The Neutron Time-of-Flight Cross Section Program at the University of Kentucky

University of Kentucky
50 years

UK
1964-2014
Accelerator Laboratory

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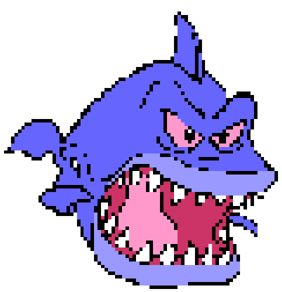
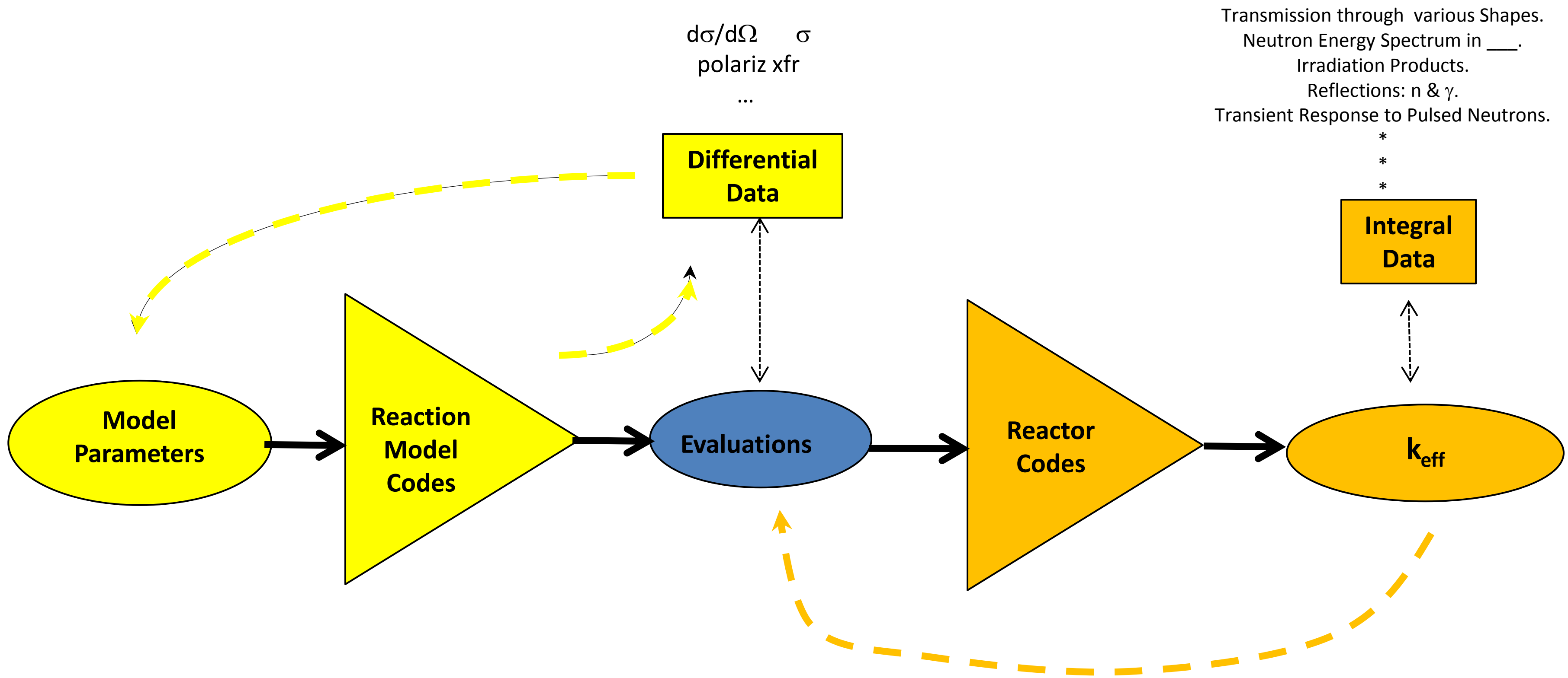
- General Intro to the Laboratory
- What is nuclear data?
- Sample results for recent ^{23}Na, ^{54}Fe, ^{nat}Fe (n,n') & (n,n'γ)
- Is there any physics in this?
- Adventures in Analysis
  - Tails and backgrounds
    - Can we understand peak shapes in a TOF spectrum?
  - Verifying the finite geometry corrections
    - What angle is the scattering sample?
- Summary

Association for Research at University Nuclear Accelerators

- “Nuclear Data” are:
  - Collection of self-consistent cross sections
  - Nuclear Reaction Model calculations guided by experimental data
  - …heavily supplemented by experimental data
  - Judged by a specific evaluation team
    - ENDF
    - JENDL
    - JEFF
  - for the evaluation team’s focus



- Consumed by:
  - Nuclear Power Industry
  - Nuclear Propulsion
  - Dosimetry & Cancer Treatment Centers
  - Nuclear Weapons
  - Physicists & Chemists



Resonance Params
Opt Model Params

<< misc processes >>

Vibration
Rotation

Ex Jpi
B(XL)
*
*
*

DWBA
Coupled Channels

EMPIRE
TALYS
ECIS
*
*
*

ENDF
JENDL
JEFF
*
*
*

MCNP
GEANT
FLUKA
*
*
*

ZEPHER
*
*
*

Mike Herman's (NNDC, BNL) view of "nuclear data"

(n,γ)

elastic

(n,n'γ)

Table 1. Cross section data needs extracted from Ref [6][a].

Target	Cross Section Type[b]	19.6-6.07 MeV (%)	6.07-2.23 MeV (%)	2.23-1.35 MeV (%)	1.35-0.50 MeV (%)	0.5-0.18 MeV (%)
		Uncertainities in Energy Regions (present/desired)				
			SFR			
56Fe	capt	40 / 21				
	el		20 / 7	10 / 7	10 / 5	10 / 4
	inel	20 / 12	15 / 6	10 / 5	20 / 4	
23Na	inel		30 / 12	30 / 13	30 / 5	
90Zr	el					20 / 14
	inel		20 / 12			
10B	capt				15 / 13	15 / 7
52Cr	el				10 / 13	10 / 8
	n,2n	100 / 17				
			VHTR			
C	scatt		35 / 12			
			PWR			
O	capt		20 / 7			
Zr	scatt		20 / 6			
			EFR			
23Na	inel		30 / 13		30 / 9	
16O	capt		20 / 12			
	el					5 / 5
56Fe	inel		15 / 7	10 / 7	20 / 9	
52Cr	n,2n	100 / 22				

[a] Reactor types are specified by the codes *SFR*=sodium-cooled fast reactor in a transuranics burning configuration, *VHTR*=very high temperature reactor, *PWR*=pressurized water reactor, and *EFR*=a SFR with recycling of the minor actinides.
[b] Cross section types are specified by the codes: *capt*=(n,g), *el*=elastic scattering (n,n), *inel*=inelastic scattering (n,n') or (n,n'g), and *scatt*=*el*+*inel*.

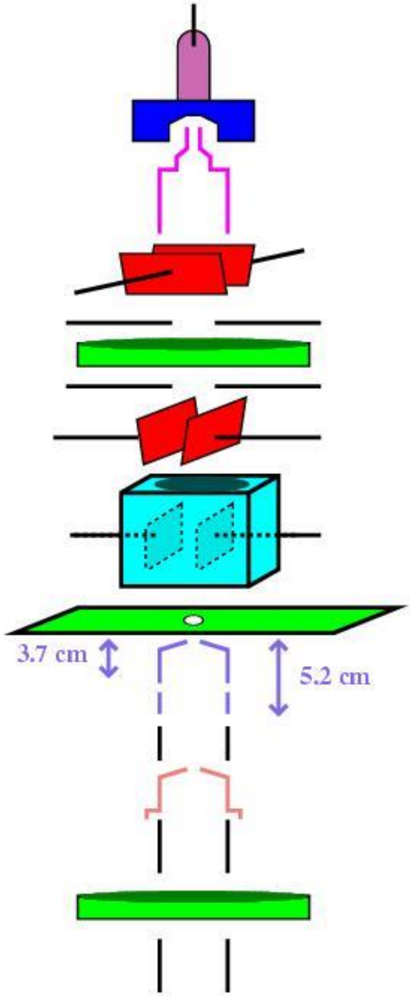
In general, many data sets exist from the 1960s-1970s, involving N_A hours of beamtime,

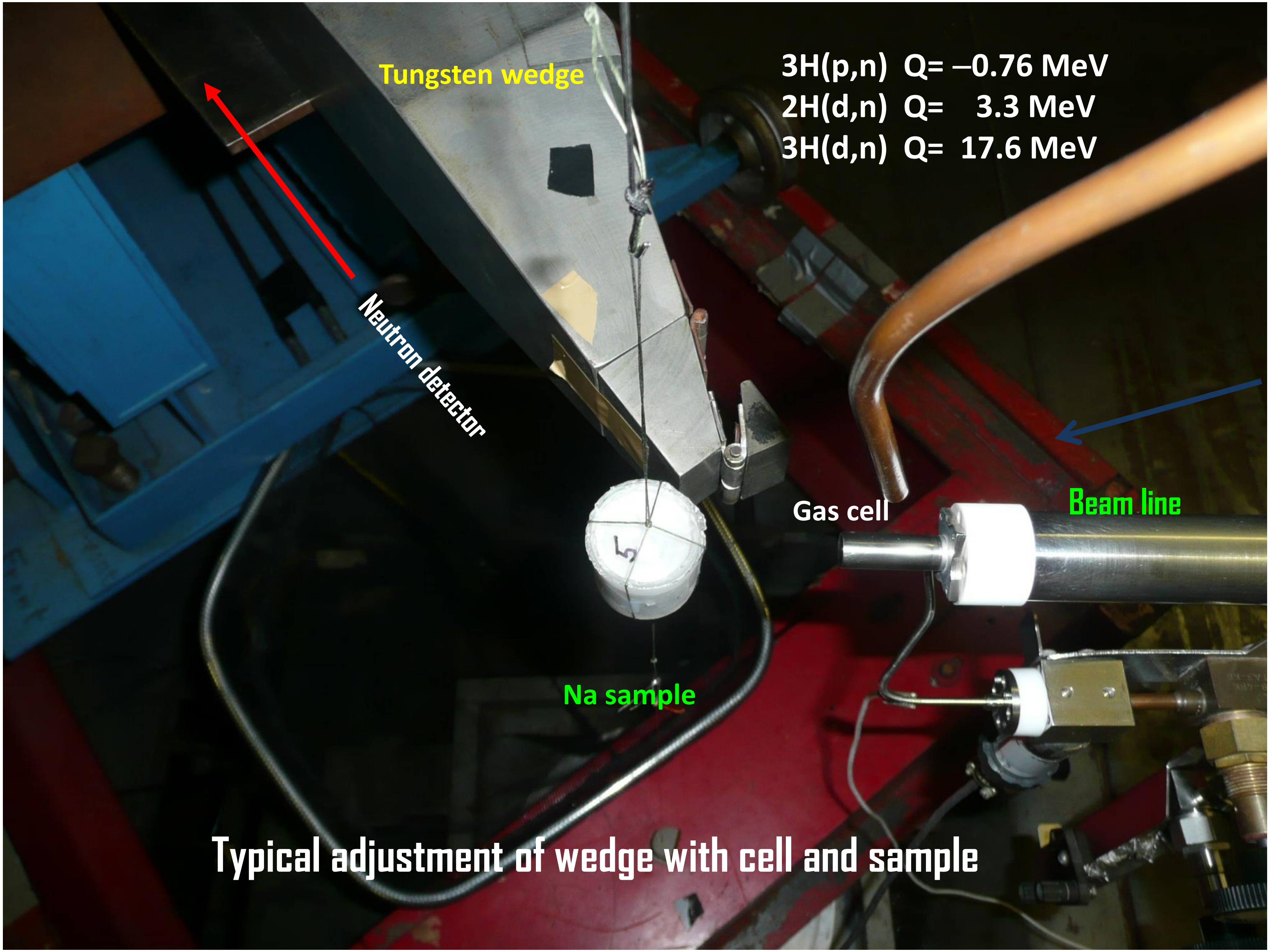
but details of spectra, analysis procedures, & correction techniques

have been lost or forgotten.

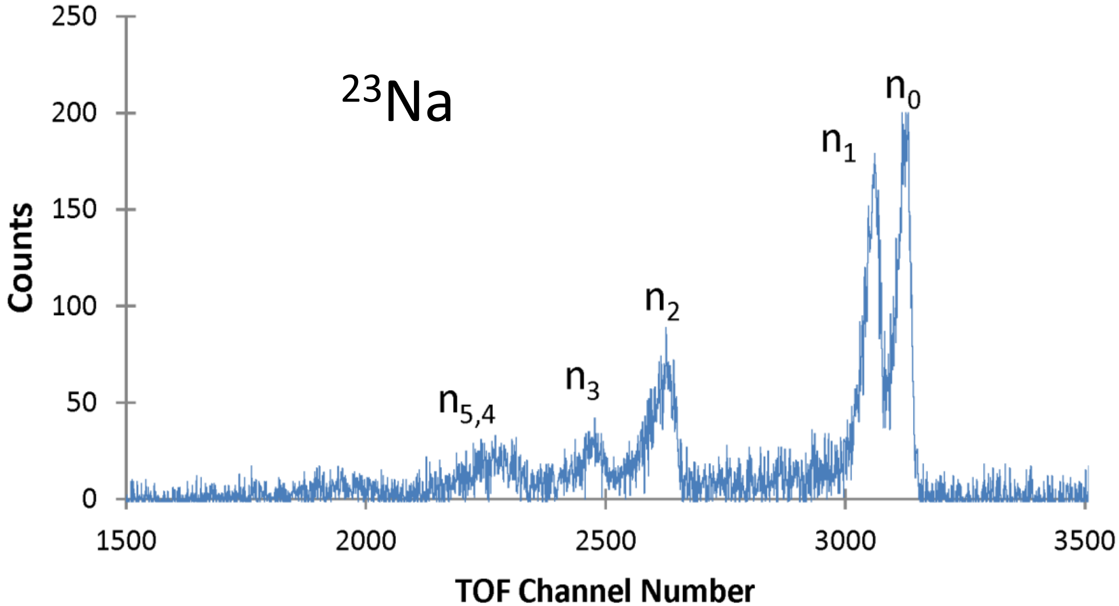
Aliberti, Ann Nucl Energy 33, 70 (2006)

