Spectroscopy of trans-plutonium nuclei

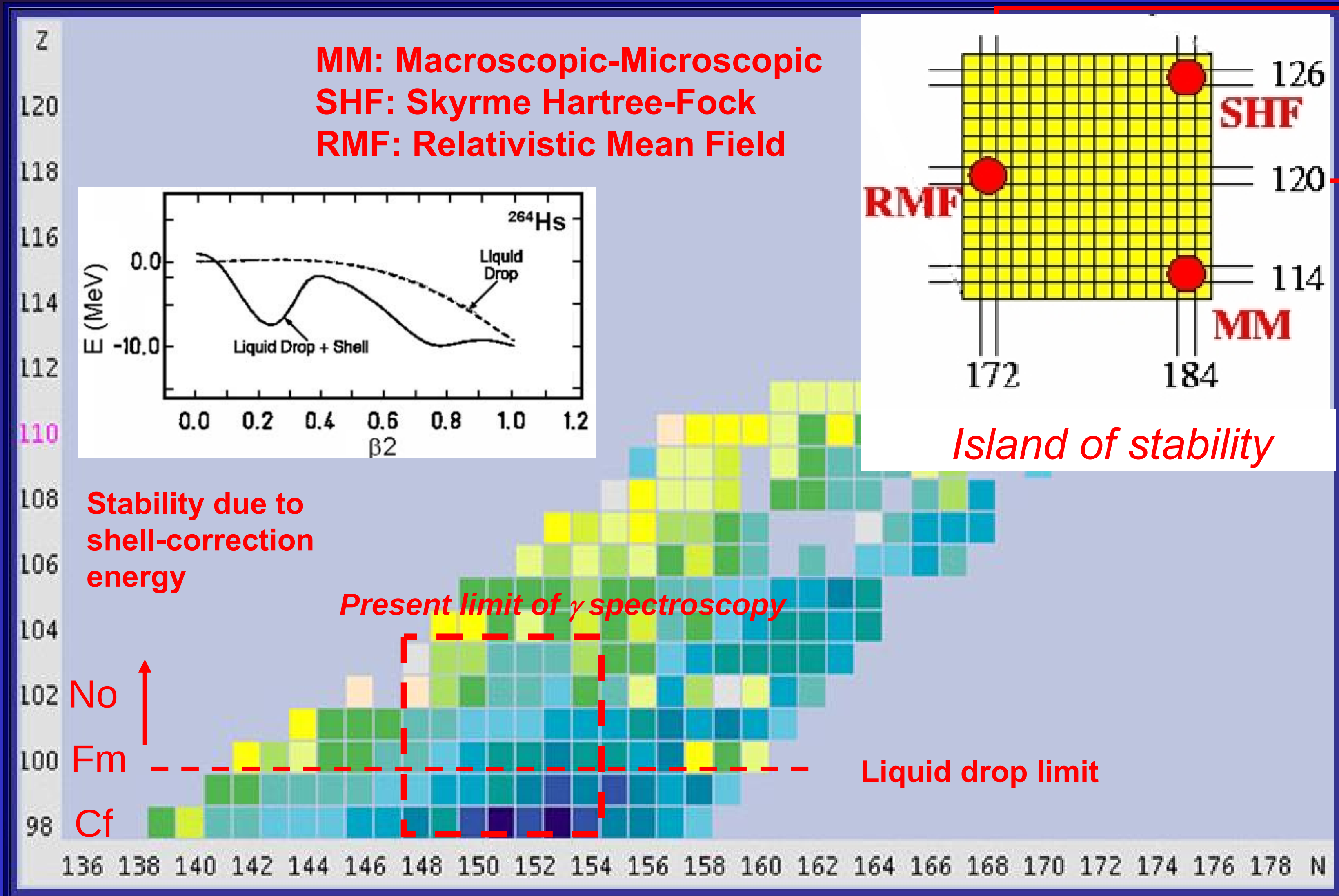
Sujit Tandel

University of Massachusetts Lowell

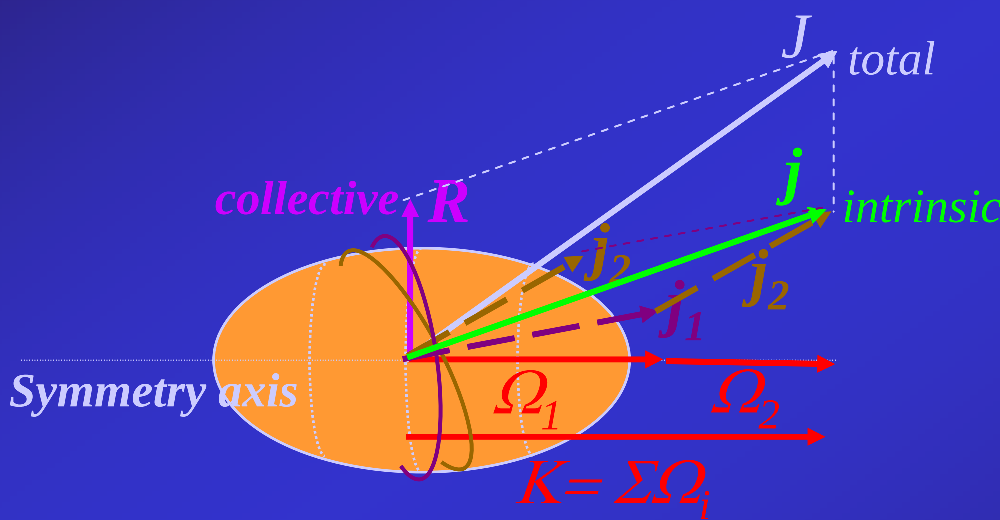
K isomers in heavy actinides

^{254,252}No (Z=102) and ^{250}Fm (Z=100)
^{248,246}Cm (Z=96) and ^{244}Pu (Z=94)

Shell gaps beyond Z=82 and N=126



K-isomerism in nuclei

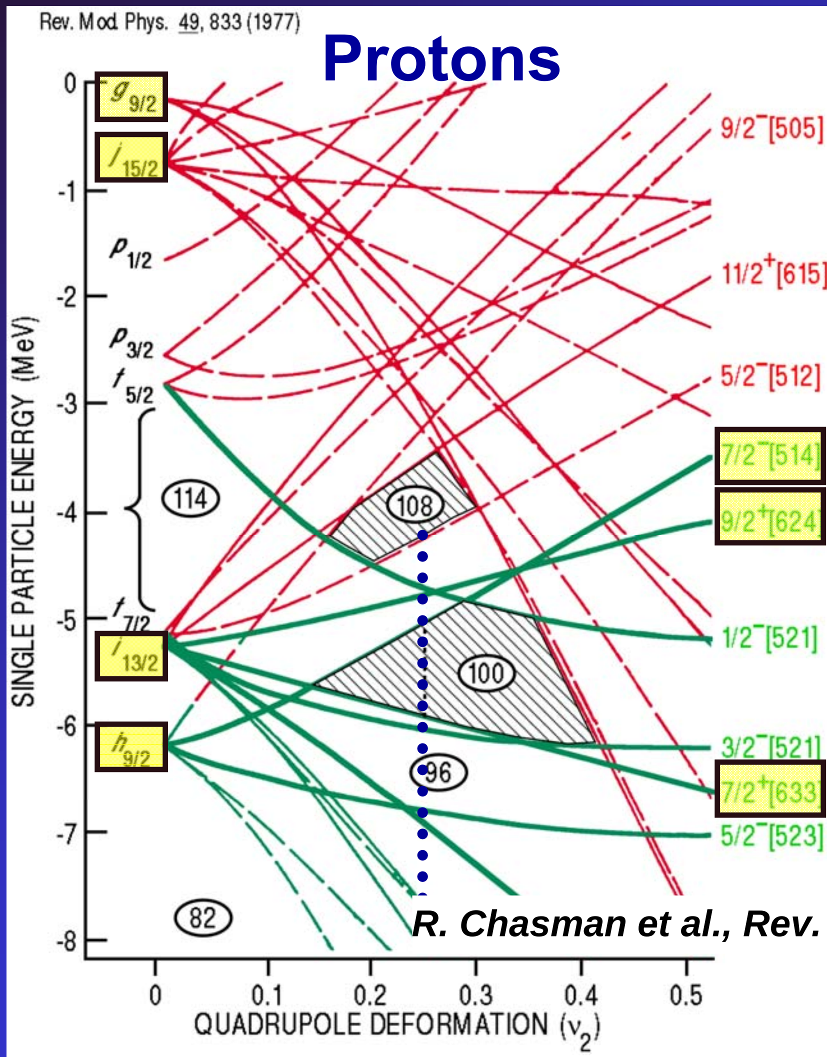


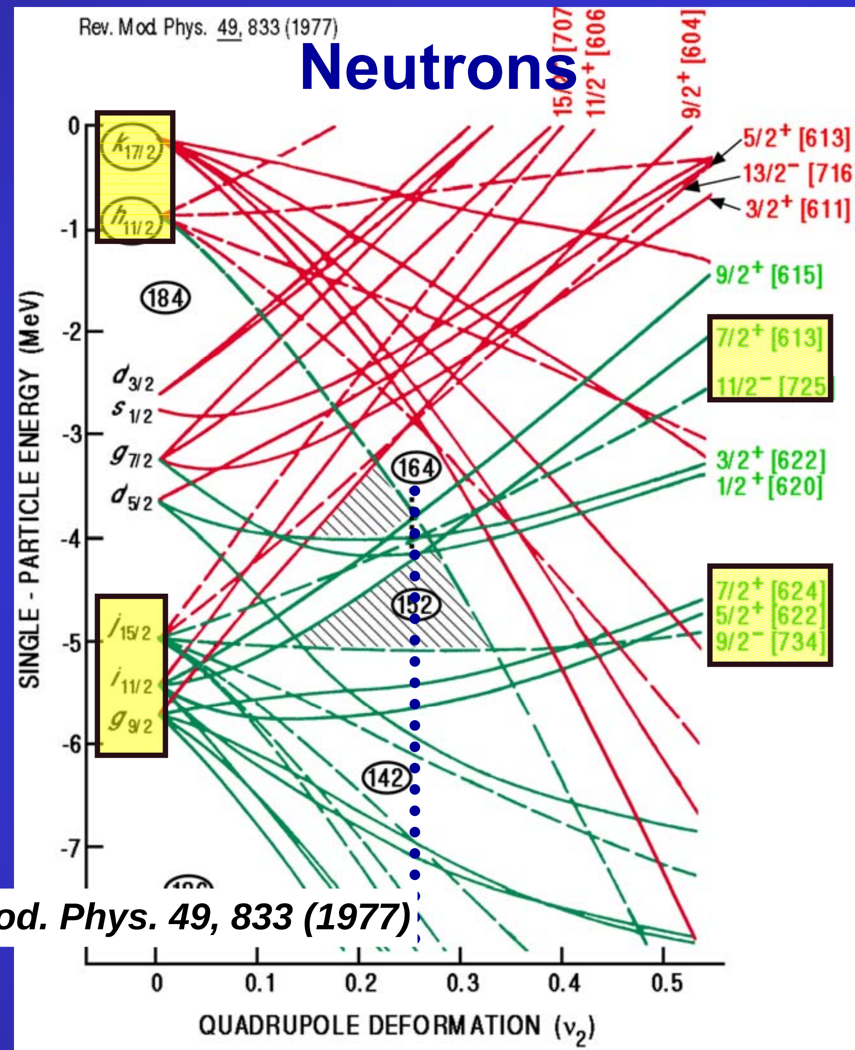
- K is an approximately conserved quantum number
- Transitions hindered if: $\Delta K > L$; degree of hindrance: $\nu = \Delta K - L$
- Energy of 2 quasiparticle, high-K state in even-even nuclei (E_{2qp}):

$$E_{2qp} = E_1 + E_2 \quad ; \quad E_1 = \sqrt{(e_1 - \lambda)^2 + \Delta^2} \text{ and } E_2 = \sqrt{(e_2 - \lambda)^2 + \Delta^2}$$

Information about single-particle energies (e_1, e_2) and pair gap (Δ)

Proton and neutron single-particle levels (Woods-Saxon potential)

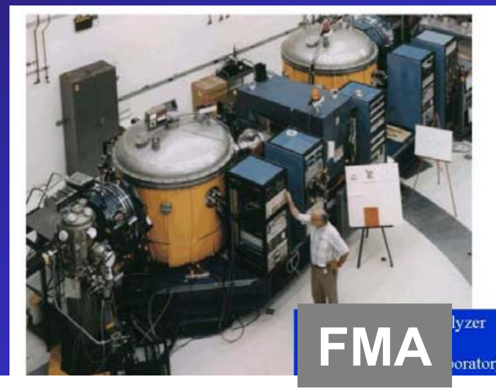


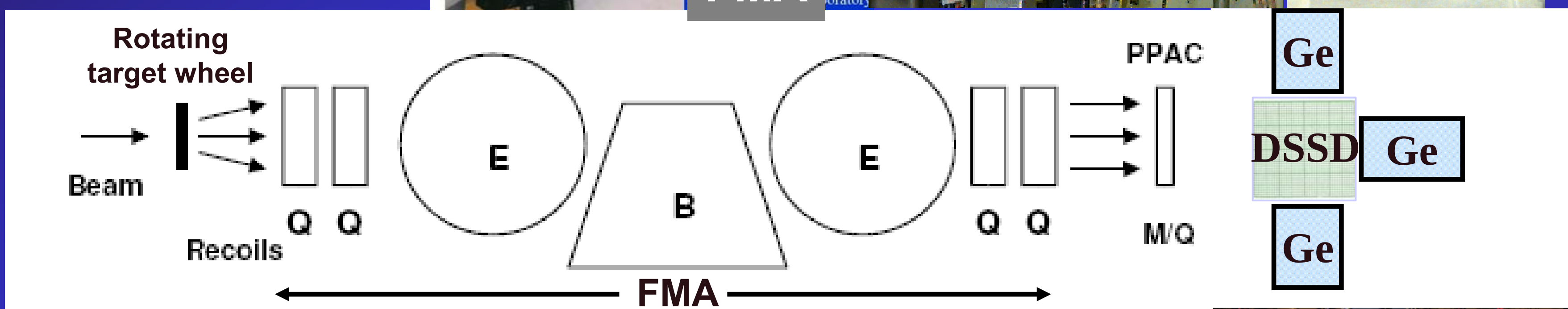


R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)

Deformed nuclei and high-Ω orbitals near the Fermi surface $\Rightarrow$ ***K isomers***

Experimental setup at ANL





$$^{48}_{20}Ca + ^{208}_{82}Pb \rightarrow ^{254}_{102}No + 2n \qquad \sigma_{^{254}No} \approx 1\,\mu b$$

