Experimental Studies of Isospin Breaking Interactions

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- **Introduction**
- **What can we learn about effective isospin-non-conserving (INC) interactions in the shell-model?**
- **Spectroscopy of exotic IAS using knockout reactions (MSU) - spectroscopy of proton-rich ^{52}Co**
- **Recent results for ^{70}Kr from JYFL - Isospin symmetry of the A=70 triplet**

Isospin Symmetry and Isospin Breaking

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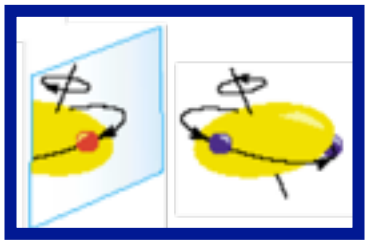
Charge symmetry



$$V_{pp}^{J} = V_{nn}^{J}$$

Charge independence

$$\left(\frac{V_{pp}^{J} + V_{nn}^{J}}{2}\right) = V_{np}^{J}$$

Isospin invariance

Isospin non-conserving interactions (INC)

$$V^{(1),J} = V_{pp}^{J} - V_{nn}^{J}$$

Isovector interaction

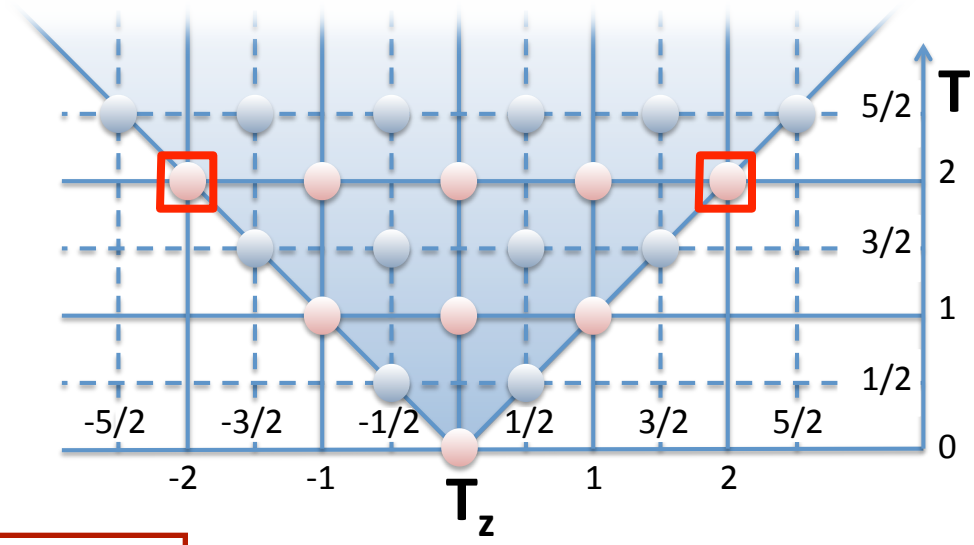
$$V^{(2),J} = V_{pp}^{J} + V_{nn}^{J} - 2V_{np}^{J}$$

Isotensor interaction

Probed in mirror nuclei (MED)

Probed in T=1 triplets (TED)

Mirror Energy Differences

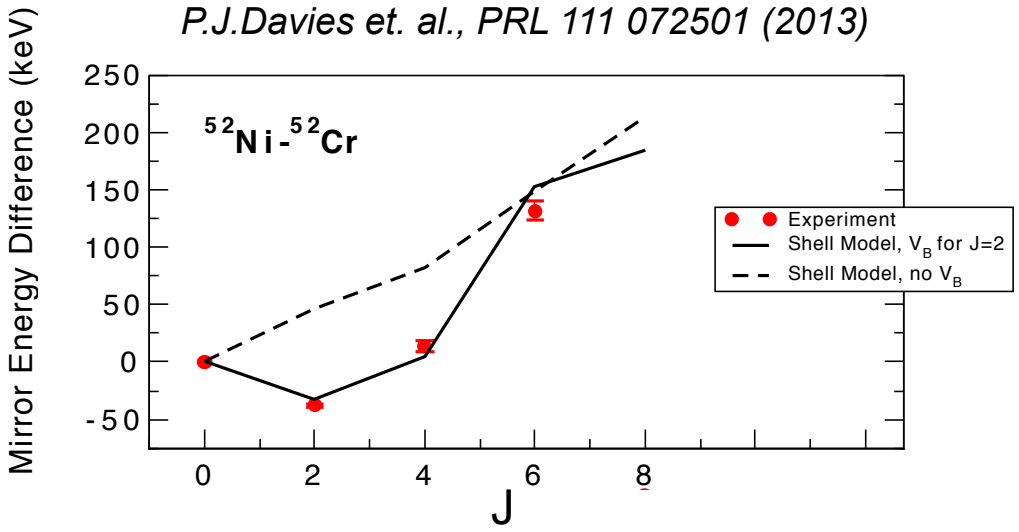


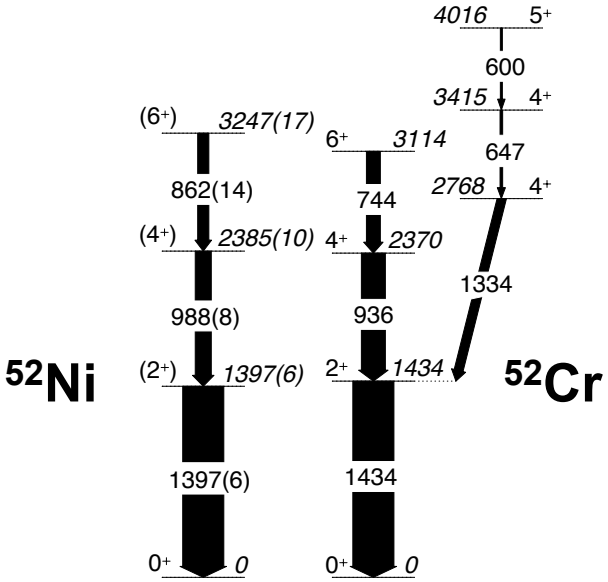
Shell Model

Description of **Zuker *et al***, PRL 89 (2002) 142502

$$V^{(1),J} = V^J_{pp} - V^J_{nn} = V^{(1),J}_C + V^{(1),J}_B$$

P.J.Davies et. al., PRL 111 072501 (2013)





What can we learn about effective INC interactions?

$$V^{(1),J} = V^J_{pp} - V^J_{nn} = V^{(1),J}_C + V^{(1),J}_B$$

Coulomb two-body ME

additional isospin-non-conserving term - INC

What can we learn about effective INC interactions?

$$V^{(1),J} = V^J_{pp} - V^J_{nn} = V^{(1),J}_C + \boxed{V^{(1),J}_B}$$

Extract from fit?

Coulomb two-body ME

additional isospin-non-conserving term - INC

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$$V^{(1),J} = V^J_{pp} - V^J_{nn} = V^{(1),J}_C + V^{(1),J}_B$$

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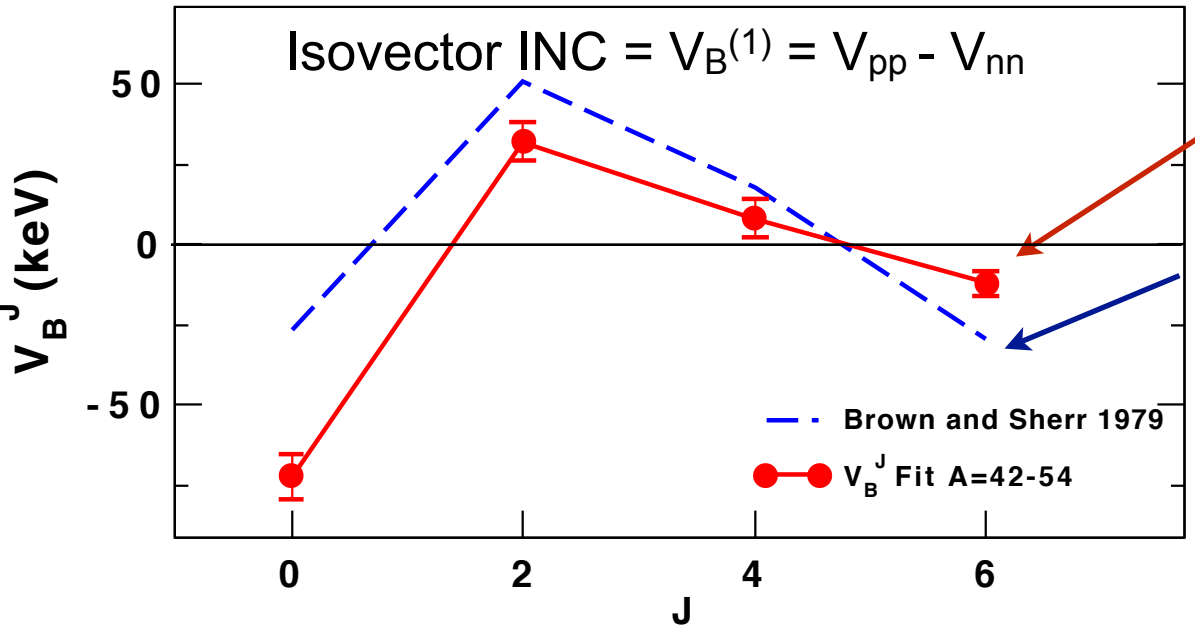
additional isospin-non-conserving term - INC



From fitted excitation energy (MED)

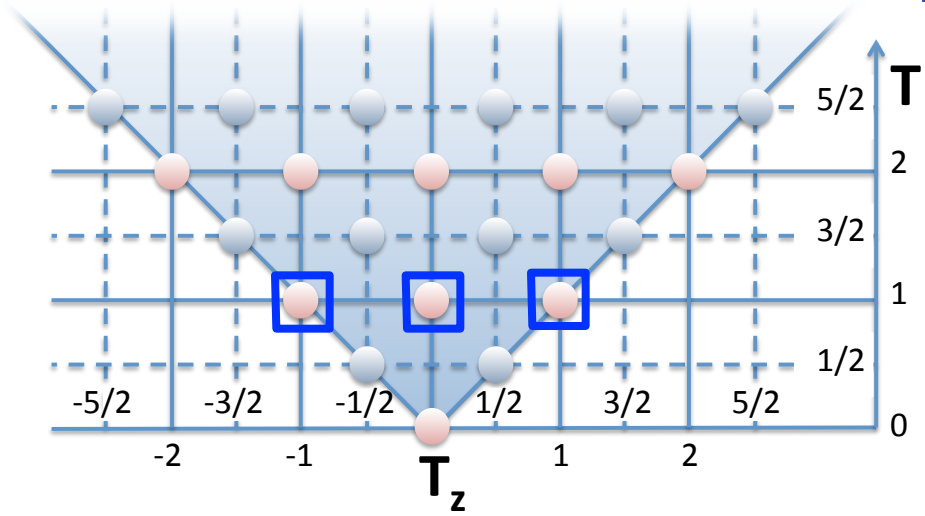
From binding energy (displacement energies)