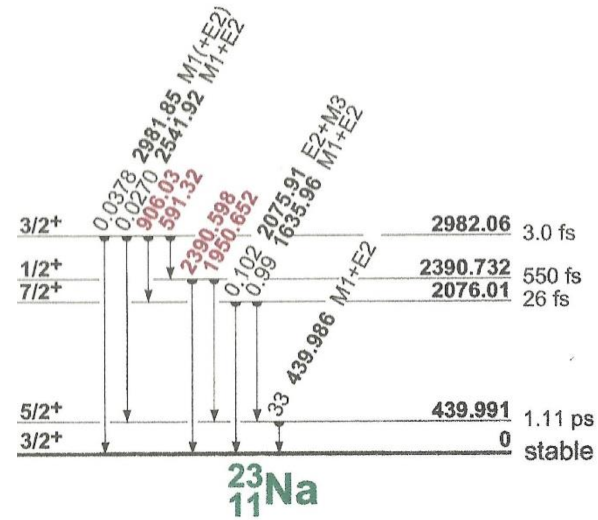
- **Accelerator**
  - HVEC Model CN: 7 MV
  - rf source
  - p, d, ^{3}He, α, … ions
  - Authorized for 3H gas targets
  - measure exit neutron energy
  - 1 ns pulse widths
- **Basic Nuclear Science**
  - Nuclear Structure via (n,n'γ)
    - Level Schemes & Transitions
    - Spectroscopic Information
    - DSAM Lifetimes
  - (3He,nγ)
- **Applied Nuclear Science**
  - Differential (n,n') Cross Sections
    - ^{23}Na, ^{54}Fe, ^{56}Fe
  - Detector Development
    - Univ Guelph
    - Univ Mass @ Lowell
    - RMD




Tungsten wedge
3H(p,n) Q= –0.76 MeV
2H(d,n) Q= 3.3 MeV
3H(d,n) Q= 17.6 MeV
Neutron detector
Gas cell
Beam line
Na sample
Typical adjustment of wedge with cell and sample

n TOF Spectrum





Sample of Interest

Small polyethylene
Big polyethylene
<blank>

Carbon
<natFe>

flight time
from ‘target’ to detector

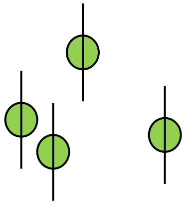
(n,n) Data Analysis, Simplified

All ya gotta do is,,,,,

$$\frac{{}^{ds}\!/_{d\Omega}}{{}^{ds}\!/_{d\Omega\, ref}} = \frac{Yield / I_o \quad / N \quad / d\Omega}{Yield_{ref} / I_{o,ref} \quad / N_{ref} \quad / d\Omega_{ref}}$$

H(n,n)

- Appropriately strip peak yields
- Neutron detector efficiency
  fn($E_{scattered}$)
- Drifts or shifts in monitor detectors
- Subtract sample-out backgrounds
  appropriately
- Properly account for Divergent
  n-beam illumination
- Sample dimensions
- Sample shape
- neutron attenuation in samples
- neutron multiple scattering in samples
- Solid angle x-form cm ←→ lab
- γ-rays: γ-ray feeding
- γ-ray absorption
- Accuracy of reference standards



Uncertainties

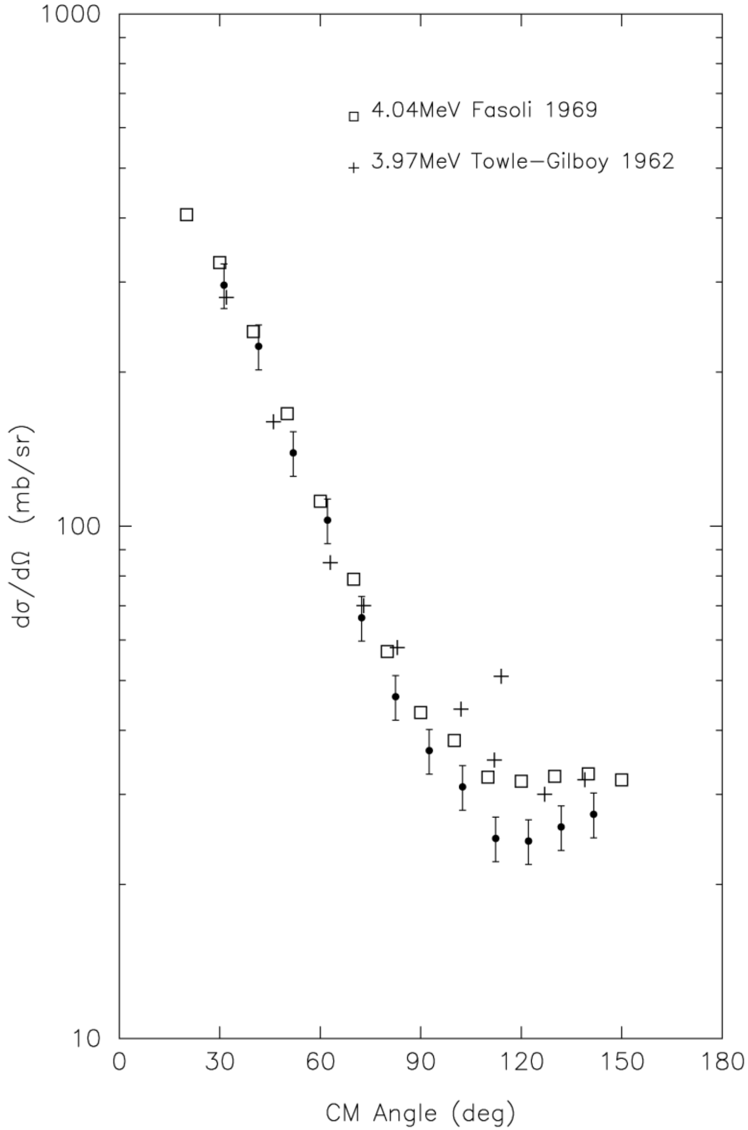
Issue	
Counting Statistics n_0, n_1	<1%
Ability to Extract Yield from Peaks in Spectra (elas)	~1-2% usually …hum
Ability to Extract Yield from Peaks in Spectra (inel)	…hum
Monitoring Neutron Production	<1%
Sample Mass	<<1%
H(n,n) reference XS	<0.5%
Detector Efficiency	
3H(p,n) $d\sigma/d\Omega$	~3%

Issue	
Atten & Mult Scat	
$n\sigma$	0.3 %
sample radius	0.3 %
sample-Tcell dist	0.2 %
method	<5% …hum

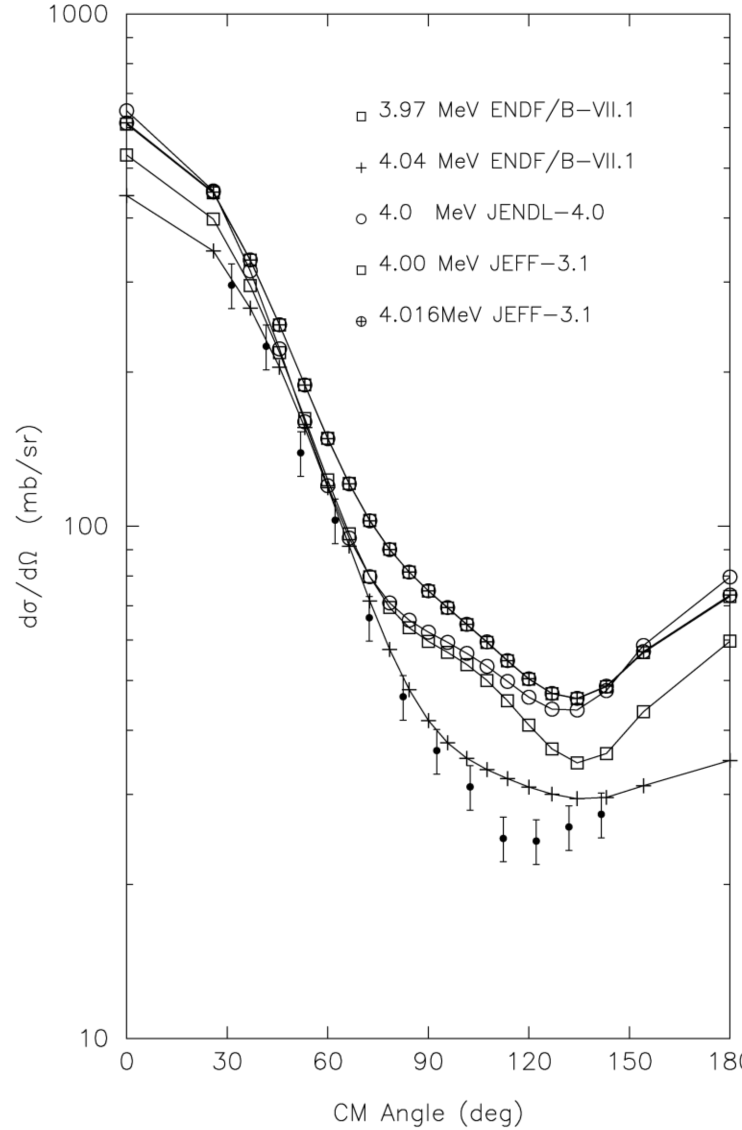
Overall during 23Na runs: elastics ~8-10%
inelastics ~13-18%

23Na(n,n) E_n = 4.00 MeV

Comparison to *real* exptl data



Comparison to "databases"

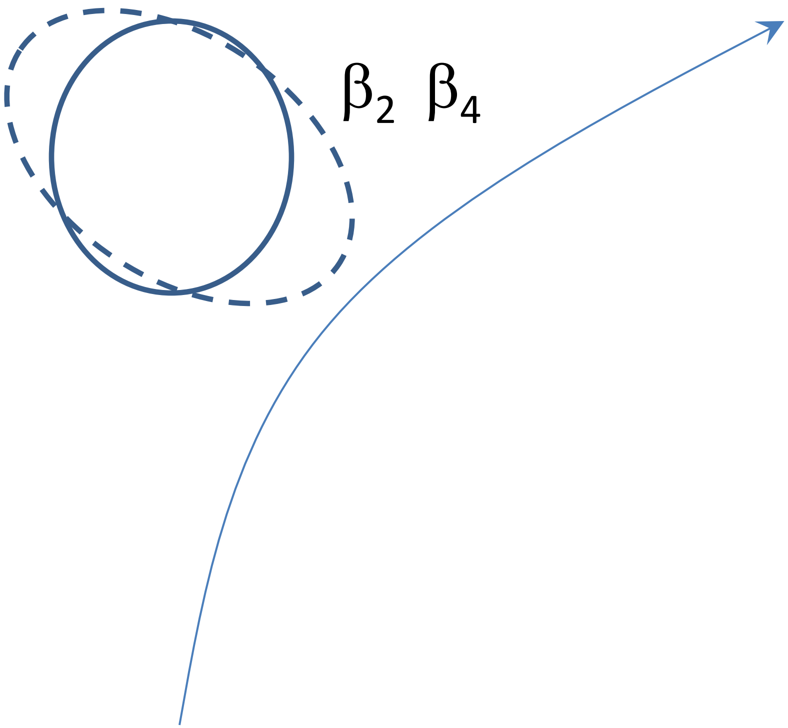


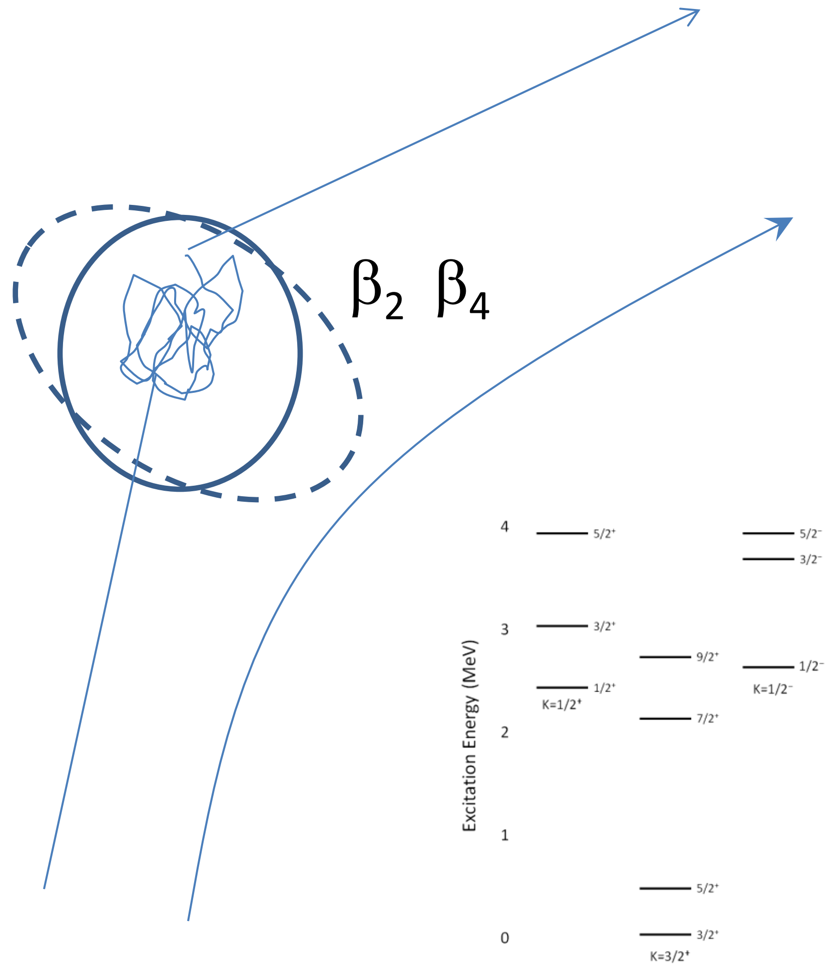
Where's the Physics?