E_{beam} (mid-target) = 217 MeV

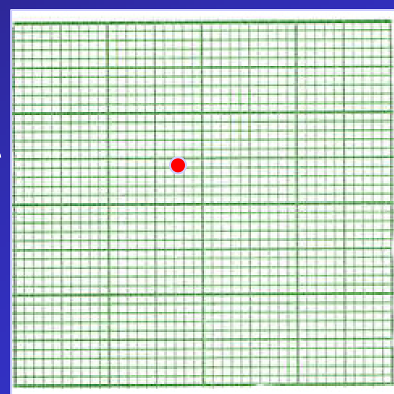
$I_{beam} \approx 100$ pnA

$$^{48}_{20}Ca + ^{206}_{82}Pb \rightarrow ^{252}_{102}No + 2n \qquad \sigma_{^{252}No} \approx 500\,nb$$

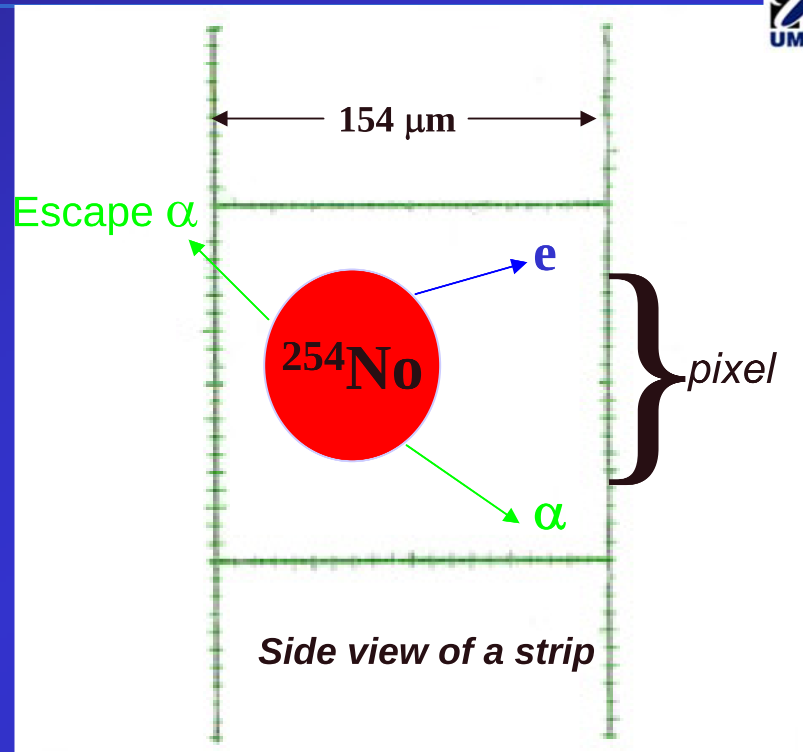
DSSD as calorimeter

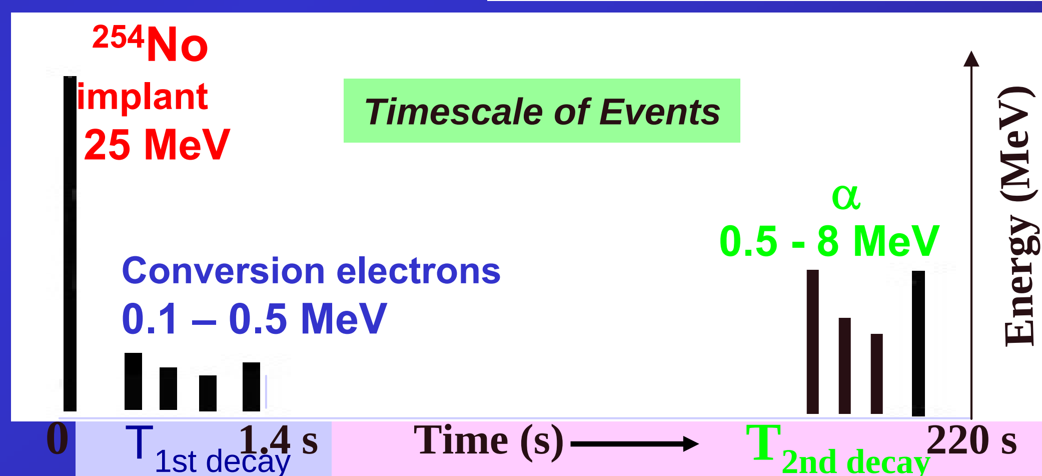
40 x 40 strips
1600 pixels

40mm X 40mm



Front view of DSSD

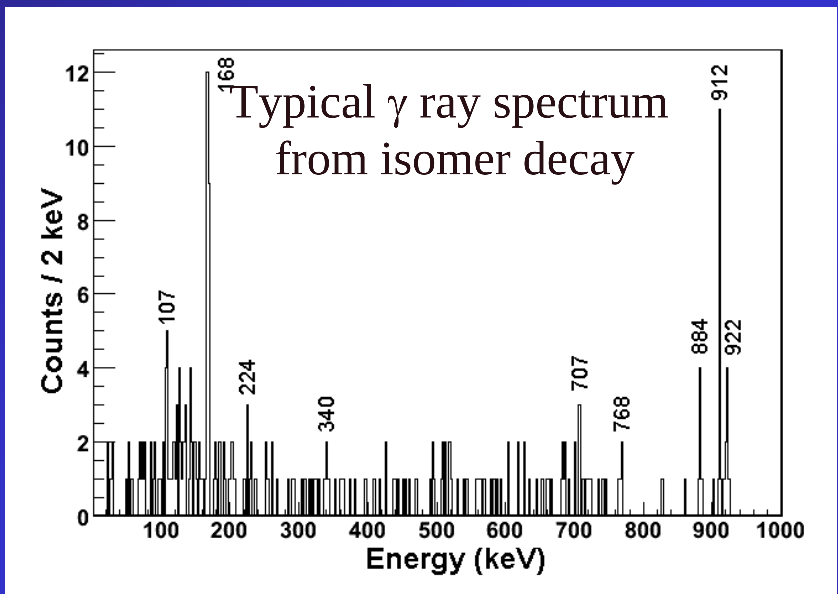


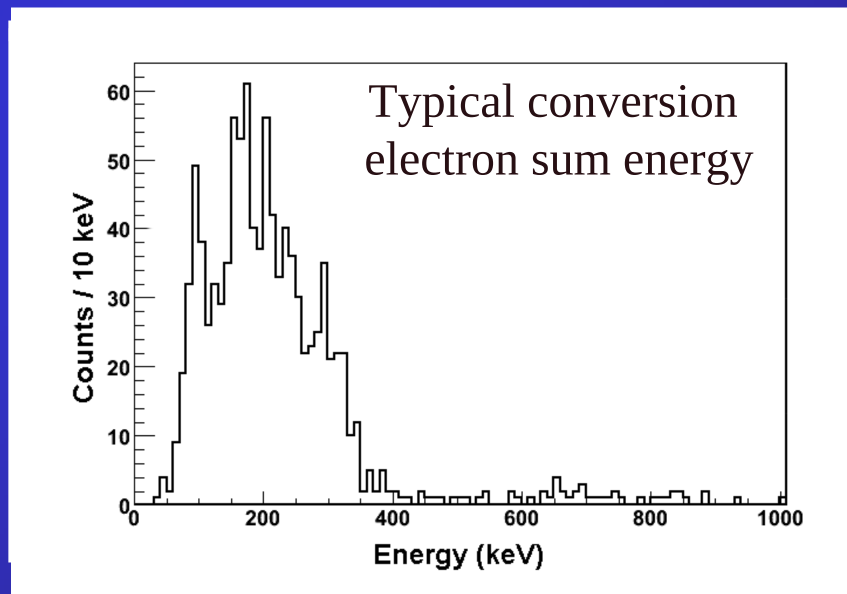


G.D. Jones,
NIM A 488, 471 (2002)

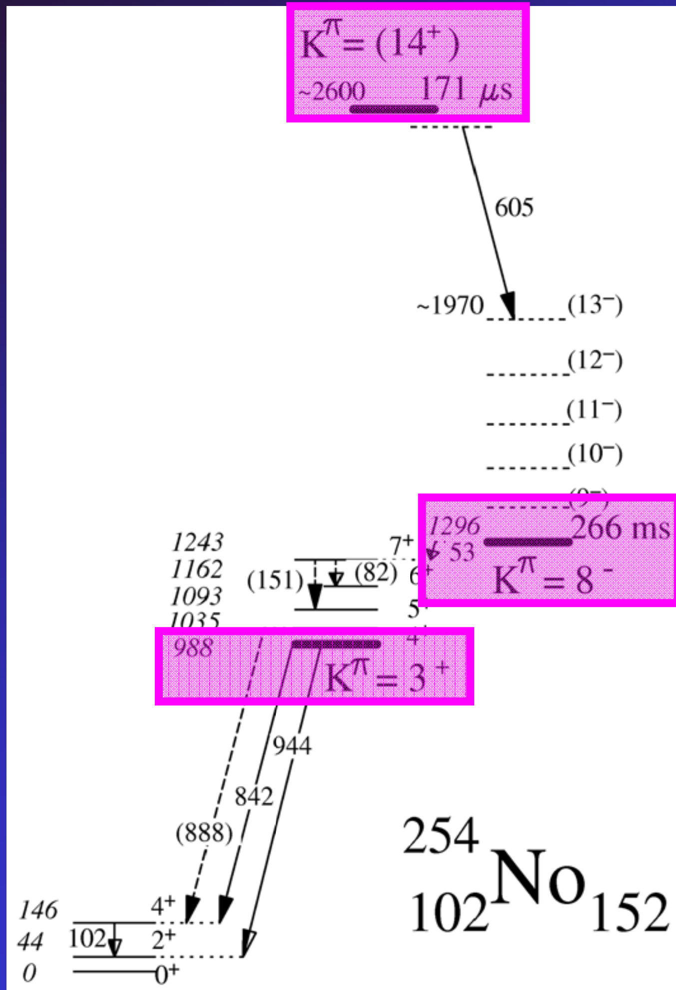
Decay of K isomers

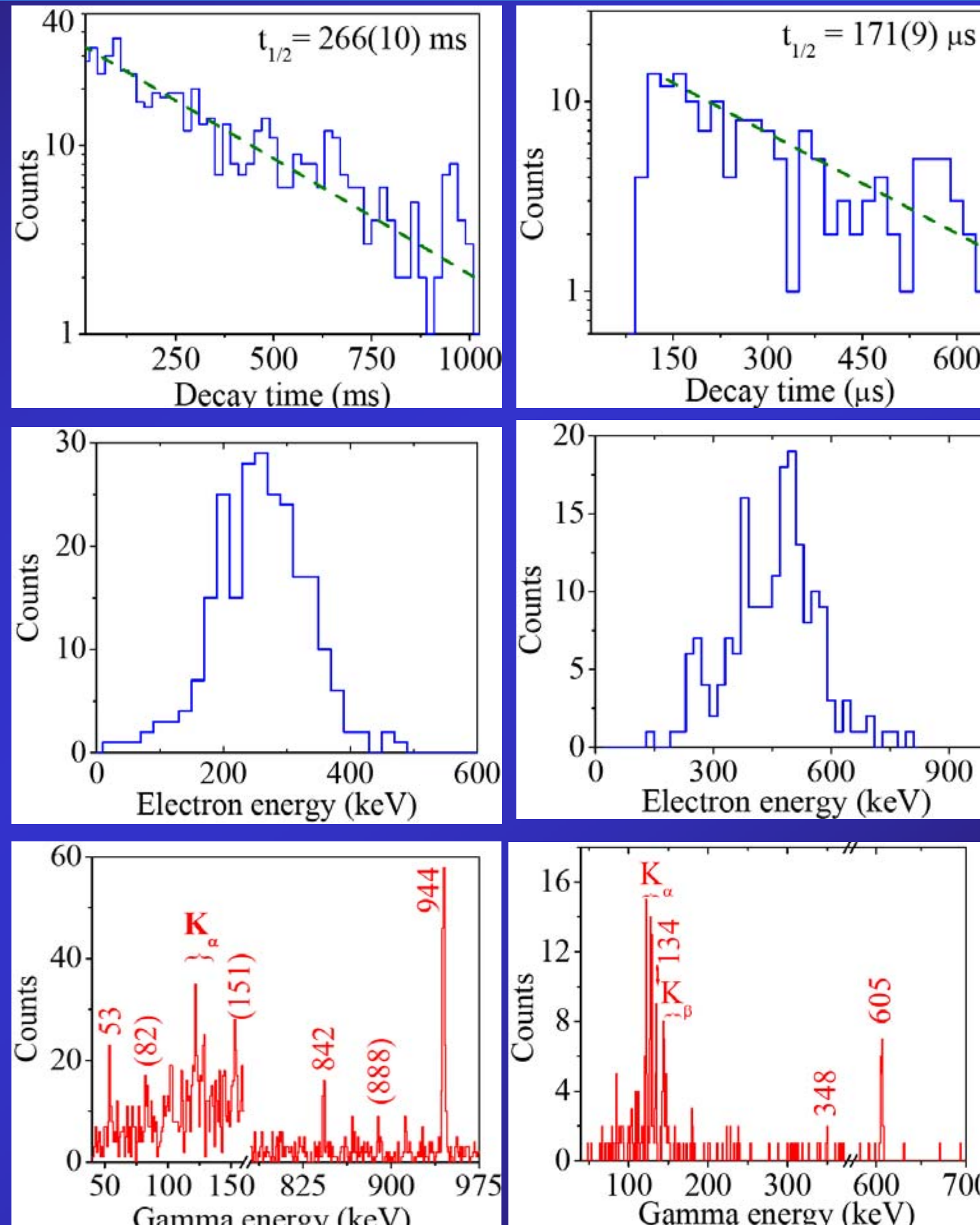
- *Correlate recoil in PPAC, implant and decay products (e, α) in a single DSSD pixel and γ rays in clover detectors*
- *Conventional approach (γ-γ coincidence analysis) for building decay schemes fails: use γ-energy sums and conversion electron sum-energy*





K isomers in ^{254}No





266 ms isomer first proposed by Ghiorso et al., PRC 7, 2032 (1973)
No information about decay paths

