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The Resolved Resonance
Region of Hafnium
JEF/DOC-1297

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Tim Ware

JEFF Meeting, OECD NEA Paris

Thursday 26th November 2009

Collaboration

- Peter Schillebeeckx (Geel) - new capture and transmission measurements + data reduction
- Jack Harvey (ORNL) - measurement data (1963)
- Mike Trbovich (RPI) - measurement data (2003)
- Natalia Janeva (INRNE) - enriched Hf samples
- Gilles Noguere (CEA) - unresolved + high energy evaluation with co-variances via CONRAD
- Mick Moxon - REFIT + evaluation
- Chris Dean (Serco) - processing + benchmarks
- David Weaver (U. Birm.) - PhD supervisor
- + many others...

Overview

- Need for hafnium measurements
- New measurements
- Resonance analysis
- Comparison with JEFF3.1
- Conclusions

Need for Hafnium Measurements

- Previous CEA criticality calculations imply overestimation of the ^{nat}Hf capture cross-section
- Hafnium placed on High Priority Request List
- Measurements required to:
 - Extend RRR to higher energies
 - Allocate resonances correctly to isotopes above 200eV
 - Confirm/improve data below 200eV
- Support for measurements gained through NUDAME and EUFRAT programmes.

Properties of Hafnium

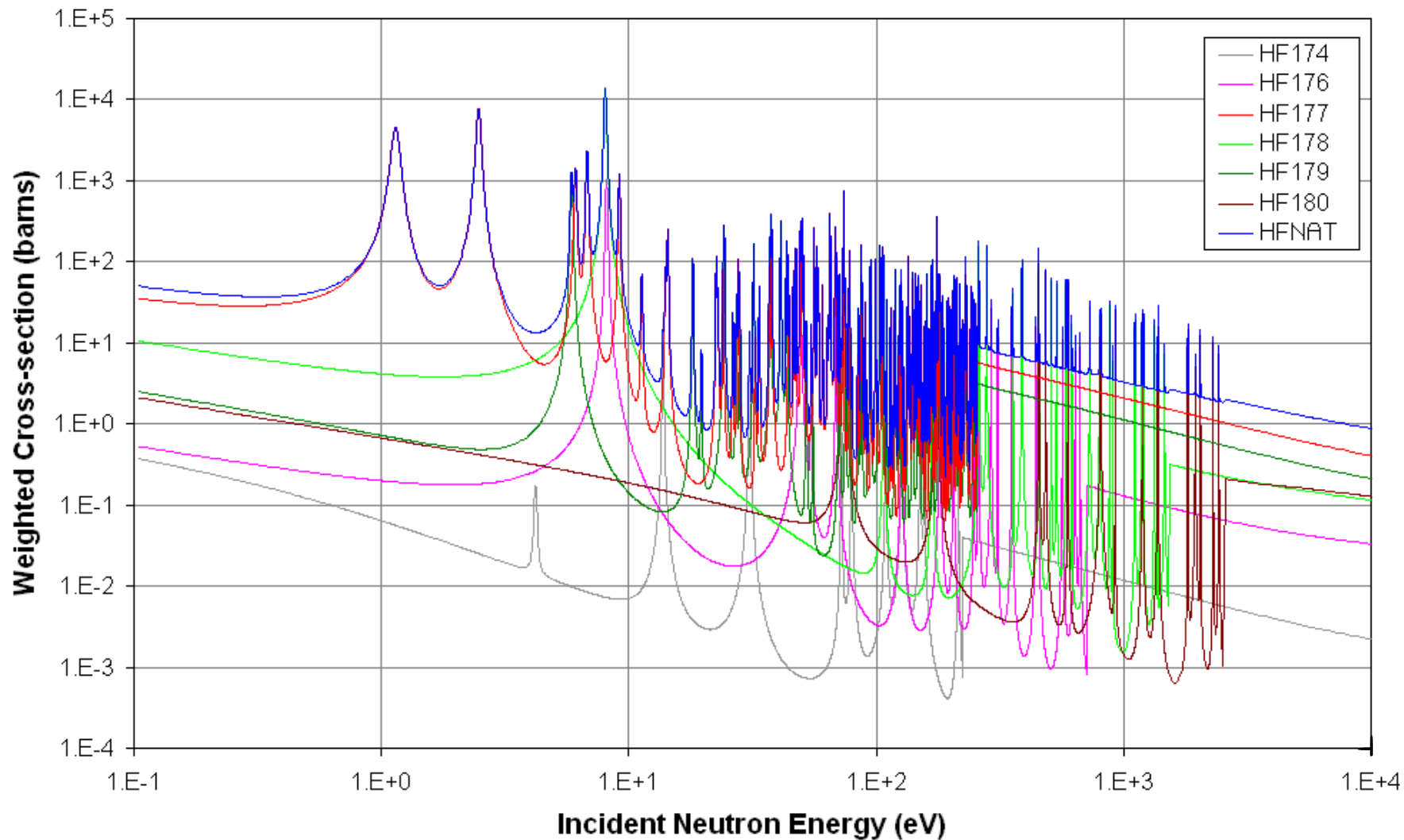
- Metallic element ($A = 72$)
- High absorption cross-section in RRR ($\sim 1\text{eV} - 1\text{keV}$)
- Use in control rods of reactors with hard neutron spectra
- Six naturally occurring hafnium isotopes;

^{174}Hf (0.16%)
 ^{176}Hf (5.26%)
 ^{177}Hf (18.60%)

^{178}Hf (27.28%)
 ^{179}Hf (13.62%)
 ^{180}Hf (35.08%)

- Complex resonance structure – requires isotopically enriched measurements

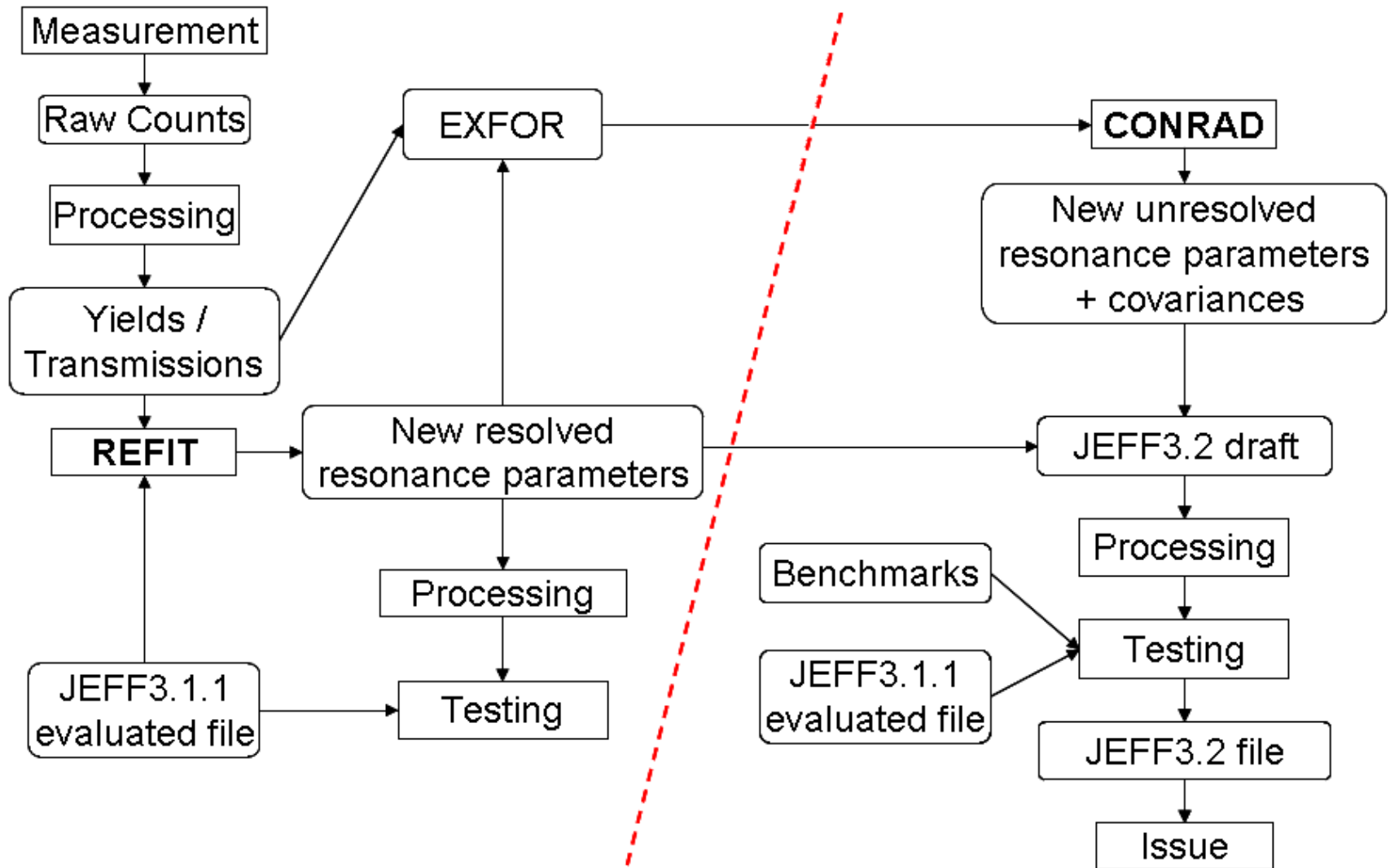
Hafnium Capture Cross-Sections (JEFF3.1)



