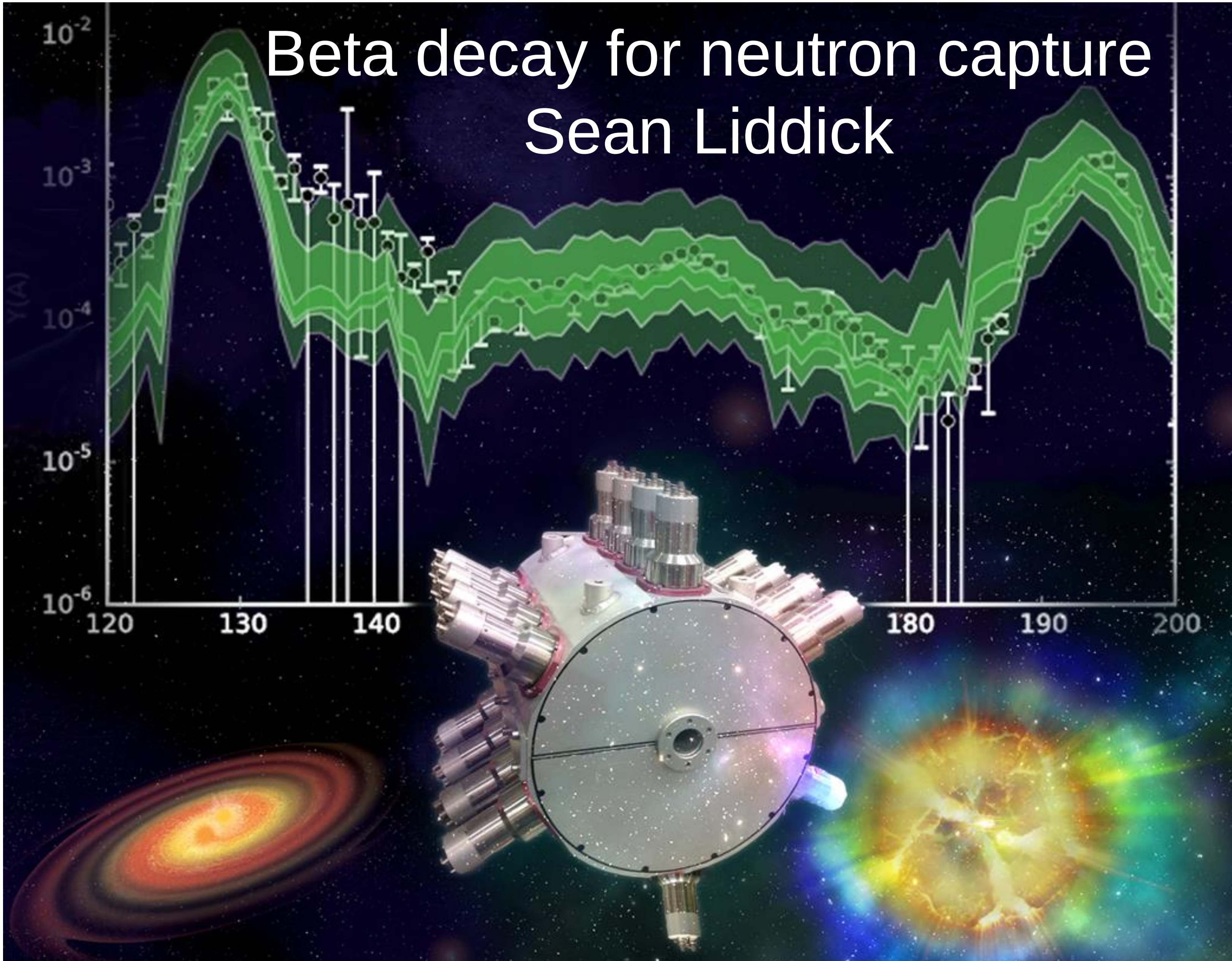
Beta decay for neutron capture

Sean Liddick

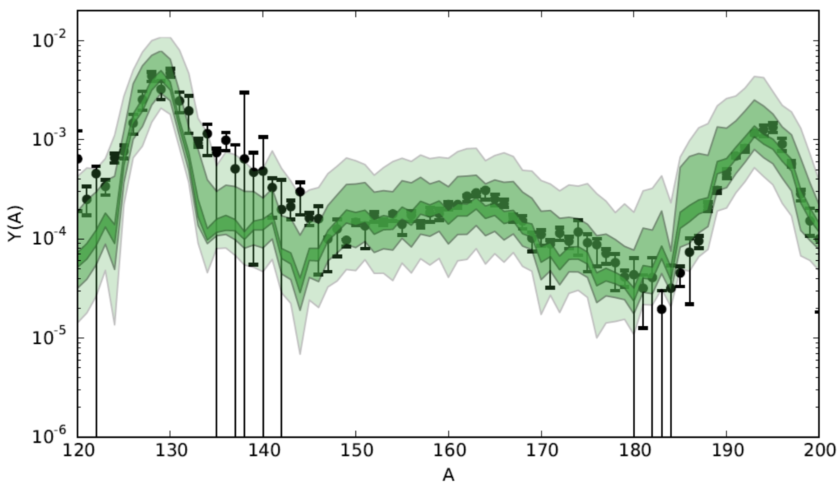


National Science Foundation
Michigan State University

6th Oslo Workshop on Strength and Level Density,

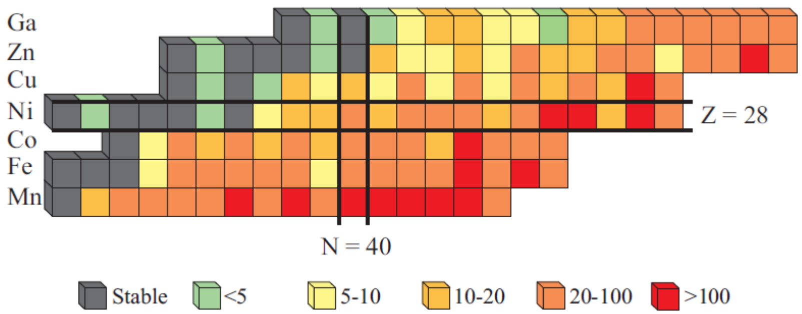
May 8-12, 2017

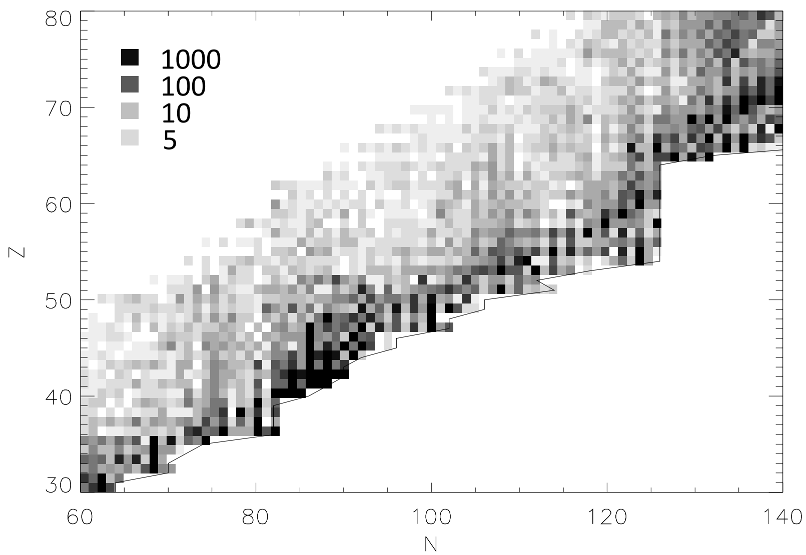
Nuclear Physics Uncertainties for r-process: (n,γ)



Monte-Carlo variations of (n,γ) rates within a factor 100 – 10 – 2 (light – darker – dark bands)

(n,γ) uncertainties

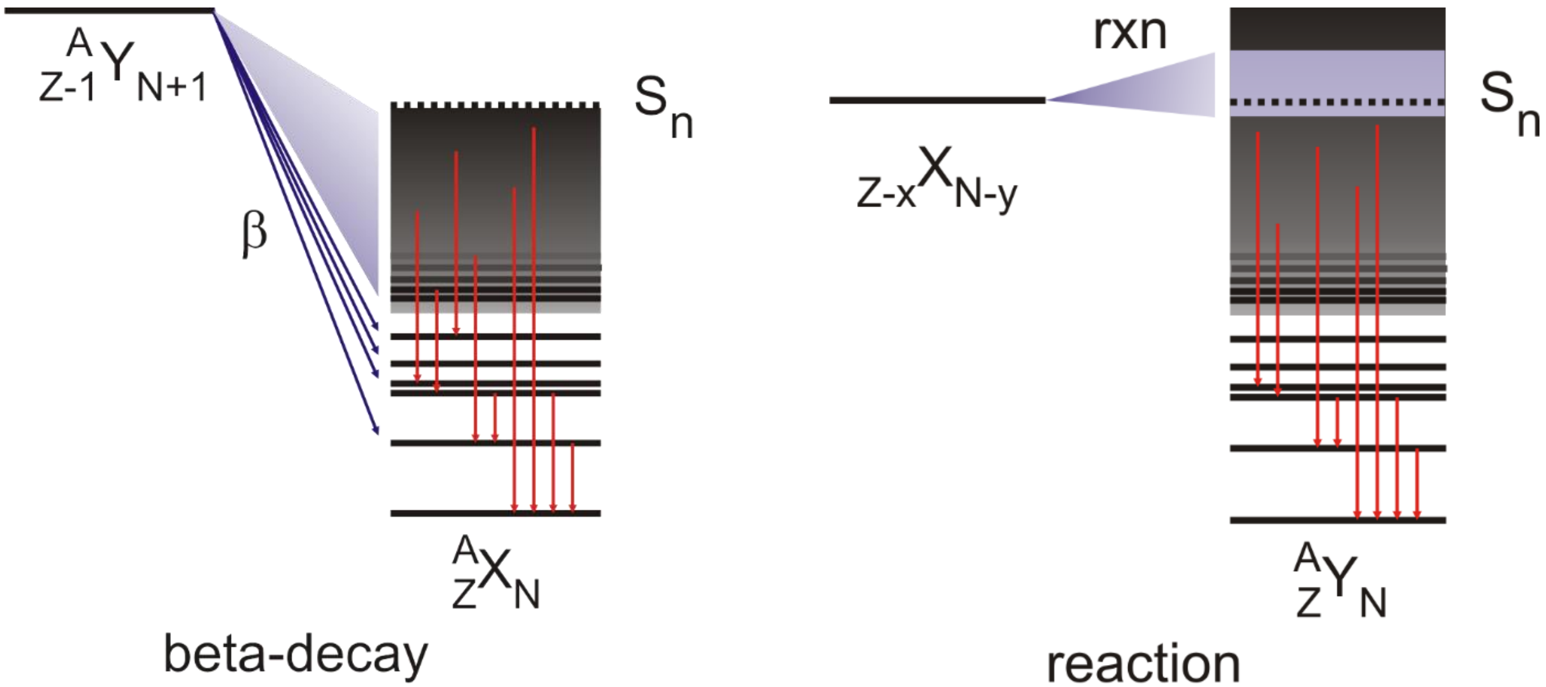




S.N. Liddick, A. Spyrou, *et al.*, Phys. Rev. Lett. 116, 242502 (2016)
R. Surman and J. Engel, Phys. Rev. C, **64**, 035801 (2001)

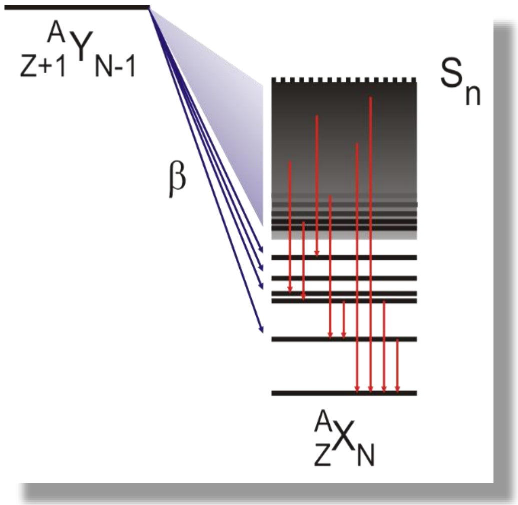
Beta decay and reactions

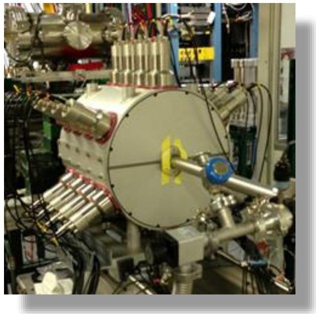
- Use Oslo technique combined with β decay.
- Measure beta decay of nucleus.
  - Extract level densities and gamma-ray strength function
- Need total excitation energy of the daughter isotope.