Scattering in the Coulomb Field (*sub-Barrier* height)

VS

Scattering in the n-A Potential Field





Quick Reaction Models

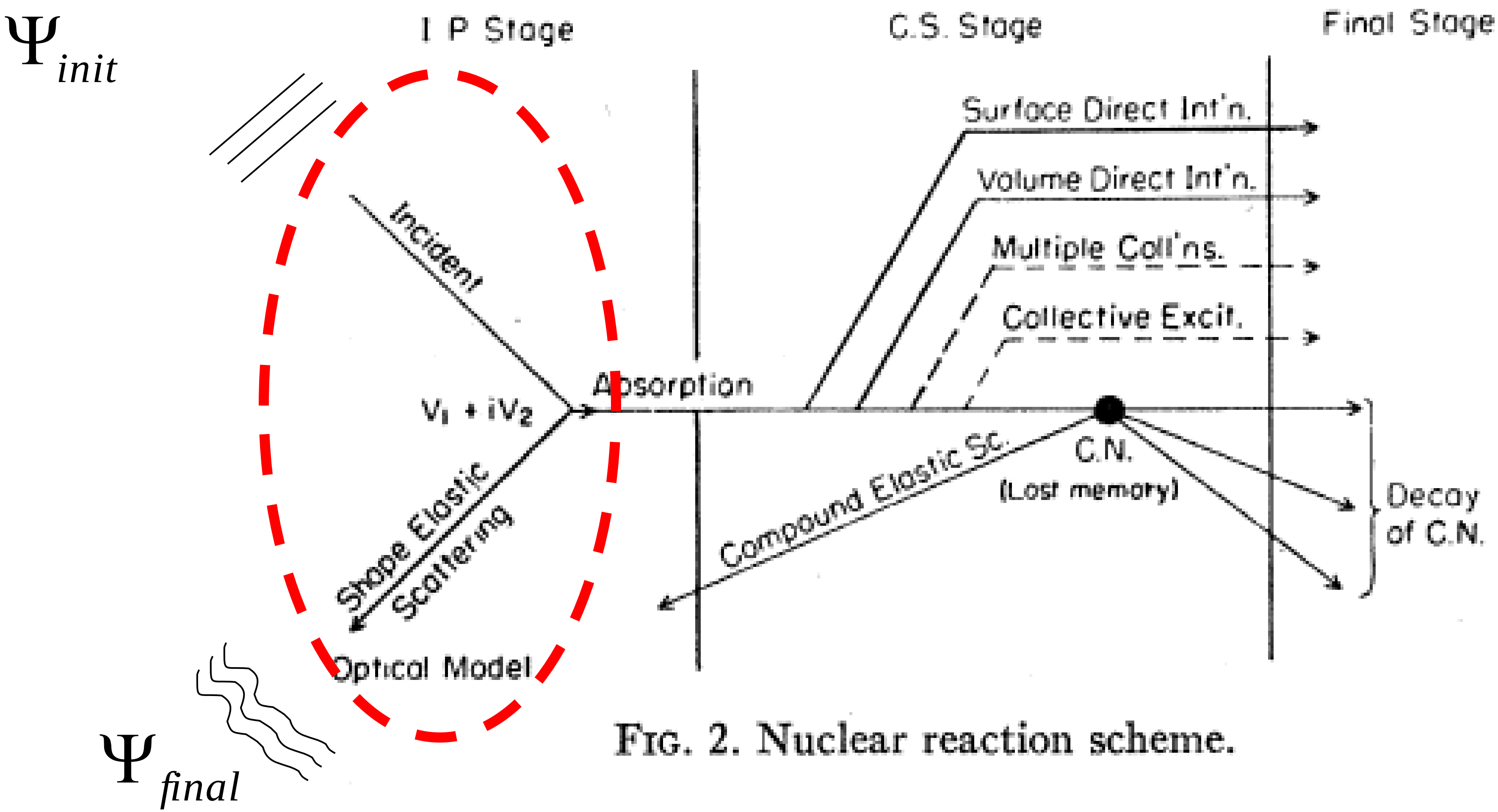


FIG. 2. Nuclear reaction scheme.

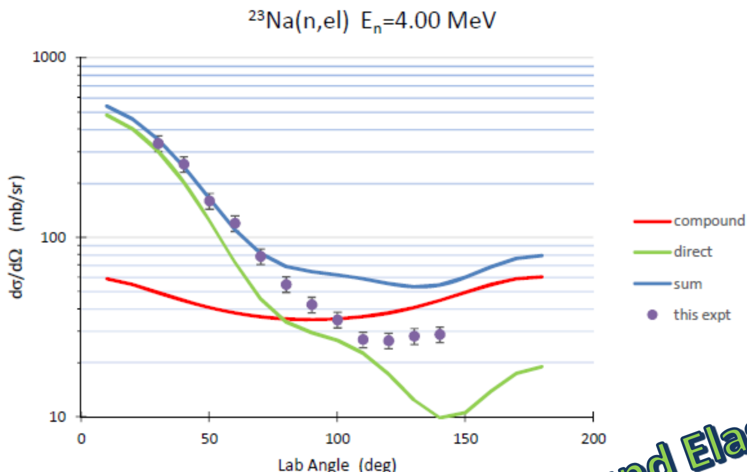
Weisskopf, Reviews of Modern Physics, 29, 174 (1957)

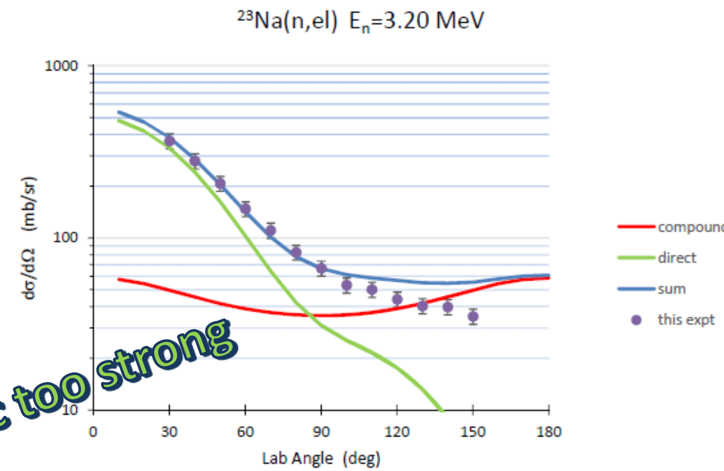
$$\frac{d\sigma}{d\Omega}$$

$^{23}Na(n,n)$

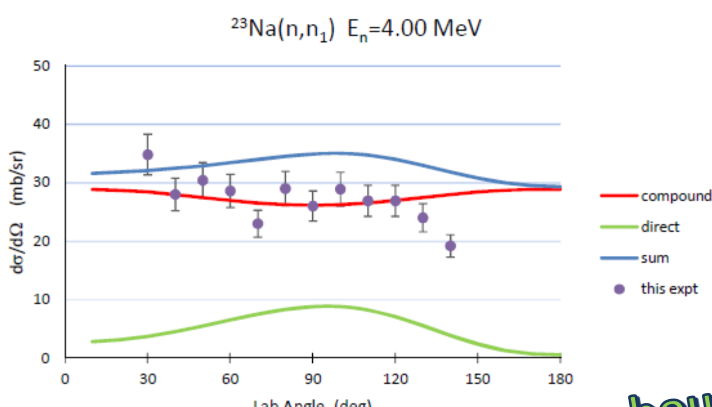
comparison to
"best available"
model calculations
Strohmaier, Ann Nucl Energy 20, 533 (1993)

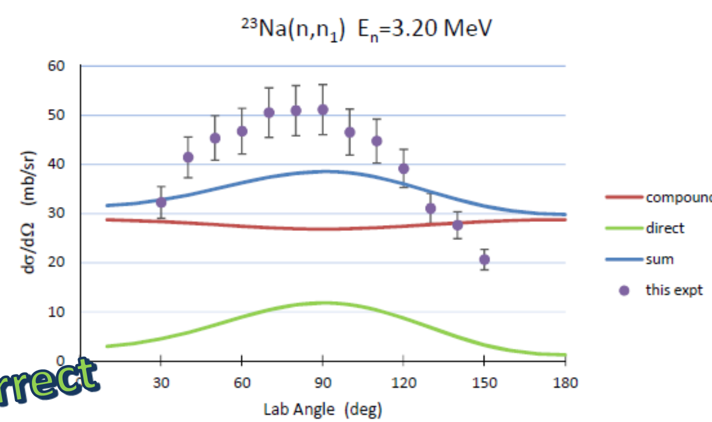
ECIS06 Calculations



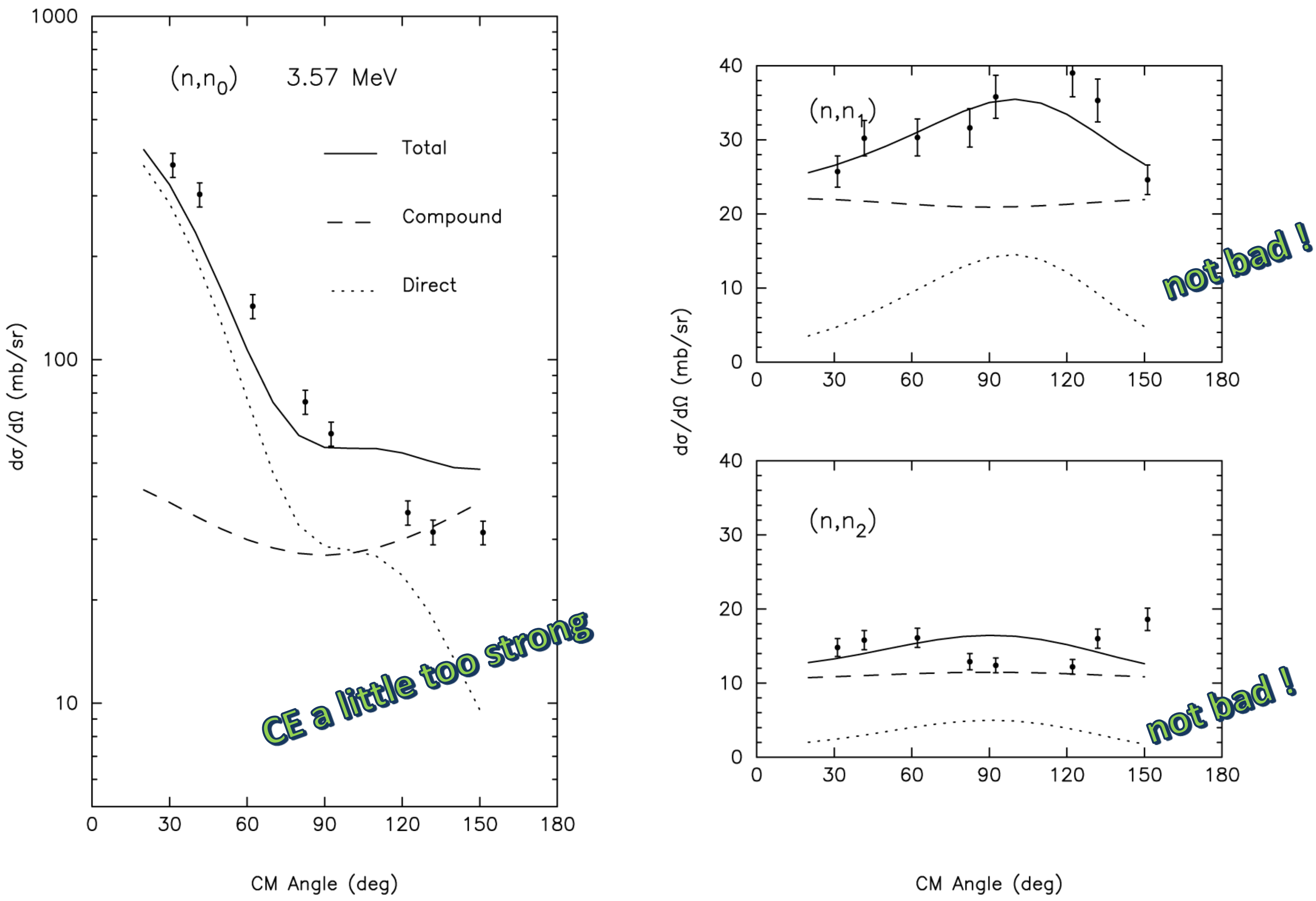


Compound Elastic too strong

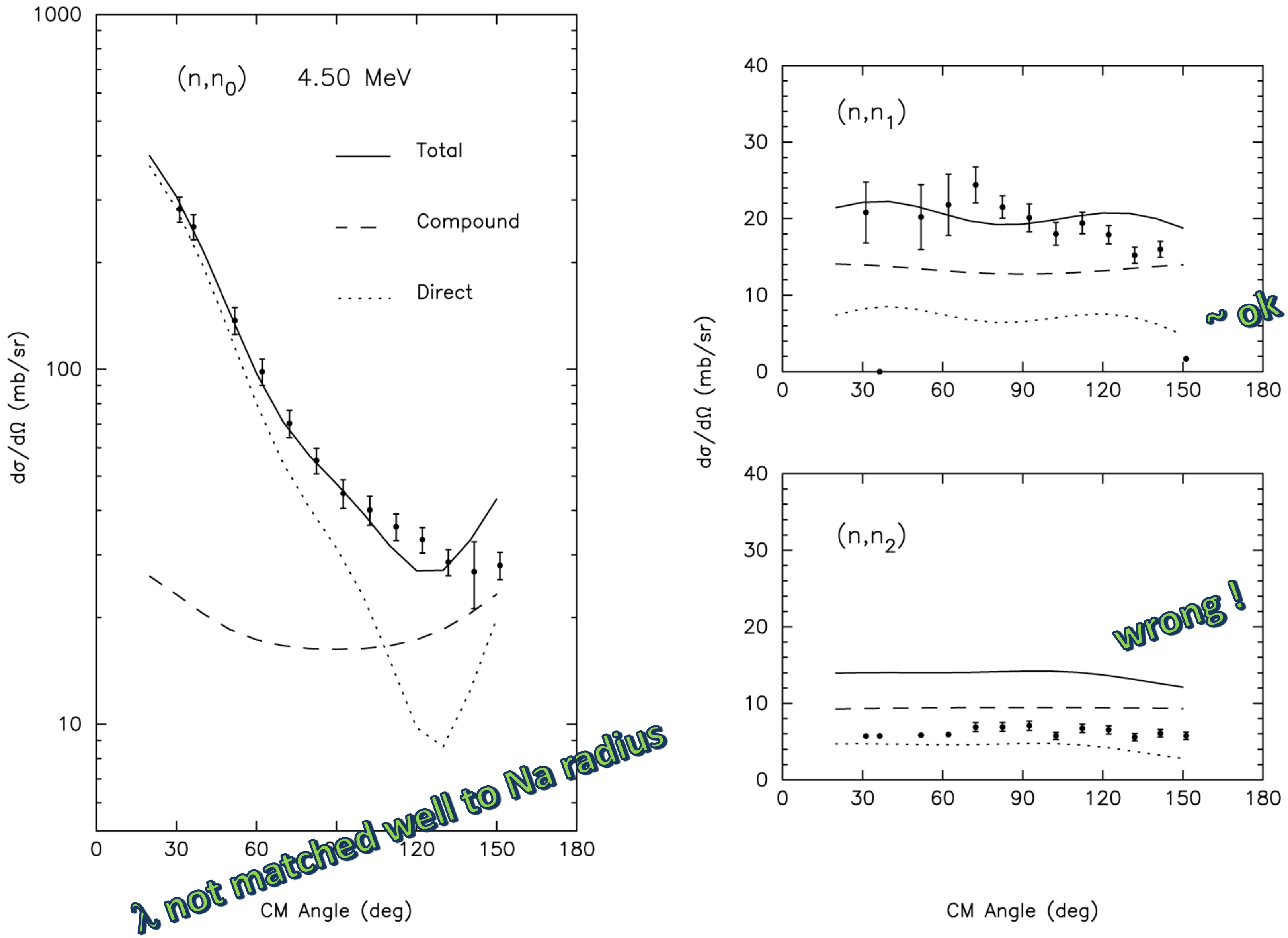




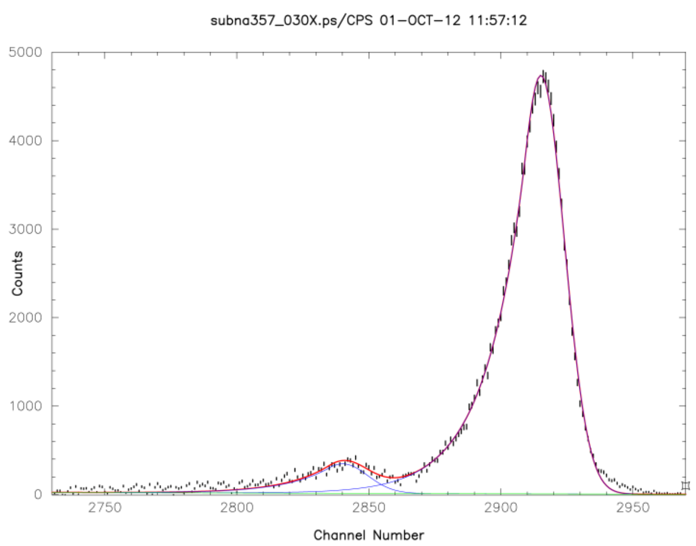
n_1 just about correct



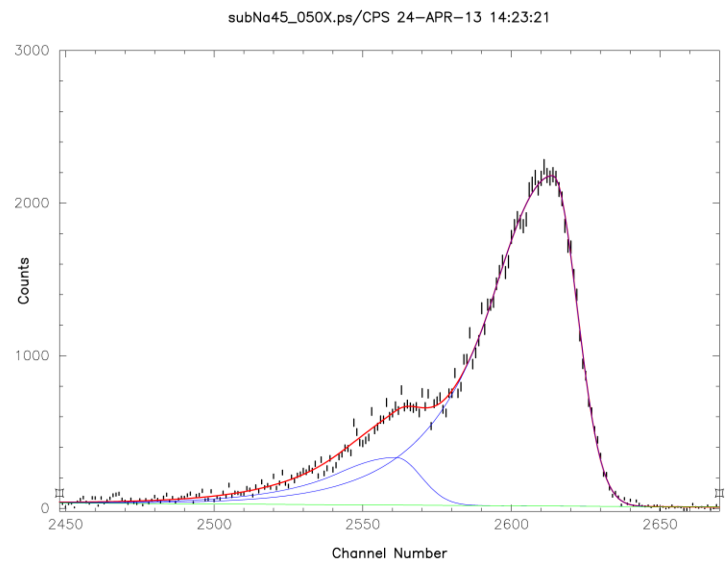
(n,n0) 3.57 MeV
Total
Compound
Direct
dσ/dΩ (mb/sr)
CM Angle (deg)
CE a little too strong
(n,n1)
not bad !
(n,n2)
not bad !
dσ/dΩ (mb/sr)
CM Angle (deg)


