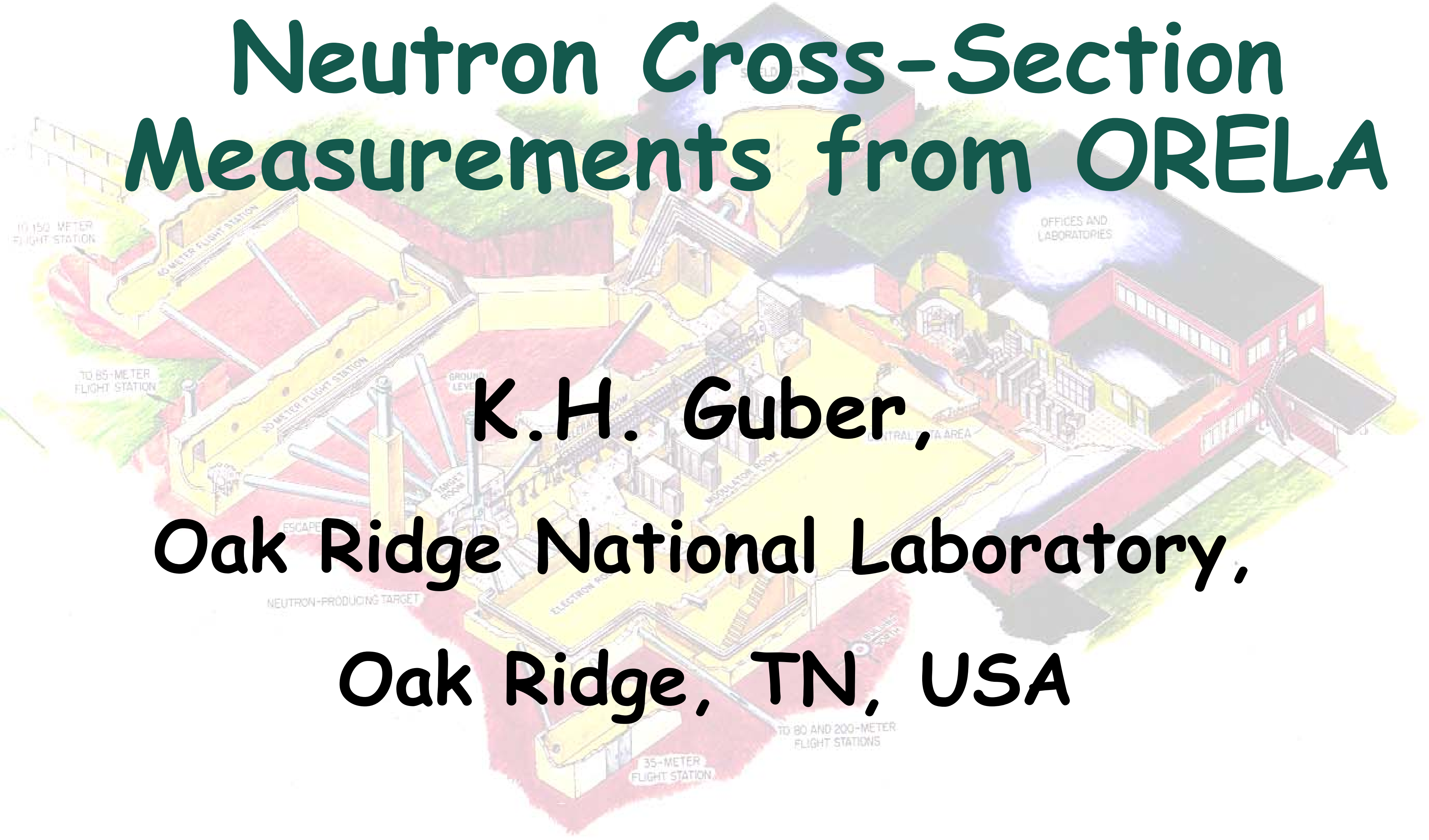
Neutron Cross-Section Measurements from ORELA



K.H. Guber,

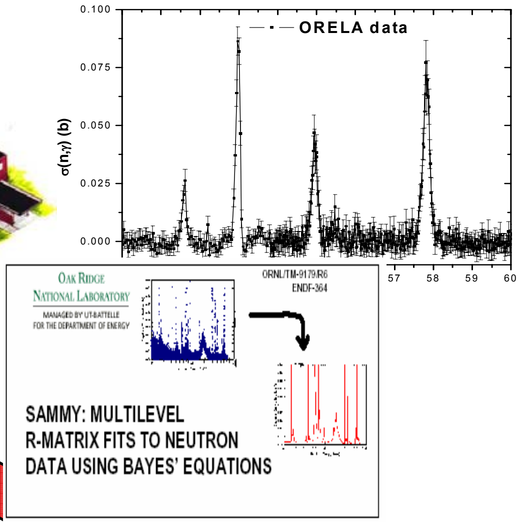
Oak Ridge National Laboratory,

Oak Ridge, TN, USA

ORNL Data Support for Nuclear Applications

ORELA

Basic Science



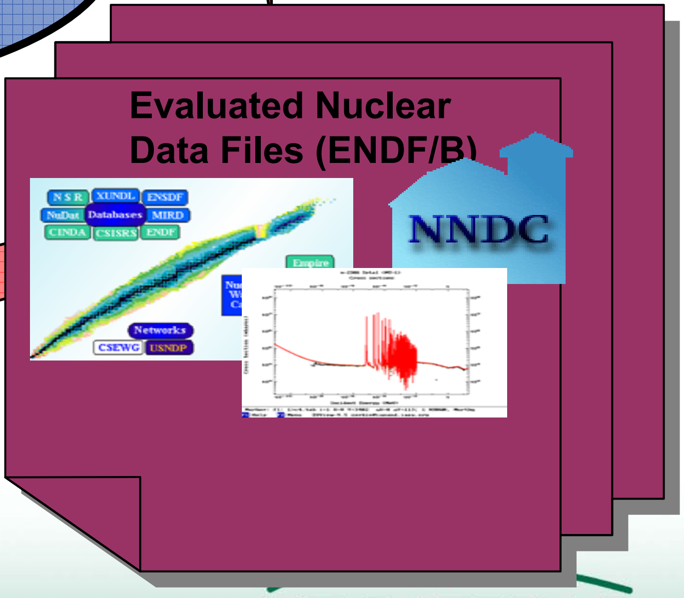
OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

ORNL/TM-9179/R6
ENDF-364

SAMMY: MULTILEVEL
R-MATRIX FITS TO NEUTRON
DATA USING BAYES' EQUATIONS

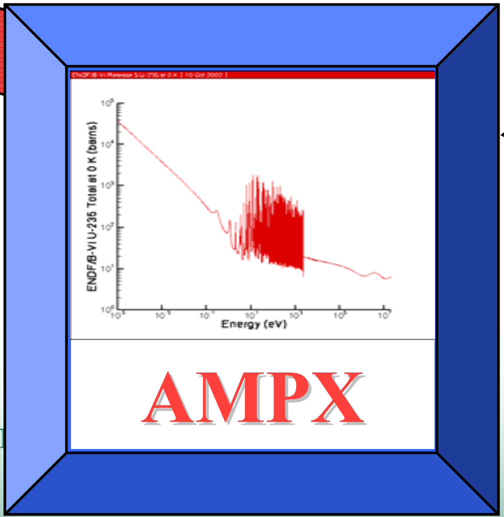
SAMMY

Cross-Section Evaluations

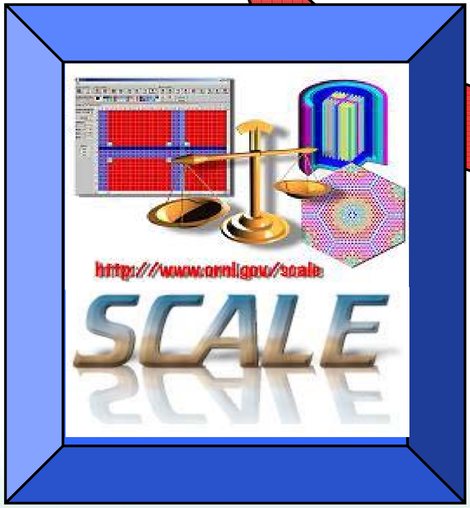


Evaluated Nuclear Data Files (ENDF/B)

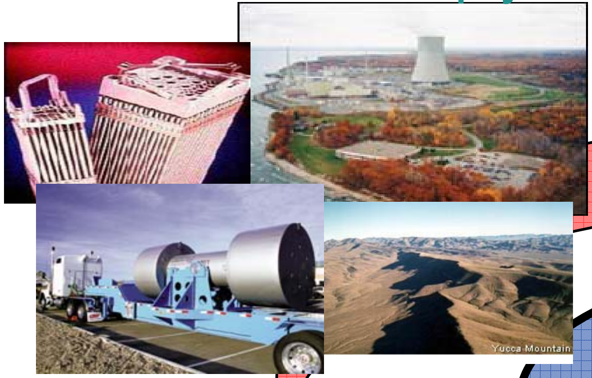
Computational modeling



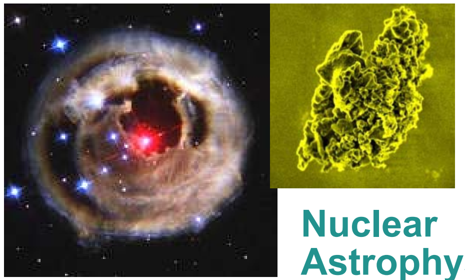
AMPX



SCALE



Applications



Nuclear Astrophysics

OAK RIDGE NATIONAL LABORAT
U. S. DEPARTMENT OF ENERGY

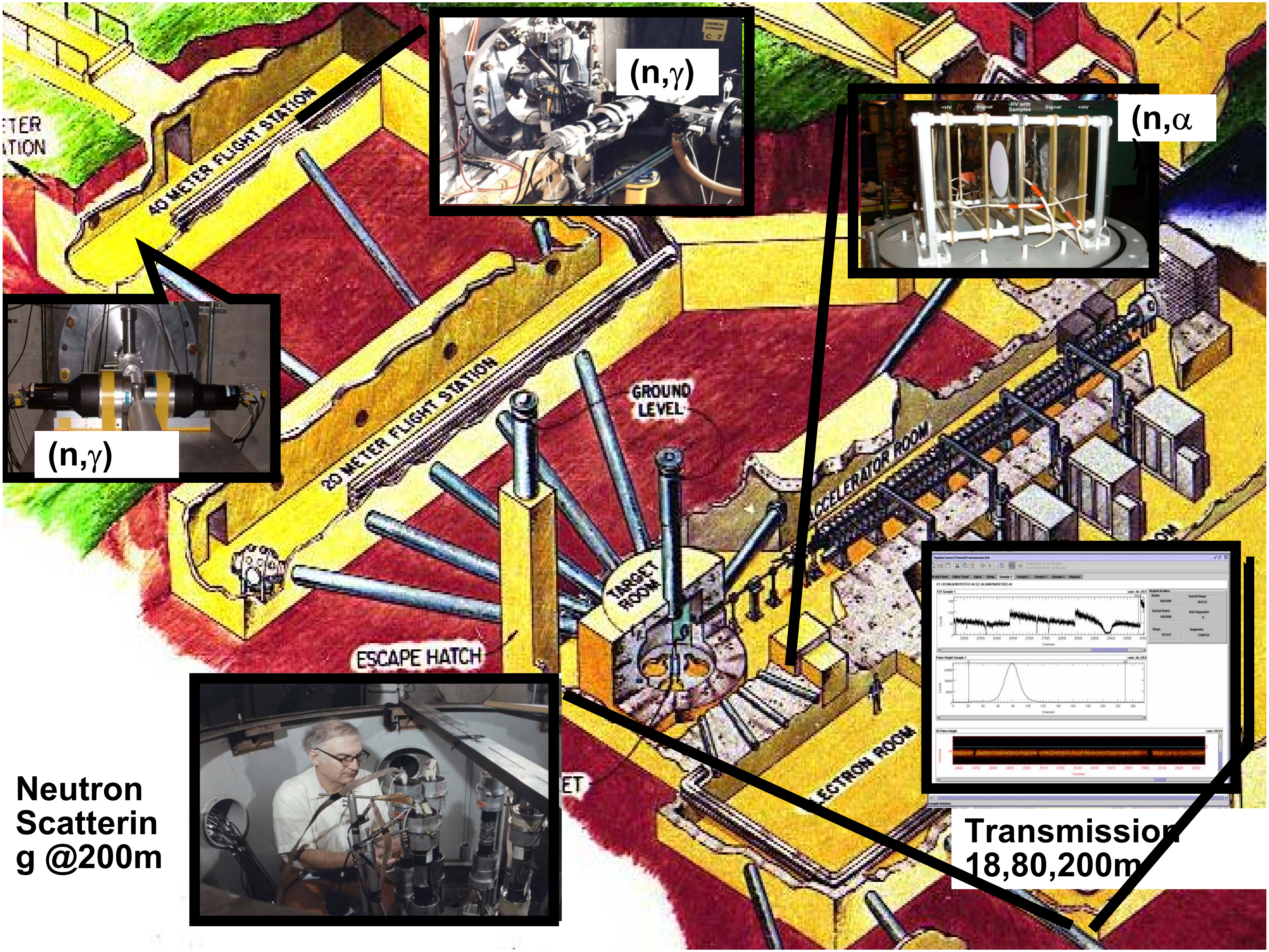
UT-BATTELLE

Oak Ridge Electron Linear Accelerator

- High intensity, pulsed neutron, positron and γ-ray source
- Four section, L-band electron linear accelerator, Peak current: **40 amps**, Electron energy: **180 MeV**, Rep. rate: **1 -1000 Hz**, Pulse width: **2 - 30 nsec**, Power on target: **60 kW** maximum
- Neutron production: **10^{14} n/sec, 10^{11} n/pulse**, Positron production: **10^{8} e^{+}/sec**
- Facility capabilities: simultaneous experiments at different flight -paths (10), -stations (18), and -lengths (9-200m, underground).

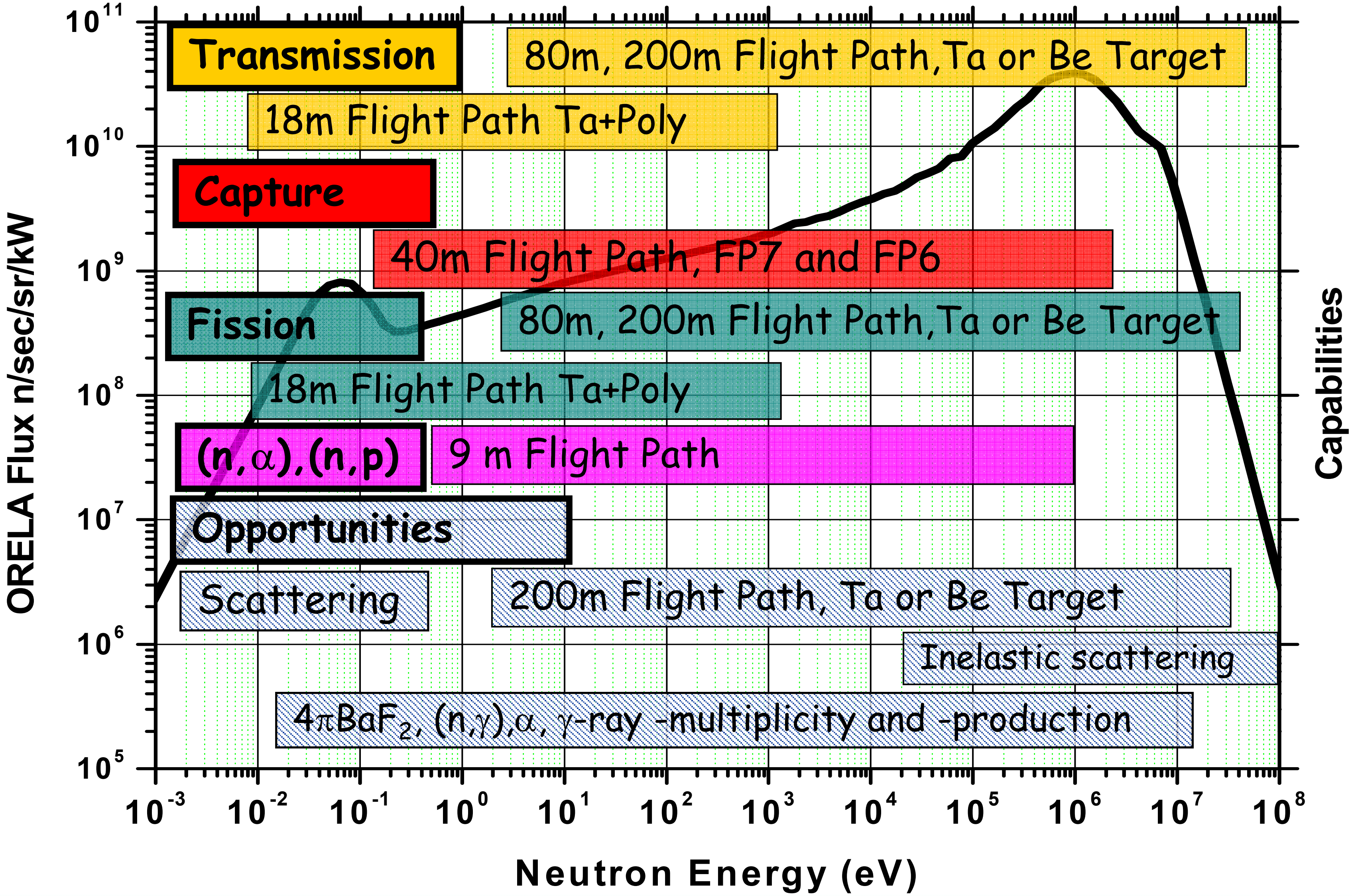
Oak Ridge Electron Linear Accelerator

- High flux (10^{14} n/sec) => gram-sized, affordable samples
- Excellent resolution (Δt=2-30 ns) => good S/N facilitates better evaluations
- "White" neutron spectrum from E_n ~ 0.01 eV - 80 MeV => reduces systematic uncertainties
- Measurement systems and backgrounds well understood => very accurate data
- Simultaneous measurements => (n,γ), (n,α), (n,n'), (n,f), and σ_{total} experiments at the same time on different beam lines
- Measurements on over 180 Isotopes: ORELA measurements have contributed to ~80% of U.S. Evaluated Nuclear Data File (ENDF/B) evaluations



Neutron Scattering @200m

Transmission 18,80,200m


Transmission
80m, 200m Flight Path,Ta or Be Target
18m Flight Path Ta+Poly
Capture
40m Flight Path, FP7 and FP6
Fission
80m, 200m Flight Path,Ta or Be Target
18m Flight Path Ta+Poly
(n,α),(n,p)
9 m Flight Path
Opportunities
Scattering
200m Flight Path, Ta or Be Target
Inelastic scattering
4πBaF2, (n,γ),α, γ-ray -multiplicity and -production
ORELA Flux n/sec/sr/kW
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
Neutron Energy (eV)
Capabilities

Experiment Requirements

- Duration: ~ week

$$R = n\sigma\phi\varepsilon + R_{bkg}.$$

Maximize n, ϕ, and ε, minimize R_{bkg}.

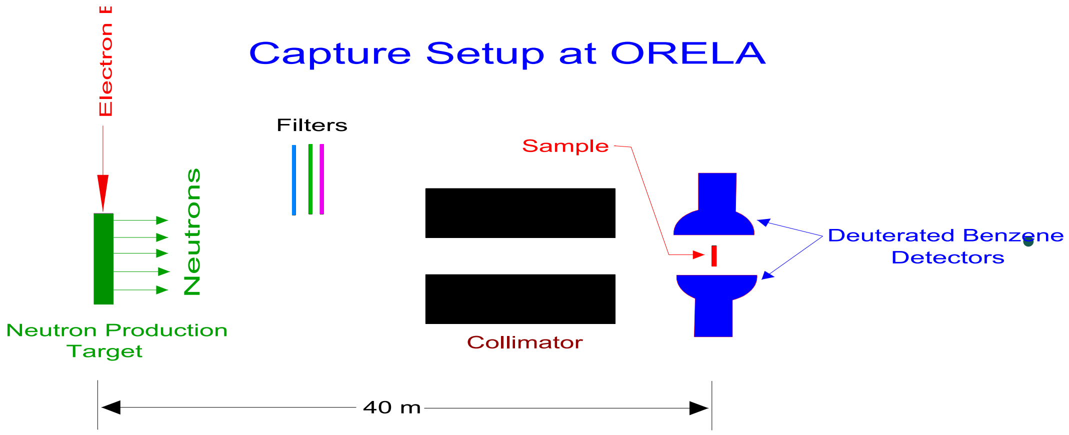
Except: minimize n because samples can be expensive (enriched isotopes) and radioactive samples contribute to background. Increasing ε may lead to worse background. Increasing ϕ may lead to counting-rate problems.

