Studies of ^{54,56}Fe Neutron Scattering Cross Sections

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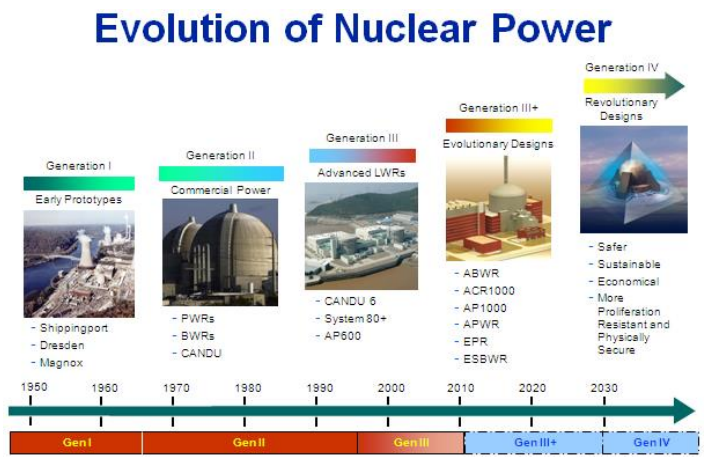
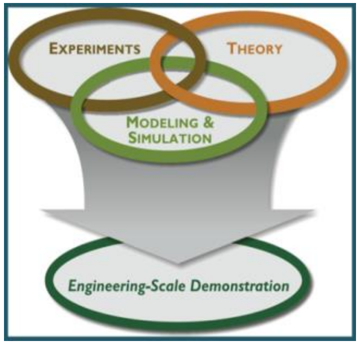
Advanced Elastic and Inelastic Nuclear Data Development Project



http://www.gen-4.org/Technology/evolution.htm

Goals of AFCI Gen IV:

i) Safer
ii) Sustainable
iii) Economical
iv) Physically Secure



<http://nuclearpowertraining.tpub.com/h1019v1/css/h1019v1_69.htm.>

Data Modeling

i) Data needed over a large energy range.
ii) Better understanding of the nuclear force properties.
iii) Needed for reactor design.

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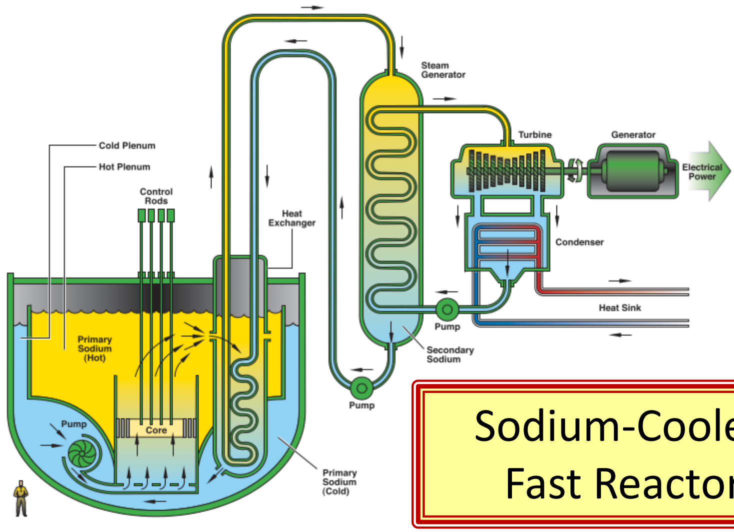
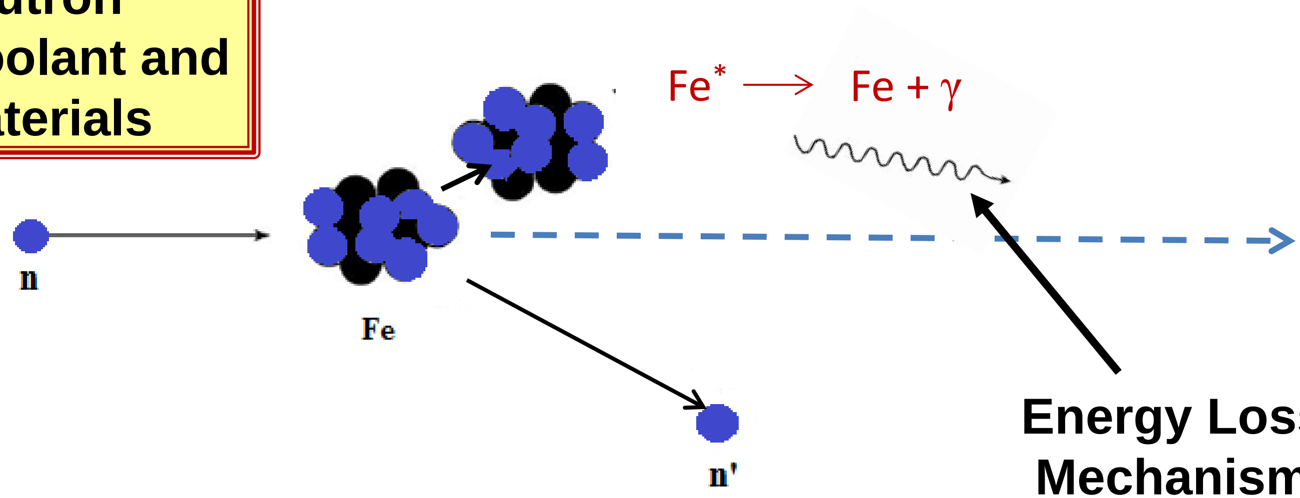
One of the Six Generation IV Nuclear Energy Systems



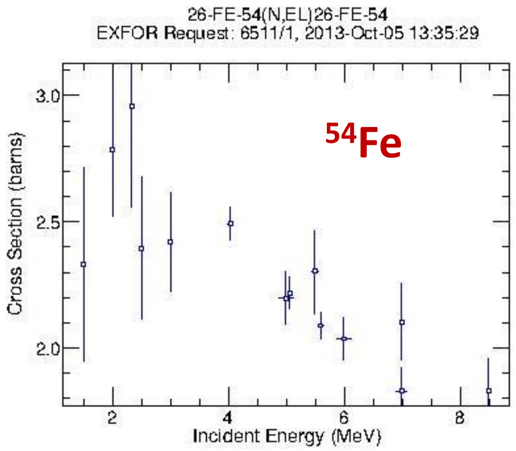
Sodium-Cooled Fast Reactor

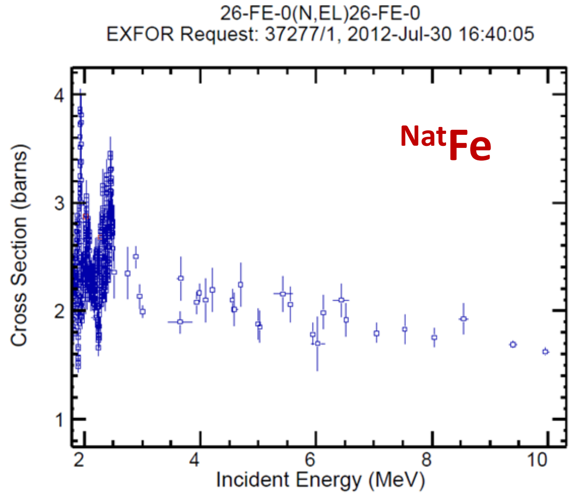
"A Technology Roadmap for Generation IV Nuclear Energy Systems," Generation IV International Forum, December 2002.

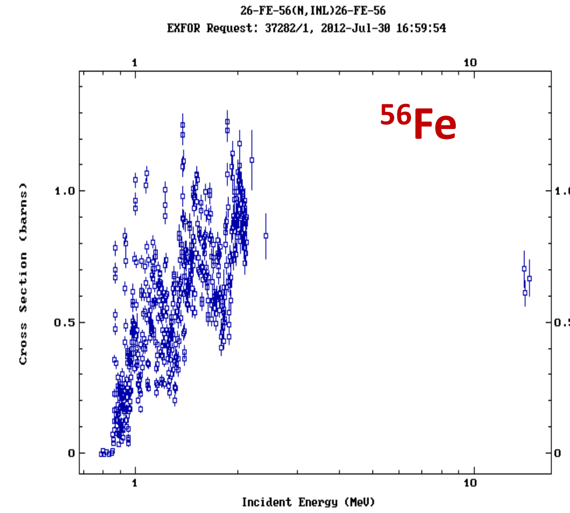
Inelastic Neutron Scattering off coolant and structural materials



Energy Loss Mechanism







Existing ^{54,56}Fe(*n*, elastic) data:

- **Sparse data above 2 MeV, especially for inelastic scattering**
- **Uncertainties missing or not well defined.**
- **Finite sample corrections ?**

Existing ^{54,56}Fe(*n,n'*) data:

- **Inelastic neutron scattering cross sections are less well known and have higher uncertainties.**

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Modified Model CN VDG.