K isomers in ^{254}No

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

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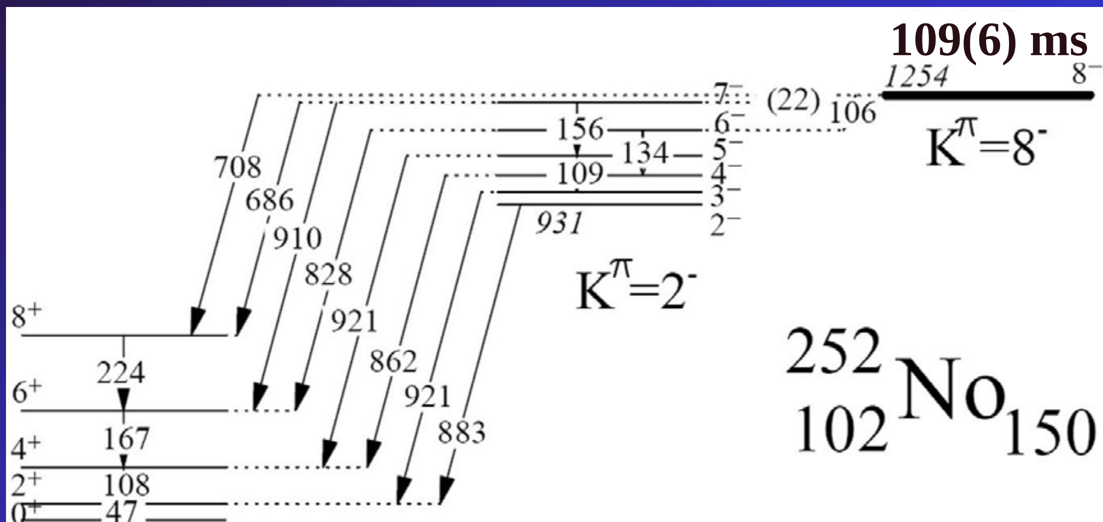
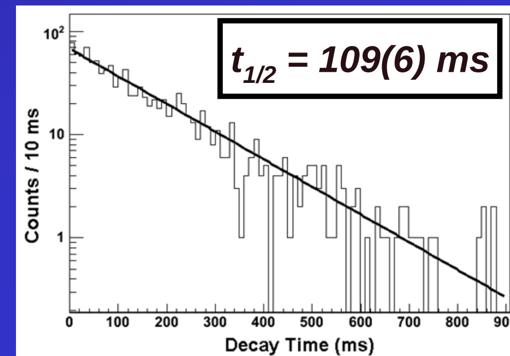
LETTERS

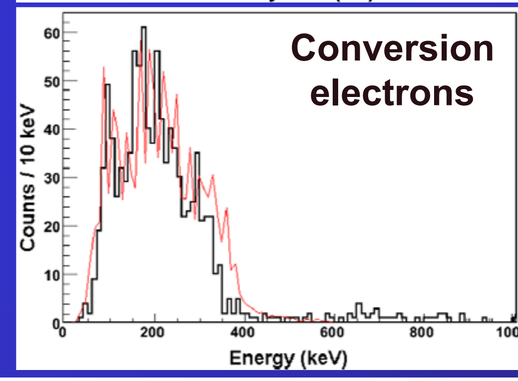
Nuclear isomers in superheavy elements as stepping stones towards the island of stability

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]

K^{π}=8^{-} isomer in ^{252}No

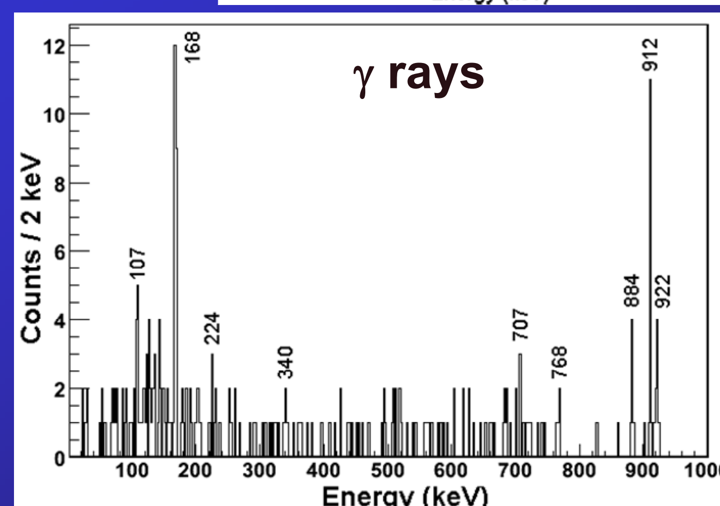






K^{π} = 8^{-} isomer decays to:

- *K^{π} = 2^{-} octupole vibrational band*
- *K^{π} = 0^{+} ground state band (weak branch)*



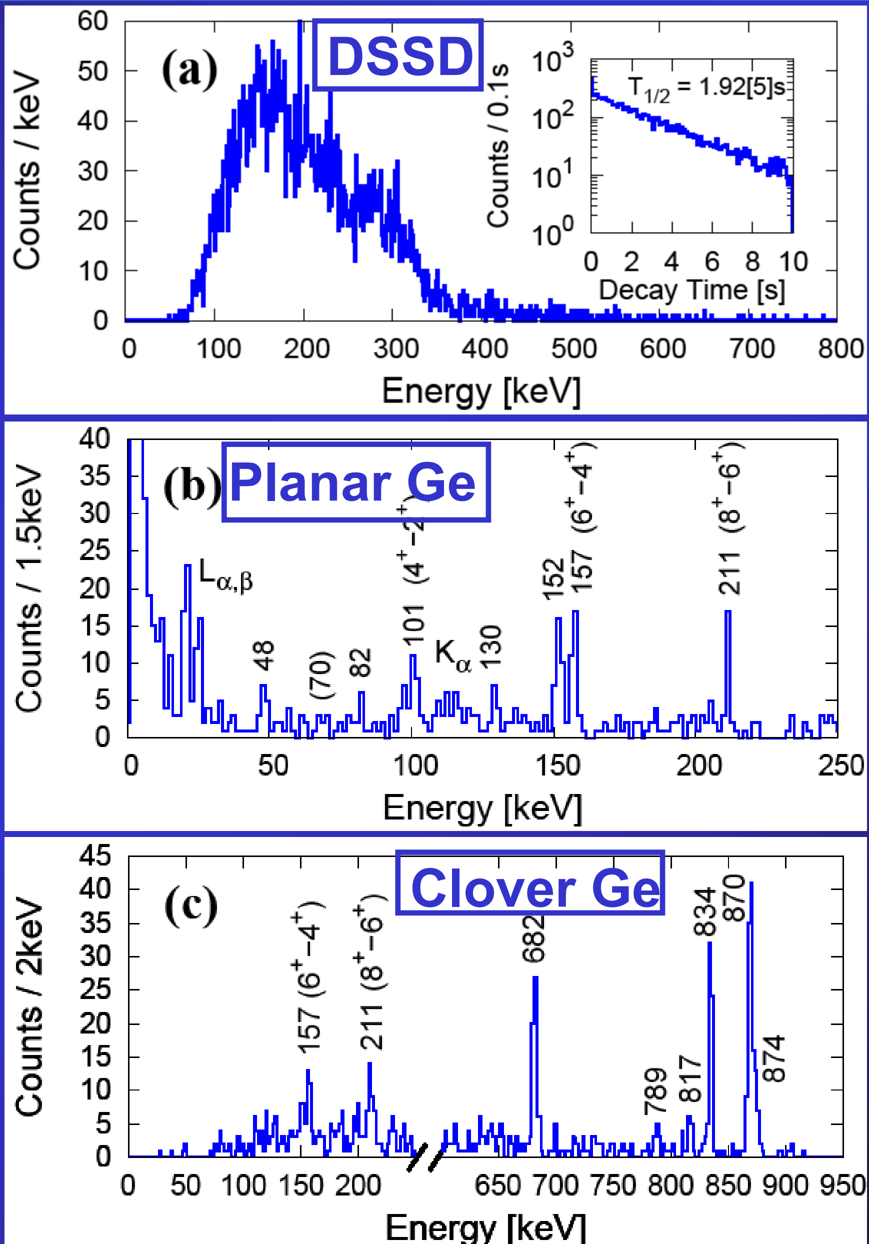
*A.P. Robinson, T.L. Khoo, I. Ahmad, **S.K. Tandel** et al., Phys. Rev. C 78, 034308 (2008)*

Also: B. Sulignano et al., Eur. Phys. J. A 33, 327 (2007)

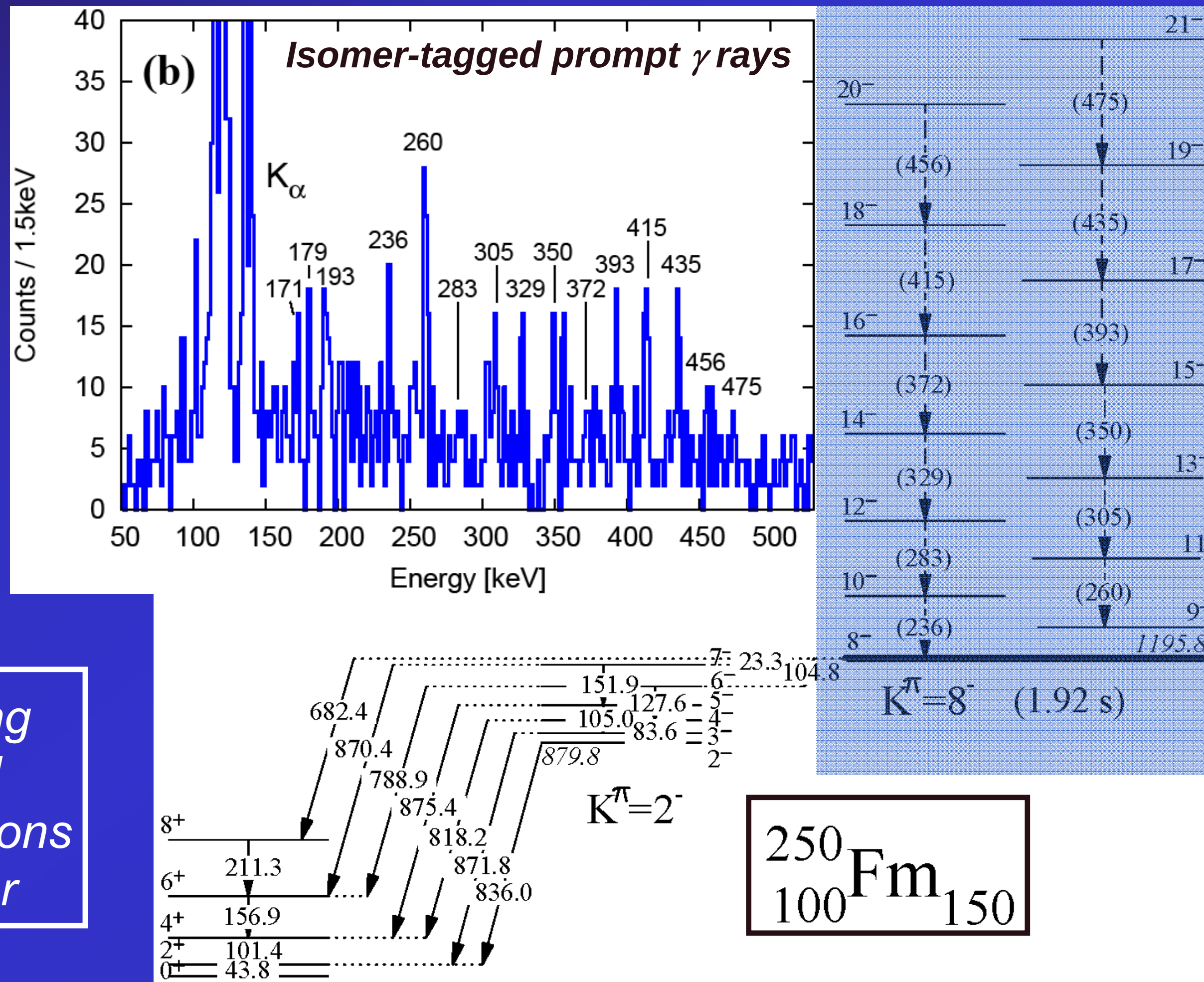
$K^{\pi} = 8^{-}$ isomer in ^{250}Fm (JYFL)

- *RITU: Gas-filled separator*
- *GREAT spectrometer: Focal plane detectors (MWPC, DSSD, Si PIN diodes, planar and clover Ge)* *R.D. Page et al., NIM B 204, 634 (2003)*
- *JUROGAM: Large gamma array at target position*

^{48}Ca + ^{204}HgS → ^{250}Fm + 2n
(213 MeV)



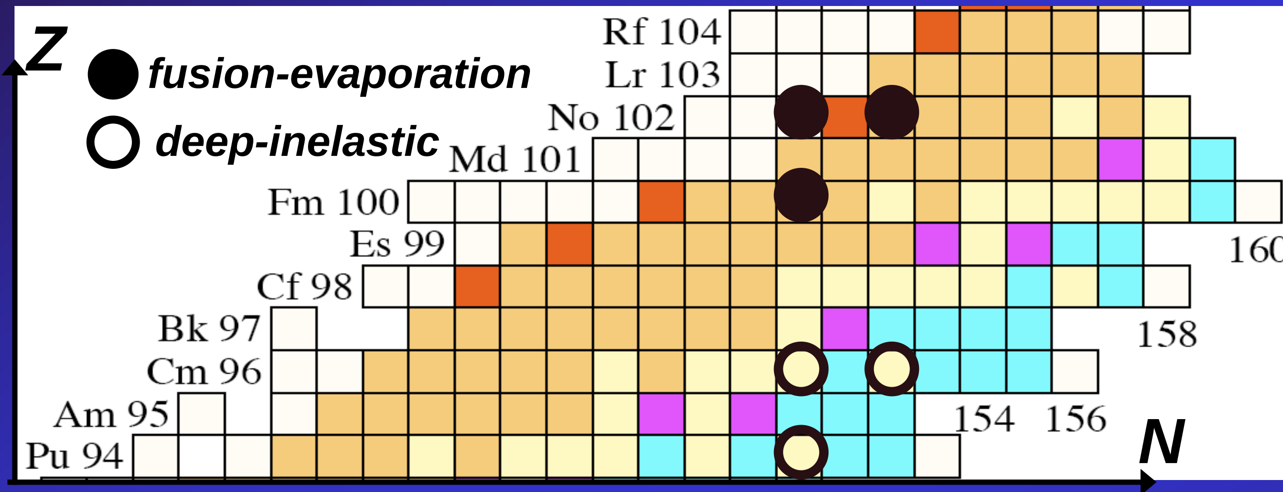
$K^{\pi} = 8^{-}$ isomer in ^{250}Fm (JYFL)



Prompt γ rays feeding $K^{\pi}=8^{-}$ isomer tagged by conversion electrons from decay of isomer

P.T. Greenlees, R.-D. Herzberg,…, S.K. Tandel et al., Phys. Rev. C 78, 021303(R) (2008)

