LLNL Evaluations

CSEWG 2013

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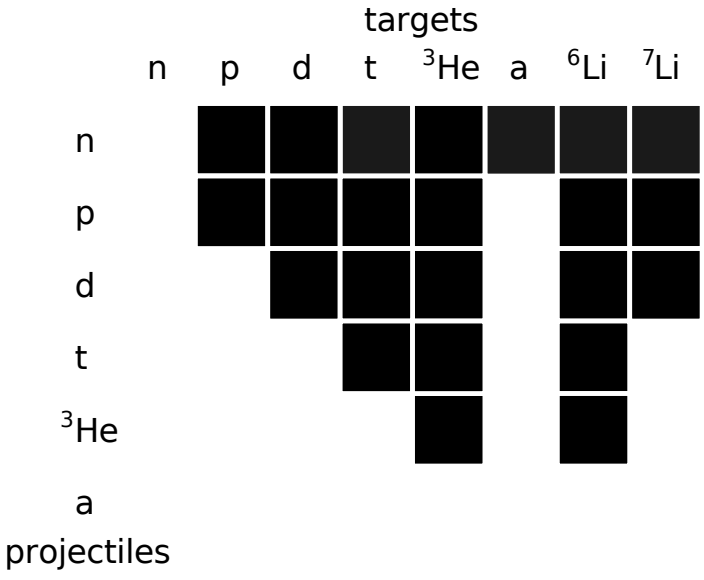
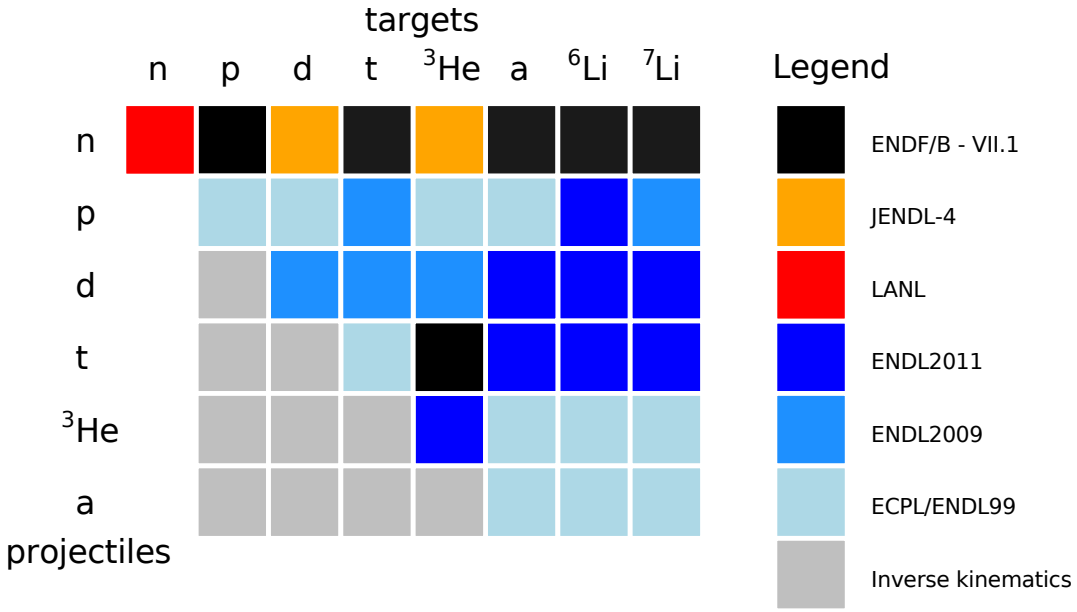
Thermonuclear Reaction Library

- 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)
- New 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
- LANL n+n evaluation by Gerry Hale
- JENDL-4 n+d, n+He3 evaluations
- Inverse kinematics used for remaining evaluations

Evaluations in ENDF/B-VII.1



Evaluations in ENDL2011.0

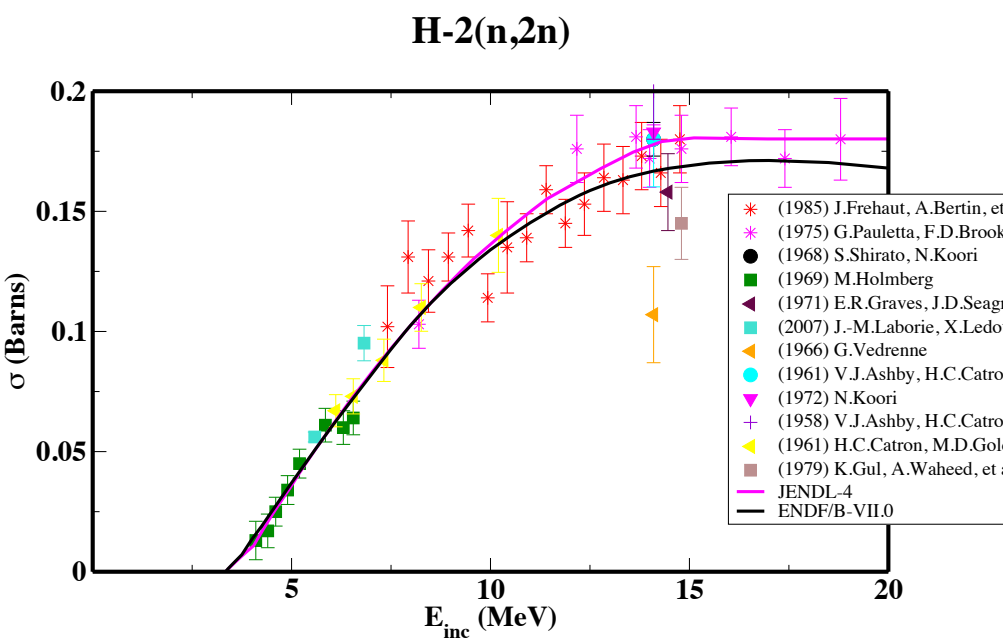


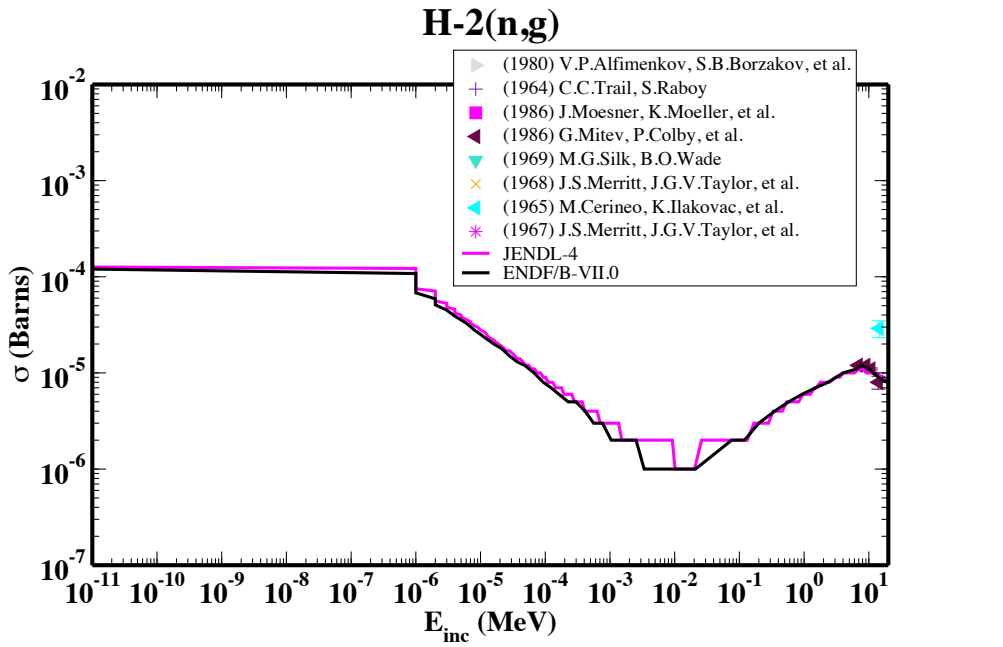
Review of ENDL evaluations

- Following slides review ENDL evaluations
- Highlight differences with ENDF
  - Many plots, maybe not enough time to go over them all here
  - Include them so can view in proceedings
- Many cross sections available in both ECPL and ENDF, similar in value, no data to distinguish
  - ENDL favors ECPL, continuity of data library
  - ENDF may want to keep ENDF if similar to ECPL

n+H2 evaluation

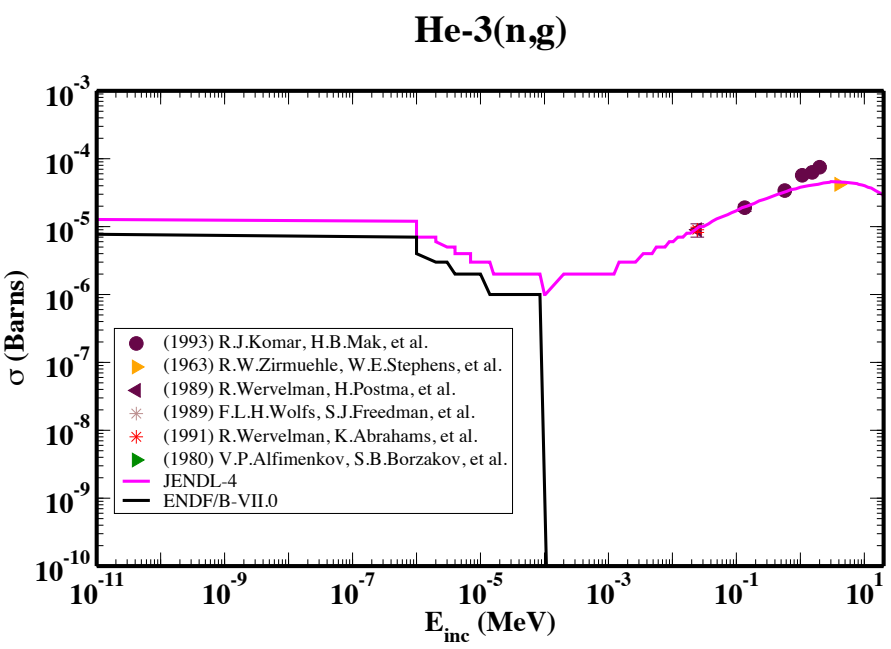
- ENDF/B-VII.0 (Chadwick 1997)
- JENDL-4 revised JENDL-3.3
  - Fadeev calc. for (n,el) ang. dist.
- JENDL-4 (n,2n) better fit to Pauletta (1975) data at high energies
- Differences with (n,g), JENDL-4 staggered