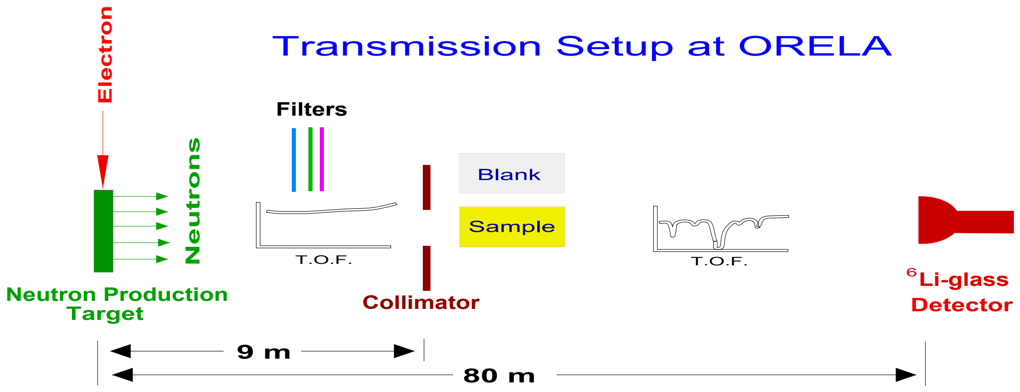
Minimize R_{bkg}, especially sample-dependent part. Measure as much as possible (e.g. σ_t, standards).

Experimental Techniques

Type	White Source	Monoenergetic
Facilities	Van de Graaff, Electron and Proton Linacs, Lead Slowing-Down Spectrometer	Van de Graaff, Reactor, Electron Linac
Pros	All energies at once. Wide energy range. Moderate to high flux. Excellent to modest resolution. Simultaneous experiments. More information (e.g. resonance parameters).	High flux. Simpler experiments. Activation and quasi-Maxwellian spectrum possible.
Cons	Backgrounds may be more troublesome: γ-flash, neutron sensitivity and other sample-dependent backgrounds. More complicated analysis.	Only one energy and one experiment at a time. Poor or no resolution.

Neutron Capture and Total Cross Section Experiments at a White Neutron Source:





- Time-of-flight technique used to determine incident neutron energy. "Clocks" used have typically 1nsec resolution.

- Pulsed electron beam starts clock. γ-ray or neutron detector stops clock.

$v_n = L/t$

$E_n = m_n v^2/2$

- Filters used to reduce frame-overlap background from low-energy neutrons and to reduce γ-flash effects.

Cross-Section Measurement Facilities

Facility Parameters	United States				Europe	
	ORELA	LANSCE	IPNS	RPI	GELINA	n_TOF
Source	e^- linac	p spallation	p spallation	e^- linac	e^- linac	p spallation
Particle E (MeV)	140	800	450	>60	120	20000
Flight Path (m)	10-200	7-55	~6-20	10-250	8-400	185
Pulse Width (ns)	2-30	125	70-80	15-5000	1-2000	7
Max Power (kW)	50	64	6.3	>10	11	45
Rep Rate (Hz)	1-1000	20	30	1-500	Up to 900	0.278-0.42
Best Intrinsic Resolution (ns/m)	0.01	3.9	3.5	0.06	0.0025	0.034
Neutrons/s	1×10^{14}	7.5×10^{15}	8.1×10^{14}	4×10^{13}	3.2×10^{13}	8.1×10^{14}

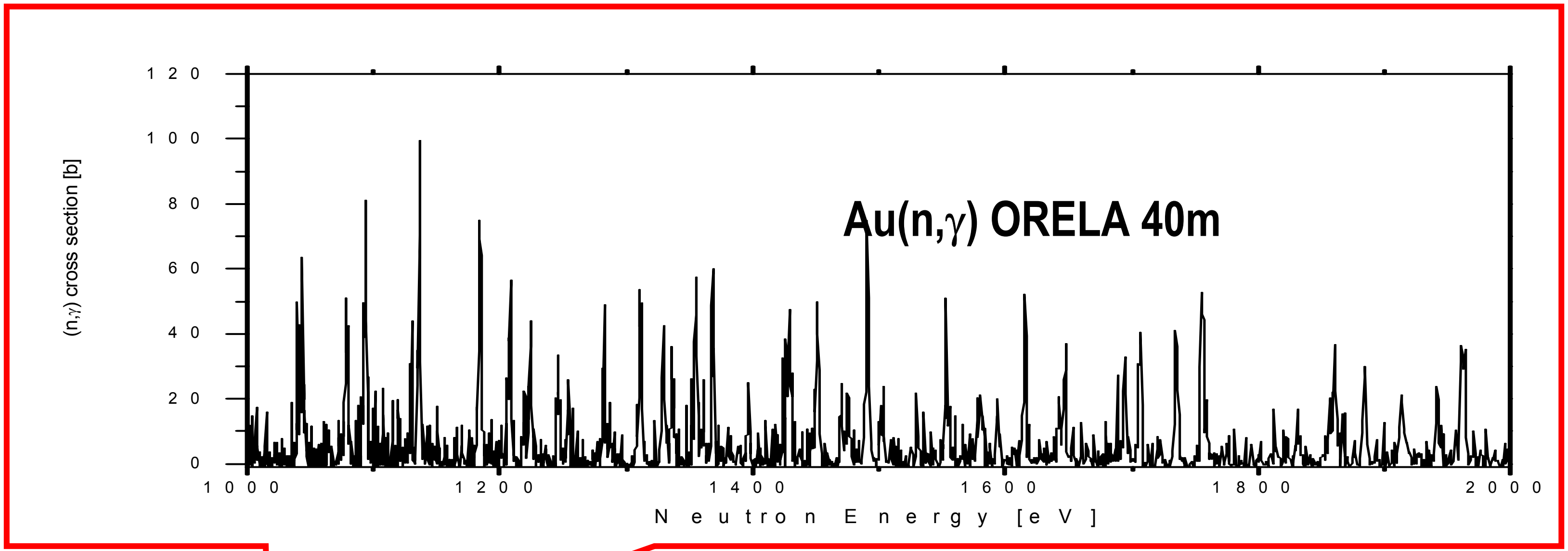
Facilities Comparison for 20m Flight path

	ORELA	GELINA	LANSCE	IPNS	n_TOF
Hypothetical Flight path length [m]	20	20	20	20	20
Pulse width [ns]	24	1	125	80	7
Power [kW]	50	11	64	6.3	45
Repetition Rate [Hz]	1000	800	20	30	0.42
Neutron Flux @ 1keV [neutron/s/cm2/eV]	2.50E+01	1.00E+01	1.20E+02	1.00E+02	2.50E+02
Neutron Flux @ 1keV [neutron/s/cm2]	2.50E+04	1.00E+04	1.20E+05	1.00E+05	2.50E+05
Intrinsic Resolution [ns/m]	1.2	0.05	6.25	4	0.35
Realistic Resolution dE@ 1keV [eV]	0.97	0.98	3.48	2.25	4.49
FOM @ 1keV (Flux/(dE/E)^2) [n/s/cm2]	2.67E+10	2.60E+10	9.93E+09	1.97E+10	1.24E+10

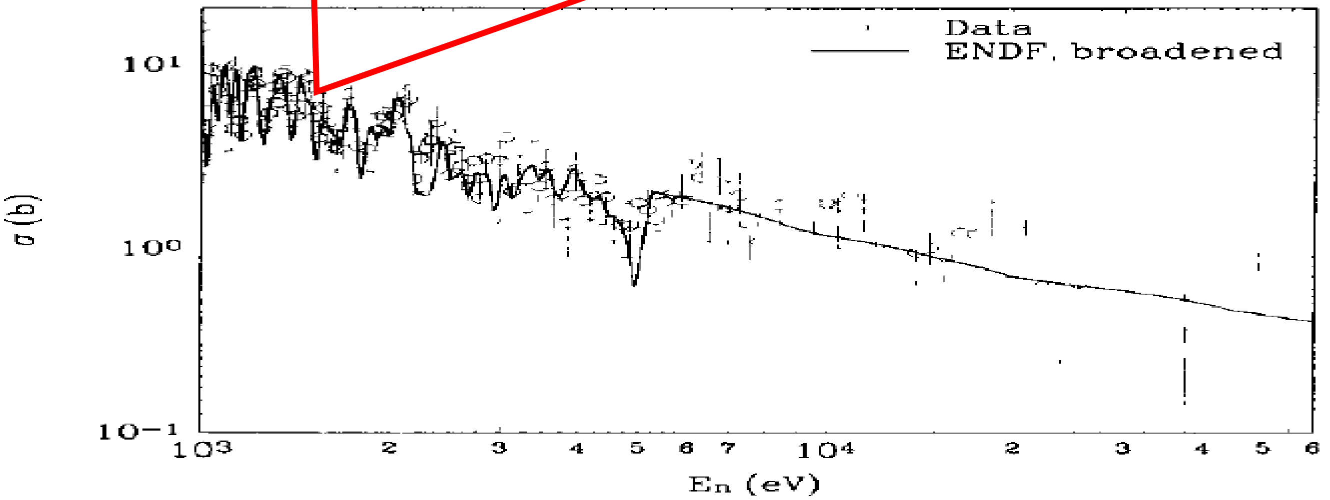
Neutron Cross-Section Measurements In The Resolved Resonance Range

- Neutron flux is important but alone cannot guarantee accurate measurements.
- Neutron Energy resolution is important.
  - Goal to resolve many resonances in order to obtain reliable average resonance parameters. These are important to perform the analysis of the unresolved energy range and statistical model calculations.
  - Resolved resonances help to identify and disentangle isotopic impurities in the sample.
  - Resolved resonances help to apply individual and no average correction to the data (self-shielding, multiple-scattering).

Neutron Cross-Section Measurements

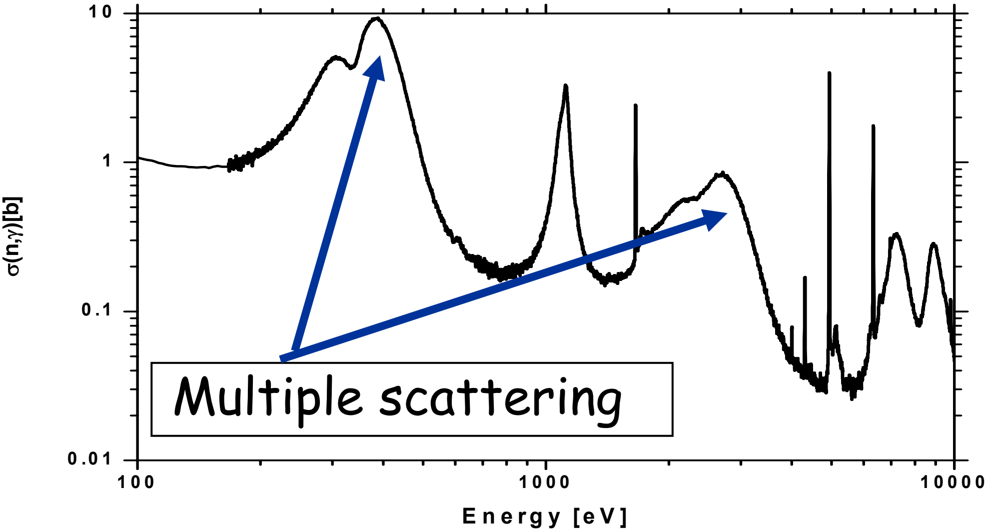


Au(n,γ) ORELA 40m

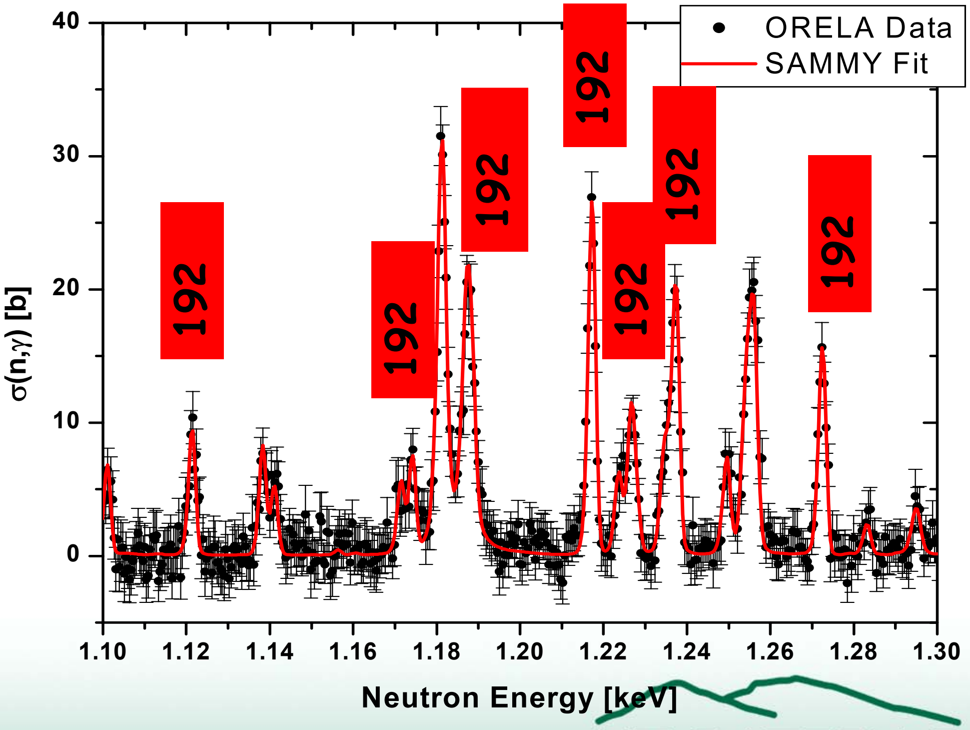


Au(n,γ) LANSCE 8m

Resolved resonances help to apply individual and no average correction to the data (self-shielding, multiple-scattering).



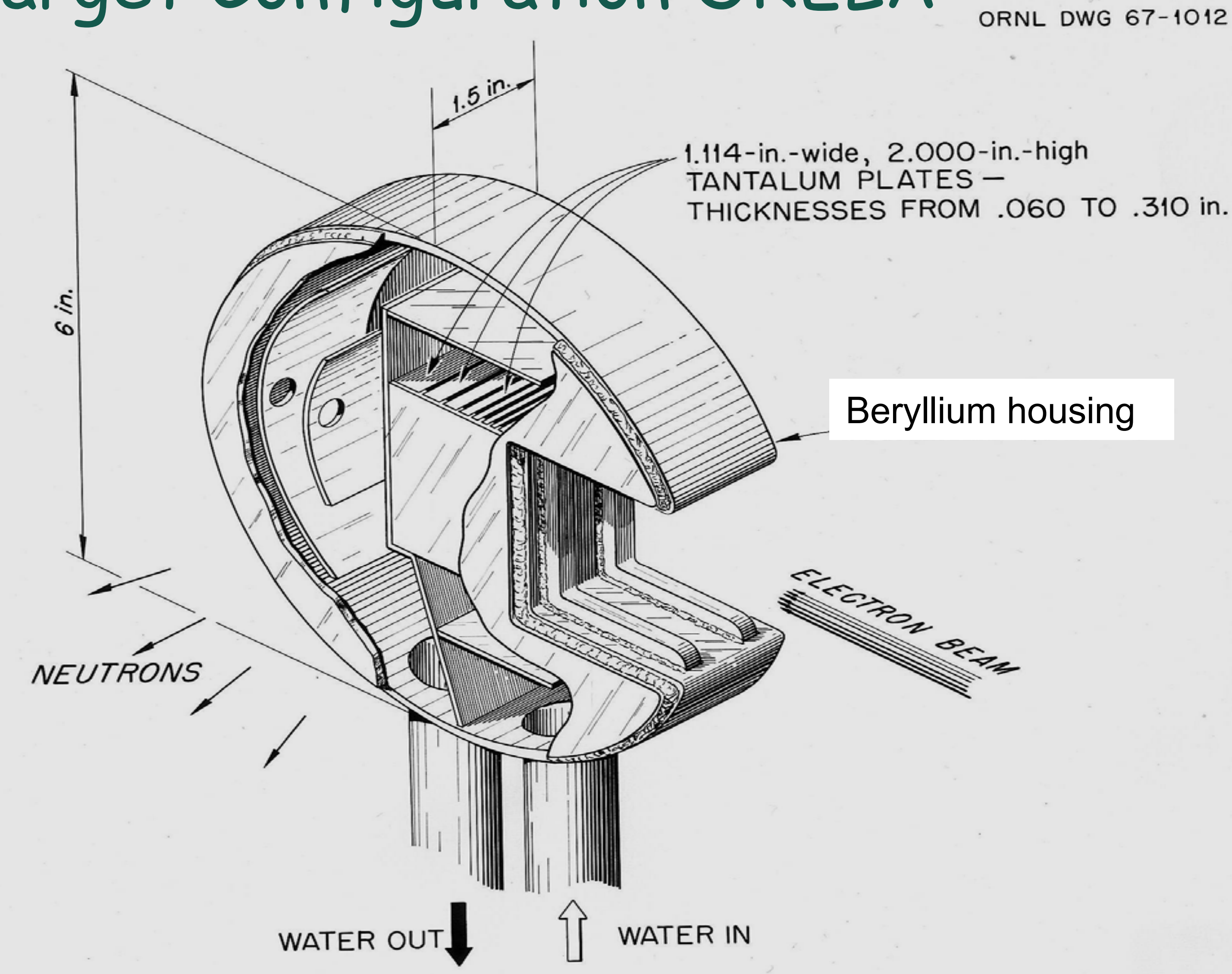
High resolution data help to identify and disentangle isotopic impurities. Example: ^{192}Pt, one of the rarest isotopes in the world, only 700mg with 57% enrichment.



Neutron Energy Resolution

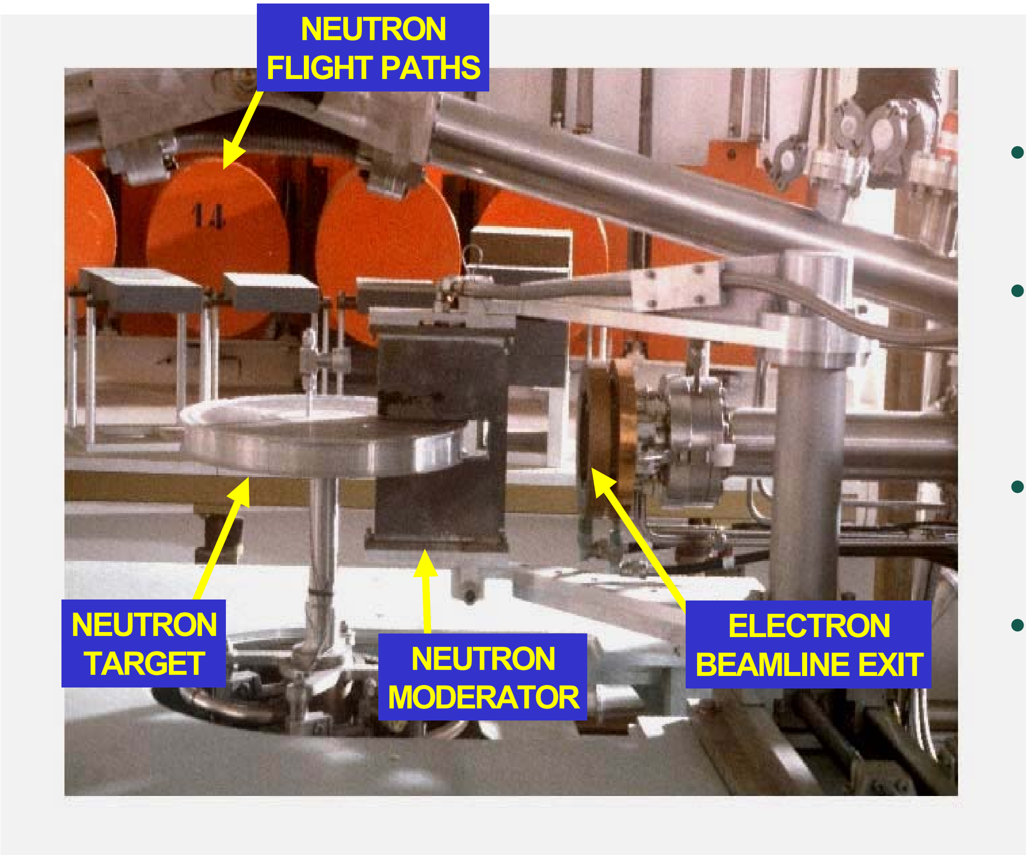
- Flight path length, the longer the better.
- Pulse width of the neutron burst, the shorter the better:
  - Typically fixed with spallation sources (tens of ns to hundreds of ns)
  - Linac sources can vary pulse width (1ns up to tens of ns).
- Source moderation distance
  - The uncertainty of the creation location of the neutron inside the target/moderator has to be taken into account for the resolution function.
  - ORELA is an undermoderated source with relatively small neutron production target. Spallation sources are usually optimized for thermal neutron flux, this requires large moderators.
    - The moderation effect put tails on resonances due to delayed neutrons.
    - Hinders resolution of closely spaced resonances.
    - Produces background in unresolved energy range which cannot be corrected. This effect is of the order of 16% for 20 keV (Coceva et al. 2002) for n_TOF and can not be estimated quantitatively.

