Nuclear Structure Studies of Heavy Nuclei

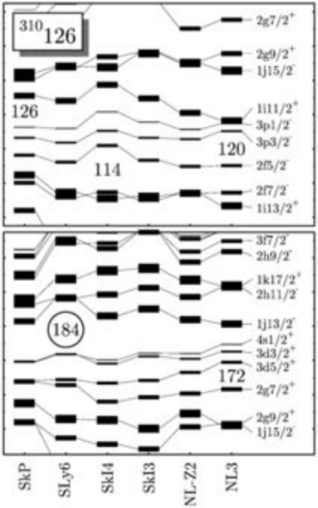
Paul Greenlees

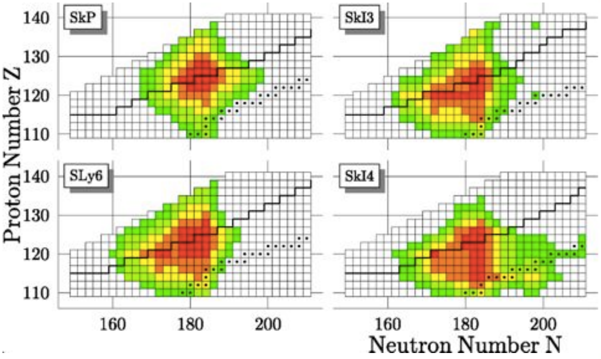
Department of Physics
University of Jyväskylä
and
Collaborators

Nuclear Structure Physics with Advanced Gamma-Detector Arrays
10.6.-12.6.2013
Palazzo del Bo', Padova, Italy

Outline

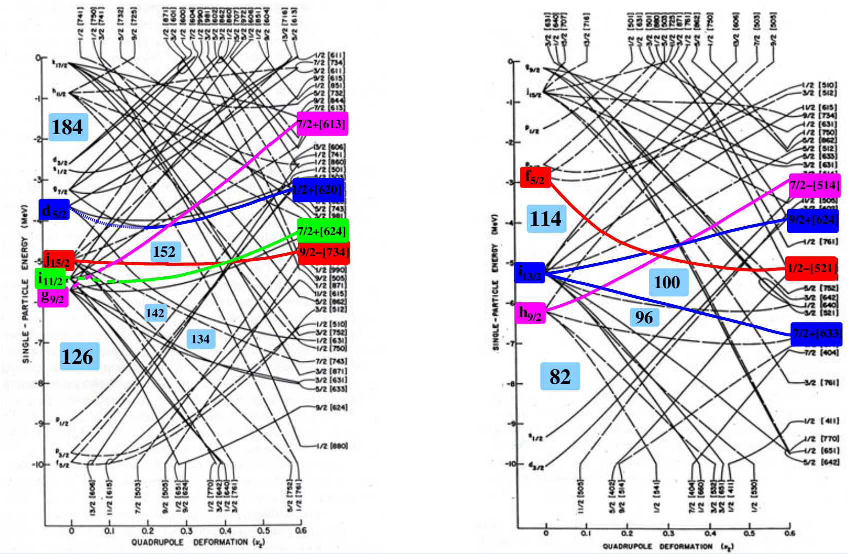
SHE - Shell Correction and Single-Particle Levels





M. Bender, W. Nazarewicz, P.-G. Reinhard, PLB **515**, 42 (2001)

Single-Particle Orbitals in Region of ^{254}No

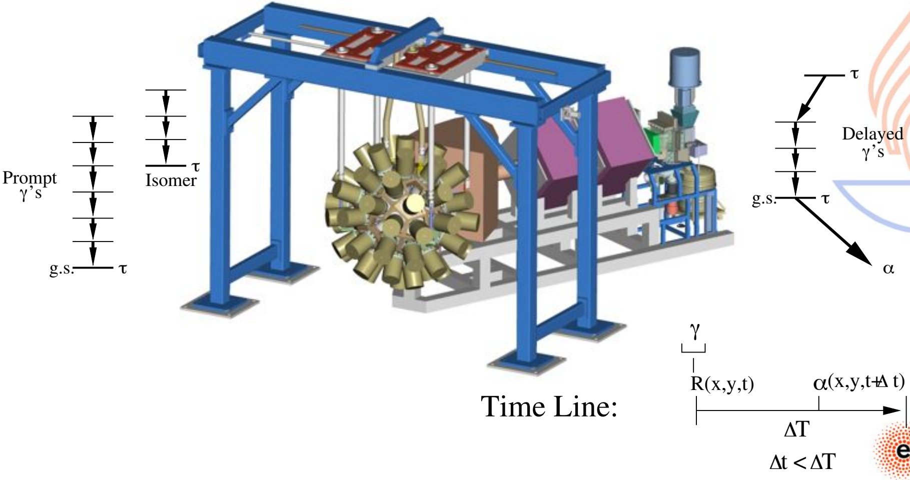


R.R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)

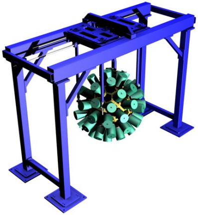
In-beam Spectroscopy: Principles of RDT

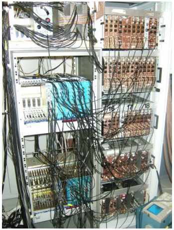
Tagging Techniques

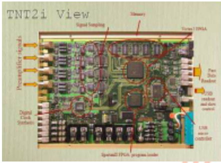
Recoil, Recoil–Decay, Isomer



Recent history of JUROGAM







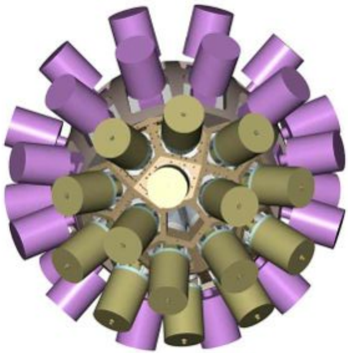
- Fifth and final campaign ended May 2008
- 2003 - 2008: 67 experiments, 11000 hours beam on target
- 2008: Fully instrumented with TNT2 digital electronics
- TNT2 cards in collaboration with CNRS/IN2P3 GABRIELA
- Superseded by JUROGAM II

PRL **102,** 212501 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

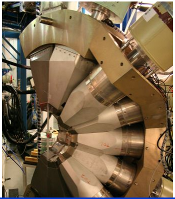
γ-Ray Spectroscopy at the Limits: First Observation of Rotational Bands in ^{255}Lr