K isomers thru deep inelastic and transfer reactions

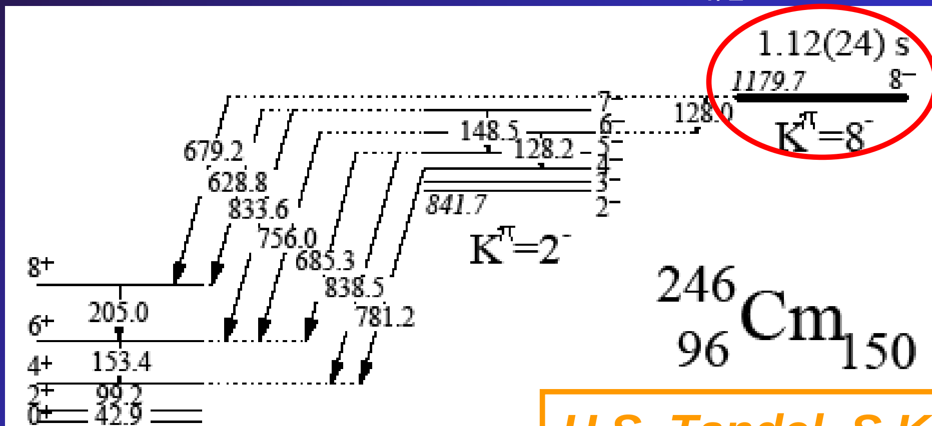


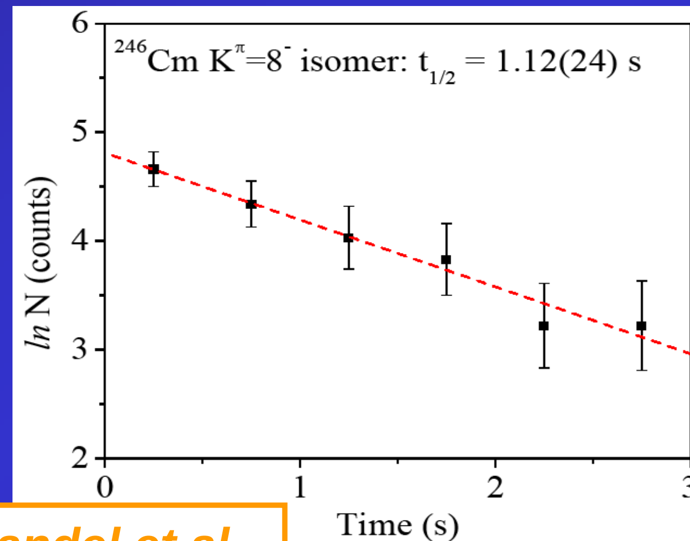
- *Cross-sections: deep-inelastic (mb) compared to fusion-evaporation (μb)*
- *Auxiliary detectors not required, thick targets and large gamma arrays*
- *High statistics - detection of weaker γ branches from isomer decays*

^{209}Bi (1450 MeV) on ^{248}Cm *^{47}Ti (305 MeV) on ^{244}Pu*	} *≈15% above barrier* *ATLAS at ANL +* ***Gammasphere***

K isomers in Cm isotopes

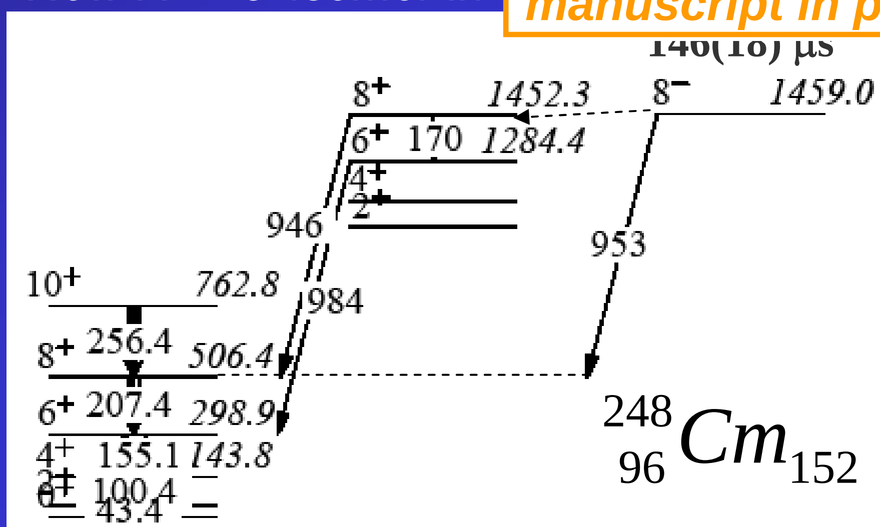
$K^{\pi} = 8^{-}$ isomer in ^{246}Cm (N=150): $t_{1/2}$=1.12(24) s

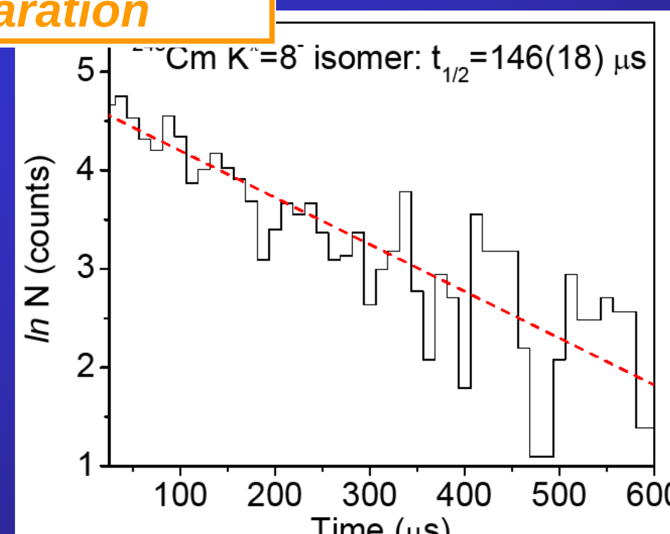




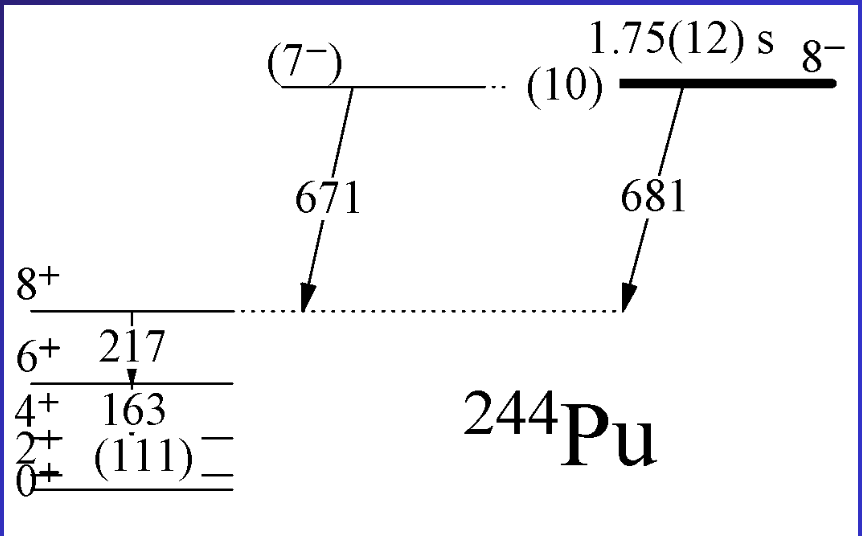
U.S. Tandel, S.K. Tandel et al., manuscript in preparation

