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(New) Shell Structure in Neutron-Rich Nuclei Above ^{48}Ca

Robert V. F. Janssens

Joint JUSTIPEN – LACM Meeting

ORNL, March 5 -9, 2007

U.S. Department of Energy

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

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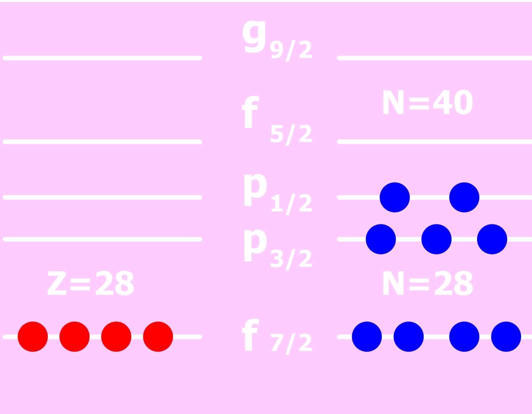
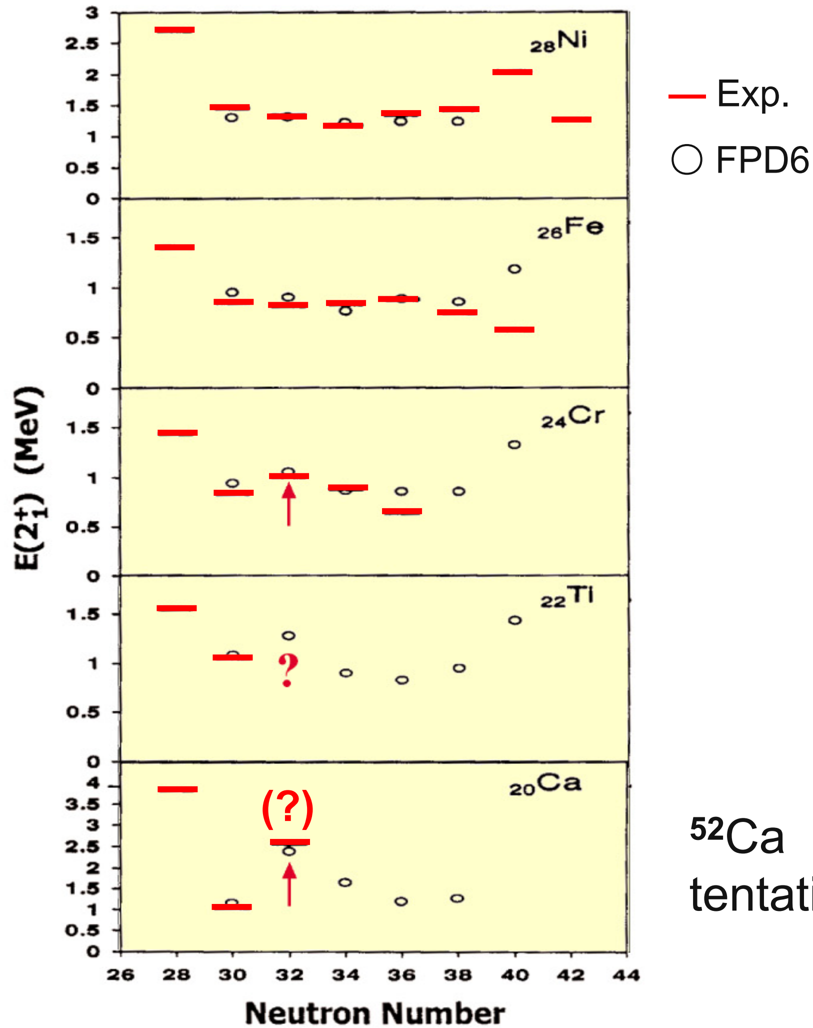
First Experimental Evidence for N=32 Gap



As protons are removed from the $f_{7/2}$ shell (Z=28 to Z=20), the $\pi f_{7/2}$-$\nu f_{5/2}$ monopole interaction strength weakens and the $\nu f_{5/2}$ orbital pushes up in energy.
→possible shell gaps at N=32 and N=34.

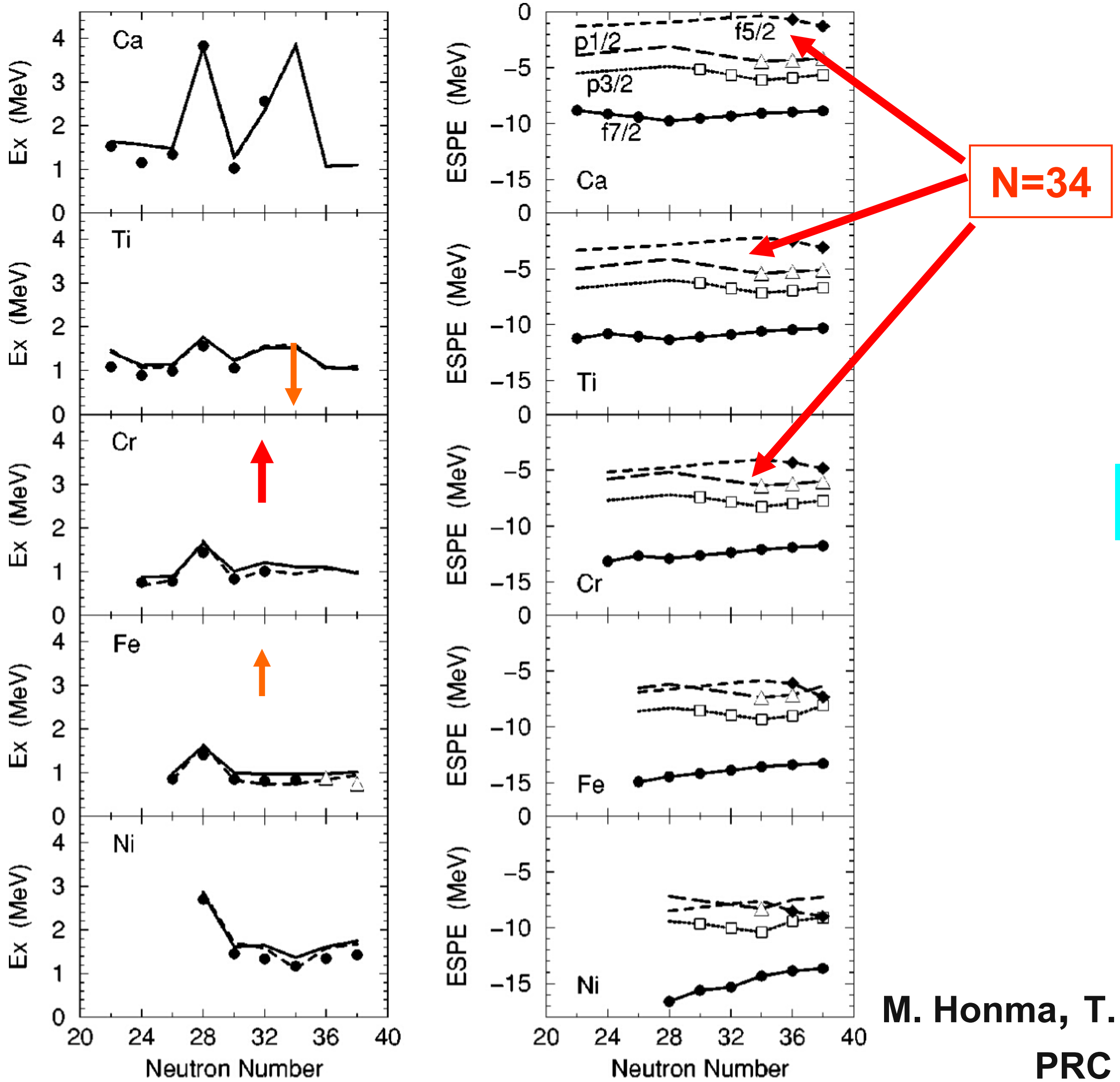
Shell model calculations with new GXPF1 interaction predict shell gaps at :
N=32, 34 for Z≤ 24 (Cr) and for Z≤22 (Ti).

J.I. Prisciandaro et al., PLB **501**, 17 (2001)



^{52}Ca tentative

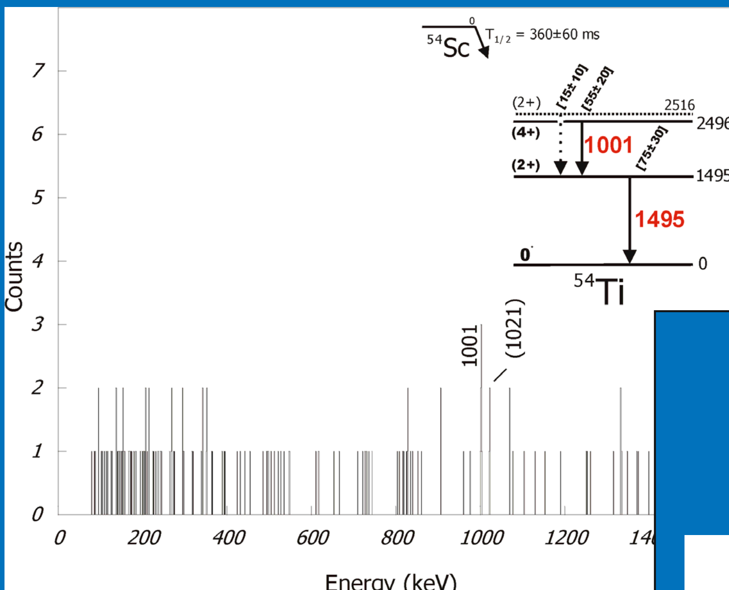
GXPF1: A New Effective Interaction for pf Shell



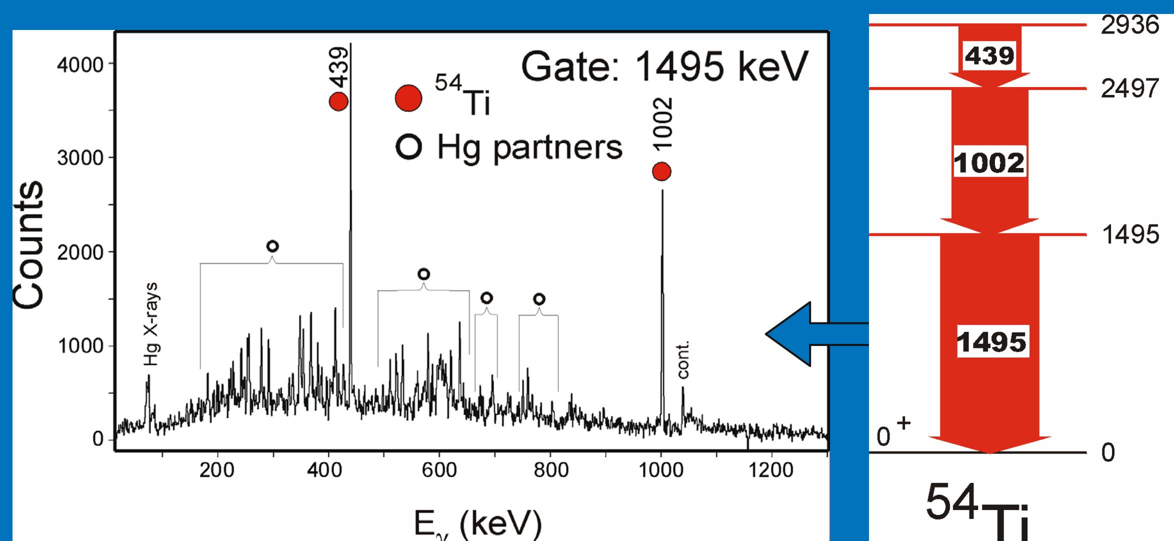
N = 32 or N=34 ?

M. Honma, T. Otsuka, B.A. Brown, T. Mizusaki
PRC 65, 061301(R) (2002)

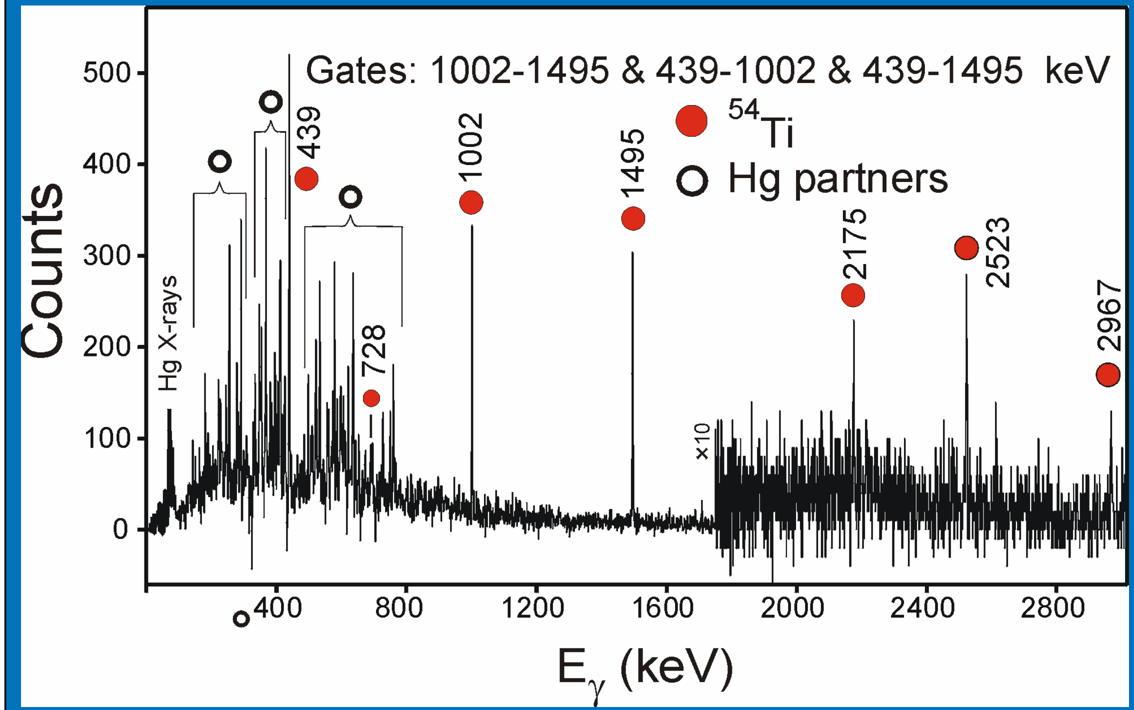
Beta-decay of the ^{54}Sc parent measured at NSCL following fragmentation of a Kr beam

