Mirror Isomers in the $1f_{7/2}$ Shell

D. Rudolph
for the RISING Stopped Beam Collaboration

Department of Physics
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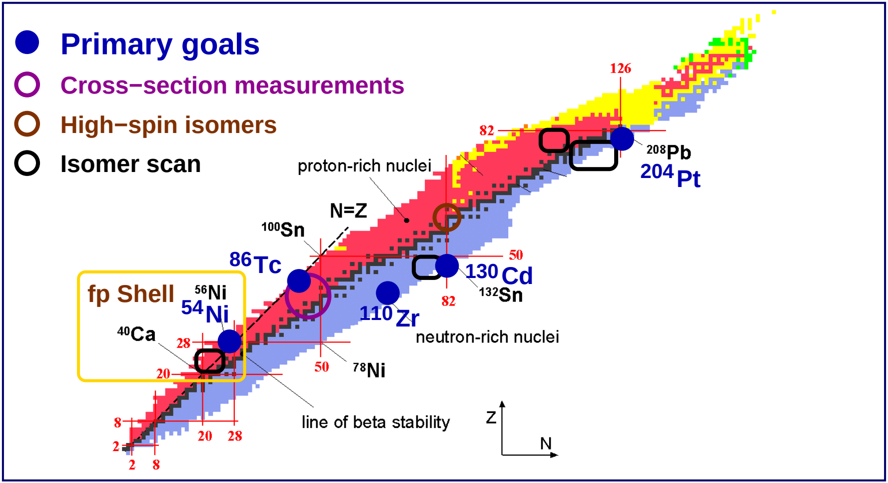
European Gammapool Workshop, Paris, May 2008

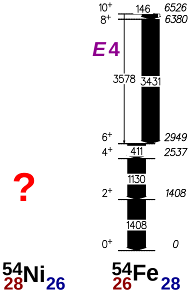
Contents

RISING Stopped Beam Campaign



Why ^{54}Ni?

- Close to a (soft) doubly-magic nucleus, namely $N = Z = 28$ ^{56}Ni.
- Efficiently probes isospin symmetry breaking effects if the *fp* shell.
- The *fp* shell is a well confined, well established shell-model configuration space.
- Spherical shell-model calculations usually provide excellent spectroscopic information, including well-deformed structures and transition rates.



10^+ isomer:

364(7) ns halflife
el. quad. moment
magnetic moment

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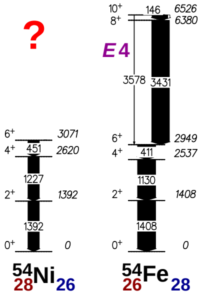

10^+ isomer:

364(7) ns halflife
el. quad. moment
magnetic moment

A. Gadea *et al.*,
PRL 97, 152501 (2006)

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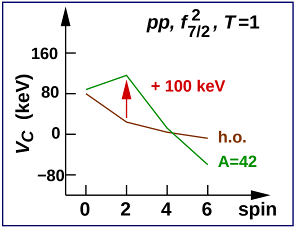
Isospin Symmetry Breaking

- Coulomb multipole contributions.
- Coulomb monopole contributions (radii, deformation, shell effects).
- Electromagnetic spin-orbit interaction.
- Nuclear isospin breaking components, V_{BM}.

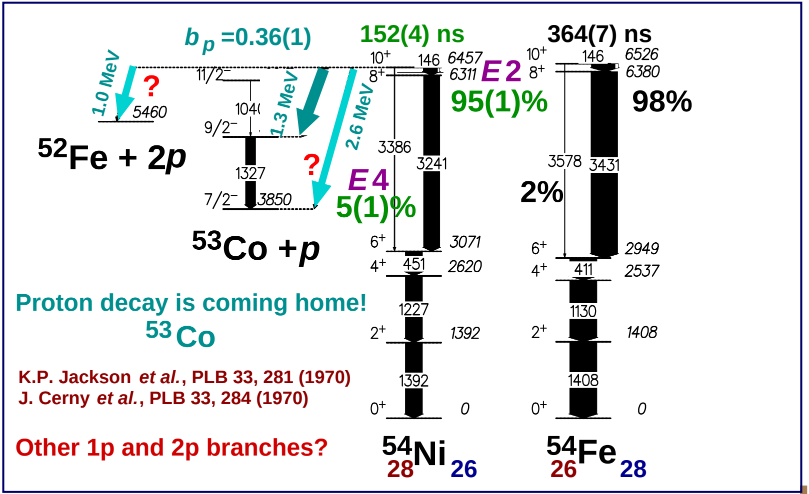


A.P. Zuker et al., PRL 89, 142502 (2002)

