Isomer Studies of the Heaviest Atomic Nuclei

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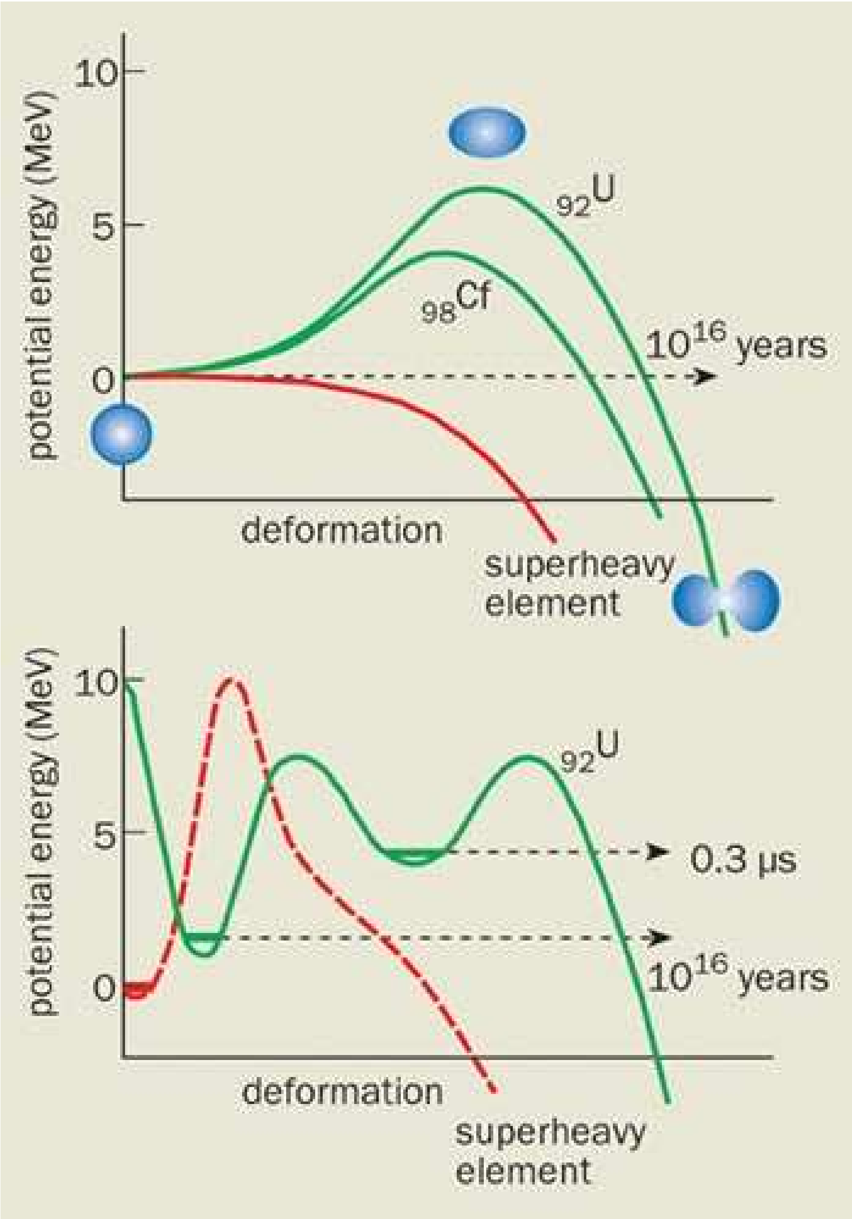
Outline

- Motivation for studying structure of heaviest nuclei
- The Berkeley Gas-Filled Separator (BGS)
- Recent results on nuclei from Z=102 (No) to Z=106 (Sg)
- Future Plans
- Summary

Why Do Heavy Nuclei Exist?



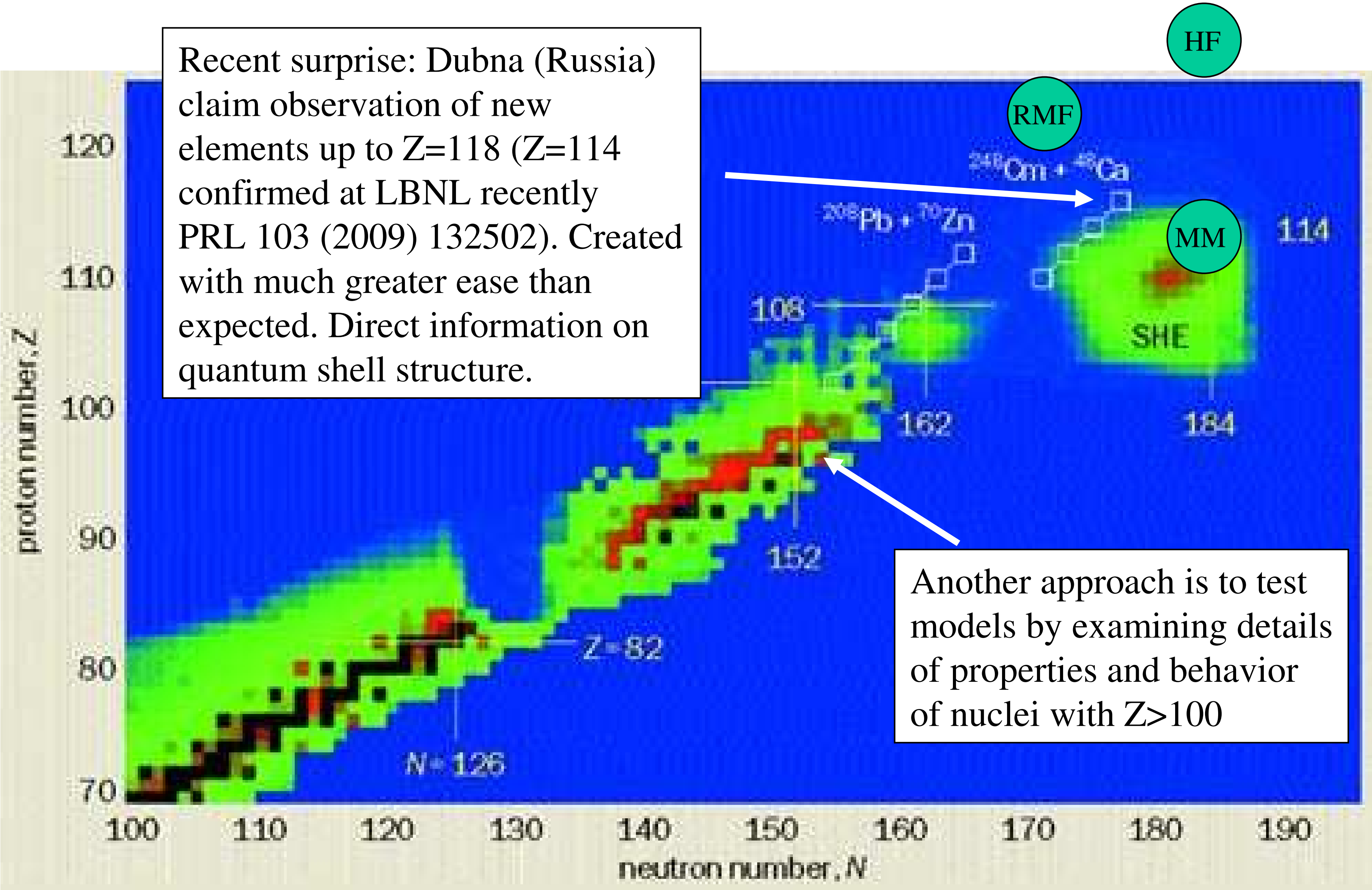
Physics World, July 2004

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

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

Different Theories, Different Shell Gaps

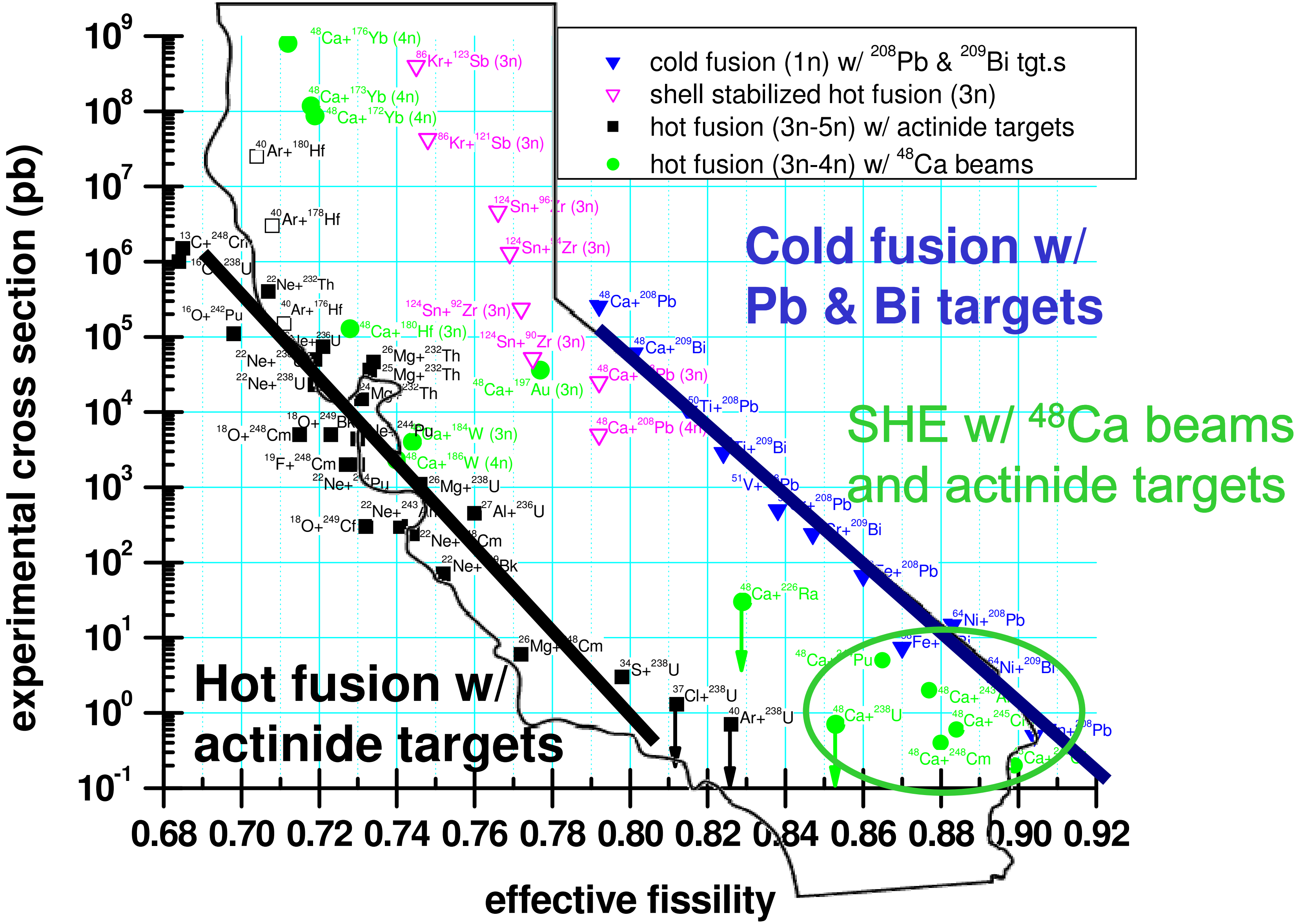
Recent surprise: Dubna (Russia) claim observation of new elements up to Z=118 (Z=114 confirmed at LBNL recently PRL 103 (2009) 132502). Created with much greater ease than expected. Direct information on quantum shell structure.



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

Difficult to Make Direct Measurements

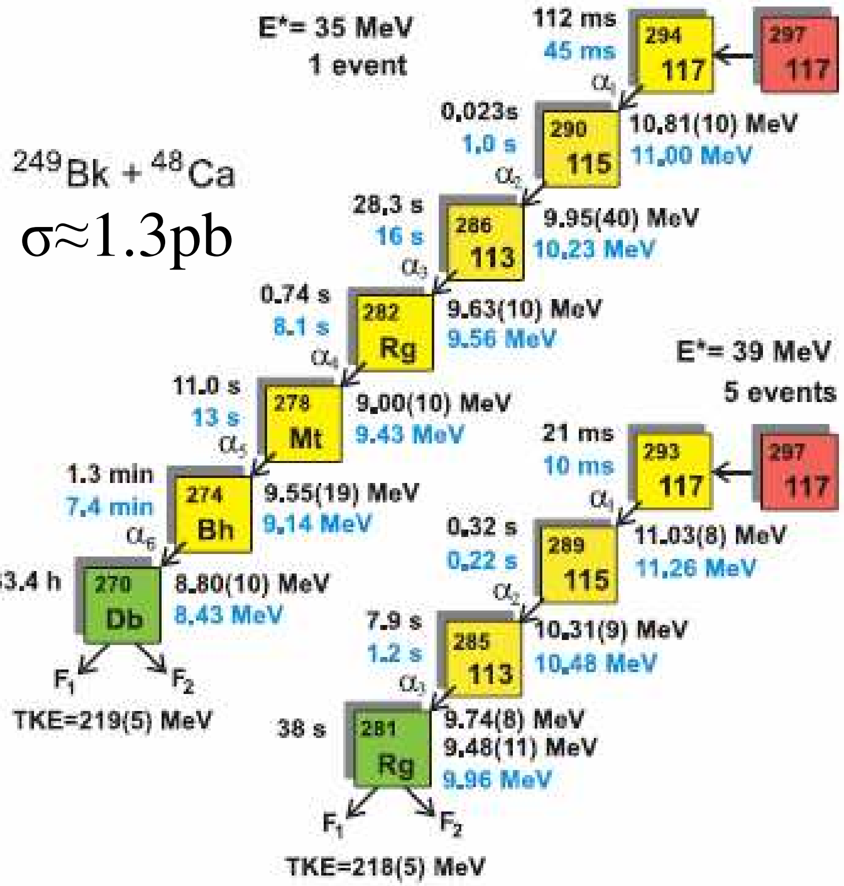
The California Plot . . .

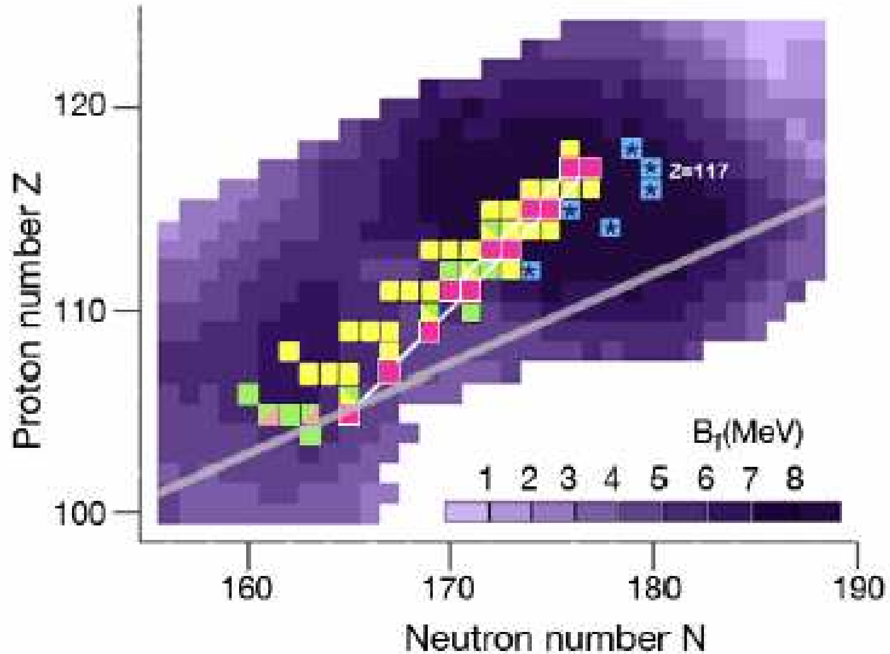


PRL 104, 142502 (2010) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Synthesis of a New Element with Atomic Number Z = 117

Yu. Ts. Oganessian,[1,*] F. Sh. Abdullin,[1] P. D. Bailey,[2] D. E. Benker,[2] M. E. Bennett,[3] S. N. Dmitriev,[1] J. G. Ezold,[2] J. H. Hamilton,[4] R. A. Henderson,[5] M. G. Itkis,[1] Yu. V. Lobanov,[1] A. N. Mezentsev,[1] K. J. Moody,[5] S. L. Nelson,[5] A. N. Polyakov,[1] C. E. Porter,[2] A. V. Ramayya,[4] F. D. Riley,[2] J. B. Roberto,[2] M. A. Ryabinin,[6] K. P. Rykaczewski,[2] R. N. Sagaidak,[1] D. A. Shaughnessy,[5] I. V. Shirokovsky,[1] M. A. Stoyer,[5] V. G. Subbotin,[1] R. Sudowe,[3] A. M. Sukhov,[1] Yu. S. Tsyganov,[1] V. K. Utyonkov,[1] A. A. Voinov,[1] G. K. Vostokin,[1] and P. A. Wilk[5]





Sigurd Hofmann, Physics 3 (2010) 31

Single Particle Structure and Collectivity in Z>100 Nuclei

- Single-particle levels → shell structure
    - Next major spherical gaps
    - Deformed gaps
- Deformation and collectivity
    - Meta-stable states
    - Rotation and vibration
    - Pairing (superfluidity)