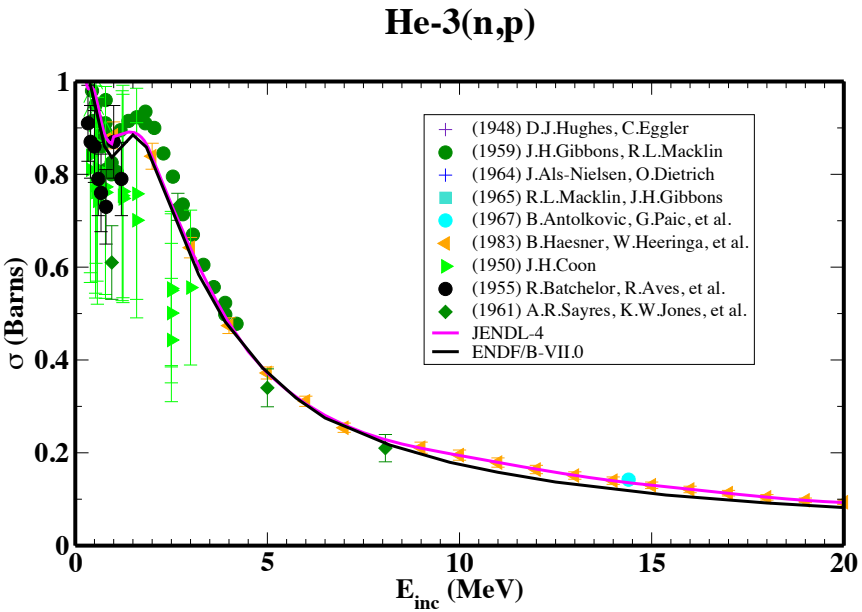


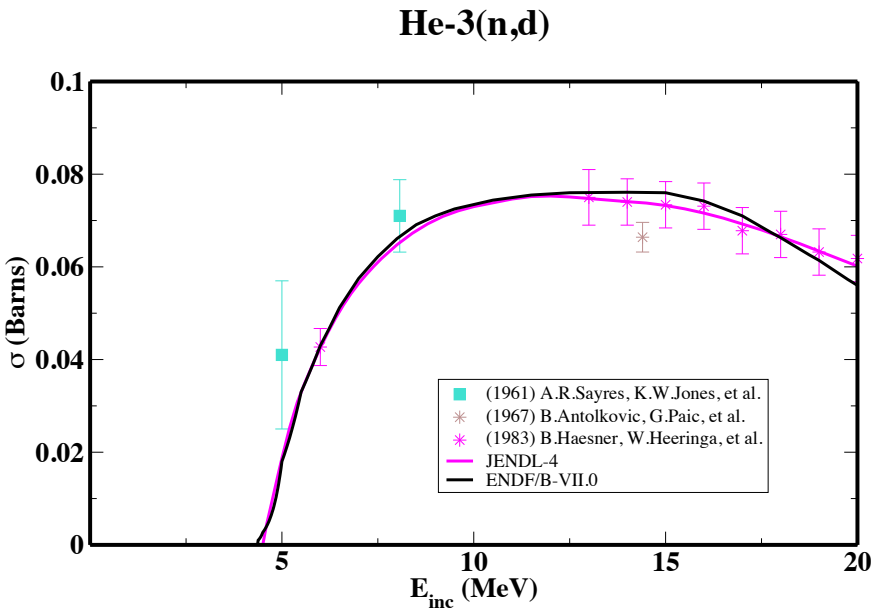


n+He3 evaluation

- ENDF/B-VII.0 (Hale 1990)
- JENDL-4 = JENDL-3.3
  - 1987 evaluation by SHIBATA

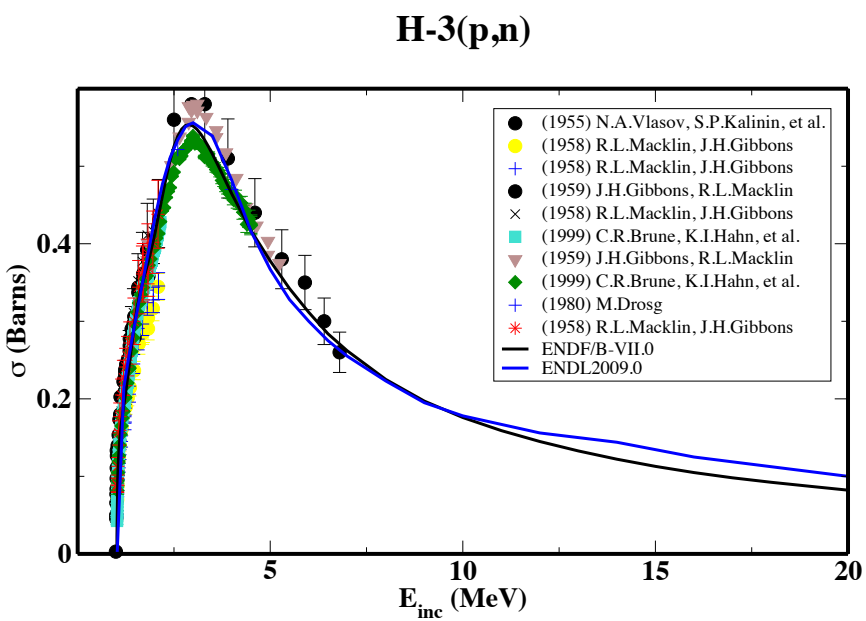


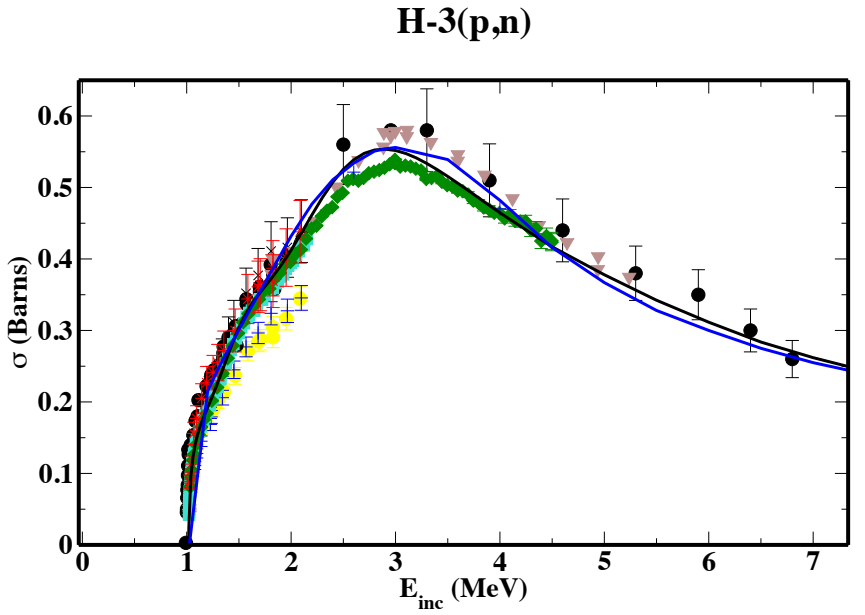




p+H3 evaluation

- ENDF/B-VII.1 (Hale 1999)
  - (p,el), (p,n_0), (p,d_0) [0-12 MeV]
- ENDL2009 (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)





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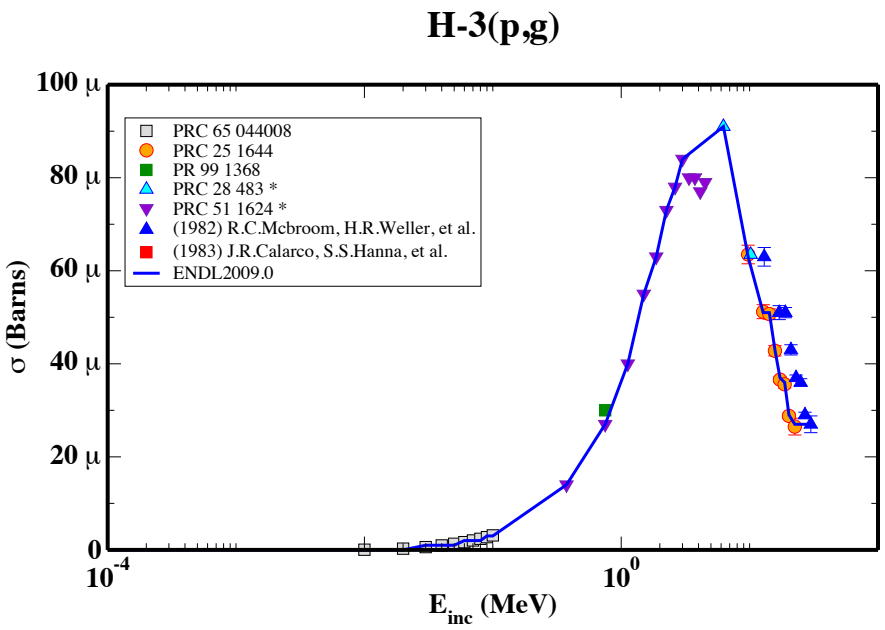
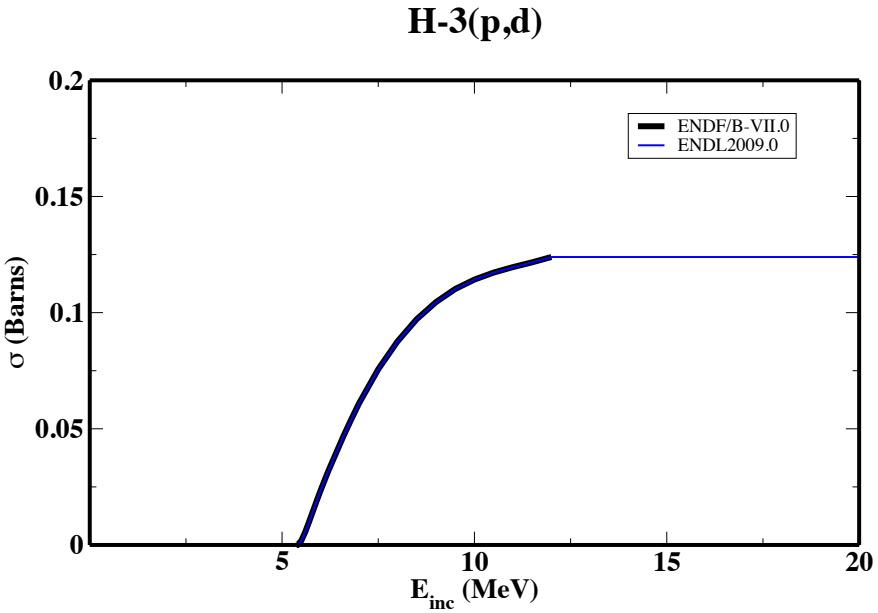
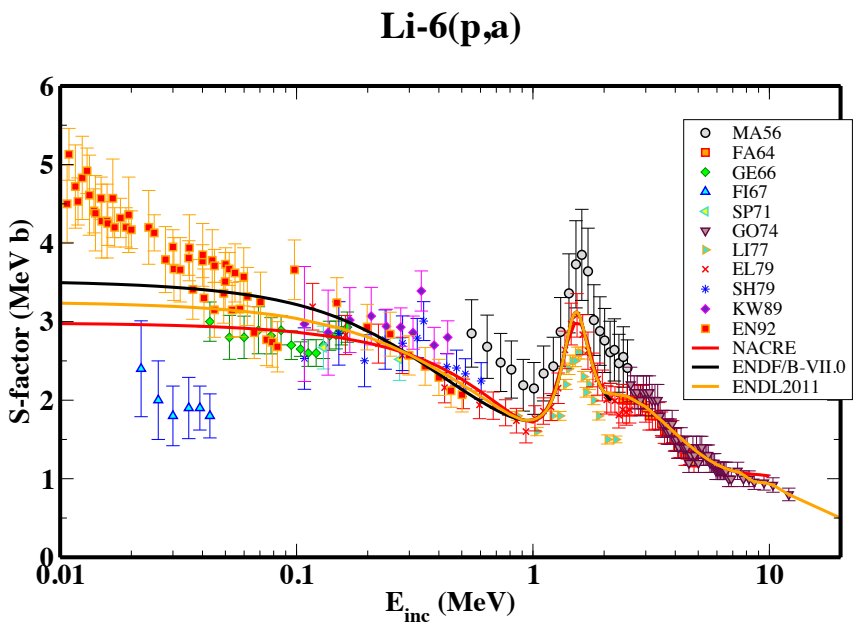
    - [6] Calarco et al., Phys. Rev. C 28, 483 (1983) [EXFOR problem].
    - [7] Phys. Rev. C 51, 1624 (1995).