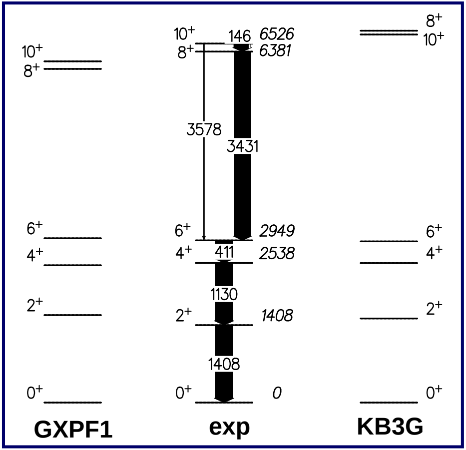
**J. Duflo & A.P. Zuker,
PRC66, 051304(R) (2002)**

**Recent Review:
M.A. Bentley and S.M. Lenzi,
Prog. Part. Nucl. Phys. 59, 497 (2007)**

Experimental Results A = 54



Shell-Model Calculations ^{54}Fe

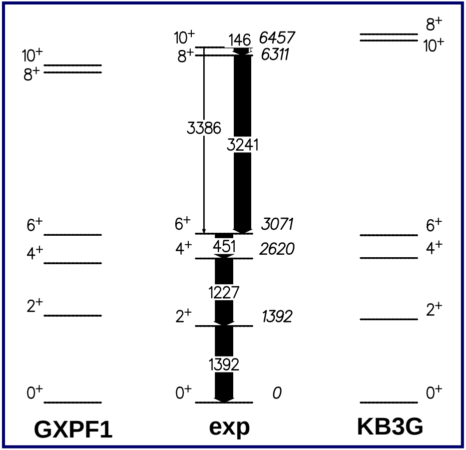


ANTOINE shell−model code
Full *fp* space, *t* =6
Including Coulomb effects and V_{BM}
E2 eff. charges: ε_p =1.15 and ε_n =0.80
(R. du Rietz *et al*.,PRL93, 222501 (2004))
E4 eff. charges: ε_p =1.50 and ε_n =0.50

	exp	GXPF1	KB3G
B(E2) (W.u.)	1.69(4)	1.95	2.03
B(E4) (W.u.)	0.79(8)	1.55	1.30
$\tau_{(\gamma + CE)}$ (ns)*	525(10)	453	437
b (*E*4) (%)*	1.8(2)	3.0	2.4
$\mu(10^+)$ (μ_N^2)	7.281(10)	7.23	6.82
Q (10^+)(efm^2)	52(8)	60.7	55.6

* using the experimental level scheme

Shell-Model Calculations ^{54}Ni



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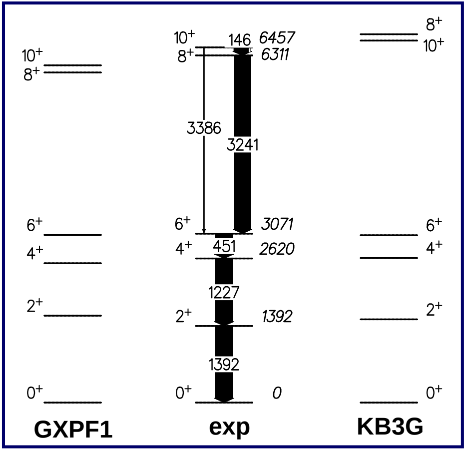
Full *fp* space, *t* =6
Including Coulomb effects and V_{BM}
E2 eff. charges: ε_p =1.15 and ε_n =0.80
(R. du Rietz *et al*.,PRL93, 222501 (2004))
E4 eff. charges: ε_p =1.50 and ε_n =0.50

	exp	GXPF1	KB3G
B(E2) (W.u.)	2.48(7)	1.86	2.06
B(E4) (W.u.)	5.7(13)	5.28	4.66
$\tau_{(\gamma+CE)}$ (ns)*	342(9)	452	413
b (*E*4) (%)*	5.1(11)	6.2	5.0
$\mu(10^+)$ (μ_N^2)		3.93	4.24
Q (10^+)(efm^2)		63.7	58.5