NATURE | VOL 433 | 17 FEBRUARY 2005 | review article

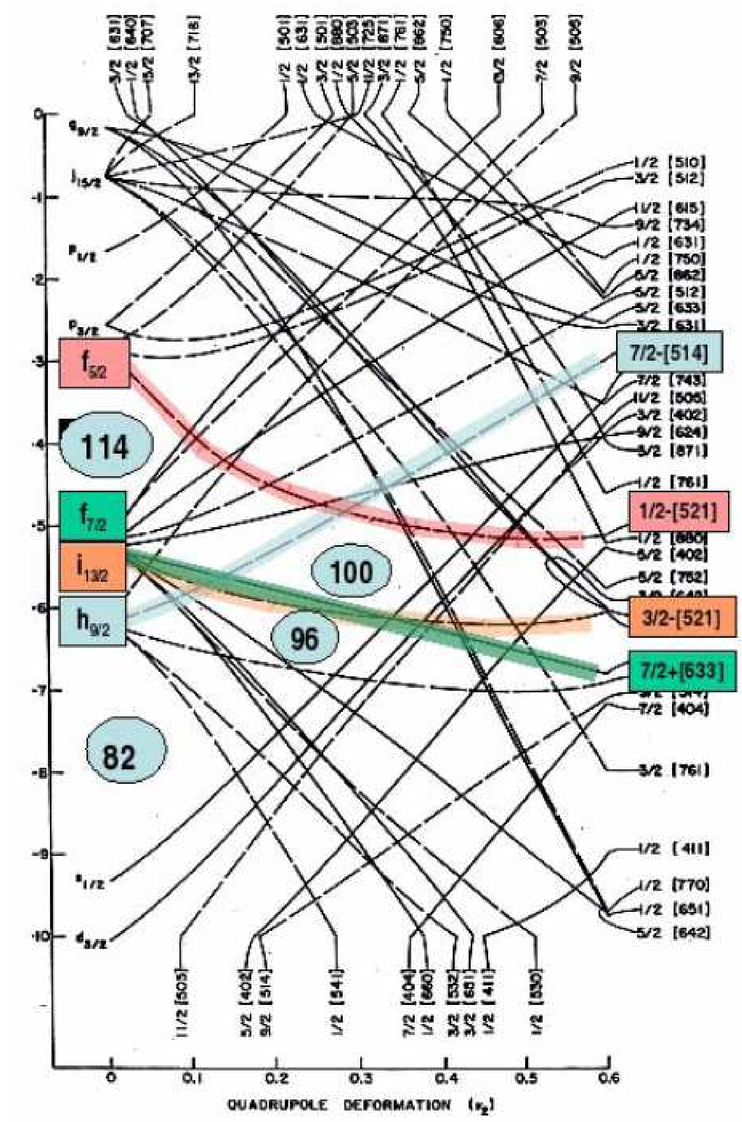
Shape coexistence and triaxiality in the superheavy nuclei

S. Ćwiok[1]*, **P.-H. Heenen**[2] **& W. Nazarewicz**[3,4,5]

[1] *Institute of Physics, Warsaw University of Technology, ul. Koszykowa 75, PL-00662, Warsaw, Poland*
[2] *Service de Physique Nucléaire Théorique, Université Libre de Bruxelles, CP 229, B-1050 Brussels, Belgium*
[3] *Department of Physics and Astronomy, The University of Tennessee, Knoxville, Tennessee 37996, USA*
[4] *Physics Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, Tennessee 37831, USA*
[5] *Institute of Theoretical Physics, Warsaw University, ul. Hoza 69, PL-00681, Warsaw, Poland*

* Deceased

Superheavy nuclei represent the limit of nuclear mass and charge; they inhabit the remote corner of the nuclear landscape, whose extent is unknown. The discovery of new elements with atomic numbers $Z \geq 110$ has brought much excitement to the atomic and nuclear physics communities. The existence of such heavy nuclei hangs on a subtle balance between the attractive nuclear force and the disruptive Coulomb repulsion between protons that favours fission. Here we model the interplay between these forces using self-consistent energy density functional theory; our approach accounts for spontaneous breaking of spherical symmetry through the nuclear Jahn–Teller effect. We predict that the long-lived superheavy elements can exist in a variety of shapes, including spherical, axial and triaxial configurations. In some cases, we anticipate the existence of metastable states and shape isomers that can affect decay properties and hence nuclear half-lives.



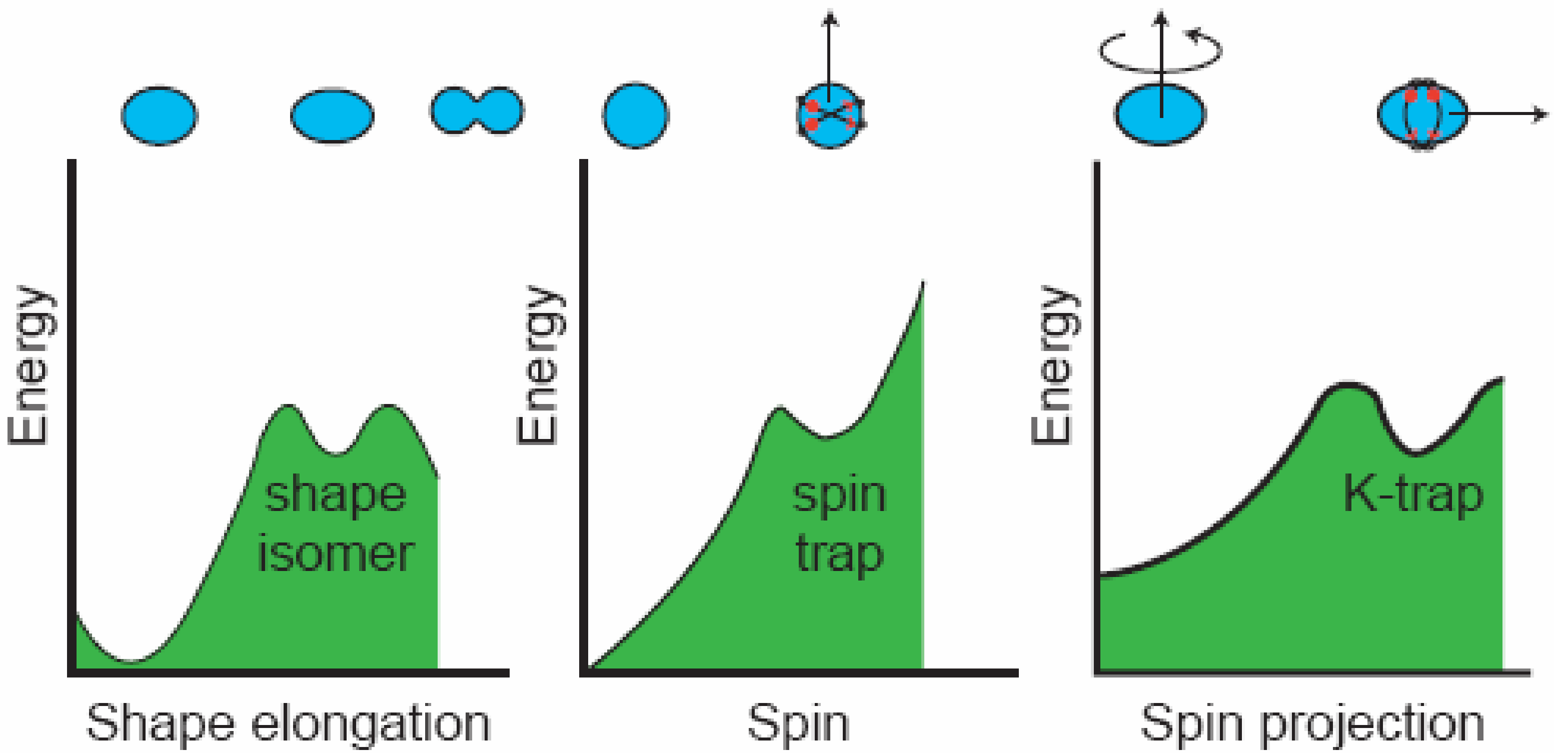
NATURE | VOL 399 | 6 MAY 1999 | www.nature.com

review article

Energy traps in atomic nuclei

Philip Walker & George Dracoulis

A small proportion of atomic nuclei can form highly excited metastable states, or isomers. Of particular interest is a class of isomers found in deformed axially symmetric nuclei; these isomers are among the longest-lived and have the potential to reach the highest energies. By probing their properties, insights into nuclear structure have been gained. The possibility of stimulated isomer decay may ultimately lead to new forms of energy storage and γ-ray lasers.



K-Isomers in Z≥100 Nuclei

RITU at JYFL

nature

Nature 422 896 (2006)

Nuclear isomers in superheavy elements as stepping stones towards the island of stability

R.-D. Herzberg[1], P. T. Greenlees[2], P. A. Butler[1], G. D. Jones[1], M. Venhart[3], I. G. Darby[1], S. Eeckhaudt[2], K. Eskola[4], T. Grahn[2], C. Gray-Jones[1], F. P. Hessberger[5], P. Jones[2], R. Julin[2], S. Juutinen[2], S. Ketelhut[2], W. Korten[6], M. Leino[2], A.-P. Leppänen[2], S. Moon[1], M. Nyman[2], R. D. Page[1], J. Pakarinen[1,2], A. Pritchard[1], P. Rahkila[2], J. Sarén[2], C. Scholey[2], A. Steer[2], Y. Sun[7], Ch. Theisen[6] & J. Uusitalo[2]

FMA at ANL

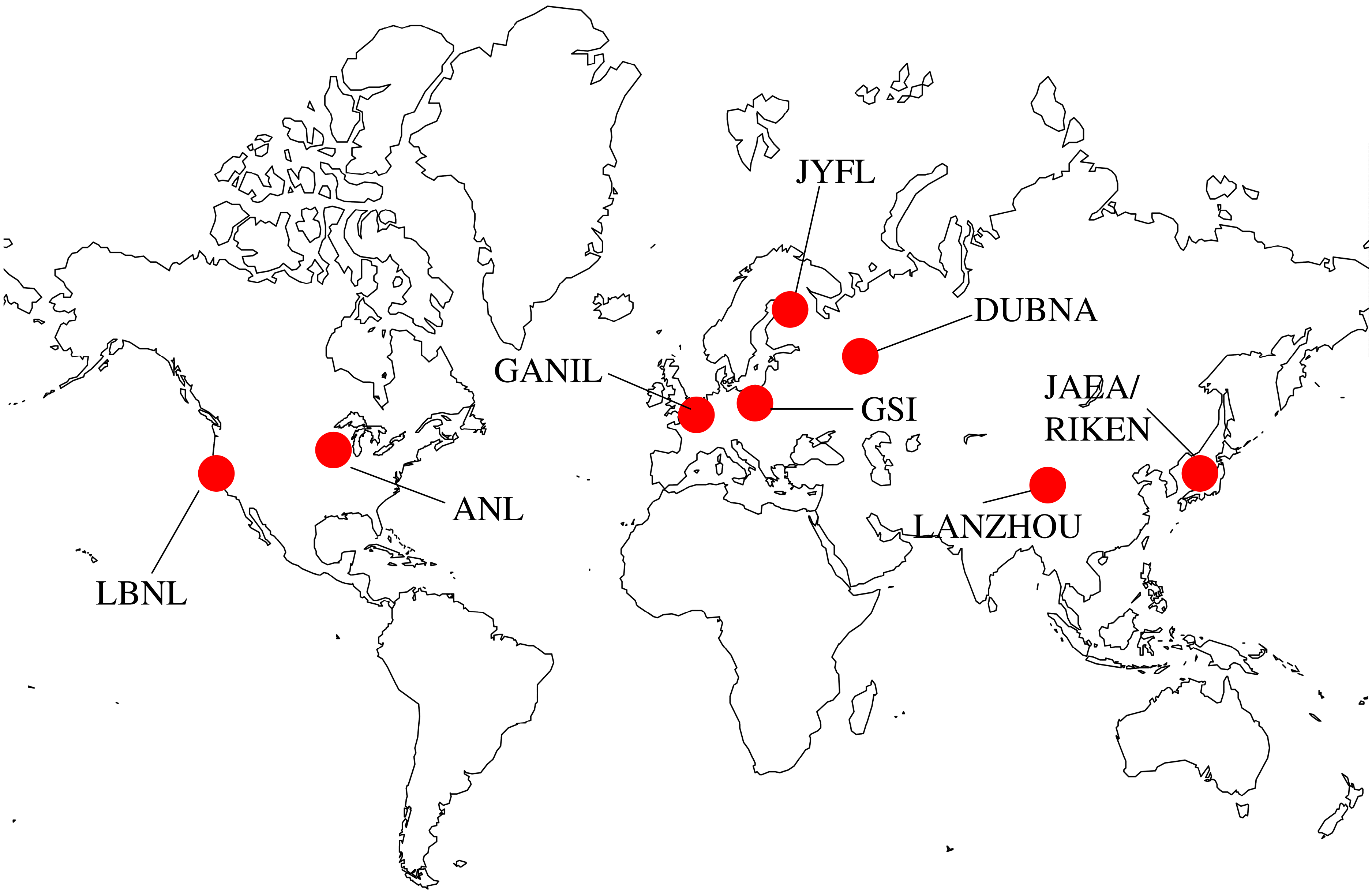
PRL 97, 082502 (2006) PHYSICAL REVIEW LETTERS week ending 25 AUGUST 2006

K Isomers in ^{254}No: Probing Single-Particle Energies and Pairing Strengths in the Heaviest Nuclei

S. K. Tandel,[1] T. L. Khoo,[2] D. Seweryniak,[2] G. Mukherjee,[1,2,*] I. Ahmad,[2] B. Back,[2] R. Blinstrup,[2] M. P. Carpenter,[2] J. Chapman,[2] P. Chowdhury,[1] C. N. Davids,[2] A. A. Hecht,[2,4] A. Heinz,[5] P. Ikin,[3] R. V. F. Janssens,[2] F. G. Kondev,[2] T. Lauritsen,[2] C. J. Lister,[2] E. F. Moore,[2] D. Peterson,[2] P. Reiter,[6] U. S. Tandel,[1] X. Wang,[2,7] and S. Zhu[2]

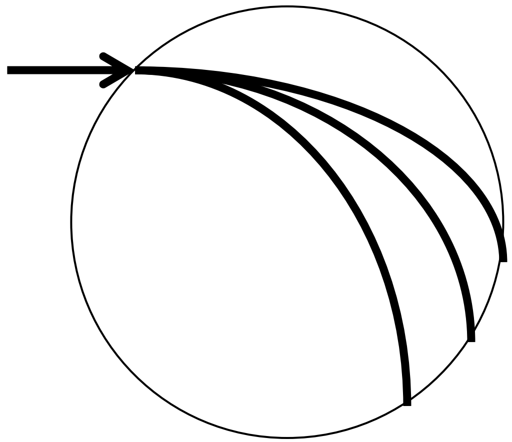
The claims of new elements and the possibility of performing detailed measurements on nuclei with Z>100 have resulted in a wave of renewed interest in super-heavy nuclei.

The Resurgence of Heavy Element Research



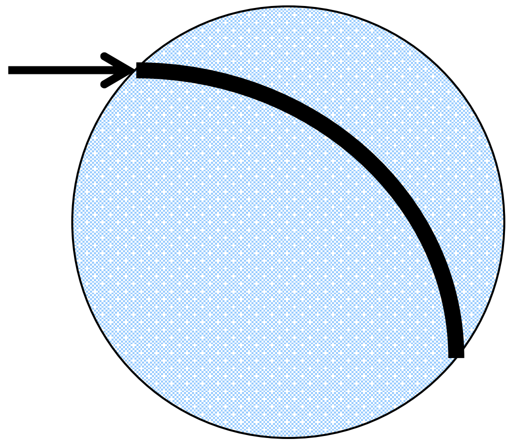
Principle Behind a Gas-Filled Separator

Vacuum



$B\rho_i = p/q_i$

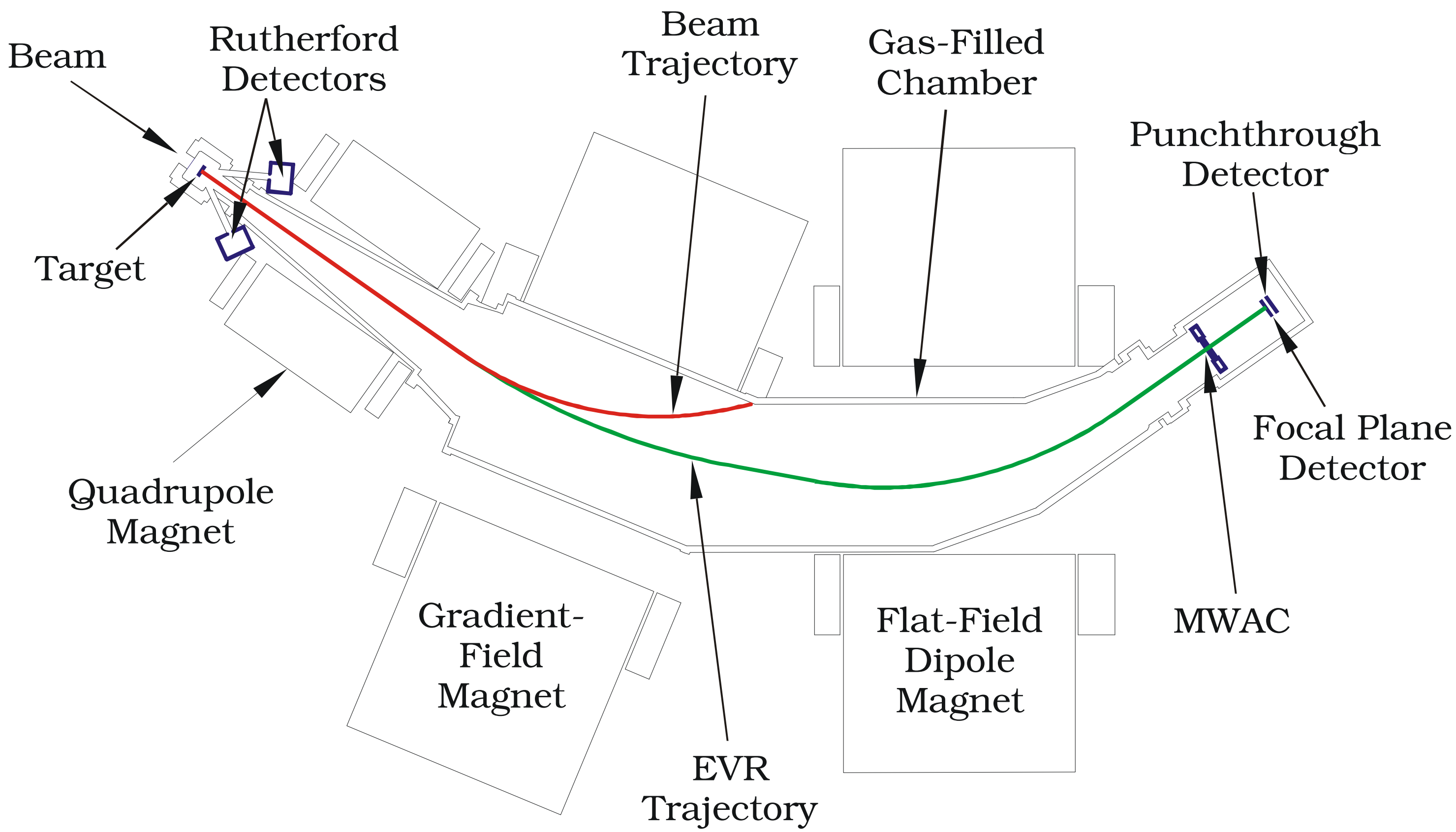
Gas



$B\rho = p/q_{ave}$

In a gas-filled separator there is no mass resolution but you get very high efficiency