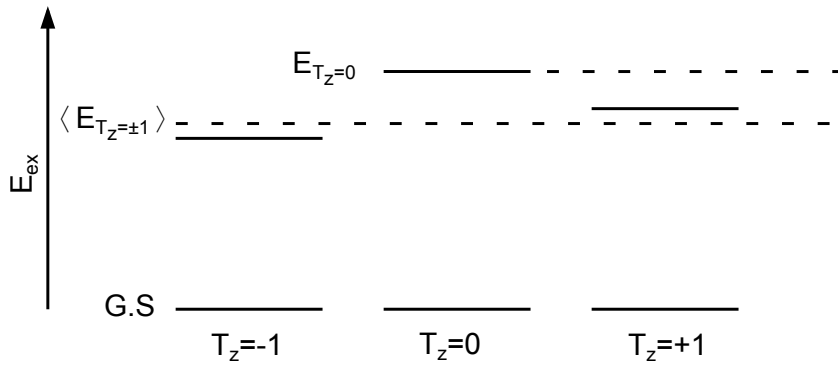
B.A.Brown and R.Sherr
Nucl Phys A322 (1979) 61-91

- Hard to reconcile with CSB seen in NN scattering….(both sign and magnitude)

Bentley, Lenzi, Simpson, Diget, Phys. Rev. ***C92*** *024310 (2015)*

Triplet energy differences

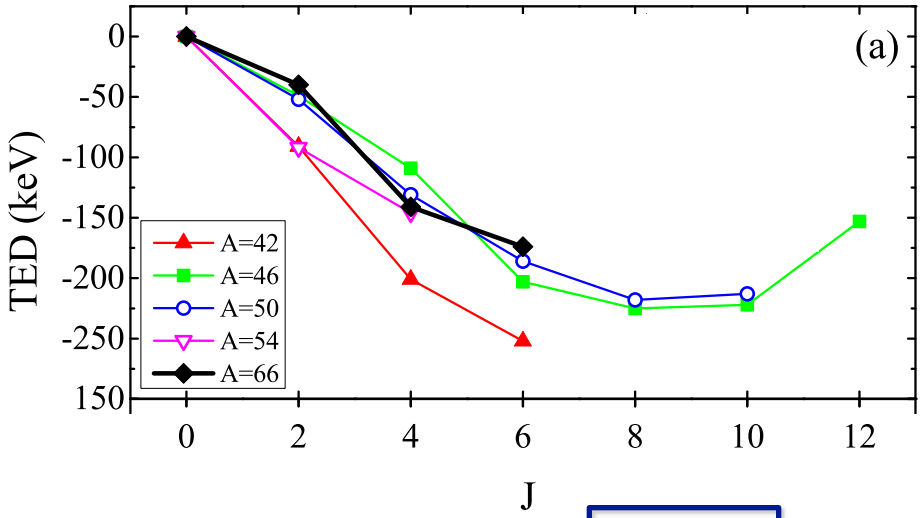




$$TED(\alpha) = E^*_{J,T,T_z=-1} + E^*_{J,T,T_z=+1} - 2E^*_{J,T,T_z=0}$$

TED are:

- **Very** sensitive to details of two-body interaction
- **Isotensor** in nature:
- Always negative

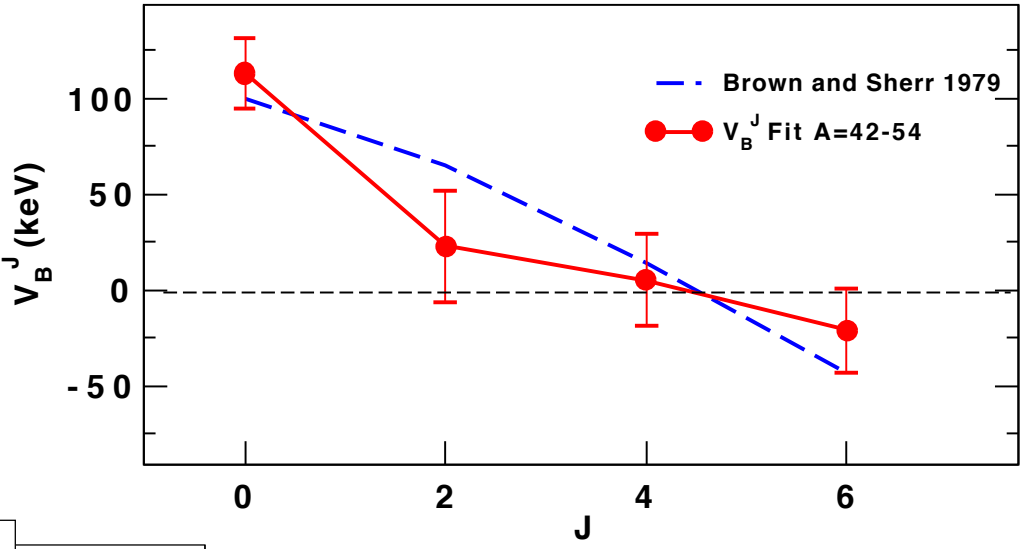


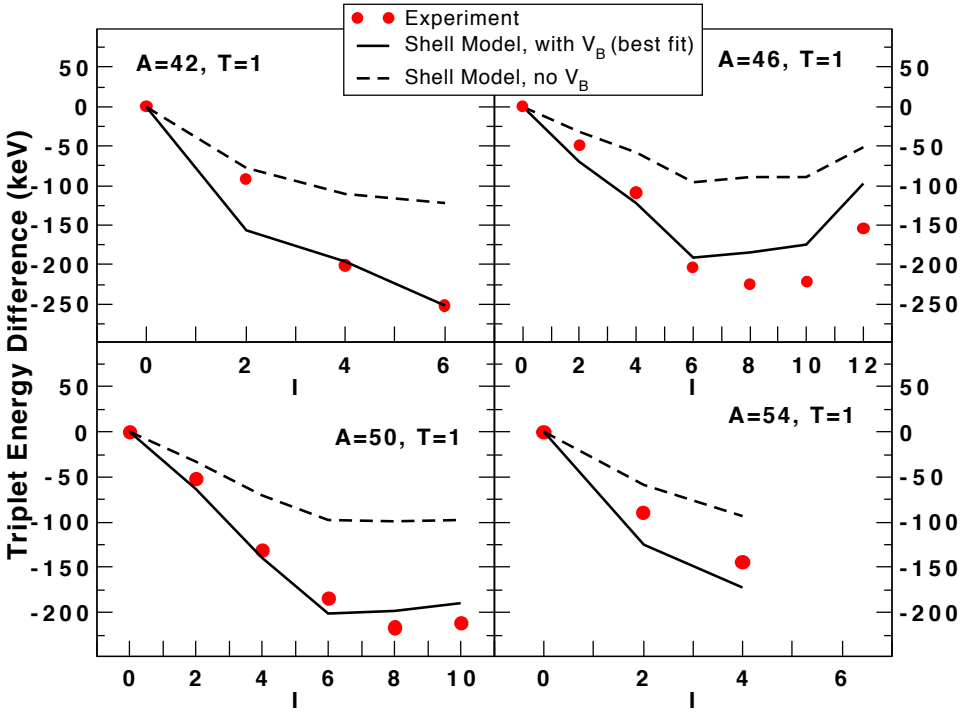
$$V^{(2),j} = V^j_{pp} + V^j_{nn} - 2V^j_{np} = V^{(2),j}_C + \boxed{V^{(2),j}_B}$$

Triplet energy differences

Isotensor INC = $V_B^{(2)} = V_{pp} + V_{nn} - 2V_{np}$

- **TEDs**: *Zuker et al, PRL 89 (2002) 142502*
  Gadea et al PRL 97 (2006) 152501
- **Displacement Energies:**
  Kaneko et al PRL110 (2013) 172505





- Strong *J*-dependent terms (positive at J=0 only)
- **Consistent with NN scattering data**
- np interaction ~ 2-3% stronger than nn or pp.
- Consistent across mass regions

