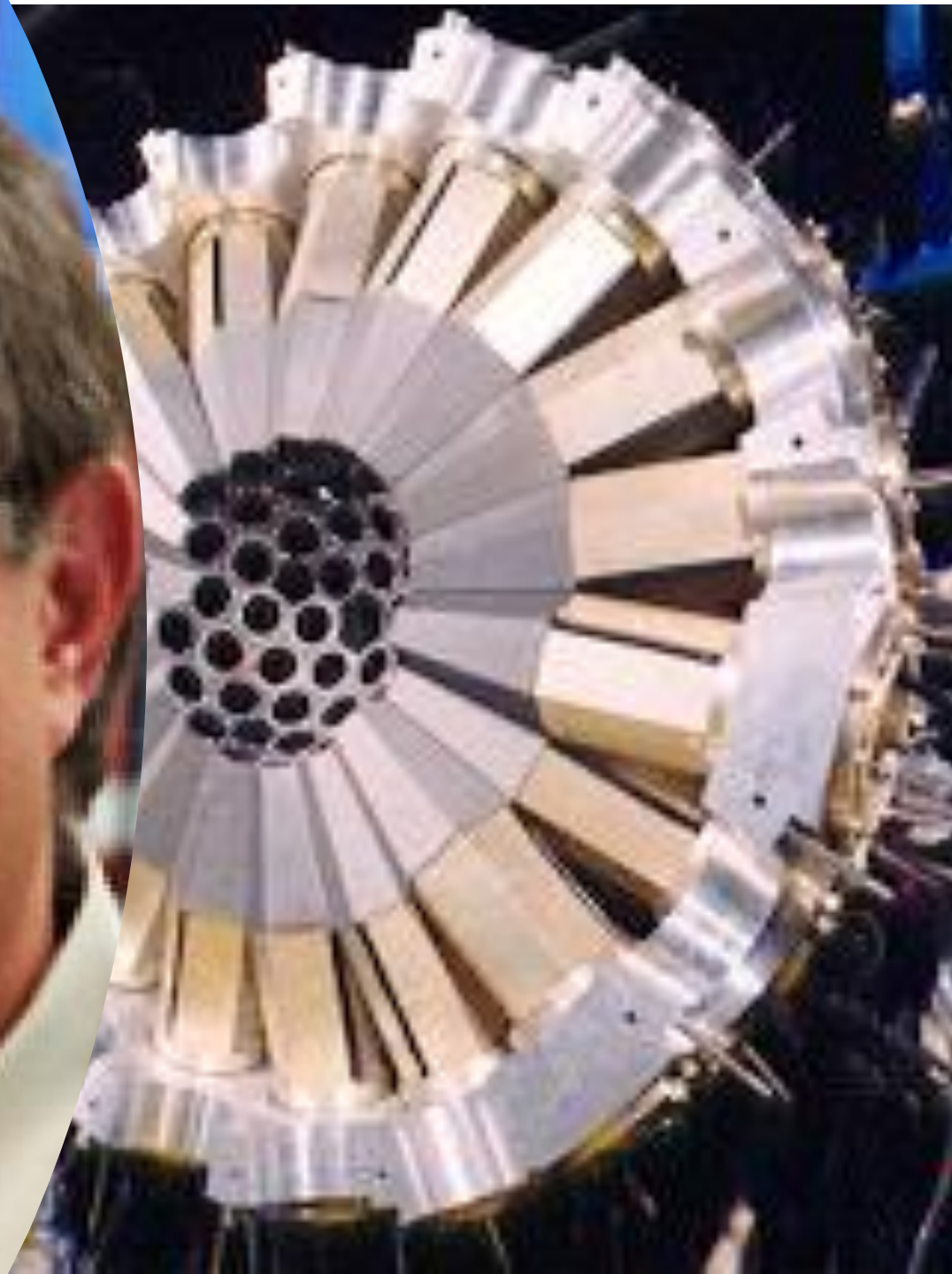
Symposium:
„Nuclear Physics Over The Years: From the high spin era to rare isotopes”
19-20 September 2025
Chapel Hill, NC, USA

The Thrill of Searching for Hidden Shell Gaps Together

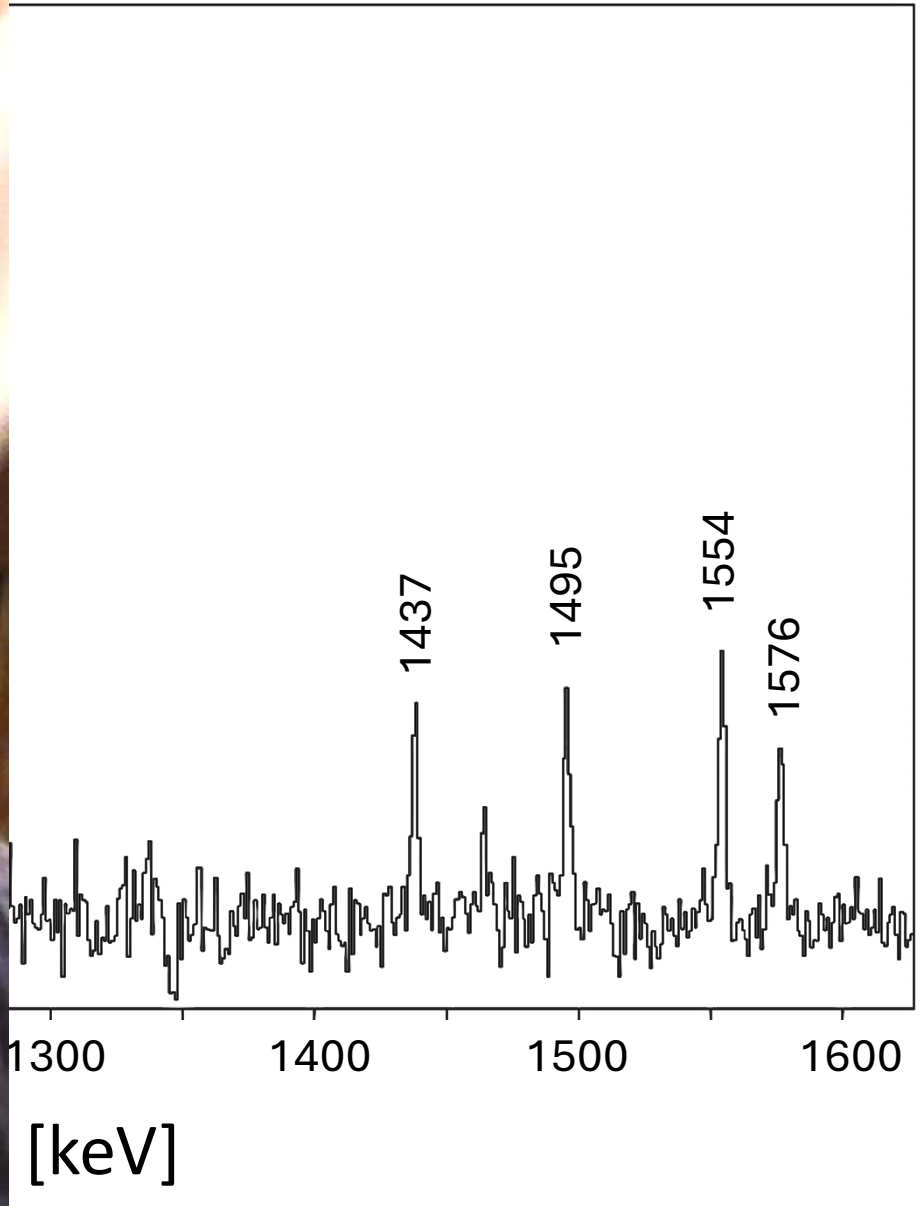
Bogdan Fornal
Institute of Nuclear Physics
Polish Academy of Sciences
KRAKÓW, Poland



The Physics Building at Purdue University in West Lafayette, Indiana
April 23, 2001

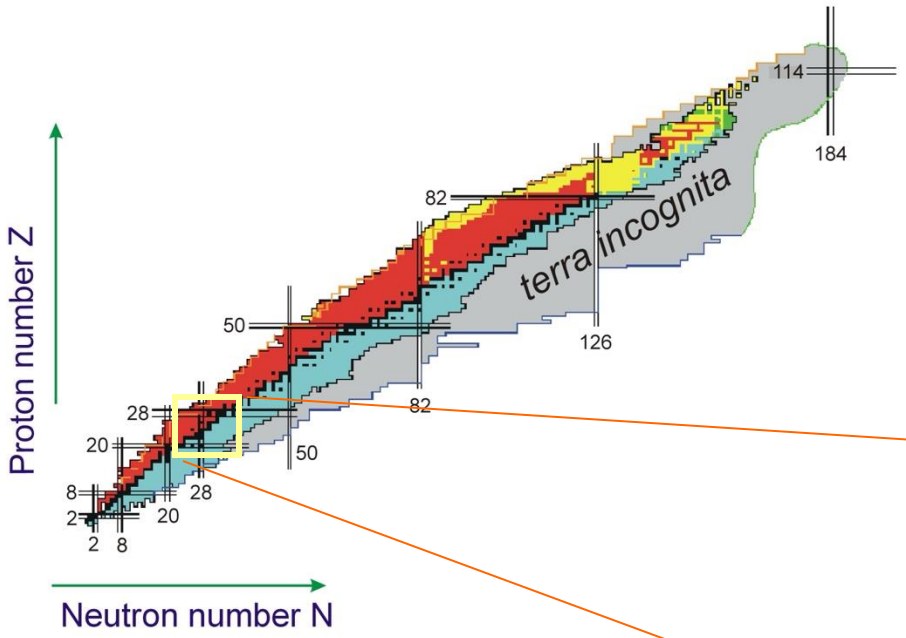
Gamma-ray spectrum from a GAMMASPHERE experiment

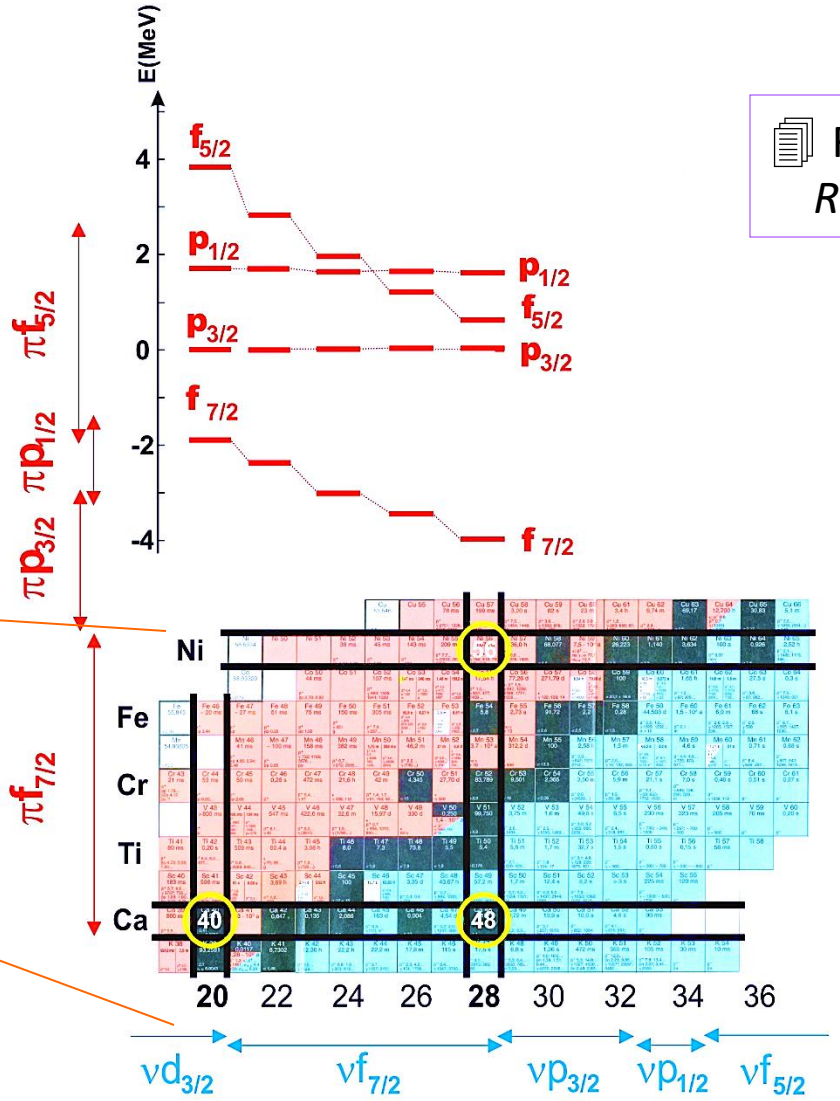
- Purdue University, **April 23, 2001** - seen by Robert and me for the first time

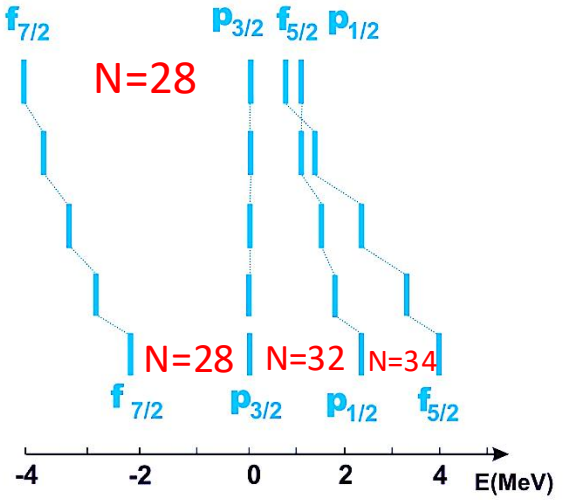


32 years earlier

Evolution of single particle orbitals around the doubly magic ^{40}Ca, ^{48}Ca and ^{56}Ni







R.A. Ricci, P.R. Maurenzig
Riv. Nuovo Cim. 1, 291 (1969).

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

4th INTERNATIONAL CONFERENCE ON
NUCLEI FAR FROM STABILITY

L.O. Skolen, Helsingor (Denmark)
7-13 June, 1981

PROCEEDINGS

Vol. I

SELF-CONSISTENT STUDY OF NUCLEI FAR FROM STABILITY
WITH THE ENERGY DENSITY METHOD

F. Tondeur

Institut Superieur Industriel de Bruxelles, and Universite
Libre de Bruxelles, Belgium.

Among the new neutron magic numbers predicted far from stability: 16, 28, 32, 34, 40, 50 and 58, only **N= 32** could be checked experimentally in a near future.

In particular, it would be interesting to obtain information about $^{52}Ca_{32}$, which is predicted to be doubly magic.