(n,n$_0$) 4.50 MeV
Total
Compound
Direct
dσ/dΩ (mb/sr)
CM Angle (deg)
λ not matched well to Na radius
(n,n$_1$)
~ ok
(n,n$_2$)
wrong !
dσ/dΩ (mb/sr)
CM Angle (deg)

3.57 MeV 30 deg



4.5 MeV 50 deg



ADVENTURES IN ANALYSIS
-- TAILS, TAILS, TAILS or are they?

Tails -- hard to know what is correct.

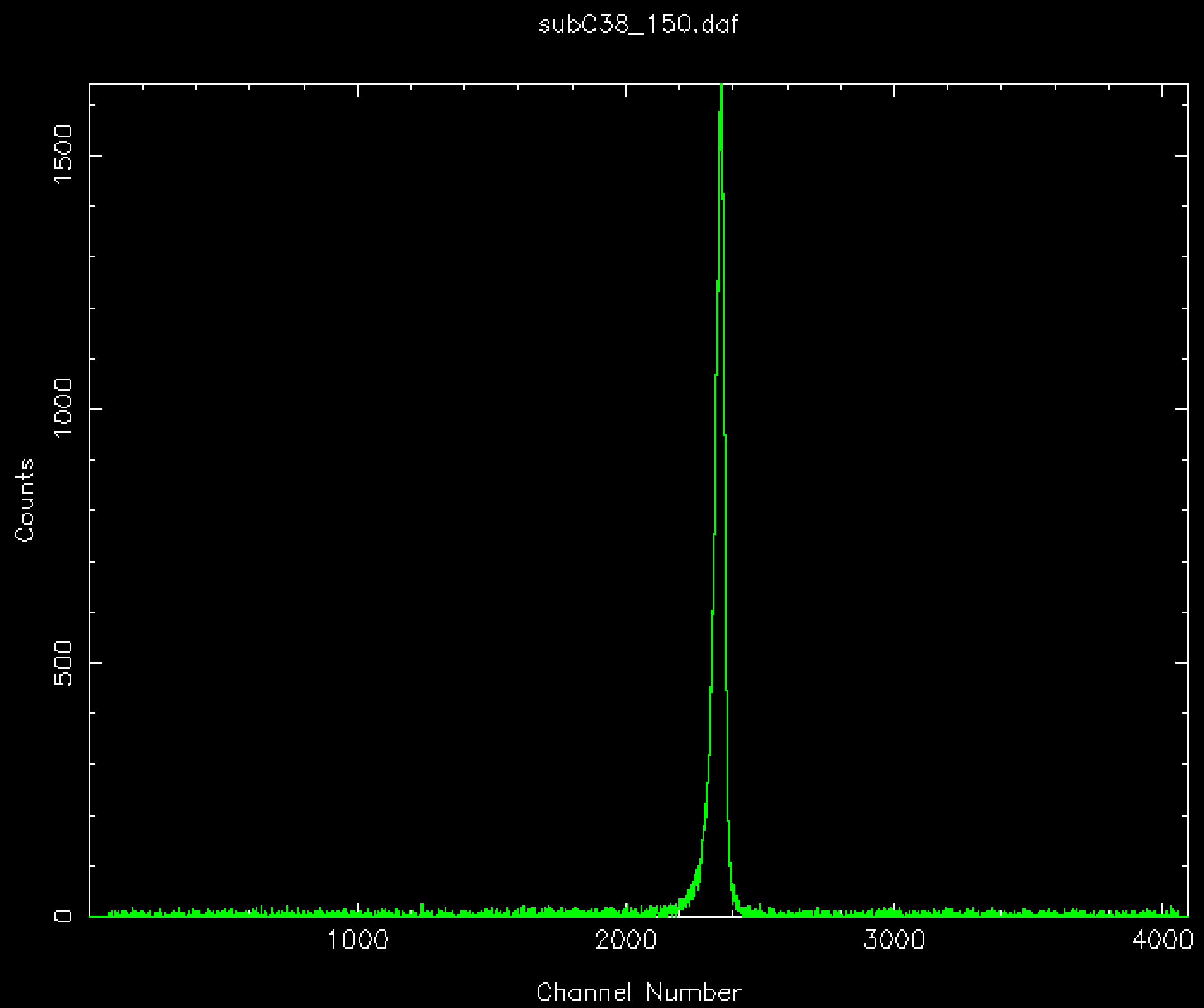
How can we eliminate tails?

  beam pulse tuning?