Mirror nuclei at large isospin - knockout reactions

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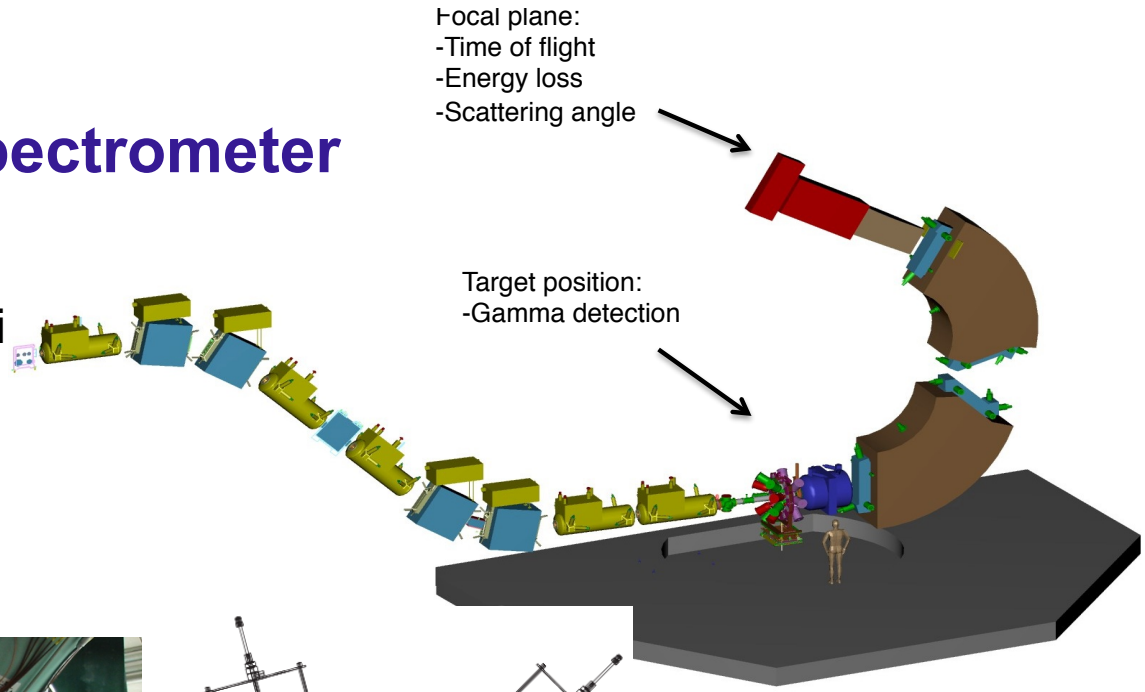
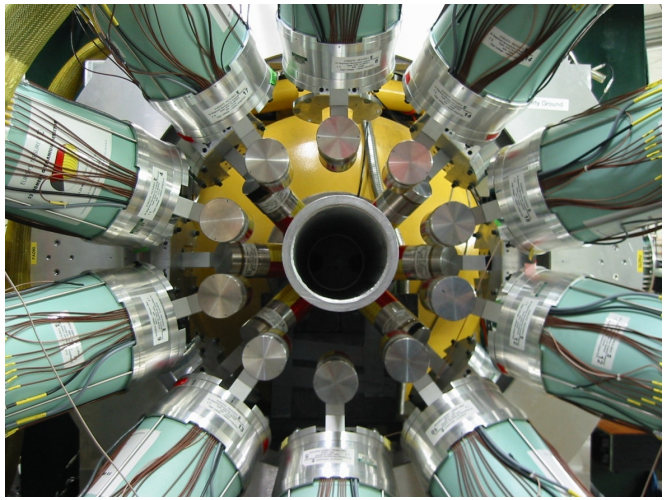
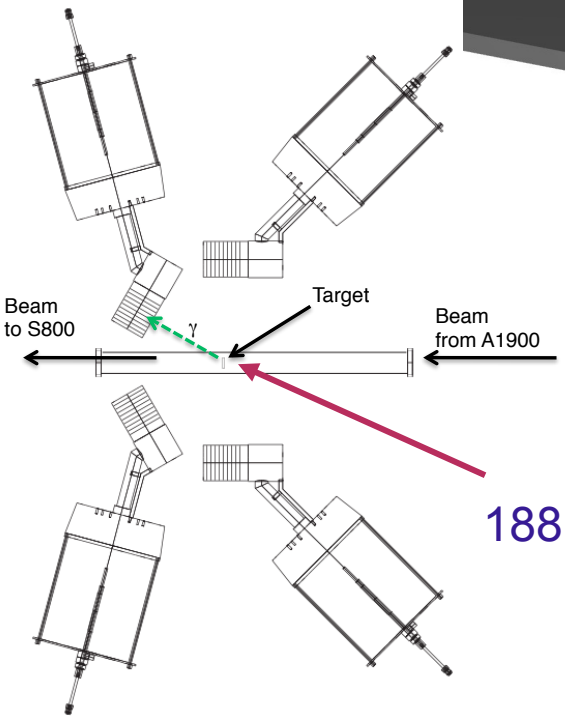
S800 Spectrometer

4x10^3 Hz ^{54}Ni







SeGA

188 mg/cm2 Be target

Spectroscopy of T=1 mirrors using 1N knockout

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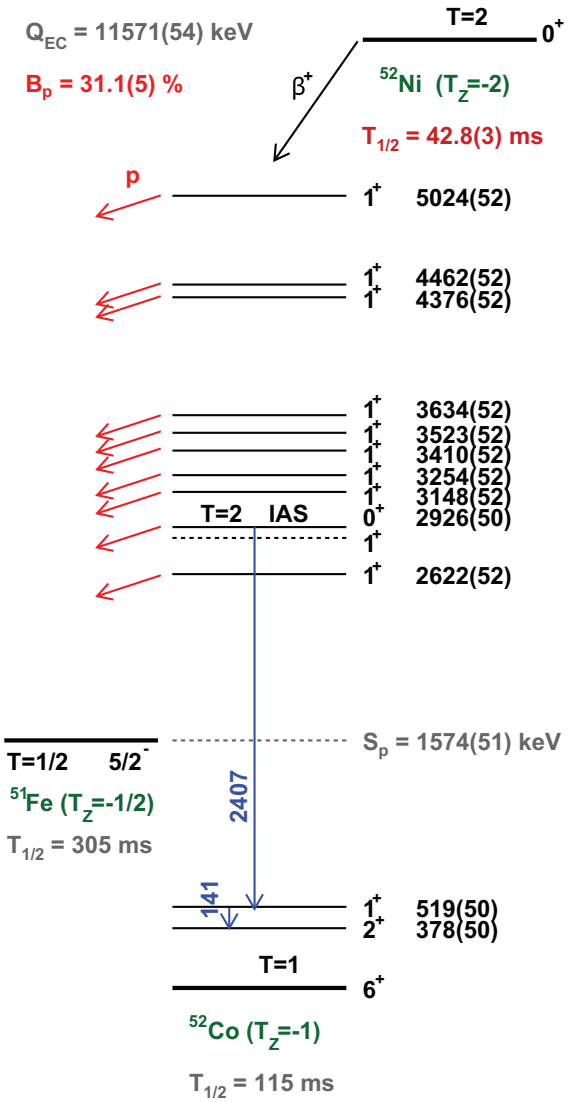
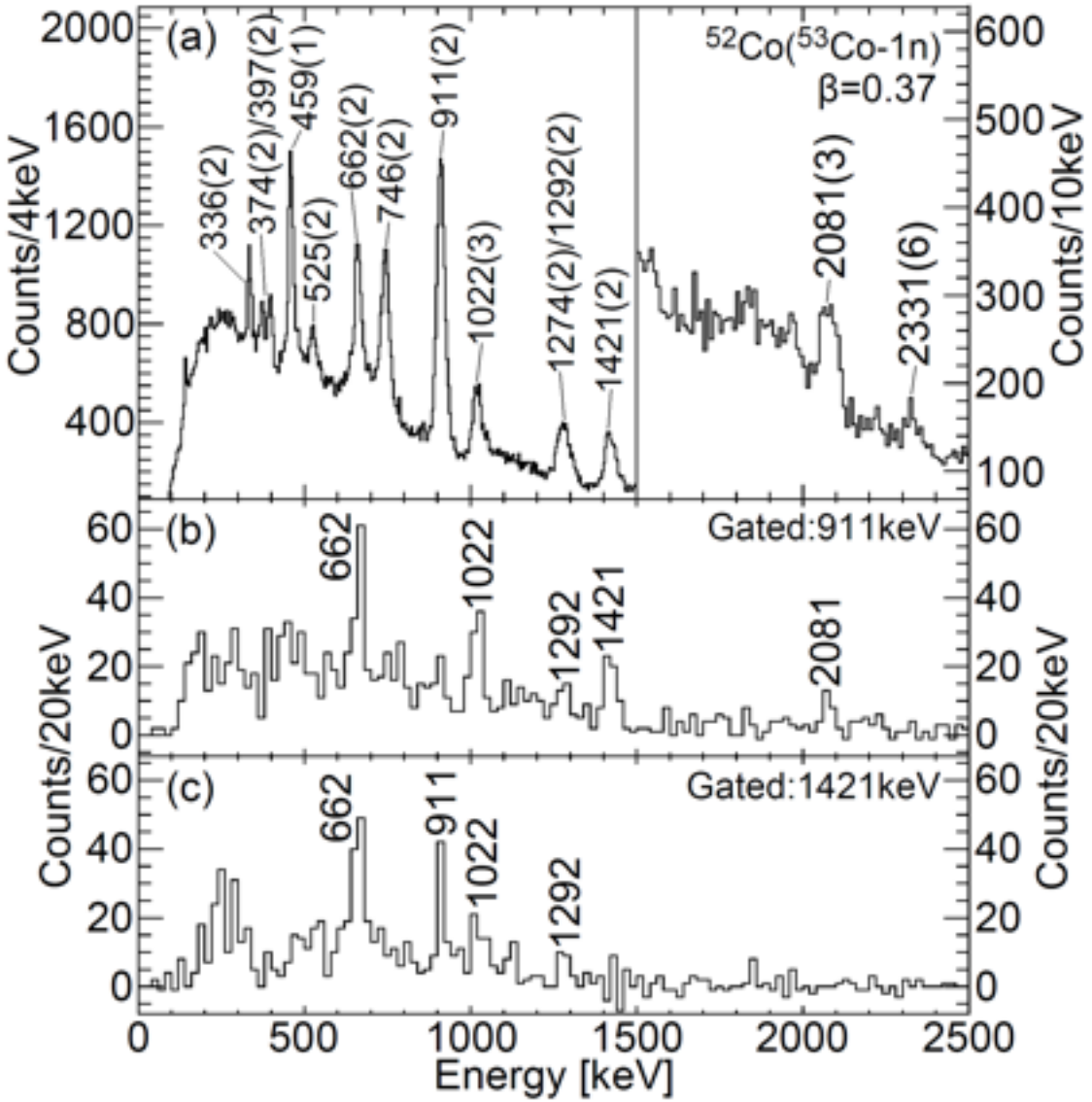
1n knockout $^{53}Co \xrightarrow{1n} {}^{52}Co$

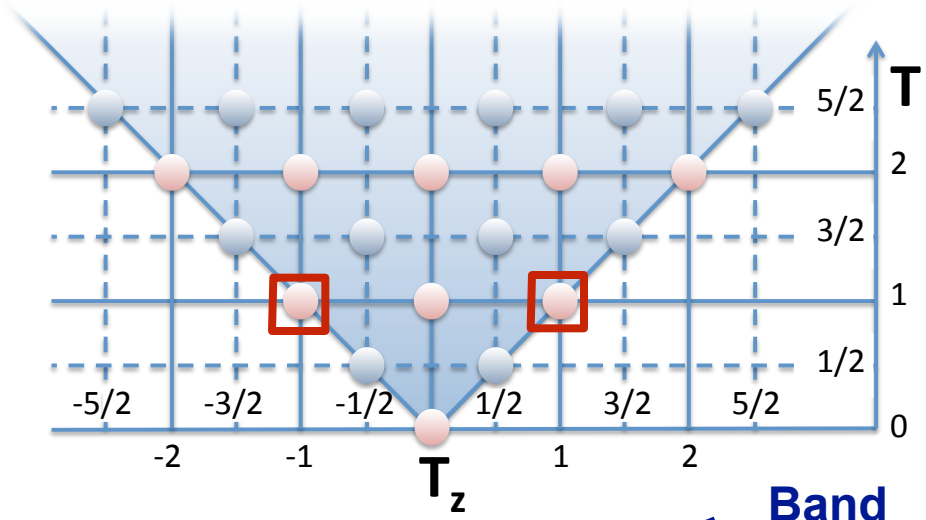
S.A.Milne et al (York), submitted to PRL