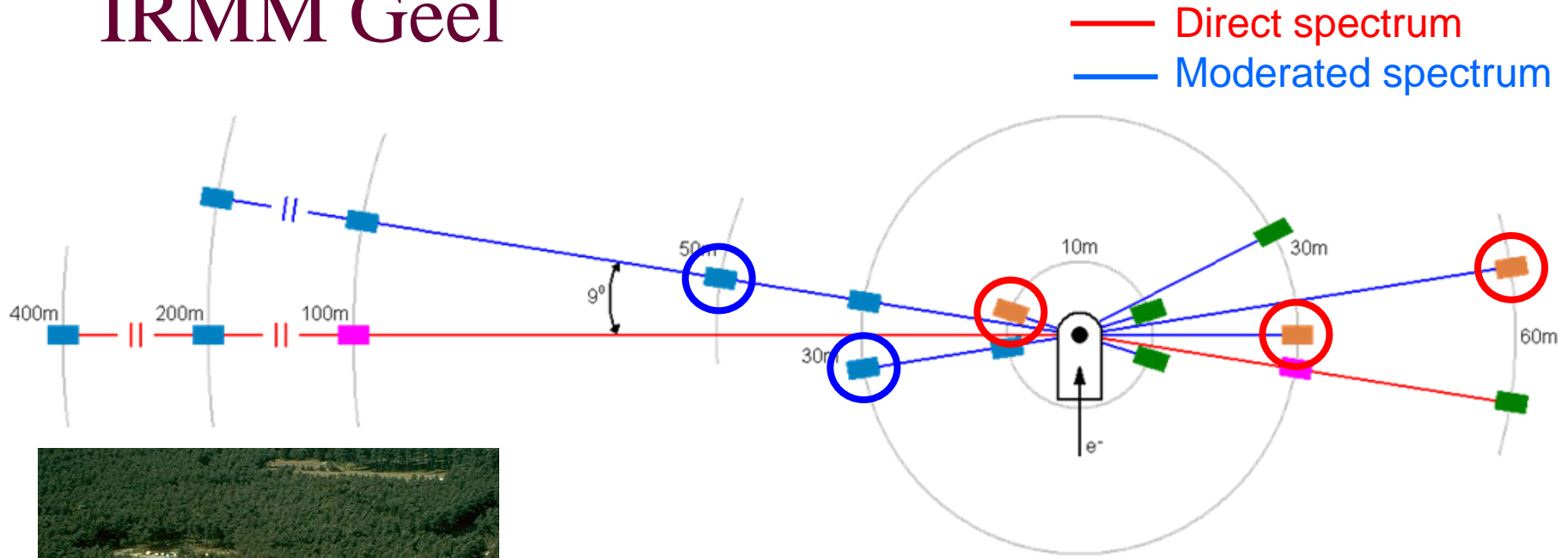
JEFF Resonance Evaluations for $^{177,179}\text{Hf}$

- JEFF3.1.1 (= JEFF3.1)
 - resolved: RPI to 200eV, ENDF/B-VI to 250eV
 - unresolved: JENDL-3.3 to 10keV
- JEFF3.2 resolved data to 1keV via REFIT:
 - Geel measurements (natural & enriched)
 - Harwell 1974 measurements (^{180}Hf enriched)
 - RPI reanalysed for 8eV doublet (JEF/DOC-1313)
- JEFF3.2 unresolved data via CONRAD
 - G. Noguere/CEA (to be developed)
- JEFF3.2 co-variance data via CONRAD
 - G. Noguere/CEA (to be developed)

