

Isospin Triplets studied using fragmentation beams: *HISPEC(-type) experiments*

Mike Bentley

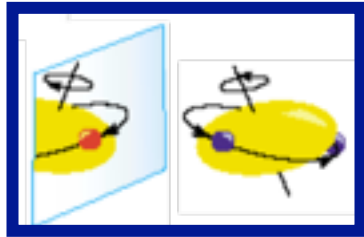
University of York, UK

- **Introduction**
- **HISPEC-type 'techniques'**
- **Lifetime and Coulex measurements in the A=46 triplet (GSI-AGATA) - a pre-HISPEC experiment**
- **Spectroscopy of A=62 Triplet (^{62}Ga studied as NSCL)**
- **Some thoughts on knockout and HISPEC**



Isospin Symmetry and Isospin Breaking

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

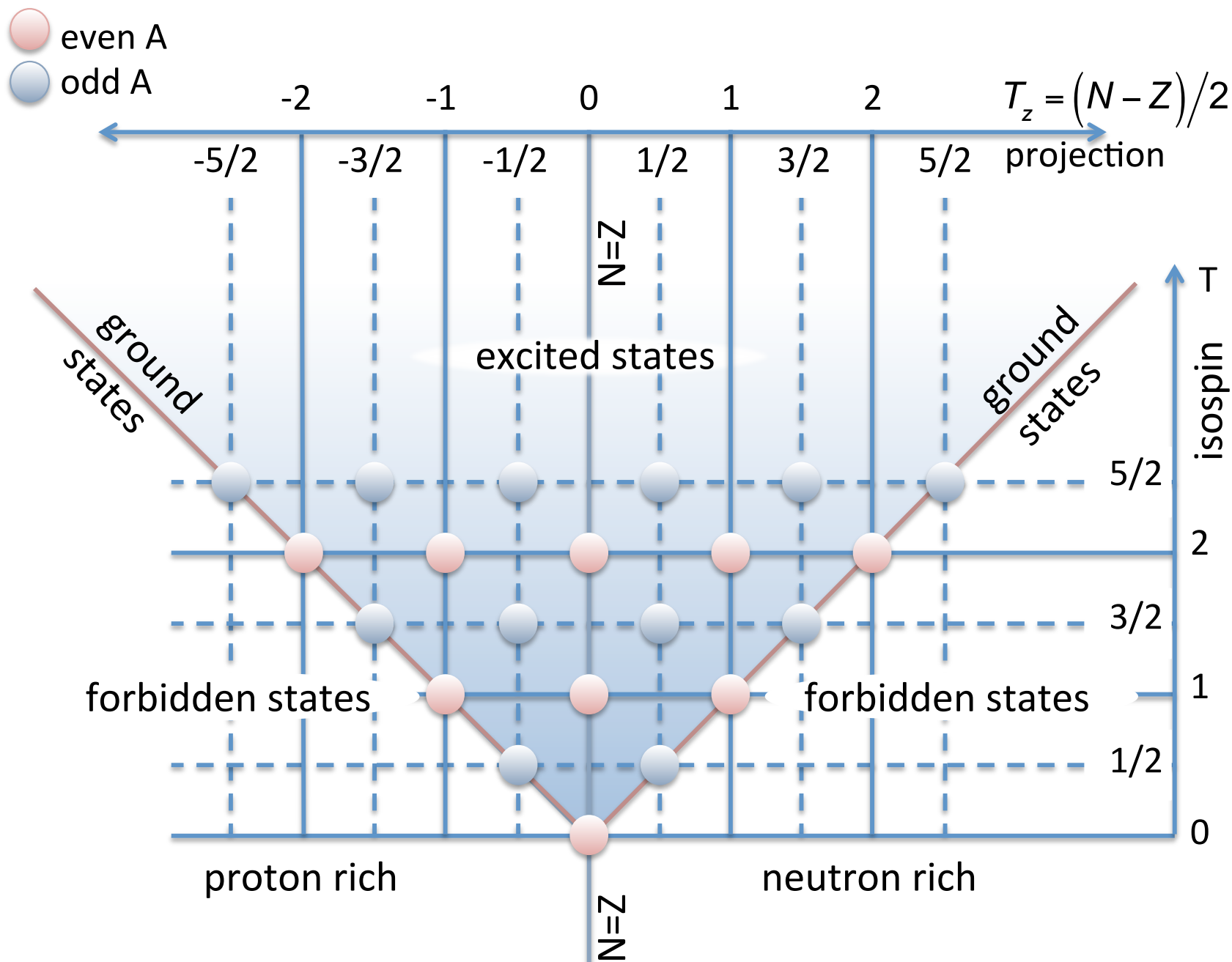
$$V^{(2),J} = V_{pp}^J + V_{nn}^J - 2V_{np}^J$$

Isotensor interaction

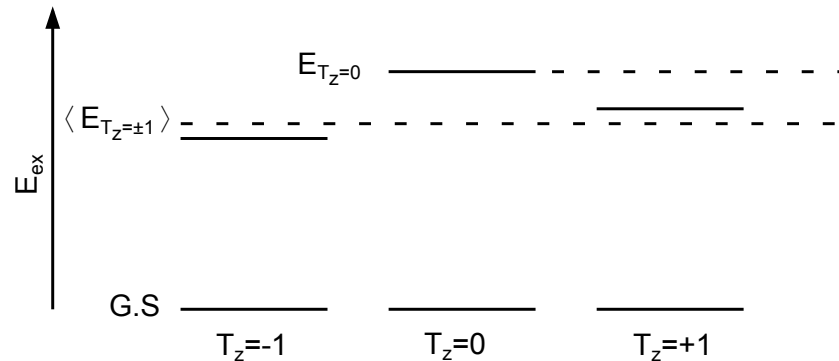
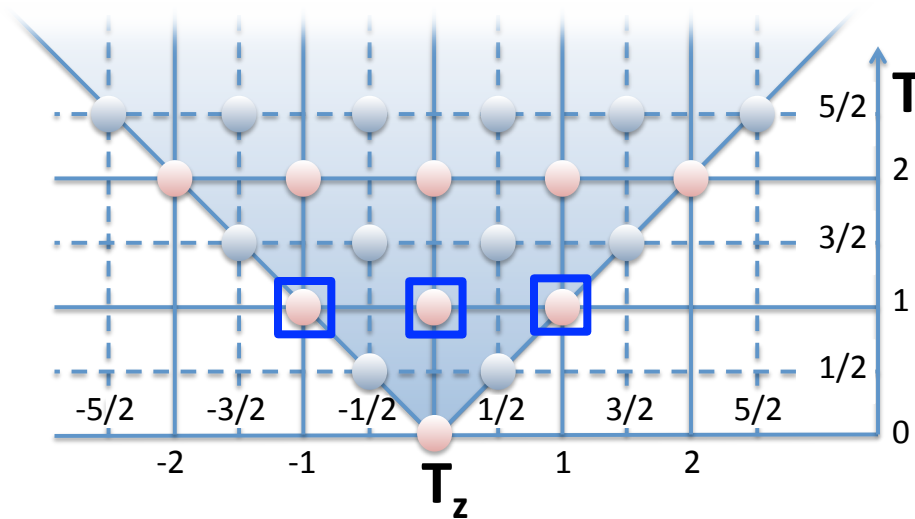
Probed in mirror nuclei (MED)

Probed in T=1 triplets (TED)

Isobaric Spin (Isospin)



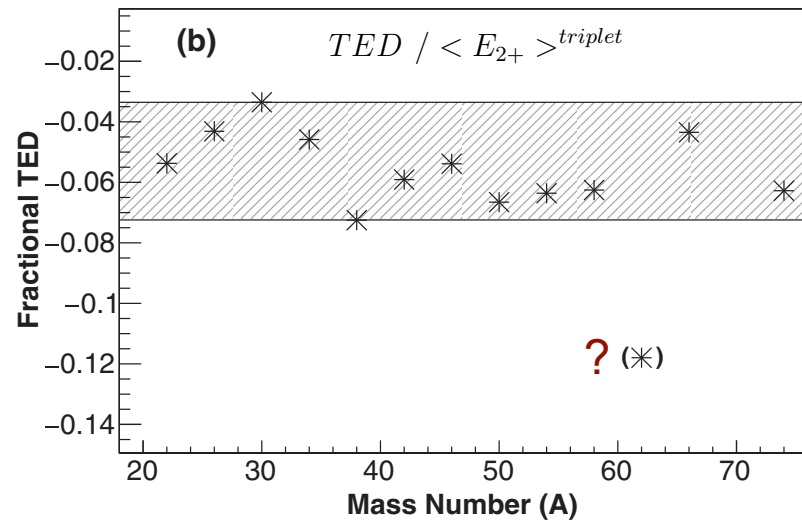
T=1 isospin triplets



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

TED are:

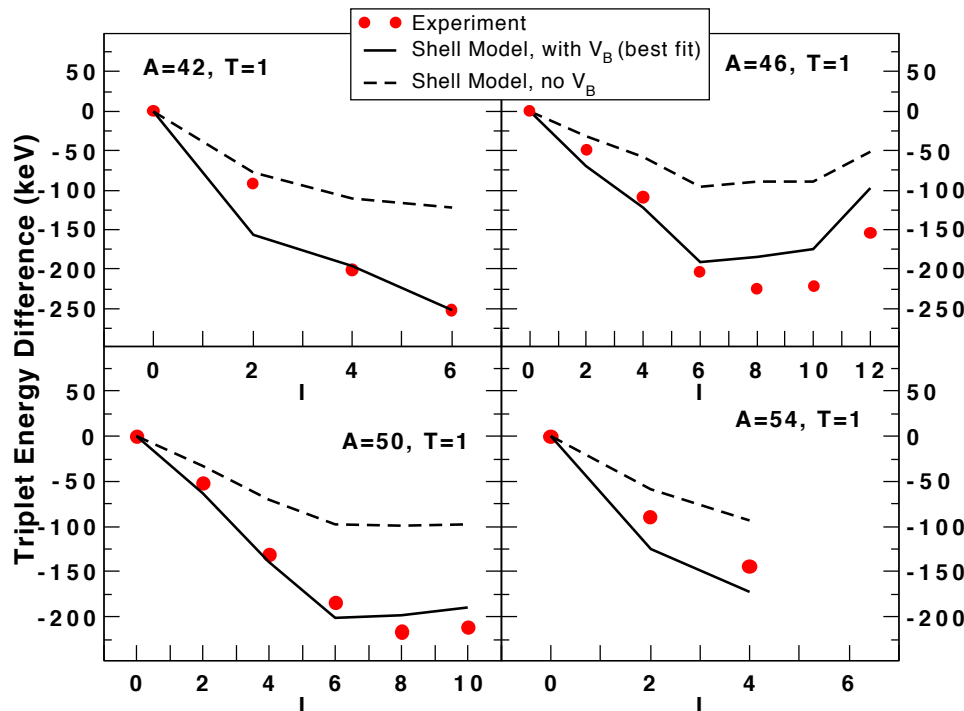
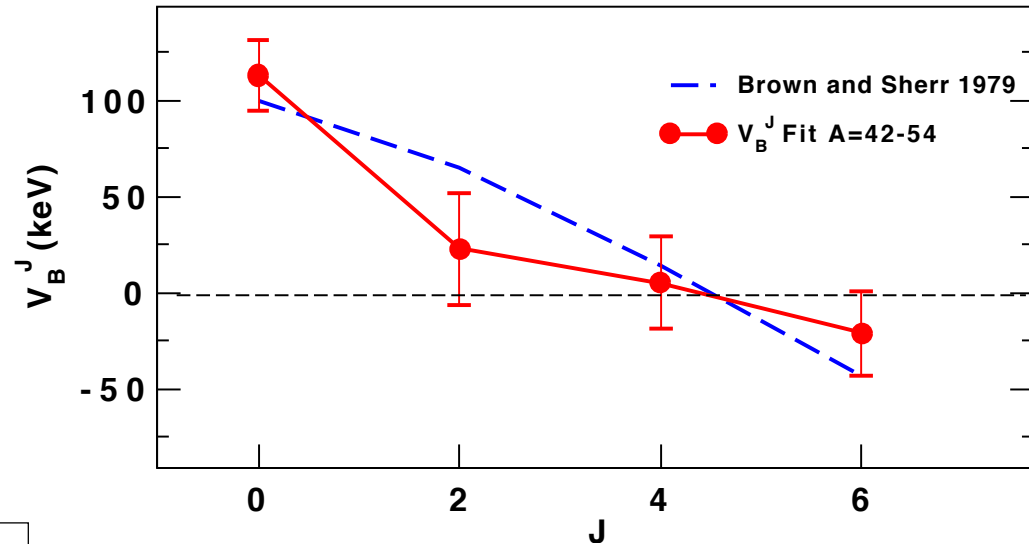
- **Very** sensitive to details of two-body interaction
- **Isotensor** in nature:
- Always negative
- Remarkably **consistent**....