University of Kentucky Accelerator Laboratory (UKAL) - Neutron production and detection facility.

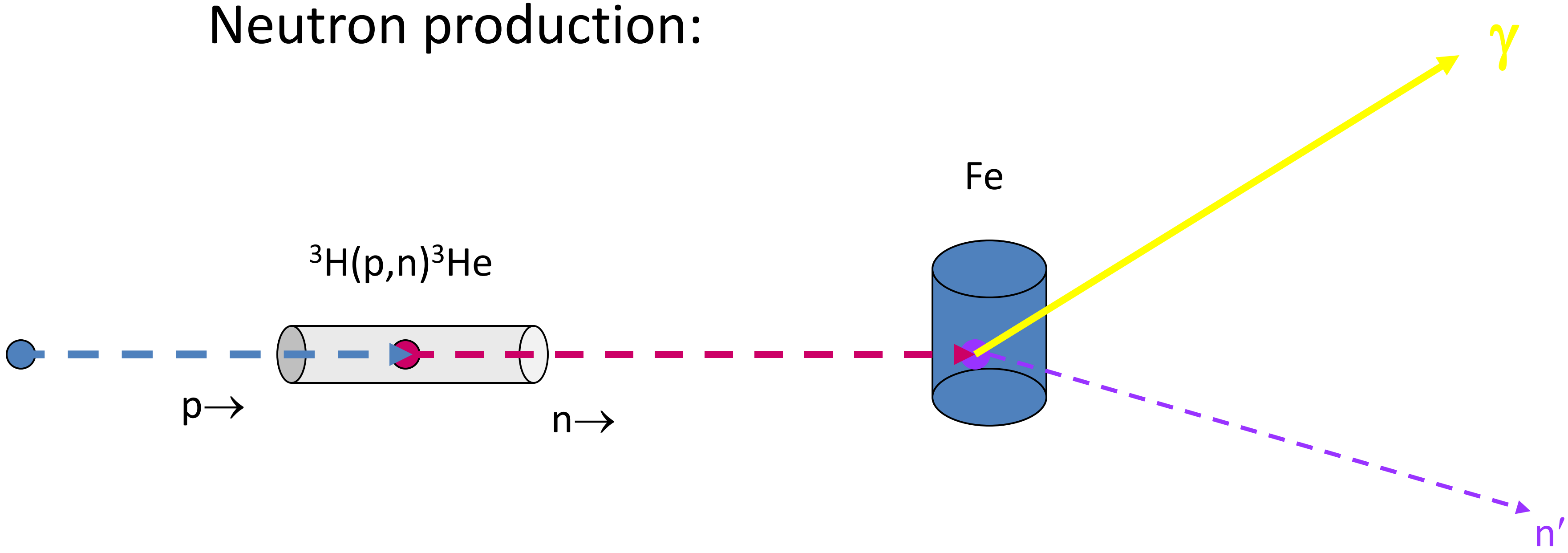

Tank On

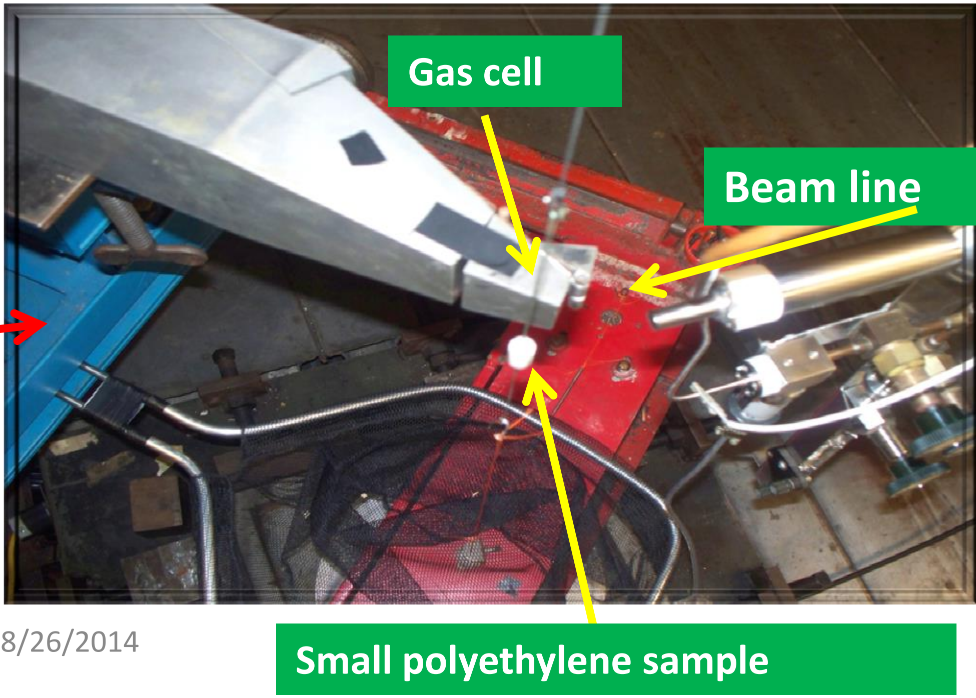

Tank Off

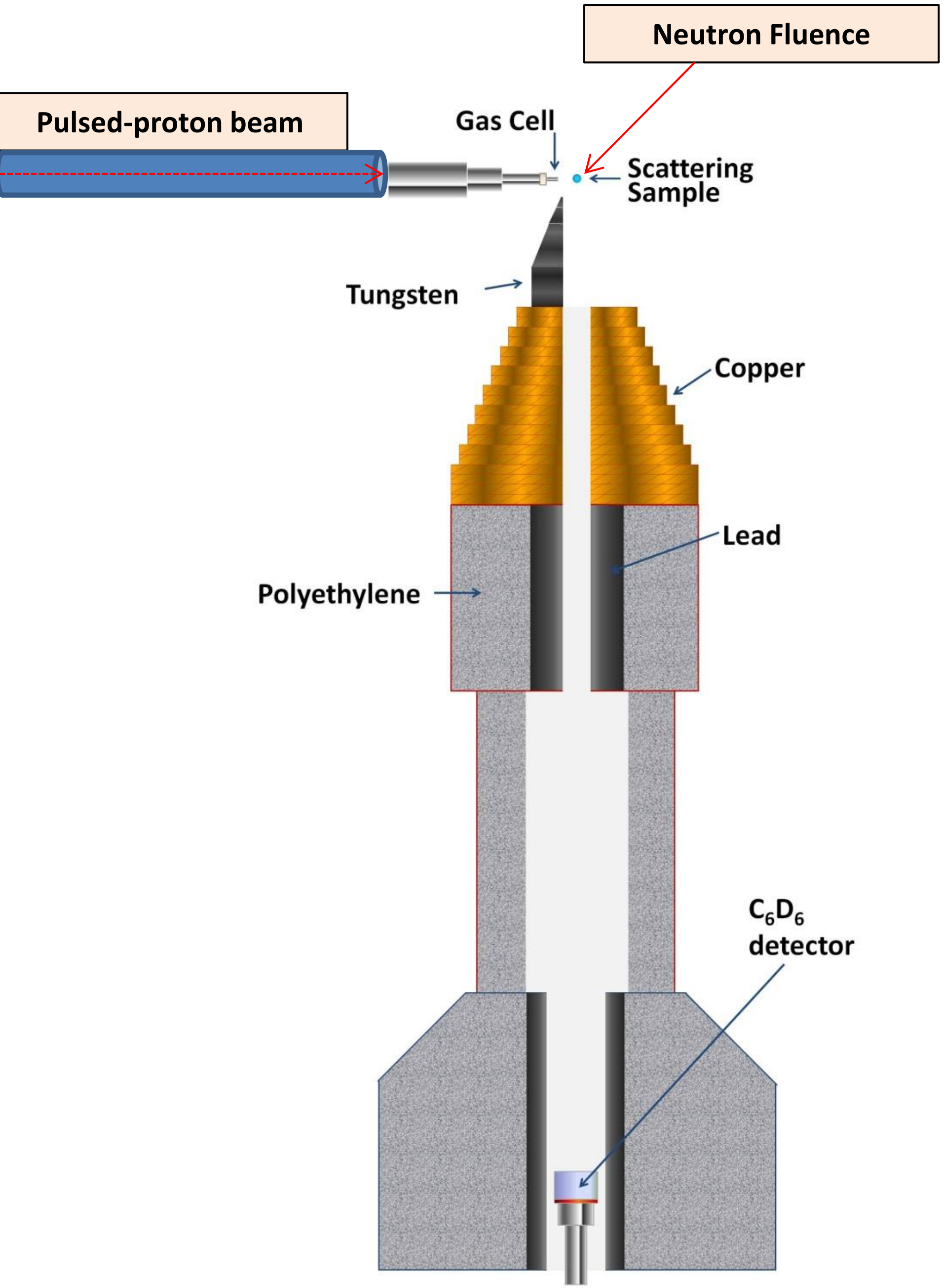

Terminal Off

- ❑ **7 MV maximum terminal voltage**
- ❑ ***p*, *d*, ^{3}He, and α beams**
- ❑ **pulsed and DC beams , repetition rate of 1.875 MHz.**
- ❑ **Bunch beam pulses with FWHM Δt≈1 ns pulse width.**
- ❑ **Pulsed beams necessary for neutron time-of-flight measurements.**