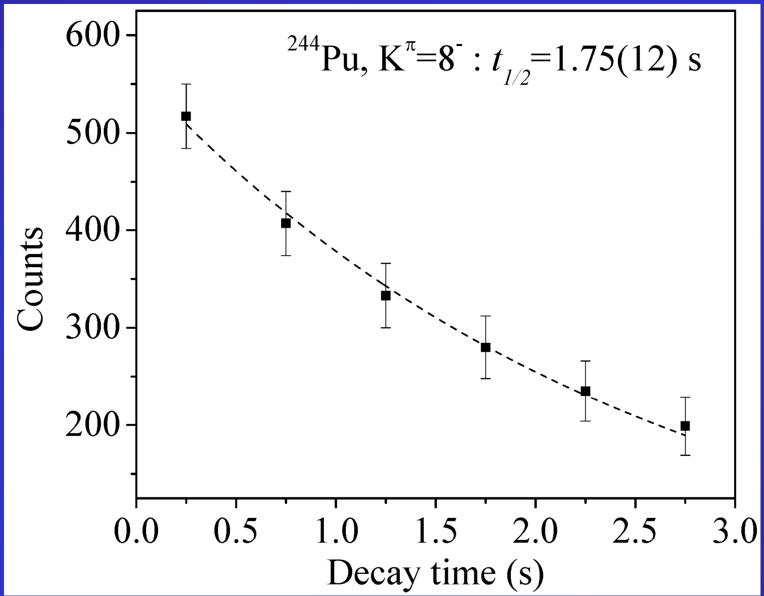
New K^{π} = 8^{-} isomer in

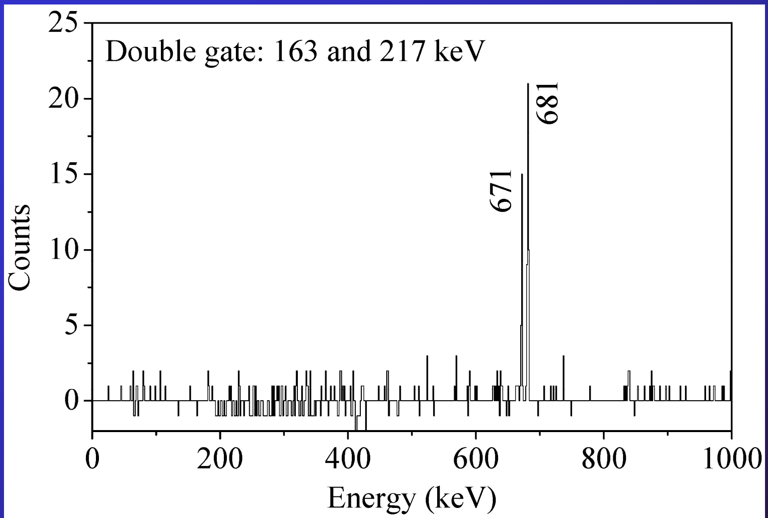




K^{π}=8^{-} isomer in ^{244}Pu

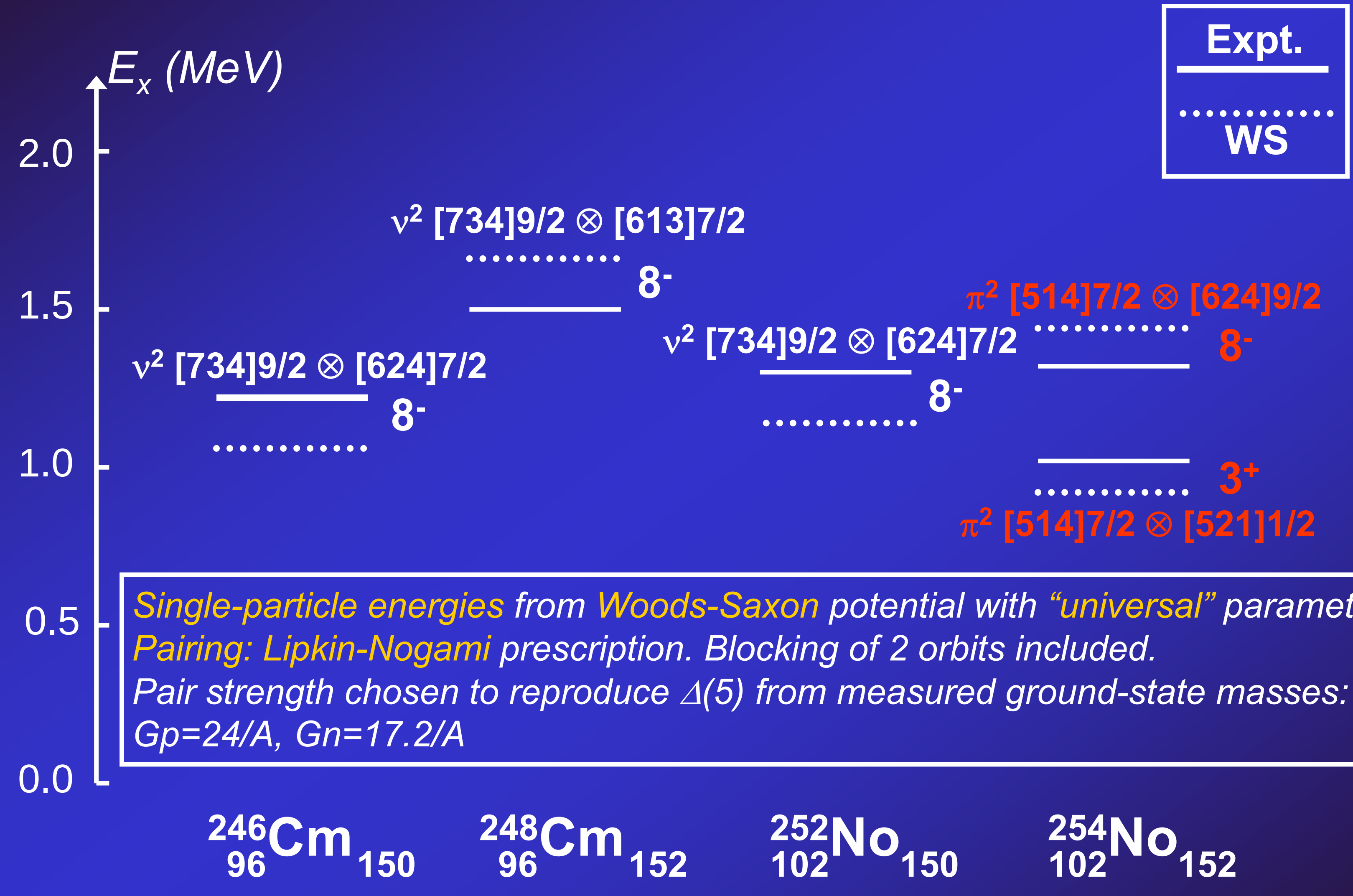






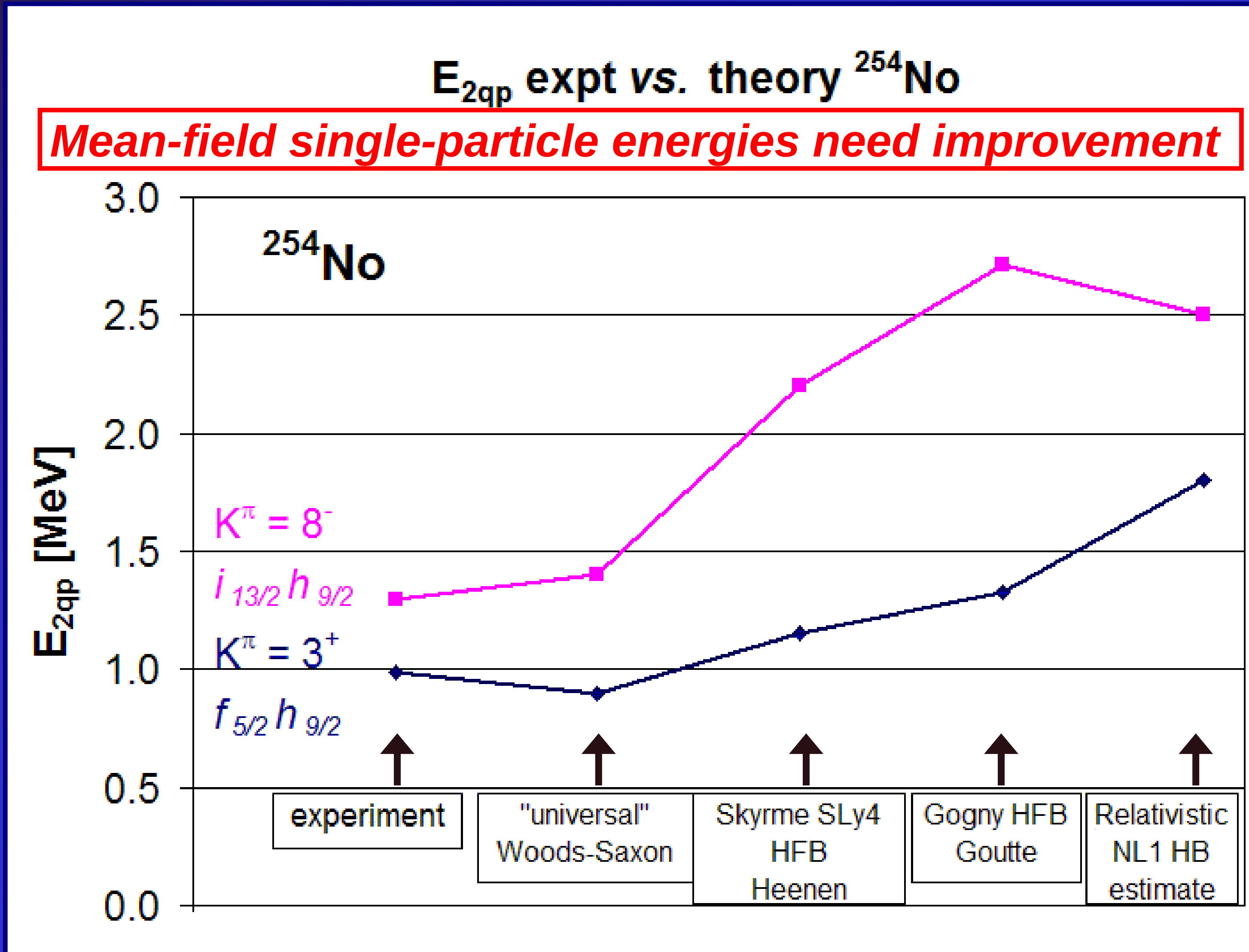
S.K. Tandel et al.,
manuscript in preparation

Comparison of Woods-Saxon and experiment

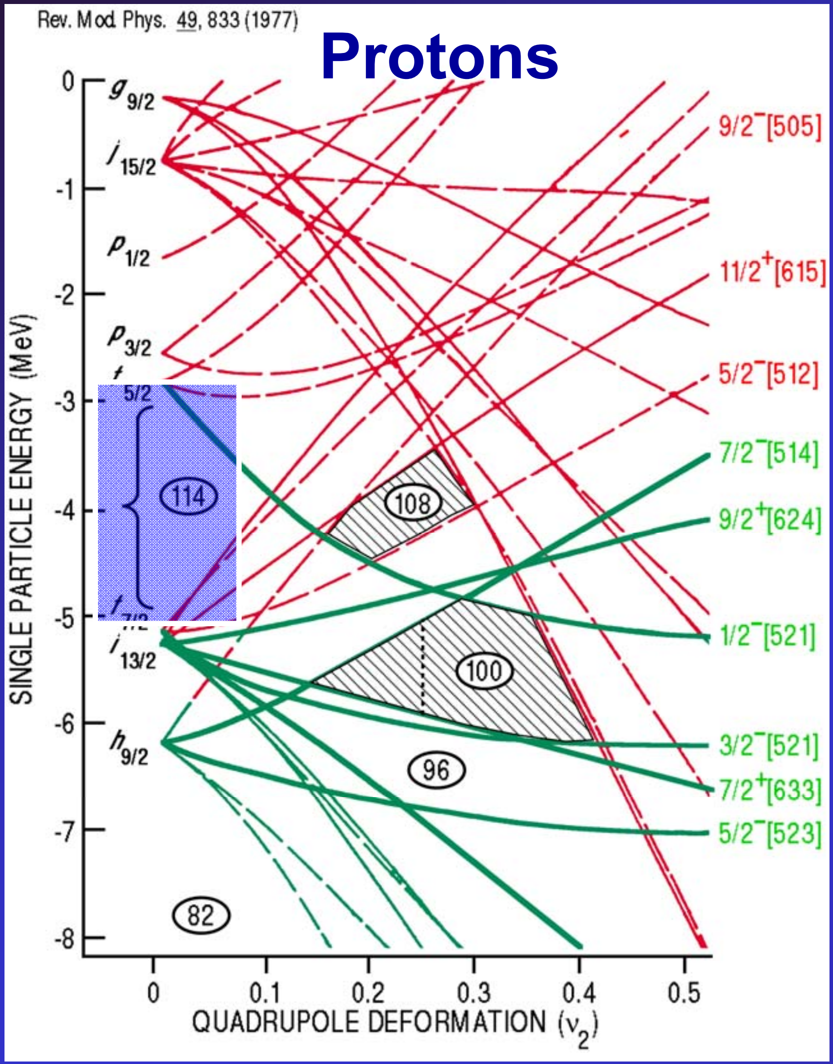


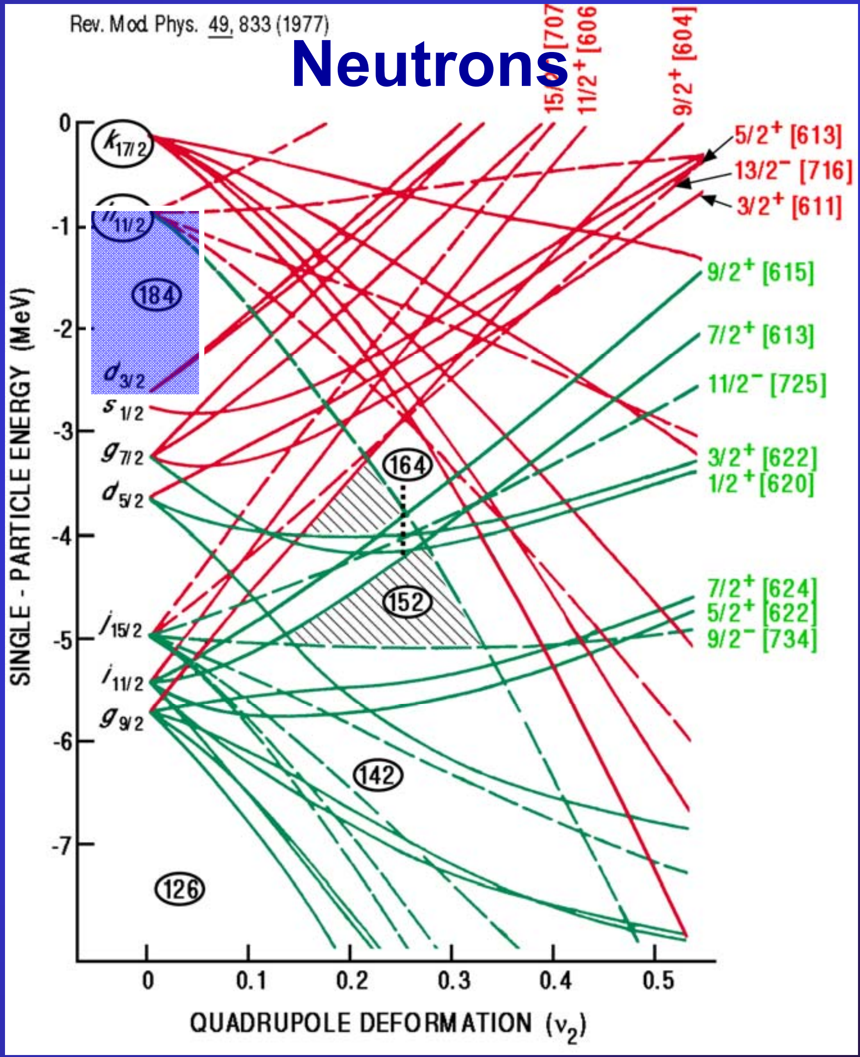
Single-particle energies from Woods-Saxon potential with "universal" parameters.
Pairing: Lipkin-Nogami prescription. Blocking of 2 orbits included.
Pair strength chosen to reproduce Δ(5) from measured ground-state masses:
Gp=24/A, Gn=17.2/A

Woods-Saxon and mean-field predictions



Proton and neutron single-particle levels (Woods-Saxon potential)





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

Summary (K isomers)

- *High-K states probe single particle energies*
- *Good agreement between experiment and Woods-Saxon (universal parameters) energies – validity extended to Z=102*
- *Spherical, magic gaps at Z=114 and N=184 ? (reliability of extrapolation of Woods-Saxon unknown)*
- *Density-functional (mean-field) theories probably need improved effective interactions*

High-spin rotational structures in odd-A, Z≈100 nuclei

Odd-A nuclei through deep-inelastic and transfer

Motivation

- ➢ *Single-particle energies from 1-qp states*
- ➢ *Moment-of-inertia of specific qp excitations and evolution of pairing correlations with spin*
- ➢ *Discriminate between different effective interactions used in mean-field approaches*

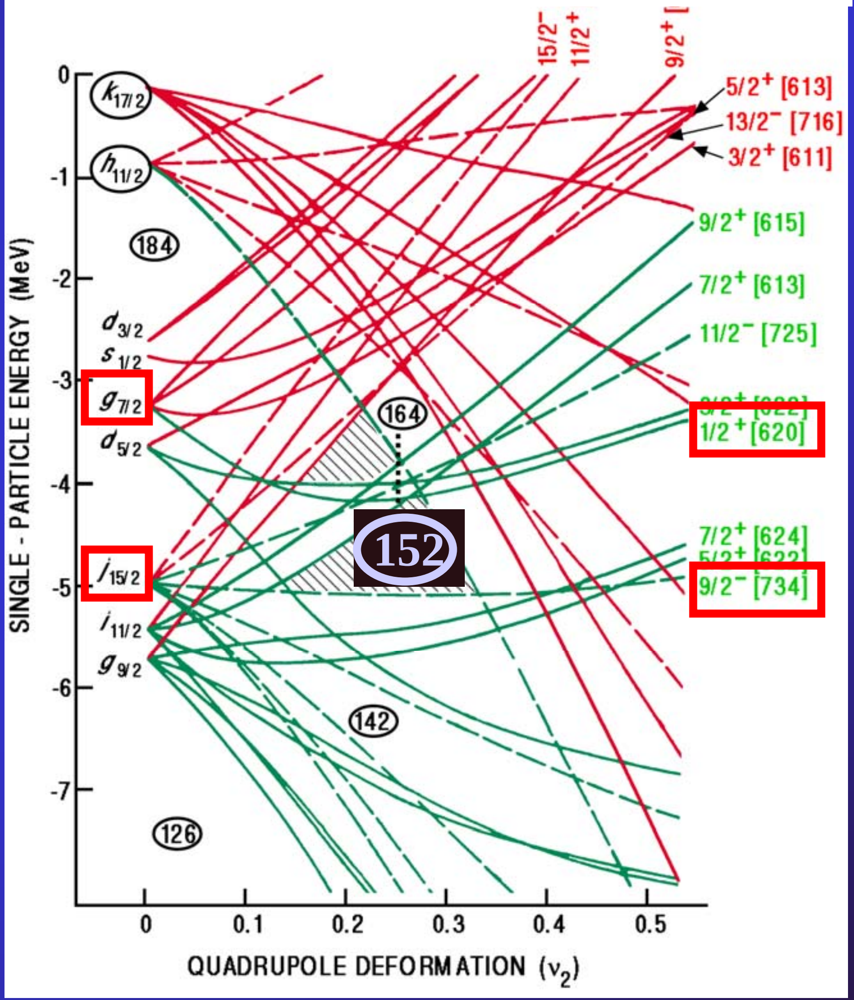
Experiments with Gammasphere @ ANL

- *1450 MeV ^{209}Bi on ^{248}Cm* } *≈50 mg/cm^2*
- *1430 MeV ^{207}Pb on ^{249}Cf* } *Au backing*

Selectivity and identification

- ➢ *x-γ coincidences for Z-identification*
- ➢ *Cross-coincidences with reaction partners*
- ➢ *Band search techniques*
- ➢ *Development of new analysis techniques e.g. gated cube from a Radware hypercube*

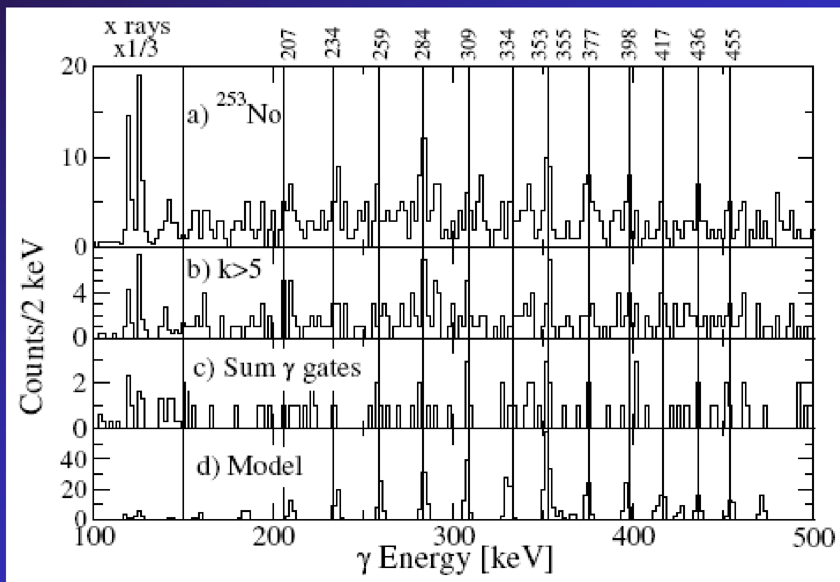
R.R. Chasman et al., Rev. Mod. Phys. 49, 833 (1977)



Neutron single-particle levels (Woods-Saxon potential)