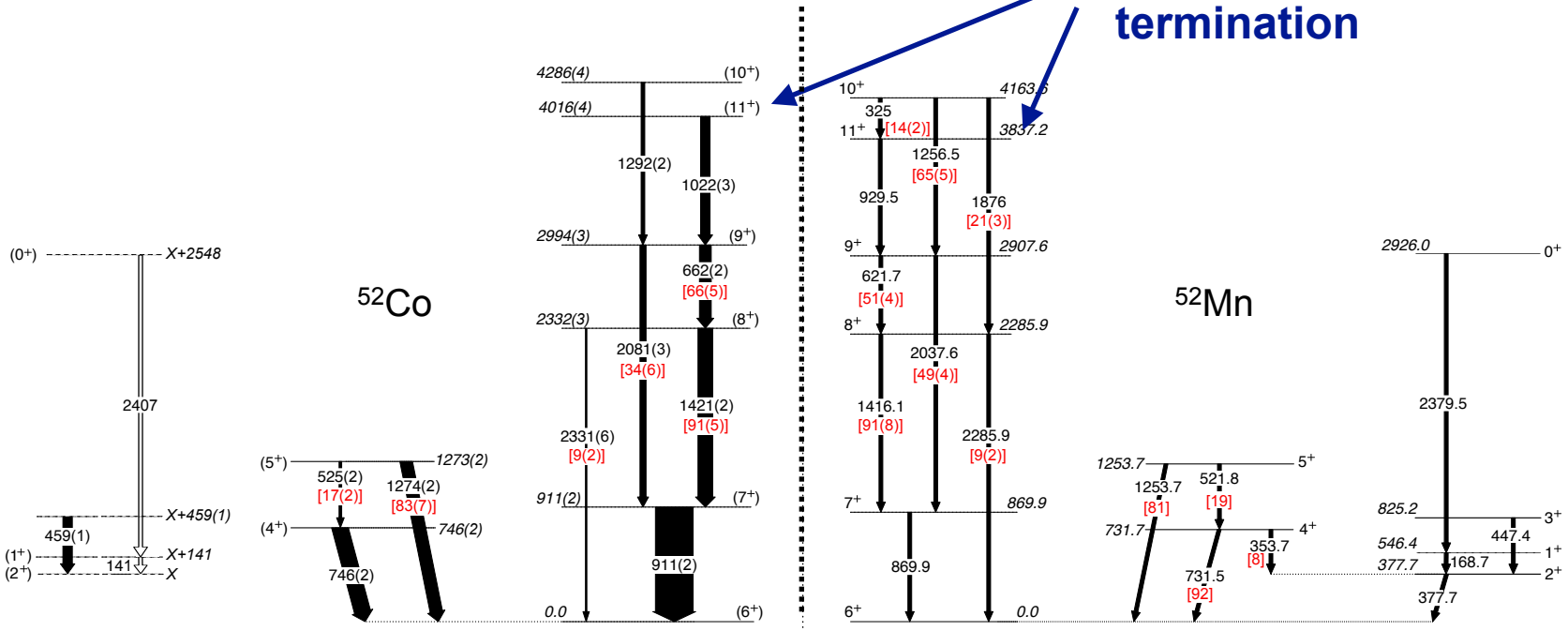


S. E. A. ORRIGO *et al.* PHYSICAL REVIEW C **93**, 044336 (2016)

Odd-odd T=1 mirror nuclei – ^{52}Co and ^{52}Mn



Band termination



Odd-odd T=1 mirror nuclei – ^{52}Co and ^{52}Mn

^{52}Co - knockout from ^{53}Co 7/2$^-$ g.s?

^{53}Co^m: A PROTON-UNSTABLE ISOMER†

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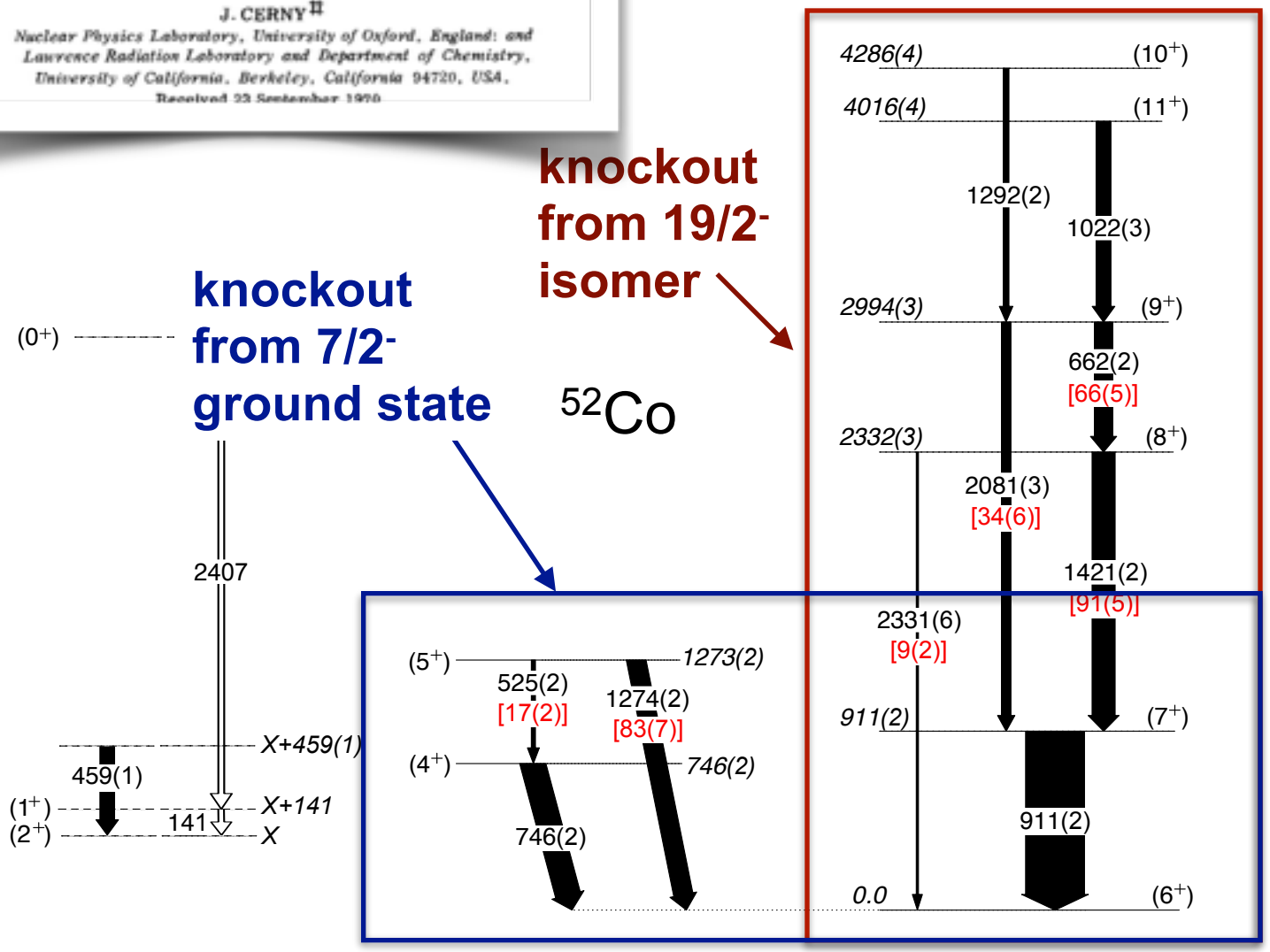
Received 23 September 1970

