Neutron Standards
The Evolution of Methods with Time

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ENDF/B-IV

- The evaluations were done by drawing smooth curves through plots contating the measured values.
  - Uncertainties were obtained in an approximate manner
  - there was no thought of covariances.

ENDF/B-V

- Generalized Least Square was used for the $^{235}U(n,f)$ evaluation for the energy range from 100keV to 20 MeV -Poenitz

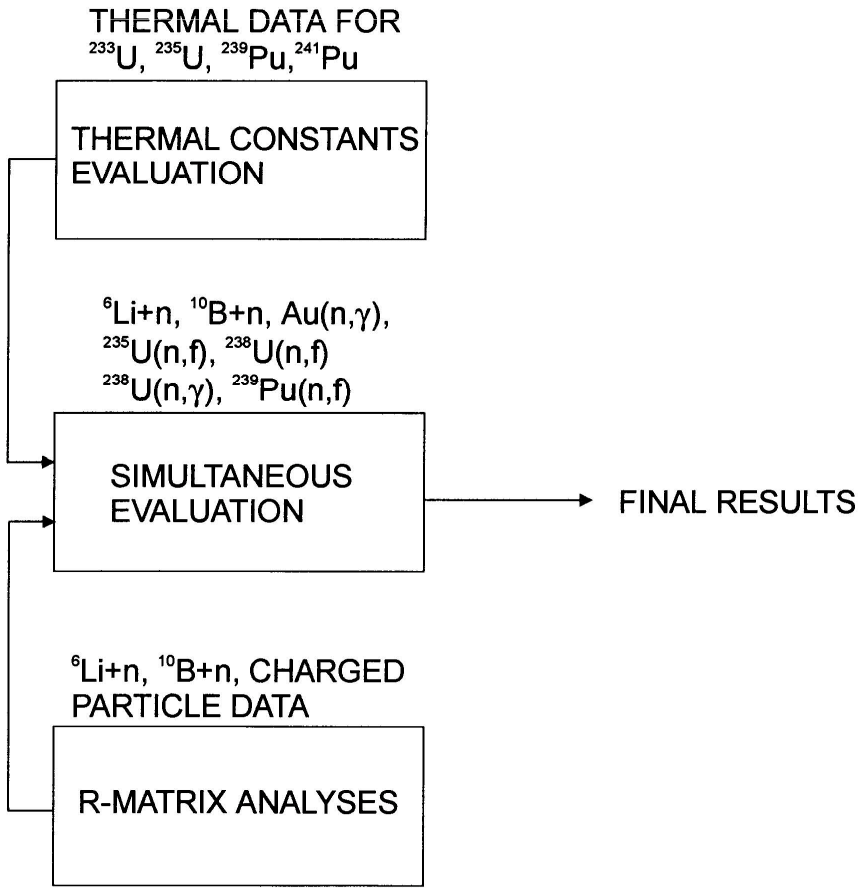
ENDF/B-VI

- The Generalized Least Square method was applied for all the standard cross section data except the $^{1}H(n.n)$ and $^{3}He(n,p)$ standard. The code used is GMA by Poenitz
  - A rather complete set of measurement types were possible.
- R-matrix evaluations were done for the ^{7}Li and ^{11}B compound nuclei yielding $^{6}Li(n,t)$, the $^{10}B(n,\alpha)$ and $^{10}B(n,\alpha_1\gamma)$ standard cross sections-Hale
- A method was established to combine the GMA and R-matrix results
- Also R-matrix evaluations were done for the $^{1}H(n,n)$, $^{3}He(n,t)$ and C(n,c) standards