$$V^{(2),j} = V_{pp}^j + V_{nn}^j - 2V_{np}^j = V_C^{(2),j} + \boxed{V_B^{(2),j}}$$

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

- **TEDs:** Zuker et al, PRL 89 (2002) 142502
Gadea et al PRL 97 (2006) 152501
- **Displacement Energies:** Kaneko et al PRL 110 (2013) 172505

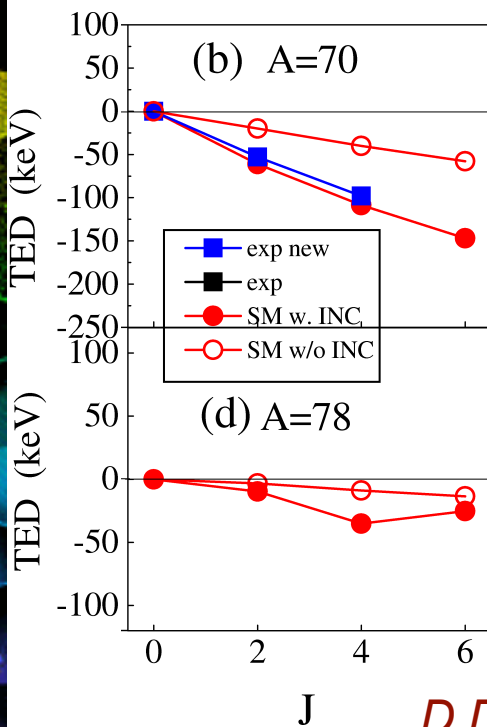
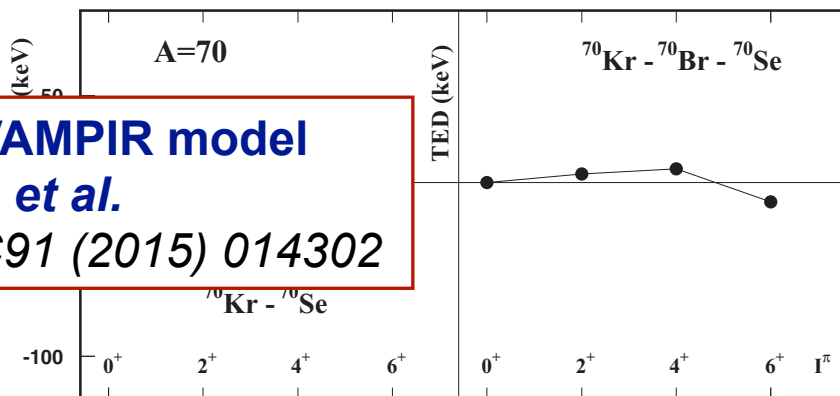


- Strong J -dependent terms (positive at $J=0$ only)
- **Consistent with NN scattering data**
- np interaction $\sim 2\text{-}3\%$ stronger than nn or pp.
- Consistent across mass regions

Triplet energy differences for A=70

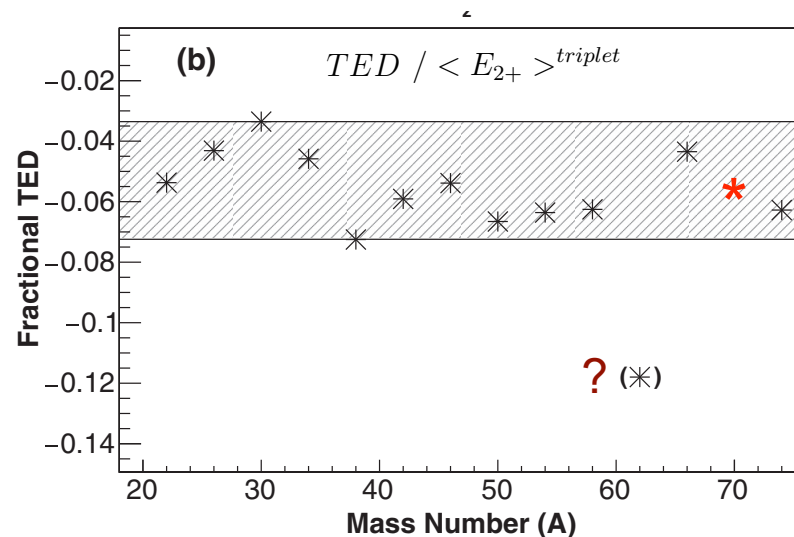
Shape coexistence in $A \sim 70 \longrightarrow$ Breakdown of symmetry across triplet?

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



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

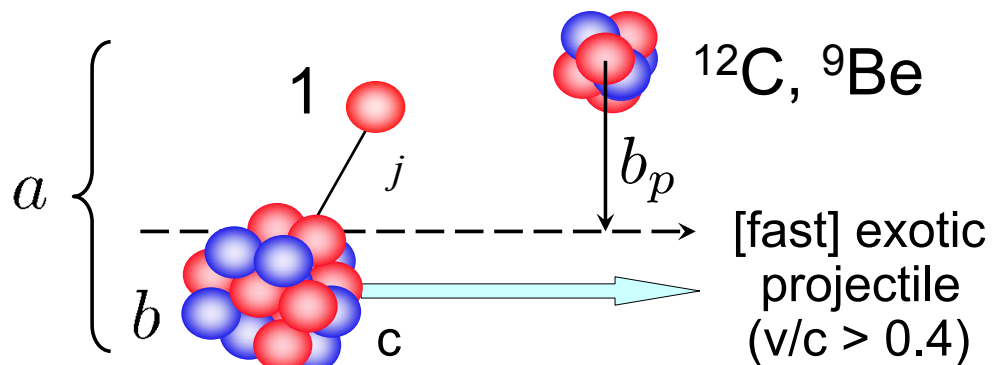
Includes
isotensor INC of
+100keV ($J=0$)



D.Debenham et al., submitted to PRC

Utilising the features of relativistic fragmentation beams...

- High velocity
- Thick targets
- Population of isomers



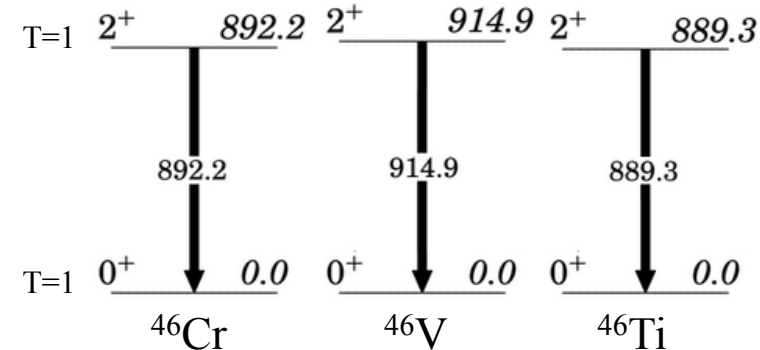
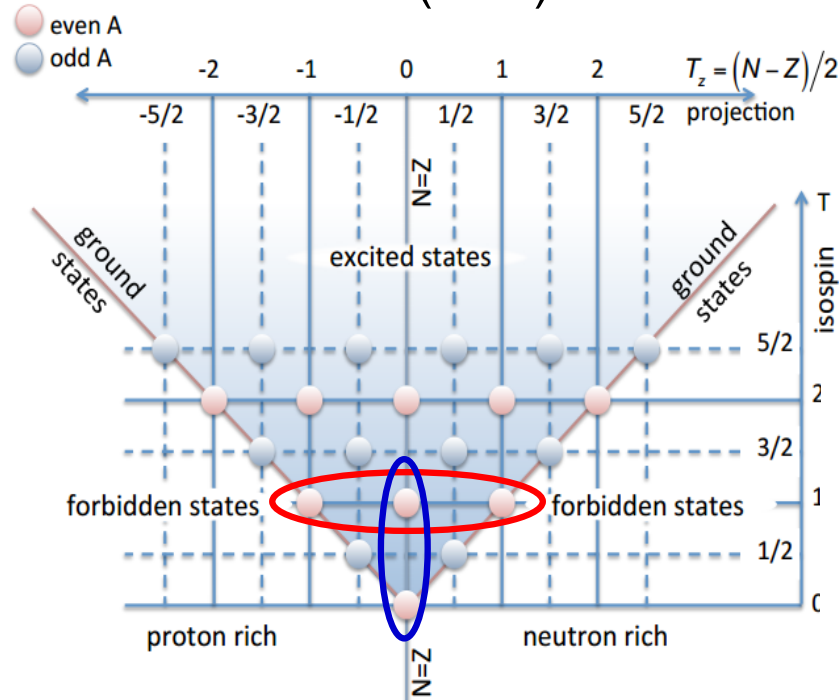
Applications to isospin-symmetry studies:

- Knockout reactions to exotic nuclei - **1n and 2n removal**
- Direct reactions on **high-spin isomers**
- Lifetime measurements through a “**stretched-target**” technique.

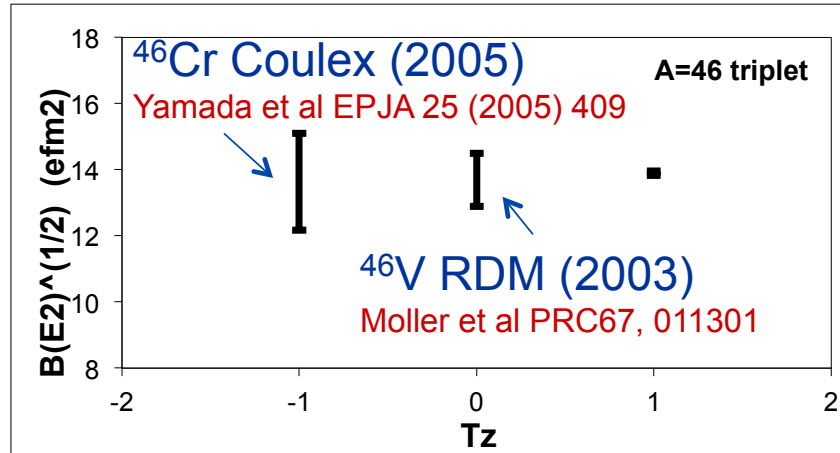
Isospin mixing in the A=46 Isobaric Triplet



AGATA-PRESPEC Experiment, April 2014 - analysis by:
Scott Milne (York) and Alberto Boso (Padova)

