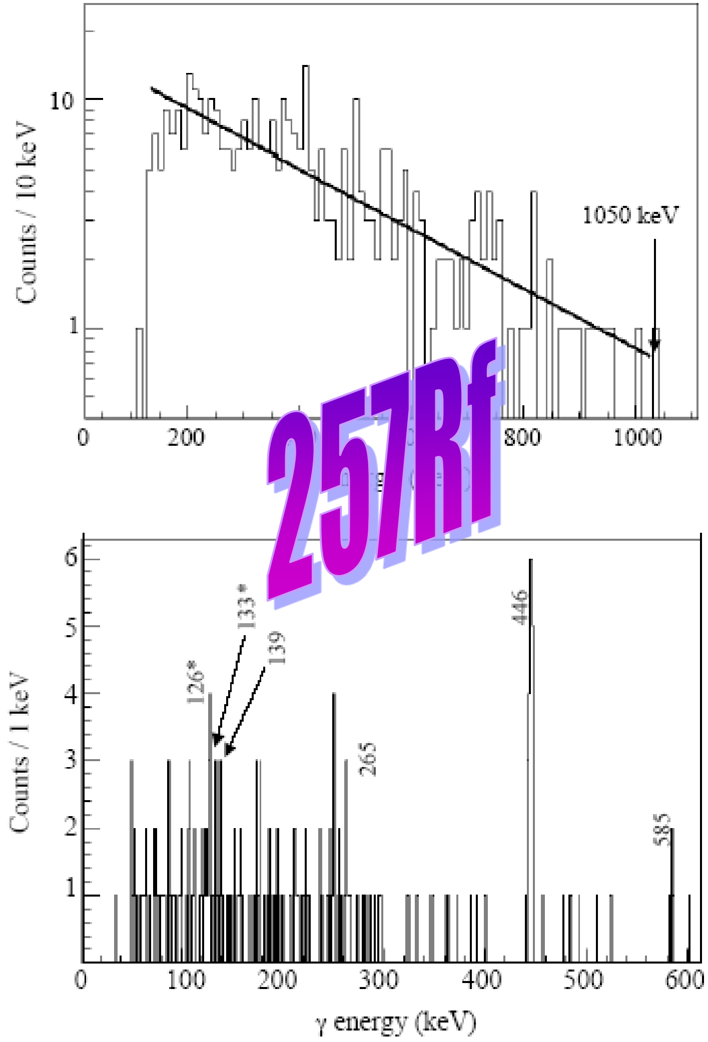
Involves a proton in the **$f_{5/2}$** orbit (remember the pink one from above the Z=114 gap!)

R.M. Clark et al., PLB 690 19 (2010)

Results on Rutherfordium (Z=104)