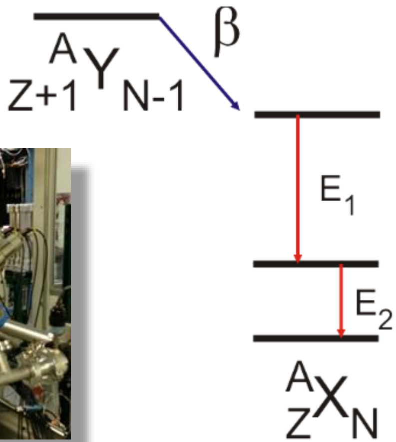


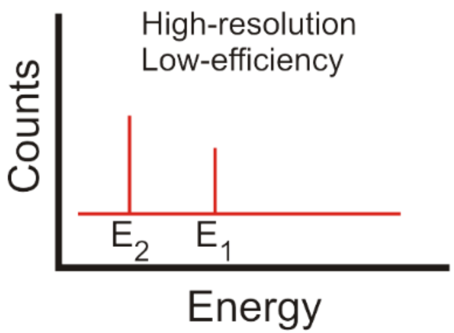
Total Absorption Spectroscopy

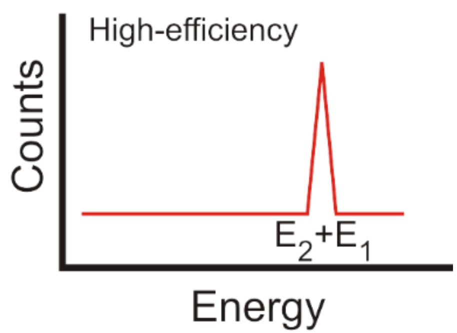
- Need to know initial excitation energy
- Can’t use beta-decay electron (three body process).
- Measure total γ-ray energy.
- Require high detection efficiency (low resolution detector).
- Knowledge of multiplicities.







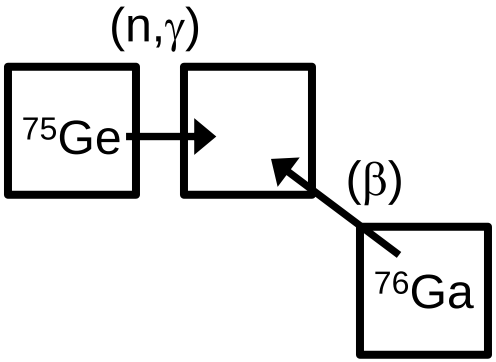


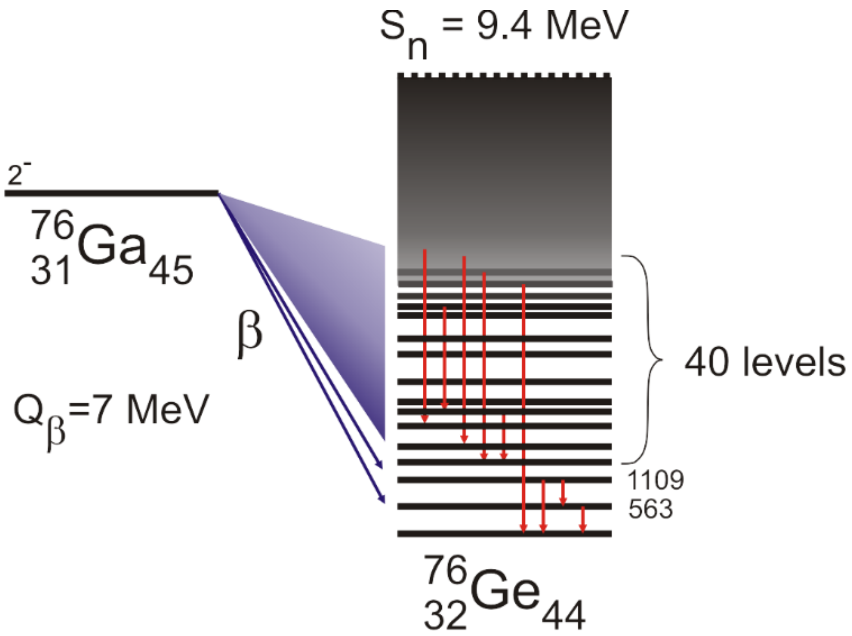


Application of technique to ^{76}Ga

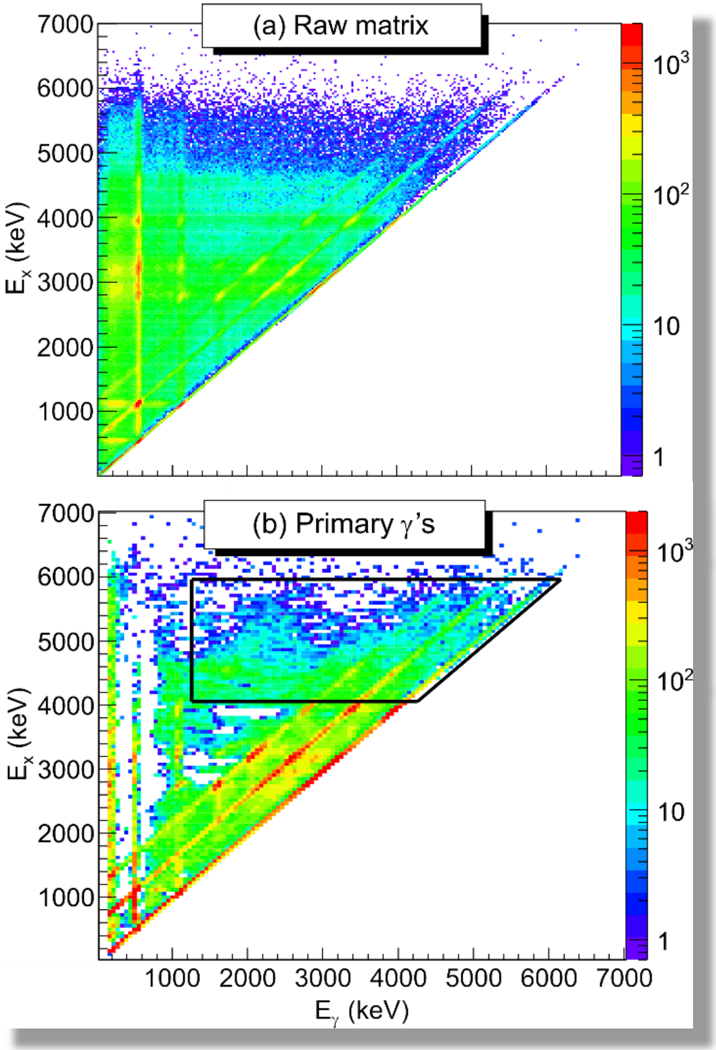
- Applied technique to beta decay of ^{76}Ga.
- Infer neutron capture cross section of ^{75}Ge.
- Unfortunately, no direct measurement for comparison (^{75}Ge is radioactive).

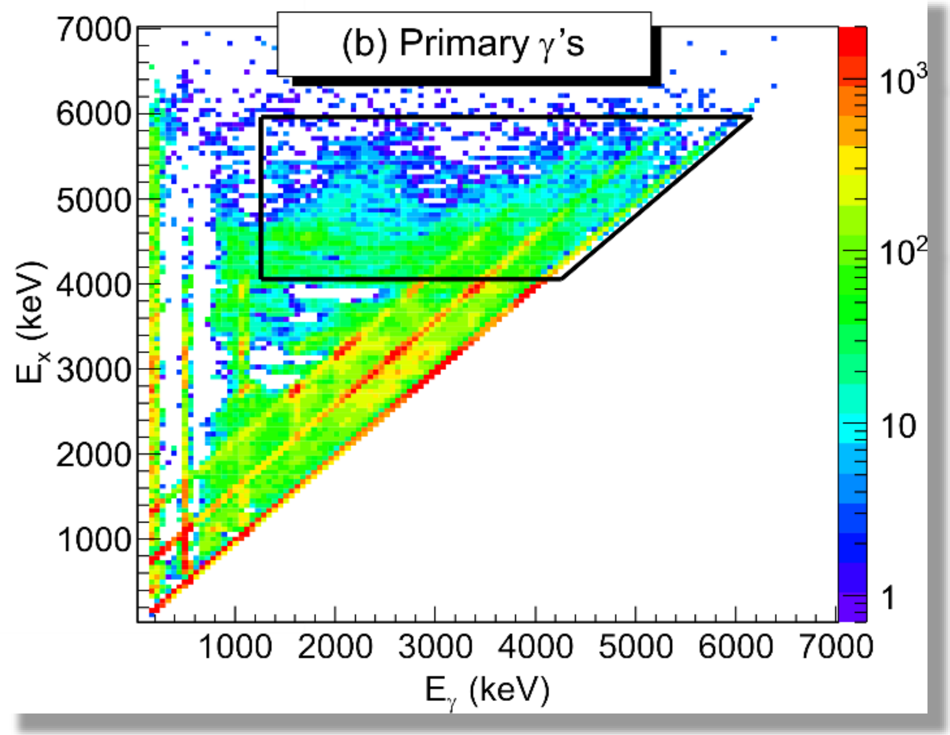
- Not optimum candidate but experimentally easy to get pure source.
- ^{76}Ga $t_{1/2}$ = 32.6 s
- ^{76}Ge - stable





