



Study of proton-neutron multiplets in ^{134}Sb populated in the $^{133}\text{Sb}(\text{d},\text{p})$ reaction in inverse kinematics with T-REX and MINIBALL

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A. Gargano, K. Arnswald, A. Fernández, G. Fernández Martínez, A.-L. Hartig, C. Henrich, I. Homm, A. Illana, L. Kaya, T. Koiwai, Th. Kröll, E. Nácher, R. Orlandi, H.-B. Rhee, P. Reiter, D. Rosiak, Ph. Schrock, M. Seidlitz, M. Siciliano, Ch. Sürder, J.J. Valiente-Dobón and N. Warr

INFN Napoli, Italy – IKP, Uni Köln, Germany – TU Darmstadt, Germany

LNL-INFN Legnaro, Italy – Japan Atomic Energy Agency, Japan

Previous studies in the ^{132}Sn region: Decay spectroscopy EURICA experiment NP1112-RIBF85 (December 2012)

		$134\pm$		$136\pm$		$138\pm$		$140\pm$		$142\pm$
Te										
Sb		$133\pm$	$134\pm$		$136\pm$		$138\pm$		$140\pm$	
Sn		$132\pm$	$133\pm$	$134\pm$	$135\pm$	$136\pm$ 6^+		$138\pm$ 6^+		$140\pm$
In	$129\pm$ b	$130\pm$ b	$131\pm$ b, bn	$132\pm$ bn	$133\pm$	$134\pm$		$136\pm$		
Cd	$128\pm$	$129\pm$	$130\pm$ 8^+	$131\pm$	$132\pm$	$133\pm$	$134\pm$			
Ag										
Pd			$128\pm$ 8^+		$130\pm$					

82

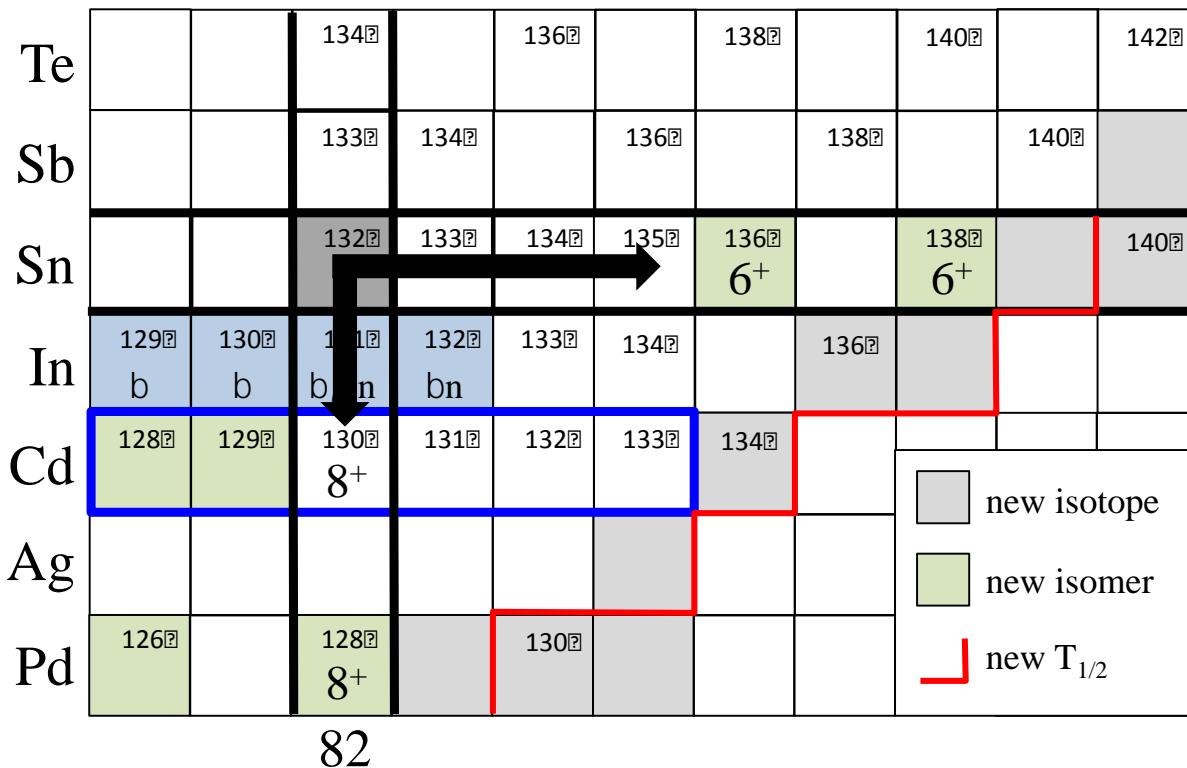
10 new isotopes produced !

110 $T_{1/2}$ measured,
40 new !

8-10 pnA ^{238}U beam

Only factor 10 below RIBF design value !

Previous studies in the ^{132}Sn region: Decay spectroscopy EURICA experiment NP1112-RIBF85 (December 2012)



New seniority isomers
along $Z=50$ and $N=82$!

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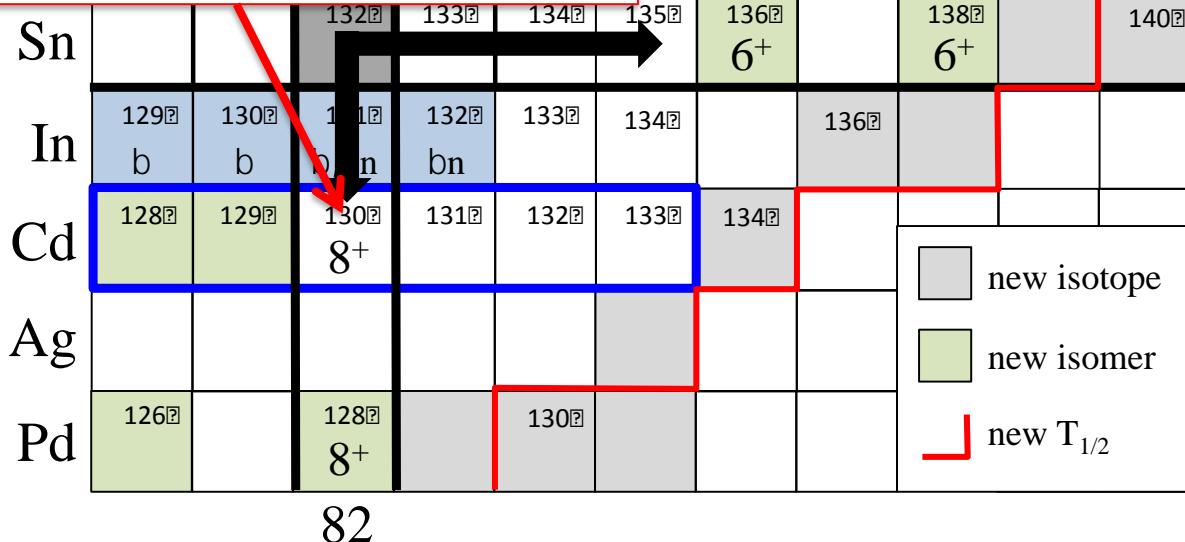
- H. Watanabe et al., Phys. Rev. Lett. 111, 152501 (2013)
 G.S. Simpson et al., Phys. Rev. Lett. 113, 132502 (2014)
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 Y. Shimizu et al., J. Phys. Soc. Japan, in press

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RISING@GSI 2006:

Factor ~ 200 less ^{238}U !

A. Jungclaus et al., PRL 99, 132501 (2007)



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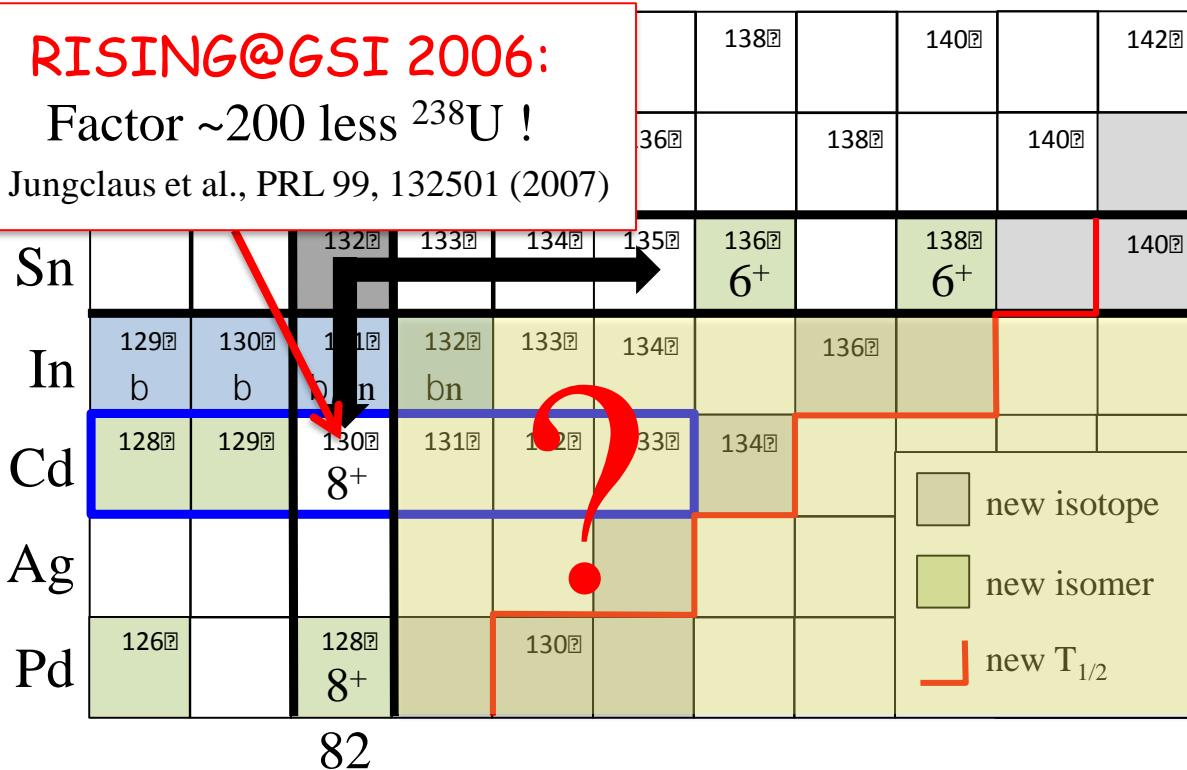
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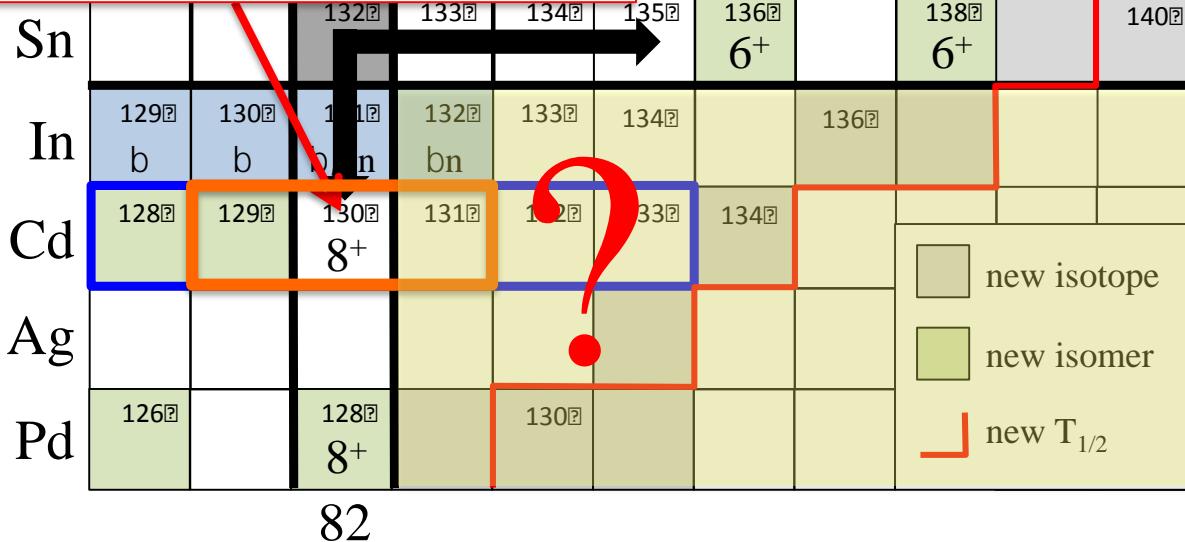
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Masses from ISOLTRAP and IMS@ESR

D. Atanasov et al., PRL 115 (2015) 232501

R. Knöbel et al., PLB 754 (2016) 288

H. Watanabe et al., Phys. Rev. Lett. 111, 152501 (2013)

G.S. Simpson et al., Phys. Rev. Lett. 113, 132502 (2014)

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Sn		$132\pm$	$133\pm$	$134\pm$	$135\pm$	$136\pm$ 6^+		$138\pm$ 6^+		$140\pm$
In	$129\pm$ b	$130\pm$ b	$131\pm$ b, bn	$132\pm$ bn	$133\pm$	$134\pm$		$136\pm$		
Cd	$128\pm$	$129\pm$	$130\pm$ 8^+	$131\pm$	$132\pm$	$133\pm$	$134\pm$			
Ag										
Pd	$126\pm$		$128\pm$ 8^+		$130\pm$					

Legend:

- new isotope (light gray)
- new isomer (light green)
- new $T_{1/2}$ (red bracket)



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PhD May 2015
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J. Taprogge, A. Jungclaus et al., Phys. Rev. Lett. 112, 132501 (2014)