Berkeley Gas-filled Separator



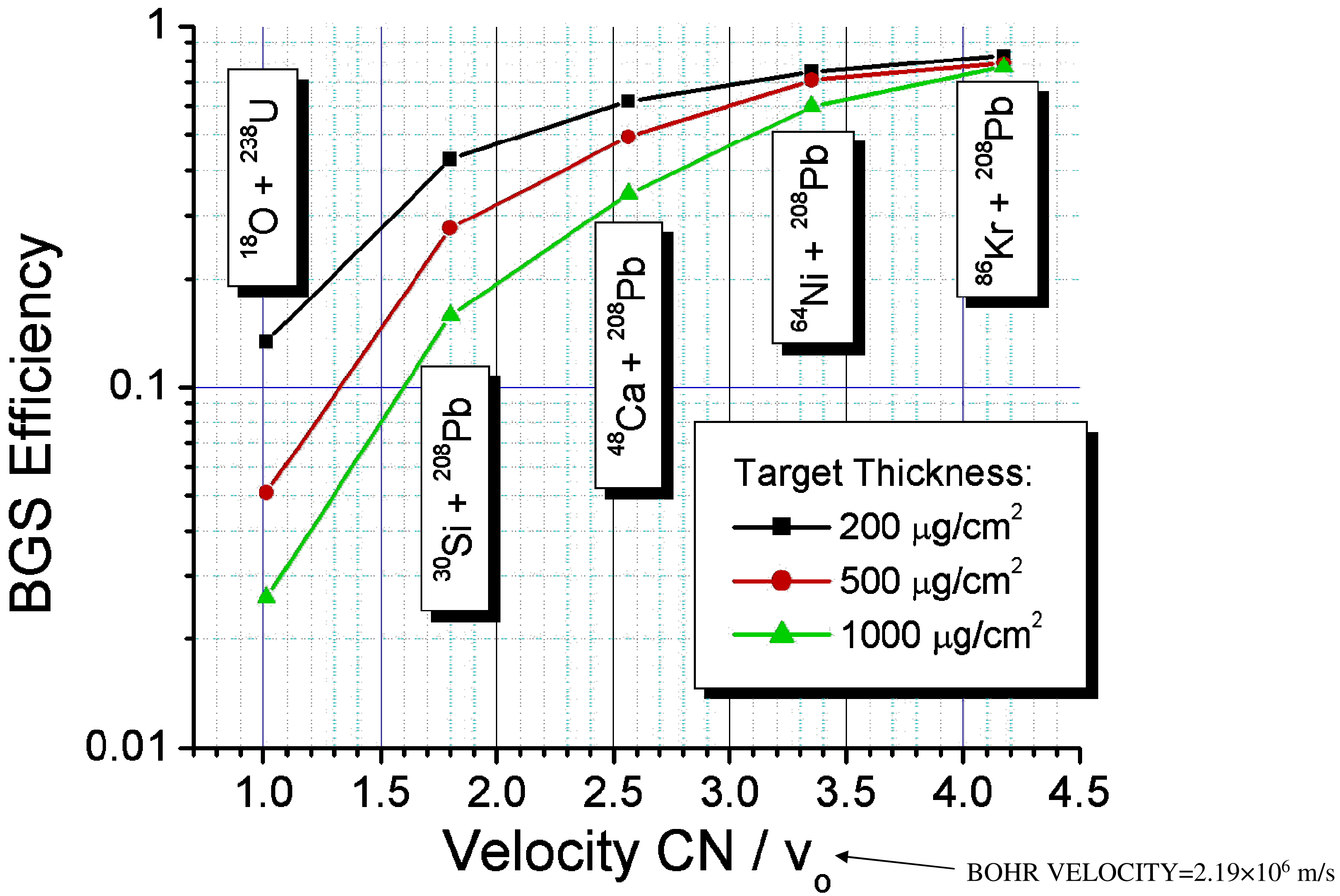
Large acceptance: 45 msr (± 9° vertical, ±4.5° horizontal)

Highest transmission (Ni+Pb: 70% Ca+Pb: 60% Mg+U: 18%)

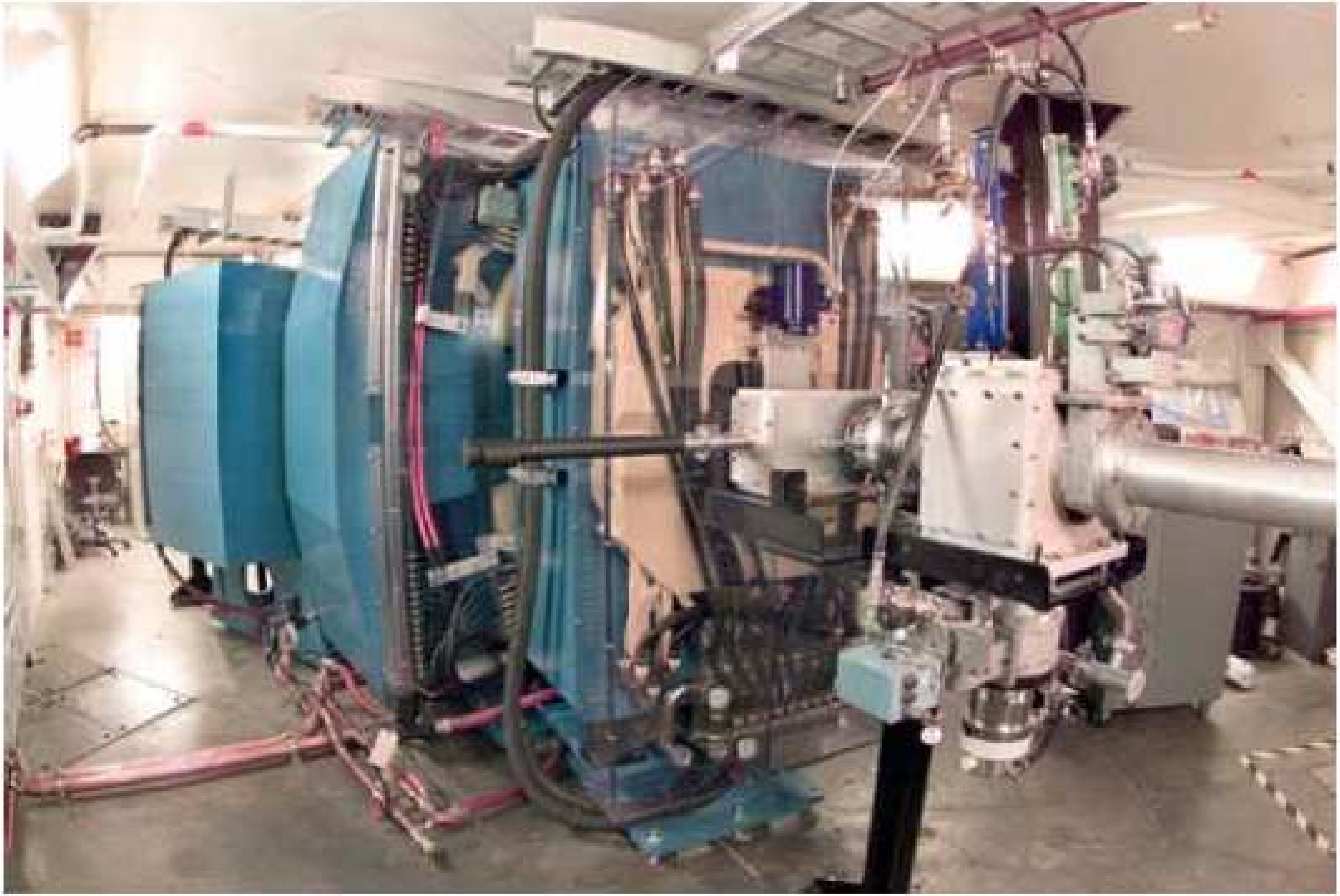
Large bend angle: 70°

Lowest background rates (40Hz/pµA 20Hz/pµA 100Hz/pµA)

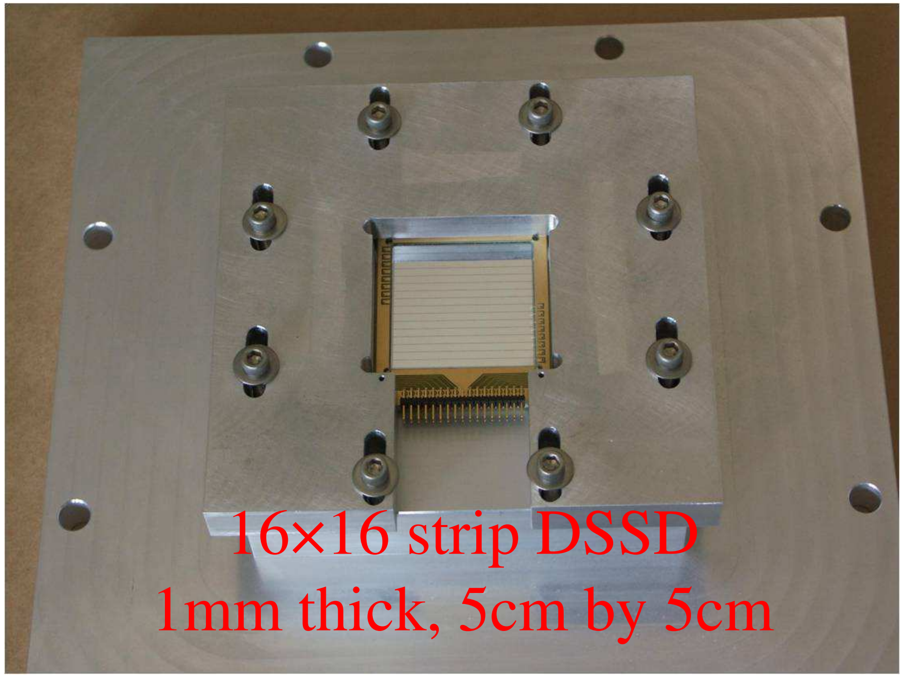
Calculated BGS Efficiencies

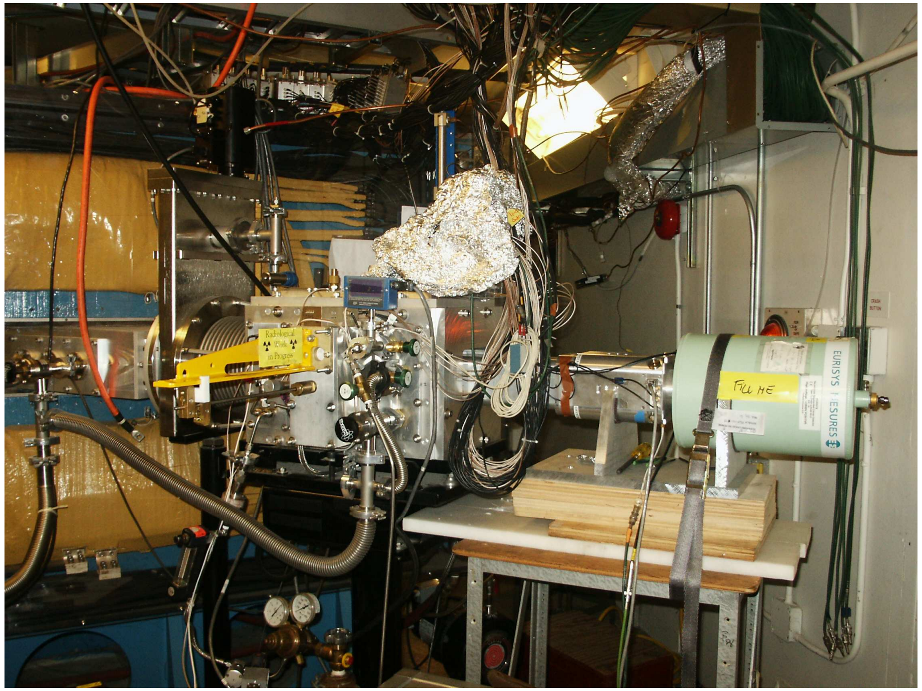


BGS+GRETINA is powerful combination for broad range of decay tagging experiments using intense stable beams.



Focal Plane Detectors





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

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

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

^{254}No

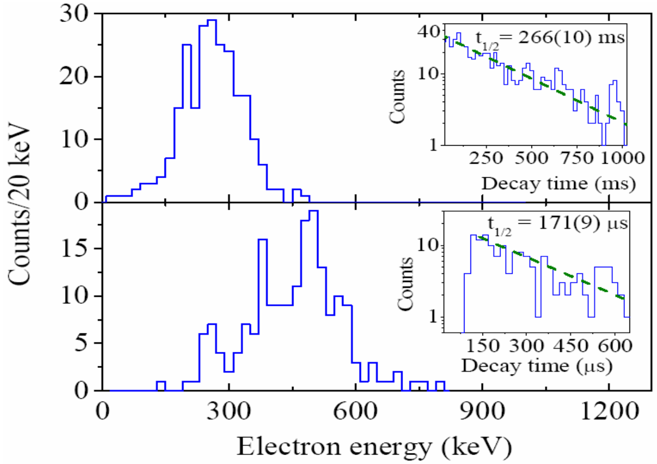
Nobelium

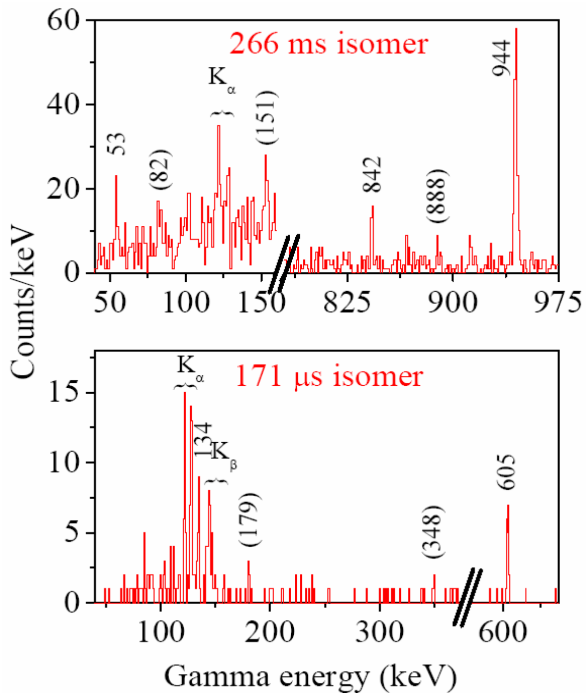
102 152

$^{48}Ca + ^{208}Pb \rightarrow ^{254}No + 2n$

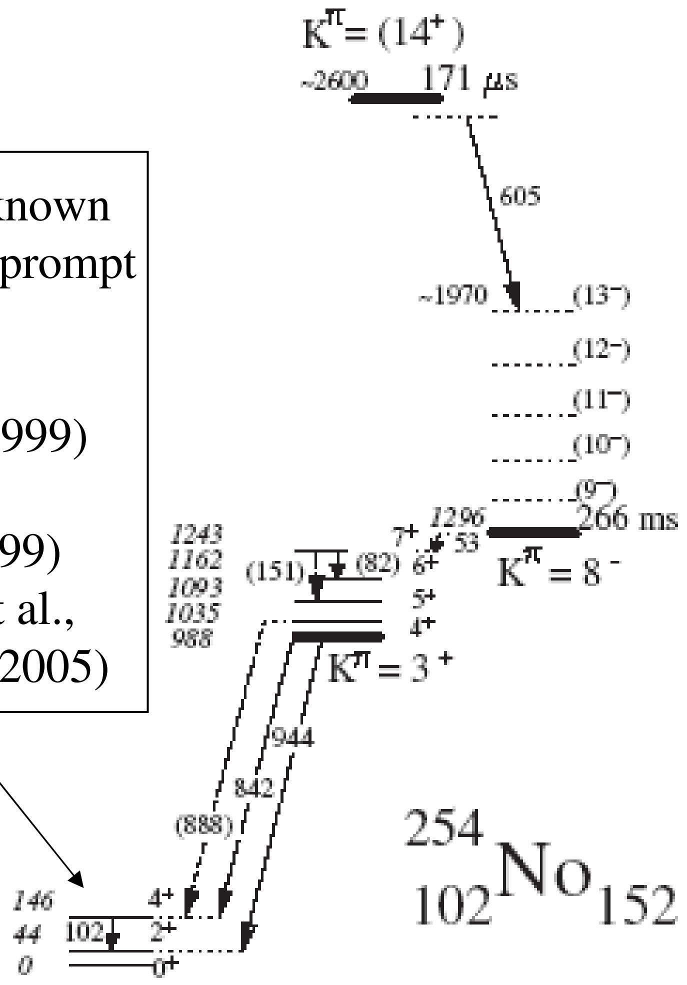
$\sigma \approx 2\ \mu b$ (or, about 1 recoil into our detector per second)

