Charged Particle Evaluations

plans for post - ENDF/B-VIII.0

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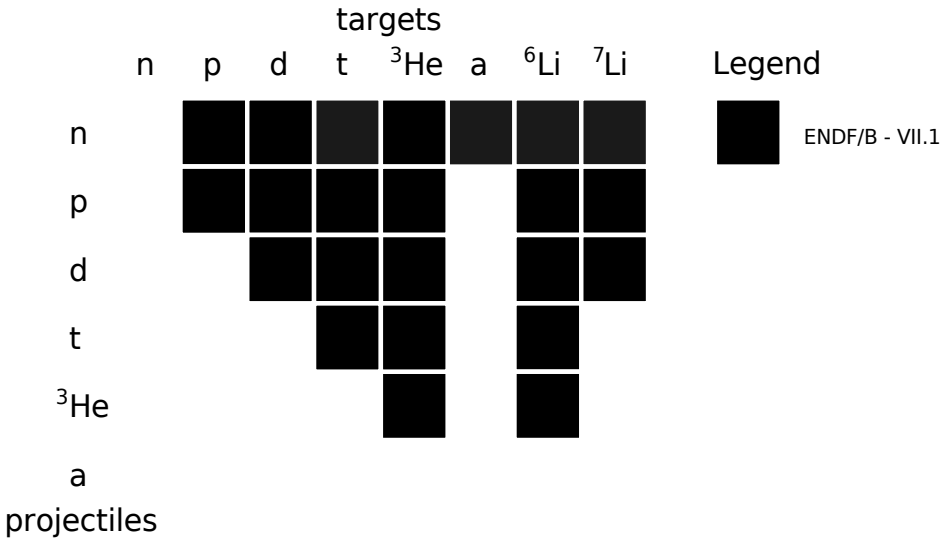
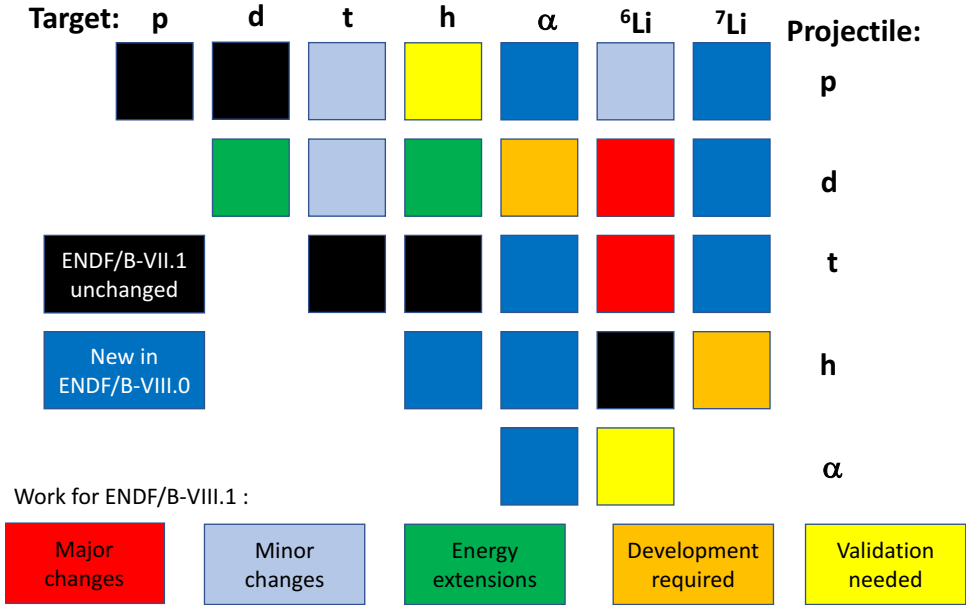
Past, Present and Future Evaluations

Evaluations in ENDF/B-VII.1



Evaluations in ENDF/B-VIII.0 and 1



Submitted from LLNL in October 2016:

ENDF for a+a, d+7Li, h+h, h+a, p+a, p+7Li, t+a, t+7Li

Thermonuclear Reaction Library

- Legacy ECPL/ENDL99 evaluations
  - Incident charged particles (p,d,t,He3,He4), light targets Z<=3 (p,d,t,He3,He4,Li6,Li7)
  - R.M. White, D.A. Resler, S.I. Warshaw 'Evaluation of Charged-Particle Reactions for Fusion Applications,' Proc. from Nuclear Data for Sci. and Tech., Ed. S.M. Qaim, Juelich, Fed. Rep. Germany, 13-17 May (1991)
  - S.T. Perkins, D.E. Cullen, 'Elastic Nuclear plus Interference cross sections for light-charge particles' Nucl. Sci. Eng. 77, 20-39 (1981)

- 2010 evaluations at LLNL by Petr Navratil, David Brown & Chris Hagmann
  - Main sources for new evaluations
    - Descouvemont R-Matrix analysis
      - P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, E. Vangioni-Flam, Atomic Data & Nucl. Data Tables 88, 203 (2004)
    - NACRE (Nuclear Astrophysics Compilation of REaction rate)
      - C. Angulo et al., Nucl. Phys. A656 (1999)3-187
    - Experimental data not in EXFOR

- Include also parts from:
  - LANL n+n evaluation by Gerry Hale
  - JENDL-4 n+d, n+He3 evaluations

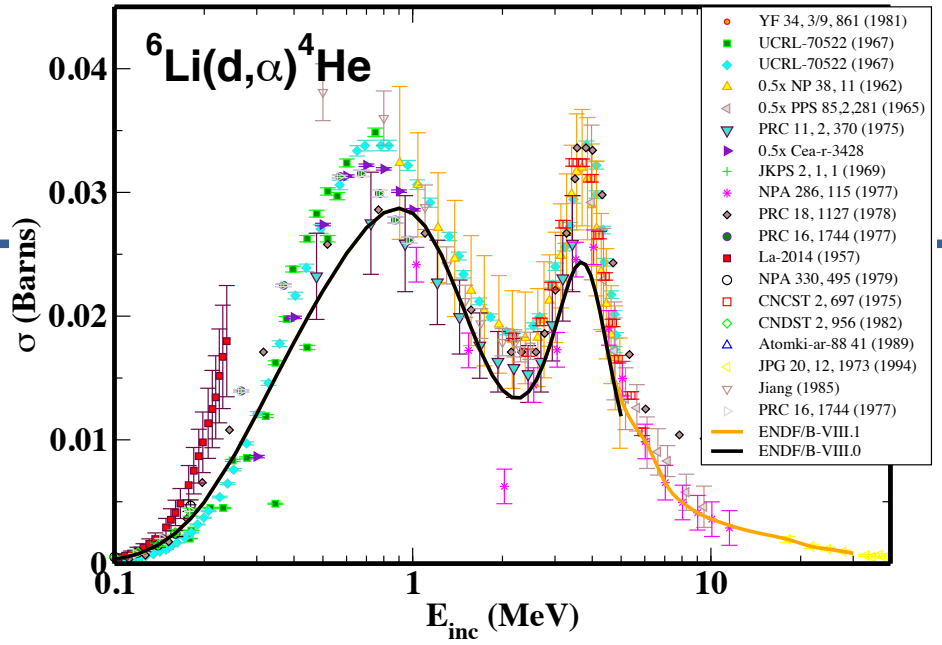
- All the new evaluations are already in ENDL2011, and tested in applications.