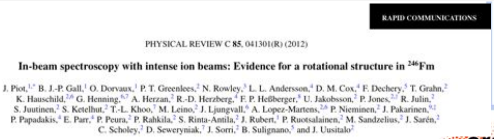
S. Ketelhut,[1,*] P. T. Greenlees,[1] D. Ackermann,[2] S. Antalic,[3] E. Clément,[4] I. G. Darby,[5,†] O. Dorvaux,[6] A. Drouart,[4] S. Eeckhaudt,[1] B. J. P. Gall,[6] A. Görgen,[4] T. Grahn,[1,‡] C. Gray-Jones,[5] K. Hauschild,[7] R.-D. Herzberg,[5] F. P. Heßberger,[2] U. Jakobsson,[1] G. D. Jones,[5] P. Jones,[1] R. Julin,[1] S. Juutinen,[1] T.-L. Khoo,[8] W. Korten,[4] M. Leino,[1] A.-P. Leppänen,[1,§] J. Ljungvall,[4] S. Moon,[5] M. Nyman,[1] A. Obertelli,[4] J. Pakarinen,[1,‡] E. Parr,[5] P. Papadakis,[5] P. Peura,[1] J. Piot,[6] A. Pritchard,[5] P. Rahkila,[1] D. Rostron,[5] P. Ruotsalainen,[1] M. Sandzelius,[9] J. Sarén,[1] C. Scholey,[1] J. Sorri,[1] A. Steer,[10] B. Sulignano,[4] Ch. Theisen,[4] J. Uusitalo,[1] M. Venhart,[3,†] M. Zielinska,[11] M. Bender,[12,13] and P.-H. Heenen[14]

The JUROGAM II Germanium Array



- 24 Clover and 15 Tapered Ge detectors - GAMMAPOOL resource
- Total Photopeak Efficiency ≃6% @ 1.3 MeV
- Excellent γ-γ efficiency
- Autofill system built by University of York, part of GREAT
- Instrumented with TNT2 / Lyrtech digital electronics
- Higher counting rates, higher beam intensities
- 20,000 hours in-beam γ-ray spectroscopy passed in 2011





RAPID COMMUNICATIONS

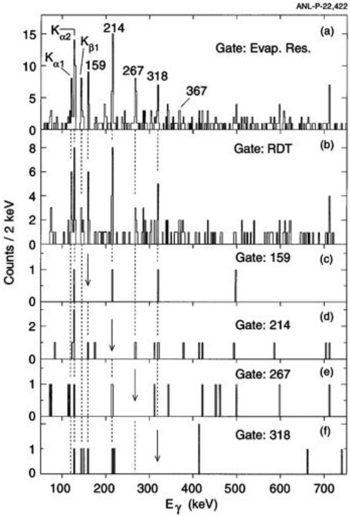
PHYSICAL REVIEW C **85**, 041301(R) (2012)

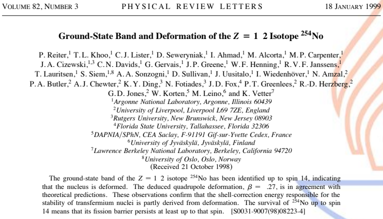
In-beam spectroscopy with intense ion beams: Evidence for a rotational structure in ^{246}Fm

J. Piot,[1,*] B. J.-P. Gall,[1] O. Dorvaux,[1] P. T. Greenlees,[2] N. Rowley,[3] L. L. Andersson,[4] D. M. Cox,[4] F. Dechery,[5] T. Grahn,[2] K. Hauschild,[2,6] G. Henning,[6,7] A. Herzan,[2] R.-D. Herzberg,[4] F. P. Heßberger,[8] U. Jakobsson,[2] P. Jones,[2,‡] R. Julin,[2] S. Juutinen,[2] S. Ketelhut,[2] T.-L. Khoo,[7] M. Leino,[2] J. Ljungvall,[6] A. Lopez-Martens,[2,6] P. Nieminen,[2] J. Pakarinen,[9,‡] P. Papadakis,[4] E. Parr,[4] P. Peura,[2] P. Rahkila,[2] S. Rinta-Antila,[2] J. Rubert,[1] P. Ruotsalainen,[2] M. Sandzelius,[2] J. Sarén,[2] C. Scholey,[2] D. Seweryniak,[7] J. Sorri,[2] B. Sulignano,[5] and J. Uusitalo[2]

In-beam studies in region of ^{254}No

P.Reiter et al., PRL **82**, 509 (1999)

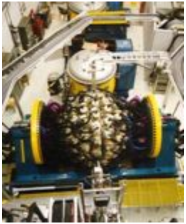



Volume 82, Number 3 PHYSICAL REVIEW LETTERS 18 January 1999

Ground-State Band and Deformation of the $Z = 1\ 2$ Isotope ^{254}No

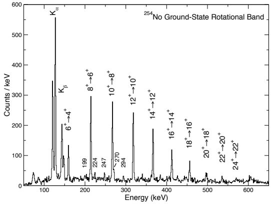
P. Reiter,[1] T. L. Khoo,[1] C. J. Lister,[1] D. Seweryniak,[1] I. Ahmad,[1] M. Alcorta,[1] M. P. Carpenter,[1] J. A. Cizewski,[1,3] C. N. Davids,[1] G. Gervais,[1] J. P. Greene,[1] W. F. Henning,[1] R. V. F. Janssens,[1] T. Lauritsen,[1] S. Siem,[1,8] A. A. Sonzogni,[1] D. Sullivan,[1] J. Uusitalo,[1] I. Wiedenhöver,[1] N. Amzal,[2] P. A. Butler,[2] A. J. Chewter,[2] K. Y. Ding,[3] N. Fotiades,[3] J. D. Fox,[4] P. T. Greenlees,[2] R.-D. Herzberg,[2] G. D. Jones,[2] W. Korten,[5] M. Leino,[6] and K. Vetter[7]
[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*University of Liverpool, Liverpool L69 7ZE, England*
[3]*Rutgers University, New Brunswick, New Jersey 08903*
[4]*Florida State University, Tallahassee, Florida 32306*
[5]*DAPNIA/SPhN, CEA Saclay, F-91191 Gif-sur-Yvette Cedex, France*
[6]*University of Jyväskylä, Jyväskylä, Finland*
[7]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[8]*University of Oslo, Oslo, Norway*
(Received 21 October 1998)