Neutron production:

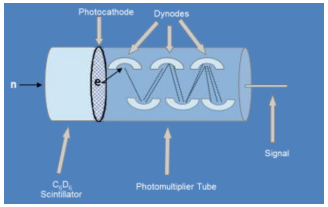




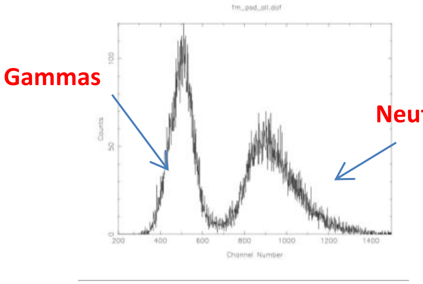


- Neutron TOF techniques

- Neutrons detected in a C_6D_6 detector.

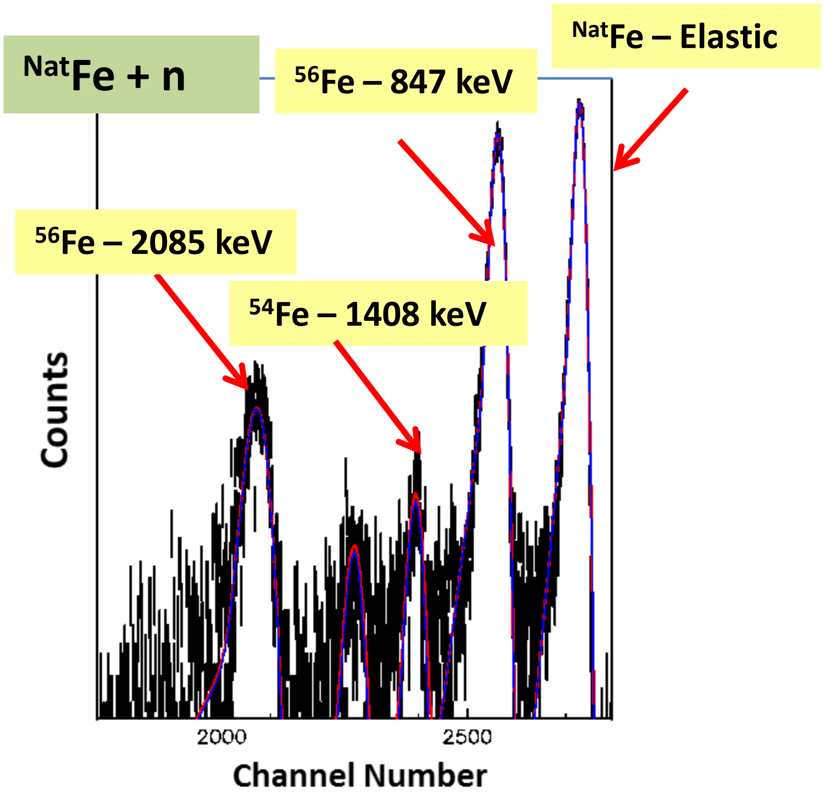


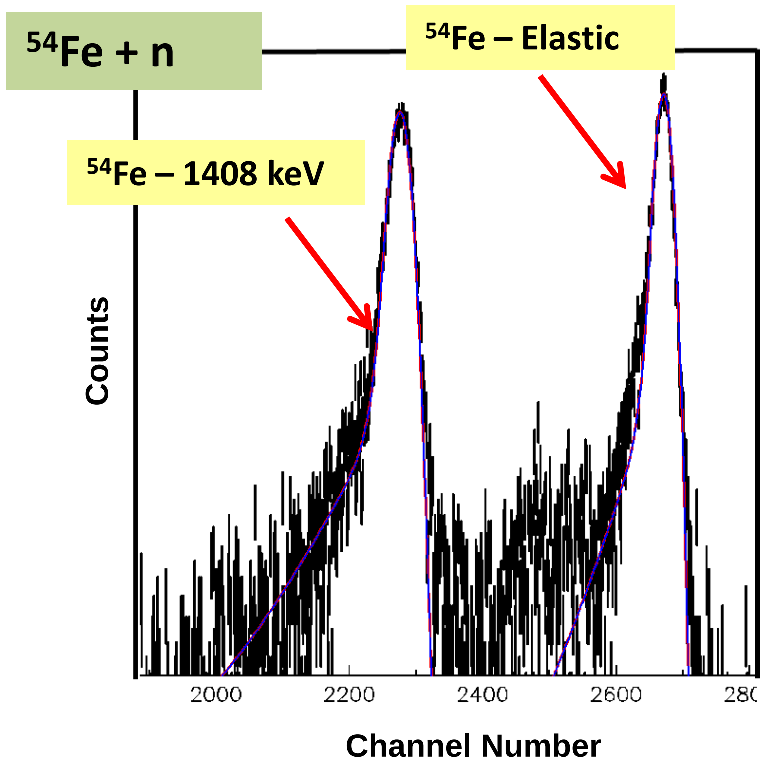
- PSD used to eliminate unwanted γ-ray events.



- Additional scintillation detector used for normalization – $Y_{monitor}$.

- Detector carriage rotated about the center of sample - 30^o to 150^o.





Neutron Time-of-Flight Spectra at E_n=3.5 MeV (^{Nat}Fe) and 4.0 MeV (^{54}Fe) [time ←]

E_n = 1.75 MeV, 3.19 MeV, 3.4 MeV, 3.5 MeV, 3.6 MeV, 3.7 MeV, 3.9 MeV

Cross Section Determination

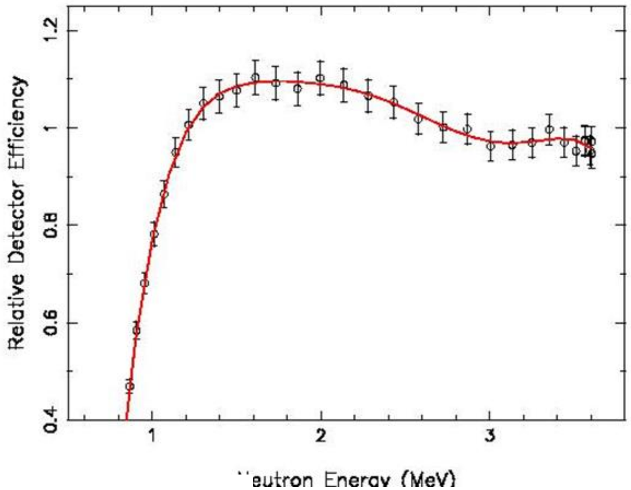
$$\frac{d\sigma}{d\Omega}(\theta) = \frac{N_{abs} Y_{main}}{Y_{monitor} Eff(E_n)}$$

- Y_{main} is the main detector yield,
- $Y_{monitor}$ is the monitor detector yield,
- θ is the scattering angle,
- $Eff(E_n)$ is the neutron detection efficiency at E_{n},
- N_{abs} is the absolute normalization factor.