Target Configuration ORELA



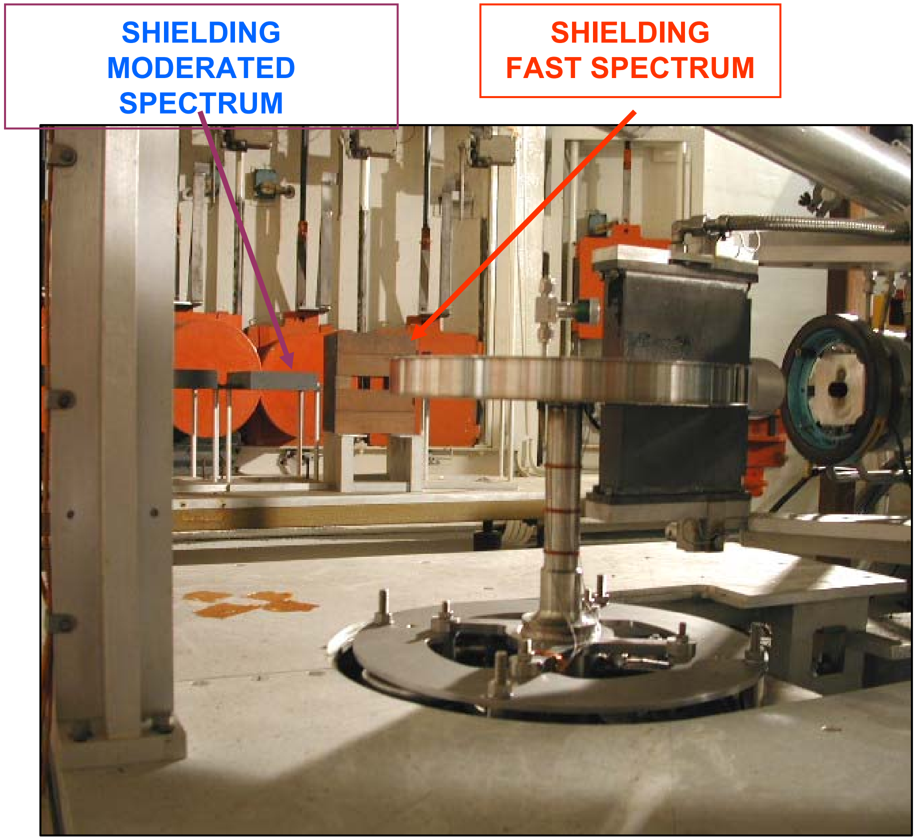
Beryllium housing

Neutron Production GELINA



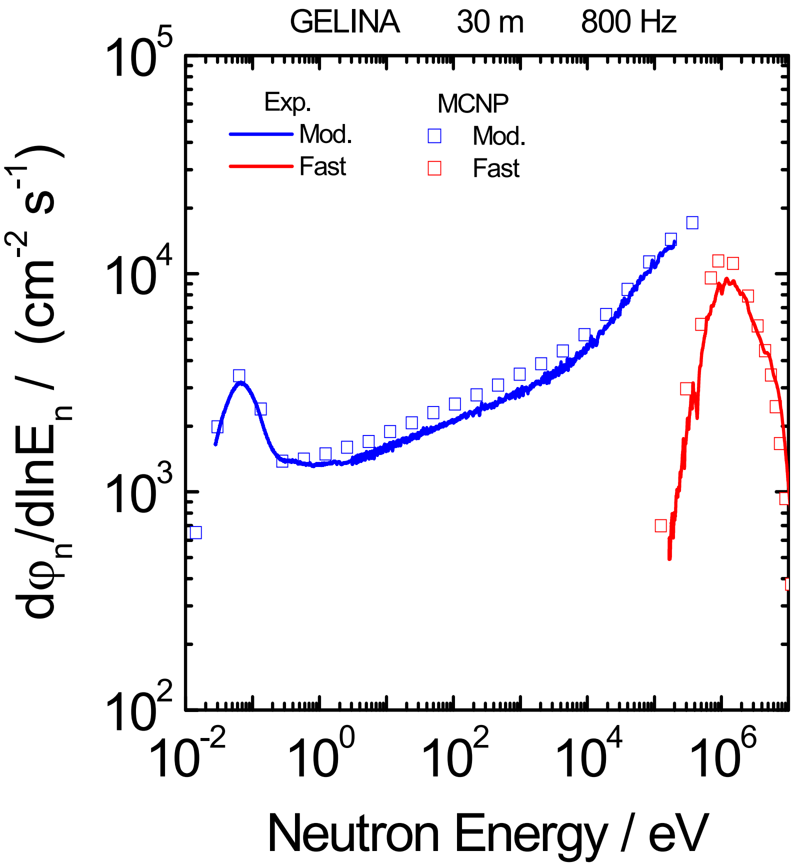
- e^- accelerated to $E_{e-,max} \approx$ 140 MeV
- (e^-, γ) Bremsstrahlung in U-target (rotating & Hg-cooled)
- (γ , n) , (γ , f) in U-target
- Low energy neutrons by water moderator in Be-canning

Neutron Production GELINA



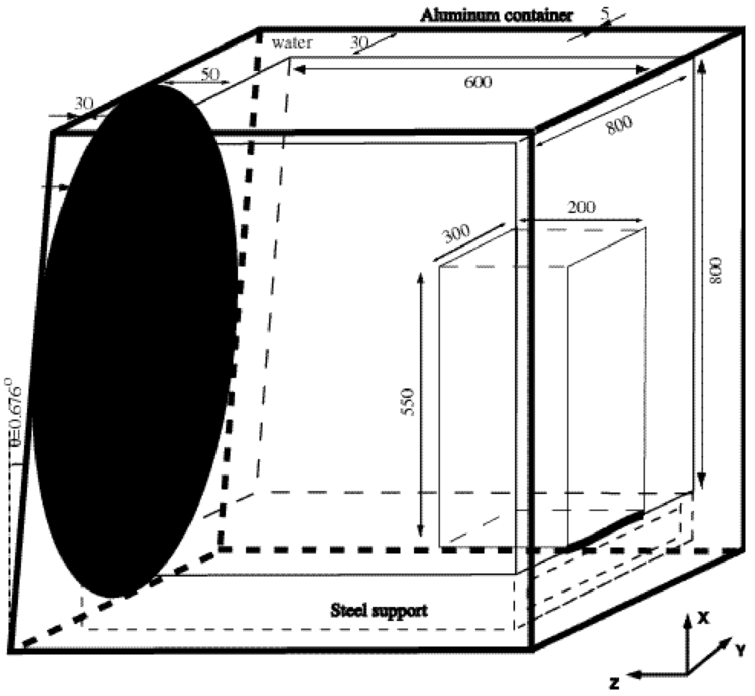
SHIELDING MODERATED SPECTRUM

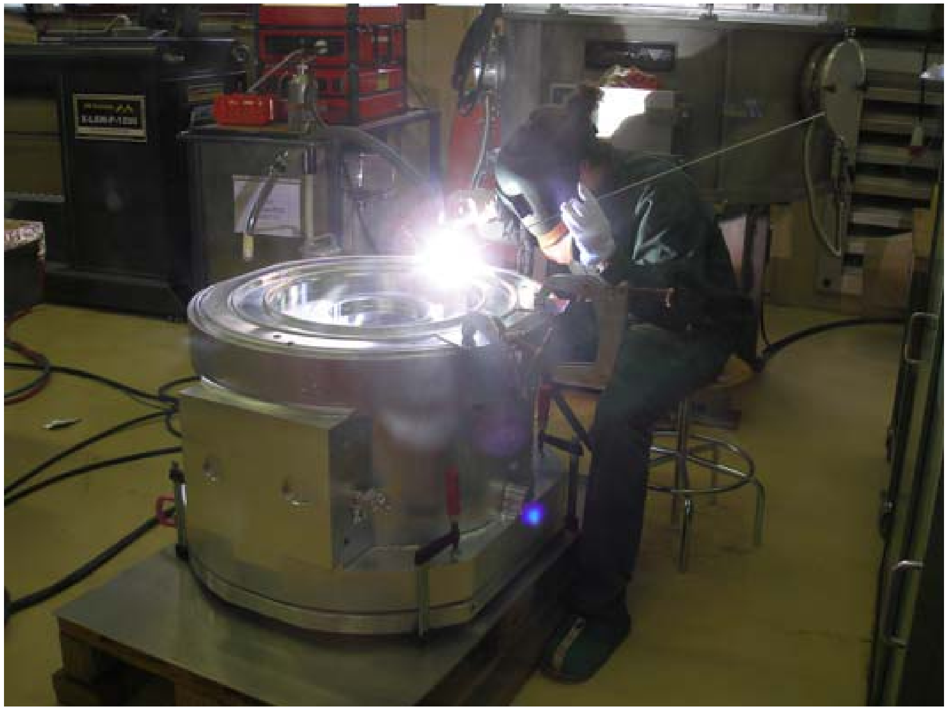
SHIELDING FAST SPECTRUM



Average Current : 75 μA
Average Electron Energy : 100 MeV
Pulse Width : 1ns
Frequency : 40 – 800 Hz

Neutron Target n_TOF

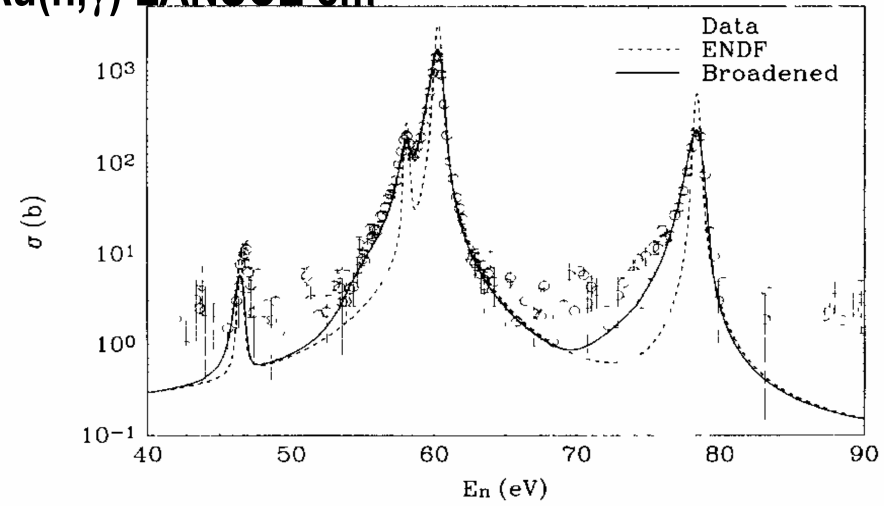




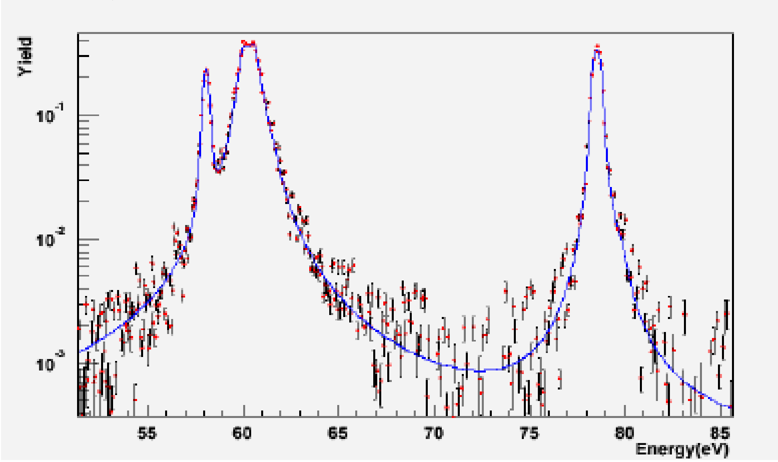
Old Pb block 80cm

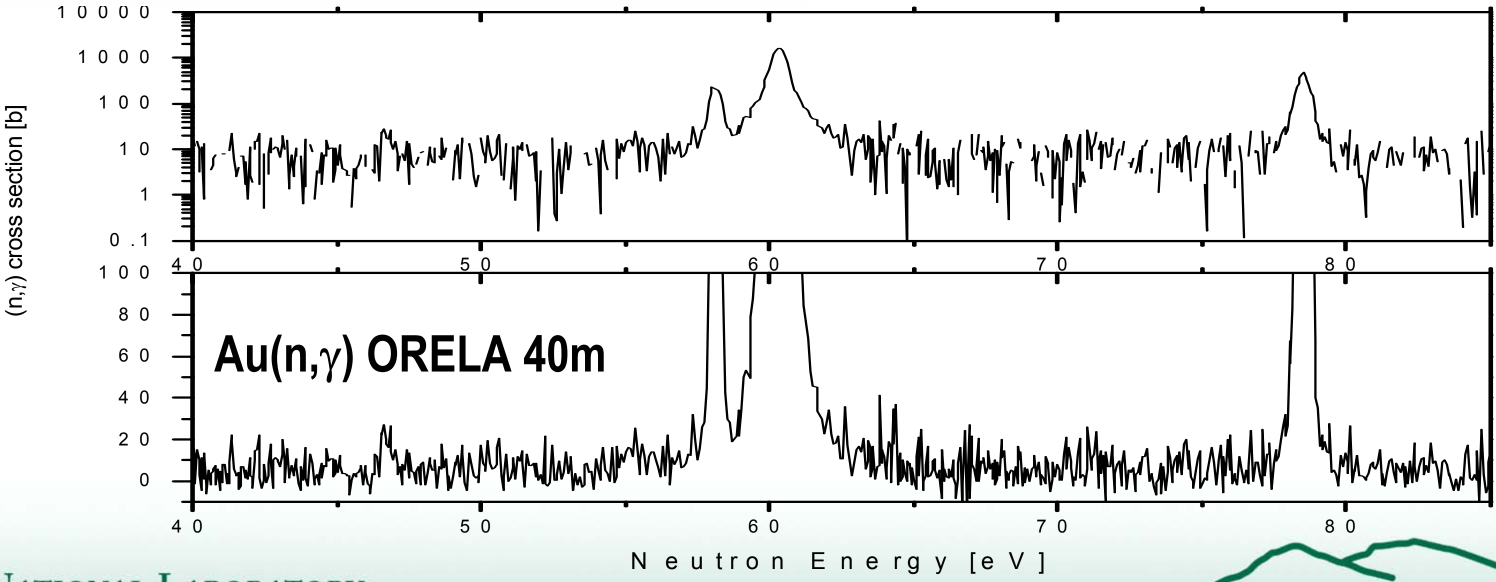
Neutron Energy Resolution

Au(n,γ) LANSCE 8m



Au(n,γ) n_TOF CERN 185m



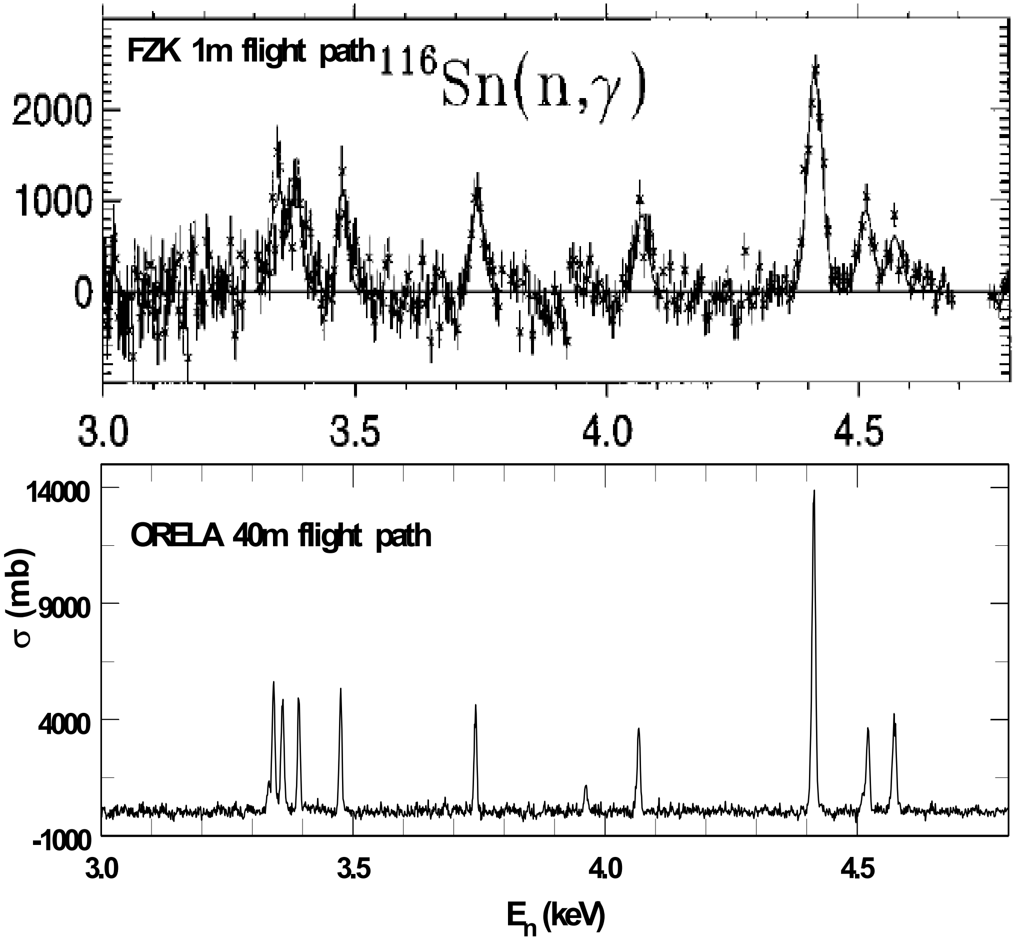


Au(n,γ) ORELA 40m

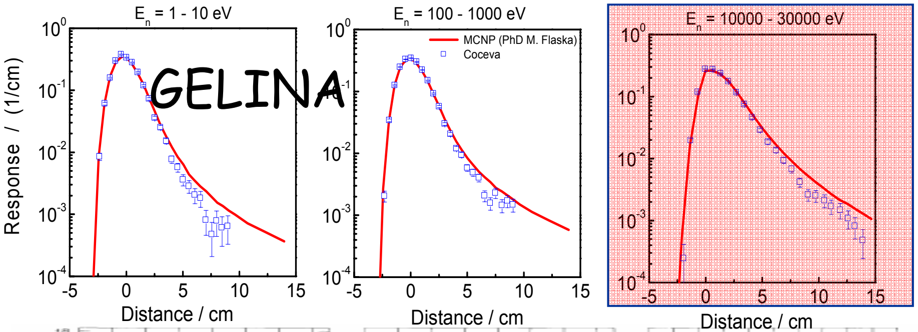
Superior Resolution at ORELA Results in Much Better S/N

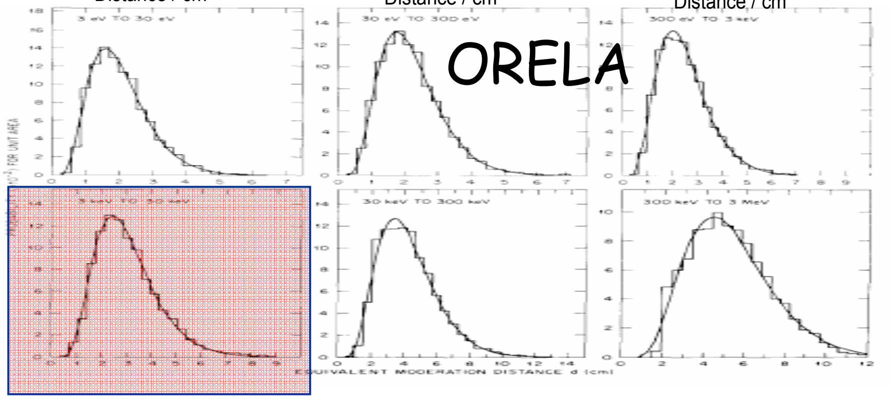
- Measured using BaF_2 ball at FZK.

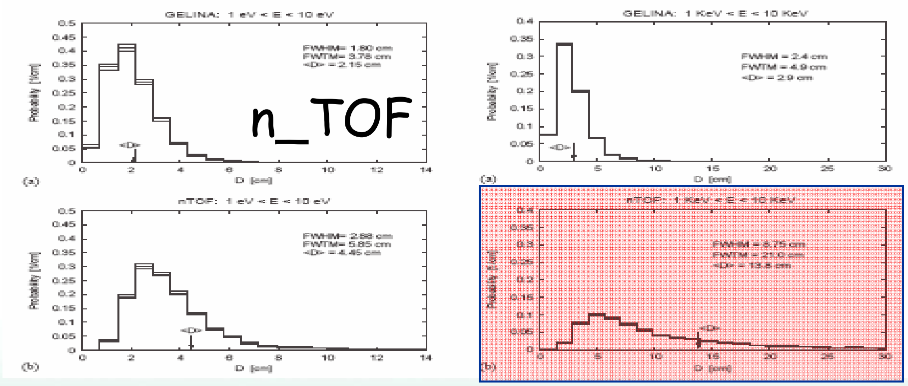
- Measured using C_6D_6 at ORELA.