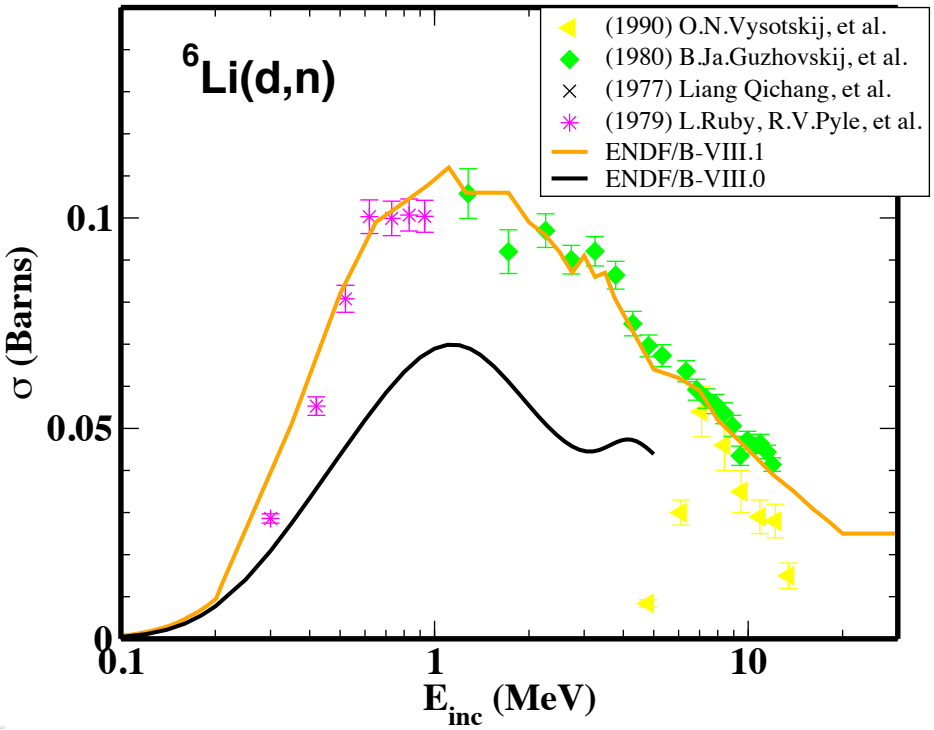
Major Improvements

- d+Li6 evaluation
- t+Li6 evaluation

d+Li6 evaluation

- ENDF/B-VIII.0 (Page 2004)
  - (d,el), (d,n_0), (d,p_0), (d,a_0)
- ENDF/B-VIII.1 (Navratil 2010)
  - (d,el) from ENDF (extended to higher energies)
  - (d,a) from ENDF (up to 4.55 MeV)
    - extended to higher energies to match data from [3,4]
    - ENDF low, needs re-evaluating
  - (d,n+He3) from ECPL



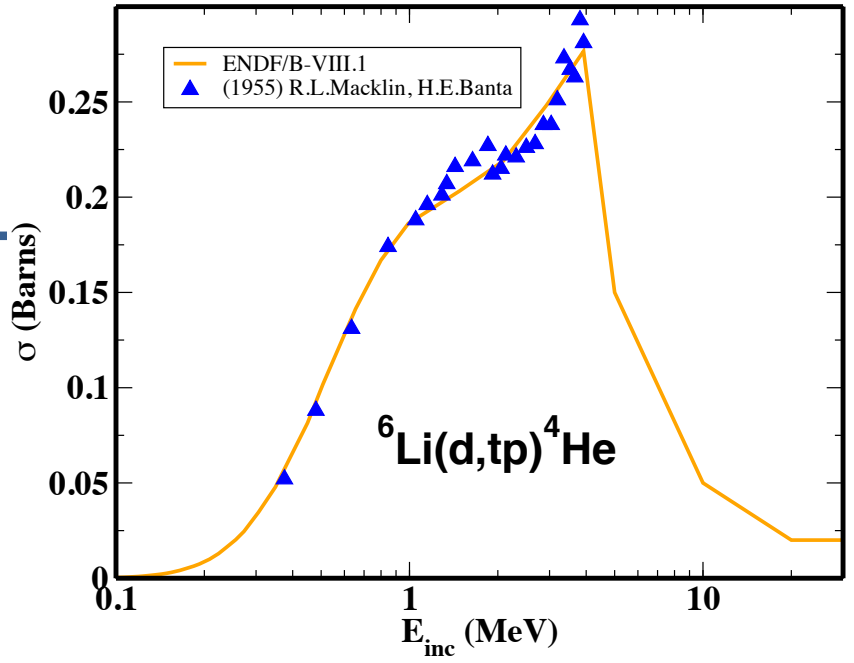


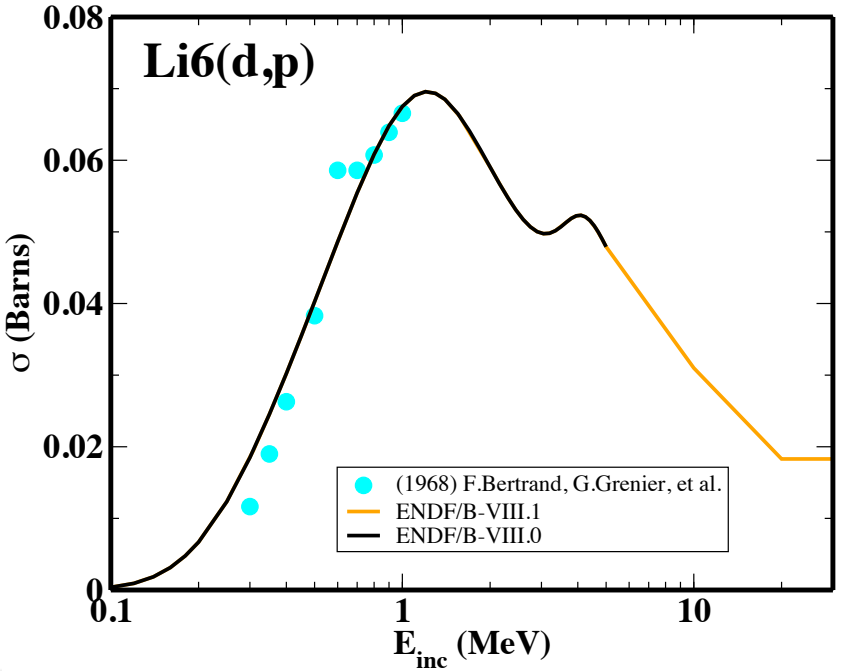
[3] R. Risler, W. Gruebler, A. A. Debenham, V. Koenig, P. A. Schmelzbach, D. O. Boerma, Nucl. Phys. A 286, 115 (1977)

[4] N Arena, I Ya Barit, S Cavallaro, A d'Arrigo, G Fazio, G Giardina, V V Ostashko, M Sacchi, V N Urin and S V Zuyev, J. Phys. G 20, 12, 1973 (1994)

d+Li6 evaluation

- ENDF/B-VIII.0 (Page 2004)
  - (d,el), (d,n_0), (d,p_0), (d,a_0)
- ENDF/B-VIII.1 (Navratil 2010)
  - (d,n) from ECPL
  - (d,p) from ENDF (extended to higher energies)
  - (d,t+p) from ECPL, expt data labeled as (d,t)