Prior Knowledge of ^{254}No Level Structure



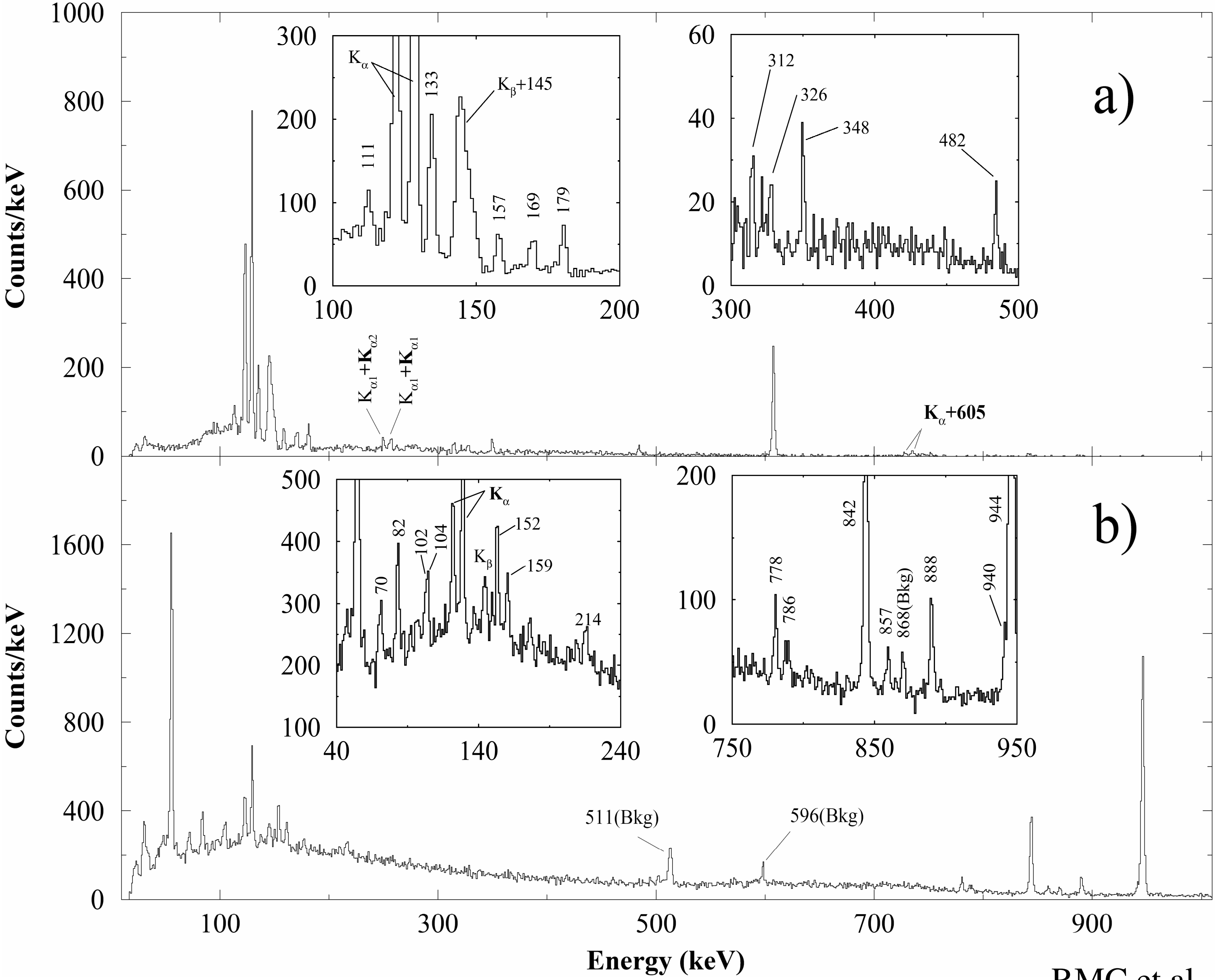


Ground band known to I=24ħ from prompt spectroscopy.
P.Reiter et al., PRL 82 509 (1999)
M.Leino et al., EPJ A6 63 (1999)
S.Eeckhaudt et al., EPJ A26 227 (2005)



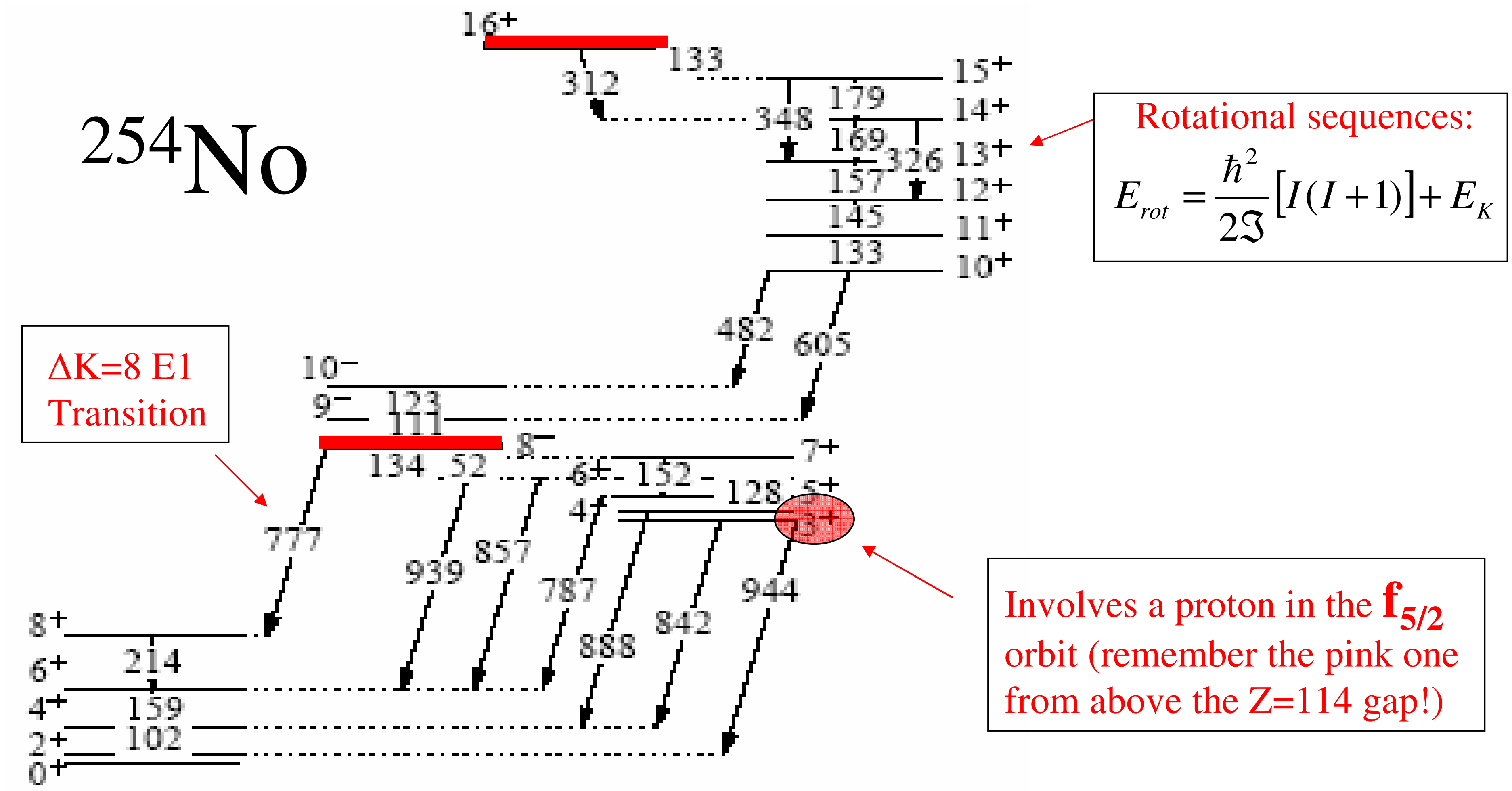
S.K.Tandel et al., PRL 97 082502 (2006)
R.D.Herzberg et al., Nature 442 896 (2006)
[F.P.Hessberger et al. EPJ A 43 55 (2010)]

New Results on ^{254}No



RMC et al., PLB in press

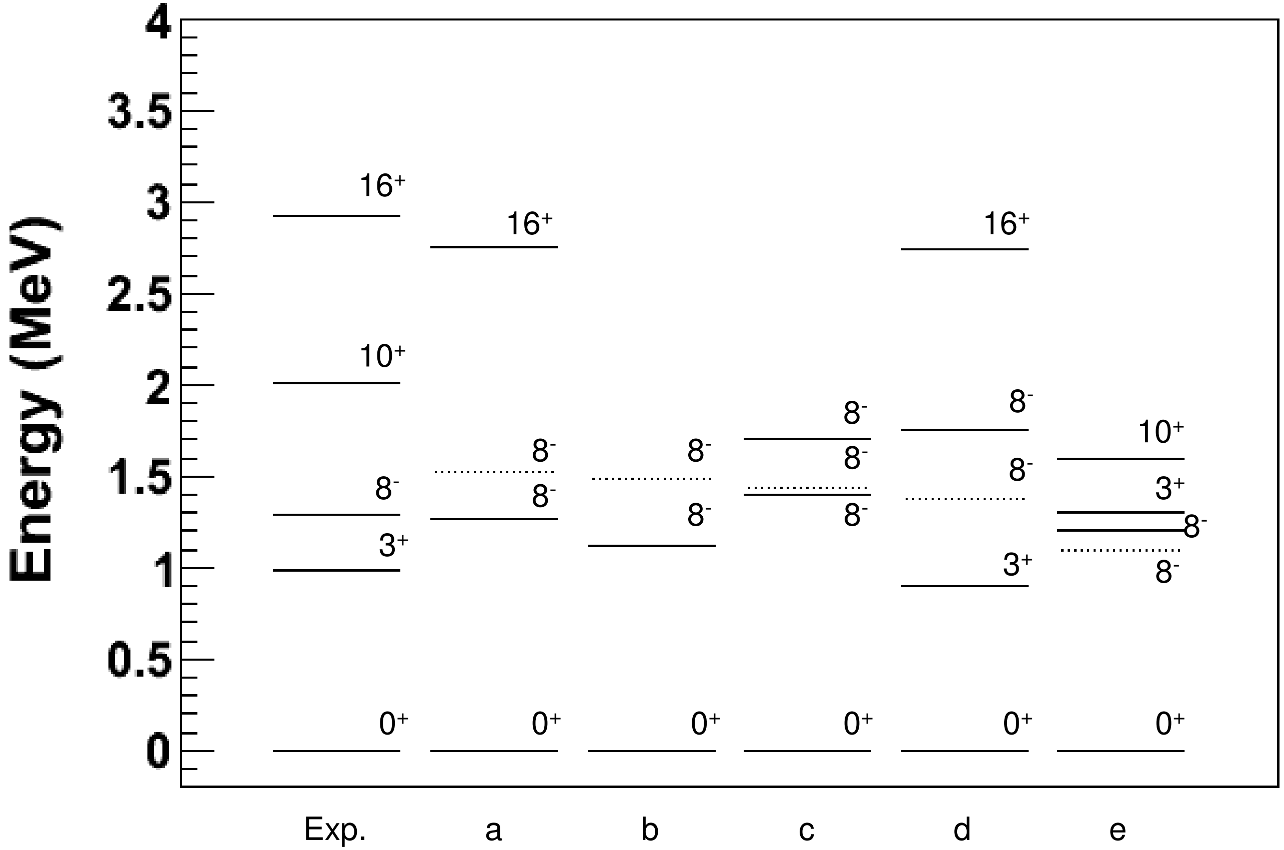
New Results on ^{254}No



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

RMC et al., PLB in press

Comparison With Theory



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

Pairing and Rotational Moments of Inertia

High-K Band

K+2

K+1

K

$$E_{K+1}-E_K = \frac{\hbar^2(K+1)}{\mathcal{J}_K}$$

Ground-State Band

4+

2+

0+

$$E(2+) = \frac{\hbar^2 3}{\mathcal{J}_{GS}}$$

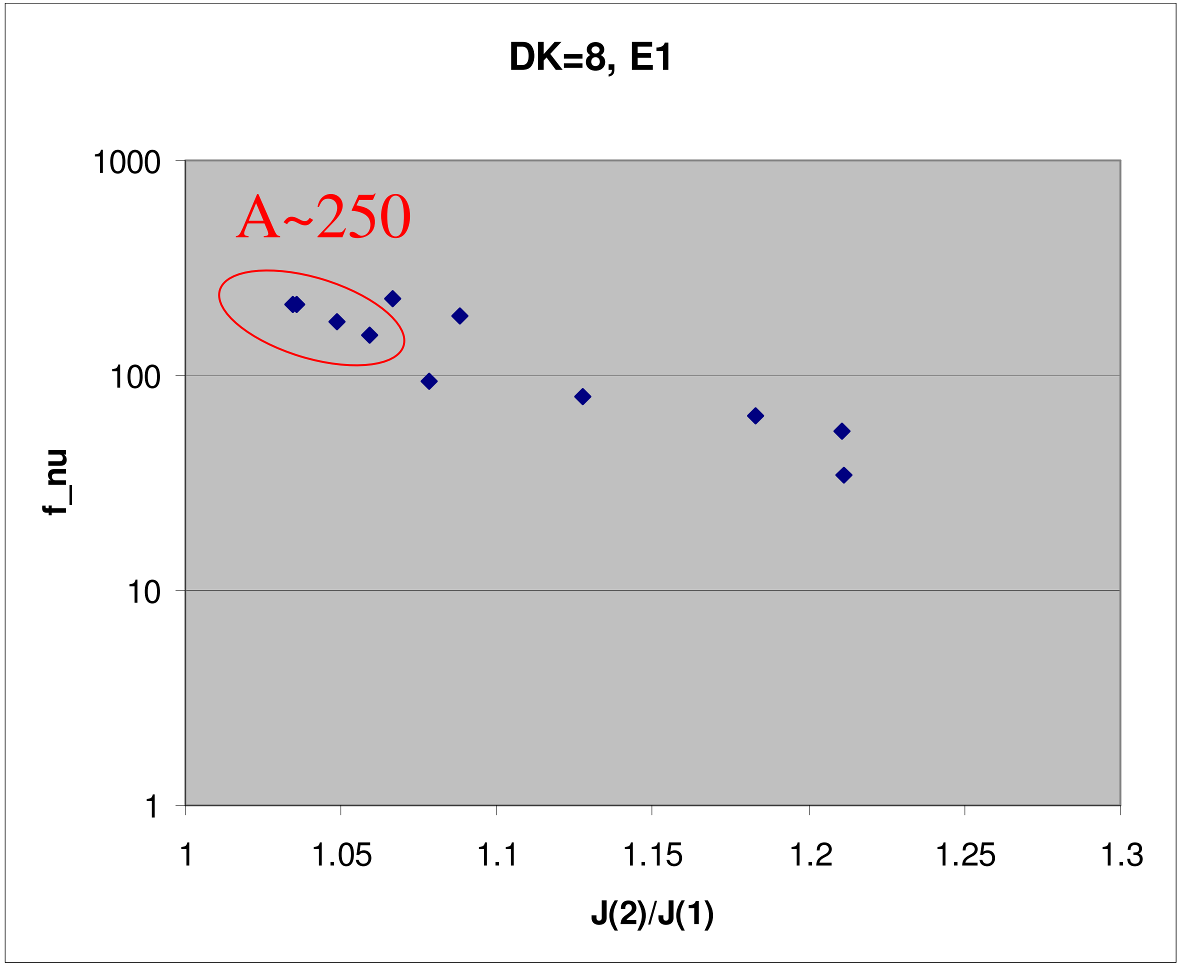
$\mathcal{J}_K/\mathcal{J}_{GS}$

	^{254}No	^{174}Hf	^{176}Hf	
$K^\pi=3^+$	1.27	1.33	1.20	} 2qp
$K^\pi=8^-$	1.19	1.19	1.17	} 2qp
$K^\pi=10^+$	1.22	-	-	} 2qp
$K^\pi=16^+$	-	1.95	1.83	4qp

Increase of moment of inertia, $\mathcal{J}_K$, implies $\Delta_K \approx 0.8 \times \Delta_{GSB}$ (taking Migdal and assuming all other things, like deformation, are equal). ($\rightarrow K^\pi=10^+$ state is likely a two-quasiparticle state).

