Experimental Neutron Capture Measurements and Nuclear Theory Needs

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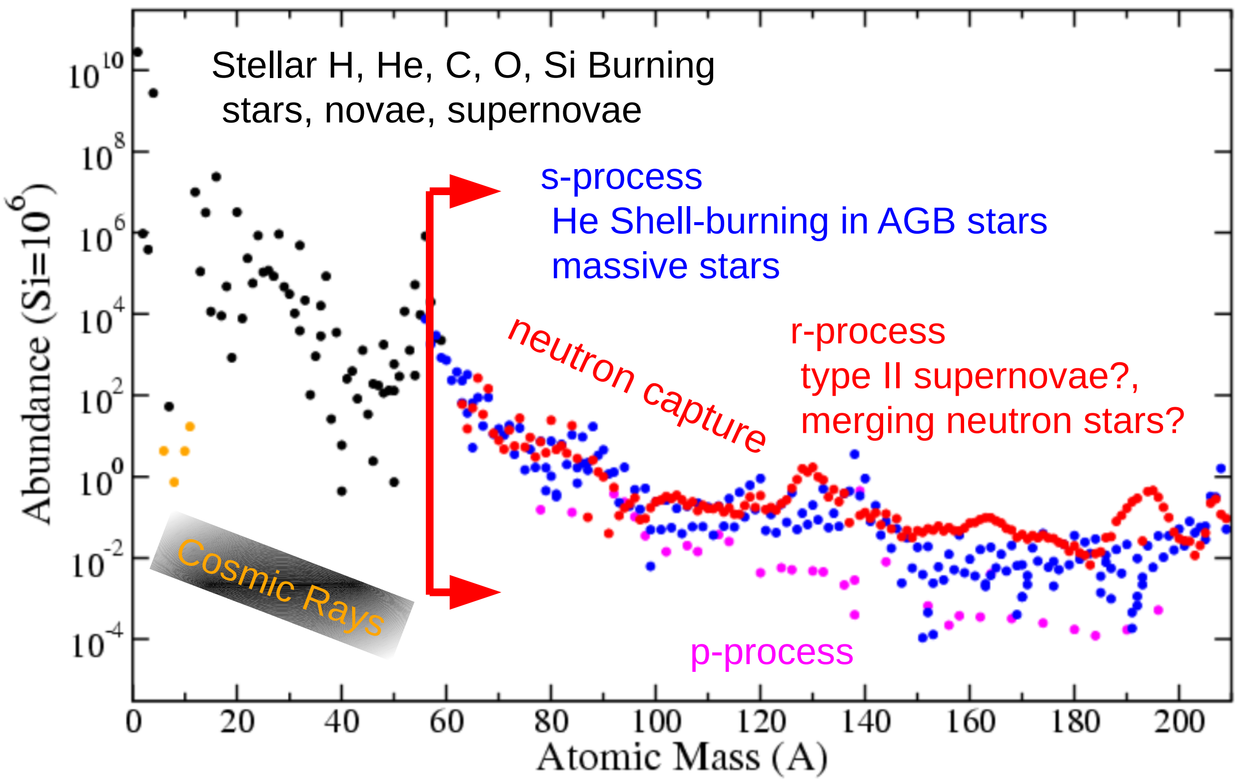
LA-UR-17-22343

Outline

- Why do we need neutron capture
- Traditional (n,γ) measurements
- Determining (n,γ) on radioactive isotopes
- Questions and challenges for (n,γ)

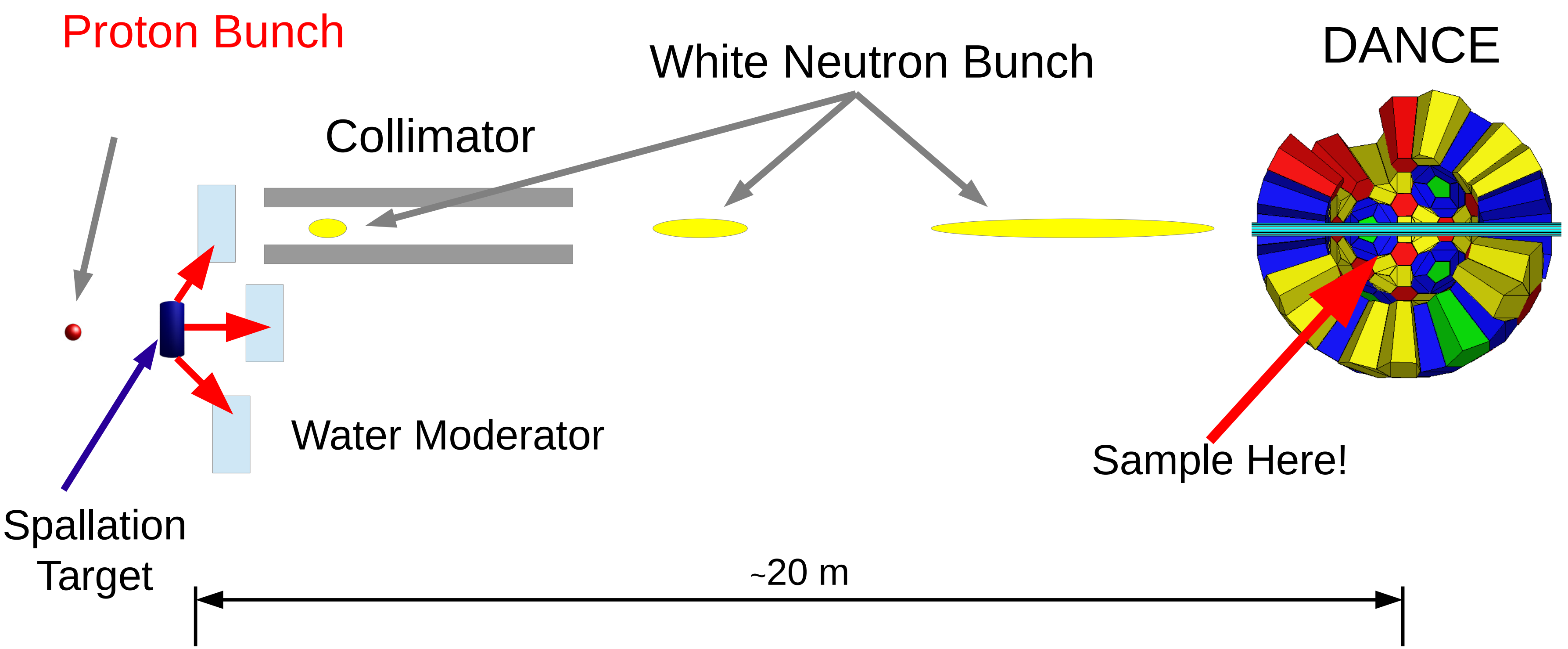
The heavy elements are produced through neutron capture