Phys. Lett. B33 (1970) 281

knockout from 19/2$^-$ isomer

knockout from 7/2$^-$ ground state

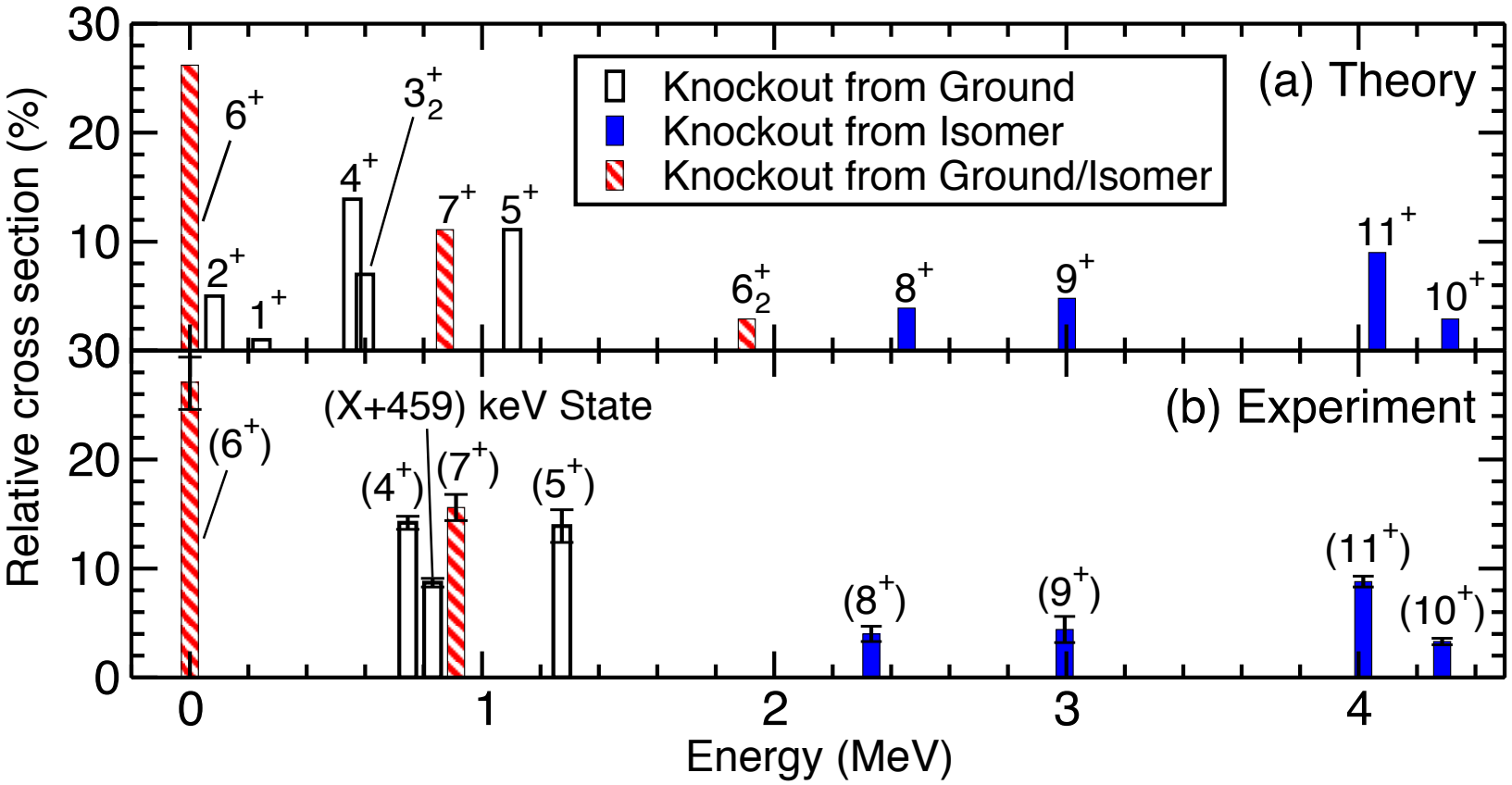
^{52}Co



Odd-odd T=1 mirror nuclei – ^{52}Co and ^{52}Mn

^{52}Co - knockout from ^{53}Co $7/2^-$ g.s. and $19/2^-$ isomer...

Theoretical cross sections from
E.C.Simpson (ANU)



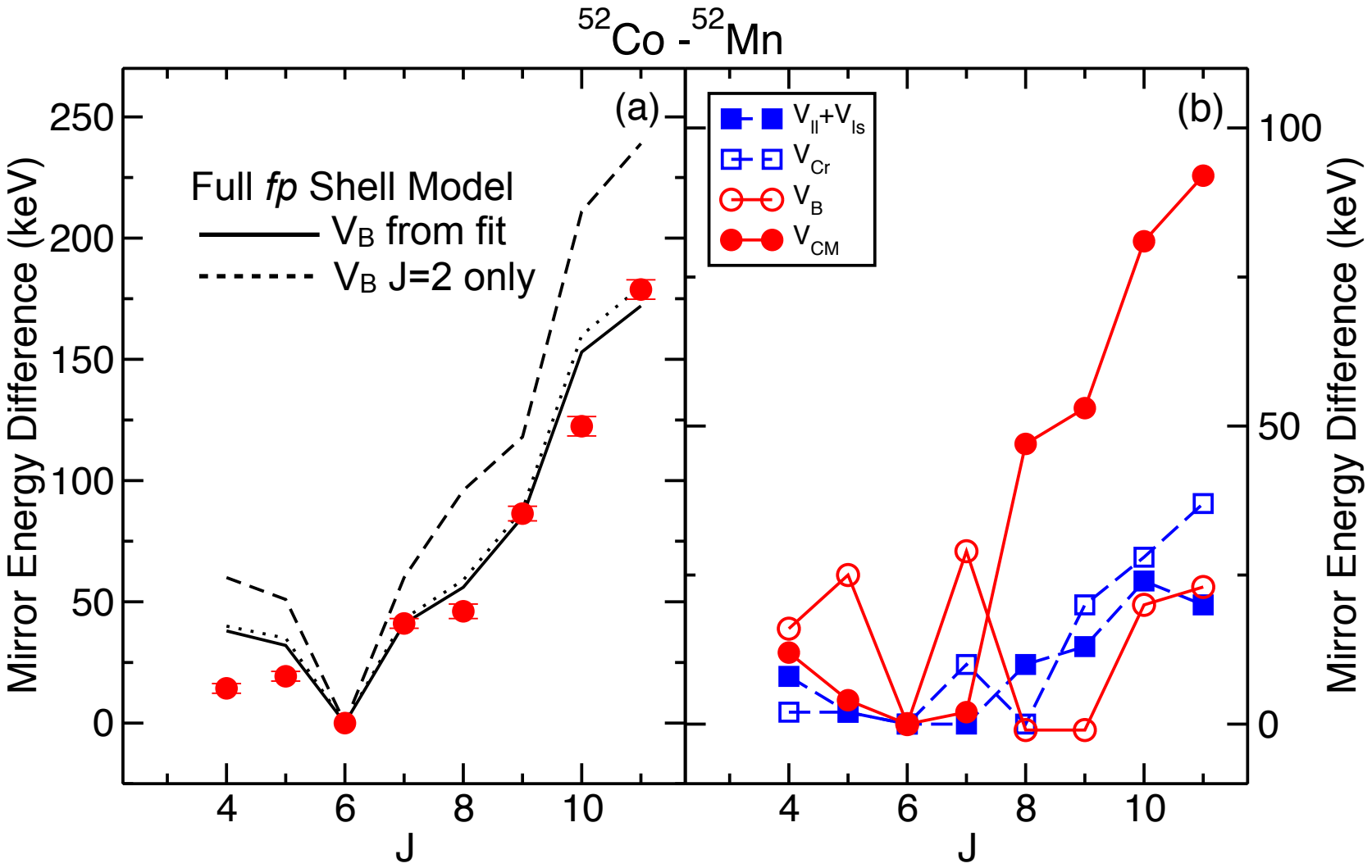
Spectroscopic factors from *fp*-shell model

- **Isomeric ratio: ~27%** (from theory vs expt branching)

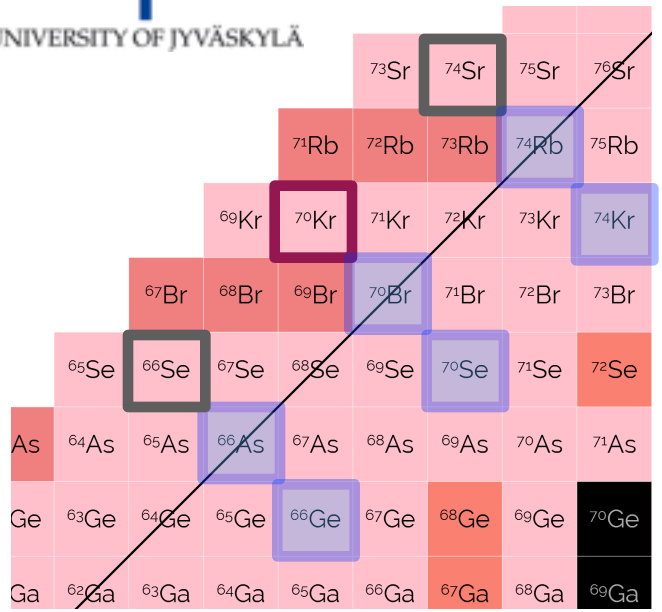
Odd-odd T=1 mirror nuclei – ^{52}Co and ^{52}Mn

- V_B term for J=2 not good enough
- New V_B parameters excellent
- Total V_B effect small!

S.A.Milne et al, *submitted PRL*

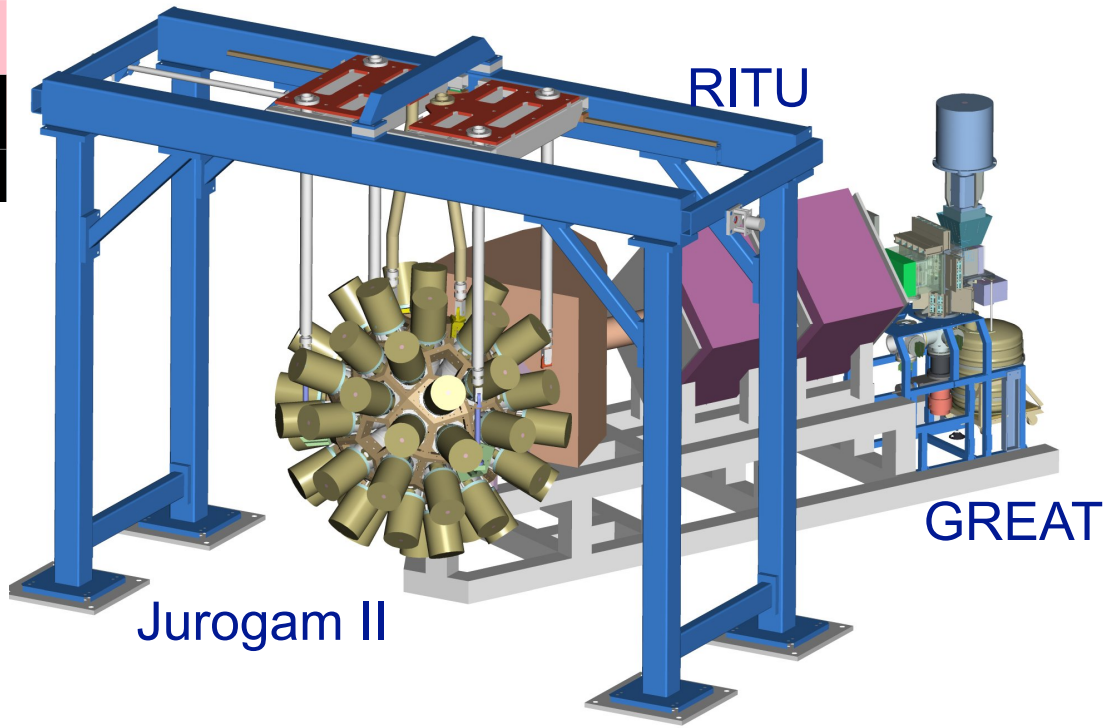


Triplet energy differences for A=70



- T=1 isospin triplets with A=66 and 74:
- **New spectroscopy of proton-rich ^{70}Kr**