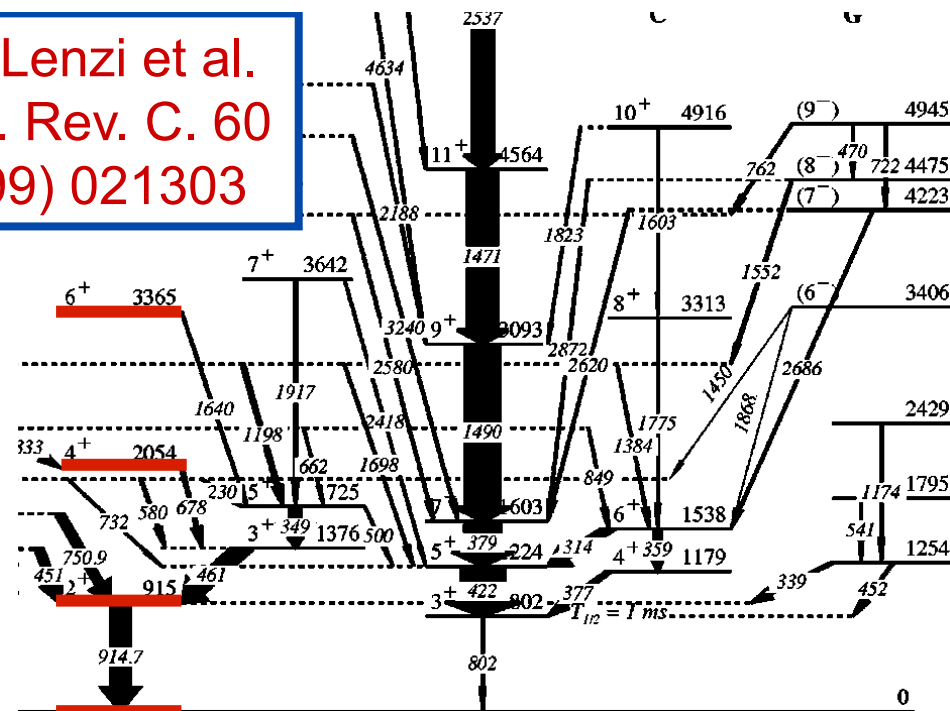


Test linearity of E2 matrix element
with T_z - isospin selection rule

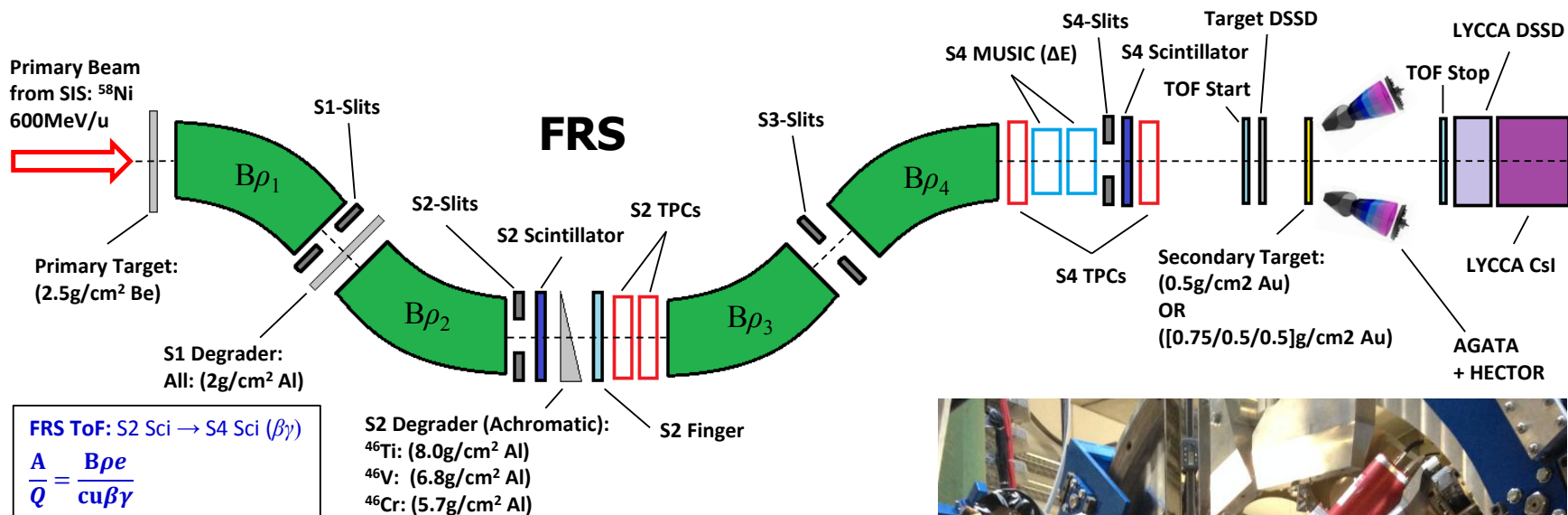


Isoscalar + isovector

- S.M.Lenzi et al.
Phys. Rev. C. 60
(1999) 021303

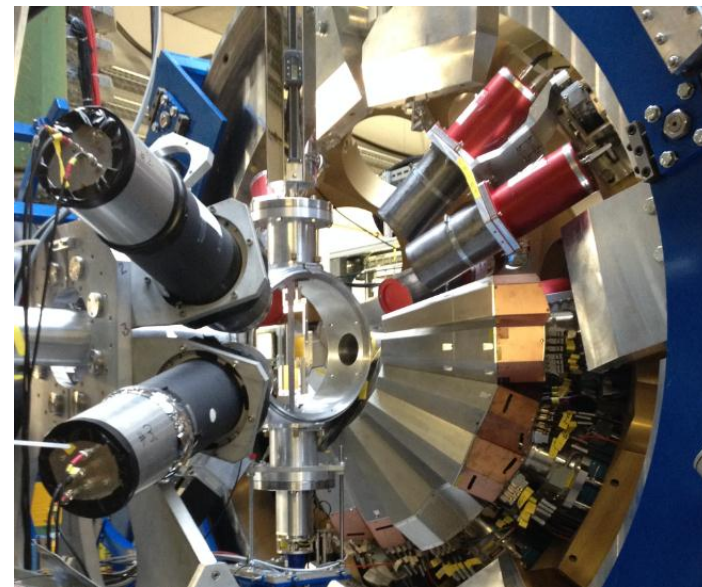
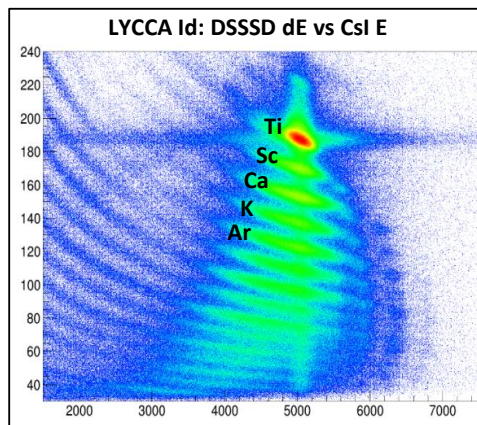
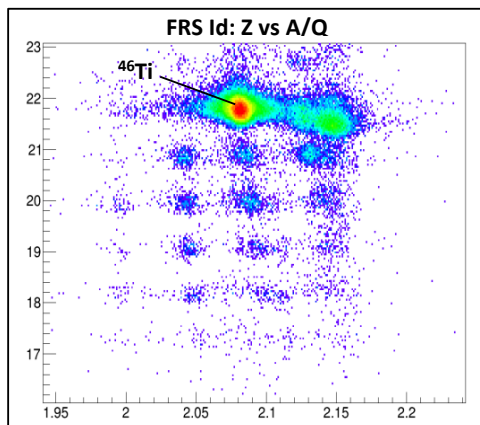


Isospin mixing in the A=46 Isobaric Triplet

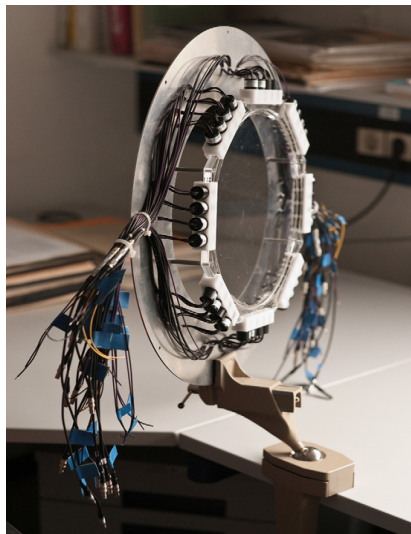
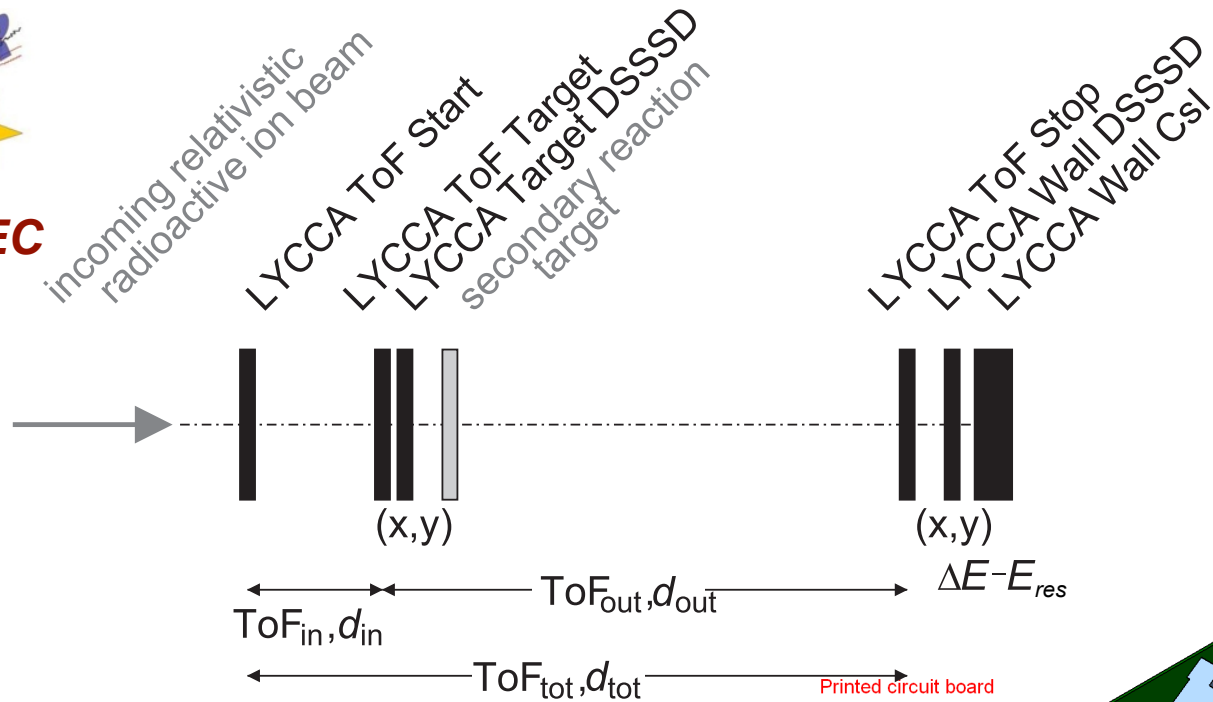


FRS ToF: S2 Sci \rightarrow S4 Sci ($\beta\gamma$)

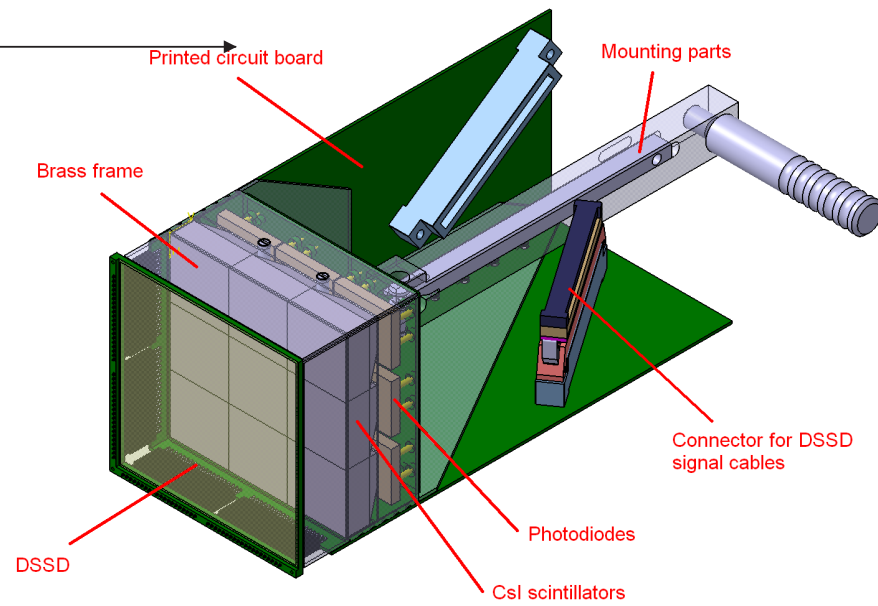
$$\frac{A}{Q} = \frac{B\rho e}{cu\beta\gamma}$$