* using the experimental level scheme

Shell-Model Calculations ^{54}Ni

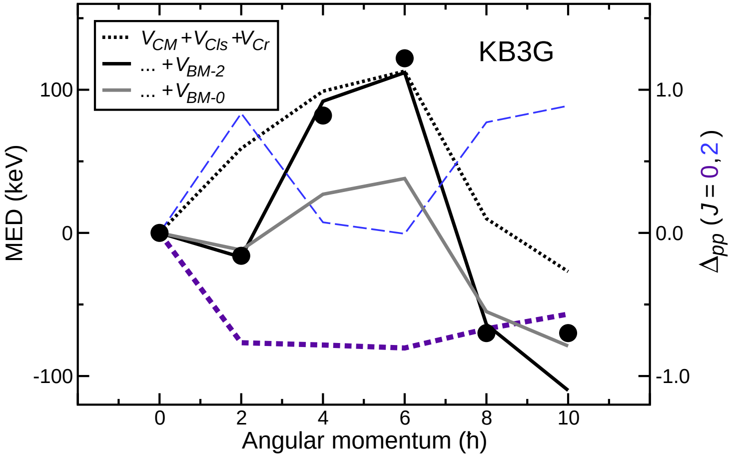


ANTOINE shell−model code
Full *fp* space, $t = 6$
Including Coulomb effects and V_{BM}
E2 eff. charges: $\varepsilon_p = 1.15$ and $\varepsilon_n = 0.80$
(R. du Rietz *et al*.,PRL93, 222501 (2004))
E4 eff. charges: $\varepsilon_p = 1.50$ and $\varepsilon_n = 0.50$

	exp	GXPF1	KB3G
B(E2) (W.u.)	1.98(6)	1.86	2.06
B(E4) (W.u.)	4.6(10)	5.28	4.66
$\tau_{(\gamma + CE)}$ (ns)*	427(11)	452	413
b (*E*4) (%)*	5.1(11)	6.2	5.0
$\mu(10^+)$ (μ_N^2)	GANIL	3.93	4.24
$Q(10^+)$(efm^2)		63.7	58.5

* using the experimental level scheme
adding 25% ground−state proton decay

Mirror Energy Differences – KB3G



Mirror Configurations

Example: 10^+ states in A=54 mirrors:

Configuration	Partition (%) Fe	Partition (%) Ni	Interaction
$f_{7/2}^{-2} \times f_{7/2}^{-1}\, p_{3/2}$	34.3	38.8	GXPF1A
	38.4	43.1	KB3G
$f_{7/2}^{-2} \times f_{7/2}^{-1}\, f_{5/2}$	14.8	11.0	GXPF1A
	11.9	7.9	KB3G

} + 4%

} − 3%

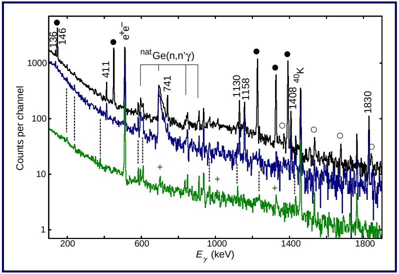
$\Delta \sim +/- 4\%$

Summary 10^+ States in A = 54 Mirrors

- The 10^+ mirror isomer in ^{54}Ni has been identified.
- Different *fp* interactions have different (minor but interesting) problems in describing the 8^+ and 10^+ states.
- The MED values for the 2^+, 8^+, and 10^+ states call for an isospin breaking nuclear $J = 2$ proton-proton interaction.
- The first observation of a discrete energy, $\ell = 5$ proton decay from an isomeric state competing with γ radiation via a fragmentation reaction ($fph_{11/2}$ model space?).
- Likely $\ell = 7$ proton decay branch into the ground state of ^{53}Co.
- $E4$ effective charges – the ratio of the two $B(E4)$ values requires negative isovector charges.