Our carbon $d\sigma/d\Omega$ ‘feel’ low at 70-90 deg

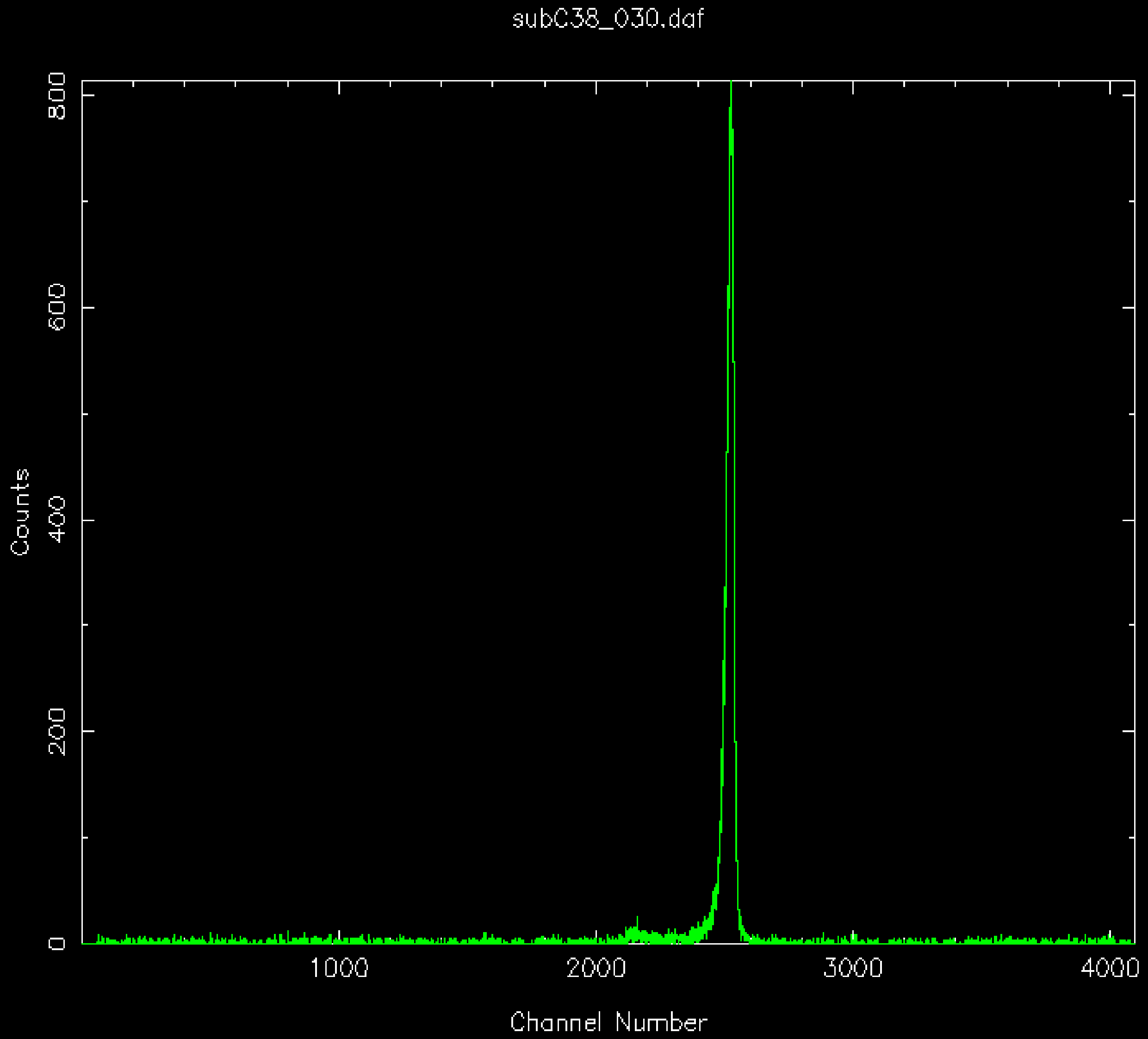
3.8 MeV 150 deg

TOF spectra on C



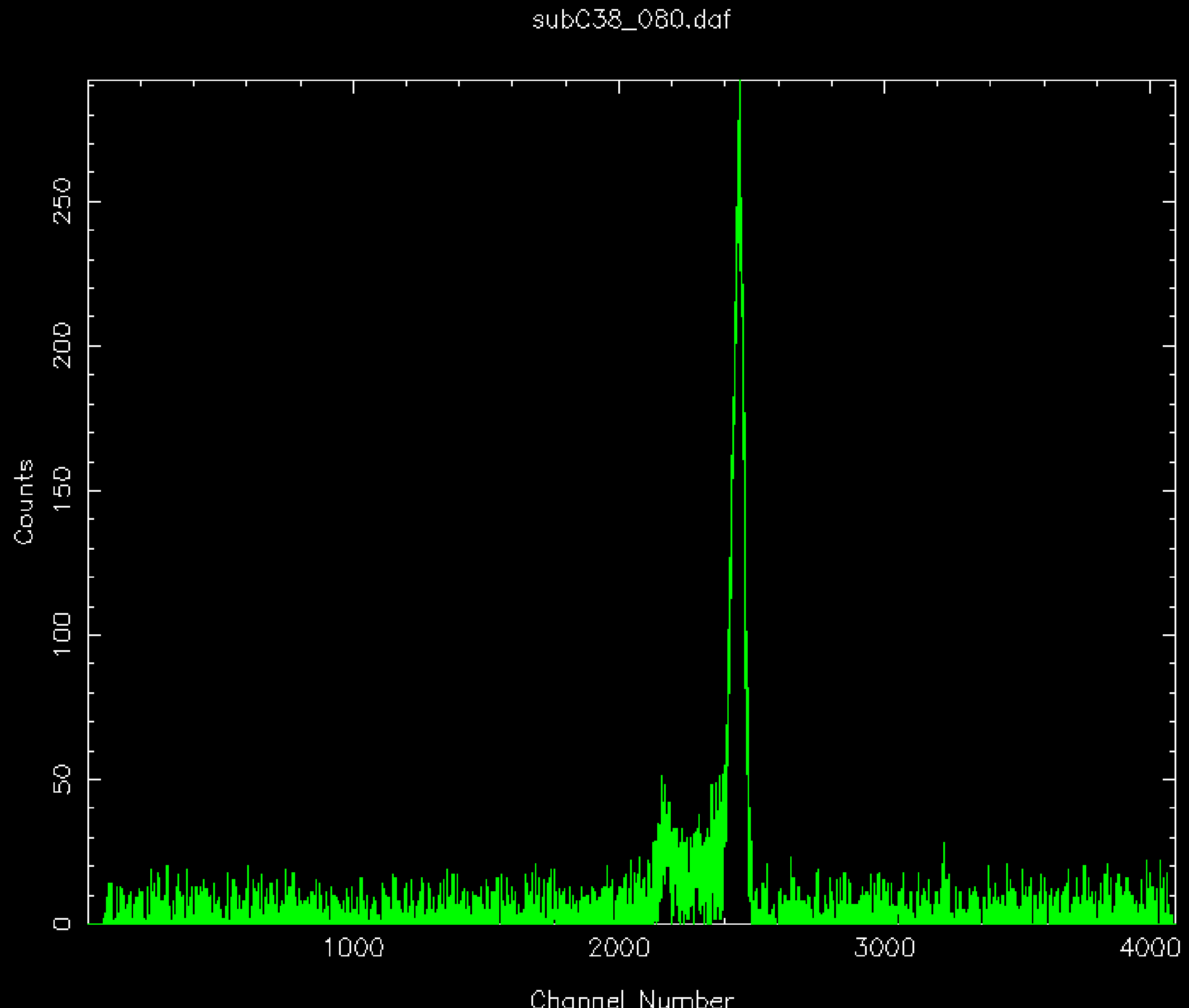
3.8 MeV 30 deg

TOF spectra on C

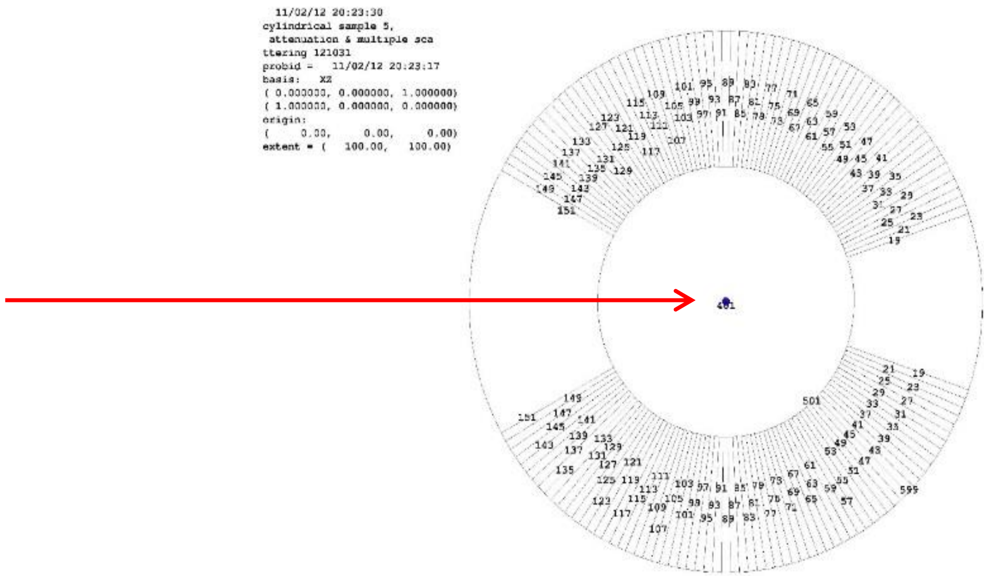


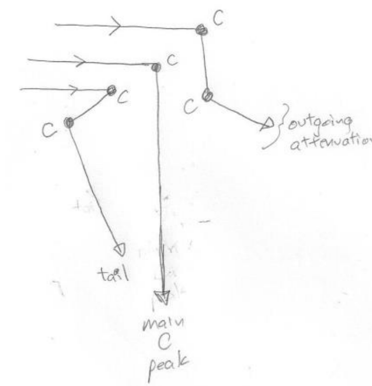
3.8 MeV   80 deg

TOF spectra on C



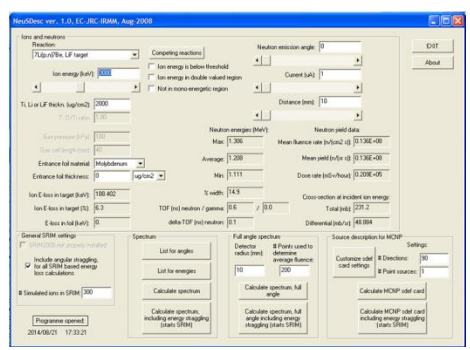
TAILS, TAILS, TAILS,…



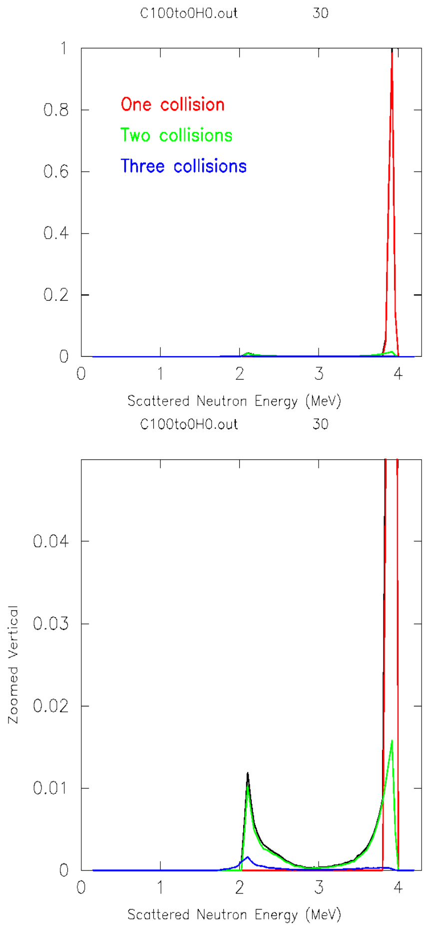


Simulate events in the Carbon sample with MCNP

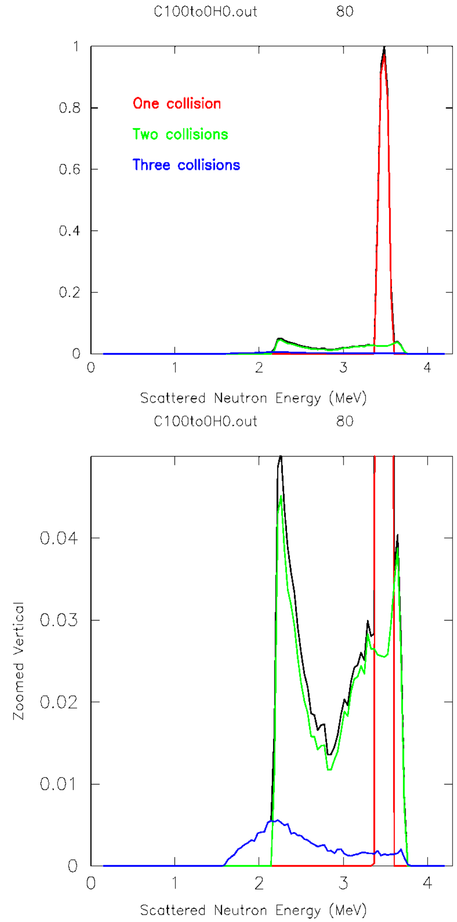
‘realistic’ neutron source: NeuSDesc from JRC