Abundances and Attribution from Anders & Grevesse, 1989 and Käppeler, Beer, and Wisshak, 1989

- The s-process and r-process are each thought to make ~50% of the heavy elements
- Radioactive isotopes play a critical or dominant role in the nucleosynthesis
  - Information on unstable isotopes can reveal stellar conditions
- i-process throws new wrinkles in these predictions
- s-process abundance predictions are critical—r-process predictions are *residuals*
- The different scenarios have different nuclear data needs
  - Energies (Temperatures)
  - Accuracy
  - Systematics

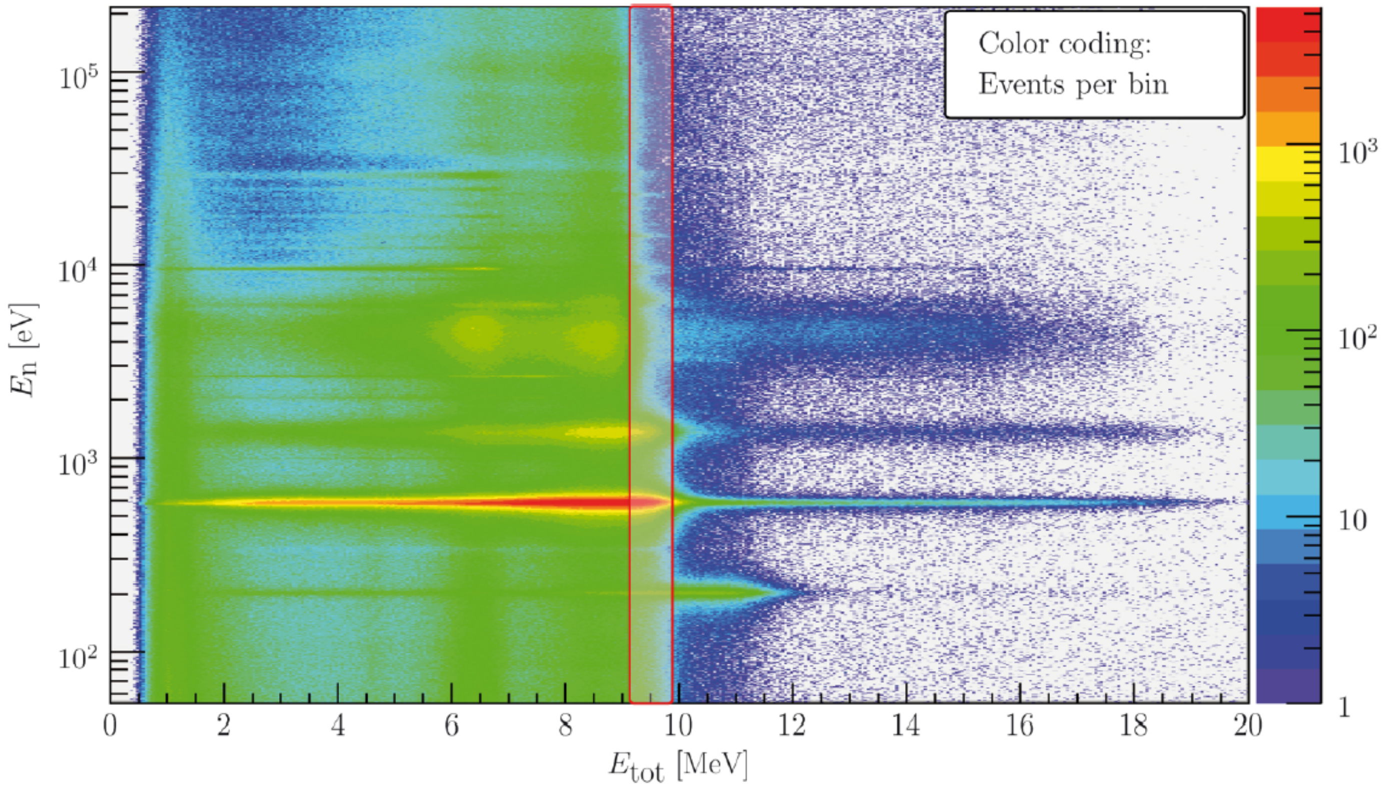
Traditionally Measure Neutrons on Samples—A direct measure of neutron capture