Measurement & Evaluation Process



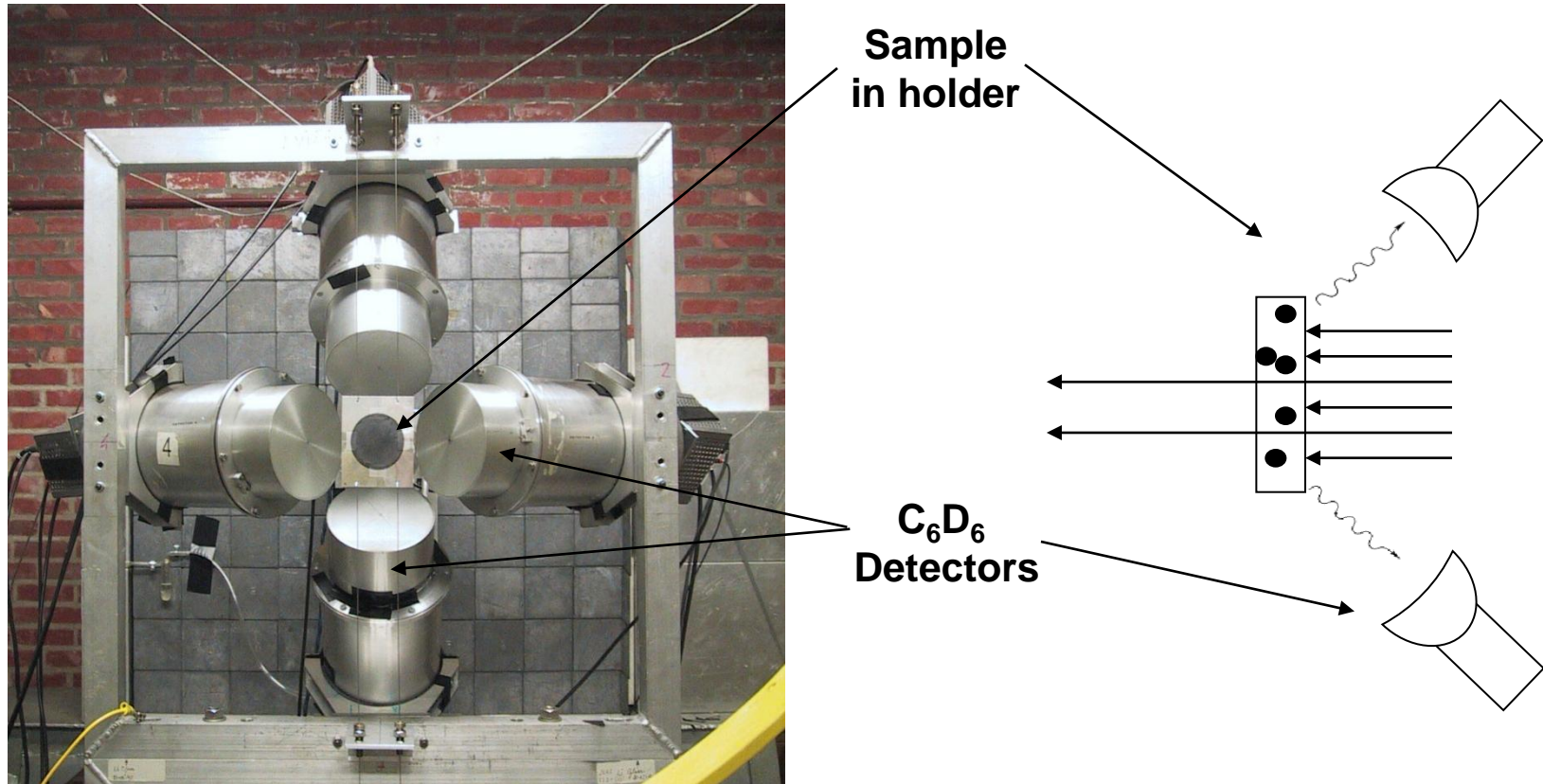
IRMM Geel



- radiative capture
- total
- fission, charged particle
- inelastic scattering

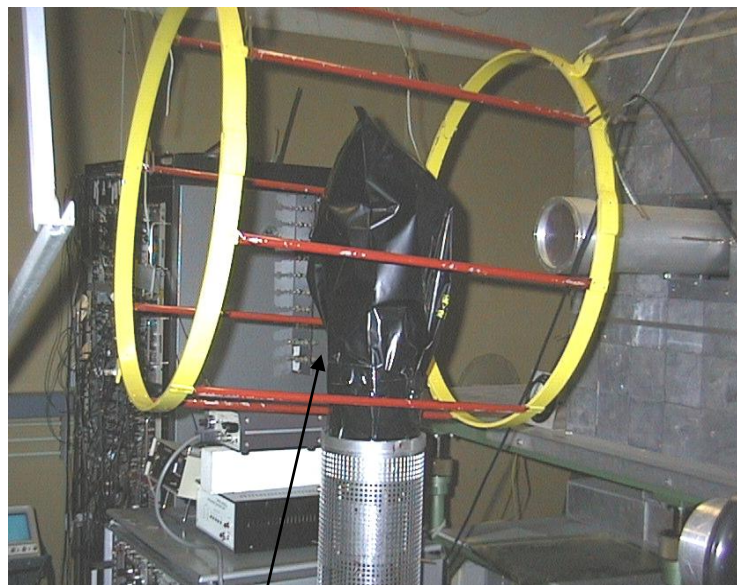
Capture Measurements

Natural & enriched samples

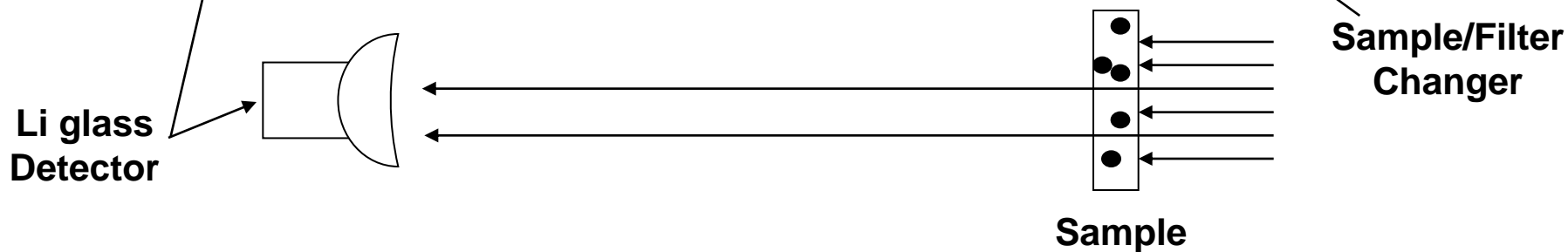


Transmission Measurements

Natural samples (incl. P. Siegler's)



~20m



Enriched Hafnium Oxide Samples

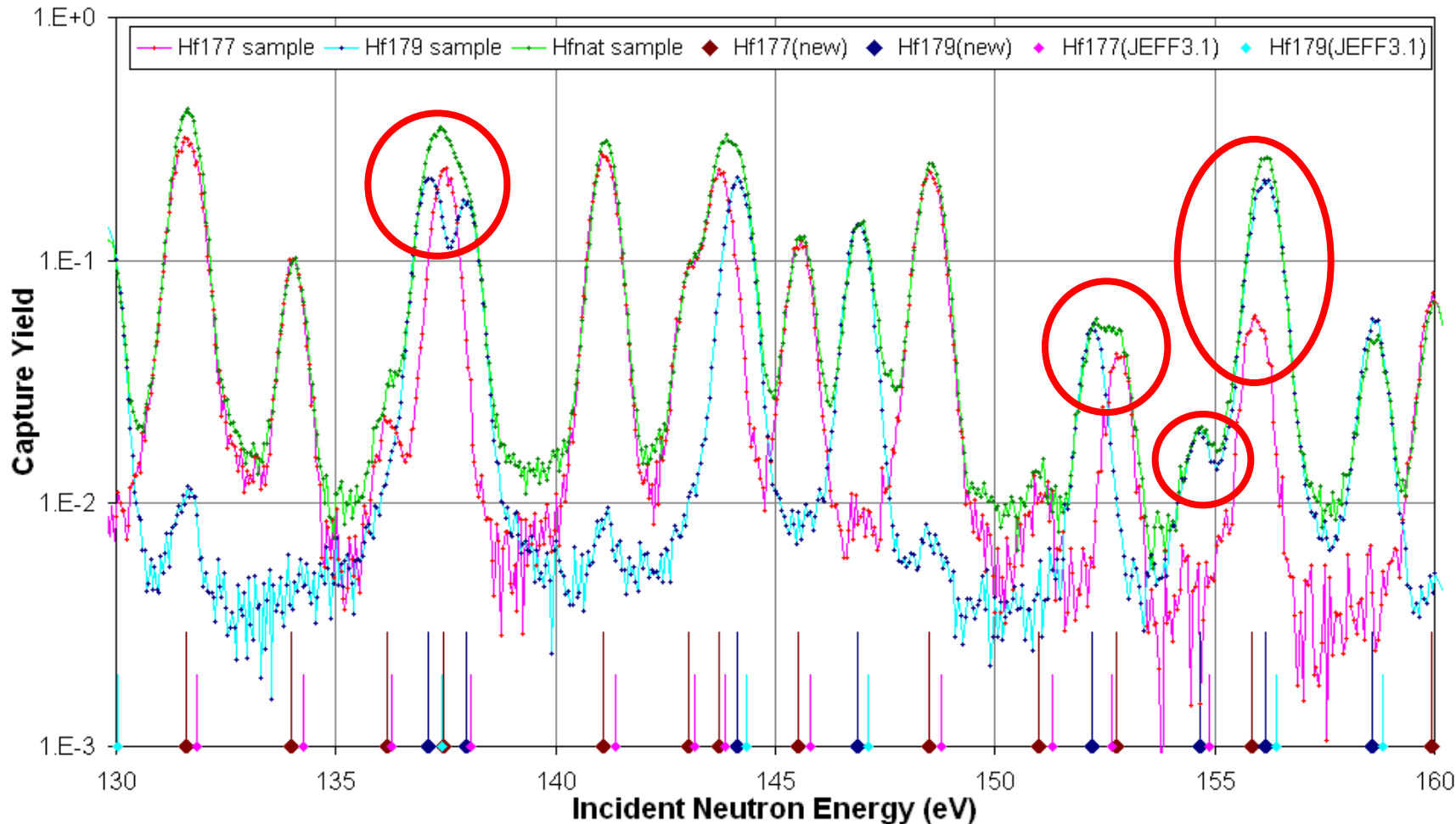
Kindly loaned by INRNE, Sofia

Sample	Abundance (%)					
	^{174}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf
c.f. natural	0.16	5.26	18.6	27.3	13.6	35.1
^{176}Hf	<0.05	65.0	22.9	6.3	1.8	4.0
^{177}Hf	<0.05	1.0	85.4	11.3	0.9	1.4
^{178}Hf	<0.05	0.8	1.9	92.4	3.3	1.6
^{179}Hf	<0.05	0.2	1.3	4.1	72.1	22.3