Primary gamma rays



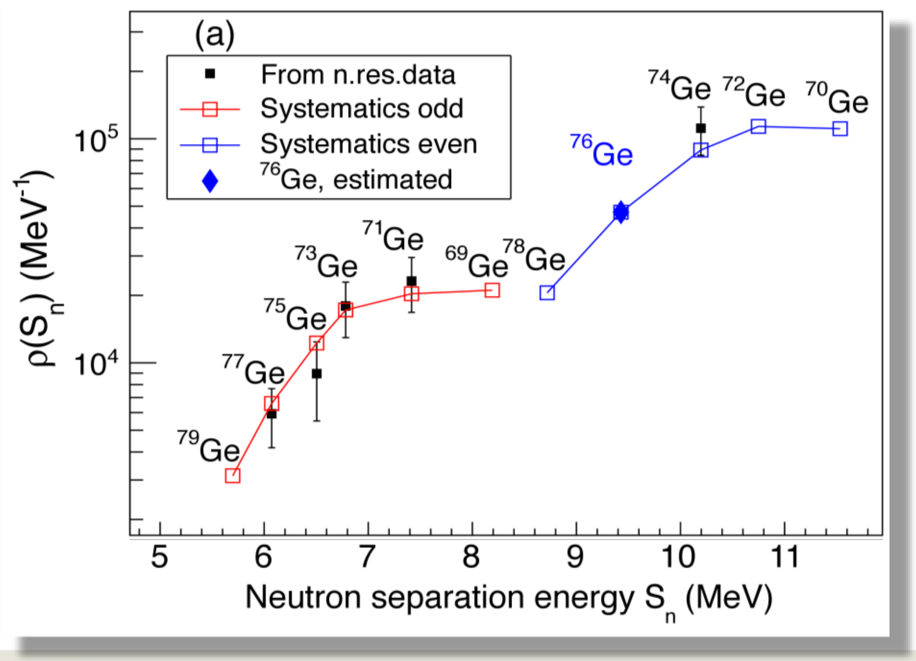


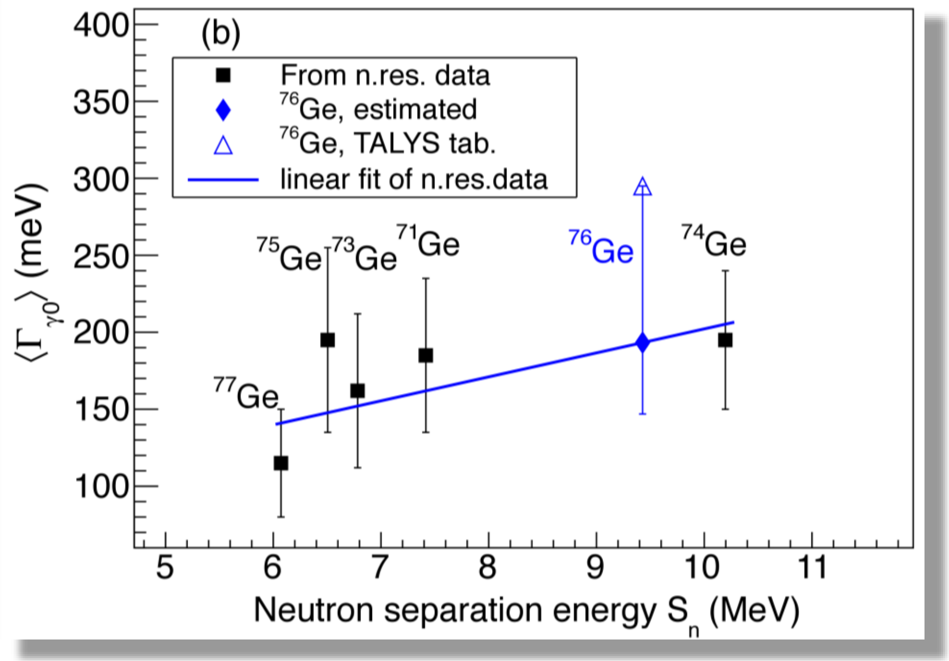
$$P\left(E_\gamma, E_x\right) = \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL 113, 232502 (2014)

Normalizations

- Functional forms need to be normalized.
- Three normalization points
  - Low-energy level density.
  - Level density at S_n.
  - Average radiative width at S_n.

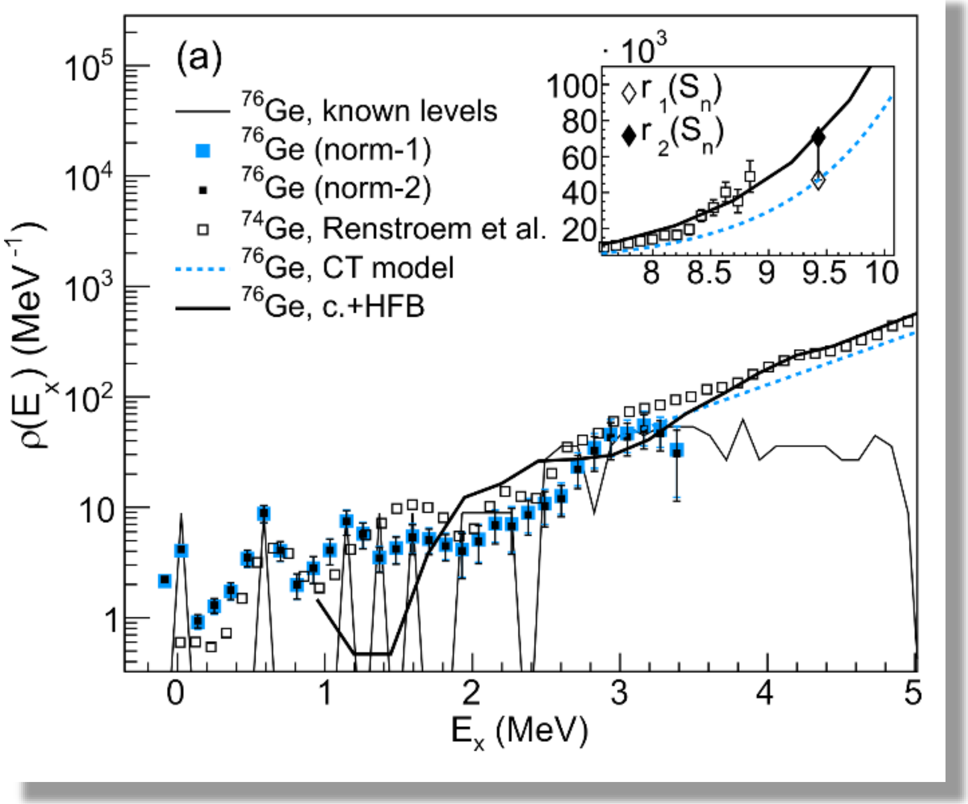


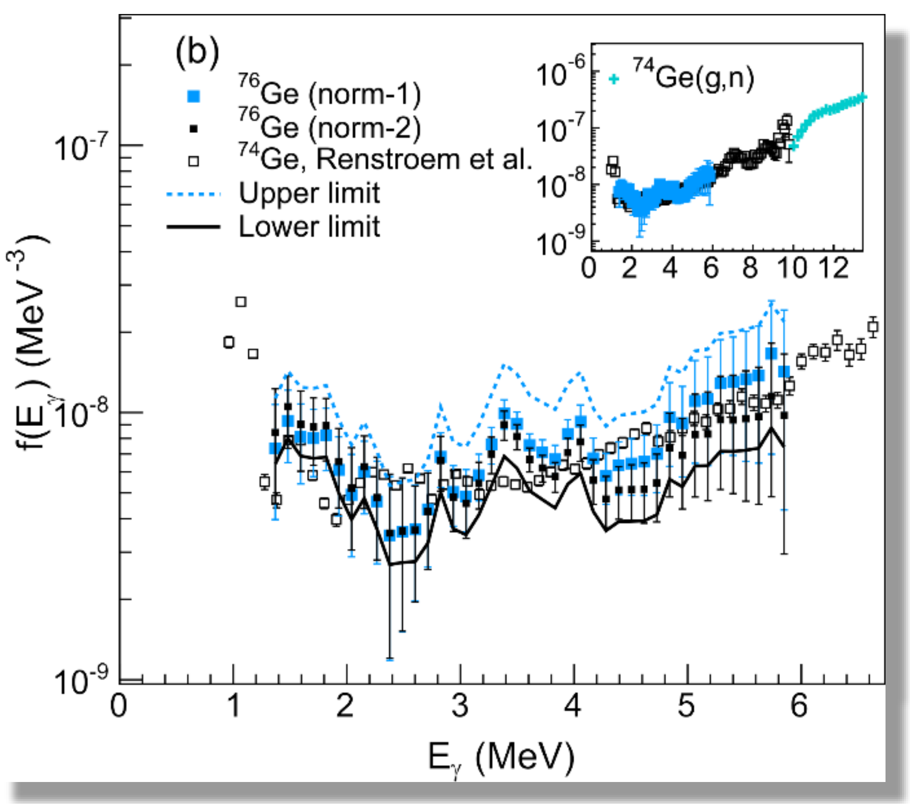


- $\rho(S_n)$ from
  - Systematics
  - Microscopic calculations
- $\langle\Gamma_\gamma\rangle$ from systematics

A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL 113, 232502 (2014)

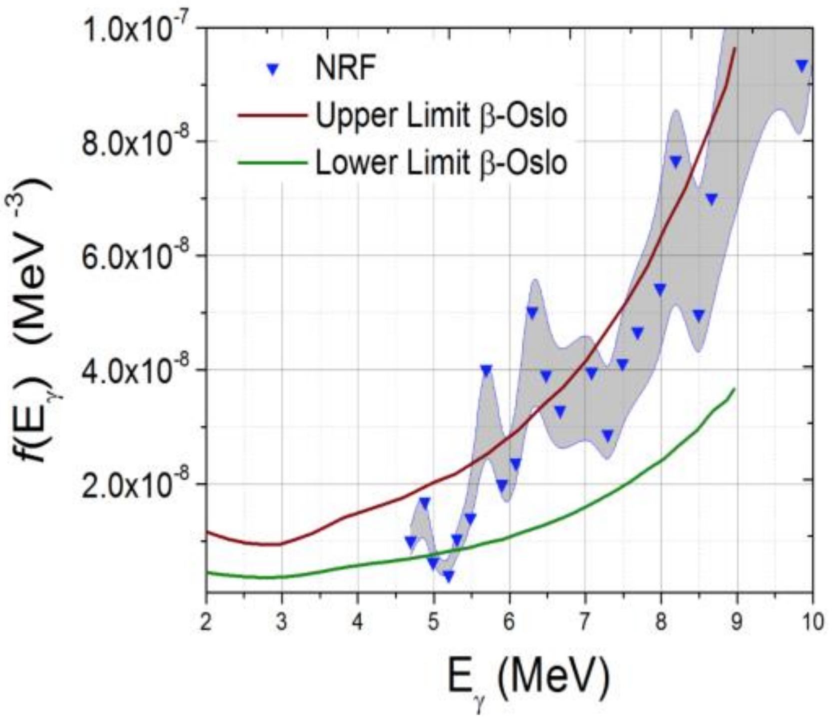
Normalized NLD and γSF

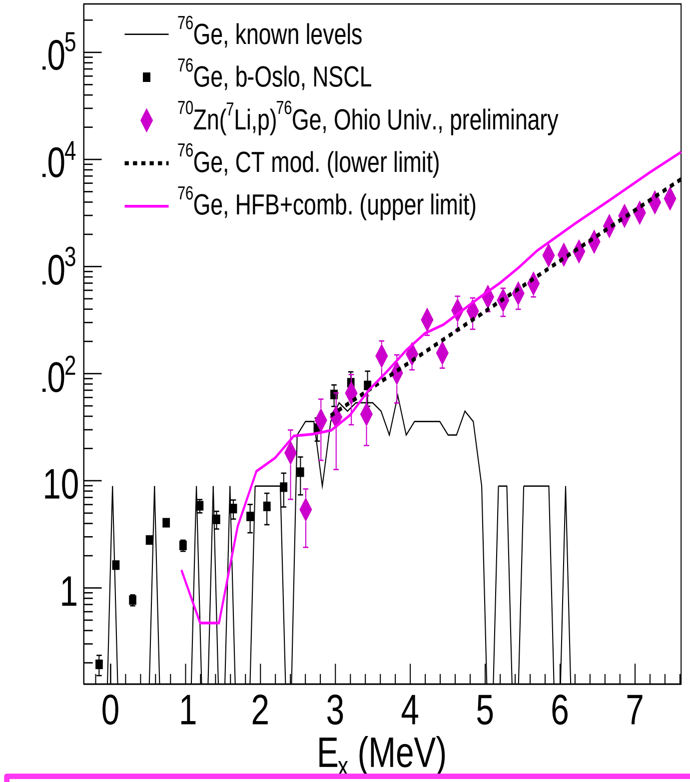




A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL 113, 232502 (2014)