The ground-state band of the $Z = 1\ 2$ isotope ^{254}No has been identified up to spin 14, indicating that the nucleus is deformed. The deduced quadrupole deformation, $\beta = .27$, is in agreement with theoretical predictions. These observations confirm that the shell-correction energy responsible for the stability of transfermium nuclei is partly derived from deformation. The survival of ^{254}No up to spin 14 means that its fission barrier persists at least up to that spin. [S0031-9007(98)08223-4]

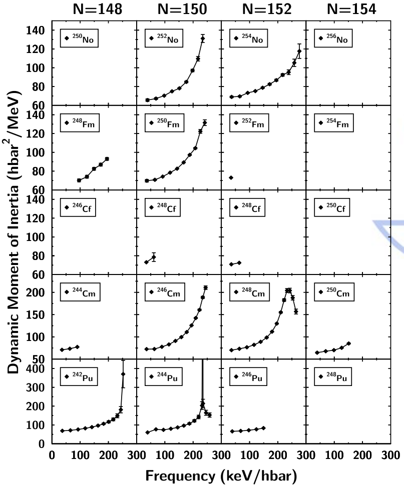


In-beam studies in region of ^{254}No

S. Eeckhaudt, P.T. Greenlees et al., EPJA **26**, 227 (2005)

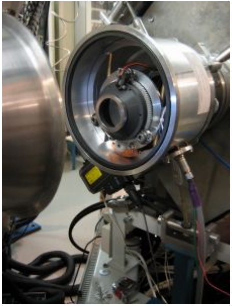


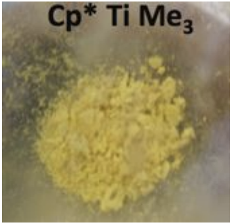
- Confirmed deformed nature of nuclei around ^{254}No
- Showed fission barrier robust with spin ($> 20\hbar$)
- Faster alignment at N=150 compared to N=152 ($\pi i_{13/2}$, $\nu j_{15/2}$)
- Excellent testing ground for theory; e.g. Duguet et al., NPA **679**, 427 (2001), Bender et al., NPA **723**, 354 (2003), Afanasjev et al., PRC **67**, 024309 (2003), Egido and Robledo, PRL **85** 1198 (2000)



Next step - push to Rutherfordium Z=104

- Can produce ^{256}Rf using:
  ^{50}Ti + ^{208}Pb $\rightarrow$ ^{256}Rf + 2n
- Cross section below 20 nb
- Need high intensity ^{50}Ti beam
- Used up to 70 pnA in ^{246}Fm experiment
- Rotating target wheel built at IPHC Strasbourg

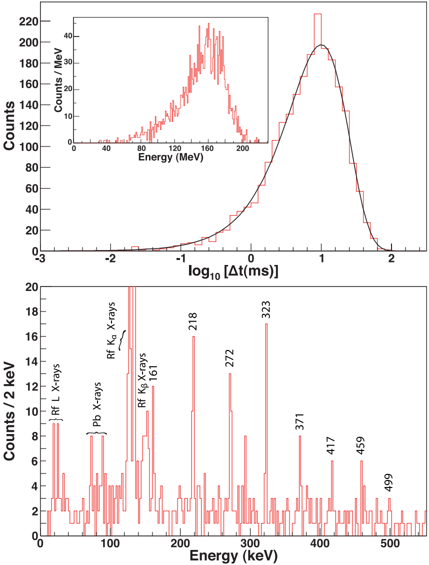




^{50}Ti MIVOC beam development

- Metallic Ions from VOlatile Compounds
- Method developed at JYFL
- Synthesis of enriched ^{50}Ti compound led by IPHC Strasbourg
- Several years of hard work!
- 19 μA of ^{50}Ti^{11+} from ECR
- 490 enA on target
- Low consumption - 0.2 mg/hr
- See J.Rubert et al., NIMB **276**, 33 (2012)

In-beam spectroscopy of SHE: ^{256}Rf

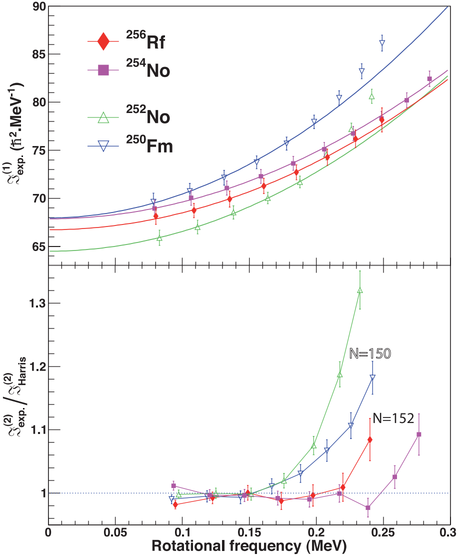


Experimental Details

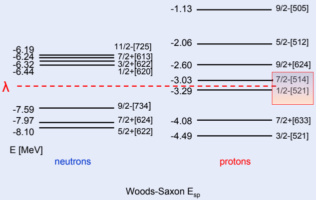
- ^{50}Ti + ^{208}Pb $\Rightarrow$ ^{256}Rf + 2n
- JUROGAM II, RITU, GREAT
- Enriched ^{50}Ti beam from MIVOC
- 450 hours, 29pnA beam, 2210 observed fissions
- Cross section 17 nb

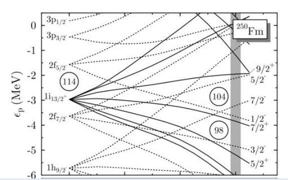
P.T.Greenlees, J.Rubert et al., PRL **109**, 012501 (2012)