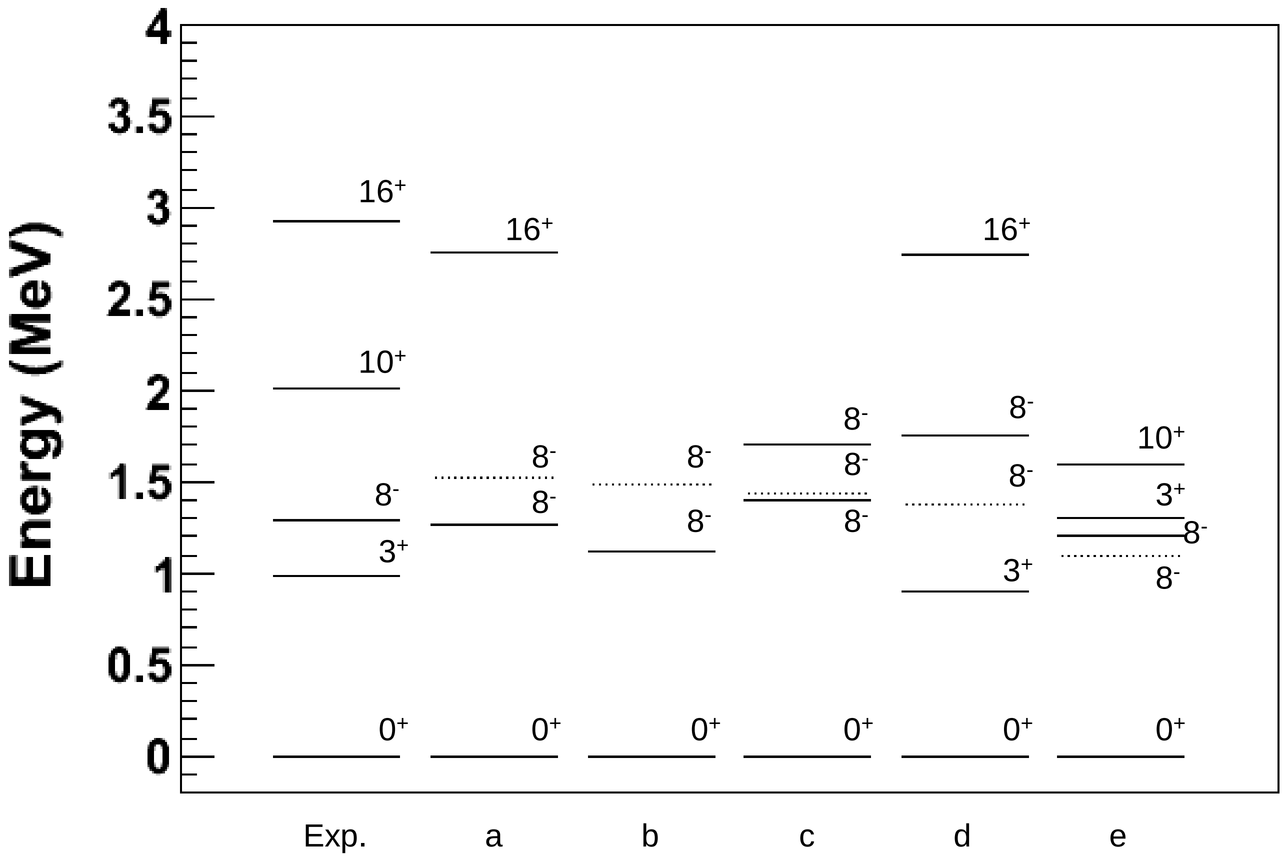


H.B. Jeppesen et al., PRC 79 (2009) 031303



J.S.Berryman et al., PRC 81 064325

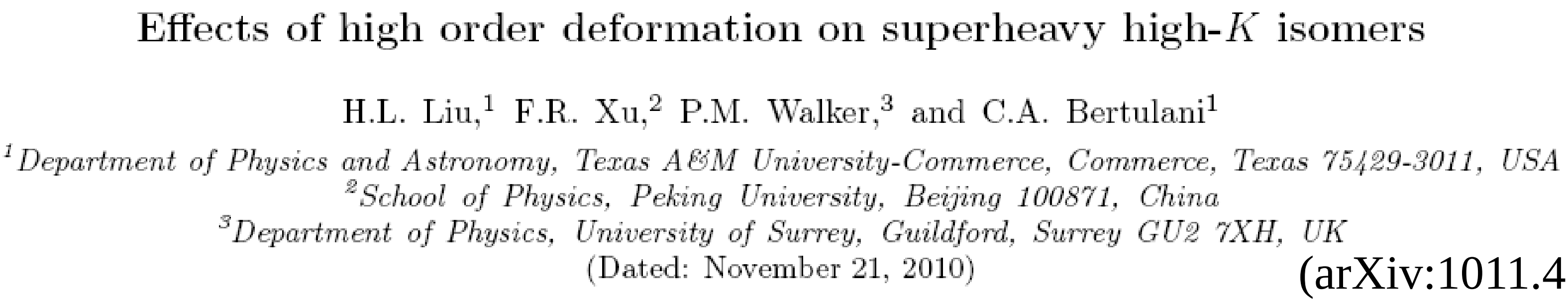
Comparison With Theory



Dashed lines are 2-quasiproton excitations.

Various calculations based on macroscopic-microscopic approaches seem to do a reasonable job describing experimental multi-qp states.