Resonance Allocation

Capture measurements, enriched & natural Hf at 30m

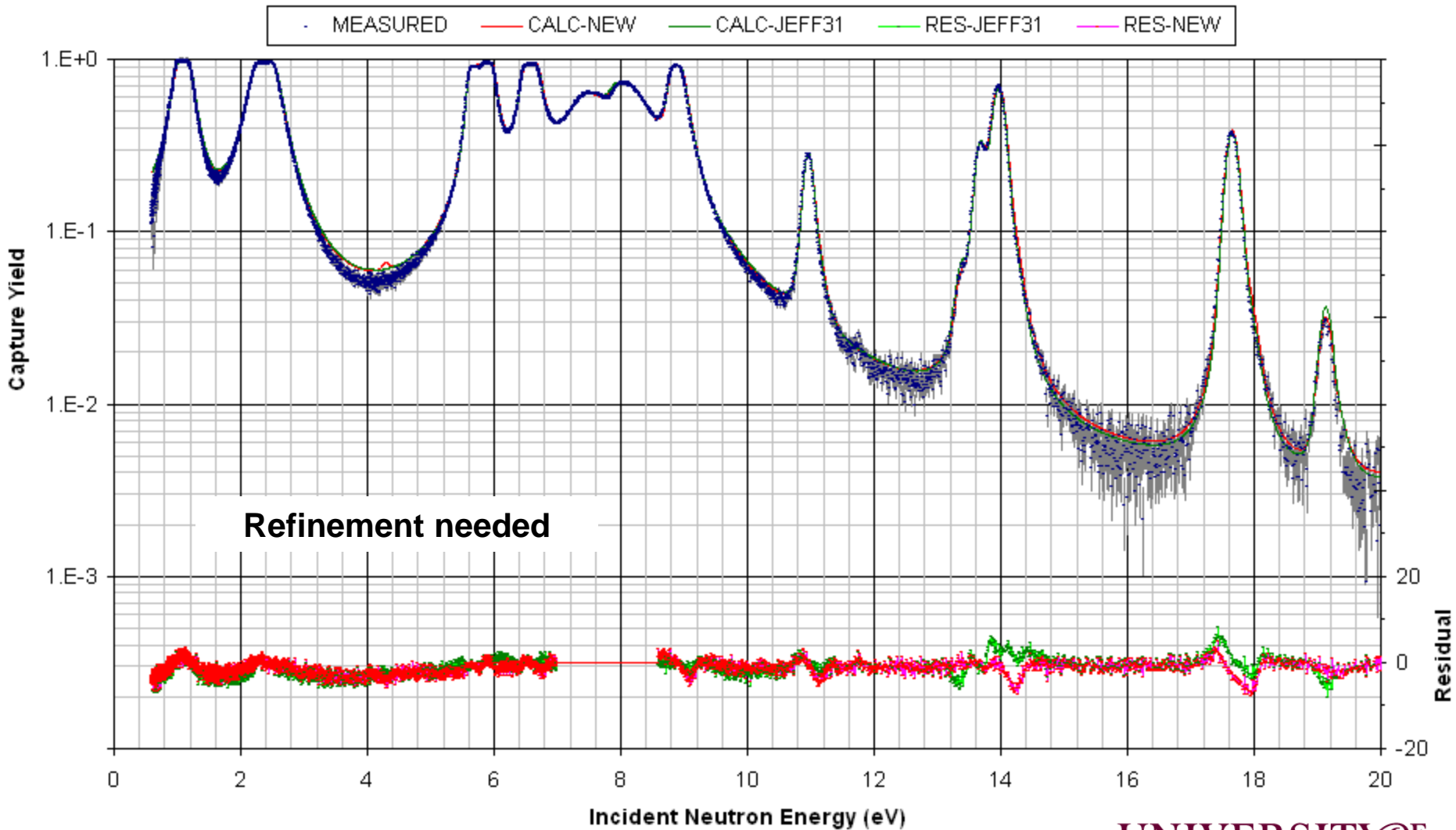


REFIT

- Resonance analysis code
- Calculation of capture yield / transmission from nuclear and experimental parameters
- Includes Doppler & resolution broadening
- Models scattering within capture samples
- Simultaneous fit to many measurements (<30) by adjustment of selected nuclear and experimental parameters via least square fitting method
- Resonance parameters input from and output to ENDF6 format