PHYSICAL REVIEW C VOLUME 31, NUMBER 6

June 1985

Beta decay of the new isotopes ^{52}K, ^{52}Ca, and ^{52}Sc; a test of the shell model far from stability

A. Huck, G. Klotz, A. Knipper, C. Miehé, C. Richard-Serre, and G. Walter
Centre de Recherches Nucléaires, 67037 Strasbourg Cedex, France

A. Poves
Departamento de Fisica Teorica, Universidad Autonoma, Madrid 34, Spain

H. L. Ravn
The Isolde Collaboration, CERN 1211 Geneva 23, Switzerland

G. Marguier
Institut de Physique Nucléaire, Université Lyon 1, 69622 Villeurbanne Cedex, France
(Received 4 September 1984)

ISOLDE CERN

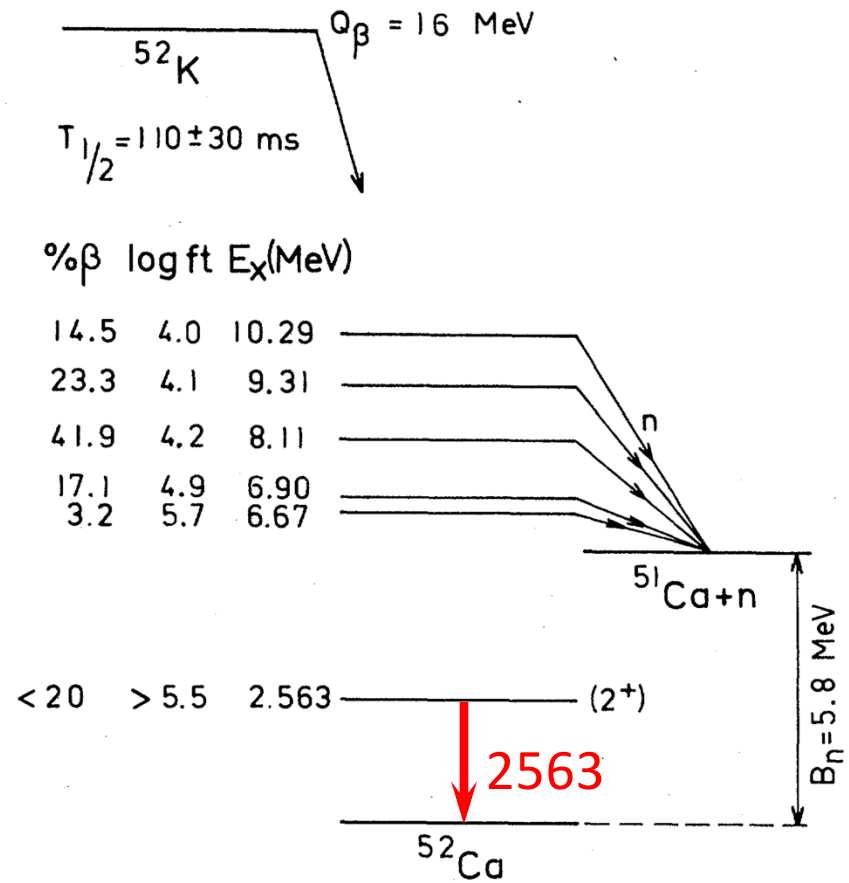


FIG. 5. Decay scheme of ^{52}K.

PHYSICAL REVIEW C VOLUME 31, NUMBER 6 JUNE 1985

Beta decay of the new isotopes ^{52}K, ^{52}Ca, and ^{52}Sc; a test of the shell model far from stability

A. Huck, G. Klotz, A. Knipper, C. Miehé, C. Richard-Serre, and G. Walter
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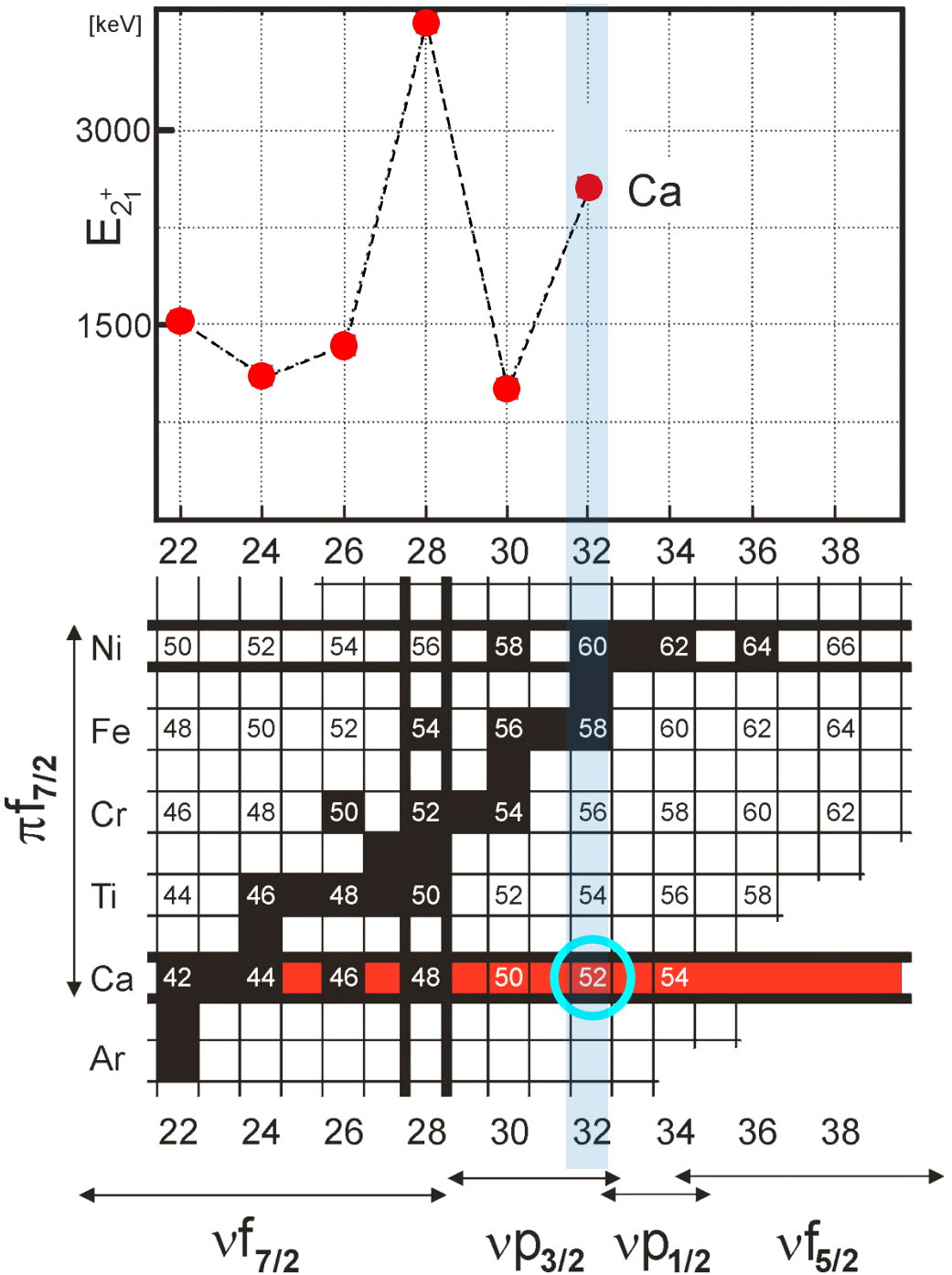
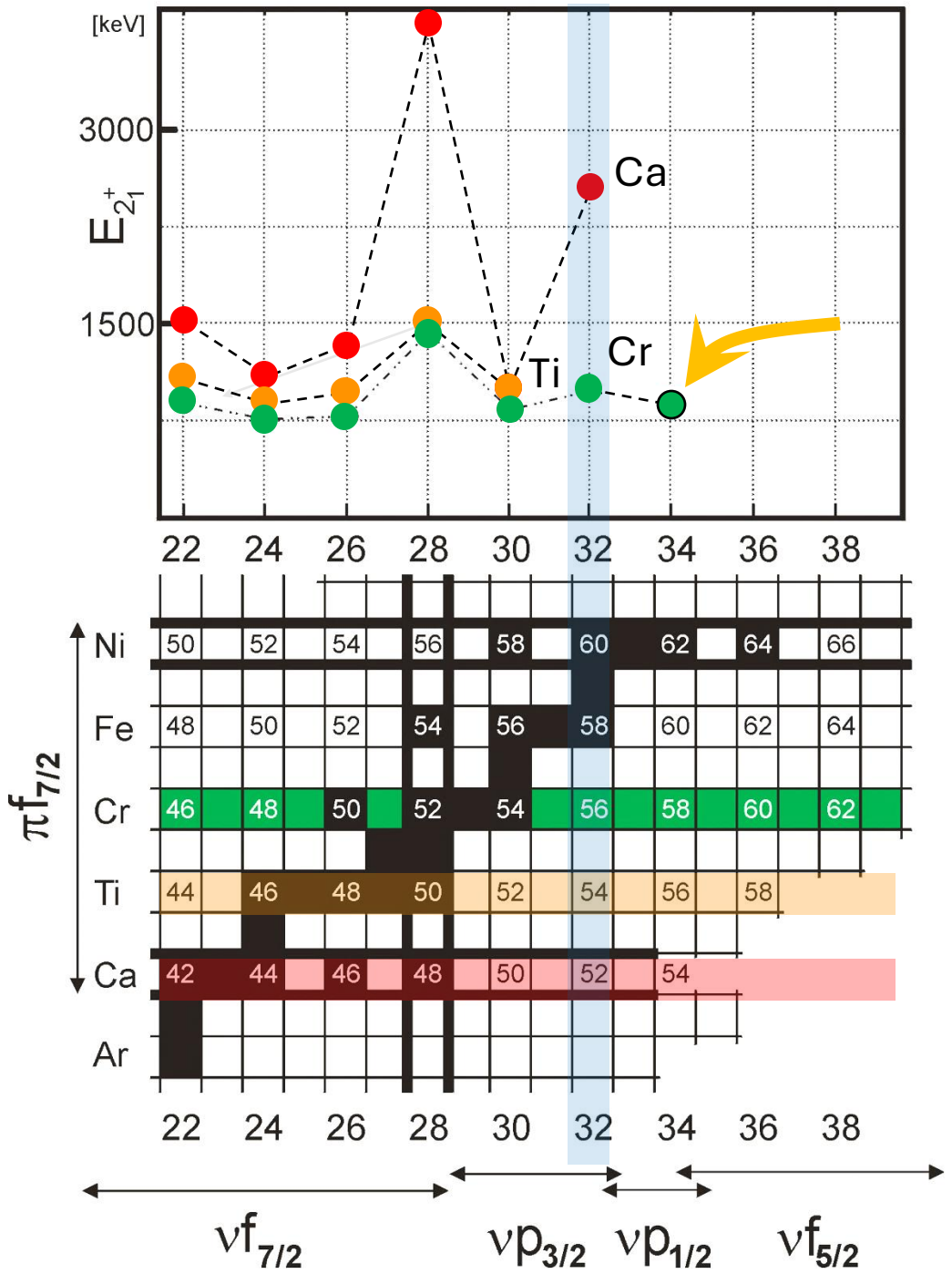
(Received 4 September 1984)



February 2001:
I was asked to referee the manuscript
„New Evidence for a Subshell Gap at N=32”



ELSEVIER

21 June 2001

PHYSICS LETTERS B

Phys. Lett. B 510, 2001, 17-23

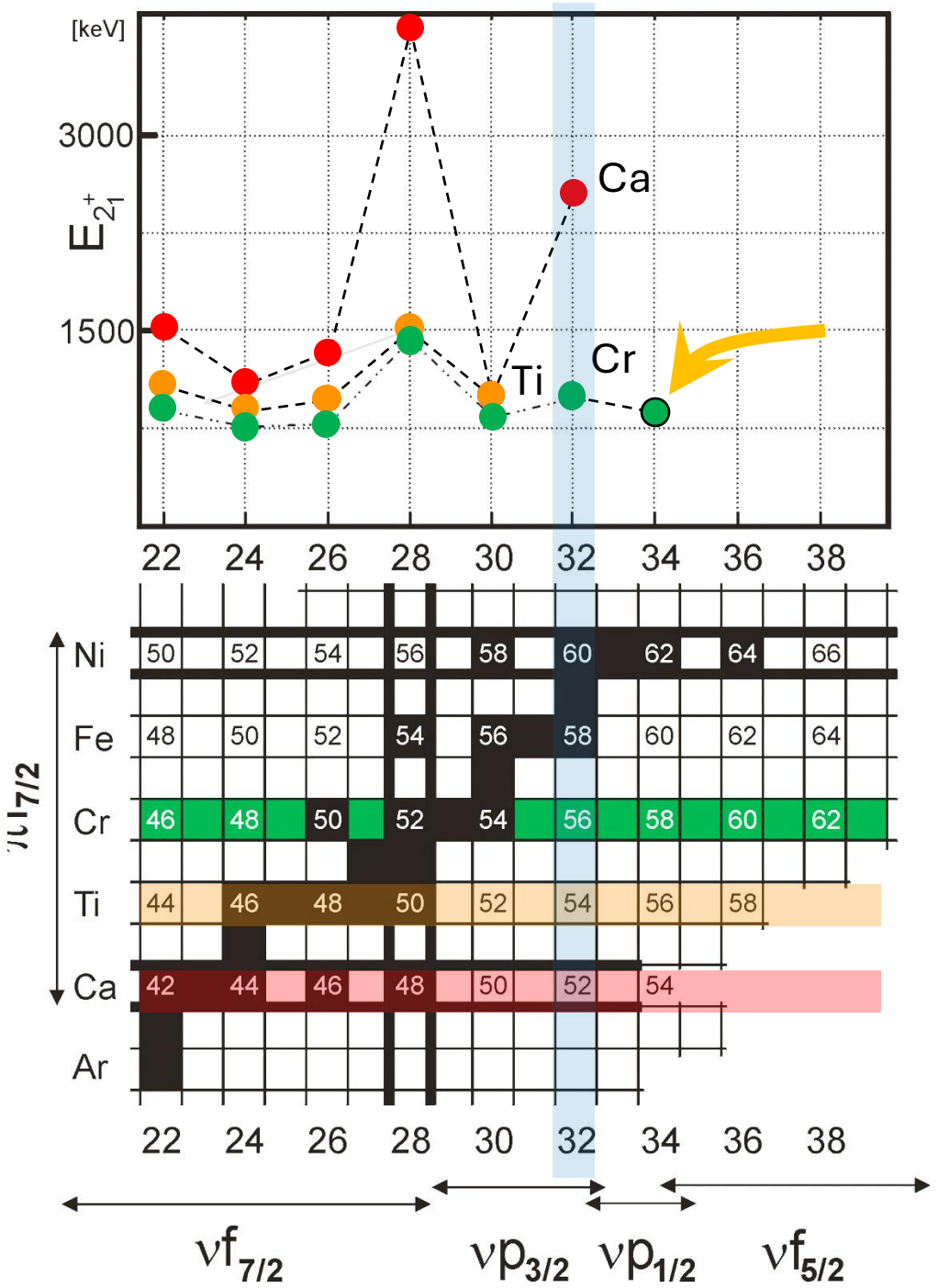
www.elsevier.nl/locate/npe

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]