In-beam spectroscopy of SHE: ^{256}Rf



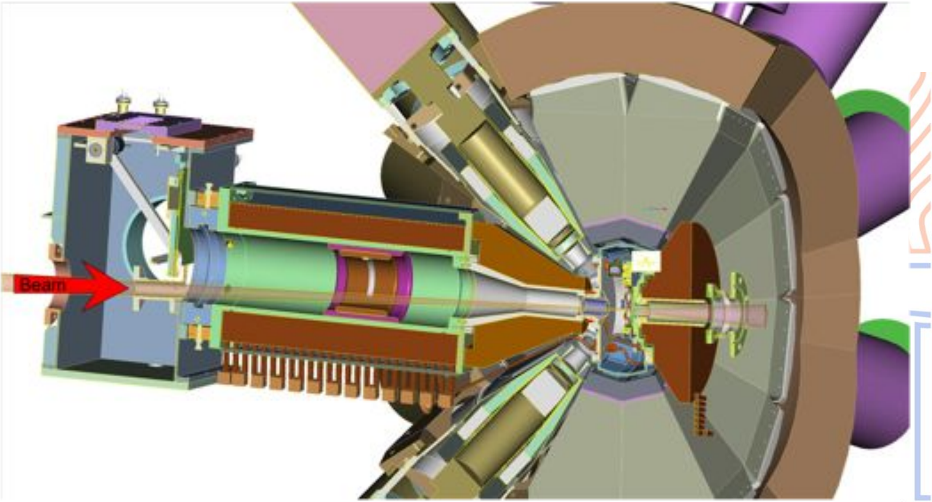
Single-particle energies





P.T.Greenlees, J.Rubert et al., PRL **109**, 012501 (2012)

Anatomy of the SAGE Spectrometer



P. Papadakis et al., AIP Conf. Proc. **1090**, 14 (2009)

SAGE experiments to date

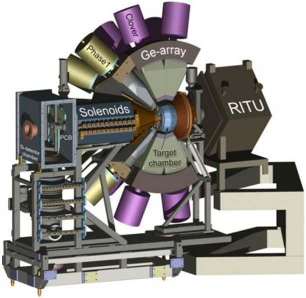
Campaign 2010

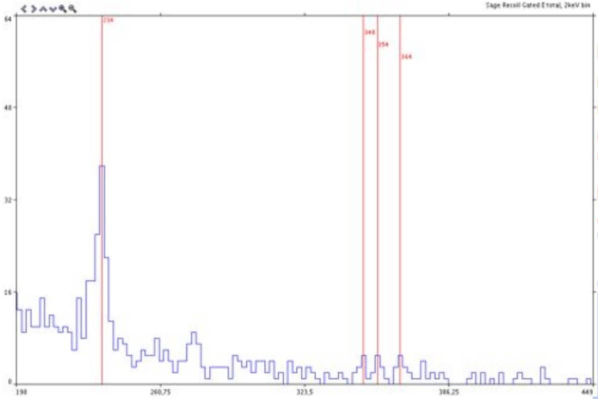
- S01: Commissioning of the SAGE spectrometer, R.-D. Herzberg
- S02: Simultaneous conversion-electron and gamma-ray spectroscopy using SAGE; an in-beam study of ^{253}No, R.-D. Herzberg
- S04: Exploring shape co-existence in ^{202,204}Rn, D.Jenkins, A.P.Robinson, P.Rahkila
- S05: Shape co-existence in $^{182-188}$Hg, P.A.Butler, P.Rahkila, P. Van Duppen

Campaign 2011/2012

- S11: Commissioning of the SAGE spectrometer through in-beam investigation of ^{177}Hg , P.Papadakis
- S06: Exploring nuclear shapes in the transitional region of N 90: Coulomb excitation of ^{152,154}Sm to study E0 transitions with SAGE, P.Davies, C.Barton
- S07: Probing E0 transitions in ^{188}Pb using the SAGE spectrometer, J.Pakarinen
- S10: Spectroscopy of the odd-proton ^{249,251}Md, Ch.Theisen
- S08: Simultaneous conversion-electron and gamma-ray spectroscopy using SAGE; an in-beam study of ^{253}No, R.-D. Herzberg
- S09: Complete spectroscopy of the transfermium nucleus ^{255}Lr, M.Sandzelius, K.Hauschild, A.Lopez-Martens

Multipolarity Assignments from In-Beam Data

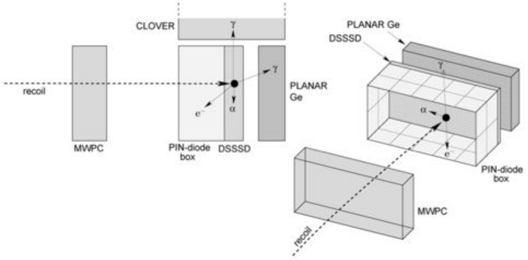


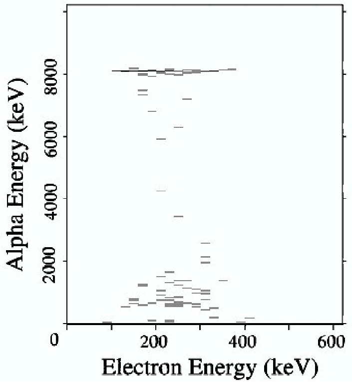


$^{48}Ca + ^{205}Tl \Rightarrow ^{251}Md + 2n$, $\sigma \simeq 1\ \mu b$, F.Dechery, Ch.Theisen to be published
Preliminary data, suggests 390 keV $M1$ transition

Studies of K-Isomerism - Calorimetric Method

- Isomeric states in ^{250}Fm and ^{254}No first postulated by Ghiorso et al., PRC7 (1973) 2032
- Powerful method proposed by Jones, NIM A488 (2002) 471
- Low-energy transitions highly converted, look for Recoil-electron-α correlated chains in DSSSD

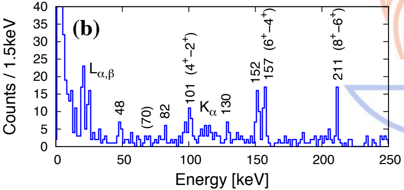


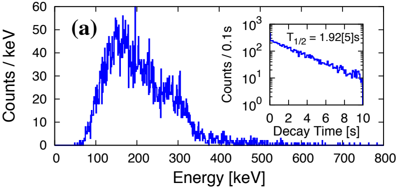


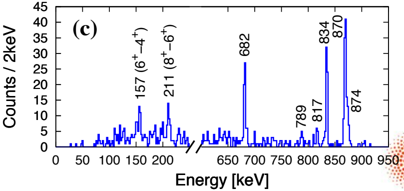
K-Isomerism in ^{250}Fm

^{48}Ca + ^{204}HgS ⇒ ^{250}Fm + 2n,JUROGAM+RITU+GREAT, P.T. Greenlees et al., PRC **78**, 021301(R) (2008)