J. Taprogge, A. Jungclaus et al., Phys. Lett. B 738, 223 (2014)

J. Taprogge, A. Jungclaus et al., Phys. Rev. C 91, 054324 (2015)

J. Taprogge, A. Jungclaus et al., Eur. Phys. J. A 52, 347 (2016)

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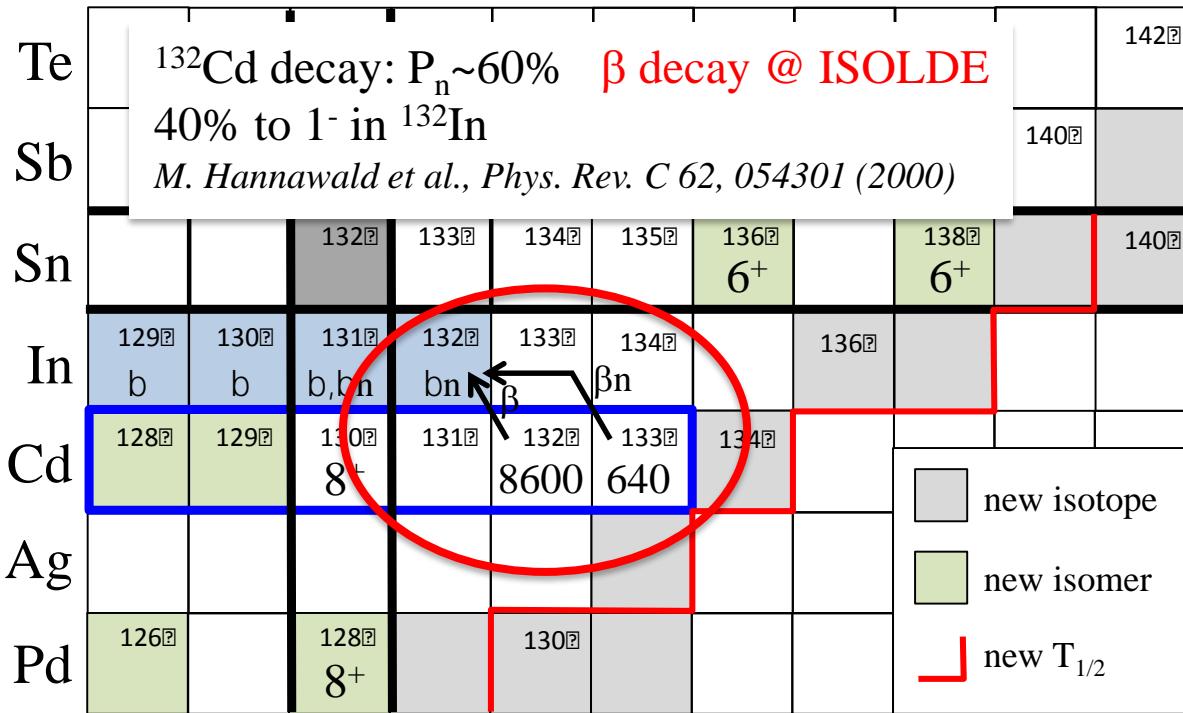
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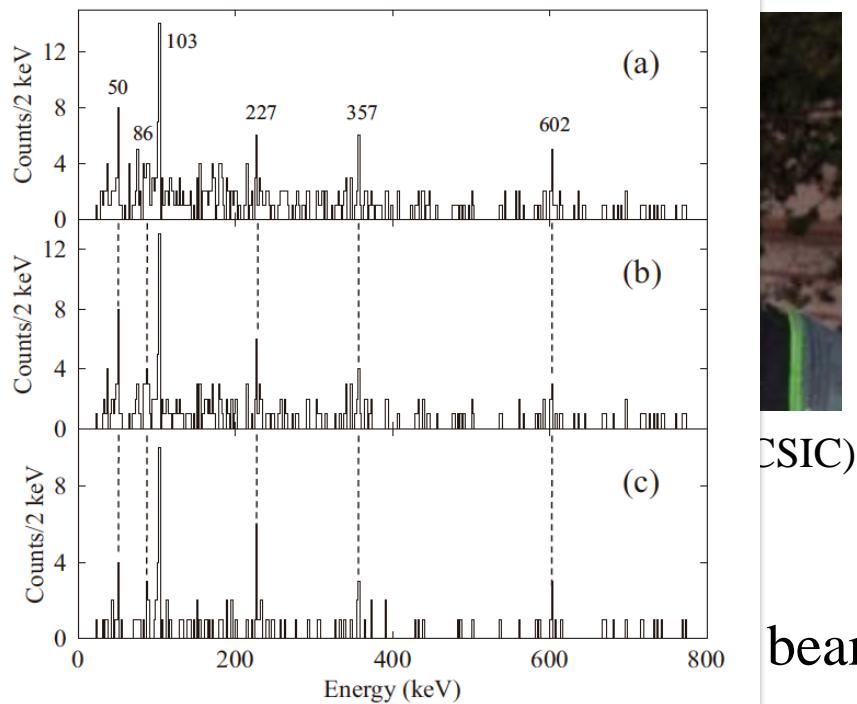
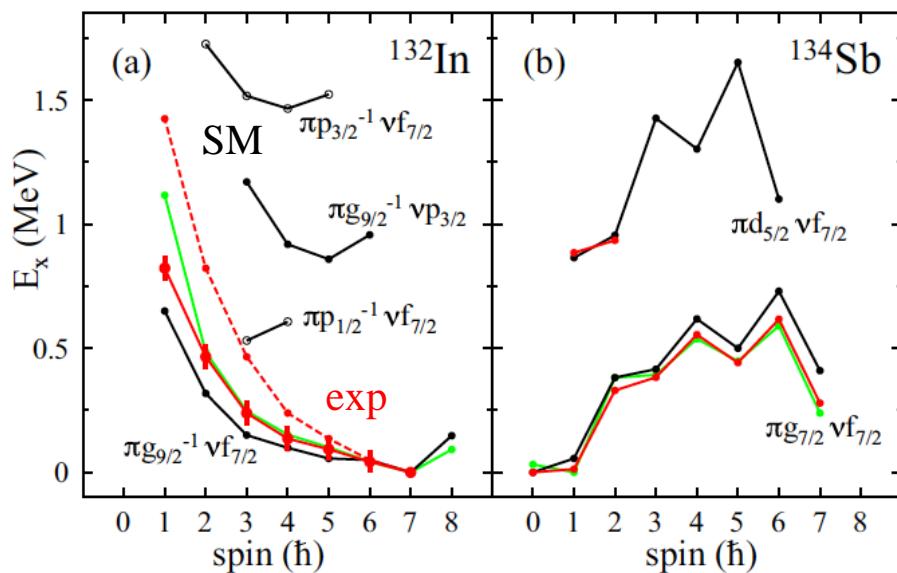
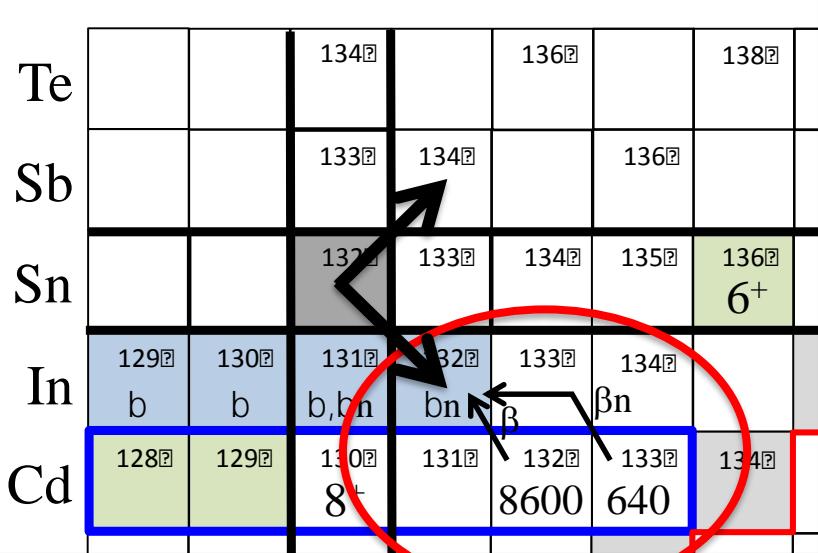
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A. Jungclaus et al., PRC 93, 041301(R) (2016)
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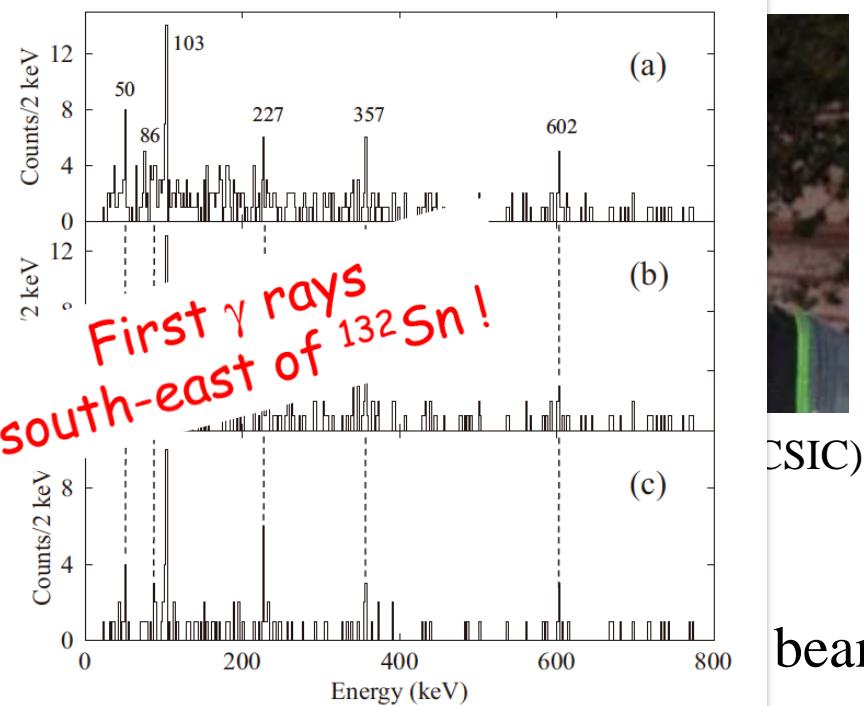
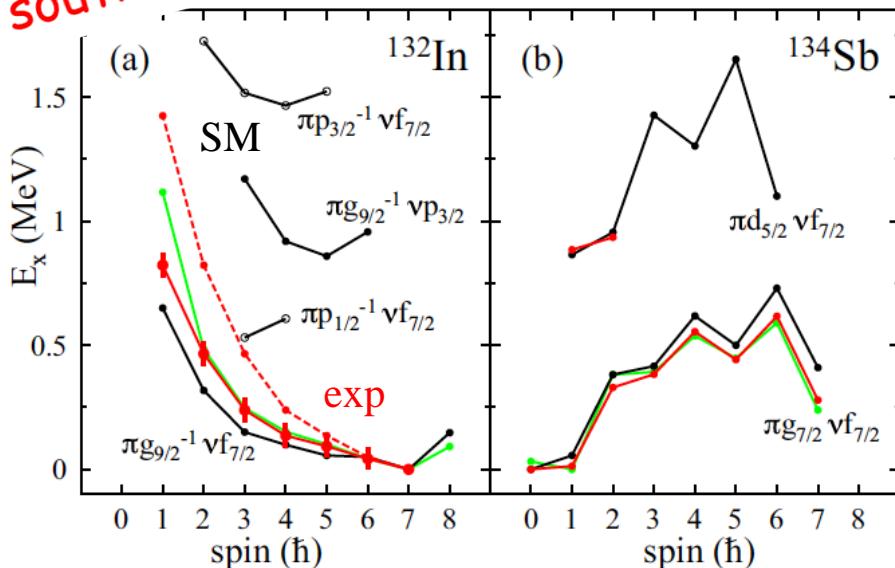
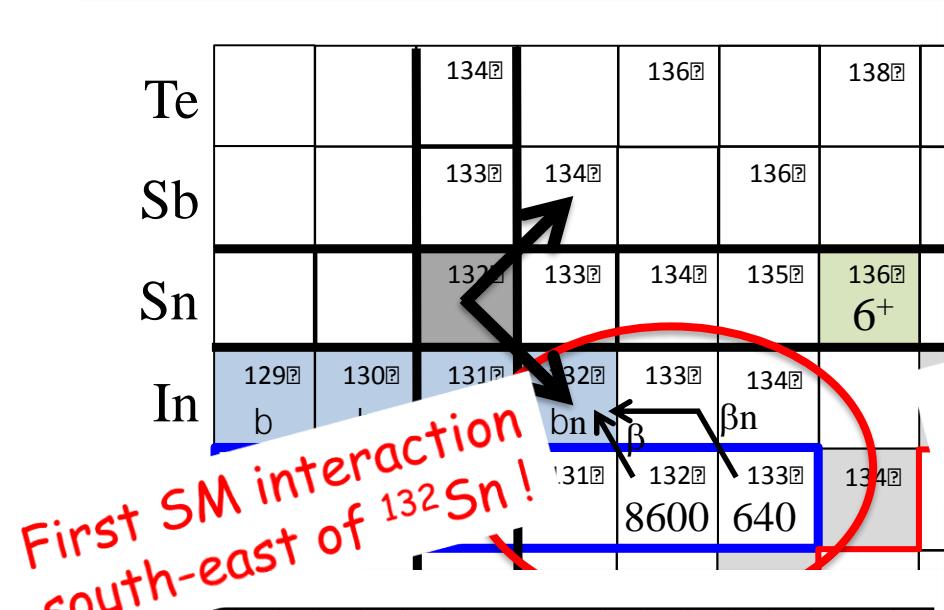
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beam

tor 10

below RIBF design value !

Previous studies in the ^{132}Sn region: Decay spectroscopy EURICA experiment NP1112-RIBF85 (December 2012)

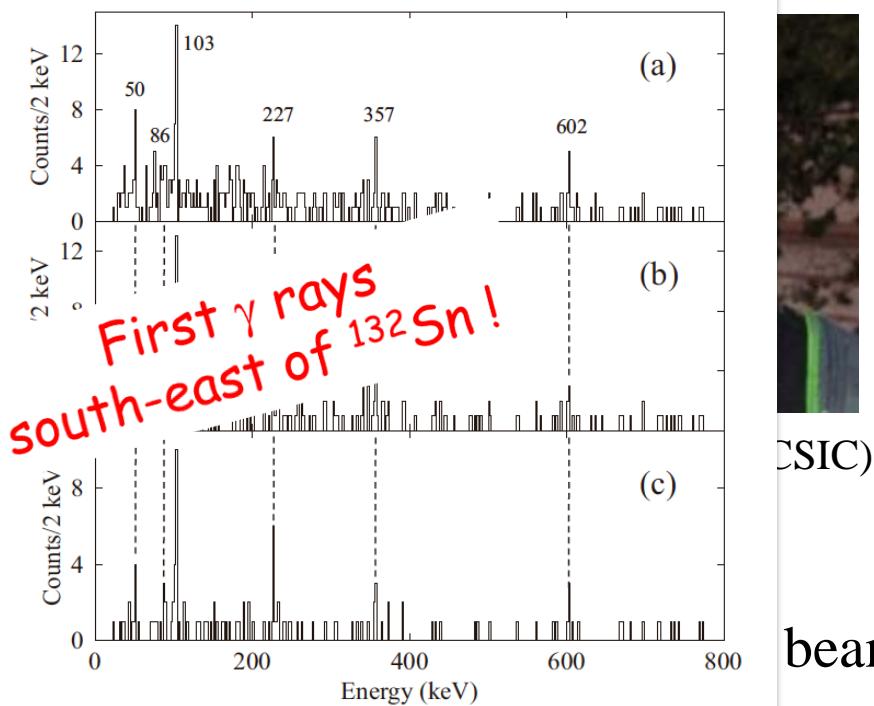
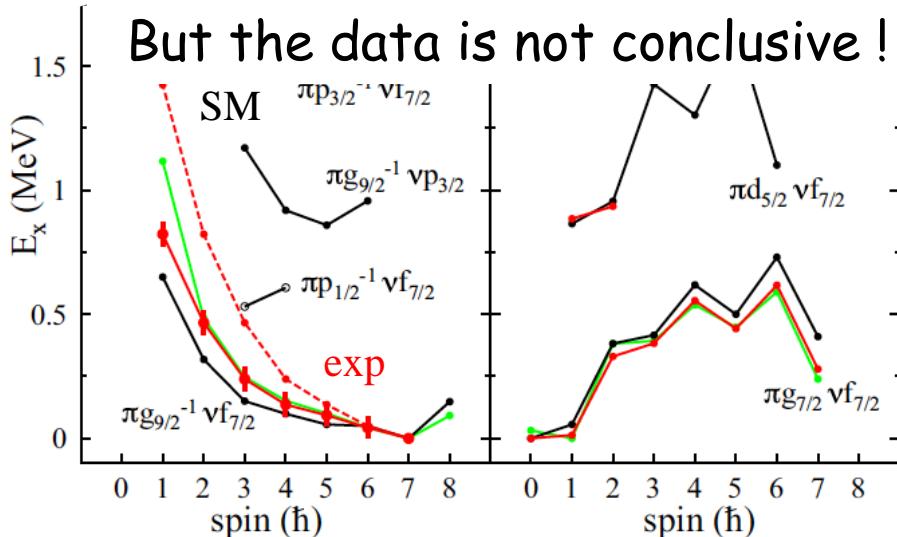
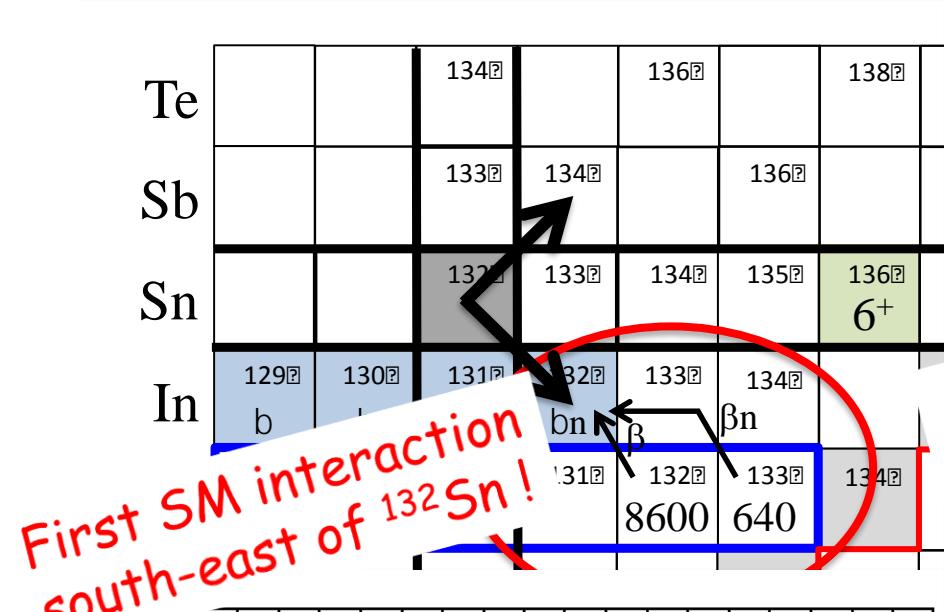


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Sn		$132\pm$	$133\pm$	$134\pm$	$135\pm$	$136\pm$ 6^+		$138\pm$ 6^+		$140\pm$
In	$129\pm$ b	$130\pm$ b	$131\pm$ b,bn	$132\pm$ bn	$133\pm$ β	$134\pm$ βn		$136\pm$		
Cd	$128\pm$	$129\pm$	$130\pm$ 8^+	$131\pm$	$132\pm$ 8600	$133\pm$ 64	$134\pm$			
Ag										
Pd		$126\pm$		$128\pm$ 8^+		$130\pm$				

Legend:

- new isotope
- new isomer
- new $T_{1/2}$

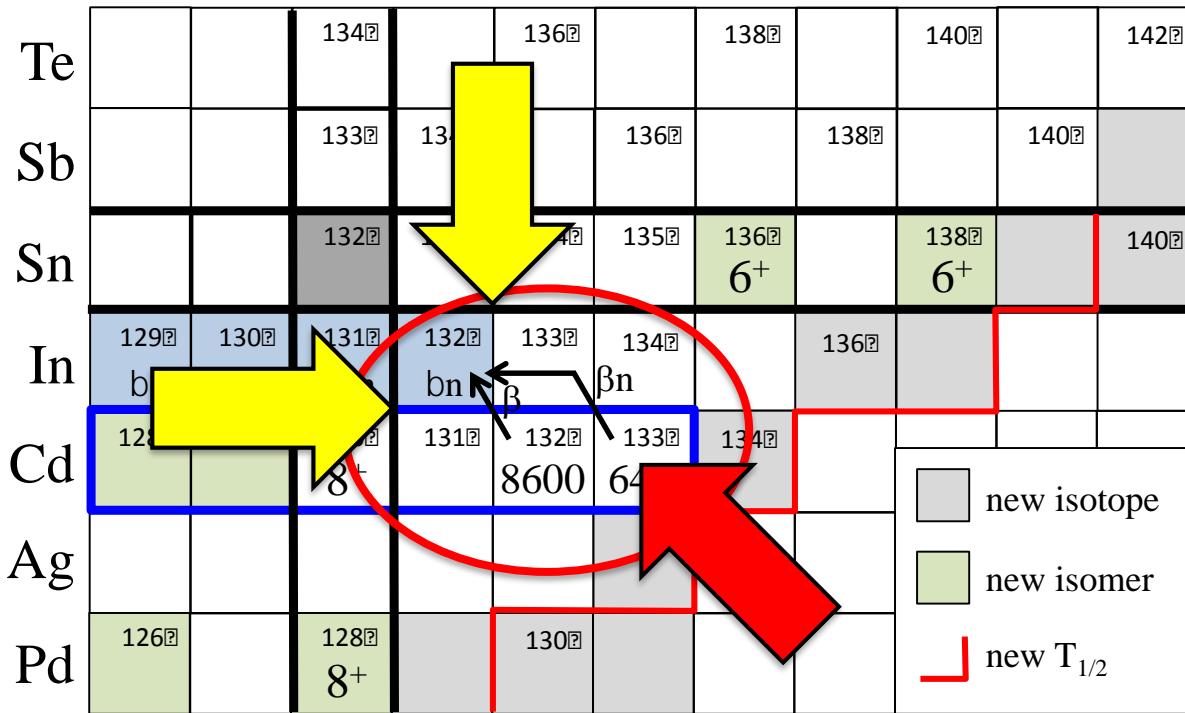


Jan Taprogge (IEM-CSIC)
PhD May 2015
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Only factor 10 below
RIBF design value !

It is (and will be) very difficult to do γ -ray spectroscopy
in the quadrant south-east of ^{132}Sn following β decay !

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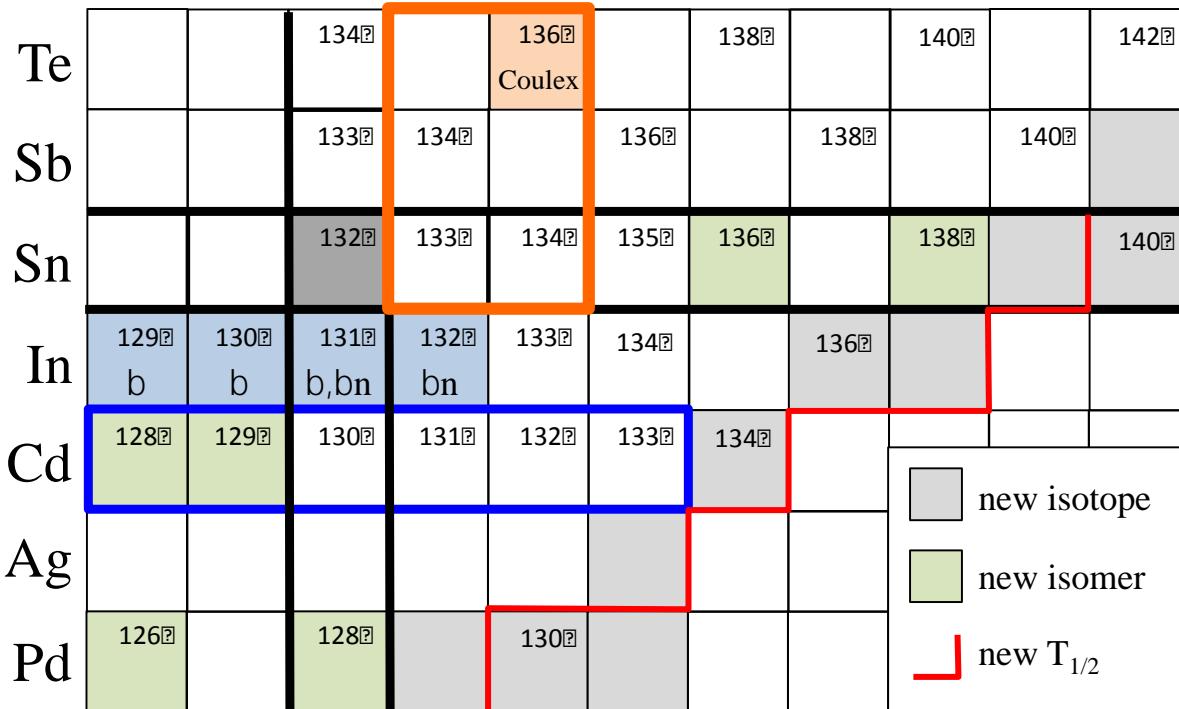
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It is (and will be) very difficult to do γ -ray spectroscopy
in the quadrant south-east of ^{132}Sn following β decay !

Is it easier using nuclear reactions ?