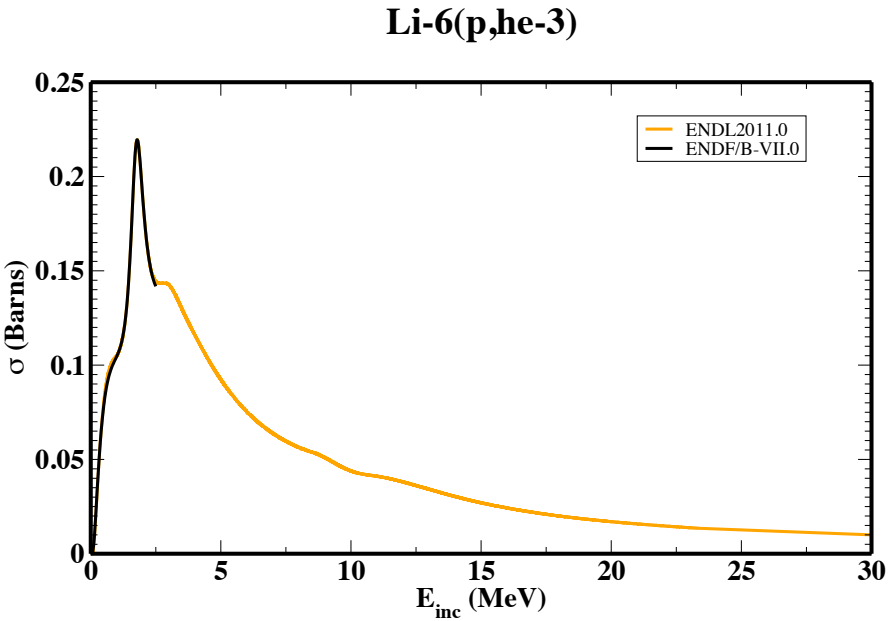




p+Li6 evaluation

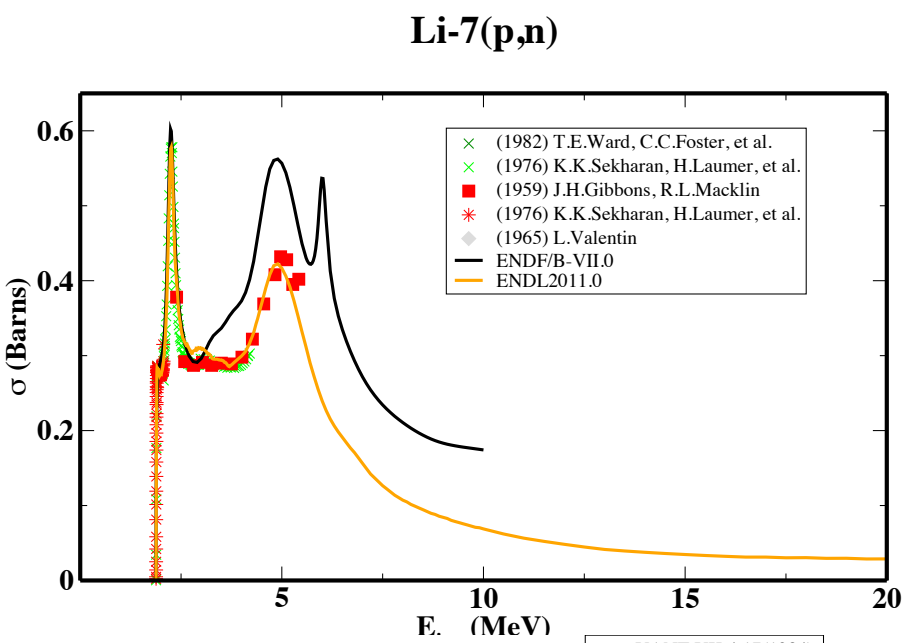
- ENDF/B-VII.1 (Hale 2001)
  - R-matrix analysis of reactions in the A=7 system, which included data for the 6Li(p,p) and 6Li(p,3He) reactions at energies up to about 2.5 MeV.
  - (p,el), (p,He3)
- ENDL2011.0 (Navratil et al. 2010)
  - (p,el) from ECPL and ENDF
  - (p,He3) cross section from Hale, NACRE 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

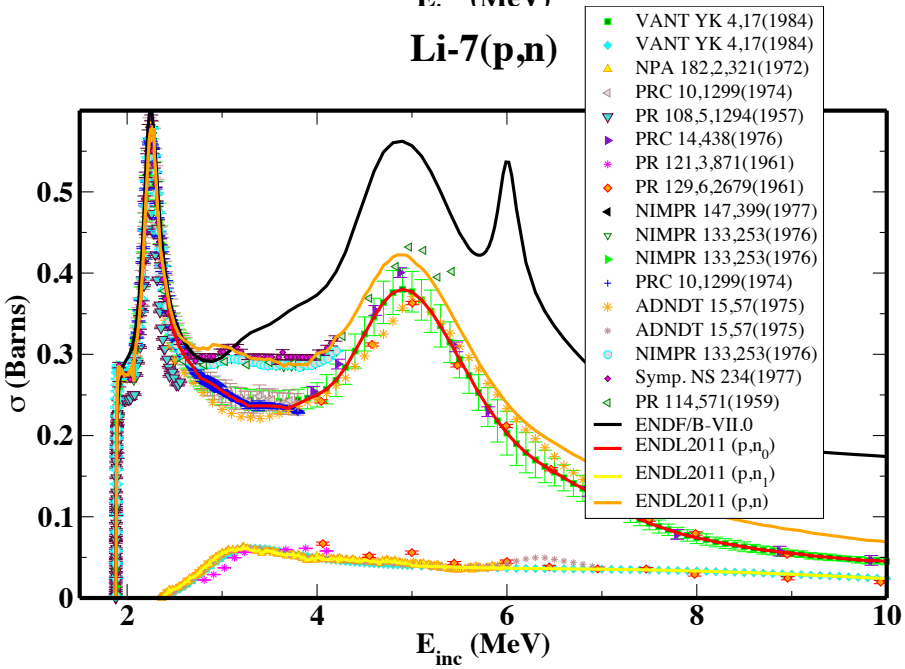




p+Li7 evaluation

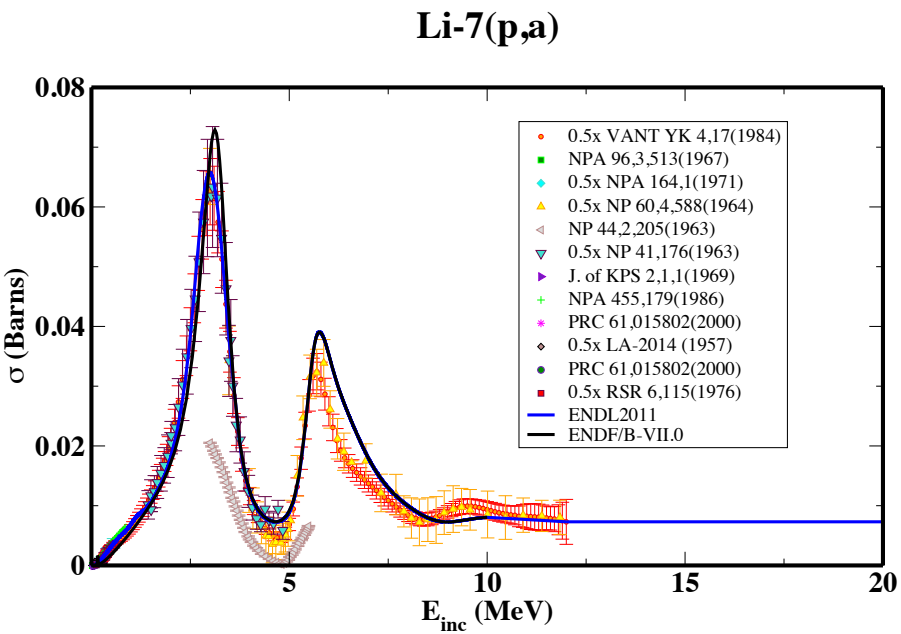
- ENDF/B-VII.1 (Page 2004)
  - (p,el), (p,n'$_0$), (p,d$_0$), (p,α$_0$)
- ENDL2009 (Navratil 2008)
  - 7Li(p,n)
  - Both ECPL and ENDF/B-VII.0 cross-sections were discarded. Evaluation is based purely on data
  - (p,n$_0$) [ground state]:
    - NIMPR 133, 253 (1976) for 0-2.35 MeV
    - PRC 10, 1299 (1974) for 2.4-3.6 MeV
    - VANT YK 4, 17 (1984) for 3.6-25 MeV
    - PRC 14, 438 (1976) for 25-26 MeV
    - Datasets matched with splines.
  - (p,n$_1$) [0.4291 MeV excited state):
    - NPA 182, 2, 321 (1972) for 2.3-5 MeV
    - VANT YK 4, 17 (1984) for 5-25 MeV
    - PRC 14, 438 (1976) for 25-26 MeV
    - Datasets matched with splines
  - Angular distributions
    - Taken from Page's ENDF/B-VII.0 evaluation
    - Distribution for excited state is same as ground state, but threshold is shifted.

