Neutron Elastic Scattering Differential Cross Sections on ^{13}C

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LLNL
Anthony Ramirez

FiberTek, Inc
Jarrod Marsh

- Preface: What are "nuclear data"?
- Motivations for ^{13}C measurements
- Measurement Techniques
- ^{13}C Results to date

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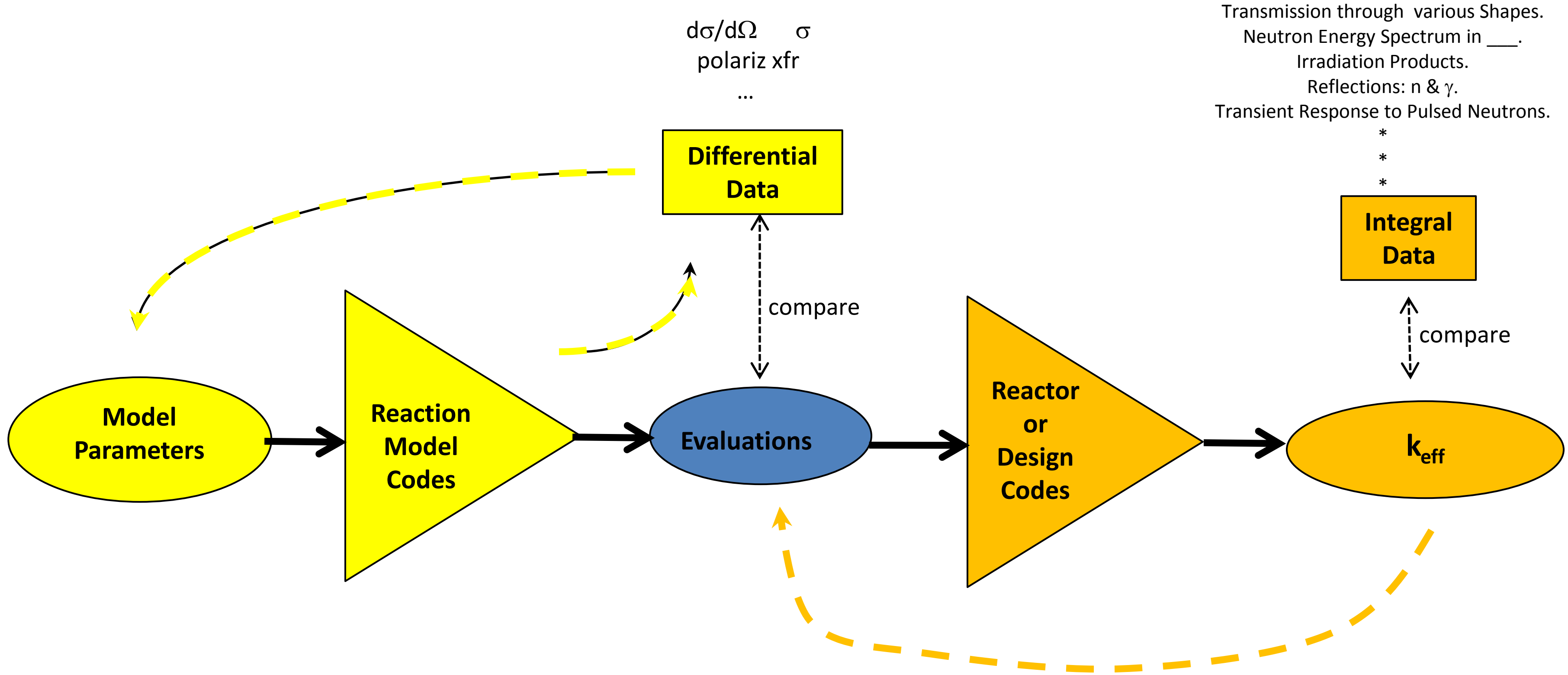
SC0021424, SC0021243, SC0021175, SSC000056

NSF 1913028 / 2209178

- "Nuclear Data" or "the Evaluations" or "Data Libraries" are:
  - Recommended set of cross sections intended to be used together
  - Experimental "differential" data guided by reaction model calculations.
  - Reaction Model calculations guided by "differential" & "integral" experimental data
  - Judged by a specific evaluation team
    - ENDF
    - JENDL
    - JEFF
  - for the evaluation team's directed purpose
  - These are **not** "standards" (as in NIST stds or JRC/BRC/IRMM stds)

- Consumed by:
  - Nuclear Power Industry
  - Nuclear Propulsion
  - Dosimetry & Cancer Treatment Centers
  - "Stockpile Stewardship"
  - Physicists & Chemists

Shockingly, we are not the big users.



Resonance Params
Opt Model Params

<< misc processes >>

Vibration
Rotation

Level Schemes
Ex Jpi
B(XL)
*
Strength Fns
*

EMPIRE
TALYS
ECIS
SAMMY
CO3H
EDA
DWBA
Coupled Channels
*
*
*

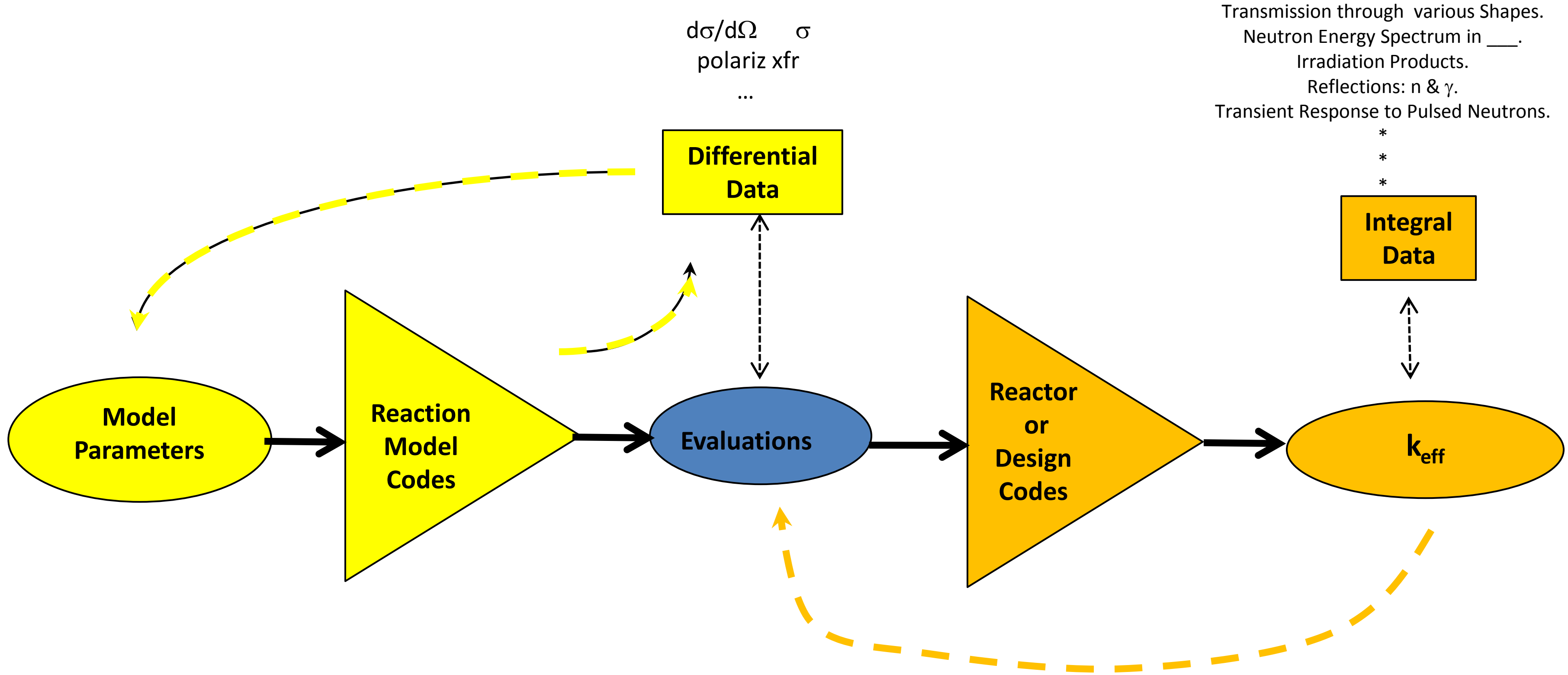
ENDF
JENDL
JEFF
*
*
*

MCNP
GEANT
FLUKA
Reactor Design Software
*
*

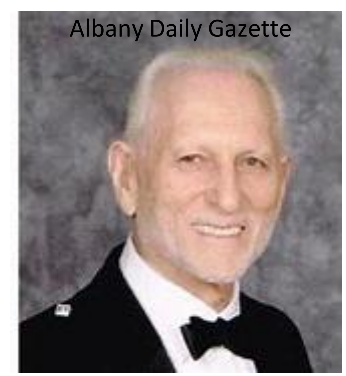
IRPhE
ICSBEP
NDaST
ZEPHER
FLATTOP
*
*

Mike Herman's explanation of how everything fits together

yellow – the physicist's view of the world
orange – the engineer's view of the world.