E_p = 800 MeV ν_p =20 Hz   10 meV < E_n < 500 keV

$\varphi_n = 3 \bullet 10^5$ n/s/cm^2/decade

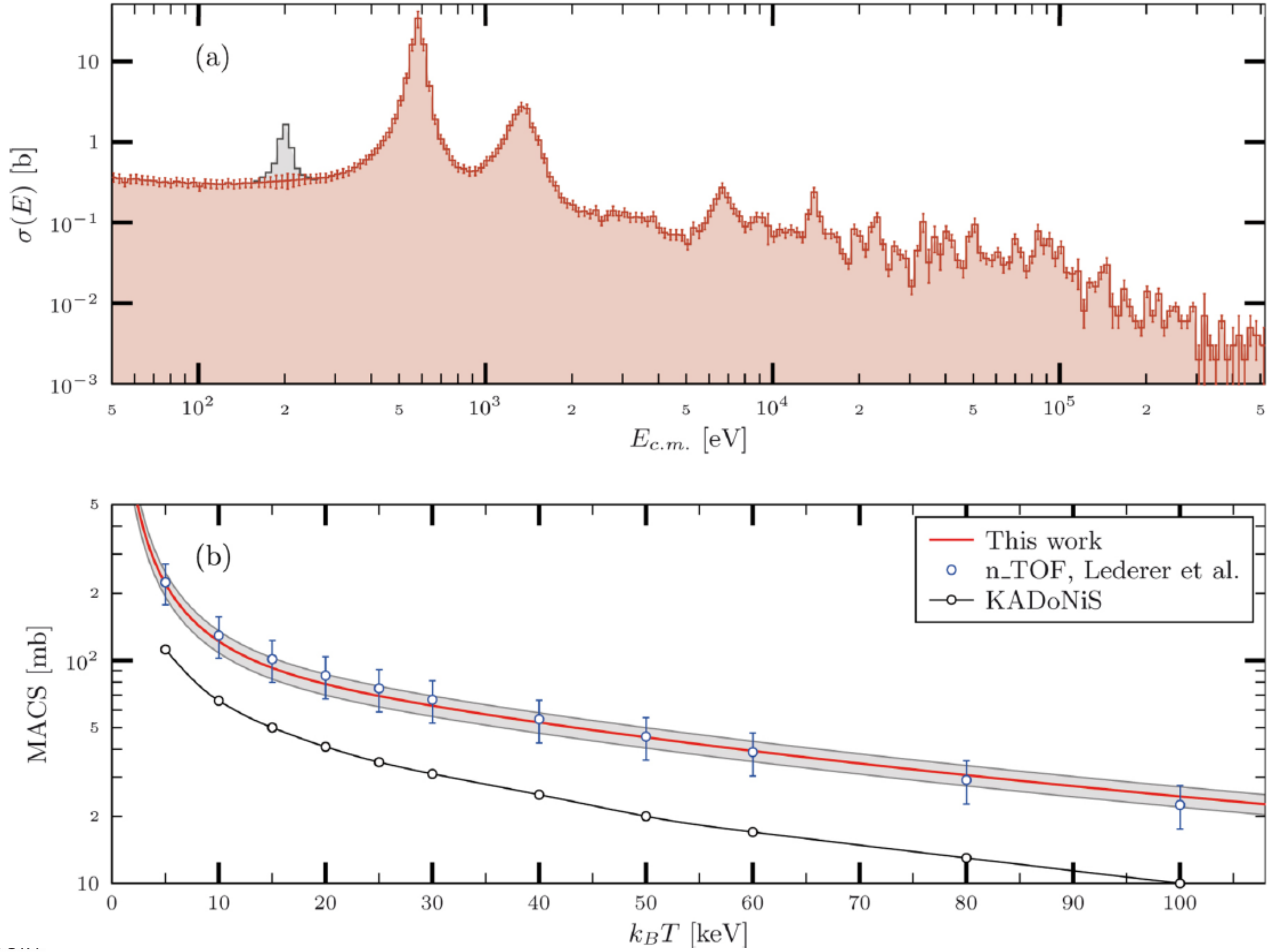
DANCE data on ^{63}Ni(n,γ)



- ~350 mg sample of Ni
- 11% enriched in ^{63}Ni (~38 mg ^{63}Ni)
- Sample activity ~80 GBq
- Ph. D Thesis of M. Weigand (Univ. of Frankfurt)
- Data shown is for multiplicity > 2