G.Dracoulis, F.G.Kondev, P.M.Walker, PLB 419 (1998) 7

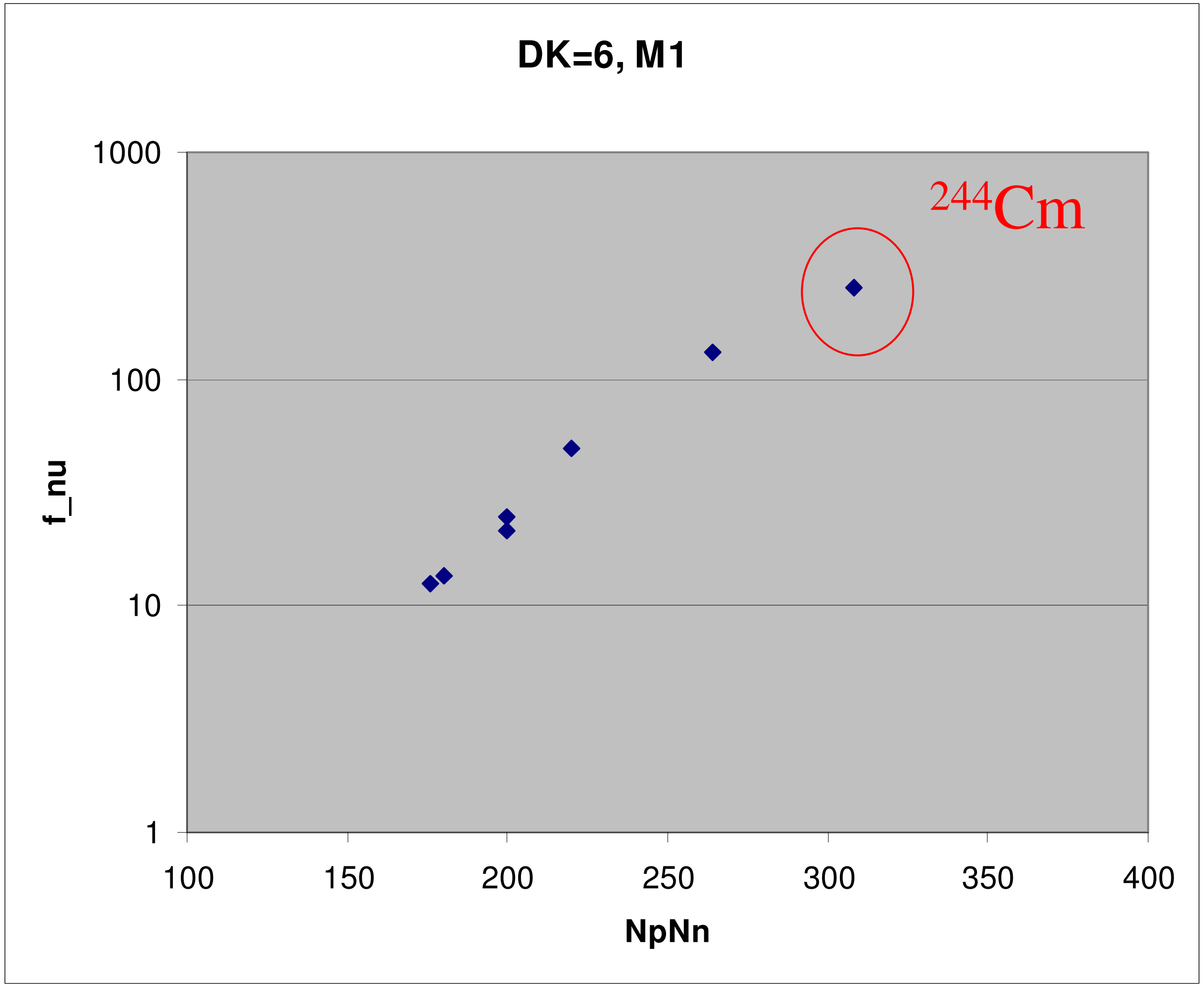
ΔK=8 E1 Reduced Hindrances for A~180 and A~250



- $J^{(2)}/J^{(1)}$ reflects Coriolis mixing → high-K components in g.s. band
- Lower $J^{(2)}/J^{(1)}$ implies less Coriolis mixing → higher hindrances

Based on idea by P.M.Walker et al., Phys. Rev. C 49 (1994) 1718

K-forbidden Transitions and the N_pN_n Scheme



• Larger N_pN_n reflects stiffer axial deformation → lower K-mixing

Based on idea by P.M.Walker, J. Phys. G 16 (1990) L233

256

Rf

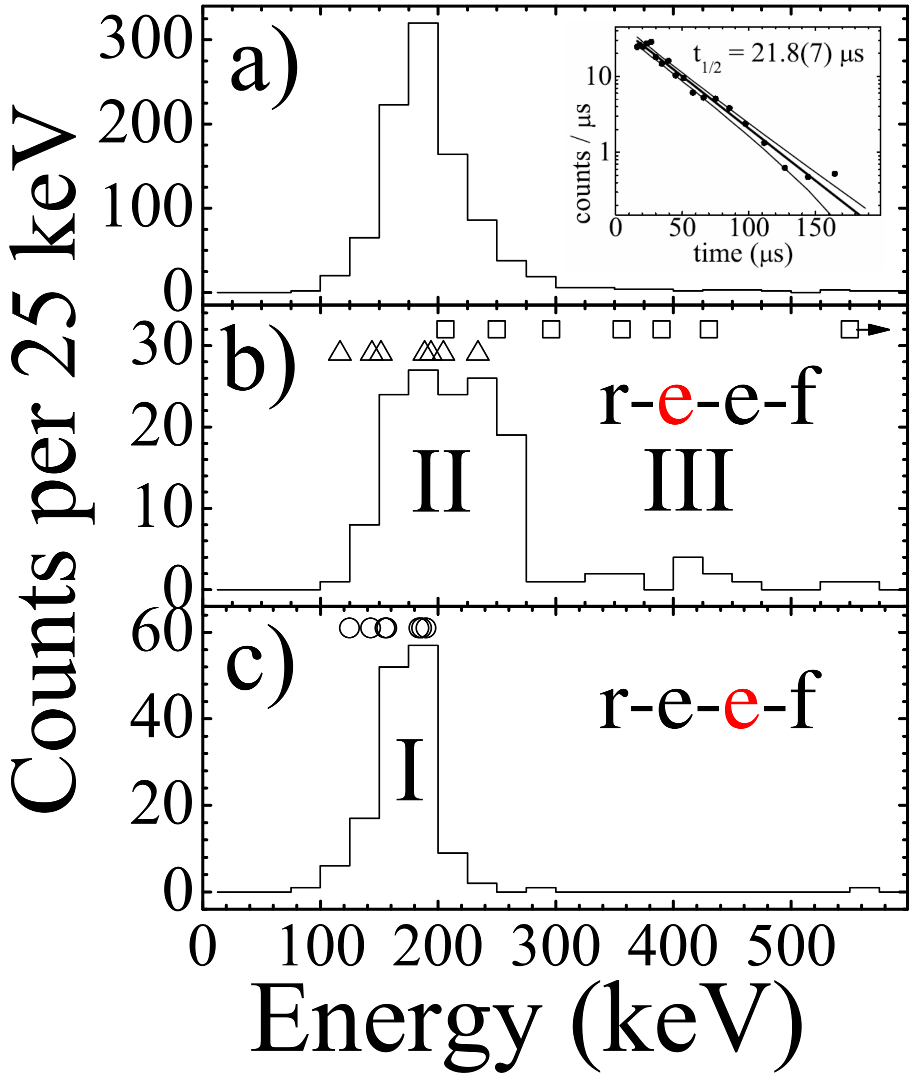
Rutherfordium

104 152

$^{50}Ti + ^{208}Pb \rightarrow ^{256}Rf + 2n$

$\sigma \approx 20$ nb (or, about 1 recoil into our detector per minute)

Conversion Electron Spectra



Events statistics:

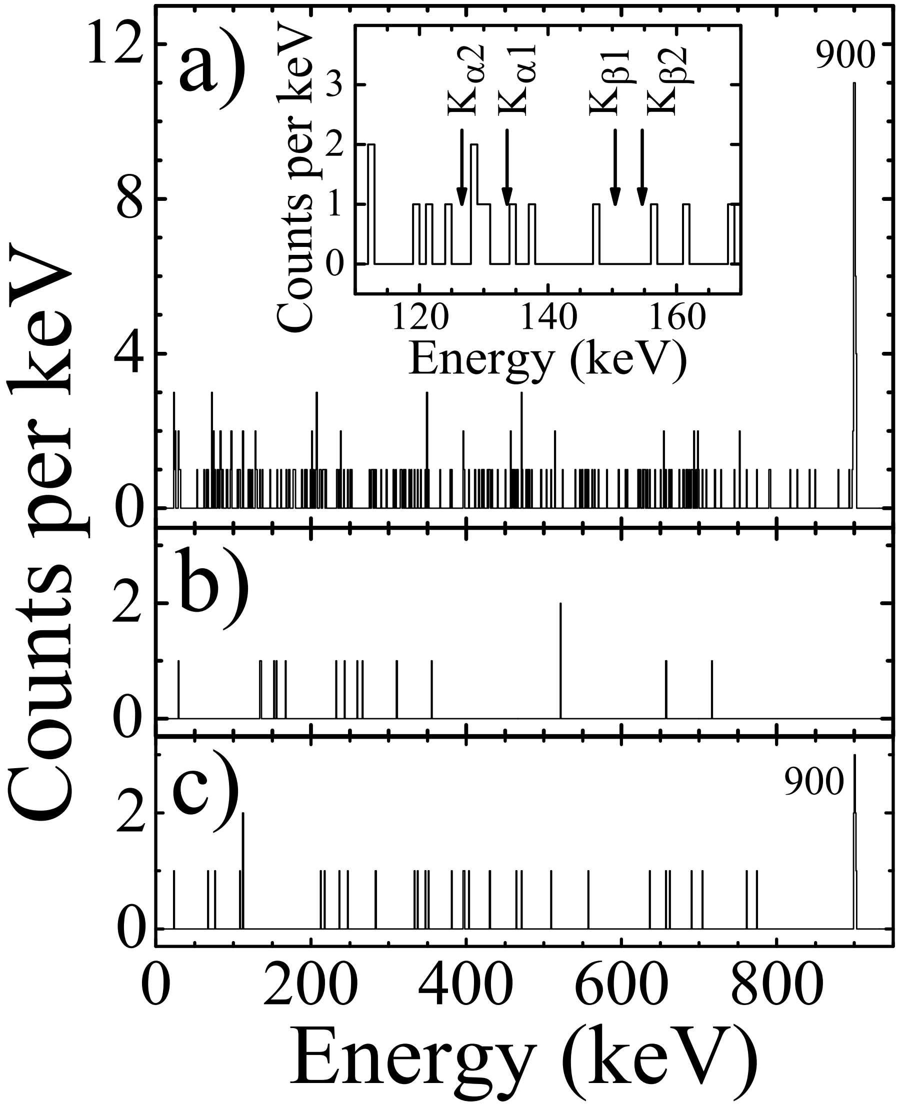
985 r-e-f events
147 r-e-e-f events
7 r-e-e-e-f events

Three different sum-electron energy distributions (with very similar half-lives).

→ Three different isomers

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

Gamma-Ray Spectra



Photopeak efficiency

17% at 122 keV

3.5% at 1 MeV

227 total coincident γ's

35 in peak at 900 keV

Spectrum consistent with single 900 keV transition and its Compton scatters.

Expected X-ray yields:

~17 K X-rays if M1

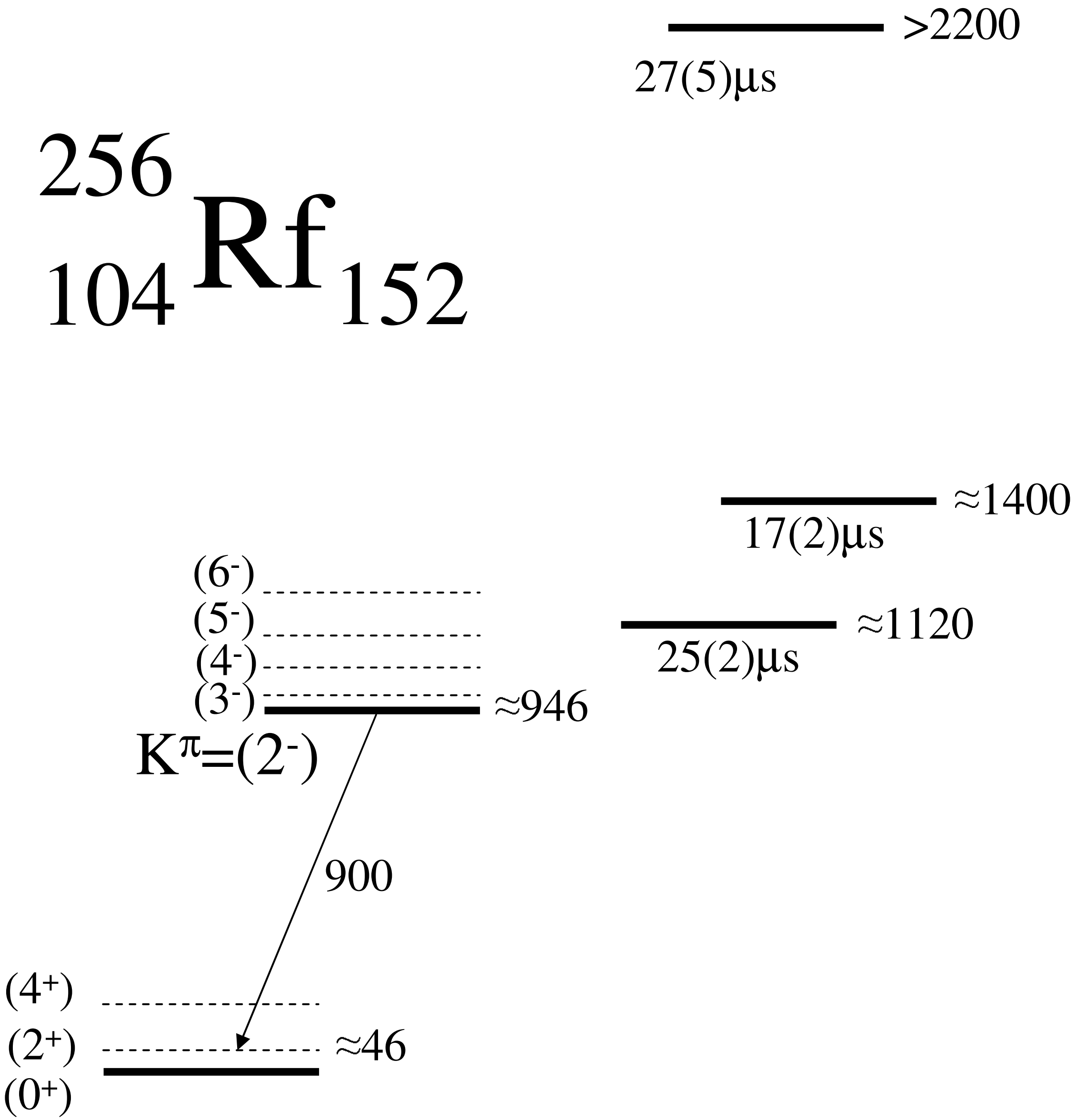
~4 K X-rays if E2

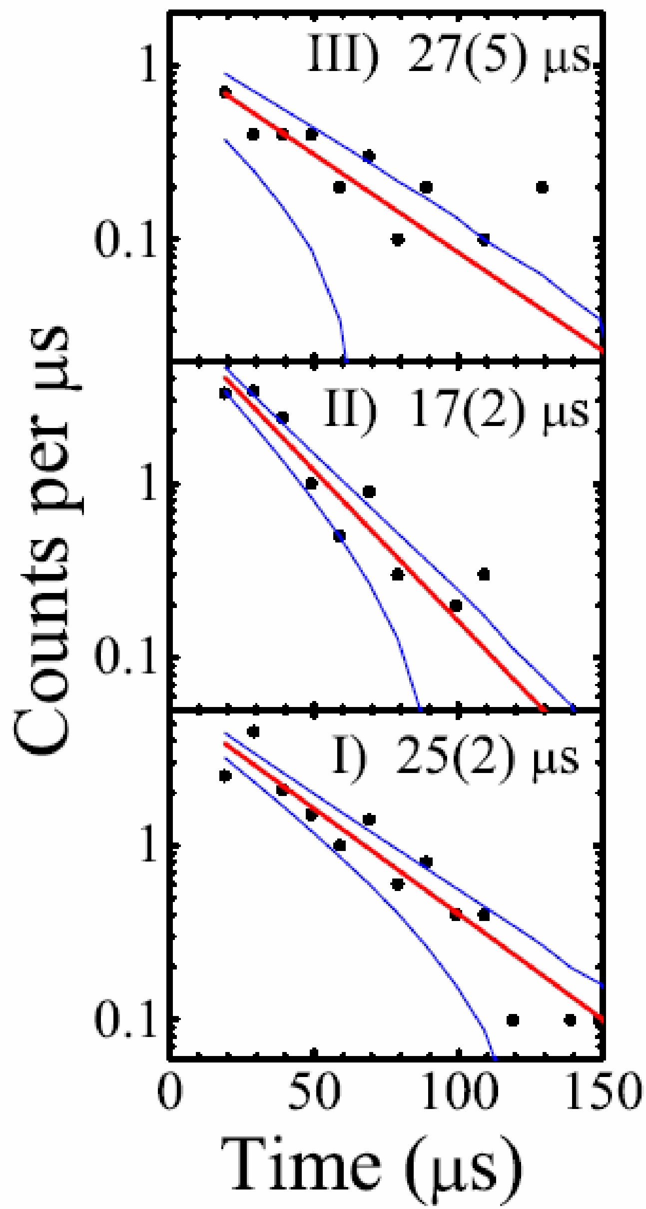
~1 K X-ray if E1

→ Probable E1 character

A single 900 keV E1 transition associated with lowest isomer

Level Structure of ^{256}Rf



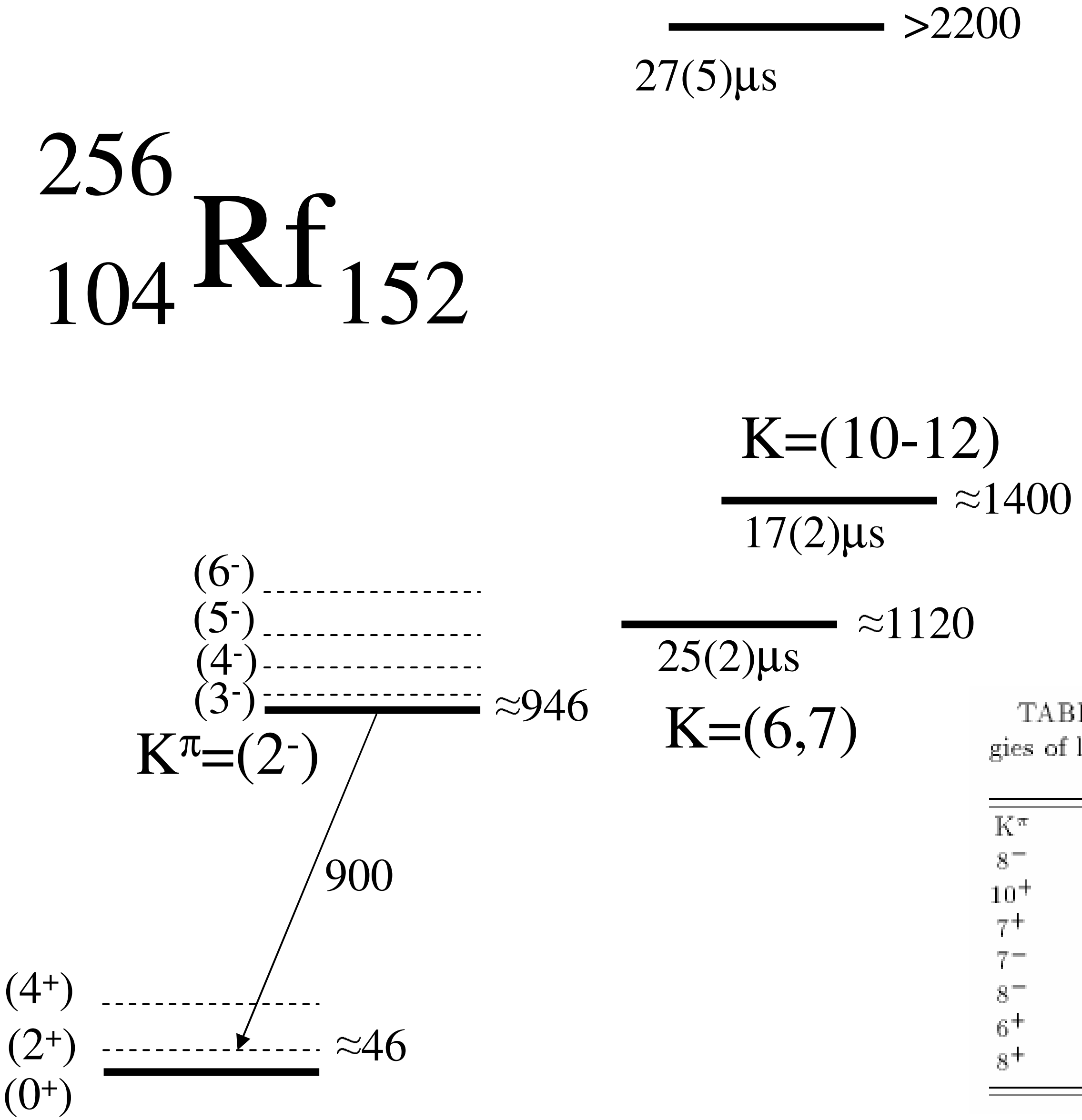


Two-Quasiparticle Configurations

Macroscopic-microscopic WS calculations with "universal parameters"