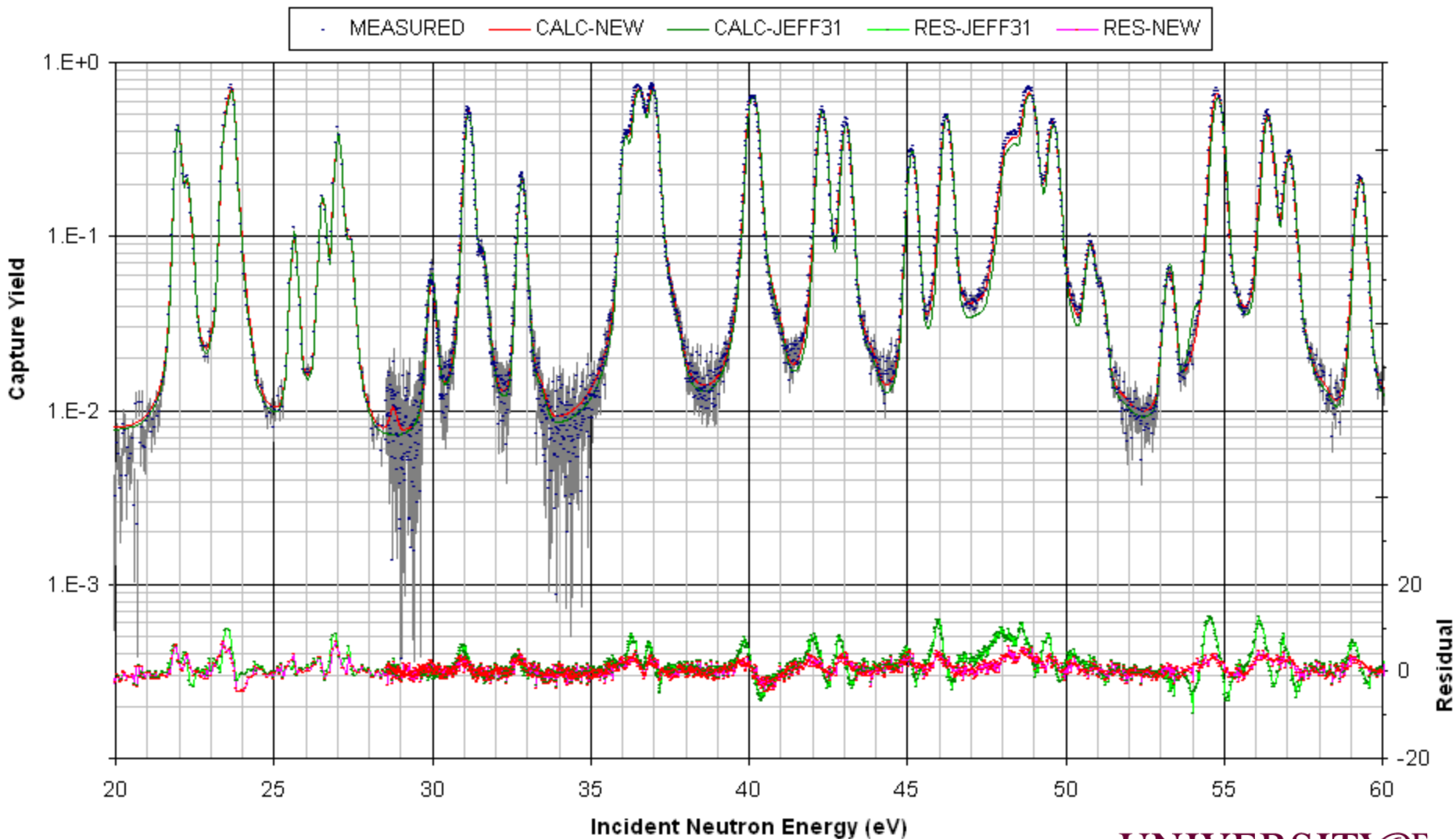
Calculated Yields from REFIT

Hf-nat 1mm sample @ 12m



Calculated Yields from REFIT

Hf-nat 1mm sample @ 28m

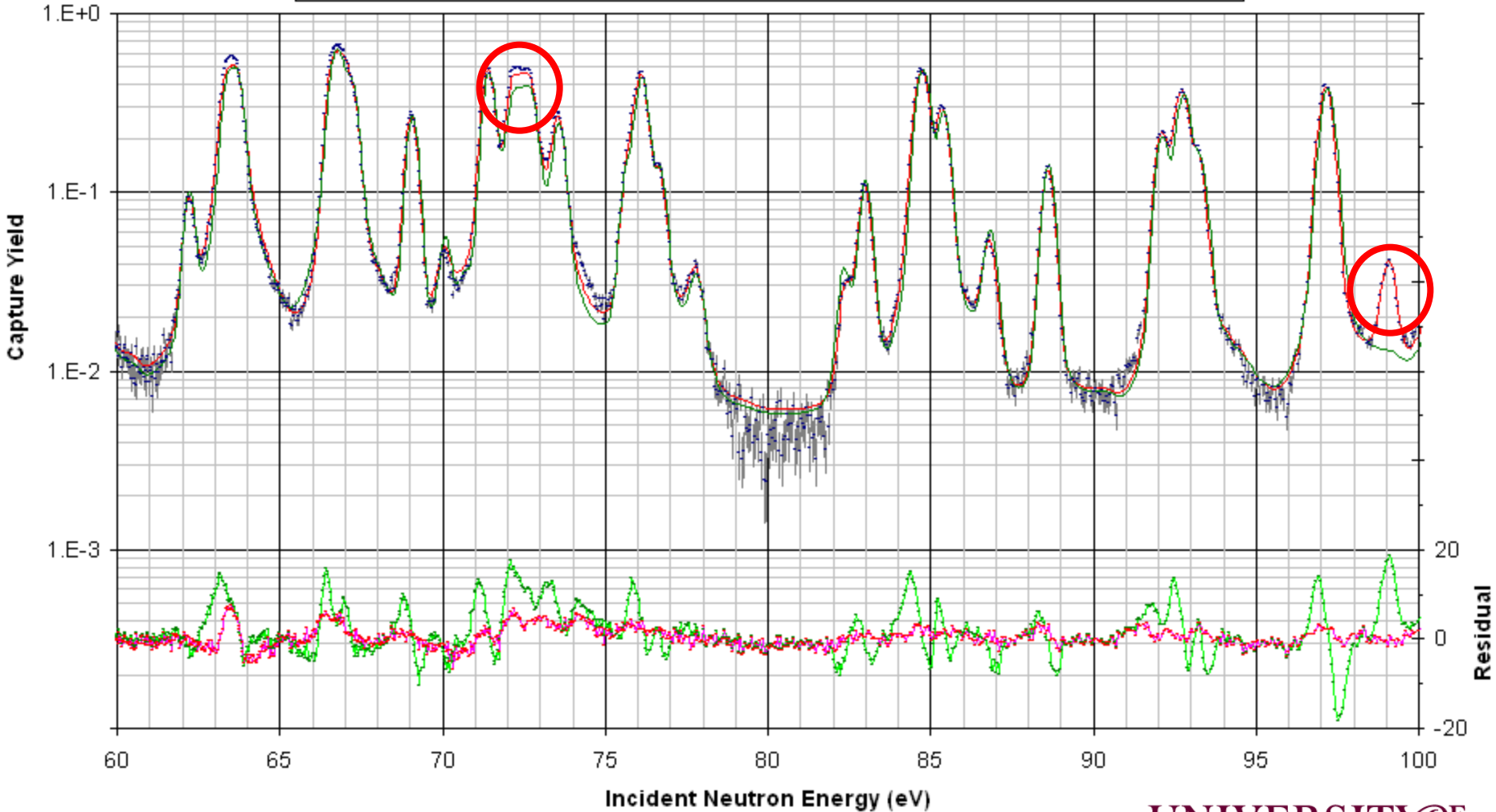
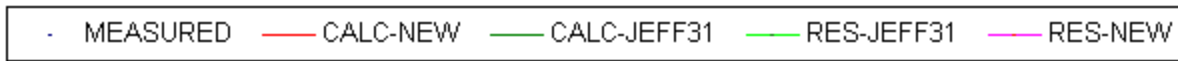


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Calculated Yields from REFIT