Odd-A nuclei through fusion-evaporation

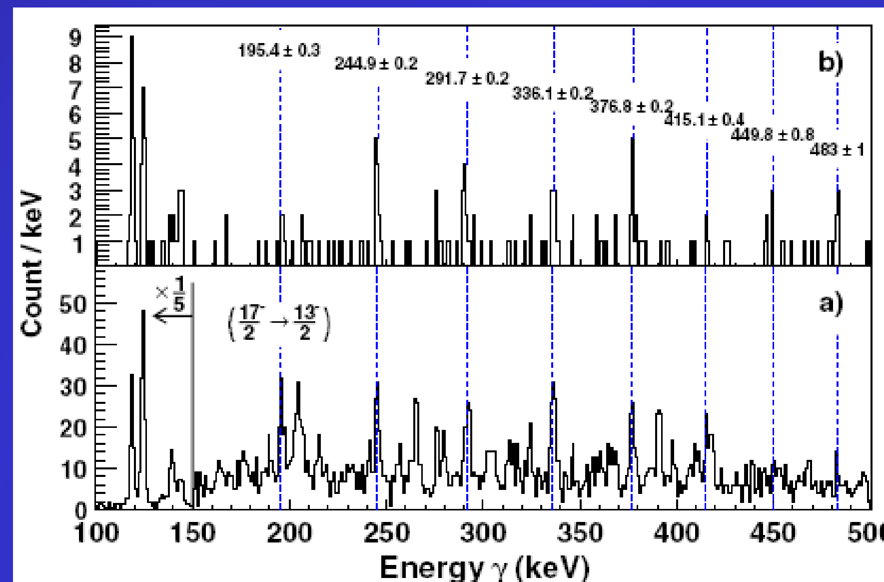
^{253}No (Z=102)



$^{207}Pb(^{48}Ca,2n)^{253}No$ @ 219 MeV

P. Reiter et al., PRL 95, 032501 (2005)
S. Eeckhaudt, PhD thesis 2006 (unpublished)

^{251}Md (Z=101)

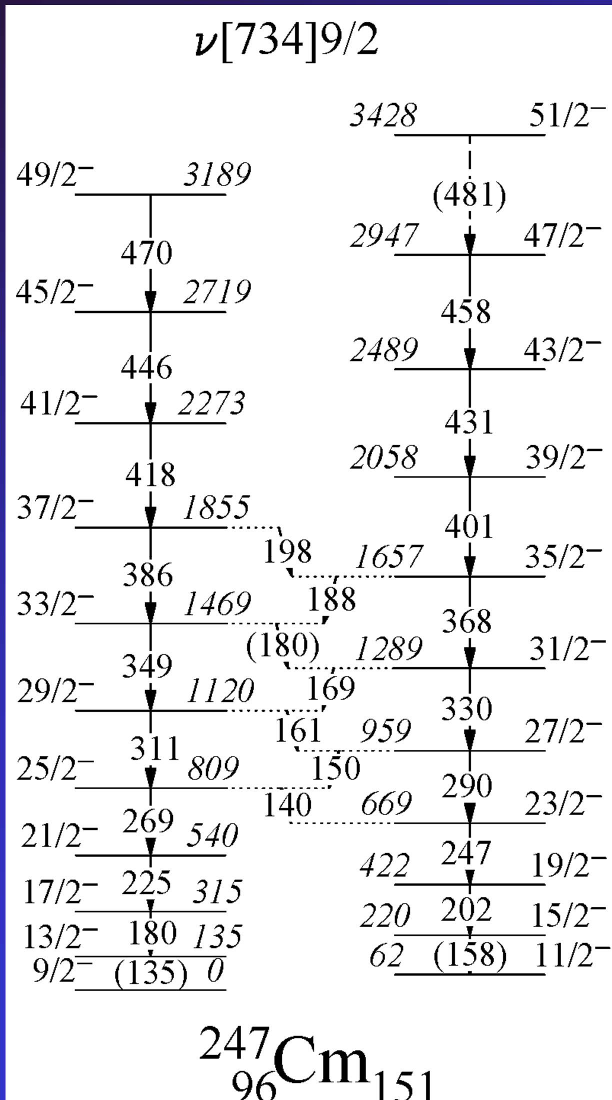


$^{205}Tl(^{48}Ca,2n)^{251}Md$ @ 214 MeV

A. Chatillon et al., PRL 98, 132503 (2007)

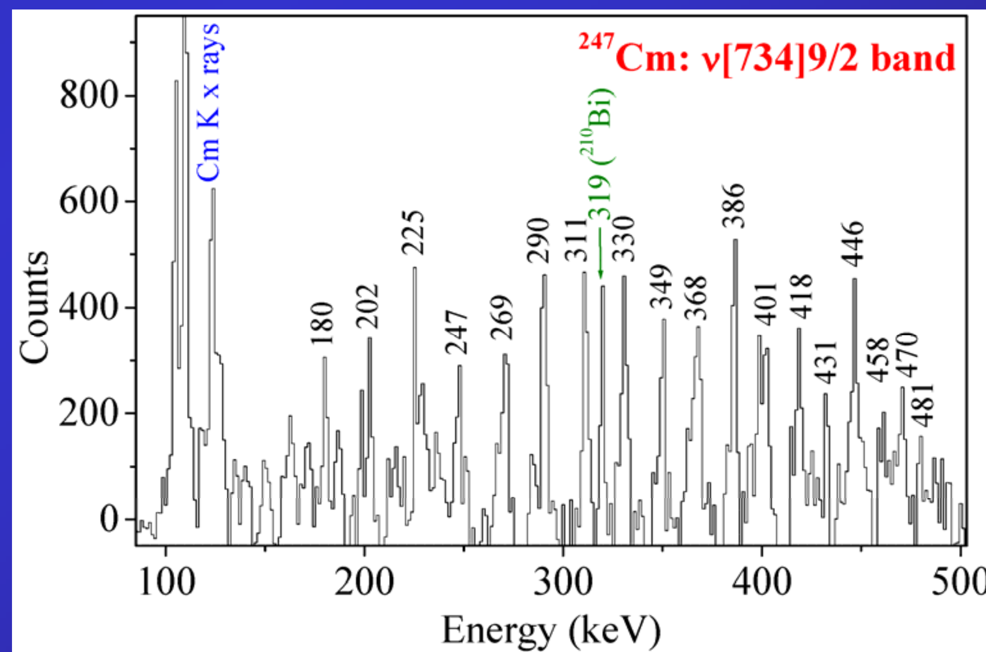
Extremely poor statistics – unambiguous configuration assignments difficult
Only two cases studied yet.

^{247}Cm : ν[734]9/2 ($j_{15/2}$) band

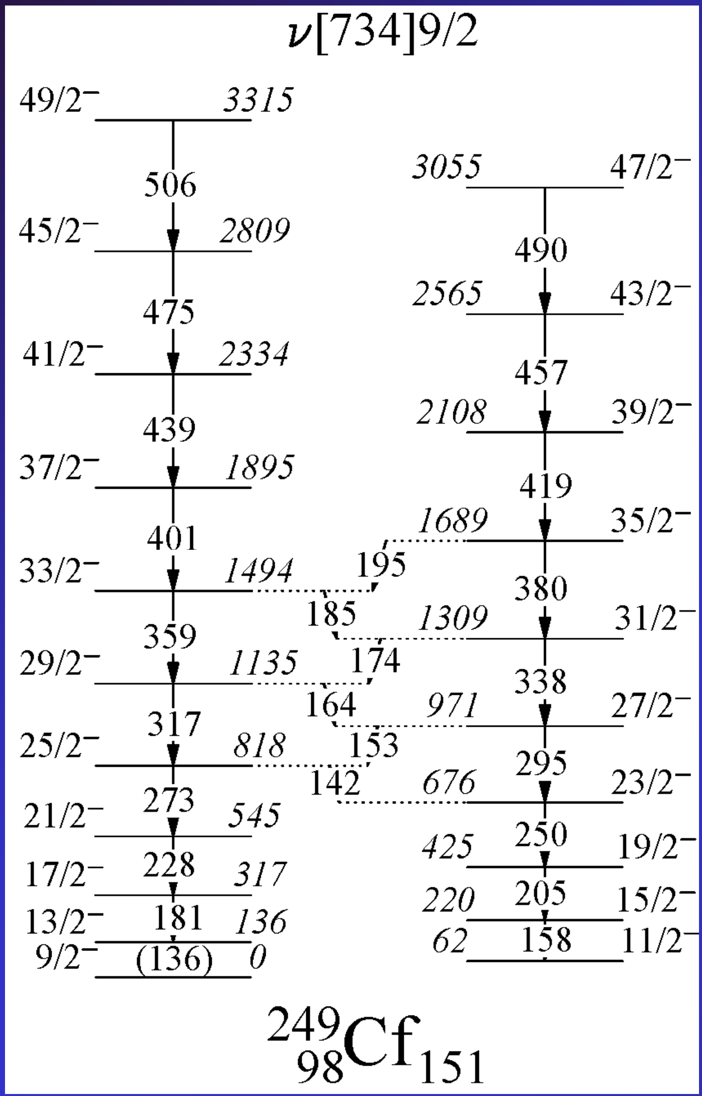


Previous work: $^{251}Cf \rightarrow {}^{247}Cm + \alpha$
I. Ahmad et al, PRC68, 044306 (2003)

Present work: 1450 MeV ^{209}Bi on ^{248}Cm



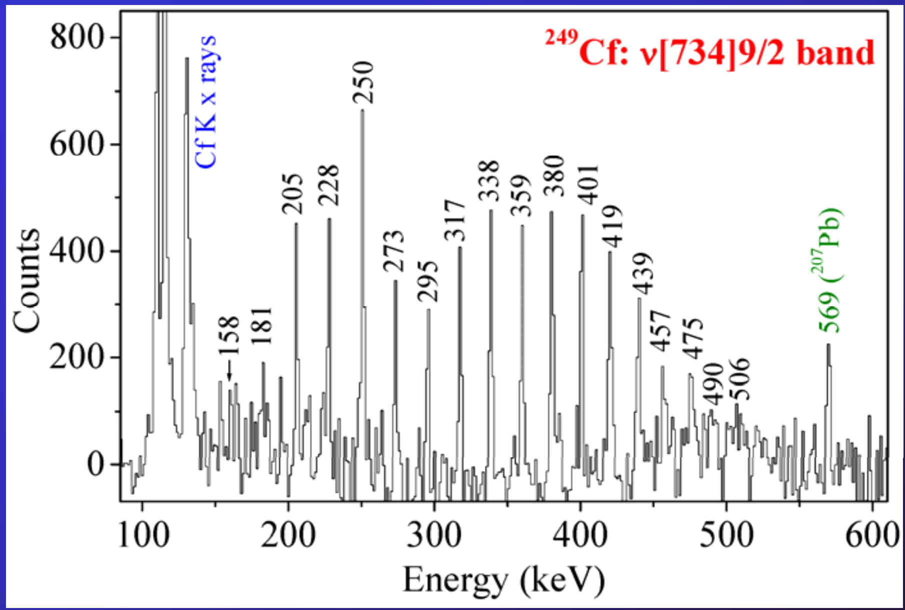
^{249}Cf : ν[734]9/2 ($j_{15/2}$) band



^{247}Cm and ^{249}Cf
(N=151 isotones)

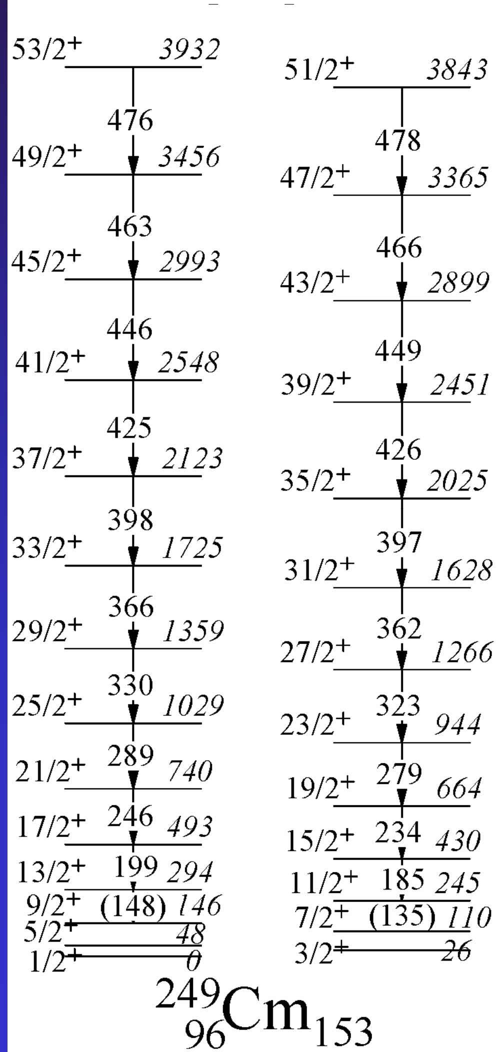
Previous work: ^{249}Cf(d,d')
S.W. Yates et al, PRC12, 442 (1975)

