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Dipping a toe in the neutron-rich waters of the *fp* shell and some ancient history

≈ *My life as a γ-ray spectroscopist!*

Sean J Freeman
The University of Manchester, UK.

Similar physics and other parts of the fp shell studied by Robert in other ways, here concentrate on studies of nuclei produced by fusion-evaporation reactions with Gammasphere.

Some background: a partial history of recoil-γ at the FMA

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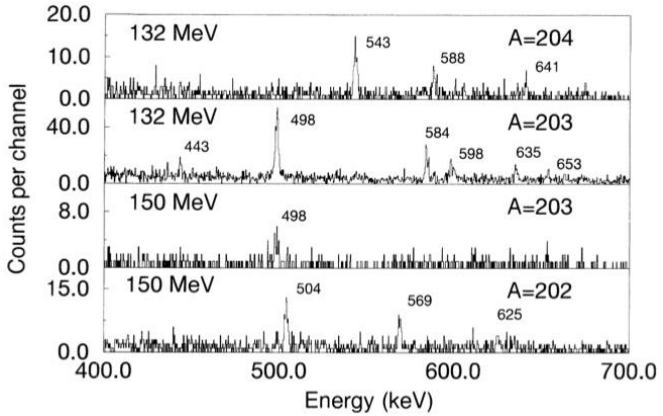
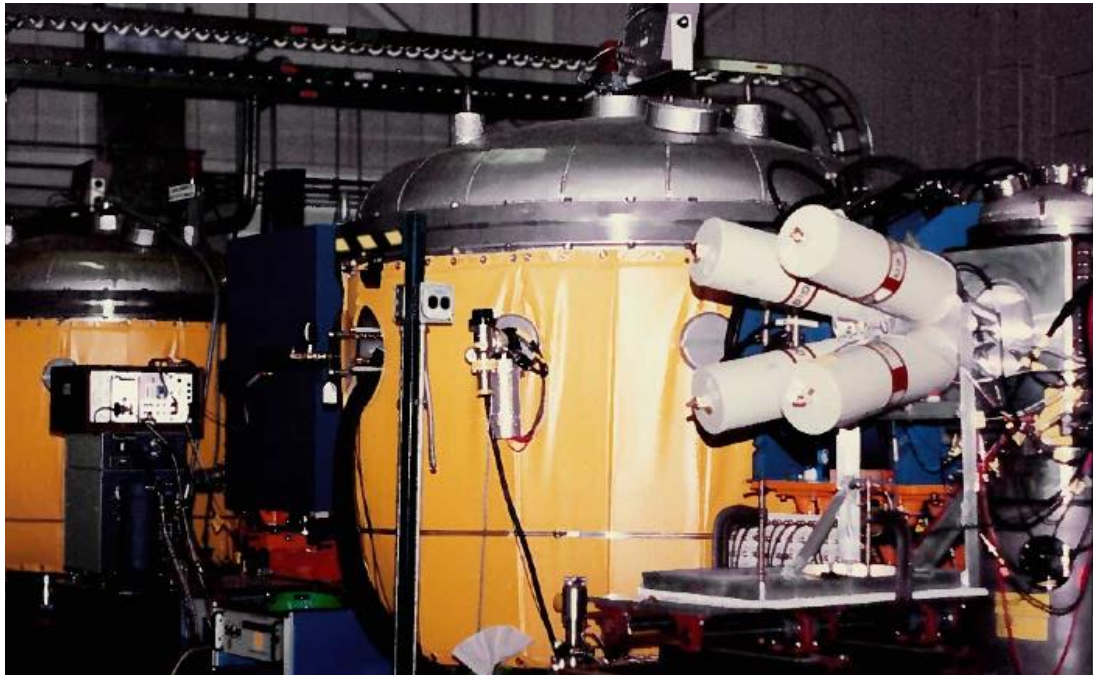
^{181}Ta(^{27}Al,6n)
@132,150 MeV
~5 mb





RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 50, NUMBER 4 OCTOBER 1994

Low-lying structure of the neutron-deficient isotope ^{202}Rn

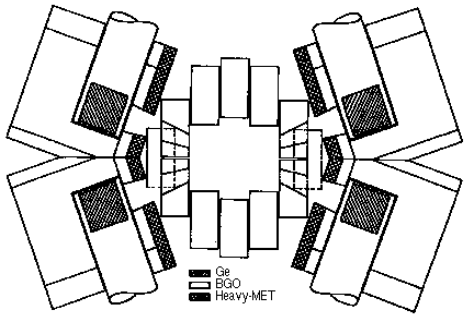
S. J. Freeman, A. G. Smith, and S. J. Warburton
Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom

B. B. Back, I. G. Bearden,* D. J. Blumenthal, M. P. Carpenter, B. Crowell, C. N. Davids, D. Henderson, R. V. F. Janssens, T. L. Khoo, T. Lauritsen, C. J. Lister, D. Nisius, and H. T. Penttilä†
Argonne National Laboratory, Argonne, Illinois 60439

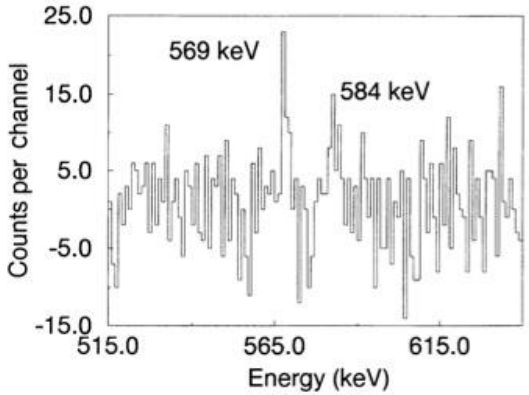
J. A. Becker
Lawrence Livermore National Laboratory, Livermore, California 94550

P. Chowdhury
Wellesley College, Wellesley, Massachusetts 02181

E. F. Moore
North Carolina State University, Raleigh, North Carolina 27695
and Triangle Universities Nuclear Laboratories, Durham, North Carolina 27708
(Received 27 June 1994)



Vertical section of detector assembly in a plane defined by the target and the center of a Ge crystal. Four Compton-suppression spectrometers are shown around the BGO array. The internal space within the array could accommodate a chamber (or other apparatus) of 11.5 cm diameter and 8 cm height.