Moderation Distance Distribution

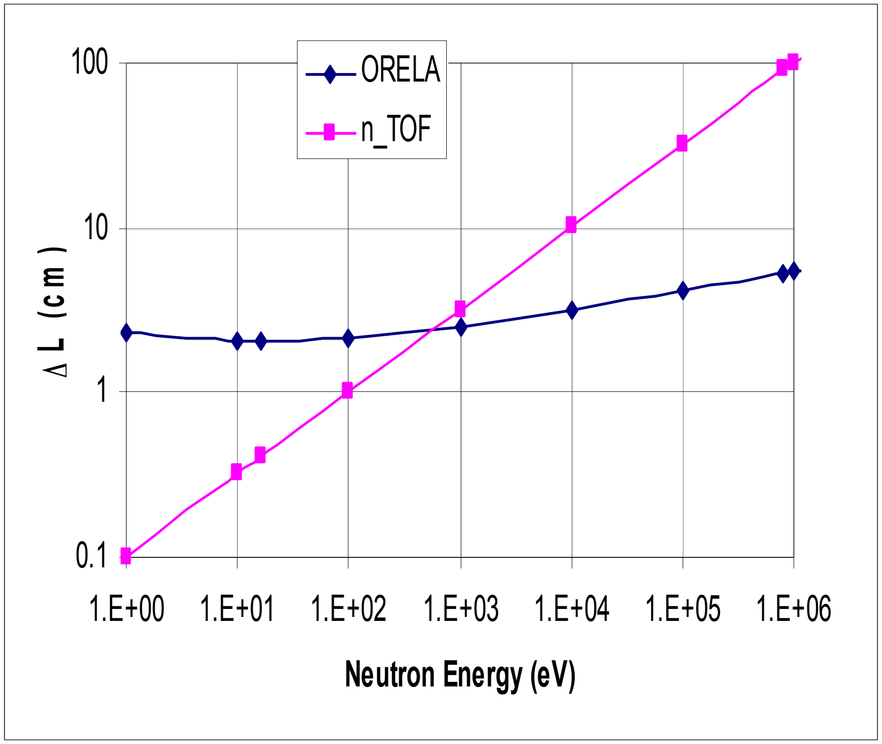






- The uncertainty of the creation location of the neutron inside the moderator has to be taken into account for the resolution function.
- This can be quite sizeable for large target and moderator assemblies.
- The effect is that it will put tail on the resonances in the resolved neutron energy region.
- Additionally it will produce a back-ground in the unresolved region which can not be corrected for.
- This effect is of the order of 16% for 20 keV (Coceva et al. 2002) for n_TOF and can not be estimated quantitatively.

Average Moderation Distance



- Due to moderation the neutron flight path is energy dependent.

$$L(E) = L_0 + \Delta L$$

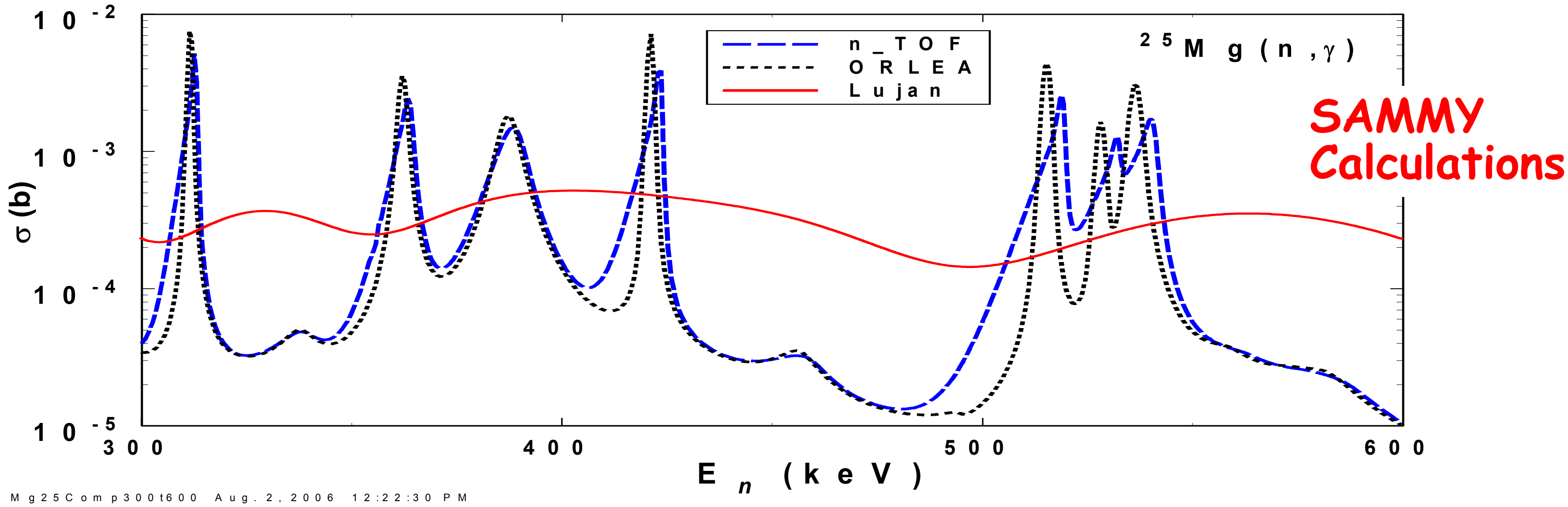
- n_TOF [cm]:

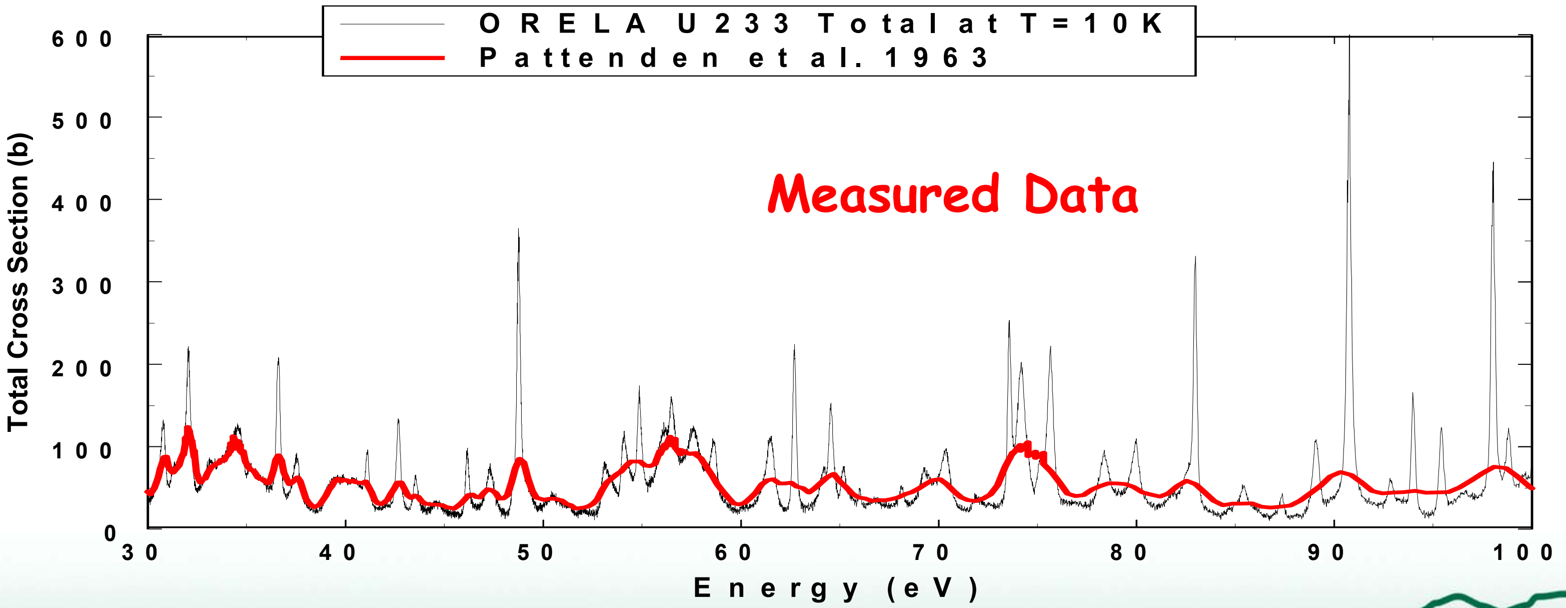
$$\Delta L = 0.101 \cdot \sqrt{E}$$

- ORELA [mm]:

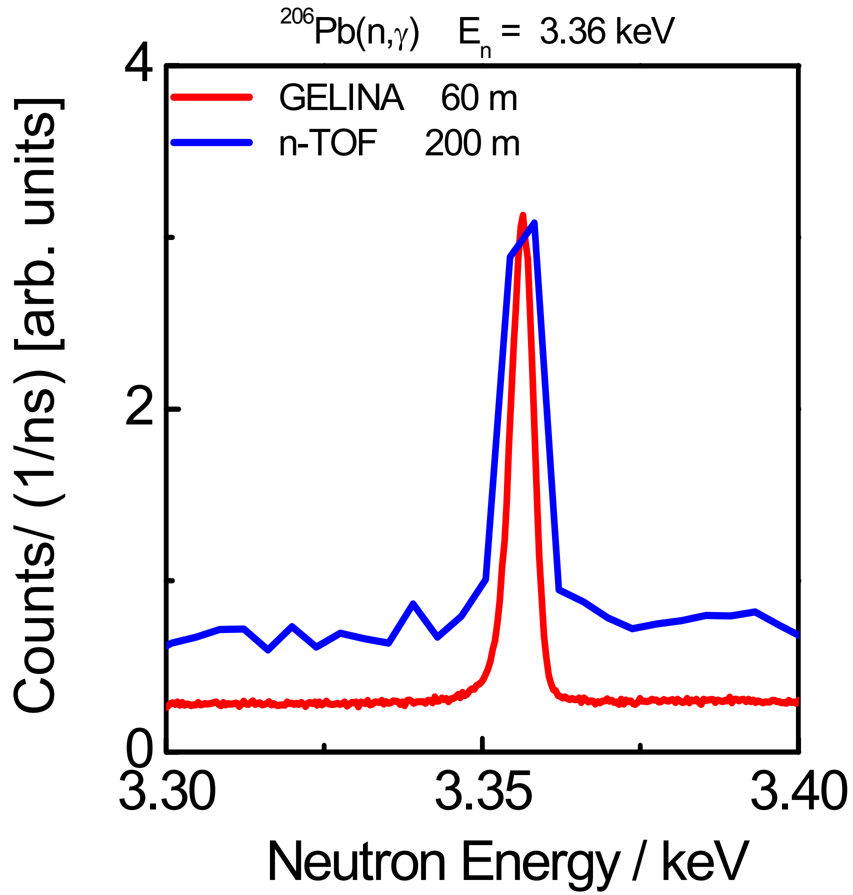
$$\Delta L = 22.1 - 1.6 \cdot \ln E + 0.283 \cdot (\ln E)^2$$

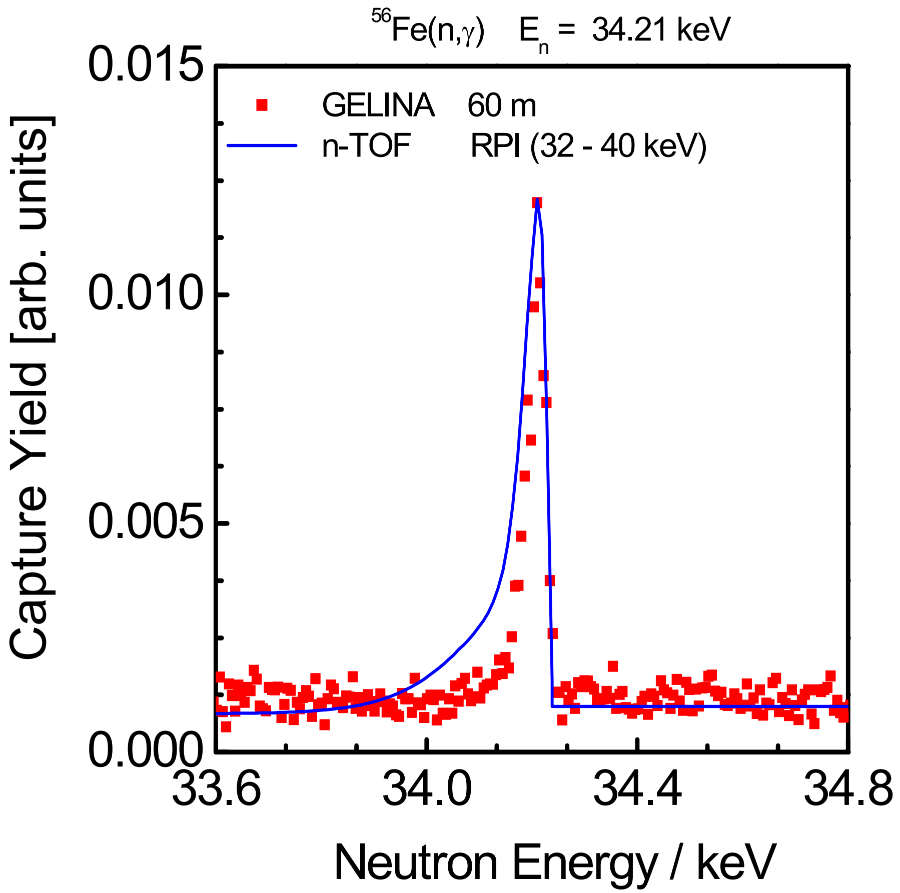
The Influence of Resolution





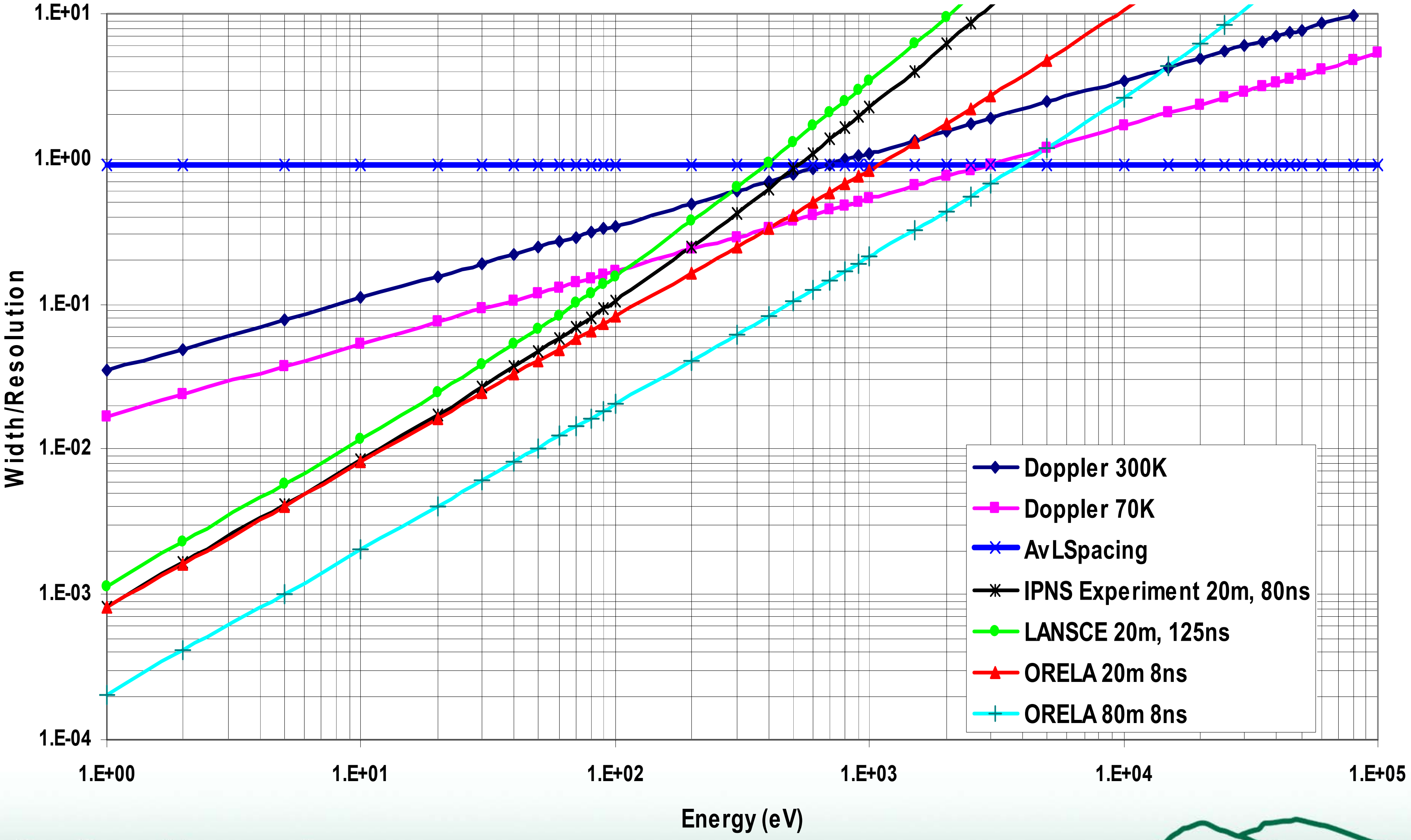
n-TOF (180 m) <--> GELINA (60 m)





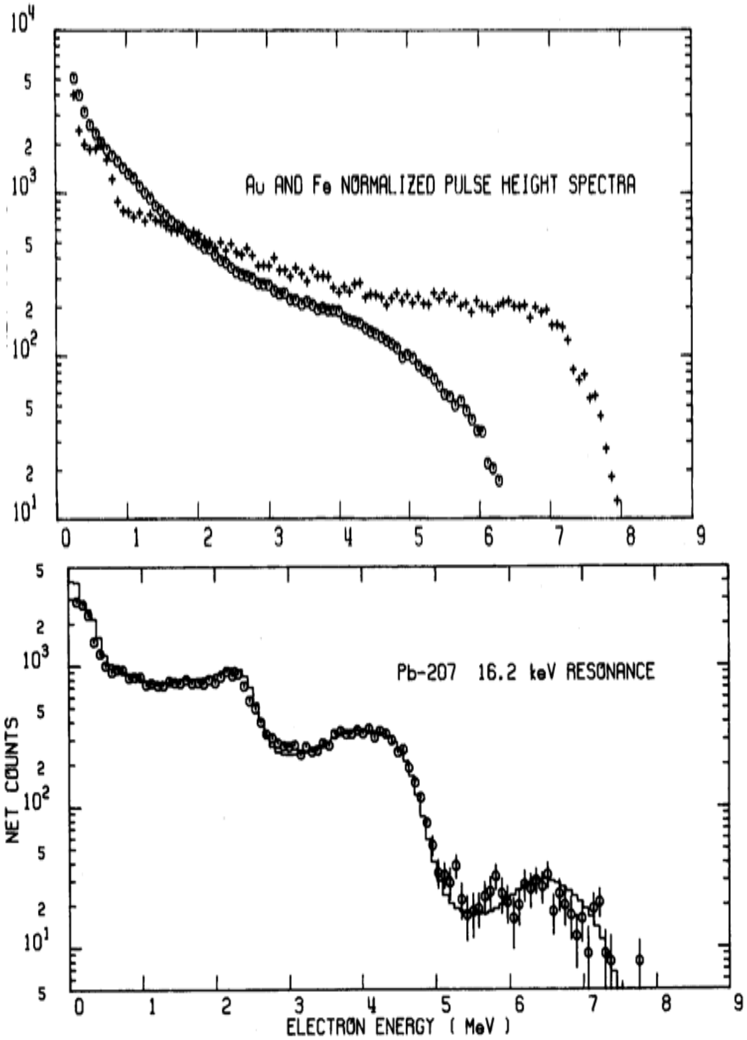
P. Schillebeeckx, IRMM

Doppler - Resolution Broadening @20 m for 241Pu



Trouble with Weighting Functions

- 20% discrepancy found in neutron width of 1.15-keV resonance in Fe measured with C_6D_6 compared to transmission measurements. Fe cascade is hard while those for Au and Ag are soft.
- Corvi *et al*. (1988) showed that measured weighting functions could solve discrepancy.
- Perey *et al*. (1988) showed that EGS simulations agreed with ^{207}Pb(n,γ) cascades and that EGS-4 weighting functions also solved Fe discrepancy. Sample and surrounding material was neglected in previous weighting function calculations.