Hf-nat 1mm sample @ 28m

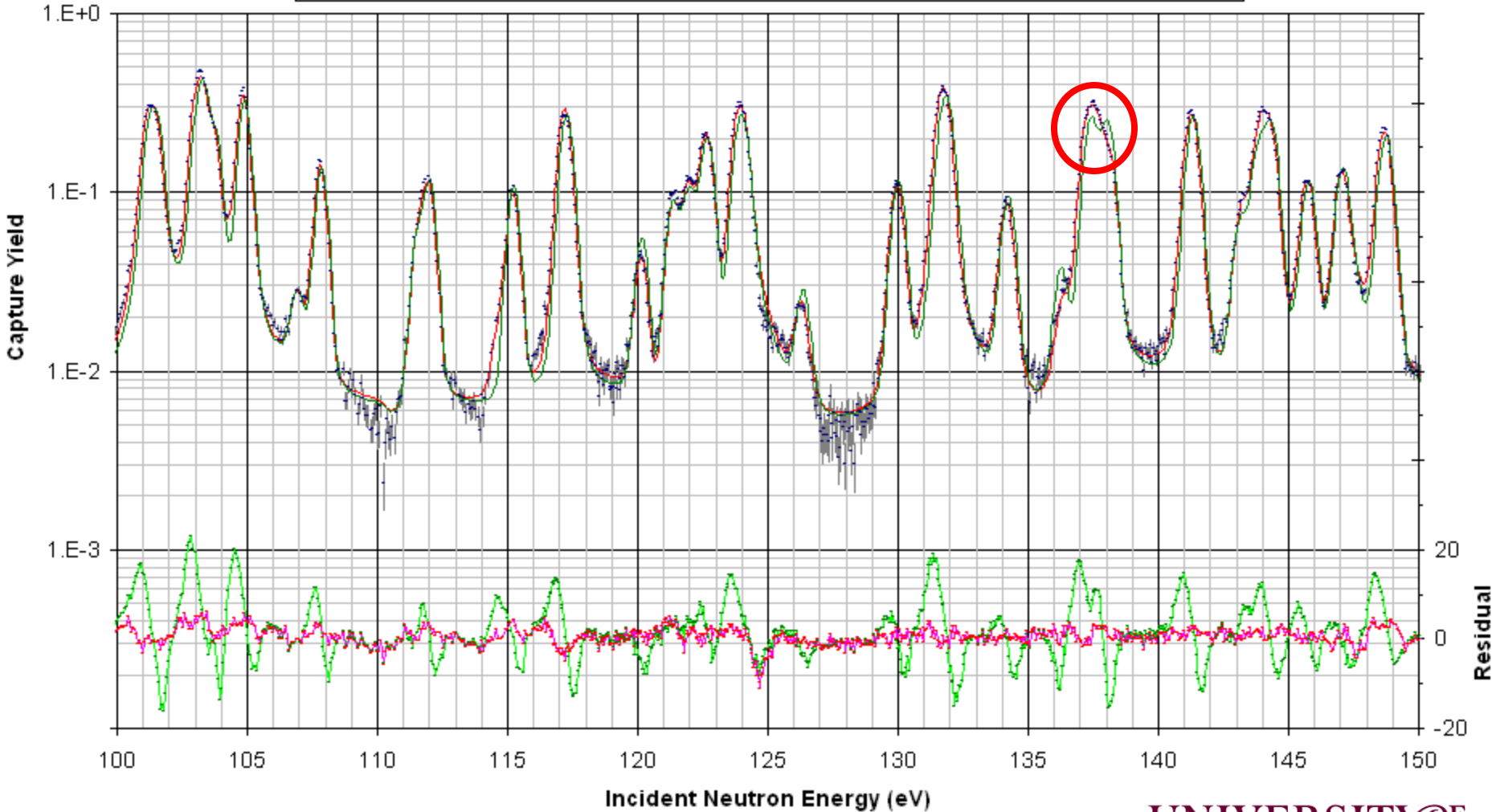
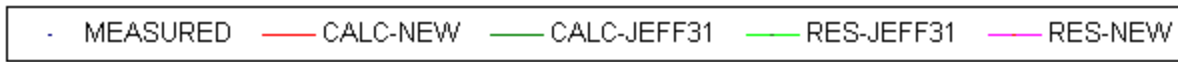


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Calculated Yields from REFIT