Focal Plane Gamma Rays



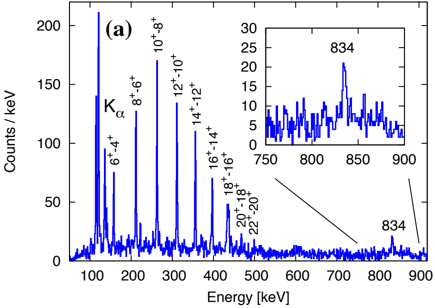




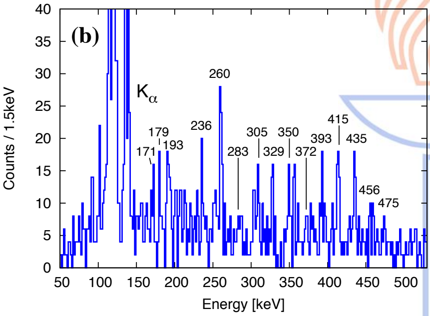
K-Isomerism in ^{250}Fm

^{48}Ca + ^{204}HgS $\Rightarrow$ ^{250}Fm + 2n,JUROGAM+RITU+GREAT, P.T. Greenlees et al., PRC **78**, 021301(R) (2008)

Ground State Band

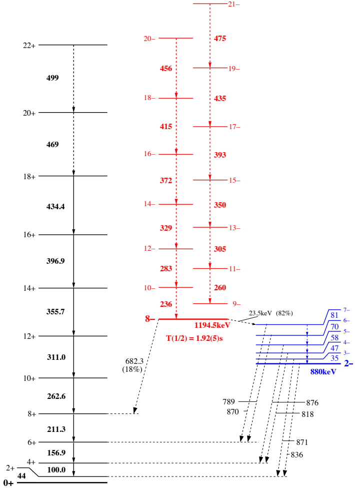


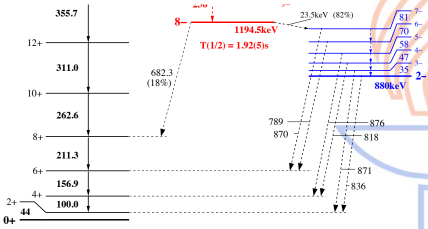
Isomer-Tagged Transitions



K-Isomerism in ^{250}Fm

^{250}Fm: P.T. Greenlees et al. PRC **78**, 021301(R) (2008)





8^- - $\nu[624]7/2^+ \otimes \nu[734]9/2^-$

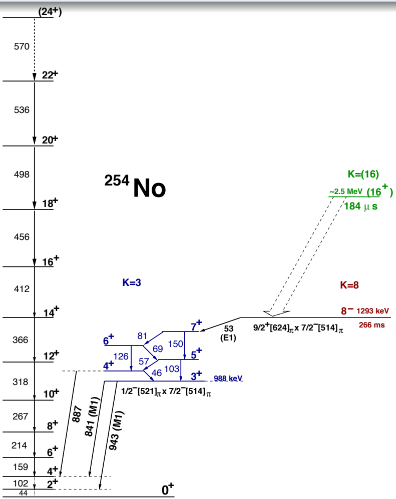
2^- - $\nu[622]5/2^+ \otimes \nu[734]9/2^-$ dominates

682 keV E1 $\Delta K=8$: $f_\nu = 213$

23.5 keV M1 $\Delta K=6$: $f_\nu = 192$

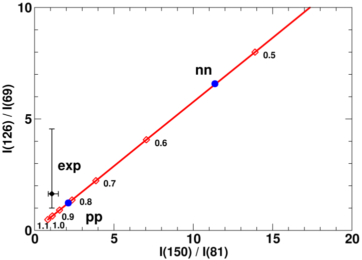
K-Isomerism in ^{254}No

R.-D. Herzberg et al., Nature **442**, 896-899 (2006)
S.K. Tandel et al., PRL **97**, 082502 (2006)

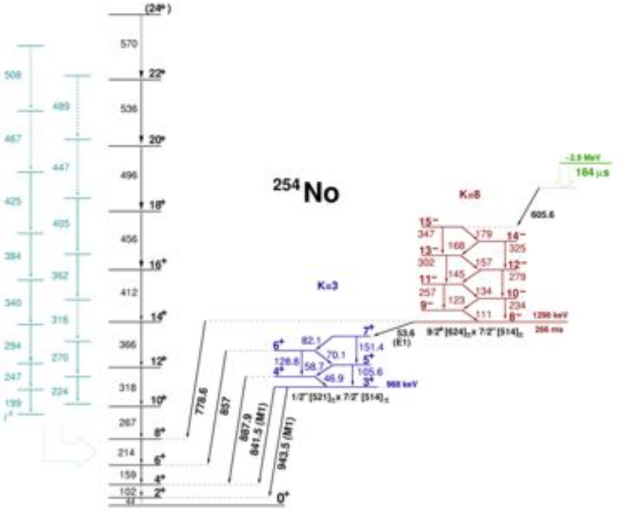


"Determined" Configurations:

3^+ - $(\pi[514]7/2^- \otimes \pi[521]1/2^-)$
8^- - $(\pi[514]7/2^- \otimes \pi[624]9/2^+)$
53keV E1 ΔK=5: f_ν = 804

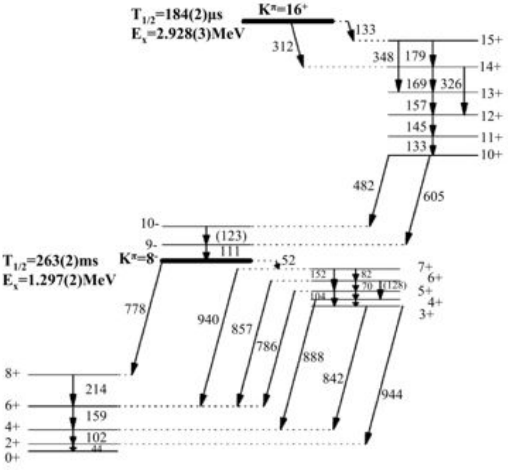


K-Isomerism in ^{254}No



F.P. Hessberger et al., EPJA **43**, 55 (2010) / C.Gray-Jones, Thesis, University of Liverpool