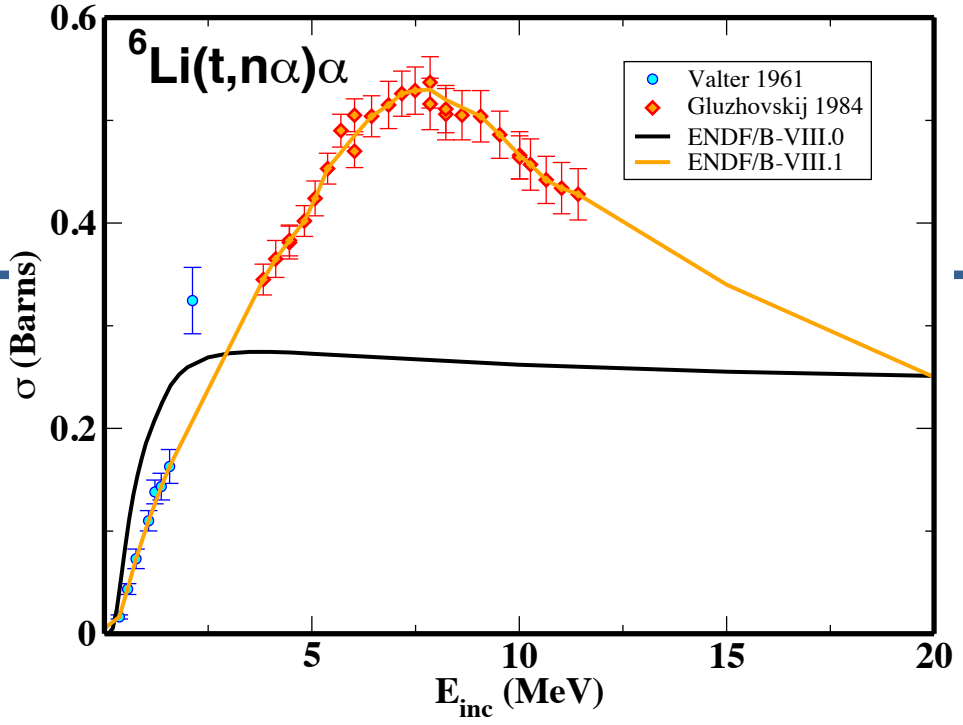


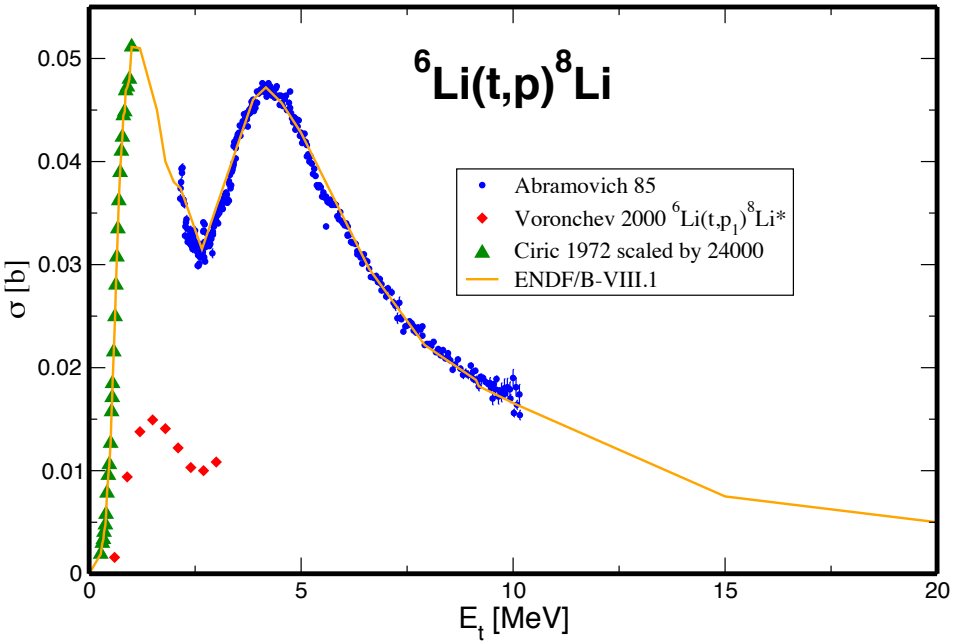


t+Li6 evaluation

- ENDF/B-VIII.0 (Hale 2001)
  - (t,el), (t,na), (t,d_0)
- ENDF/B-VIII.1 (Navratil, Brown, Hale 2010)
  - (t,el) from ENDF
  - (t,2n) from ECPL
  - (t,na)
    - Based on data by Valter et al. [3] and Gluzhovskij et al. [4]
    - Angular distributions: From ECPL
  - (t,p)
    - Based on data by Abramovich [7].
    - Un-normalized data by Ciric [6] scaled by 24000 to match [7]
    - Voronchev data [5] for cross section of 8Li excited state seems to justify existence of peak around 1.5 MeV
    - Angular distributions: proton distribution same as neutron distribution from the (n2a) reaction, ignoring the mass differences
  - (t,d) from ENDF

[3] A.K.Valter, P.I.Vacet, L.Ja.Kolesnikov, S.G.Tonapetjan, K.K.Chernjavskij, A.I.Shpetnyj, Atomnaya Energiya 10, (6), 577 (1961)
[4] B.Ja.Guzhovskij, S.N.Abramovich, A.G.Zvenigorodskij, S.V.Trusillo, Prikladnaya Yadernaya, Spektroskopiya 13, 135 (1984)
[5] V T Voronchev, V I Kukulin, J. Phys. G: Nucl. Part. Phys. 26 L123 (2000)
[6] D.Ciric, B.Stepancic, R.Popic, D.Stanojevic, M.Aleksic, Fizika, 4, 193, (1972)
[7] S.N.Abramovich, B.Ja.Guzhovskij, A.G.Zvenigorodskij, S.V.Trusillo, S.A.Dunaeva, Izv. Rossiiskoi Akademii Nauk, Ser.Fiz. 50, (1), 65 (1986)