Finite Sample Corrections:
- Multiple scattering
- Attenuation
- MULCAT

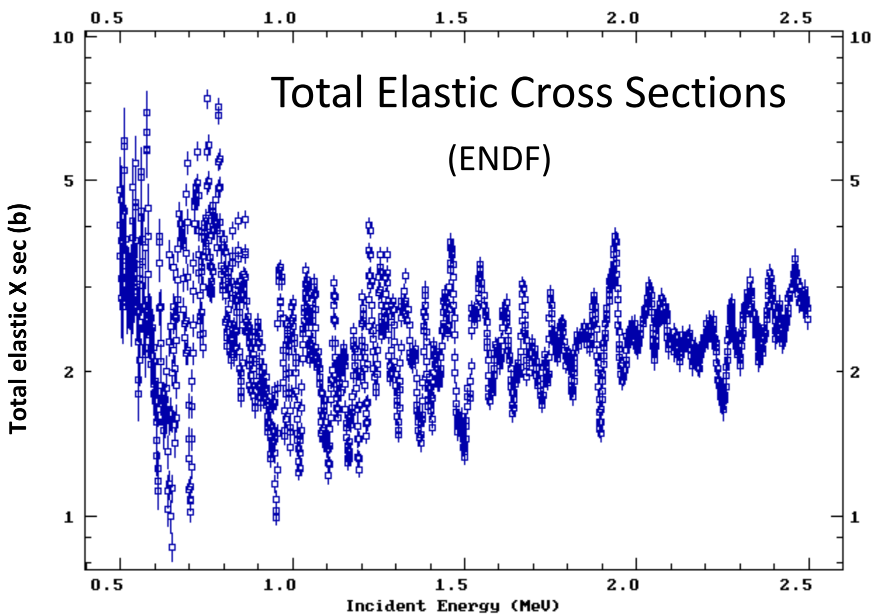
Absolutely Normalization:
- *np* scattering
- carbon elastic scattering

Relative Detector Efficiency



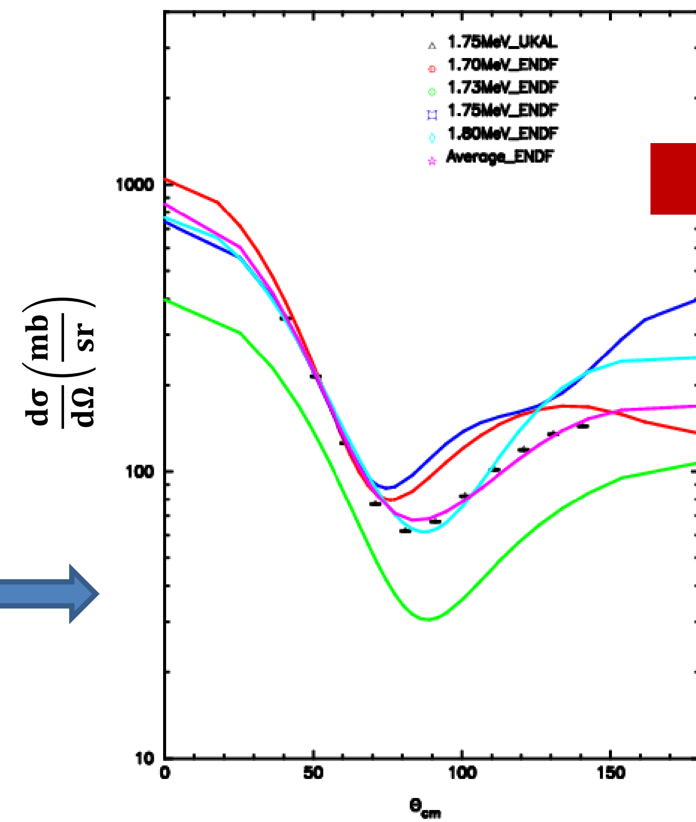
- **Efficiency *Eff*(E_n) measured *in situ* by measuring the angular distribution of source neutrons.**
- **Largest single contributor to the uncertainty is the T(p,n)^{3}He cross sections.**

np scattering



At E_n=1.75 MeV, the total elastic cross sections fluctuate by a few barns.

The solid lines show ENDF neutron elastic differential cross sections at E_n = 1.70-1.80 MeV.



Average

Energy spread of incident neutrons: $\Delta E_n \approx 90$ keV.

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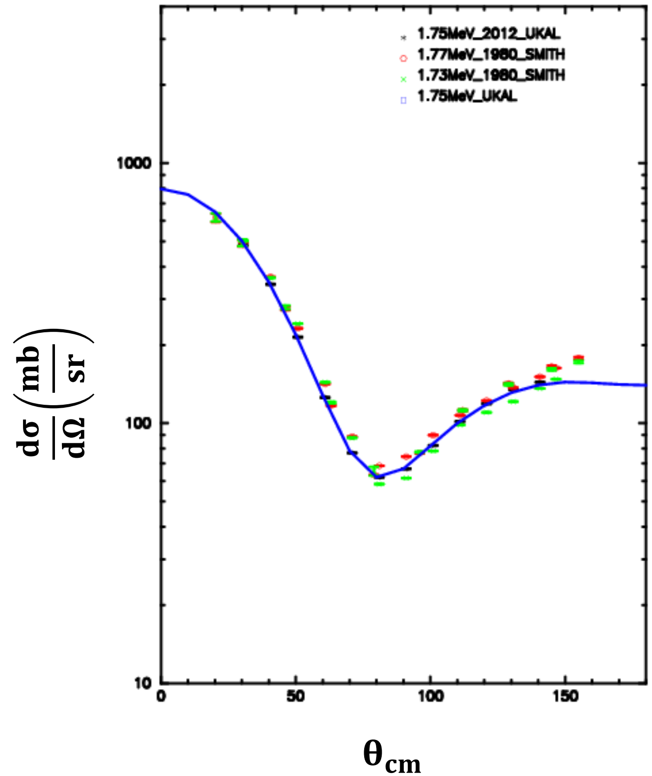
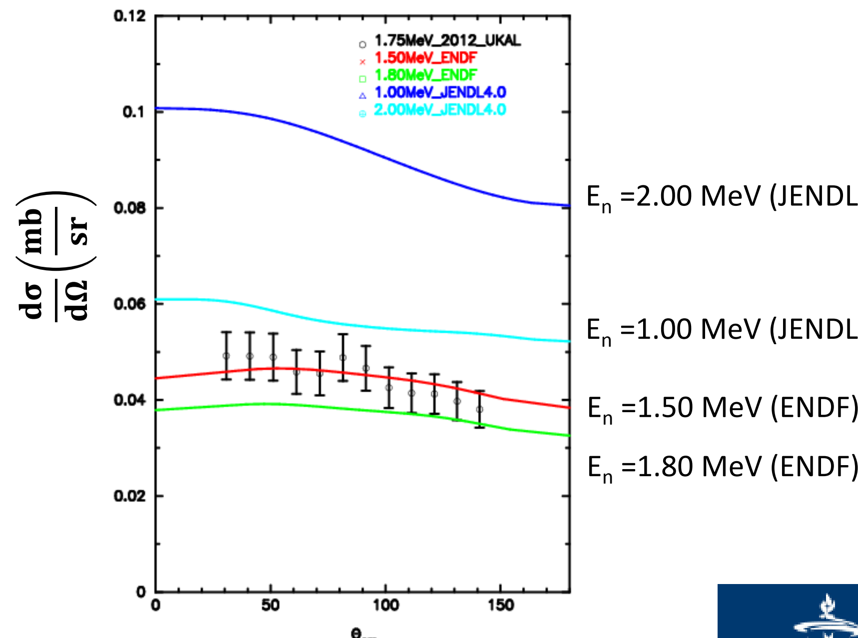
Comparison of UKAL neutron elastic scattering data from ^{nat}Fe at E_n=1.75 MeV to previous measurements by Smith *et al.* 1980.



One might wonder if these new measurements are necessary?

Neutron inelastic scattering from the ^{56}Fe 847-keV level at E_n=1.75 MeV.