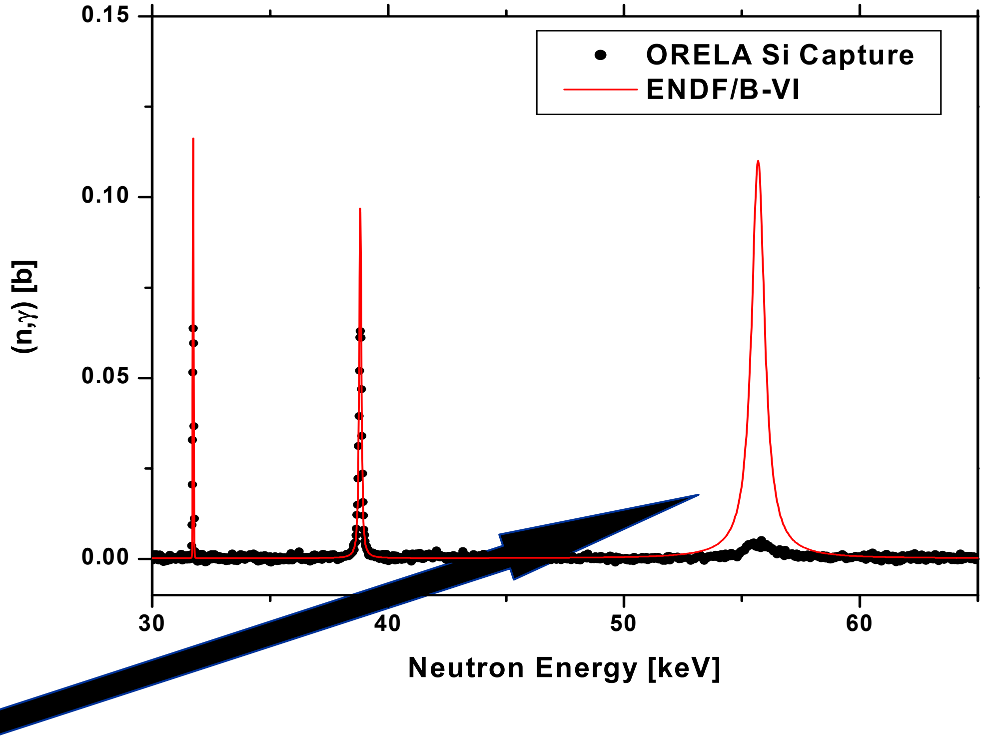


Results for ^{56}Fe with Weighting Functions for C_6D_6 Detectors

Exp. Type	Lab	Year	Det.Type	WeightF.	$g\Gamma_n\Gamma_\gamma/\Gamma$ [meV]	Γ_n [meV]
Capture	Geel	1991	C_6D_6	Experim.	56.7± 1.9	62.9± 2.1
Capture	Harwell	1988	C_6D_6	EGS4	59.5± 3.0	66.4 ± 3.3
Capture	Oak Ridge	1988	C_6F_6	EGS4	58.0± 2.9	64.5 ± 3.0
Capture	Oak Ridge	1988	C_6D_6	EGS4	56.8± 2.3	63.0± 2.5
Capture	Oak Ridge	1994	C_6D_6	EGS4	55.8 ±1.7	61.8 ±1.9
Trans-mission	Oak Ridge	1985			55.7± 0.8	61.7± 0.9

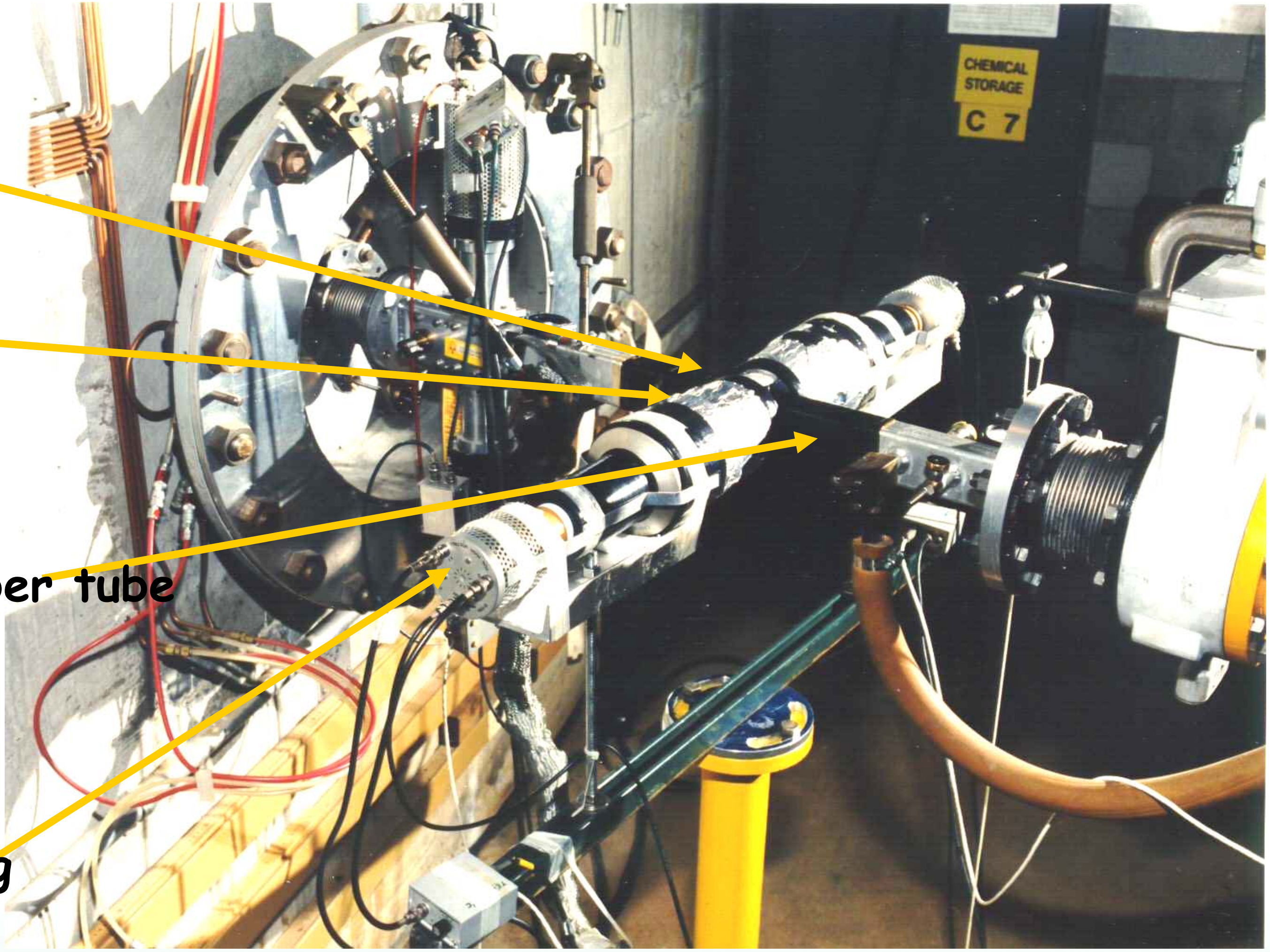
Much of the Old Neutron Data (on Which Current Evaluations Are Based) Are Seriously Incorrect

- Some problems with the old data:
  - Underestimated neutron sensitivity correction
  - Low-energy cut off of 3 keV
  - No high energy (>100 keV) data
  - Incorrect weighting function
  - Poor resolution
  - Poorly characterized samples, i.e. water in the sample



Ex: Large neutron sensitivity of older measurements led to many erroneously-large resonance areas in current evaluations.

Modified capture data measurement system has significantly less structure



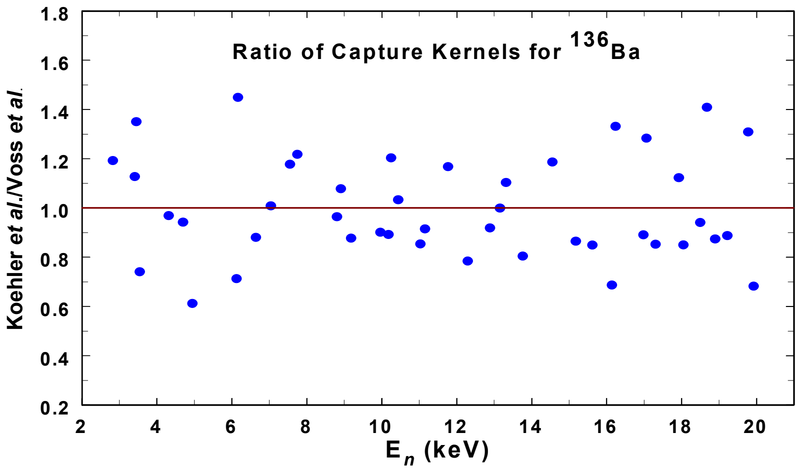
Sample changer replaced

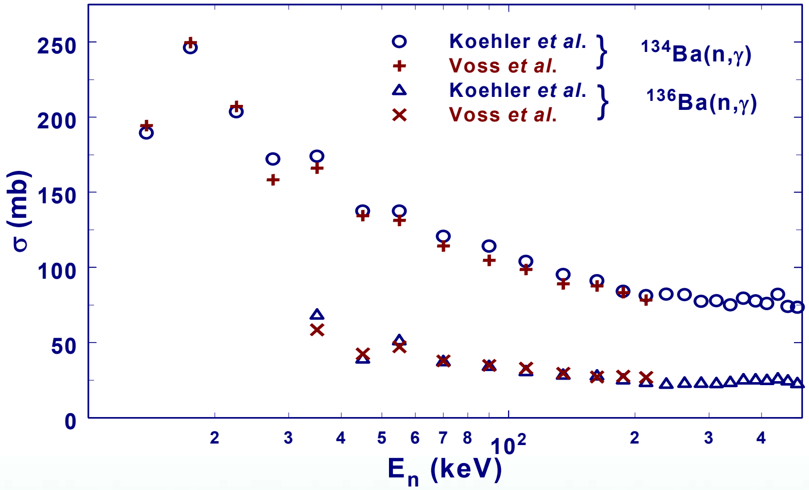
C_6F_6 Scintillator replaced

Aluminum guide replaced by C-fiber tube

Detector housing removed

New ORELA Weighting Functions Demonstrated to be Accurate to Better Than 3%





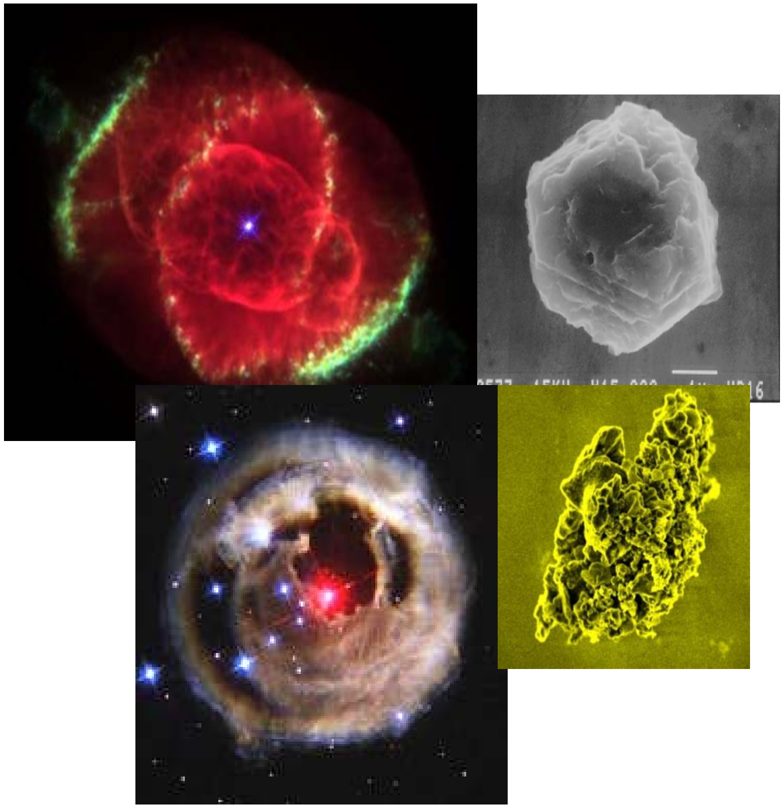
Excellent agreement between ORELA C_6D_6 (Koehler *et al.*) and FZK BaF_2 (Voss *et al.*) ^{134,136}Ba(n,γ) measurements.

Hardness of cascade varies considerably from resonance-to-resonance, but no systematic difference between capture kernels observed.

Excellent (<3%) agreement for average cross sections.

New ^{95}Mo(n,γ) experiments

- AGB stellar models over predict the abundance of ^{95}Mo compared to observation in SiC grain which origin from an AGB star where the s-process takes place.
- M. Lugaro et. al. 2003: calculations show a 30% enhancement in the (n,γ) cross section for ^{95}Mo would solve the problem.



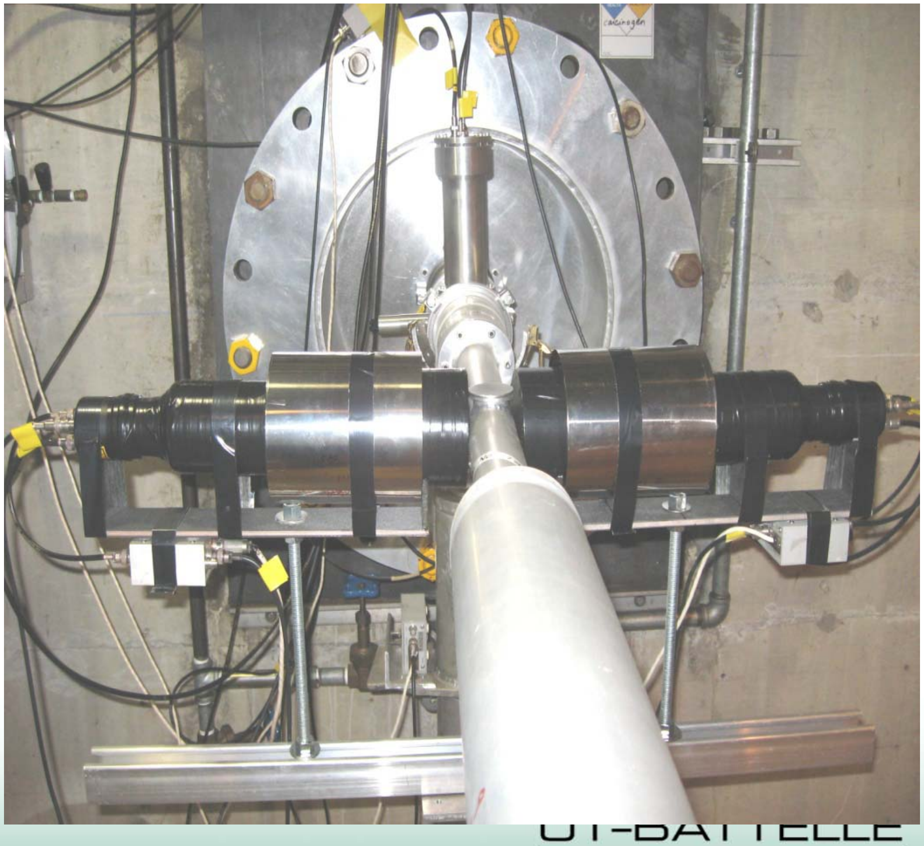
New ^{95}Mo(n,γ) and σ_T Measurements at the Oak Ridge Electron Linear Accelerator (ORELA)

- ^{95}Mo(n,γ) measured using new apparatus on F.P. 6 at 40 m.
  C_6D_6 using PHWT.
  ^{6}Li-glass flux monitor.
  Separate background measurements.
  <u>Modified to measure coincidence PH data.</u>

- ^{95}Mo σ_t measured on F.P. 1 at 80 m.
  ^{6}Li-glass detector.
  Separate sample-out, CH_2, and Bi measurements.
  Transmission.

"CINDORELA"

Capture of Incident Neutrons Detector at ORELA



New ^{95}Mo(n,γ) and σ_t Data from ORELA

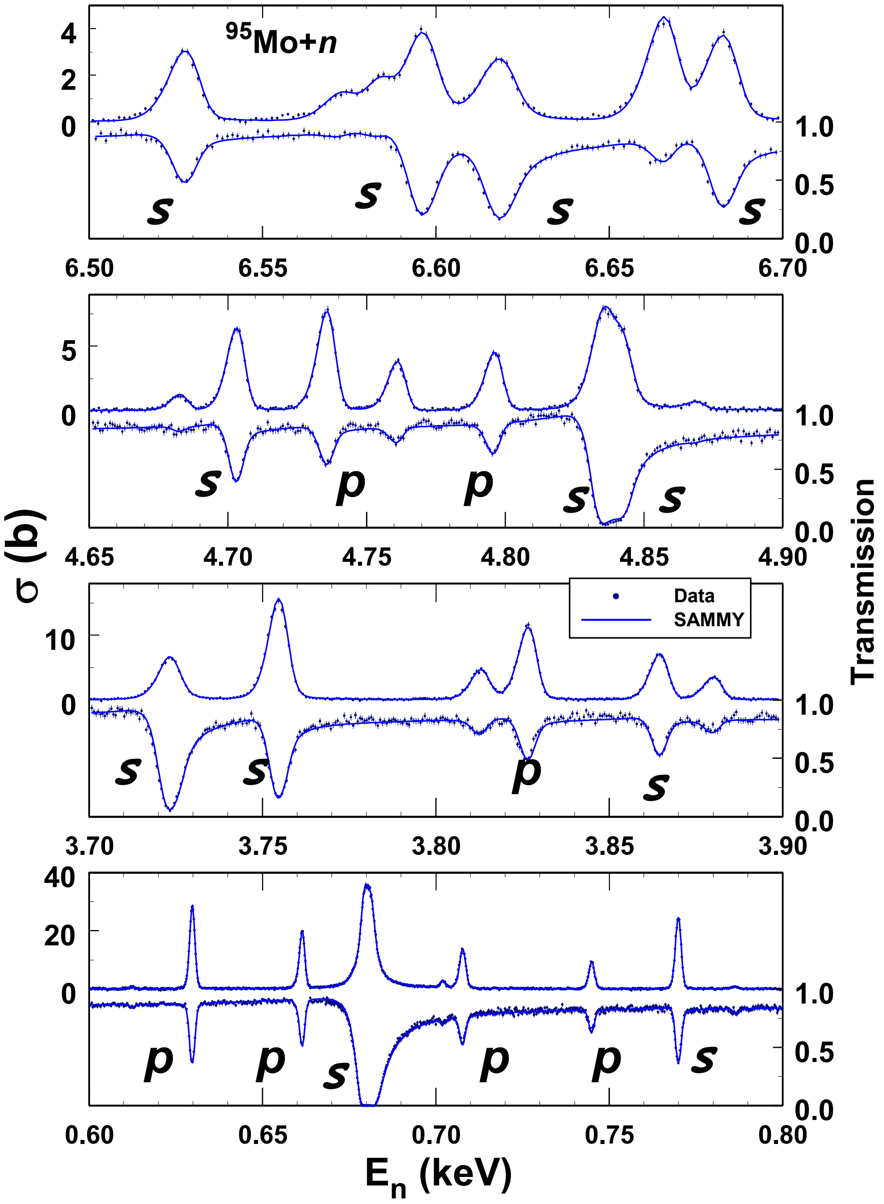
Resonance analysis using SAMMY.

318 resonances to 10 keV.

Only 106 previously known.

Only 32 previous firm J^{π} assignments.

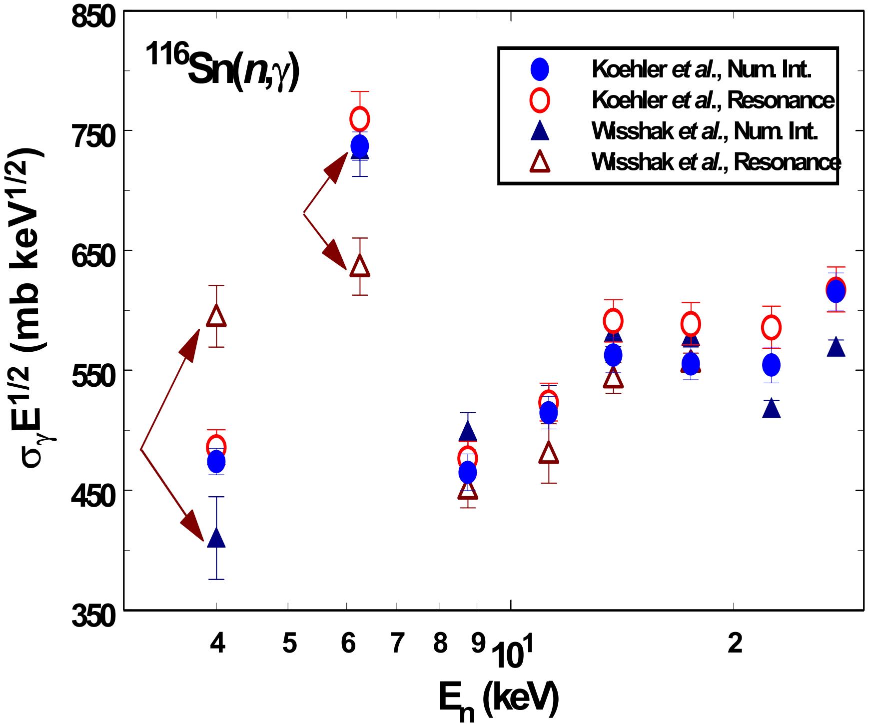
- Transmission data yield parity of resonance if neutron width is large enough.