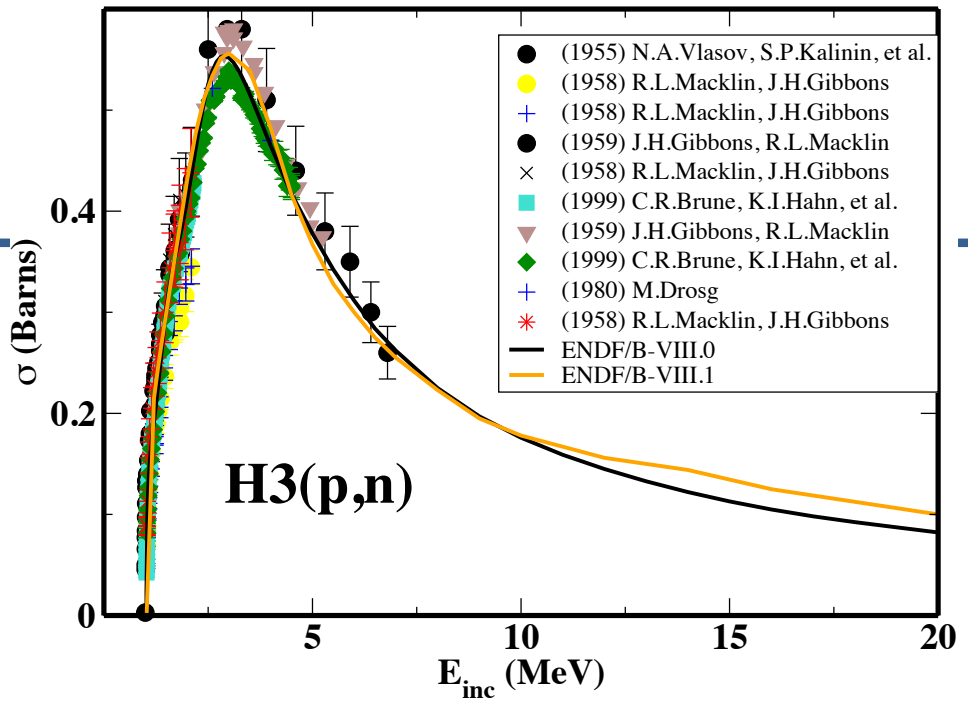
Minor Improvements

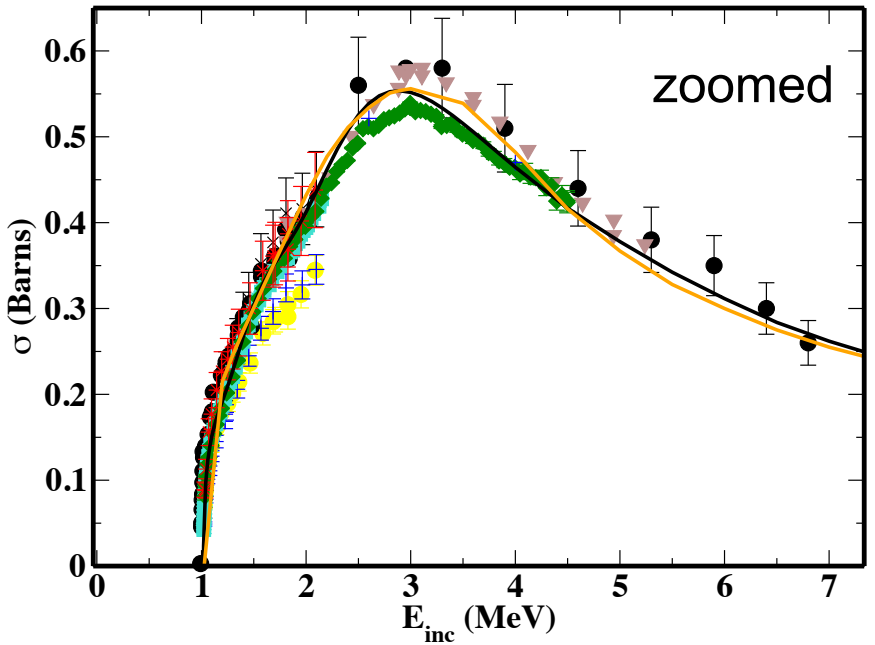
- Better fits within error bars
  - p+H3 evaluation p+t
  - p+Li6 evaluation
  - d+t evaluation

- Adding gamma capture channels
  - p+H3 evaluation p+t
  - d+t evaluation

p+H3 evaluation

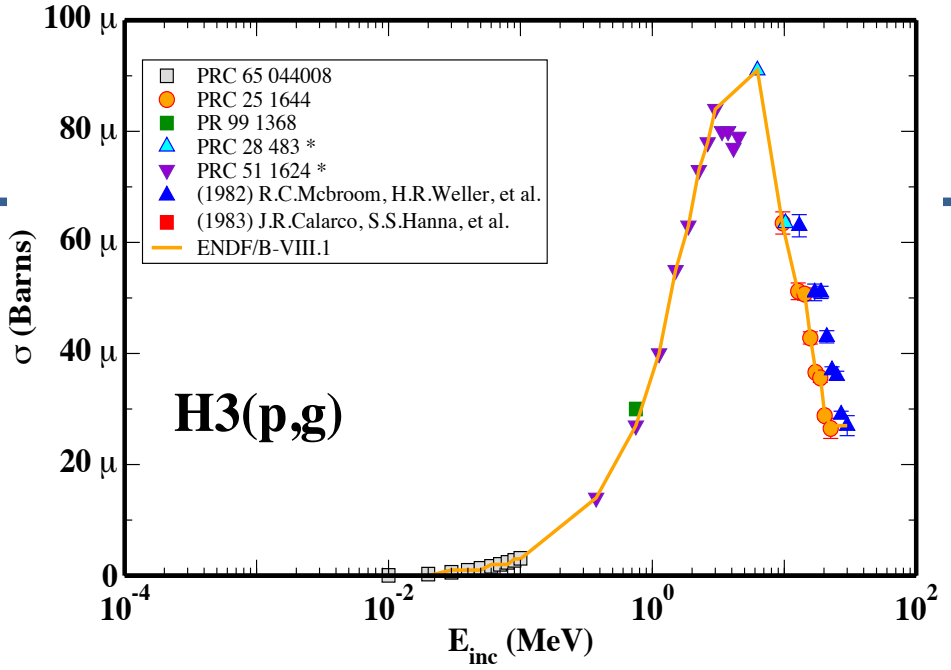
- ENDF/B-VIII.0 (Hale 1999)
  - (p,el), (p,n_0), (p,d_0) [0-12 MeV]
- ENDF/B-VIII.1 (Navratil et al., 2009)
  - (p,el) from ECPL
  - (p,n_0) from ECPL (ENDF newer fit with more recent data)
  - (p,d_0) from ENDF/B-VIII.0
    - An extension to 20 MeV is given for the T(p,n) reaction, based on the inverse of the 3He(n,p) reaction given in the ENDF/B file.
  - (p,g) fit to 5 new data sets from PRC
    - [3] Phys. Rev. C 65: 044008 (2002)
    - [4] McBroom et al., Phys. Rev. C 25, 1644 (1982) [in EXFOR]
    - [5] Phys. Rev. 99, 1368 (1955).
    - [6] Calarco et al., Phys. Rev. C 28, 483 (1983) [EXFOR problem]
    - [7] Phys. Rev. C 51, 1624 (1995)