D. Rudolph *et al.*, submitted to Phys. Rev. Lett.

'In-Situ' Production of Isomers



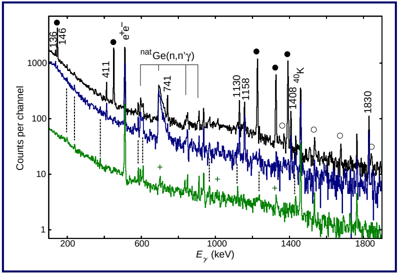
^{54}Ni gated

^{52,53}Co gated

} **time: 0.1 – 1.0 μs**

^{54}Ni gated **15 – 16 μs**

'In-Situ' Production of Isomers



● ○ ^{54}Ni 10^+ isomer related

+ specific long−lived background

time:

^{54}Ni gated
^{52,53}Co gated
} 0.1 − 1.0 μs

^{54}Ni gated 15 − 16 μs

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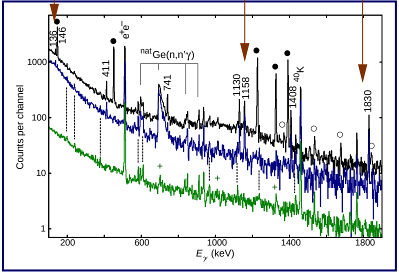
'In-Situ' Production of Isomers

136, 1158, 1830 keV: 19/2$^-$ isomer in ^{43}Sc (470 ns)



● ○ ^{54}Ni 10$^+$ isomer related

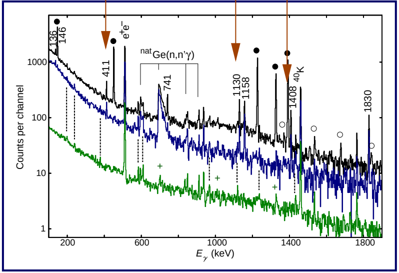
+ specific long−lived background

		time:
^{54}Ni gated	}	0.1 − 1.0µs
^{52,53}Co gated		
^{54}Ni gated		15 − 16µs

'In-Situ' Production of Isomers

136, 1158, 1830 keV: $19/2^-$ isomer in ^{43}Sc (470 ns)

411, 1130, 1408 keV: 10^+ isomer in ^{54}Fe (365 ns)



● ○ ^{54}Ni 10^+ isomer related

+ specific long−lived background

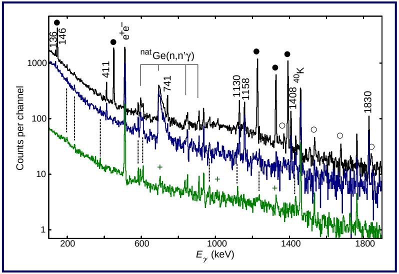
	time:
^{54}Ni gated, ^{52,53}Co gated	0.1 − 1.0 μs
^{54}Ni gated	15 − 16 μs

'In-Situ' Production of Isomers

136, 1158, 1830 keV: $19/2^-$ isomer in ^{43}Sc (470 ns)

411, 1130, 1408 keV: 10^+ isomer in ^{54}Fe (365 ns)

Secondary reactions in the passive stopper!



● ○ ^{54}Ni 10^+ isomer related

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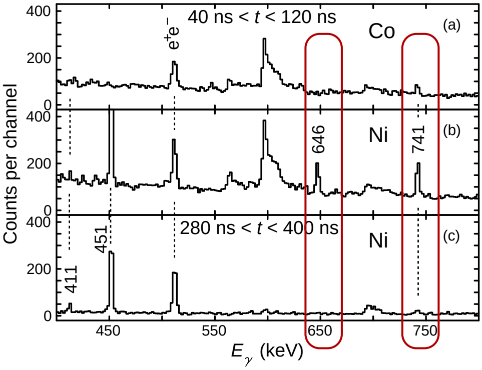
	time:
^{54}Ni gated, ^{52,53}Co gated	0.1 − 1.0 μs
^{54}Ni gated	15 − 16 μs