Validation of NLD and γSF – ^{76}Ge



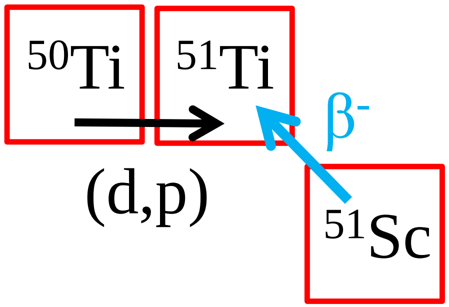


A. Tonchev, *et al.*
Photoscattering exeriment – HIγS
Talk at Oslo workshop 2015

A. Voinov, T. Renstrom, A.-C. Larsen, *et al.*
Preliminary Analysis - *^{70}Zn(^{7}Li,p)^{76}Ge reaction*
Experiment at Ohio University

Preliminary

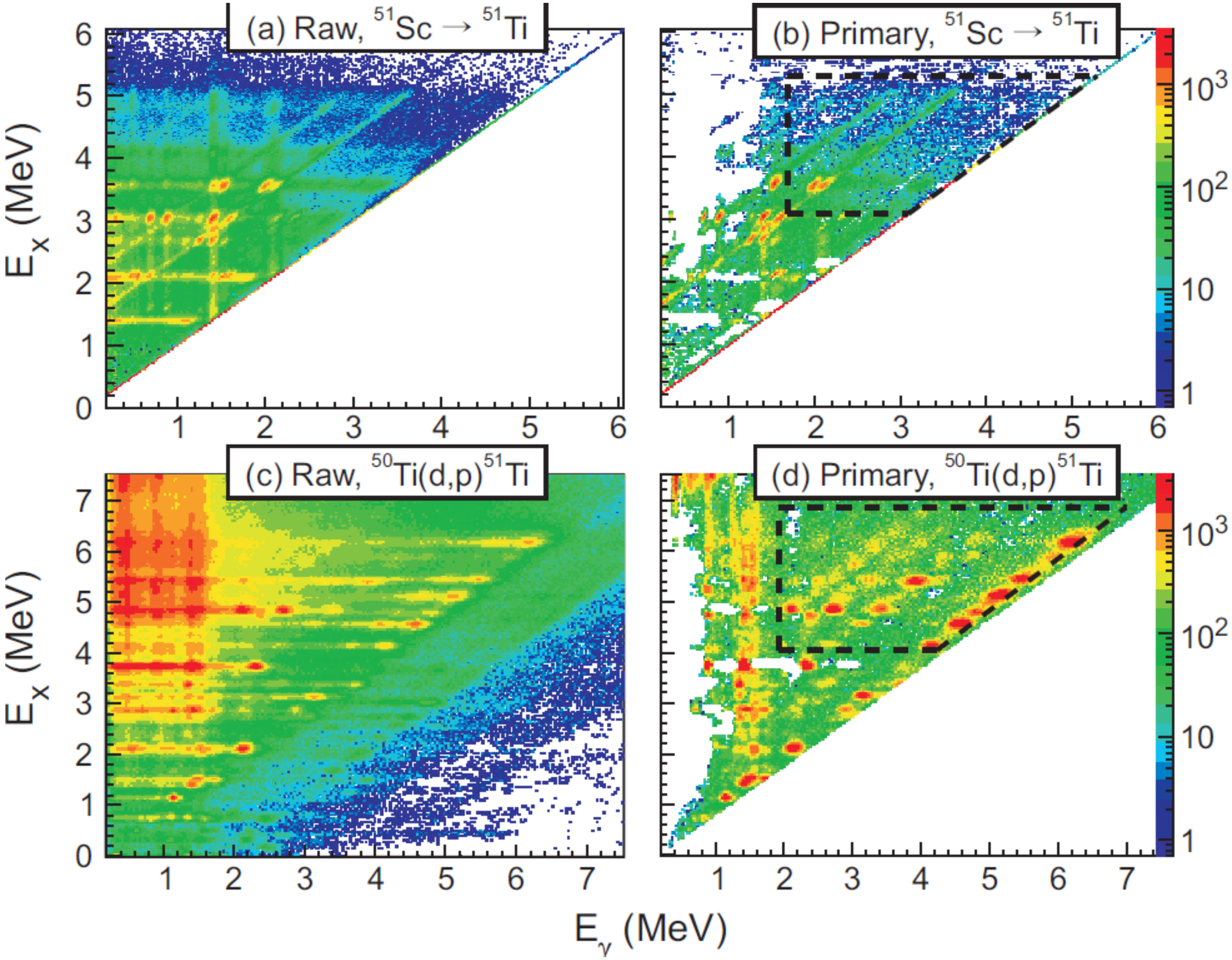
Comparison to a known neutron capture – ^{51}Ti



^{51}Sc: $T_{1/2}$ = 12.4 s
$Q_{\beta-}$ = 6.5 MeV
S_n (^{51}Ti) = 6.7 MeV

- ^{50}Ti(d,p)^{51}Ti performed at Oslo.
- ^{51}Sc beta decay performed at NSCL.
- NLD and γSF extracted from both experiments.

Raw and primary matrices – ^{51}Ti



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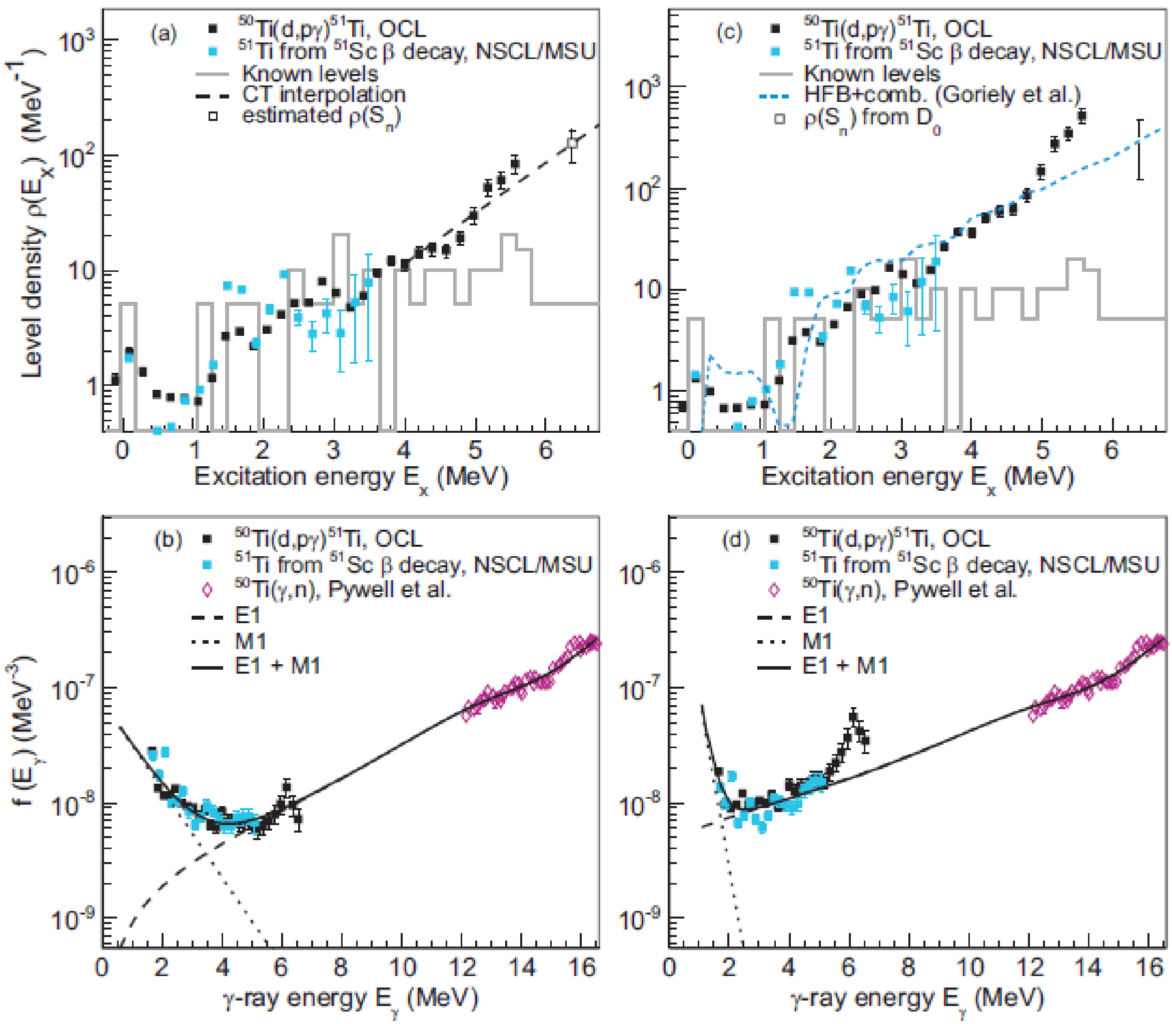
Liddick, Larsen, Guttormsen, Spyrou, et al. – submitted

NLD and γSF – ^{51}Ti



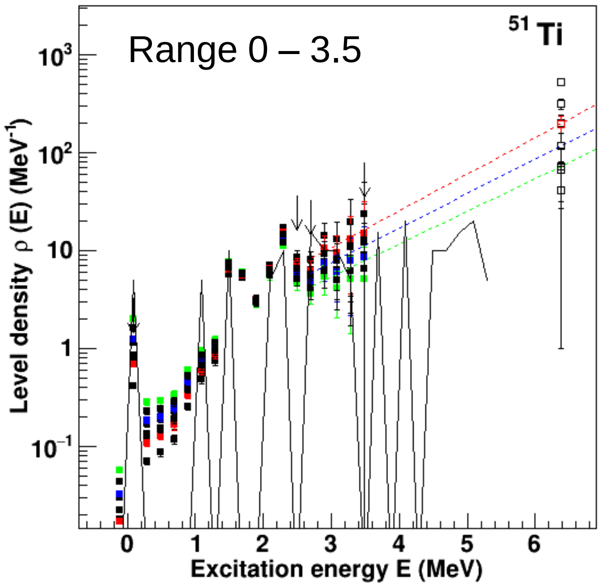
- ^{50}Ti(d,p)^{51}Ti performed at Oslo.
- ^{51}Sc beta decay performed at NSCL.
- NLD and γSF similar in both cases.