Lund York Cologne CALorimeter

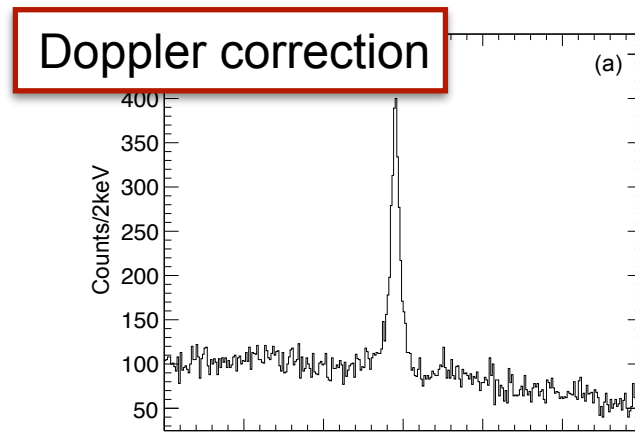
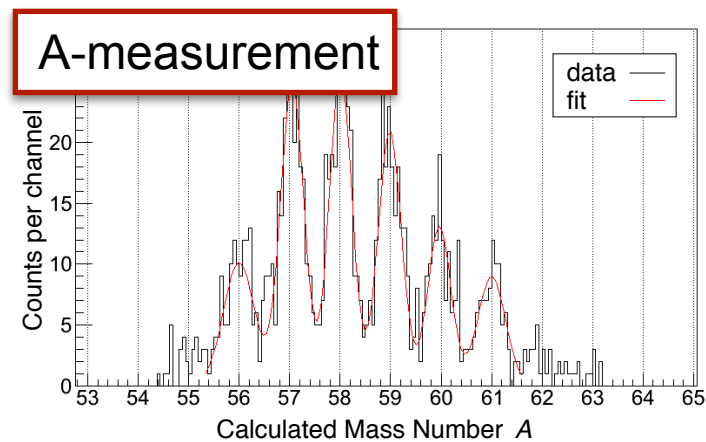
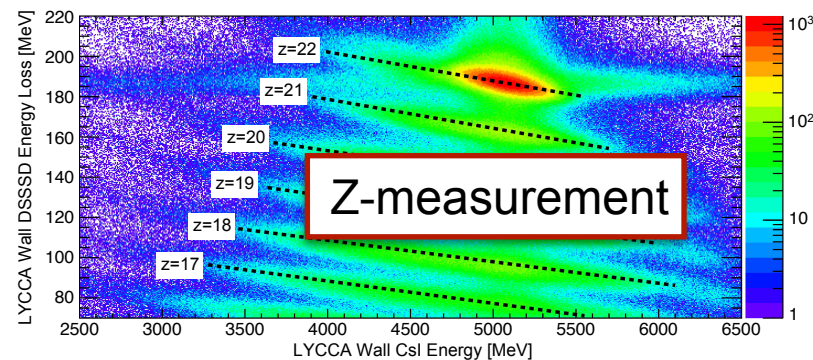
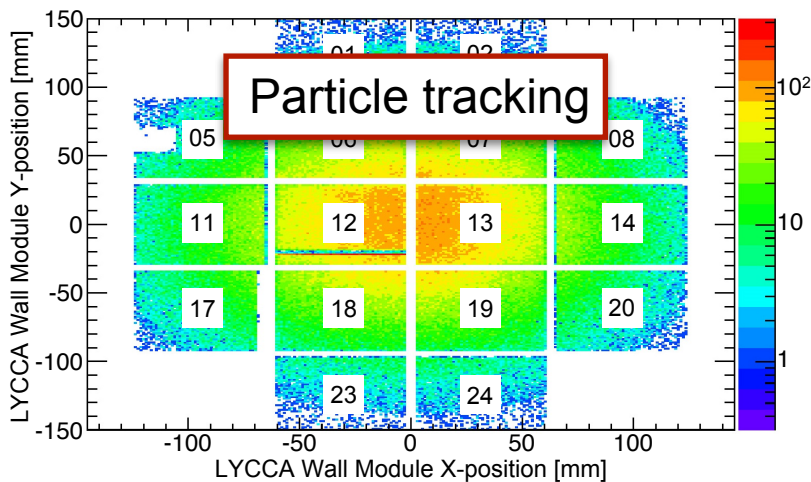
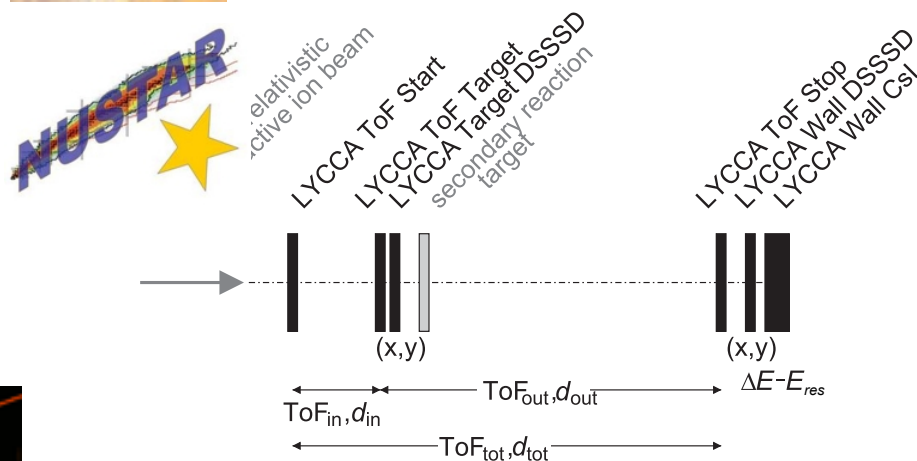


P. Golubev et al. NIMA. 723, 55-66 (2013)

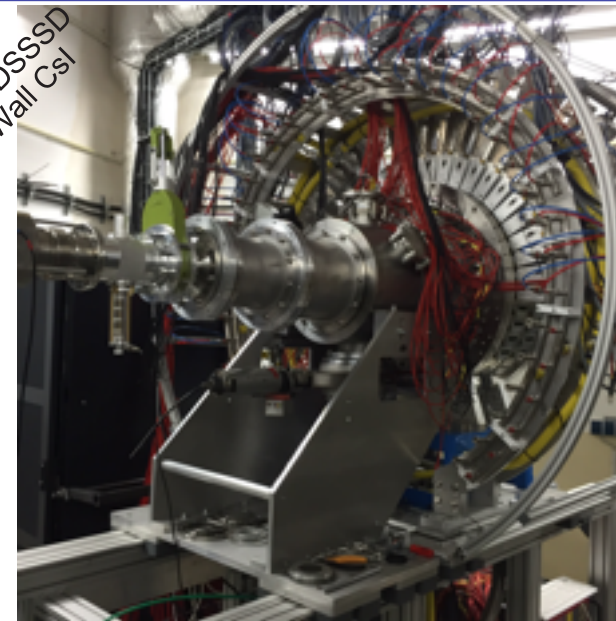
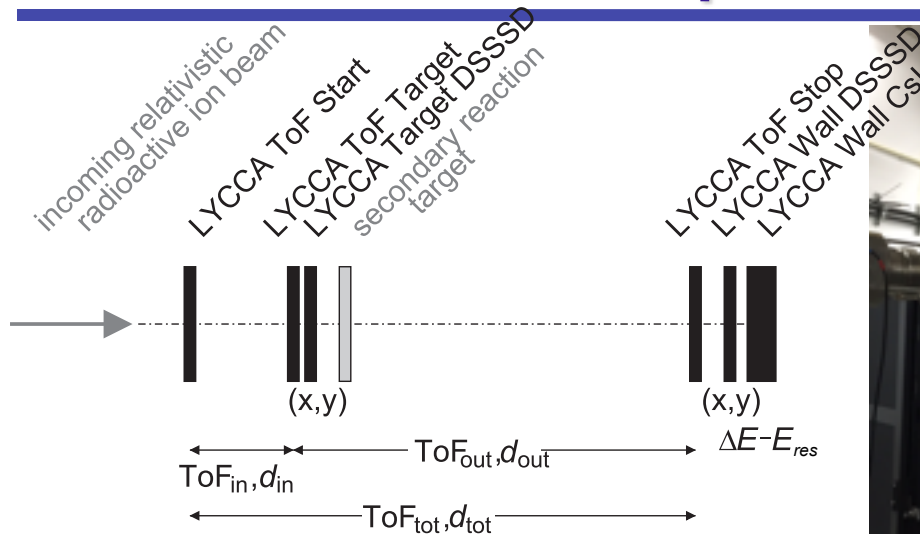




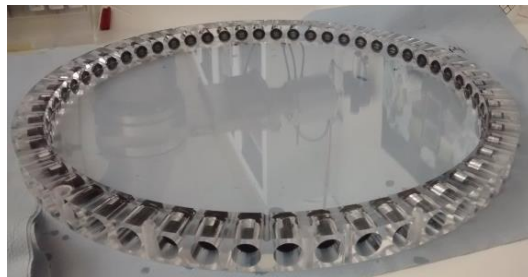
P. Golubev et al. NIMA. 723, 55-66 (2013)



LYCCA - an operational HISPEC device



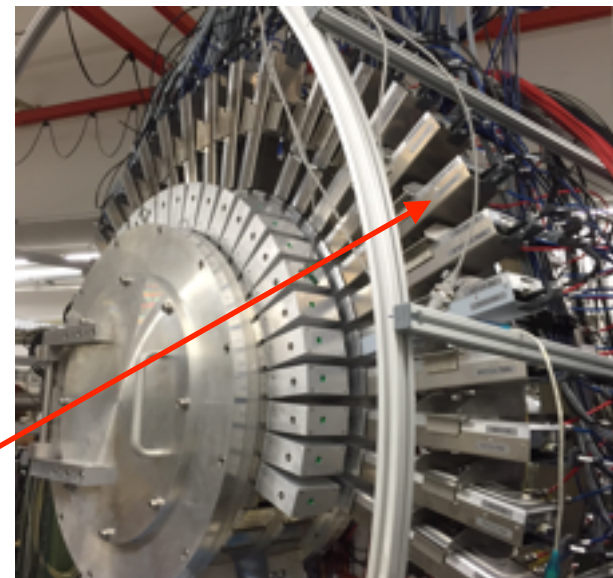
UK contribution of LYCCA:



Large-area time-of-flight detectors

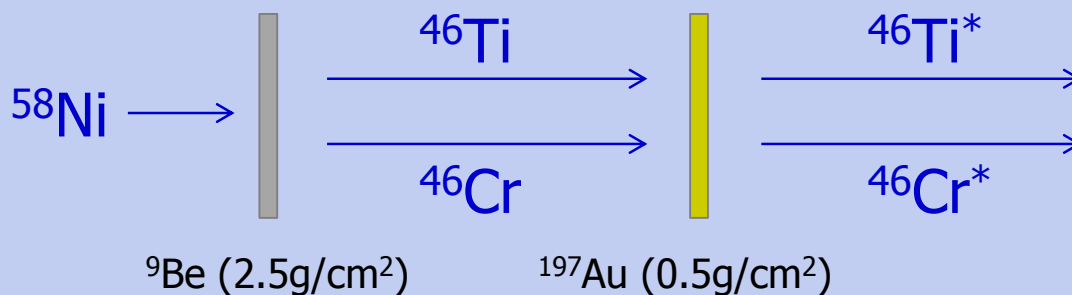


ASIC-based signal-processing and DAQ



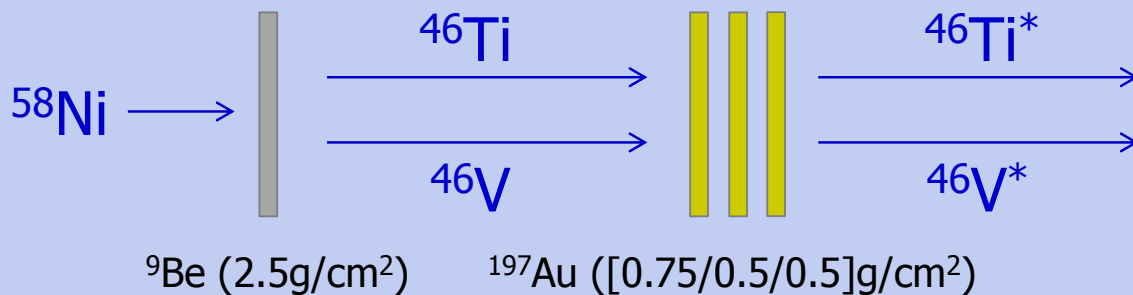
Isospin mixing in the A=46 Isobaric Triplet