F.R.Xu et al., PRL 92 252501 (2004)

$^{256}_{104}Rf_{152}$



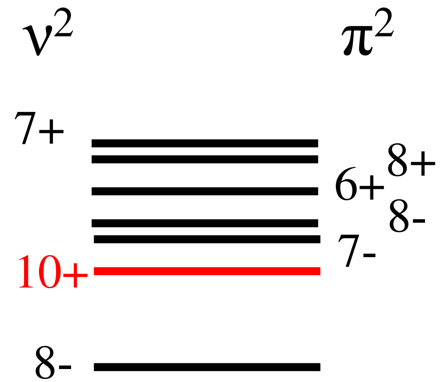


TABLE I. Calculated configurations and excitation energies of low-lying high-K two-quasi-particle states in ^{256}Rf.

K^π	Configuration	E_x(MeV)
8^-	$\nu^2([734]9/2^- \otimes [613]7/2^+)$	1.16
10^+	$\nu^2([734]9/2^- \otimes [725]11/2^-)$	1.36
7^+	$\nu^2([613]7/2^+ \otimes [624]7/2^+)$	1.66
7^-	$\pi^2([624]9/2^+ \otimes [512]5/2^-)$	1.41
8^-	$\pi^2([514]7/2^- \otimes [624]9/2^+)$	1.45
6^+	$\pi^2([514]7/2^- \otimes [512]5/2^-)$	1.53
8^+	$\pi^2([624]9/2^+ \otimes [633]7/2^+)$	1.64

$K^\pi=10^+$ state is also seen in ^{254}No

Results Confirmed in Recent Experiment

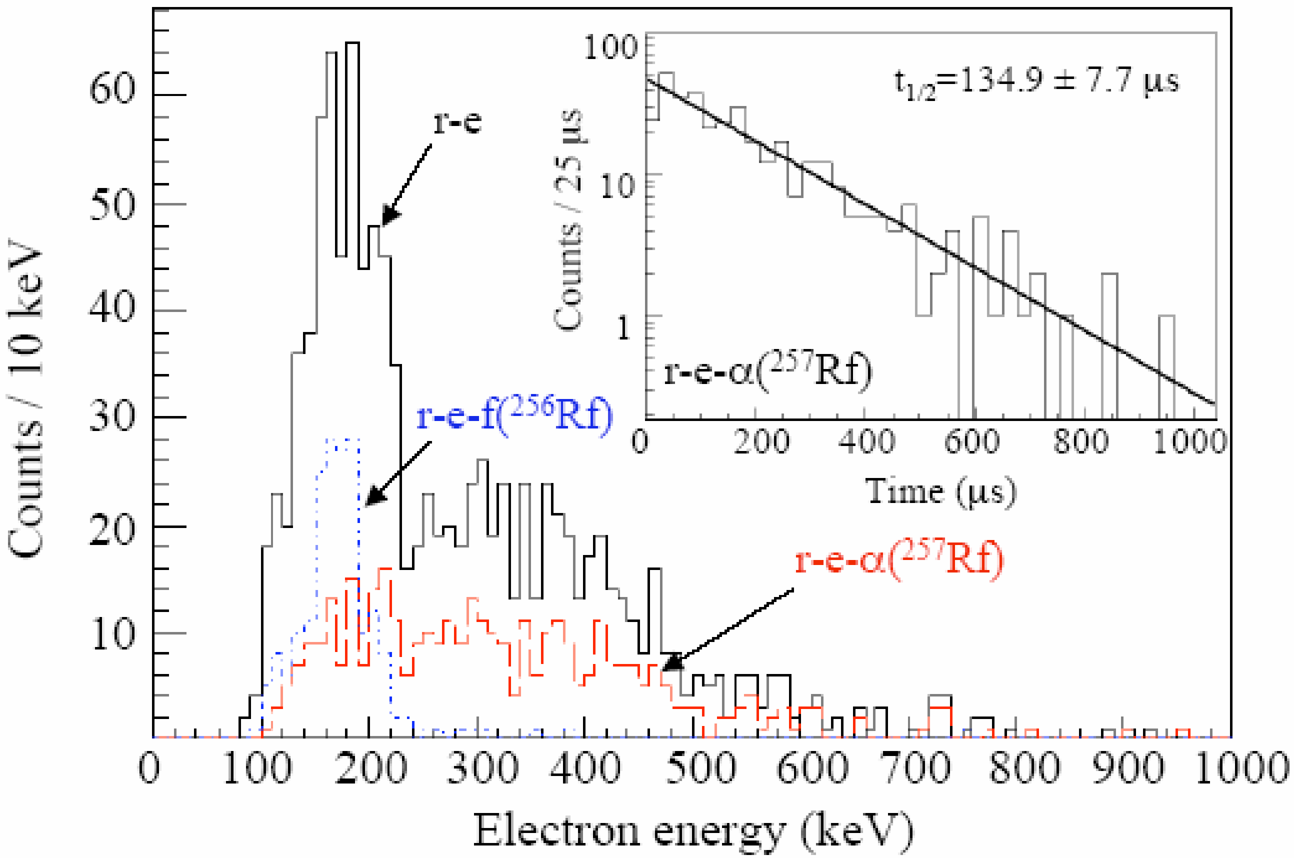


FIG. 3. (Color online) Energy spectrum from r-e, r-e-f(^{256}Rf), and r-e-α(^{257}Rf) events with an inset showing the electron decay curve for all r-e-α(^{257}Rf) events.

J.S.Berryman et al., submitted PRC

261

Sg

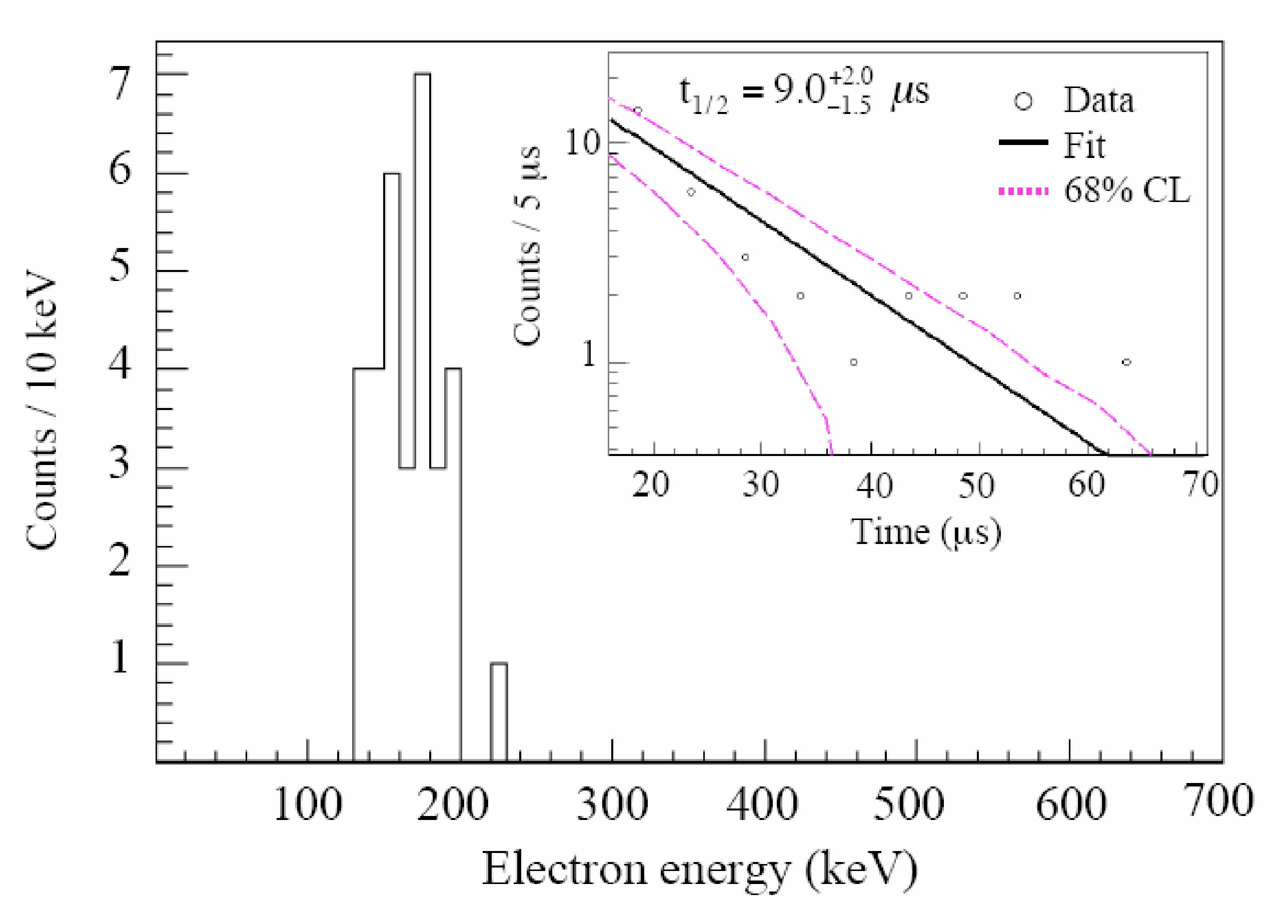
Seaborgium

106 155

$$^{54}Cr + ^{208}Pb \rightarrow ^{261}Sg + 1n$$

$\sigma \approx 2$ nb (or, a few recoils into our detector per hour)

Conversion Electrons Observed in ^{261}Sg (Z=106)



Events statistics:
393 r-α(-α)
39 r-e- α(-α)

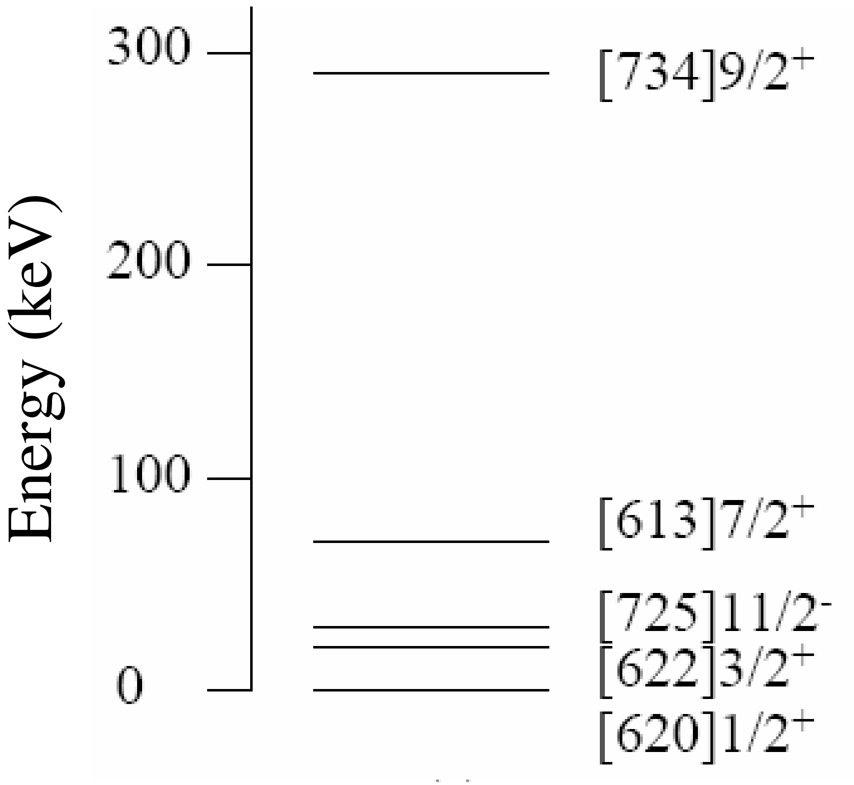
(Deadtime of DAQ is ~15μs – we are losing events)

Evidence for a ~10μs isomer with a total decay energy of about 200keV → likely a low-lying one-quasineutron state.

J.S.Berryman et al., submitted PRC

What Could It Be?

Almost nothing known experimentally for excited states in N=155 nuclei

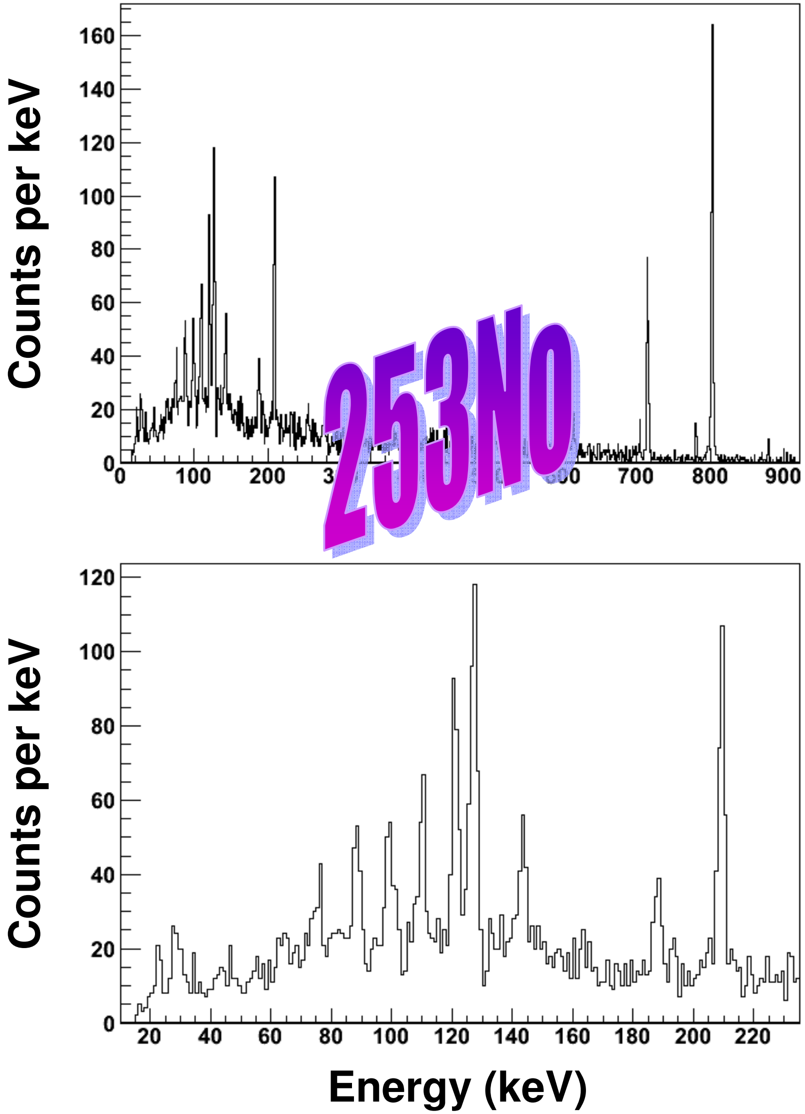


S.Cwiok, S.Hofmann, W.Nazarewicz, NPA611 (1996) 211

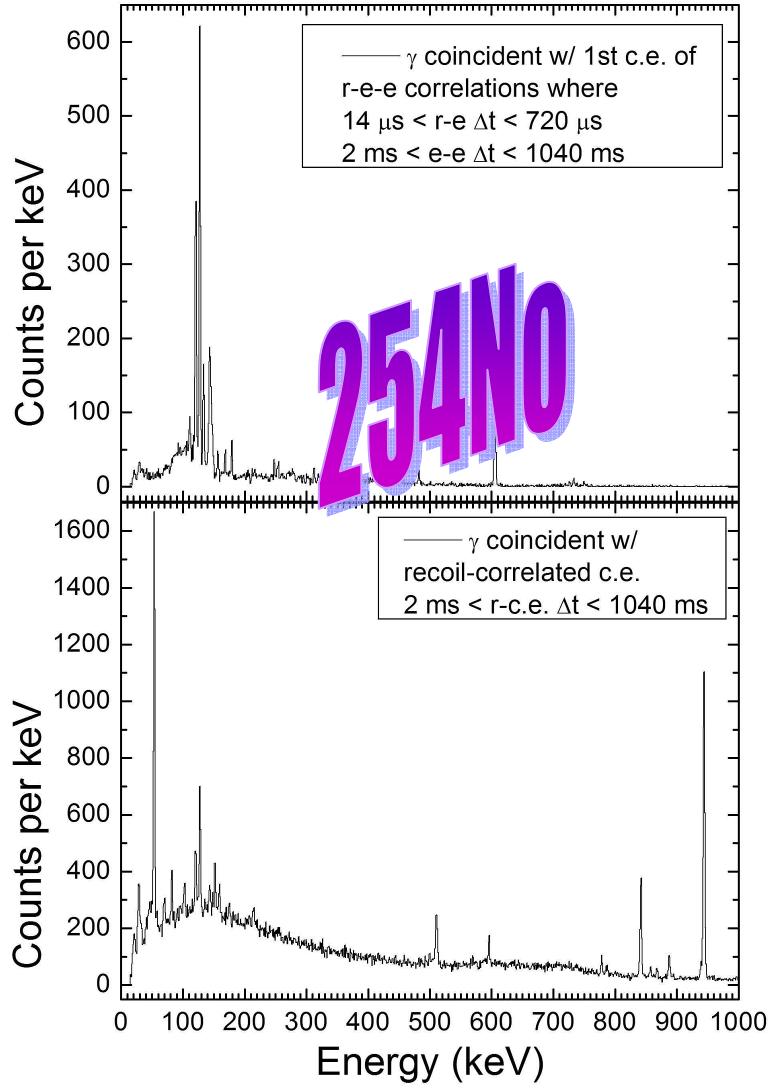
- Ground-state of ^{261}Sg assigned [622]3/2^{+} from α-decay studies.
- Likely +ve pairty states will all decay quickly to the ground state
- [725]11/2^{-} is the most likely assignment for isomer.