Transmission = exp(-nσ_t)

The Importance of Total Cross Section Data

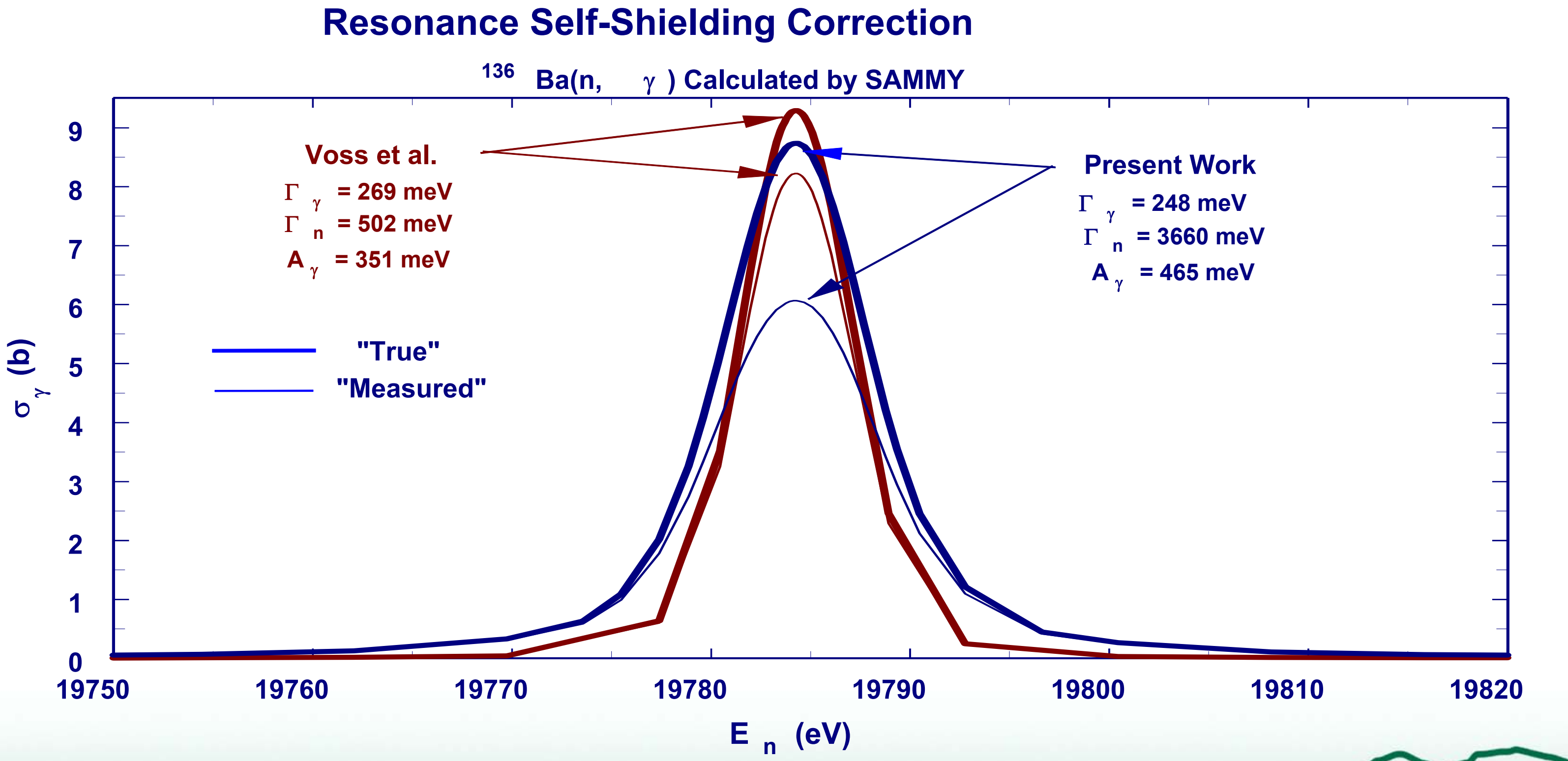
- More complete resonance parameter data will help improve nuclear statistical model.
- Is indispensable for obtaining the most accurate (n,γ) reaction rates. See resonances not visible in (n,γ) data. Improved self-shielding and multiple scattering corrections.
- Lack of good total cross section data can lead to serious errors in these corrections and hence in the cross sections.



- **Ex: ^{116}Sn Use of incorrect neutron widths led to incorrect low-energy cross sections (Wisshak et al.).**

The Importance of Total Cross Section Data

- No high-quality σ_t data available previously. Needed for accurate determination of reaction rate from resonance region because measurements made with thick samples.
- Compare results from pulse-height weighting technique to results from 4π BaF_2 detector.



thin <--> thick transmission Determination of statistical factor g

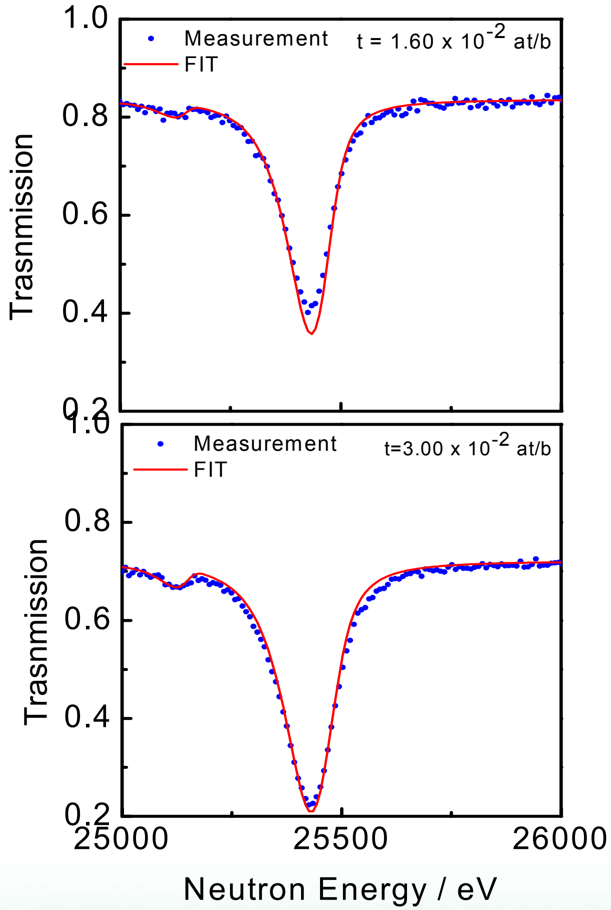
$$A_{t,thin} \propto n g \Gamma_n$$

$$A_{t,thick} \propto \sqrt{n g \Gamma_n \Gamma}$$

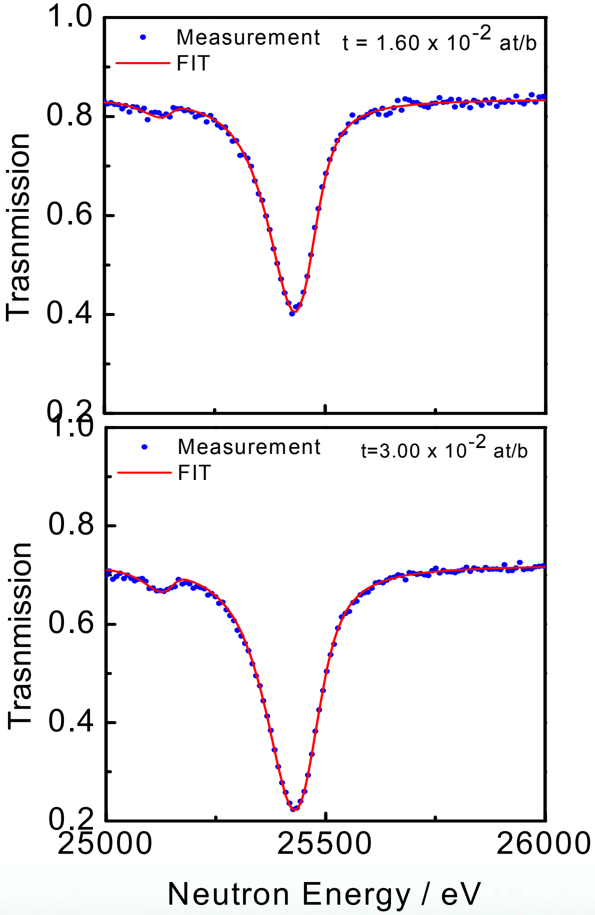
$$g = \frac{2J+1}{2(2I+1)}$$

P. Schillebeeckx, IRMM

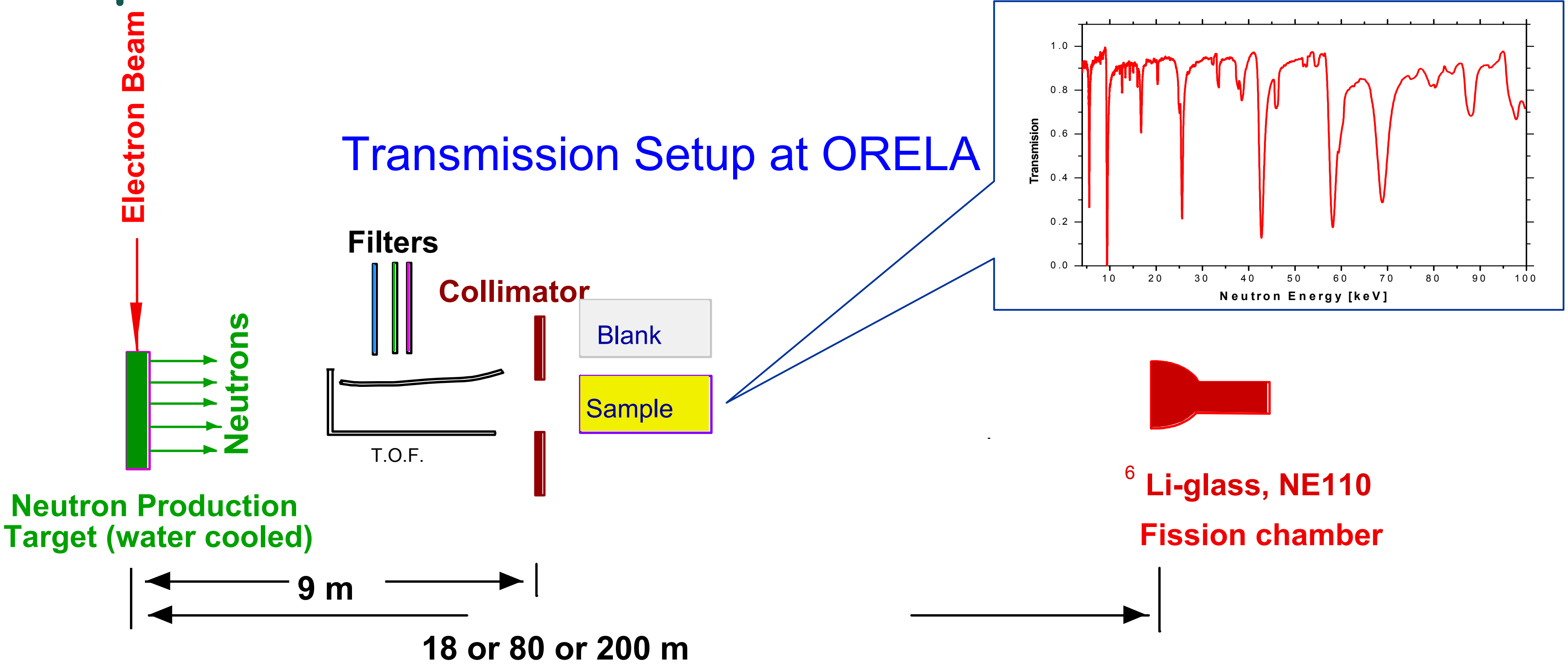
$g=2 \quad \frac{\chi^2}{\nu} = 2.25$



$\boxed{g=1 \quad \frac{\chi^2}{\nu} = 0.95}$



Simplified schematic of neutron transmission



Transmission Setup at ORELA

Electron Beam

Neutrons

Neutron Production Target (water cooled)

Filters

T.O.F.

Collimator

Blank

Sample

^{6} Li-glass, NE110

Fission chamber

9 m

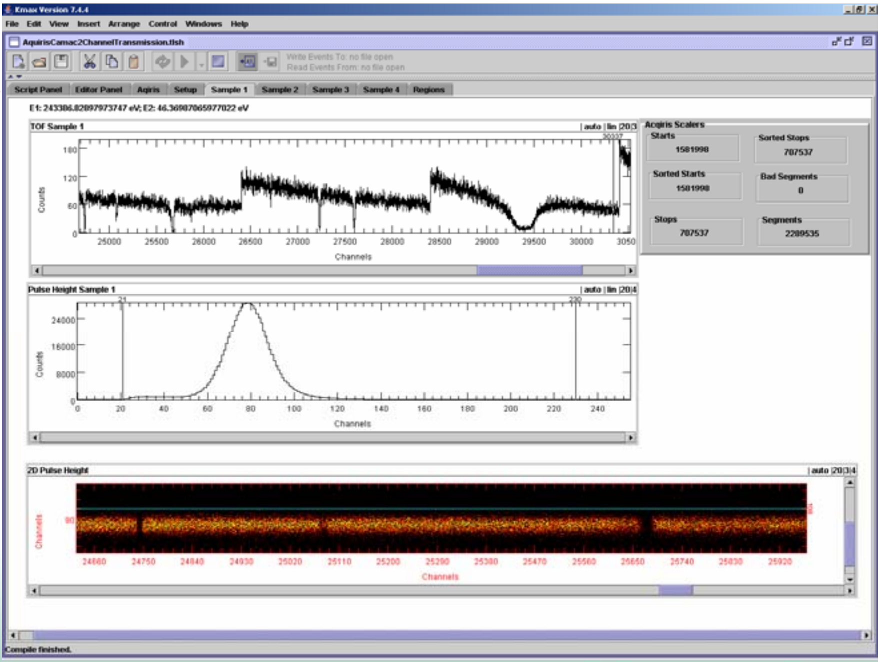
18 or 80 or 200 m

- For transmission, separate measurements of sample in and sample out

$$T = e^{-N\sigma_T d}$$

New & Improved ORELA Transmission Apparatus

- Transient digitizer (Acqiris DC-270) replaced old CAMAC TDC and several NIM modules.
- Allows simultaneous measurement of time of flight and pulse height
  Previous system for ^{6}Li-glass detector was 1-D (TOF only), and for NE-110 detector had only 4 pulse-height channels.
  Allows simultaneous use of both types of detectors.
- Unlimited stops per start
  Previous system limited to 8 stops/start (LeCroy 4208 TDC)
- Fewer NIM and CAMAC modules
  Simpler and more reliable



Write Events To: no file open
Read Events From: no file open

E1: 243386.82897973747 eV; E2: 46.36987065977022 eV

Starts 1581998
Sorted Stops 707537
Sorted Starts 1581998
Bad Segments 0
Stops 707537
Segments 2289535

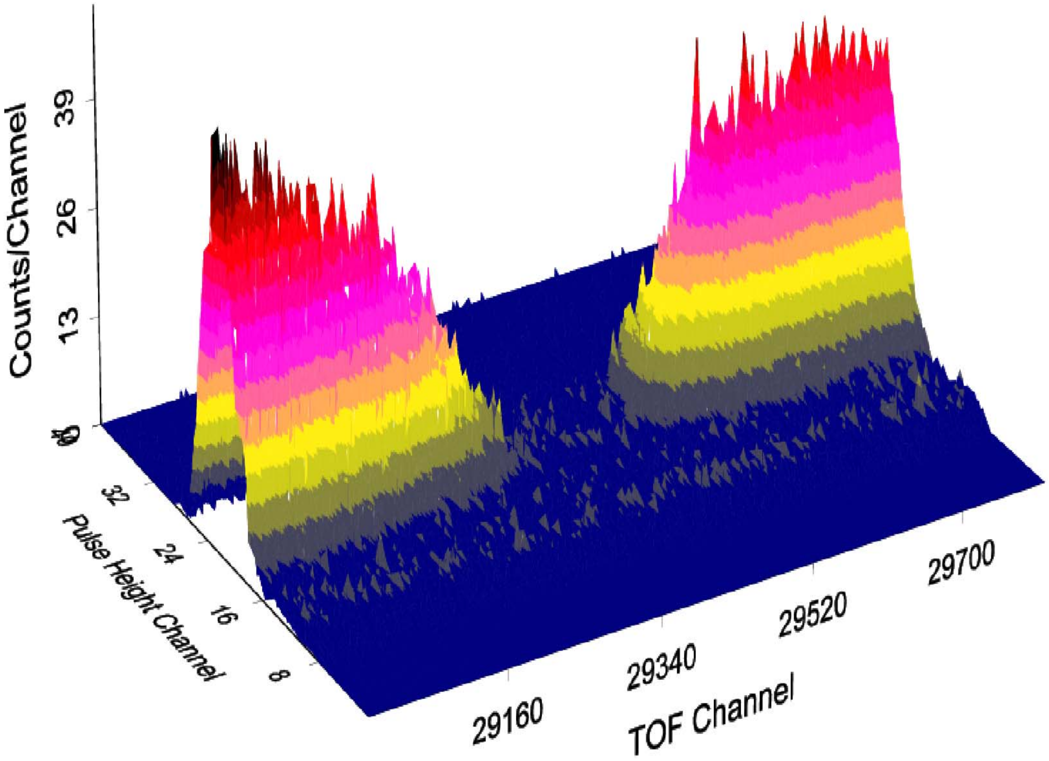
Compile finished.

Test of New Transmission Apparatus: ^{95}Mo

^{6}Li-glass detector at 80 m

ORELA at 525 Hz, 8 ns pulse width and 4 kW power

Computer-controlled cycling between ^{95}Mo, blank, Bi, and CH_2 samples

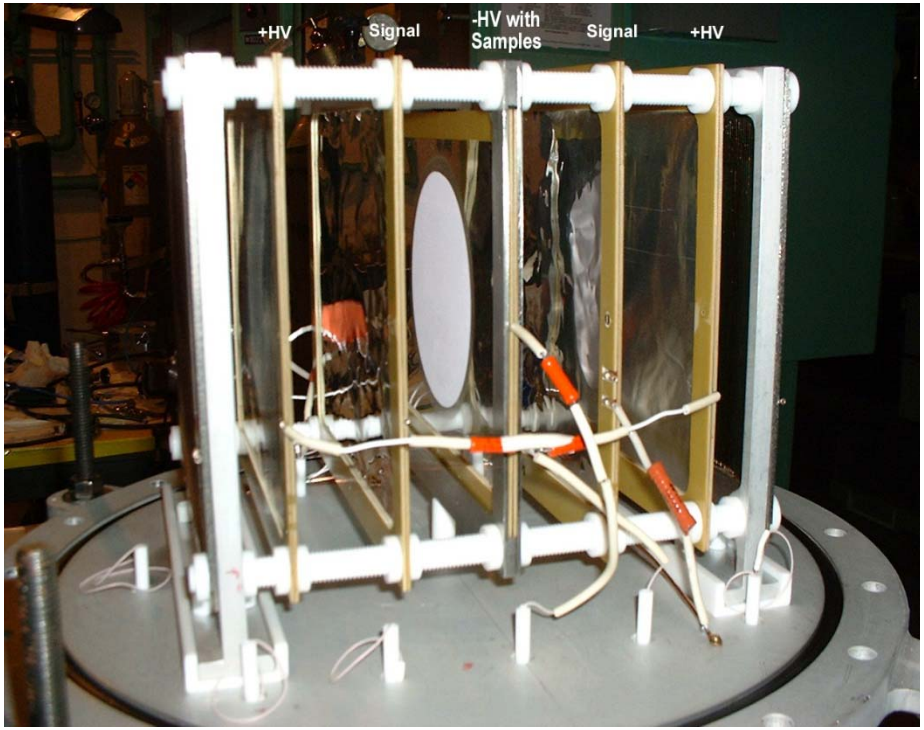


Pulse Height vs. TOF vs. Counts in Region Near “Black” Resonance at 45 eV

(n,α) measurements for explosive nucleosynthesis calculations

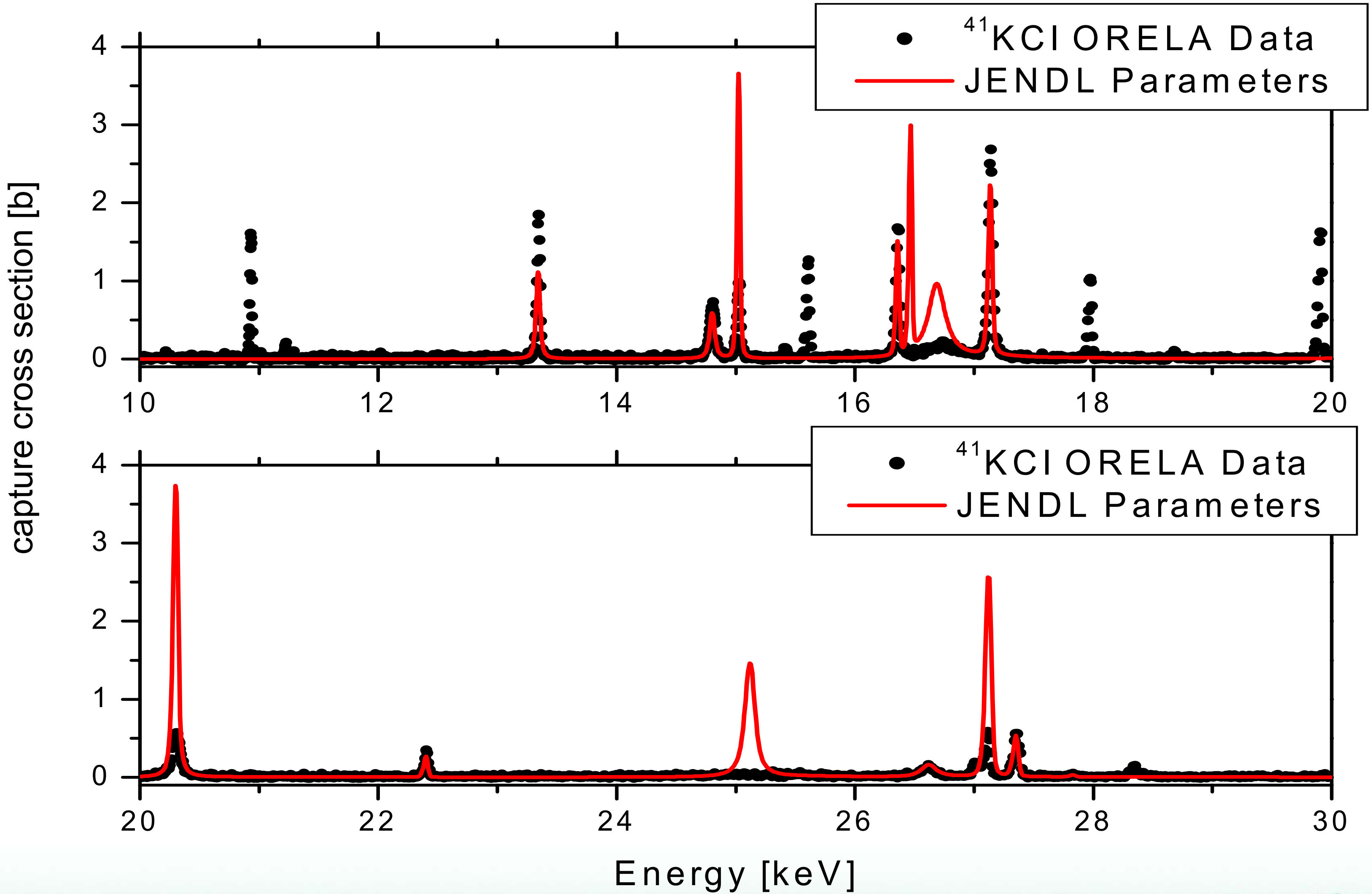
- Improve α+nucleus potential for explosive nucleosynthesis calculations
- Compensated ion chamber (CIC) on FP 11, L = 8.9 m
  CIC suppresses γ flash. Allows measurements to much higher energies, larger samples (10 cm dia.), and high efficiency for measuring small ($\sigma_{ave} \approx 10$ μb) cross sections
  ^{64}Zn(n,α) meas. in progress