Primary → **Secondary** → **Excited Secondary**



Coulex:
Cross section

Primary → **Secondary** → **Excited Secondary**



TCP:
Lifetime

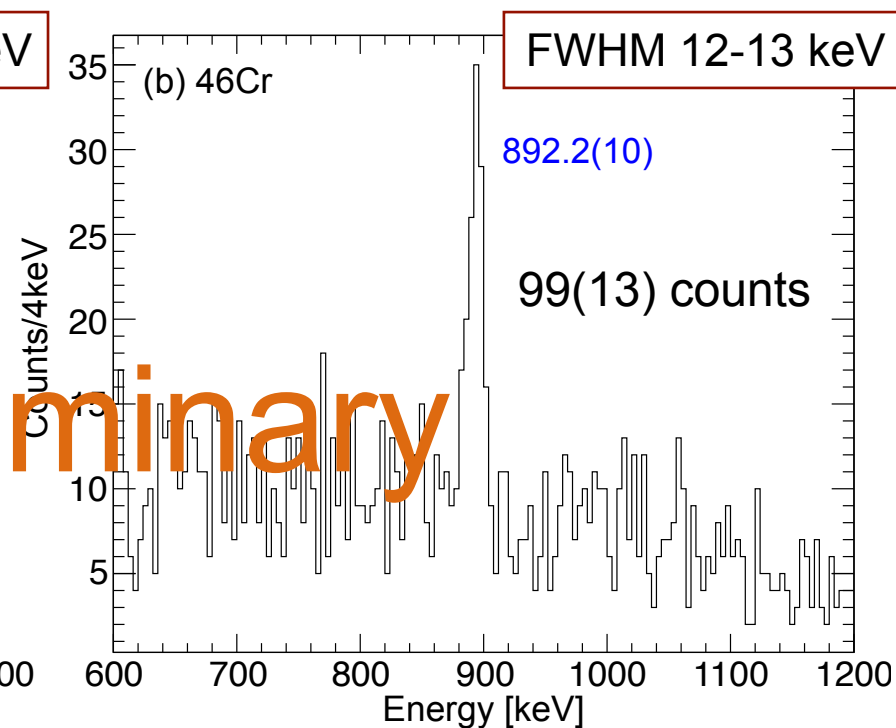
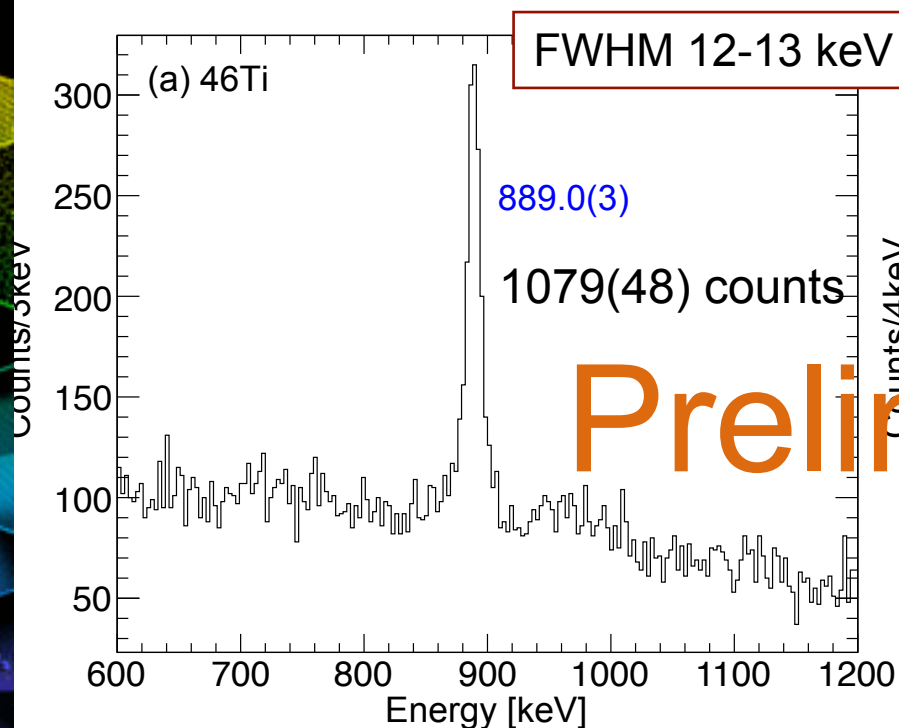
Isospin mixing in the A=46 Isobaric Triplet

After much optimisation !!

(event-by-event beta corrections, LYCCA ToF corrections,
x,y, and z offsets - peak-shape sensitive to these effects
at the mm level

^{46}Ti Coulex

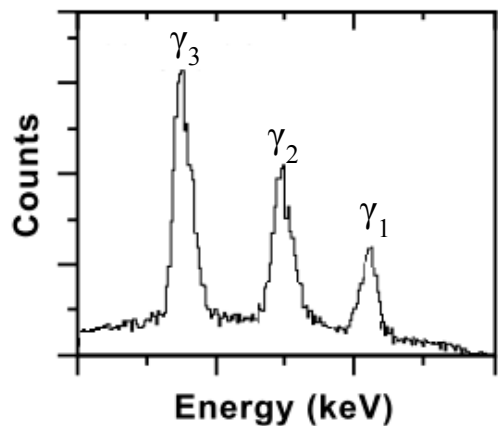
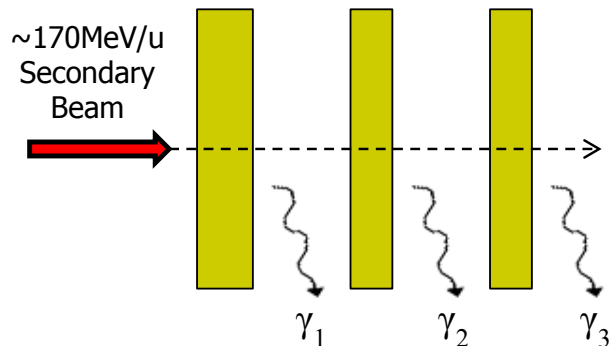
^{46}Cr Coulex



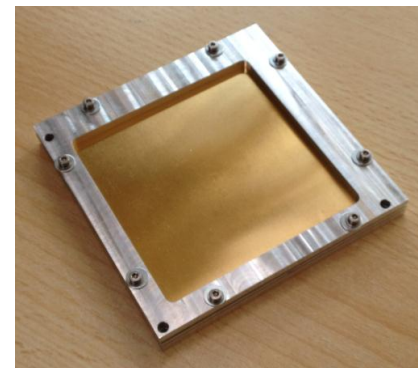
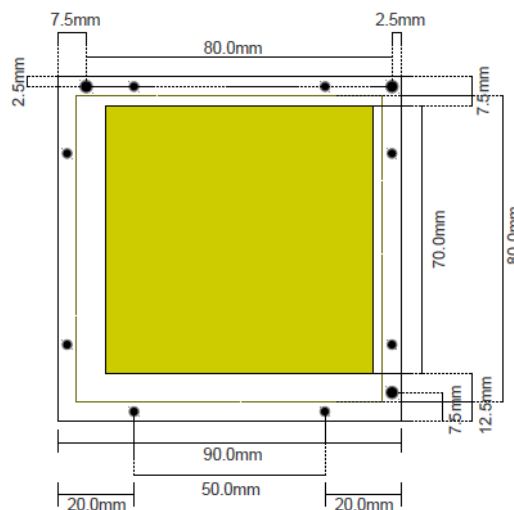
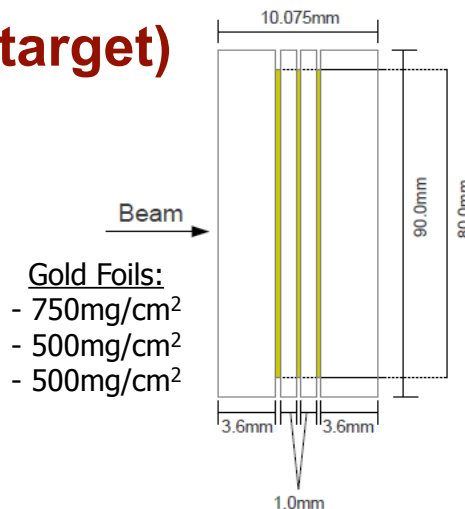
Preliminary

Isospin mixing in the A=46 Isobaric Triplet

Triple Gold Foil (stretched target)



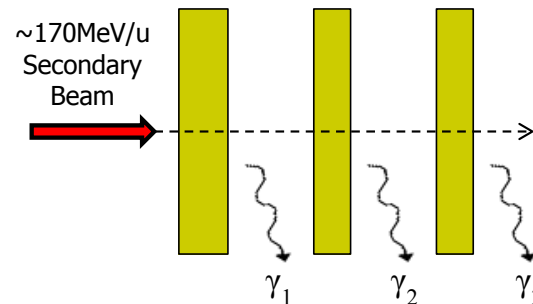
Doppler Shift:
$$E_{exp} = E_{cor} \frac{\sqrt{(1-\beta^2)}}{[1-\beta \cos(\theta_{dop})]}$$



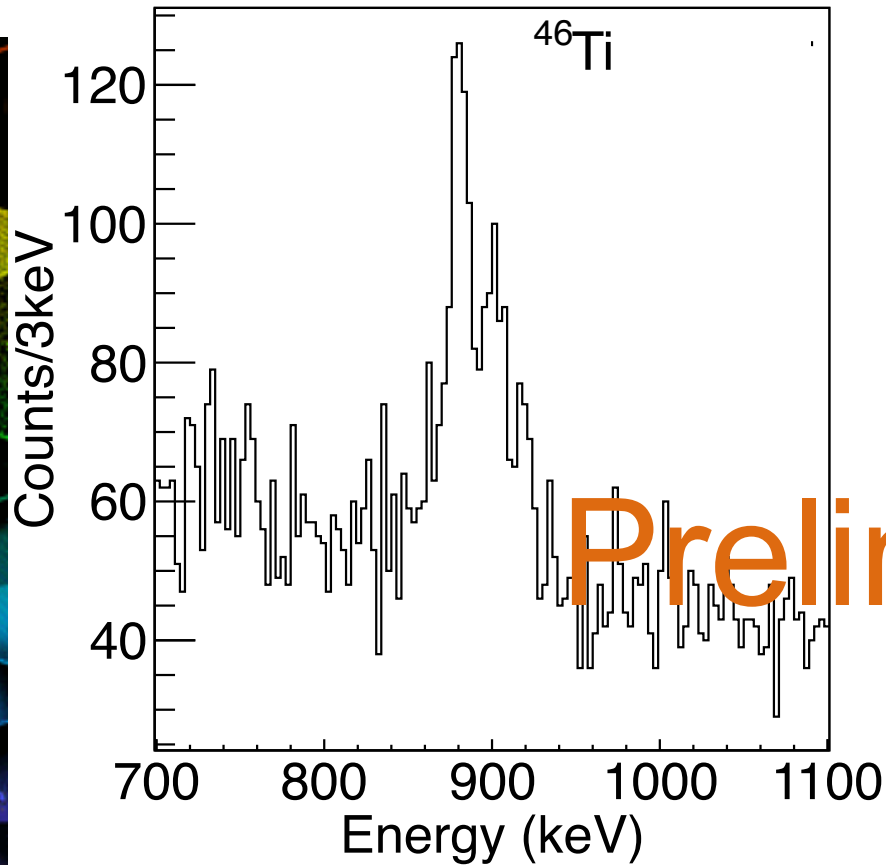
Isospin mixing in the A=46 Isobaric Triplet

After much optimisation !!