Highest Z for which electromagnetic decay of an excited state has been observed (alpha decay of excited isomers observed in Ds)!

Results on Nobelium (Z=102)

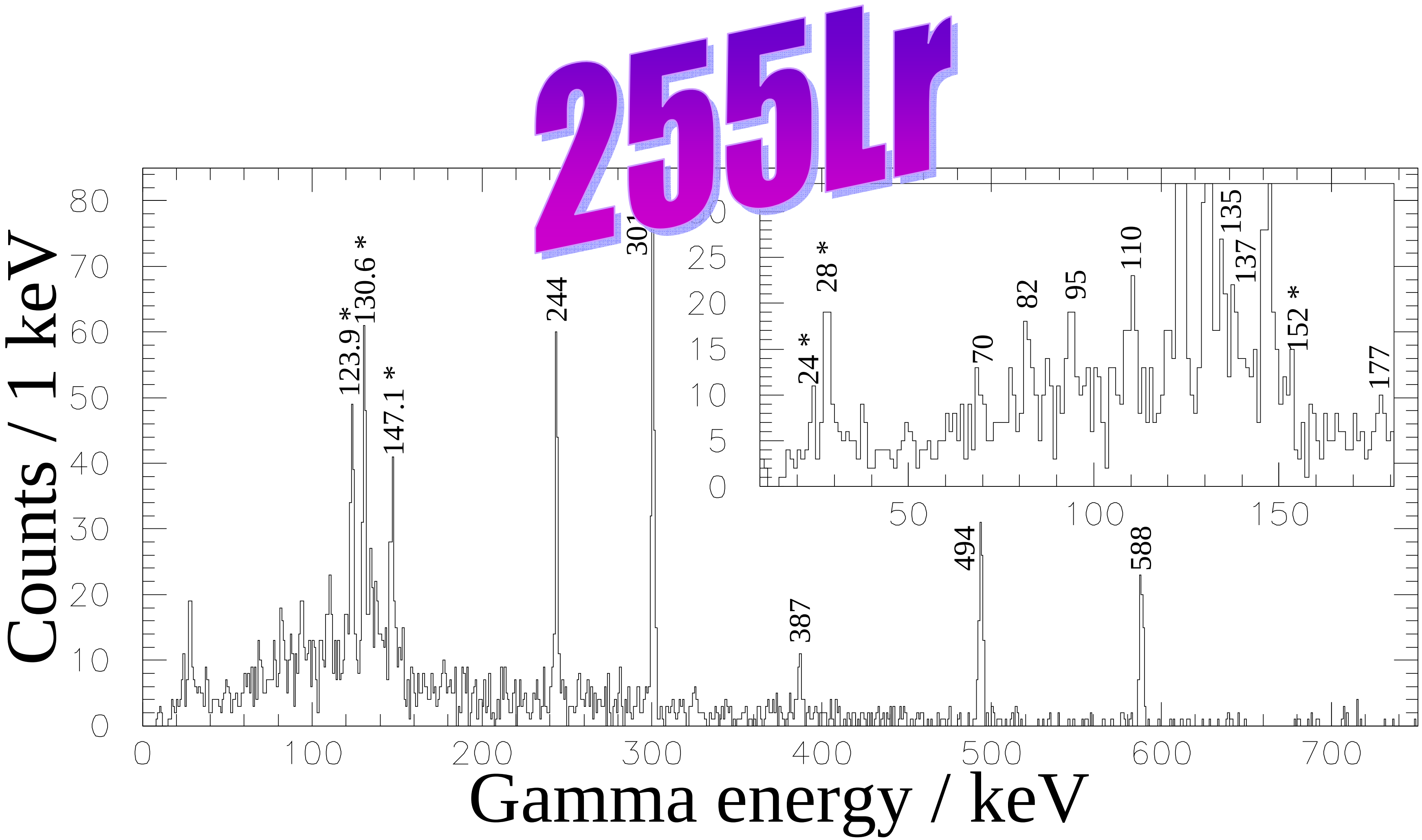


J.S.Berryman et al., to be published



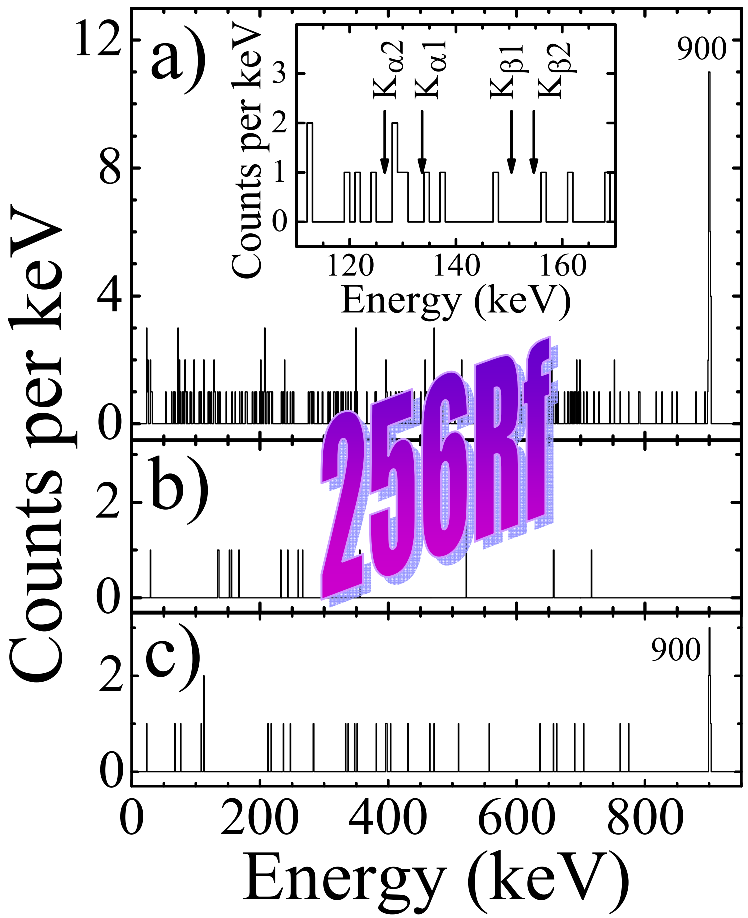
RMC et al., PLB in press

Results on Lawrencium (Z=103)

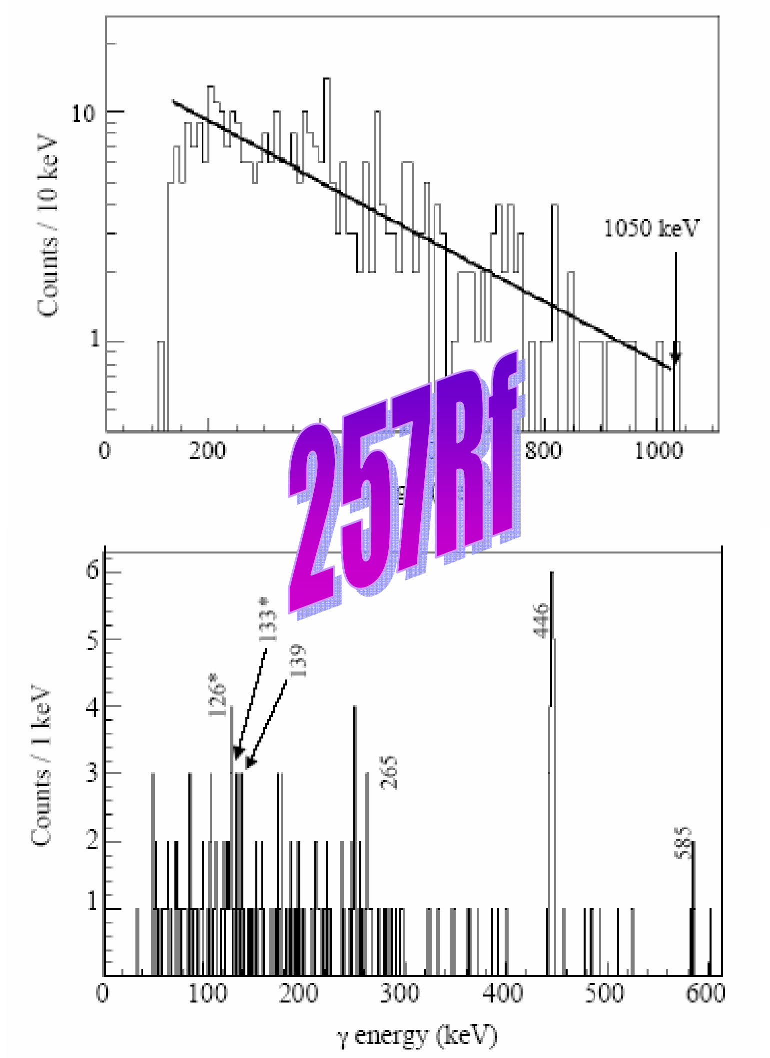


H.B.Jeppesen et al., PRC 80 (2009) 034324

Results on Rutherfordium (Z=104)

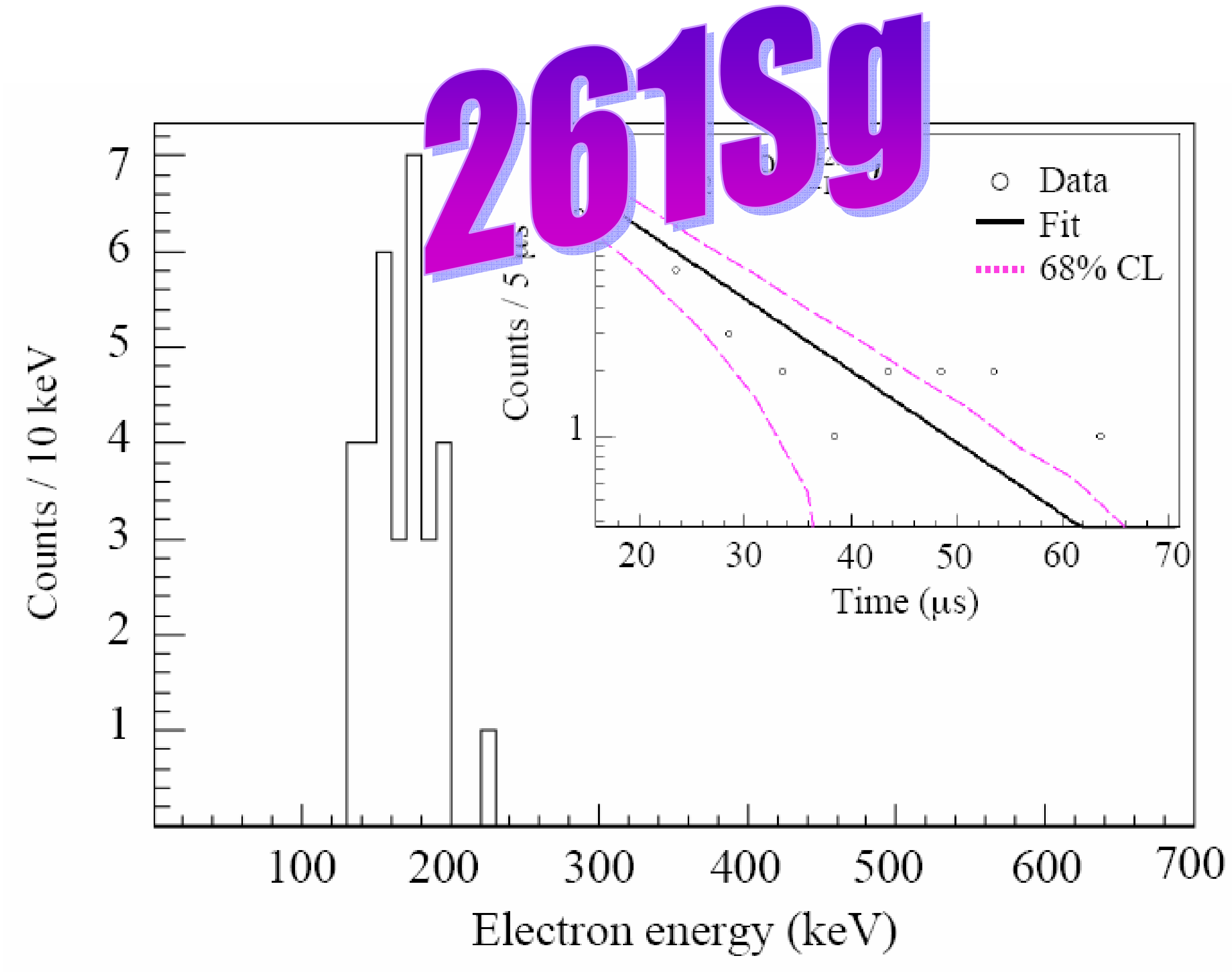


H.B. Jeppesen et al., PRC 79 (2009) 031303



J.S.Berryman et al., submitted PRC

New Results on Seaborgium (Z=106)



J.S. Berryman et al., submitted PRC

Seaborgium is at the current limit for spectroscopy measurements

Clover Corner Cube (C^3) Detector Upgrade

- The BGS has been used to study nuclear structure of ^{261}Sg, ^{255}Lr, ^{256,257}Rf, $^{253\text{-}255}$No by K-isomer decay.

- Presently, BGS @ the 88-Inch Cyclotron, single DSSD+single Ge clover detector configuration

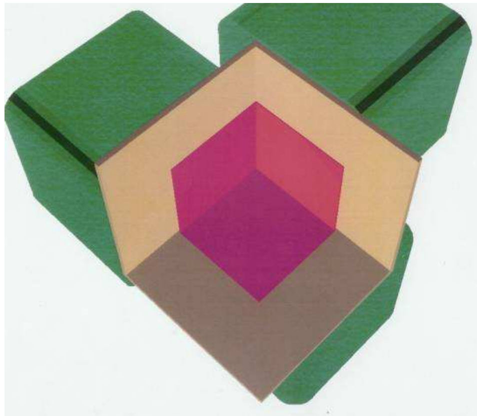
- An off-the-shelf detector/electronics upgrade can increase our efficiency further by a factor of 6.

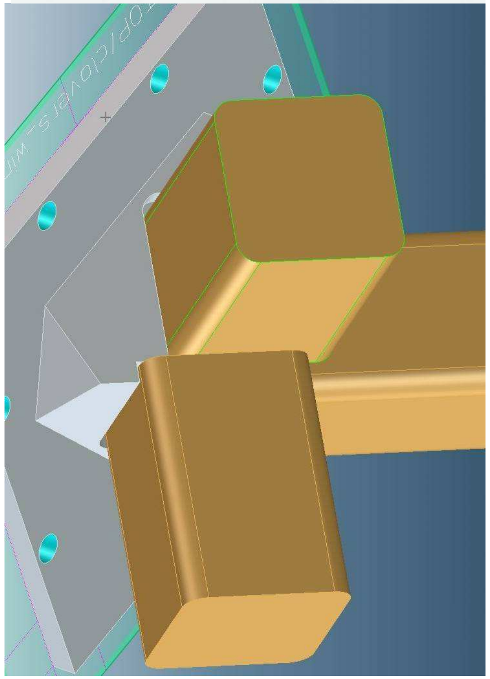
- Nuclear structure measurements can be made up to Z=108.

- The same detector will be used for superheavy element experiments and with the gas catcher/mass analyzer.

Ready for action Fall 2010!