Data types used with GMA

Type	Data Type	Example
1	Absolute cross section	$\sigma_{nf}(^{235}U)$
2	Cross section shape	$c*\sigma_{n\alpha}$ (^{6}Li), c is unknown
3	Absolute cross section ratio	$\sigma_{nf}(^{238}U)/ \sigma_{nf}(^{235}U)$
4	Ratio shape	$c_{*} \sigma_{nf}(^{235}U)/ \sigma_{n\alpha}(^{6}Li)$, c is unknown
5	Sum of cross sections	$\sigma_{tot}(^{6}Li)= \sigma_{nn}(^{6}Li)+ \sigma_{n\alpha}$ (^{6}Li)
6	Spectrum averaged cross section	$\sigma_{nf}(^{235}U)$ averaged over ^{252}Cf spontaneous fission spectrum
7	Absolute ratio of cross section/ sum of cross sections	$\sigma_{nf}(^{235}U)/ \sigma_{n\alpha}$ (^{10}B), where $\sigma_{n\alpha}$ (^{10}B)= $\sigma_{n\alpha_0}(^{10}B)+ \sigma_{n\alpha_1}(^{10}B)$
8	Shape of Type 5 data	
9	Shape of Type 7 data	

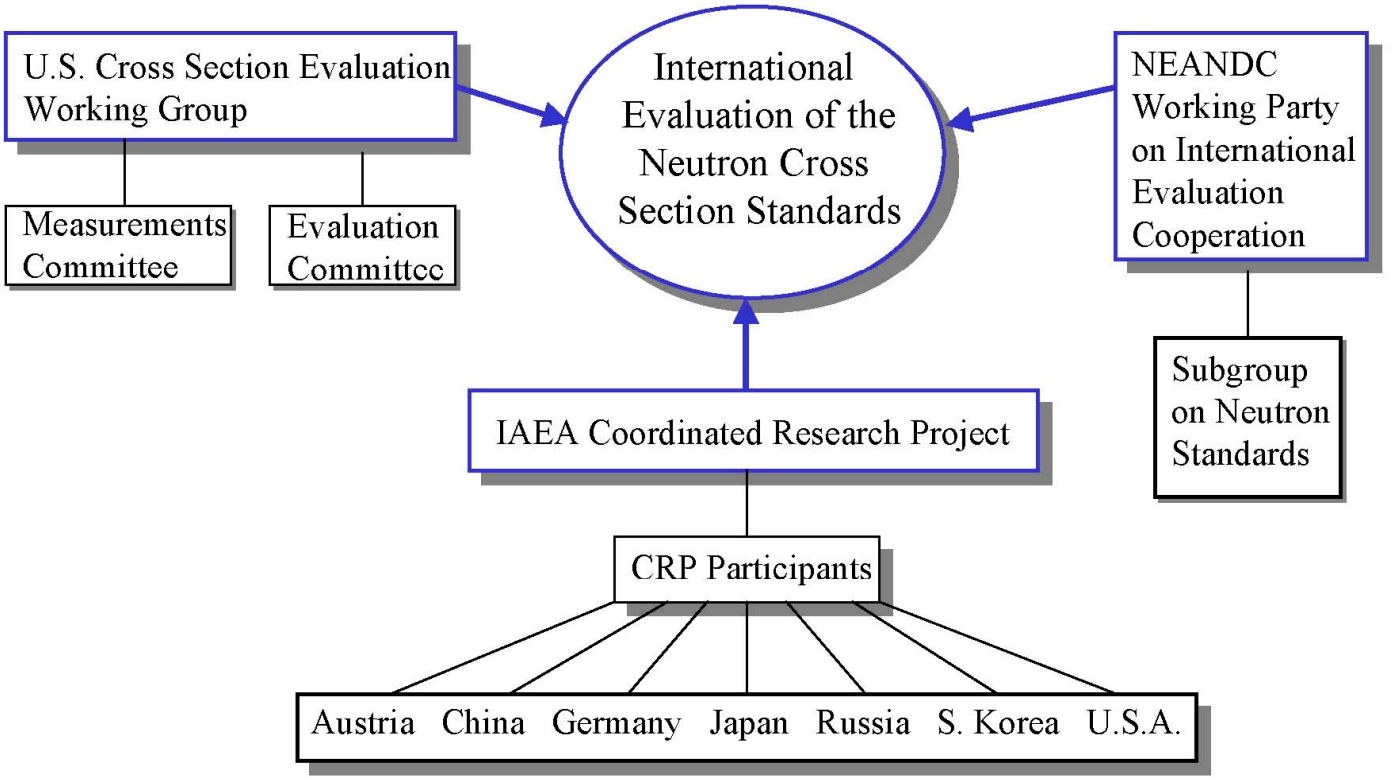
Evaluation Procedure



ENDF/B-VII – the 2006 Standards Evaluation

- ENDF/B-VII evaluation was done realizing it was important to have **international involvement** to provide improved evaluations.
  - To make this happen, an IAEA Data Development Project was initiated focused on the maintenacce of the neutron cross section standards. This project should provide a method for obtaining standards evaluations that are up-to-date whenever they are needed by any nuclear data evaluation project, not just the ENDF/B files.
  - The IAEA provided a Coordinated Research Project with participants from several countries
  - We obtained mostly experimental support from the NEANDC WPEC.
    - Subgroup on Neutron Standards
  - The CSEWG supported the effort
    - Measurements Committee
    - Evaluation Committee
- The IAEA support was very important in actually producing the ENDF/B-VII standards evaluations.
- The methodology was very similar to that used for the ENDF/B-VI evaluations but two independent R-matrix codes were used.

International Collaboration for the Standards Evaluation



ENDF/B-VII – the 2006 Standards Evaluation (cont.)

- For this evaluation (ENDF/B-VII), many comparisons of codes were made to show consistency.