^{192}Pt(^{16}O,6n) @110 MeV

Argonne-Yale-European (AYE) Ball

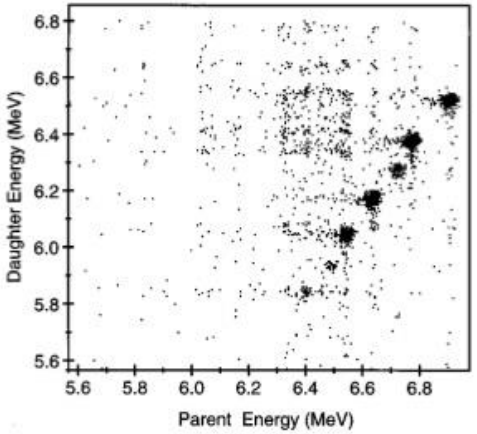
PHYSICAL REVIEW C VOLUME 54, NUMBER 6 DECEMBER 1996

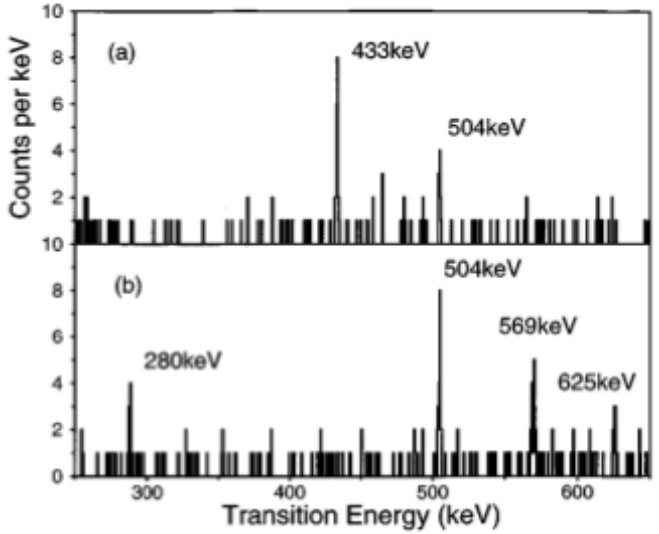
γ decay from states at low excitation energy in the neutron-deficient isotope, ^{200}Rn, identified by correlated radioactive decay

R. B. E. Taylor, S. J. Freeman, J. L. Durell, M. J. Leddy, and A. G. Smith
Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom

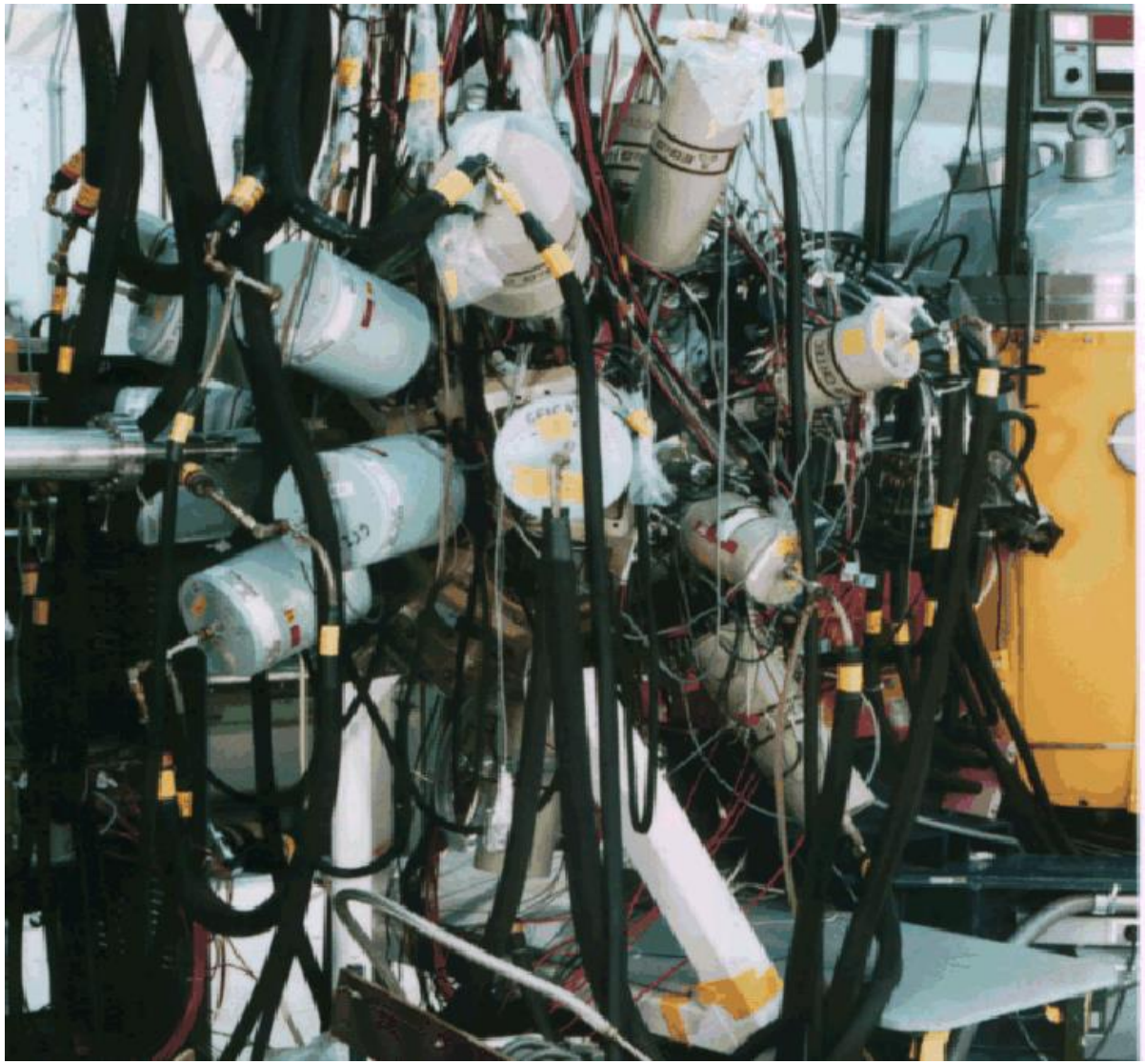
D. J. Blumenthal,* M. P. Carpenter, C. N. Davids, C. J. Lister, R. V. F. Janssens, and D. Seweryniak
Argonne National Laboratory, Argonne, Illinois 60439

(Received 23 August 1996)