- Few existing data
- Large discrepancies between evaluations.
- Uncertainties



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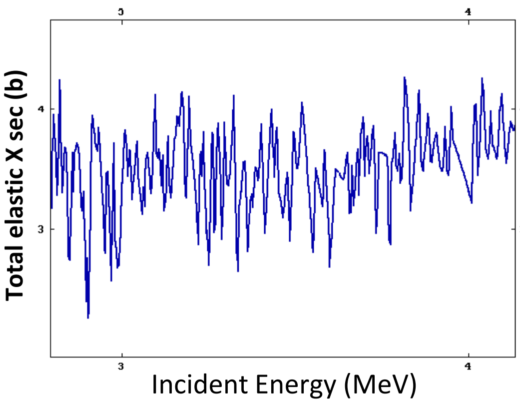
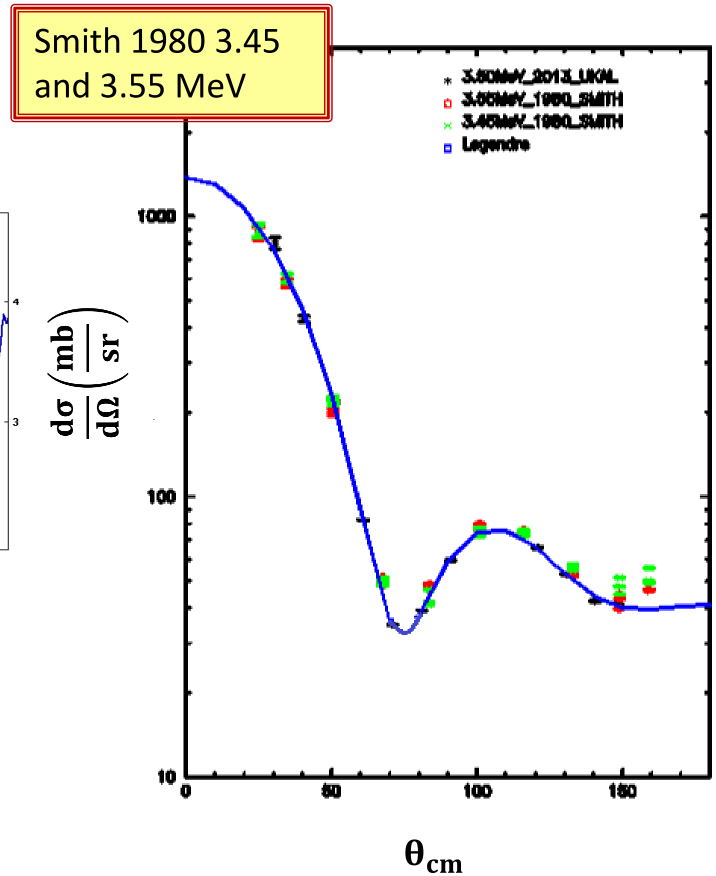
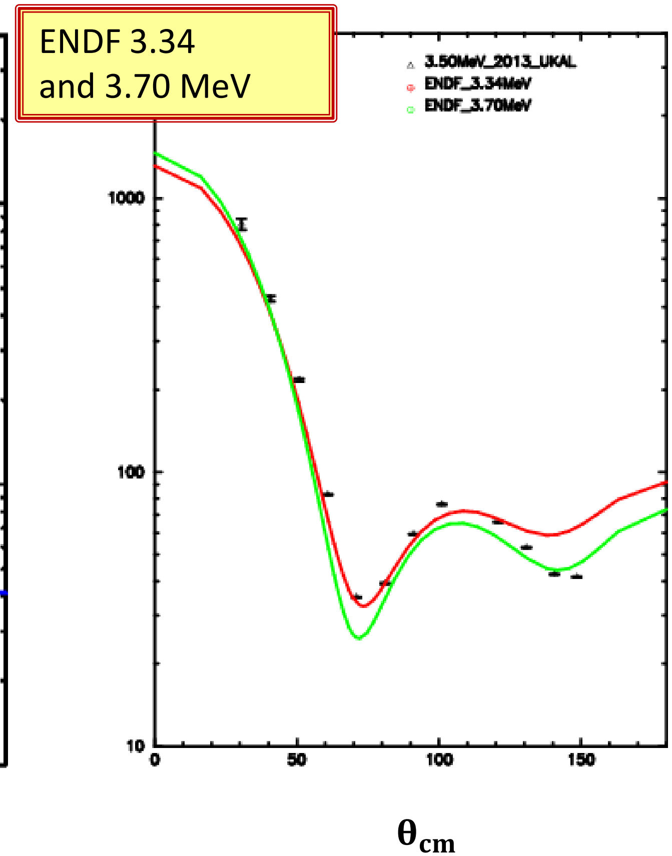
^{Nat}Fe elastic at E_n = 3.50 MeV – Comparison to CSISRS (left) and ENDF (right)







- **Agreement with existing data very good forward of 120 degrees.**
- **Significant deviations between existing data and ENDF at 3.50 MeV**

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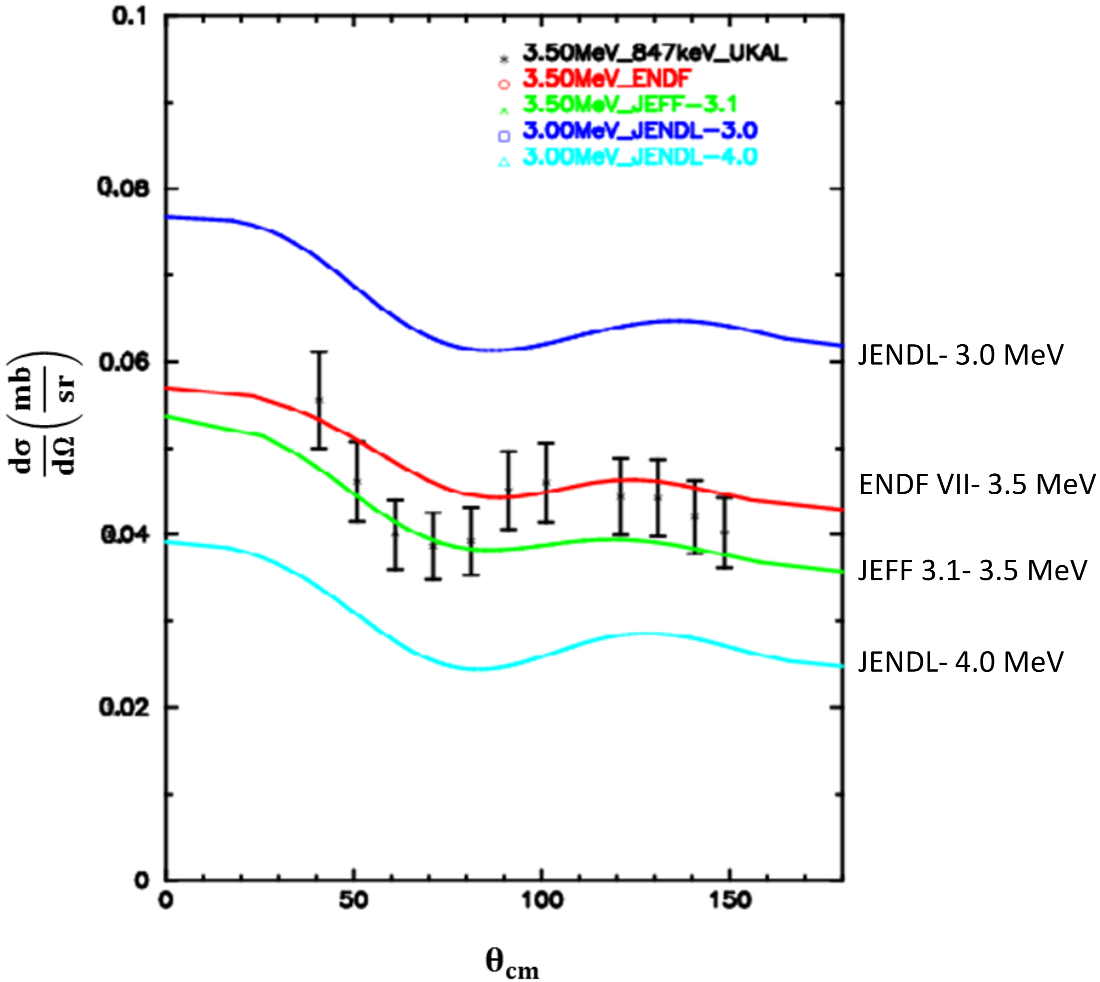
E_n = 3.50 MeV

Neutron inelastic scattering from the 847-keV level in ^{56}Fe.

- **First minimum not well described relative to second maximum.**
- **Very forward angles difficult to fit confidently.**
- **Experimental first minimum appears forward of model calculations.**