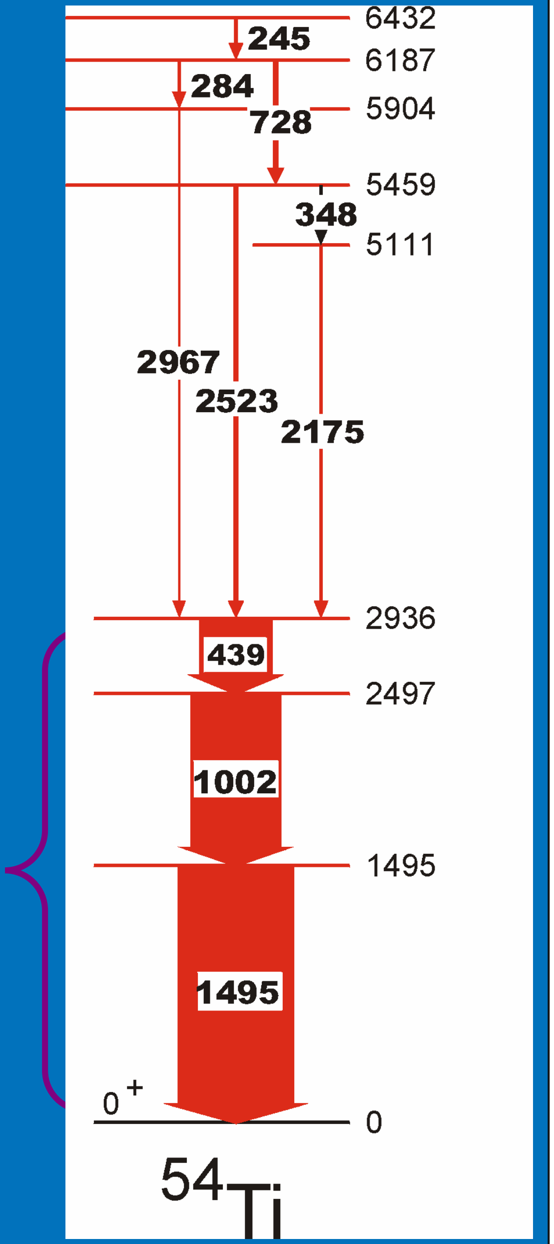


Deep-inelastic reaction data ^{48}Ca + ^{208}Pb, Gammasphere, ATLAS

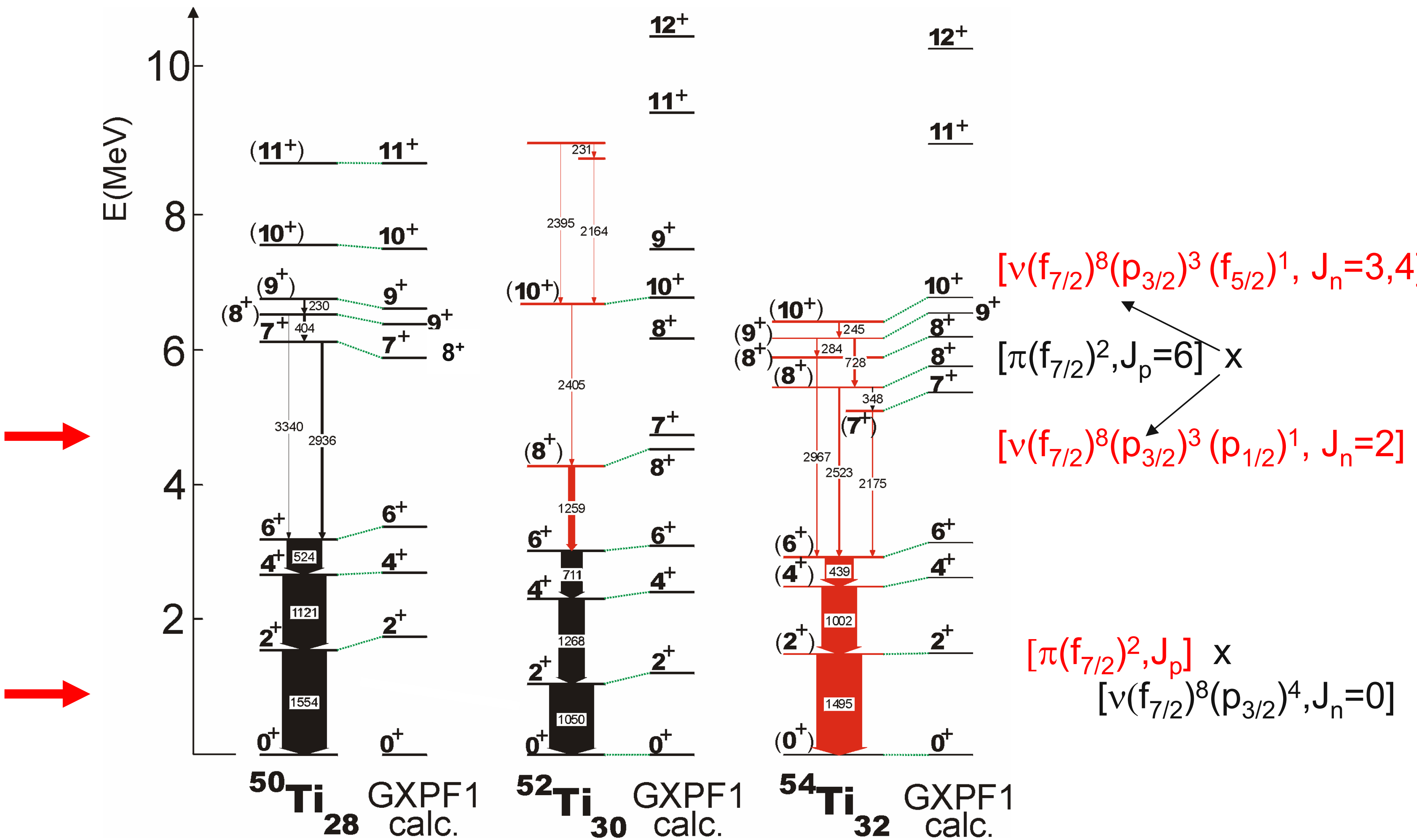


Power of Gammasphere:
- *coincidences*
- *angular correlations*

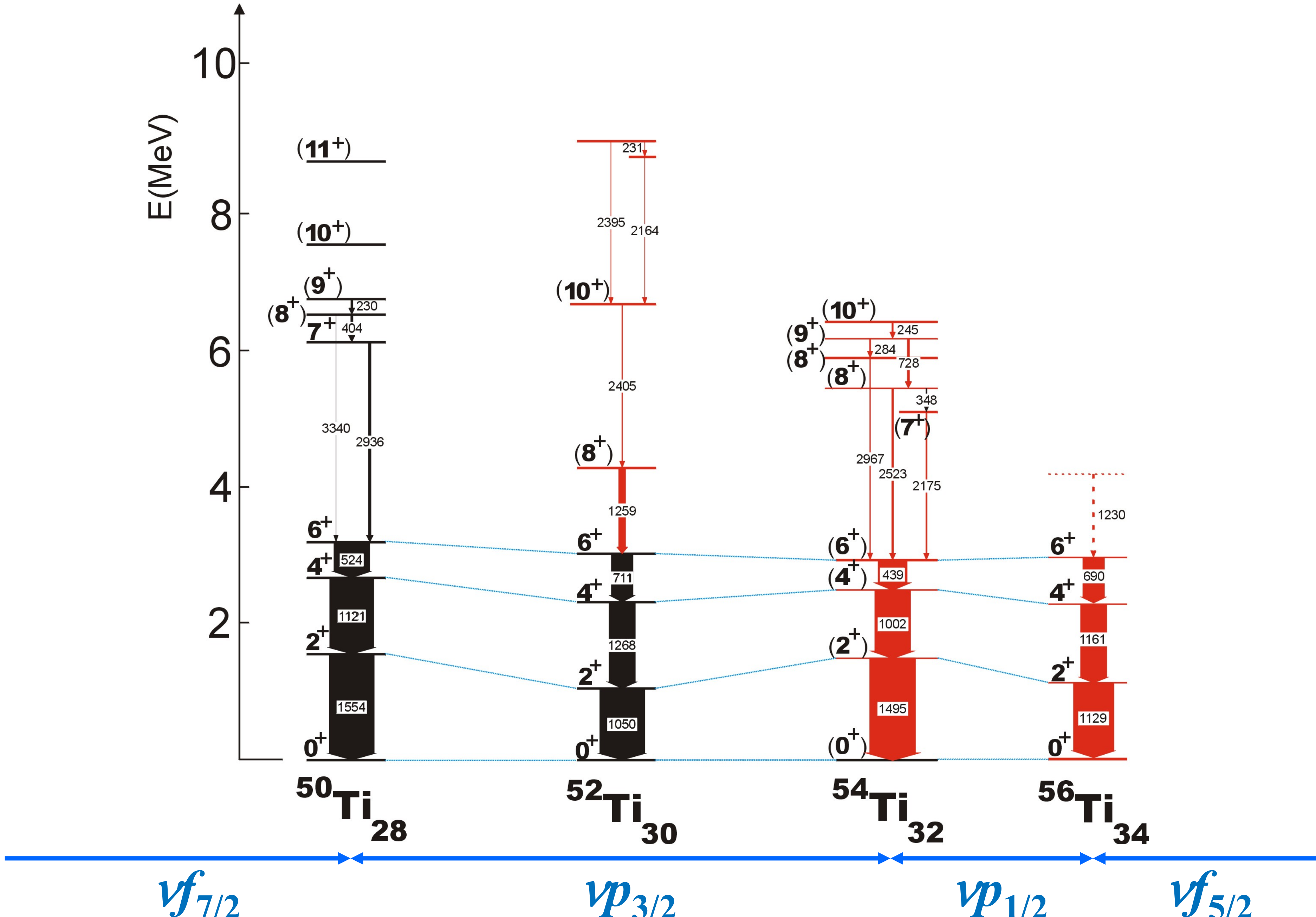




Shell Model Interpretation and N = 32 Gap

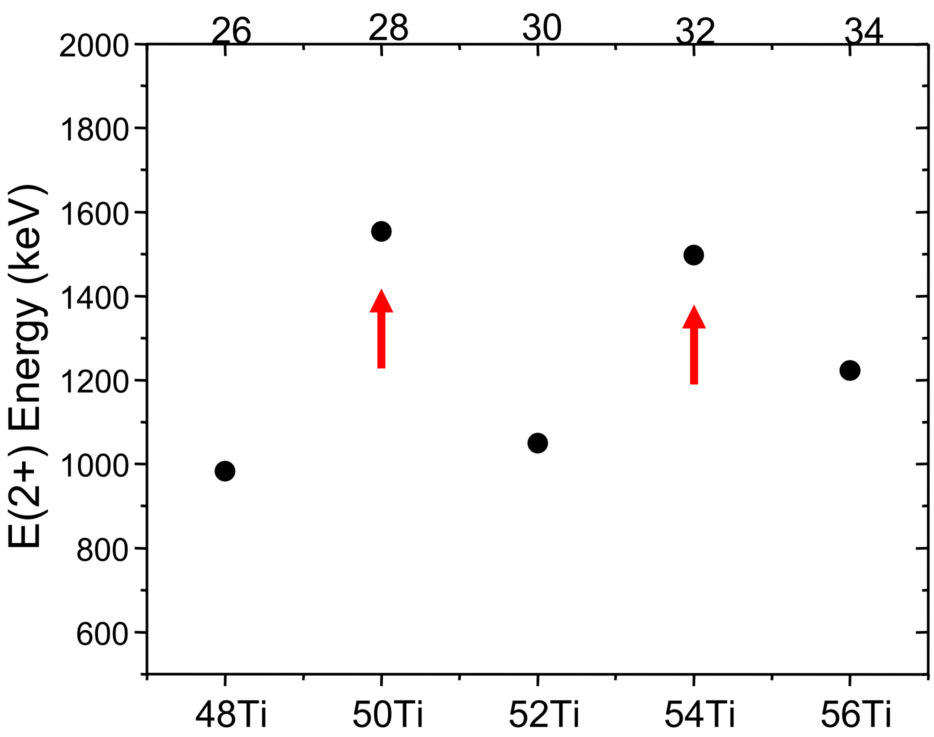


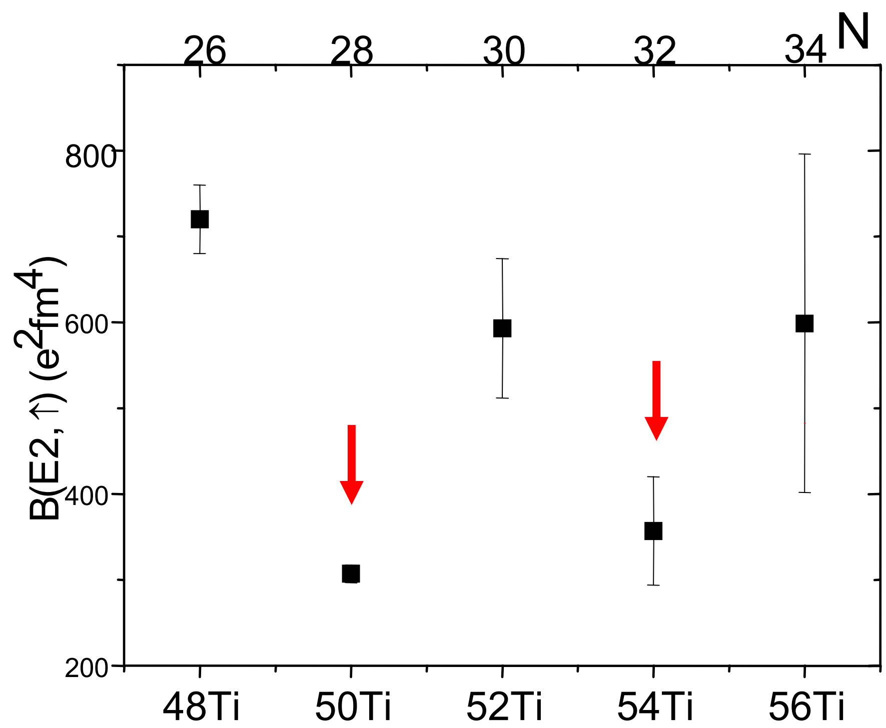
R.V.F. Janssens *et al.*, PLB **546**, 22 (2002)


E(MeV)
10
8
6
4
2
(11+)
(10+)
(9+)
(8+)
7+
230
404
3340
2936
6+
4+
2+
0+
524
1121
1554
231
2395
2164
(10+)
2405
(8+)
1259
6+
4+
2+
0+
711
1268
1050
(10+)
(9+)
(8+)
(8+)
245
284
728
348
(7+)
2967
2523
2175
(6+)
(4+)
(2+)
(0+)
439
1002
1495
1230
6+
4+
2+
0+
690
1161
1129
50Ti28
52Ti30
54Ti32
56Ti34
νf7/2
νp3/2
νp1/2
νf5/2

Shell Effects in Ti isotopes: Energies and B(E2)'s

Intermediate Energy Coulex at NSCL





From an experimentalist's point of view: N = 28 and N=32 gaps are quite visible in BOTH the $E(2^+)$ energies and in the $B(E2;0^+ \rightarrow 2^+)$ values and there is no experimental evidence for a N=34 gap

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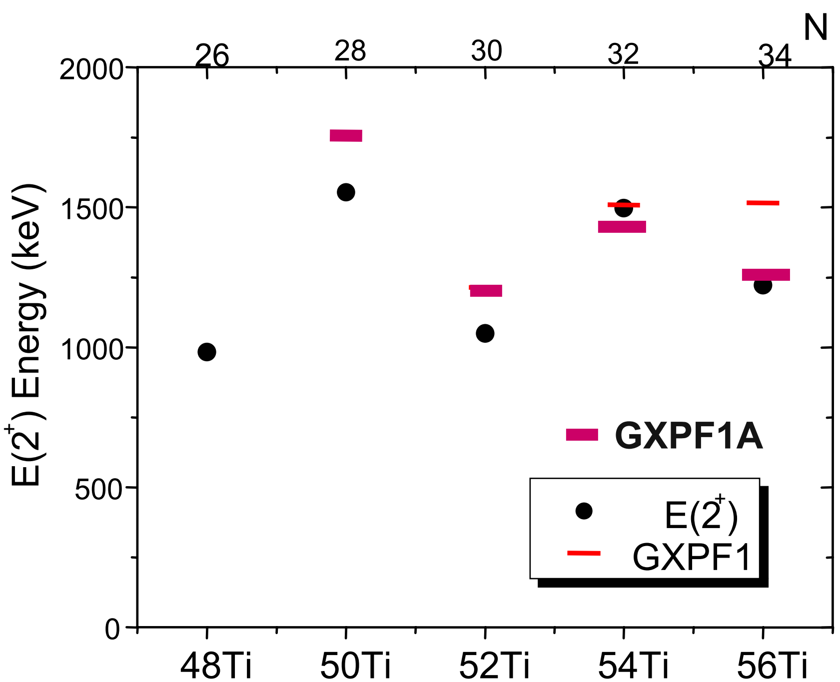
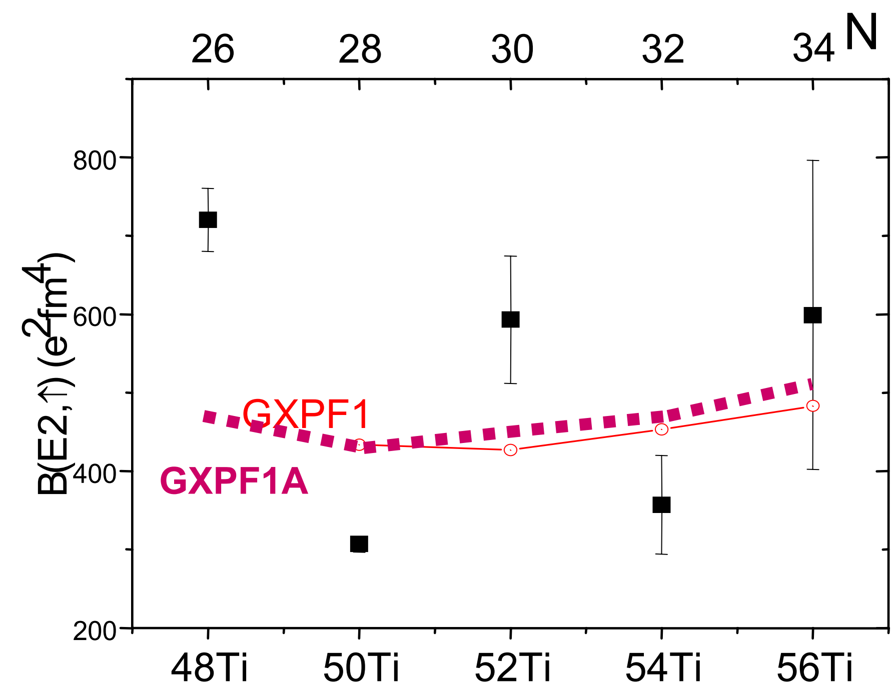
D.-C. Dinca *et al.,* PRC **71**, 041302(R) (2005)

From GXPF1 to GXPF1A





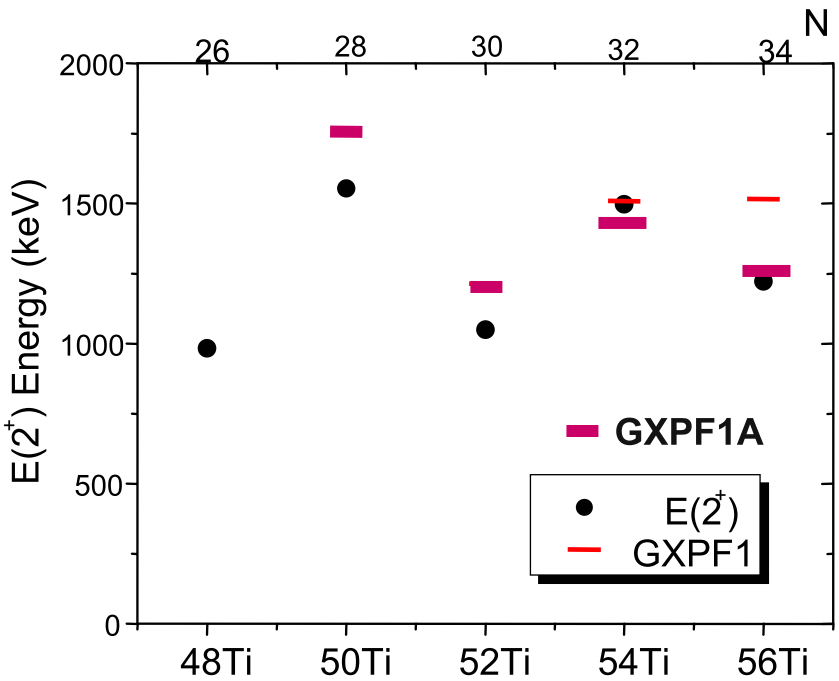
e_p = 1.5, e_n = 0.5

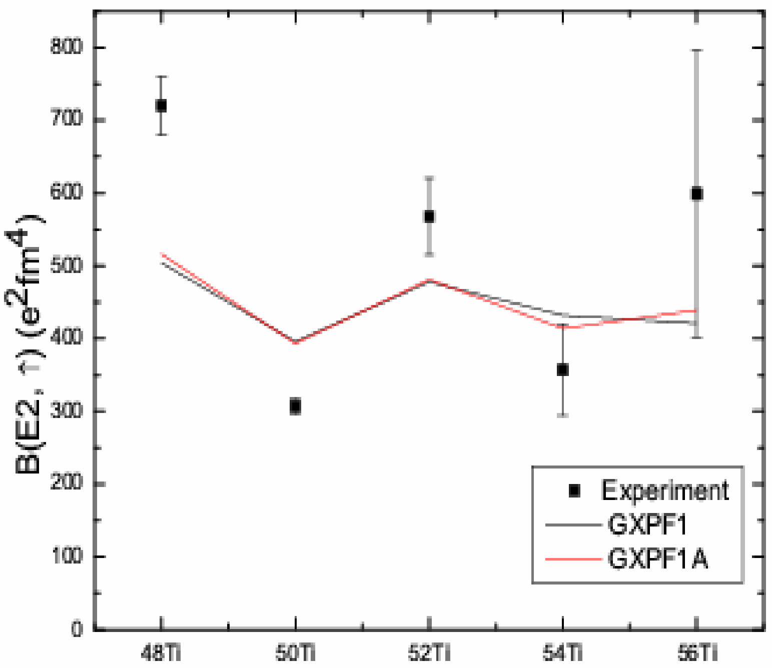
GXPF1A vs GXPF1:

T=1 matrix elements involving
$\nu p_{1/2}$ and $\nu f_{5/2}$ modified

($\nu p_{1/2}$ - $\nu f_{5/2}$) gap
reduced by ~0.5 MeV

From GXPF1 to GXPF1A





GXPF1A vs GXPF1:

T=1 matrix elements involving

$\nu p_{1/2}$ and $\nu f_{5/2}$ modified

($\nu p_{1/2}$ - $\nu f_{5/2}$) gap

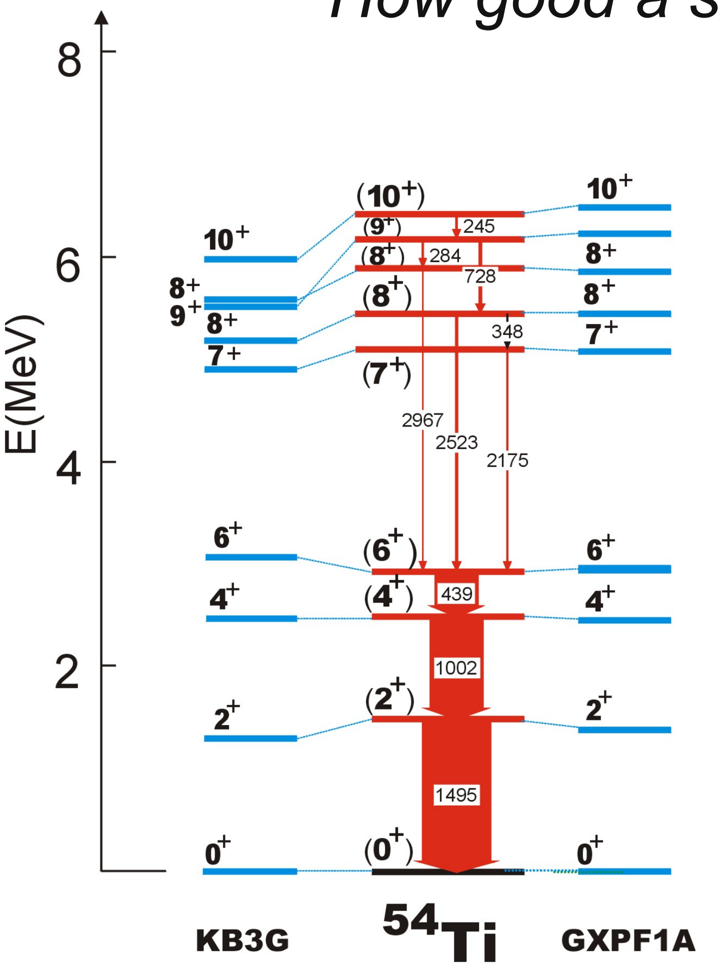
reduced by ~0.5 MeV

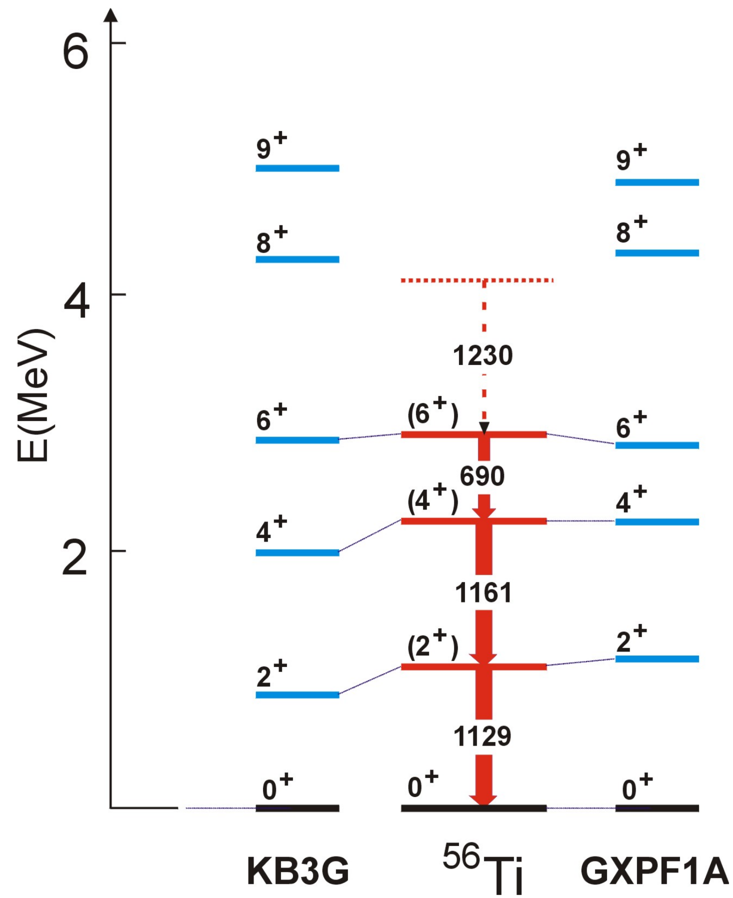
e_p= 1.15 e_n= 0.8

du Rietz et al., PRL **93**, 222501 (2004)

Testing GXPF1A Further

How good a semi-magic nucleus is ^{54}Ti?