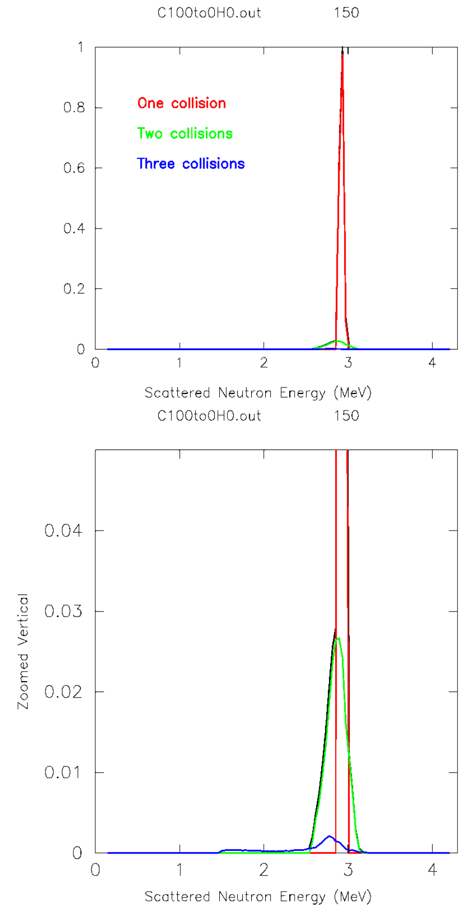
30 deg



80 deg

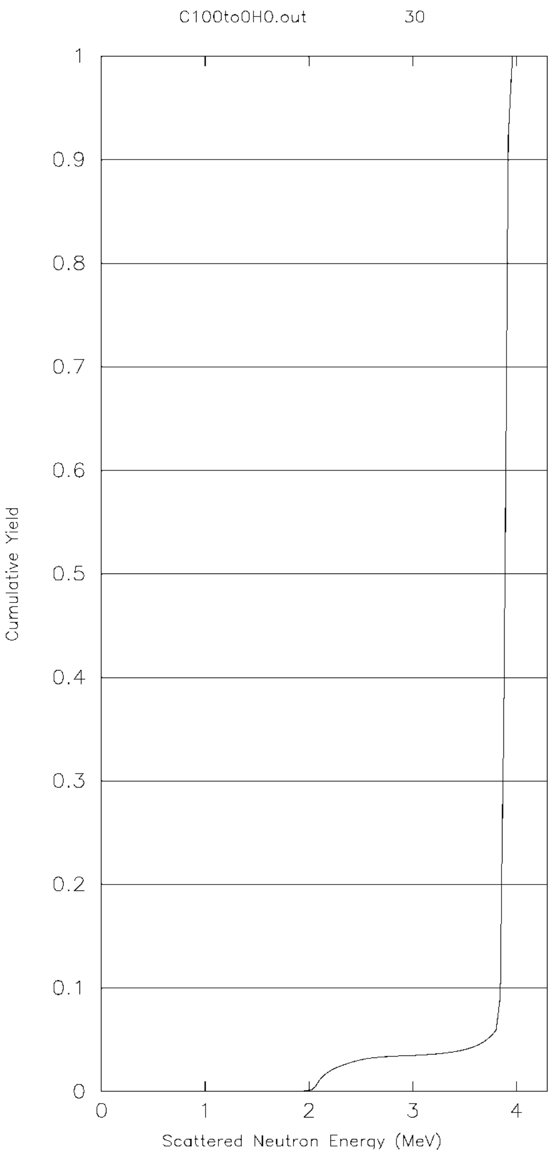


150 deg

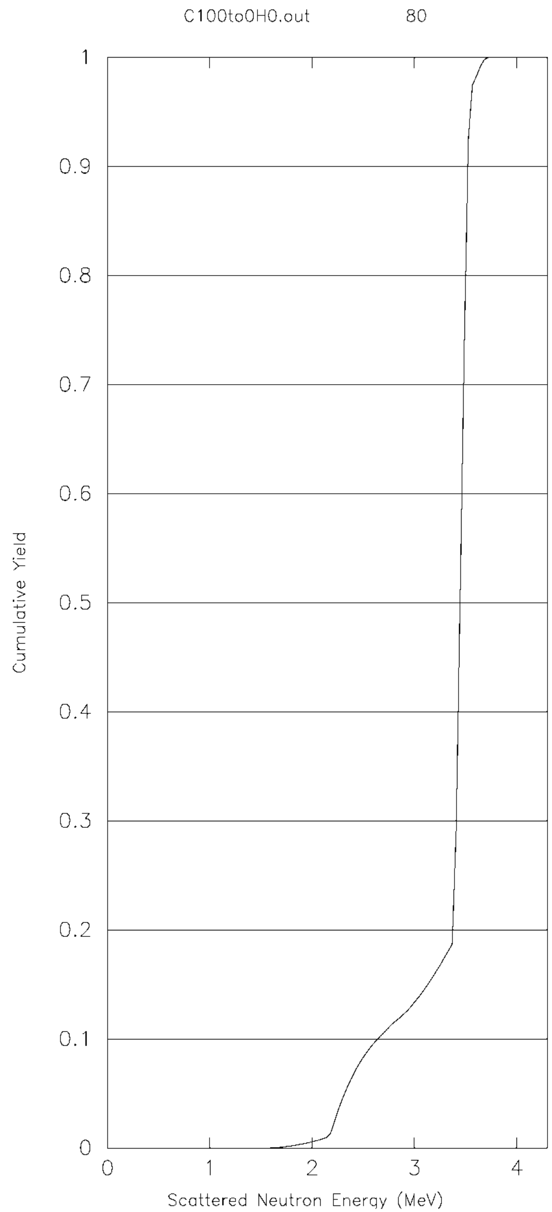


Carbon En=3.8 MeV

30 deg



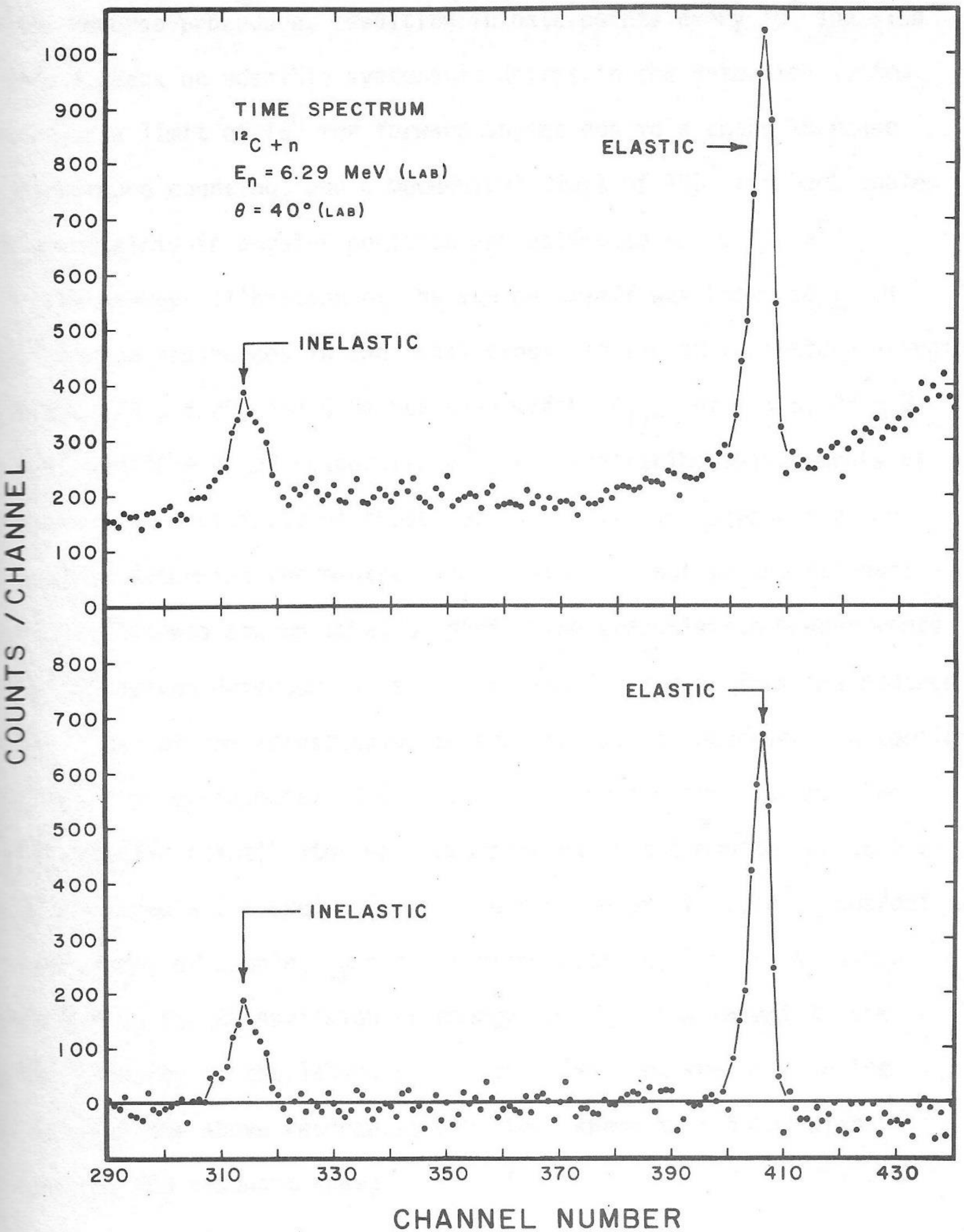
80 deg



$$\int_0^E spectrum \, \mathrm{dE}$$

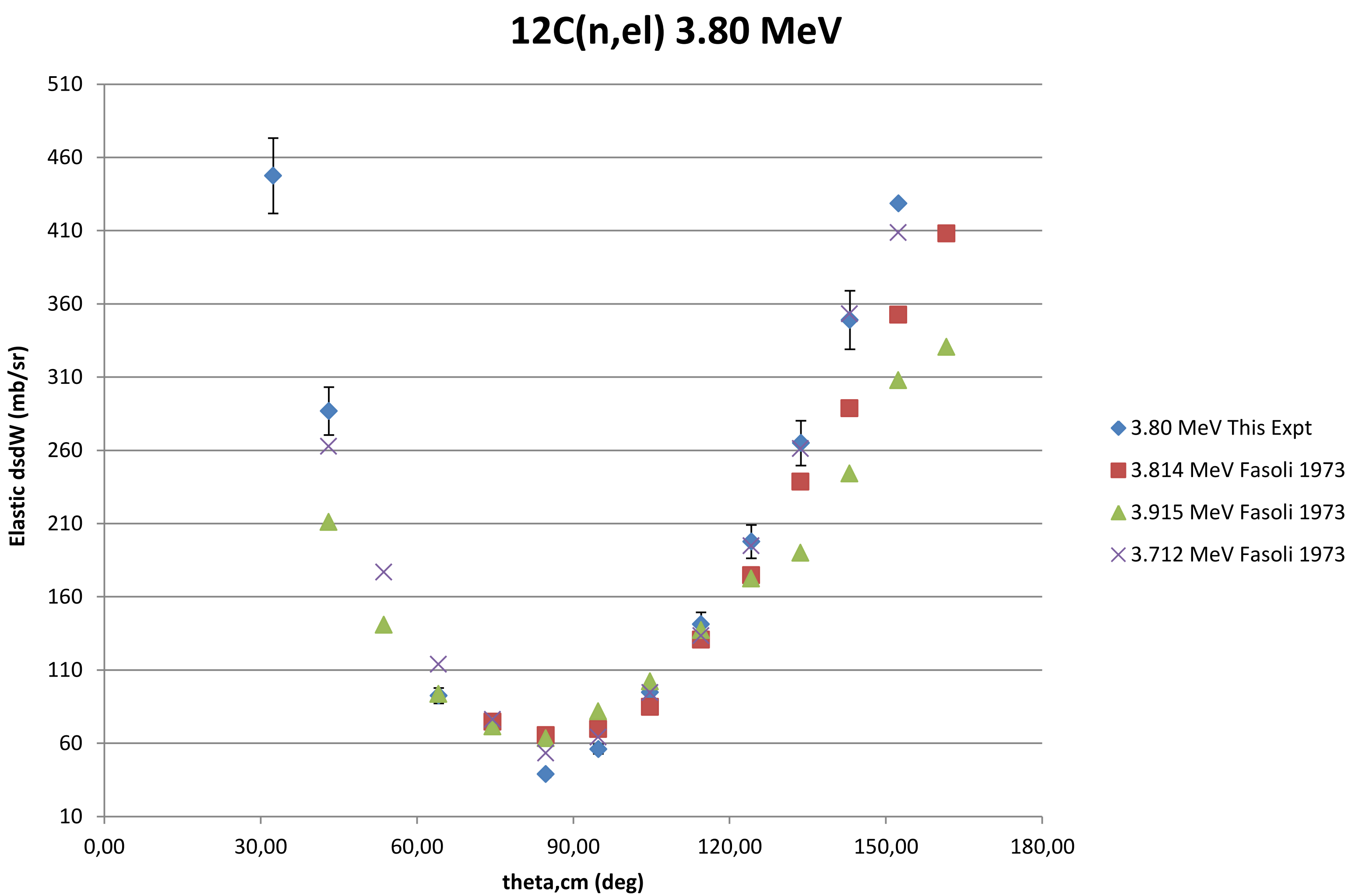
Carbon

E_n=3.8 MeV

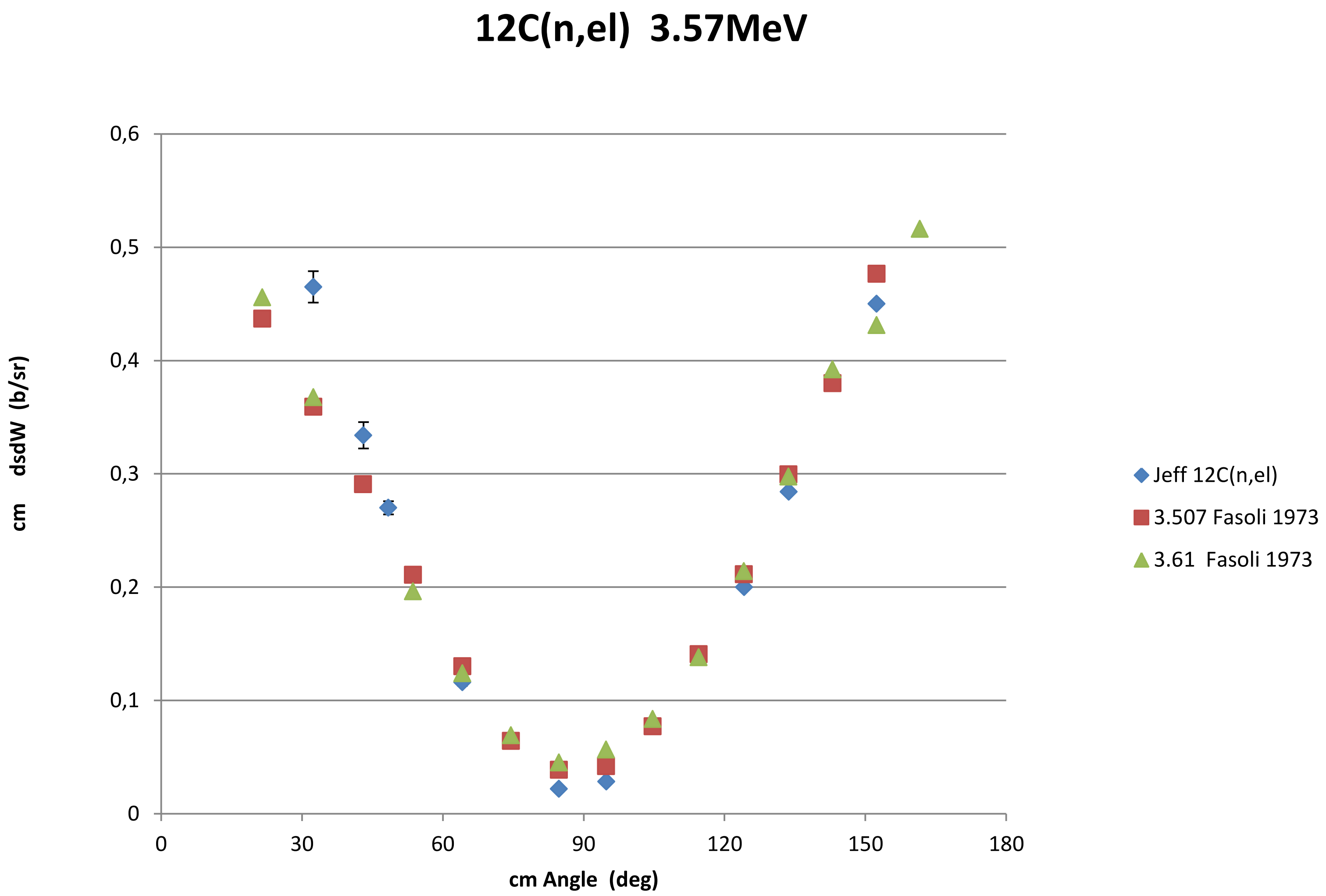


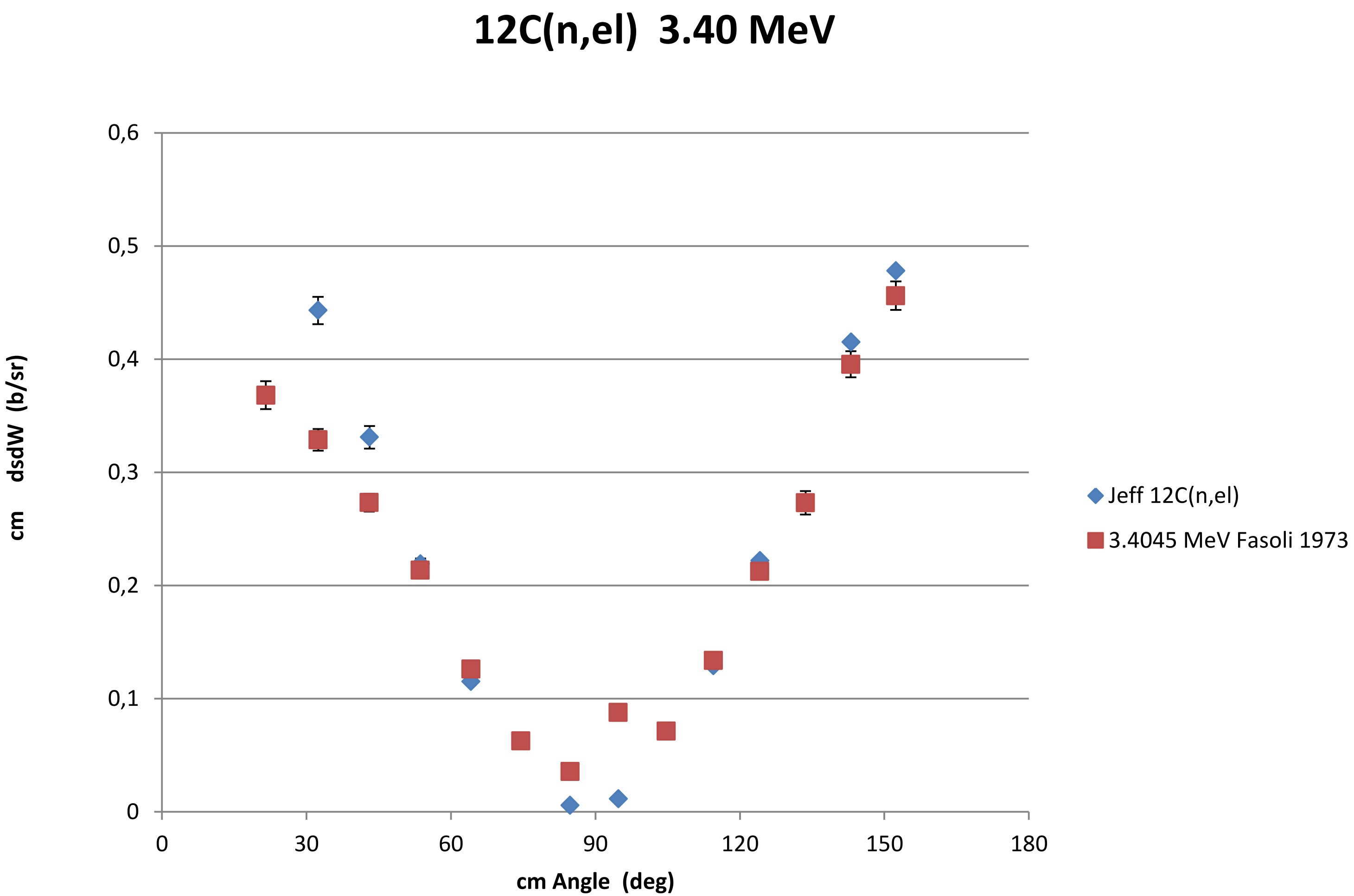
Galati Thesis 1969

Fig 4. TOF spectrum for 6.29 MeV neutrons scattered from carbon. The flight path was 1.7 meters. The time calibration was 0.51 ns/channel.

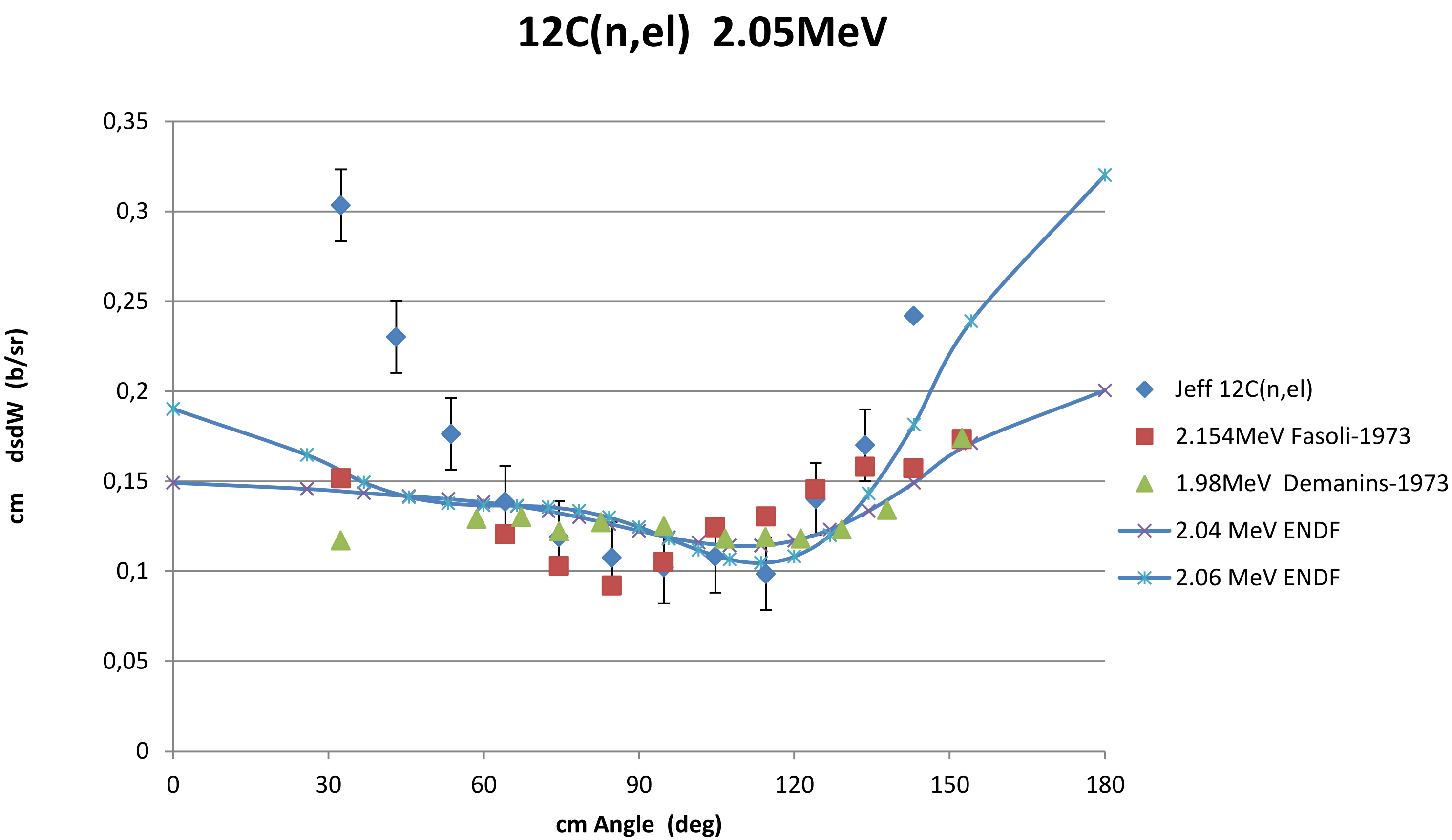


12C(n,el) 3.80 MeV
510
460
410
360
310
260
210
160
110
60
10
Elastic dsdW (mb/sr)
0,00
30,00
60,00
90,00
120,00
150,00
180,00
theta,cm (deg)
3.80 MeV This Expt
3.814 MeV Fasoli 1973
3.915 MeV Fasoli 1973
3.712 MeV Fasoli 1973