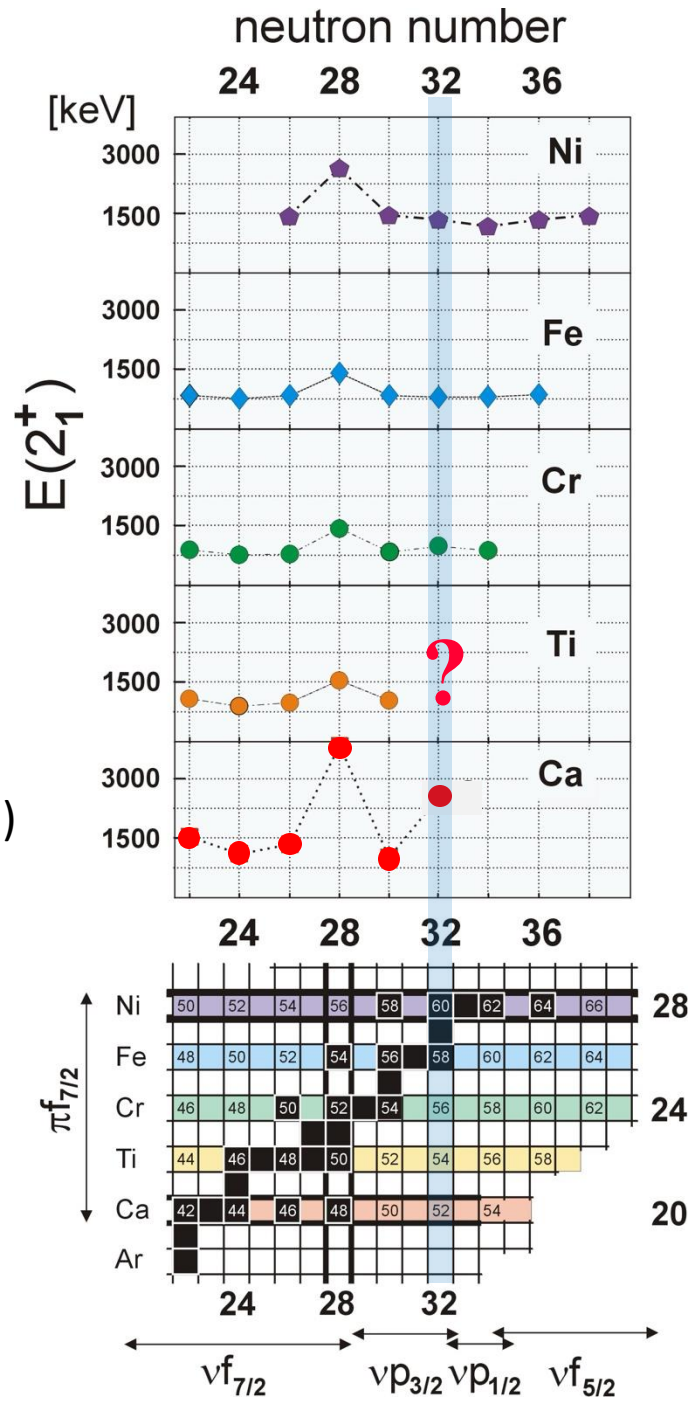
[a] *Department of Chemistry, Michigan State University, East Lansing, MI 48824, USA*
[b] *National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA*
[c] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824, USA*
[d] *Department of Physics, Florida State University, Tallahassee, FL 32306, USA*
[e] *Department of Physics, University of Notre Dame, Notre Dame, IN 46556, USA*

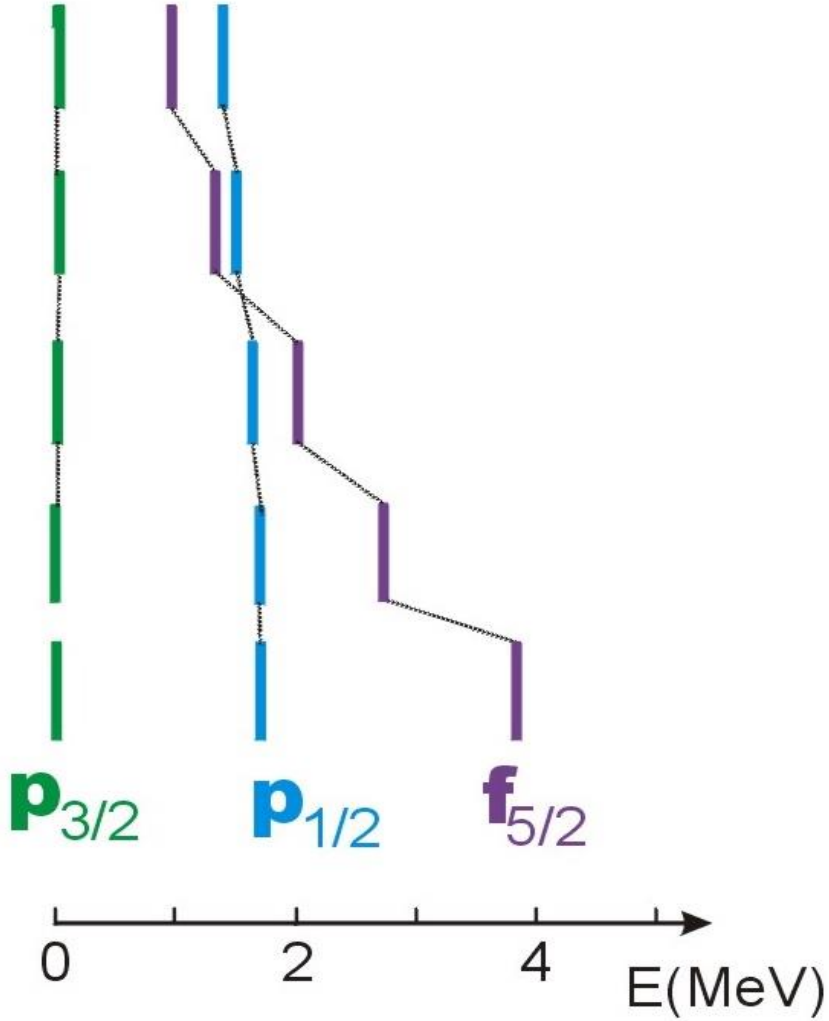
Received 28 March 2001; received in revised form 24 April 2001; accepted 1 May 2001
Editor: J.P. Schiffer



J.I. Prisciandaro *et. al*.,
Phys. Lett. B 510, 17 (2001)

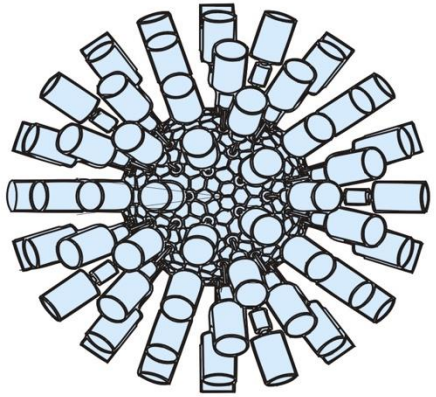
A. Huck *et al.*,
Phys. Rev. C 31, 2226 (1985)

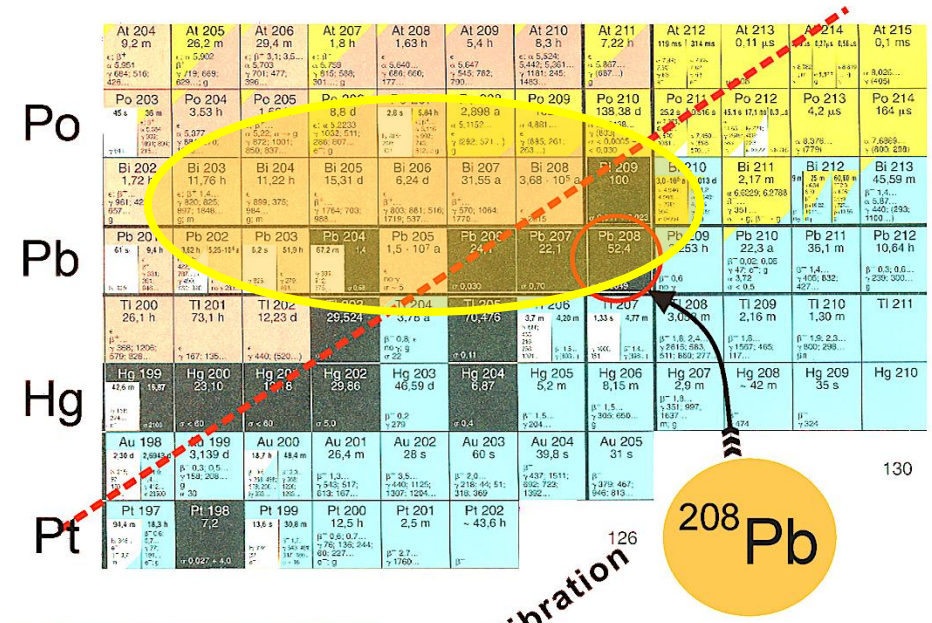


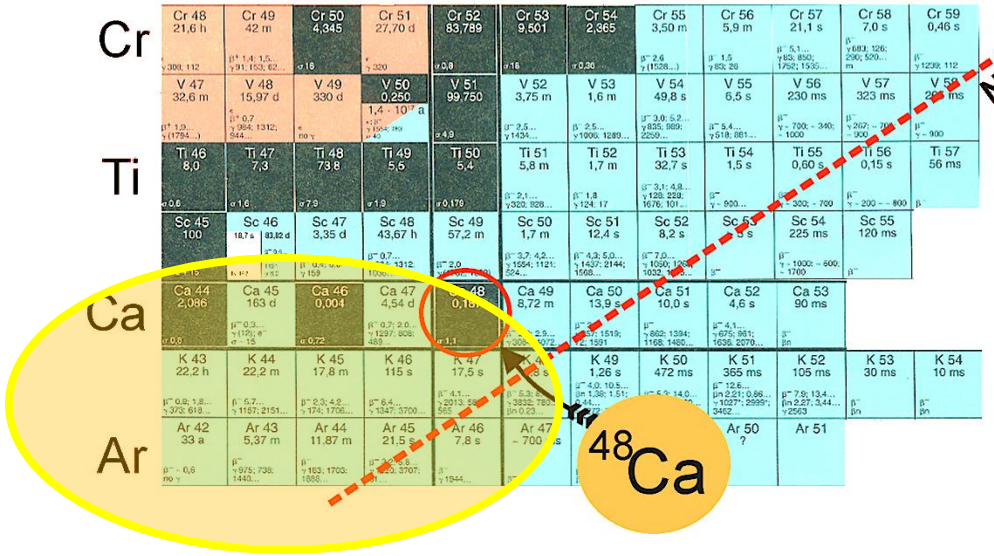


^{48}Ca (305 MeV) + ^{208}Pb (thick) ATLAS + GAMMASPHERE at Argonne

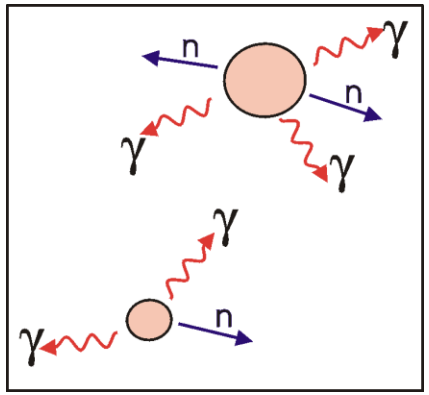
Gammasphere







two excited products



^{48}Ca (305 MeV) + ^{208}Pb (thick) ATLAS + GAMMASPHERE at Argonne

Gamma Spectroscopy of Neutron-Rich N=20-2[illegible]
Deep-Inelastic Heavy-Ion Reactions

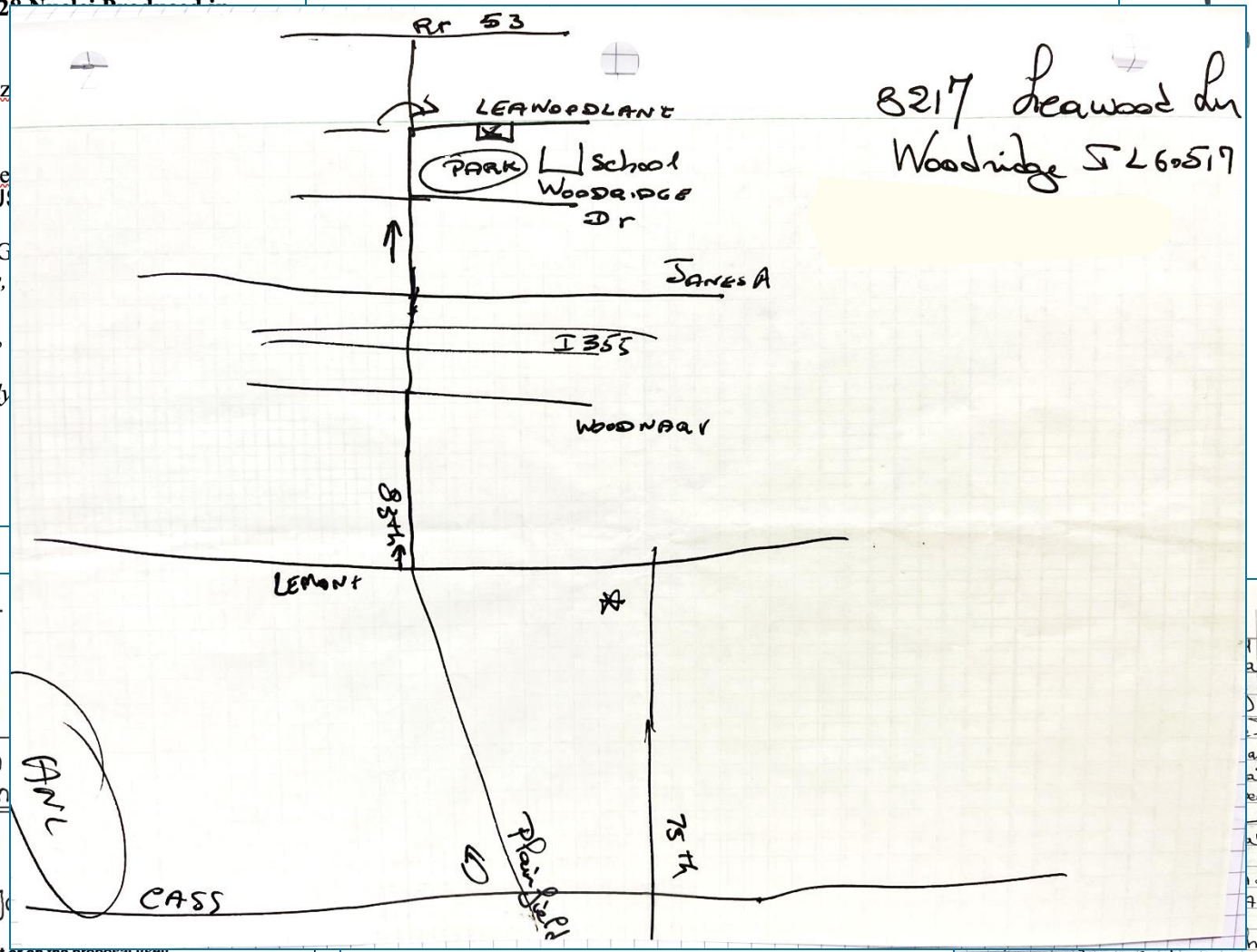
B. Fornal, R. Broda, W. Królas, T. Paw³at, J.Wrz
Institute of Nuclear Physics, Cracow, Poland