Present work: 1430 MeV ^{207}Pb on ^{249}Cf

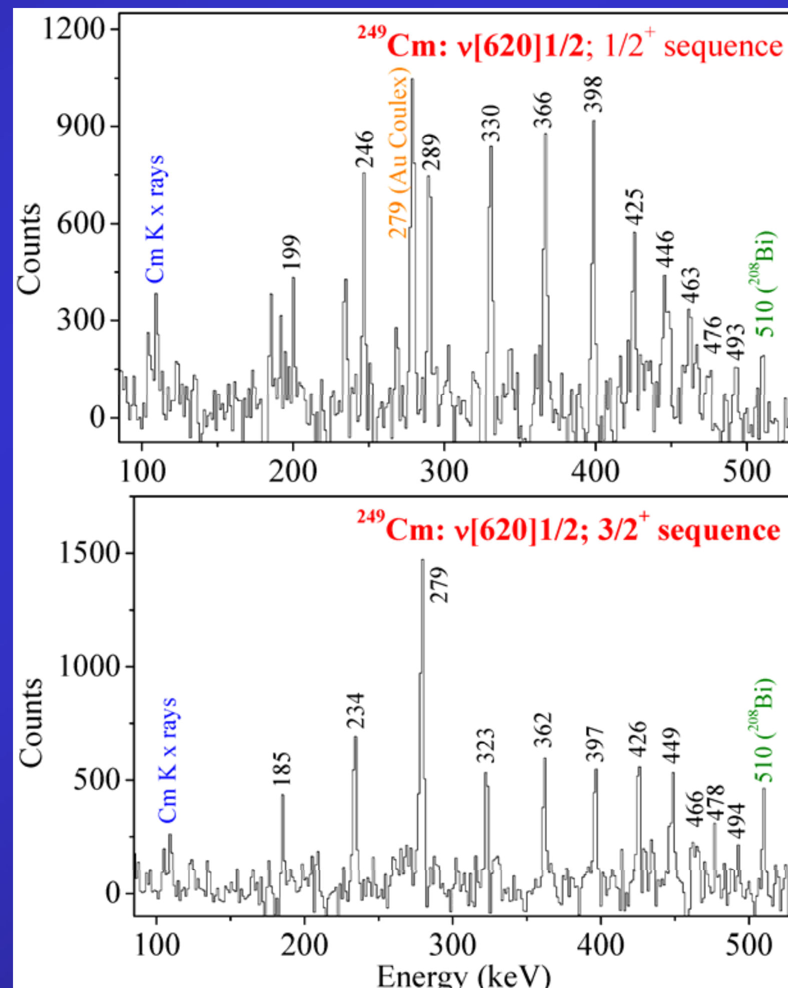


^{249}Cm : ν[620]1/2 ($2g_{7/2}$) band

ν[620]1/2: Highest-lying neutron orbital studied up to high spin



Present work: 1450 MeV ^{209}Bi on ^{248}Cm

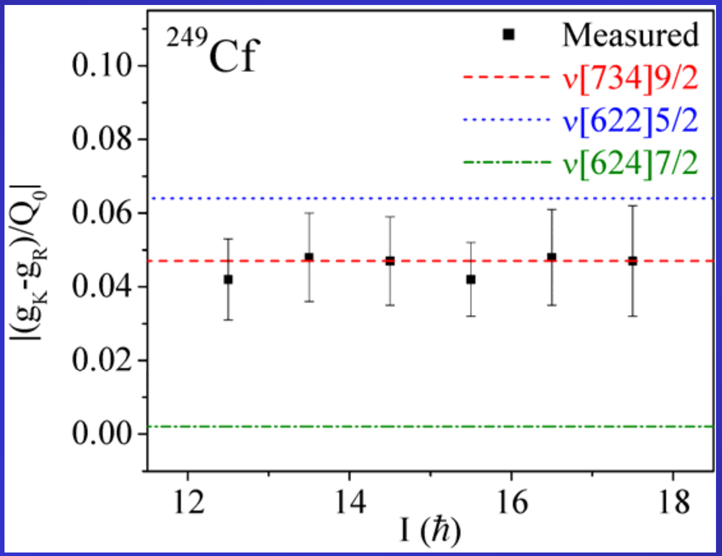


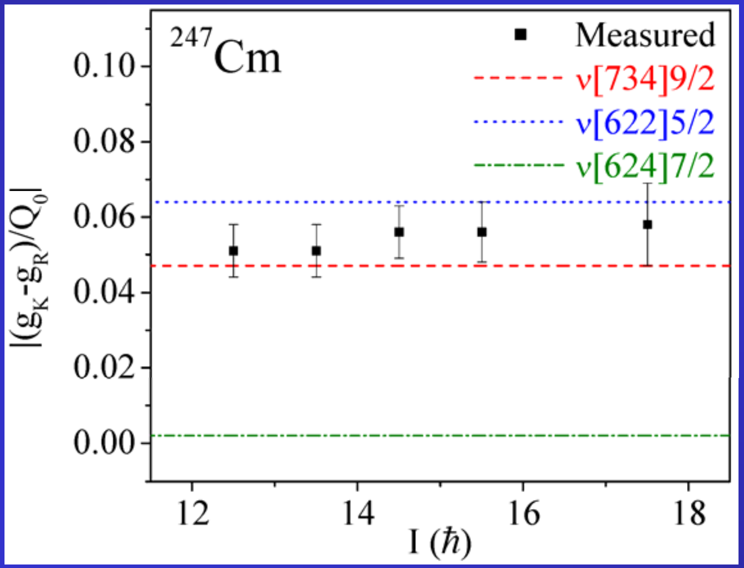
Configuration assignments

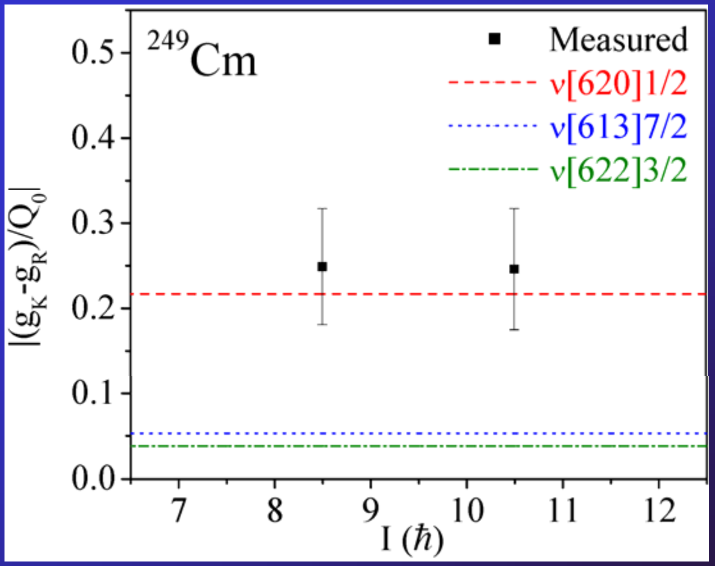
Configurations of bands assigned based on in-band M1/E2 branching ratios

$$\left|\frac{g_K - g_R}{Q_0}\right| = 0.933\frac{E_1}{\delta\sqrt{I^2 - 1}}$$

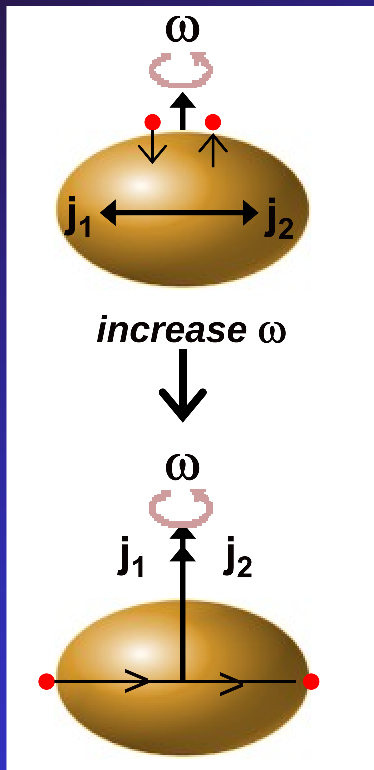
$$\frac{\delta^2}{1+\delta^2} = \frac{2K^2(2I-1)}{(I+1)(I+K-1)(I-K-1)}\left(\frac{E_1}{E_2}\right)^5\frac{T_2}{T_1}$$





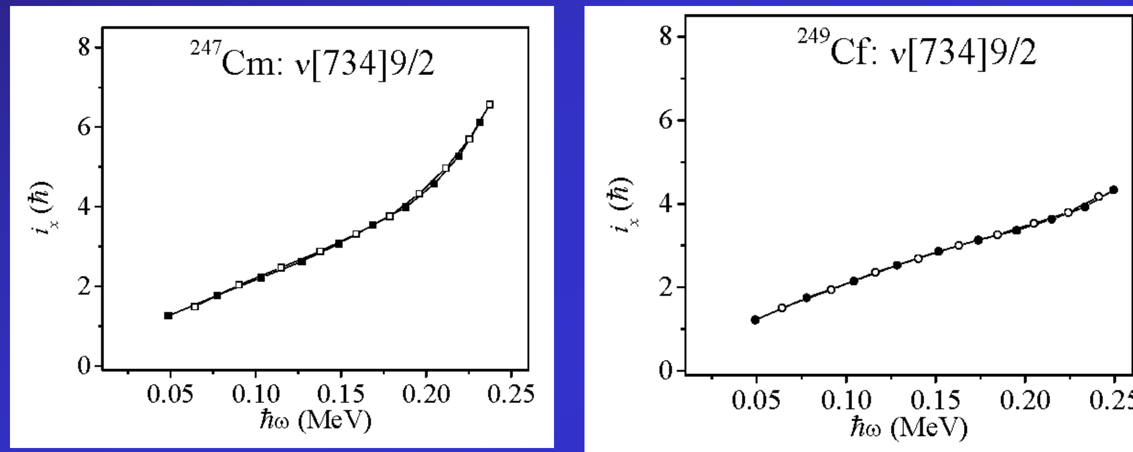


Rotation alignments in ^{247}Cm and ^{249}Cf

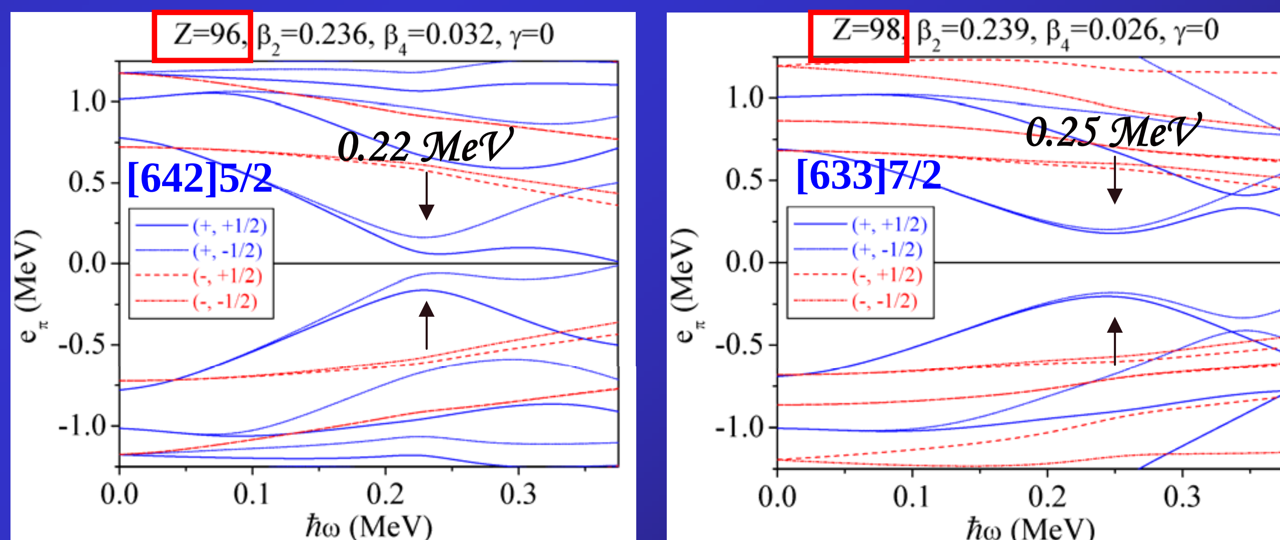


Rotation alignment of nucleons due to Coriolis force

Experimental $\pi i_{13/2}$ alignment ($\nu j_{15/2}$ Pauli blocked)

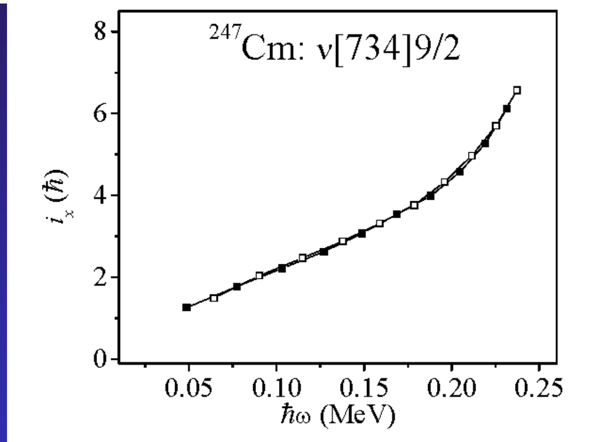


Proton quasiparticle levels (Woods-Saxon)

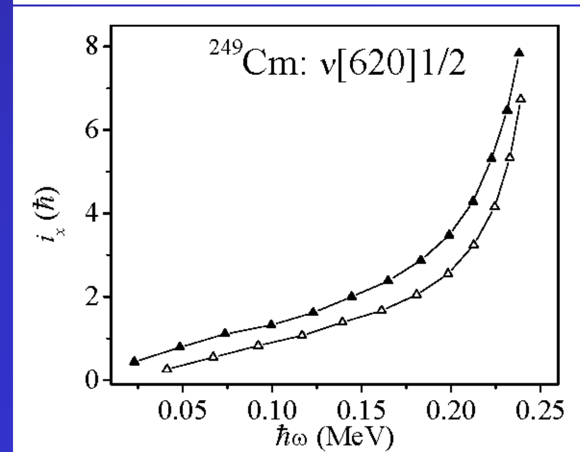


Rotation alignments in ^{247}Cm and ^{249}Cm

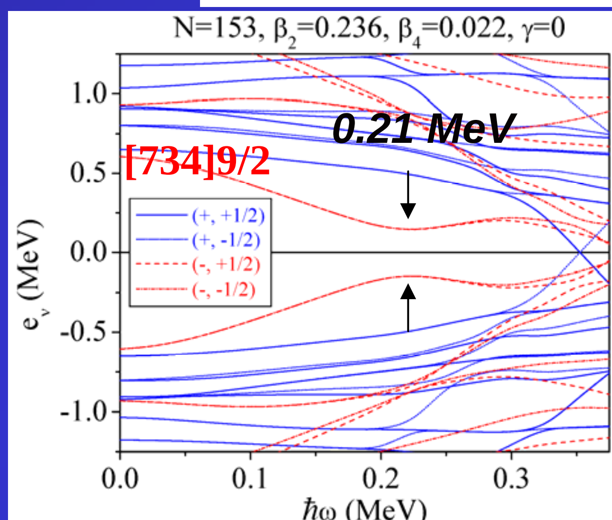
$\pi i_{13/2}$ alignment ($\nu j_{15/2}$ blocked)

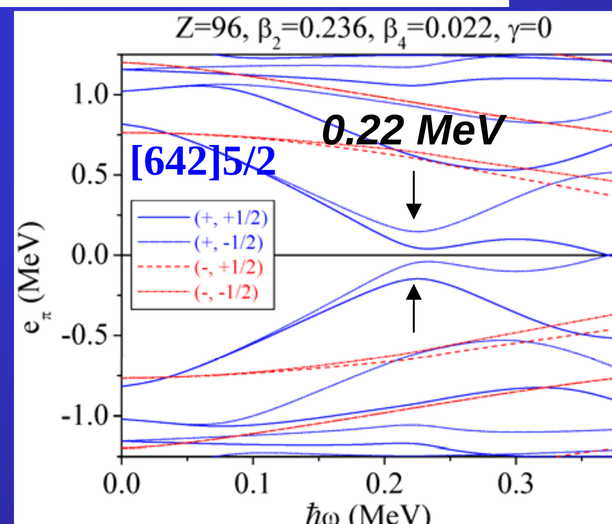


$\pi i_{13/2}$ and $\nu j_{15/2}$ alignments



Quasiparticle levels for ^{249}Cm (Woods-Saxon)