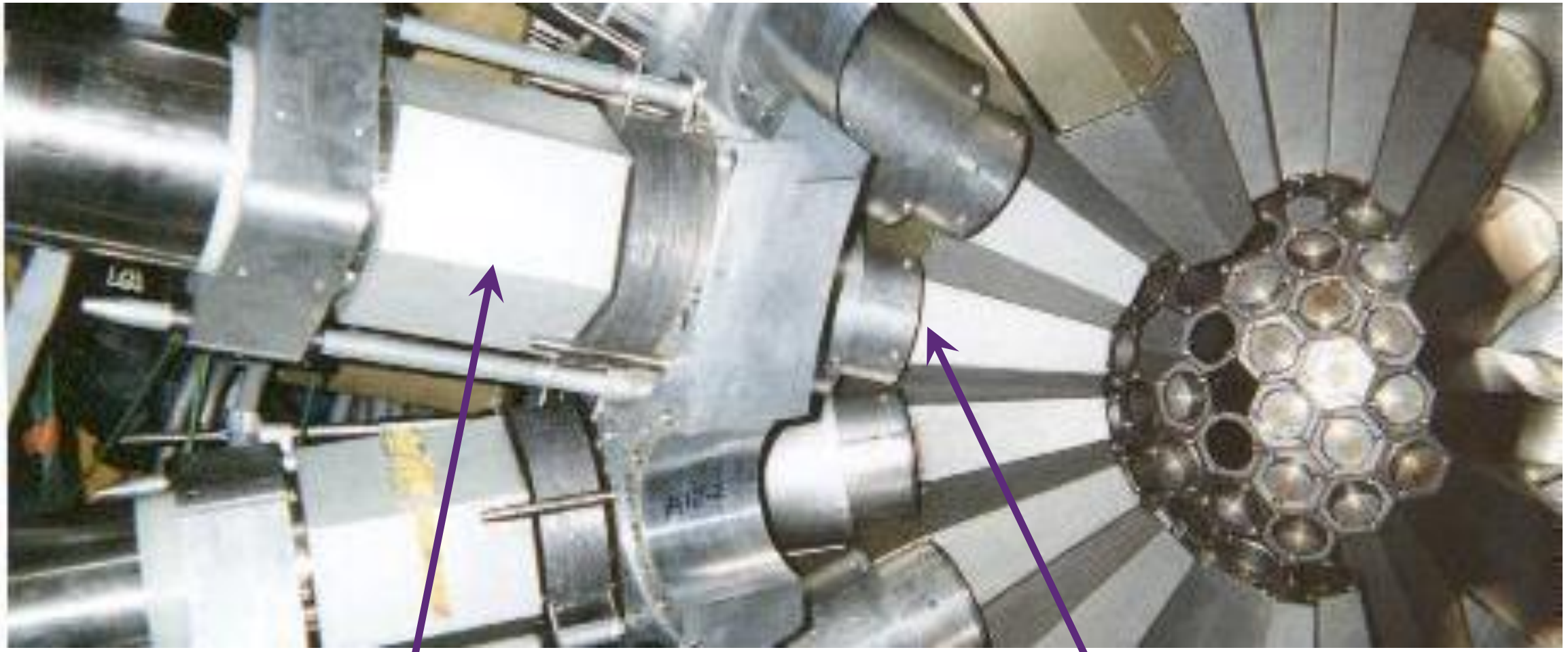




^{176}Hf(^{28}Si,4n) @142 MeV 5μb
[then went sub-μb at Jyväskylä].



Early implementation of neutron detectors with Gammasphere at LBL and ANL.



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Gammasphere @ ANL: the Second Campaign

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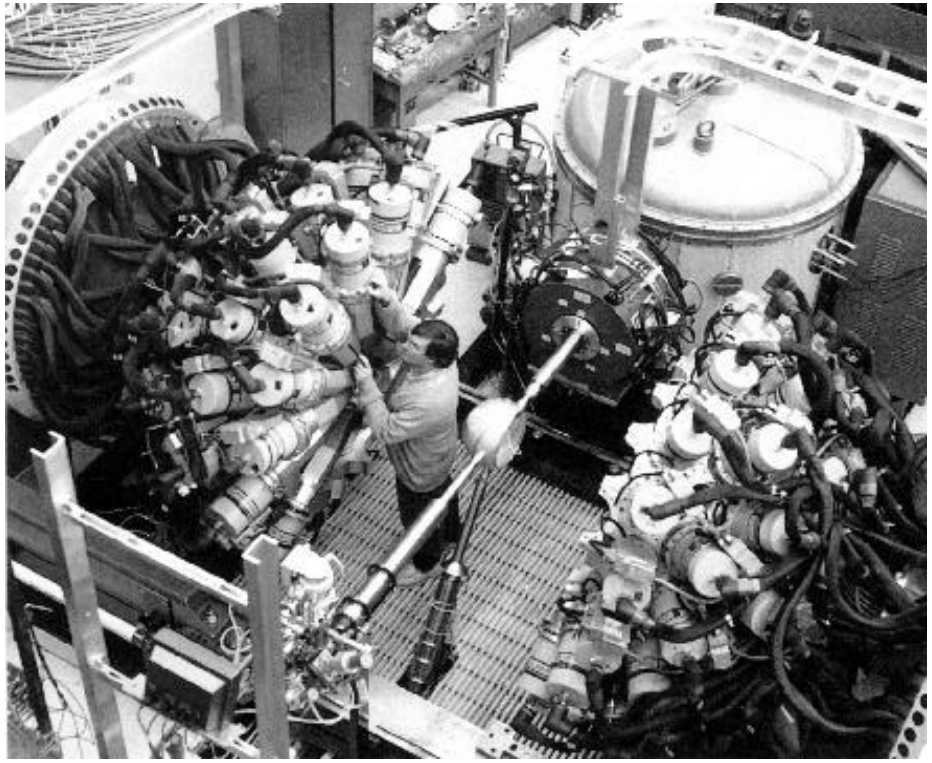
Gammasphere @ ANL: the Second Campaign



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Neutron-rich fp shell

ELSEVIER

21 June 2001

Physics Letters B 510 (2001) 17–23

PHYSICS LETTERS B

www.elsevier.nl/locate/npe

New evidence for a subshell gap at $N = 32$

J.I. Prisciandaro [a,b], P.F. Mantica [a,b], B.A. Brown [a,c], D.W. Anthony [a,b], M.W. Cooper [d], A. Garcia [e], D.E. Groh [a,b], A. Komives [e], W. Kumarasiri [a,b], P.A. Lofy [a,b], A.M. Oros-Peusquens [b], S.L. Tabor [d], M. Wiedeking [d]

$^{58}V \rightarrow {}^{58}Cr + \beta$

Could you probe nuclei in this region to higher spin with CN reactions?

Perhaps take the most neutron-rich stable beams and targets, fuse and select channels with evaporated charged particles to look for electromagnetic decays of the most neutron-rich residues?