M. Carpenter, **R.V.F. Janssens,** C.J. Lister, D. Se
Argonne National Laboratory, Argonne, IL, U

P. J. Daly, C.T. Zhang, P. Bhattacharyya, Z.W. G
Chemistry and Physics Depts, Purdue University,

D.Bazzacco, S.Lunardi, G.Viesti, G. de Angelis,
l'Universita' and INFN, Padova, Italy
and INFN Laboratori Nazionali di Legnaro, Italy

J. Gerl
GSI, Darmstadt, Germany



ATLAS PROPOSAL FACT

Date: April 26, 1999

Title: Gamma Spectroscopy of Neutron-Rich
Produced in Deep-Inelastic Heavy Ion

Spokesperson and Alternate:	Telephone and e-mail:
B. Fornal	011 48 12 637 0222
R. V. F. Janssens	(630) 252 8426

** Please list all Participants and their home institute on a separate sheet or on the proposal itself.

Targets:	Beams:	Energies (MeV):	Intensities (pnA):	Beam Stop Material:
^{208}Pb, ^{238}U	^{48}Ca	285, 305 MeV	1.5 pnA	

LOGBOOK

Argonne

^{48}Ca + ^{208}Pb
17 - 20 Jan 2000

apes
Tape 9A&B Cont on Tape 2
-Trig: 12K Events/s 8.74
a/Ta 9.6K
ate 9.6K
ead+Pu 300
ape 8A&B
1&B Run 10
7&B
has problems - Should probably
have cleaned it - Decided to continue on Tape 1 alone.
16:16 Start ~~Run~~ Run 11 on Tape 11A&B (continued)
- Ic leaned Taper 3 (A&B) and Tape 12A & 12B are ready to go (once 11A &B are finished).

LOGBOOK

Argonne

$^{48}Ca + ^{208}Pb$
17 - 20 Jan 2000

42

8/16 9:30 am End Tapes
9:36 am Starting Tape 9A&B Coul on Tape 2

Rates: Ge FND 2.3K Pre-Trig: 12K Events/s 8.74
90° 2.1K Master 9.6K
Bckw 2.1K Date 9.6K
Dead+PU 300

13:13 End Tape 8A&B

13:16 Start Tape 11A&B Run 10
12A&B

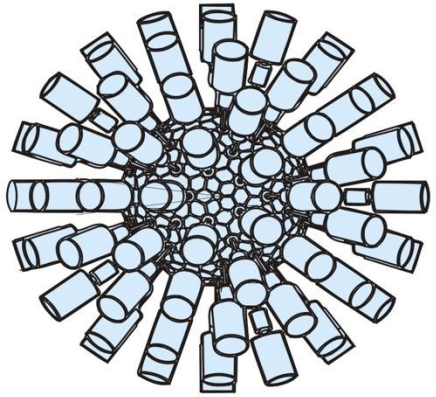
14:15 Tape 3 Tape B has problems - ~~Should~~ Should probably have cleaned it - Decided to continue on Tape 1 alone.

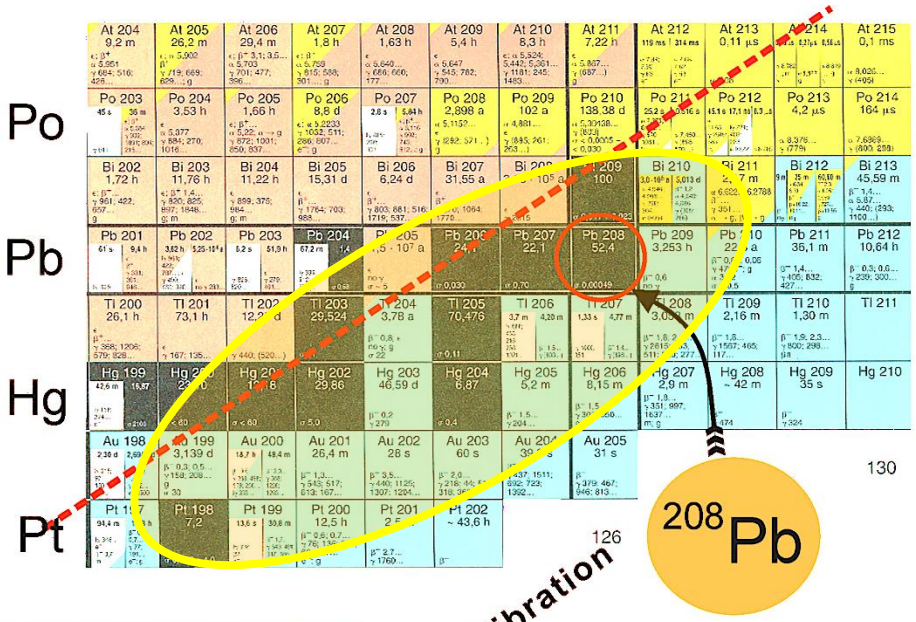
16:16 Start ~~Run~~ Run 11 on Tape 11A&B (continued)

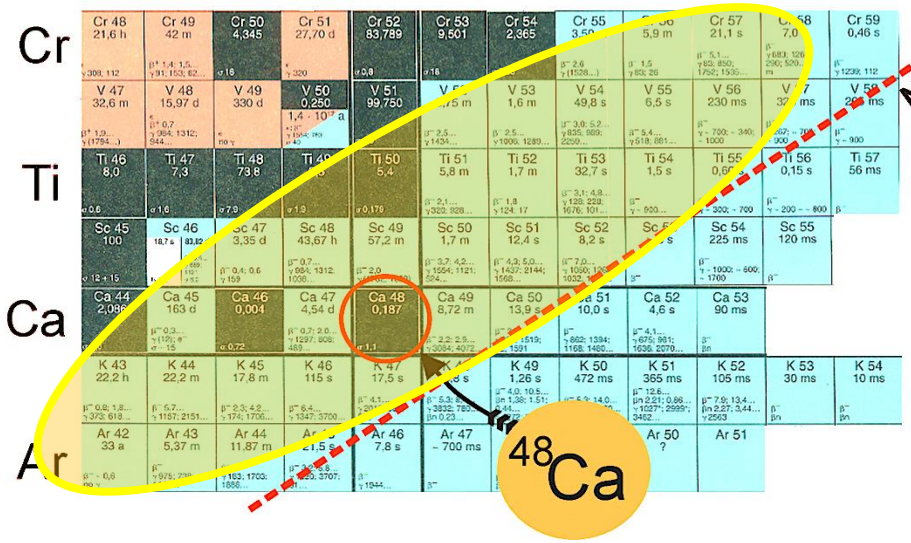
→ I cleaned Taper 3 (A&B) and Tape 12A & 12B are ready to go (once 11A & B are finished).

^{48}Ca (305 MeV) + ^{208}Pb (thick) ATLAS + GAMMASPHERE at Argonne

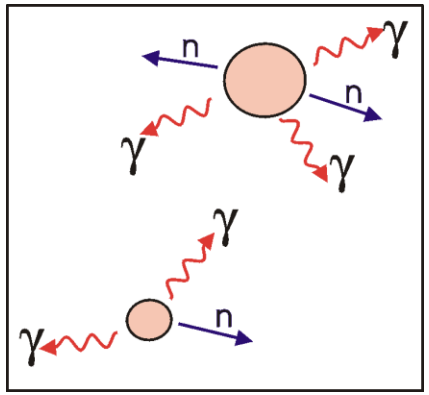
Gammasphere







two excited products

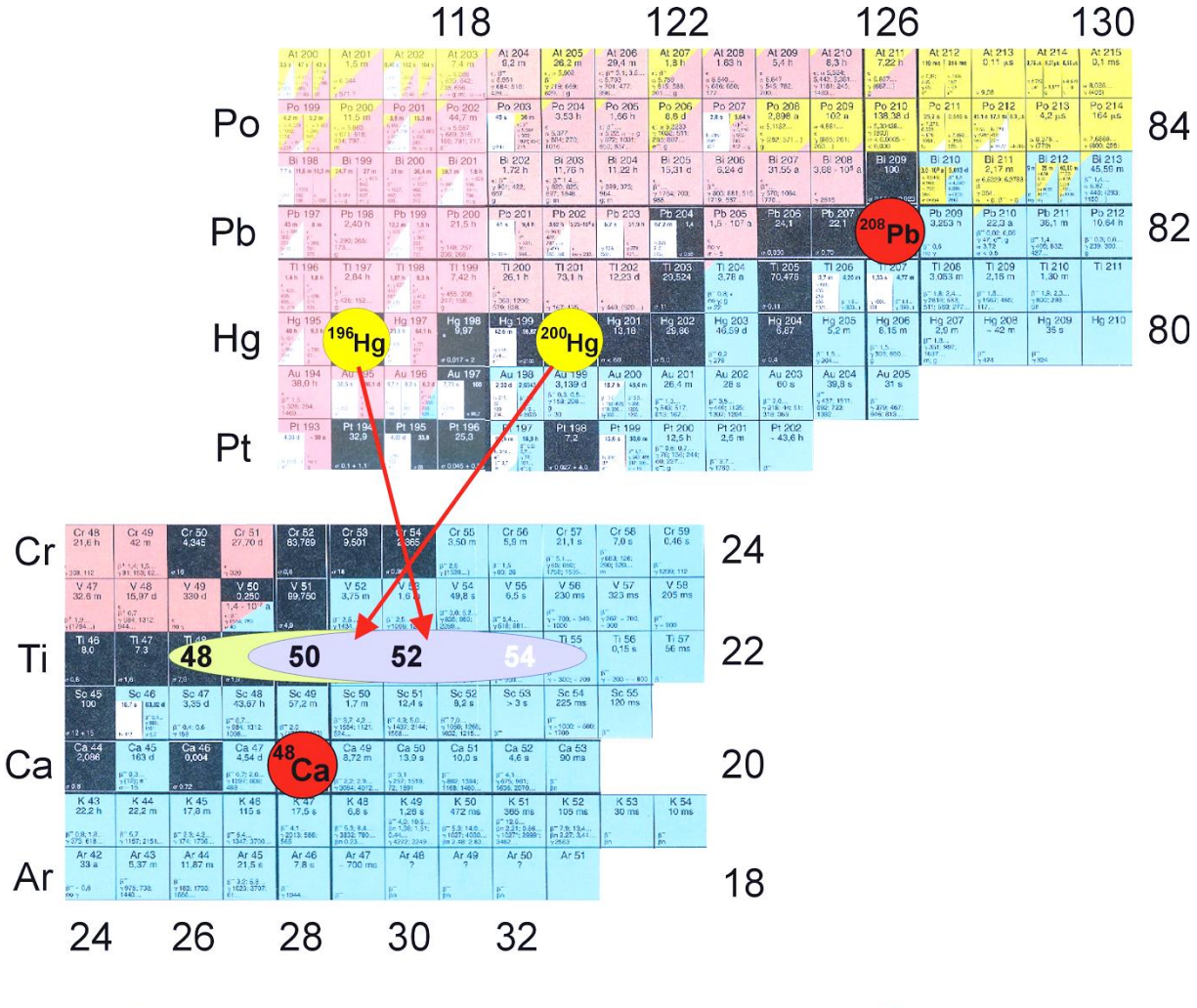


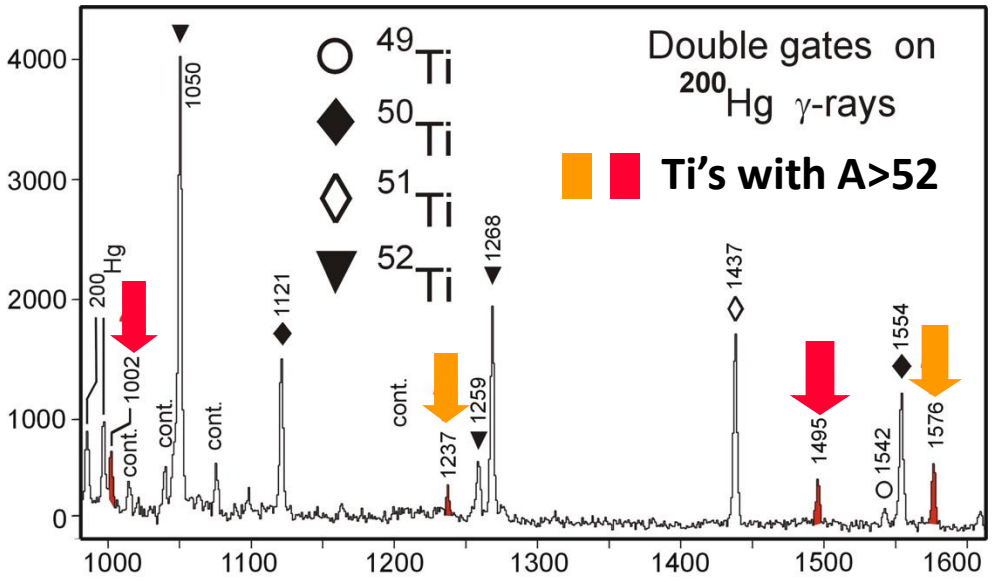
Robert's visit to Purdue University – April 2001