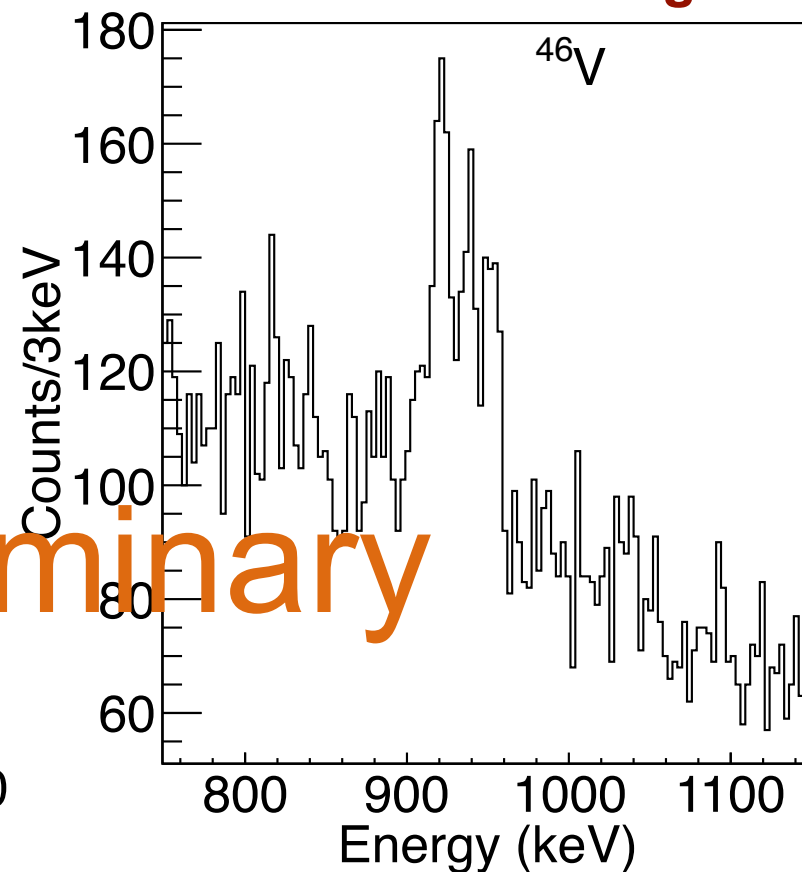
Using an angle-cut of $30 \pm 5^\circ$



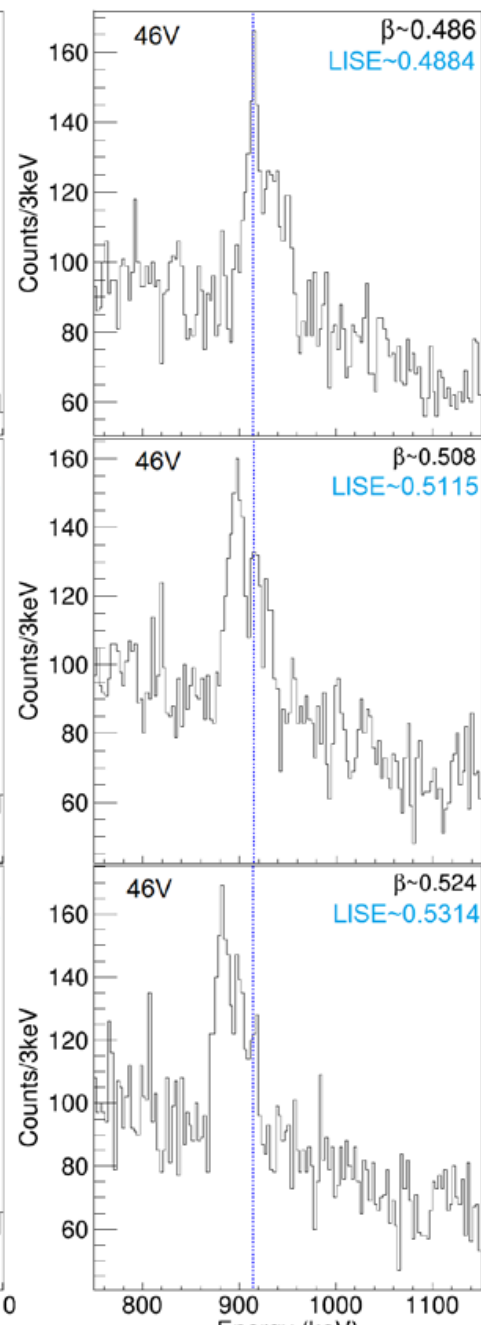
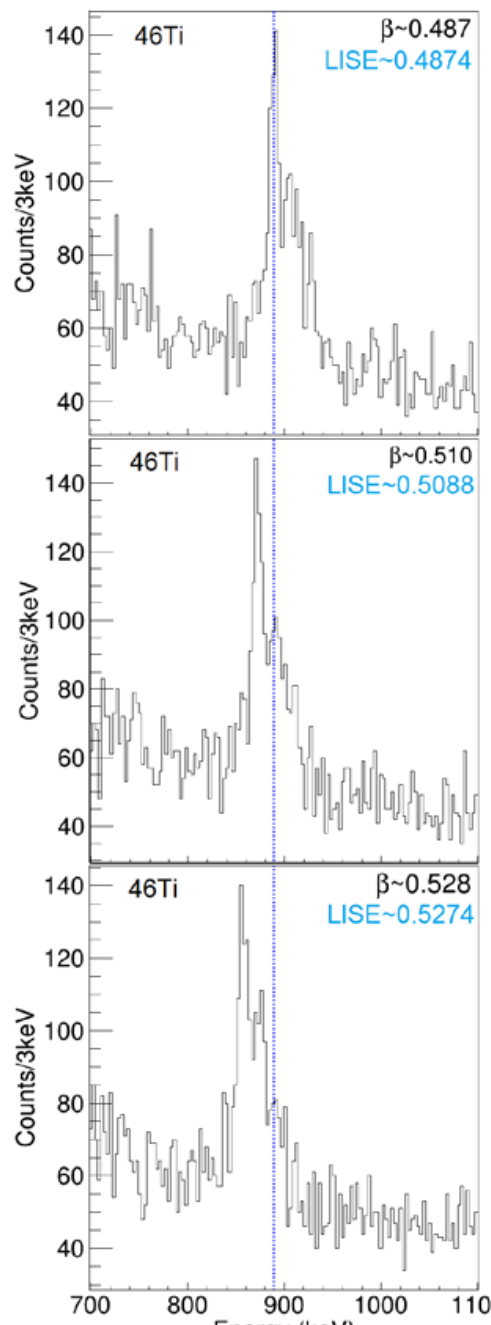
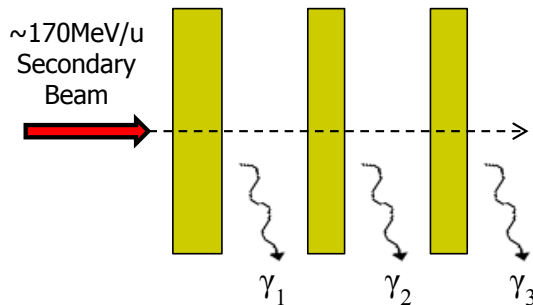
^{46}Ti Stretched Target



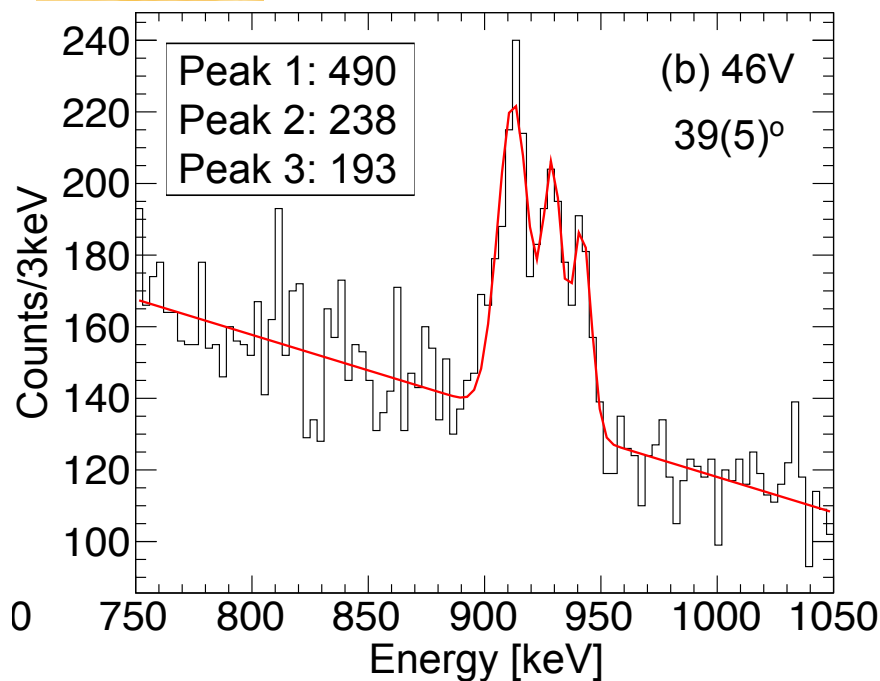
^{46}V Stretched Target



Isospin mixing in the A=46 Isobaric Triplet



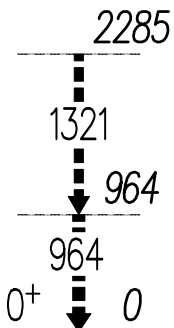
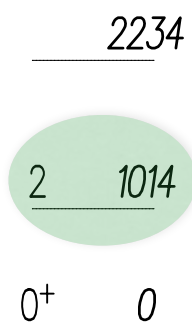
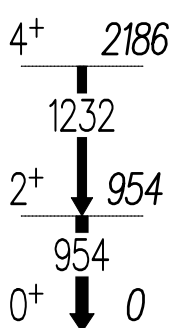
Isospin mixing in the A=46 Isobaric Triplet



Status of results

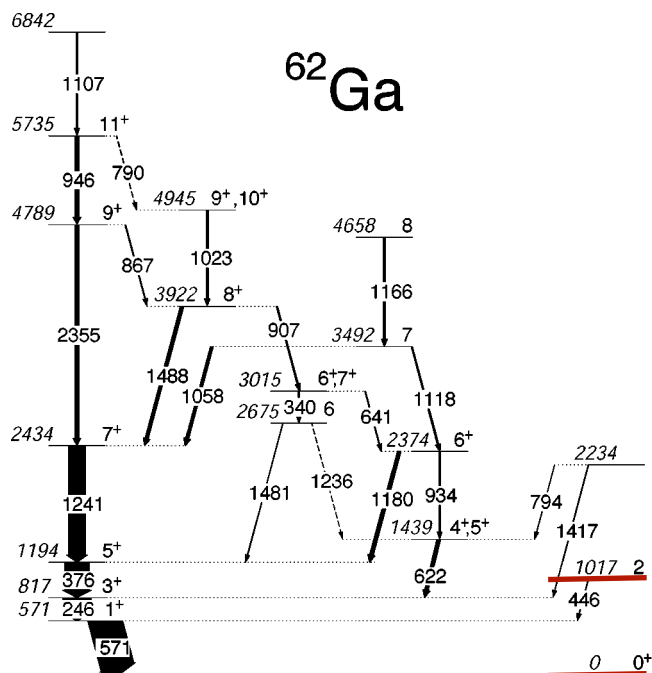
- Full AGATA simulation required for line shape analysis - collaborating with our session convenor...
- Analysis of Coulex cross-sections look promising - can reproduce ^{46}Ti literature cross-section...
- Error bars on the $B(E2)$?