12C(n,el) 3.57MeV
cm dsdW (b/sr)
0,6
0,5
0,4
0,3
0,2
0,1
0
0
30
60
90
120
150
180
cm Angle (deg)
Jeff 12C(n,el)
3.507 Fasoli 1973
3.61 Fasoli 1973



12C(n,el) 3.40 MeV
0,6
0,5
0,4
0,3
0,2
0,1
0
0
30
60
90
120
150
180
cm Angle (deg)
cm dsdW (b/sr)
Jeff 12C(n,el)
3.4045 MeV Fasoli 1973

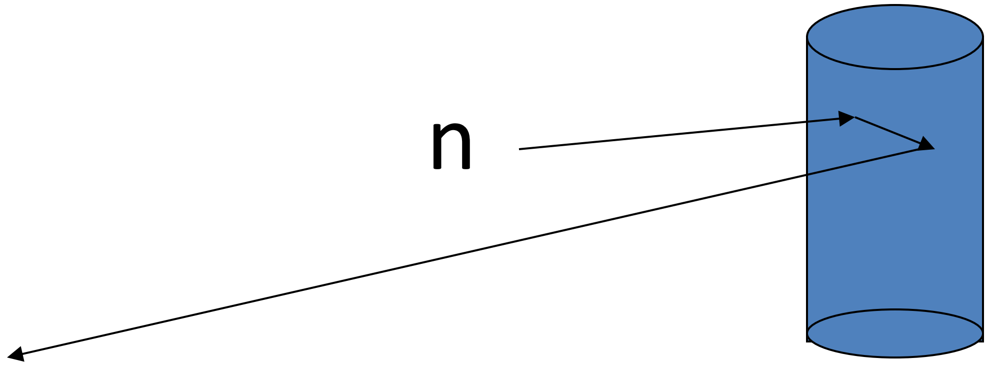

12C(n,el) 2.05MeV
0,35
0,3
0,25
0,2
0,15
0,1
0,05
0
cm dsdW (b/sr)
0
30
60
90
120
150
180
cm Angle (deg)
Jeff 12C(n,el)
2.154MeV Fasoli-1973
1.98MeV Demanins-1973
2.04 MeV ENDF
2.06 MeV ENDF

σ_{elas} and $d\sigma/d\Omega_{elas}$ control the size of the MS effect at each E_n .

Target	Conclusion
54,56Fe	MS resides under main elastic peak and contributes slightly to the tailing.
23Na	MS produces significant tails which cause ambiguities for inelastic yields.
12C	MS produces extensive shelf below the main peak. (n,n_1) not seriously impacted.
7Li	MS produces extensive shelf. (n,n_1) seriously impacted.

- Traditional fitting routines
  - Gaussian + tail
  - The "Hypermet function" (intended for γ-rays)
  - Gaussian + tail + empirical kinematic constraints (SAN12 @ UnivKY, PKS @ OhioU)
- Low-mass samples require a new specialized fitting procedure
  - Use MCNP to estimate peak shapes?

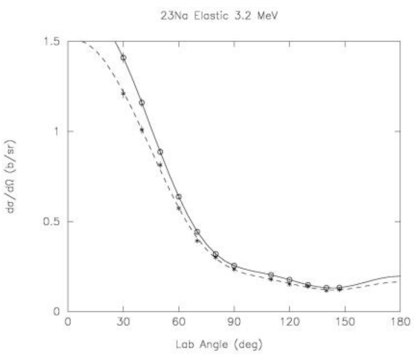
3



ADVENTURES IN ANALYSIS
-- VERIFYING
ATTENUATION AND MULTIPLE SCATTERING CORRECTIONS

MT McEllistrem MULCAT (…)
JR Lilley "…Monte Carlo Multiple Scattering Correction…", CEA-DAM P2N-934-80 (1980)
DE Velkey, "… with Analytic & Monte Carlo Methids", NIM 129, 231 (1975)
WE Kinney "Finite Sample Corrections…" NIM 83, 15 (1970).

3 Multiple Scattering and Attenuation Correction using MULCAT



for a typical sample:

$\Sigma_{tot}^{-1} \sim 16$ cm

double/singl = 10^{-4}

triple/dble = 10^{-4}

- Issues
  - Single element
  - Extensive experience using the routine on medium-mass nuclei
  - Limited # of $\sigma_{tot}(E_n)$ values
  - Elastic angular distribution used at one E_n
  - Runs **** histories

$init\ guess\ at\ \text{`}true\text{`}\ \hat{\sigma}(\theta)$

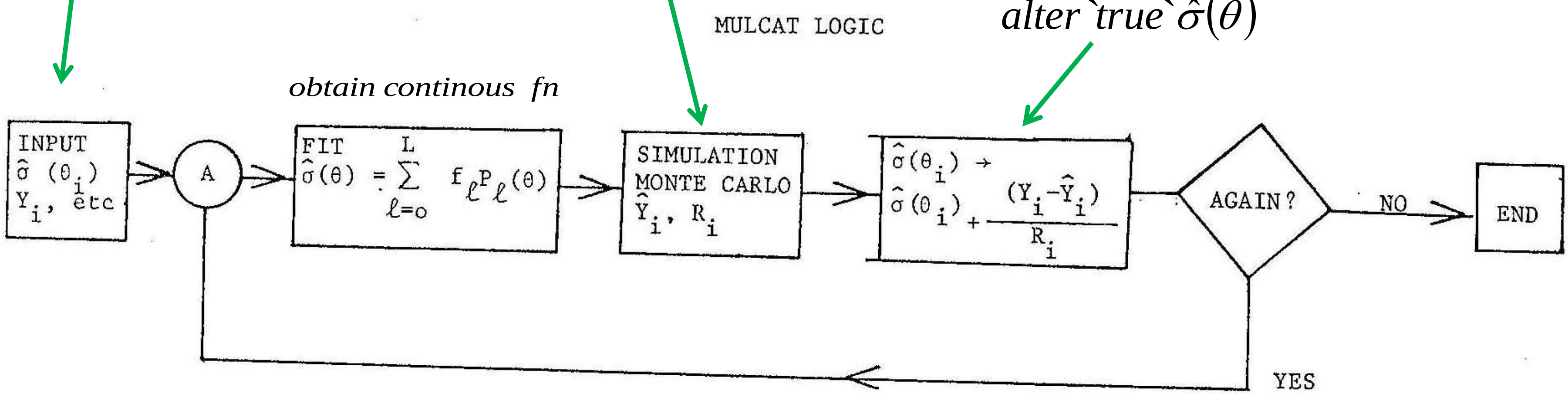
$finite\ sample\ Y(\theta)$

$predict\ perturbed\ \hat{Y}(\theta)$

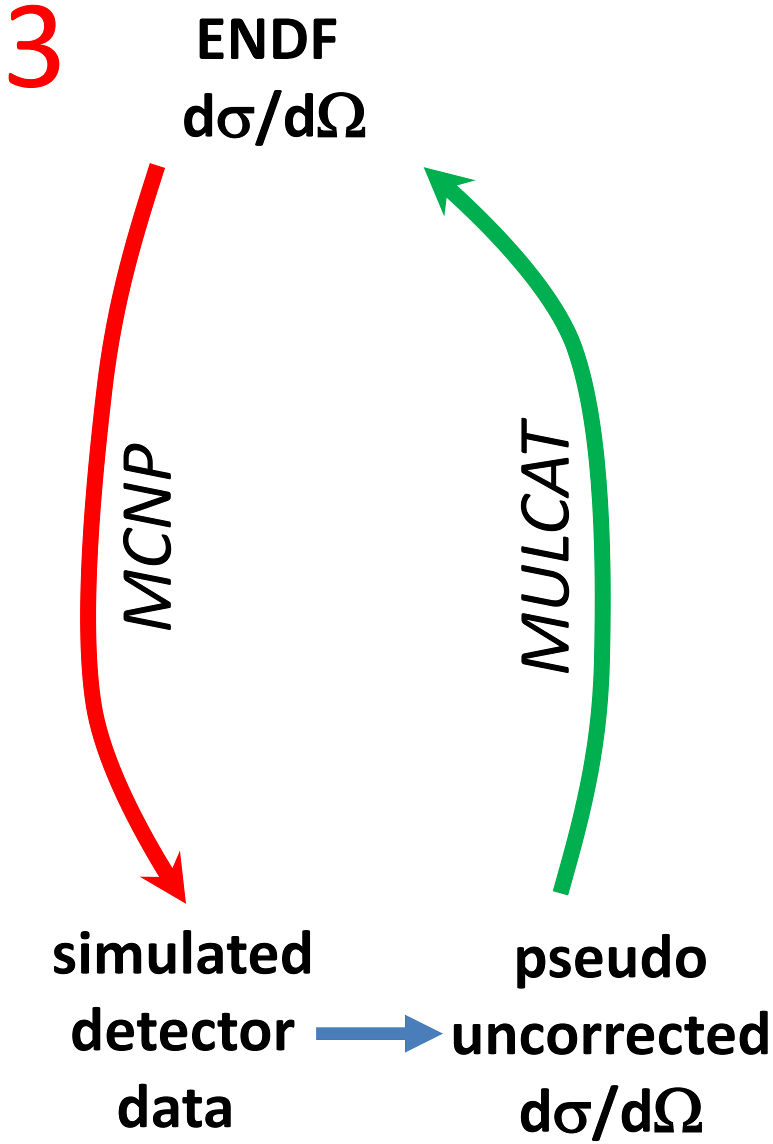
$finite\ sample\ correction\ R(\theta)$

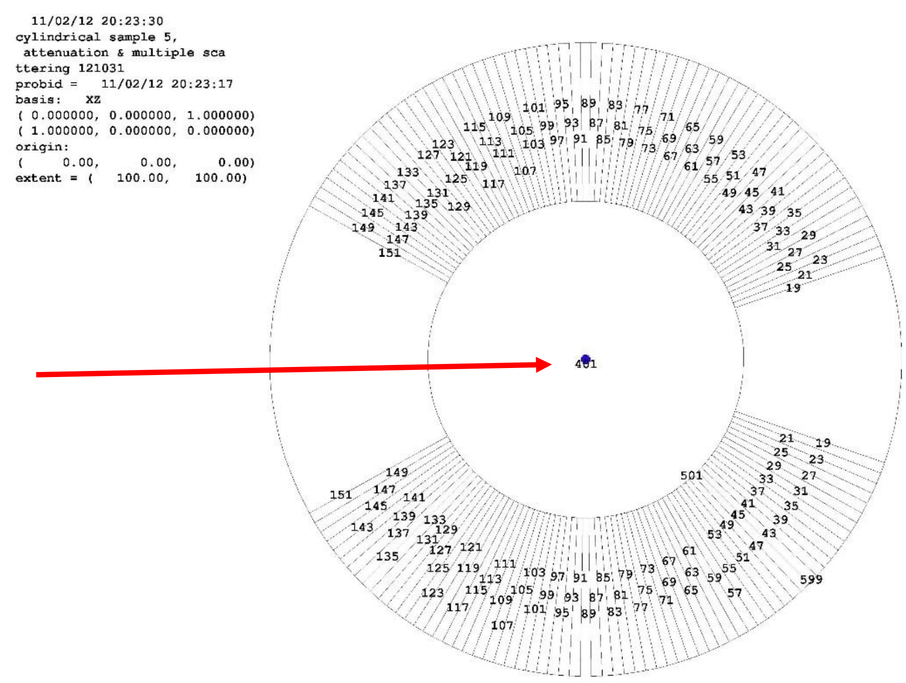
$alter\ \text{`}true\text{`}\ \hat{\sigma}(\theta)$