Cecil Lubitz' Rules about data:



1925-2021
USNA '45
One of the
ENDF founders

- We will never be able to measure XS well enough for the reactor design codes.
- We will never be able to calculate XS well enough for the reactor design codes.
- When we measure cross section, we have no to way to objectively determine the true accuracy.
- What we can check are the agreements between differential & integral data.
- Experimental measurements establish a "volume" for the answer rather than the "value".
- The Evaluator is free to change the values for the integral measurement to be best.
- If two things agree, they both may be wrong.

Motivations

from Sally Hicks

Undergraduate students on the nat Carbon paper

data taken 2011-2016 & 2016-2020

64 (n,n') ang distrib at 45 incident energies btw 0.5 - 8 MeV
+ 12 (n,n'γ) btw 5.6-7.8 MeV

a monster project

ELSEVIER Nuclear Physics A 1023 (2022) 122446
www.elsevier.com/locate/nuclphysa

Neutron elastic and inelastic scattering differential cross sections on carbon

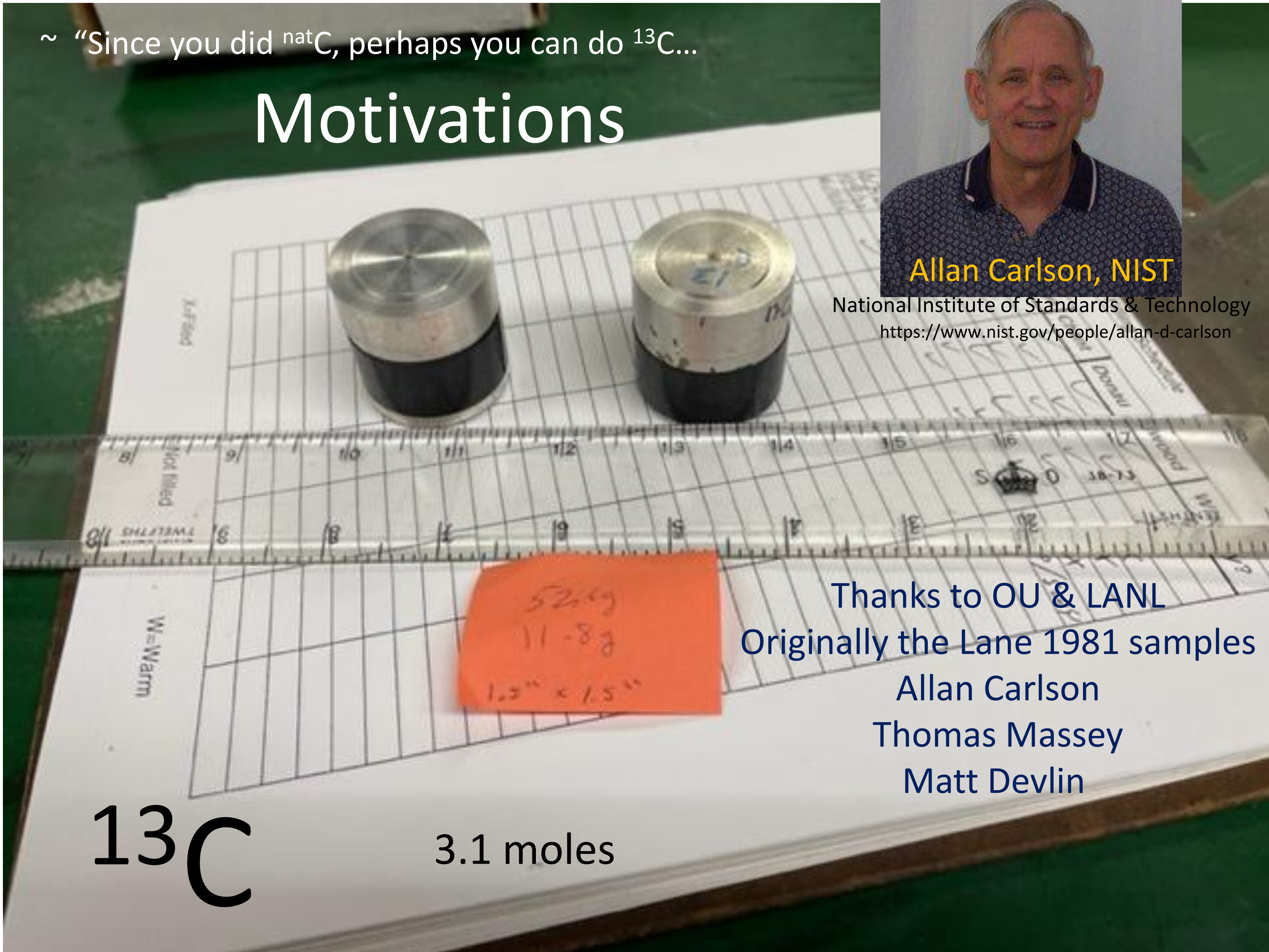
A.P.D. Ramirez [a,b], E.E. Peters [a], J.R. Vanhoy [c,*], S.F. Hicks [d,b], L.A. Alasagas [c], D.K. Alcorn-Dominguez [c], S.T. Block [d], S.T. Byrd [d], E.A. Chouinard [d], B.M. Combs [d], B.P. Crider [b], E.C. Derdyn [d], L. Downes [d], J.A. Erlanson [c], S.E. Evans [d], A.J. French [d], E.A. Garza [c], J. Girgis [d], T.D. Harrison [c], S.L. Henderson [d], T.J. Howard [d], D.T. Jackson [d], L.J. Kersting [d], A. Kumar [a], S.H. Liu [a], C.J. Lueck [d], E.M. Lyons [d], P.J. McDonough [d], M.T. McEllistrem [b,1], T.J. Morin [d], S. Mukhopadhyay [b], T.A. Nguyen [d], M. Nickel [d], S. Nigam [a], R.L. Pecha [d], J. Potter [a], F.M. Prados-Estévez [a,b], B.G. Rice [c], T.J. Ross [a,b], Z.C. Santonil [d], J. Schneiderjan [d], L.C. Sidwell [d], A.J. Sigillito [d], J.L. Steves [c], B.K. Thompson [c], D.W. Watts [c], Y. Xiao [a,b], S.W. Yates [a,b]

Industry, Compass Minerals
Ministry
MD U. Of KY (radiation oncology)
High school physics teacher
Unknown
Laboratory Tech, Eastfield College
Ph.D. U. of Wisc (Nuc Eng) **Sandia National Lab**
Industry, Raytheon
Ph.D. Texas Tech (CE), Jacobs
Ph.D. Candidate U. of FL (Nuc Eng) **LANL**
M.S. Notre Dame (EE), RF Eng at Lockheed Martin
Data analyst
Nurse
Ph.D. Candidate, U. of Kansas (particle)
M.S. UTA (EE), SPARX Engineering
GNC Engineer, Lockheed Martin
UD Student
Ph.D. candidate, TAMU (Nuc Eng)
M.S. U. of KY (Rad Oncology)
Ph.D Notre Dame (Nuc Phy)
MD, Psychiatry, U. of Southern CA
Ph.D. Candidate, UC Santa Barbara, Photonics
MD U. Of KY, Internal Medicine
Ph.D. Princeton (EE); Faculty U. of PA

Ramirez, Phys Rev C 1023, 122446 (2022)