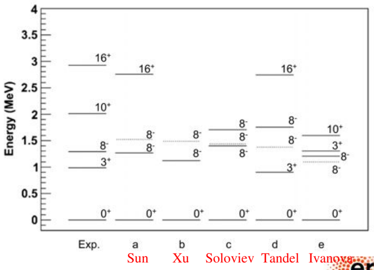
K-Isomerism in ^{254}No



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

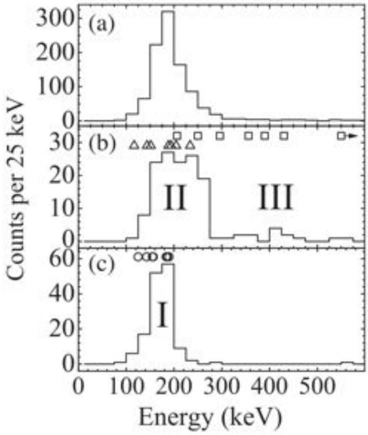
"Determined" Configurations:

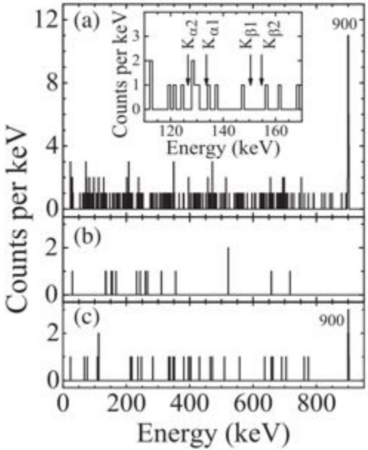
3^+ - $(\pi[514]7/2^- \otimes \pi[521]1/2^-)$
8^- - $(\nu[734]9/2^- \otimes \nu[624]7/2^+)$
or 8^- - $(\nu[734]9/2^- \otimes \nu[613]7/2^+)$
10^+ - $(\nu[734]9/2^- \otimes \nu[725]11/2^-)$
16^+ - $(\pi[514]7/2^- \otimes \pi[624]9/2^+)$ + $(\nu[734]9/2^- \otimes \nu[613]7/2^+)$



K-isomers in ^{256}Rf from Berkeley

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





K-isomers in ^{256}Rf from Berkeley

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

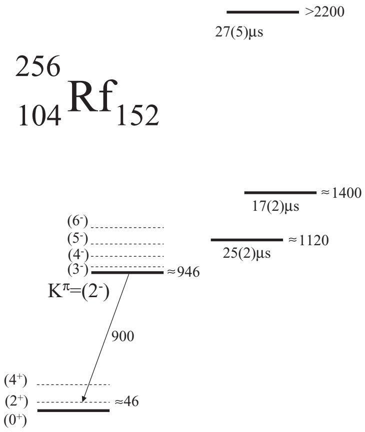


FIG. 3. Proposed decay scheme for ^{256}Rf. Energies are given in keV. Half-lives are written beneath each isomer.

Observed Decays

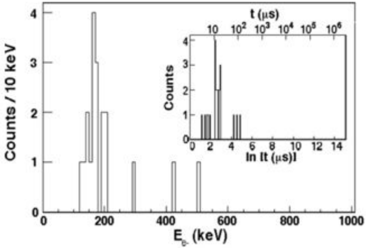
Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	5400	6.67(9) ms
R-e-F	985 (18%)	25(2) μs
R-e-e-F	147 (2.7%)	17(2) μs
R-e-e-e-F	7 (0.13%)	27(2) μs

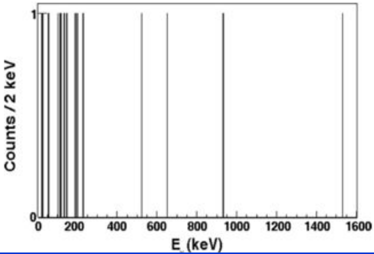
Interpretation

- Lowest isomer 2QP K=6,7
- Second isomer 2QP K=10-12:
  possibly 10^+ - $\nu[734]9/2^- \otimes \nu[725]11/2^-$
- Highest isomer? - not discussed

K-isomers in ^{256}Rf from ANL

A.P.Robinson et al., PRC **83**, 064311 (2011)





Observed Decays

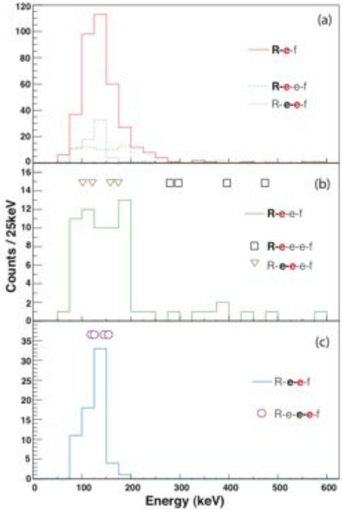
Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	1322	6.9(4) ms
R-e-F	19 (1.4%)	17(5) μs

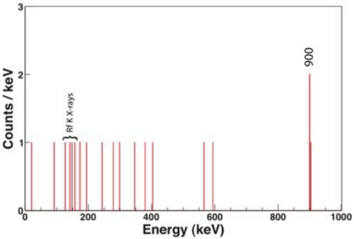
Interpretation

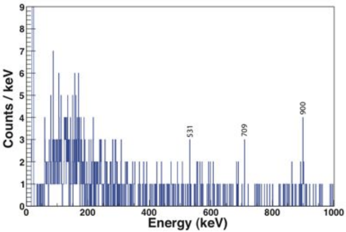
- Low population of isomer - similar to 4QP in ^{254}No, etc
- Conclude isomer is 4QP
- Non-observation of EM decay from 2QP suggests direct fission
  - fission half-life same as g.s.

K-isomers in ^{256}Rf from JYFL - PRELIMINARY!!

J.Rubert, P.T.Greenlees et al., to be published

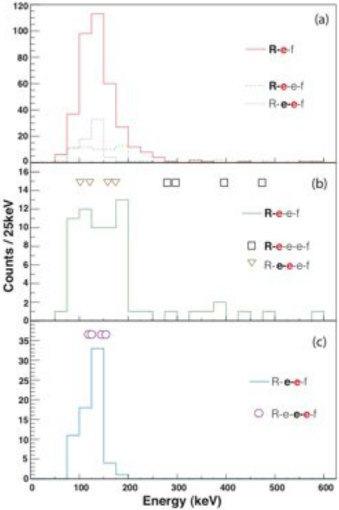


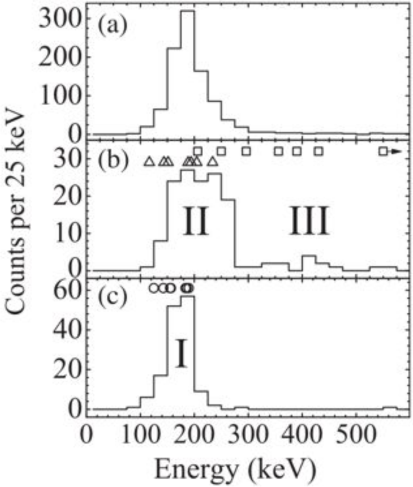




K-isomers in ^{256}Rf from JYFL - PRELIMINARY!!