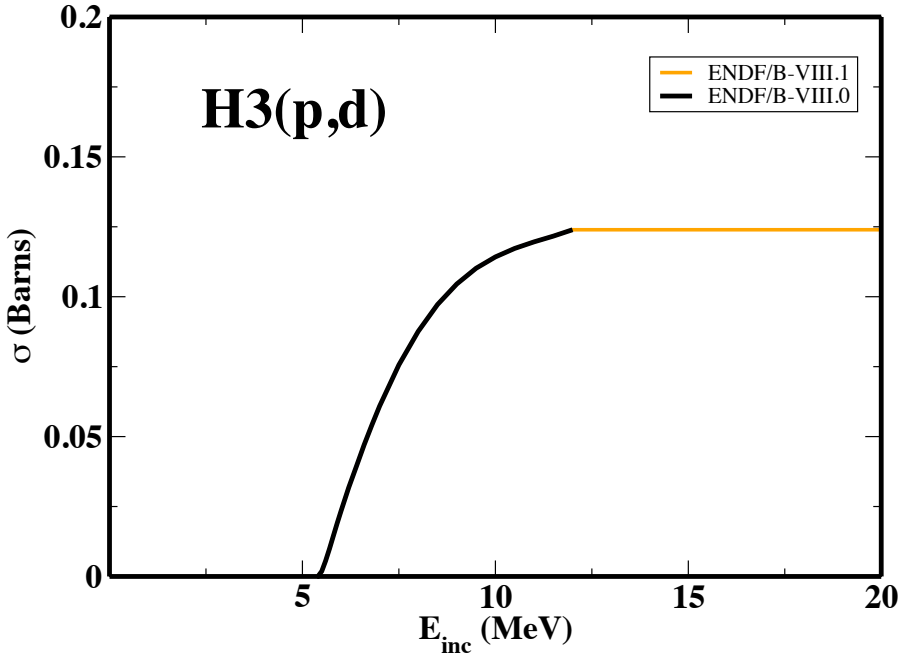




p+H3 evaluation

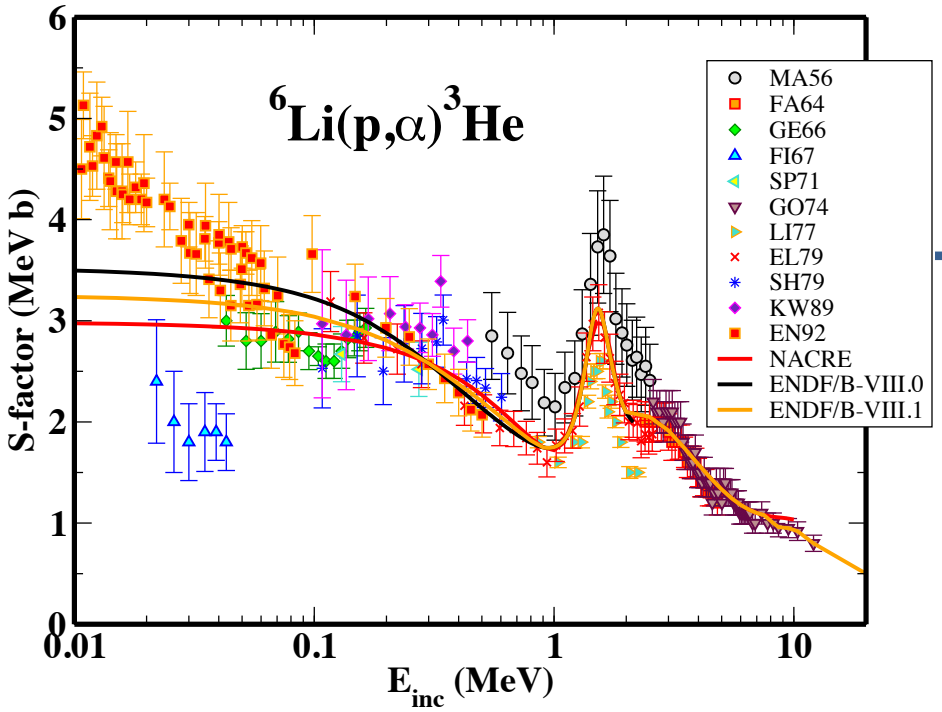
- ENDF/B-VIII.0 (Hale 1999)
  - (p,el), (p,n_0), (p,d_0) [0-12 MeV]
- ENDF/B-VIII.1 (Navratil et al., 2009)
  - (p,el) from ECPL
  - (p,n_0) from ECPL (ENDF newer fit with more recent data)
  - (p,d_0) from ENDF/B-VII.0
    - An extension to 20 MeV is given for the T(p,n) reaction, based on the inverse of the 3He(n,p) reaction given in the ENDF/B file.
  - (p,g) fit to 5 new data sets from PRC
    - [3] Phys. Rev. C 65: 044008 (2002).
    - [4] McBroom et al., Phys. Rev. C 25, 1644 (1982) [in EXFOR]
    - [5] Phys. Rev. 99, 1368 (1955).
    - [6] Calarco et al., Phys. Rev. C 28, 483 (1983) [EXFOR problem].
    - [7] Phys. Rev. C 51, 1624 (1995).

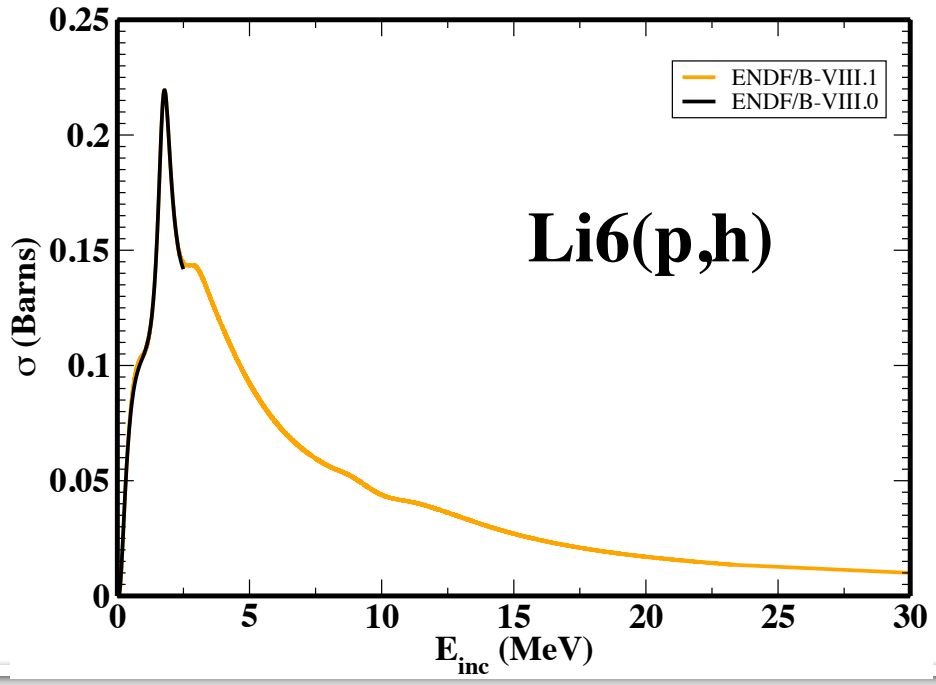




p+Li6 evaluation

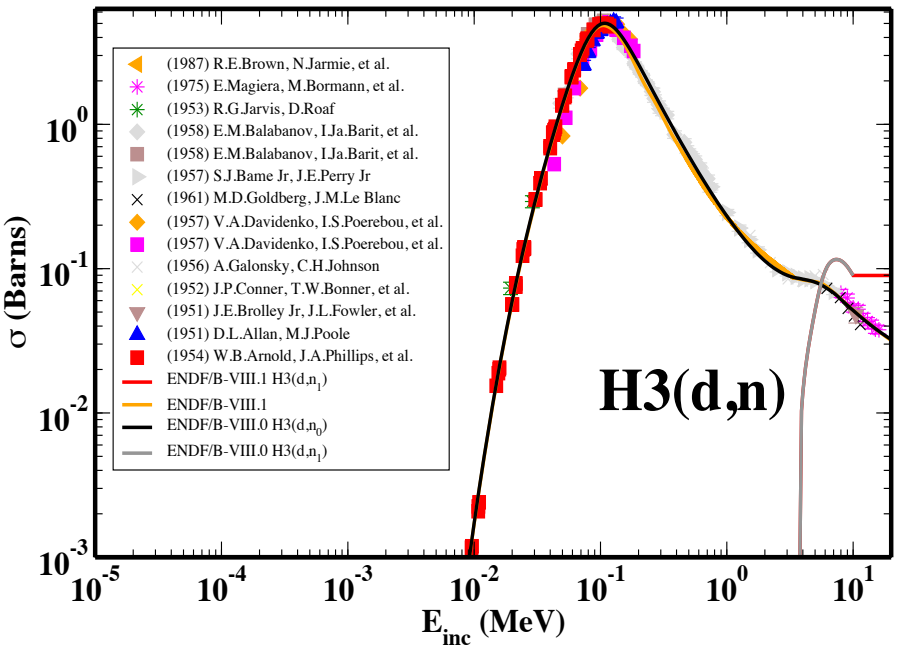
- ENDF/B-VIII.0 (Hale 2001)
  - R-matrix analysis of reactions in the A=7 system, which included data for the 6Li(p,p) and 6Li(p,3He) reactions at energies up to about 2.5 MeV.
  - (p,el), (p,He3)
- ENDF/B-VIII.1 (Navratil et al. 2010)
  - (p,el) from ECPL and ENDF
  - (p,He3) cross section from Hale, NACRE and Gould
    - 0 - 0.9 MeV average of NACRE [2] and Hale S-factors
    - 0.9 - 2 MeV, Hale S-factor
    - 2 - 7.5 MeV, NACRE S-factor
    - 8 MeV - 12 MeV, S-factor data from [3]
    - 12 MeV - 30 MeV, extrapolation
  - Angular distributions: From ECPL.
- NACRE
  - [2] C. Angulo et al., Nucl. Phys. A656 (1999)3-187.
- [3] C. R. Gould, R. O. Nelson, J. R. Williams, J. R. Boyce, "Cross-Section Requirements for Charged-Particle Fusion Reactors: The 6Li(p,3He)alpha Reaction." Nucl. Sci. Eng. 55 (1974) 267