Previous studies in this region: In-beam spectroscopy

DALI2 experiment NP1306-RIBF98R1 (April 2015)

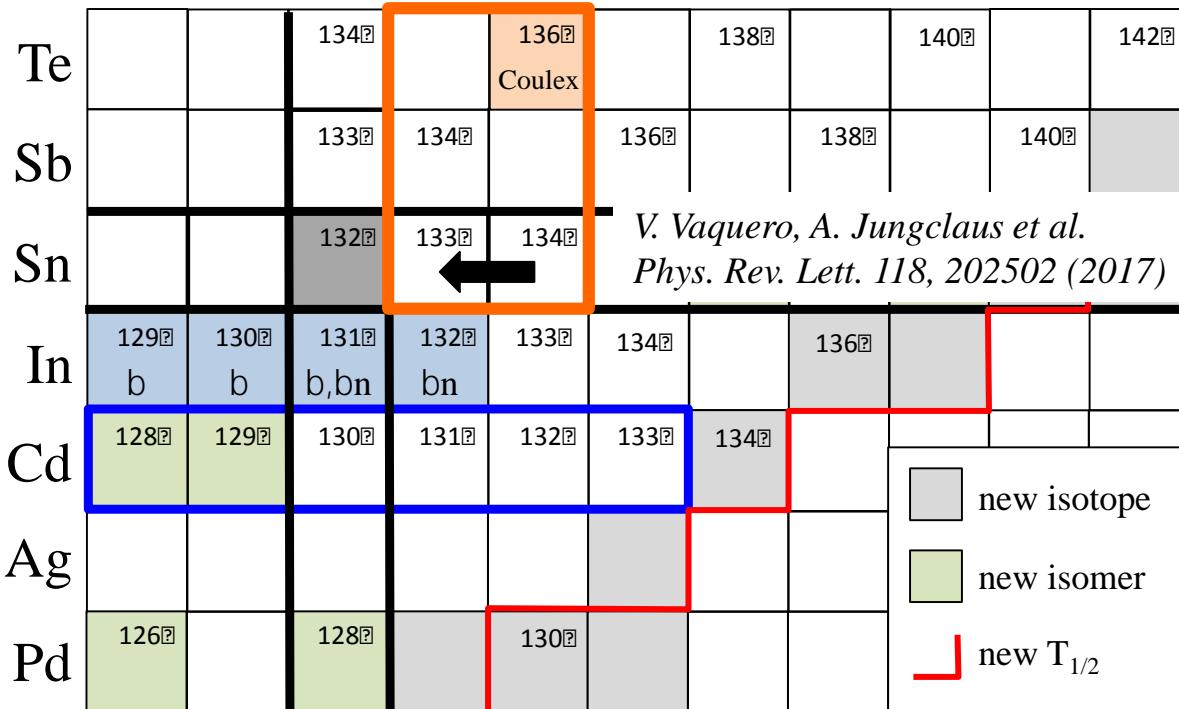


Víctor Vaquero (IEM-CSIC)
PhD student

High statistics Coulex of ^{136}Te and knockout reactions

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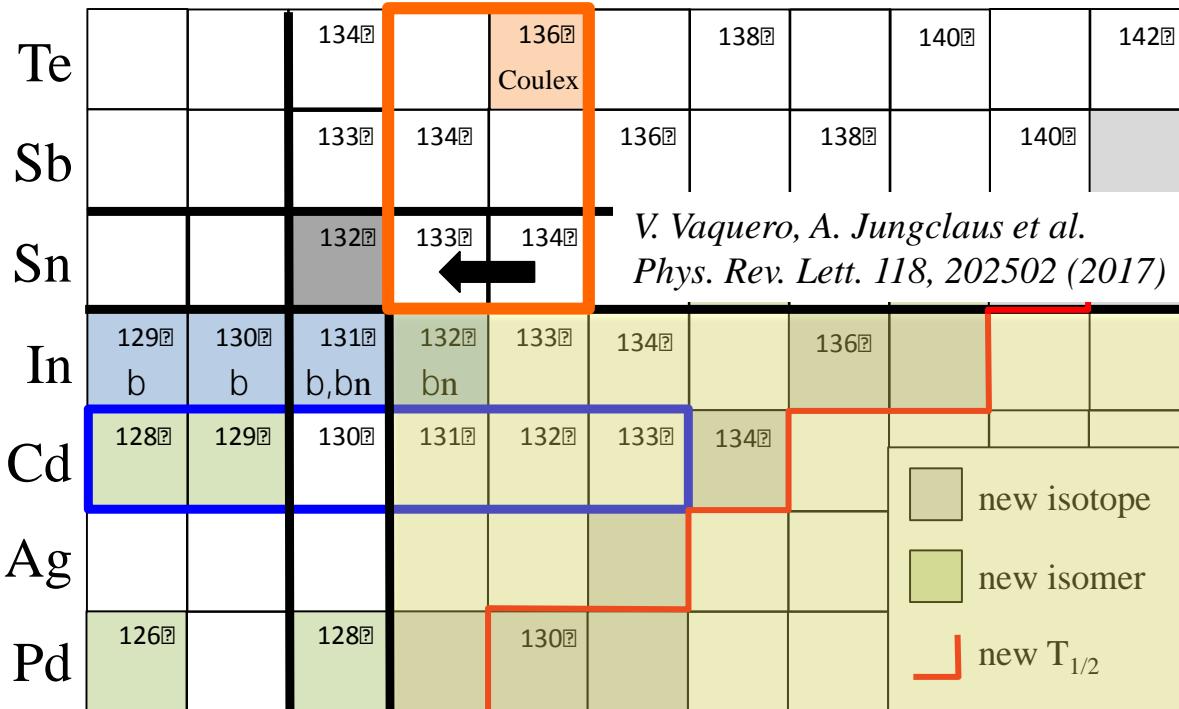


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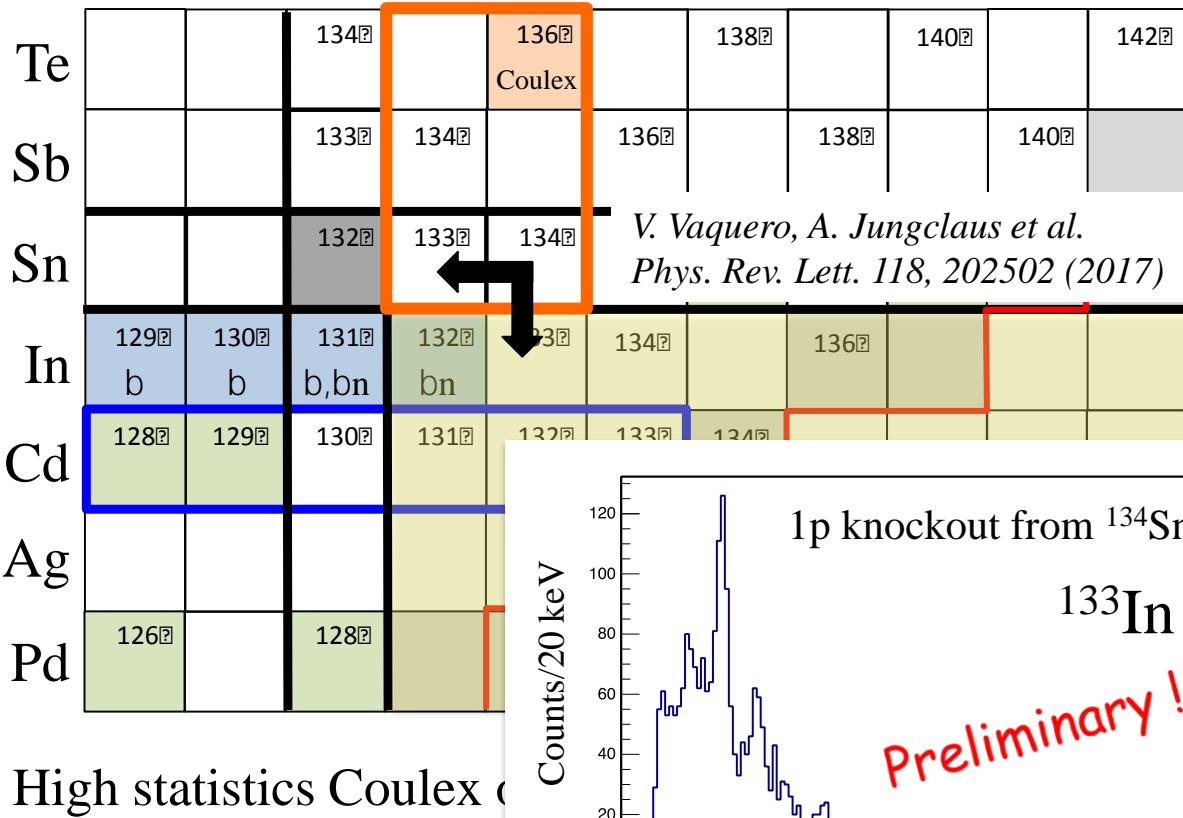


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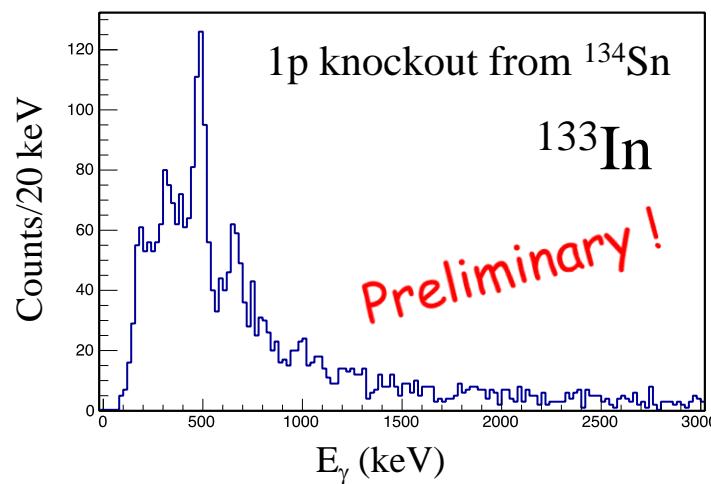
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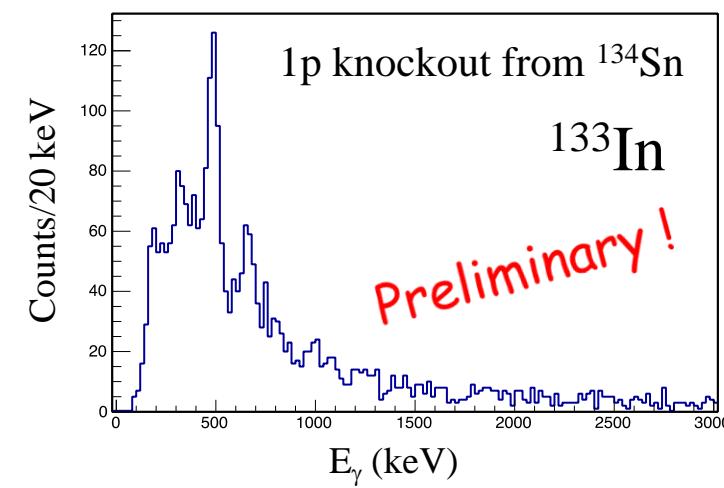
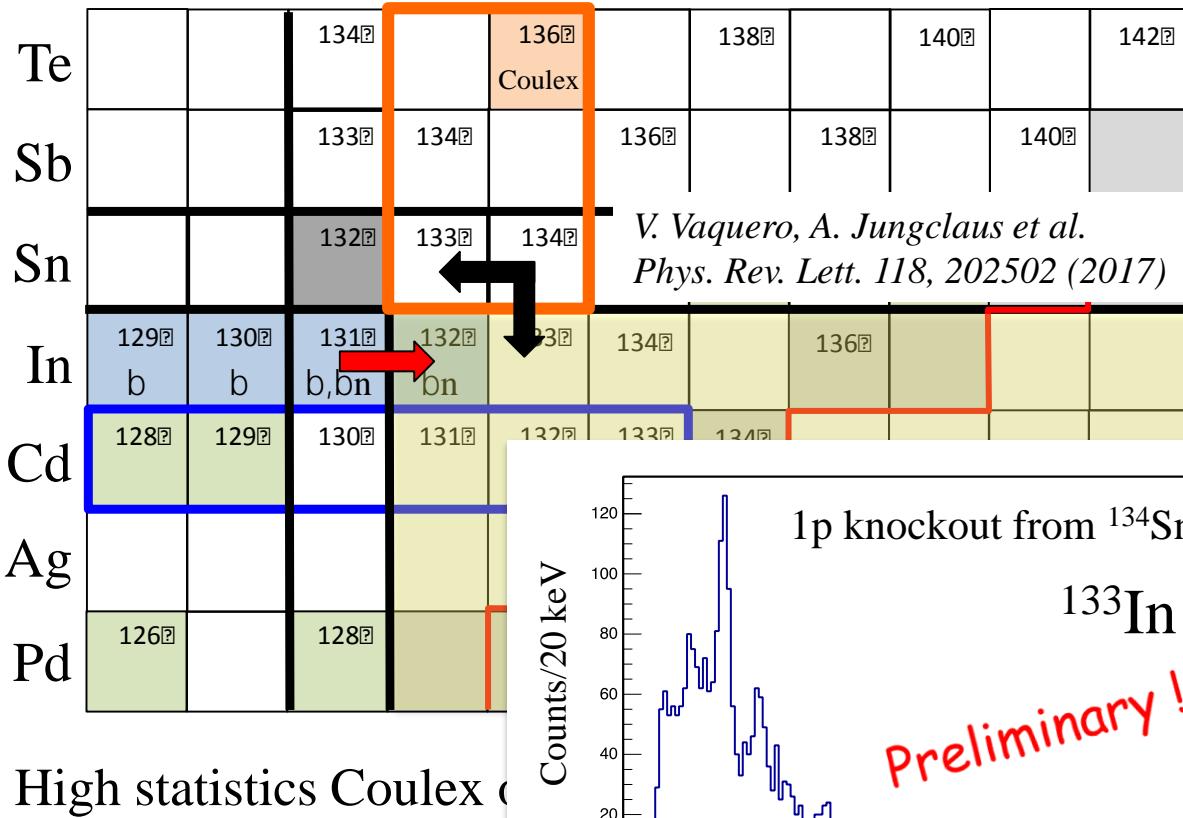


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Na(I) resolution,
no $\gamma\gamma$ coincidences,
no γ at low-energy !

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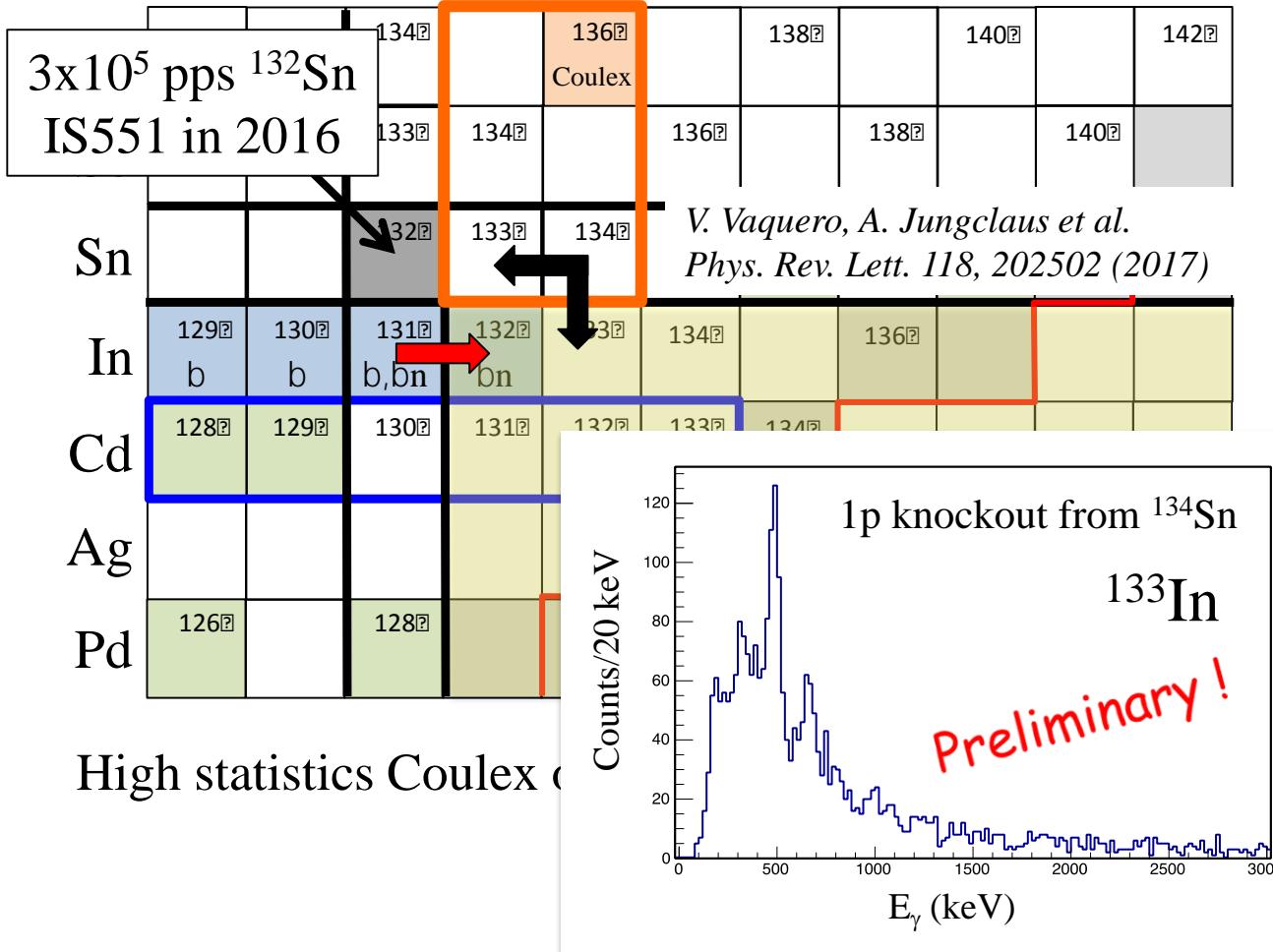
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Can we do better with low-energy transfer reactions ?