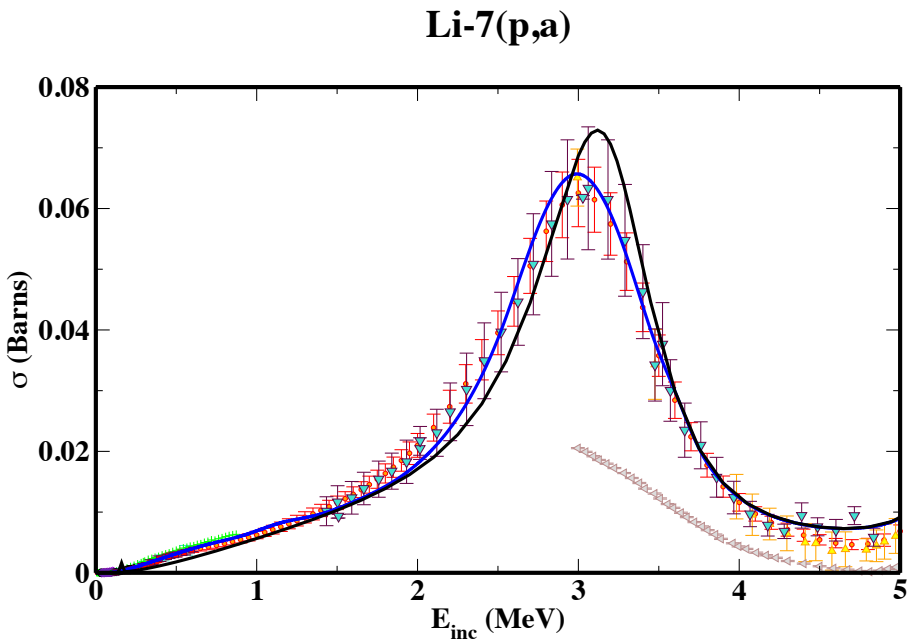




p+Li7 evaluation

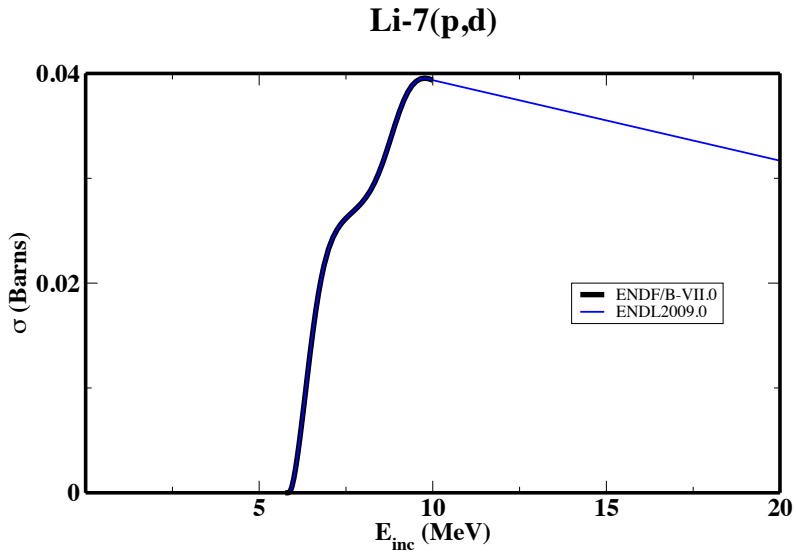
- ENDF/B-VII.1 (Page 2004)
  - (p,el), (p,n'$_0$), (p,d$_0$), (p,α$_0$)
- ENDL2009 (Navratil 2008)
  - (p,el) from ECPL
  - (p,a)
  - Cross-section
    - < 2.6 MeV : Descouvemont [3] S-factor
    - 2.6 - 3.15 MeV : three experimental points from the Rice measurement
    - > 3.15 MeV : Page evaluation
    - Note EXFOR file with the NP 33, 449 (1962) data is wrong as there was an erratum in NP 41, 176 (1963) (data needs to be multiplied by 10/7), divided by 2 as normalization based on 1958 measurement that counted alphas
  - Angular distributions from ENDF/B-VII.0
- Decouvemont 2004
  - [3] P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, E. Vangioni-Flam, Atomic Data and Nuclear Data Tables 88, 203 (2004).





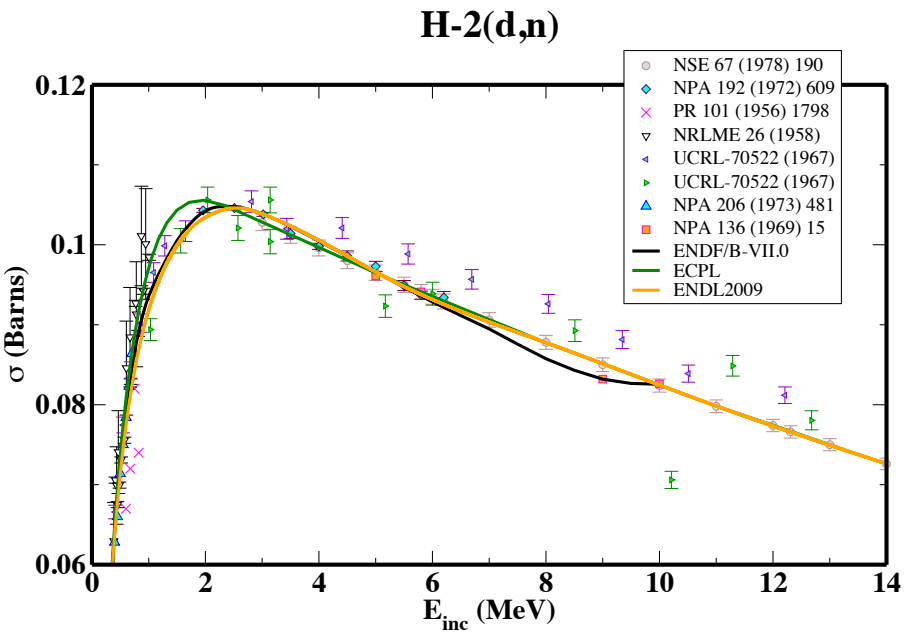
p+Li7 evaluation

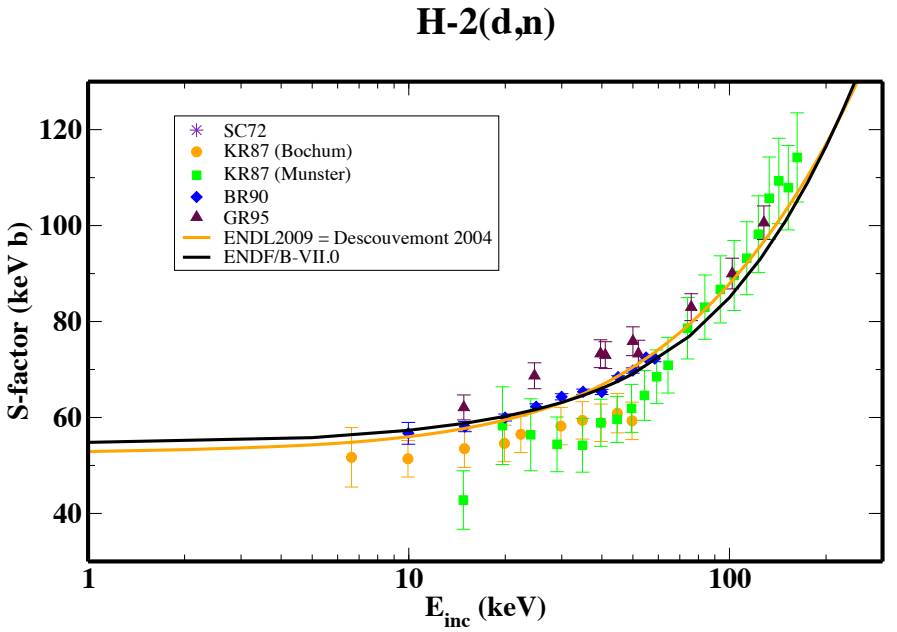
- ENDF/B-VII.1 (Page 2004)
  - (p,el), (p,n'$_0$), (p,d$_0$), (p,α$_0$)
- ENDL2009 (Navratil 2008)
  - 7Li(p,d)
  - Cross-section
    - < 10 MeV from ENDF/B-VII.0
    - To extrapolate to 30 MeV, integrated the cross section from Fig. 6 of PR 163,4,1066 (1967) and got 24 mb. Measurement was at 33.6 MeV proton energy. Recommend to use 24 mb at 30 MeV and make a linear interpolation to the 10 MeV point of Page
  - Angular distributions from ENDF/B-VII.0