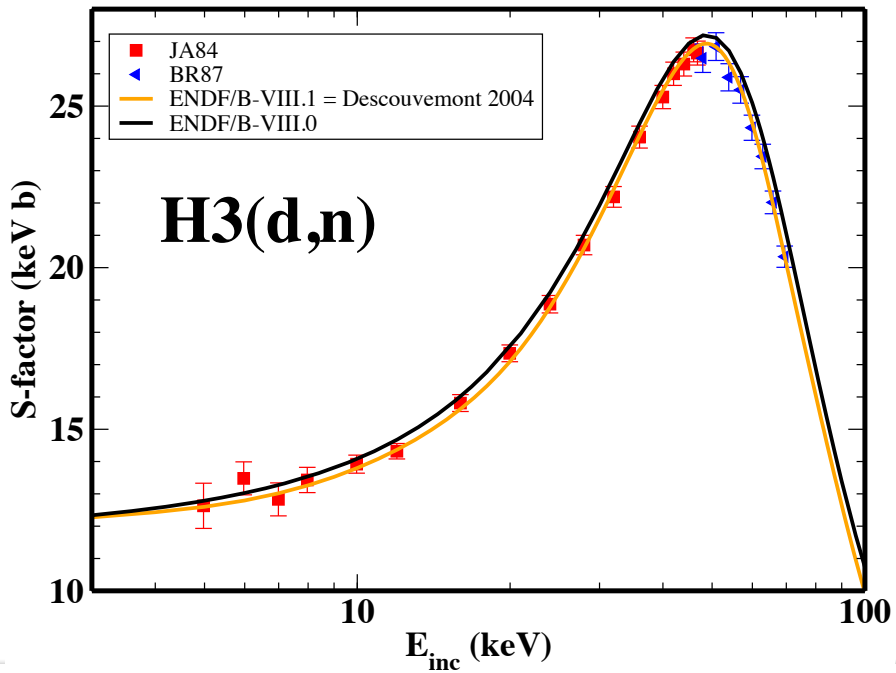




d+t evaluation

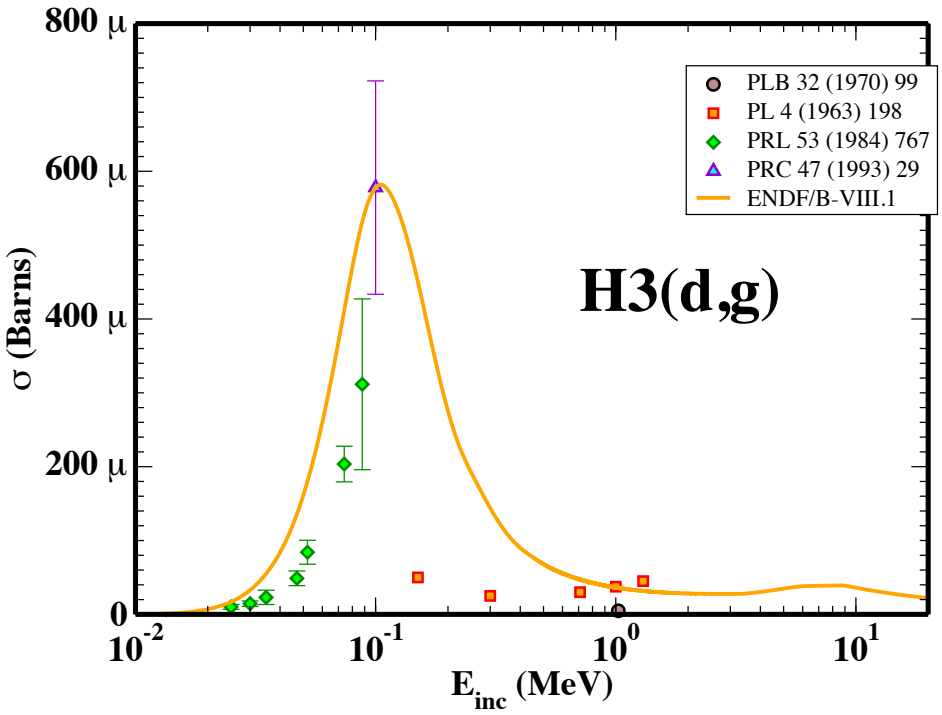
- ENDF/B-VIII.0 (Hale 1995)
  - (d,el), (d,n_0), (d,n_1)
- ENDF/B-VIII.1 (Navratil 2009)
  - (d,el) from ECPL
  - H3(d,n_0)
  - Cross-section:
    - Low energy Descouvemont [3]
    - High energy ECPL
    - Peak at 105 keV of 4.85 b
    - TUNL evaluation peak 4.88 b at 105 keV
    - ECPL 4.99 b at 107 keV
    - ENDF 5.01b at 108 MeV
  - Angular distributions: Taken from ECPL
  - H3(d,n_1)He4* -> p+t
    - ENDF evaluation extended up to 30 MeV
- Decouvemont 2004
  - [3] P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, E. Vangioni-Flam Atomic Data and Nuclear Data Tables 88, 203 (2004)
- [4] Nucl. Phys. A 192 (1972) 609





d+t evaluation

- ENDF/B-VIII.0 (Hale 1995)
  - (d,el), (d,n_0), (d,n_1)
- ENDF/B-VIII.1 (Navratil 2009)
  - d + t -> g + 5He* -> g + n + 4He
  - Cross-section
    - The t(d,g) evaluation is based on Ref. [4]. Several experiments agree that the cross-section ratio is constant at resonance. At higher energies, the ratio appears to rise. In particular, there is a Caltech measurement going up to 9 MeV. Therefore, we did the following:
    - Below 0.4 MeV, we took the ratio 1.2 x 10-4 from the above Ref. [4]
    - From 0.4 to 9 MeV we assumed a linear increase up to 7 x 10-4 according the Caltech data referenced in the above Ref. [4]
    - At higher energies, there is no information. Therefore, we kept the 9 MeV ratio also beyond
    - Note that the EXFOR files with the PRL 53, 767 (84) data appear to be incorrect
  - Angular distributions: Taken from ECPL