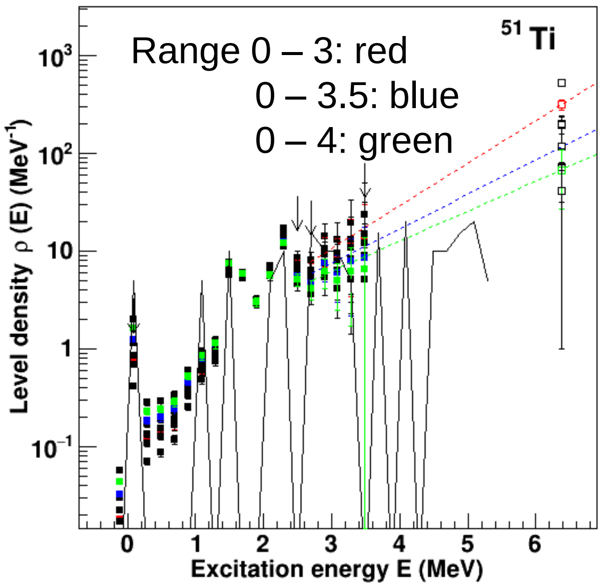
Liddick, Larsen, Guttormsen, Spyrou, et al. – submitted

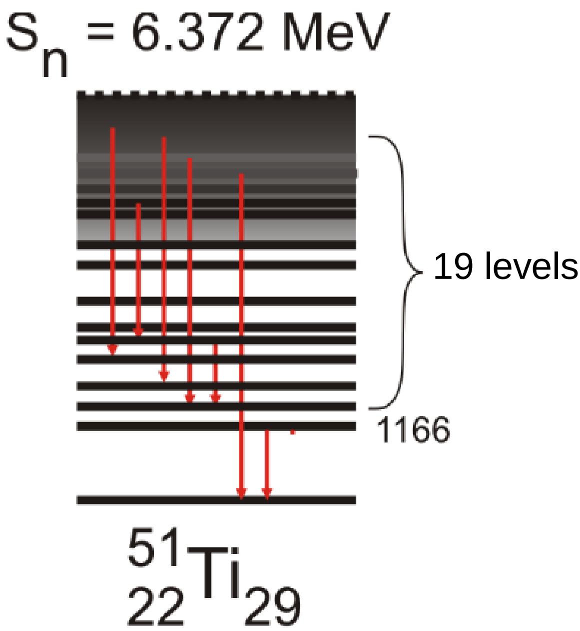
^{51}Ti variations – fit ranges

- Use known level scheme of ^{51}Ti
- Fit cumulative distribution of levels to a constant temperature model
- Results in different T and E_0.
- Use S_n to normalize NLD.

Range	T	E_0
0 – 3	0.99(0.05)	0.43(0.11)
0 – 3.5	1.23(0.07)	0.00(0.18)
0 – 4	1.41(0.08)	-0.37(0.23)







Liddick, Larsen, Guttormsen, Spyrou, et al. – submitted

^{51}Ti variations – γSF

- Normalized NLD and γSF share the same energy dependent correction.
- Some of the resulting γSF are incompatible with (γ,n) data.

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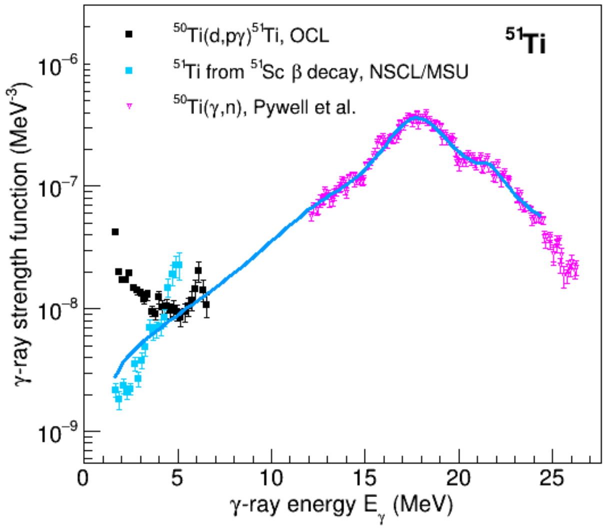

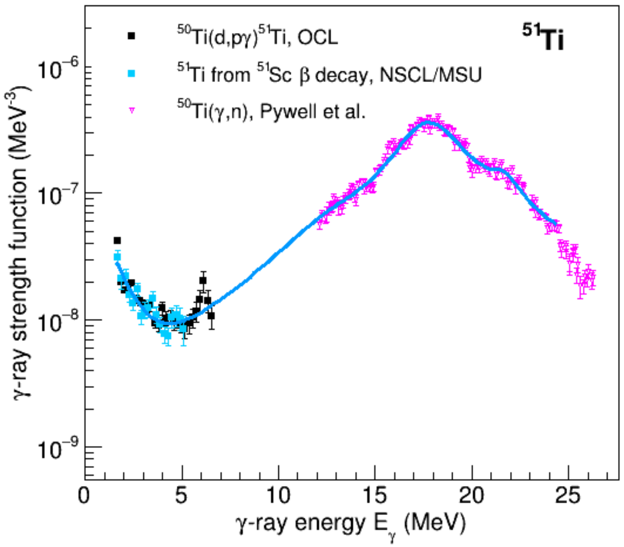

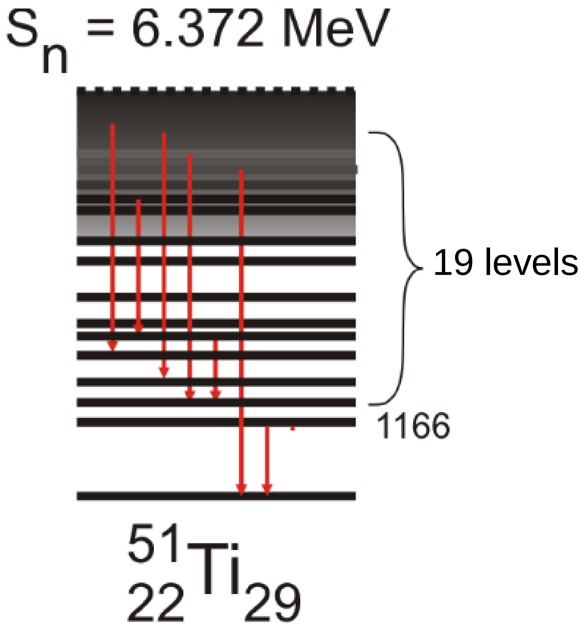

Liddick, Larsen, Guttormsen, Spyrou, et al. – submitted

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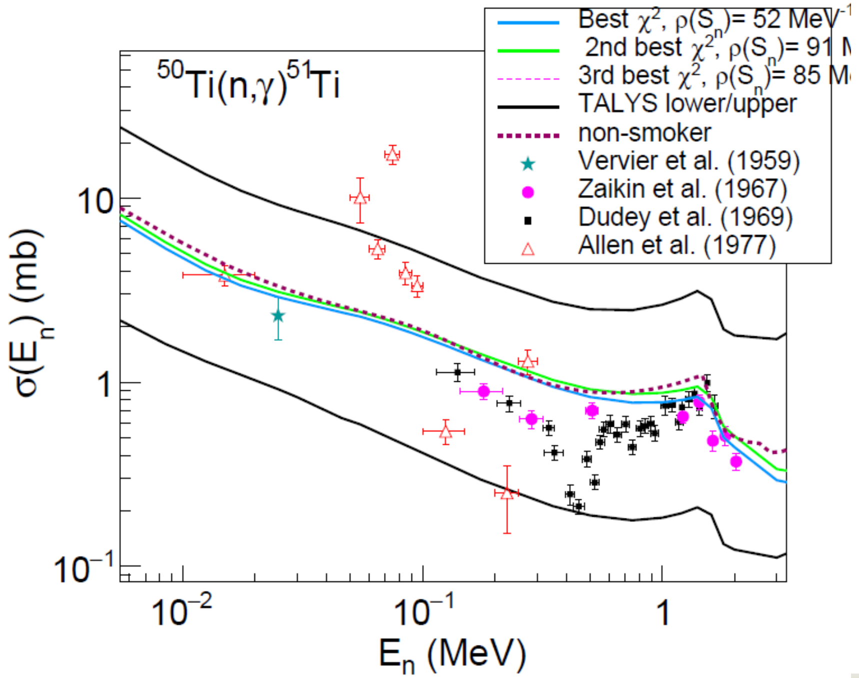
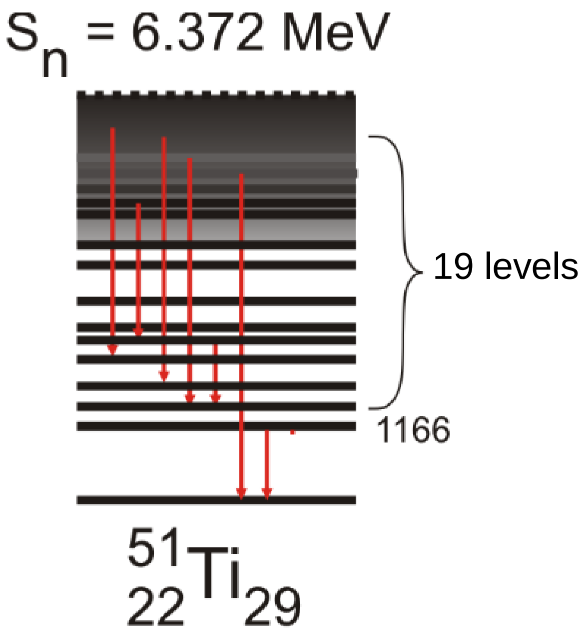


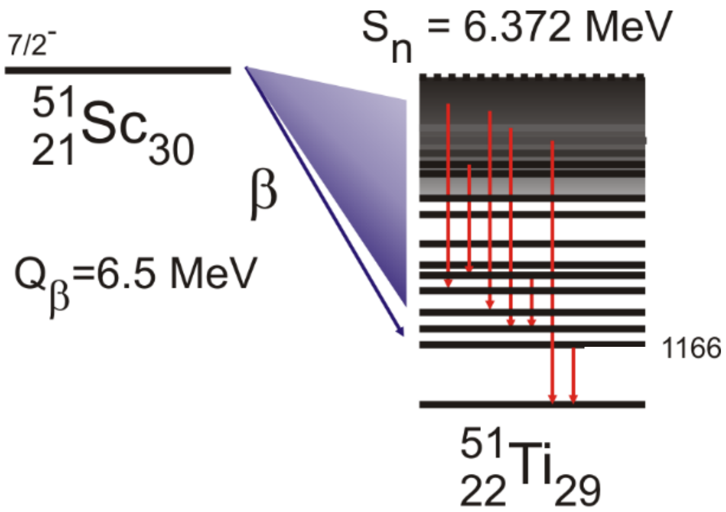


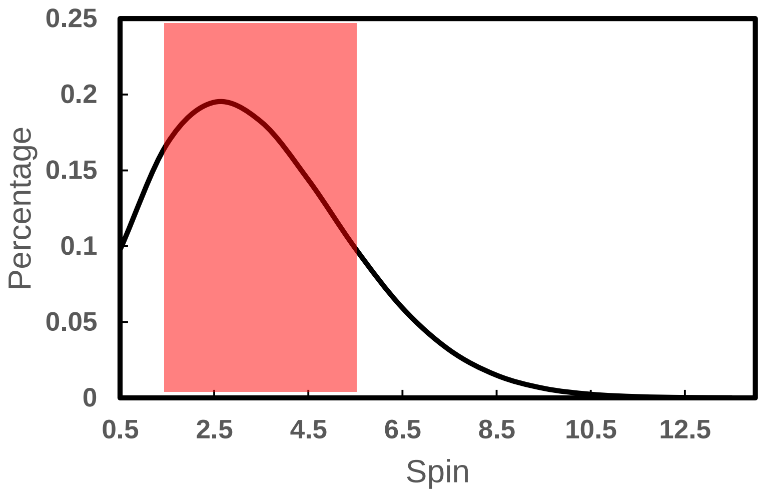
Liddick, Larsen, Guttormsen, Spyrou, et al. – submitted

^{51}Ti variations – spin cut-off

- Correct for reduced spin window of beta decay
- Assume allowed beta decay transitions
- After one dipole photon emission the spin range is within 2 units of the parent spin.
- Determine fraction of total levels within this subset.