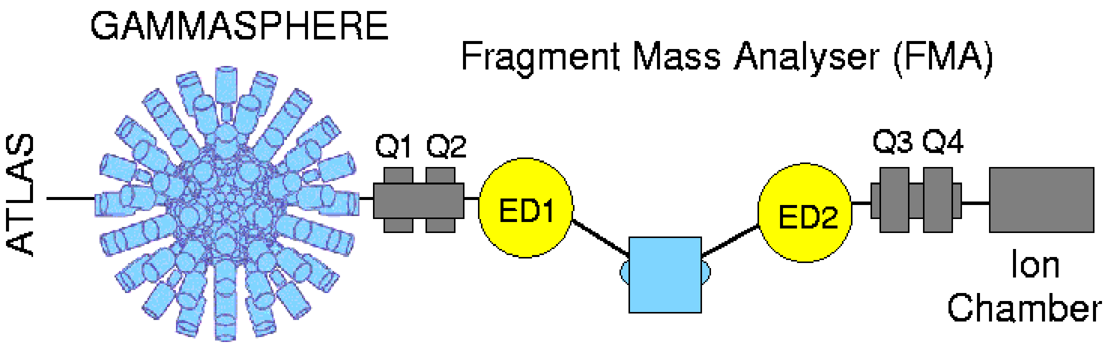




^{55}Ti & ^{55}V

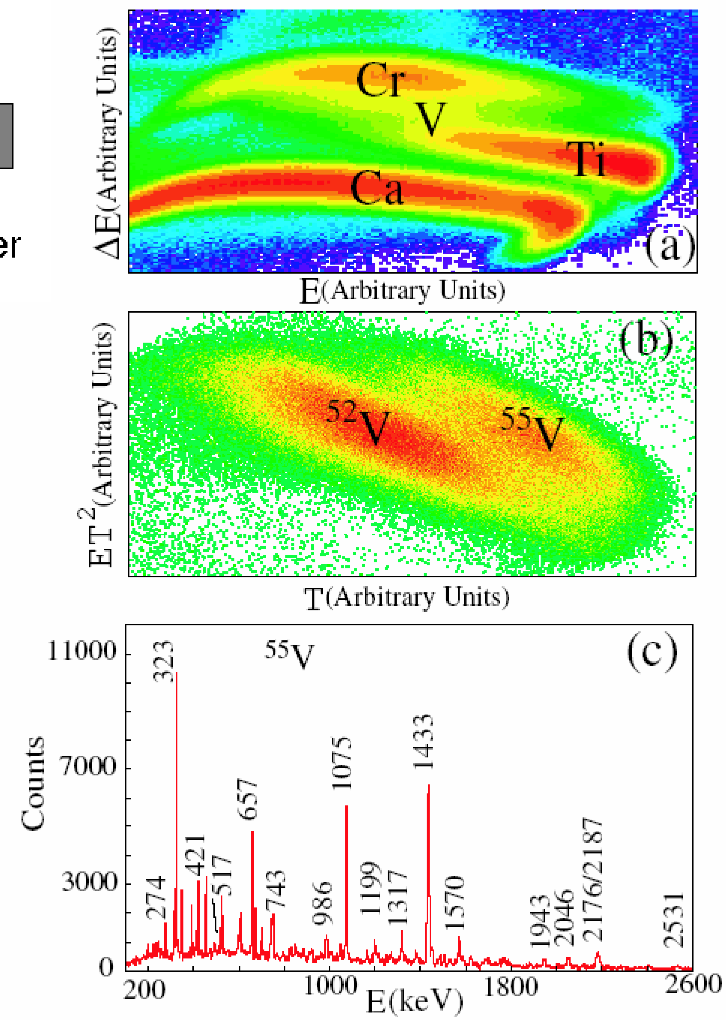
Let's look at particle excitations

New data: ^{55}V and another technique



^{55}V from ^{48}Ca(^{9}Be,pn)^{55}V at 172 MeV

$\sigma(2p) < 1\ \mu b$ ←→ $\sigma(3n/4n) \sim 100$ mb



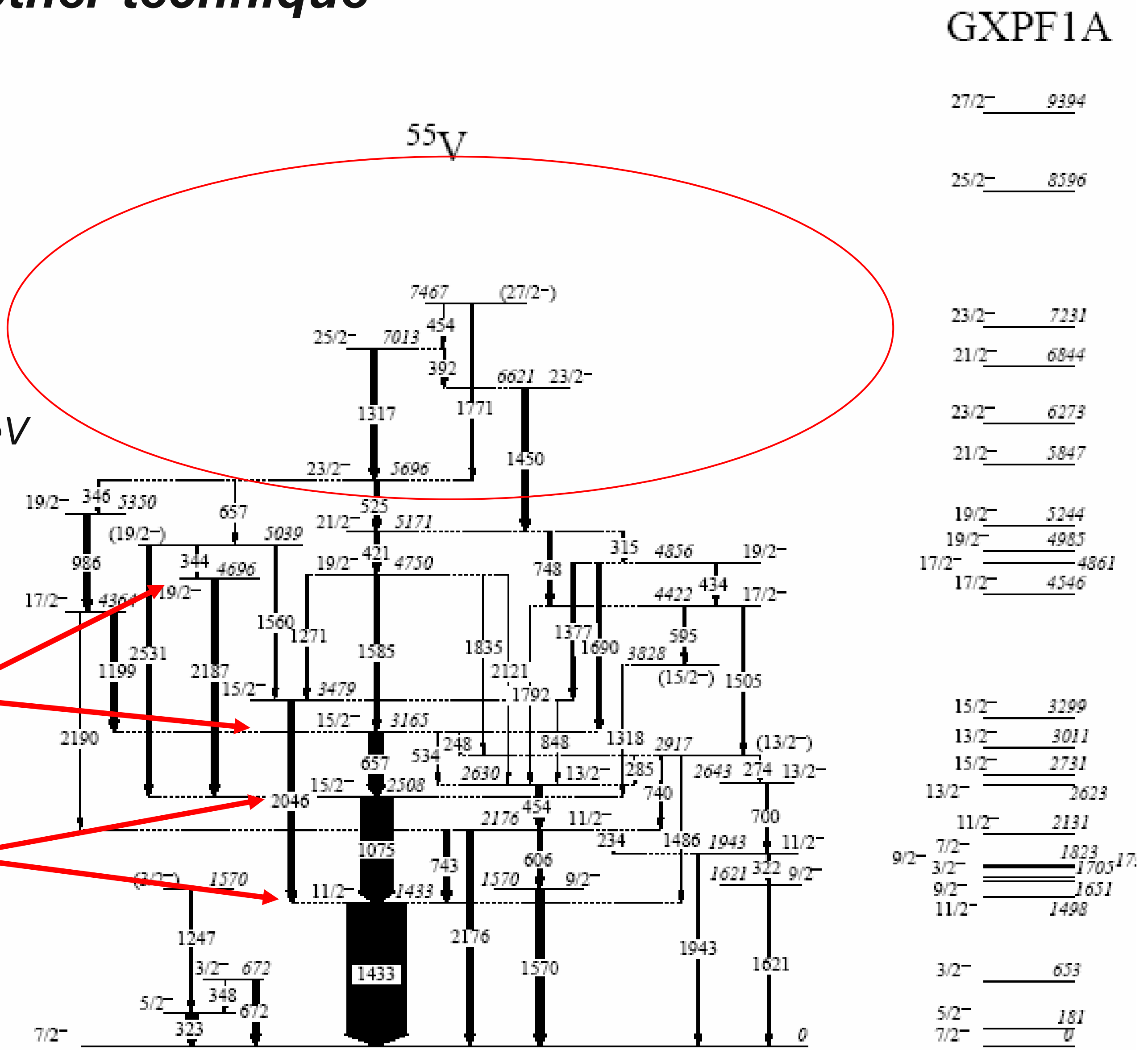
New data: ^{55}V and another technique

Problems above 19/2

N=32 gap present by $E_\gamma \sim 1.8$ MeV just like in ^{54}Ti

$\pi(f^3_{f/2}) \times \nu(f^8_{7/2}p^3_{3/2}f_{5/2})$

$\pi(f^3_{f/2}) \times \nu(f^8_{7/2}p^4_{3/2})$

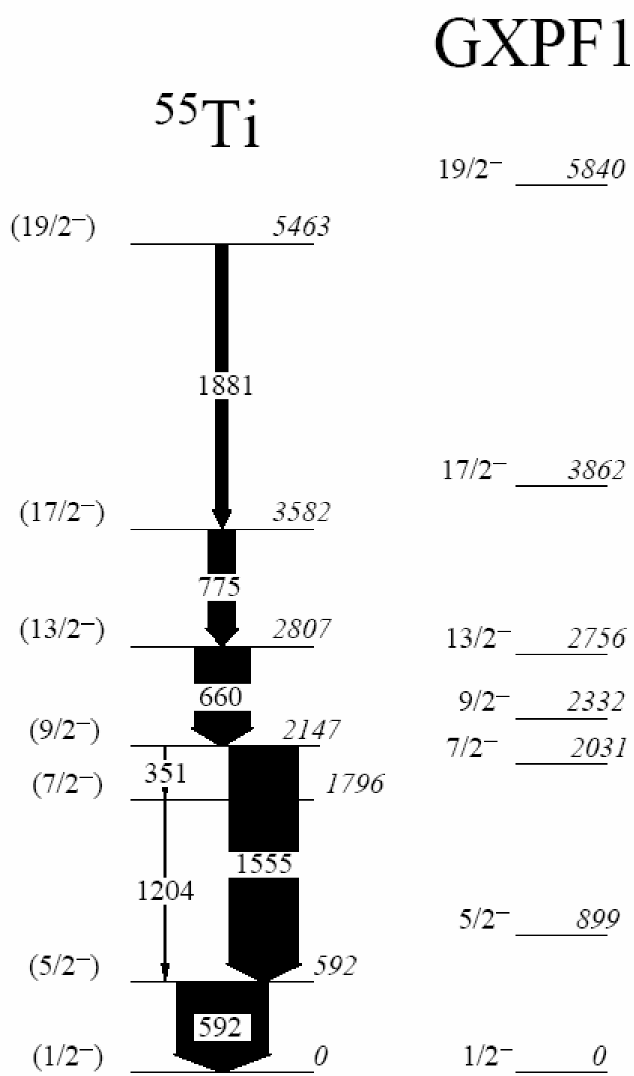


S. Zhu *et al.*, to be published

New data: ^{55}Ti (still from deep inelastic reactions)

Experimental note:

Spins are uncertain, but values given are most consistent with all available data



^{54}Ti Core broken (~ 1.8 MeV as in ^{54}Ti)

^{54}Ti(4$^+$) x $\nu f_{5/2}$

^{54}Ti(6$^+$) x $\nu p_{1/2}$

^{54}Ti(4$^+$) x $\nu p_{1/2}$

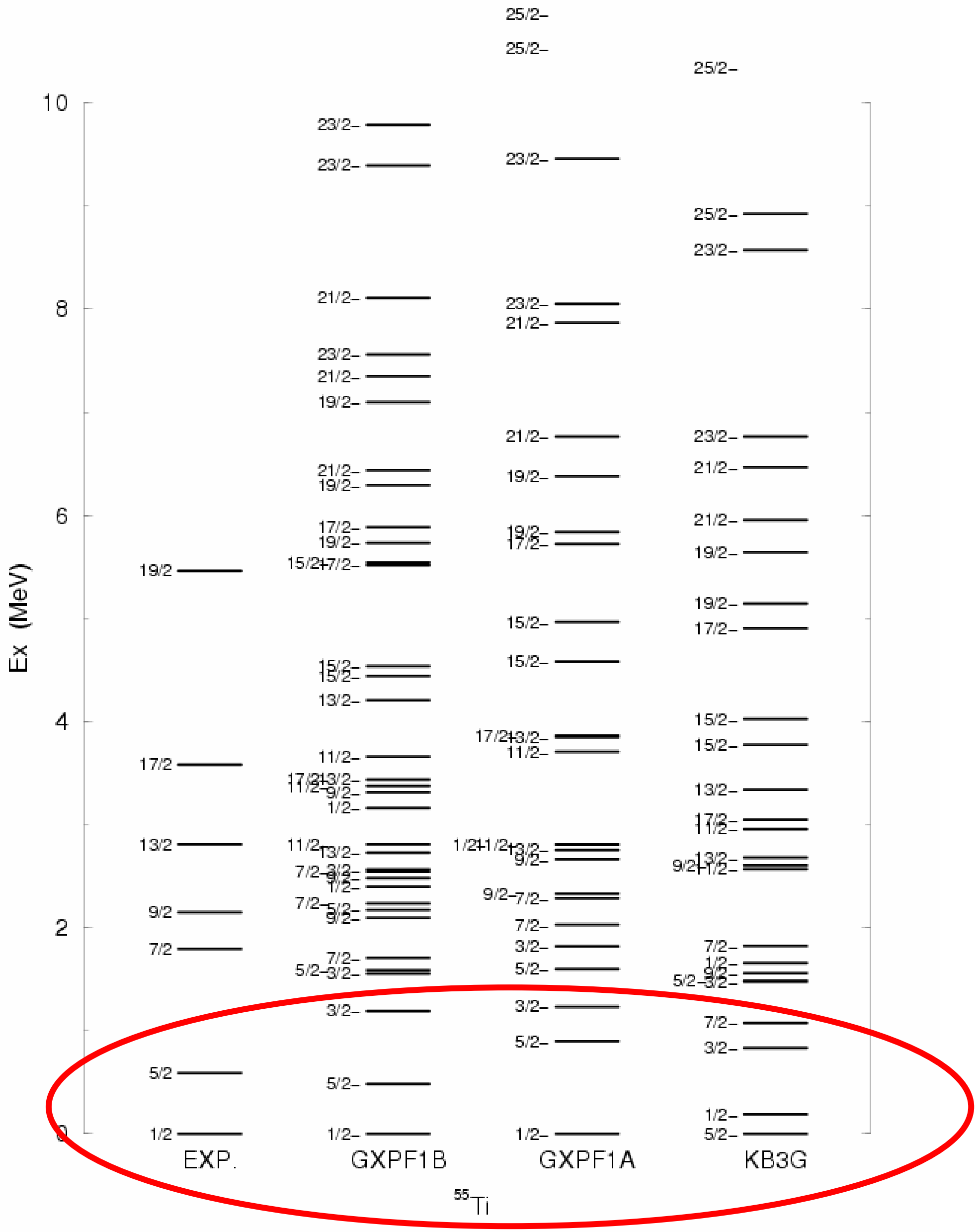
^{54}Ti x $\nu f_{5/2}$

^{54}Ti x $\nu p_{1/2}$

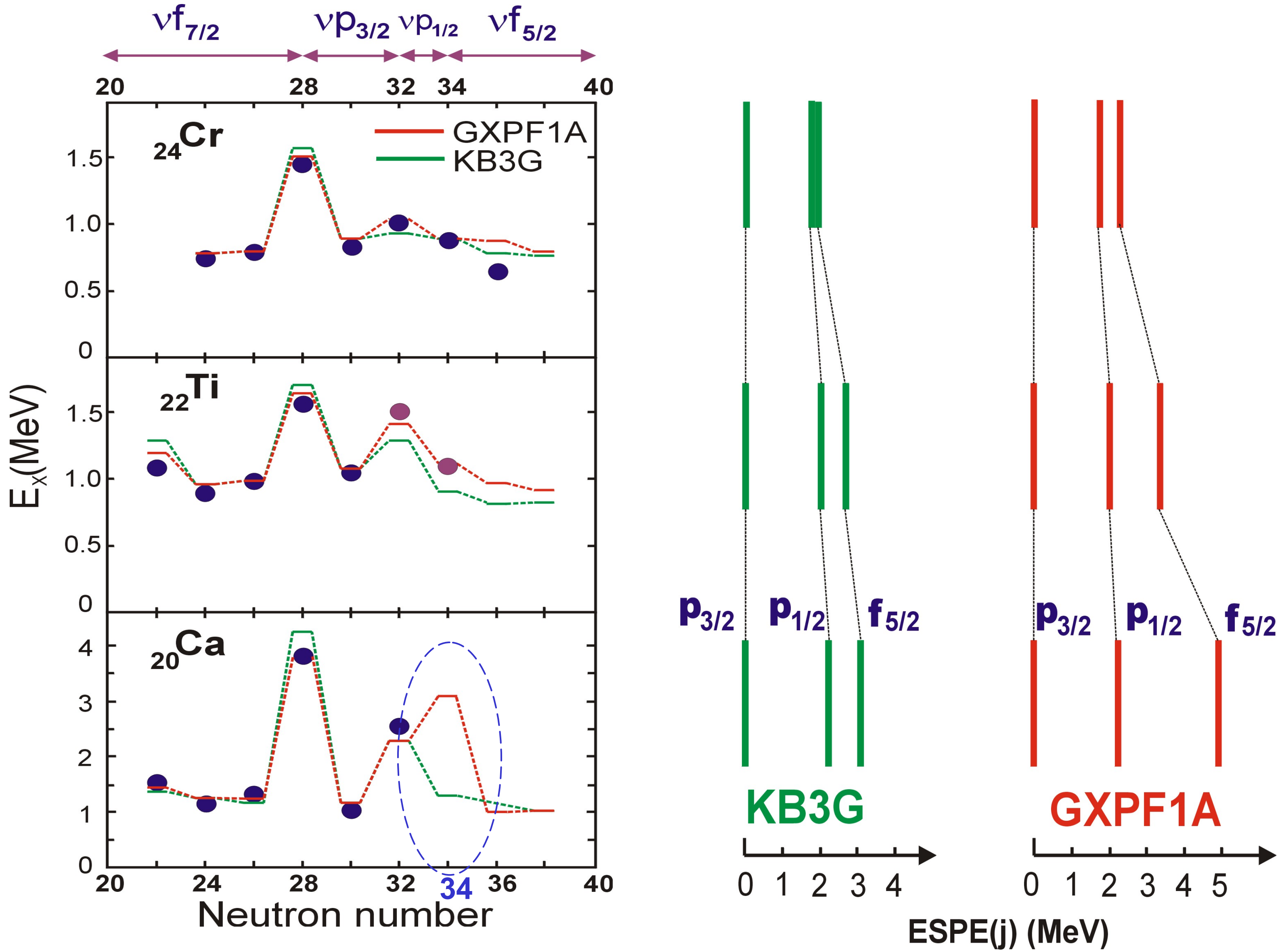
300 keV difference → $\nu f_{5/2}$ - $\nu p_{1/2}$ too large?

S. Zhu *et al*., to be published

New data: ^{55}Ti



T. Otsuka, private communication



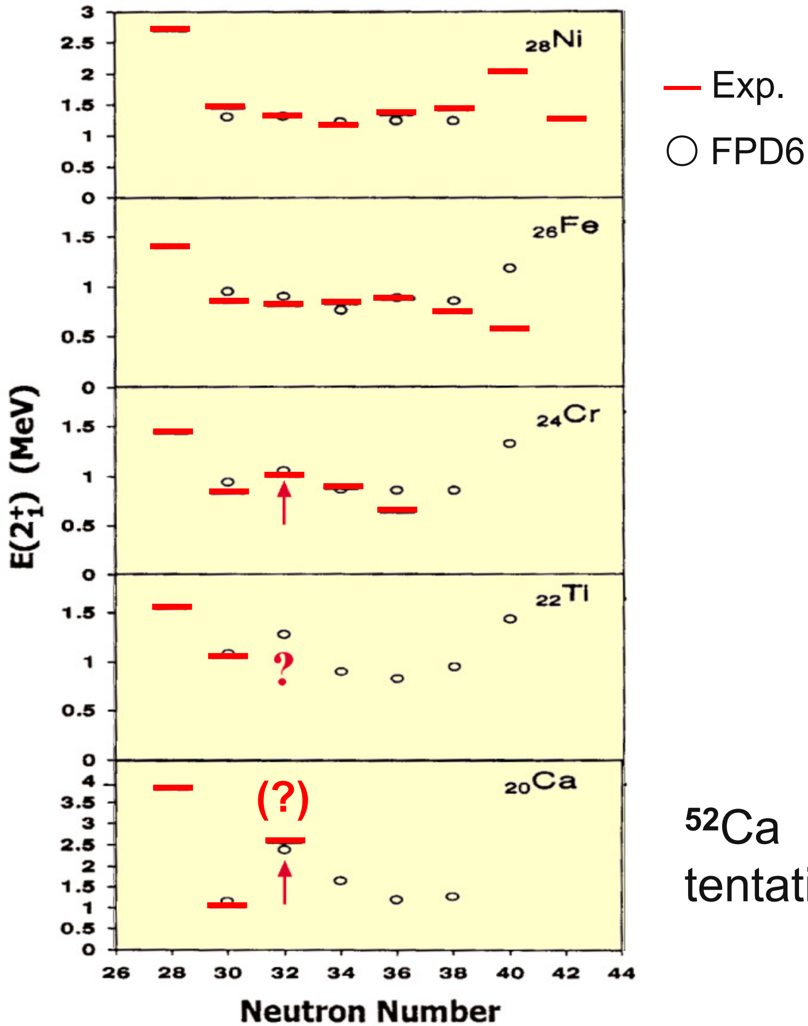
νf7/2
νp3/2
νp1/2
νf5/2
20
28
32
34
40
24Cr
GXPF1A
KB3G
22Ti
20Ca
Ex(MeV)
Neutron number
34
p3/2
p1/2
f5/2
KB3G
GXPF1A
ESPE(j) (MeV)

Experimental Evidence for N=32 Gap: ^{52}Ca

E(2$^+$) in ^{52}Ca comes from a 1983 ISOLDE β-decay study (A.Huck *et al*., PRC 31, 2226 (1985)) where the separation between β decay and n-delayed β decay was a problem

At CCF ^{52}Ca intensity is too small for a Coulex experiment

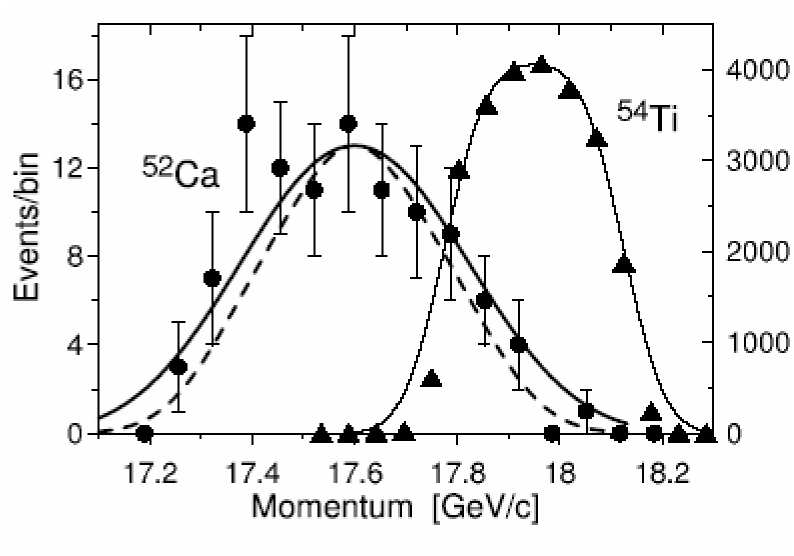
→ 2p knockout!!