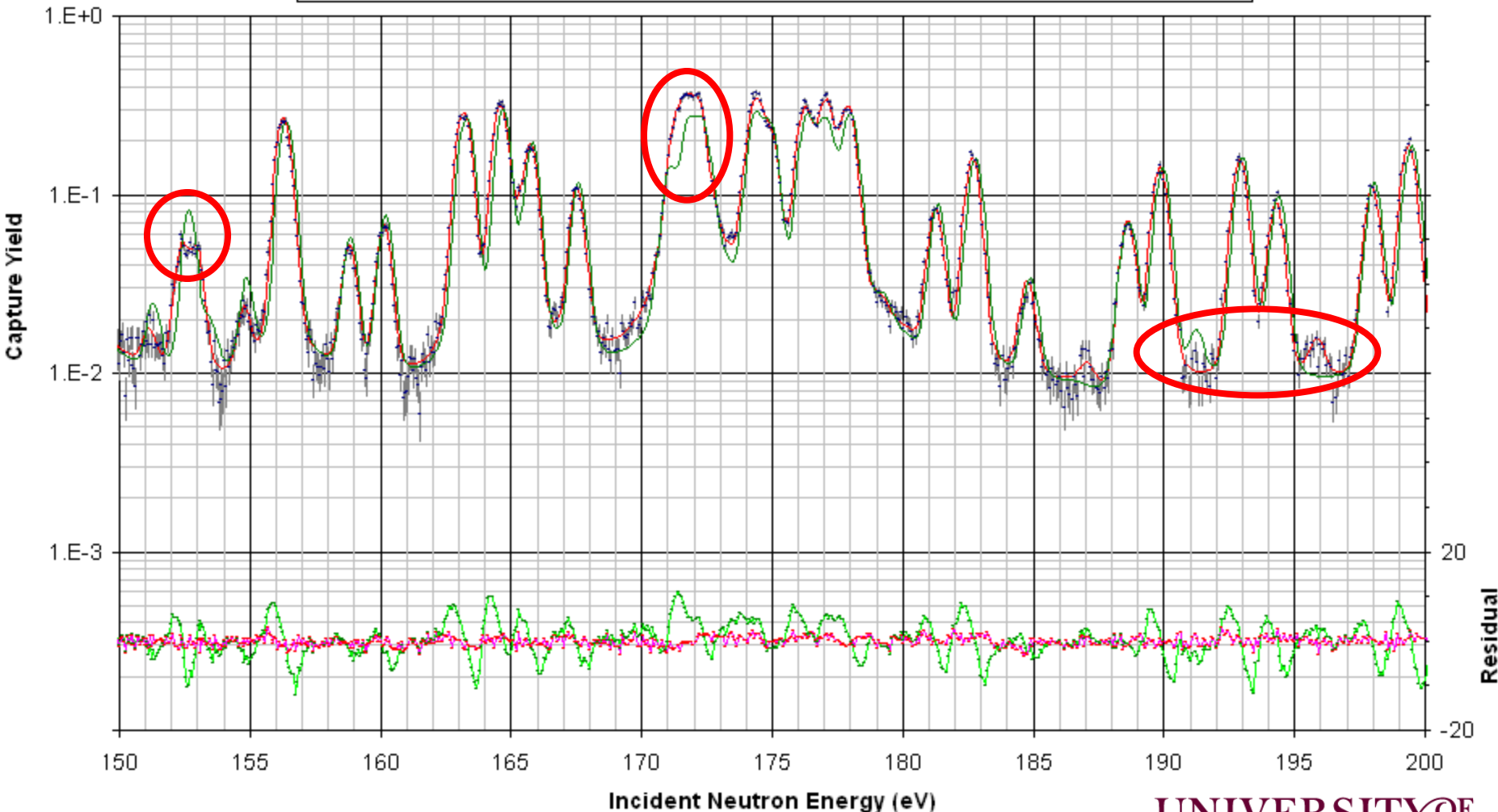
Hf-nat 1mm sample @ 28m



Calculated Yields from REFIT

Hf-nat 1mm sample @ 58m

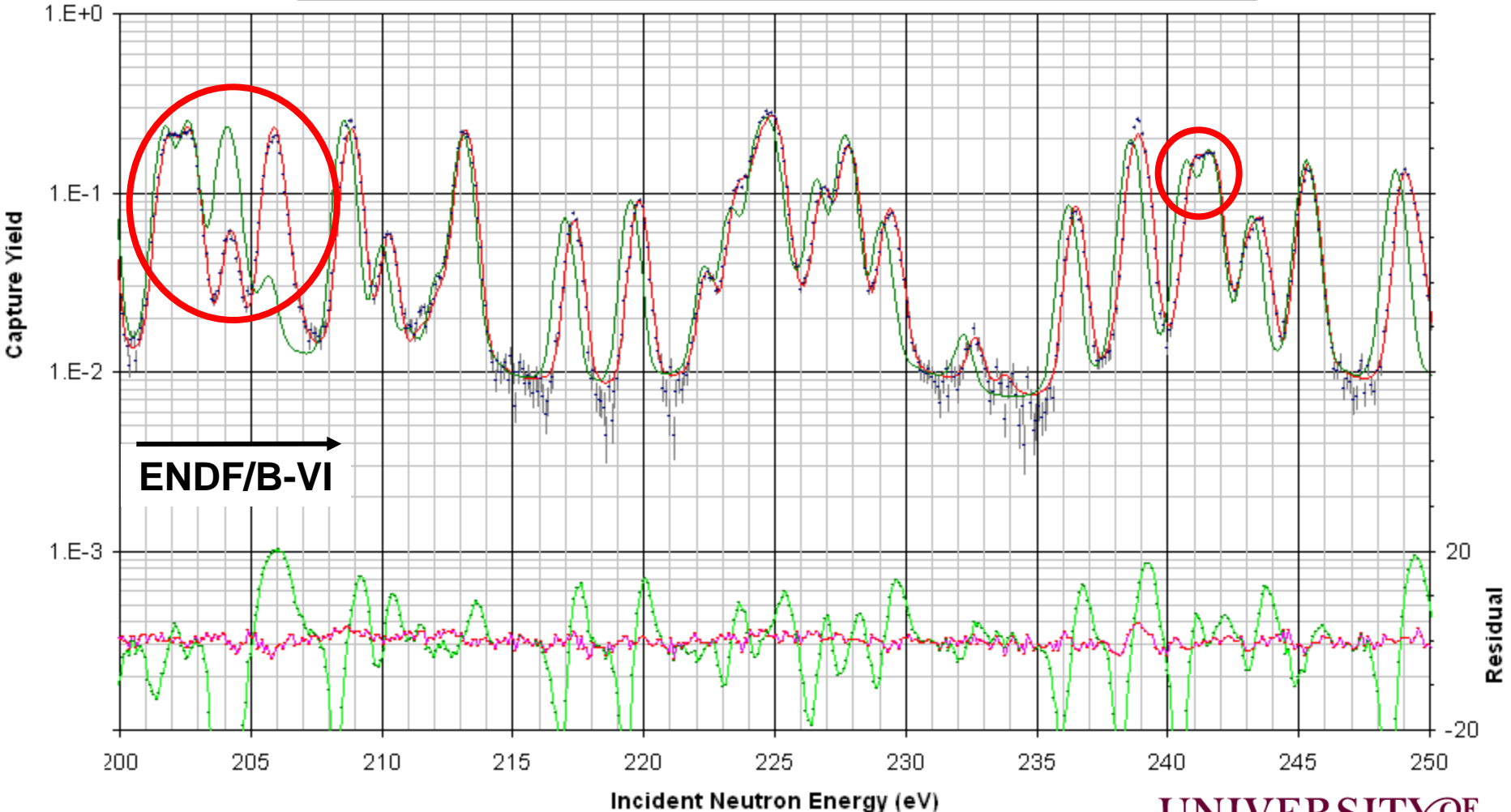
MEASURED CALC-NEW CALC-JEFF31 RES-JEFF31 RES-NEW



Calculated Yields from REFIT

Hf-nat 1mm sample @ 58m

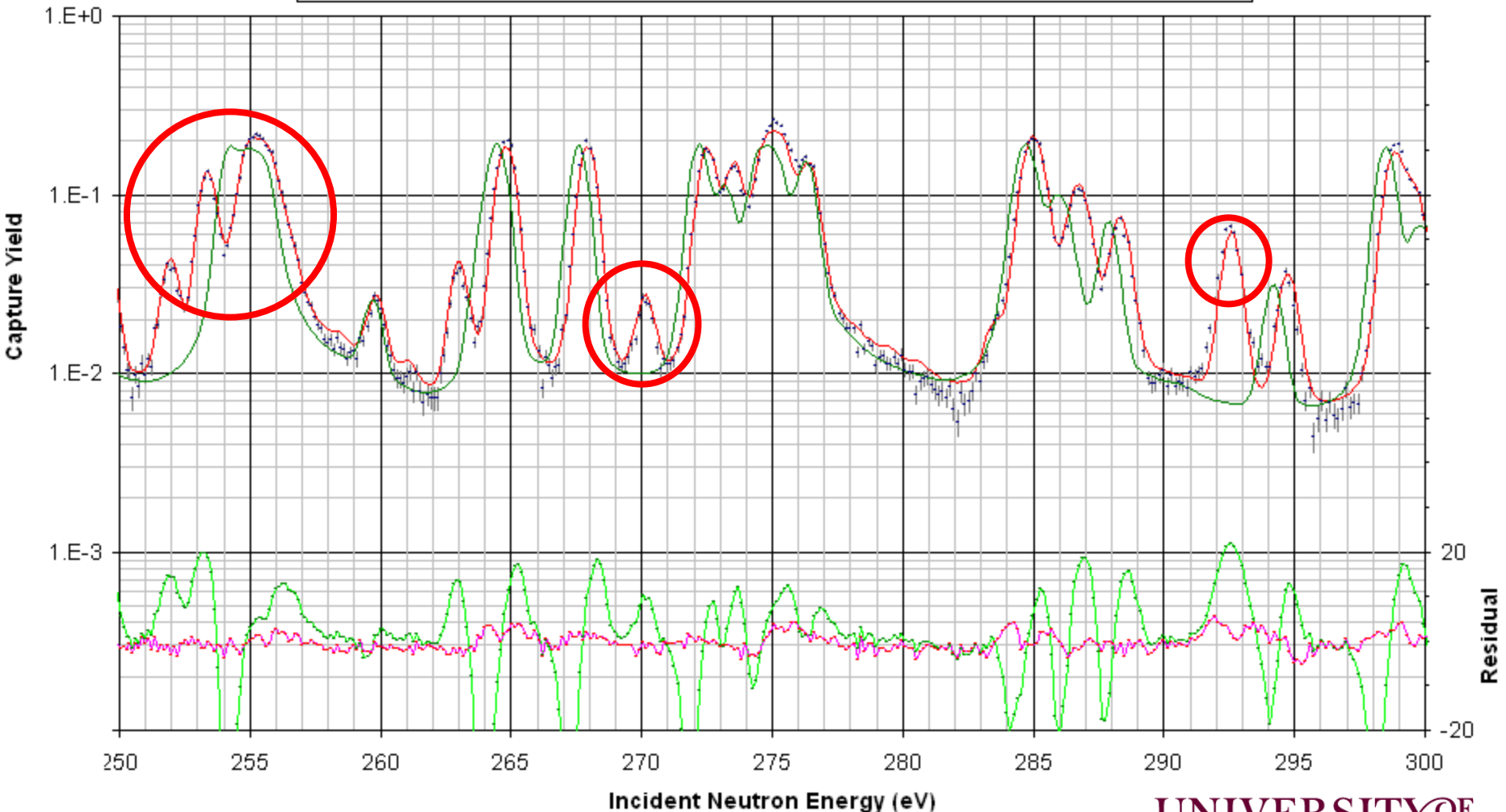
MEASURED CALC-NEW CALC-JEFF31 RES-JEFF31 RES-NEW