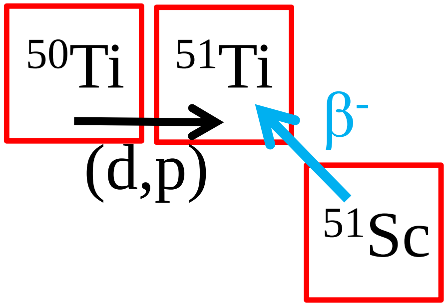
Spin Cut-off	Relative change
3.01	1.013
3.12	1
3.23	0.985



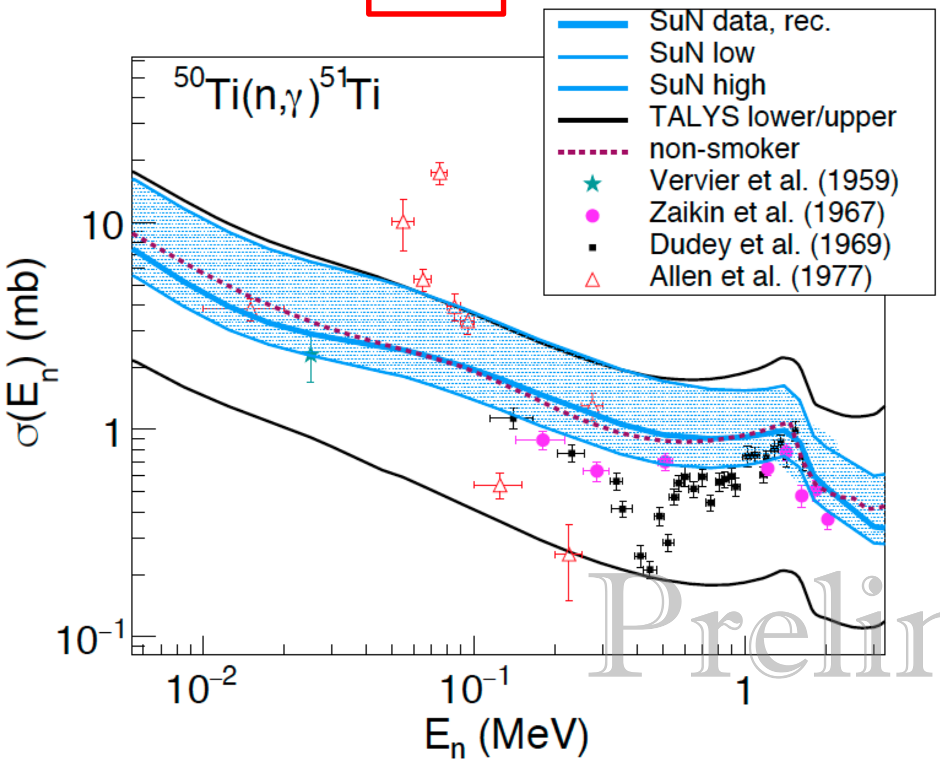


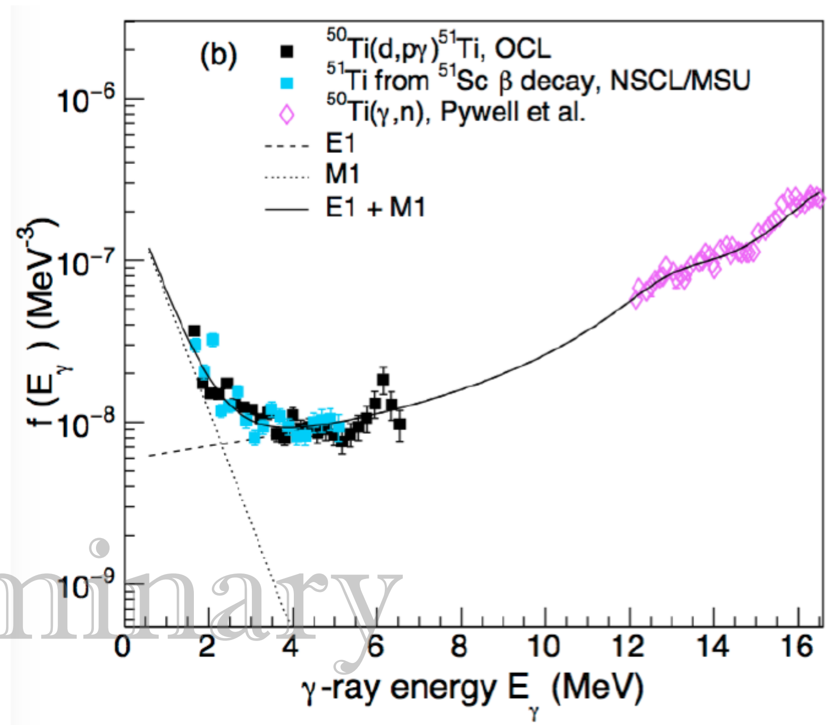
Liddick, Larsen, Guttormsen, Spyrou, et al. – submitted
T. Von Egidy and D. Bucurescu PRC **80**, 054310 (2009)

Validation – ^{51}Ti



^{51}Sc: $T_{1/2}$ = 12.4 s
$Q_{\beta-}$ = 6.5 MeV
S_n (^{51}Ti) = 6.7 MeV
D_0 = 125(70) keV
$\langle\Gamma_\gamma\rangle$ = 1100(300) meV

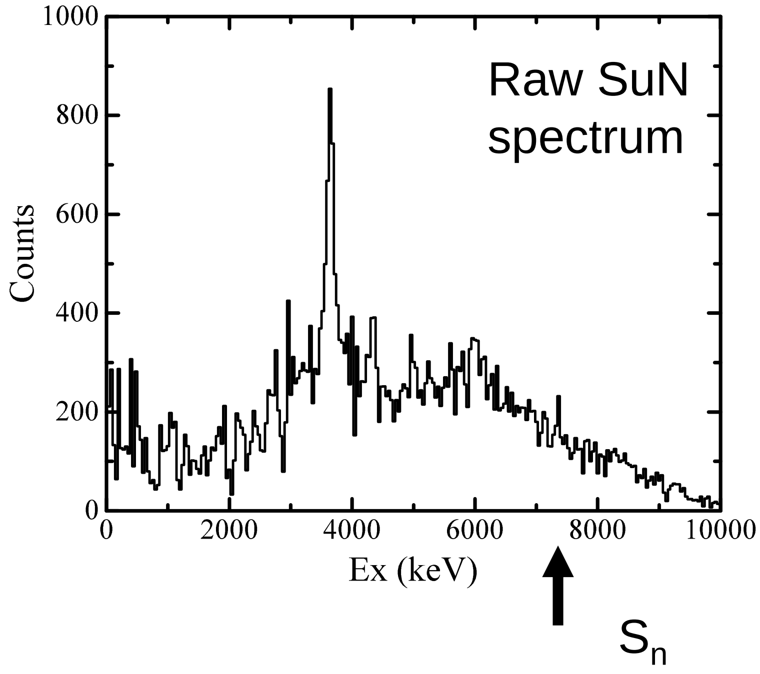




Liddick, Larsen, Guttormsen, Spyrou, et al. – submitted

Correction of excitation energy response

- E_γ unfolding demonstrated.
- E_x unfolding can be performed.
- Complicated since it depends on both
  - Detector response to all possible individual γ rays.
  - Multiplicity of γ-ray cascade.



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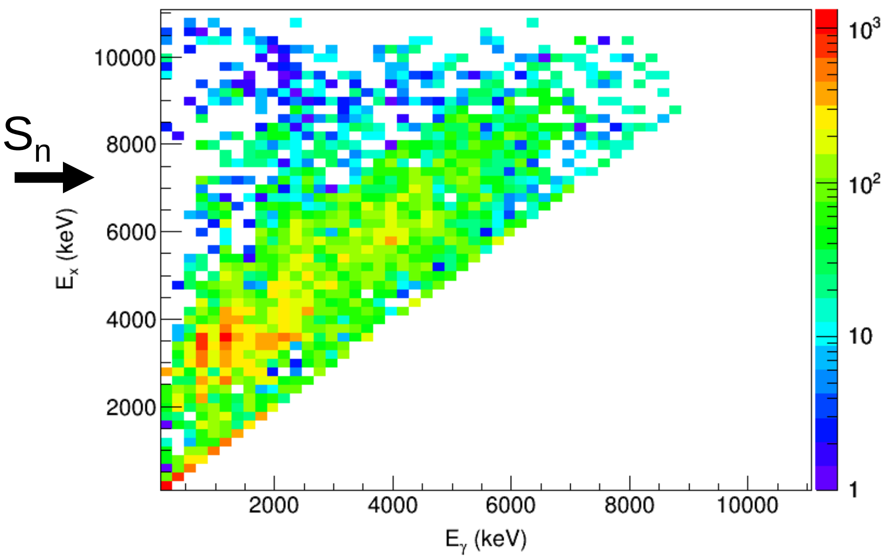
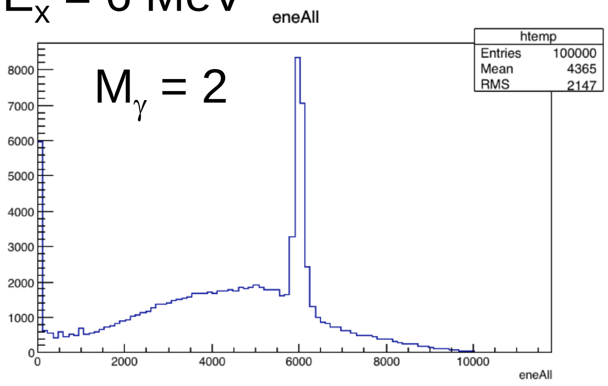
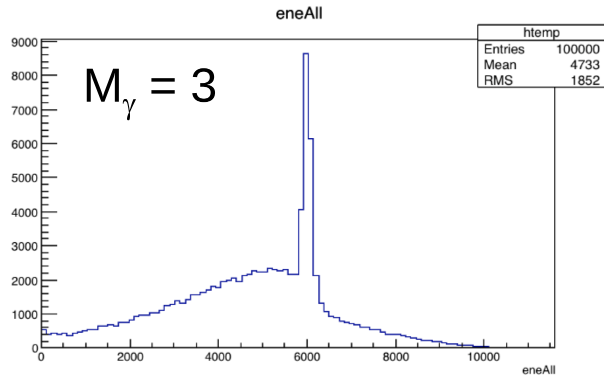
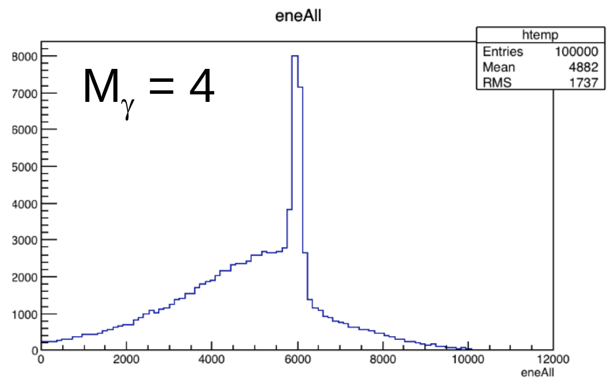