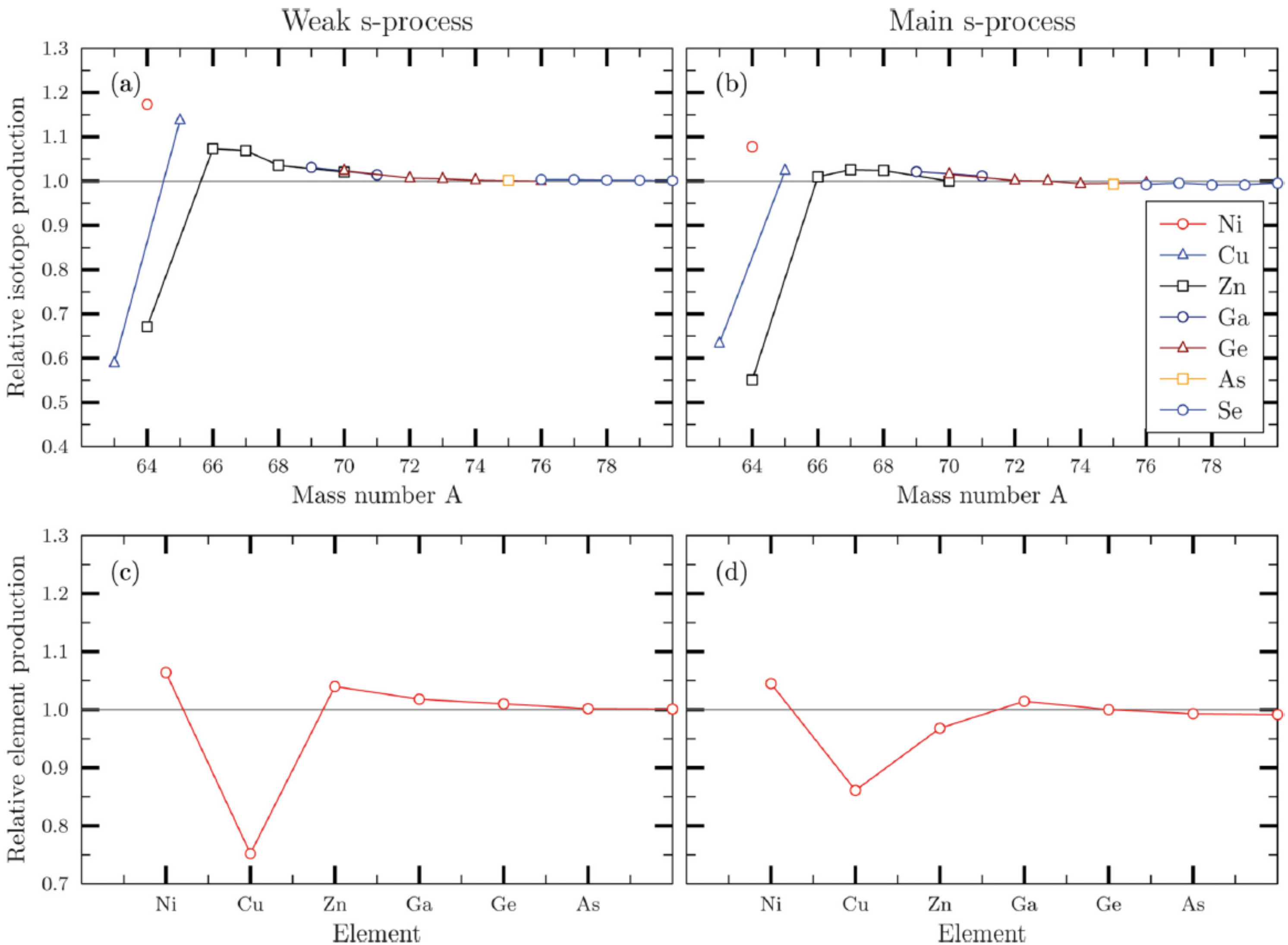
Weigand *et al.* PRC (2015)

^{63}Ni Cross Section and MACS



Impact on ^{63}Cu, ^{64}Zn Production

Simplified post-processing results from NETZ

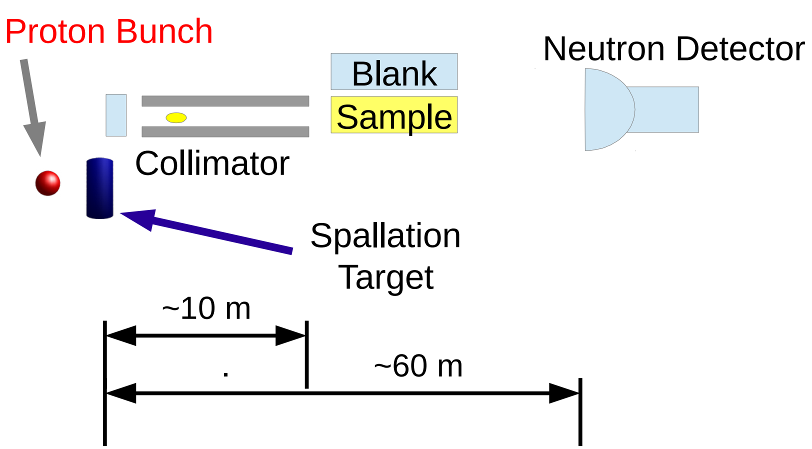


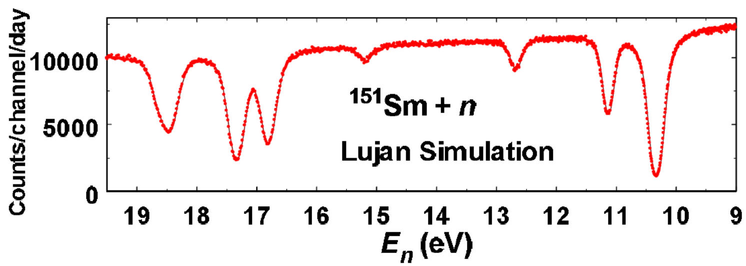
What to do when direct measurement are not possible?