^{52}Ca tentative

J.I. Prisciandaro et al., PLB **501**, 17 (2001)

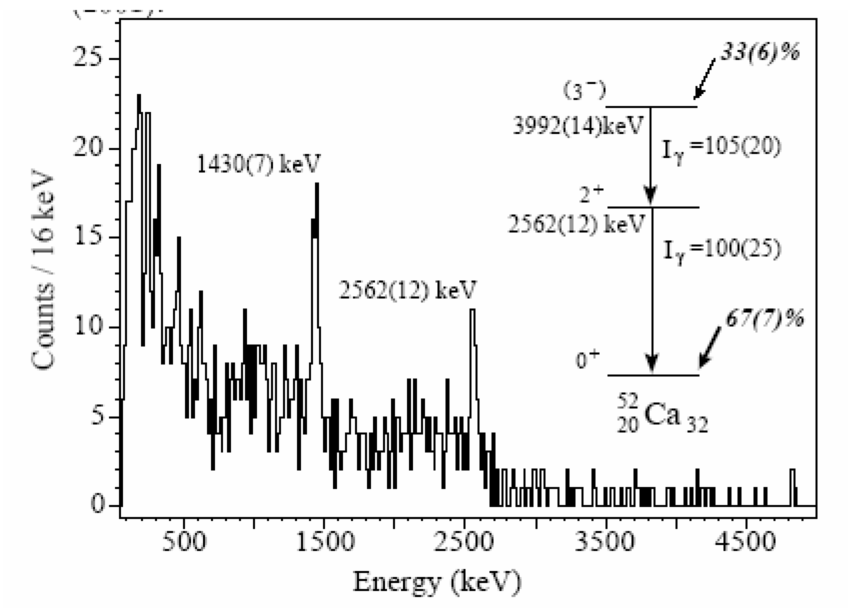
2p knockout into ^{52}Ca



Direct process

Knock-out of 2 $f_{7/2}$ protons from ^{54}Ti

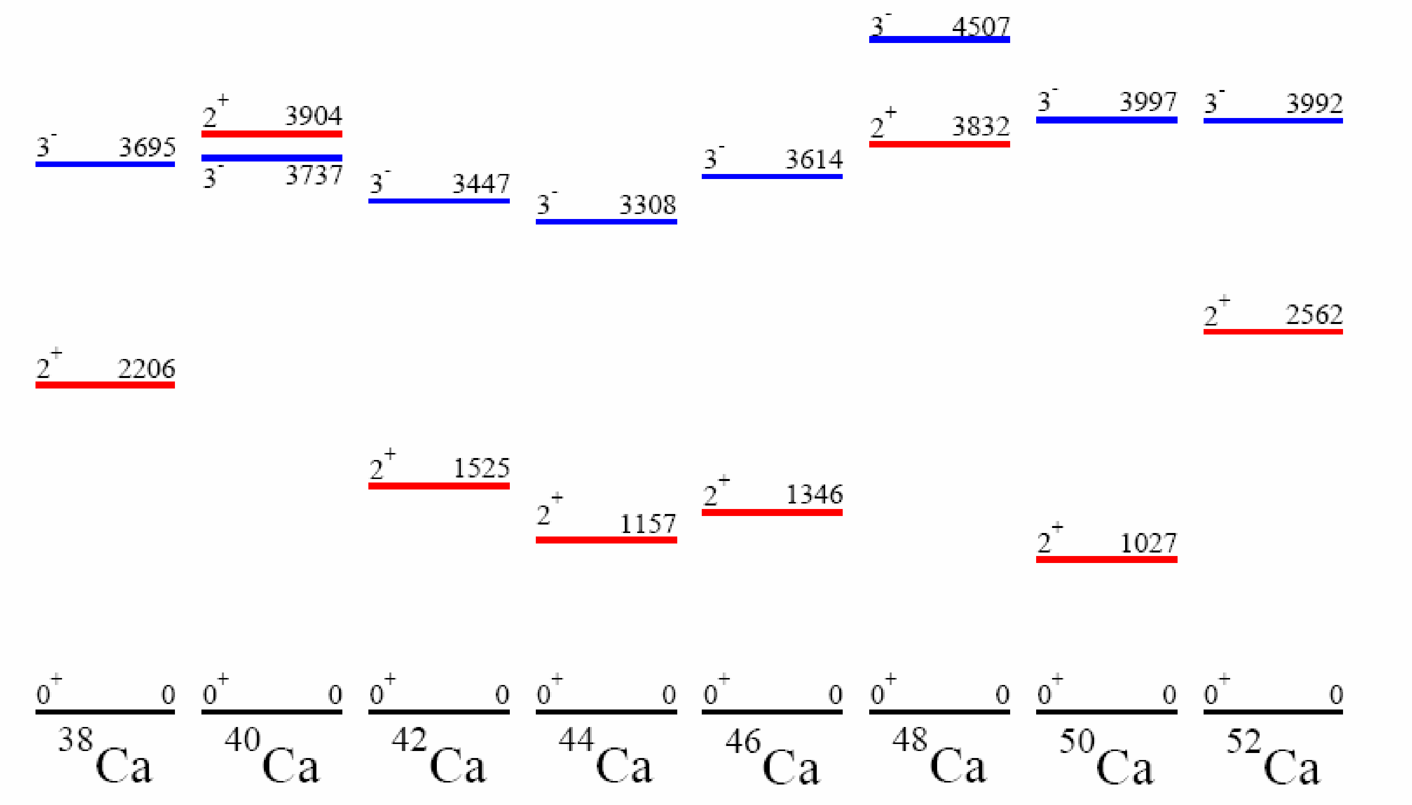
Cross section is small (~ 0.32 mb)
→ ^{52}Ca is magic



No direct feeding of 2⁺ state:
→ Consistent with a Neutron excitation

A. Gade *et al.*, PRC 74, 0211302(R) (2006)

2p knockout into ^{52}Ca

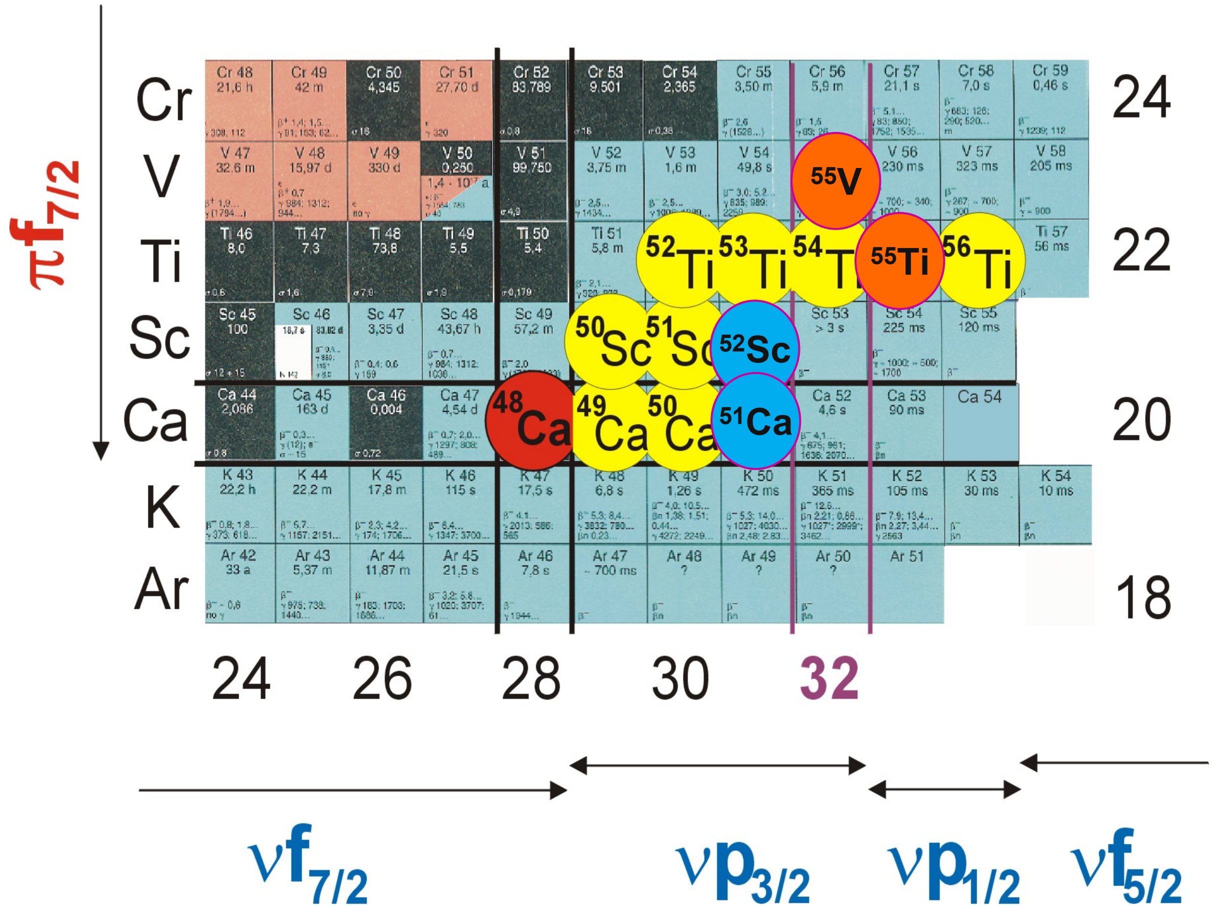


3^- is $\pi((d_{3/2}$ or $s_{1/2})^{-1}(f_{7/2}))$ excitation

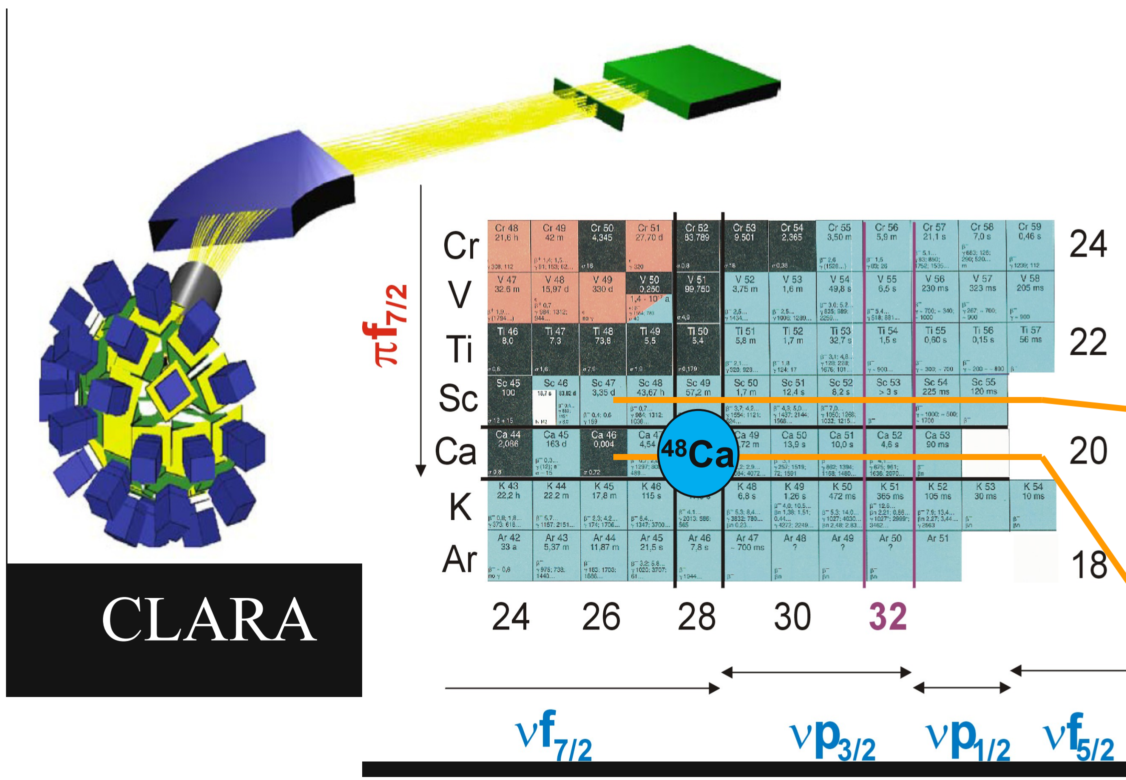
2p knockout provides a way to study p cross-shell excitations in n-rich nuclei

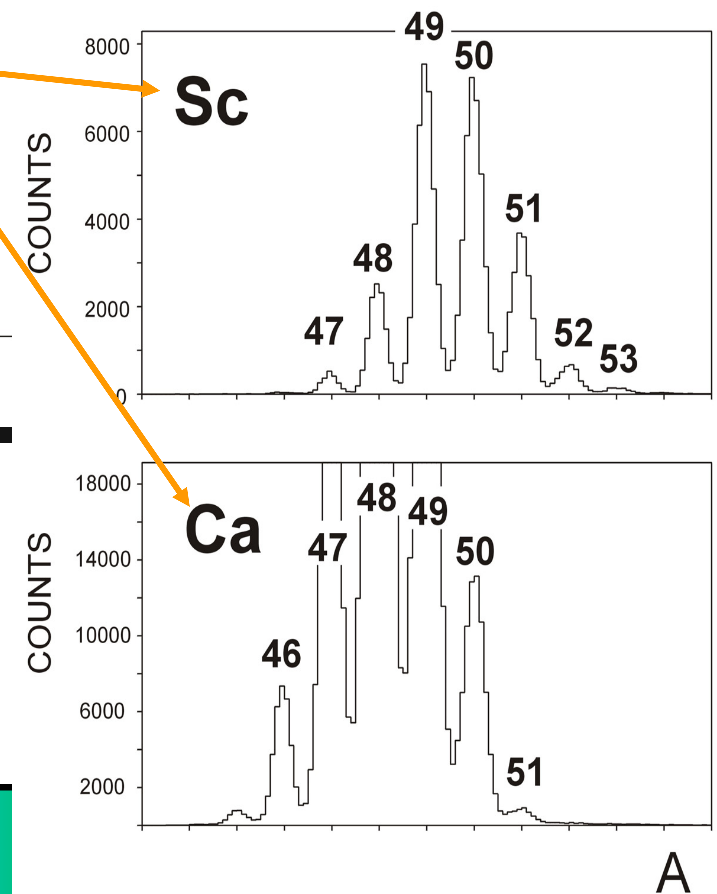
A. Gade *et al.*, PRC 74, 0211302(R) (2006)

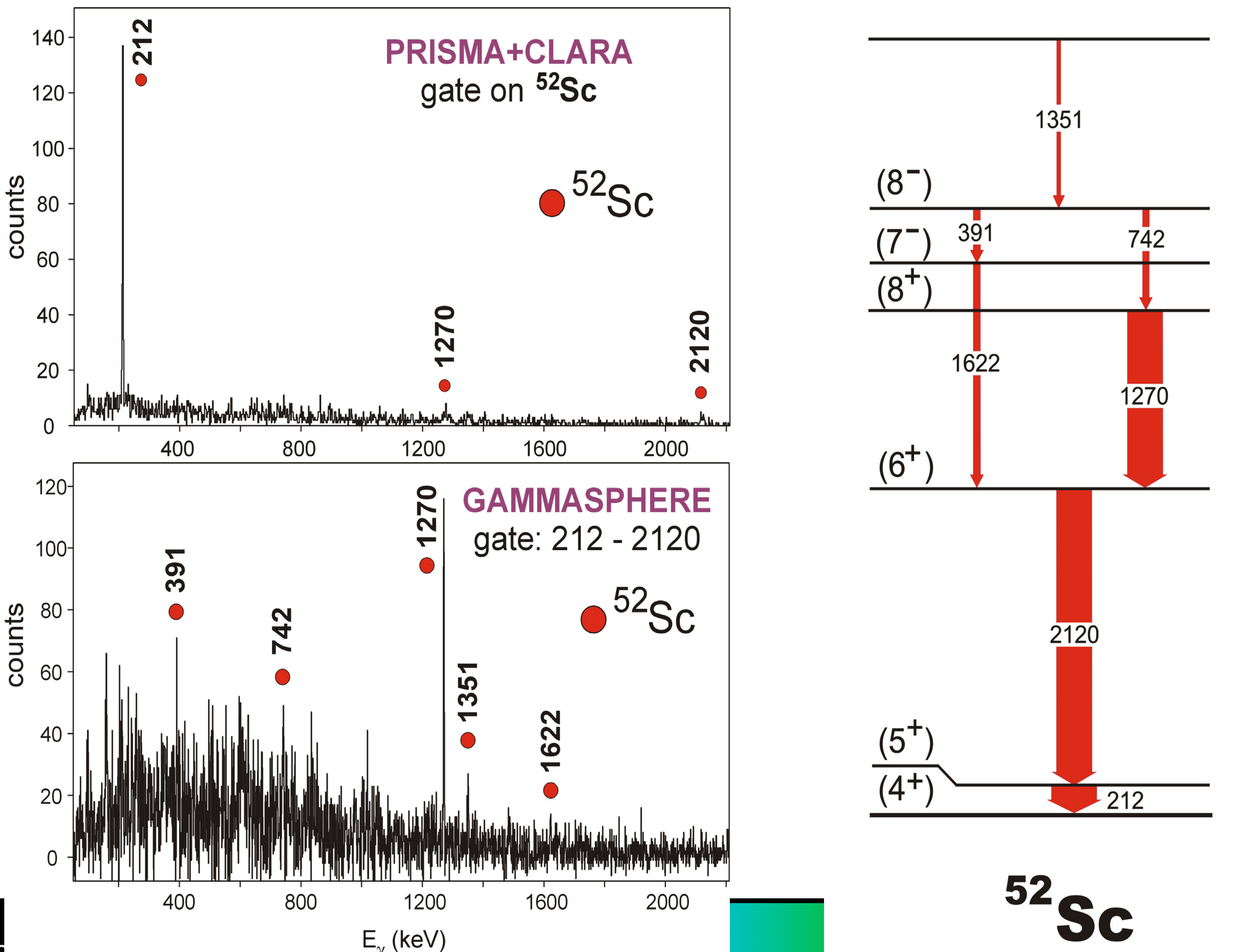
GXPF1A Further: the N=31 nuclei

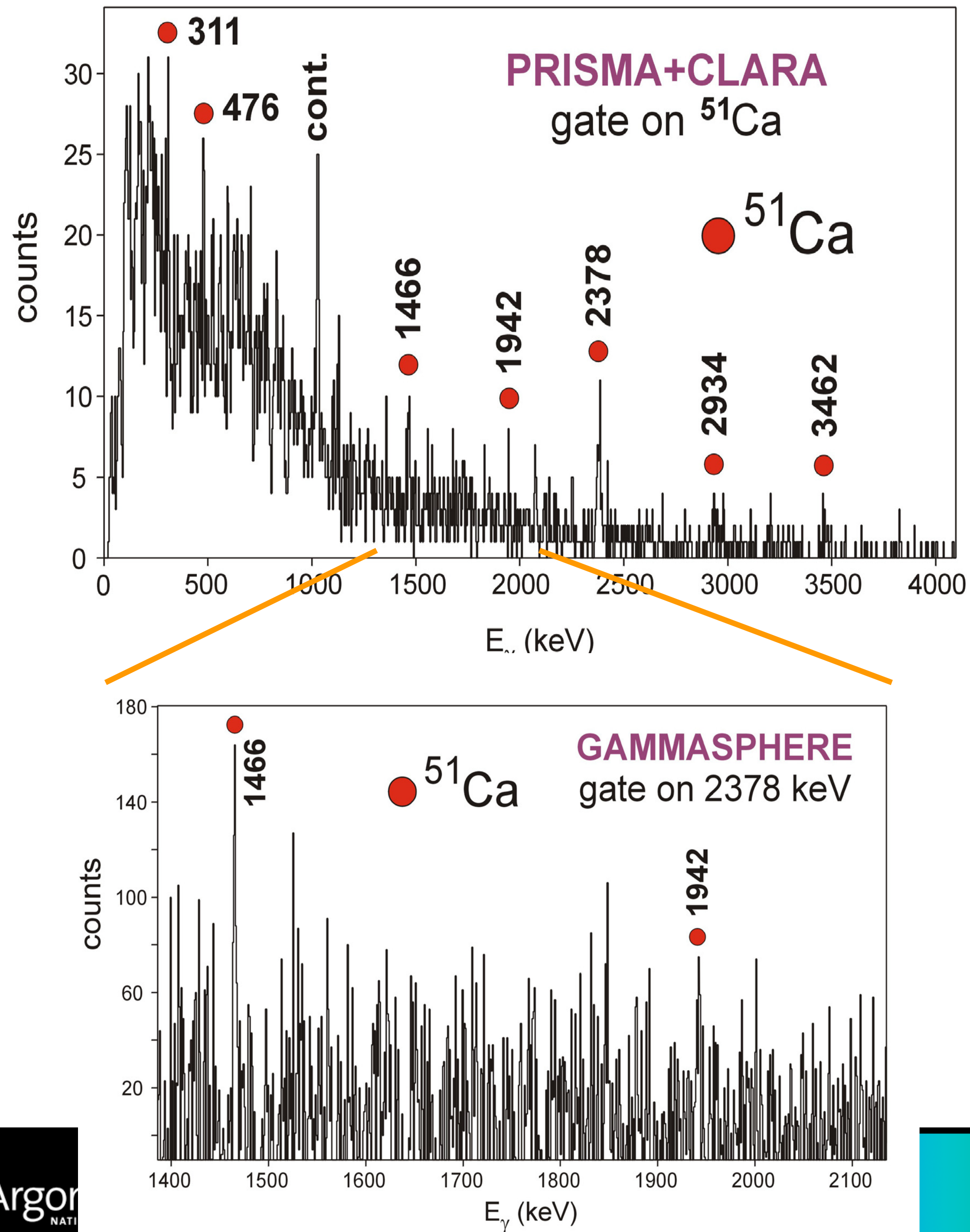


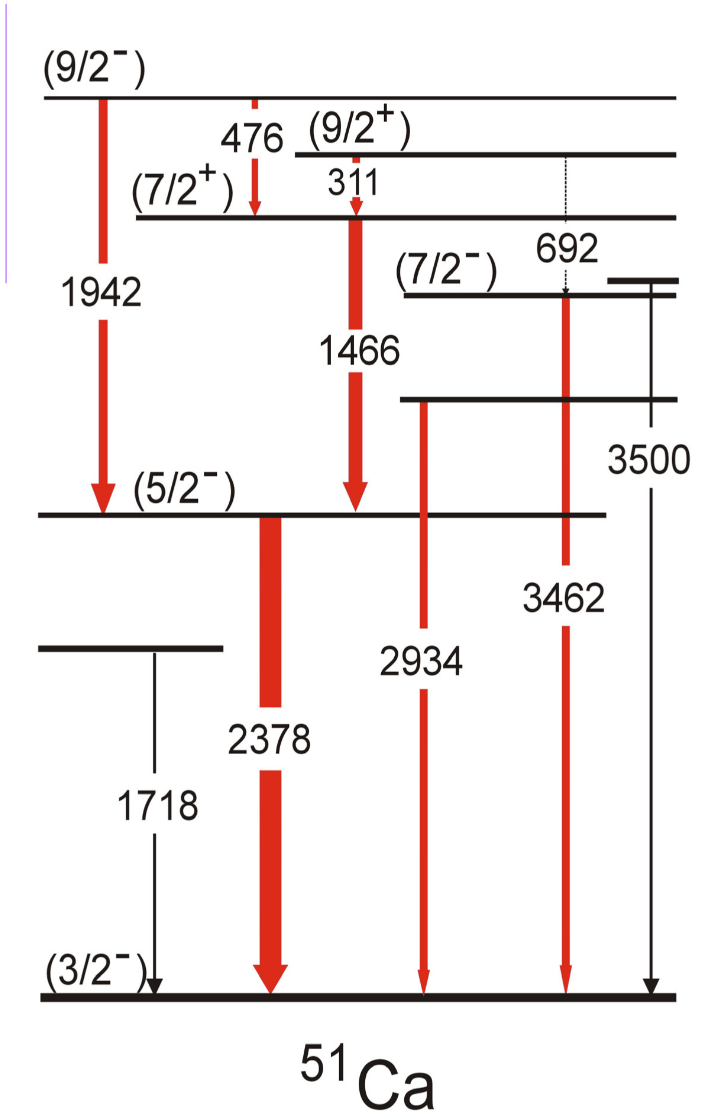
^{48}Ca (330 MeV) + ^{238}U at LNL Legnaro with PRISMA+CLARA