~ “Since you did ^{nat}C, perhaps you can do ^{13}C…

Motivations



Allan Carlson, NIST

National Institute of Standards & Technology

https://www.nist.gov/people/allan-d-carlson

Thanks to OU & LANL

Originally the Lane 1981 samples

Allan Carlson

Thomas Massey

Matt Devlin

^{13}C

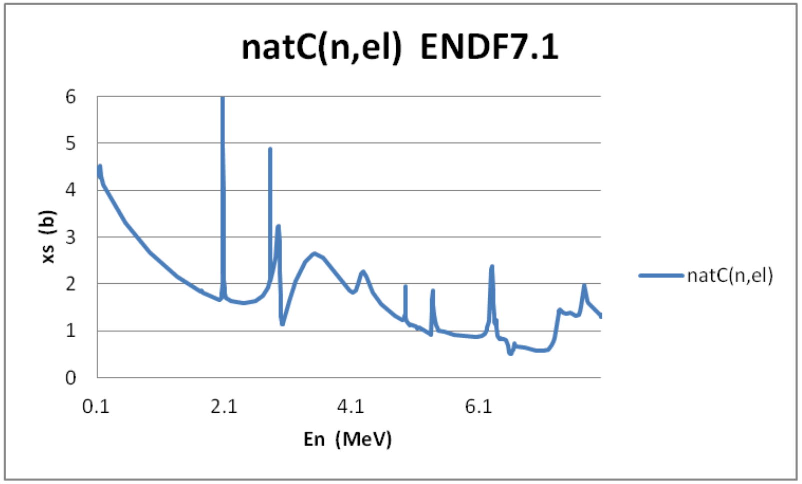
3.1 moles

Motivations

ENDF 7.1 → ENDF 8.0 → ENDF 8.1

2011 2018 soon

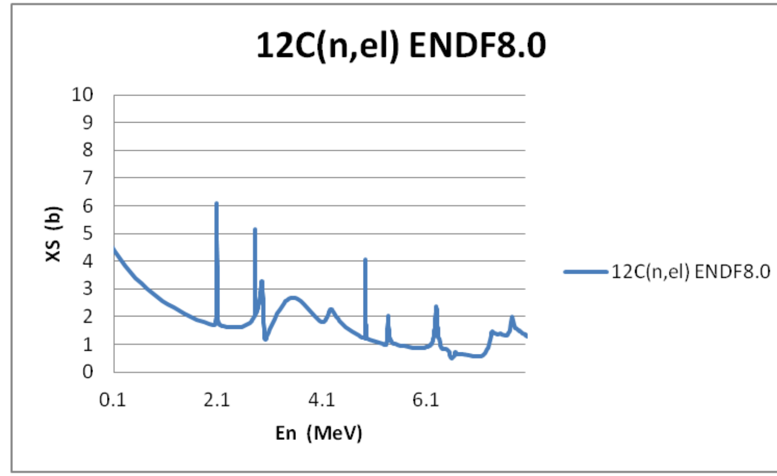
some were happy
some were surprised
some were upset
some were mad



very small
abundance fluctuations

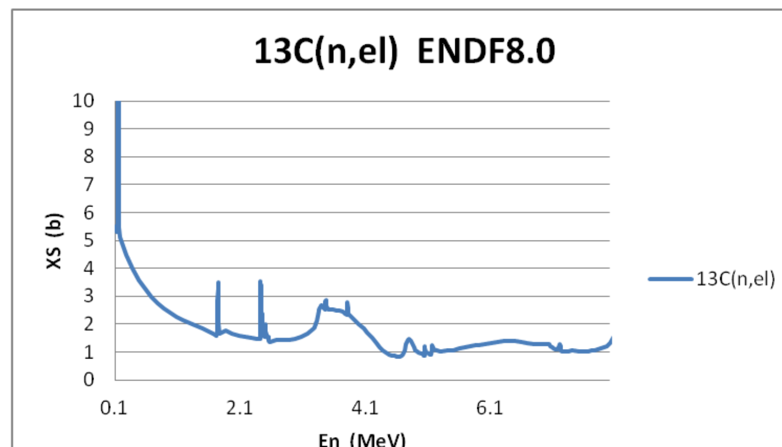
±5

0.9890



0.0110

±5



^{nat}C is a xs ***standard***

btw 1 keV and 1.8 MeV

uncert 0.68 - 0.71%

Carlson NDS 110, 3215 (2009)
Carlson NDS 148, 143 (2018)

“Evaluation of Nuclear Data Stds”

Motivations

Carlson NDS 148, 143 (2018) “Evaluation of Nuclear Data Stds”

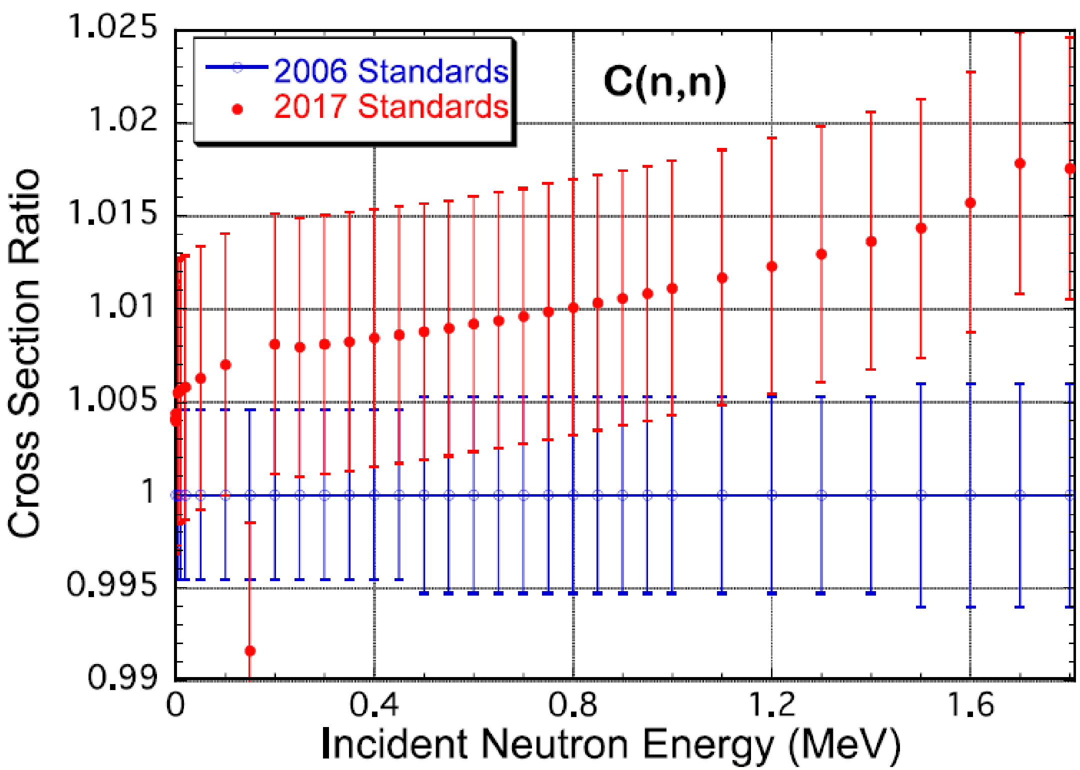


FIG. 18. (Color online) Comparison of the carbon total elastic cross section for the 2017 evaluation with the 2006 standards evaluation. The unrecognized systematic uncertainty of 0.65 % has been included in the 2017 data. The baseline at 1.00 is the 2006 standards evaluation. The structures at about 0.15 MeV and 1.76 MeV are a result of changes in the evaluated ^{13}C total cross section.