Previous studies in this region: In-beam spectroscopy

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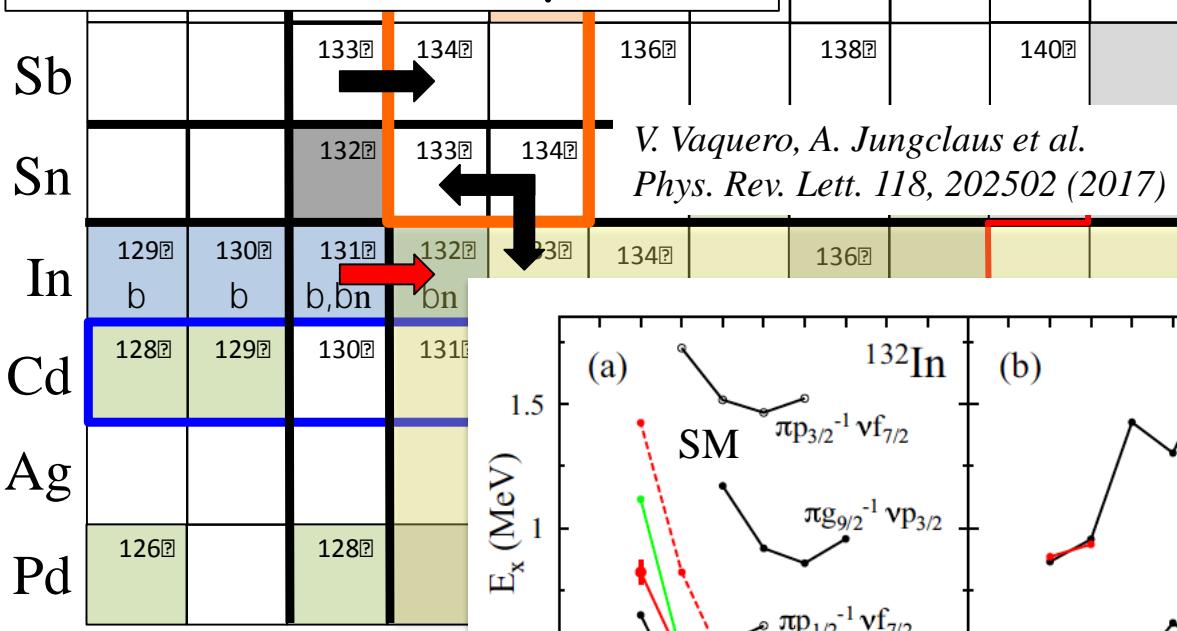
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To learn: $^{133}\text{Sb}(\text{d},\text{p})^{134}\text{Sb}$

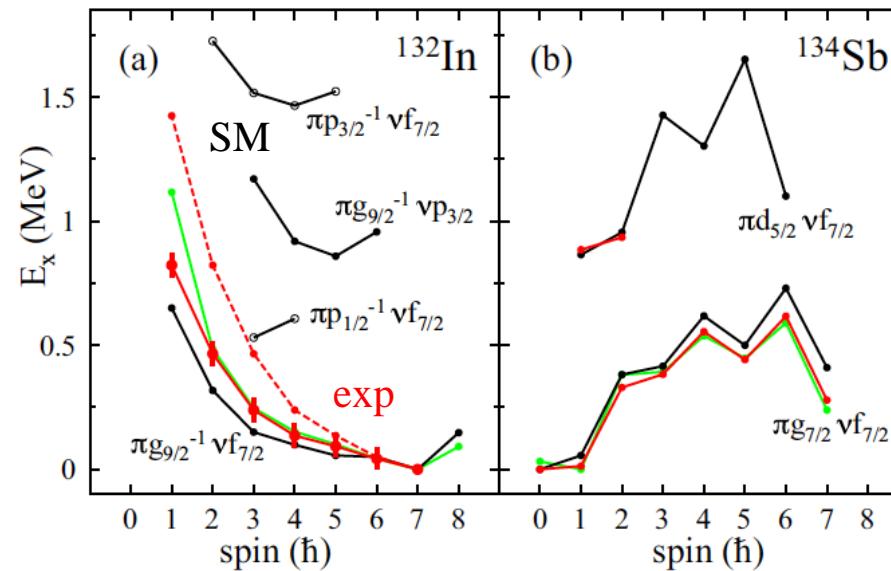


V. Vaquero, A. Jungclaus et al.
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PhD student

High statistics Coulomb



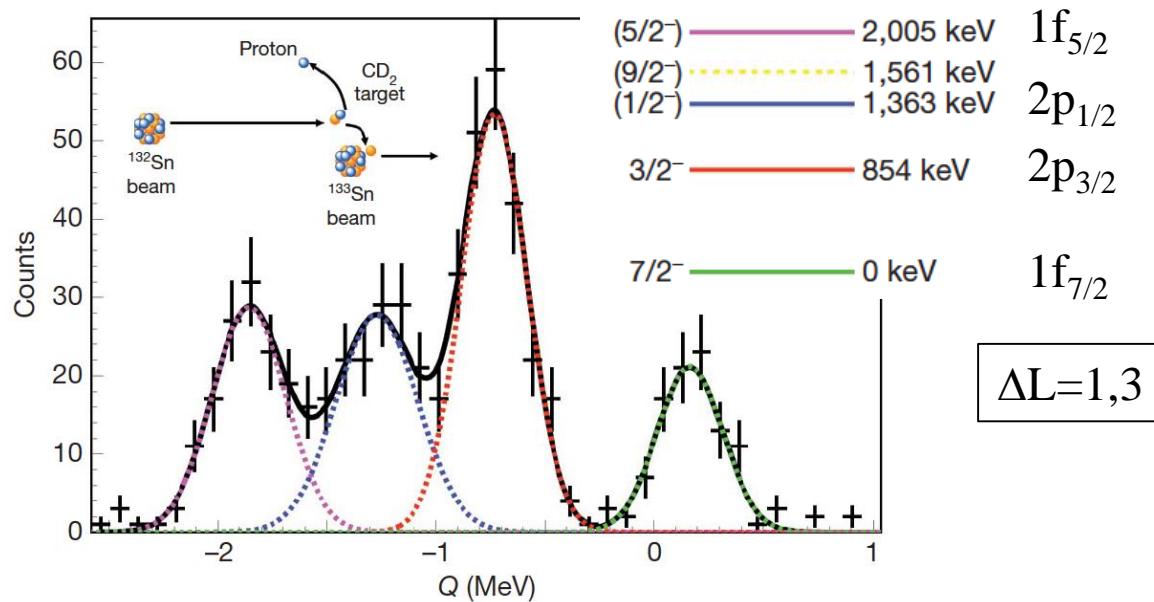
I) resolution,
coincidences,
at low-energy !

Can we do better with low-energy transfer reactions ?

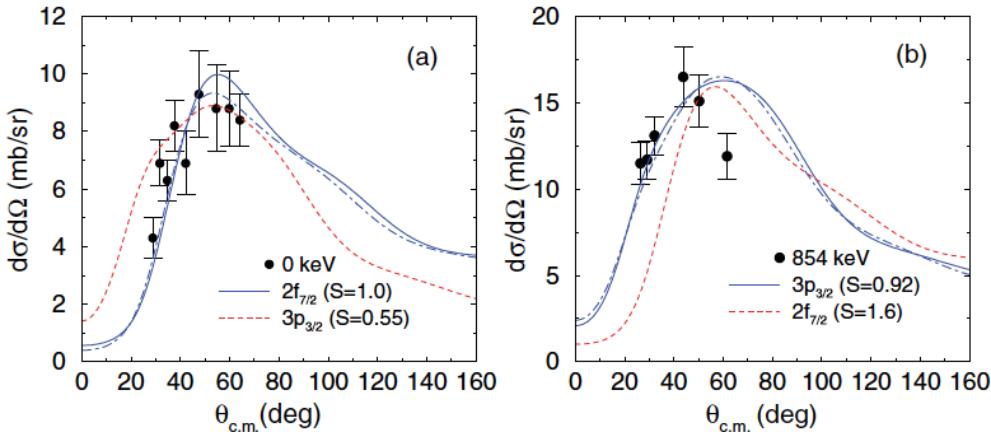
$^{132}\text{Sn}(\text{d},\text{p})^{133}\text{Sn}$ at HRIBF, Oak Ridge

Sb	132	133 $0g_{7/2}$	134
Sn	131	132	133
In	130	131	132

$E_b = 4.77 \text{ MeV/u}$



Differential cross sections



E_x (keV)	J^π	Configuration	S
0	$7/2^-$	$^{132}\text{Sn}_{\text{gs}} \otimes \nu_{f7/2}$	0.86 ± 0.16
854	$3/2^-$	$^{132}\text{Sn}_{\text{gs}} \otimes \nu_{p3/2}$	0.92 ± 0.18
$1,363 \pm 31$	$(1/2^-)$	$^{132}\text{Sn}_{\text{gs}} \otimes \nu_{p1/2}$	1.1 ± 0.3
2,005	$(5/2^-)$	$^{132}\text{Sn}_{\text{gs}} \otimes \nu_{f5/2}$	1.1 ± 0.2

K.L. Jones *et al.*
Nature 465, 454 (2010)
Phys. Rev. C 84, 034601 (2011)

β decay @ ISOLDE

P. Hoff *et al.*, *Phys. Rev. Lett.* 77, 1020 (1996)

$^{132}\text{Sn}(\text{d},\text{p})^{133}\text{Sn}$ vs. $^{133}\text{Sb}(\text{d},\text{p})^{134}\text{Sb}$

Sb	132	133 $0g_{7/2}$	134
Sn	131	132	133
In	130	131	132

Neutron single-particle states

$1f_{5/2}$ (5/2 $^{-}$) ————— 2,005 keV

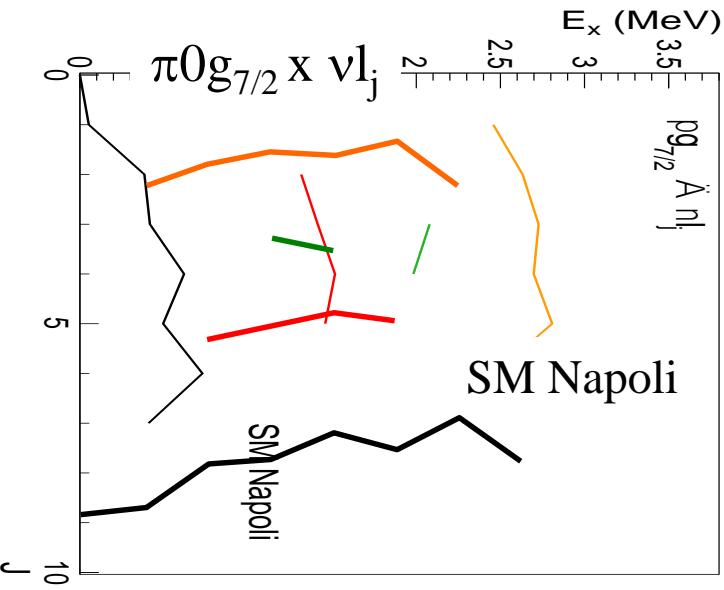
$2p_{1/2}$ (1/2 $^{-}$) ————— 1,363 keV

$2p_{3/2}$ 3/2 $^{-}$ ————— 854 keV

$1f_{7/2}$ 7/2 $^{-}$ ————— 0 keV

Sb	132	133 $0g_{7/2}$	134
Sn	131	132	133
In	130	131	132

Proton-neutron multiplets



Proposal P-524: $^{133}\text{Sb}(\text{d}, \text{p})^{134}\text{Sb}$

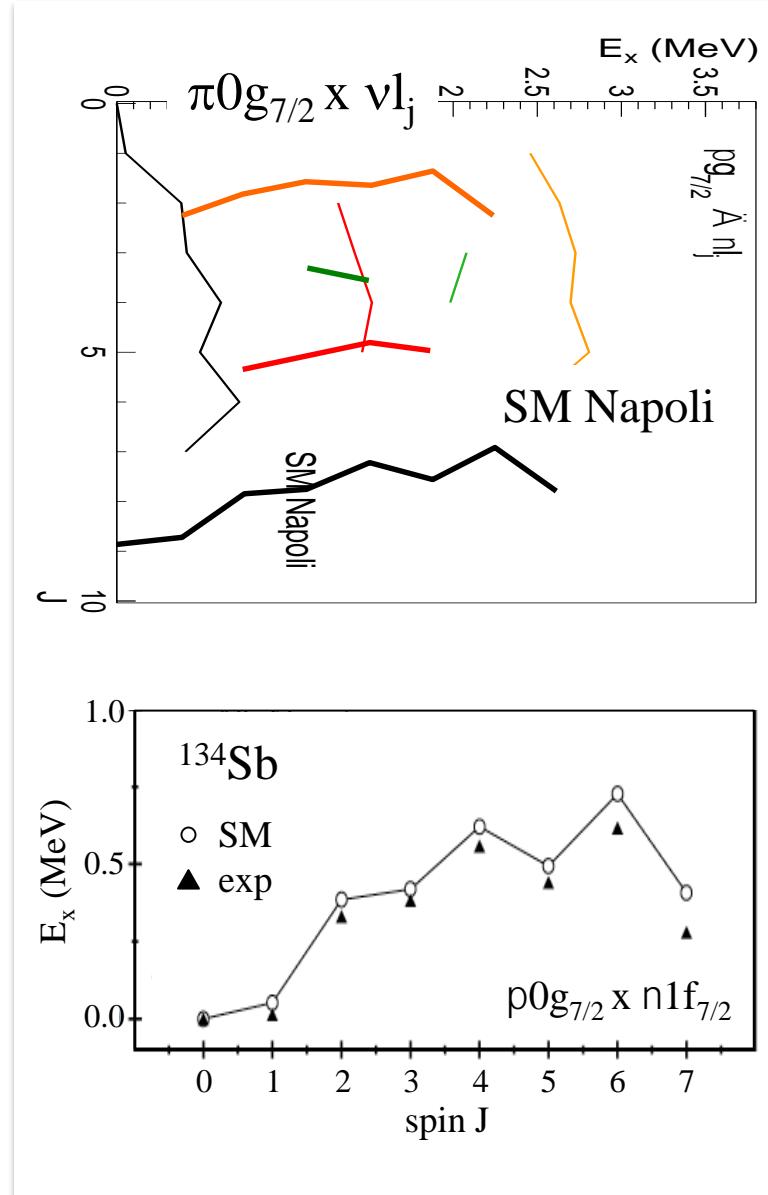
Goal of the proposed experiment:

Determination of the excitation energies
of the members of the three multiplets

$\pi 0g_{7/2} \times \nu 2p_{3/2}$

$\pi 0g_{7/2} \times \nu 2p_{1/2}$

$\pi 0g_{7/2} \times \nu 1f_{5/2}$



Proposal P-524: $^{133}\text{Sb}(\text{d}, \text{p})^{134}\text{Sb}$

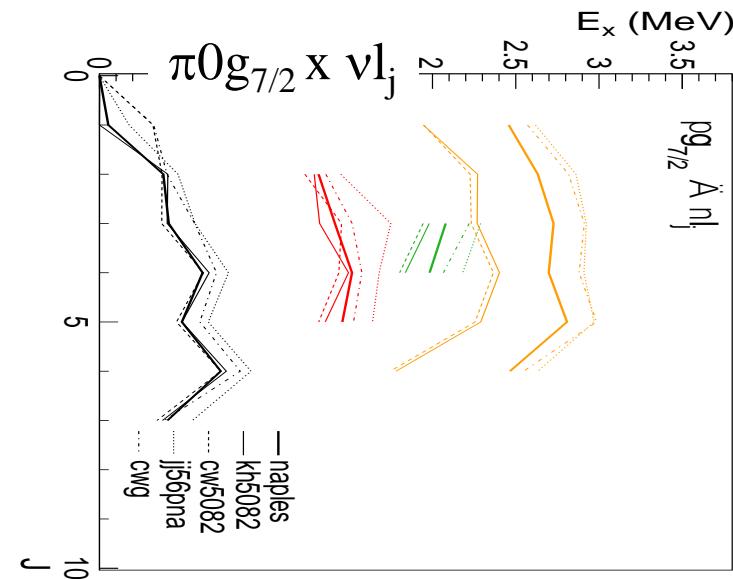
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$\pi 0g_{7/2} \times \nu 2p_{1/2}$

$\pi 0g_{7/2} \times \nu 1f_{5/2}$



Variety of SM predictions !

Proposal P-524: $^{133}\text{Sb}(\text{d},\text{p})^{134}\text{Sb}$

Goal of the proposed experiment:

Determination of the excitation energies of the members of the three multiplets

$\pi 0g_{7/2} \times v 2p_{3/2}$

$\pi 0g_{7/2} \times v 2p_{1/2}$

$\pi 0g_{7/2} \times v 1f_{5/2}$

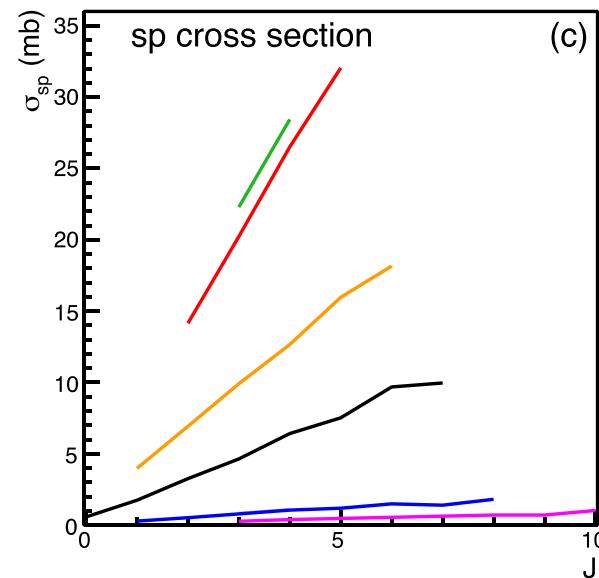
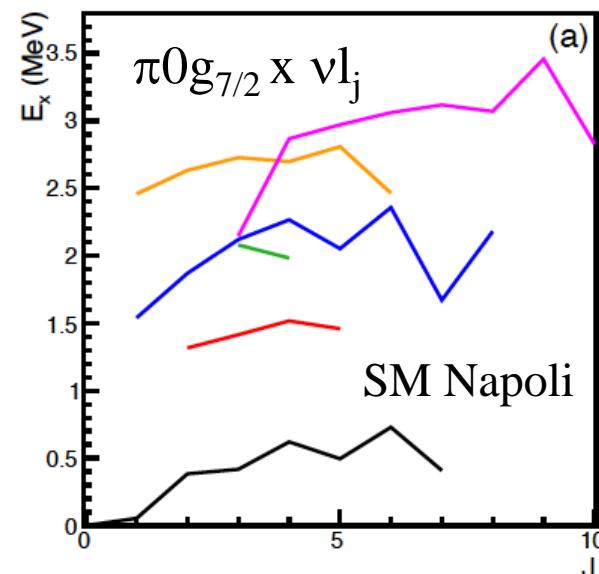
At 5.0 MeV/u much smaller cross sections to the members of the multiplets

$\pi 0g_{7/2} \times v 0h_{9/2} \quad \Delta L=5$

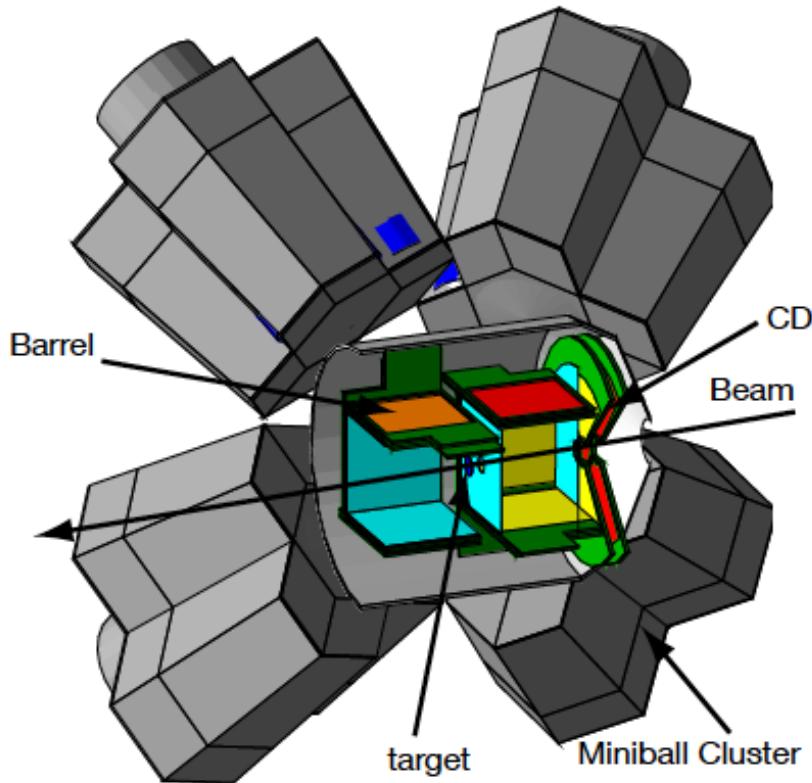
$\pi 0g_{7/2} \times v 0i_{13/2} \quad \Delta L=6$

^{134}Sb is an odd-odd nucleus with a high level density, **but**:

The (d,p) reaction allows to selectively populate only these multiplets ($\Delta L=1,3$), i.e. 12 excited states with unknown E_x !