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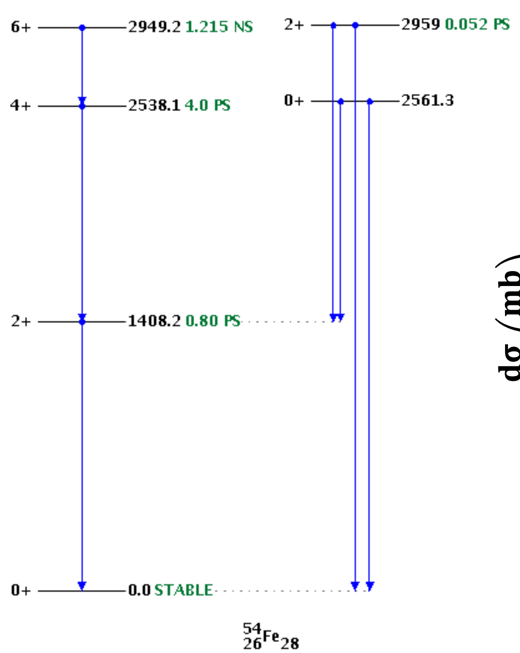
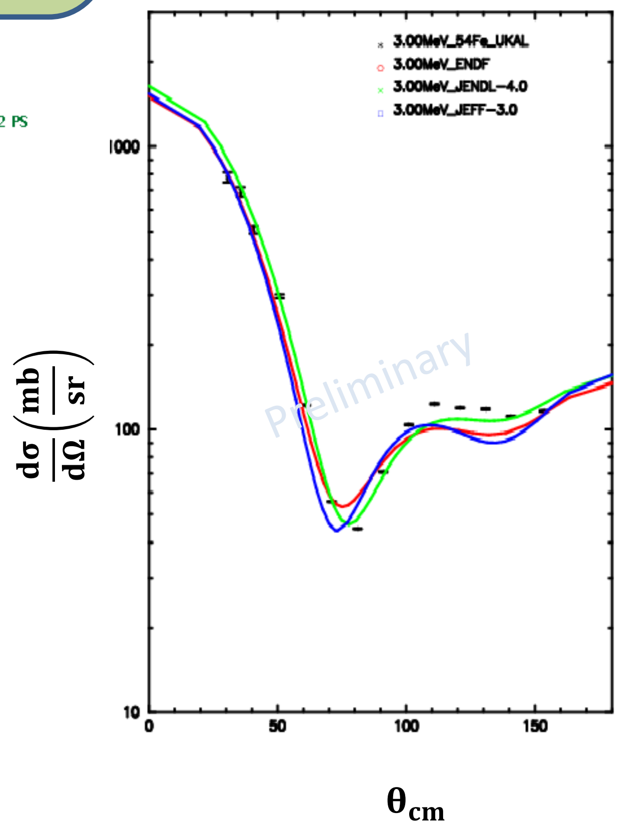
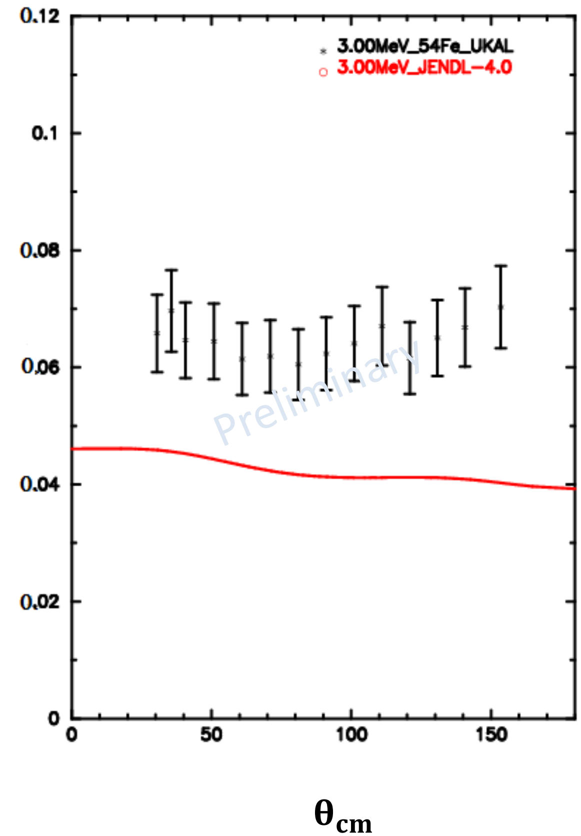
Experiments have been performed on ^{54}Fe and are in progress on ^{56}Fe enriched samples.

Sample	Isotopic Abundance	Mass (g)	Diameter (cm)	Height (cm)
^{54}Fe	97.6000	18.046	1.45	1.50



http://www.nndc.bnl.gov/chart/replotband.jsp





$^{54}Fe + n$ at E_n=3.0 MeV

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Challenges in determining neutron scattering inelastic cross sections:

- **Fitting uncertainties– especially at forward angles where the elastic cross section is very large. Tails – Tails –Tails**
- **Finite Sample Corrections – multiple-scattering and attenuation**
- **Length of experiments to get reasonable statistics**

For details attend Jeff Vanhoy's talk Wednesday at 11:00, Session 18, Room 028.

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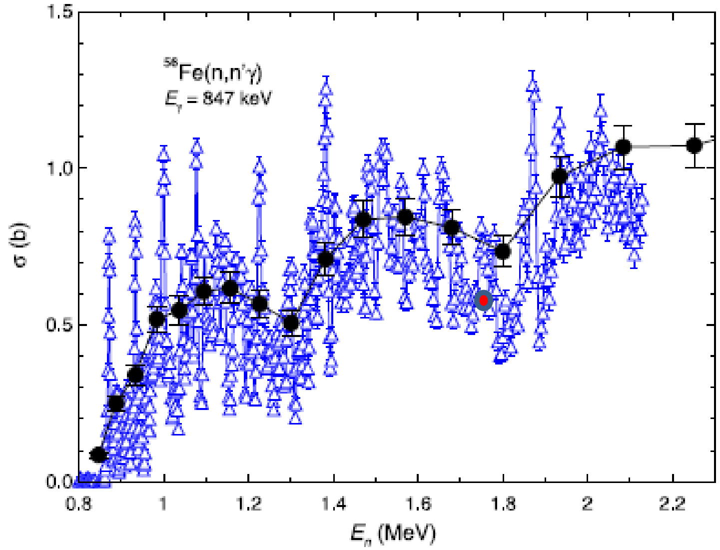
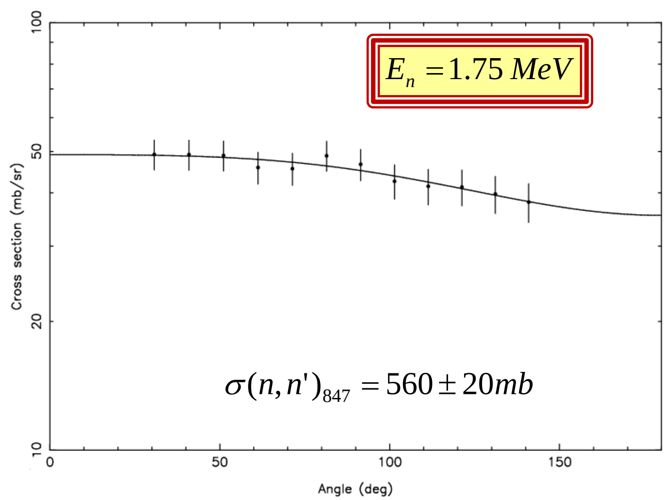
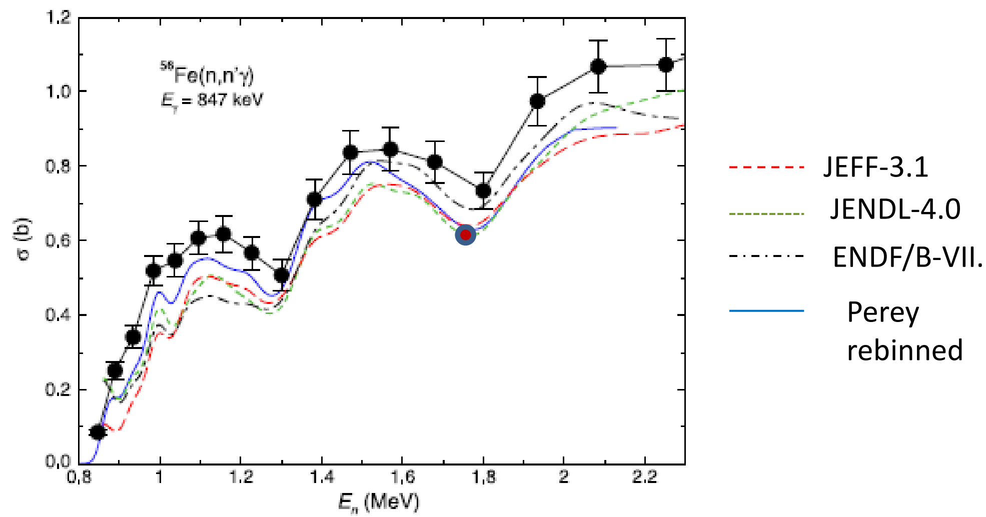
Neutron inelastic scattering cross sections can be deduced from γ-ray production cross sections.