Worries

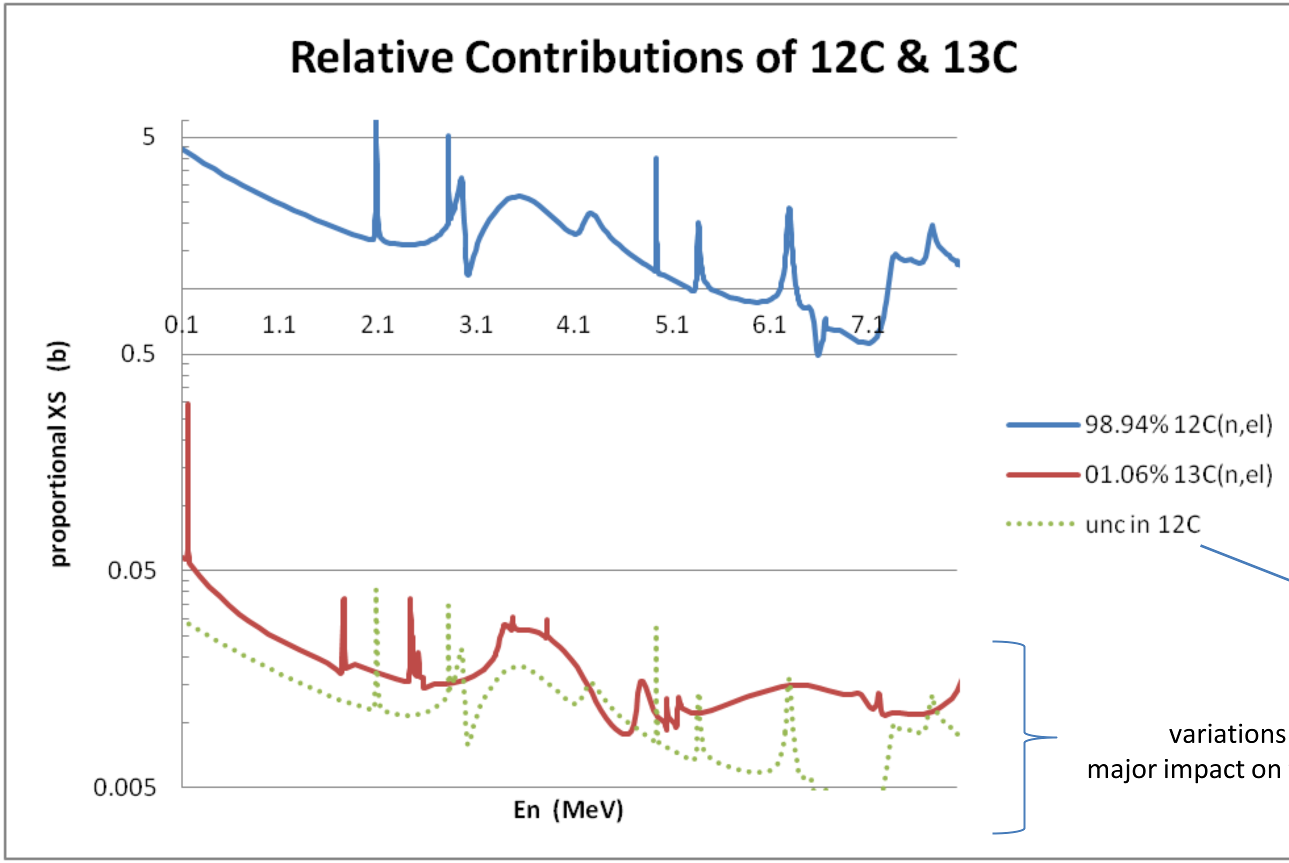
that the 2017 & 2006 values differ by more than the uncertainty

Alan Carlson “Recent Standards Work” CSEWG 2023 @ BNL Nov 2022

Differences are due to addition of 13C information

Recent RPI data indicate less discrepancy in 0.15 - 0.40 MeV region.

Motivations



0.68 – 0.69%

variations in 13C xs can have major impact on the quoted uncertainties.

Modeling cross sections (even in the 'plain' regions) requires a huge amount of information.

Potential scattering (think: OM + corrections)

Resonances (+ CN state properties, mixing, interference, subthreshold tails)

ALSO: The ENDF recommended values are deduced by examination of the CN and not an individual reaction channel.

Gerry Hale
Mark Paris

Motivations

Previous work on 13C

PHYSICAL REVIEW C VOLUME 23, NUMBER 5 MAY 1981

States in ^{14}C from σ_T and $\sigma_{el}(\theta)$ for ^{13}C+n: Measurement, R-matrix analysis, and model calculations

R. O. Lane, H. D. Knox, and P. Hoffmann-Pinther
John E. Edwards Accelerator Laboratory, Ohio University, Athens, Ohio 45701
R. M. White
University of California, Lawrence Livermore National Laboratory, Livermore, California 94550
G. F. Auchampaugh
University of California, Los Alamos National Scientific Laboratory, Los Alamos, New Mexico 87545
(Received 16 October 1980)

Experimental σ_{tot} total Cross section measured at the old LANL Tandem.

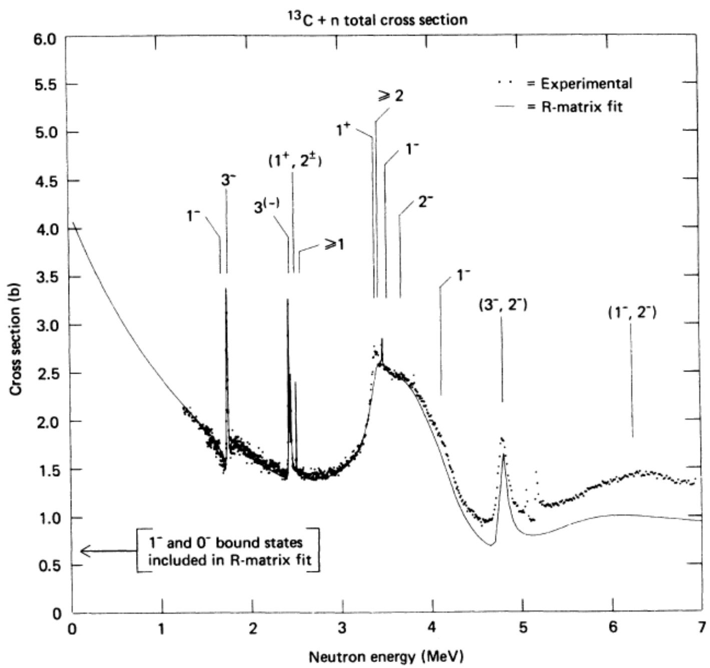


FIG. 3. Total cross section σ_T (points) from Ref. 7 and integrated elastic scattering cross section σ_{el} (curve) from R-matrix analysis for ^{13}C+n. The J^π assignments and approximate locations for states in ^{14}C resulting from the R-matrix analysis are indicated in the figure. Only a representative number from the full set of data points for σ_T are shown to portray adequately the features of the total cross section. The scatter in the points is taken as the measure of errors on σ_T. For the 1^- resonance near 1.75 MeV the location of the resonance dip is indicated rather than the calculated resonance energy (see Fig. 4).

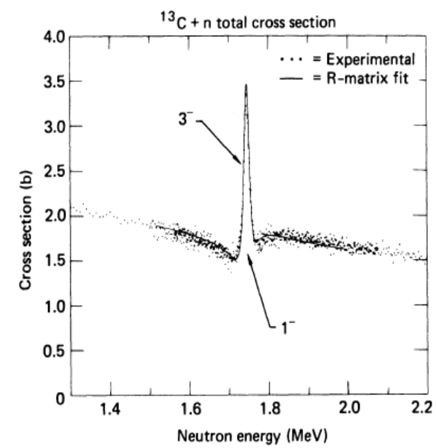
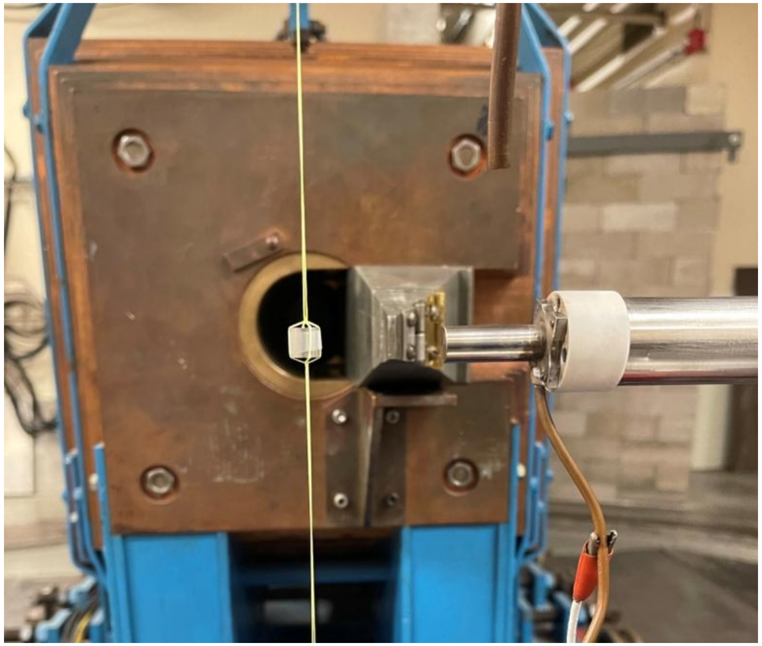


FIG. 4. Expanded plot of the total cross section (points) from Ref. 7 and integrated elastic scattering cross section (curve) from R-matrix analysis for ^{13}C+n for the resonances near 1.75 MeV. The curve has been averaged over the experimental resolution of FWHM $\approx$ 3.5 keV. Note that in Table I the energy of the 3^- resonance (peak) is actually slightly lower than that of the 1^- resonance (dip). The apparent reversal of this order occurs in this case because of the slight asymmetry of the 1^- dip and the nearly equal energies of the resonances. The full data set for σ_T is shown from $E_n \simeq 1.6$ to 2.0 MeV while only a partial set is displayed outside this region to aid in relating to other figures. The scatter in the points is taken as a measure of the errors.