ELSEVIER

Physics Letters B 546 (2002) 55–62

PHYSICS LETTERS B

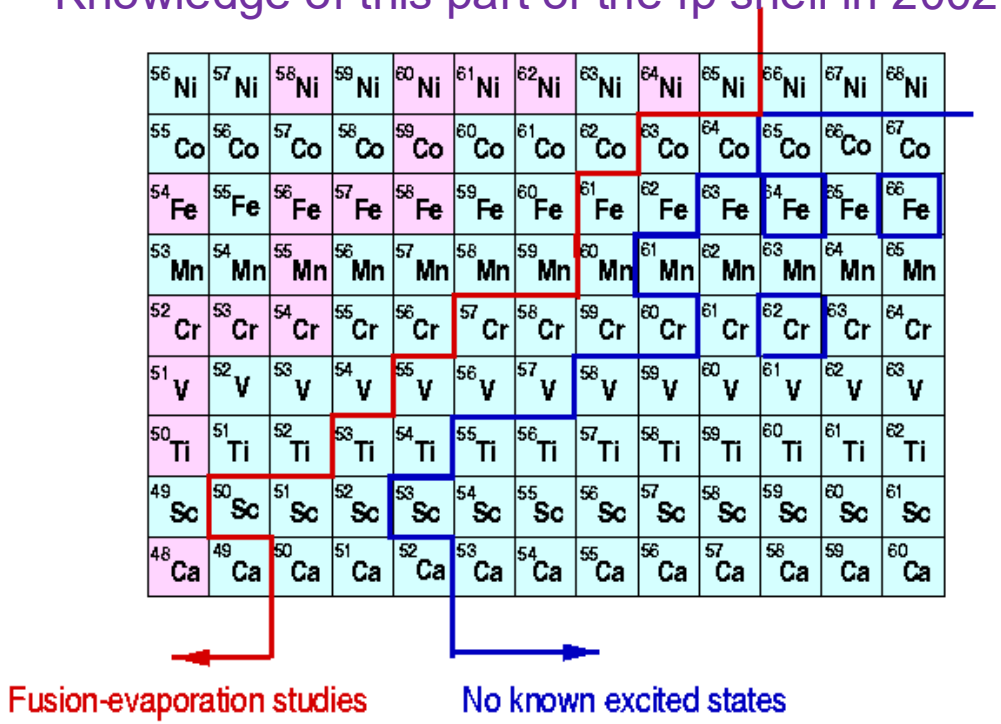
www.elsevier.com/locate/npe

Structure of ^{52,54}Ti and shell closures in neutron-rich nuclei above ^{48}Ca

R.V.F. Janssens [a,*], B. Fornal [b], P.F. Mantica [c,d], B.A. Brown [c,e], R. Broda [b], P. Bhattacharyya [f], M.P. Carpenter [a], M. Cinausero [g], P.J. Daly [f], A.D. Davies [c,e], T. Glasmacher [c,e], Z.W. Grabowski [f], D.E. Groh [c,d], M. Honma [h], F.G. Kondev [a], W. Królas [b], T. Lauritsen [a], S.N. Liddick [c,d], S. Lunardi [i], N. Marginean [g], T. Mizusaki [j], D.J. Morrissey [c,d], A.C. Morton [c], W.F. Mueller [c], T. Otsuka [k], T. Pawlat [b], D. Seweryniak [a], H. Schatz [c,e], A. Stolz [c,e], S.L. Tabor [l], C.A. Ur [i], G. Viesti [i], I. Wiedenhöver [a,l], J. Wrzesiński [b]

$^{54}Sc \rightarrow {}^{54}Ti + \beta$ and $^{48}Ca + ^{208}Pb$ @GS

Knowledge of this part of the fp shell in 2002



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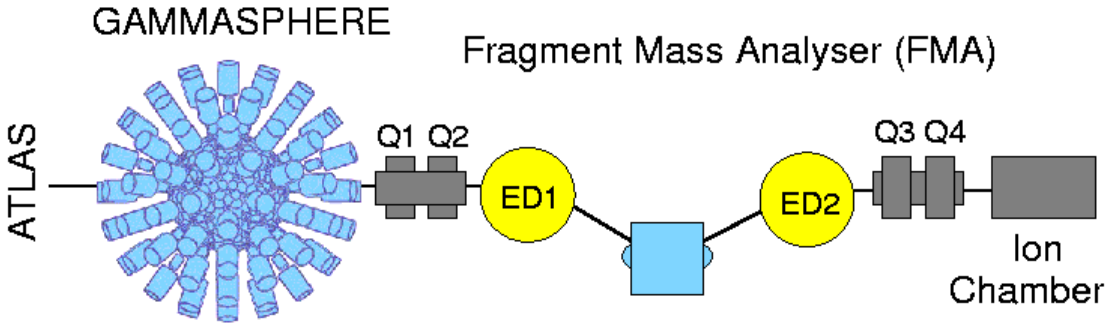
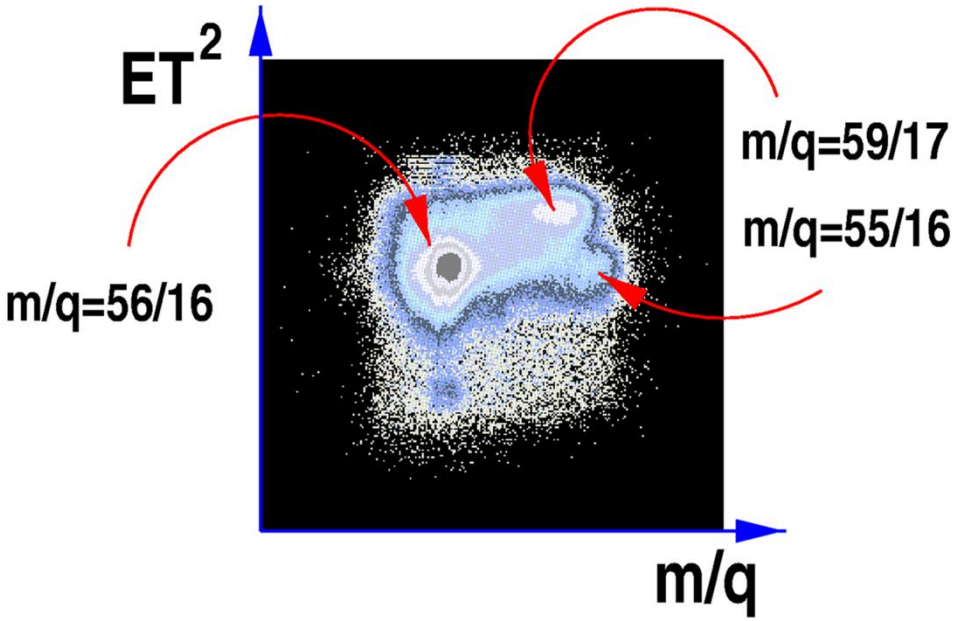
Yes, you can…

Gammasphere: E_γ, t_γ

FMA: m/q, TOF, E, ΔE





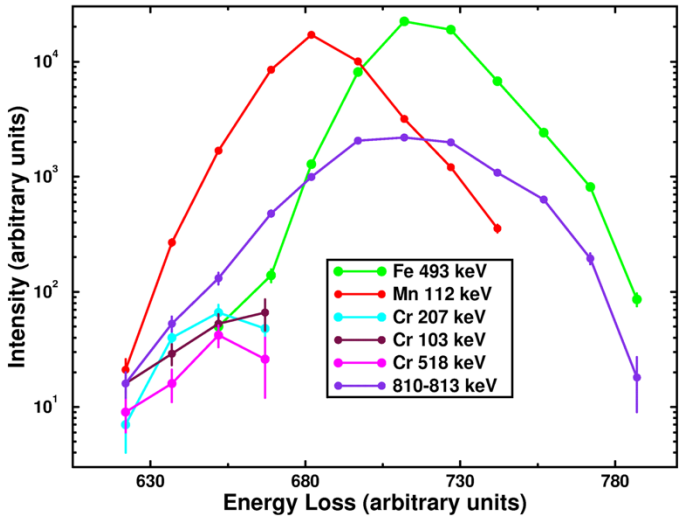
PHYSICAL REVIEW C **69**, 064301 (2004)