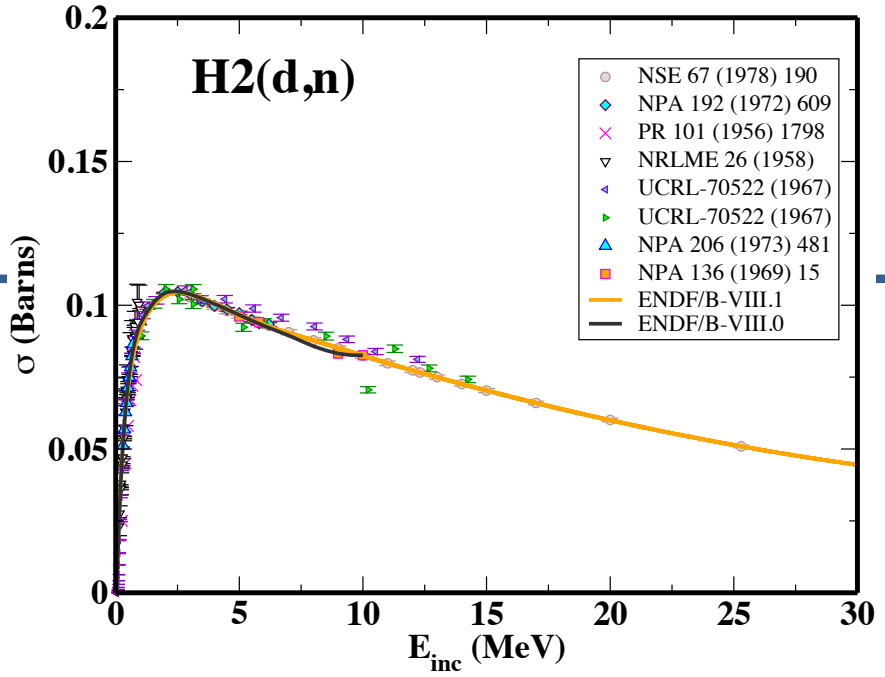


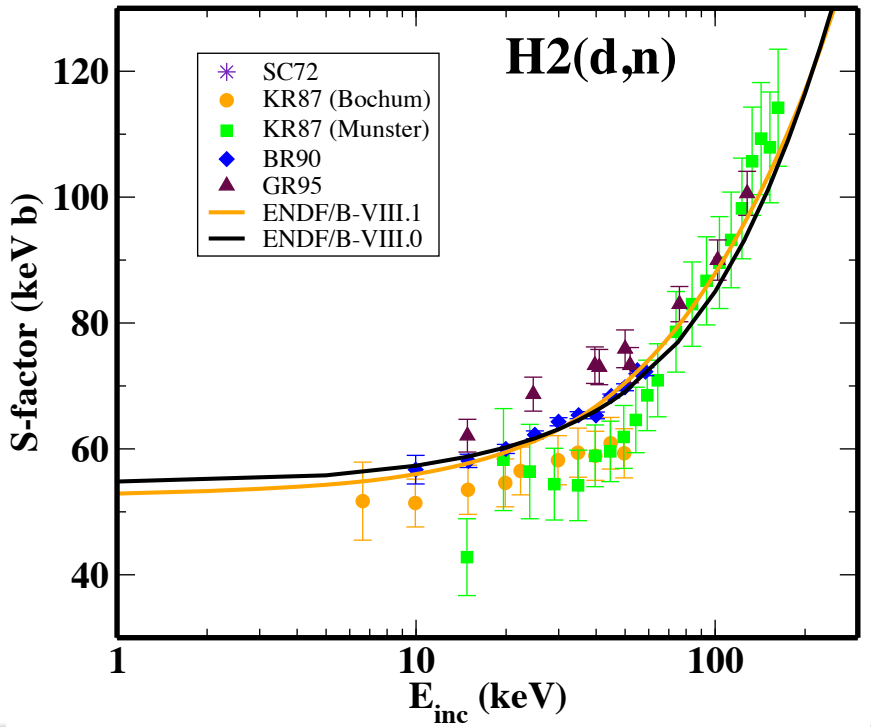
Extensions to higher projectile energies

- d+d evaluation
- d+He3 evaluation d+h

d+d evaluation

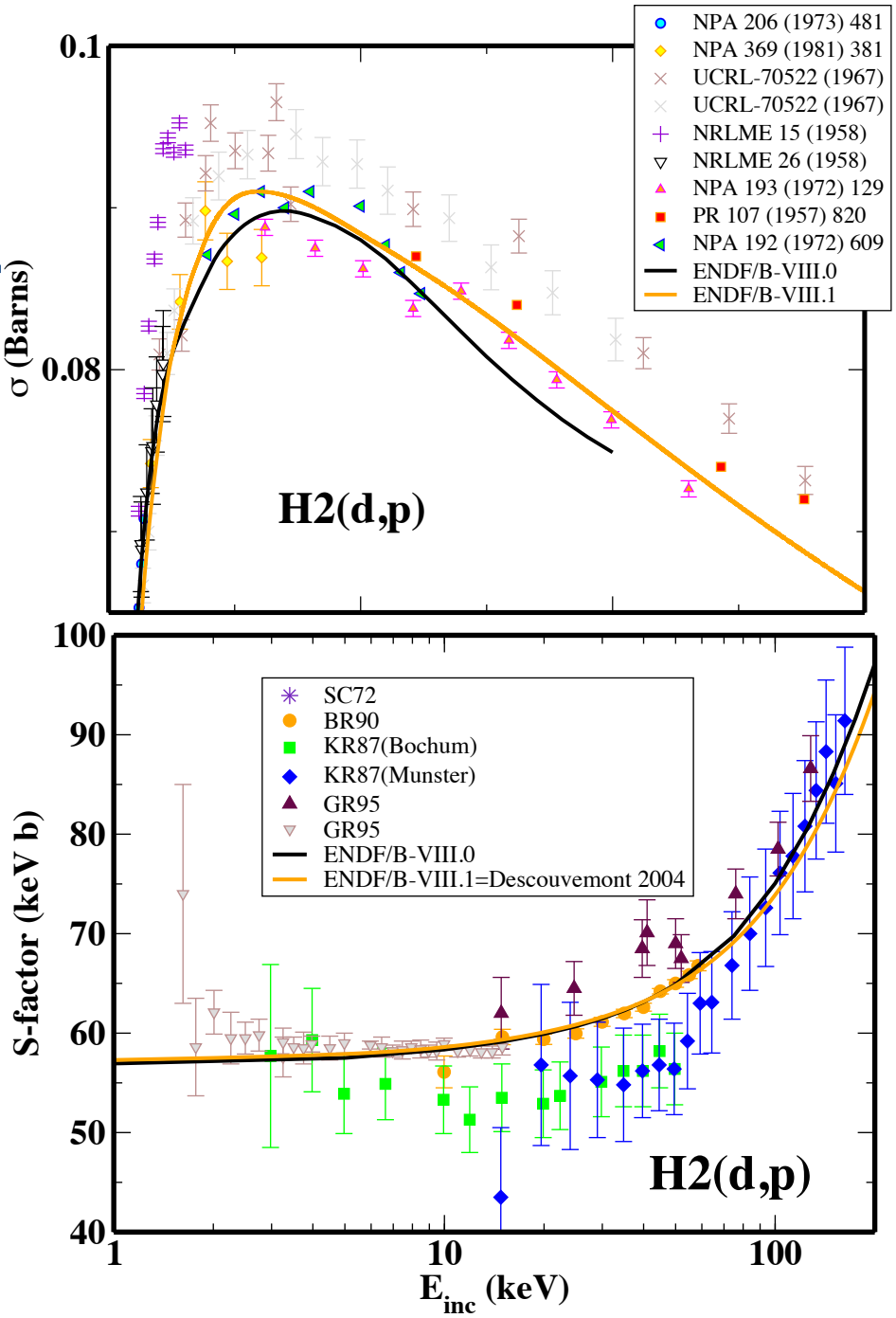
- ENDF/B-VIII.0 (Hale 2001)
  - (d,el), (d,n), (d,p)
- ENDF/B-VIII.1 (Navratil 2009)
  - (d,el) from ECPL
  - H2(d,n) and H2(d,p)
  - Cross-section:
    - < 1.96 MeV Descouvemont [3] S-factor R-matrix
    - 1.96 - 5 MeV spline to Ref [4]
    - > 5MeV ECPL
  - Angular distributions: From ECPL
  - Note: The slight mass differences between the p & n and between the t & 3He were ignored in the creation of the angular distributions in ECPL
- Decouvemont 2004
  - [3] P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, E. Vangioni-Flam Atomic Data and Nuclear Data Tables 88, 203 (2004)
- [4] Nucl. Phys. A 192 (1972) 609