  - For the two codes used for the R-matrix analyses, EDA and RAC, the results for a simple ^{6}Li+n database were in agreement. The SAMMY code was instrumental in making some comparisons.
  - For the full database, the R-matrix codes gave slightly different results due to different forms of chi-square expression
- For the ENDF/B-VI evaluations there were problems with unusual results combining inconsistent data that were highly correlated. In that case uncertainties were increased to remove the problem.
  - For ENDF/B-VII, the problem of inconsistent data that were highly correlated was looked at in detail leading to studies of different ways of treating the PPP effect.
    - It was decided to accept the Chiba-Smith method to minimize the effect (using percentage uncertainties)
- This evaluation process produced results for all the standards except ^{1}H(n,n) which was an evaluation by Hale, and ^{3}He(n,p) and C(n,n) that were not evaluated (but brought over from the previous evaluation).

ENDF/B-VIII (the 2017 Standards Evaluation)

- The methodology was very similar to that used for the ENDF/B-VI evaluations.
- New evaluiations were obtained for all the standards except ^{3}He(n,p) which was carried over from the last evaluation.
- It was noted that the 30 keV Maxwellian average cross section from this evaluation differed from the value used by the astrophysics community.
  - This led to an investigation that showed there were problems with the Ratyuski and Kaeppeler measurement that was the basis of the astrophysics result.
    - The astrophysics community now has accepted a value consistent with that obtained from our work.
- The 30 keV Au(n,γ) MACS of our data is now a neutron cross section standard
- Work was done on reference cross sections, that are not known as well as the standards but measurements can be made relative to them.
  - High energy reference fission cross section-up to 1 GeV
    - ^{235}U(n,f), ^{238}U(n,f) and ^{239}Pu(n,f)
  - Prompt gamma –ray production reference cross sections
    - ^{10}B(n,$\alpha_1\gamma$) thermal to 1 MeV
    - ^{7}Li(n,n'γ) 0.8 MeV to 8 MeV
    - ^{48}Ti(n,n'γ) 3 to 16 MeV

ENDF/B-VIII (the 2017 Standards) (cont.)