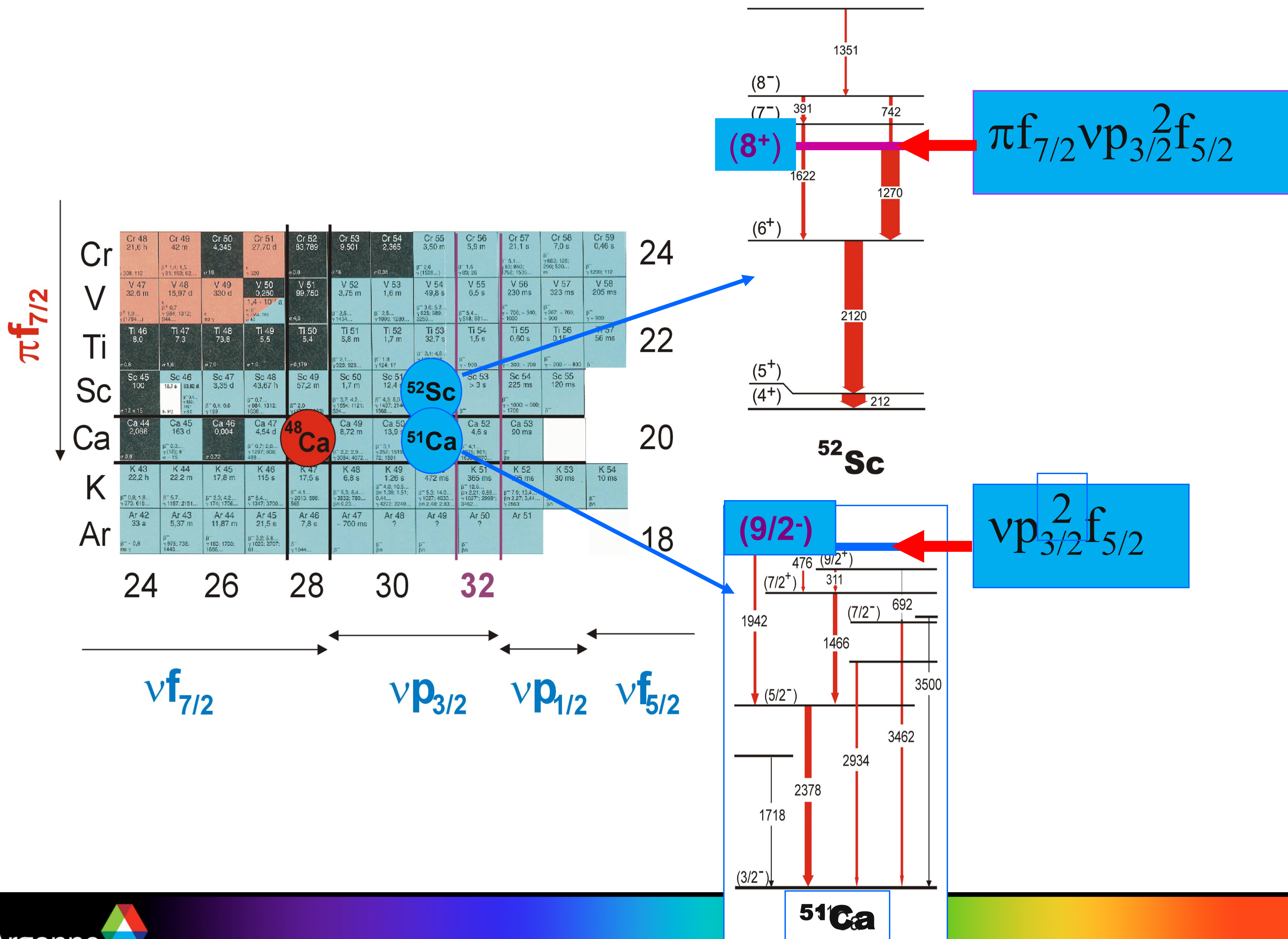




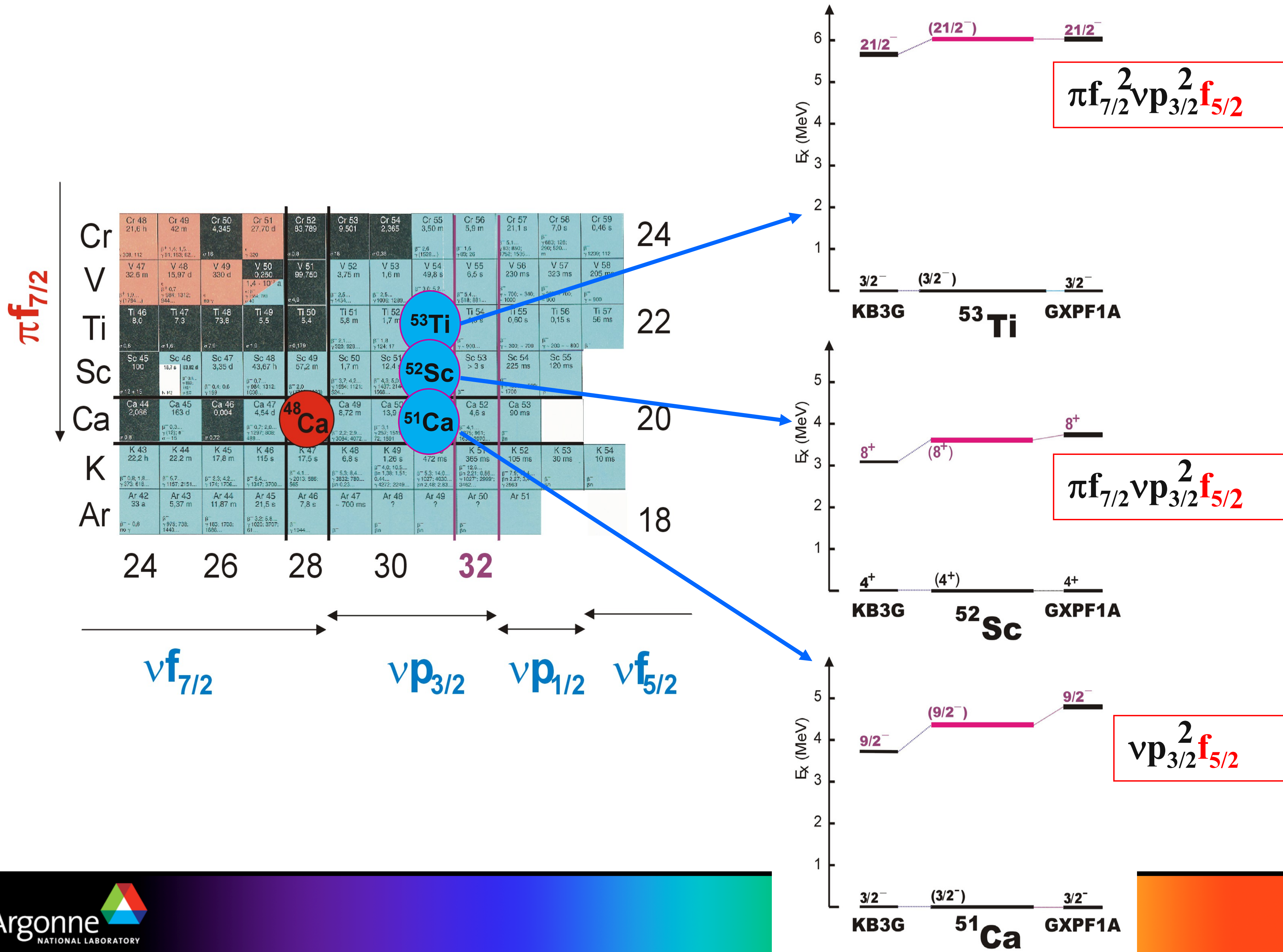

PRISMA+CLARA
gate on 52Sc
52Sc
212
1270
2120
counts
140
120
100
80
60
40
20
0
400
800
1200
1600
2000
GAMMASPHERE
gate: 212 - 2120
52Sc
391
742
1270
1351
1622
counts
Eγ (keV)
(8−)
(7−)
(8+)
(6+)
(5+)
(4+)
1351
391
742
1622
1270
2120
212
52Sc


PRISMA+CLARA
gate on 51Ca
51Ca
311
476
cont.
1466
1942
2378
2934
3462
counts
0
5
10
15
20
25
30
500
1000
1500
2000
2500
3000
3500
4000
Eγ (keV)
GAMMASPHERE
gate on 2378 keV
51Ca
1466
1942
counts
20
60
100
140
180
1400
1500
1600
1700
1800
1900
2000
2100
Eγ (keV)


(9/2⁻)
476
(9/2⁺)
(7/2⁺)
311
692
(7/2⁻)
1942
1466
3500
(5/2⁻)
3462
2934
2378
1718
(3/2⁻)
51Ca



Cr
V
Ti
Sc
Ca
K
Ar
24
22
20
18
24
26
28
30
32
$\pi f_{7/2}$
$\nu f_{7/2}$
$\nu p_{3/2}$
$\nu p_{1/2}$
$\nu f_{5/2}$
48Ca
52Sc
51Ca
1351
(8−)
(7−)
391
742
(8+)
1622
1270
(6+)
2120
(5+)
(4+)
212
$\pi f_{7/2} \nu p_{3/2}^2 f_{5/2}$
$\nu p_{3/2}^2 f_{5/2}$
(9/2-)
476
(9/2+)
(7/2+)
311
692
(7/2−)
1942
1466
3500
(5/2−)
3462
2934
2378
1718
(3/2−)



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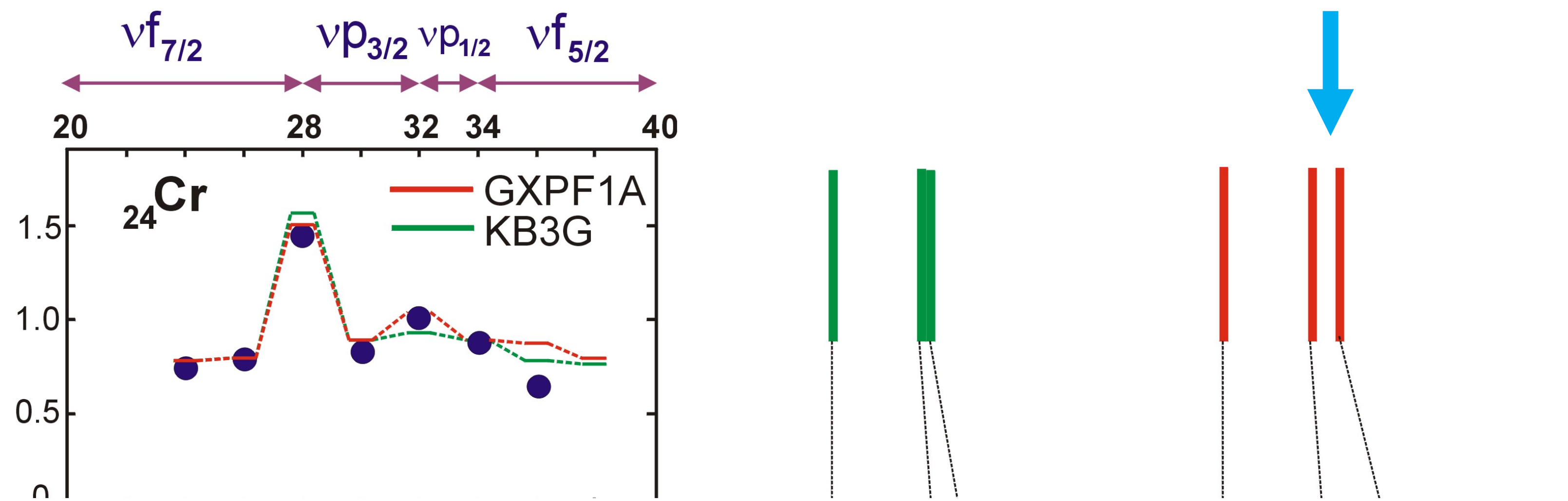
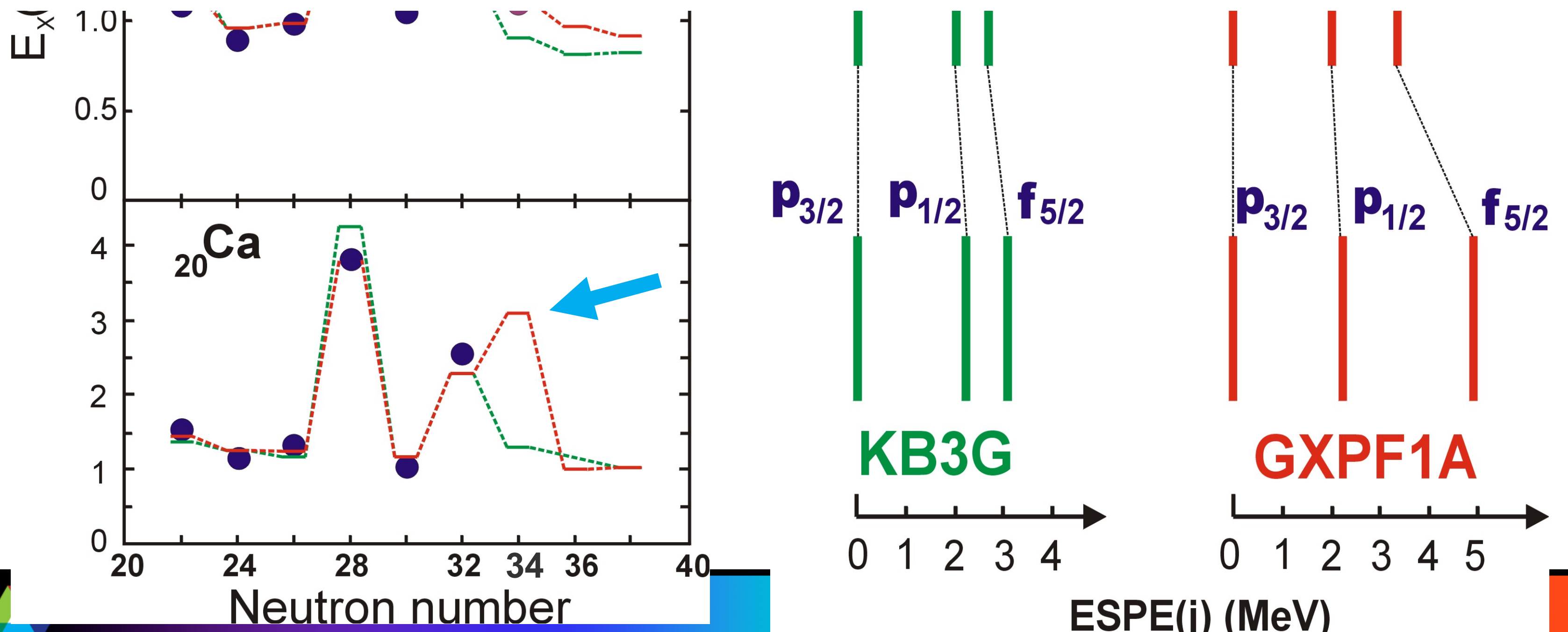


Thus far, I see no reason to doubt the prediction of high 2^+ energy at N=34 ^{54}Ca



Conclusions & Outlook

- Neutron-rich nuclei continue to surprise us!
  - progress is being made combining a large number of techniques
  - there is a N=32 shell gap just above ^{48}Ca
    - → in Ti (and Cr) confirmed by level structure and B(E2; ↑)
    - → in ^{52}Ca from 2p knockout
  - there is no N=34 shell gap in Ti and Cr
    but should not be ruled out in Ca
- Theory needs work
  - the GXPF1A interaction may or may not the complete answer for ^{54}Ca
  - the location of the $p_{1/2}$ and $f_{5/2}$ orbitals in n-rich nuclei above ^{48}Ca needs further study
  - the $g_{9/2}$ intruder needs to be included as N increases
  - we badly need an effective interaction for the protons

THANK YOU!!

S. Zhu,[1] R. V. F. Janssens,[1] B. Fornal,[2] S. J. Freeman,[3] M. Honma,[4] R. Broda,[2] M. P. Carpenter,[1] A. N. Deacon,[3] B. P. Kay,[3] F. G. Kondev,[5] W. Królas,[2] J. Kozemczak,[6] A. Larabee,[6] T. Lauritsen,[1] S. N. Liddick,[7,8] C. J. Lister,[1] P. F. Mantica,[7,8] T. Otsuka,[9,10] T. Pawłat,[2] A. Robinson,[1] D. Seweryniak,[1] J. F. Smith,[3,*] D. Steppenbeck,[3] B. E. Tomlin,[7,8] J. Wrzesiński,[2] and X. Wang[1,11]

1,5: ANL 2: Krakow 3: U. Manchester 4:U. Aizu 6: Greenville C. 7,8:NSCL
9,10: Tokyo & RIKEN 11: U. Notre Dame

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CARIBU: The CAlifornium Rare Isotope Breeder

Robert V. F. Janssens

U.S. Department of Energy

UChicago Argonne LLC

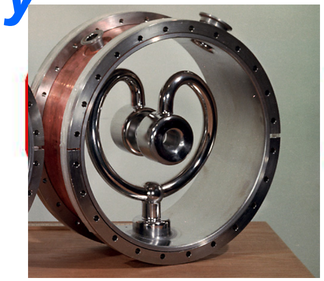
Office of Science U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

Joint JUSTIPEN – LACM Meeting

ORNL, March 5 -9, 2007

The ATLAS Facility Today

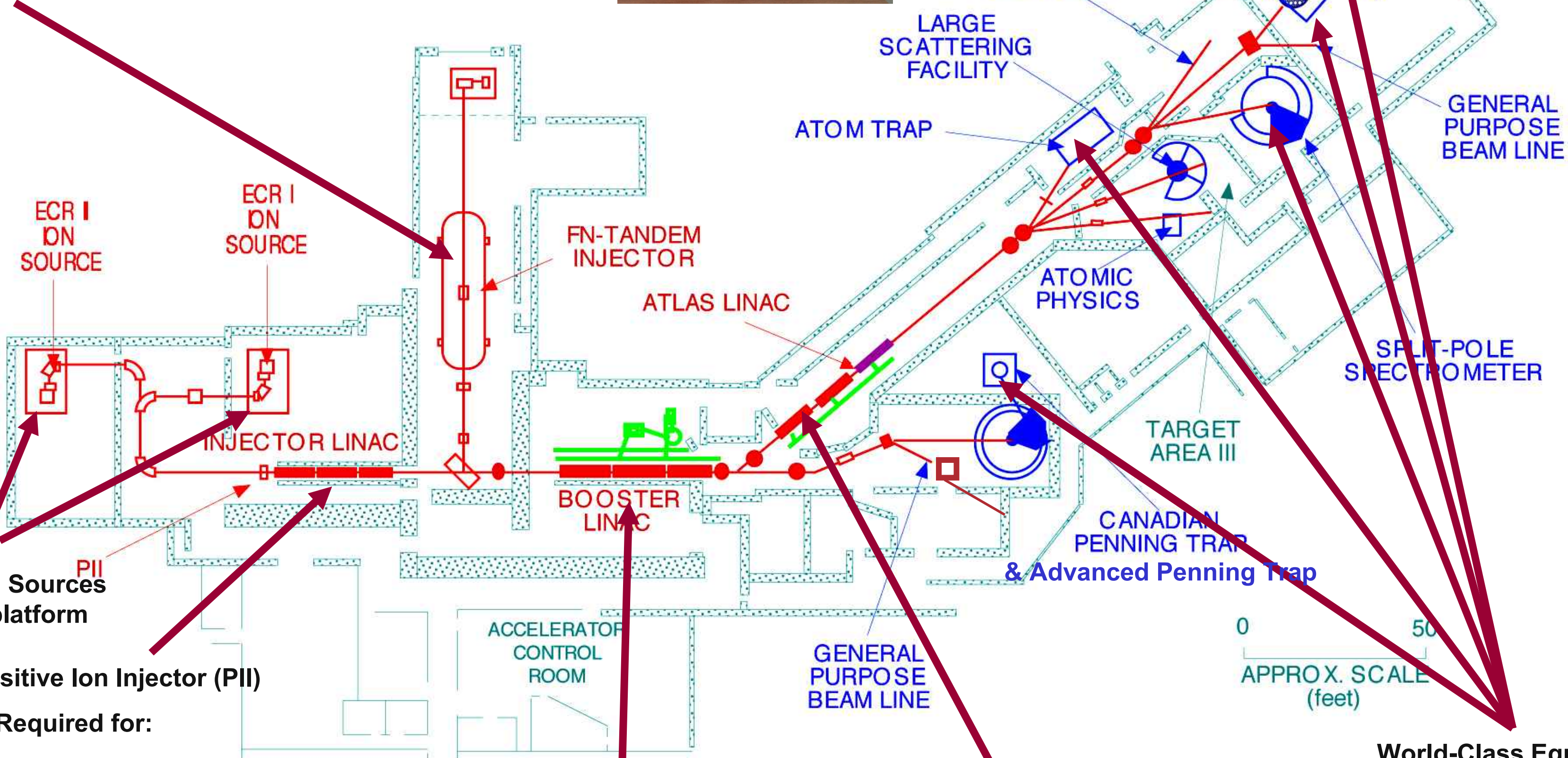


8.5-MV Tandem Injector

Important for:

Beams of A<58

Long-lived RIB's



2 ECR Ion Sources on HV platform

12-MV Positive Ion Injector (PII)

Required for:

Beams with A>58

Noble gases

High current

18 Quarter-wave SC resonators

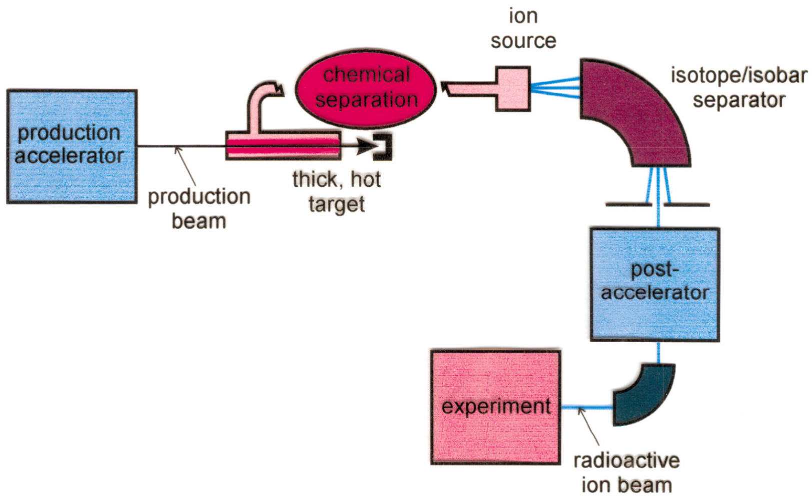
24-Resonator Booster

19-Resonator ATLAS

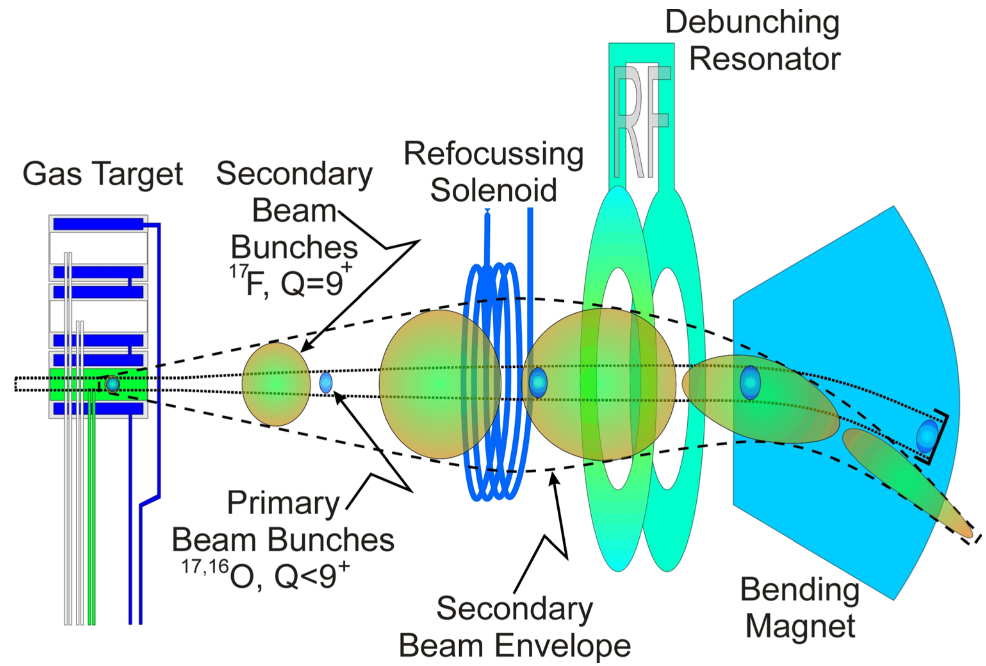
World-Class Equipment

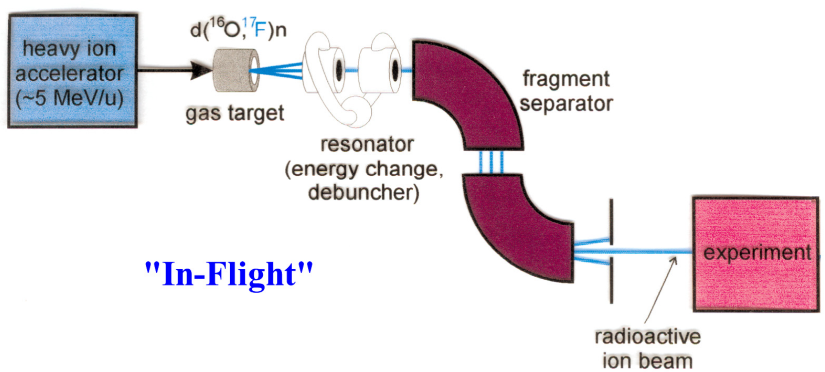
ATLAS: Exotic Beam Production – Techniques Today

" ISOL "
"Two-Accelerator"



Most recent beam: ^{44}Ti, ^{56}Ni





"In-Flight"

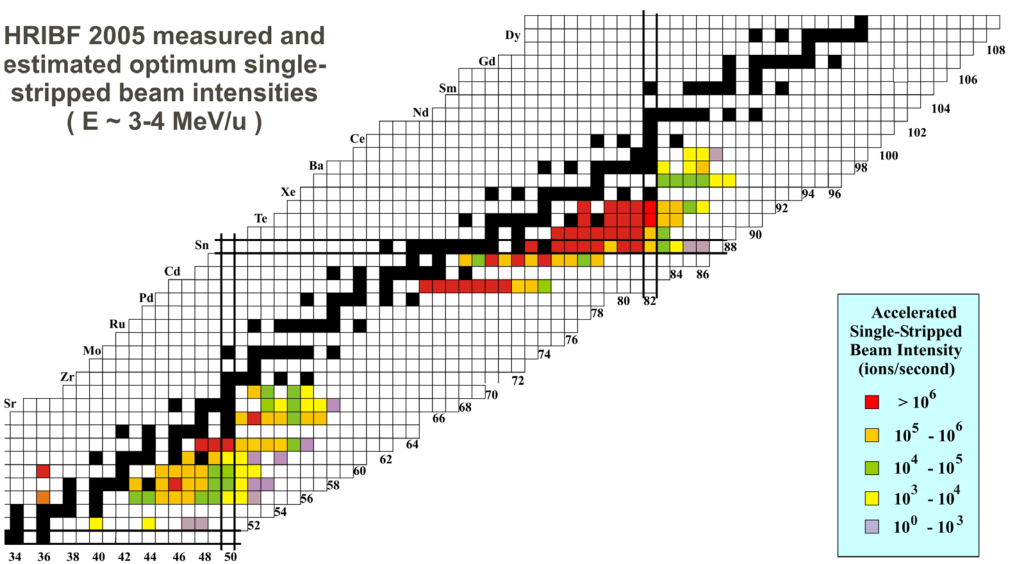
Most recent beams:
^{6}He, ^{8}Li, ^{12}B, ^{15}O, ^{16}N, ^{19}Ne

19 different exotic beams thus far

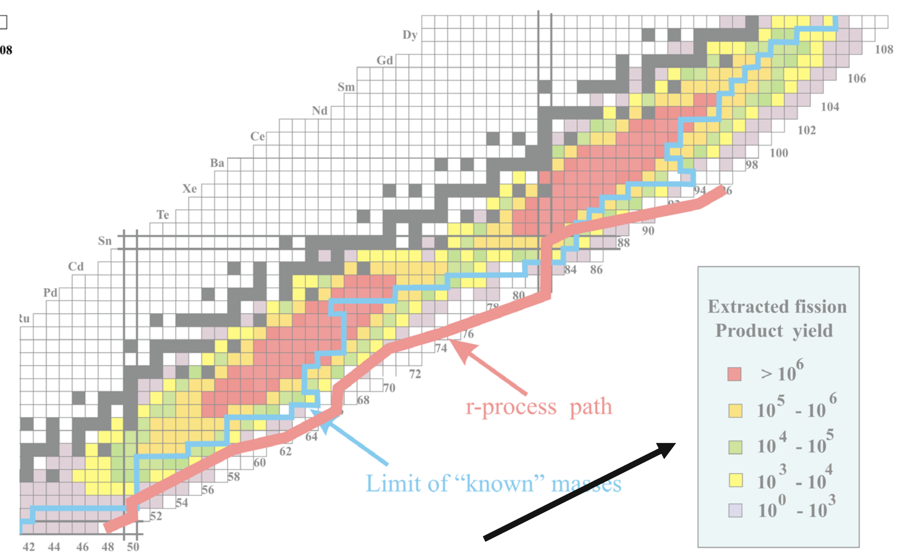
CARIBU - CAlifornium Rare Ion Breeder Upgrade

- ^{252}Cf fission yield is complementary to uranium fission
- Provides access to unique, important areas of the N/Z plane
- Significant yield extends into r-process region
- Available energy exceeds that from HRIBF and ISAC

HRIBF yields from ^{238}U



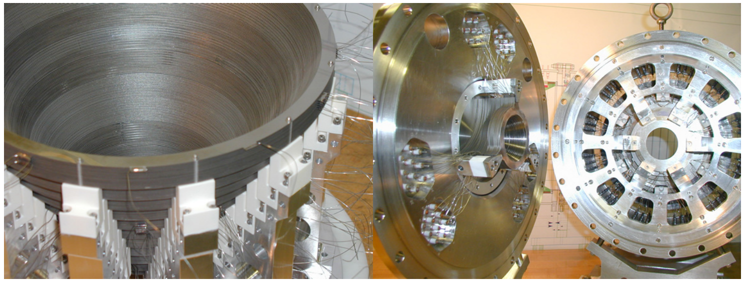
^{252}Cf spontaneous fission yield



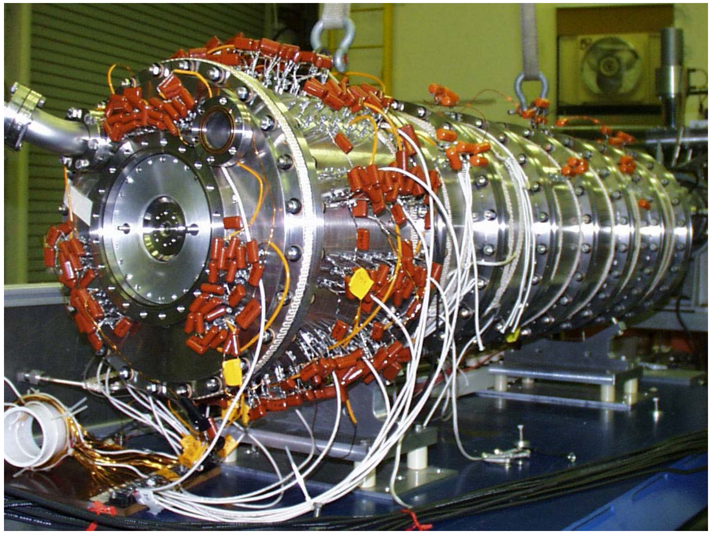
Accelerated yields are ~5% of these numbers

CARIBU - New opportunity: ^{252}Cf source (1Ci) + large gas catcher as neutron-rich isotope source

- Shortened version of RIA gas catcher can efficiently stop fission products from a fission source
  - ~ 50% stopped in gas for backed source
  - required capabilities of catcher have been demonstrated (G. Savard et al.)
- About 45% of those can be extracted as charged ions
- Very efficient and fast source, provides cooled bunched beams for post-acceleration
- Production peaks in new regions and extraction is element independent … new isotopes available

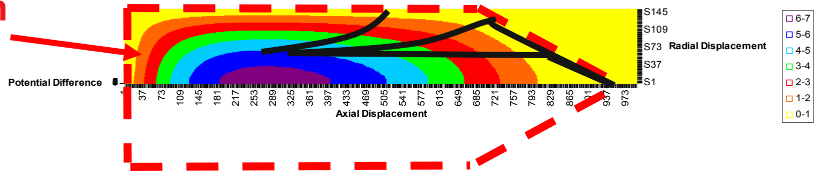


Gas catcher technology developed, tested and now routinely used at ATLAS for CPT and RIA programs



Progress in gas catcher development: dealing with high space charge density & working at high energy

Potential from space charge

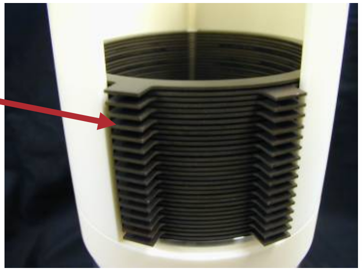


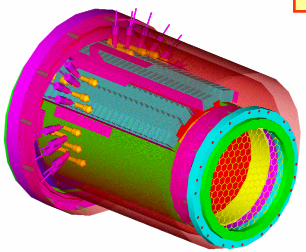
ANL Gas catcher test at GSI

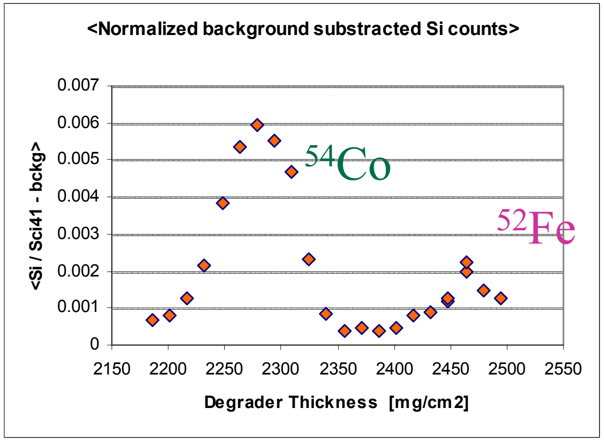
~ 50 % of radioactive ions stopped in the gas catcher were extracted as a radioactive ion beam in <50 msec!

Ions are lost radially, can be corrected by:

- Larger DC field
- RF focusing on gas catcher body, not just cone
- Improved gas purity







This approach can handle the space charge from:

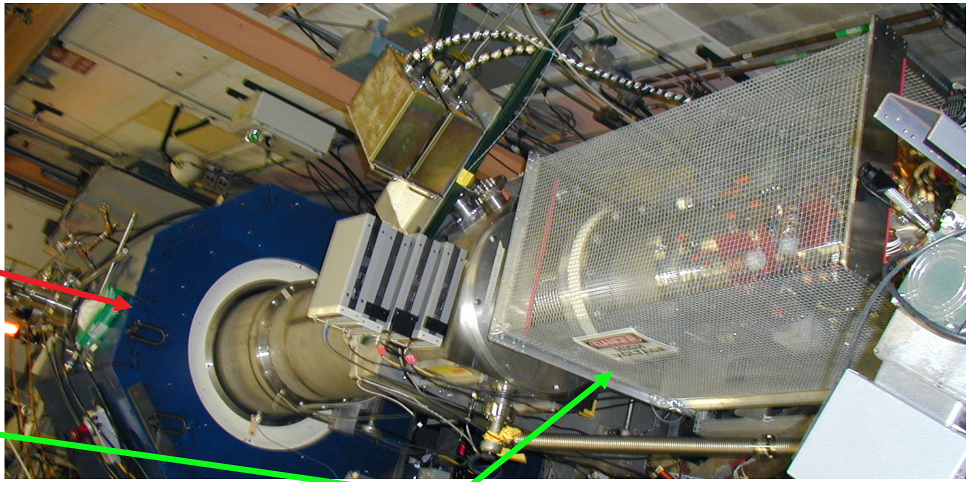
- the 50 millions Cs ions incident in the ~ 600 cm^3 volume of the CPT catcher
- the similar conditions from the roughly 10^9 fragments entering the ~ 30000 cm^3 volume of the gas catcher in the RIA and CARIBU applications.

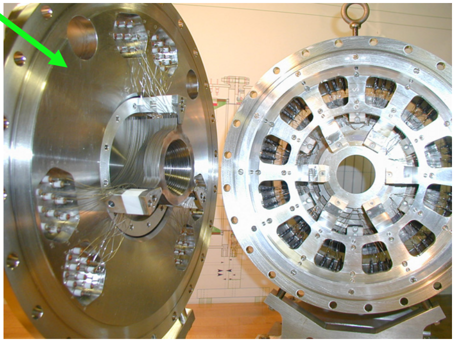
No saturation up to the maximum radioactive beam intensity that the FRS could deliver!

(~ 10^6 ions in the cell per spill)

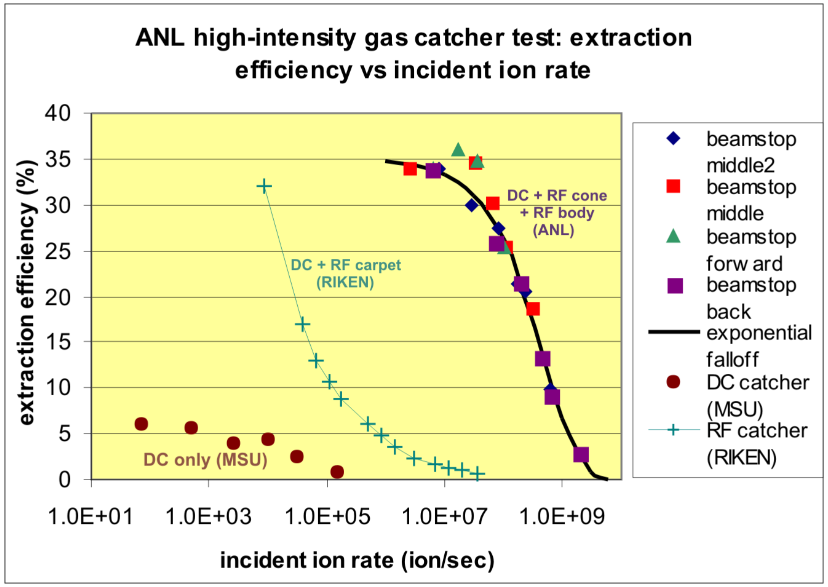
Gas catcher operation at RIA/AEBL/CARIBU intensity

- **High intensity beam line built at ANL to reproduce ion distribution expected behind RIA/AEBL fragment separator**
  - **Focusing by 68 cm bore superconducting solenoid**
- **Large gas catcher using large RF cone developed for high energy test at GSI, combined to full body RF focusing**
  - **Over 8000 components prepared to UHV standards**





- **First tests at high intensity beamline in Sept and Oct 06**
  - **High efficiency obtained at up to 10^9 incoming particles per second**



CARIBU - Examples of Yields for Representative Species

Calculated maximum beam intensities for a 1 Ci ^{252}Cf fission source using expected efficiencies.