'In-Situ' Production of Isomers



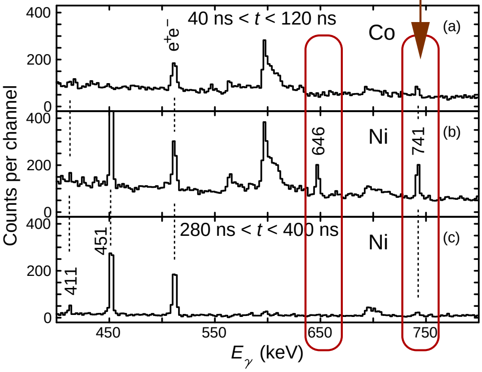
Co−gated

Ni−gated

Ni−gated

'In-Situ' Production of Isomers

741 keV: known 3/2− isomer in ^{53}Fe (63.5 ns)



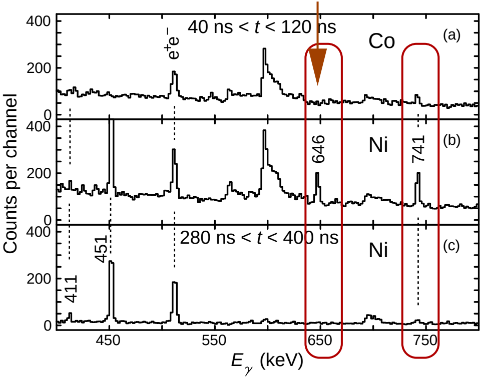
Co−gated

Ni−gated

Ni−gated

'In-Situ' Production of Isomers

741 keV: known 3/2− isomer in ^{53}Fe (63.5 ns)
646 keV: mirror isomer in ^{53}Co!?



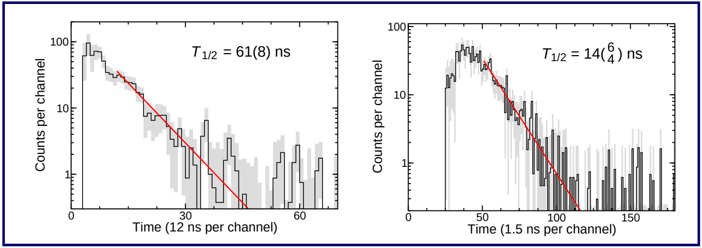
Co−gated

Ni−gated

Ni−gated

Verification via Half-Life Analysis

741 keV **^{53}Fe** **646 keV** **^{53}Co**



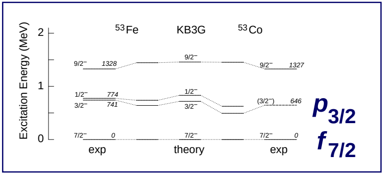
Literature: $T_{1/2}$ =63.5(14) ns

Comparison with Shell Model – Energies

***t* =7 isospin dependent shell−model calculations**

ANTOINE code, KB3G and GXPF1A interactions

Excitation energies



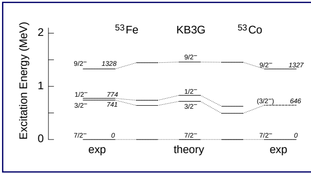
MED values (keV)

	3/2−	9/2−
exp	−95	−1
KB3G	−147	8
GXPF1A	−130	1

Comparison with Shell Model – Energies

t **=7 isospin dependent shell−model calculations**
ANTOINE code, KB3G and GXPF1A interactions

Excitation energies



$p_{3/2}$
$f_{7/2}$

MED values (keV)

	3/2−	9/2−
exp	−95	−1
KB3G	−147	8
GXPF1A	−130	1

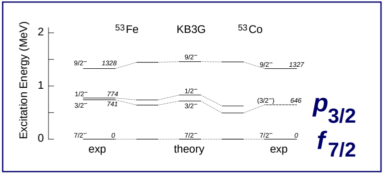
everything's fine ...

Comparison with Shell Model – Lifetimes

t **=7 isospin dependent shell−model calculations**

ANTOINE code, KB3G and GXPF1A interactions

Excitation energies



MED values (keV)

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BUT: transition rates?