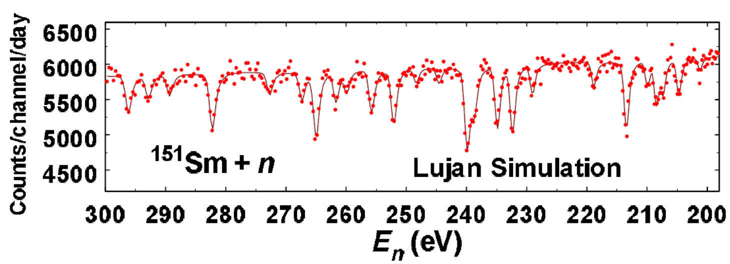
- Build a better neutron source/calorimeter!
  - There is a proposal to improve fluxes to open new measurements at LANSCE
  - Facilities such as FRANZ at Uni. Frankfurt will enhance fluxes, particularly for activation measurements
- Measure part of the reaction
  - Total cross section measurements to get at partial widths
- Eventually, the lifetimes will always get too short
  - Indirect techniques will have to be used
  - Improved RIBs make these more possible
  - Until robust neutron targets are available, transfer reactions will have to be used to get as much information as possible

Total Cross Section Measurements to Determine D_0, S_0, and $\langle \Gamma_\gamma \rangle$

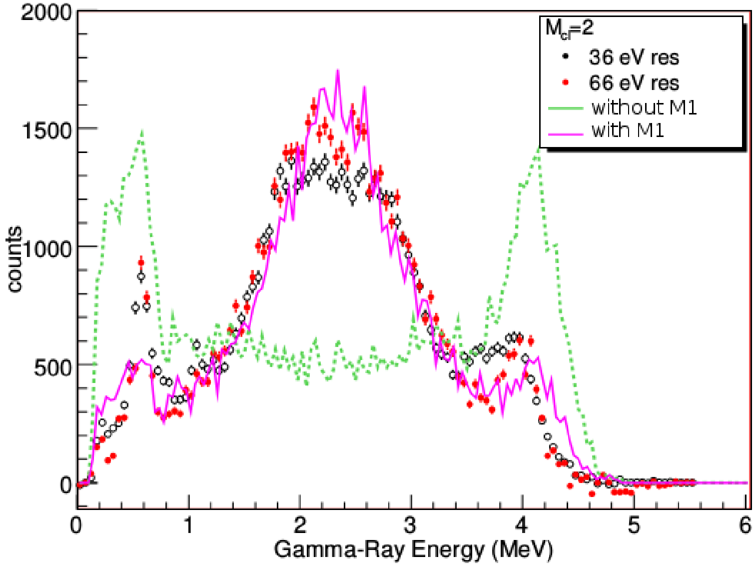
- Concept developed by P. E. Koehler
- This is a neutron time-of-flight measurement technique for LANSCE
  - Separation of sample from detector allows use of highly radioactive samples
  - Detector system is relatively straightforward
  - R-Matrix analysis extracts physical parameters of interest
  - Samples with lifetimes down to days are possible







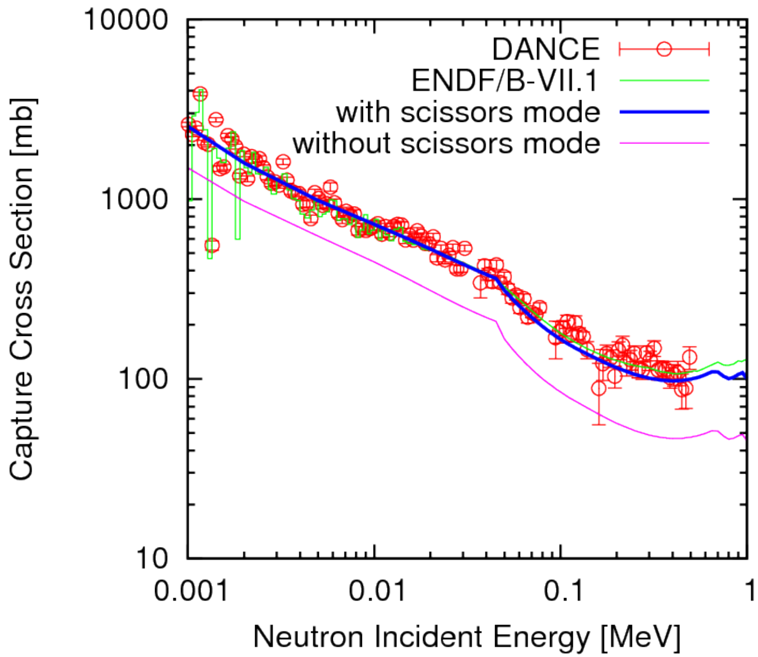
γ Cascades and Capture Cross Sections



- Including a small M1 component at low energies, the ^{238}U(n,γ) data are well-reproduced without artificial re-normalization of photon strength function or <Γγ>
- Does correlation exist between M1 and nuclear deformation?