Inside of Main CIC Detector

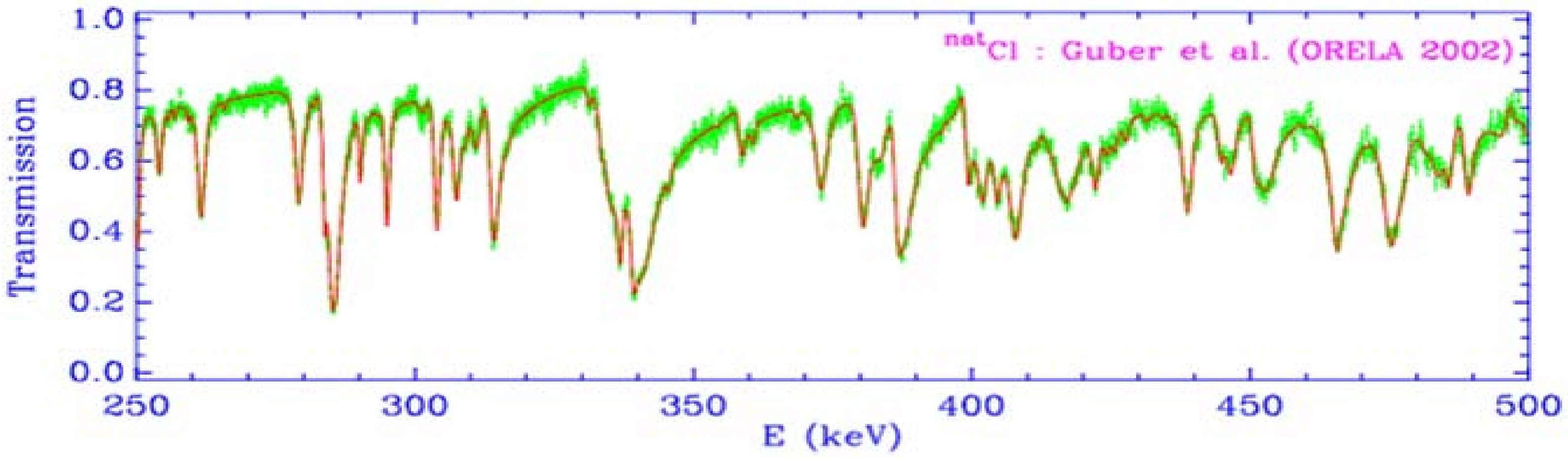


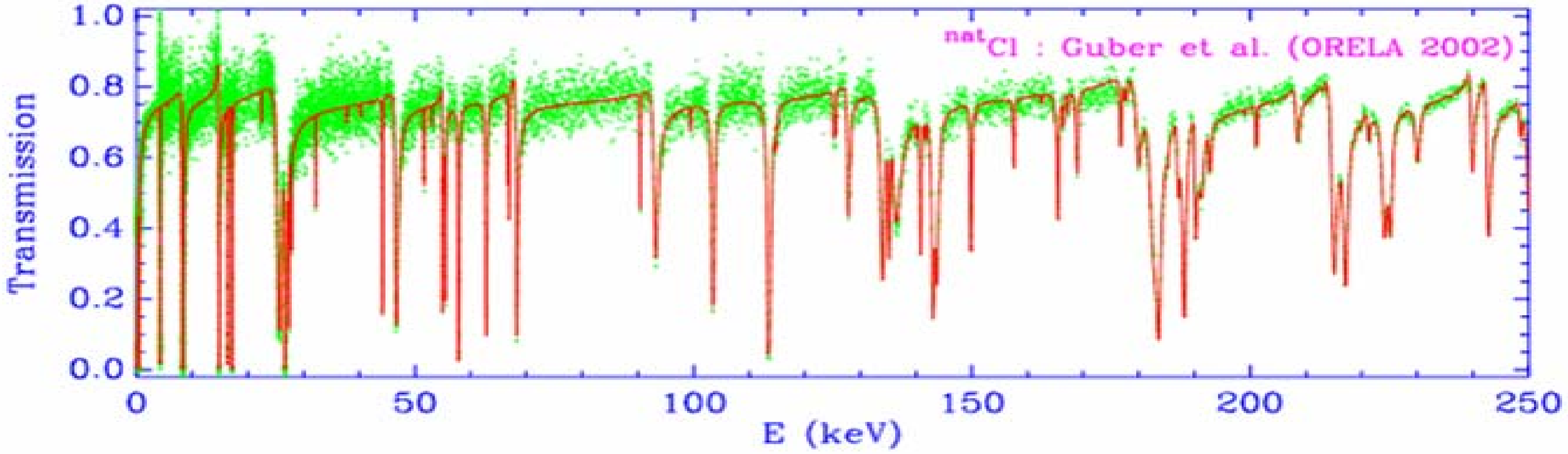
ORELA capture data for ^{41}KCl compared to JENDL3.3

Several resonance areas too large (neutron sensitivity) in evaluation

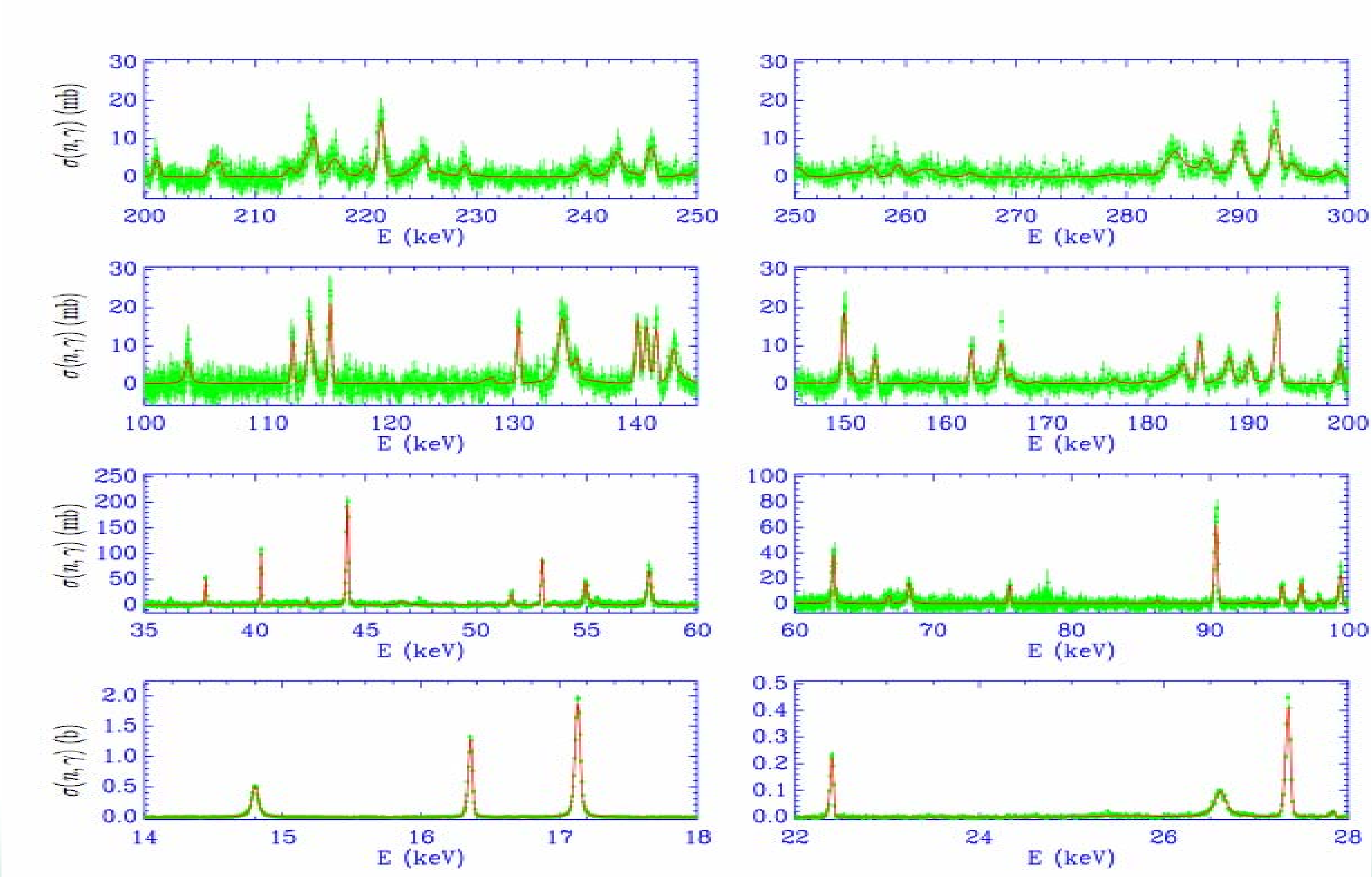


Comparison of SAMMY Fits with ORELA ^{nat}Cl transmission data



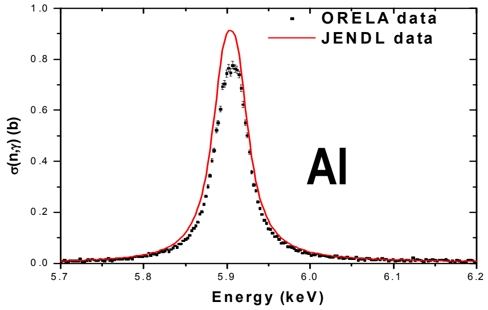


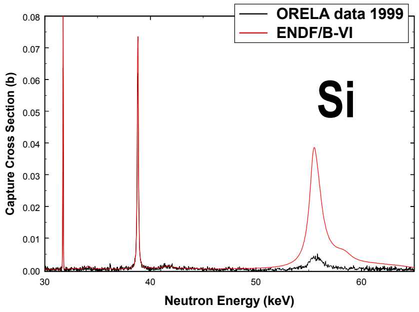
Comparison of SAMMY Fits with ORELA ^{nat}Cl capture data

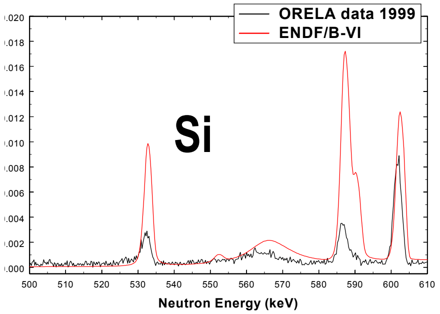


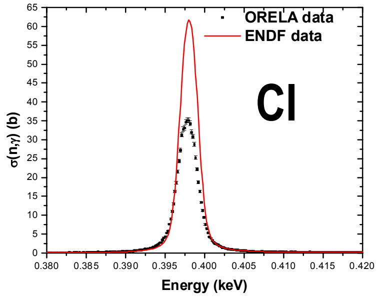
Recent ORELA capture data compared to evaluations

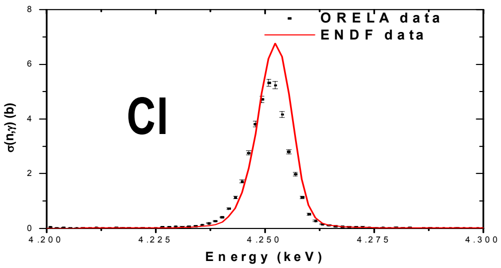
Several resonance areas are too large (neutron sensitivity?) and resonances are missing in evaluations