Comparison with Shell Model – Lifetimes

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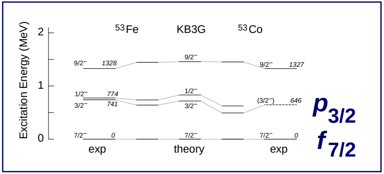
Excitation energies



MED values (keV)

	3/2−	9/2−
exp	−95	−1
KB3G	−147	8
GXPF1A	−130	1

	^{53}Fe			^{53}Co		
	exp	KB3G	GXPF1A	exp	KB3G	GXPF1A
3/2−	63.5(14) ns	7.8 ns	11 ns	$14(^{6}_{4})$	7.6 ns	7.9 ns
9/2−	17(7) fs	24 fs	28 fs		22 fs	25 fs

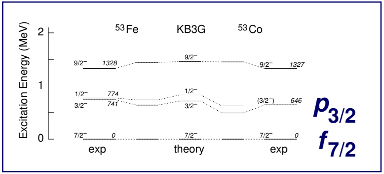
$e_{\mathrm{eff},p} = 1.15$
$e_{\mathrm{eff},n} = 0.80$

Comparison with Shell Model – Conclusion

t **=7 isospin dependent shell–model calculations**

ANTOINE code, KB3G and GXPF1A interactions

Excitation energies



MED values (keV)

	3/2–	9/2–
exp	–95	–1
KB3G	–147	8
GXPF1A	–130	1

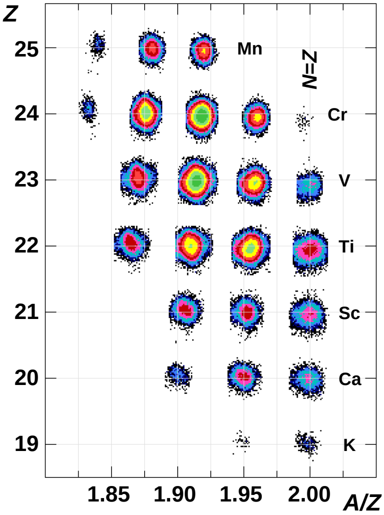
everything's fine ...

BUT: transition rates?

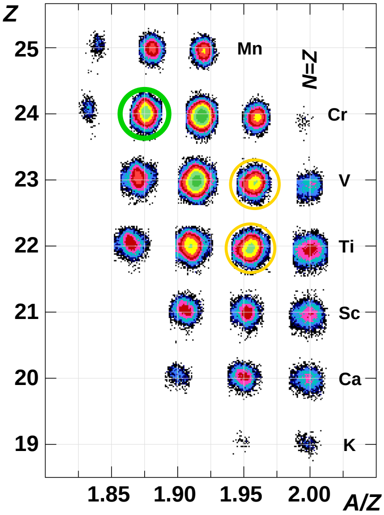
Predictions are "too fast"!

D. Rudolph *et al.*, EPJA 36, 131 (2008)

Scan of $1f_{7/2}$, $N \leq Z$ Isotopes

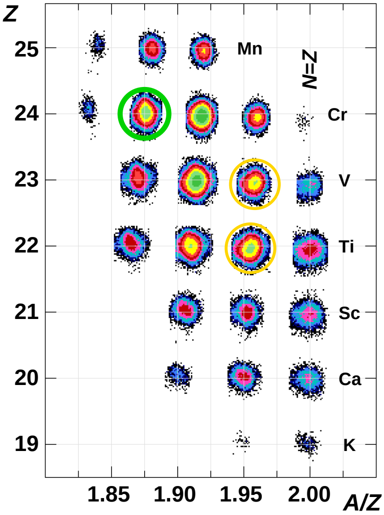


Scan of $1f_{7/2}$, $N \leq Z$ Isotopes



$^{45}_{24}Cr_{21}$	$(3/2^+)$	(M2)
$^{45}_{23}V_{22}$	$(3/2^-)$	(E2)
$^{43}_{22}Ti_{21}$	$(3/2^+)$	(M2)
	$(19/2^-)$	(E2)

Scan of $1f_{7/2}$, $N \leq Z$ Isotopes



$^{45}_{24}Cr_{21}$ $(3/2^+)$ (M2)

$^{45}_{23}V_{22}$ $(3/2^-)$ (E2)