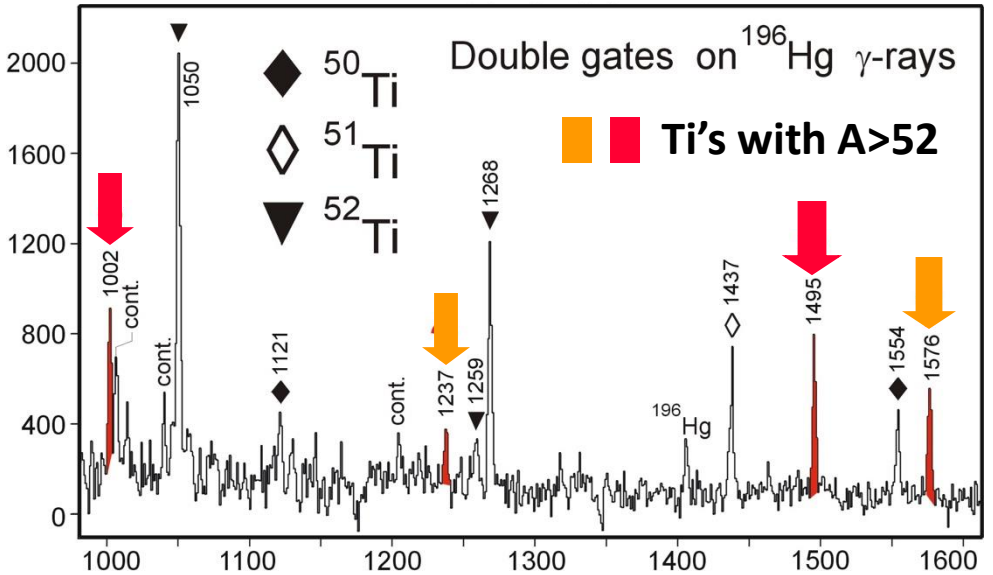
The Physics Building at Purdue University in West Lafayette, Indiana

$^{48}Ca + {}^{208}Pb \longrightarrow$ Hg + Ti + x*n*

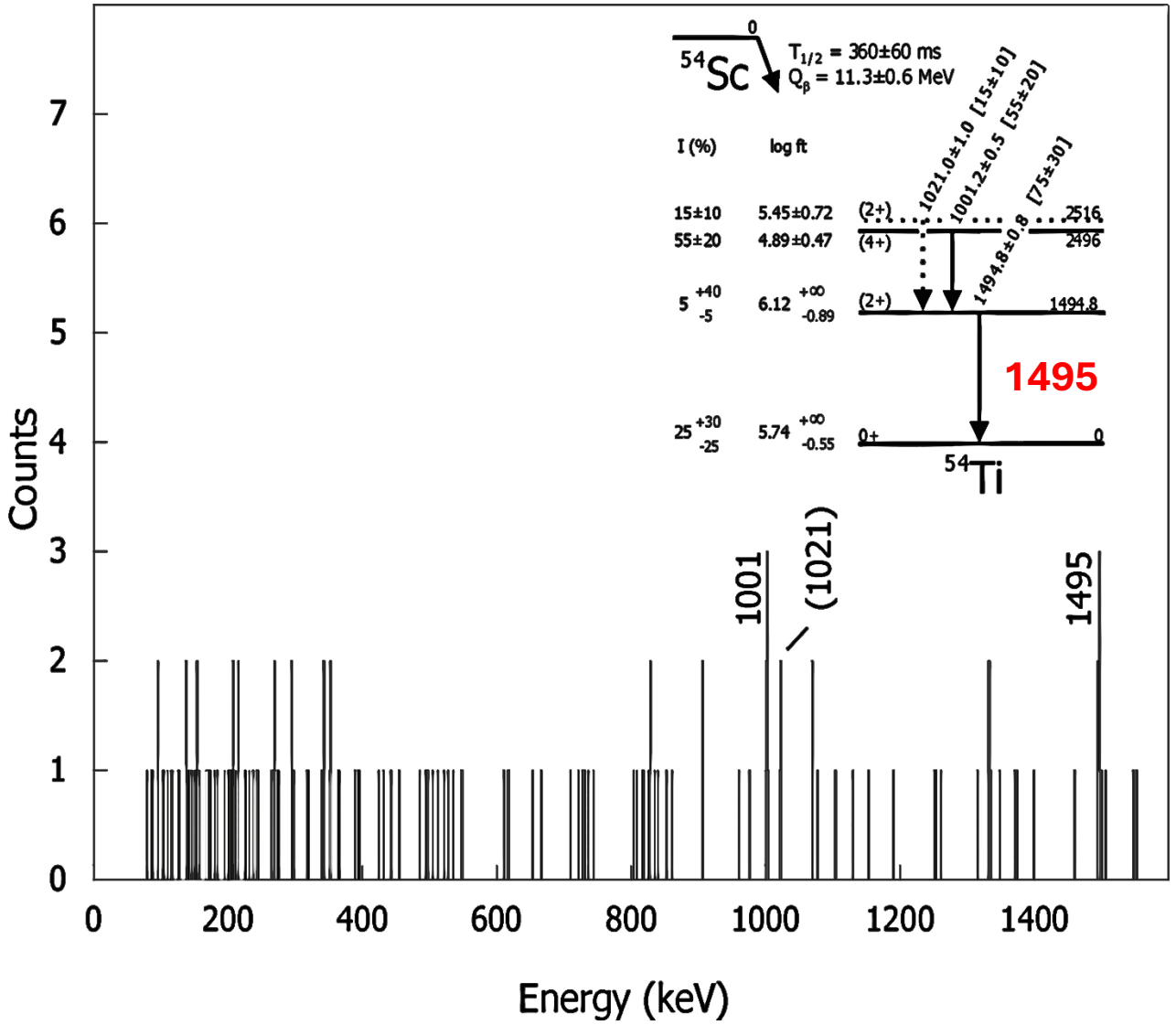
with GAMMASPHERE at ARGONNE



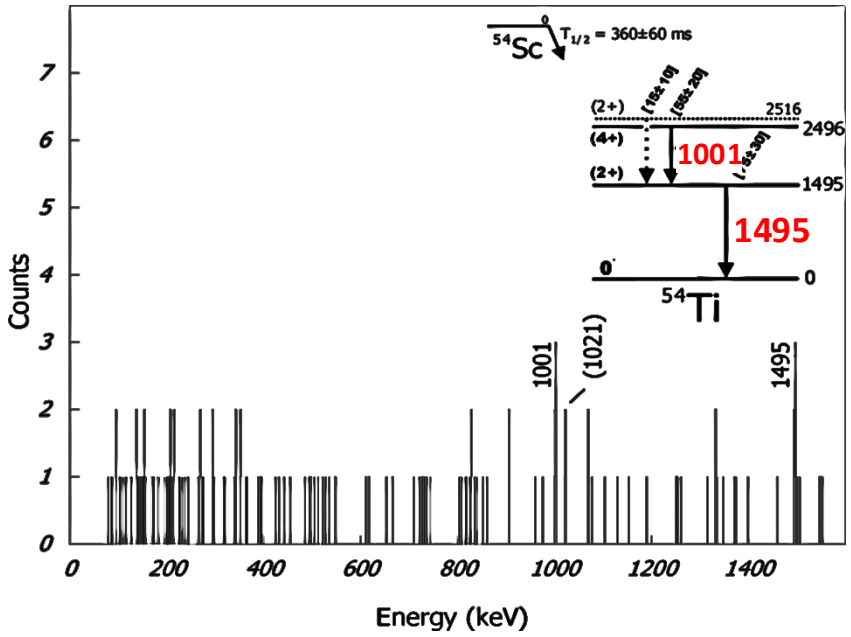




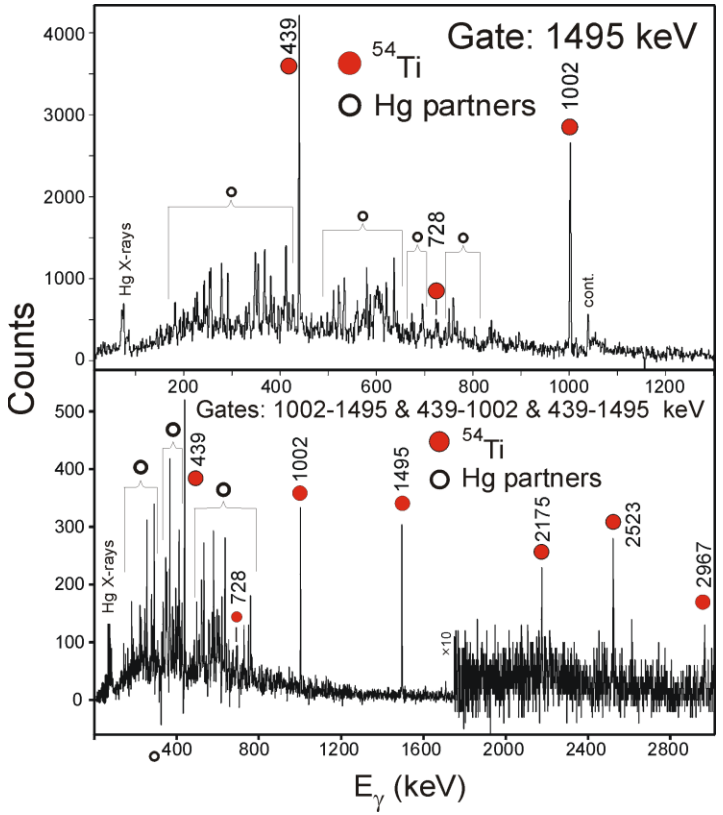
$^{48}Ca+^{208}Pb$ GAMMASPHERE results matched perfectly with β-decay measurement of ^{54}Sc performed at MSU using Kr-beam fragmentation

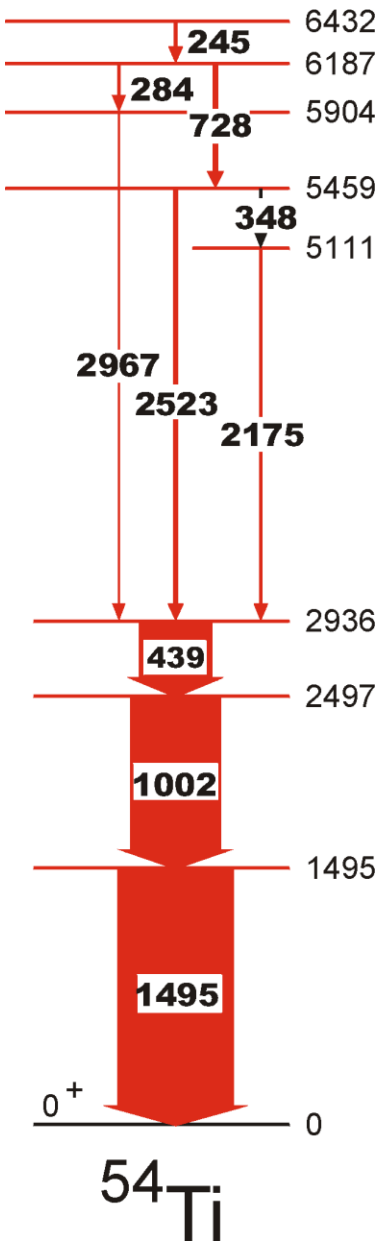


Beta-decay of the ^{54}Sc parent following Kr-beam fragmentation at MSU



Deep-inelastic reaction ^{48}Ca + ^{208}Pb with Gammasphere at Argonne





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PHYSICS LETTERS B

www.elsevier.com/locate/npe

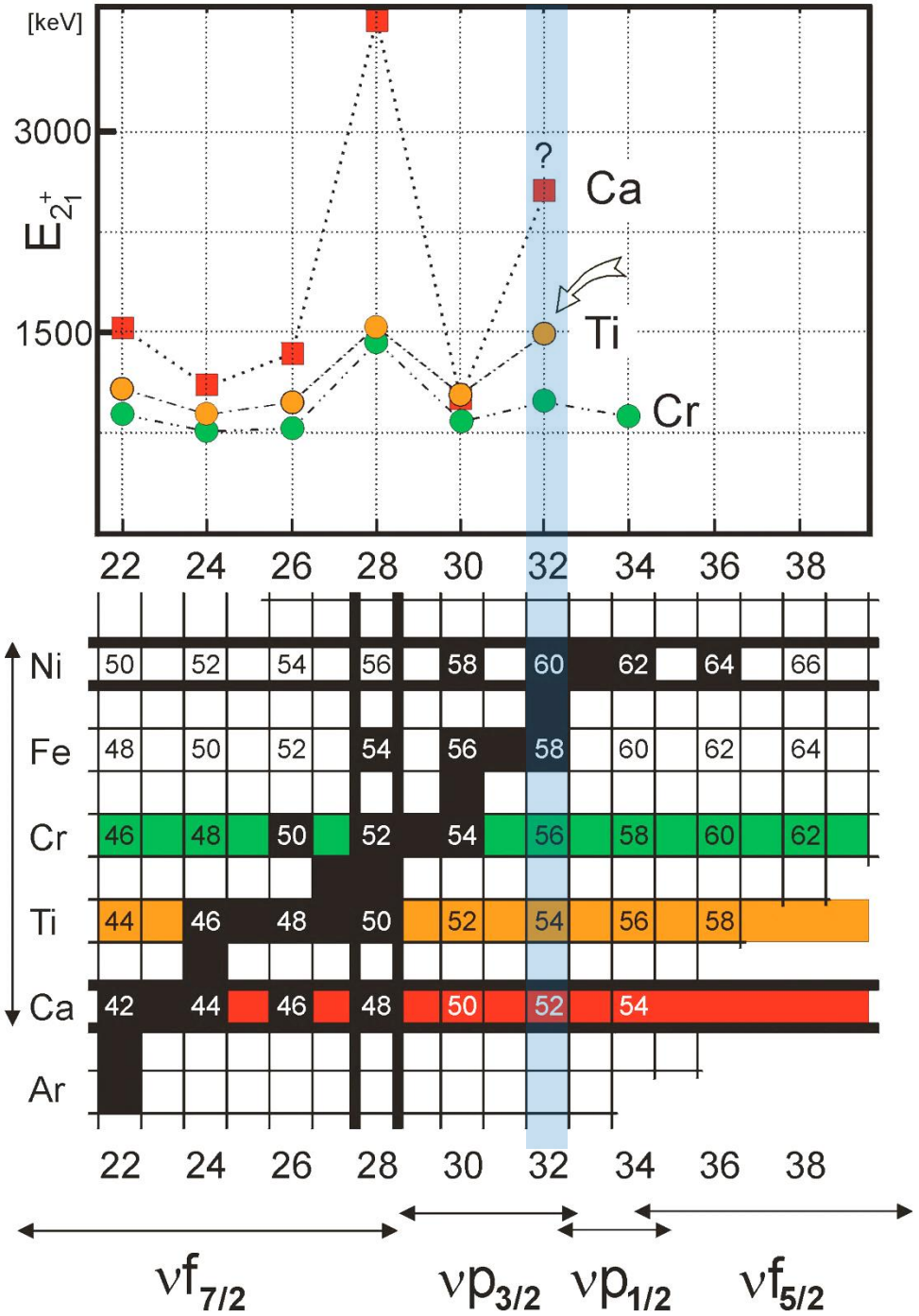
Physics Letters B 546, 2002, 55-62

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]

Abstract

The level structure of $^{54}Ti_{32}$ has been explored for the first time by combining β-decay measurements from fragmentation products with prompt γ-ray spectroscopy following deep inelastic reactions. The latter technique was also instrumental in tracing $^{52}Ti_{30}$ to higher spin. The data provide new tests of effective interactions for full *pf*-shell calculations in neutron-rich nuclei above ^{48}Ca. The data indicate the presence of a significant subshell gap at N = 32 and comparisons between theory and experiment suggest an additional shell closure at N = 34 in Ca and Ti isotopes.