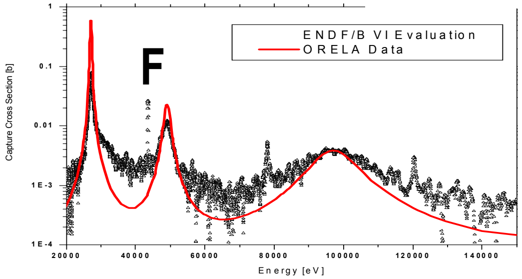


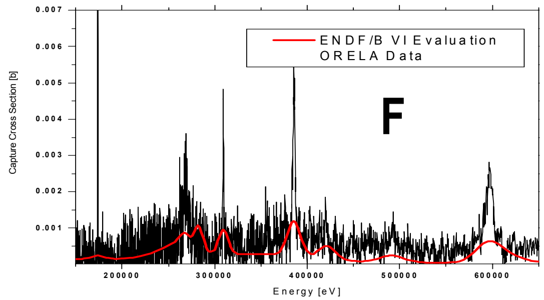


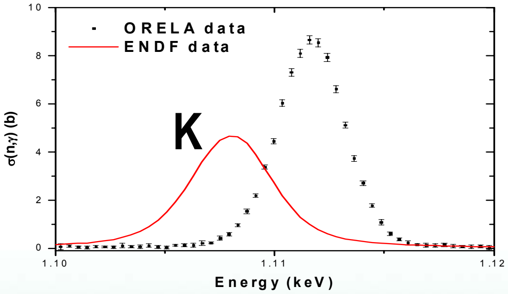


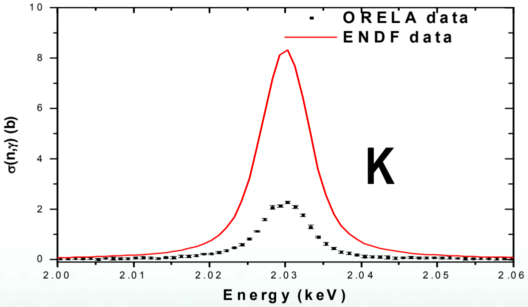


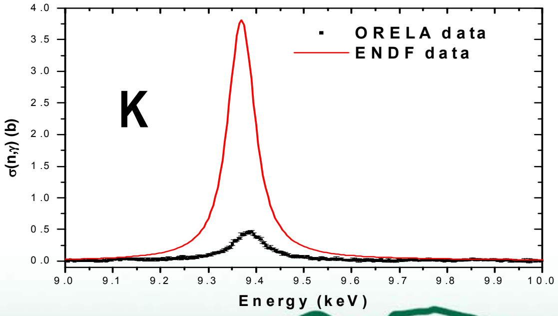




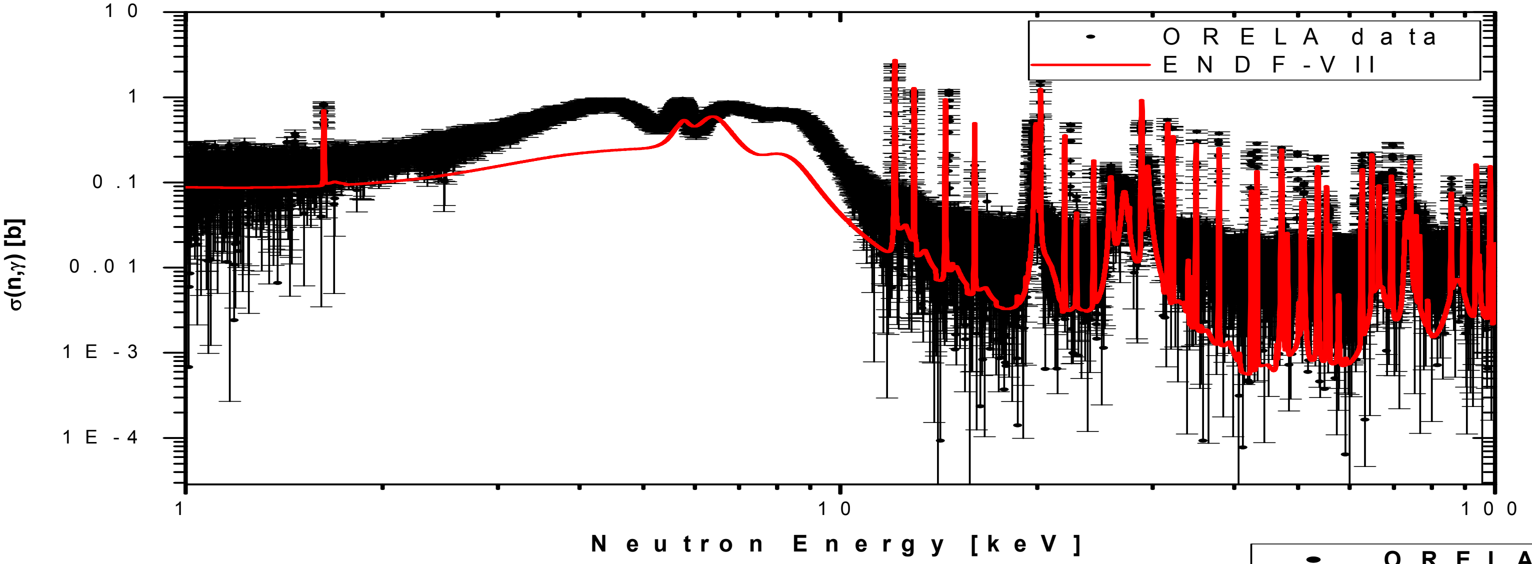


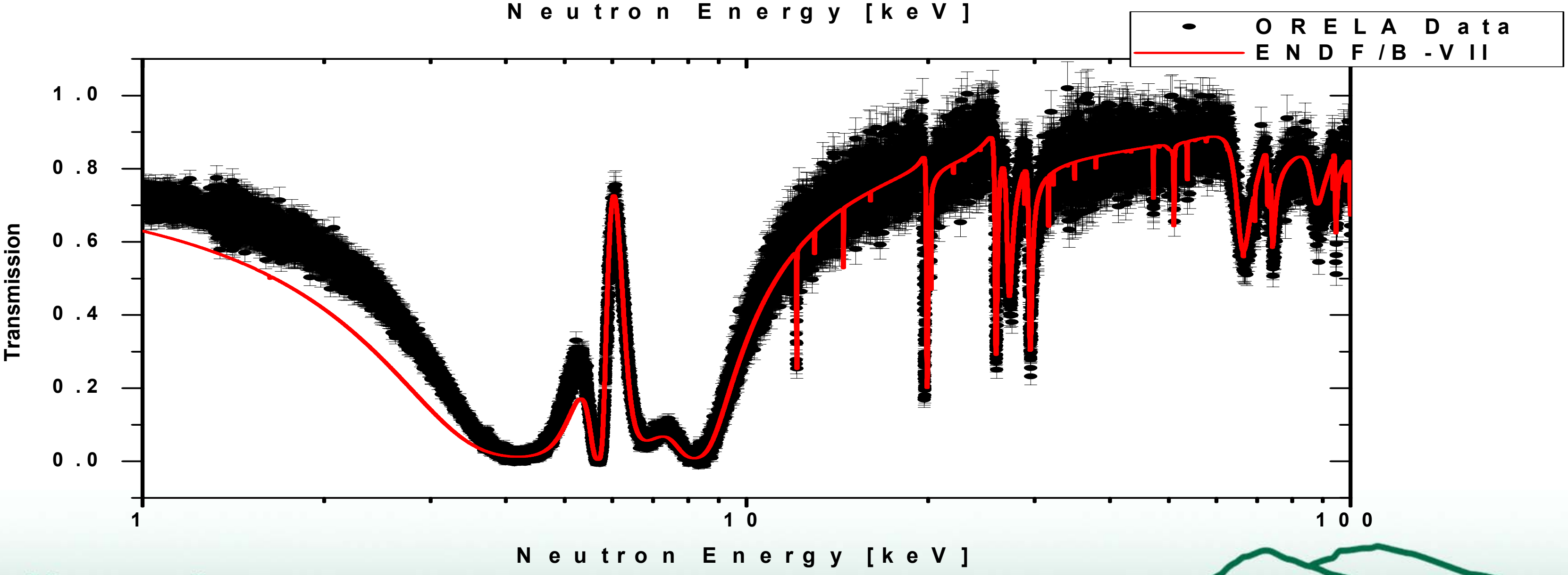




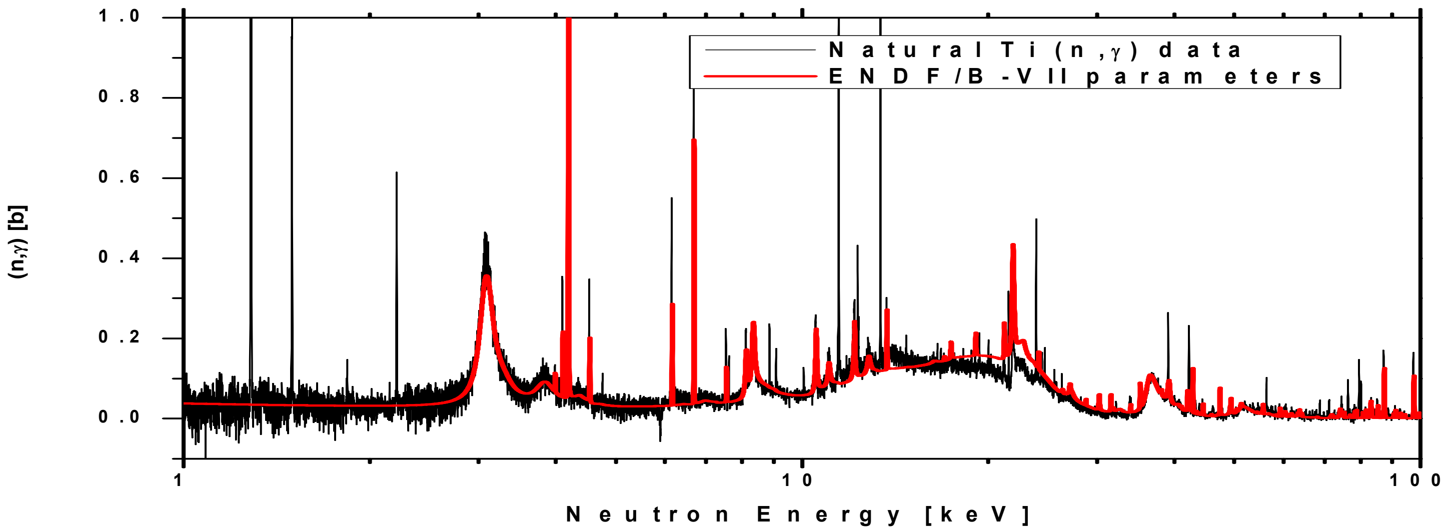


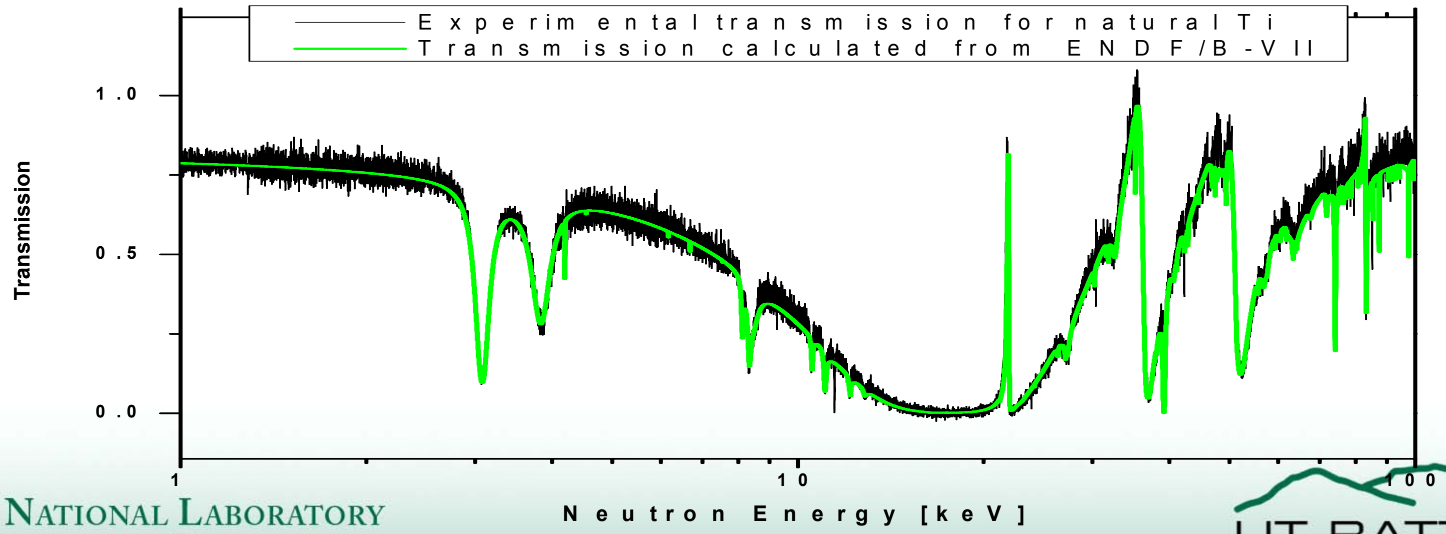
Recent (n,γ) and Transmission for 53Cr



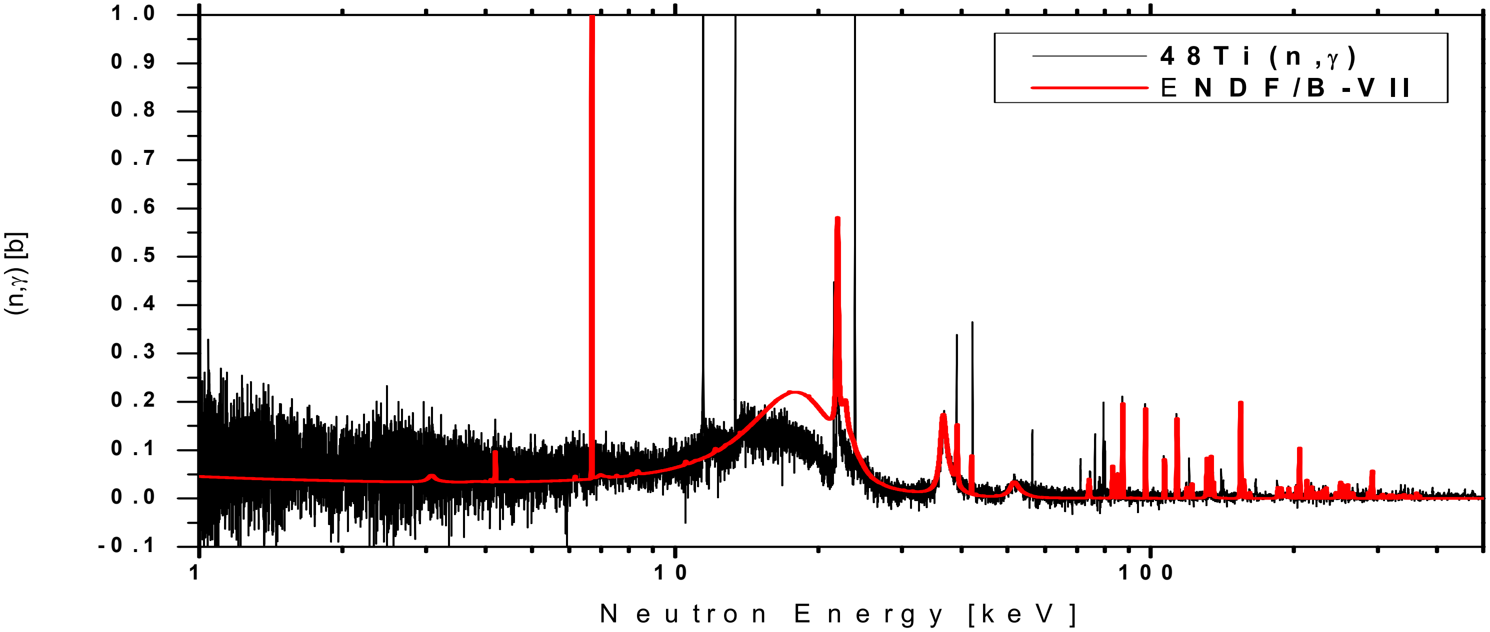


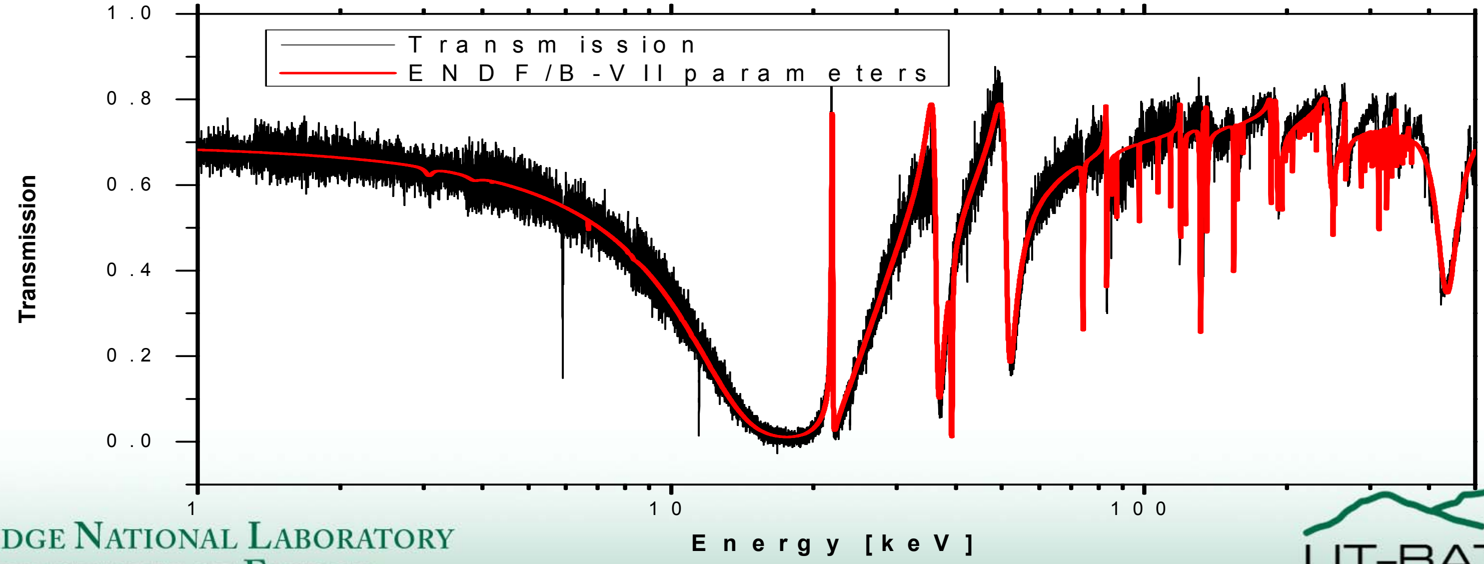
Recent (n,γ) and Transmission for natural Ti



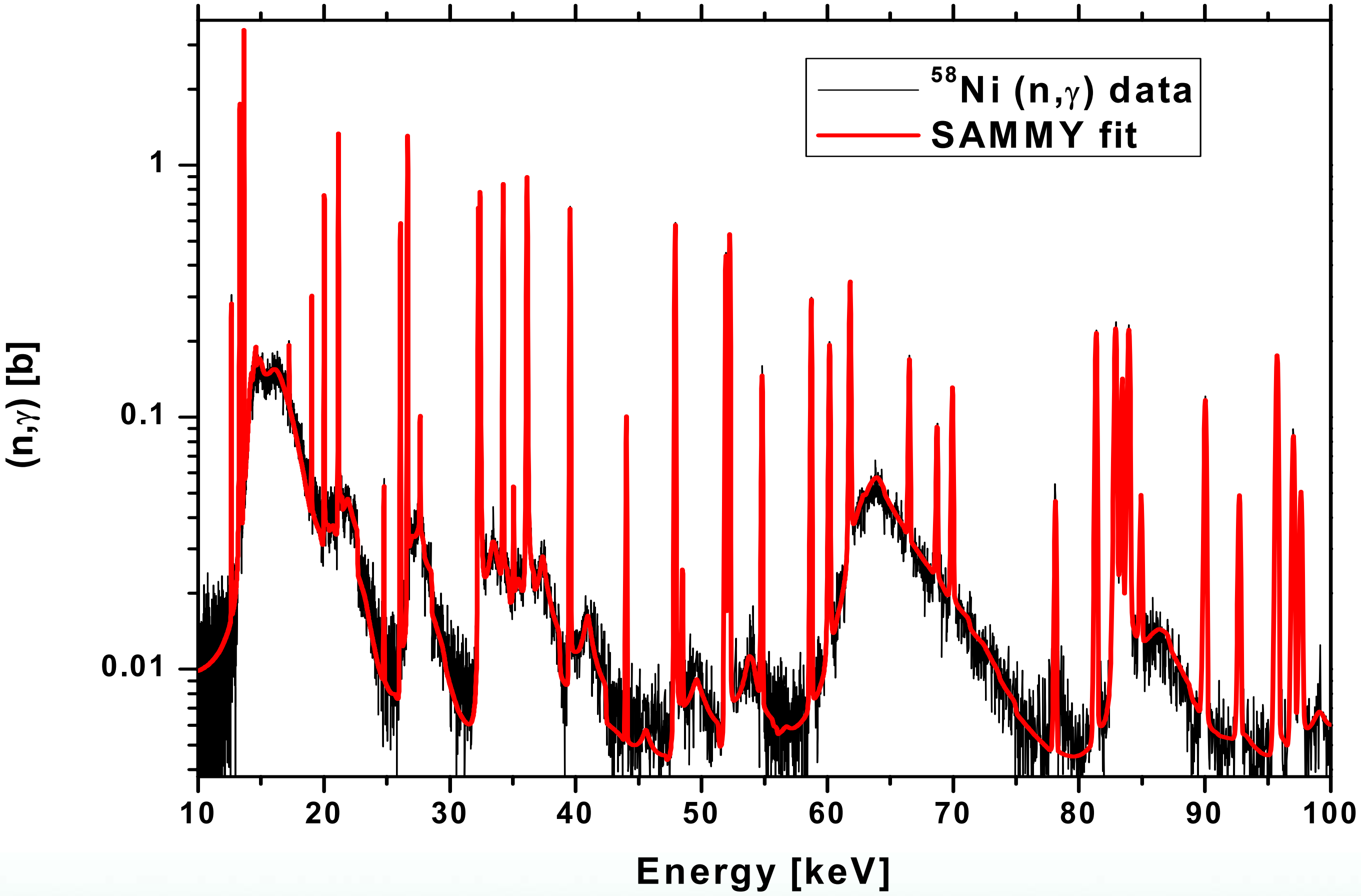


Recent (n,γ) and Transmission on ^{48}Ti

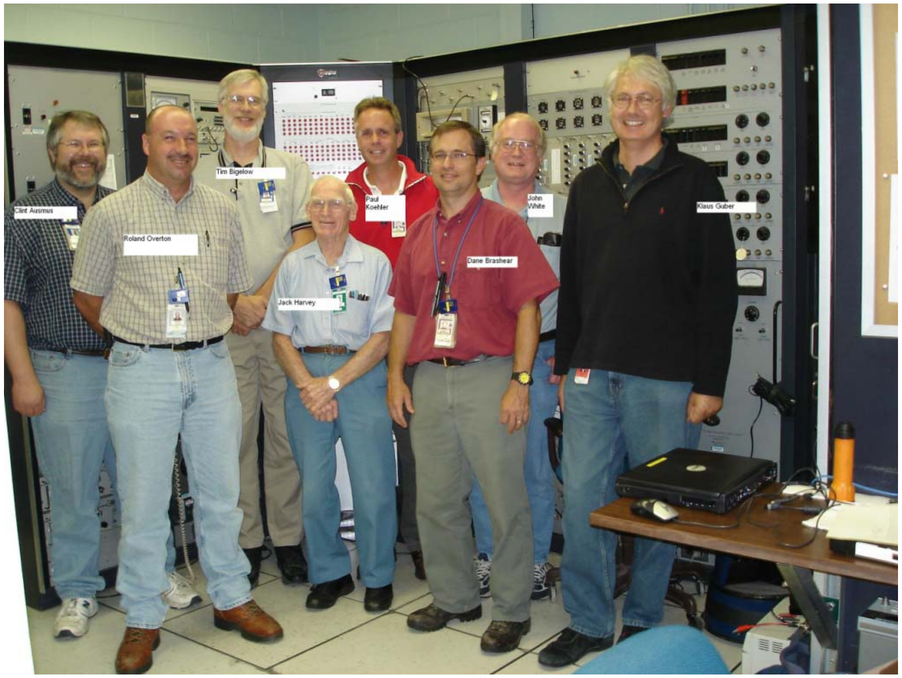




Comparison of the new ORNL ^{58}Ni evaluation with experimental (n,γ) data



Personnel



ORELA Personnel

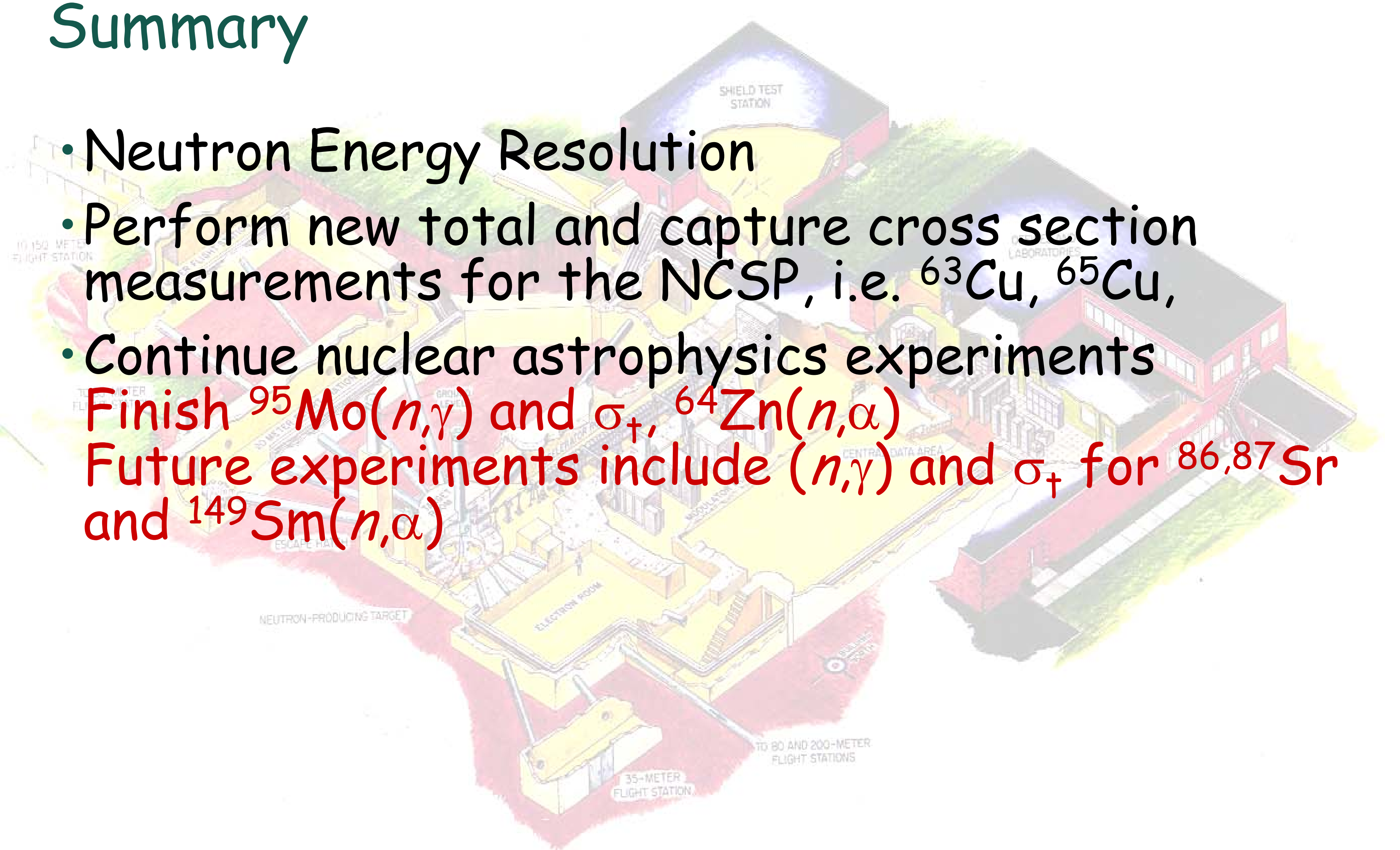
- ORELA:

  C. Ausmus, D.R. Brashear, T.S. Bigelow, K.H. Guber, J.A. Harvey, P.E. Koehler, J.A. White, D. Wiarda

- Nuclear Data Group:

  M. Dunn, G. Arbanas, K.H. Guber, H. Derrien, L.L. Leal, N.M. Larson, R.O. Sayer, D. Wiarda

Summary



- Neutron Energy Resolution
- Perform new total and capture cross section measurements for the NCSP, i.e. ^{63}Cu, ^{65}Cu,
- Continue nuclear astrophysics experiments
  Finish ^{95}Mo(n,γ) and σ_t, ^{64}Zn(n,α)
  Future experiments include (n,γ) and σ_t for ^{86,87}Sr and ^{149}Sm(n,α)

Capture and transmission are not always complementary

		$\boxed{\Gamma_\gamma \ll \Gamma_n}$	$\boxed{\Gamma_\gamma \gg \Gamma_n}$
• Capture (thin):	$A_\gamma \propto ng\frac{\Gamma_n\Gamma_\gamma}{\Gamma}$	$\propto ng\underline{\Gamma_\gamma}$	$\propto ng\underline{\Gamma_n}$
• Transmission (thin):	$A_{t,thin}$	$\propto ng\underline{\Gamma_n}$	$\propto ng\underline{\Gamma_n}$

complementary

combine capture and transmission measurements with different sample thicknesses