Most previous measurements do not go below ~1 MeV.

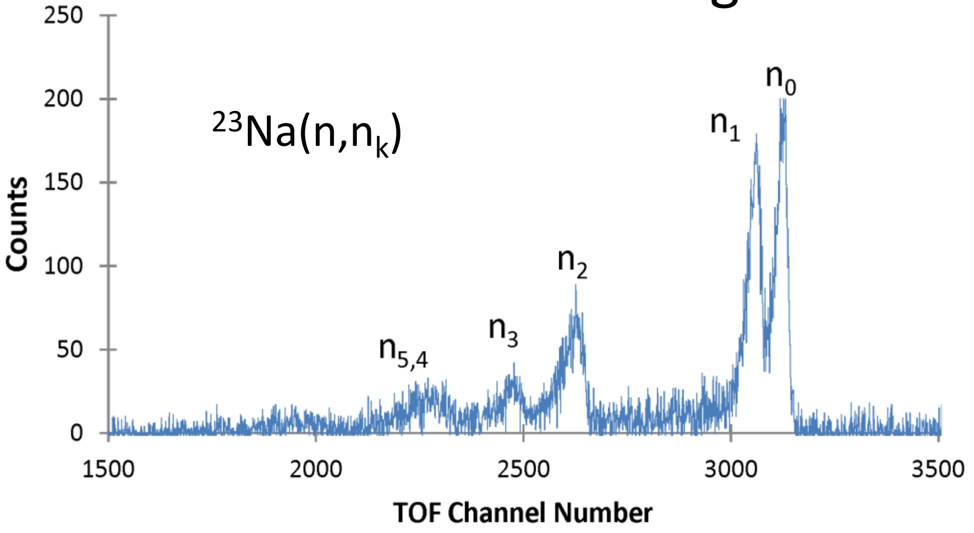
Quick reminders about the University of Kentucky Accelerator Lab programs

- **Accelerator**
  - HVEC Model CN: 7 MV
  - rf source
  - p, d, ^{3}He, α, … ions
  - Authorized for ^{3}H gas targets
  - measure exit neutron energy
  - 1 ns pulse widths every 533 ns
- **Basic Nuclear Science**
  - Nuclear Structure via (n,n'γ)
    - Level Schemes & Transitions
    - Spectroscopic Information
    - DSAM Lifetimes
  - (^{3}He,nγ)
- **Applied Nuclear Science**
  - Differential (n,n') Cross Sections
    - ^{12,13}C, ^{7}Li, ^{19}F , ^{54,56}Fe , ^{23}Na , ^{28}Si
  - Detector Development
    - Univ Guelph / TRIUMF
  - measurements for 'friends'

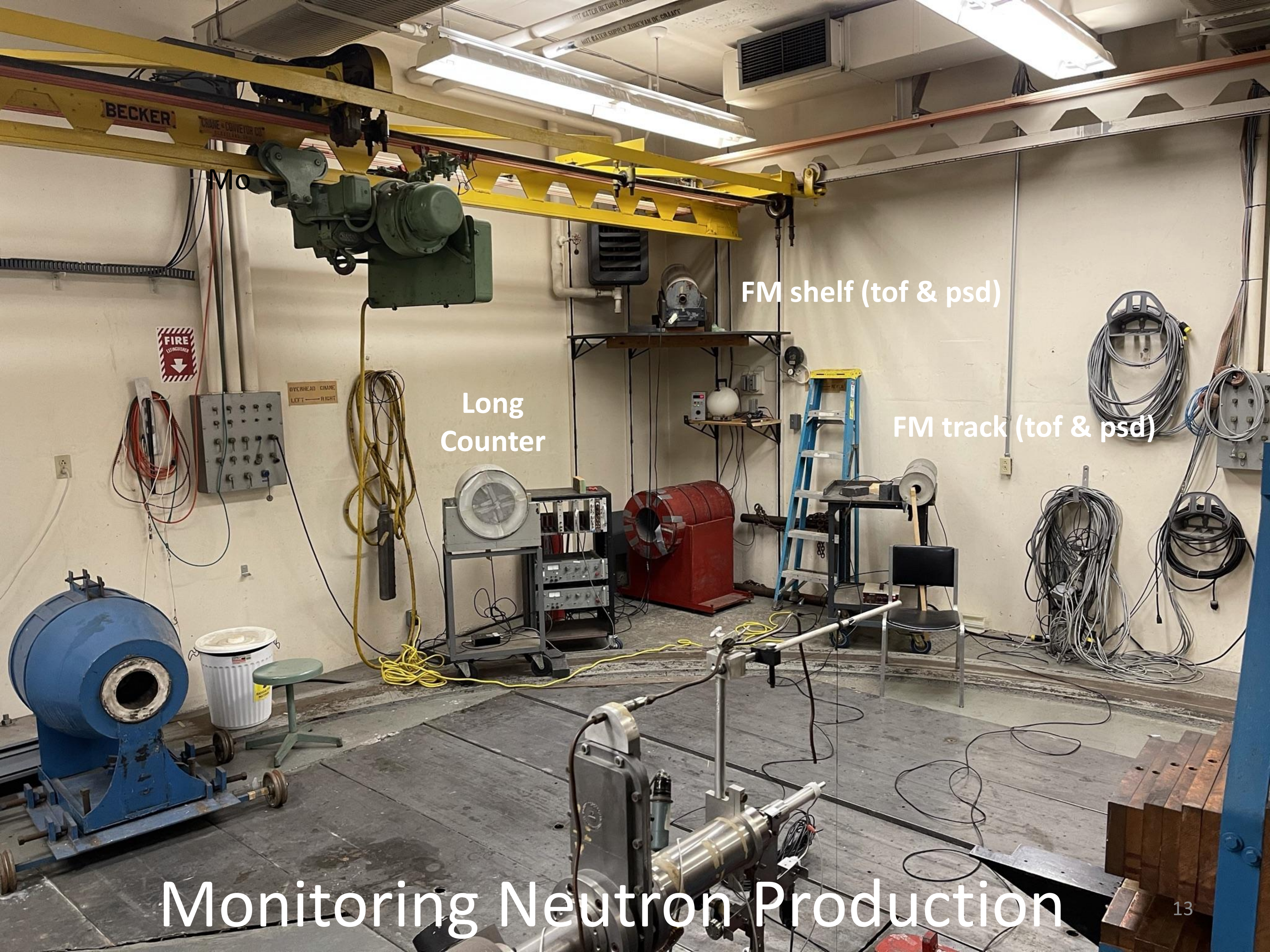


Neutron Time-of-Flight

Pulsed beam. PSD.
Exit channel neutrons sort by flight time.



Monitoring Neutron Production

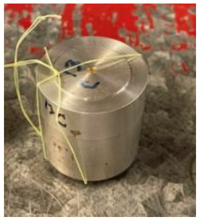


The Basic Idea for Processing Measurements

13C Differential Cross Sections are measured wrt to H(n,n)

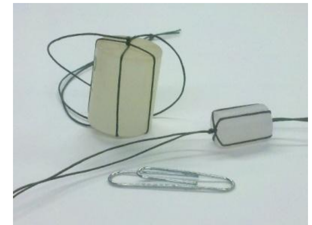
xs unc
0.35 – 0.43%
&
isotropic in cm

H(n,n)
elastic scattering
differential cross
sections are used as
our standard



Sample spectrum

Container spectrum



Polyethylene spectrum

3 13C ← Sample – Cont.