Physical Review C 65, 061301(R) (2002)

Effective interaction for *pf*-shell nuclei

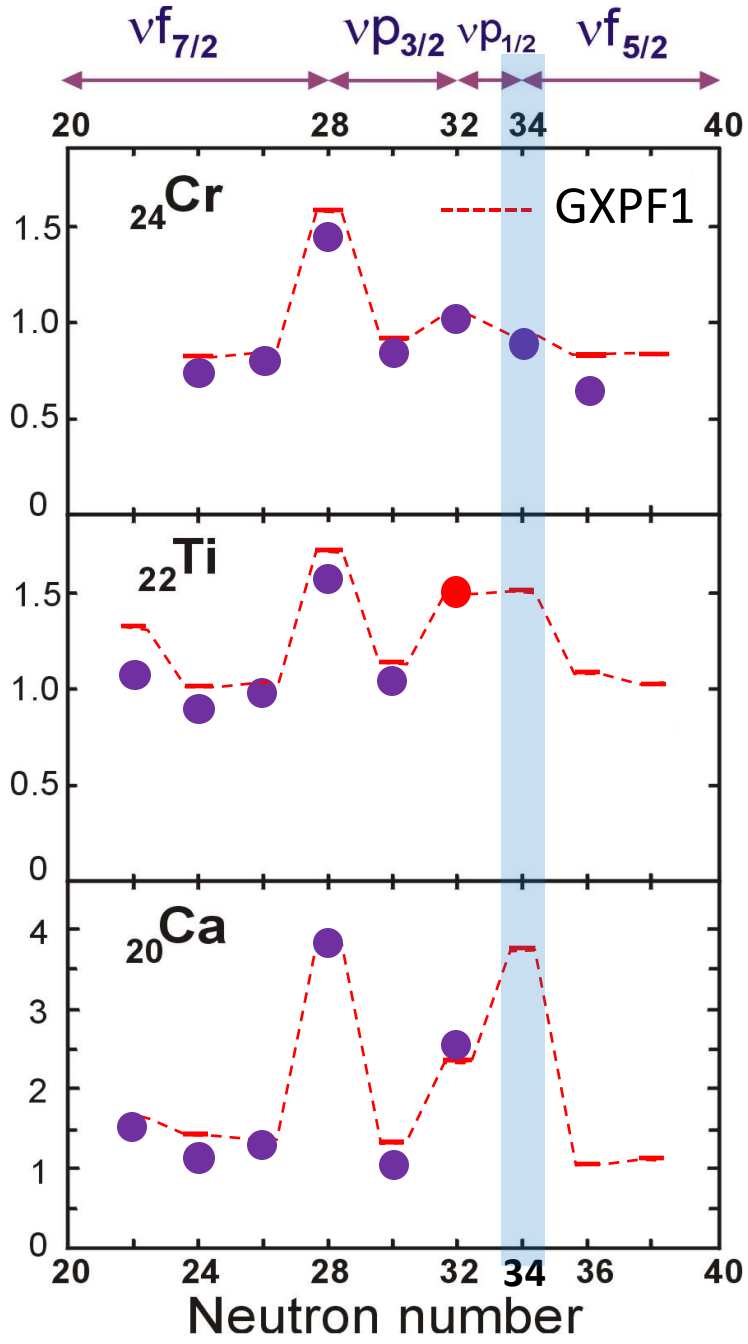
M. Honma
Center for Mathematical Sciences, University of Aizu, Tsuruga, Ikki-machi, Aizu-Wakamatsu, Fukushima 965-8580, Japan

T. Otsuka
Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan
and RIKEN, Hirosawa, Wako-shi, Saitama 351-0198, Japan

B. A. Brown
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-1321

T. Mizusaki
Institute of Natural Sciences, Senshu University, Higashimita, Tama, Kawasaki, Kanagawa 214-8580, Japan
(Received 17 October 2001; revised manuscript received 19 April 2002; published 31 May 2002)

GXPF1 Shell Model interaction

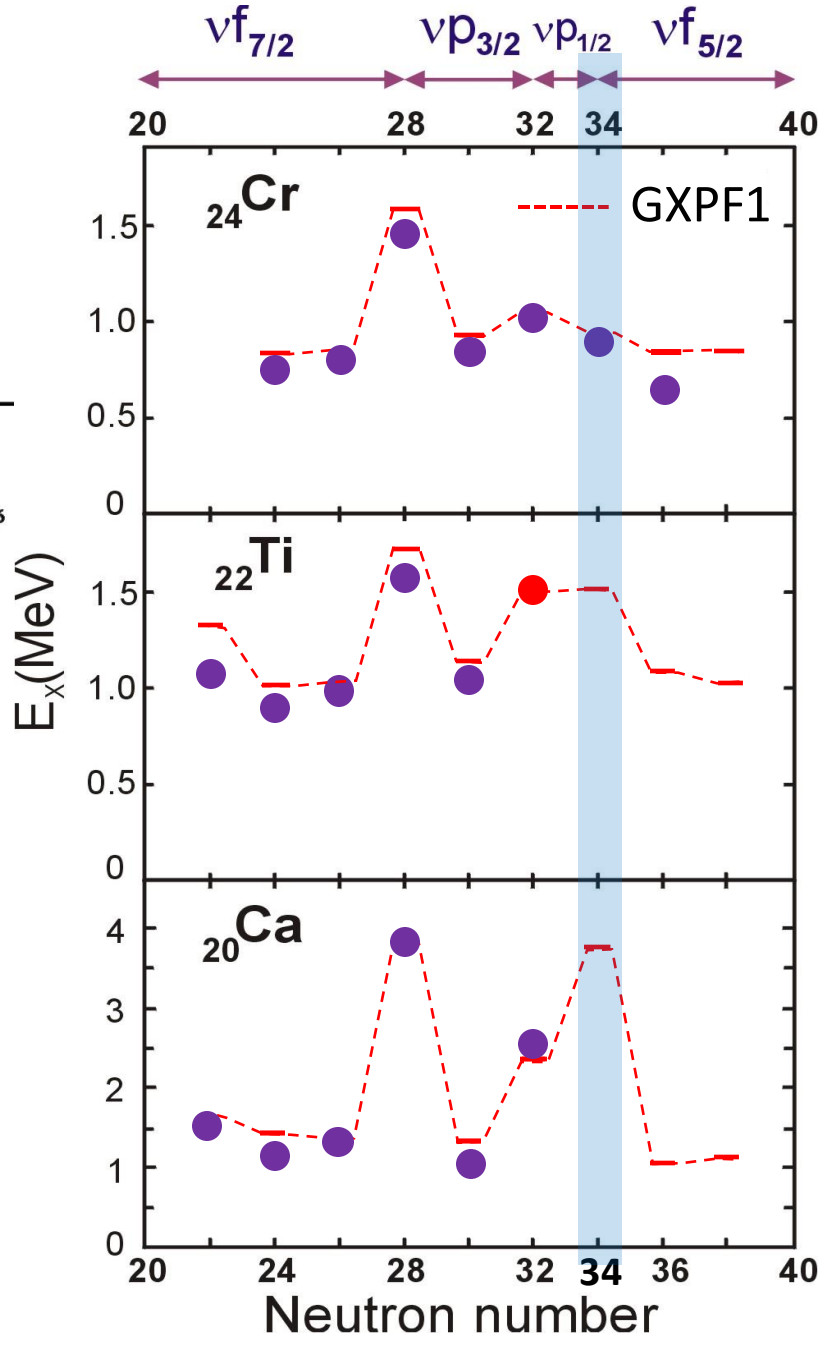


VOLUME 87, NUMBER 8 Physical Review Letters 87, 082502 (2001)

Magic Numbers in Exotic Nuclei and Spin-Isospin Properties of the *NN* Interaction

Takaharu Otsuka,[1,2] Rintaro Fujimoto,[1] Yutaka Utsuno,[3] B. Alex Brown,[4] Michio Honma,[5] and Takahiro Mizusaki[6]
[1]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan*
[2]*RIKEN, Hirosawa, Wako-shi, Saitama 351-0198, Japan*
[3]*Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan*
[4]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824*
[5]*Center for Mathematical Sciences, University of Aizu, Tsuruga, Ikki-machi, Aizu-Wakamatsu, Fukushima 965-8580, Japan*
[6]*Department of Law, Senshu University, Higashimita, Tama, Kawasaki, Kanagawa, 214-8580, Japan*
(Received 31 March 2001; published 3 August 2001)

From the strength of $V_{\tau\sigma}$ interaction, we can predict other magic numbers, for instance, N=34 associated with the $\pi f_{7/2}$ - $\nu f_{5/2}$ interaction.



Search for ^{56}Ti

Same Techniques: β decay and Deep Inelastic reactions

MSU: ^{86}Kr fragmentation
A1900 fragment separator
$1.3 \cdot 10^4$ ^{56}Sc implants

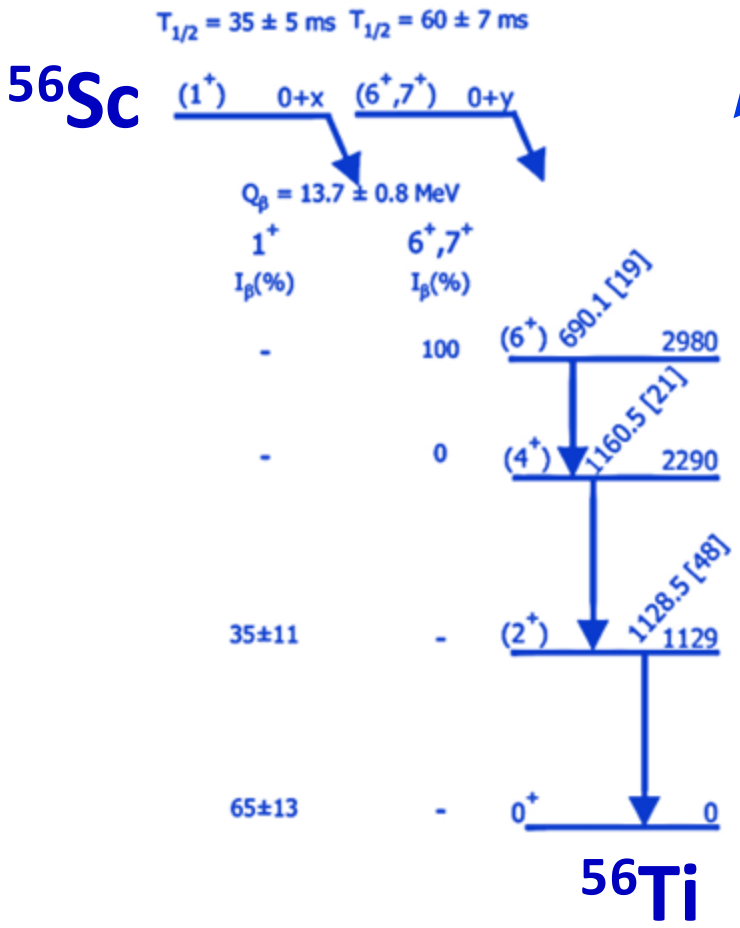
GAMMASPHEREA at ATLAS
^{48}Ca (330 MeV) + ^{238}U (thick)
Use ^{238}U as a reservoir of neutrons

- „Search for the N=34 shell closure"
  at MSU **in 2003**
  (spokespersons: P. Mantica, S. Liddick)

- „Yrast Structure of Neutron-Rich N=30-34 Nuclei – Search for the Shell Gap at N=34" ;
  GAMMASPHERE at ATLAS **in 2003**
  (spokespersons: B. Fornal, **R.V.F. Janssens**, P. Mantica)

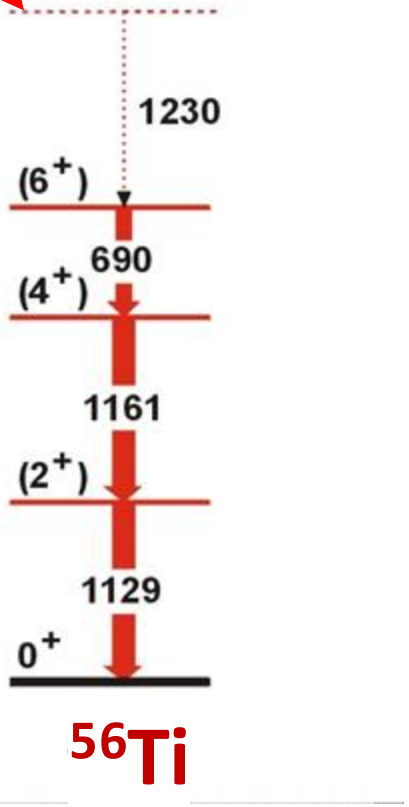
Search for ^{56}Ti

Same Techniques: β decay and Deep Inelastic reactions



S.N. Liddick et al., PRL 92, 072502 (2004)

S.N.Liddick (P.F.Mantica, R.V.F.Janssens, B.Fornal) et al., Phys. Rev. C 70, 064303 (2004)



B.Fornal (R.V.F.Janssens, P.F.Mantica) et al., Phys. Rev. C 70, 064304 (2004)