$^{43}_{22}Ti_{21}$ $(3/2^+)$ (M2)
$(19/2^-)$ (E2)

- More B(E2) mirror rates

- B(M2) mirror rates
- sdfp shell model space

to be published

Collaboration ^{54}Ni Experiment

R. Hoischen[1], D. Rudolph[1], M. Hellström[1], E.K. Johansson[1], S. Pietri[2], Zs. Podolyák[2], P.H. Regan[2]
F. Becker[3], P. Bednarczyk[3,4], L. Caceres[3,5], P. Doornenbal[3], J. Gerl[3], M. Górska[3] J. Grębosz[4,3],
I. Kojouharov[3], N. Kurz[3], W. Prokopowicz[3,4], H. Schaffner[3], H.J. Wollersheim[3] L.-L. Andersson[1],
L. Atanasova[6], D.L. Balabanski[7,8], M.A. Bentley[9], A. Blazhev[10] C. Brandau[2,3], J. Brown[8], C. Fahlander[1],
A.B. Garnsworthy[2,11], A. Jungclaus[5] S.J. Steer[2] S.M. Lenzi

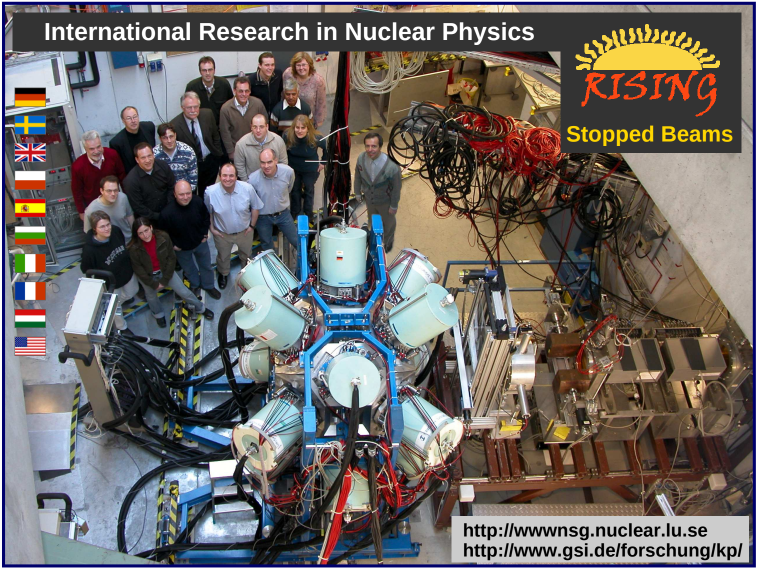
11 institutions

GSI technical & scientific work force

External preparation force (Surrey & Lund)

Theory support

Experimental Principle - Happy Physicists



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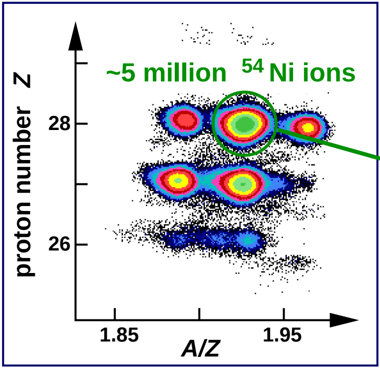
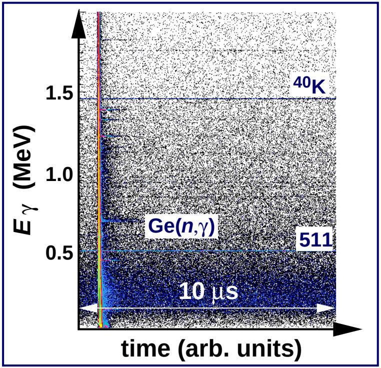
That’s it, folks ...