R. Beyer et al., Nucl. Phys. A 927, 41 (2014).



F. G. Perey et al.,





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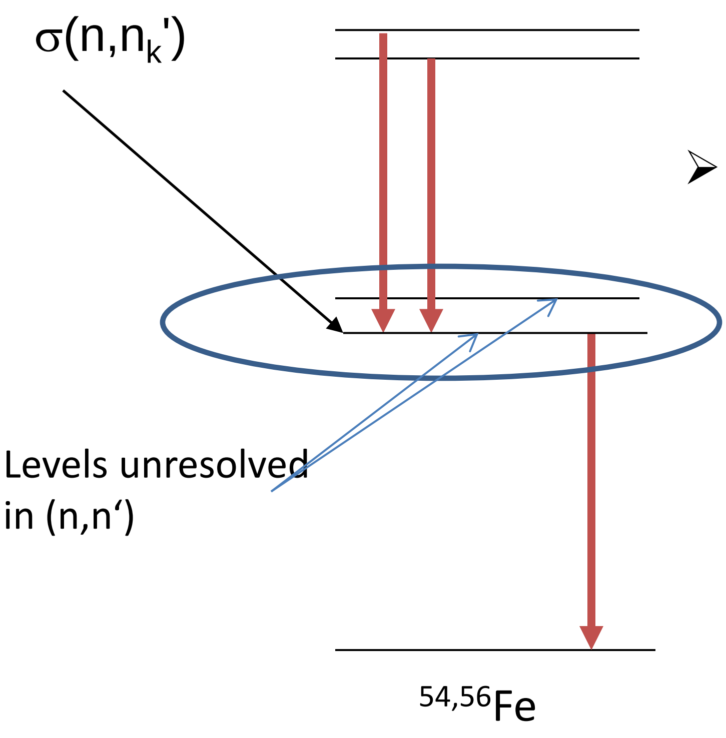
γ-ray Production Cross Sections Used to Deduce (n,n') Cross Sections

$$\frac{d\sigma}{d\Omega} \approx A_o\left[1 + a_2 P_2(x) + a_4 P_4(x)\right]$$

- a_4 values are usually very small.

$P_2 = 0.00 \quad at \quad 125^o$



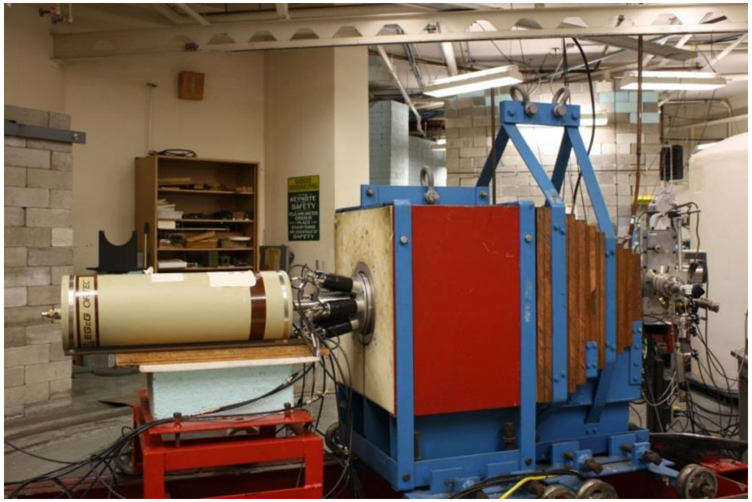
- $$\sigma_{n,n'_k} = \sum \sigma_{de-excitation} - \sum \sigma_{feeding\ transitions}$$

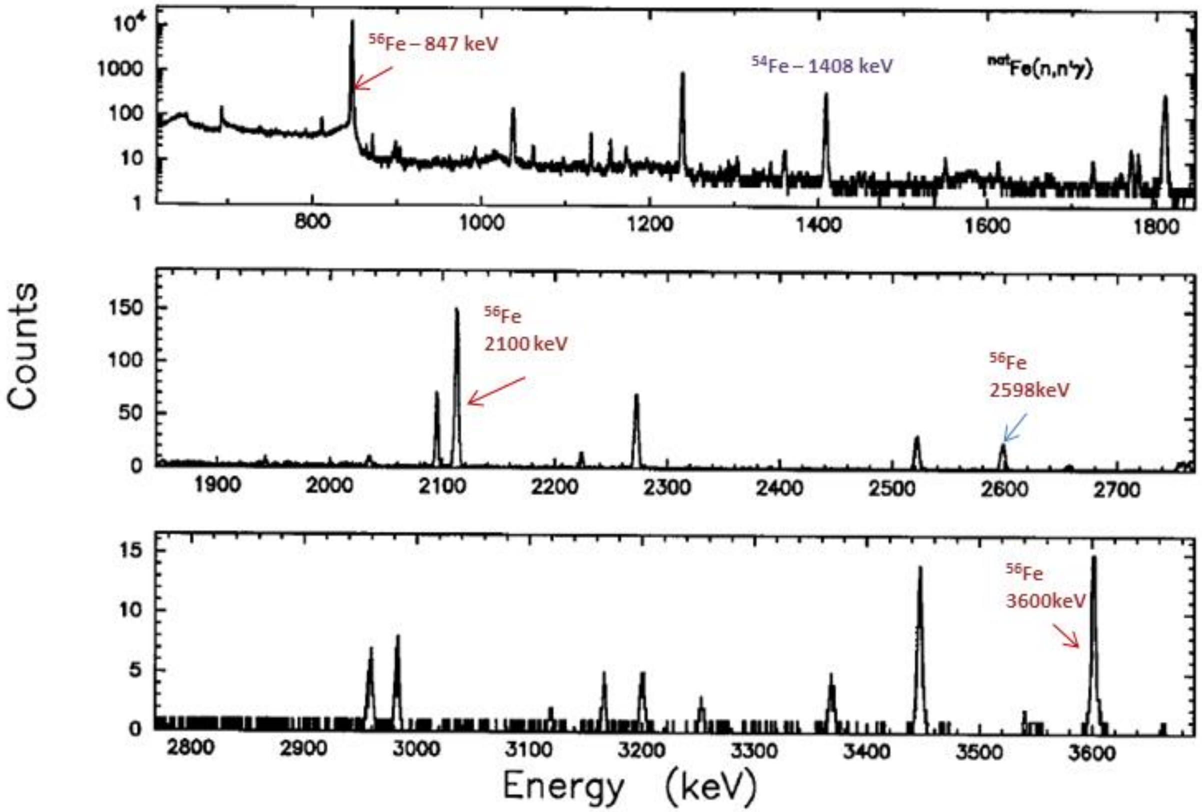
Can resolve closely spaced levels.

Data taken on ^{54,56}Fe and ^{nat}Al, ^{Nat}Ti, and ^{nat}V, but not yet analyzed completely.

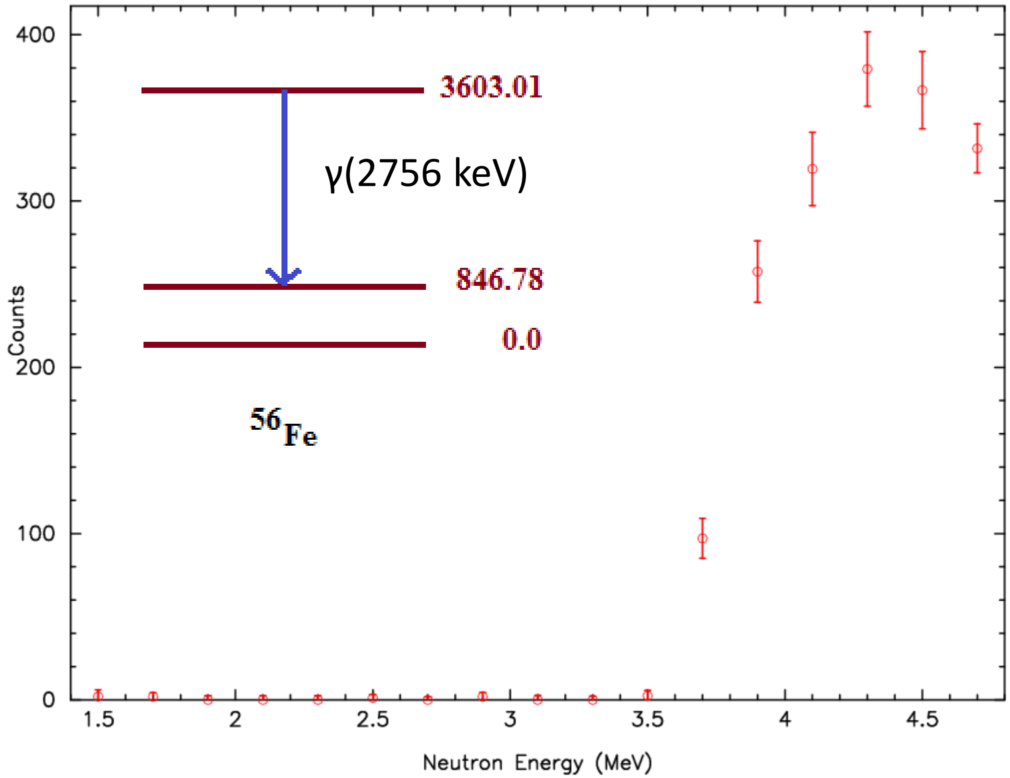
- **Deduce neutron production cross sections**
- **Consider Al, Ti, and V as absolute normalization sources.**
- **E_n = 1.5 – 4.7 MeV in 200 keV steps**