Role of Higher-Order Deformations

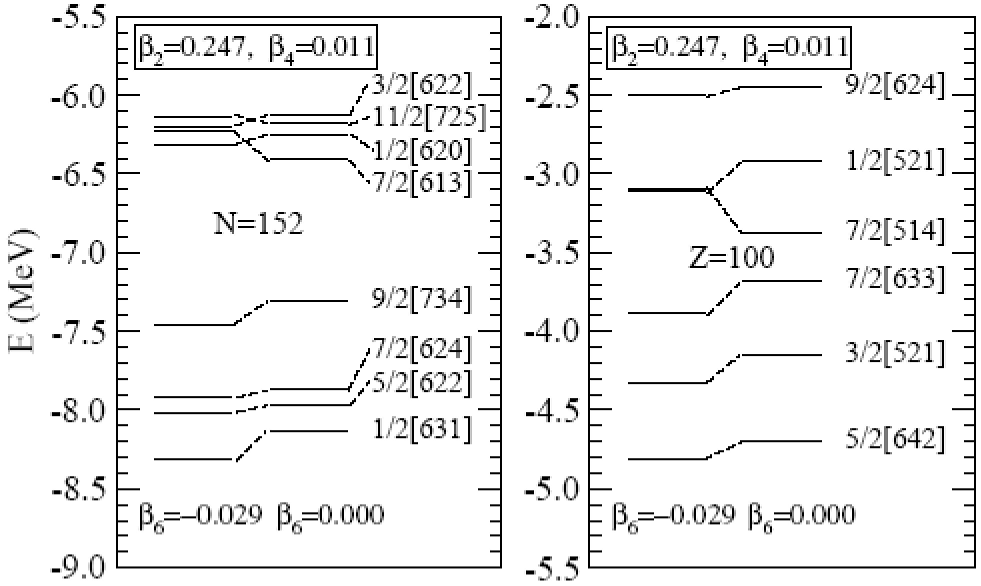


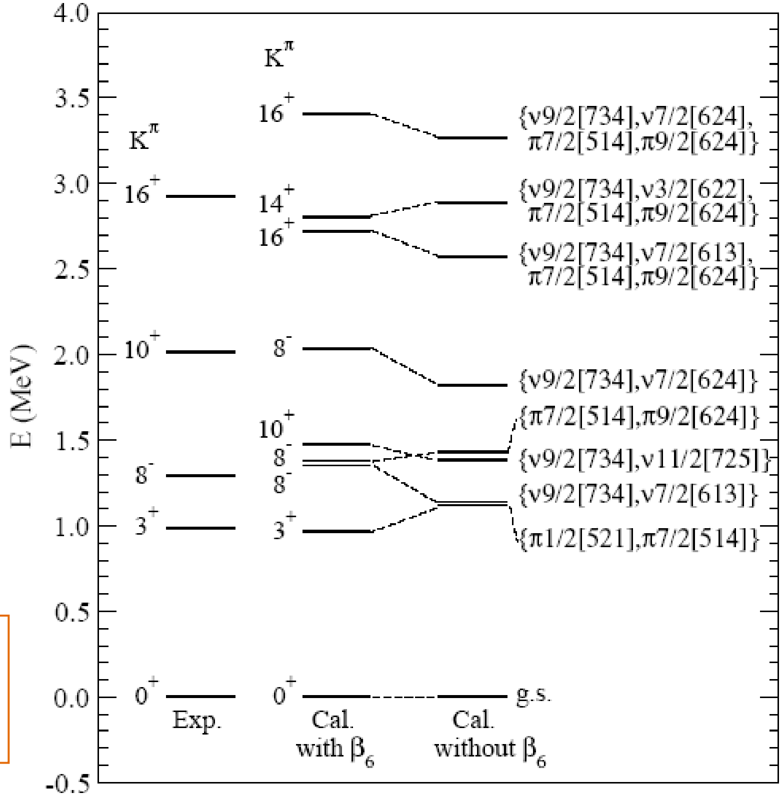
Effects of high order deformation on superheavy high-K isomers

H.L. Liu,[1] F.R. Xu,[2] P.M. Walker,[3] and C.A. Bertulani[1]

[1] *Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, Texas 75429-3011, USA*
[2] *School of Physics, Peking University, Beijing 100871, China*
[3] *Department of Physics, University of Surrey, Guildford, Surrey GU2 7XH, UK*
(Dated: November 21, 2010)

(arXiv:1011.4211v1)





- including β_4 and β_6 increases deformed gaps
- two low-lying 8^- states (π^2 and ν^2) occur

Summary

- The stability of heavy nuclei is due to largely the shell effect.
- Currently it is possible to study nuclear structure of $Z \approx 100$ elements.
- These properties are needs to validate nuclear models which will be used to predict the stability and properties of heavier nuclei ($Z > 110$)

Summary

Out look

- Experimental nuclear physics is at the beginning of an exciting period of rapid progress. Many opportunities for
  - New discoveries.
  - Comprehensive understanding of nuclear forces which can describe a wide variety of observations.

Driving forces

- New accelerator facilities, examples:
  - CARIBU: accelerated n-rich beam from ^{252}Cf
  - FRIB : fragmentation beam from a 400kW driver
- New detector technology, examples:
  - Gamma-ray track array : 100 times resolving power
  - Active target / time projection chamber :
    4π detector for both light and heavy particles
  - Cryogenic bolometer: ~ eve energy resolution
  - Fast scintillators : ~ fsec time resolution

Challenges for experiments

- Identify important nuclear properties
- Design and optimize experiments
  - Accelerator facility
  - Experimental equipment
  - Methods of analyzing and interpreting results
- Broad knowledge, new ideas, and critical thinking

Confucius: "Knowledge without thinking is a waste, thinking without knowledge is dangerous"