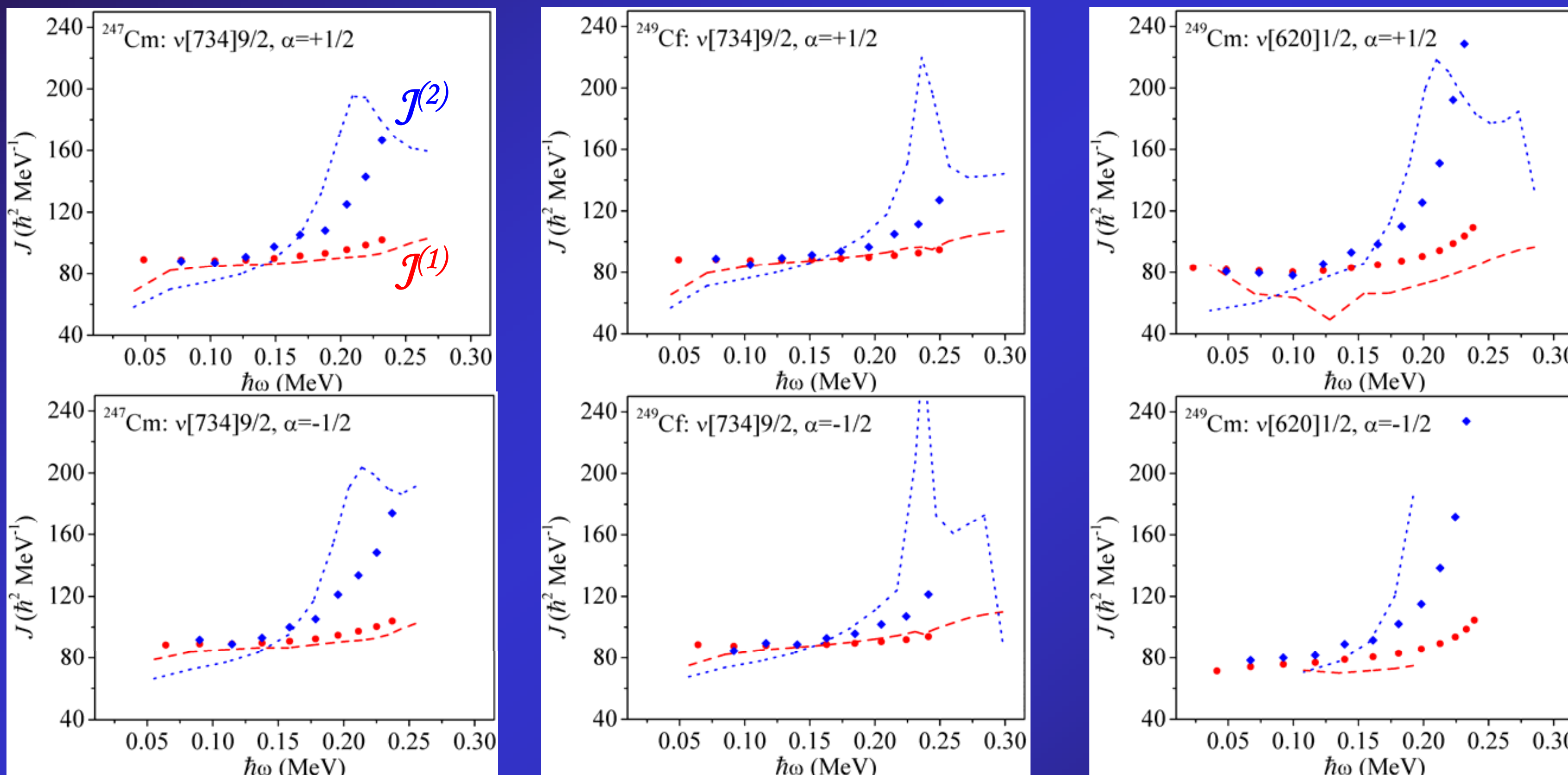




Mean-field predictions: HFB with Skyrme (SLy4)

Moments of inertia (Kinematic: $\mathcal{J}^{(1)}$ and Dynamic: $\mathcal{J}^{(2)}$)

^{247}Cm **^{249}Cf** **^{249}Cm**



M. Bender and P.-H. Heenen, private communication and Nucl. Phys. A 723, 354 (2003)

Summary (Odd A, high spin)

- ***Inelastic excitation and transfer reactions: excellent tool for exploring odd-A trans-plutonium nuclei (limited by target activities)***
- ***Rotational bands identified up to high spins in ^{247,249}Cm (Z=96) and ^{249}Cf (Z=98), with firm configuration assignments***
- ***Woods-Saxon (universal parameters) cranking calculations provide a good description of high-spin data up to No (Z=102)***
- ***Skyrme mean-field calculations also give a good account of observed rotational properties; more calculations for odd-A nuclei required to test different effective interactions***

S.K. Tandel et al., manuscript in preparation for submission to Phys. Rev. Lett.

Collaborators

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Utility of NNDC services: ENSDF

Nuclear structure information using different experimental techniques

- *In-beam γ spectroscopy*
- *Isomeric decays*
- *α,β decay*
- *Transfer reactions*
- *etc.*

Comprehensive information under one roof in ENSDF!

Progress in Particle and Nuclear Physics 61 (2008) 674–720

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Review

In-beam and decay spectroscopy of transfermium nuclei

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owes a lot to ENSDF!

Other valuable NNDC services

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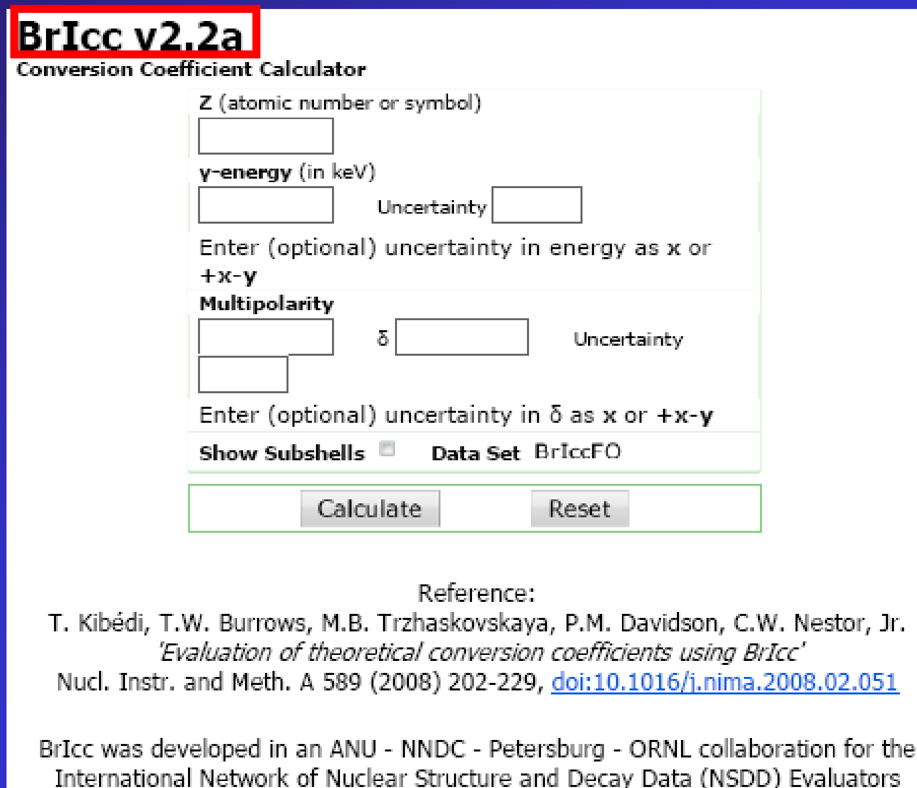
Most transitions highly converted
BrIcc *indispensable !*

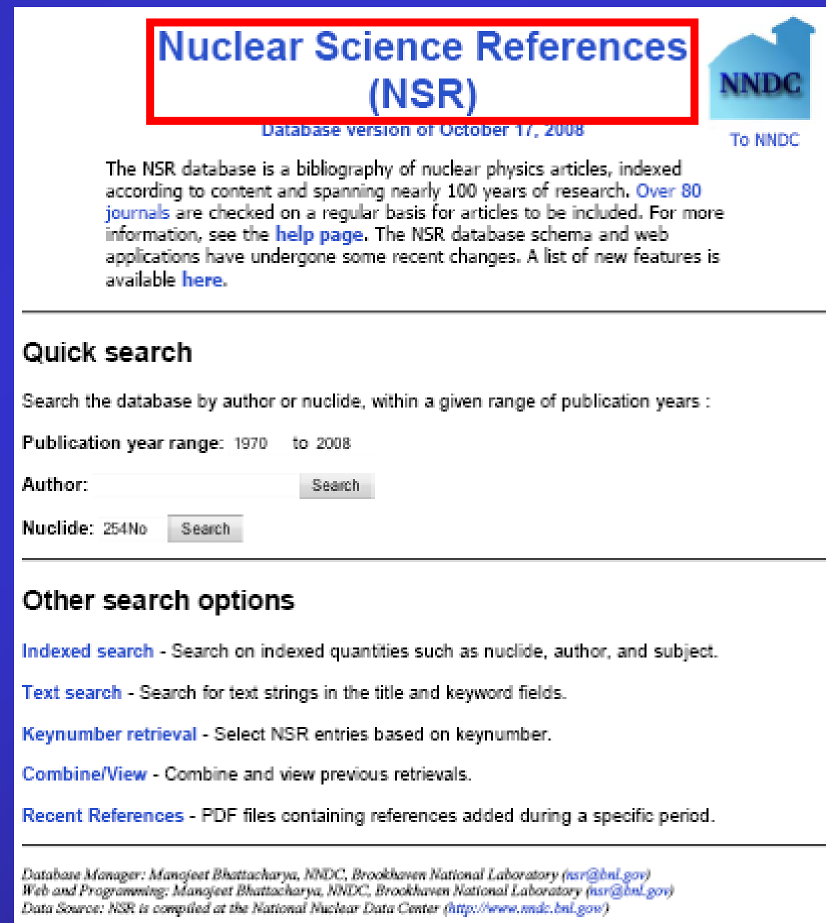


BrIcc v2.2a
Conversion Coefficient Calculator
Z (atomic number or symbol)
γ-energy (in keV)
Uncertainty
Enter (optional) uncertainty in energy as x or +x-y
Multipolarity
δ
Uncertainty
Enter (optional) uncertainty in δ as x or +x-y
Show Subshells
Data Set BrIccFO
Calculate
Reset

Reference:
T. Kibédi, T.W. Burrows, M.B. Trzhaskovskaya, P.M. Davidson, C.W. Nestor, Jr.
'Evaluation of theoretical conversion coefficients using BrIcc'
Nucl. Instr. and Meth. A 589 (2008) 202-229, doi:10.1016/j.nima.2008.02.051

BrIcc was developed in an ANU - NNDC - Petersburg - ORNL collaboration for the International Network of Nuclear Structure and Decay Data (NSDD) Evaluators

Information about all publications under one roof



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The NSR database is a bibliography of nuclear physics articles, indexed according to content and spanning nearly 100 years of research. Over 80 journals are checked on a regular basis for articles to be included. For more information, see the help page. The NSR database schema and web applications have undergone some recent changes. A list of new features is available here.

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Database Manager: Manojeet Bhattacharya, NNDC, Brookhaven National Laboratory (nsr@bnl.gov)
Web and Programming: Manojeet Bhattacharya, NNDC, Brookhaven National Laboratory (nsr@bnl.gov)
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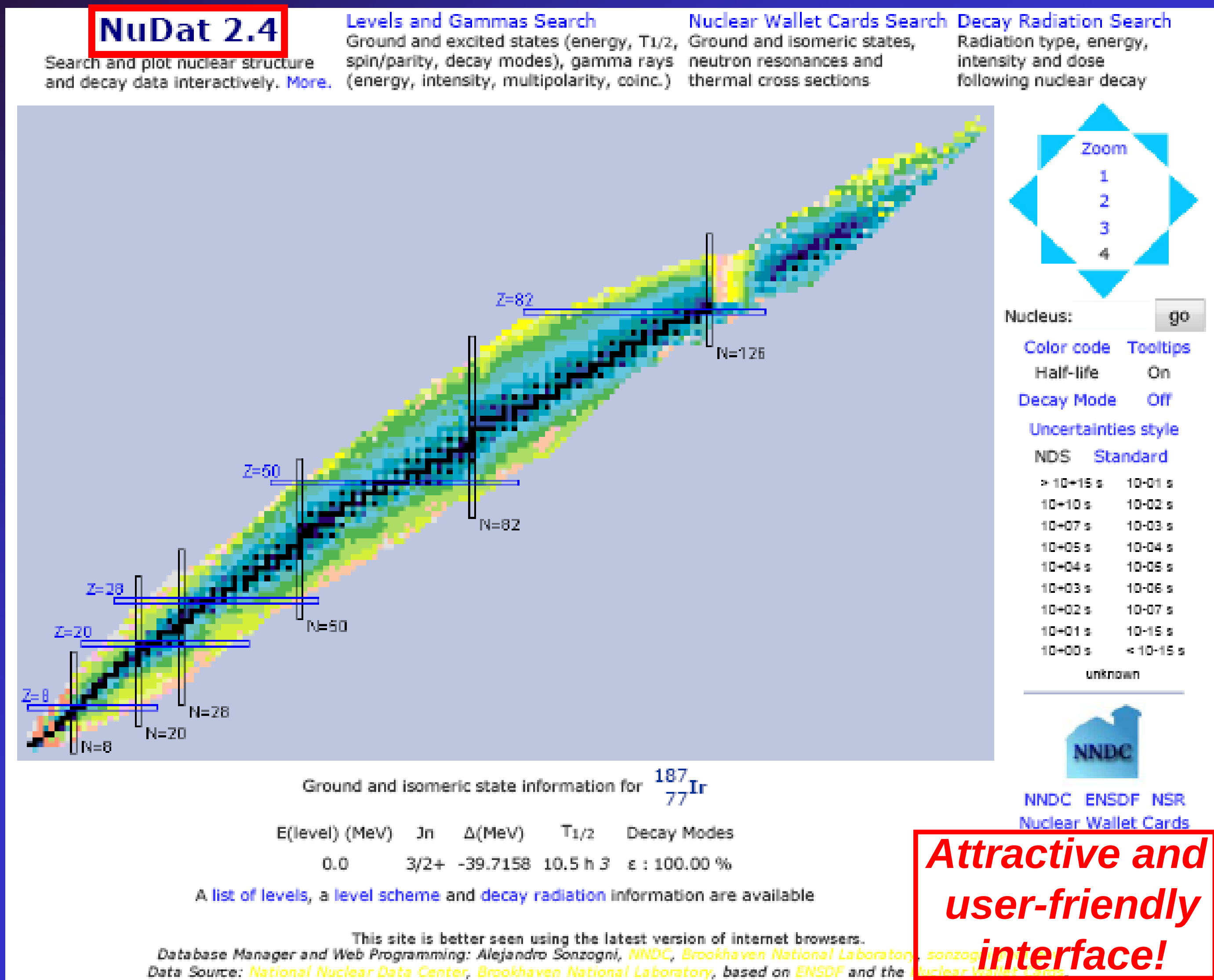
Favorite NNDC utility



Attractive and user-friendly interface!

Popular with my students!