HpGe detector – BGO Compton Suppression annulus

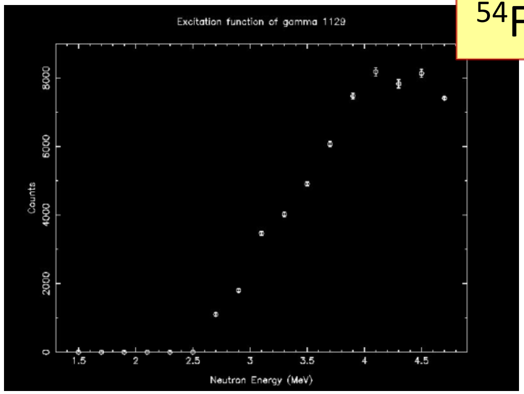




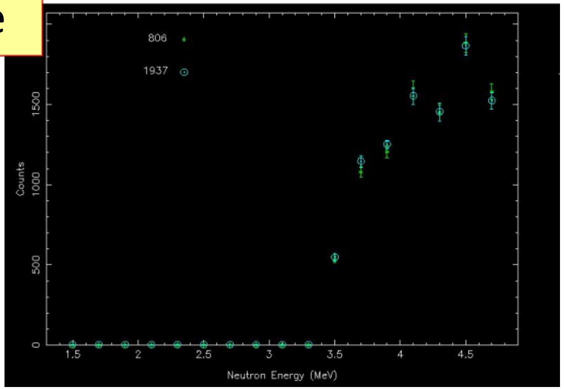
Example excitation function from $^{nat}Fe(n,n'\gamma)$



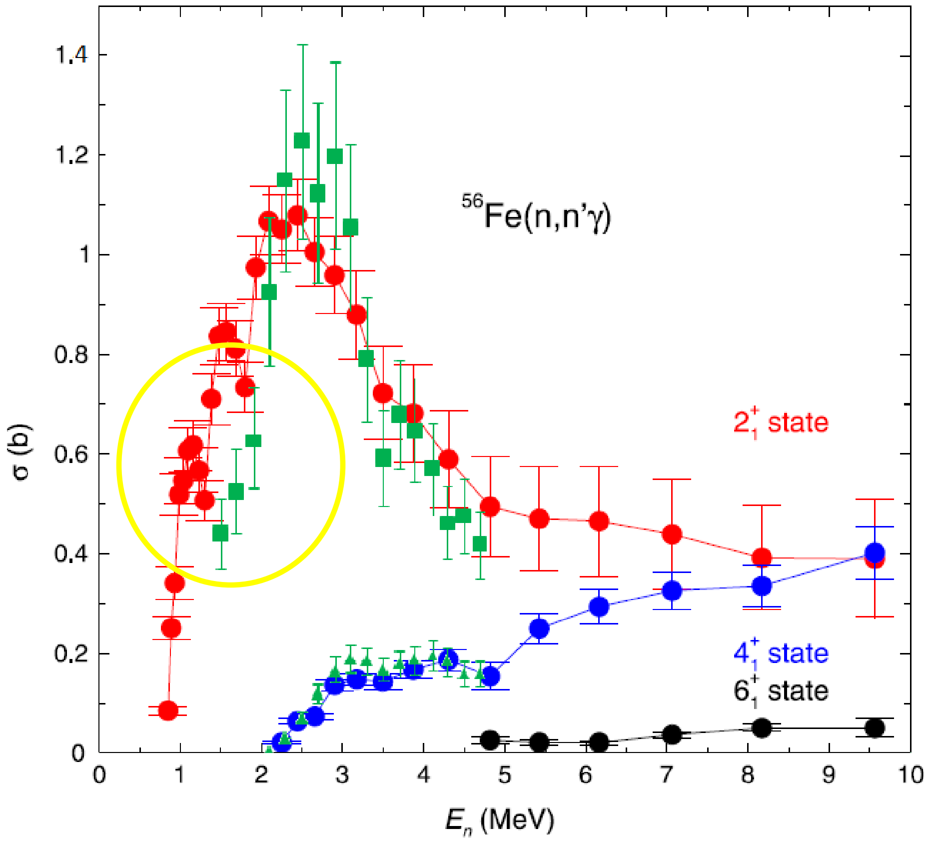
- Evaluate γ-ray branching ratios
- For ^{54}Fe finding A_o, a_2, and a_4 from γ-ray angular distribution at 4.5 MeV



^{54}Fe



And the very preliminary results are in! Data analyzed by UD undergraduate Thaddeus Howard compared to measurements by R. Beyer et al., Nucl. Phys. A 927, 41 (2014).

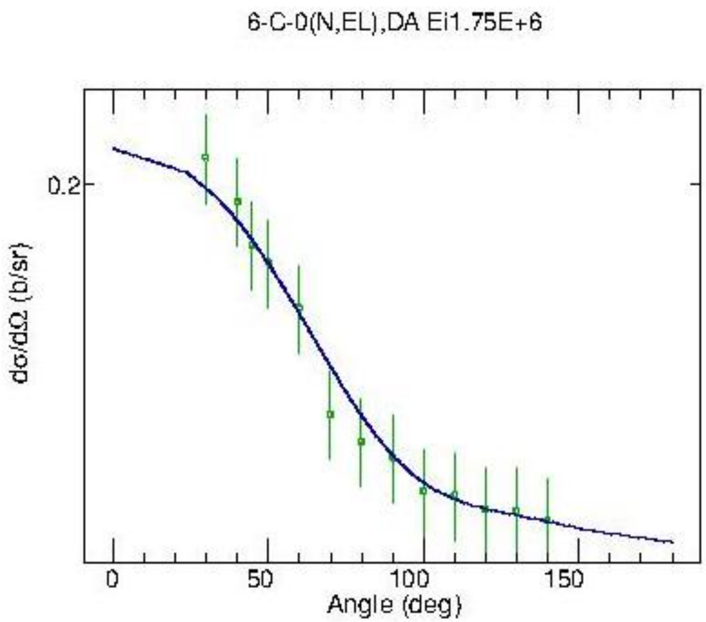


Conclusions

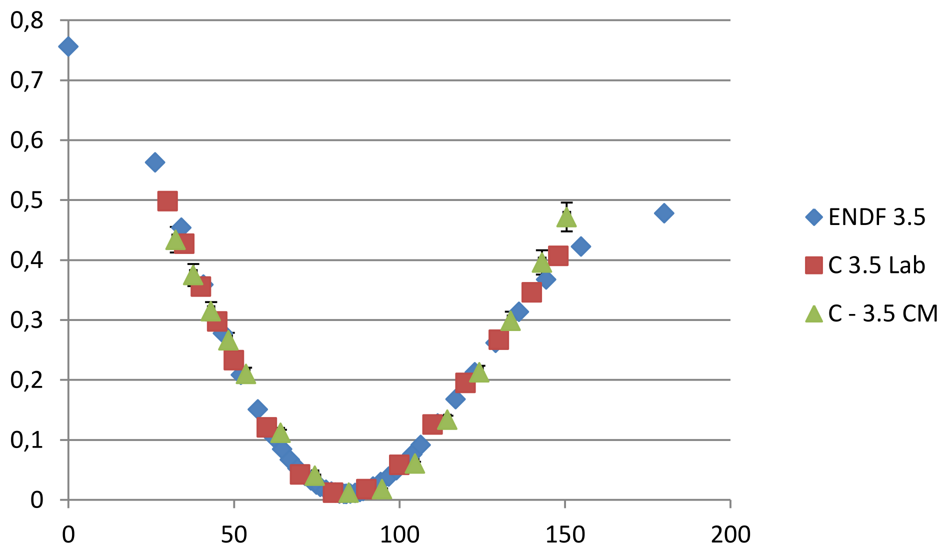
- Elastic and inelastic neutron scattering angular distributions have been measured at 6-8 incident neutron energies on ^{nat}Fe and five incident-neutron energies on ^{54}Fe .

- Comparisons to evaluated cross sections show reasonably good agreement between measured and model calculations for neutron elastic scattering cross sections. The agreement is mixed for neutron inelastic scattering cross sections.

- Neutron cross sections deduced from γ-ray production cross sections are in excellent agreement with values recently published by Beyer et al. and appear to offer a good way to get σ(n,n') total inelastic cross sections.



Carbon elastic normalized to its own total cross section at 1.75 MeV.



Carbon elastic normalized to its own total cross section at 3.50 MeV.

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