Isotope	Half-life (s)	Low-Energy Beam Yield (s^{-1})	Accelerated Beam Yield (s^{-1})
^{104}Zr	1.2	6.0×10^5	2.1×10^4
^{143}Ba	14.3	1.2×10^7	4.3×10^5
^{145}Ba	4.0	5.5×10^6	2.0×10^5
^{130}Sn	222.	9.8×10^5	3.6×10^4
^{132}Sn	40.	3.7×10^5	1.4×10^4
^{110}Mo	2.8	6.2×10^4	2.3×10^3
^{111}Mo	0.5	3.3×10^3	1.2×10^2

- **Over 200 isotopes available with accelerated beam intensity > 10^4 ions/second.**
- **Approximately 170 isotopes with accelerated beam intensity of 10^2 to 10^4.**

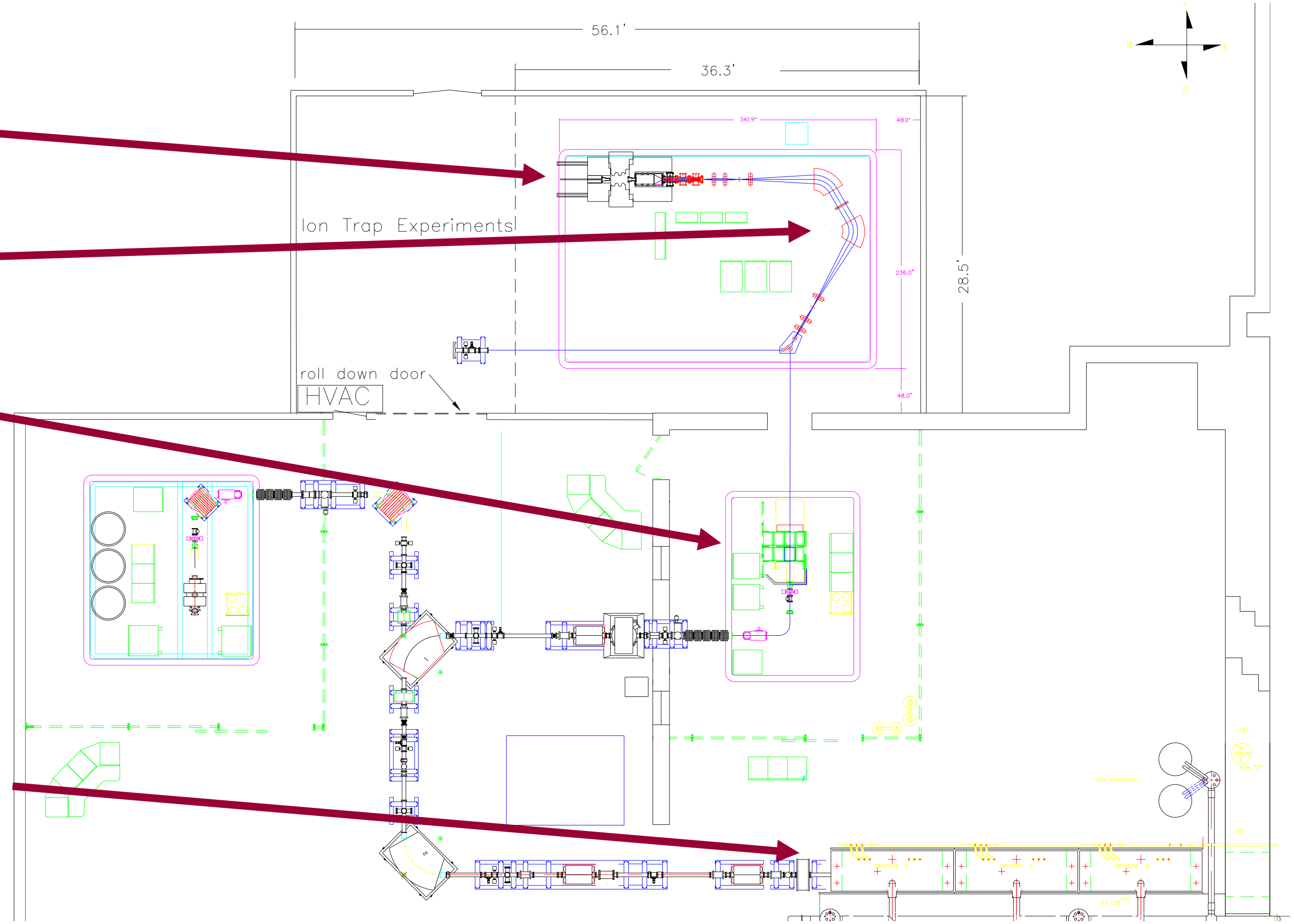
CARIBU: Integrating Concepts & Gaining Experience for AEBL

Gas Catcher

High Resolution Isotope Separator

Charge Breeding in ECR Source

Post-acceleration of weak beams



CARIBU Costs: $ 4.75 M

CARIBU Completion: first quarter FY09

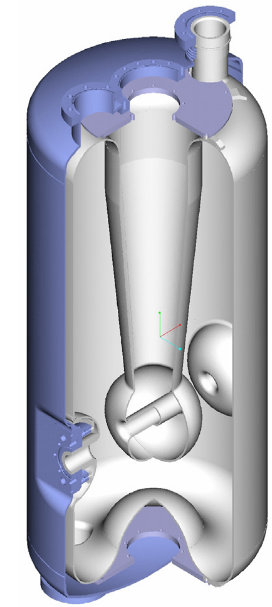
ATLAS Energy Upgrade

ATLAS Energy Upgrade will replace the last ATLAS cryostat with:

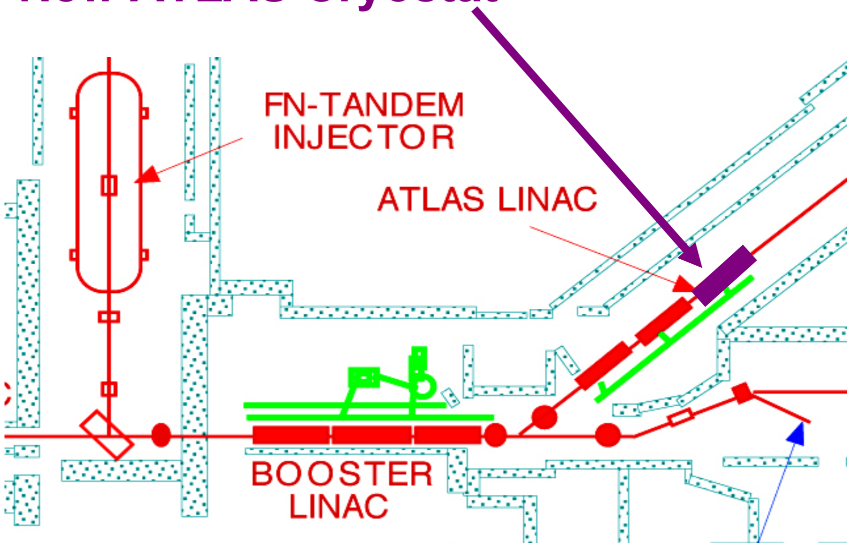
New cryostat containing a new class of resonators

- **7 ß=0.14 quarter-wave resonators**
- **ß=0.26 half-wave resonator**

109 MHz
QWR Cavity
$ß_s$ = 0.144
Length = 25cm



New ATLAS Cryostat

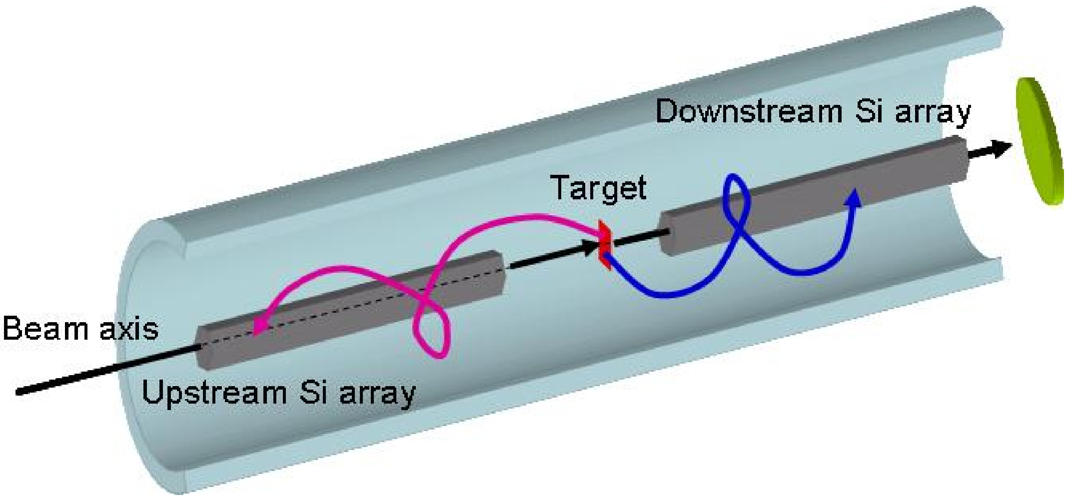


	Current ATLAS		ATLAS Upgrade	
A	No Strip	Strip	No Strip	Strip
16	13.0	15.7	18.5	21.5
40	12.4	13.4	17.5	19.9
58	9.9	11.8	13.5	17.9
78	9.5	11.2	12.8	16.7
132	8.0	9.3	10.4	13.4
197	6.6	7.9	8.4	10.9
238	6.4	7.4	7.9	10.0

Fully funded AIP project, installation in 2007.

HELIOS (Helical Orbit Spectrometer)

- 4π solid angle
- Particle I.D. from TOF
- Simple detector and electronics - few channels
- Excellent center-of-mass energy and angle resolution
- Suppression of backgrounds



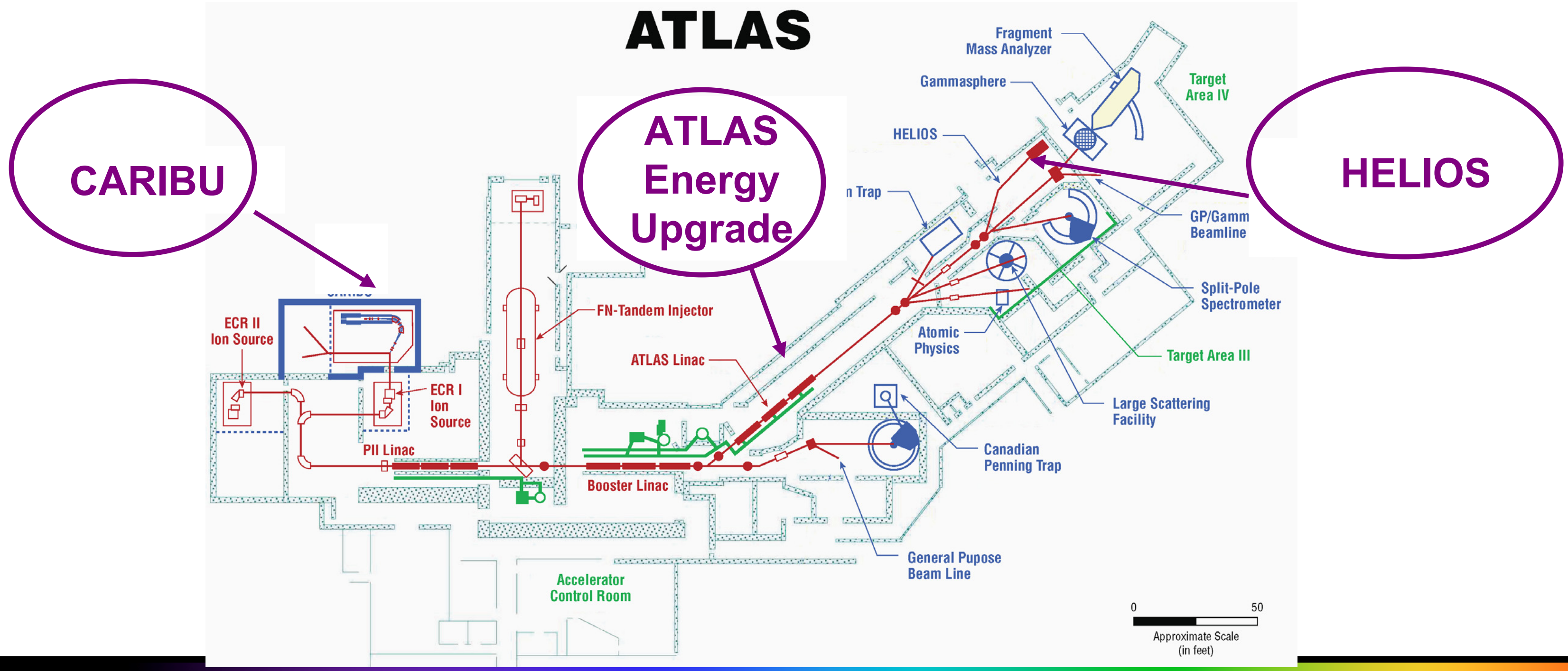
Ideal tool for reactions in inverse kinematics

Radioactive Ion Beams

Plan to build in FY07-FY08, magnet in house

CARIBU & Energy Upgrade & HELIOS: Unique Synergy

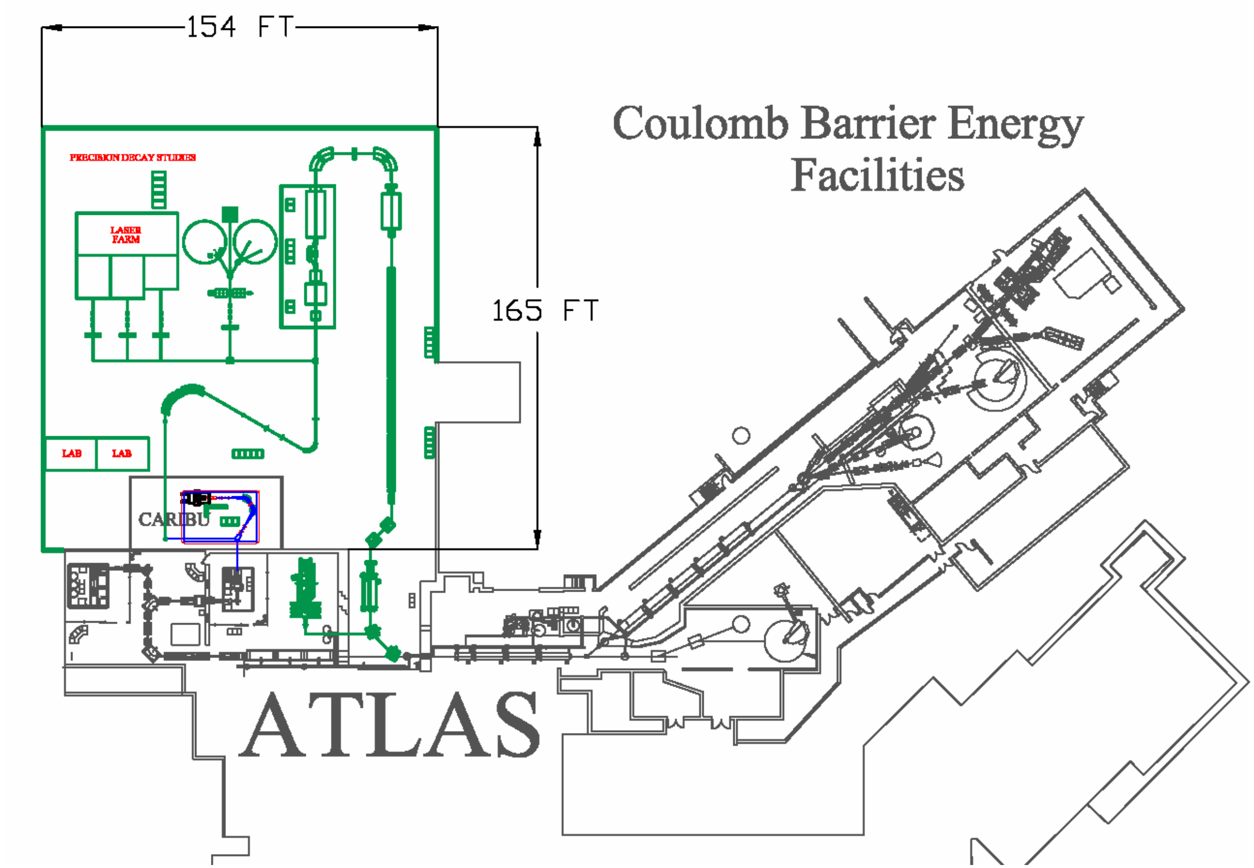
- CARIBU gives access to exotic beams not available elsewhere.
- Physics with beams from CARIBU needs the new energy regime opened by the Energy Upgrade (12 MeV/u).
- HELIOS will greatly expand the effectiveness of both the fission fragment beams and the existing in-flight RIB program at these higher energies.
- These three projects will combine to form a truly unique facility which complements the capabilities of other world facilities in the era leading to AEBL.
- The three projects are funded.



Future Plans

Beyond CARIBU: SUPER – CARIBU

- Increase available beam intensities by a factor of ~10 by:
  - doubling the ^{252}Cf source strength to 2 Ci
  - building a 1^+ injector for ATLAS (this is the AEBL post-accelerator injector)
  - considering ^{254}Cf as an alternative for operation a fraction of the time
  - providing space for a significant stopped-beam program



SuperCARIBU - Concept

SuperCARIBU is a significant upgrade of the capabilities of the ATLAS facility with CARIBU by:

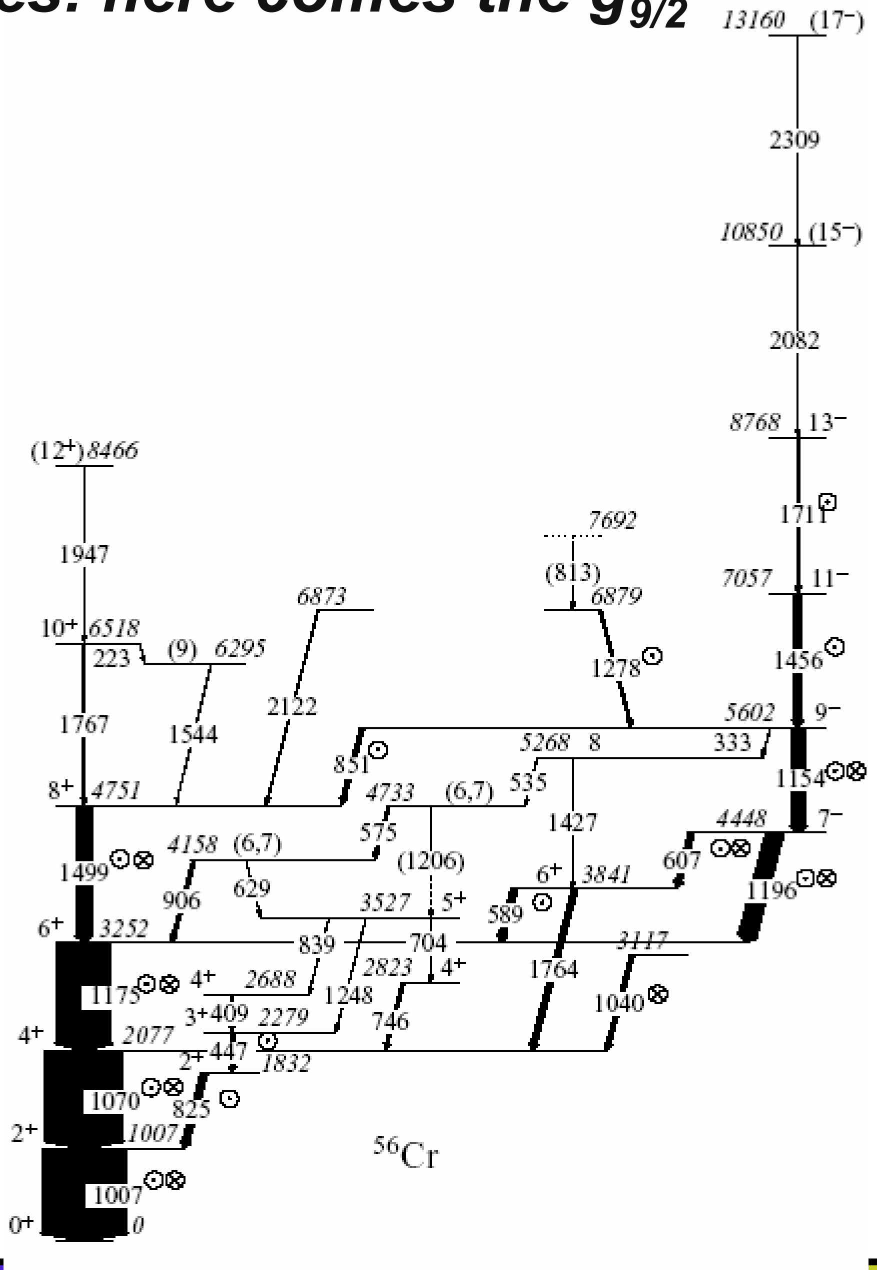
- Using low-Q acceleration and stripping to gain factors of 5 in efficiency,
- Providing increased experimental space for stopped beam and astrophysics beam experiments,
- Increasing the source fission rates, for example by using Cf-254 as the source material.