Extract Peak Yields

1 Correct for Detector Efficiency

4 Convert to raw Cross Section

2 *Correct for Atten & Multiple scatt

Extract Peak Yields

Correct for Detector Efficiency

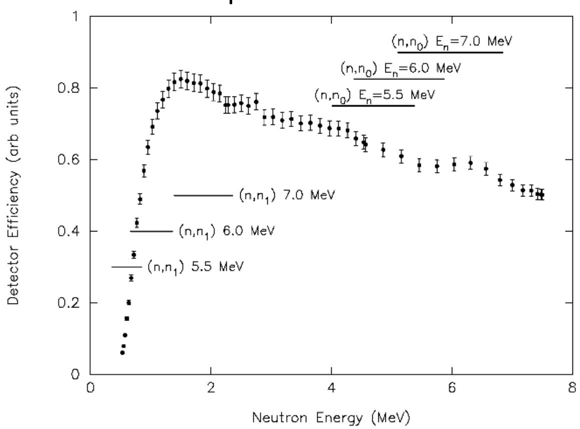
*

It's important to do the geometrical, attenuation, and multiple scattering corrections well.

http://kenokazaki.com/tag/pot-of-gold/

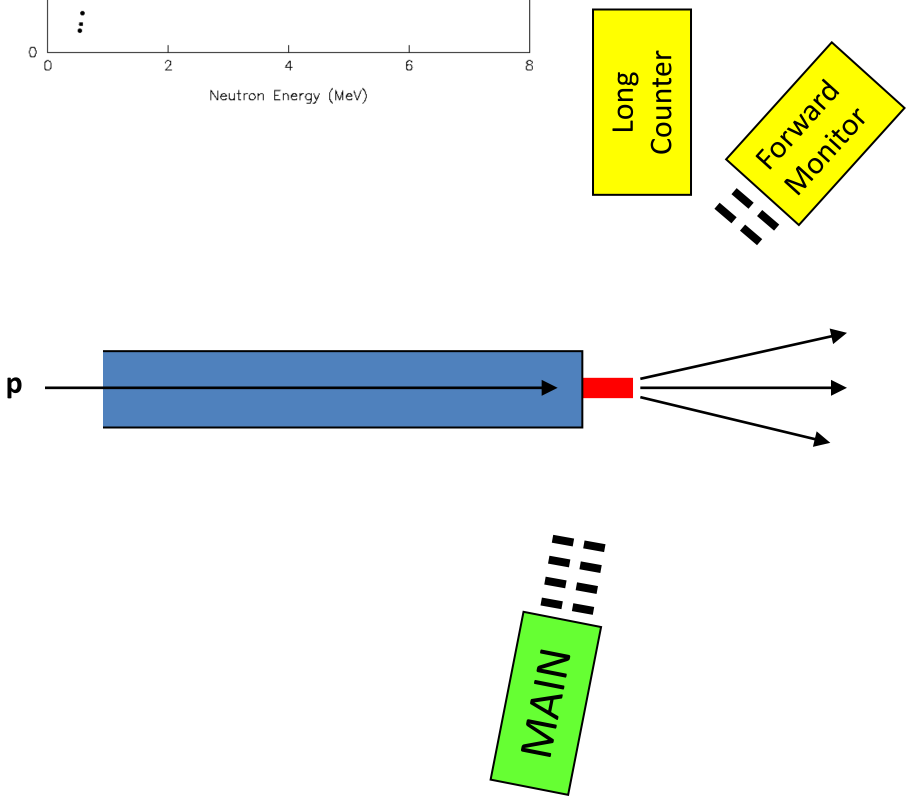
Measuring MAIN Detector Efficiency

example from former 12C



The reaction channels sample different parts of the efficiency curve at different energies.

$$eff\,(E_n) = \frac{Yield}{FM \bullet \frac{d\sigma}{d\Omega}_{Tpn}}$$



MAIN detector efficiencies must be measured because of

- **descriminator threshold effects**
- **individ scintillator assembly behaviors**
- **sub-LLD pileup**

Measure
angular / energy dependence of the
T(p,n) or D(d,n) source reactions.

Generic UKAL Uncertainties

Issue	
Counting Statistics n_0, n_1	<1%
Ability to Extract Yield from Peaks in Spectra (elas)	~2% usually
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%

making new MCNP tests with improved gas cell description to make this more definite

depends on the level scheme of the target nucleus – overlapping peaks?

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

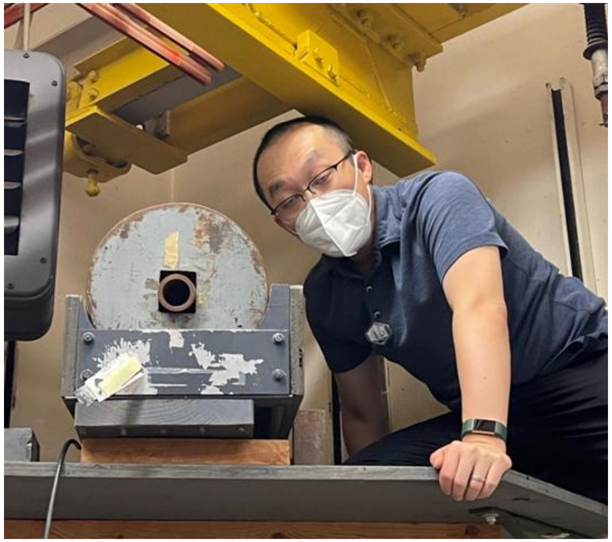
- Overall during $^{54-56}$Fe runs: elastics ~7-10%
  inelastics ~10-14%

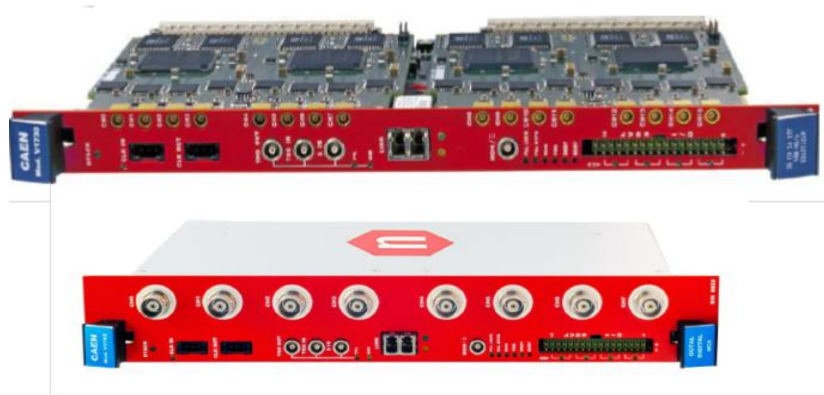
Overall during C runs: elastics ~6%
inelastics ~10%

We cannot make sub% determinations of cross section values, however our angular distributions guide selections of model parameters.

Yongchi Xiao

New Data Acquisition System



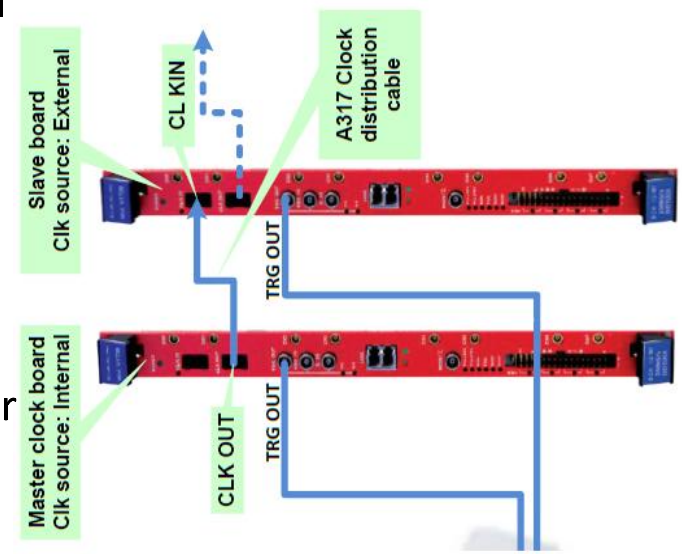


V1730 500 MS/s
scintillators nTOF
MAIN & FM
beam pulse

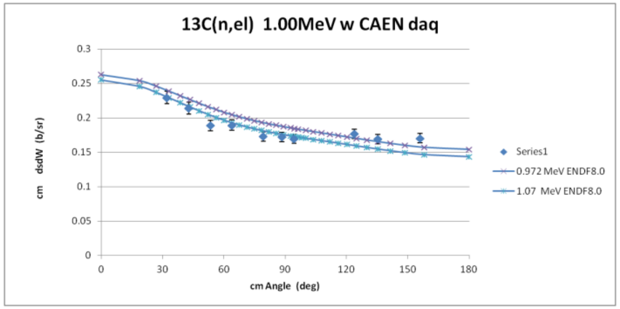
V1782 100 MS/s
HPGe
Long Counter

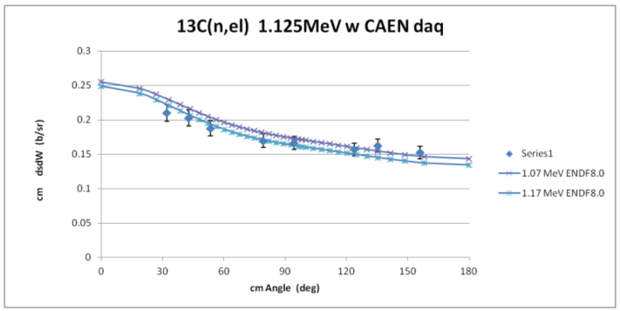
+ can record time-dependent γ-ray spectra
+ observe time dependence of background
+ trapezoidal filter can be fine tuned for each detector, kinda
+ can replay data & change your mind about settings
+ n detector efficiencies less of a hassle
+ can actually digitize the 1.875 MHz beam pulse