d+d evaluation

- ENDF/B-VII.0 (Hale 2001)
  - (d,el), (d,n), (d,p)
- ENDL2009.0 (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-VII.0 (Hale 2001)
  - (d,el), (d,n), (d,p)
- ENDL2009.0 (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
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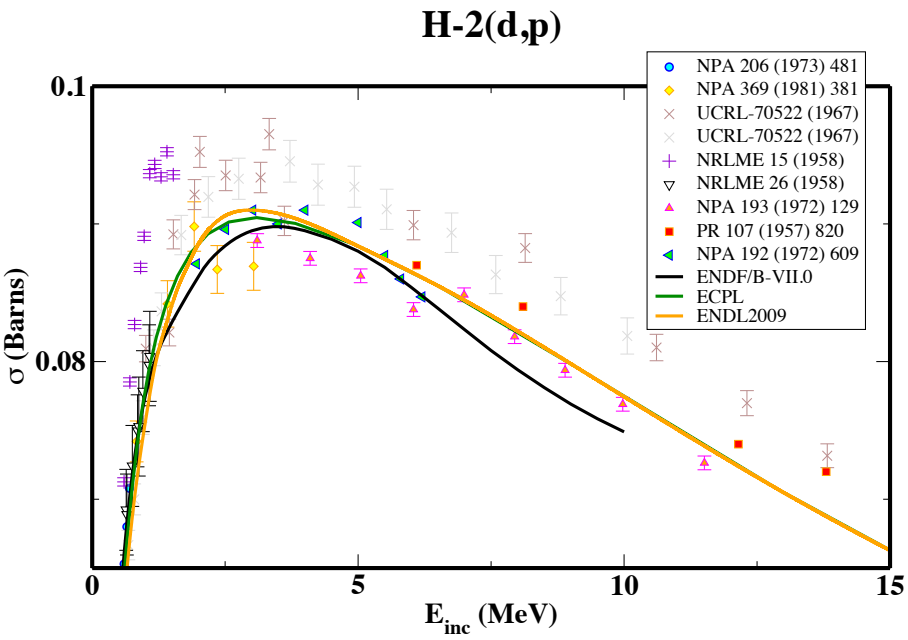
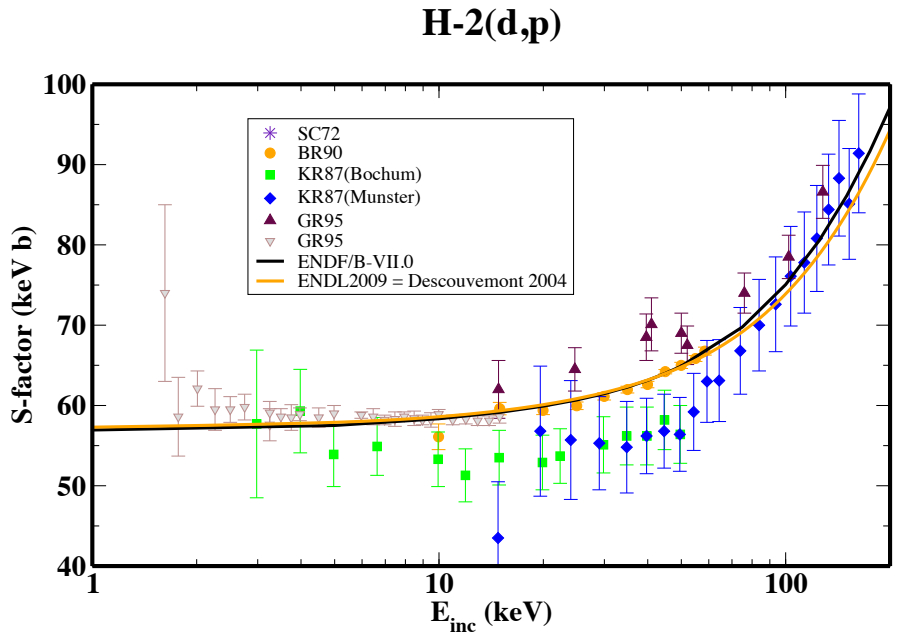
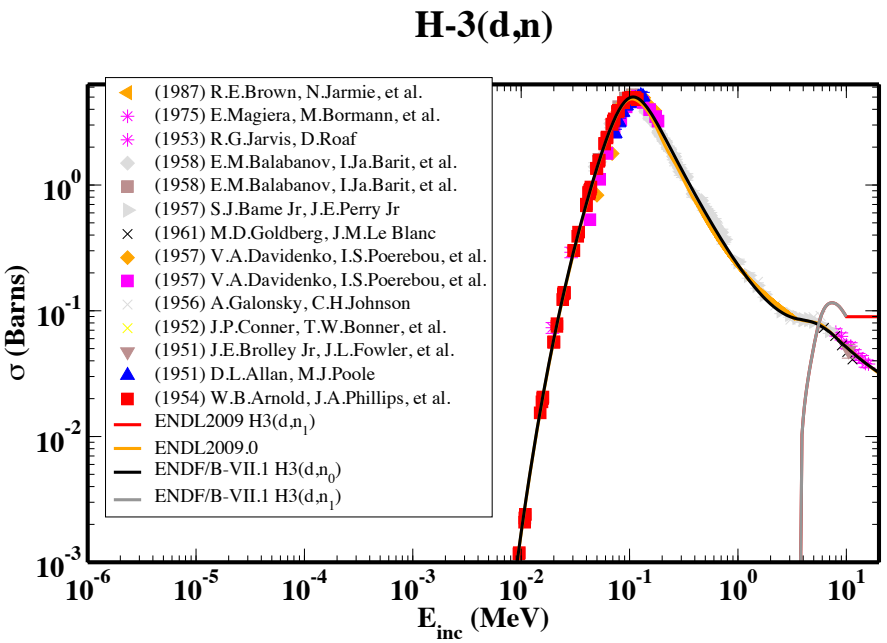
  - Note: The slight mass differences between the p & n and between the t & 3He were ignored in the creation of the angular distributions in ECPL
- Decouvemont 2004
  - [3] P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, E. Vangioni-Flam Atomic Data and Nuclear Data Tables 88, 203 (2004)
- [4] Nucl. Phys. A 192 (1972) 609

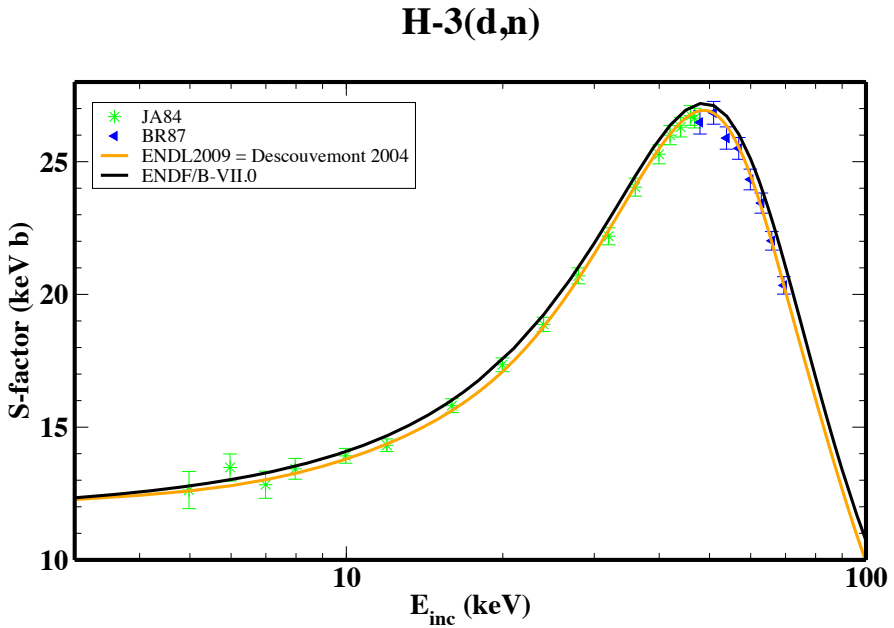




d+t evaluation

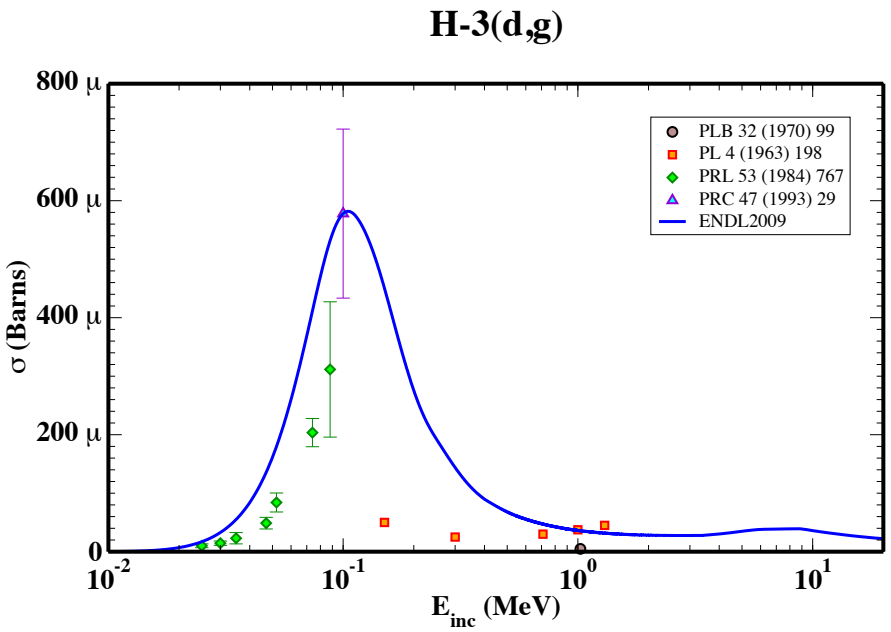
- ENDF/B-VII.0 (Hale 1995)
  - (d,el), (d,n_0), (d,n_1)
- ENDL2009.0 (Navratil 2009)
  - (d,el) from ECPL
  - H3(d,n_0)
  - Cross-section:
    - Low energy Descouvemont [3]
    - High energy ECPL
    - Peak at 105 keV of 4.85 b
    - TUNL evaluation peak 4.88 b at 105 keV
    - ECPL 4.99 b at 107 keV
    - 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
- Descouvemont 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