^{40}Ca(^{32}S,2n)^{70}Kr @ 88MeV



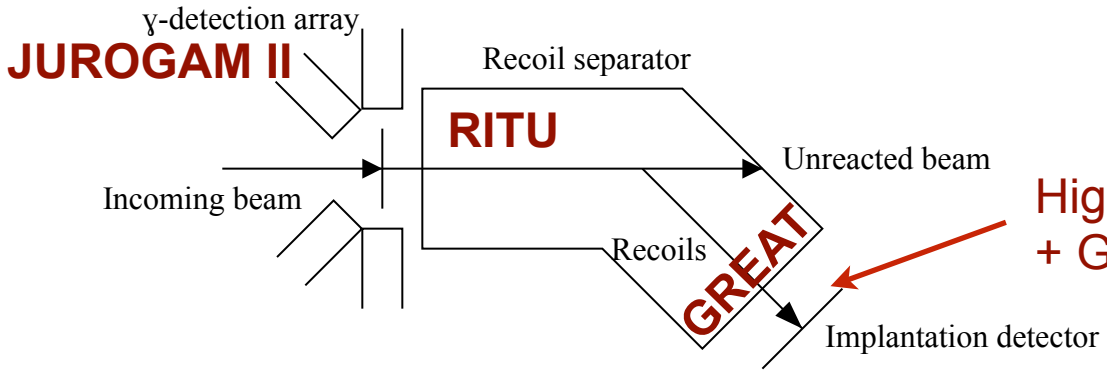
Jurgoam II +
RITU +
GREAT +
UoYTube

Technique of Recoil-Beta Tagging

A.N. Steer et al, NIMA 565 (2006) 630

Triplet energy differences for A=70

Tiny cross-sections: need to find **(a) unique detection signature** and **(b) method of suppression of unwanted channels.**



Highly pixellated DSSSD + Ge Planar

UoY Tube

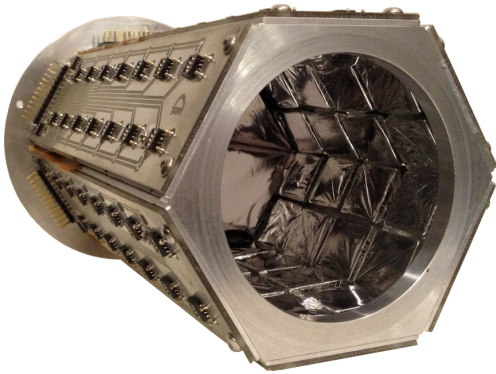
Signature = **fast beta-decay** and **high-energy betas** from super allowed decays between analogue states,

Channel of interest = **2n, pn**
Primary contaminants **= 3p,2p, …**

= Recoil-Beta Tagging
A.N. Steer et al, NIMA 565 (2006) 630

Used already in:
^{78}Y: Nara Singh et al, PRC75(2007)061301
^{66}As: Ruotsalainen et al, PRC88(2013)024320
and
^{62}Ga: David et al, PLB726(2013)665

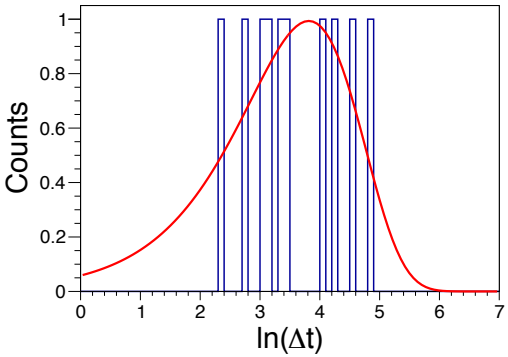
UoYTube:
- 100 CsI elements
- 75% single proton efficiency
- 98% 3p veto efficiency (for 2n analysis)



J. Henderson *et al.* JINST **8** (2013)

Triplet energy differences for A=70

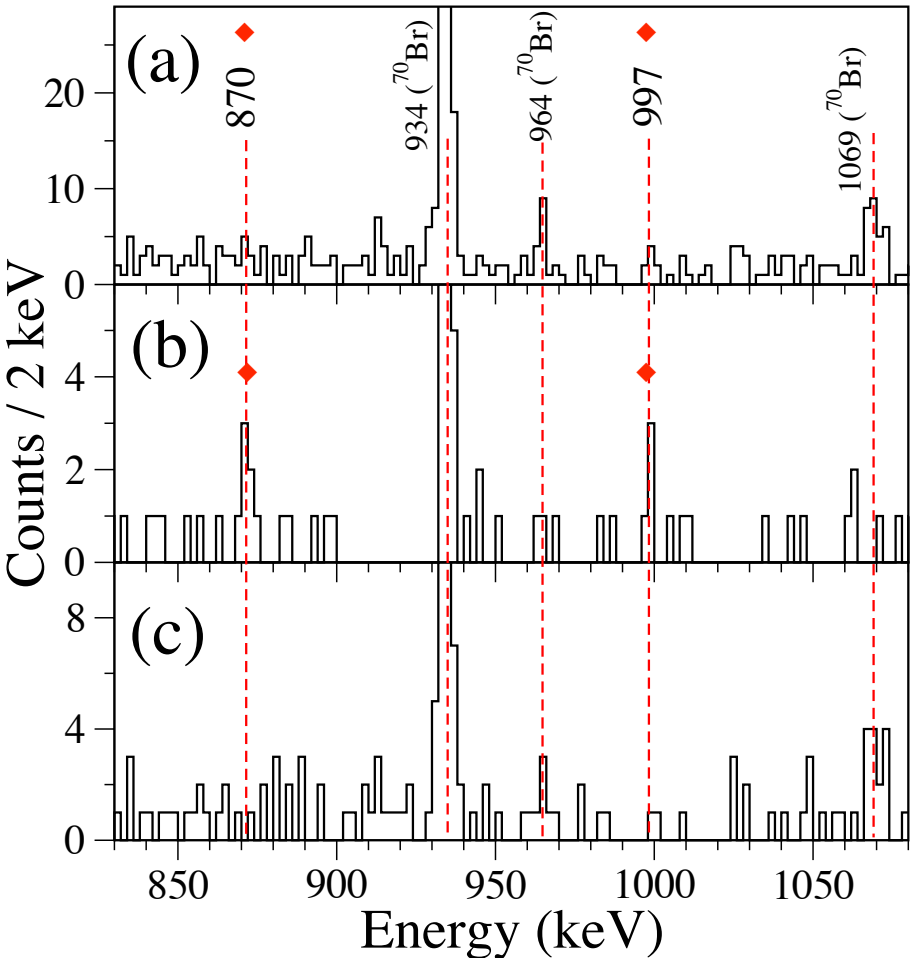
Gate on 870 + 997-keV gammas



$T_{1/2}$ = 33(15) ms (cf 40(6) ms for ^{70}Kr

^{70}Br: De Angelis et al, EPJ A12 (2001) 51

Identification of 2^+ and 4^+ states in ^{70}Kr:



Recoil-Beta tagged+ UoYTube c.p. veto

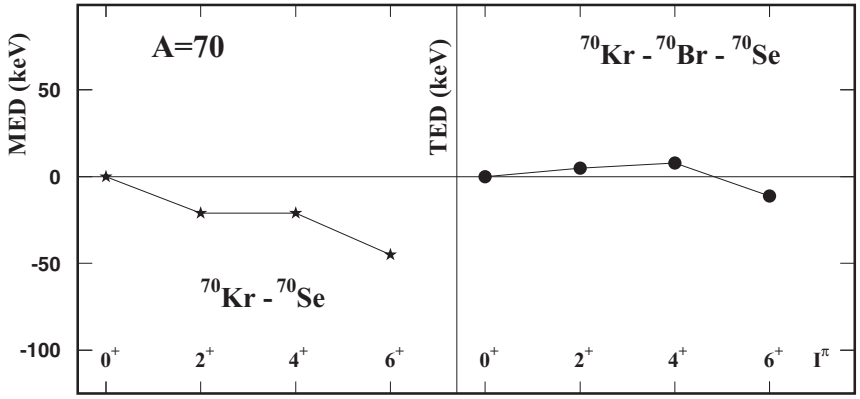
+ additional DSSSD cuts

one c.p. in UoYTube

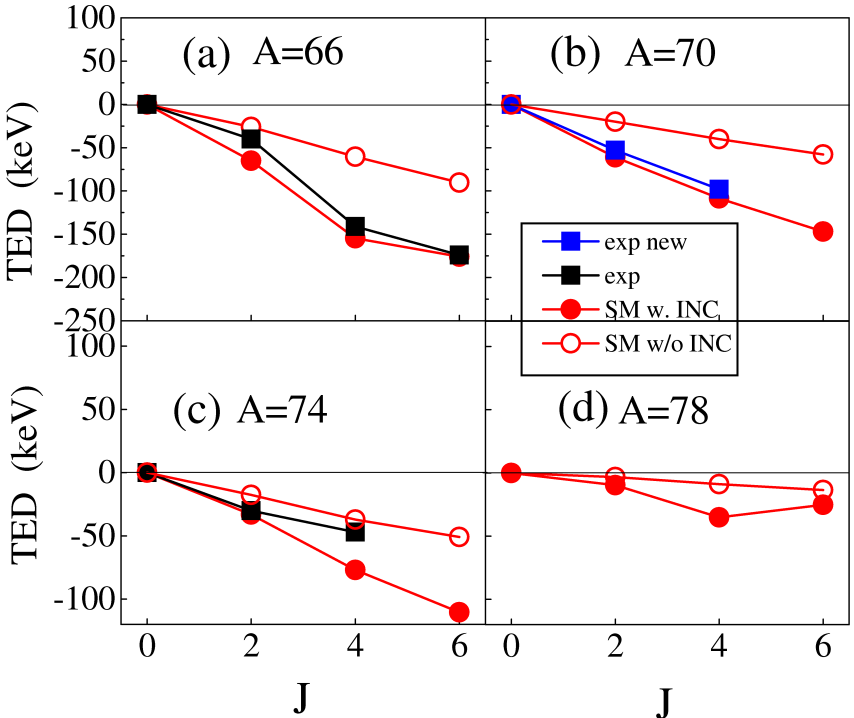
Triplet energy differences for A=70

Shape coexistence in A ~ 70 ⟶ Breakdown of symmetry across triplet?

e.g. De Angelis et al, PRC85(2012)034320



EXCITED VAMPIR model
A.Petrovici *et al.*
Phys Rev C91 (2015) 014302



Shell-model work (in parallel) by Kaneko *et al.*
Phys Rev C89 (2014) 031302(R)

- $pf_{5/2}g_{9/2}$ model space
- JUN45 interaction
- same methodology as $f_{7/2}$ shell

- **Includes isotensor INC of +100keV (J=0)**

Conclusions...