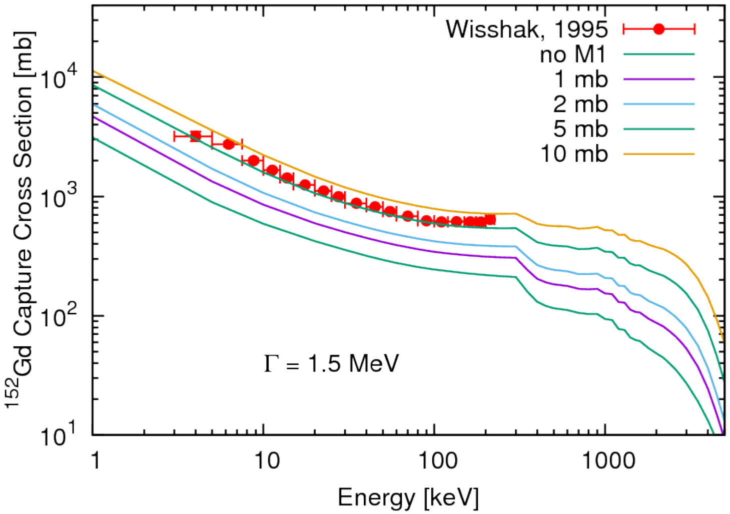
J. Ullmann, et al. PRC 89, 034603 (2014)

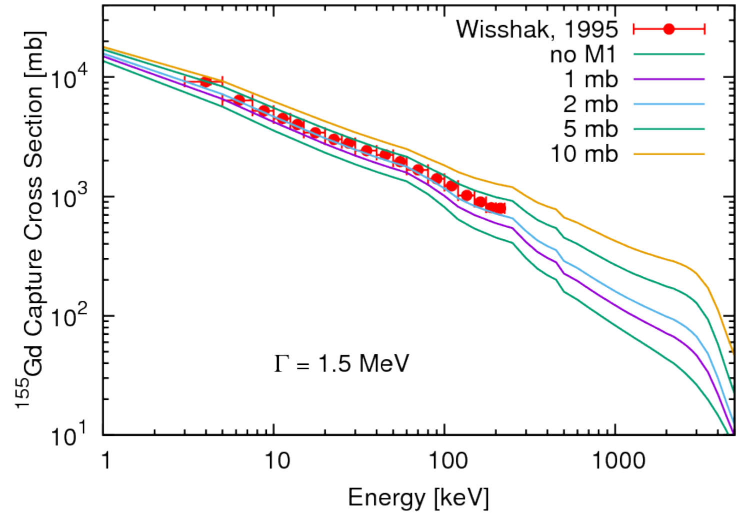
- DANCE γ-ray spectrum for multiplicity 2
  - an additional strength in the low energy region needed
  - we assume this is an M1 scissors mode

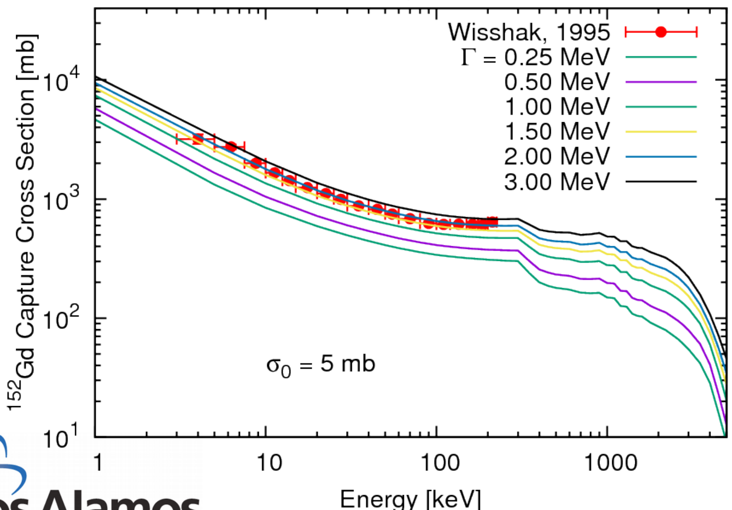


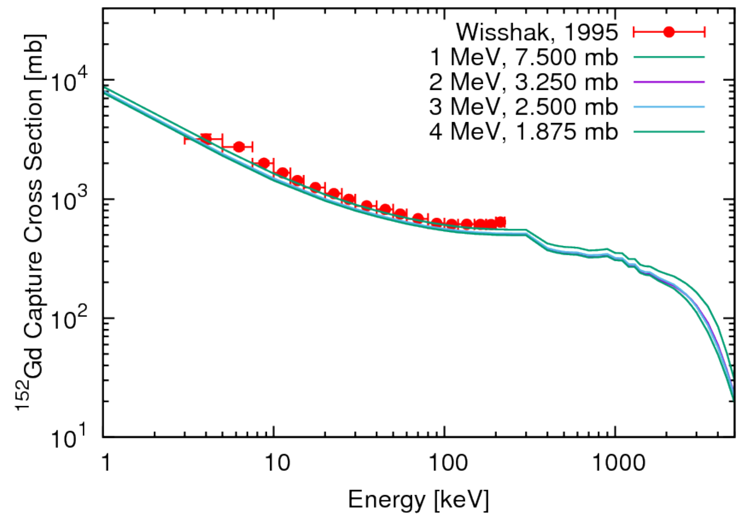
Calculated Capture Cross Section Sensitivity to M1