Physical Review C 70, 064303, 2004

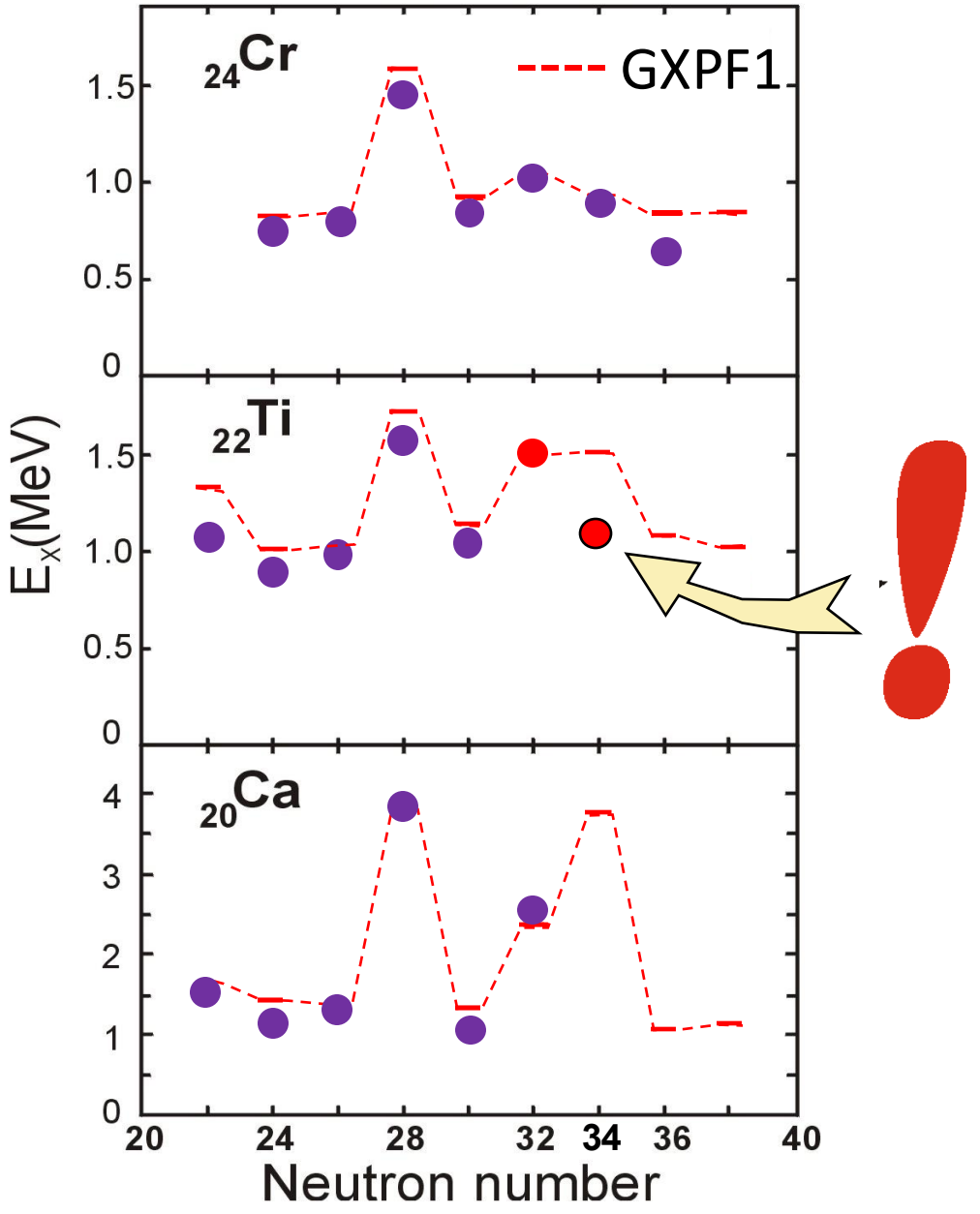
Development of shell closures at N=32,34. I. β decay of neutron-rich Sc isotopes

S. N. Liddick,[1,2] P. F. Mantica,[1,2] R. Broda,[3] B. A. Brown,[1,4] M. P. Carpenter,[5] A. D. Davies,[1,4] B. Fornal,[3] T. Glasmacher,[1,4] D. E. Groh,[1,2] M. Honma,[6] M. Horoi,[7] R. V. F. Janssens,[5] T. Mizusaki,[8] D. J. Morrissey,[1,2] A. C. Morton,[1] W. F. Mueller,[1] T. Otsuka,[9,10] J. Pavan,[11] H. Schatz,[1,4] A. Stolz,[1] S. L. Tabor,[11] B. E. Tomlin,[1,2] and M. Wiedeking[11]

Physical Review C 70, 064304, 2004

Development of shell closures at N=32,34. II. Lowest yrast excitations in even-even Ti isotopes from deep-inelastic heavy-ion collisions

B. Fornal,[1] S. Zhu,[2] R. V. F. Janssens,[2] M. Honma,[3] R. Broda,[1] P. F. Mantica,[4,5] B. A. Brown,[4,6] M. P. Carpenter,[2] P. J. Daly,[7] S. J. Freeman,[2,8] Z. W. Grabowski,[7] N. J. Hammond,[2] F. G. Kondev,[9] W. Królas,[1] T. Lauritsen,[2] S. N. Liddick,[4,5] C. J. Lister,[2] E. F. Moore,[2] T. Otsuka,[10] T. Pawłat,[1] D. Seweryniak,[2] B. E. Tomlin,[4,5] and J. Wrzesiński[1]



Modification of the GXPF1 interaction – a GXPF1A interaction

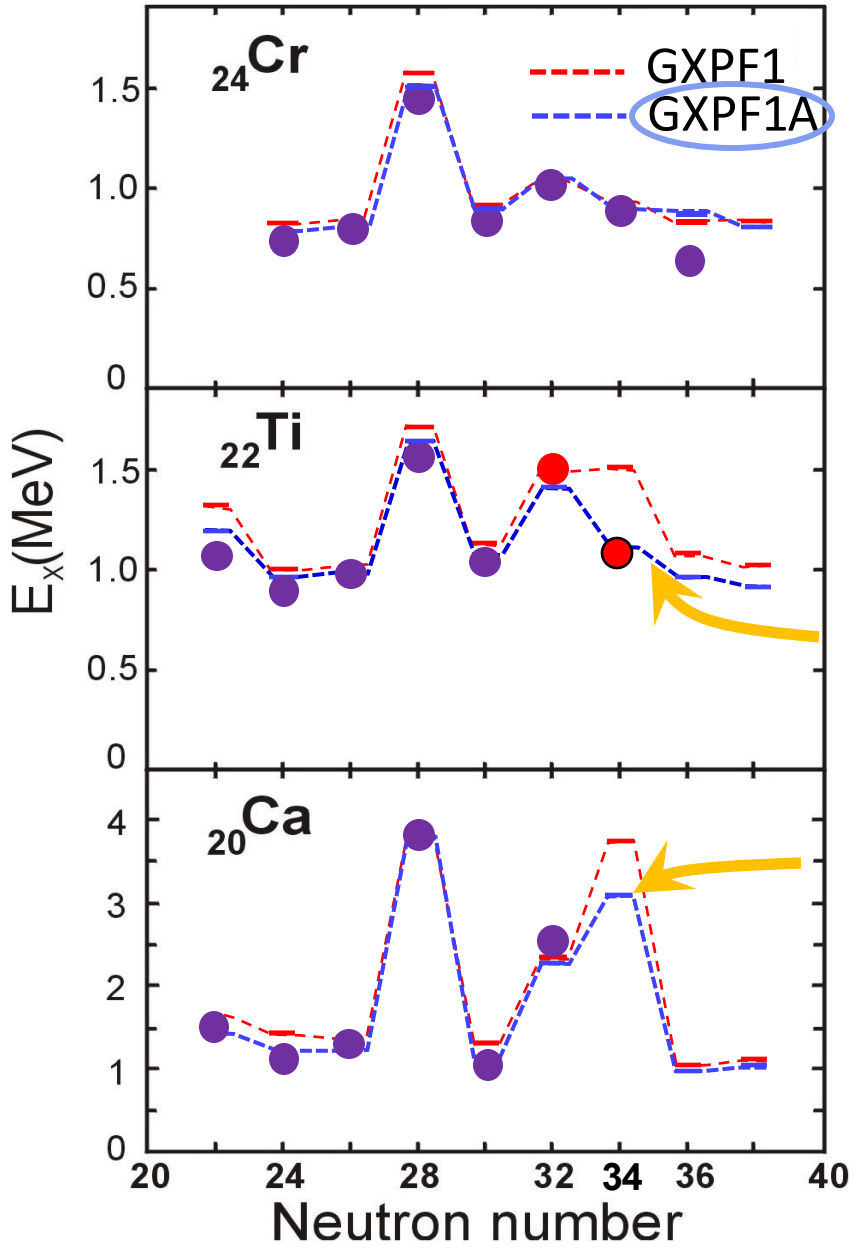
Four **T=1** two body matrix elements involving orbitals $p_{1/2}$ and $f_{5/2}$ have been changed.

Eur. Phys. J. A 25, 499 (2005)

EPJ A direct
electronic only

Shell-model description of neutron-rich pf-shell nuclei with a new effective interaction GXPF1

M. Honma, T. Otsuka, B.A. Brown, and T. Mizusaki


$_{24}$Cr
GXPF1
GXPF1A
$_{22}$Ti
$_{20}$Ca
E_x(MeV)
Neutron number
0
0.5
1.0
1.5
1
2
3
4
20
24
28
32
34
36
40

In 2006 and 2007,
we made two attempts
at MSU to identify
the first 2^+ excitation in ^{54}Ca:

- by measuring gamma rays following beta decay of ^{54}K

- by searching for a low-lying microsecond isomer in ^{54}Ca, expected to decay to the 2^+ state.

We did not succceed – the statistics were too low – however, the cumulative spectroscopic evidence that we gathered along the way on ^{53,54,55,56}Ti, ^{52,53,54,55}Sc, and ^{51}Ca indicated the presence of a shell gap at N=34!

Six years later

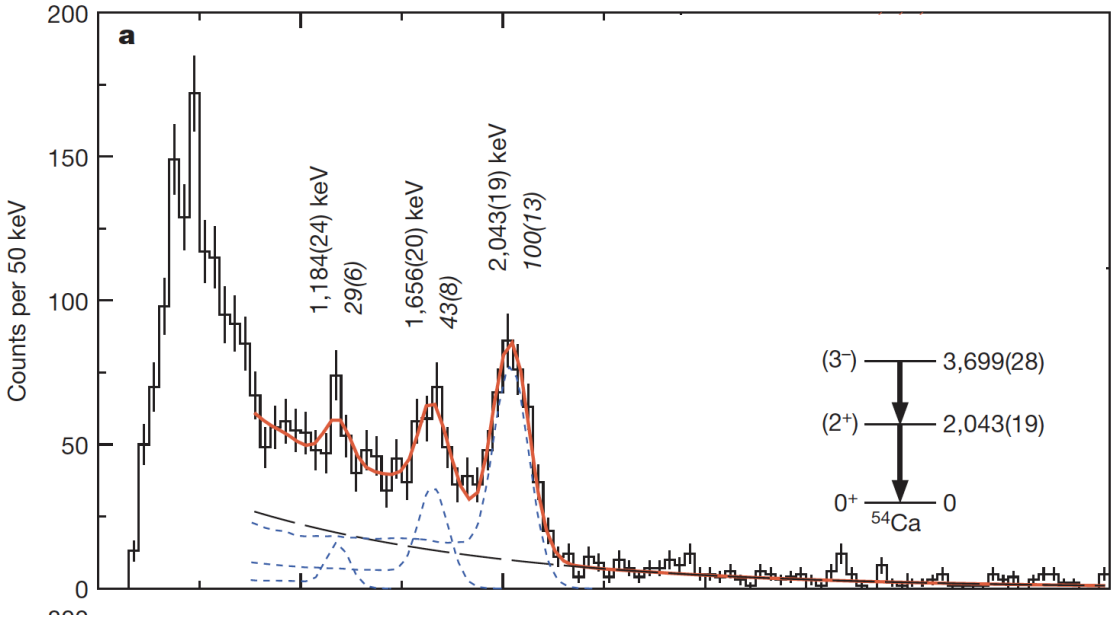
NATURE 498 (2013) 346

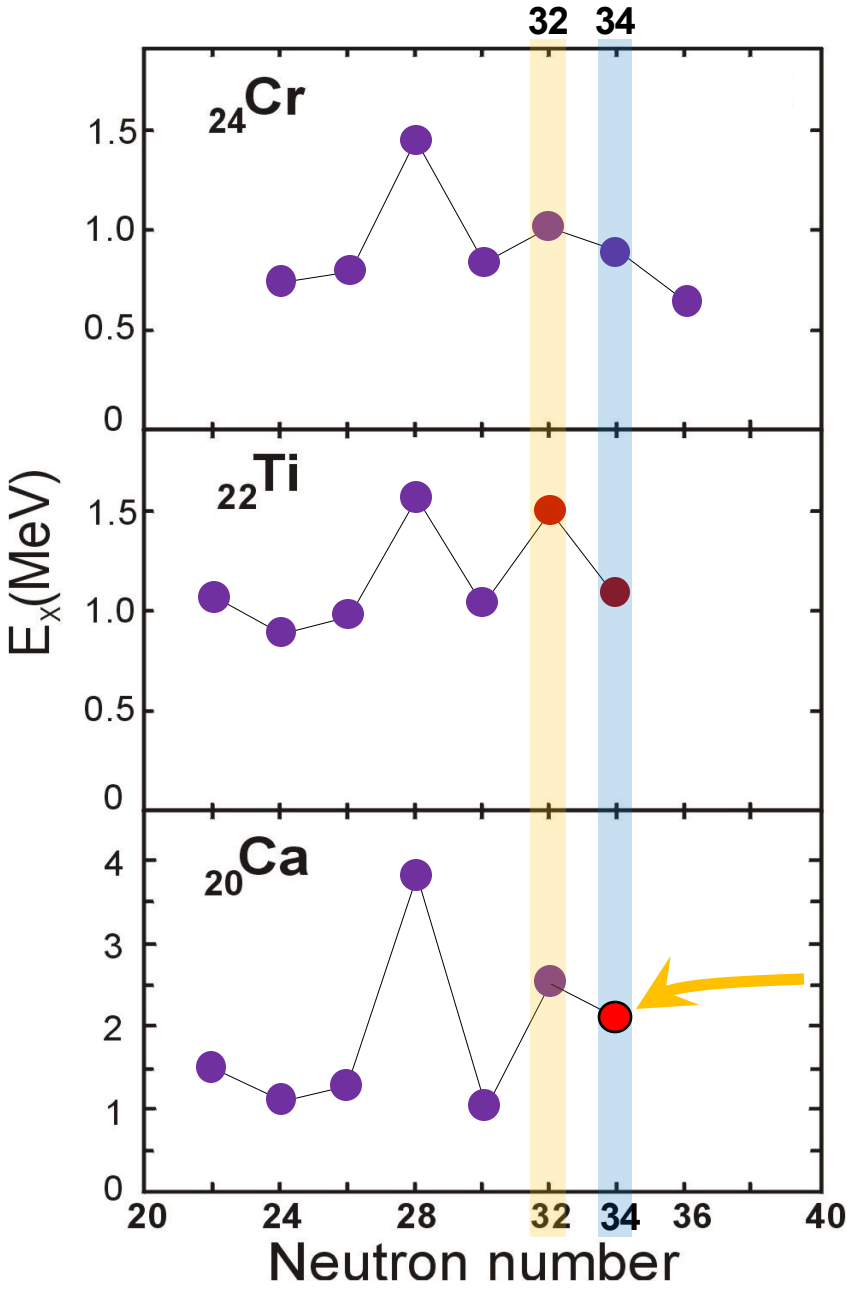
Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