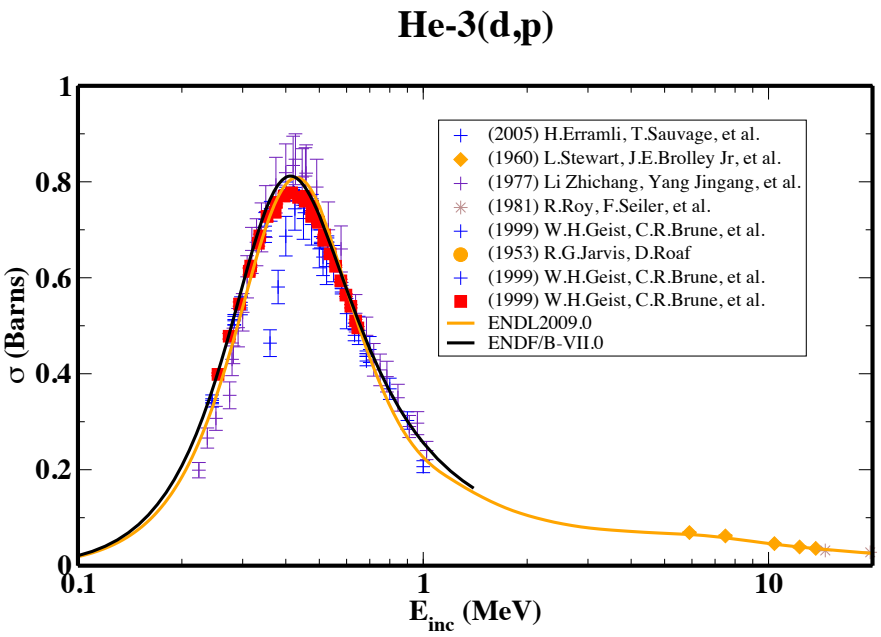
d+t evaluation

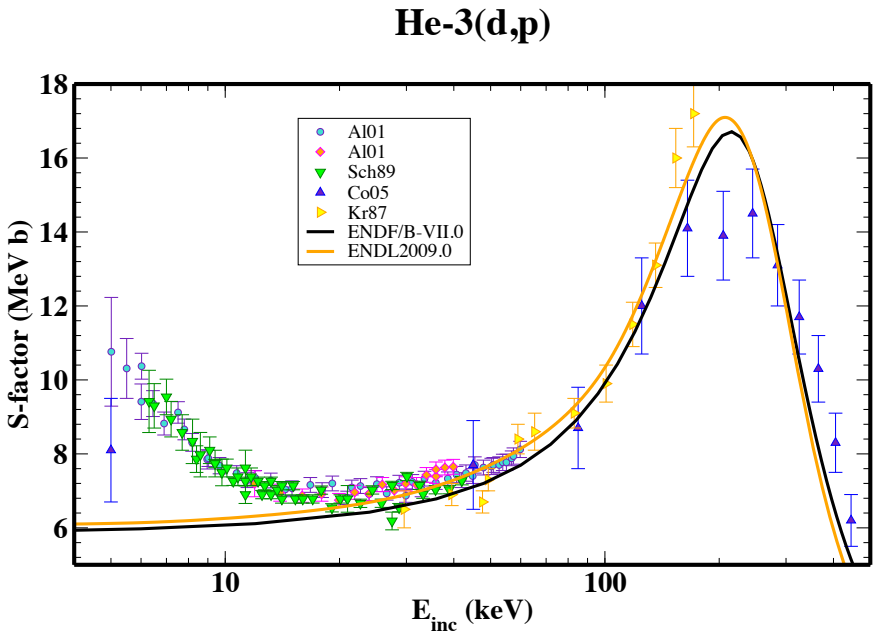
- ENDF/B-VII.0 (Hale 1995)
  - (d,el), (d,n_0), (d,n_1)
- ENDL2009.0 (Navratil 2009)
  - d + t -> g + 5He* -> g + n + 4He
  - Cross-section
    - The t(d,g) evaluation is based on Ref. [4]. Several experiments agree that the cross-section ratio is constant at resonance. At higher energies, the ratio 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



d+He3 evaluation

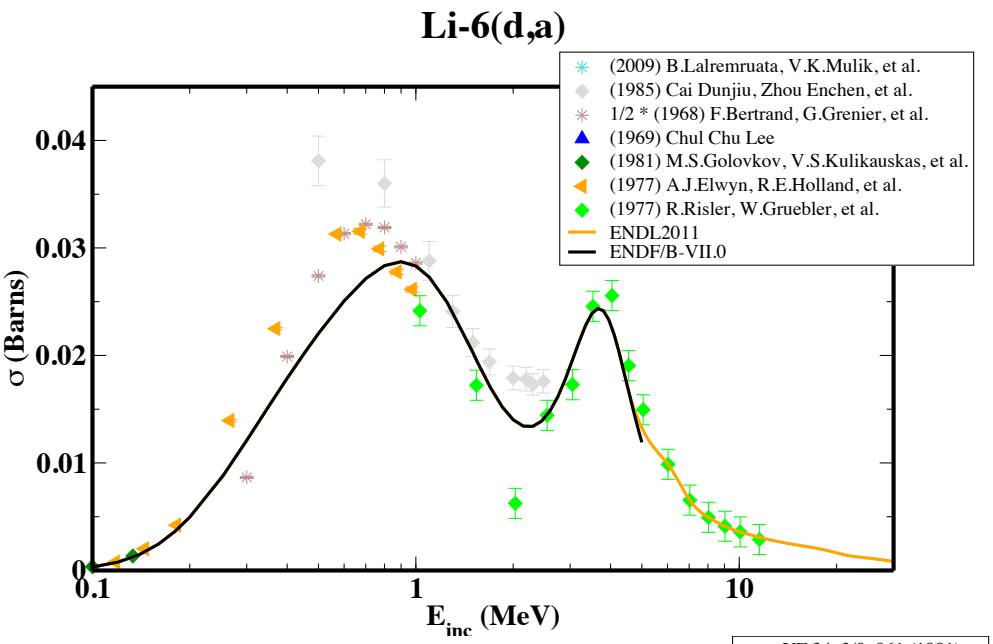
- ENDF/B-VII.0 (Hale 2001)
  - (d,el), (d,p_0)
- ENDL2009.0 (Navratil 2009)
  - (d,el) from ECPL
  - He3(d,p)
  - Cross-section:
    - low energy coming from Descouvemont 2004
    - matched at higher energies with ECPL
  - Angular distributions: From ECPL
    - Note: The slight mass differences between the p & n and between t & 3He were ignored in the creation of the angular distributions in ECPL

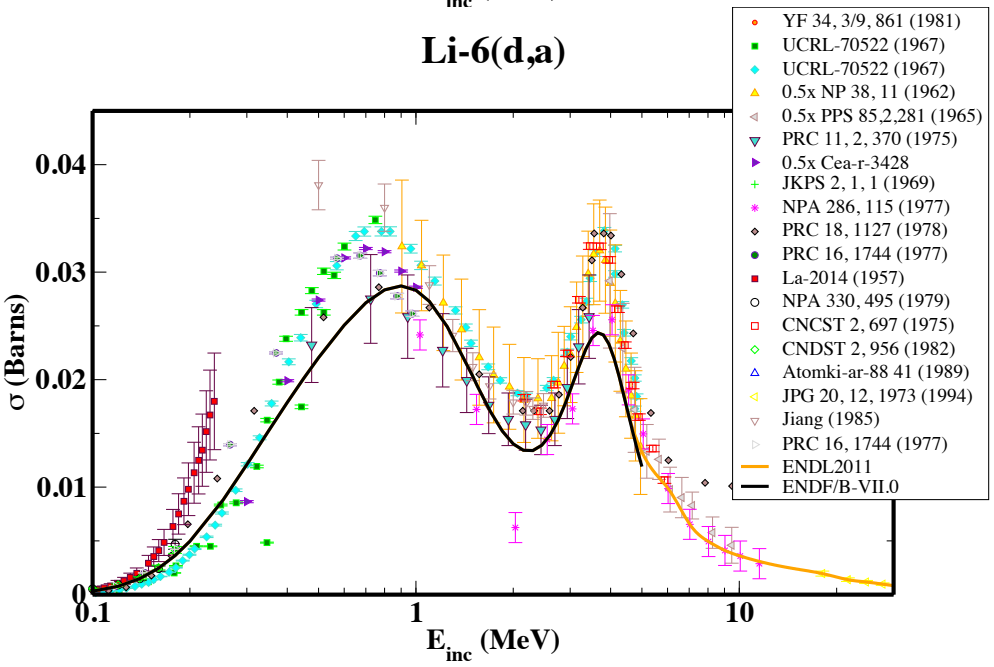




d+Li6 evaluation

- ENDF/B-VII.0 (Page 2004)
  - (d,el), (d,n_0), (d,p_0), (d,a_0)
- ENDL2011.0 (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

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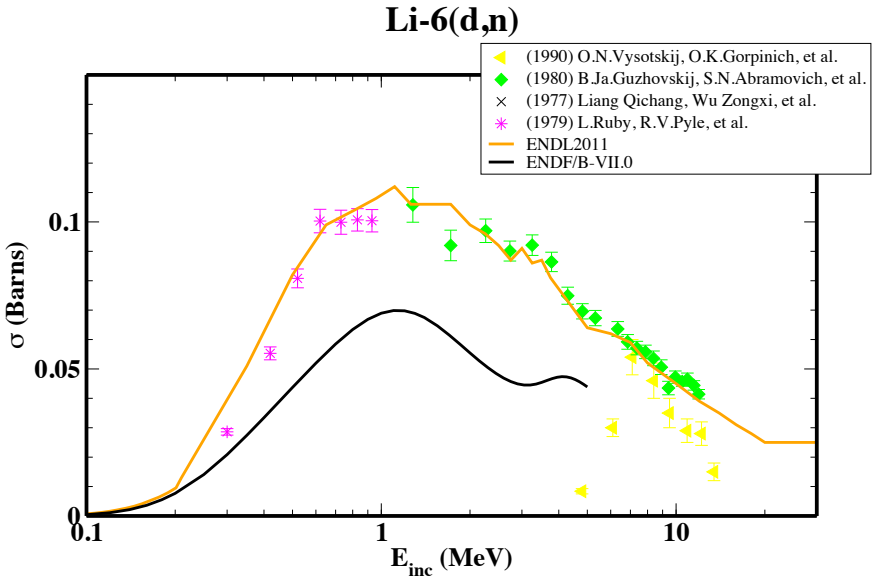
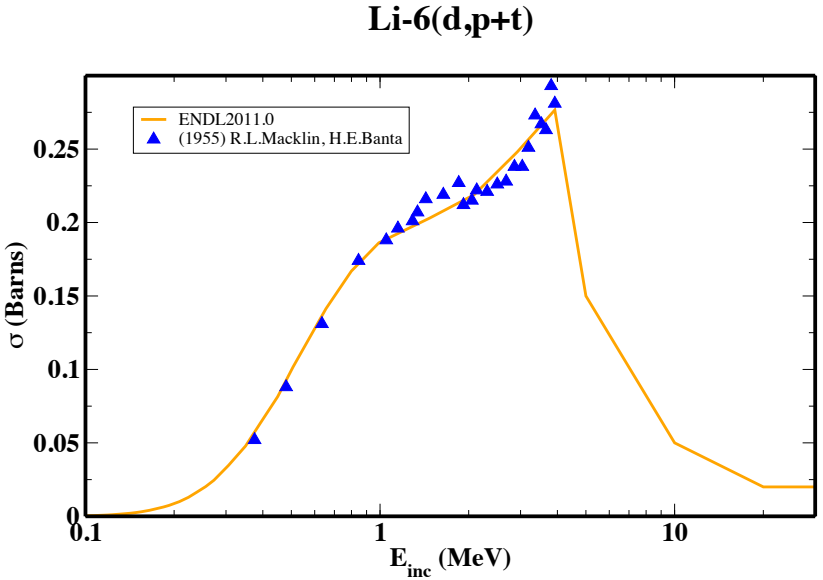
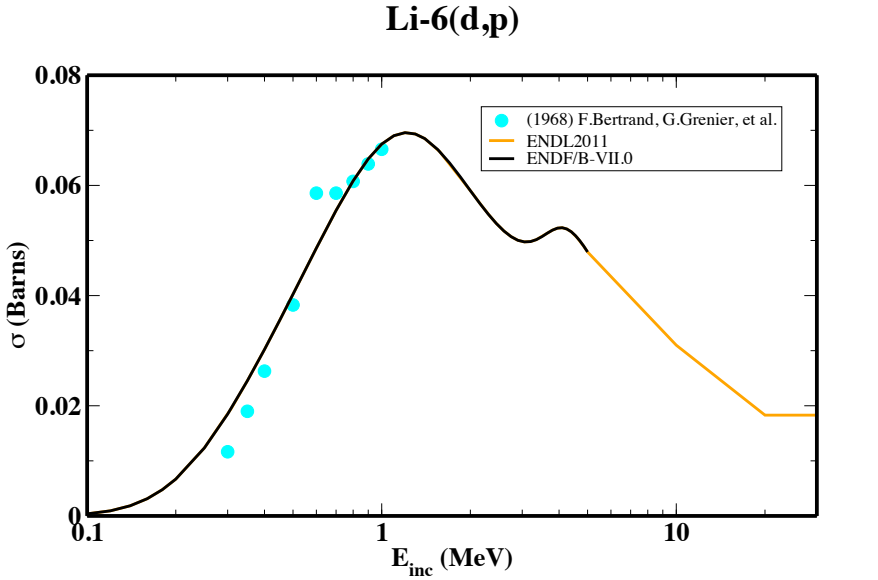
  - (d,el), (d,n_0), (d,p_0), (d,a_0)
- ENDL2011.0 (Navratil 2010)
  - (d,n) from ECPL
  - (d,p) from ENDF (extended to higher energies)
  - (d,t+p) from ECPL, expt data labeled as (d,t)