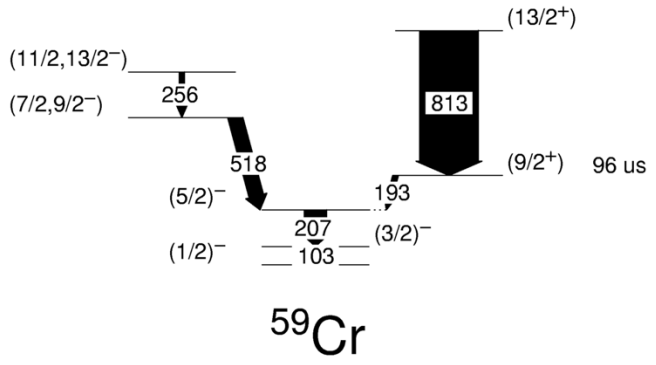
Low-lying levels in ^{59}Cr: Inadequacy of the *fp* model space and onset of deformation

S. J. Freeman,[1,2,*] R. V. F. Janssens,[2] B. A. Brown,[3] M. P. Carpenter,[2] S. M. Fischer,[2,4] N. J. Hammond,[2] M. Honma,[5] T. Lauritsen,[2] C. J. Lister,[2] T. L. Khoo,[2] G. Mukherjee,[2] D. Seweryniak,[2] J. F. Smith,[1] B. J. Varley,[1] M. Whitehead,[1] and S. Zhu[6]

[1]*Schuster Laboratory, University of Manchester, Manchester M13 9PL, United Kingdom*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*DePaul University, Chicago, Illinois 60604, USA*
[5]*Center for Mathematical Sciences, University of Aizu, Tsuruga, Ikki-machi, Aizu-Wakamatsu, Fukushima 965-8580, Japan*
[6]*University of Notre Dame, Notre Dame, Indiana 46556, USA*

^{48}Ca+^{13}C @ 130 MeV, 2p channel





9/2+ seemed oblate!
9/2+[404]?

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With ^{14}C targets you could go further with 2p and analysis across both data sets and other reaction channels were very useful…2pxn and αn to Cr, pxn to Mn and xn to Fe…

Available online at www.sciencedirect.com
SCIENCE DIRECT
PHYSICS LETTERS B
ELSEVIER
Physics Letters B 622 (2005) 151–158
www.elsevier.com/locate/physletb

Changes in $\nu g_{9/2}$ shape polarisation across the odd neutron-rich Cr isotopes

A.N. Deacon [a], S.J. Freeman [a], R.V.F. Janssens [b], F.R. Xu [c], M.P. Carpenter [b], I.R. Calderin [d], P. Chowdhury [e], N.J. Hammond [b], T. Lauritsen [b], C.J. Lister [b], D. Seweryniak [b], J.F. Smith [a], S.L. Tabor [d], B.J. Varley [a], S. Zhu [b]

PHYSICAL REVIEW C **74**, 064315 (2006)

Level structure of the neutron-rich ^{56,58,60}Cr isotopes: Single-particle and collective aspects

S. Zhu,[1] A. N. Deacon,[2] S. J. Freeman,[2] R. V. F. Janssens,[1] B. Fornal,[3] M. Honma,[4] F. R. Xu,[5] R. Broda,[3] I. R. Calderin,[6] M. P. Carpenter,[1] P. Chowdhury,[7] F. G. Kondev,[8] W. Królas,[3] T. Lauritsen,[1] S. N. Liddick,[9,10] C. J. Lister,[1] P. F. Mantica,[9,10] T. Pawłat,[3] D. Seweryniak,[1] J. F. Smith,[2] S. L. Tabor,[6] B. E. Tomlin,[9,10] B. J. Varley,[2] and J. Wrzesiński[3]

PHYSICAL REVIEW C **76**, 054303 (2007)

Yrast structures in the neutron-rich isotopes ^{59,60}Fe and the role of the $g_{9/2}$ orbital

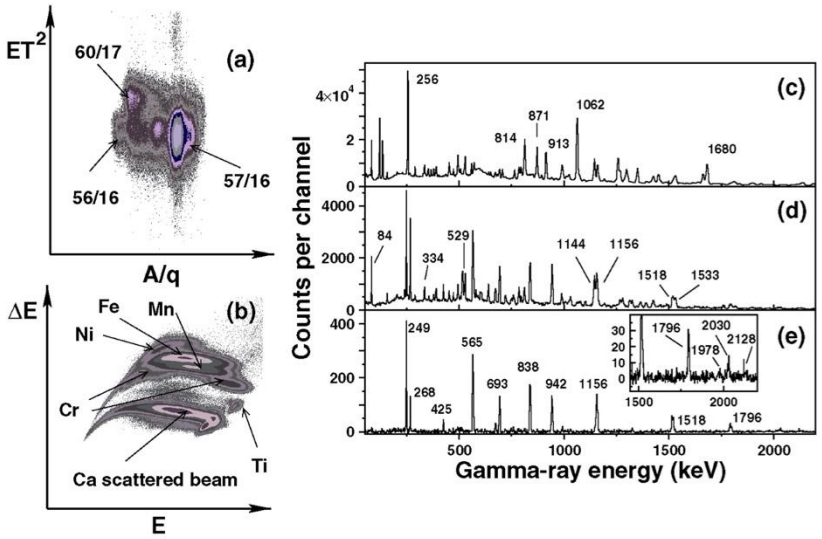
A. N. Deacon,[1,*] S. J. Freeman,[1] R. V. F. Janssens,[2] M. Honma,[3] M. P. Carpenter,[2] P. Chowdhury,[4] T. Lauritsen,[2] C. J. Lister,[2] D. Seweryniak,[2] J. F. Smith,[1,†] S. L. Tabor,[5] B. J. Varley,[1] F. R. Xu,[6] and S. Zhu[2]

PHYSICAL REVIEW C **81**, 014305 (2010)

High-spin structures in the neutron-rich isotopes $^{57-60}$Mn

D. Steppenbeck,[1,*] A. N. Deacon,[1] S. J. Freeman,[1] R. V. F. Janssens,[2] S. Zhu,[2] M. P. Carpenter,[2] P. Chowdhury,[3] M. Honma,[4] T. Lauritsen,[2] C. J. Lister,[2] D. Seweryniak,[2] J. F. Smith,[1,†] S. L. Tabor,[5] and B. J. Varley[1]