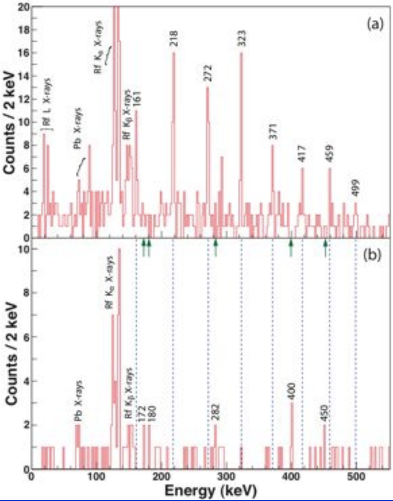
J.Rubert, P.T.Greenlees et al., to be published

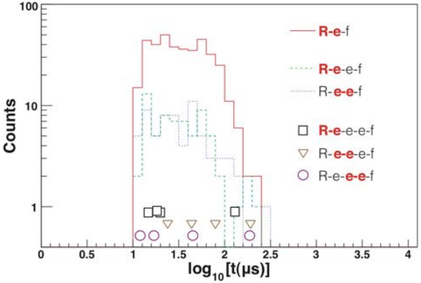




K-isomers in ^{256}Rf from JYFL - PRELIMINARY!!

J.Rubert, P.T.Greenlees et al., to be published





Observed Decays

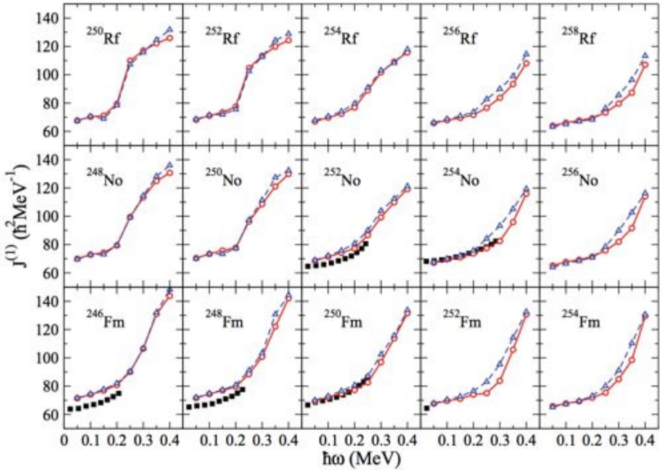
Chain	No. Events	$T_{1/2}$ (Parent-Daughter)
R-F	2210	6.9(2) ms
R-e-F	382 (17%)	23 μs
R-e-e-F	67 (3.0%)	17 μs
R-e-e-e-F	4 (0.18%)	27 μs

Theory - N=150 vs. N=152

PHYSICAL REVIEW C **86**, 011301(R) (2012)

Understanding the different rotational behaviors of ^{252}No and ^{254}No

H. L. Liu,[1,*] F. R. Xu,[2] and P. M. Walker[3,4]

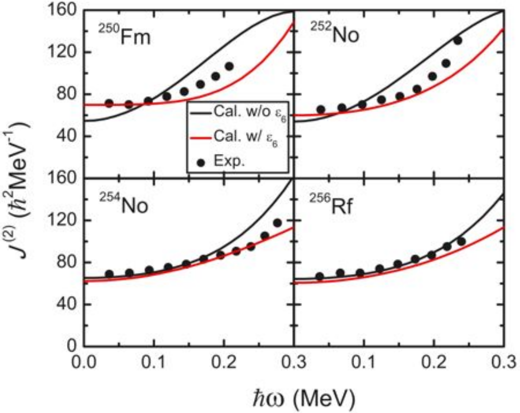


Theory - Moments of Inertia

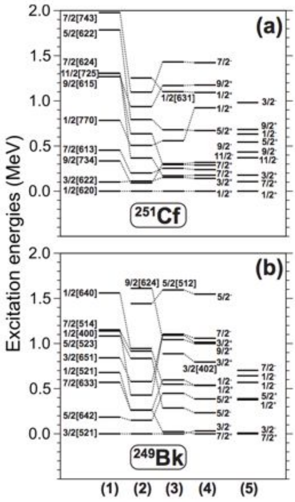
PHYSICAL REVIEW C **87**, 054308 (2013)

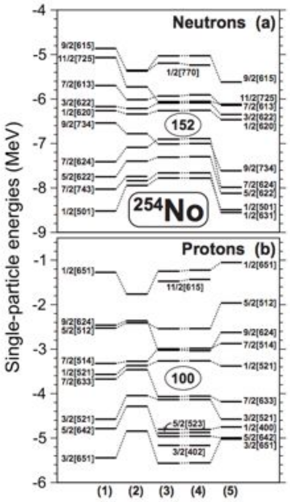
Rotational properties of the superheavy nucleus ^{256}Rf and its neighboring even-even nuclei in a particle-number-conserving cranked shell model

Zhen-Hua Zhang (张振华),[1] Jie Meng (孟杰),[1,2,3] En-Guang Zhao (赵恩广),[1,4,5] and Shan-Gui Zhou (周善贵)[4,5,*]