- Fission Neutron Spectra
  - $^{235}U(n_{th},f)$ PFNS, an evaluation was produced
  - $^{252}Cf(sf)$ PFNS several measurements were investigated but no changes were suggested to the Mannhart evaluation.
- Initial work on unrecognized systematic uncertainty (unidentified systematic uncertainty) was done (USU)
  - Assumed no energy dependence (ok for Nu bar ^{252}Cf)
- New thermal constants evaluation using only microscopic data except a Maxwellian experiment by Lounsbury.
- A new C(n,n) cross section evaluation by Hale was used
- A new $^{1}H(n,n)$ cross section evaluation by Hale that extends to 20 MeV
- The $^{3}He(n,p)$ cross section evaluation was carried over from the previous evaluation.

Work Leading to a New Standards Evaluation

- Important work was done so that ratios of SACS, that are known very well, could be used
  - GMAP can not use that data
    - Georg Schnabel has produced a Python based code that is in agreement with GMAP but can use ratios of SACS. It is GMAPy.
      - A number of different GMAPY minimization procedures are being examined with this code
        - Maximum Likelihood Estimation (MLE) and Markov Chain Monte Carlo (MCMC) have been investigated.
          - They are both valid and sound statistical approaches. The differences between them may provide as an estimate of the uncertainty due to the evaluation methods.
  - GMAPy will be investigated for possible estimates of energy dependent USU as well as the cross section evaluations
  - With GMAPy it was possible to determine the accuracy of the PPP correction used for the 2017 standards.
    - Note it was understood that the correction was minimized, not determined exactly, for previous standards evaluations.
      - The difference is in almost all cases less than 0.4%

Work Leading to a New Standards Evaluation (cont.)

- Denise Neudecker may discuss the AIACHNE collaboration work on the evaluation of the ^{252}Cf(sf) PFNS, I will only emphasize the importance of having that standard updated, agreeing with the Mannhart result and in a form that can conveniently updated in the future.
- An updated evaluation of the thermal constants (TNC) is underway.
  - Noguere has made improvements to the TNC database established by Axton, including new measurements.
    - The present TNC database supports all quantity types and correlations that were in Axton's work.
    - The TNC evaluation will use GMAPY with the TNC database and the existing GMAPY database.
      - This should lead to consistent results for ^{235}U and ^{239}Pu cross sections over a wide range of neutron energies.
    - Previously, rather than including the entire TNC database, the results of evaluations with the associated variance-covariance data, were used as a second independent data input subset to the analysis.
    - There are still concerns about whether high energy cross sections should impact the TNC.
  - The status of the TNC results is still under discussion.

Work Leading to a New Standards Evaluation (cont.)

- An R-matrix analysis is underway for the hydrogen standard, that has been limited to 20 MeV.
  - A database being developed by Paris and Hale at LANL will allow an evaluation with an extended energy range to be produced.
    - The present results are up to 100 MeV with the objective of extending the evaluation to 250 MeV.
      - Consideration must be given to a possible hydrogen "composite evaluation" that will allow data to as high as 1 GeV for use by experimenters.
- Work continues on an R-matrix analysis for the ^{6}Li(n,t) standard
  - Paris and Hale did an evaluation for ENDF/B-VIII.1 that extended beyond the standards energy region.
    - In the standards energy region, It agreed with the standard.
  - Initial efforts for an independent ^{6}Li(n,t) evaluation at LLNL by Thompson are underway.
  - It is hoped that the ^{6}Li(n,t) standard can be extended to above 1 MeV, the present maximum energy.
  - Additional R-matrix work is being considered.

Work Leading to a New Standards Evaluation (cont.)

- An evaluation of the standards will be done by combining the results of R-matrix and GMAPY analyses.
- A new R-matrix evaluation of the boron standards will not be done.
  - Some changes in that cross section may come from ratio data in the GMAPy fit
- This will be the first time we will use the IAEA Data Development Project focused on the maintenacce of the neutron cross section standards.
  - There will not be an ENDF/B-IX evaluation immediately associated with this evaluation.
  - Use of the standards from this evaluation requires associating the resulting cross sections with this process.