^{14}C(^{48}Ca,αn)^{57}Cr

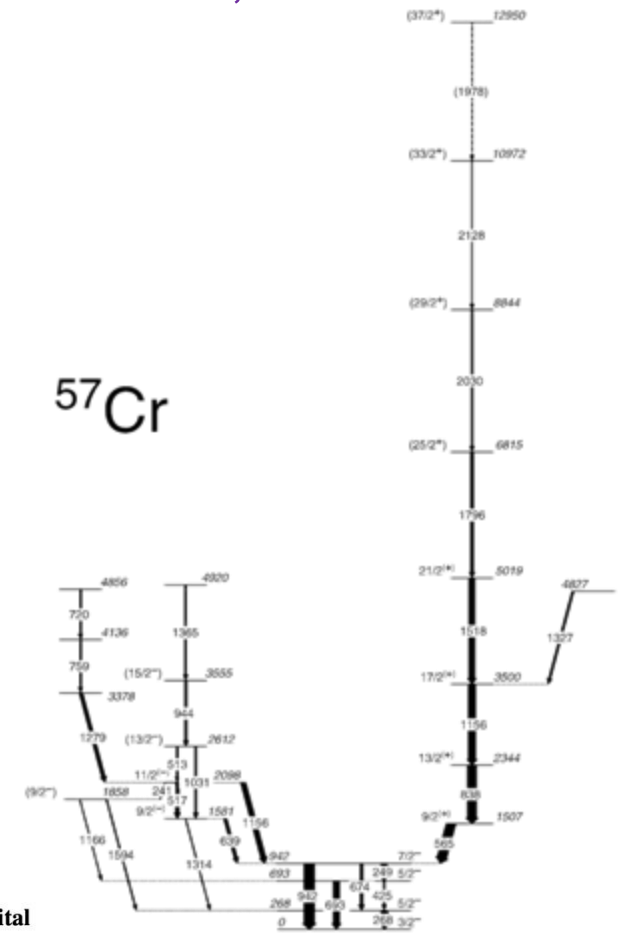


PHYSICAL REVIEW C **85**, 044316 (2012)

Magnetic rotation and quasicollective structures in ^{58}Fe: Influence of the $\nu g_{9/2}$ orbital

D. Steppenbeck,[1,*] R. V. F. Janssens,[2] S. J. Freeman,[3] M. P. Carpenter,[2] P. Chowdhury,[4] A. N. Deacon,[3,†] M. Honma,[5] H. Jin,[6] T. Lauritsen,[2] C. J. Lister,[2] J. Meng,[7] J. Peng,[8] D. Seweryniak,[2] J. F. Smith,[3,‡] Y. Sun,[6,9,10] S. L. Tabor,[11] B. J. Varley,[3] Y.-C. Yang,[6] S. Q. Zhang,[7] P. W. Zhao,[7] and S. Zhu[2]

^{57}Cr



9/2+ seemed prolate!
1/2+[440]

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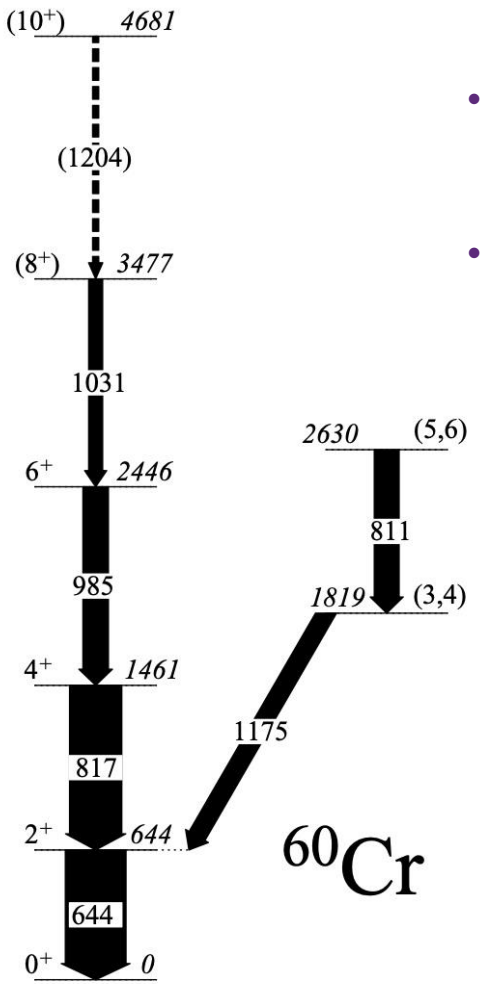
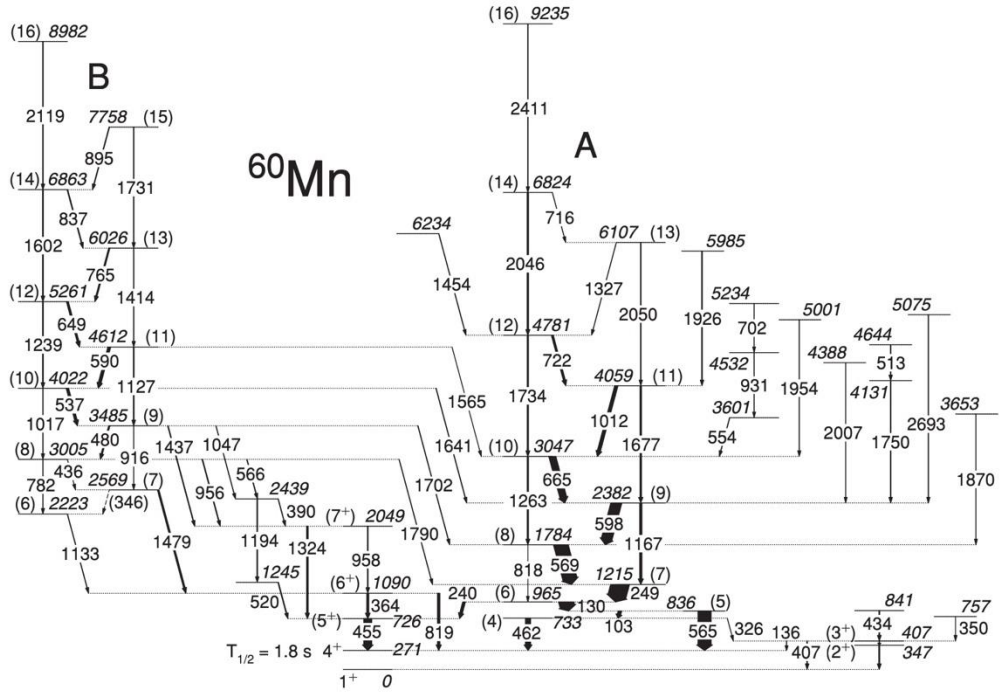
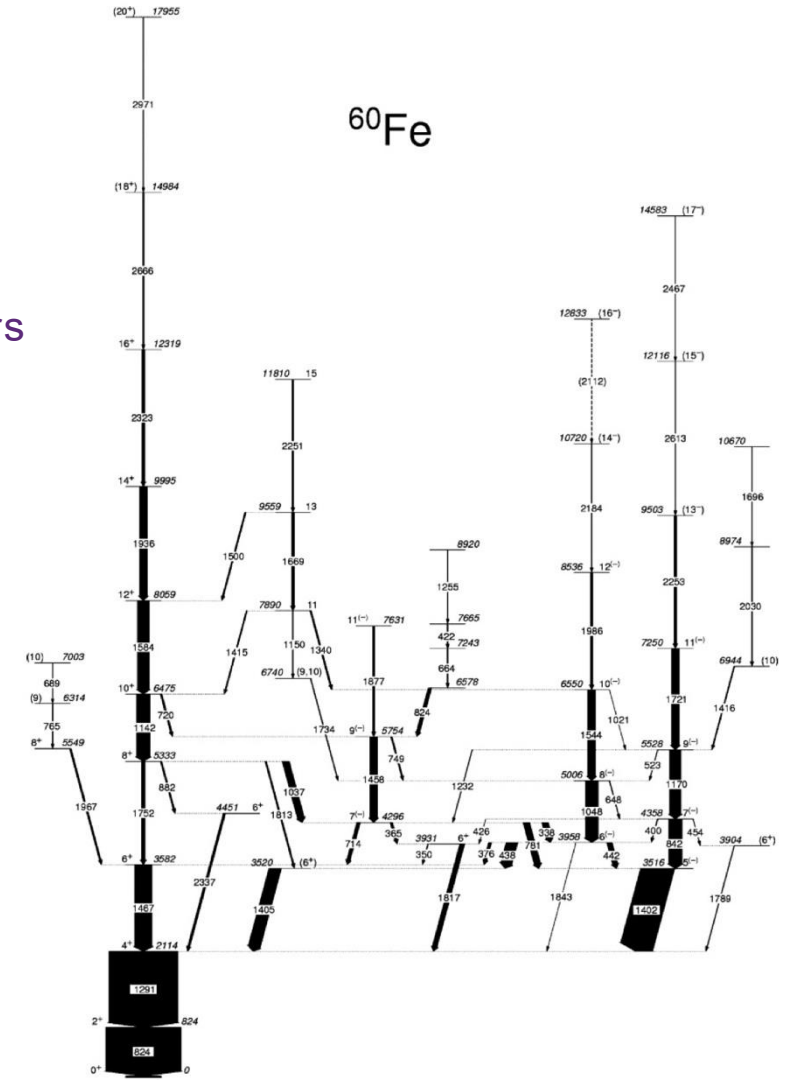
Rich detailed spectroscopy with complex low-spin levels and emergence of rotational bands to around 20ħ.