E_x = 6 MeV







Technique

- Exploit our ability to fold:
- Control by iteration:

(*i*) First trial function: $\mathbf{u}^0 = \mathbf{r}$

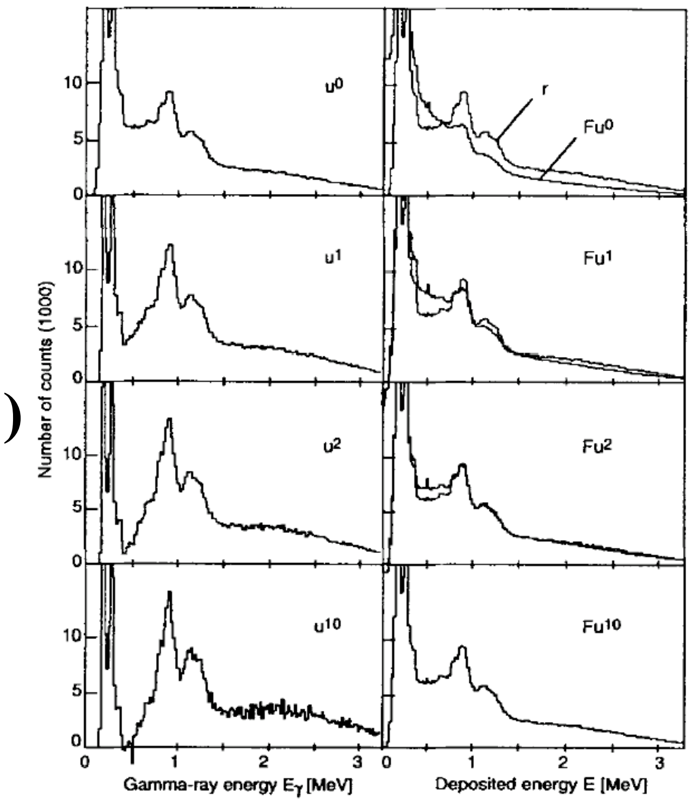
(*ii*) First folded spectrum: $\mathbf{f}^0 = \mathbf{R}\mathbf{u}^0$

(*iii*) Correct for how much we fail: $\mathbf{u}^1 = \mathbf{u}^0 + (\mathbf{r} - \mathbf{f}^0)$

(*iv*) Second folded spectrum: $\mathbf{f}^1 = \mathbf{R}\mathbf{u}^1$

(*v*) The third trial function: $\mathbf{u}^2 = \mathbf{u}^1 + (\mathbf{r} - \mathbf{f}^1)$

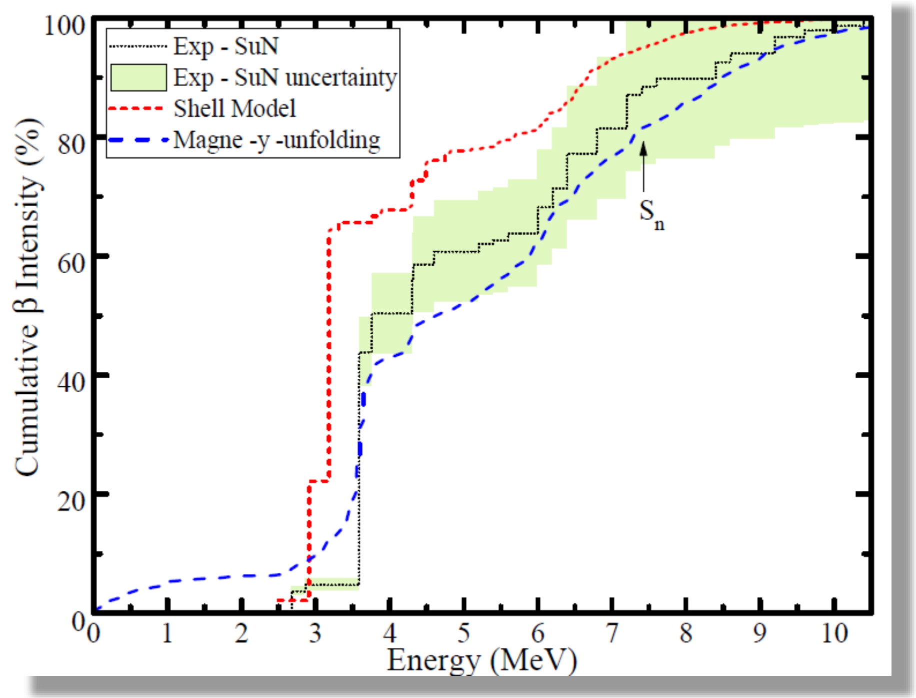
and so on until $\mathbf{f}^i$ » $\mathbf{r}$.



M. Guttormsen, et al., NIMA 374,371 (1996)
M. Guttormsen, et al., NIMA 255, 518 (1987)

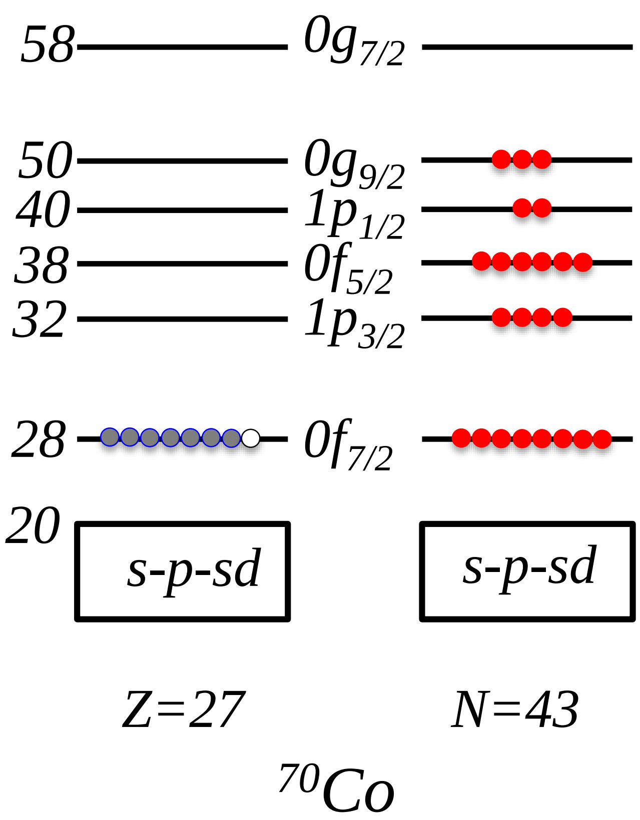
Does the E_x unfolding work? – Yes!

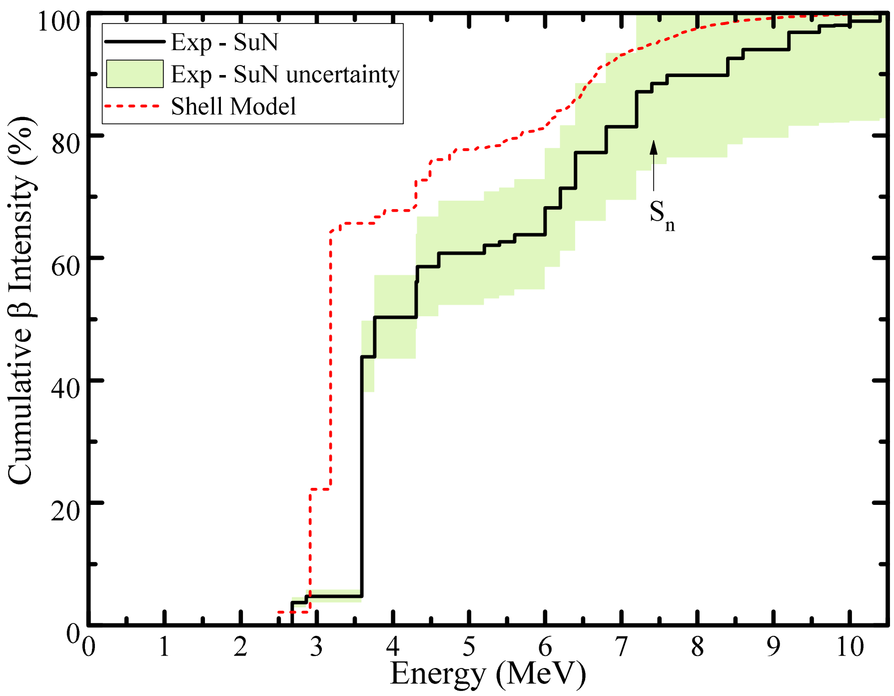
- Compare two ways to arrive at the β-decay feeding as a function of excitation energy.
- Standard:
  - Start with known level scheme
  - Perform DICEBOX simulations at higher energies.
  - Simulate resulting γ-ray cascades
  - Plot β-feeding
- Alternative:
  - Perform E_x and E_γ unfolding on primary matrix.
  - Project onto excitation energy axis.
- First test with TAS data from decay of ^{70}Co into ^{70}Ni.



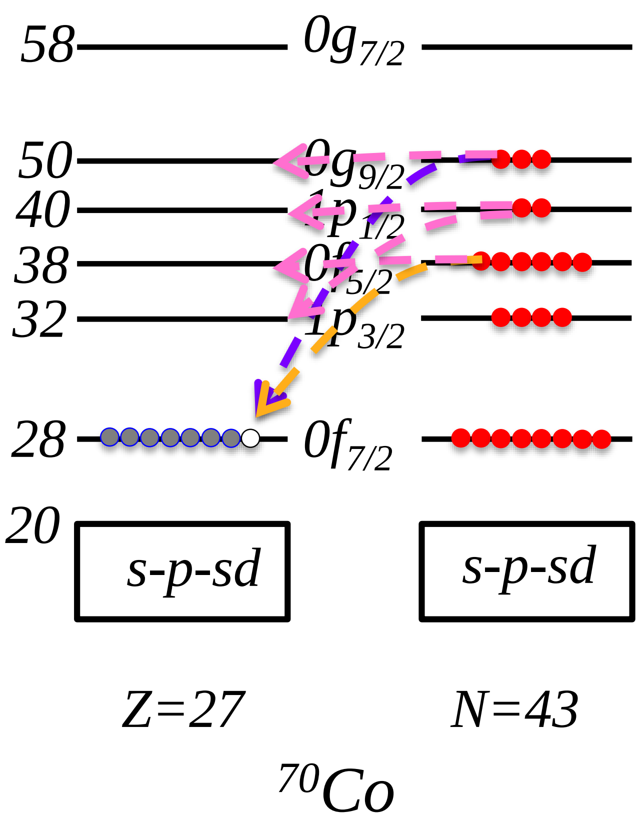
A. Spyrou, S.N. Liddick, et al. PRL **117**, 142701 (2016)