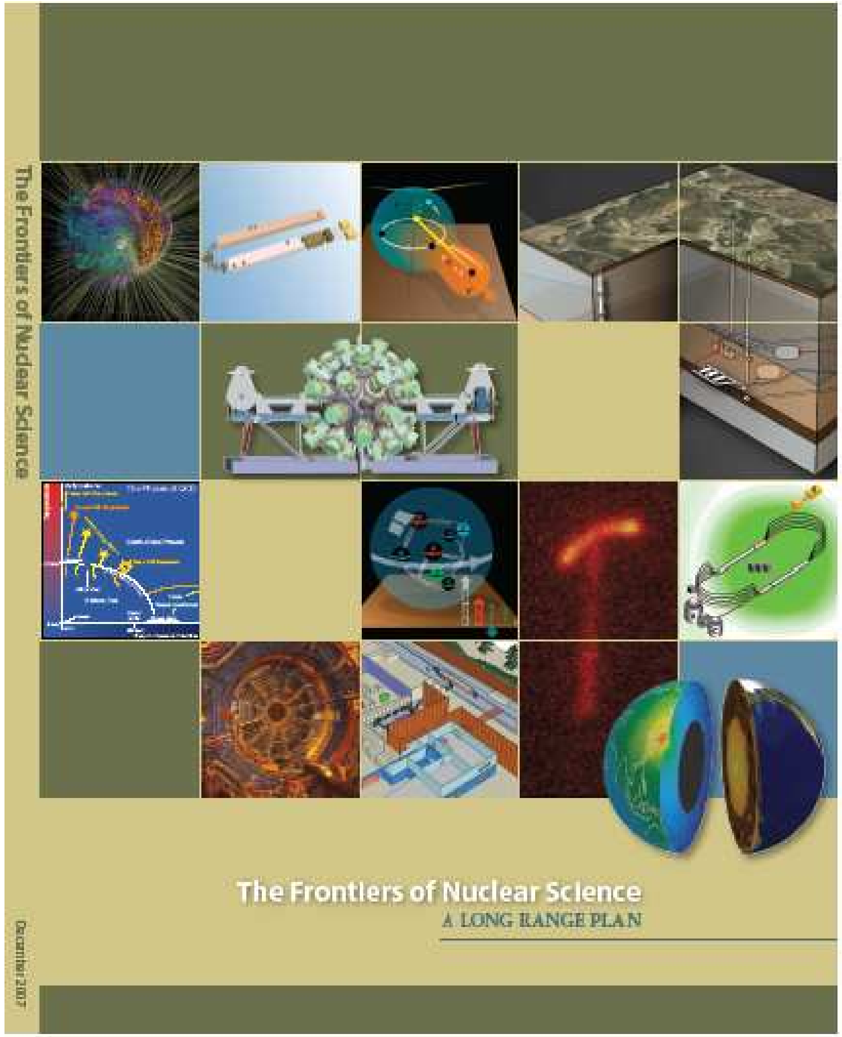
magenta = DSSD
Brown = Al vac window
Green = Ge Clover



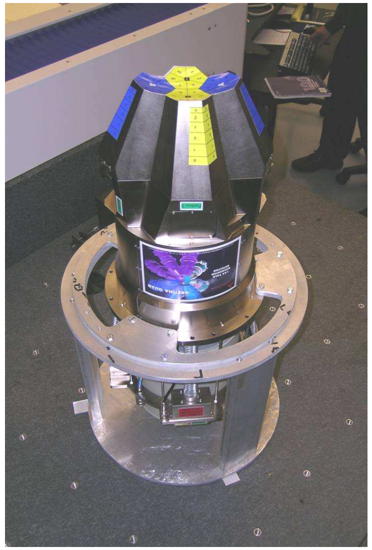


GRETINA/GRETA

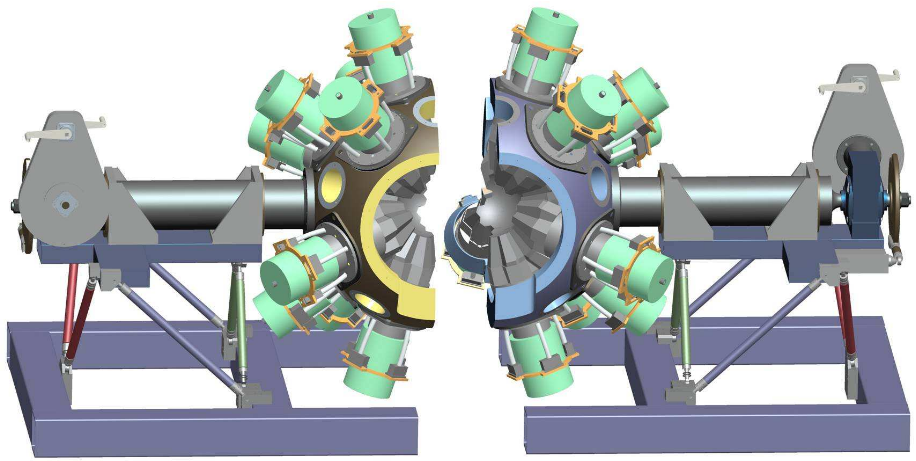
(Gamma-Ray Energy Tracking Array)



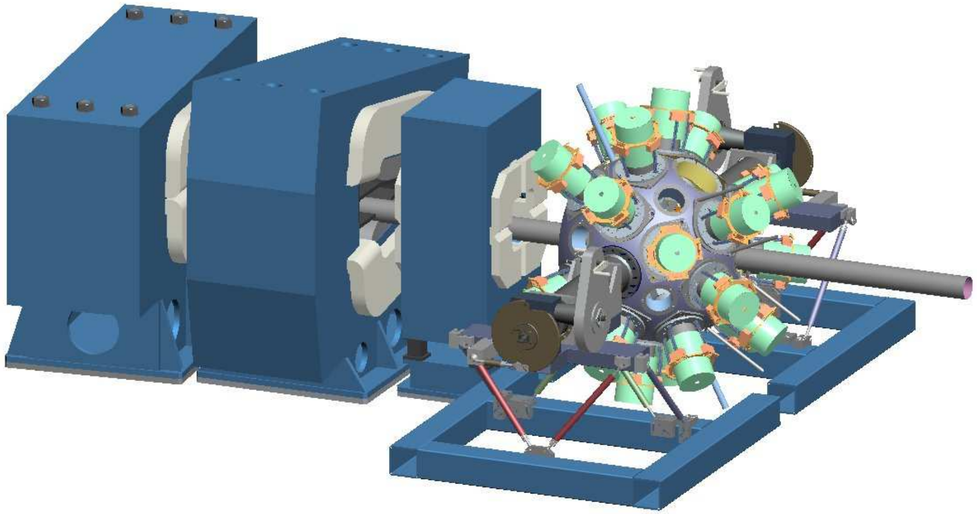
2007, NSAC Long Range Plan



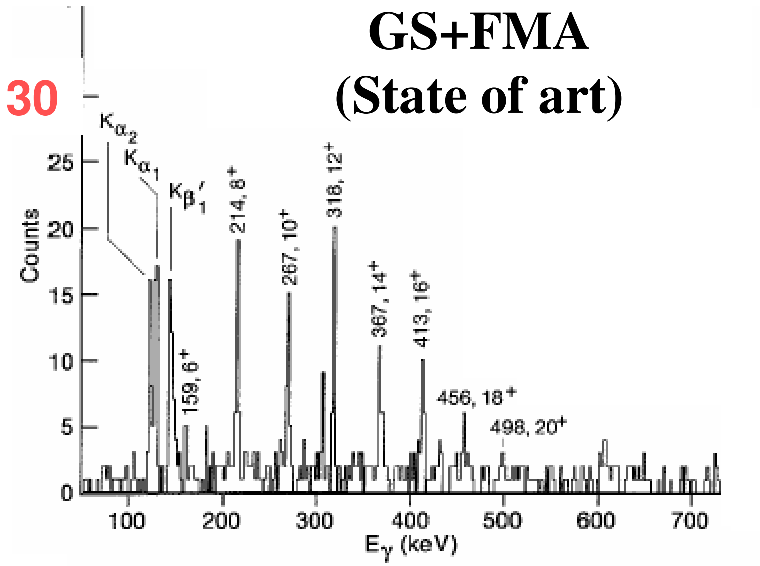
GRETINA is ¼ of full 4π array, GRETA, and is built from highly segmented Ge modules, resulting in a very high efficiency, high resolution, gamma-ray array. Conceived and led by LBNL.



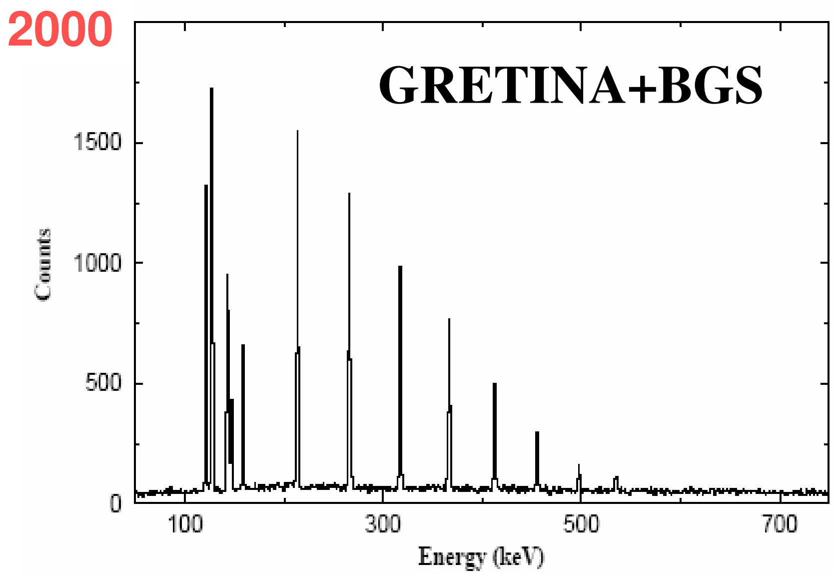
BGS+GRETINA



$^{48}Ca + ^{208}Pb \rightarrow ^{254}No + 2n$

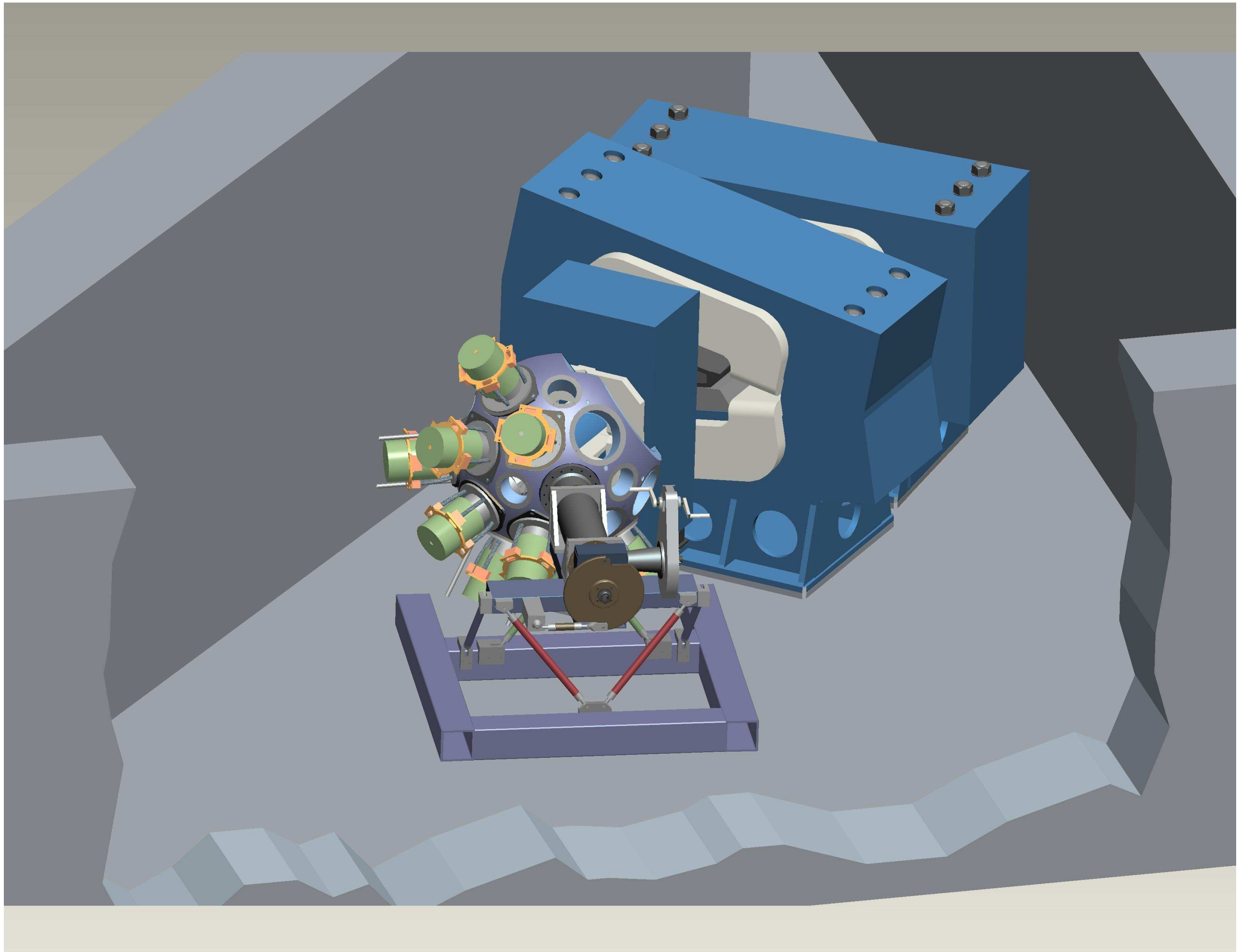


- New generation of prompt transfermium gamma-ray spectroscopy.
- Detailed γ-γ spectroscopy on even-even Z>100 nuclei possible.
- γ-spectroscopy on odd-A nuclei
- γ-spectroscopy of Rf (Z=104) possible ($^{50}Ti + ^{208}Pb \rightarrow ^{256}Rf + 2n$ with σ~20 nb).



Gamma-ray spectroscopy of Rutherfordium in the centenary of the Rutherford model (1911).

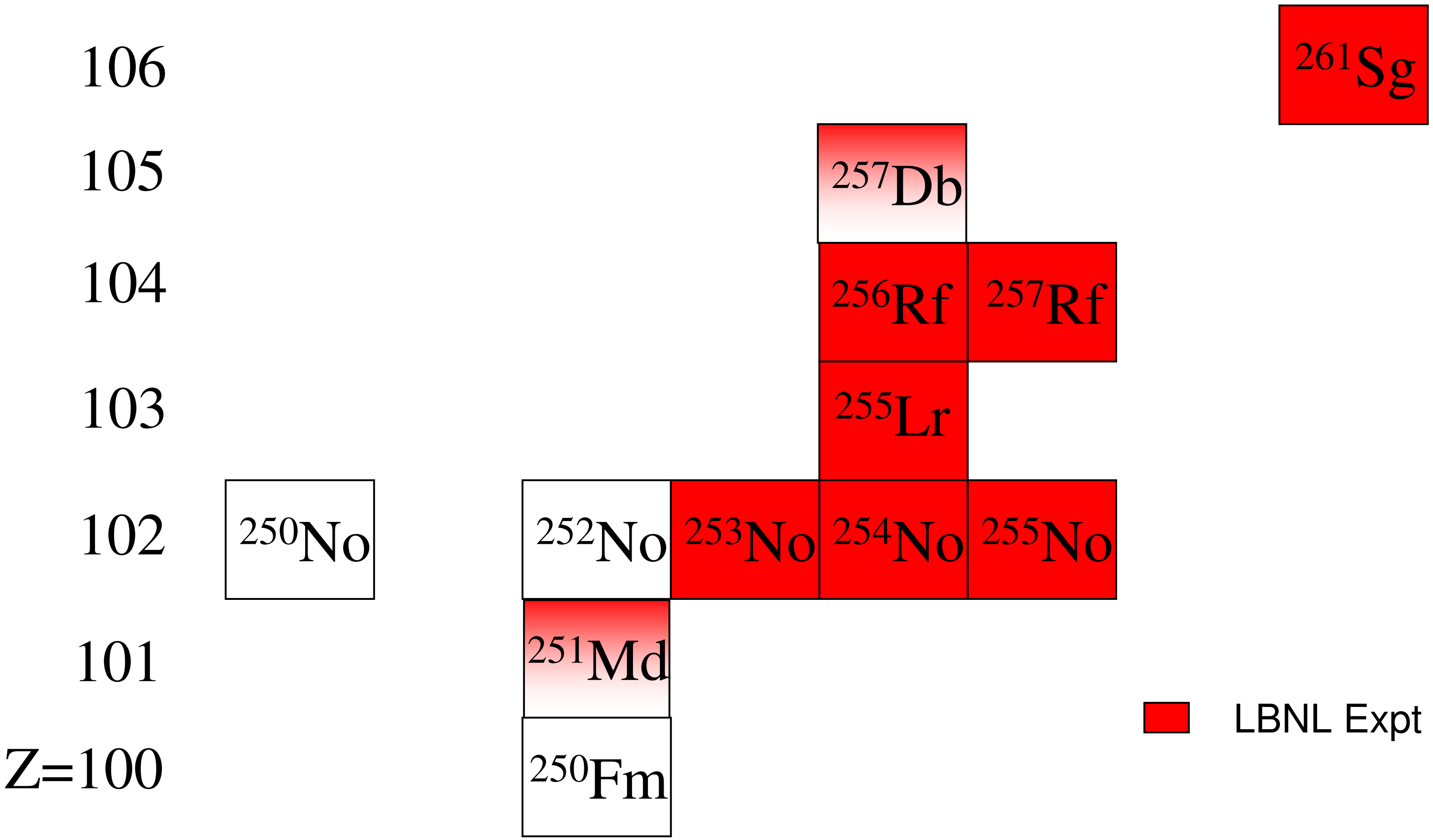
BGS+GRETINA



Community has endorsed the science case. April, 2009 workshop started planning of collaboration and scientific campaign (Fall 2011).

Summary

Known excited isomeric states in elements with Z>100



- A new generation of experiments is underway addressing the fundamental issue of the maximum limit of nuclear mass and charge.

Collaborators

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Thanks !