$obtain\ continous\ \ fn$

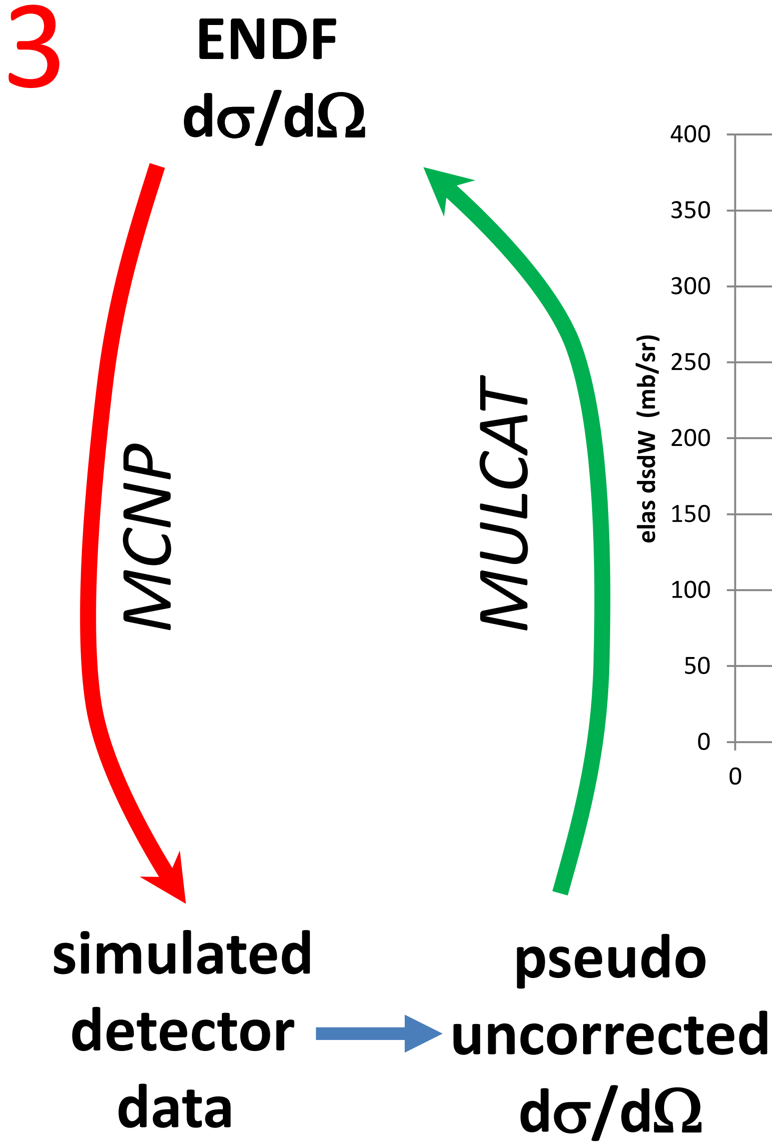


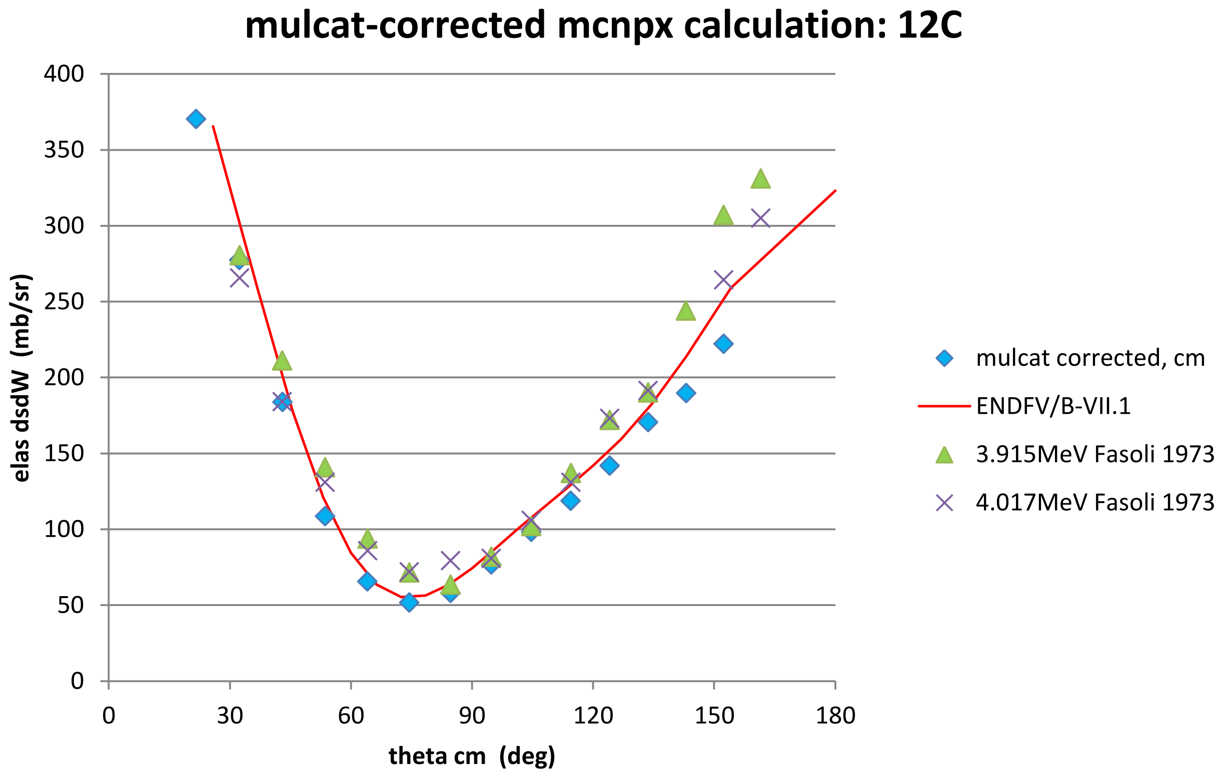
Testing MULCAT



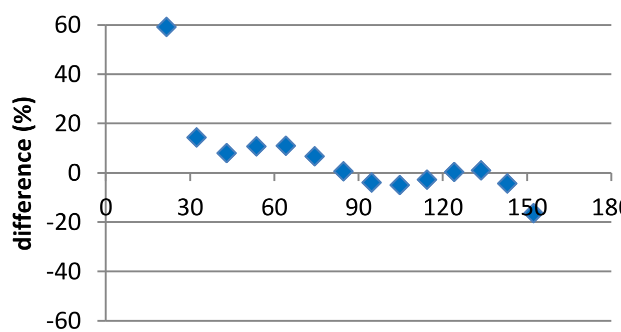


This is not quite the same as our exptl procedure. This is a 'direct' measurement, while our procedure is a relative measurement – i.e. wrt H(n,n)



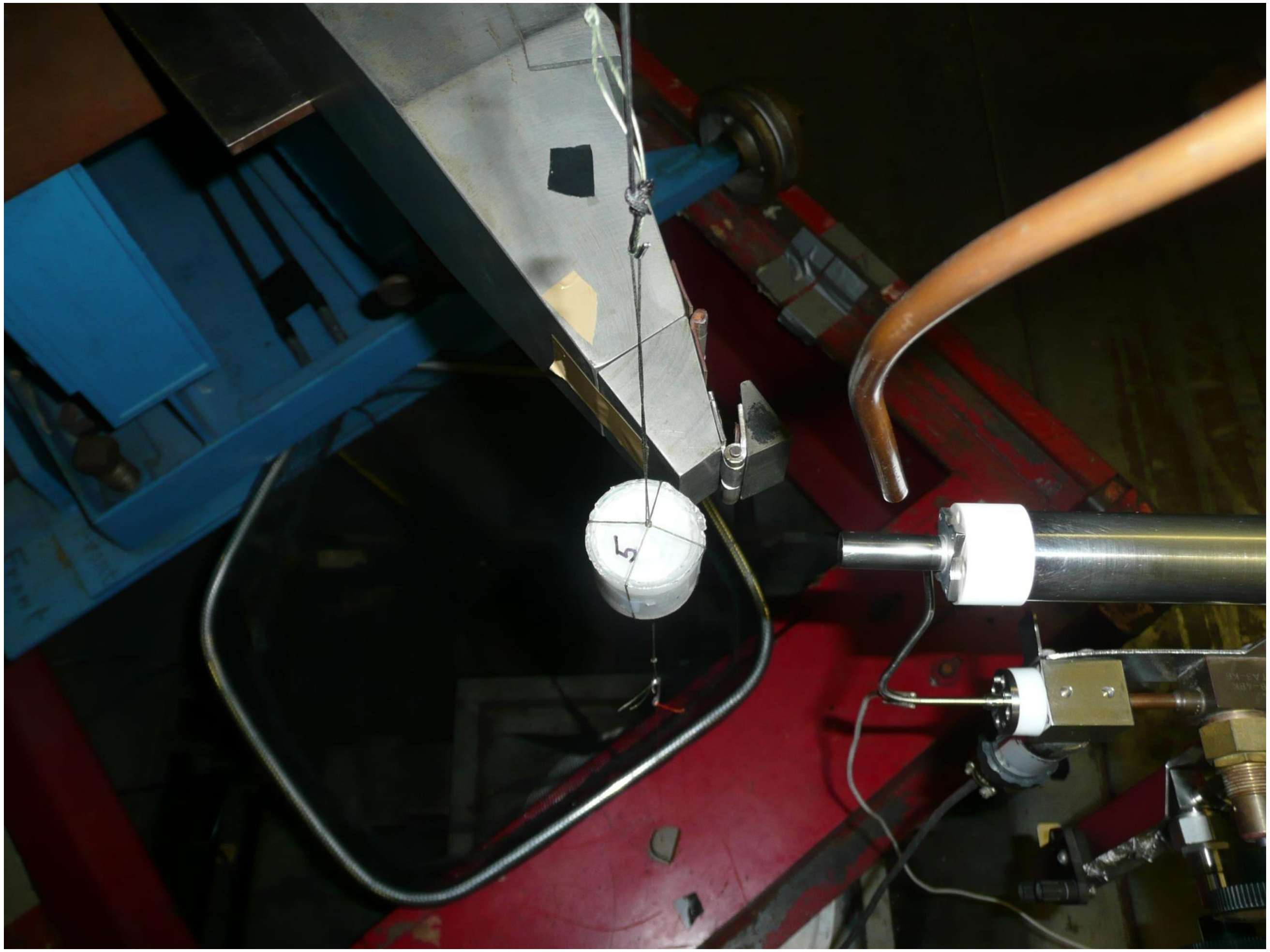


- Closing the loop w/i 5% at >70 deg



This is not quite the same as our exptl procedure. This is a 'direct' measurement, while our procedure is a relative measurement – i.e. wrt H(n,n)

At what angle is the scattering sample?



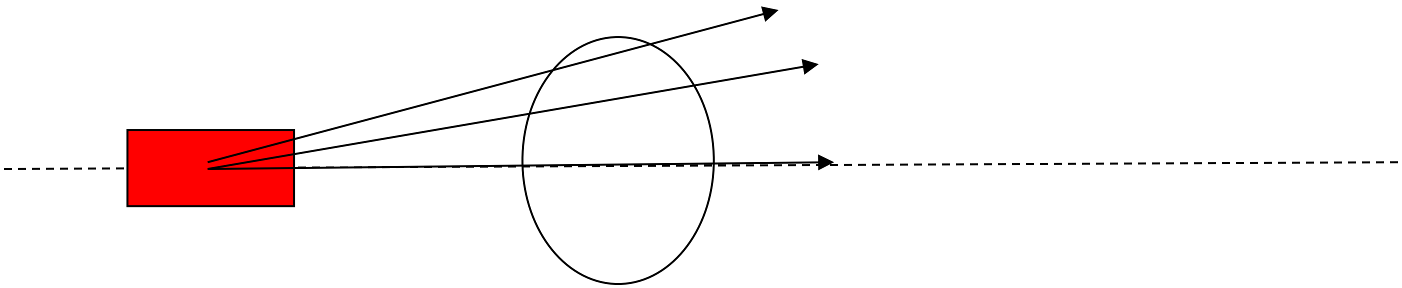


Fig III.A.3a Top-down view of gas cell and cylindrical scattering sample. Neutrons produced at larger angles have lower energies however they interact with a smaller portion of the mass in the sample from in this top-down view. This effect modifies the effective energy spread og the neutron beam.

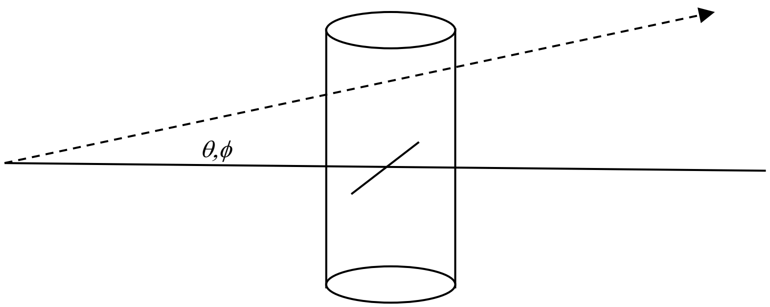
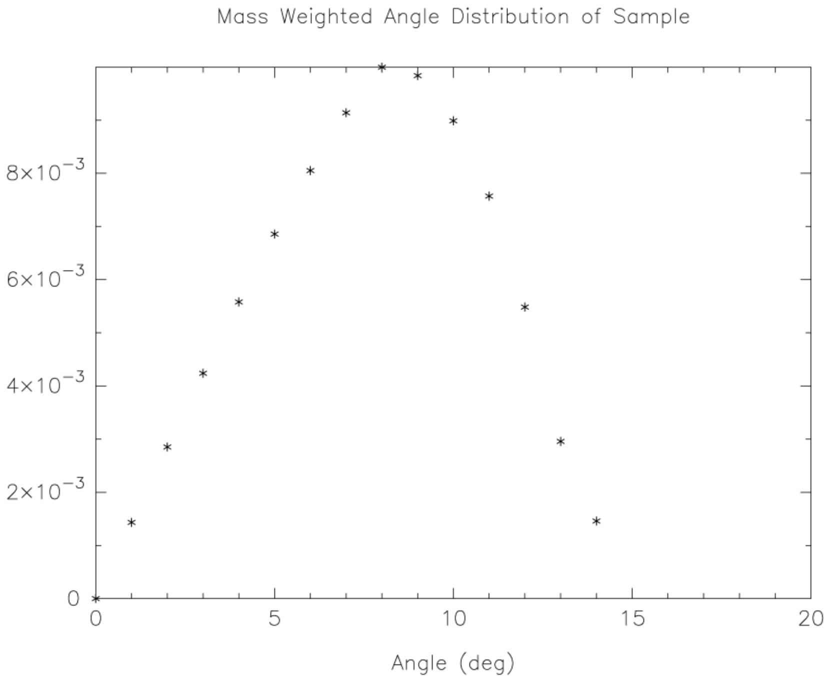


Fig III.A.3b 3-D view of gas cell and cylindrical scattering sample. The thickness of the sample at a given q,f determines the weighting of the energy spectrum at the given angle.

23Na sample, E_n= 4.0 MeV at 0°



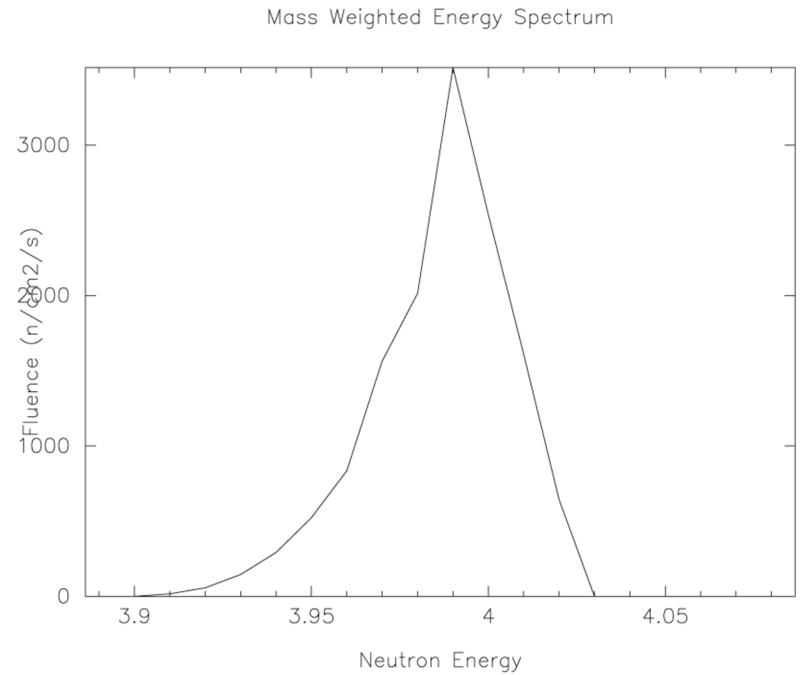


Fig III.A.3e Mass-weighted (actually path-weighted) energy spectrum. The FHWM is ~40 keV.

Summary

- “Nuclear Data”
  - Isn’t necessarily data
  - Is the opinion of it’s evaluators for a specific purpose
  - Reactor industry has a strong influence on reported values.
- UK Accelerator Lab is a unique facility
  - Measure exit channel neutron energies (UnivKY, TUNL, OhioU)
  - Measure angular distributions of n & γ reaction products
  - 3H neutron production target
- Physics learned
  - Exptl Angular distributions are only mechanism to learn about compound elastic
  - Exptl Angular distributions give coupled channels parameters
  - γ-ray cross sections quickly provide xs to inelastic channels
- Measurements
  - Analysis <=70s did not have the calculational tools available today
  - Raw data and documentation absent from old measurements.
- Analysis
  - Some standard techniques from the old days must be revised to reach <<10% uncertainties