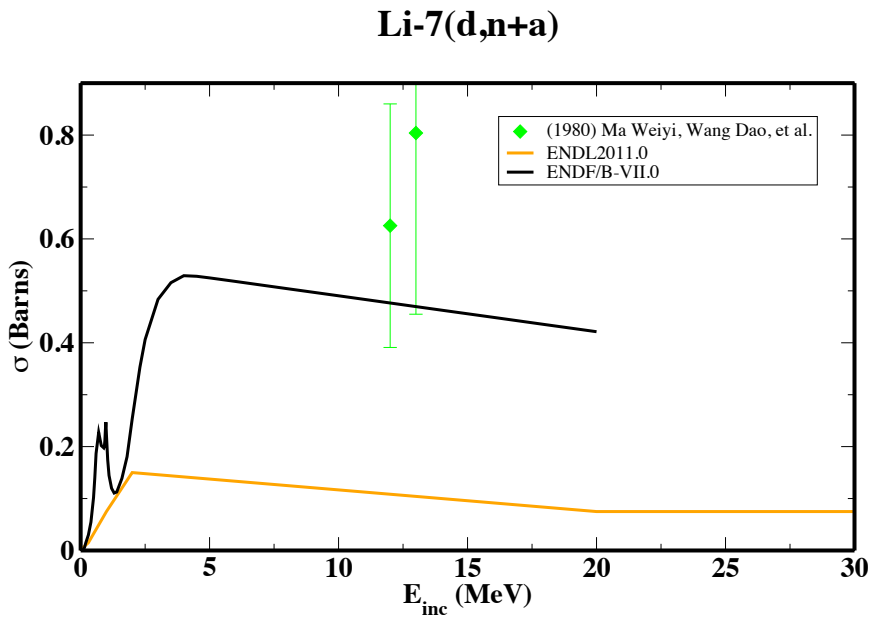


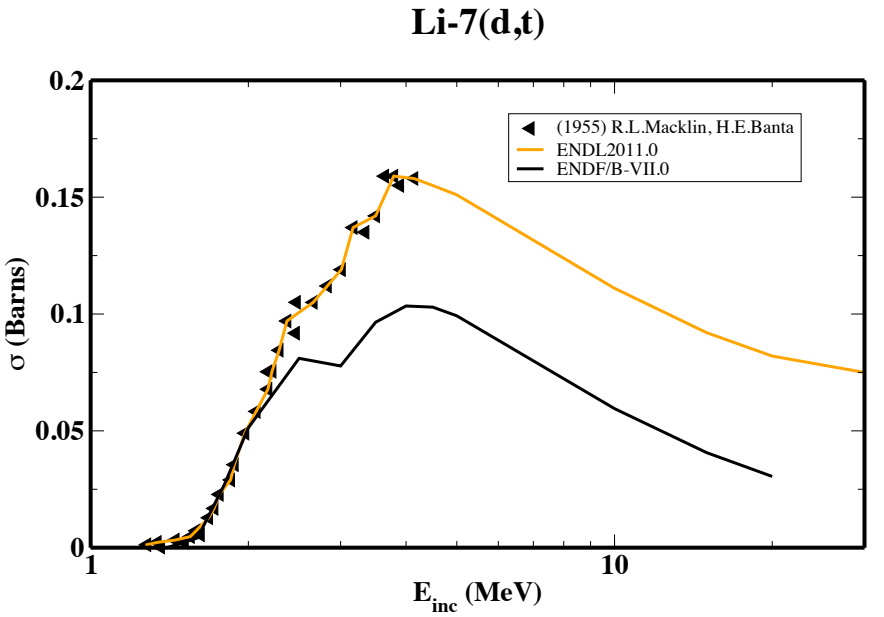


d+Li7 evaluation

- ENDF/B-VII.0 (Hale 2003)
  - (d,el), (d,na), (d,t_0)
- ENDL2011.0 (Navratil 2010)
  - (d,el) from ENDF, extended up to 30 MeV
  - (d,na) from ECPL (but ENDF better fit to data)
  - (d,t) from R.L. Macklin [5] data up to 4 MeV; at higher energies scaled ENDF
    - Angular distributions: ENDF/B-VII.0

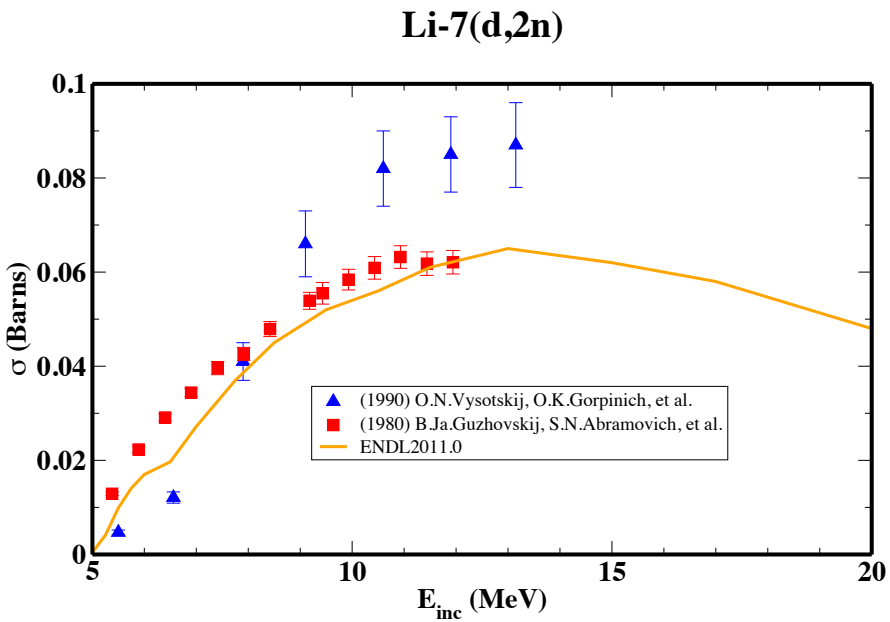
[5] R.L. Macklin, H.E. Banta, Phys. Rev., 97, 753 (1955)

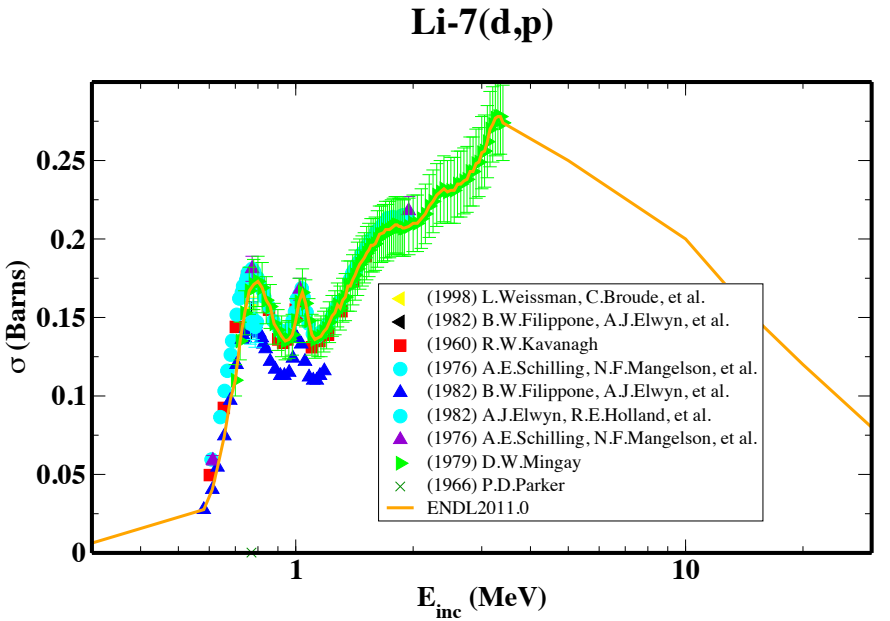




d+Li7 evaluation

- ENDF/B-VII.0 (Hale 2003)
  - (d,el), (d,na), (d,t_0)
- ENDL2011.0 (Navratil 2010)
  - (d,2n) from ECPL
  - (d,p)
    - < 0.7 MeV from Ref. [3]
    - 0.7 - 3.4 MeV from Ref. [4]
    - > 3.4 MeV educated guess
    - Angular distributions: from (d,na) neutron dist.