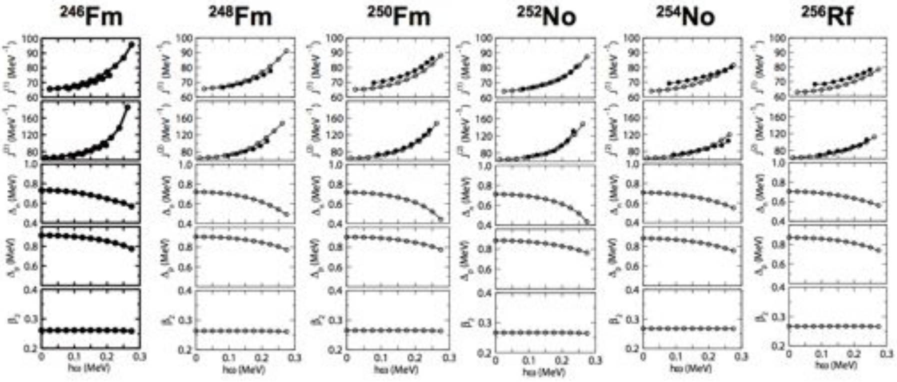
Theory - Skyrme UNEDF1^{SO}





- Based on Skyrme UNEDF1 functional (Kortelainen et al., PRC **85**, 024304 (2012))
- Re-adjustment of pairing strengths and spin-orbit coupling constants
- Pairing first adjusted to experimental 3-point mass differences of ^{249}Bk and ^{251}Cf
- Second adjustment to reproduce low-frequency MoI of ^{252}No
- Spin-orbit coupling constants adjusted to better reproduce ^{249}Bk and ^{251}Cf spectra
- Yue Shi et al., ICFN5 Proceedings (arXiv:1303.0197) and to be published

Theory - Skyrme UNEDF1^{SO}



Yue Shi et al., ICFN5 Proceedings (arXiv:1303.0197) and to be published

Summary

- Developments in instrumentation now allow in-beam γ-ray spectroscopy at 10 nb level
- First observation of rotational states in the superheavy nucleus ^{256}Rf
- Differences in MoI reveal information about underlying shell structure and pairing
- Alignment effects in N=152 isotone ^{254}No delayed compared to ^{256}Rf
- Subtle differences in MoI still not fully reproduced by theory
- New ^{256}Rf K-isomer data from JYFL seems to be consistent with data from Berkeley
- Interpretation still open, better spectroscopic data needed
- Large body of experimental data has highlighted deficiencies in modern-mean field calculations
- May have consequences for the prediction of properties of SHE
- Attempts to correct these deficiencies have been started

Collaboration

Selected for a Viewpoint in *Physics*
PRL **109,** 012501 (2012) PHYSICAL REVIEW LETTERS week ending 6 JULY 2012

Shell-Structure and Pairing Interaction in Superheavy Nuclei: Rotational Properties of the Z=104 Nucleus ^{256}Rf

P. T. Greenlees,[1,*] J. Rubert,[2] J. Piot,[2] B. J. P. Gall,[2] L. L. Andersson,[3] M. Asai,[4] Z. Asfari,[2] D. M. Cox,[3] F. Dechery,[5] O. Dorvaux,[2] T. Grahn,[1] K. Hauschild,[6] G. Henning,[6,7] A. Herzan,[1] R.-D. Herzberg,[3] F. P. Heßberger,[8] U. Jakobsson,[1] P. Jones,[1,†] R. Julin,[1] S. Juutinen,[1] S. Ketelhut,[1] T.-L. Khoo,[7] M. Leino,[1] J. Ljungvall,[6] A. Lopez-Martens,[6] R. Lozeva,[2] P. Nieminen,[1] J. Pakarinen,[9] P. Papadakis,[3] E. Parr,[3] P. Peura,[1] P. Rahkila,[1] S. Rinta-Antila,[1] P. Ruotsalainen,[1] M. Sandzelius,[1] J. Sarén,[1] C. Scholey,[1] D. Seweryniak,[7] J. Sorri,[1] B. Sulignano,[5] Ch. Theisen,[5] J. Uusitalo,[1] and M. Venhart[10]

[1]*Department of Physics, University of Jyväskylä, FIN-40014 Jyväskylä, Finland*
[2]*Institut Pluridisciplinaire Hubert Curien, F-67037 Strasbourg, France*
[3]*Department of Physics, University of Liverpool, Oxford Street, Liverpool, L69 7ZE, United Kingdom*
[4]*Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan*
[5]*CEA, Centre de Saclay, IRFU/Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France*
[6]*CSNSM, IN2P3-CNRS, F-91405 Orsay Campus, France*
[7]*Argonne National Laboratory, Argonne, Illinois, Illinois 60439, USA*
[8]*GSI, Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, 64291 Darmstadt, Germany*
[9]*CERN-ISOLDE, Building 26, 1-013, CH-1211 Geneva 23, Switzerland*
[10]*Institute of Physics, Slovak Academy of Sciences, SK-84511 Bratislava, Slovakia*
(Received 4 May 2012; published 3 July 2012)

Nuclear Instruments and Methods in Physics Research B 276 (2012) 33–37

Contents lists available at SciVerse ScienceDirect

ELSEVIER

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

First intense isotopic titanium-50 beam using MIVOC method

J. Rubert[a], J. Piot[a,1], Z. Asfari[b], B.JP. Gall[a,*], J. Ärje[c], O. Dorvaux[a], P.T. Greenlees[c], H. Koivisto[c], A. Ouadi[a], R. Seppälä[c]

[a] Département de Recherches Subatomiques, Institut Pluridisciplinaire Hubert Curien, UMR 7178, Université de Strasbourg/CNRS-IN2P3, 23 rue du Læss, F-67037 Strasbourg, France
[b] Laboratoire d'Ingénierie Moléculaire Appliquée à l'Analyse (DSA), Institut Pluridisciplinaire Hubert Curien, UMR 7178, Université de Strasbourg/CNRS-IN2P3, 23 rue du Læss, F-67037 Strasbourg, France
[c] Department of Physics, University of Jyväskylä, P.O. Box 35 (YFL), Jyväskylä FI-40014, Finland

The SAGE spectrometer: A tool for combined in-beam γ-ray and conversion electron spectroscopy.

P Papadakis[1], R-D Herzberg[1], J Pakarinen[1,4], P T Greenlees[2], J Sorri[2], P A Butler[1], P J Coleman-Smith[3], D Cox[1], J R Cresswell[1], K Hauschild[2,5], P Jones[2], R Julin[2], I H Lazarus[3], S C Letts[3], E Parr[1], P Peura[2], V F E Pucknell[3], P Rahkila[2], J Sampson[1], M Sandzelius[2], D A Seddon[1], J Simpson[3], J Thornhill[1] and D Wells[1]

[1] Department of Physics, University of Liverpool, Oxford Street, Liverpool, L69 7ZE, U.K.
[2] Department of Physics, University of Jyväskylä, FIN-40014, Jyväskylä, Finland
[3] STFC Daresbury Laboratory, Warrington, WA4 4AD, U.K.