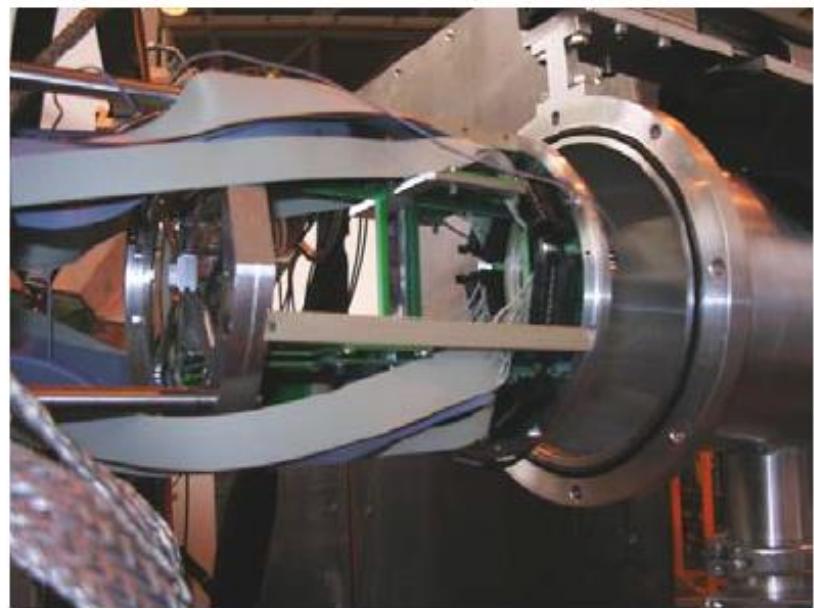
Proposal P-524: The experimental setup



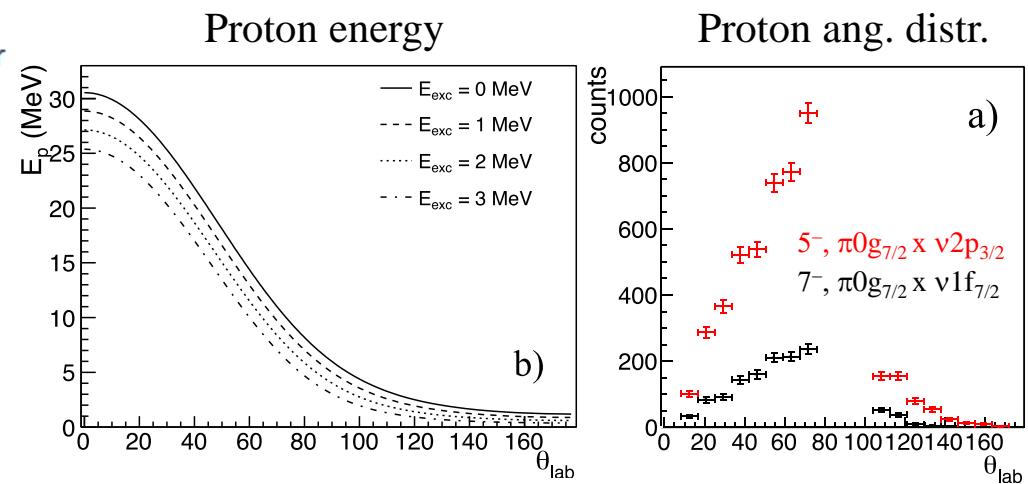
MINIBALL + T-REX

^{133}Sb @ 5 MeV/u, 10^5 pps
1 mg/cm² CD₂ target

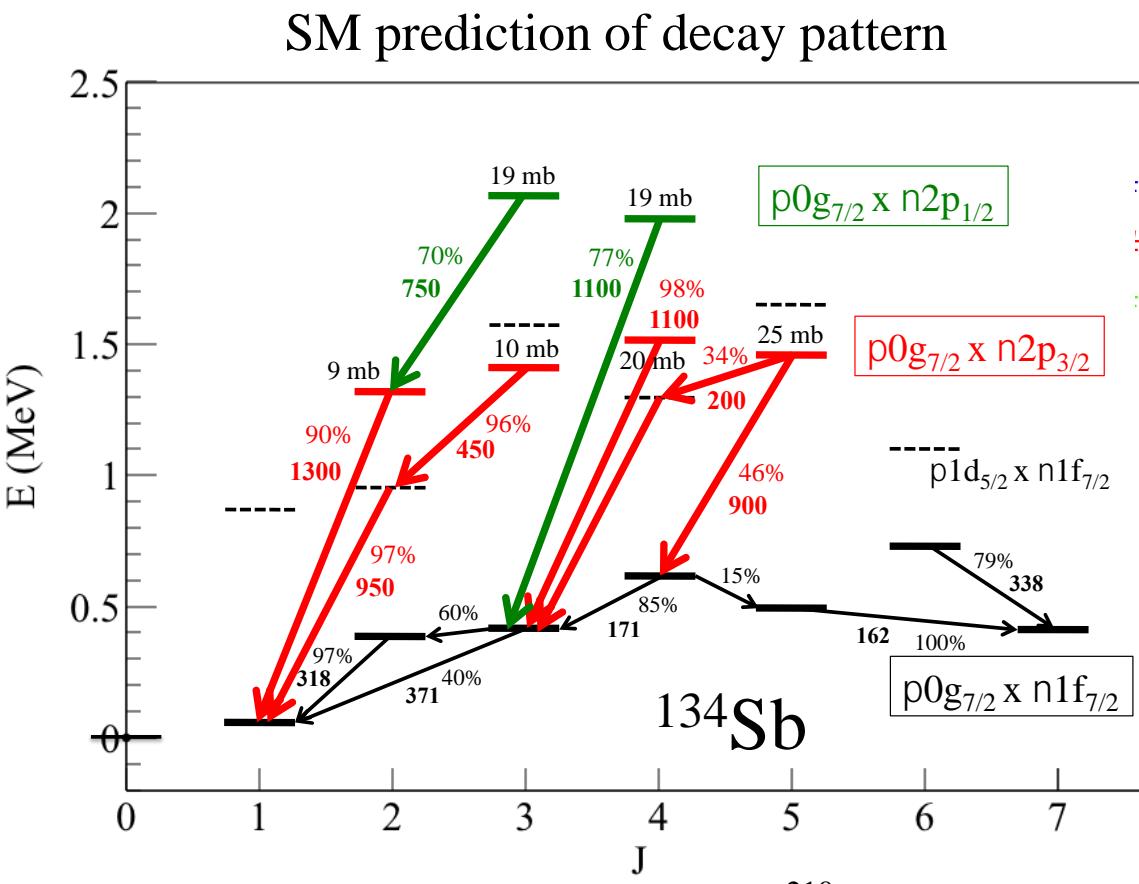
Detect protons in T-REX and
 γ rays in MINIBALL !



Kathrin Wimmer, PhD Thesis, TU München 2010



Proposal P-524: Identification of excited states

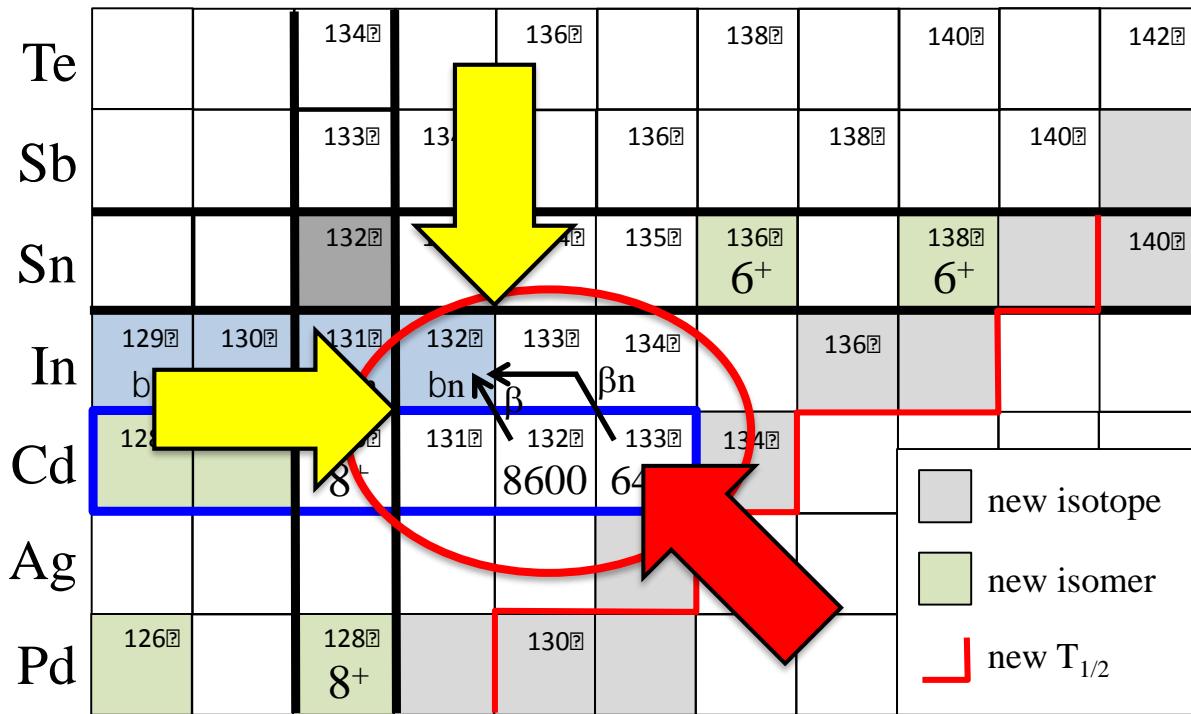


Experimental information:

- proton- γ coincidence
 - $\varepsilon_{\gamma} \sim 6\%$ for 900-1100 keV,
1750 p γ in 5 days
 - proton kinematics \rightarrow rough E_x
& differential cross section
 - \rightarrow which multiplet
 - proton- $\gamma\gamma$ coincidence
 - $\varepsilon_{\gamma} \sim 13\%$ for 160-300 keV
230 p $\gamma\gamma$ in 5 days
 - \rightarrow which state

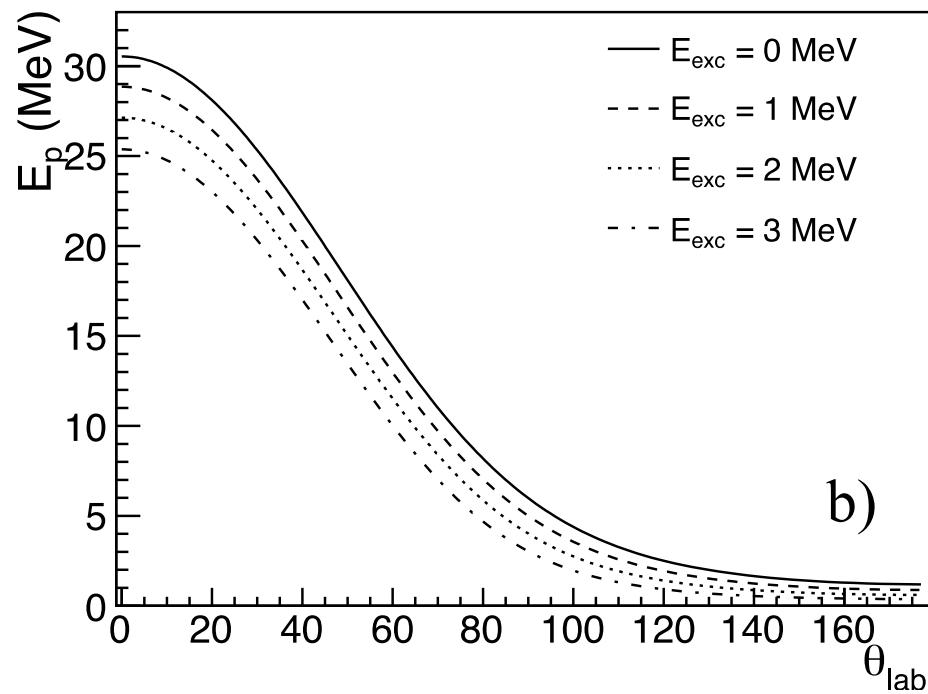
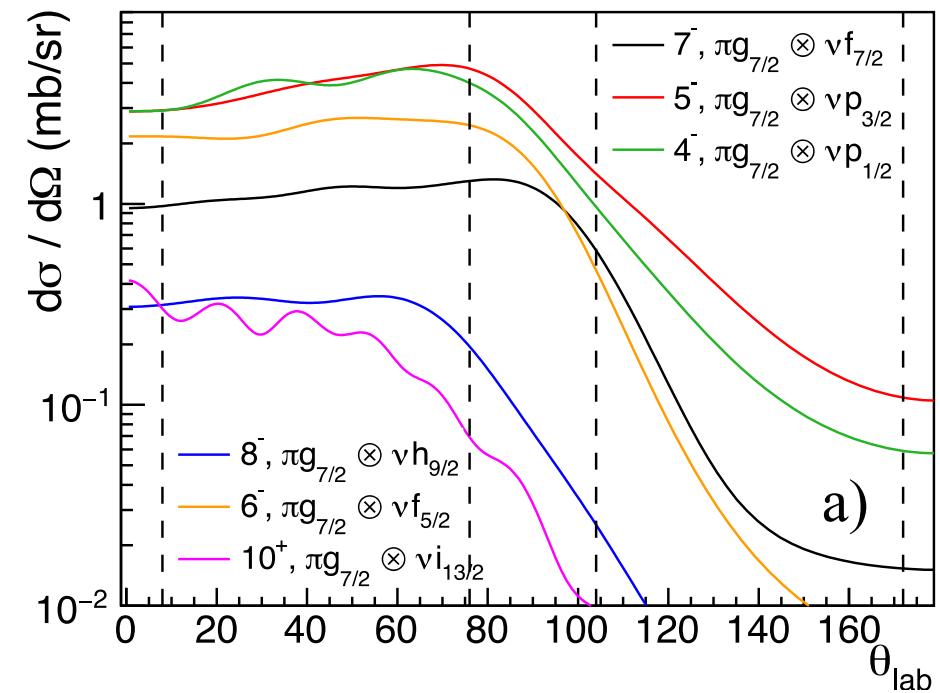
Similar to analysis presented by J. Diriken et al. for the ${}^{66}\text{Ni}(\text{d},\text{p}){}^{67}\text{Ni}$ reaction
J. Diriken et al., Phys. Rev. C 91, 054321 (2015); Phys. Lett. B 736, 533 (2014)

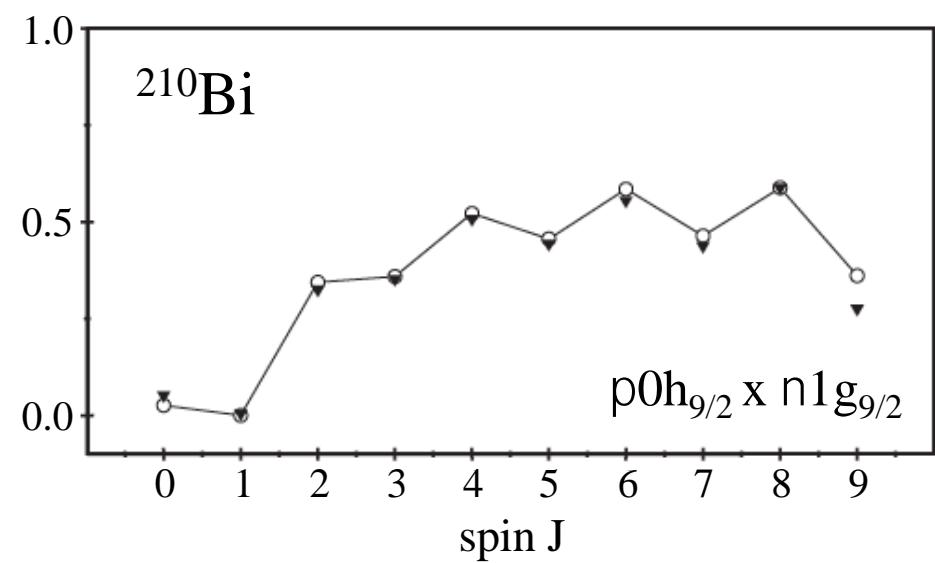
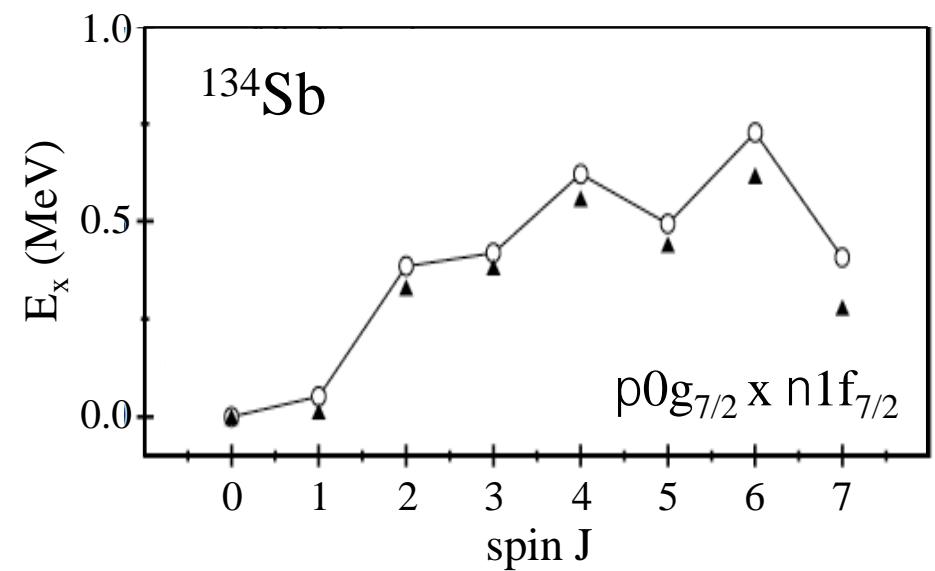
In the future ...