Identification and Energy-Time Correlations

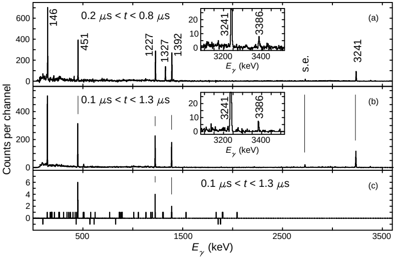
^{54}Ni: DGF–timing





~ 0.9 million entries

Gamma-Ray Spectra of ^{54}Ni



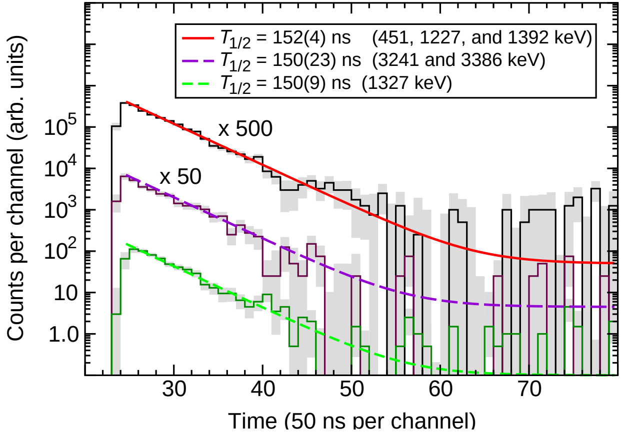
γ −singles

$\gamma\gamma$ −coincidences:

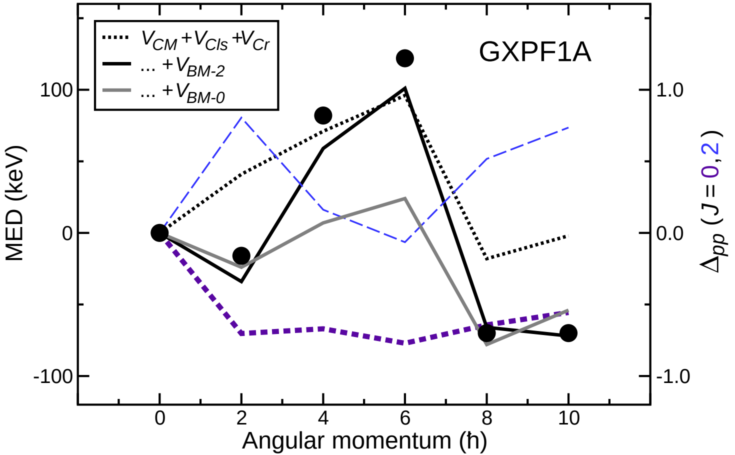
known ground−state cascade

3386 keV (E4)

Time Spectra of ^{54}Ni



Mirror Energy Differences – GXPF1A



Spectroscopic Factors

	Q_p (MeV)	ℓ_p ($\hbar$)	$T_{1/2}$ (s) WKB [1]	$T_{1/2}$ (s) exp	S_{exp}
^{53}Co [2]	1.59(3)	9	$1.3 \cdot 10^{-6}$	~17	$\sim 8 \cdot 10^{-8}$
^{54}Ni	1.27(5)	5	$7.1 \cdot 10^{-13}$	$4.1 \cdot 10^{-7}$	$1.7 \cdot 10^{-6}$
				$5.1 \cdot 10^{-7}$	$1.4 \cdot 10^{-6}$
	2.65(5)	7	$2.9 \cdot 10^{-13}$		
				$2.8 \cdot 10^{-7}$	$1.0 \cdot 10^{-6}$
^{94}Ag [3]	0.79(3)	4	$2.0 \cdot 10^{-5}$	21(6)	$1 \cdot 10^{-6}$
	1.01(3)	5	$5.5 \cdot 10^{-6}$	18(4)	$3 \cdot 10^{-7}$
^{58}Cu [4]	2.341(5)	4	$2.0 \cdot 10^{-16}$	$\sim 2 \cdot 10^{-13}$	$\sim 1 \cdot 10^{-3}$

[1] S. Hofmann, priv. comm. and in *Nuclear Decay Modes* (IOP Publishing, Bristol, 1996), p. 143

[2] K.P. Jackson *et al*., Phys. Lett. 33B, 281 (1970)

[3] I. Mukha *et al*., Phys. Rev. Lett. 95, 022501 (2005)

[4] D. Rudolph *et al*., Phys. Rev. Lett. 80, 3018 (1998); Eur. Phys. J. A14, 137 (2002)

Assuming an additional 25% proton branch into the ground state of ^{53}Co