Calculated Yields from REFIT

Hf-nat 1mm sample @ 58m

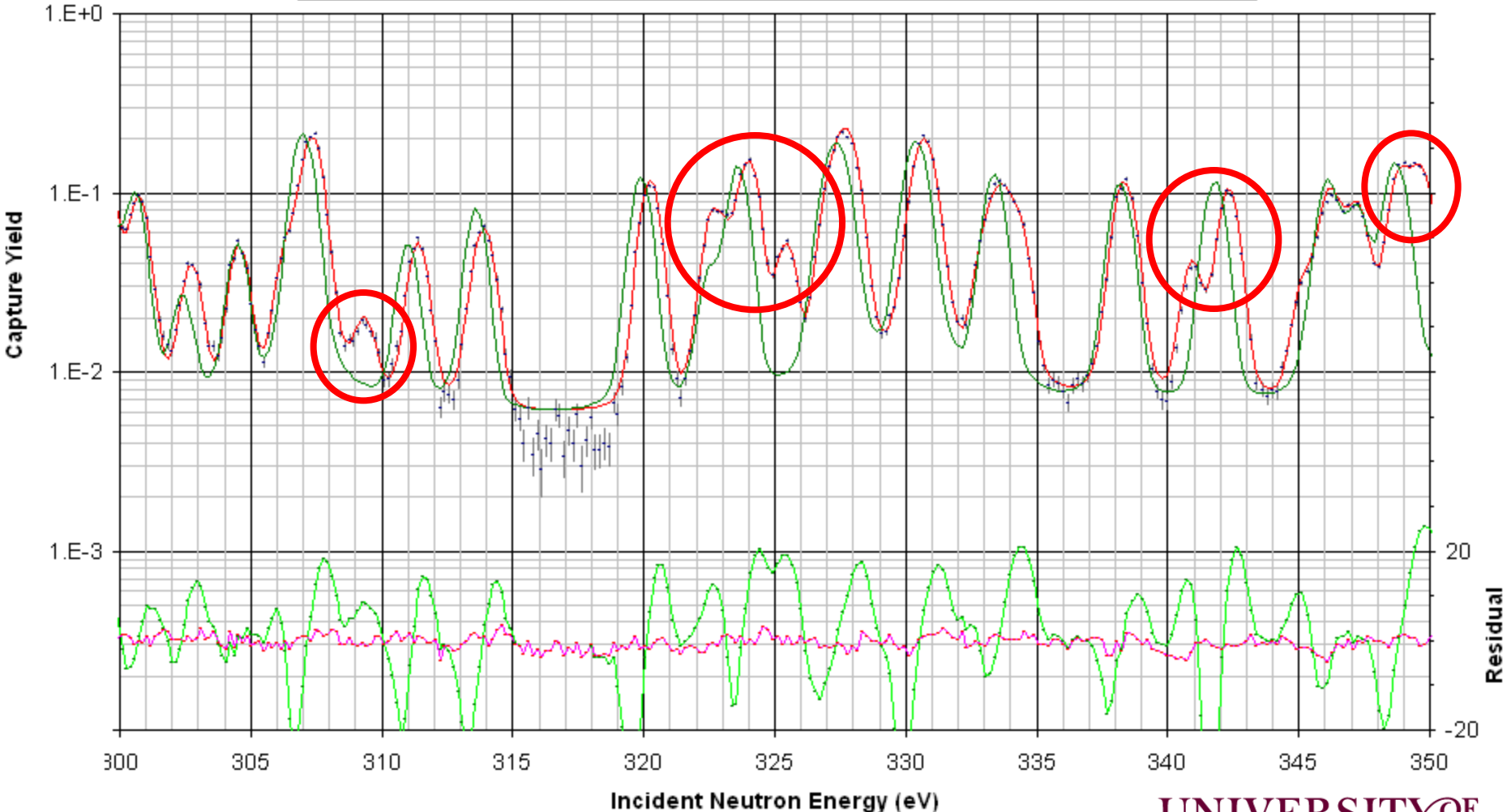
MEASURED CALC-NEW CALC-JEFF31 RES-JEFF31 RES-NEW



Calculated Yields from REFIT

Hf-nat 1mm sample @ 58m

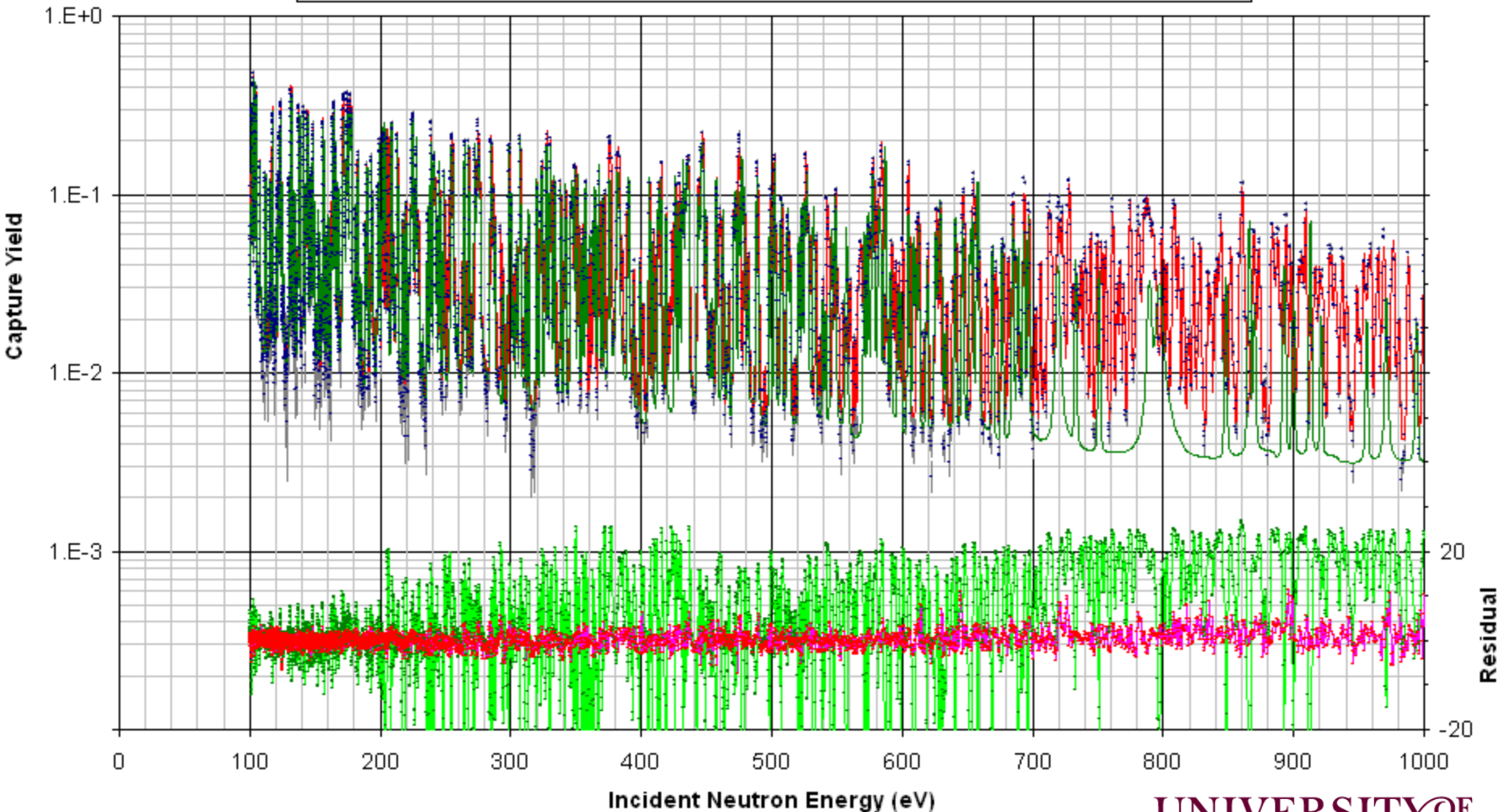
MEASURED CALC-NEW CALC-JEFF31 RES-JEFF31 RES-NEW



Calculated Yields from REFIT

Hf-nat 1mm sample @ 58m

MEASURED CALC-NEW CALC-JEFF31 RES-JEFF31 RES-NEW



Comparison with JEFF3.1 file

	RRR limit (eV)		No. of resonances in RRR	
	JEFF3.1	This work	JEFF3.1	This work
^{174}Hf	240	250	10	13
^{176}Hf	700	3000	17	72
^{177}Hf	250	1000	94	329
^{178}Hf	1500	3000	22	53
^{179}Hf	250	1000	48	217
^{180}Hf	2500	3000	14	20

Conclusions

- Work to refine parameters $< 20\text{eV}$ to be completed shortly
- Resolved resonance parameters to be passed to CEA for development of unresolved range and covariances
- Following completion of resolved analysis and testing, we recommend these parameters be included in the JEFF3.2 Hf evaluation
- Analysis will be reported in PhD thesis

Acknowledgements

- Measurements at Geel were supported by the European Commission within the NUDAME and EUFRAT projects