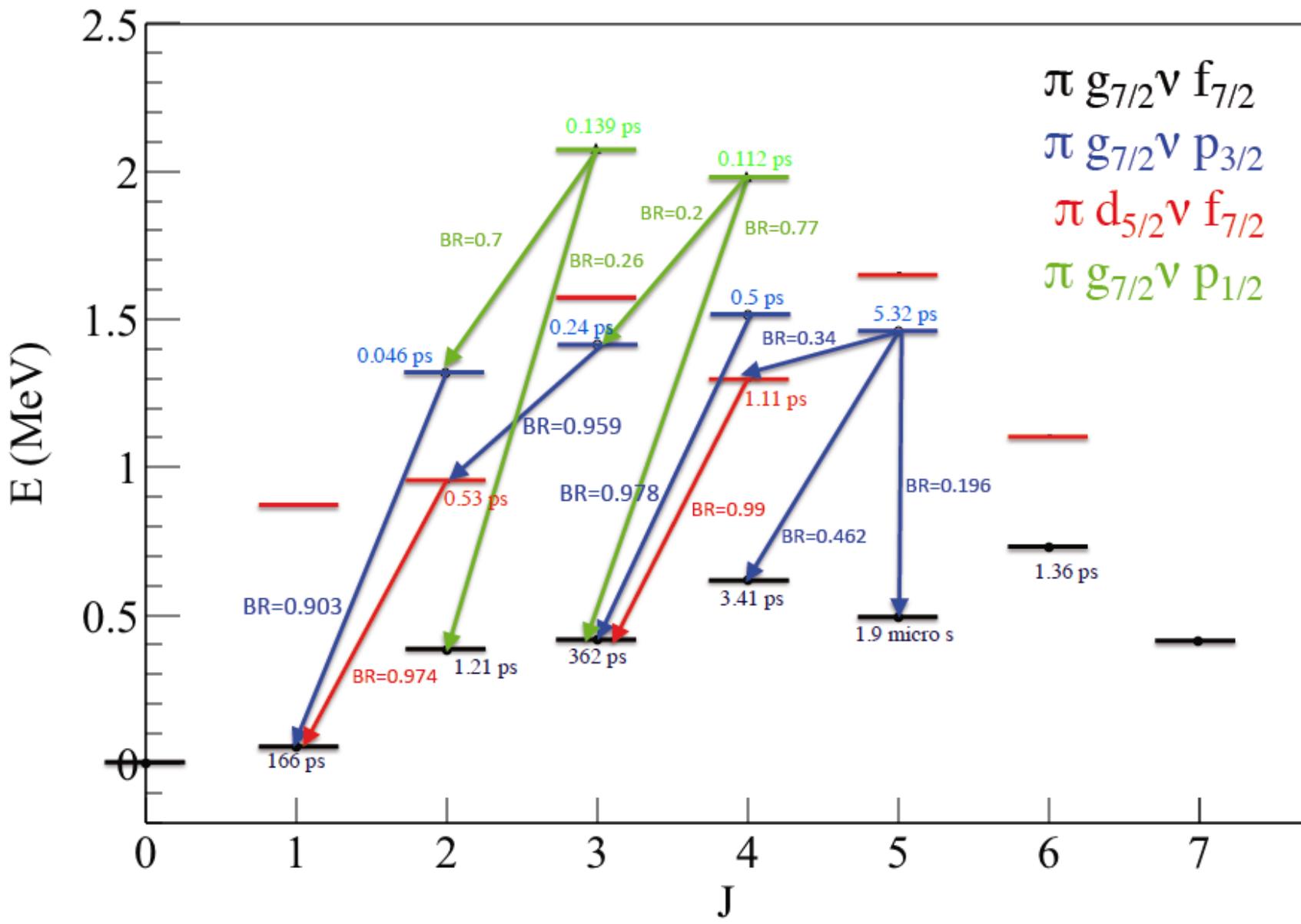


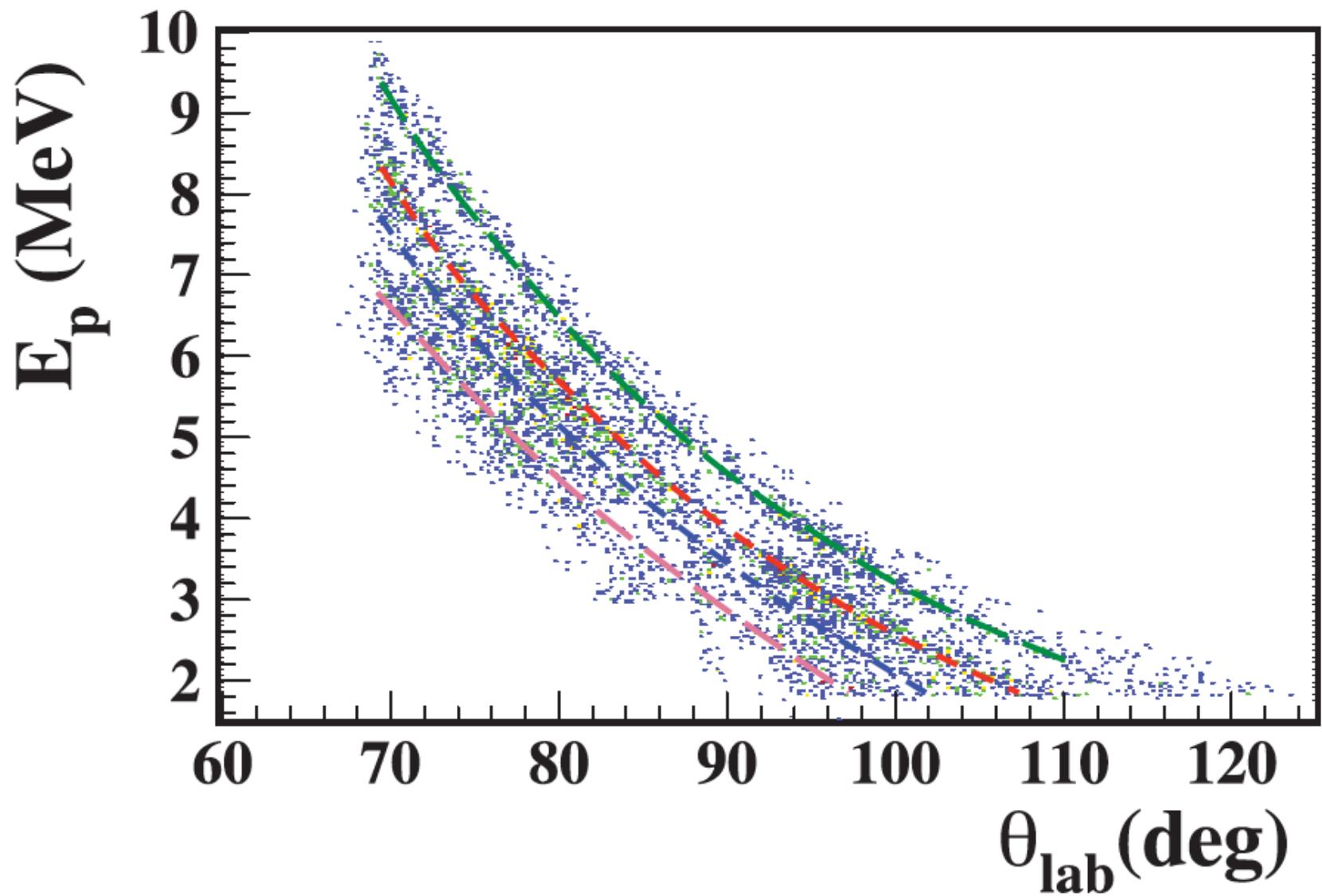
Need complementary techniques to progress in this region !

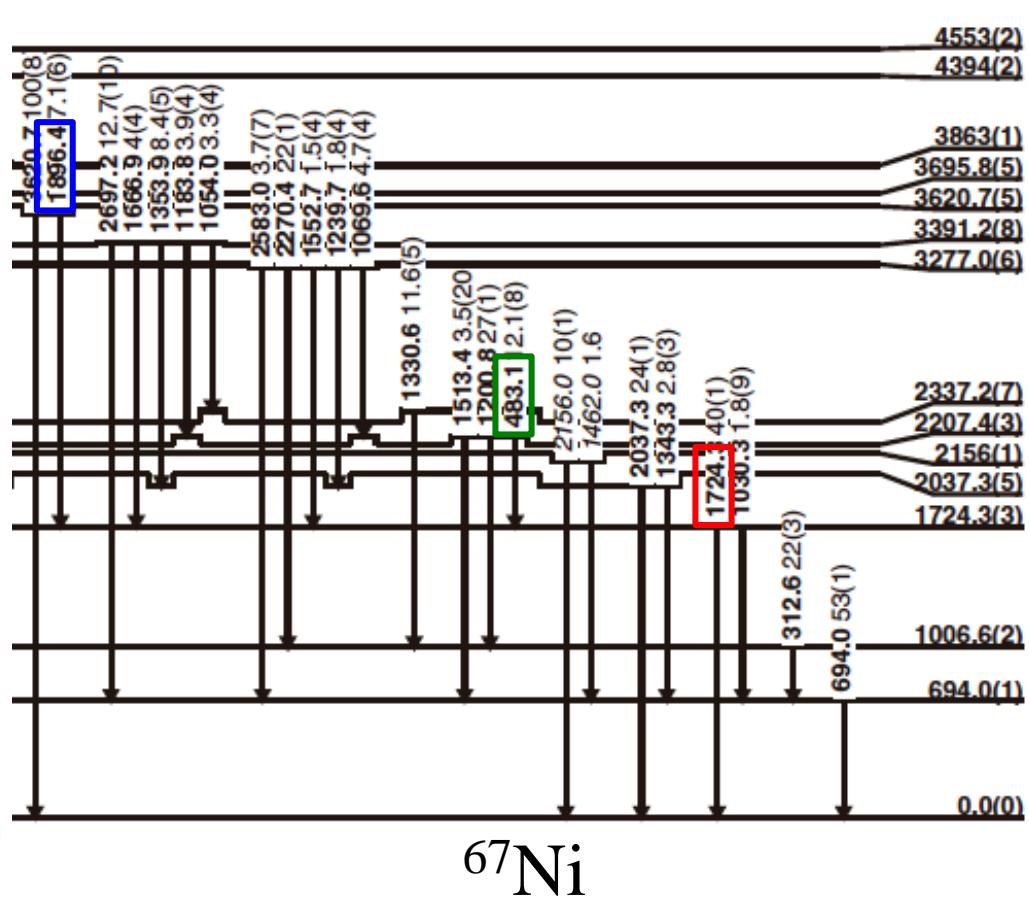
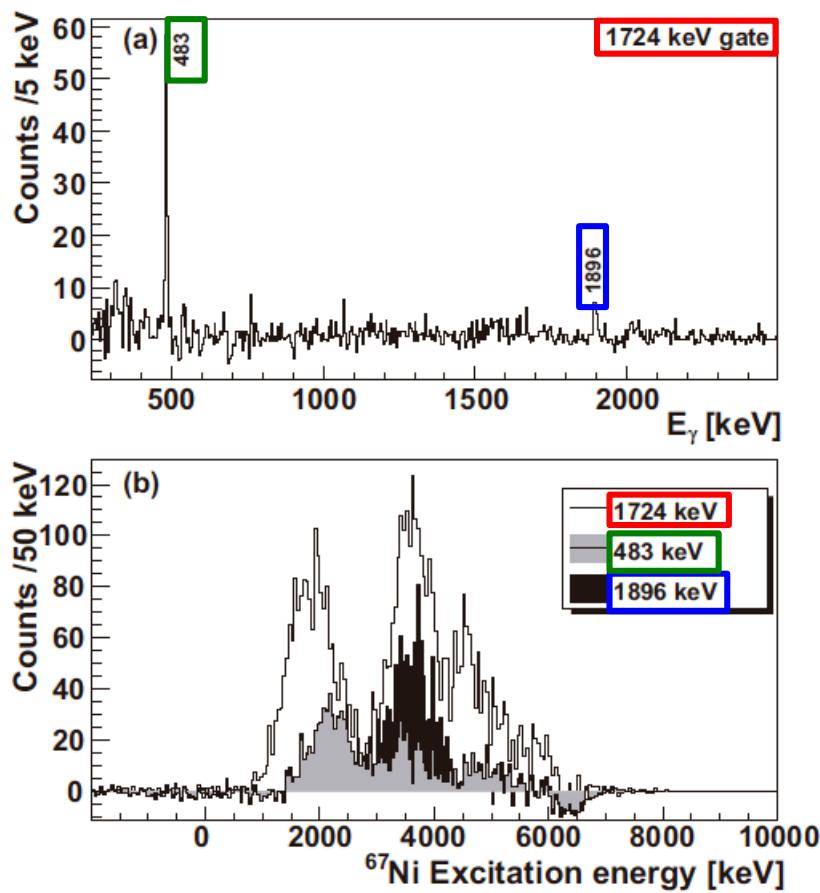
Develop low-energy reaction program at ISOLDE ...