Calculations from Kawano/CoH3







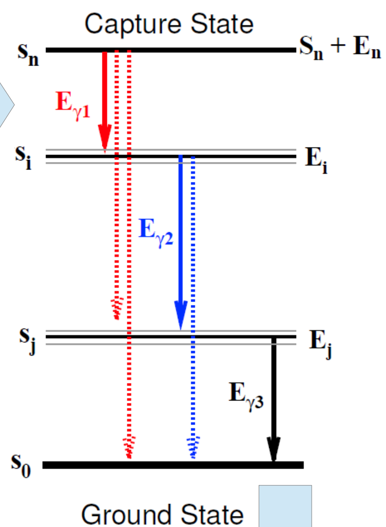


Los Alamos NATIONAL LABORATORY EST. 1943

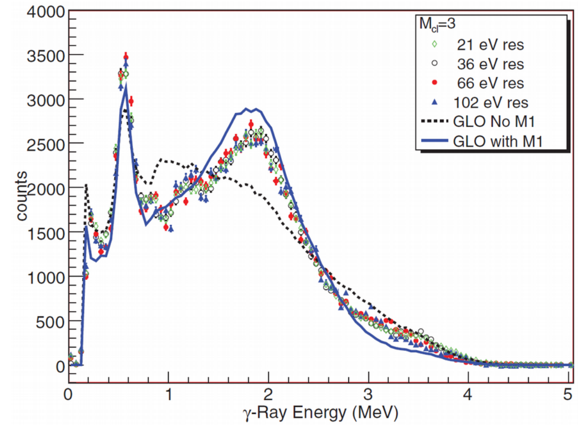
From Measurement to Reaction Rate

Data from ^{238}U DANCE work, Ullmann, Kawano *et al.* *PRC* **89** 2014

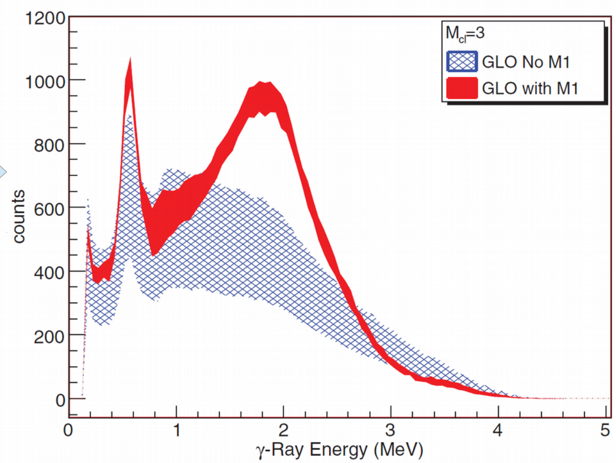
CGM produces cascades



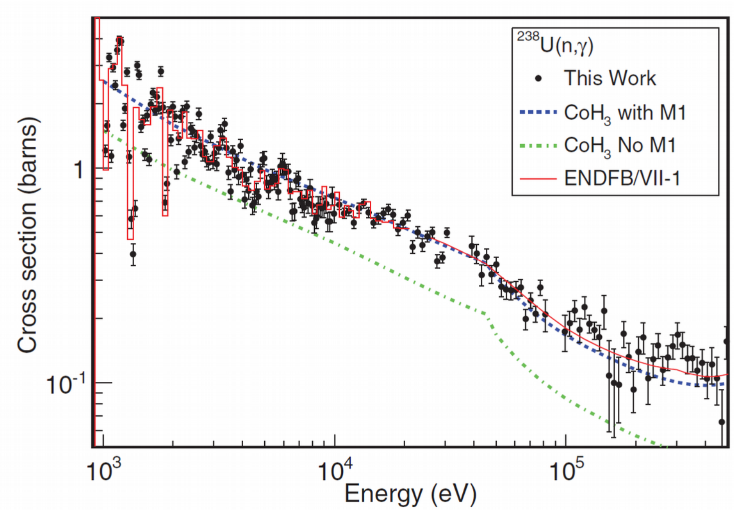
Comparison with data reveal best model of level densities, widths, etc.
(PSF in this work)