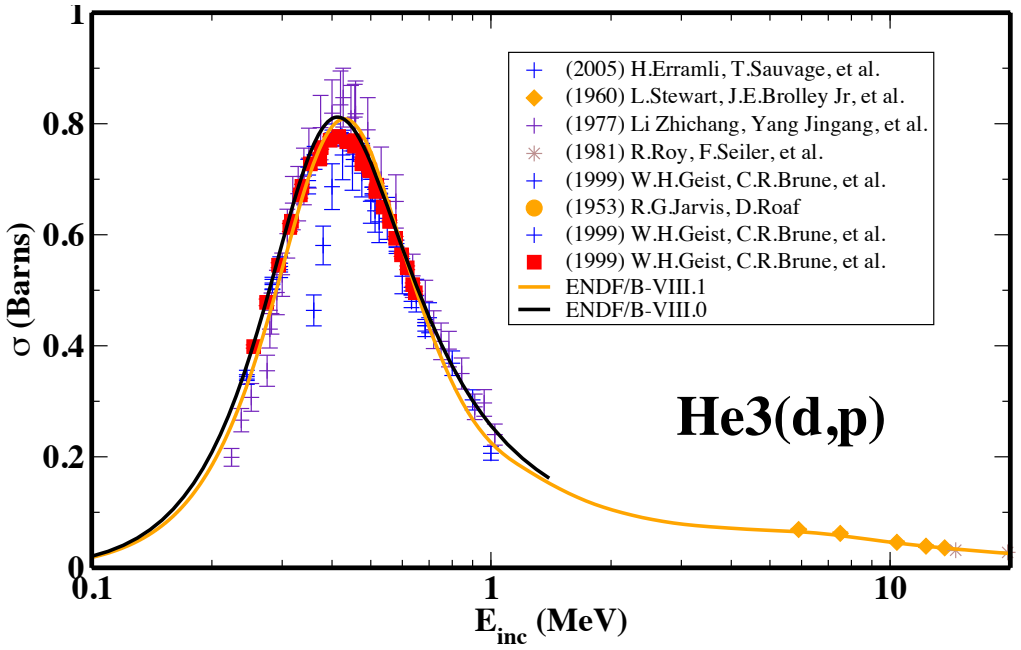
d+d evaluation

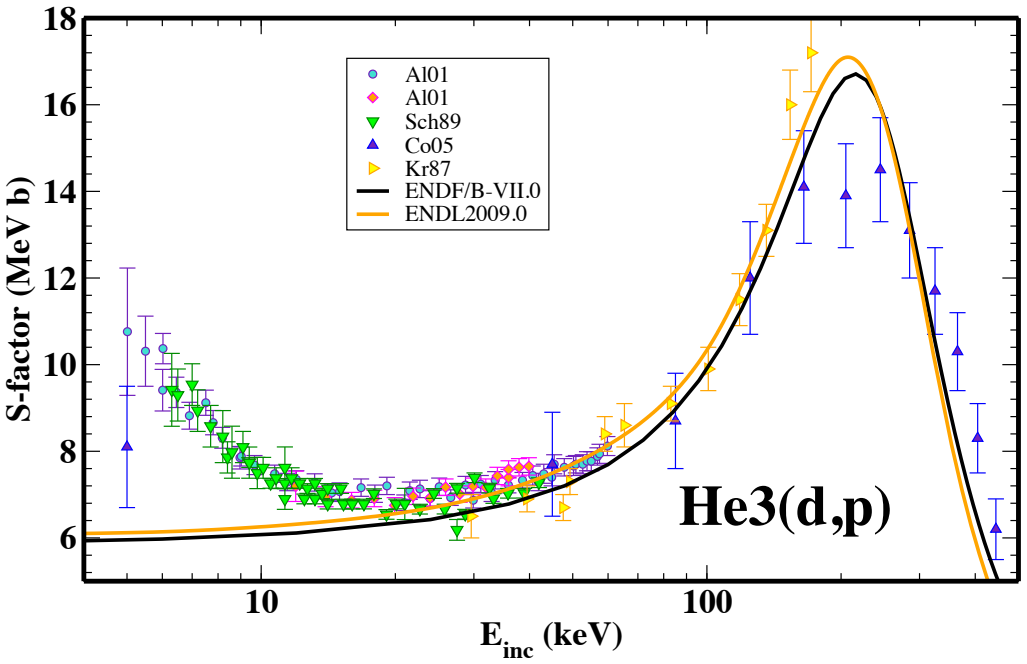
- ENDF/B-VIII.0 (Hale 2001)
  - (d,el), (d,n), (d,p)
- ENDF/B-VIII.1 (Navratil 2009)
  - (d,el) from ECPL
  - H2(d,n) and H2(d,p)
  - Cross-section:
    - < 1.96 MeV Descouvemont [3] S-factor R-matrix
    - 1.96 - 5 MeV spline to Ref [4]
    - > 5MeV ECPL
  - Angular distributions: From ECPL
  - Note: The slight mass differences between the p & n and between the t & 3He were ignored in the creation of the angular distributions in ECPL
- Decouvemont 2004
  - [3] P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, E. Vangioni-Flam Atomic Data and Nuclear Data Tables 88, 203 (2004)
- [4] Nucl. Phys. A 192 (1972) 609



d+He3 evaluation

- ENDF/B-VIII.0 (Hale 2001)
  - (d,el), (d,p_0)
- ENDF/B-VIII.1 (Navratil 2009)
  - (d,el) from ECPL
  - He3(d,p)
  - Cross-section:
    - low energy coming from Descouvemont 2004
    - matched at higher energies with ECPL
  - Angular distributions: From ECPL
    - Note: The slight mass differences between the p & n and between t & 3He were ignored in the creation of the angular distributions in ECPL





Remaining Issues: Development required

- Gamma decay of $^{6}Li(3^{+})$ resonance, after h + ^{7}Li reaction
  - Translate to ENDF MT=801, and convert γ-distribution to lab frame
- Gamma decay of $^{5}He^{*}$ resonance, during d + t reaction
  - Translate to ENDF MT=91 (inclusive n*), with lab distributions for n,He4,γ
- Three-body breakup of deuteron after d+α reaction
  - 2-steps via p + { ^{5}He = α + n resonance}
    - Translate to ENDF MT=600, with LRP=1 for n and He4
  - 2-steps via n + {^{5}Li = α + p resonance}
    - Translate to ENDF MT=50, with LRP=1 for p and He4
  - Direct 3-body decay to α + n + p (no resonances)
    - Translate to ENDF MT=28, MF=3 and 6

Future Evaluations

Use full R-matrix evaluations!!

- If possible, publish R-matrix evaluations from LANL
  - Include all R-matrix parameters
  - Include all fitted data normalization factors
- Convert from EDA format (also AZURE, RAC, FRESCO, SAMMY, HYRMA) to GNDS and then ENDF
  - Using my code Ferdinand.py
  - This is being developed with USNDP funding.
- Then can encourage, monitor and verify new R_matrix fits to data
  - Determine how to fit data above 3-body thresholds
  - Supplement with Hauser-Feschbach models above resonance region
- International effort through IAEA to verify and validate the above R-matrix codes.
  - Marco Pigni explained this in his earlier talk, and showed examples.

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