Isotope	Half-life (s)	Low-Energy Beam Yield (s-1)	CARIBU Accelerated Beam Yield (s-1)	SuperCARIBU Accelerated Beam Yield (s-1)
^{104}Zr	1.2	$6.0x10^5$	$2.1x10^4$	$1.6x10^5$
^{143}Ba	14.3	$1.2x10^7$	$4.3x10^5$	$3.2x10^6$
^{145}Ba	4.0	$5.5x10^6$	$2.0x10^5$	$1.5x10^6$
^{130}Sn	222.	$9.8x10^5$	$3.6x10^4$	$2.7x10^5$
^{132}Sn	40.	$3.7x10^5$	$1.4x10^4$	$1.1x10^5$
^{110}Mo	2.8	$6.2x10^4$	$2.3x10^3$	$1.7x10^4$
^{111}Mo	0.5	$3.3x10^3$	$1.2x10^2$	$9.0x10^2$

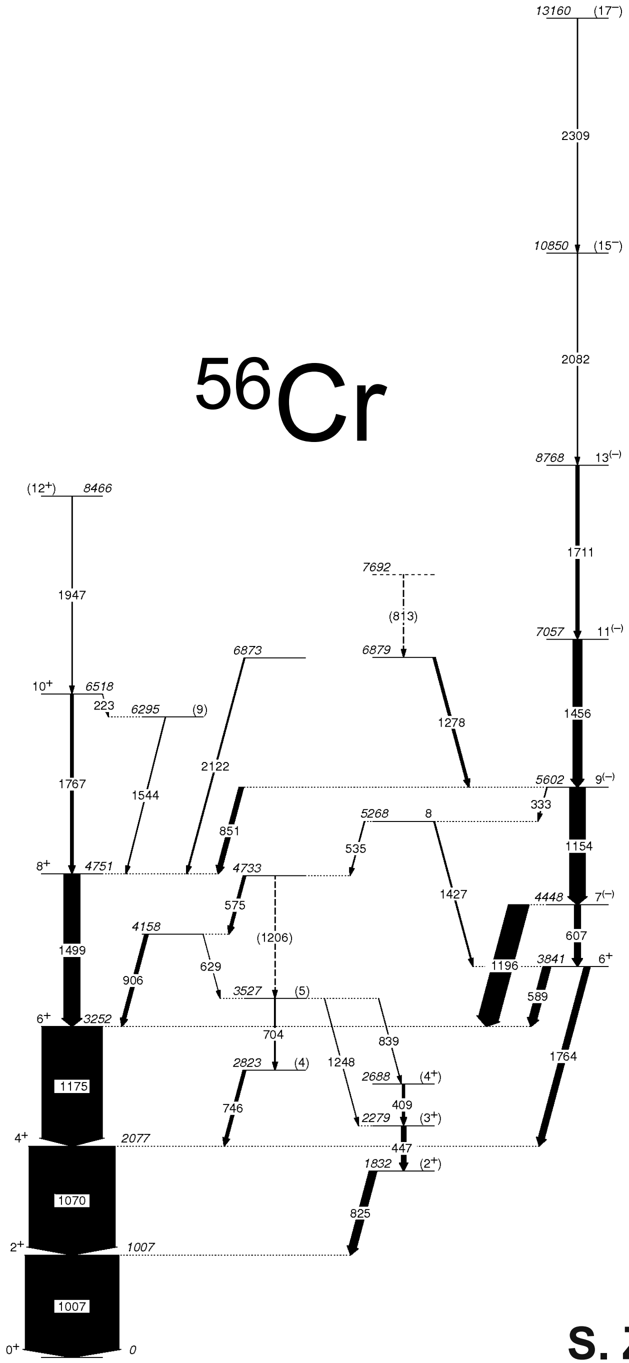
The Cr n-rich isotopes: here comes the $g_{9/2}$

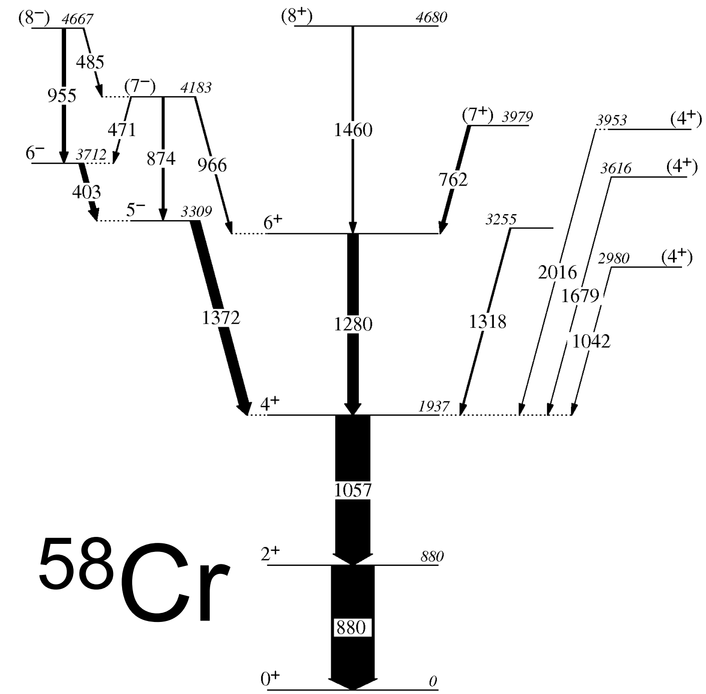
M=56, Z=24

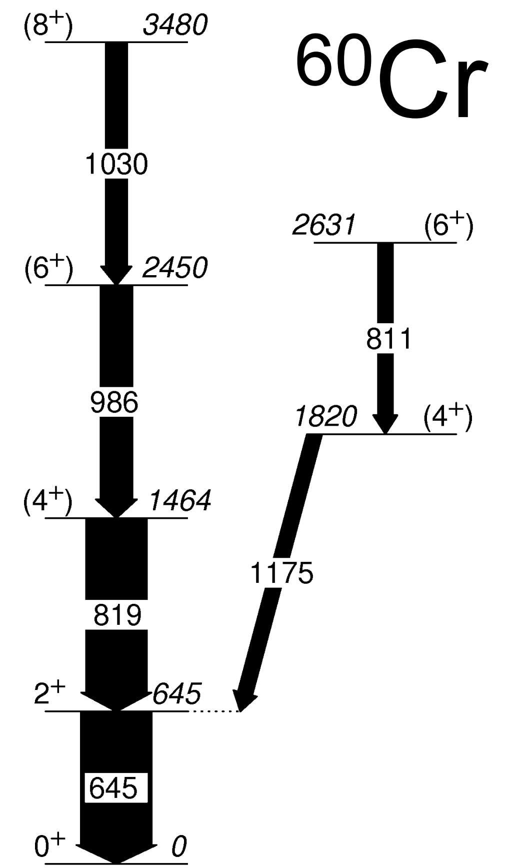
$^{14}C(^{48}Ca,\alpha 2n)^{56}Cr$



S. Zhu *et al.*, PRC 74, 064351 (2006)



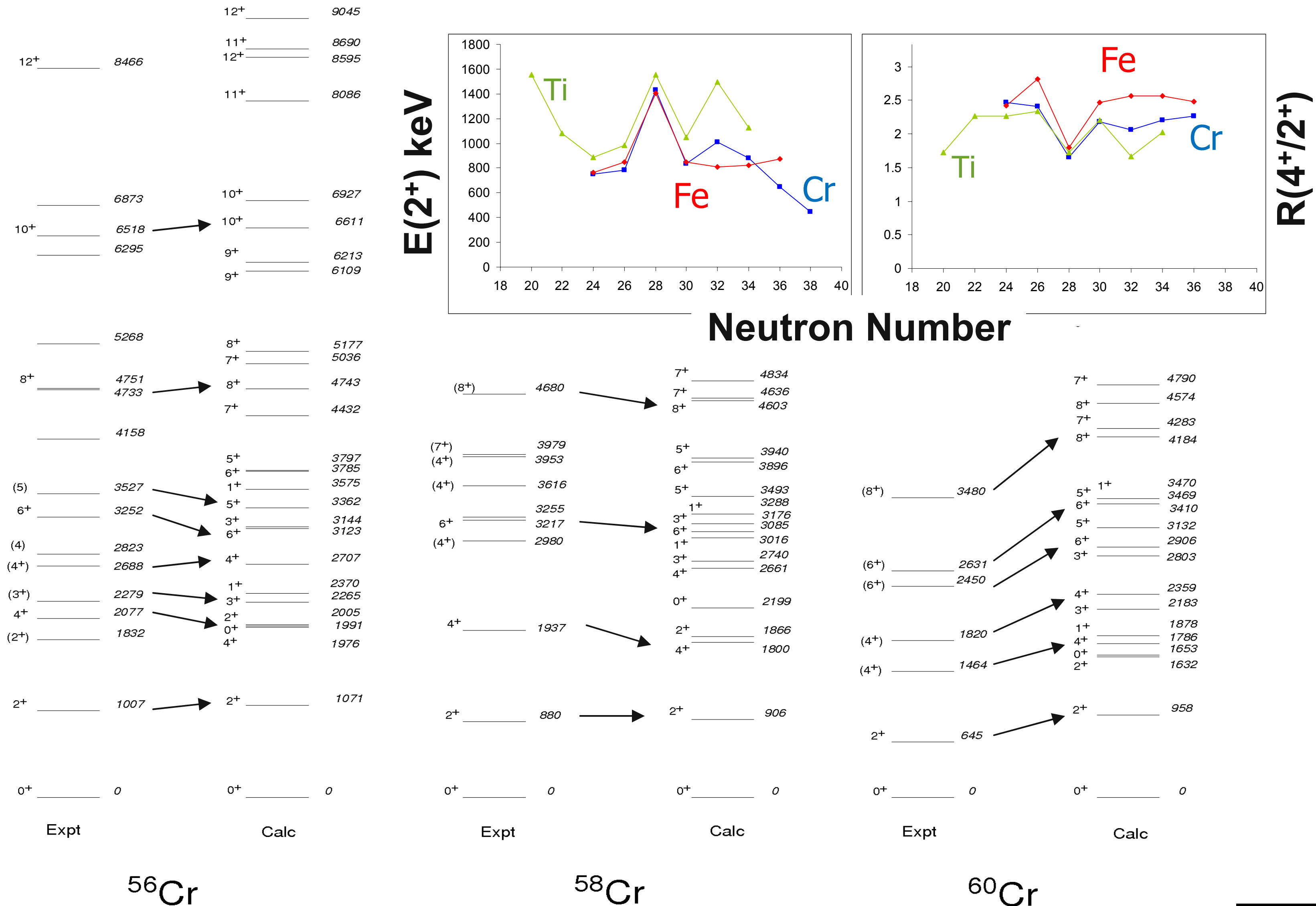




Even Cr isotopes

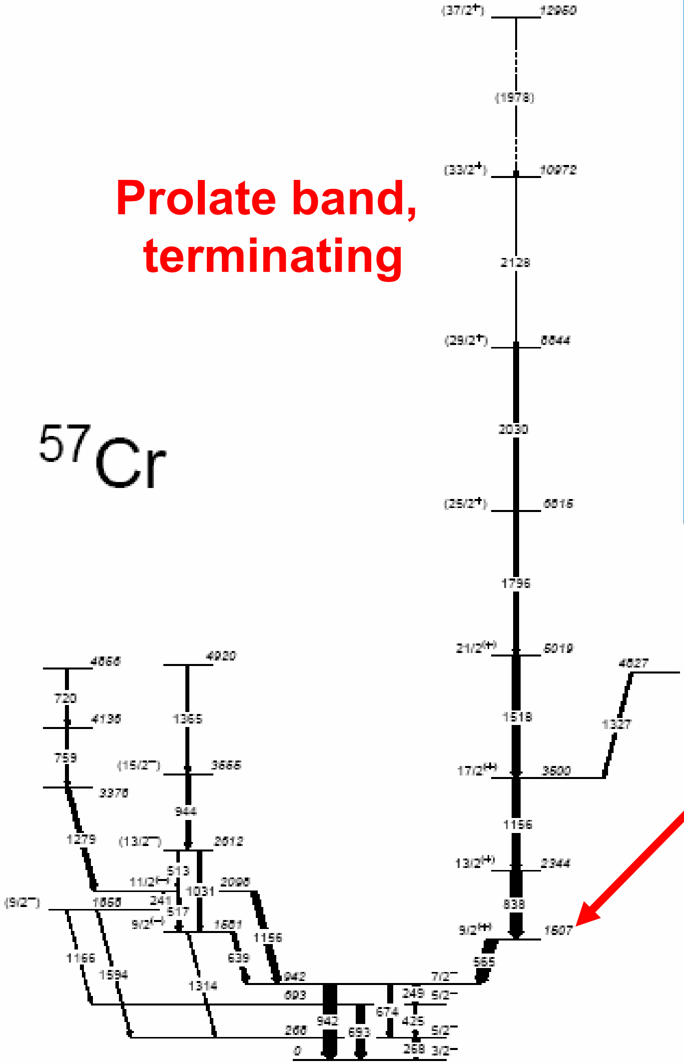
S. Zhu *et al.*, PRC 74, 064351 (2006)

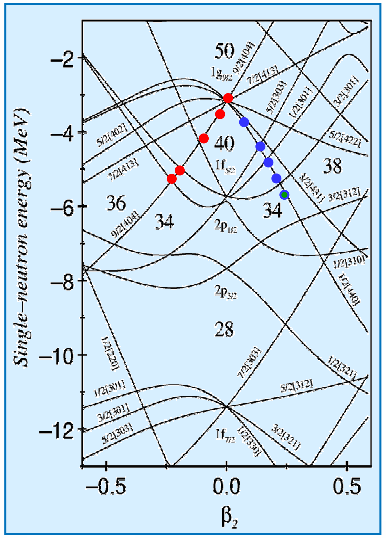
GXFP1A Shell Model Calculations



S. Zhu *et al.*, PRC 74, 064351 (2006)

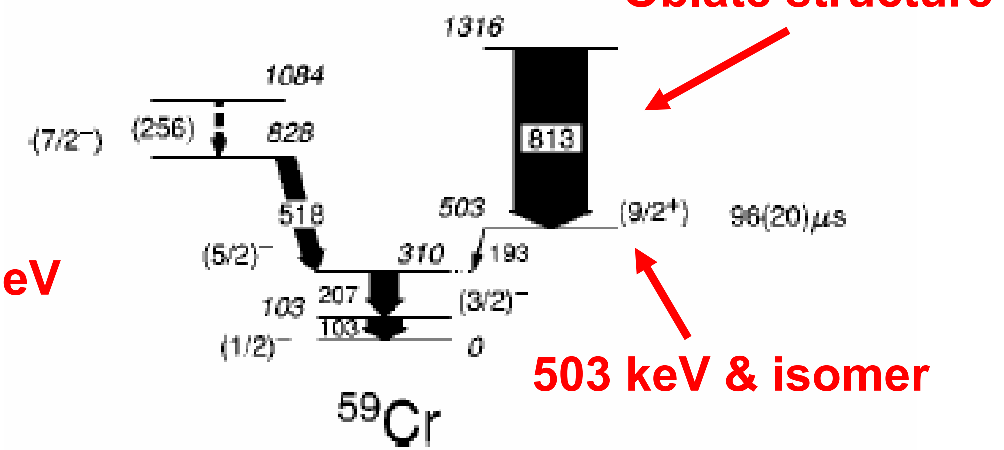
^{57,59}Cr: *Shape Driving by the $g_{9/2}$ orbital*





Freeman *et al.*
PR C 69, 064301 (2004)

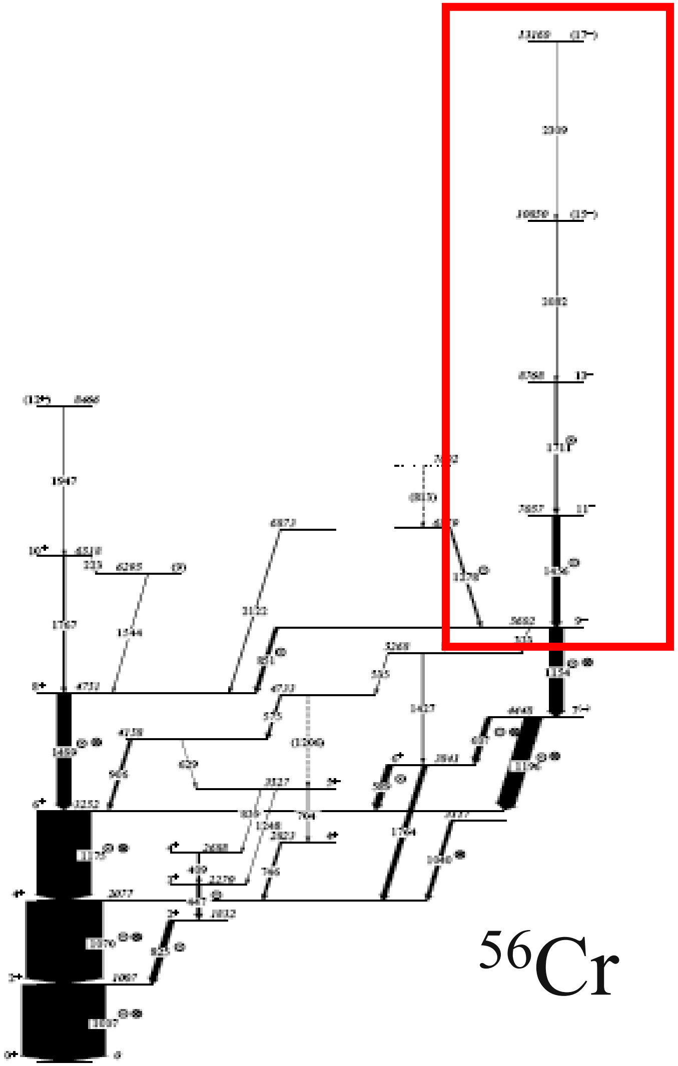
Deacon *et al.*
PLB 622, 151(2005)

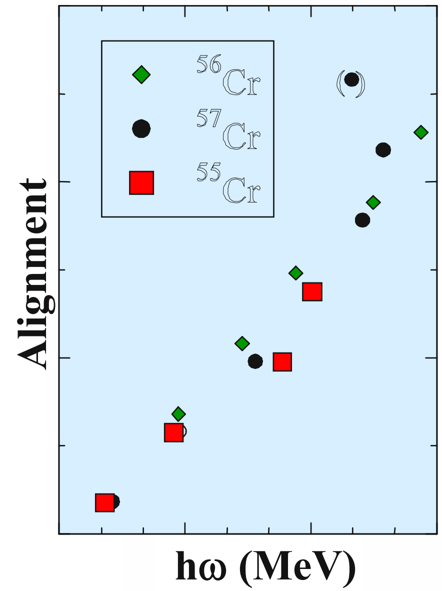


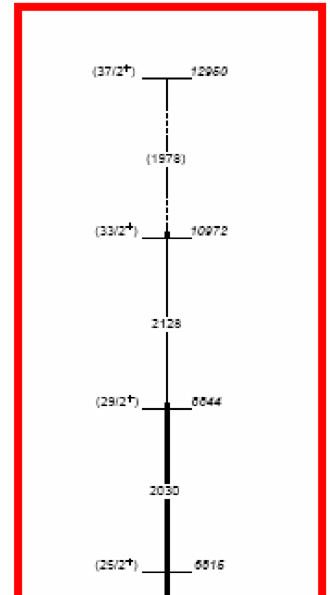
S. Zhu *et al.*, PRC 74, 064351 (2006)

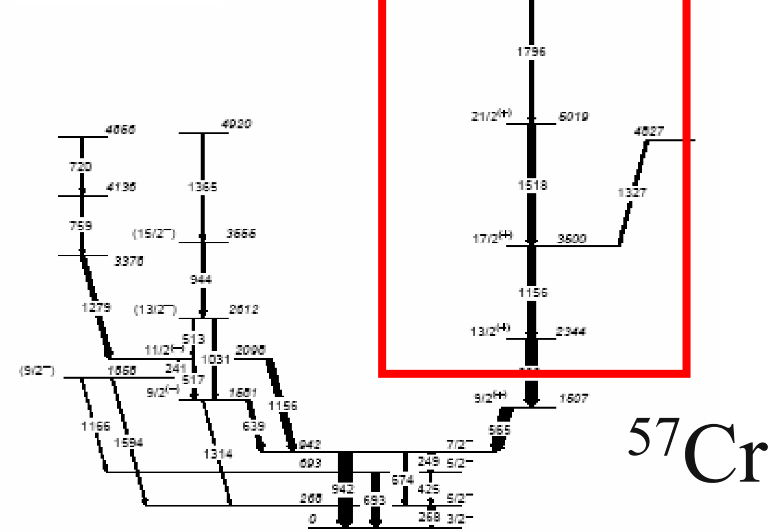
The $g_{9/2}$ is shape driving in odd and even Cr

prolate $\Omega = ½\ g_{9/2}$



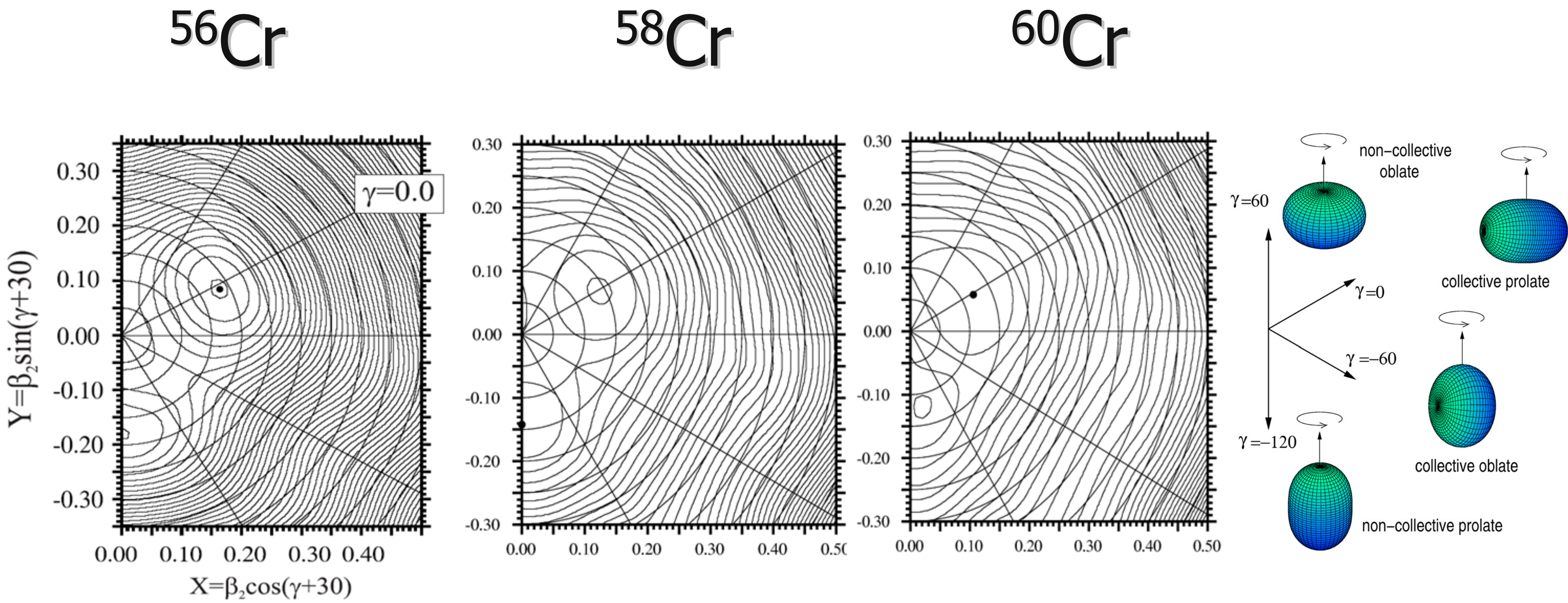






S. Zhu *et al.*, PRC 74, 064351 (2006)

Yrast Low-Spin TRS Calculations



Soft potential ...... Getting softer and softer

"Universal" parameters, contour levels 200 keV

F.R. Xu, Peking University

"Rough estimates using a tentative interaction…"

Michio Honma private communication

Full fp model space plus $g_{9/2}$

PFG9B3 interaction

Appears that a proper description might NOT need d orbitals for above N=50…