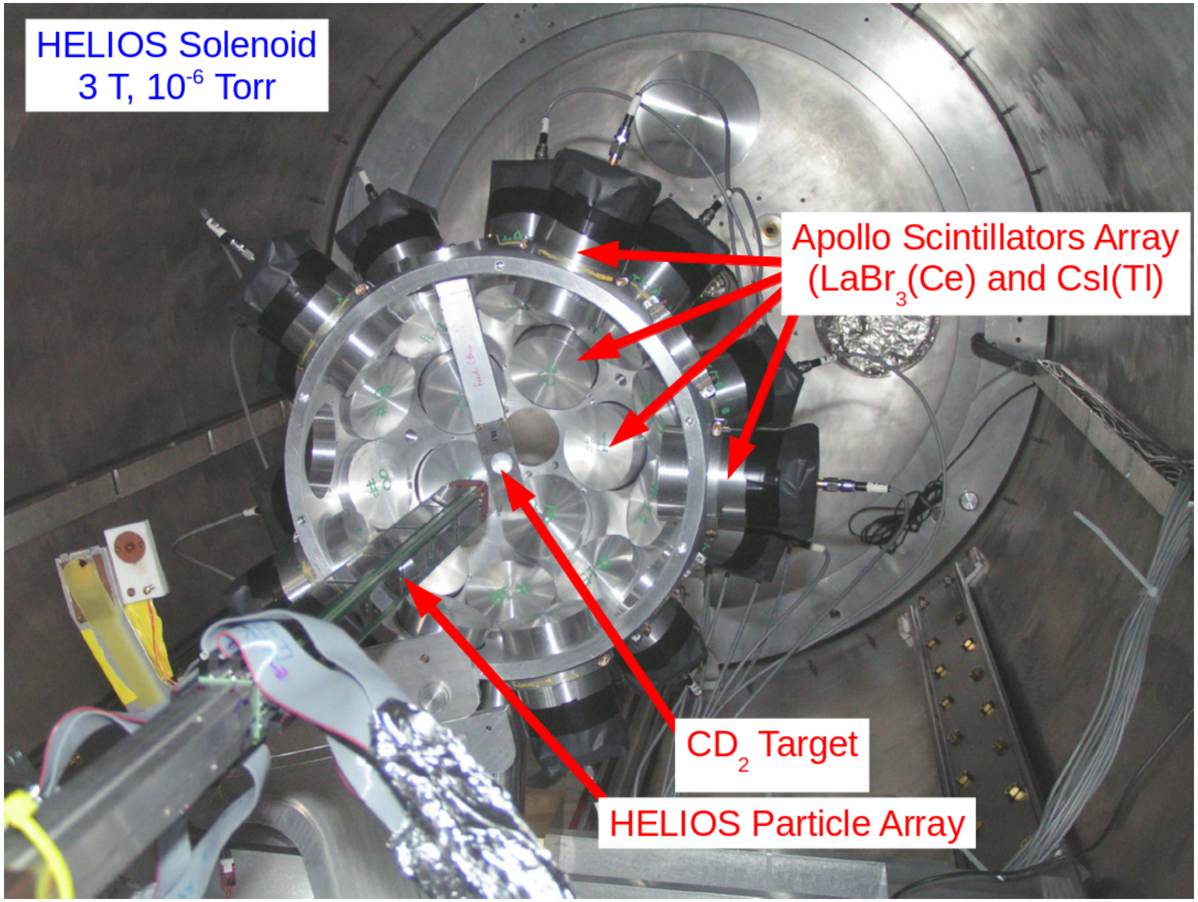
Cascade sent through GEANT simulation to create "experimental" spectrum



Once consistent input parameters are known, cross section predictions improve in accuracy



Apollo implemented inside HELIOS



- Array consists of 6 $LaBr(Ce)_3$ and 15 CsI(Tl) scintillators, each 2”x3” cylinders
- Light readout with SiPM allows use in HELIOS field and vacuum
- ~12% efficiency at 1 MeV
- A close-packed geometry design exists

Approach: Trust but Verify

Measurements are being compared to direct (n,γ) measurements

- We have completed ATLAS measurements of $^{96}Zr(d,p)$ and $^{57}Fe(d,p)$
  - We will perform a forward “Multi-step Cascade” analysis
  - We are working with the Oslo group to perform an Oslo analysis of the transfer data
- These are complemented by DANCE measurements of $^{96}Zr(n,\gamma)$ and $^{57}Fe(n,\gamma)$
  - Extract a reliable (n,g) cross section
  - Perform a forward “Multi-Step Cascade” analysis
- Compare 3 PSF results and 3 cross section results

A Plea for Help: Improved PSF Predictions

- At present, most of the pieces we use are phenomenological
  - E1 GLO/MGLO/SLO
  - M1 GLO/MGLO/SLO
  - E1 Pygmy
  - M1 Scissors
  - Low Energy “Upbends” of dubious experimental confidence
  - A discontinuous GLO in some gamma-soft nuclei
- The goal is to *predict* cross sections, not measure them
- To get there, we have to be able to reliably test predictions and verify them, hopefully tying them to a simple observable

What Keeps Me Up at Night

Statistical Approaches Won't Always Work

- Level Densities, Photon Strength Functions and Hauser Feshbach are all fundamentally *statistical concepts*
- Shell closures will, at best, be challenging
- Some r-process scenarios (notably neutron star mergers) are cold and neutron-rich
  - These will sit at the edge of the neutron drip-line
- For s-process and i-process studies, individual resonances *may* dominate the cross sections

Are we accounting for correlations?

- Given the state of the art, can I change a reaction rate for ^{90}Kr(n,γ) without affecting ^{92}Kr(n,γ)?
  - To produce a change, I have to adjust level density, optical model, a PSF, a spin or parity distribution
  - Those seem like they should propogate to near-by nuclei
- Is there sufficient data to even attempt to address correlations meaningfully?

Conclusions

- Neutron capture plays an essential role in nucleosynthesis
- Direct measurements are often possible for stable isotopes
- Indirect methods are being developed, but come with challenges
- There are challenges waiting in the future that these techniques will not address

Collaborators

Apollo

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DANCE

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Nuclear Theory & Evaluation

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Total Cross Sections

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