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Summary:

- Knockout reactions very effective tool for probing proton-rich systems
- Recoil-beta tagging highly effective for studies on N=Z line
- Strong J-dependent INC interactions present in $f_{7/2}$ shell (both isovector and isotensor)
- No evidence for breakdown in symmetry across A=70 triplet

- **Isotensor INC**

$$V^{(2),J} = V^J_{pp} + V^J_{nn} - 2V^J_{np}$$

(a) **consistent** across mass regions and
(b) in line with NN scattering data (i.e. ***np* stronger than *pp* and *nn***)

- **Isovector INC**

$$V^{(1),J} = V^J_{pp} - V^J_{nn}$$

(a) clear in $f_{7/2}$ shell
(b) has strong J-dependence
(c) harder to find consistency elsewhere, **but work underway….**

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With special thanks to…

Most importantly
Scott Milne (MSU Analysis) - York
Dawn Debenham (JYFL Analysis) - York
Silvia Lenzi (Padova, shell model),
Ed Simpson and Jeff Tostevin (ANU/Surrey, knockout calculations)
Alexandra Gade (NSCL lead)

and
NSCL team in Michigan

NSCL

and
JYFL team

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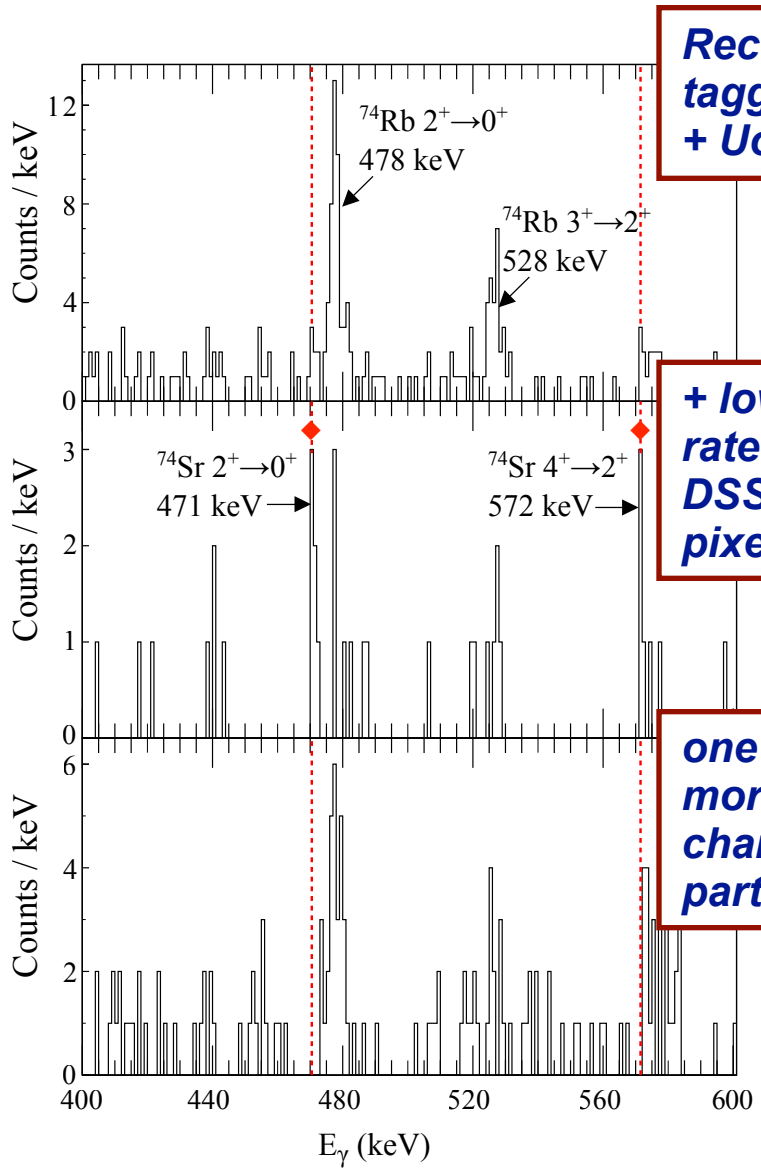
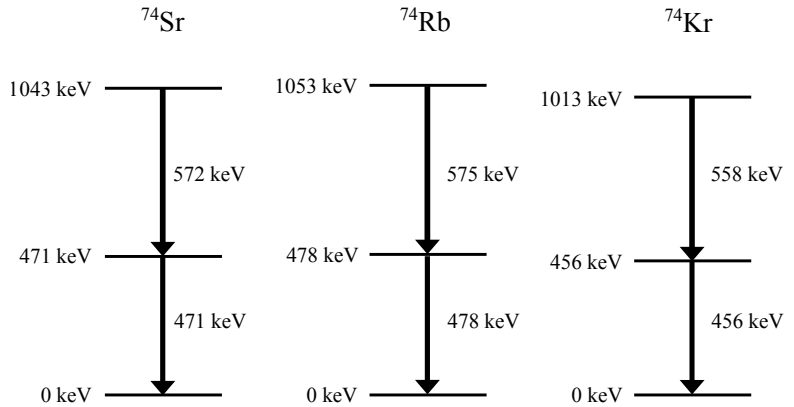
Triplet energy differences in A=74

J. Henderson et al., Phys. Rev. C 90, 051303(R) (2014)

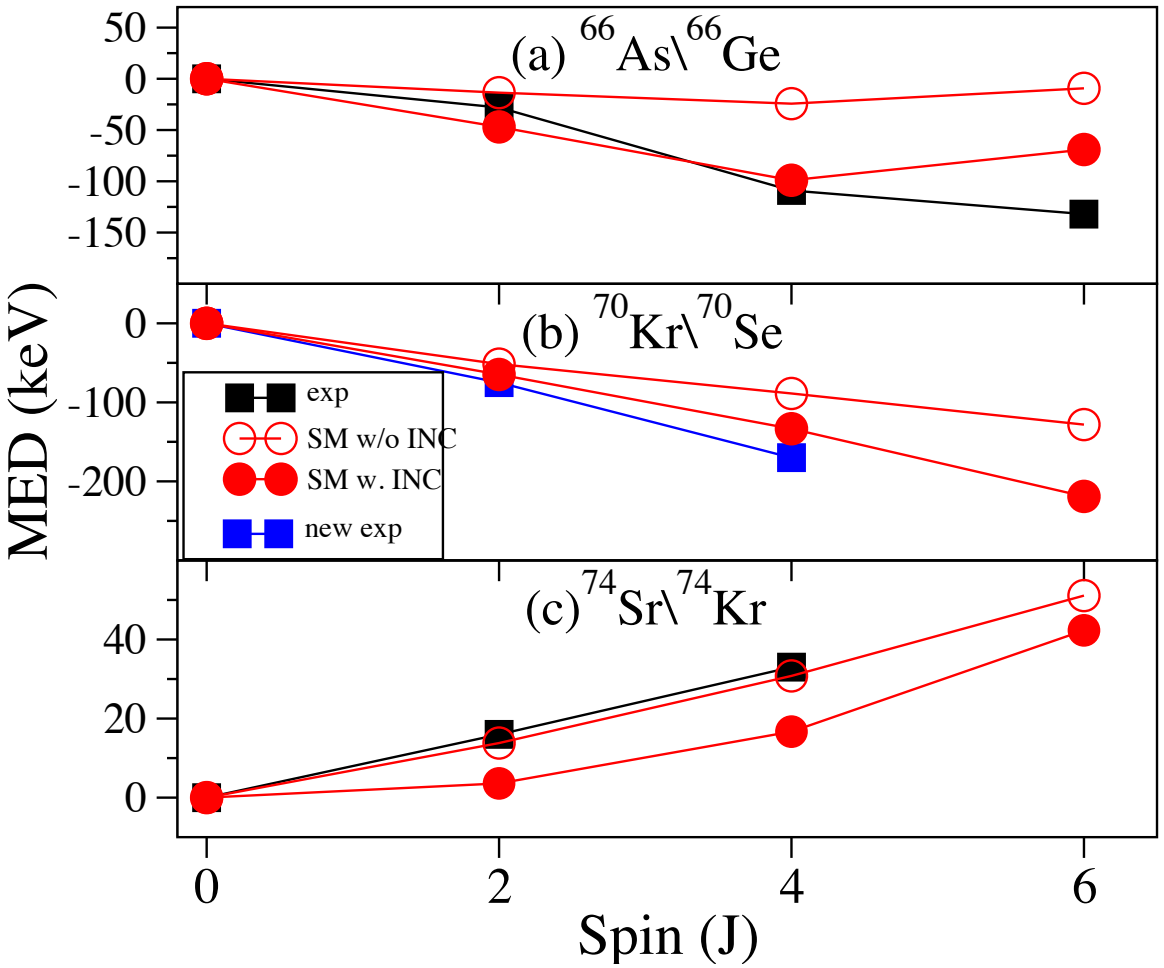


- Half-life ^{74}Sr g.s. measured at **30(3)ms** (RIKEN recent result)*
- Half-life for beta decays associated with 471keV = **27(8)ms**

*RIKEN: L.Sinclair et al, to be published.