^{62}Ga (odd-odd $N=Z$) - the $A=62$ $T=1$ Triplet

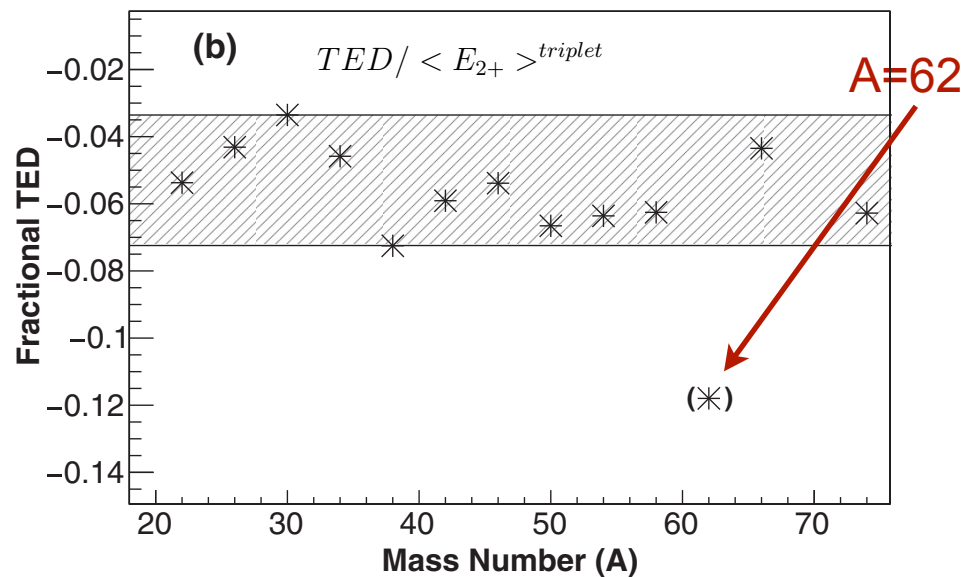
 ^{62}Ge  ^{62}Ga  ^{62}Zn 

^{62}Ge : Rudolph et al., Nucl. Phys. A752: 241c (2005)

^{62}Ga : Rudolph et al., Phys. Rev. C69: 034309 (2004)

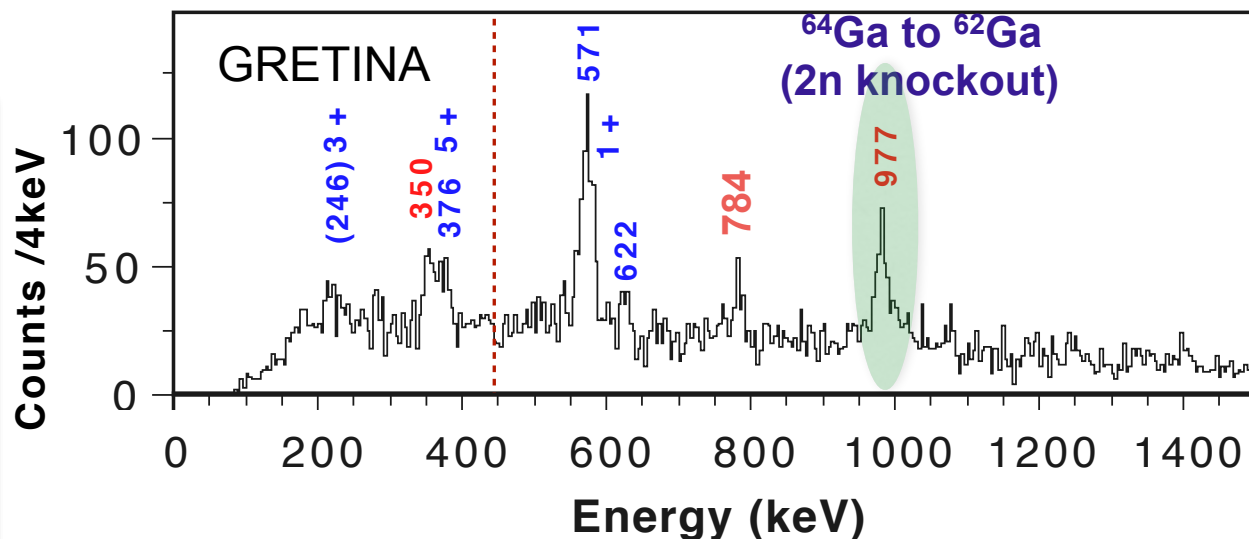
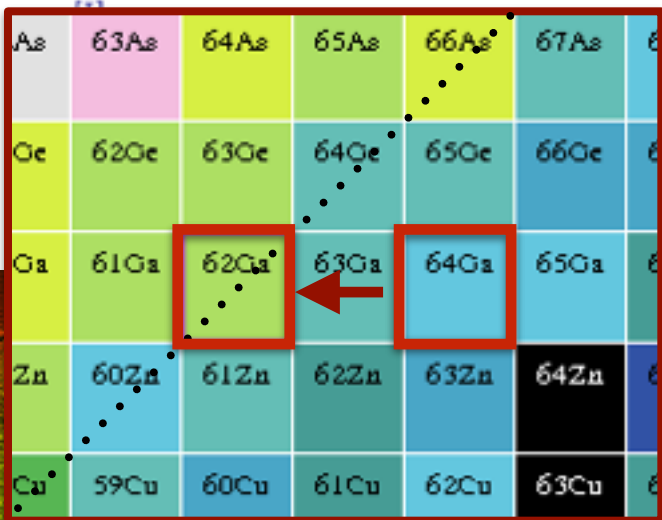


TED, normalised to 2^+ energy



^{62}Ga (odd-odd $N=Z$) - the $A=62$ $T=1$ Triplet

T.W.Henry et al, PRC 92, 024315 (2015)



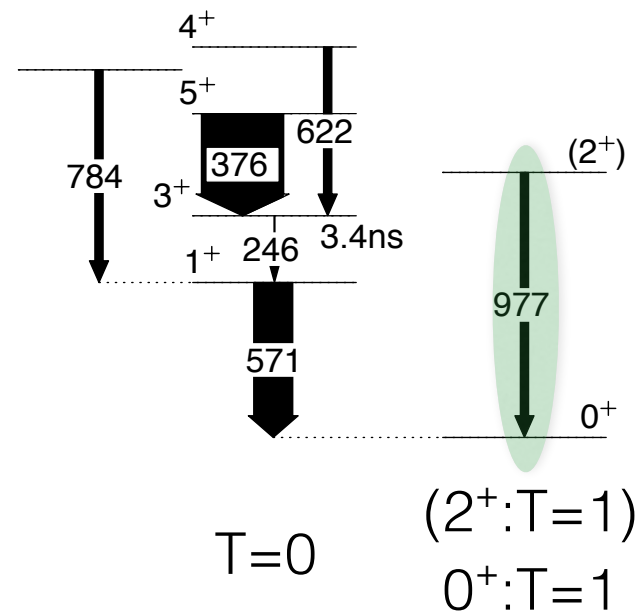
2n knockout process - **direct**:



$T=1$ 0^+ (g.s.) \longrightarrow $T=1$, 2^+ ?

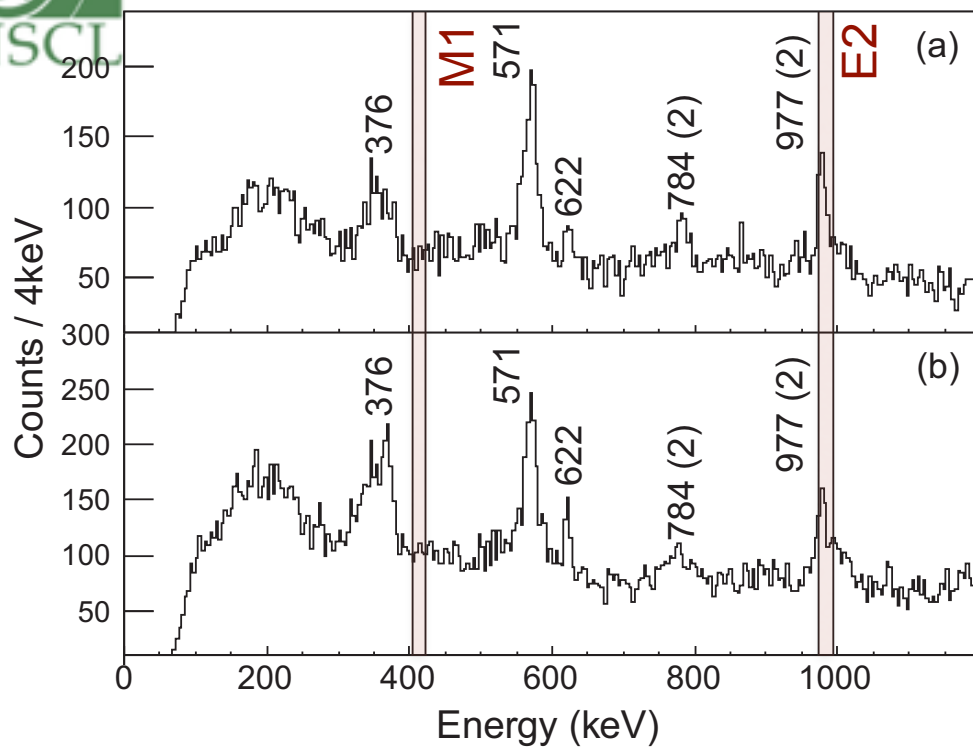
and

$T=1$ 2^+ (isomer) \longrightarrow $T=1$, 2^+ ?



^{62}Ga (odd-odd $N=Z$) - the $A=62$ $T=1$ Triplet

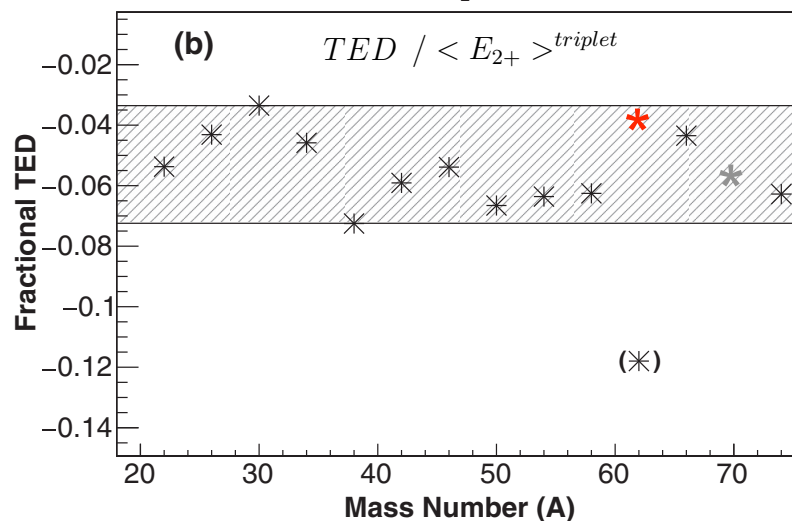
*T.W.Henry et al,
PRC 92, 024315 (2015)*



Shell-model +
reaction model
calculations

from g.s.