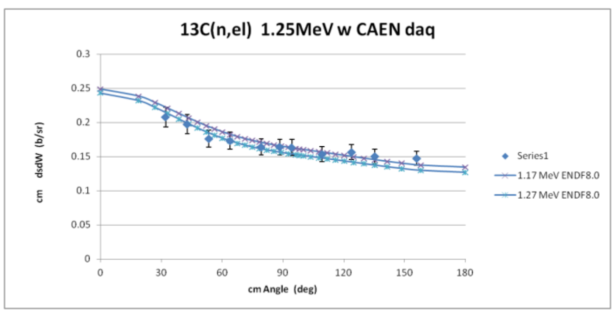
- ~~can't do detailed live-monitoring of data coming in~~
- ~~time consuming development, testing, refining~~
- modules may not perform as expected or play well together
- γ peak shapes fill hard disks & buffers fast
- new ways to do things wrong
- team members not completely satisfied with nTOF resolution yet

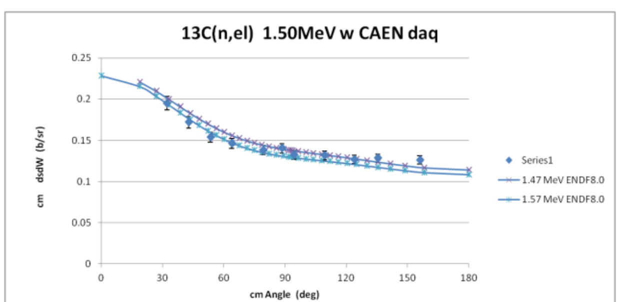


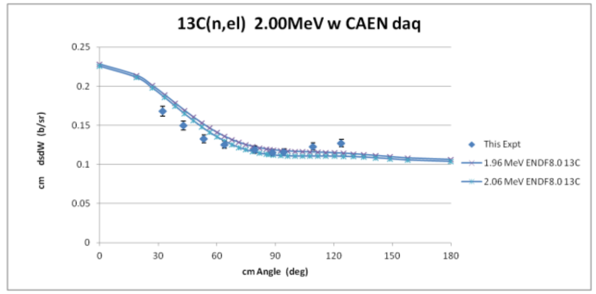
E_n > 1.0 MeV n+13C elastic scattering angular distributions (preliminary)

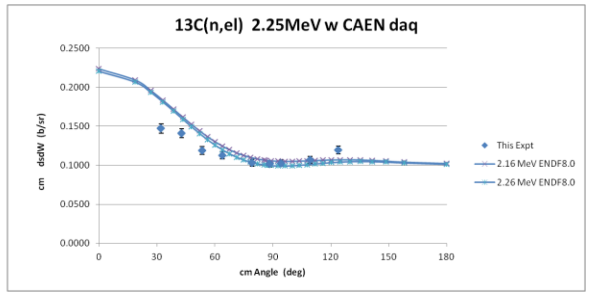


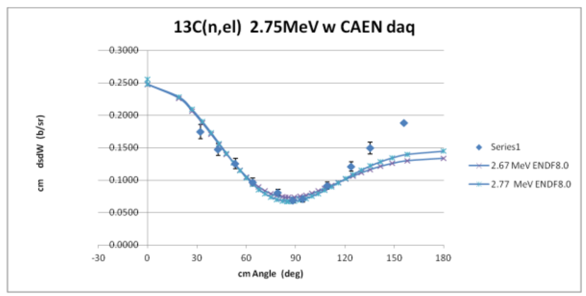


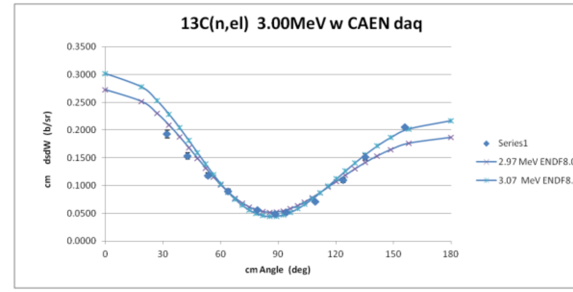


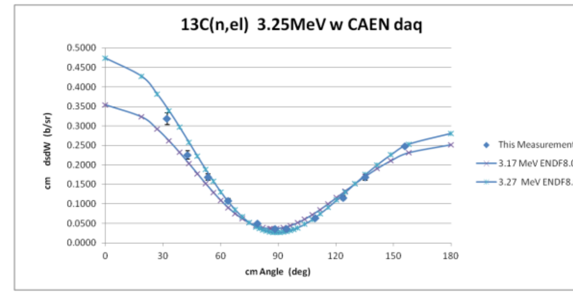












Angular distributions seem bland.

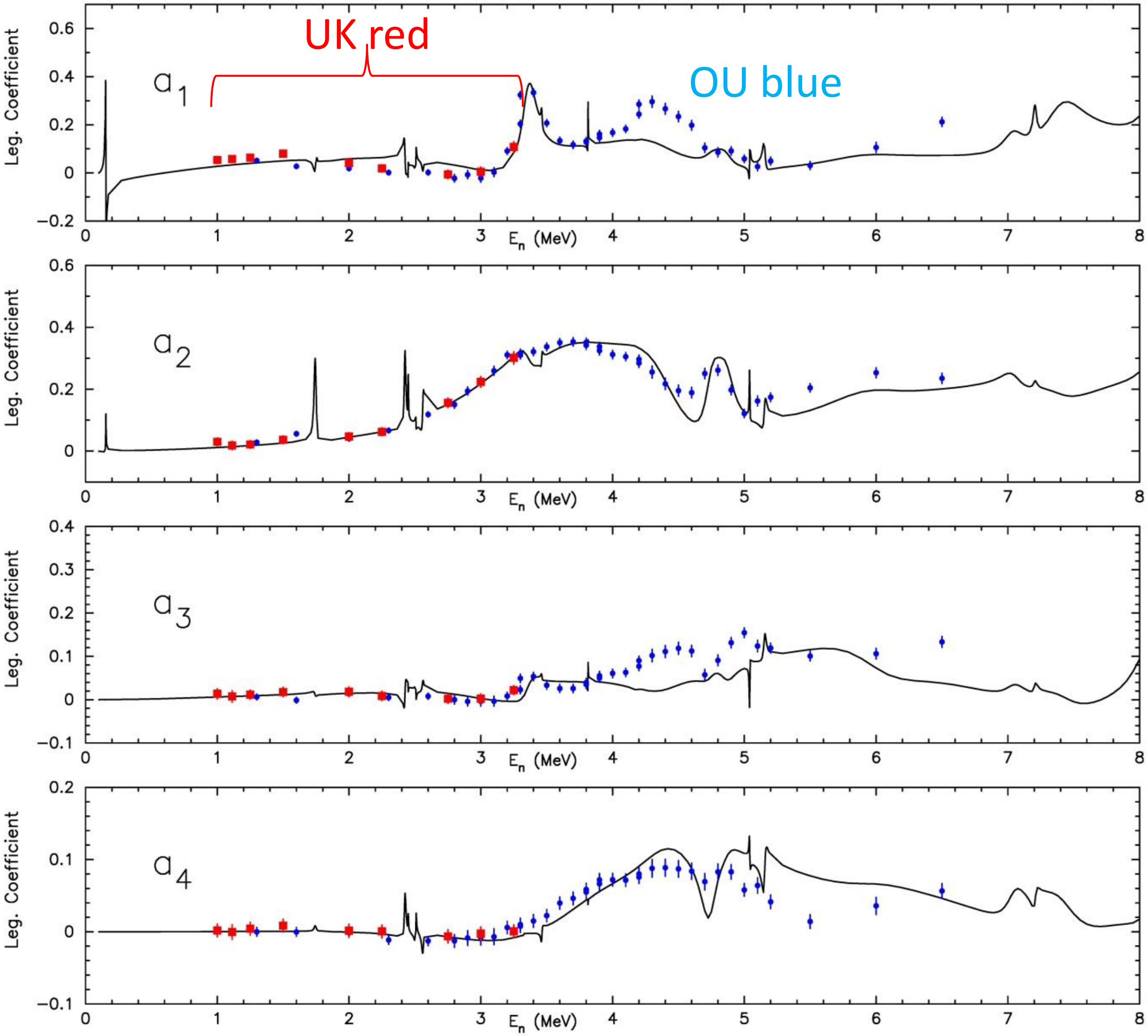
Detail is apparent if one examines Legendre expansion coefficients.