Shell-model calculations from the Japanese groups esp. Michio Honma and TRS calculations from Furong Xu.

- Low-lying natural-parity states well described by SM with GXPF1A interaction.
- Nuclei seem to have soft polarisable cores where excitations to the $g_{9/2}$ orbital can easily distort the system, mainly prolate and sometimes oblate.
- But less well described in SM – Silvia Lenzi and coworkers included *d* orbitals from above.







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Probe lower in the shell with ^{9}Be(^{48}Ca,xpyn)…

ELSEVIER
Physics Letters B
Volume 650, Issues 2–3, 28 June 2007, Pages 135-140

One-particle excitations outside the ^{54}Ti semi-magic core: The ^{55}V and ^{55}Ti yrast structures

S. Zhu [a], R.V.F. Janssens [a], B. Fornal [b], S.J. Freeman [c], M. Honma [d], R. Broda [b], M.P. Carpenter [a], A.N. Deacon [c], B.P. Kay [c], F.G. Kondev [e], W. Królas [b f], J. Kozemczak [g], A. Larabee [g], T. Lauritsen [a], S.N. Liddick [h i], C.J. Lister [a], P.F. Mantica [h i], T. Otsuka [j k], T. Pawłat [b], A. Robinson [a], D. Seweryniak [a], J.F. Smith [c 1], D. Steppenbeck [c], B.E. Tomlin [h i], J. Wrzesiński [b], X. Wang [a l]

PHYSICAL REVIEW C **83**, 064305 (2011)

Single-particle and collective structures in ^{55}Cr and ^{55}V

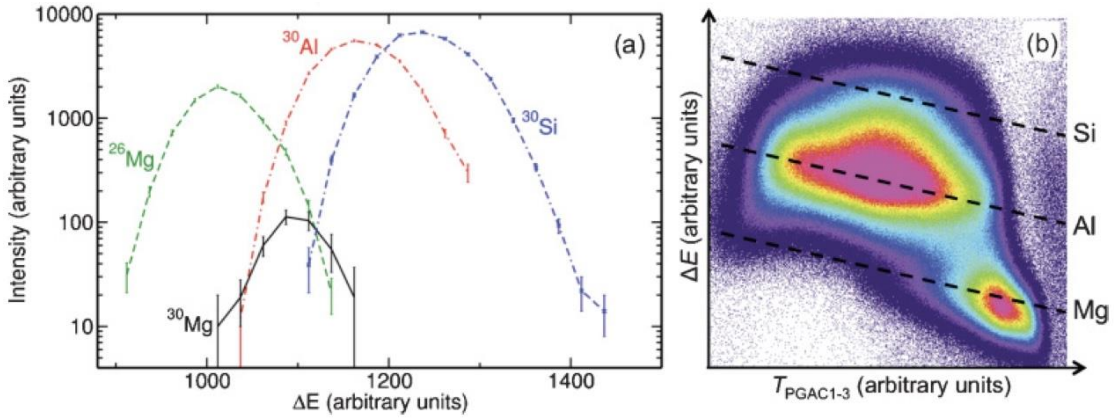
A. N. Deacon,[1,*] D. Steppenbeck,[1,†] S. Zhu,[2] S. J. Freeman,[1] R. V. F. Janssens,[2] M. P. Carpenter,[2] B. Fornal,[3] M. Honma,[4] B. P. Kay,[1,‡] F. G. Kondev,[2] J. Kozemczak,[5] A. Larabee,[5] T. Lauritsen,[2] C. J. Lister,[2] A. P. Robinson,[2,§] D. Seweryniak,[2] J. F. Smith,[1,‖] Y. Sun,[6,7,8] X. Wang,[2,¶] F. R. Xu,[9] and Y.-C. Yang[6]

PHYSICAL REVIEW C **80**, 024318 (2009)

High-lying, non-yrast shell structure in ^{52}Ti

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] E. Jackson,[1,*] B. P. Kay,[3,†] T. Lauritsen,[1] C. J. Lister,[1] P. F. Mantica,[5,6] T. Otsuka,[7,8] D. Seweryniak,[1] J. F. Smith,[3,‡] D. Steppenbeck,[3,§] and X. Wang[1,9,‖]

And to other regions…
$^{14}C(^{18}O,2p)^{30}Mg$



PHYSICAL REVIEW C **82**, 034305 (2010)