10 OCTOBER 2013 | VOL 502 | NATURE | 207

Radioactive Isotope Beam Factory at RIKEN





NATURE 498 (2013) 346

Masses of exotic calcium isotopes pin down nuclear forces

F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[7,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

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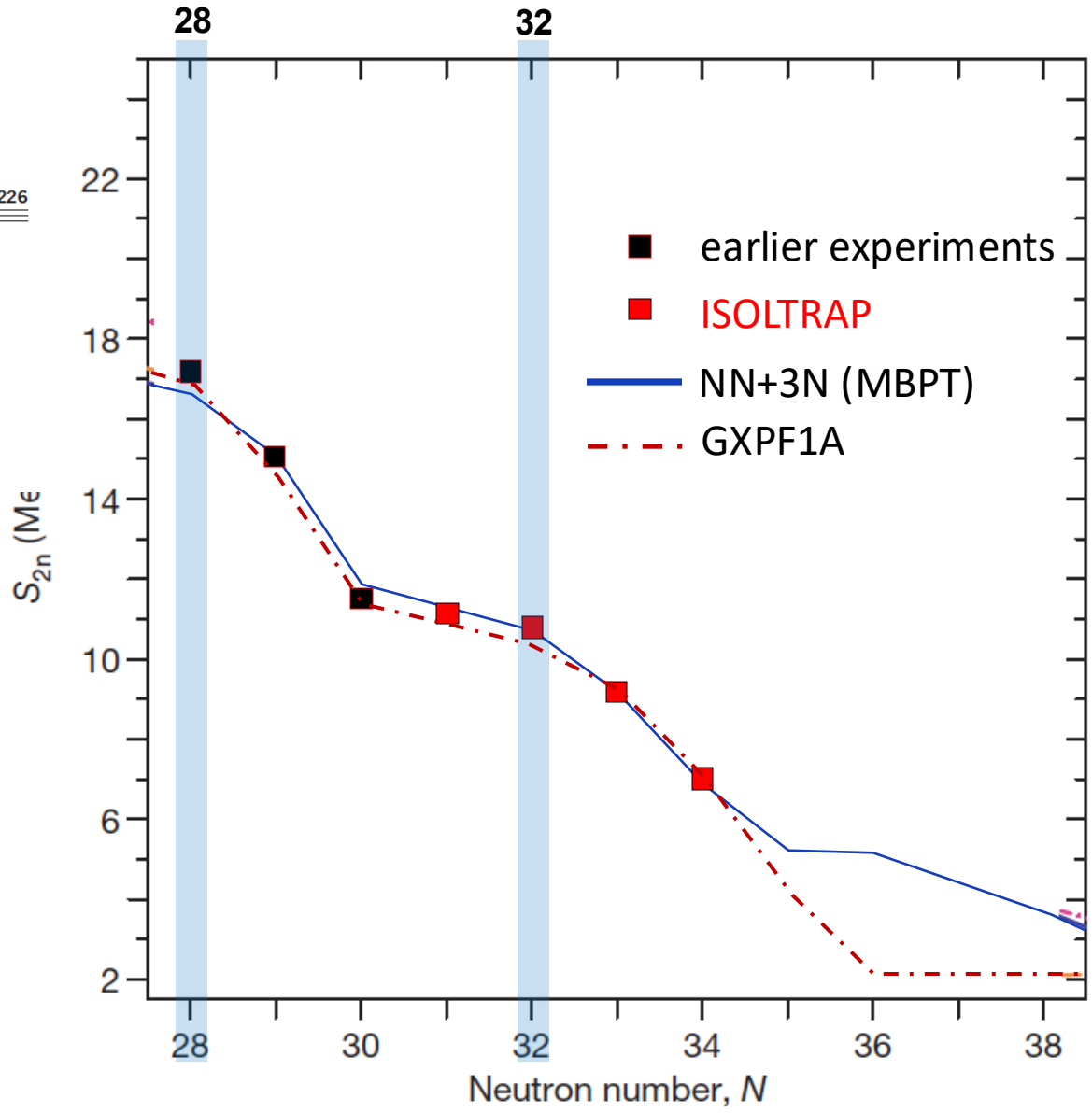
ISOLDE CERN

The measured masses unambiguously establish **a prominent shell closure at neutron number N = 32**, in excellent agreement with our theoretical calculations.



Phys. Rev. Lett. 121, 022506 (2018)

Magic Nature of Neutrons in ^{54}Ca: First Mass Measurements of $^{55-57}$Ca

S. Michimasa,[1,*] M. Kobayashi,[1] Y. Kiyokawa,[1] S. Ota,[1] D. S. Ahn,[2] H. Baba,[2] G. P. A. Berg,[3] M. Dozono,[1] N. Fukuda,[2] T. Furuno,[4] E. Ideguchi,[5] N. Inabe,[2] T. Kawabata,[4] S. Kawase,[6] K. Kisamori,[1] K. Kobayashi,[7] T. Kubo,[8,9] Y. Kubota,[2] C. S. Lee,[1,2] M. Matsushita,[1] H. Miya,[1] A. Mizukami,[10] H. Nagakura,[7] D. Nishimura,[11] H. Oikawa,[10] H. Sakai,[2] Y. Shimizu,[2] A. Stolz,[9] H. Suzuki,[2] M. Takaki,[1] H. Takeda,[2] S. Takeuchi,[12] H. Tokieda,[1] T. Uesaka,[2] K. Yako,[1] Y. Yamaguchi,[1] Y. Yanagisawa,[2] R. Yokoyama,[13] K. Yoshida,[2] and S. Shimoura[1]

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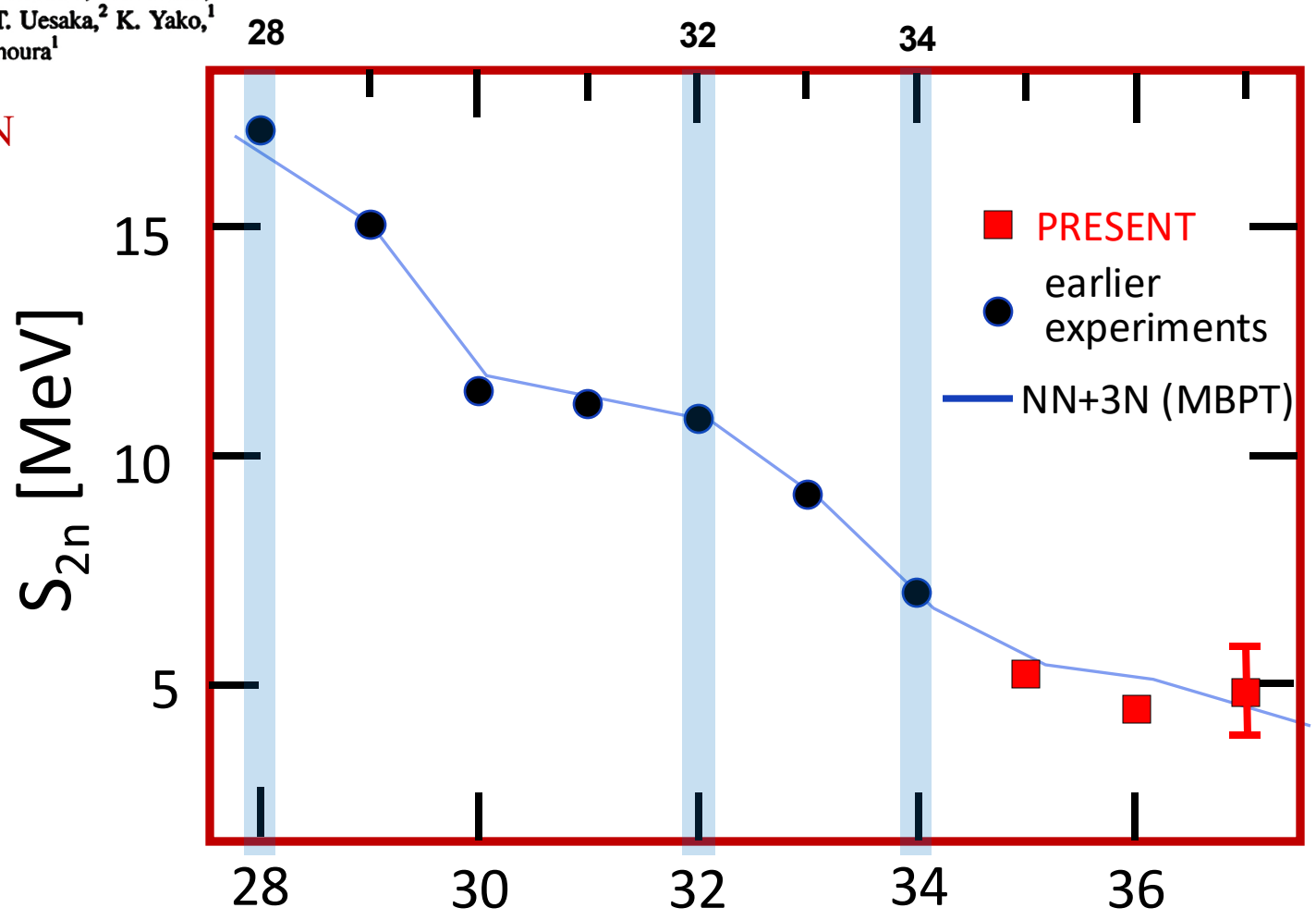
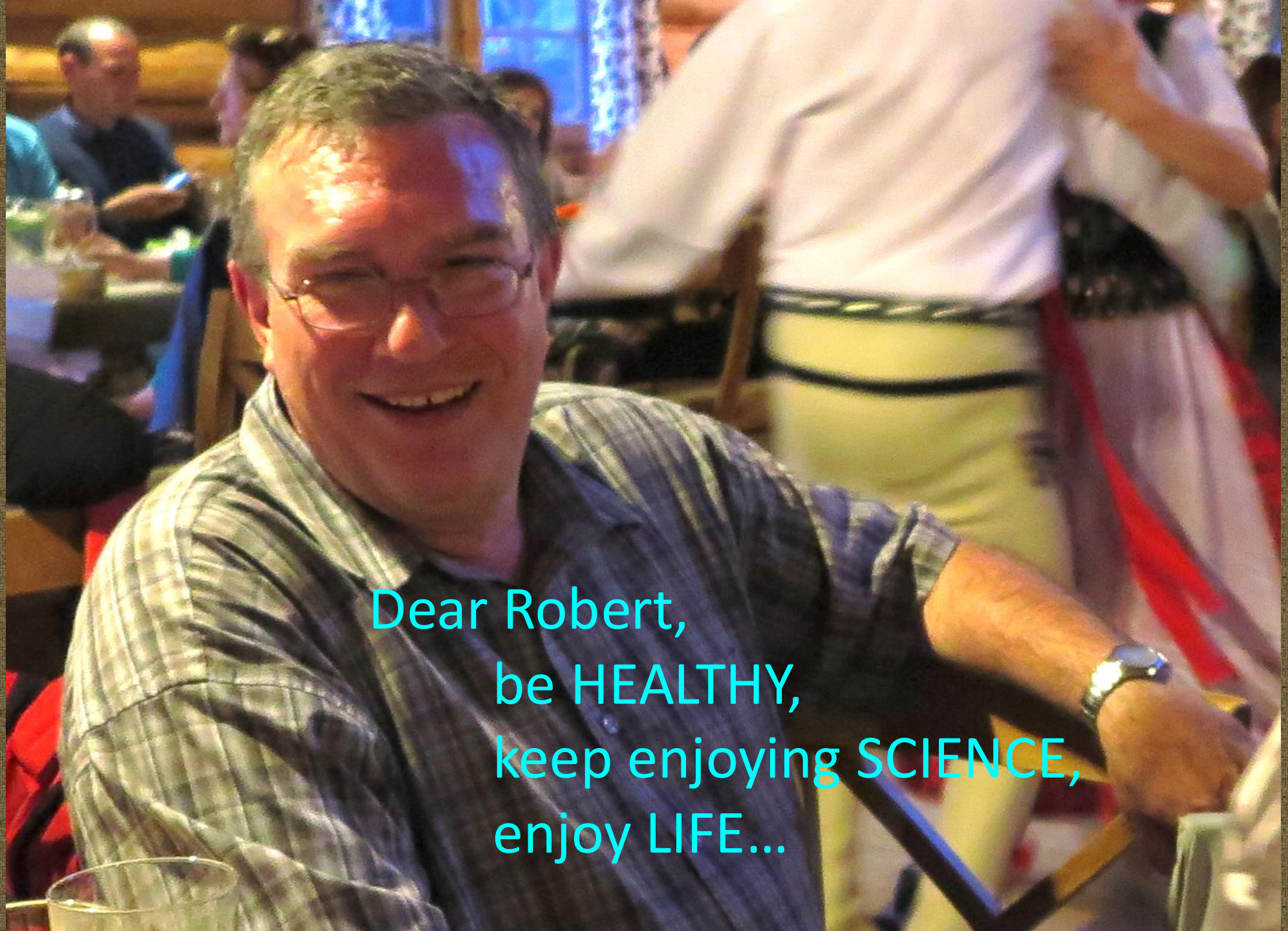
The new masses provide experimental evidence for the appearance of a sizable energy gap between the neutron $p_{1/2}$ and $f_{5/2}$ orbitals in ^{54}Ca, comparable to the gap at N=32 in ^{52}Ca.



Robert, thank you for
a wonderful journey across
the N=32 and N=34 shell gaps
in the nuclear landscape -
taken together with our
friends and collaborators.


Dear Robert,
be HEALTHY,
keep enjoying SCIENCE,
enjoy LIFE…