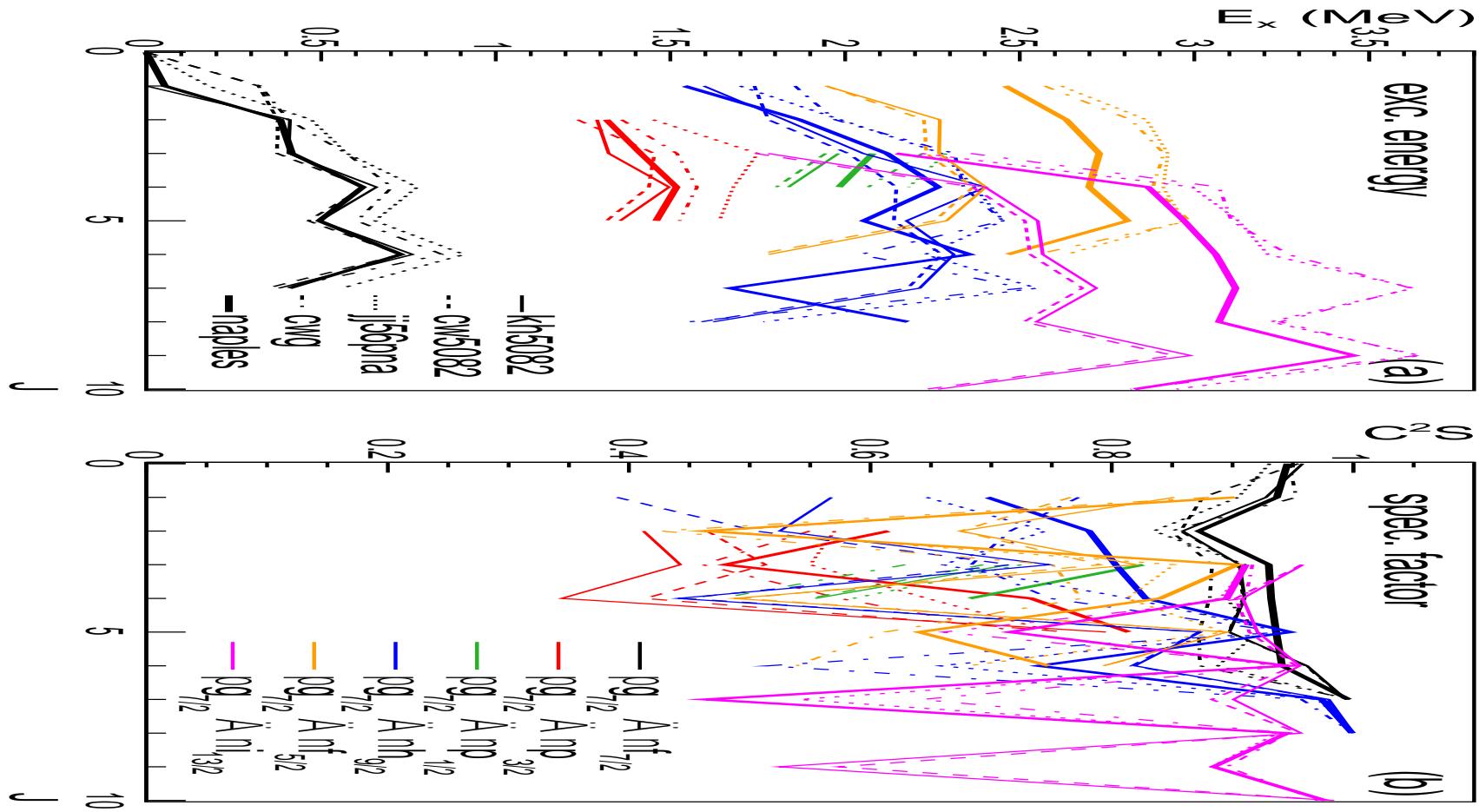


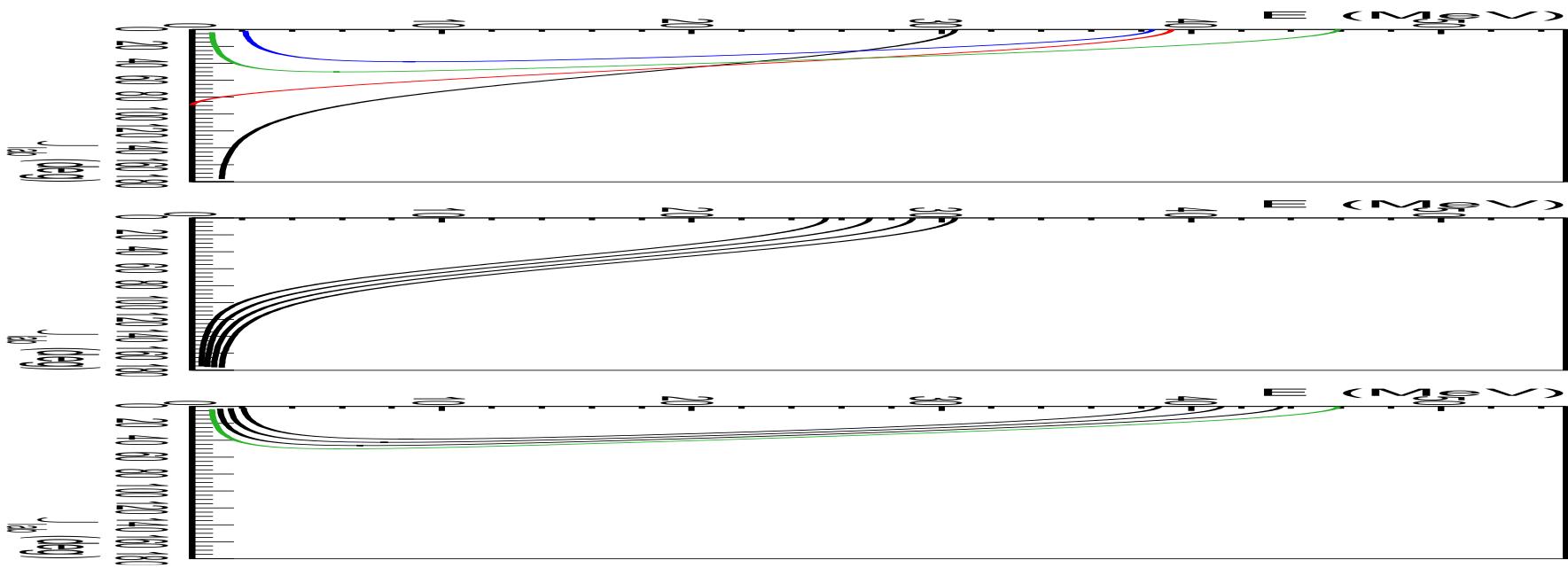


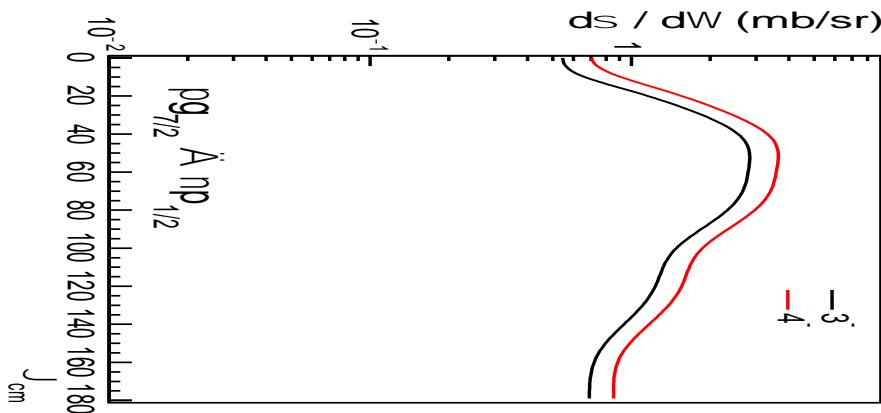
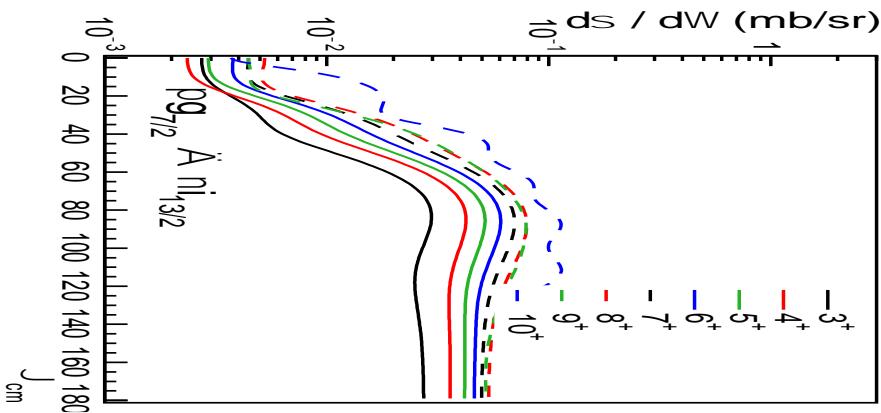
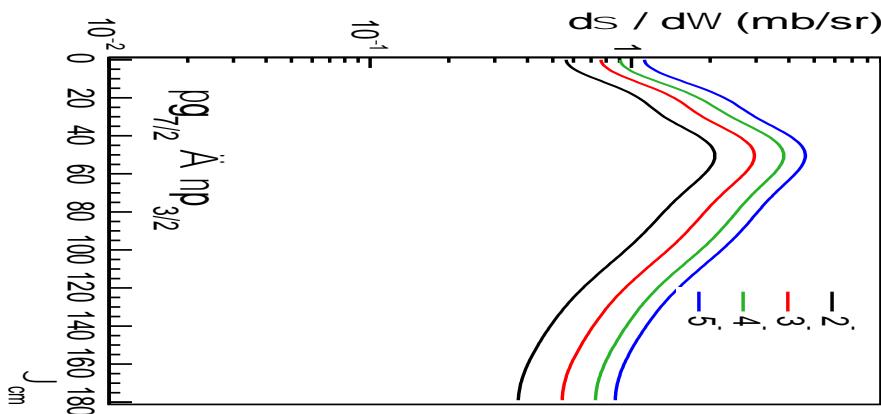
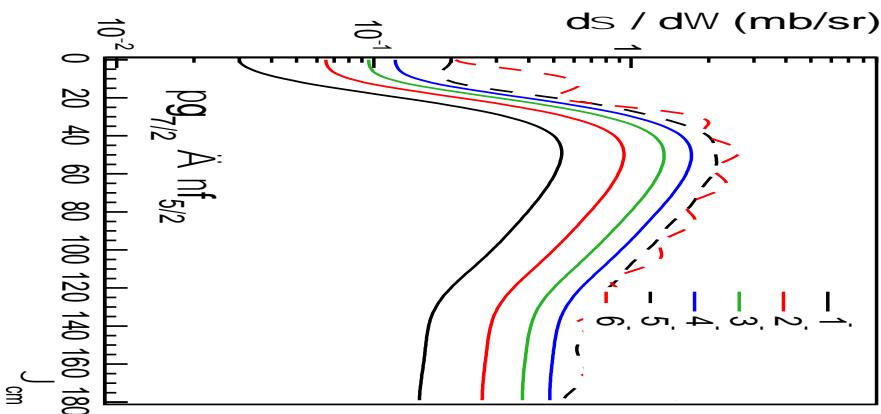
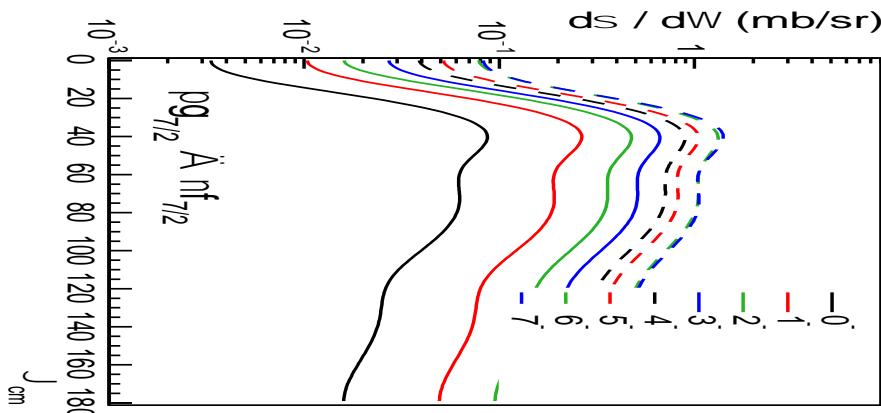
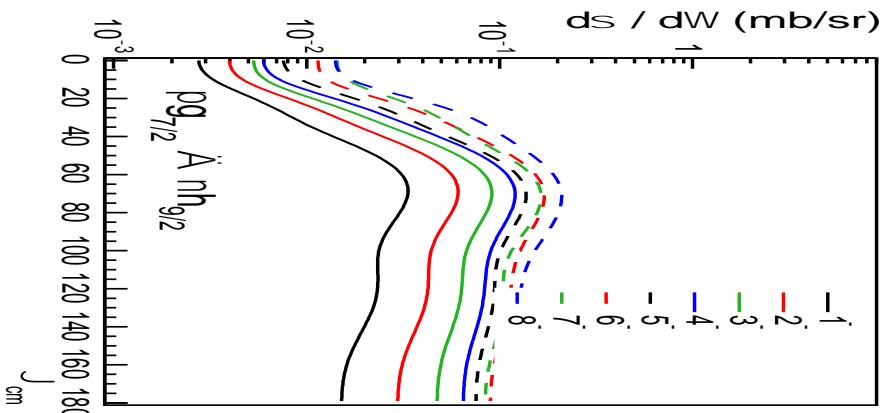


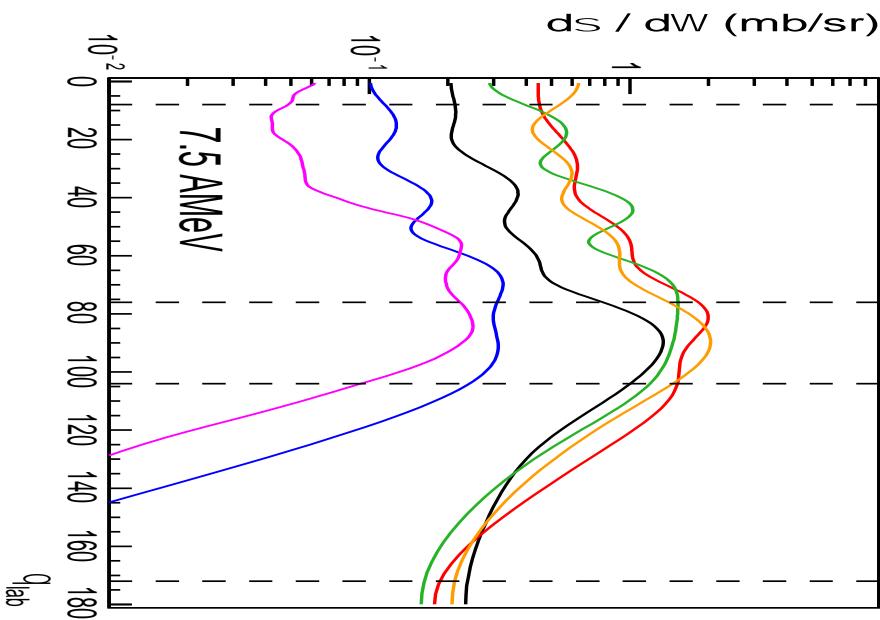
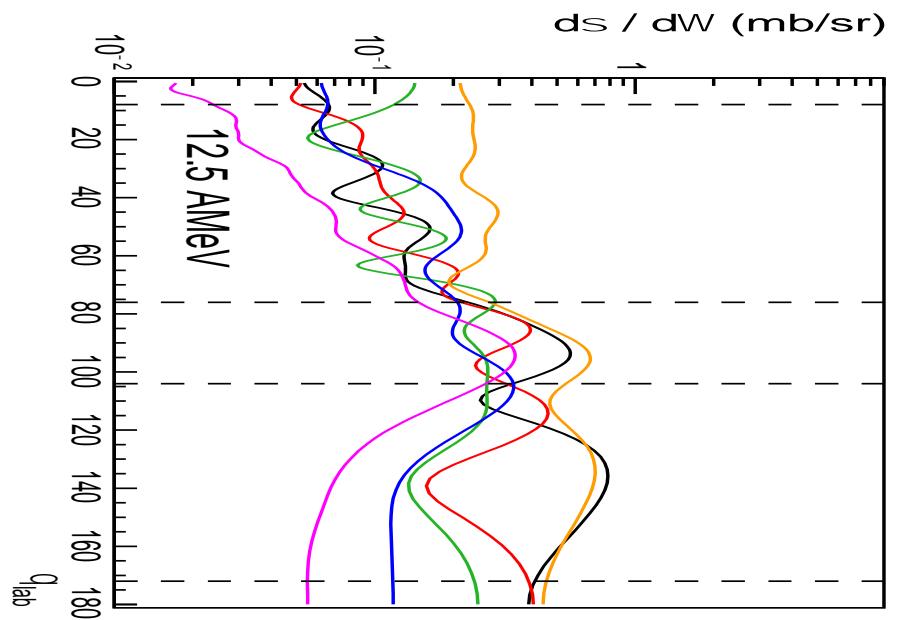
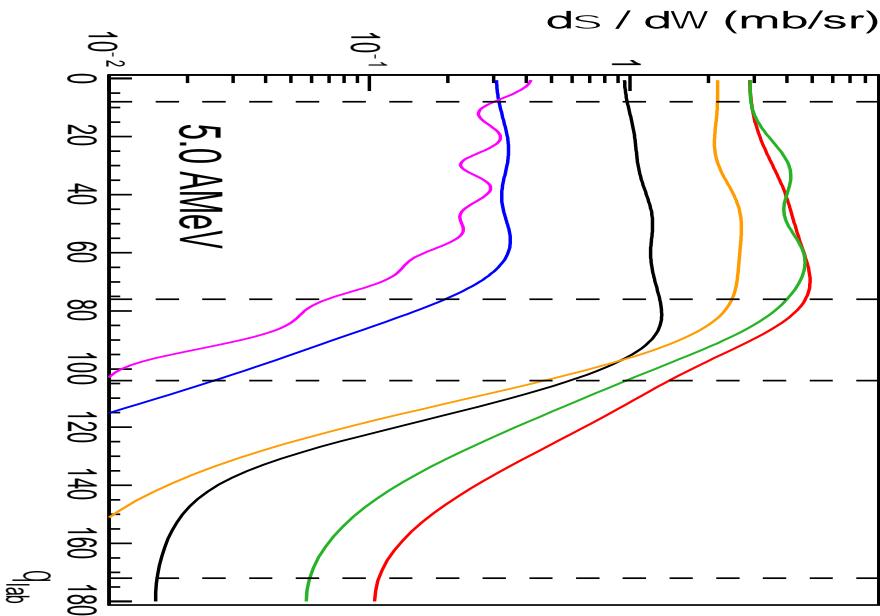
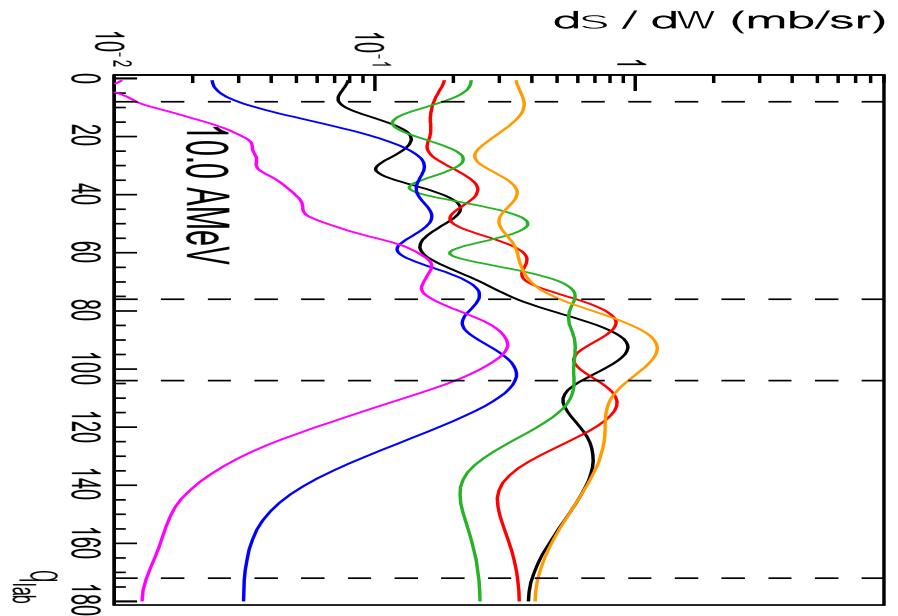


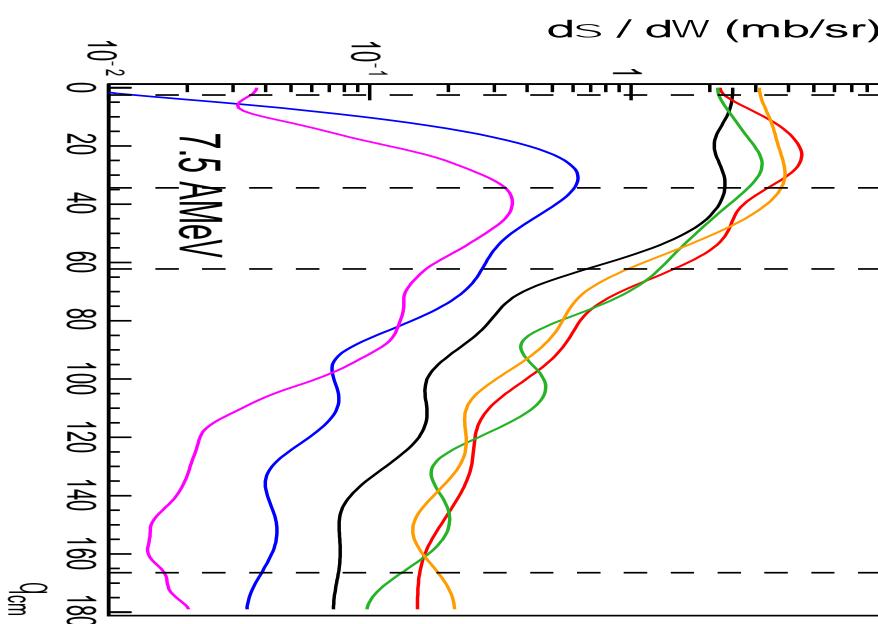
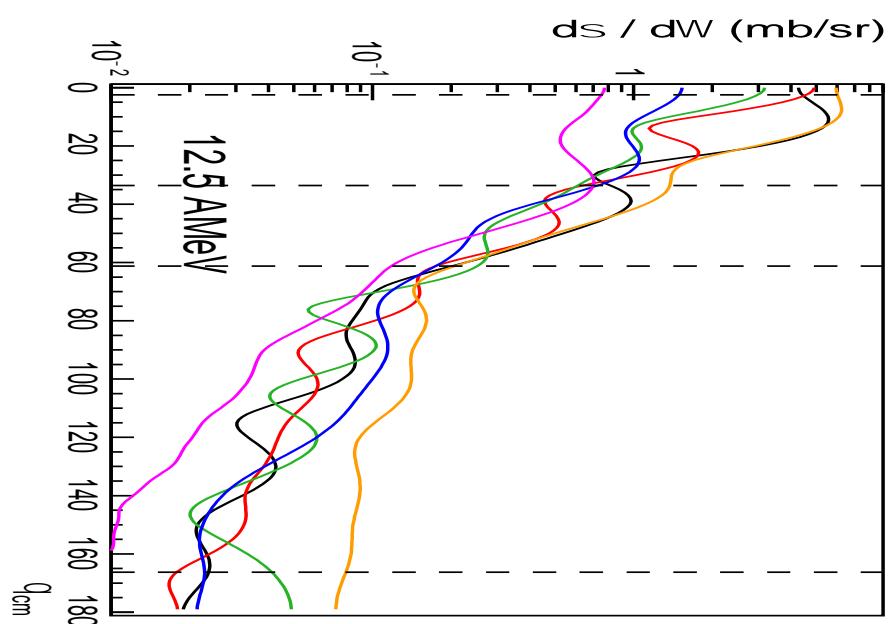
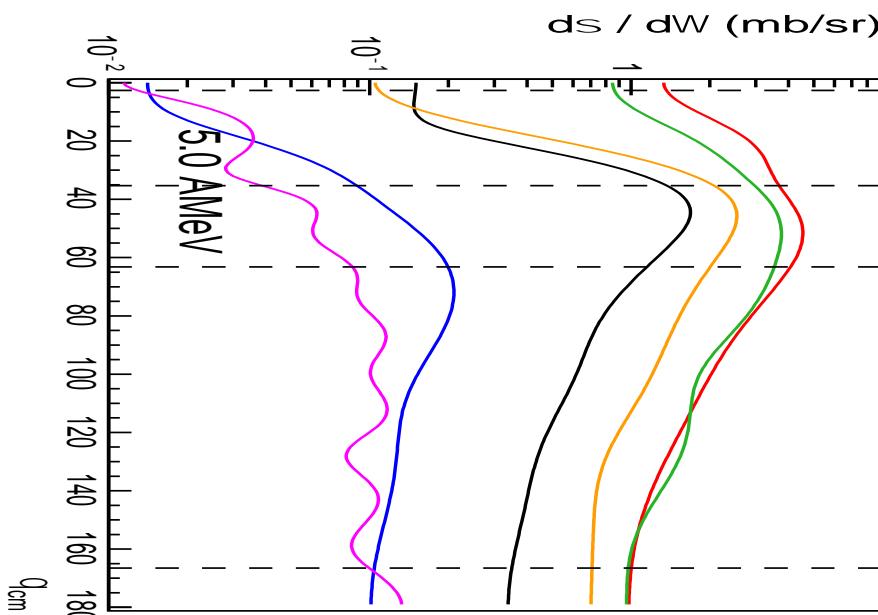
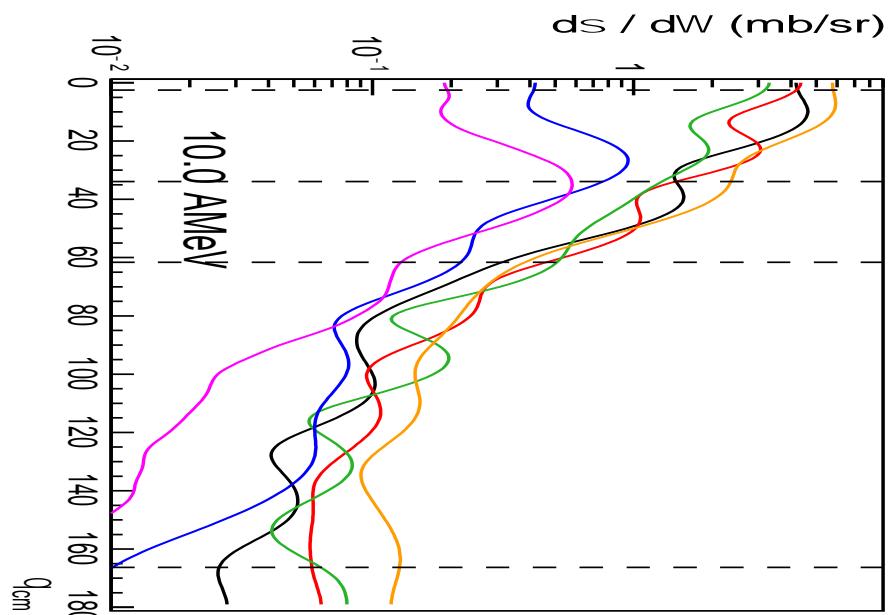






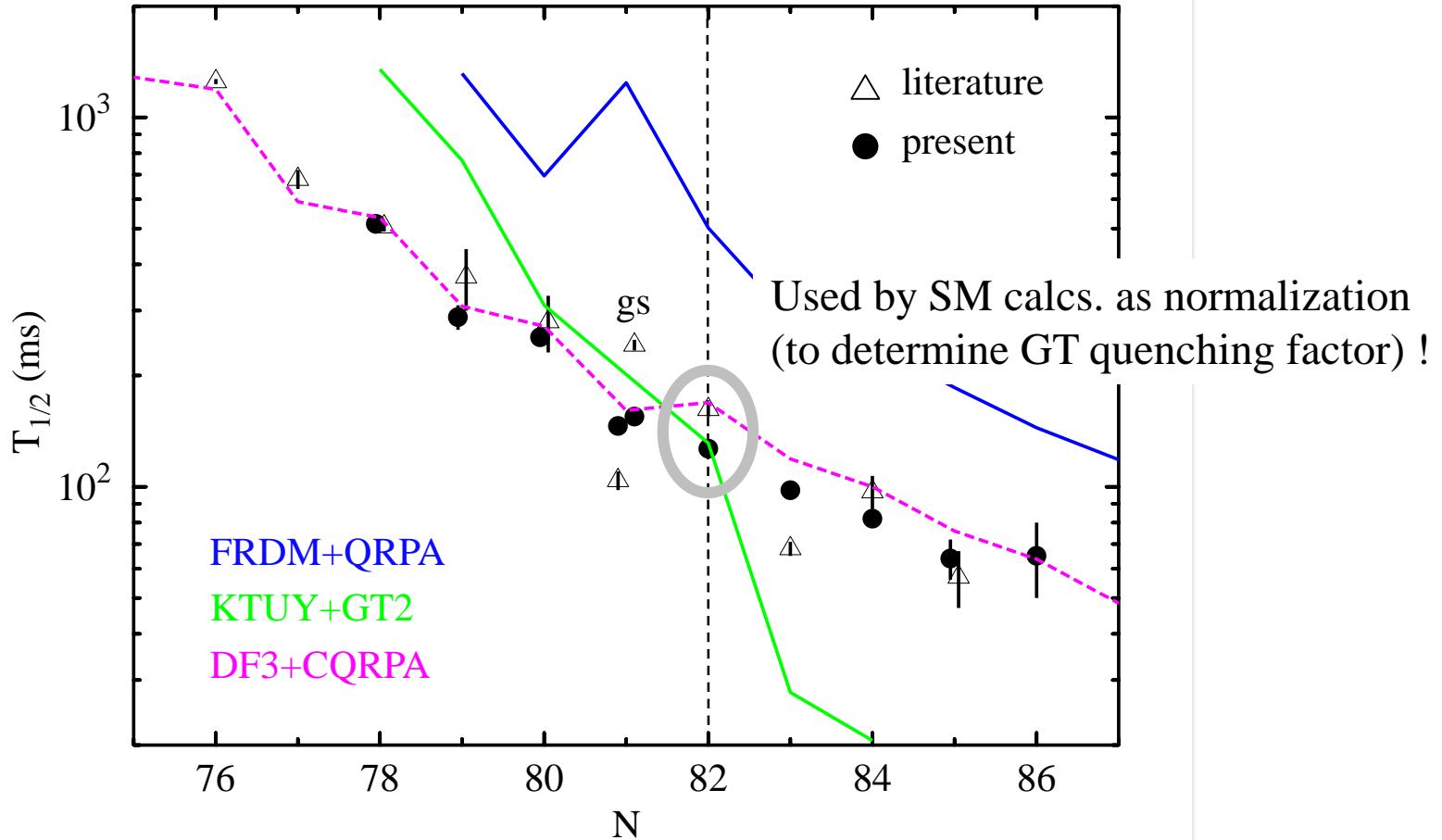






Sb	132	133	134
Sn	131	132	133
In	130	131	132

Half-life measurement for the Cd isotopes



Previous studies in the ^{132}Sn region: Decay spectroscopy EURICA experiment NP1112-RIBF85 (December 2012)

RISING@GSI 2006:

Factor ~200 less ^{238}U !