Cross-shell excitations near the "island of inversion": Structure of ^{30}Mg

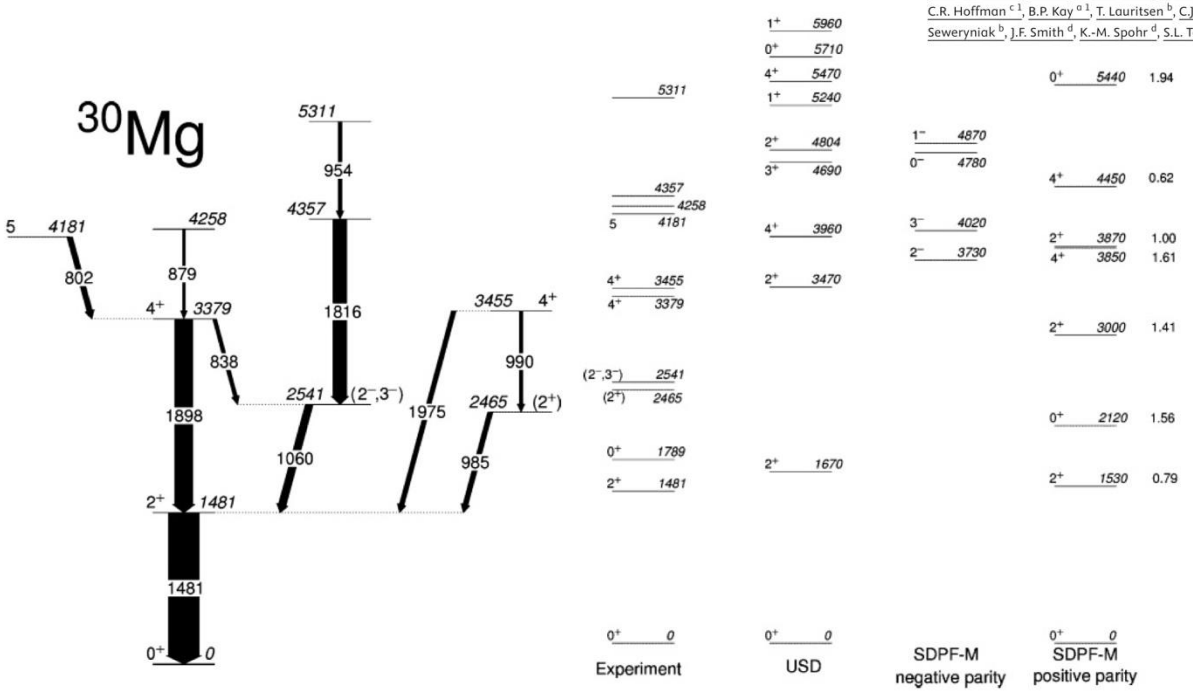
A. N. Deacon,[1,*] J. F. Smith,[2] S. J. Freeman,[1] R. V. F. Janssens,[3] M. P. Carpenter,[3] B. Hadinia,[2] C. R. Hoffman,[4,†] B. P. Kay,[3] T. Lauritsen,[3] C. J. Lister,[3] D. O'Donnell,[2,‡] J. Ollier,[2,‡] T. Otsuka,[5,6] D. Seweryniak,[3] K.-M. Spohr,[2] D. Steppenbeck,[1,§] S. L. Tabor,[4] V. Tripathi,[4] Y. Utsuno,[7] P. T. Wady,[2] and S. Zhu[3]

Tests of early cross-shell interactions…..

Nuclear Physics A
Volume 847, Issues 3–4, 8 December 2010, Pages 149-167

Cross-shell excitations in ^{30}Al and ^{30}Si at high spin

D. Steppenbeck [a], A.N. Deacon [a], S.J. Freeman [a], R.V.F. Janssens [b], M.P. Carpenter [b], C.R. Hoffman [c 1], B.P. Kay [a 1], T. Lauritsen [b], C.J. Lister [b], D. O'Donnell [d 2], J. Ollier [d 2], D. Seweryniak [b], J.F. Smith [d], K.-M. Spohr [d], S.L. Tabor [c], V. Tripathi [c], P.T. Wady [d], S. Zhu [b]

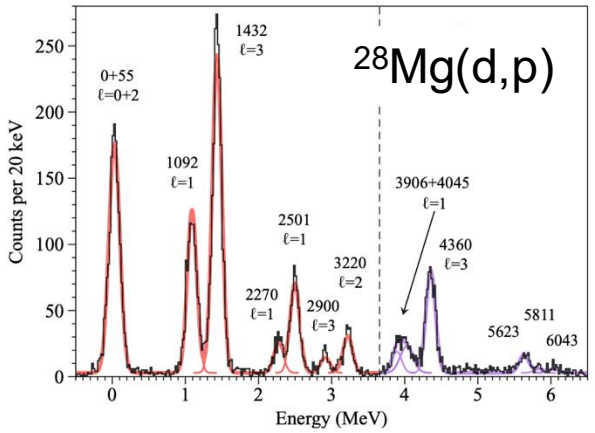


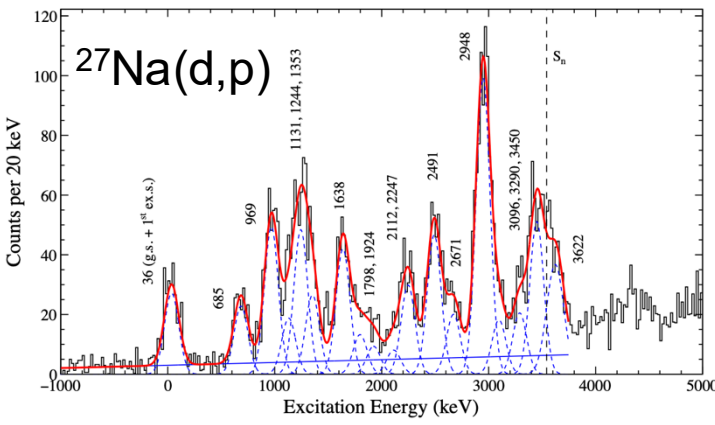
More recently solenoid + ISOL facility:
d(^{28}Mg,*p*), *d*(^{30}Mg,*p*), *d*(^{27}Na,*p*)….

PHYSICAL REVIEW C **104**, L051301 (2021)
Letter

Evolution of single-particle structure near the $N = 20$ island of inversion

P. T. MacGregor,[1] D. K. Sharp,[1,*] S. J. Freeman,[1] C. R. Hoffman,[2] B. P. Kay,[2] T. L. Tang,[2] L. P. Gaffney,[3,4] E. F. Baader,[4] M. J. G. Borge,[5] P. A. Butler,[3] W. N. Catford,[6] B. D. Cropper,[1] G. de Angelis,[7] J. Konki,[4] Th. Kröll,[8] M. Labiche,[9] I. H. Lazarus,[9] R. S. Lubna,[10,11] I. Martel,[3,12] D. G. McNeel,[13] R. D. Page,[3] O. Poleshchuk,[14] R. Raabe,[14] F. Recchia,[15,16] and J. Yang[14]





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Enthusiasm
Encouragement
Advocacy
Leadership

THANK YOU!