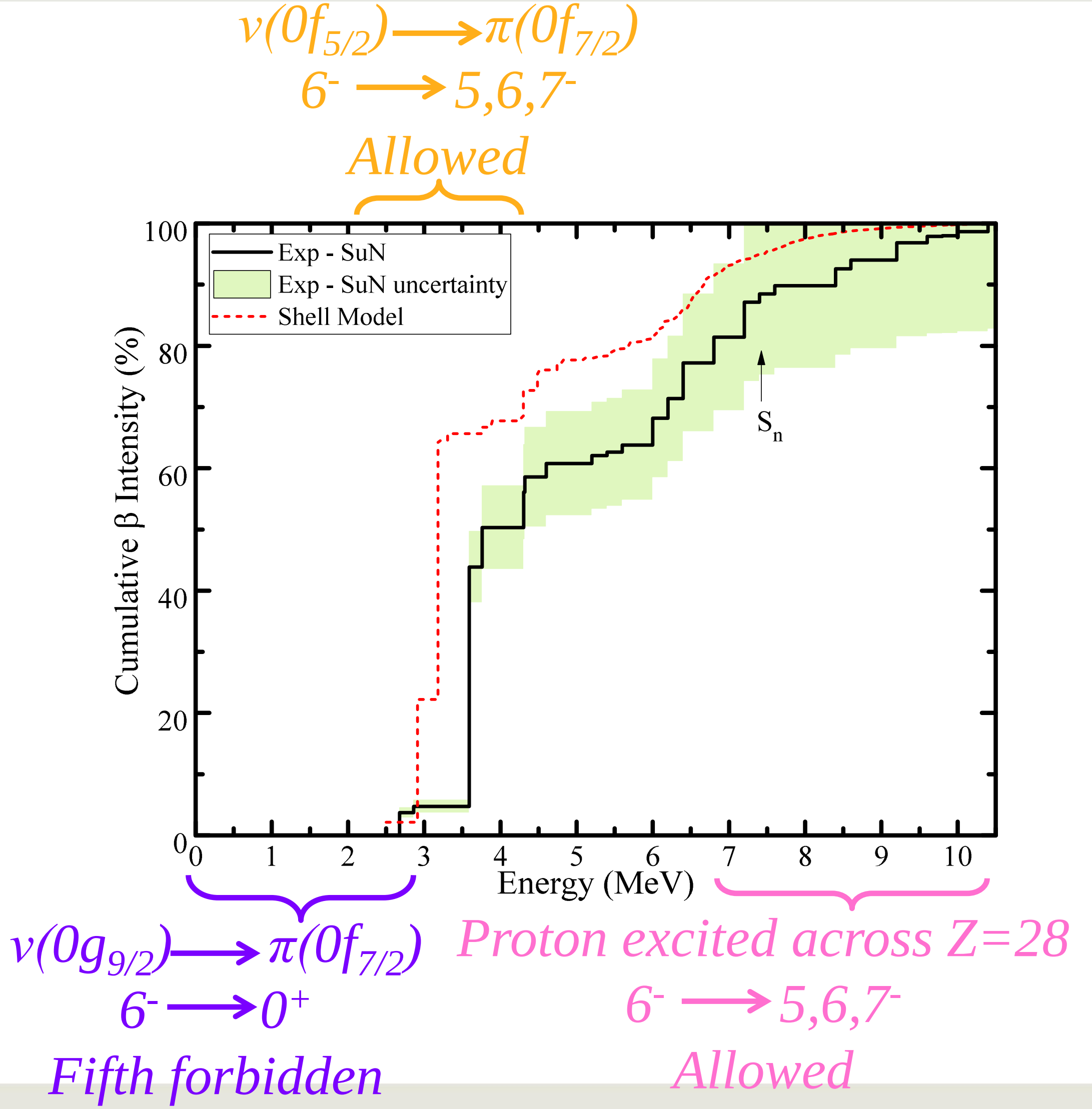
Neutron – γ competition





Neutron – γ competition





Experimental program using β-Oslo

Completed

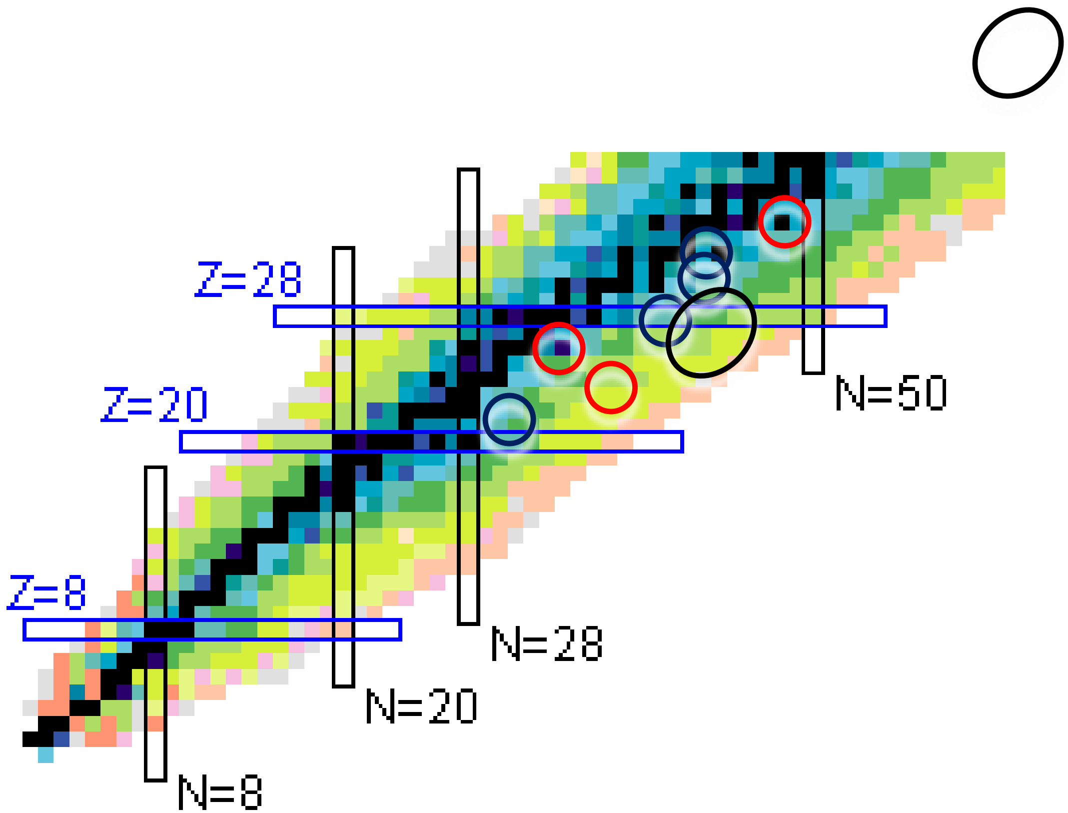
- ^{75}Ge
- ^{68,69}Ni
- ^{51}Sc
- ^{73}Zn

Data obtained

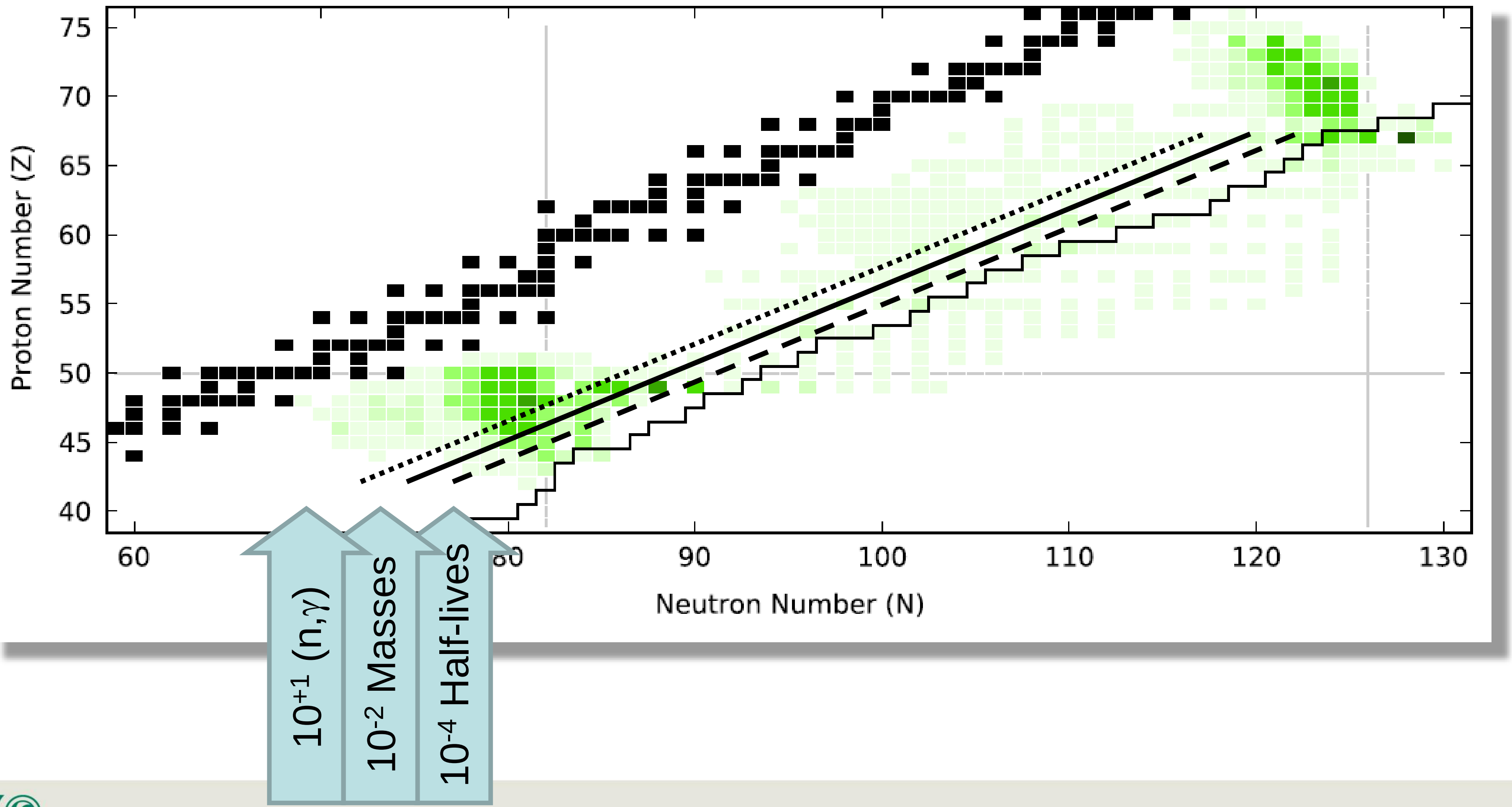
- ^{82}Se, ^{60}Fe, ^{64}V

Future work

- Fe-Co-Ni-Cu region
- In region
- neutron-rich Br



Longer term prospects – next generation radioactive ion beam facilities



Conclusions

- Novel technique to infer level densities and photon strength function using beta-Olso method.
  - Complementary to reaction based measurements
  - Applicable to low production rates far from stability
- Use extracted quantities to infer neutron capture rates.
- Demonstrated on
  - ^{76}Ga for the ^{75}Ge (n,γ) cross section.
  - ^{51}Sc for the ^{50}Ti (n,γ) cross section.
  - ^{69,70}Co for the ^{68,69}Ni (n,γ) cross section.
- Numerous further investigations on the horizon
  - Ranging from mass 60 to 130.

Thanks

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- R. Surman

LLNL

- D.L. Bluel

LANL

- A. Couture
- S. Mosby

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- B. Rubio

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