A. Jungclaus et al., PRL 99, 132501 (2007)

			132 \pm	133 \pm	134 \pm	135 \pm	136 \pm 6 $^+$	138 \pm 6 $^+$	140 \pm	142 \pm
Sn										
In	129 \pm b	130 \pm b	131 \pm bn	132 \pm bn	133 \pm	134 \pm	136 \pm	138 \pm	140 \pm	142 \pm
Cd	128 \pm	129 \pm	130 \pm 8 $^+$	131 \pm	132 \pm	133 \pm	134 \pm			
Ag										
Pd	126 \pm		128 \pm 8 $^+$		130 \pm					

Legend:
 new isotope
 new isomer
└ new $T_{1/2}$



Jan Taprogge (IEM-CSIC)
PhD May 2015
UAM Madrid

8-10 pnA ^{238}U beam

Roughly factor 10 below
RIBF design value !

J. Taprogge, A. Jungclaus et al., Phys. Rev. Lett. 112, 132501 (2014)

J. Taprogge, A. Jungclaus et al., Phys. Lett. B 738, 223 (2014)

J. Taprogge, A. Jungclaus et al., Phys. Rev. C 91, 054324 (2015)

J. Taprogge, A. Jungclaus et al., Eur. Phys. J. A 52, 347 (2016)

A. Jungclaus et al., Phys. Rev. C 93, 041301(R) (2016)

A. Jungclaus et al., Phys. Rev. C 94, 024303 (2016)

A. Jungclaus et al., Phys. Lett. B 772, 483 (2017)

SM: A. Gargano & H. Grawe

H. Watanabe et al., Phys. Rev. Lett. 111, 152501 (2013)

G.S. Simpson et al., Phys. Rev. Lett. 113, 132502 (2014)

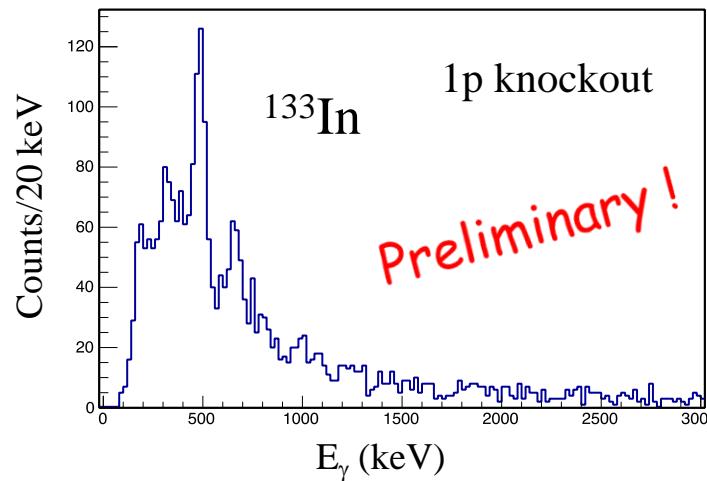
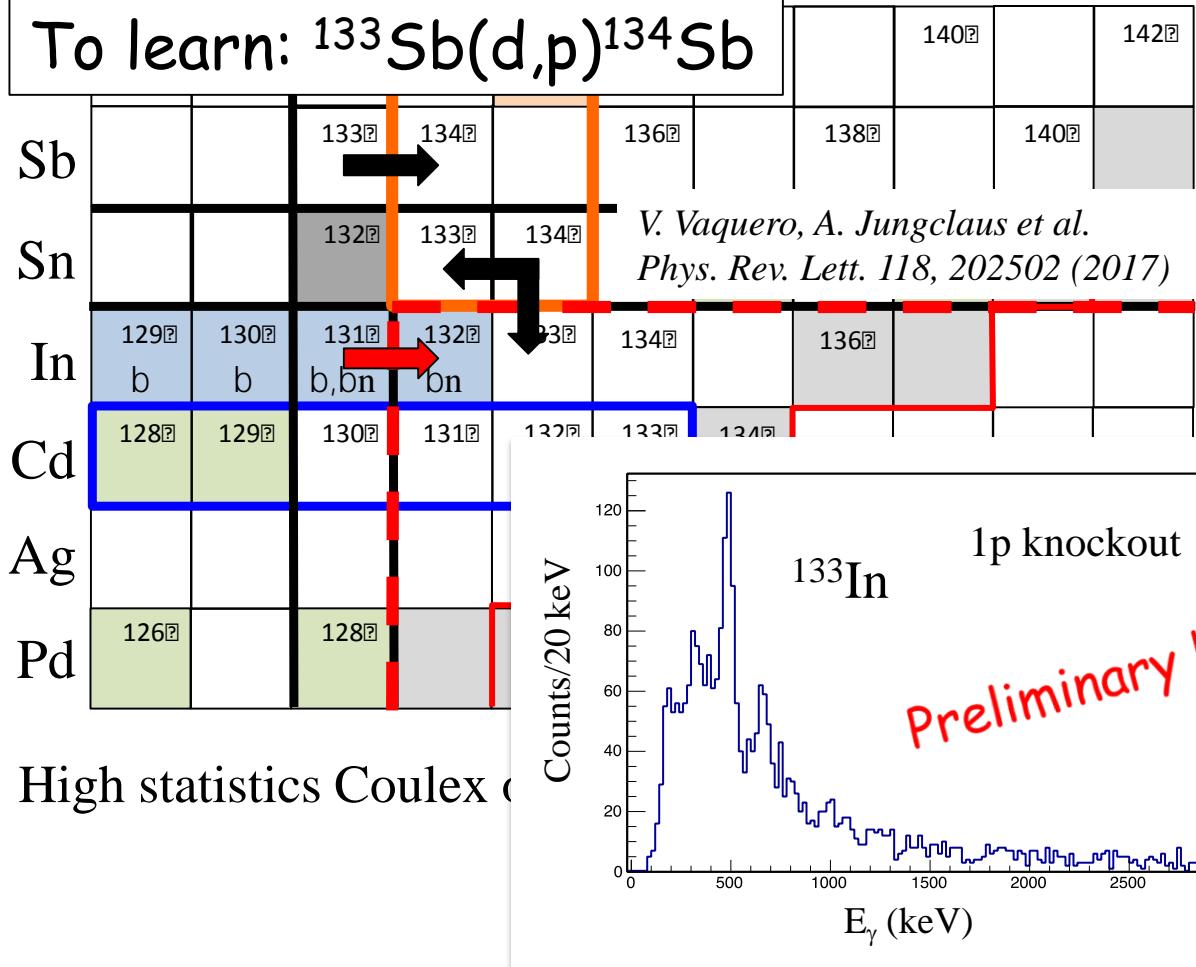
H. Watanabe et al., Phys. Rev. Lett. 113, 042502 (2014)

G. Lorusso et al., Phys. Rev. Lett. 114, 192501 (2015)

Y. Shimizu et al., J. Phys. Soc. Japan, in press

Our previous studies in this region: In-beam spectroscopy DALI2 experiment NP1306-RIBF98R1 (April 2015)

To learn: $^{133}\text{Sb}(\text{d},\text{p})^{134}\text{Sb}$



Victor Vaquero (IEM-CSIC)
PhD student

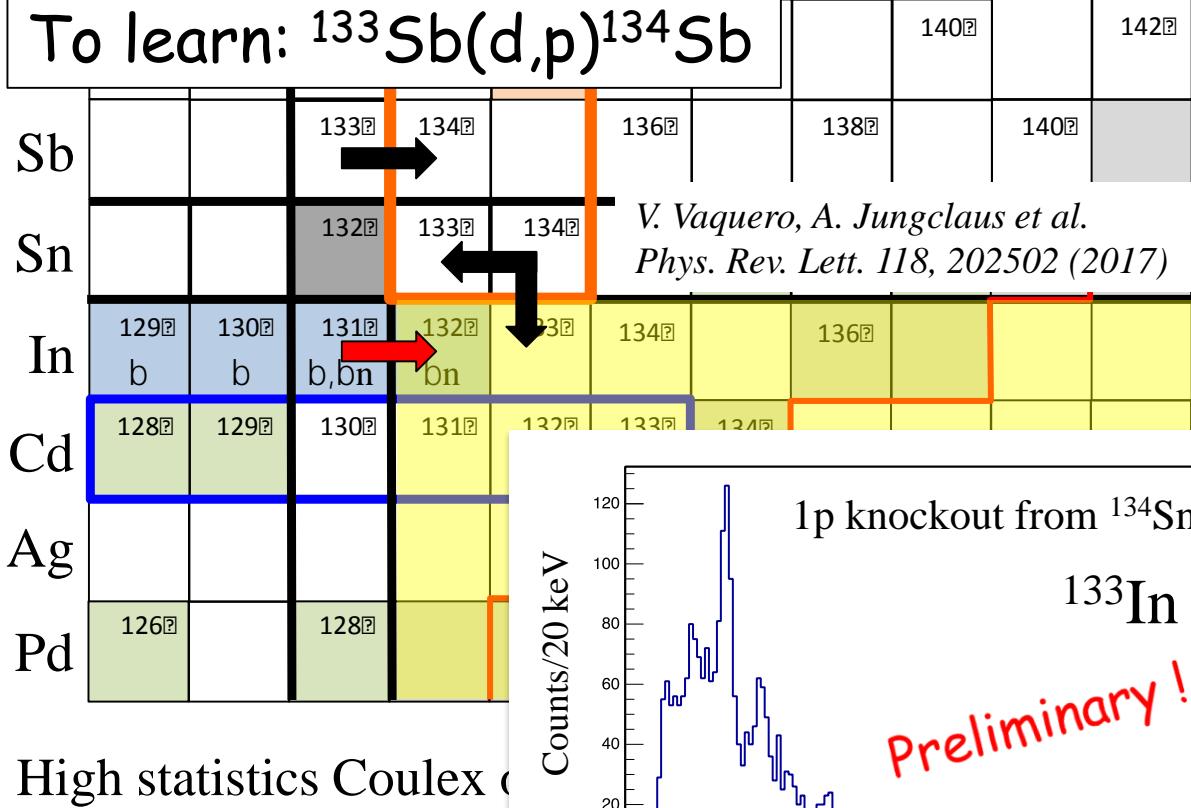
Na(I) resolution,
no $\gamma\gamma$ coincidences,
no γ at low-energy !

Can we do better with low-energy transfer reactions ?

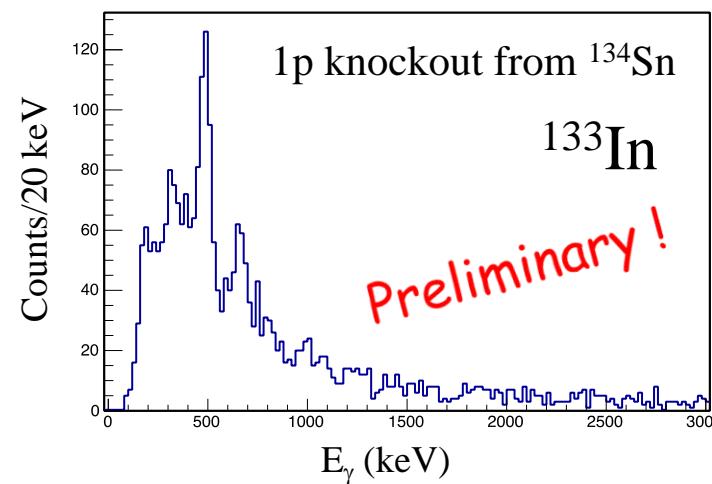
Previous studies in this region: In-beam spectroscopy

DALI2 experiment NP1306-RIBF98R1 (April 2015)

To learn: $^{133}\text{Sb}(\text{d},\text{p})^{134}\text{Sb}$



Victor Vaquero (IEM-CSIC)
PhD student



High statistics Coulex e- scattering

Na(I) resolution,
no $\gamma\gamma$ coincidences,
no γ at low-energy !

Can we do better with low-energy transfer reactions ?

$^{132}\text{Sn}(\text{d},\text{p})^{133}\text{Sn}$ vs. $^{133}\text{Sb}(\text{d},\text{p})^{134}\text{Sb}$

Sb	132	133 $0g_{7/2}$	134
Sn	131	132	133
In	130	131	132

Neutron single-particle states

$1f_{5/2}$ (5/2 $^{-}$) ————— 2,005 keV

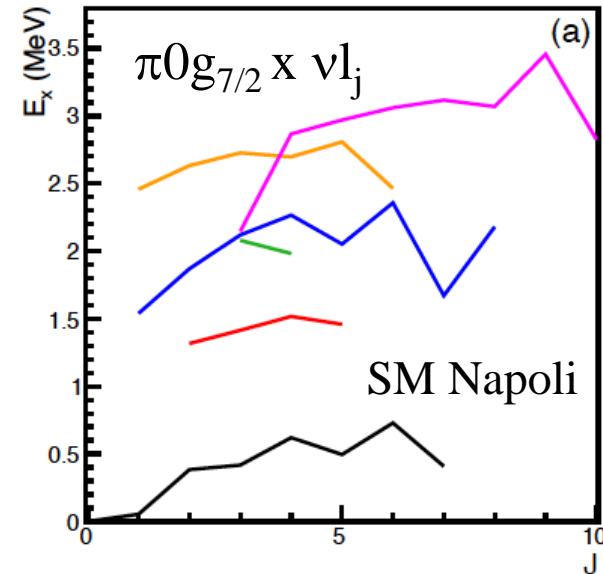
$2p_{1/2}$ (1/2 $^{-}$) ————— 1,363 keV

$2p_{3/2}$ 3/2 $^{-}$ ————— 854 keV

$1f_{7/2}$ 7/2 $^{-}$ ————— 0 keV

Sb	132	133 $0g_{7/2}$	134
Sn	131	132	133
In	130	131	132

Proton-neutron multiplets



Proposal P-524: $^{133}\text{Sb}(\text{d}, \text{p})^{134}\text{Sb}$

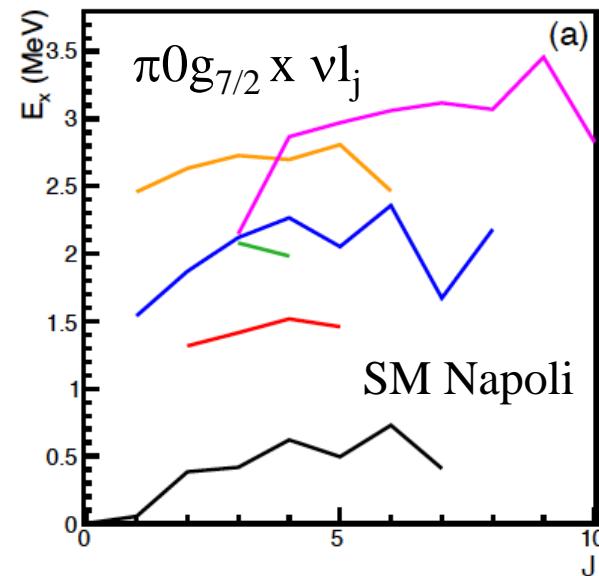
Goal of the proposed experiment:

Determination of the excitation energies
of the members of the three multiplets

$$\pi 0g_{7/2} \times \nu 2p_{3/2}$$

$$\pi 0g_{7/2} \times \nu 2p_{1/2}$$

$$\pi 0g_{7/2} \times \nu 1f_{5/2}$$



Proposal P-524: $^{133}\text{Sb}(\text{d}, \text{p})^{134}\text{Sb}$

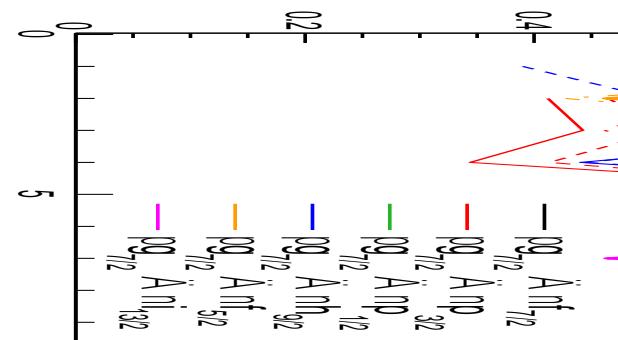
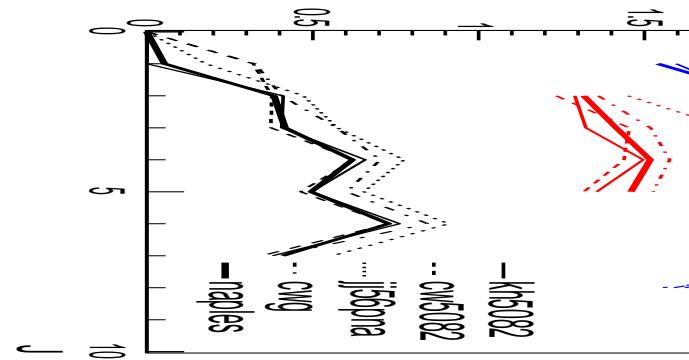
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$\pi 0g_{7/2} \times \nu 2p_{3/2}$

$\pi 0g_{7/2} \times \nu 2p_{1/2}$

$\pi 0g_{7/2} \times \nu 1f_{5/2}$



Variety of SM predictions !

Proposal P-524: $^{133}\text{Sb}(\text{d},\text{p})^{134}\text{Sb}$

Goal of the proposed experiment:

Determination of the excitation energies of the members of the three multiplets

$\pi 0g_{7/2} \times \nu 2p_{3/2}$

$\pi 0g_{7/2} \times \nu 2p_{1/2}$

$\pi 0g_{7/2} \times \nu 1f_{5/2}$

^{134}Sb is an odd-odd nucleus with a high level density, but the (d,p) reaction allows to selectively populate only these multiplets ($\Delta L=1,3$) !