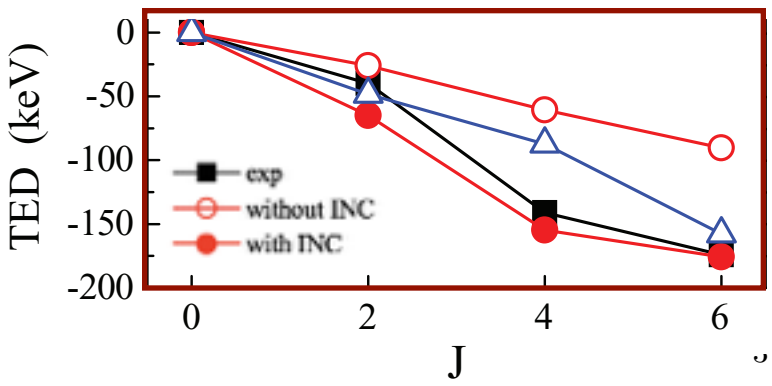


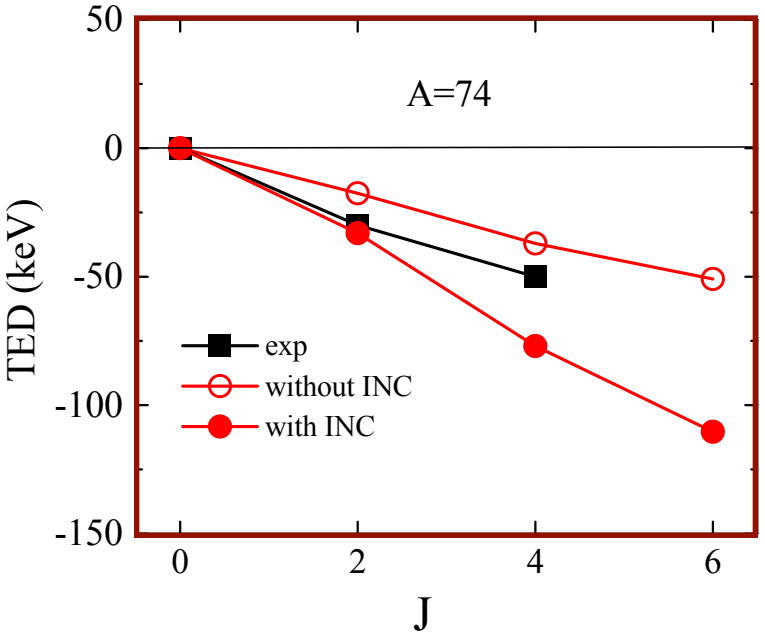
Mirror energy differences in A=70



- INC interaction (isovector) = +300 keV (J=0)
- inconsistent with lighter nuclei in $f_{7/2}$ shell

Triplet energy differences in A=66&74





^{66}As: De Angelis et al, PRC85(2012)034320
^{66}As: Ruotsalainen et al, PRC88(2013)024320

***^{66}Se**: Ruotsalainen et al, PRC88(2013) 041308*
***^{66}Se**: Obertelli et al. PLB701(2011)417*

Shell-model work by Kaneko *et al.*
Phys Rev C89 (2014) 031302(R)

- *$pf_{5/2}g_{9/2}$* model space
- JUN45 interaction
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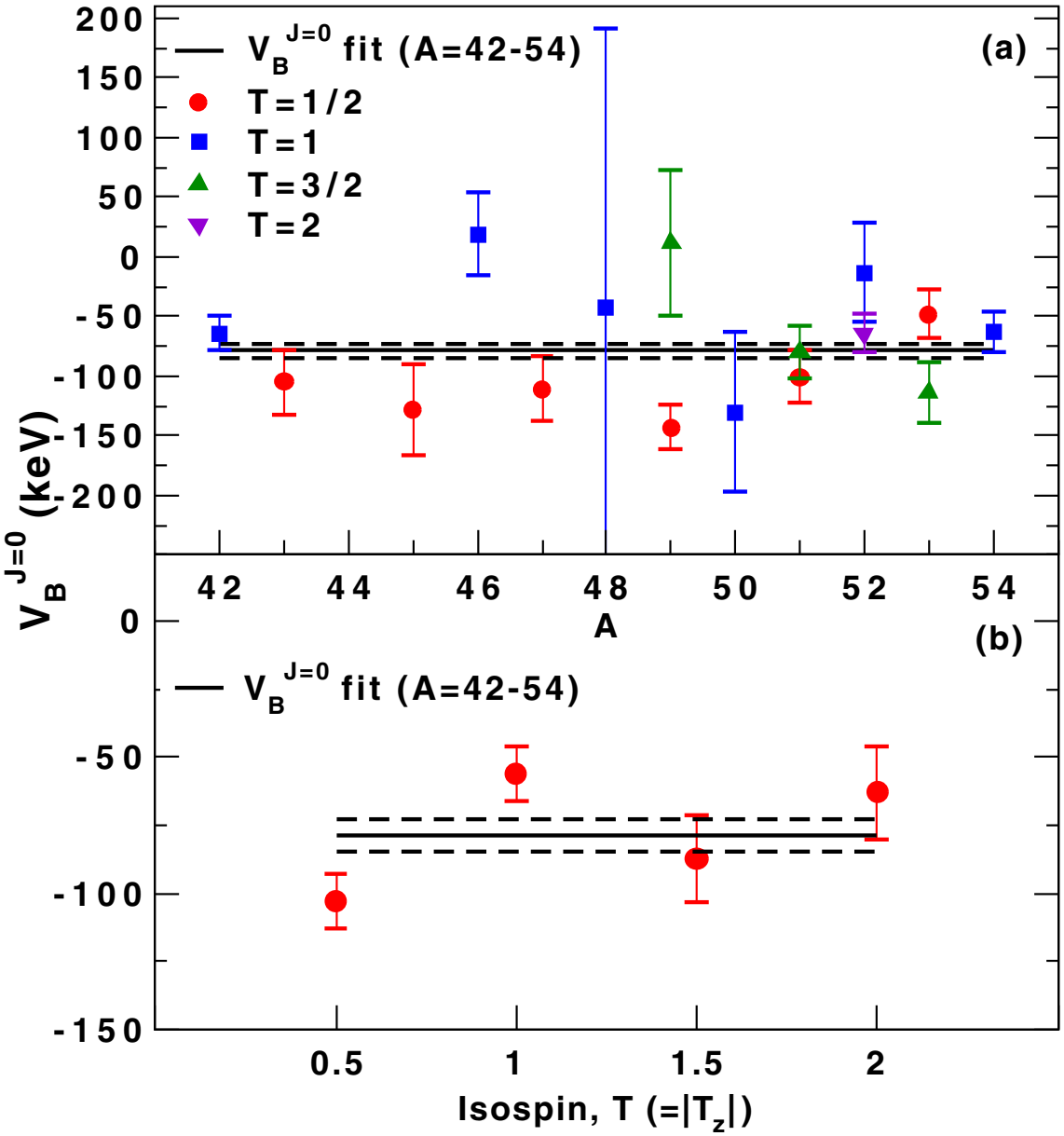
- **Includes isotensor INC of +100keV (*J=0*)**

What can we learn about effective INC interactions?

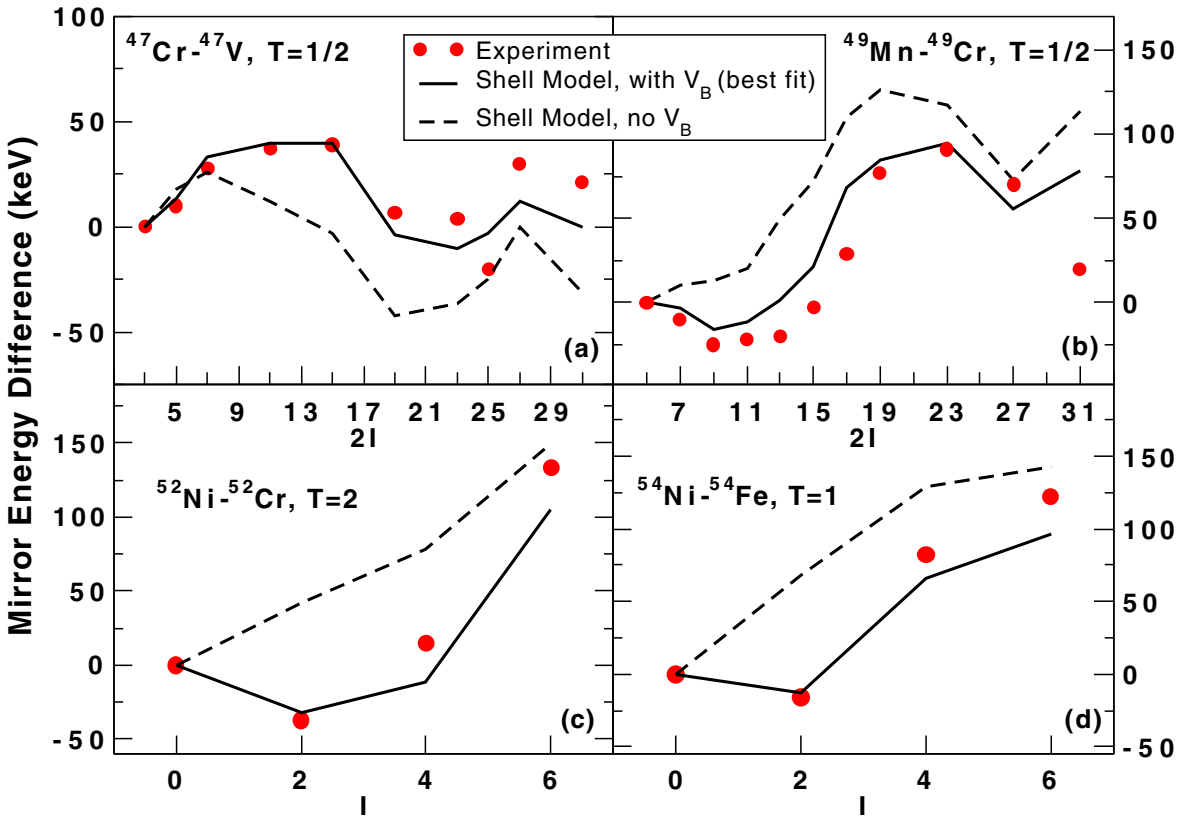


Bentley et al., Phys. Rev. ***C92*** *024310 (2015)*

What can we learn about effective INC interactions?

Range	$f_{7/2}$ matrix elements V_B^J (keV)				rms deviation	
J =	**0**	**2**	**4**	**6**	fit	No V_B
		One-parameter fit				
$A = 42$–54	–	68(6)	–	–	32	41
$A = 42$–54	−79(6)	–	–	–	26	41
		Full fit				
$A = 42$–54	−79(16)	25(13)	1(12)	−19(12)	23	41

Fit across $f_{7/2}$ shell - 93 excited states



- 17 mirror pairs in $f_{7/2}$ shell
- All MED for all excited states, except core-excited states

Bentley et al., Phys. Rev. ***C92*** *024310 (2015)*