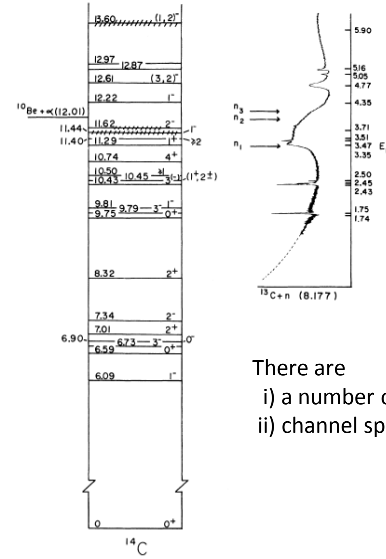
$$W(\theta) = A_0 \sum_L a_L P_L(\cos\theta) \quad ; a_0 = 1$$

$$a_L^{ENDF} = \frac{a_L^{exp}}{2L+1}$$

Comparison of the ENDF8.0 Legendre Coefficients compared to the coefficients from the LANE1981 experimental measurements (preliminary).

Detail is apparent if one examines Legendre expansion coefficients.
Legendre coeffs contain info on reaction mechanism amplitudes.





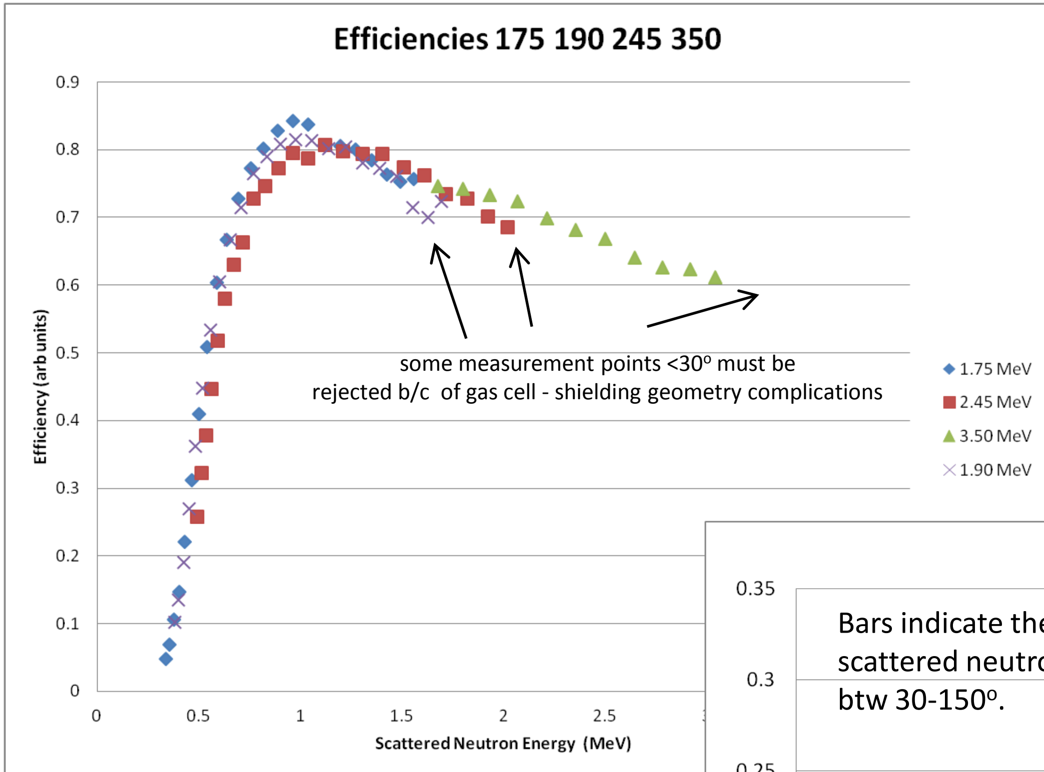
There are
i) a number of CN levels
ii) channel spin mixing.

Discrepancies btw current ENDF & 1981 experimental measurements.

So far, we are extremely consistent with OhioU values !

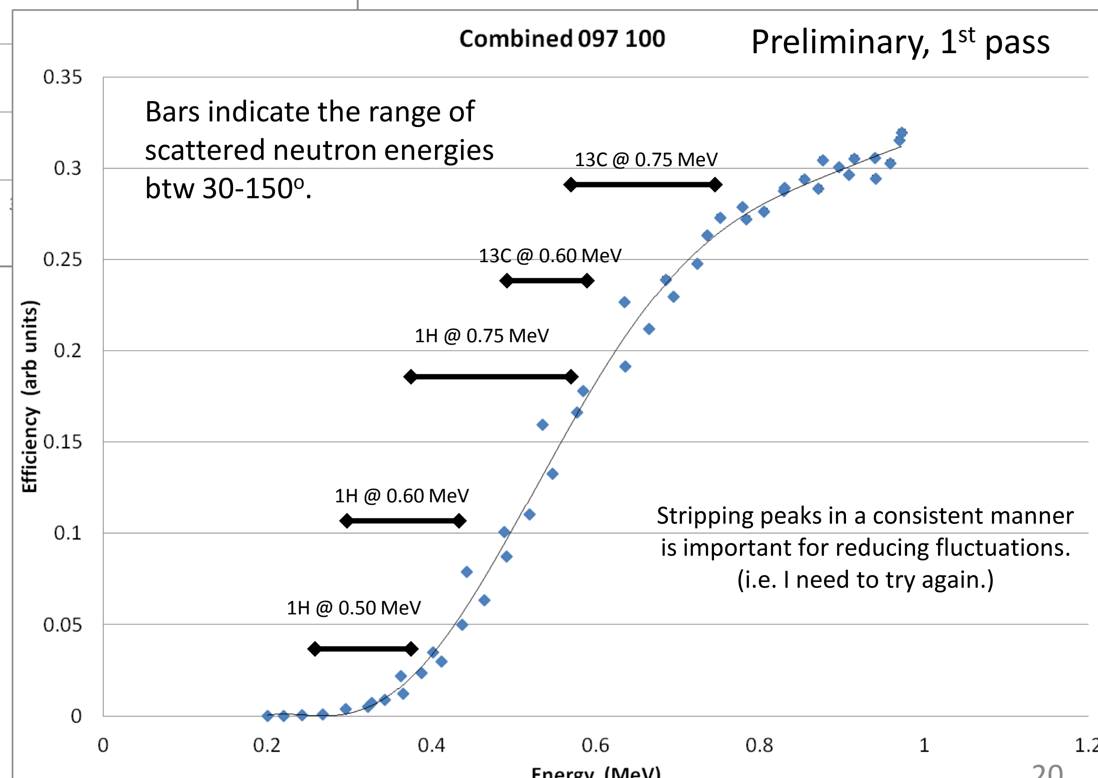
We need to go lower in energy & check out the 4-5 MeV region

Above E_n = 1 MeV measurements go well



MAIN detector efficiencies must be measured b/c

- descrim threshold effects
- individ scintillator behavior
- sub-LLD pileup



Below 1 MeV, challenges develop which require more work.

Our usual H(n,n) xs normalization reaction, not usable E_n<0.6 MeV b/c scattered neutron energies become too low for our EJ301 detectors.

Supported by U.S. DoE FY20/21/22 awards SC0021424, SC0021243, SC0021175, SSC000056

SUMMARY:

- Finishing the ^{13}C data request.

- The team is working on many projects
- Re-canned ^{7}Li and measure again.
- ^{19}F – time dependent (n,n’γ)

NSF 1913028 / 2209178

Dirty Hands
Laboratory Skills
Operation, Maintenance, Repair, Design

Dirty Hands brought to you by

University of Kentucky 60 years UK 1964-2024 Accelerator Laboratory

U.S. DEPARTMENT OF ENERGY

NSF