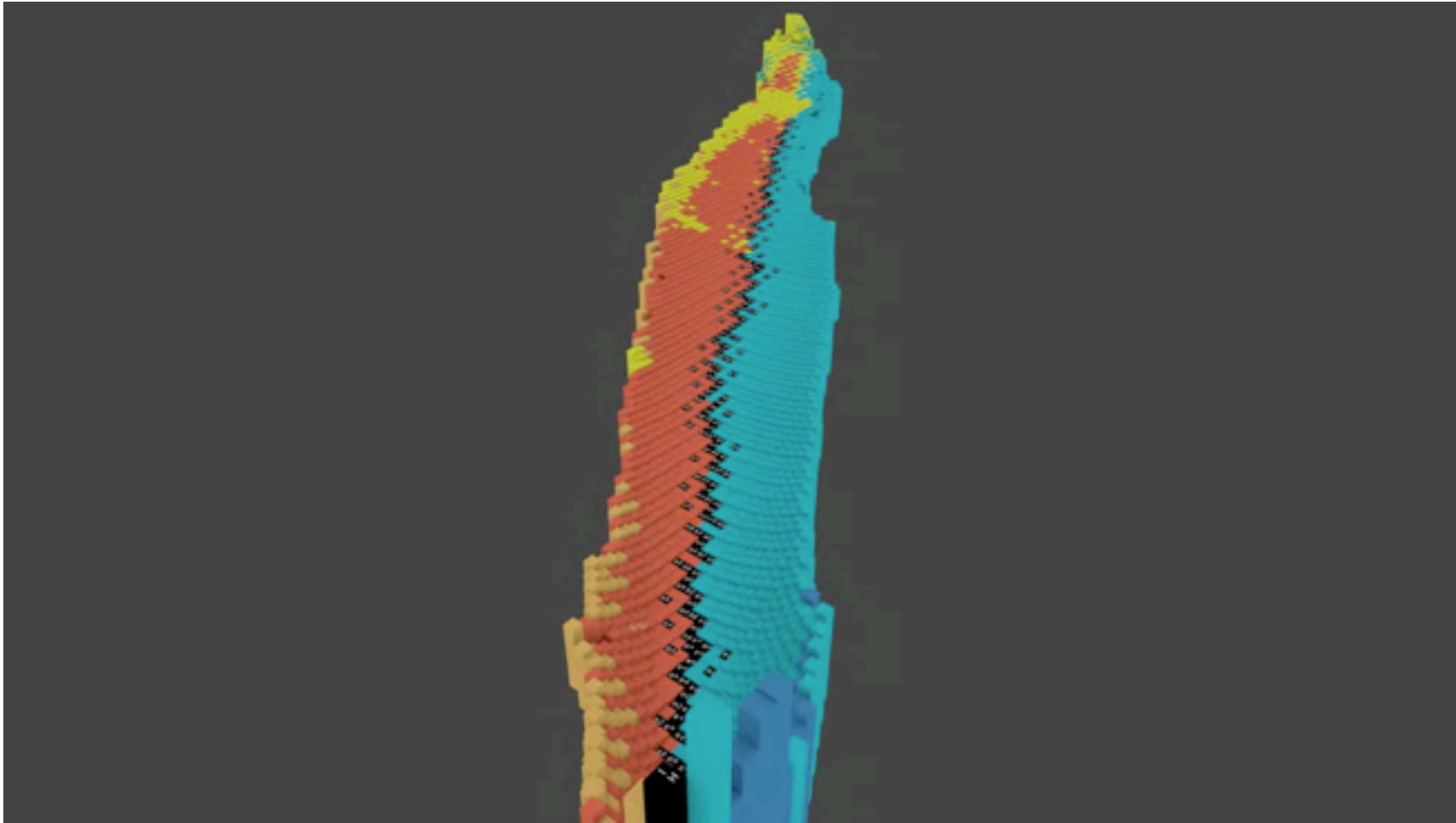
from isomer



Energy (keV)	J	π	$\sigma_{g.s.}^{rel}$	σ_{iso}^{rel}
0	0	+	3.6	3.4
0.283	1	+	1.9	3.1
0.428	3	+	1.3	7.6
0.572	1	+	4.7	6.2
0.626	3	+	2.8	10.0
0.683	2	+	27.2	5.7
0.794	5	+	0.0	4.5
0.924	1	+	0.6	3.0
1.017	2	+	11.7	16.7
1.068	2	+	8.3	8.0
1.245	3	+	3.1	4.0
1.303	4	+	8.6	1.2
1.411	4	+	1.0	4.8
1.973	4	+	2.1	9.6
2.038	6	+	0.1	2.3



Spectroscopy of T=1 mirrors using 1N knockout



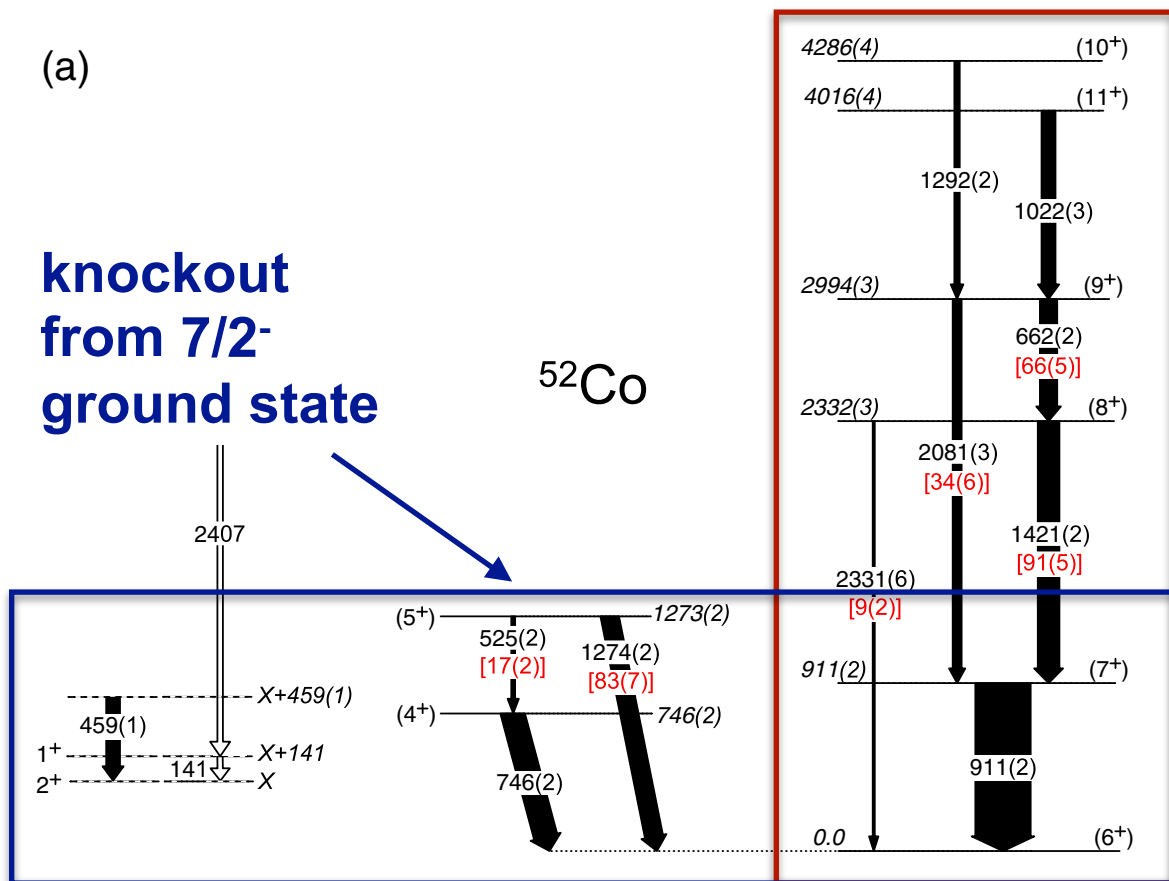
Matthew Shelley, Building Blocks project - York.

Isospin Symmetry at High Spin Studied via Nucleon Knockout from Isomeric States

S. A. Milne,¹ M. A. Bentley,¹ E. C. Simpson,² T. Baugher,^{3,4} D. Bazin,⁴ J. S. Berryman,⁴ A. M. Bruce,⁵ P. J. Davies,¹
 C. Aa. Diget,¹ A. Gade,^{3,4} T. W. Henry,¹ H. Iwasaki,^{3,4} A. Lemasson,^{4,6} S. M. Lenzi,⁷ S. McDaniel,^{3,4} D. R. Napoli,⁸
 A. J. Nichols,¹ A. Ratkiewicz,^{3,4} L. Scruton,¹ S. R. Stroberg,^{3,4,9} J. A. Tostevin,¹⁰ D. Weisshaar,⁴
 K. Wimmer,^{4,11} and R. Winkler⁴

(a)

knockout
from 7/2⁻
ground state

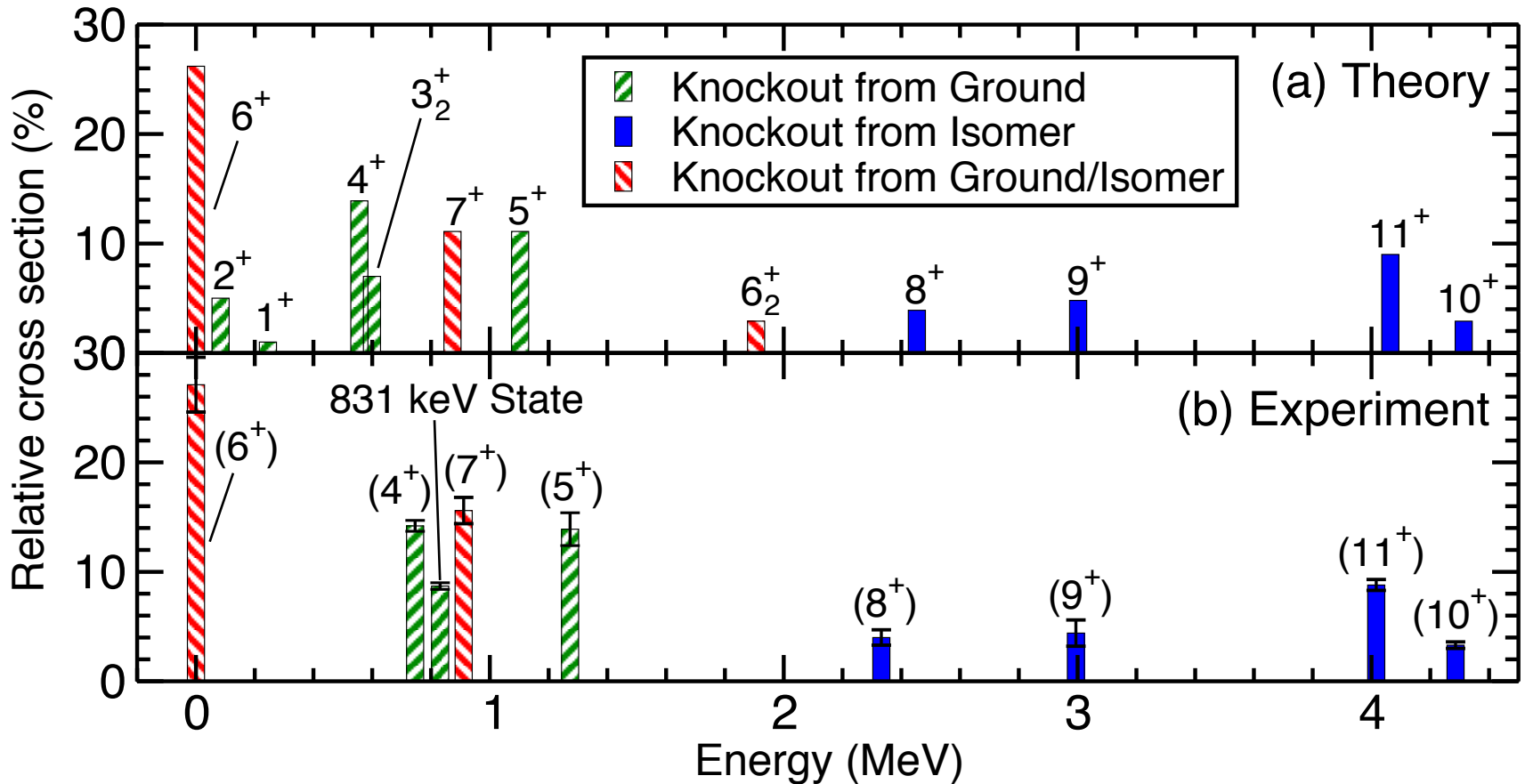
⁵²Co

knockout
from 19/2⁻
isomer

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)

S.A.Milne et al PRL117 082502 (2016)

With special thanks to...

Scott Milne (NSCL and Agata-GSI analysis) - York

Alberto Boso (Agata-GSI analysis) - Padova

Tom Henry (^{62}Ga) - York



NSCL team in Michigan, **PRESPEC@GSI** team and **AGATA** collaboration

Collaborators:

AGATA@GSI: F.Recchia, S.M.Lenzi, T.W.Henry, L.Scruton S.Afara, F.Ameil, T.Arici, S.Aydin, P.Boutachkov, A.Bruce, M.L.Cortes, C.Fahlander, J.Gerl, P.Golubev, M.Gorska, A.Gottardo, L.Grassi, T.Habermann, I.Kojouharov, N.Lalovic, M.Lettmann, C.Lizarazo, C.Louchart- Henning, D.Mengoni, V.Modamio, T.Moeller, D.Napoli, R.M.Perezvidal, N.Pietralla, S. Pietri, D.Ralet, M.Reese, D.Rudolph, L.Sarmiento, H.Schaffner, N.Singh, P.P.Singh, C.Stahl, G.Tuomas, J.Valiente + **PRESPEC@GSI** team

NSCL: R.M.Clark, E.C.Simpson, P.Dodsworth, T.Baugher, D.Bazin, C.W.Beausang, J.S.Berryman, A.M.Bruce, C.M.Campbell, H.L.Crawford, M.Cromaz, P.J.Davies, C.Aa.Diget, P.Fallon, A.Gade, J.Henderson, H. Iwasaki, D.G.Jenkins, I.Y.Lee, A.O.Macchiavelli, A.Lemasson, S.M.Lenzi, S.McDaniel, D.R.Napoli, A.J.Nichols, S.Paschalis, M.Petri, F.Recchia, A.Ratkiewicz, J.Rissanen, L.Scruton, S.R.Stroberg, J.A.Tostevin, R.Wadsworth, C.Walz, D.Weisshaar, A.Wiens, K.Wimmer and R. Winkler