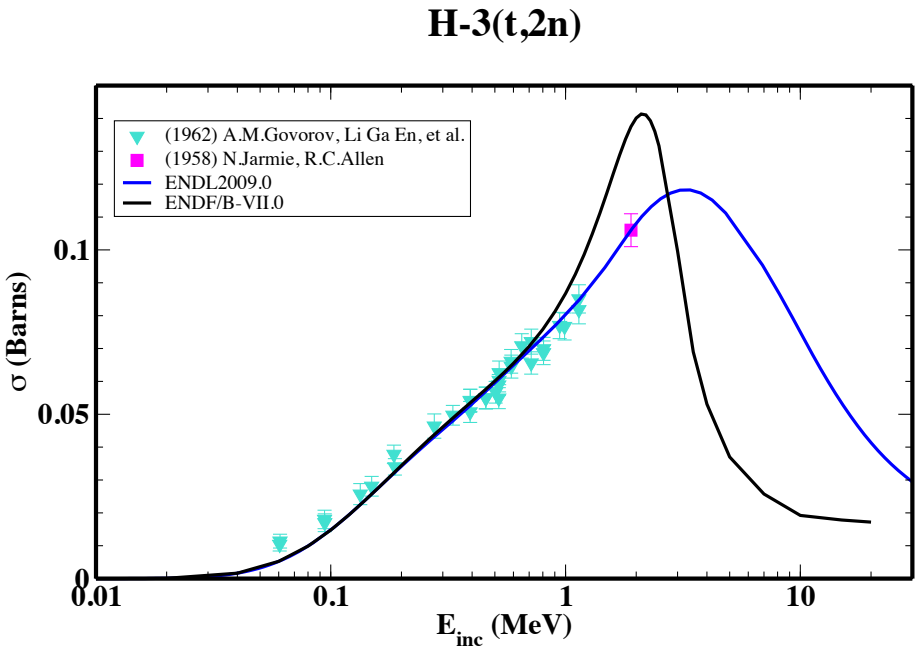


[3] B.W. Filippone, A.J. Elwyn, W. Ray Jr., D.D. Koetke, Phys. Rev. C, 25, 2174 (1982)

[4] D.W.Mingay, J, SAP, 2, (3), 107 (1979)

t+t evaluation

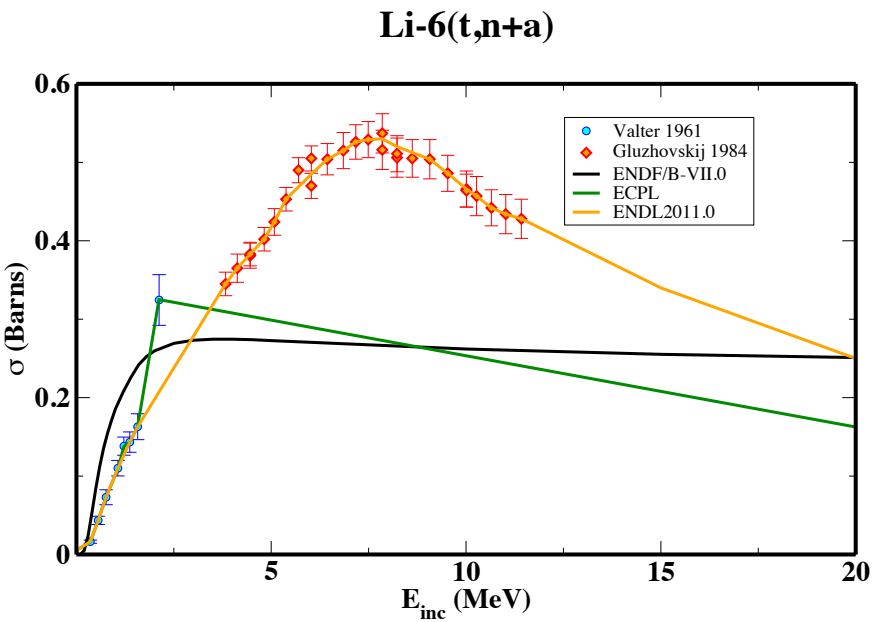
- ENDF/B-VII.0 (Hale 2001)
  - (t,el), (t,2n)
- ENDL2009.0 = ECPL
  - (t,el), (t,2n)
- Recent R-matrix work for H3(t,2n)He4
  - Dan Sayre
  - Gerry Hale (neutron spectrum)

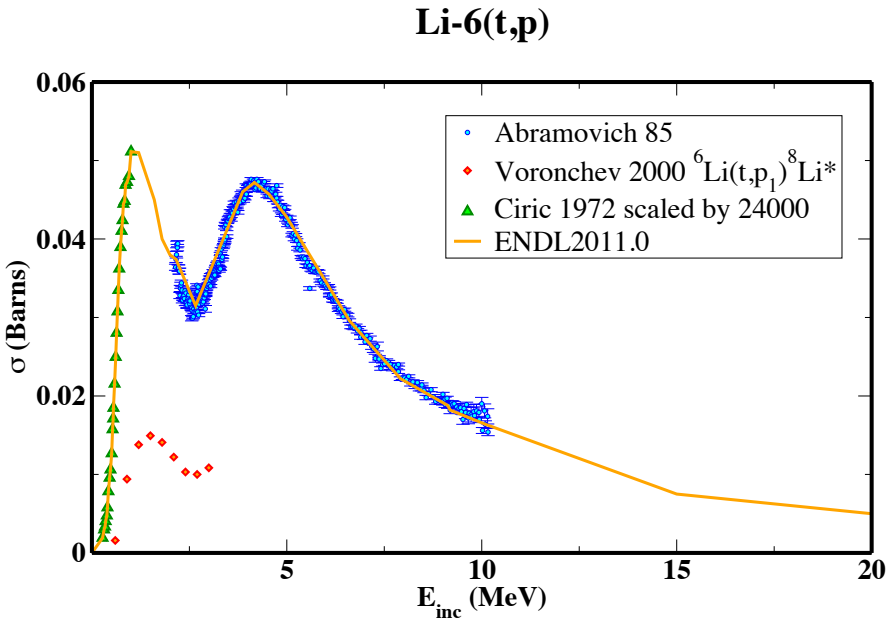


t+Li6 evaluation

- ENDF/B-VII.0 (Hale 2001)
  - (t,el), (t,na), (t,d_0)
- ENDL2011.0 (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

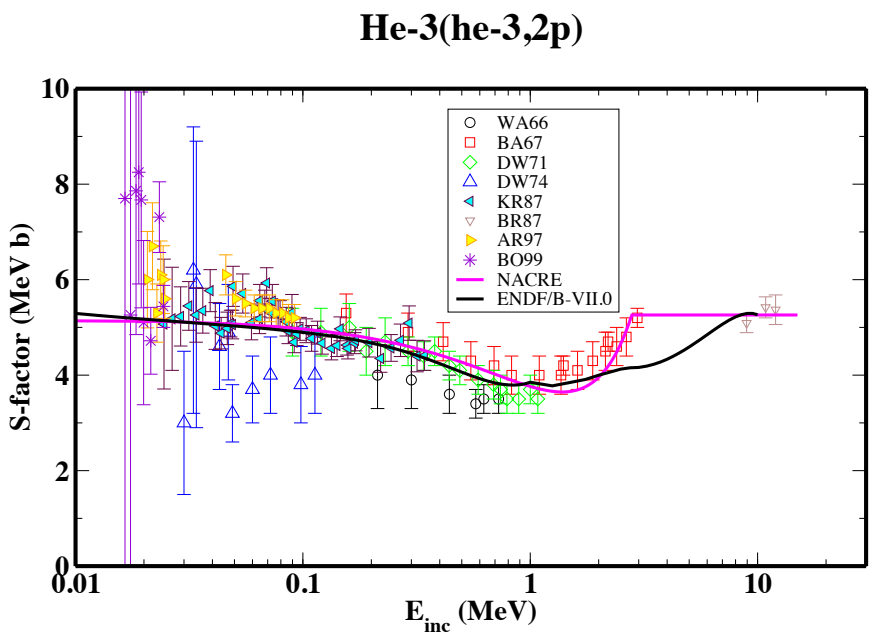
[3] A.K.Valter, P.I.Vacet, L.Ja.Kolesnikov, S.G.Tonapetjan, K.K.Chernjavskij, A.I.Shpetnyj, Atomnaya Energiya 10, (6), 577 (1961)
[4] B.Ja.Guzhovskij, S.N.Abramovich, A.G.Zvenigorodskij, S.V.Trusillo, Prikladnaya Yadernaya, Spektroskopiya 13, 135 (1984)
[5] V T Voronchev, V I Kukulin, J. Phys. G: Nucl. 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)





He3+He3 evaluation

- ENDF/B-VII.0 (Hale 2001)
  - (He3,el), (He3,2p)
- ENDL2011.0 (Navratil 2010)
  - (He3,el) from ENDF
  - (He3,2p)
    - NACRE S-factor evaluation [4] that includes LUNA data [5]
    - Angle and energy distributions: from ENDF

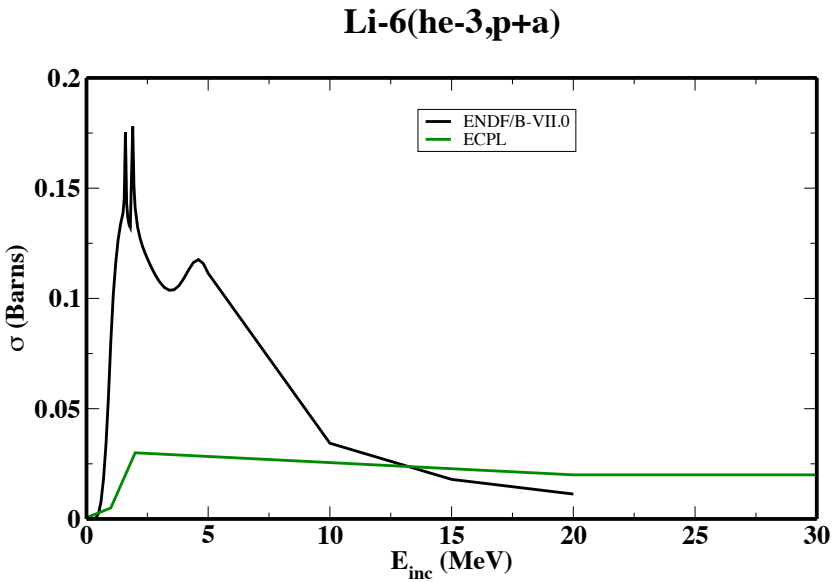


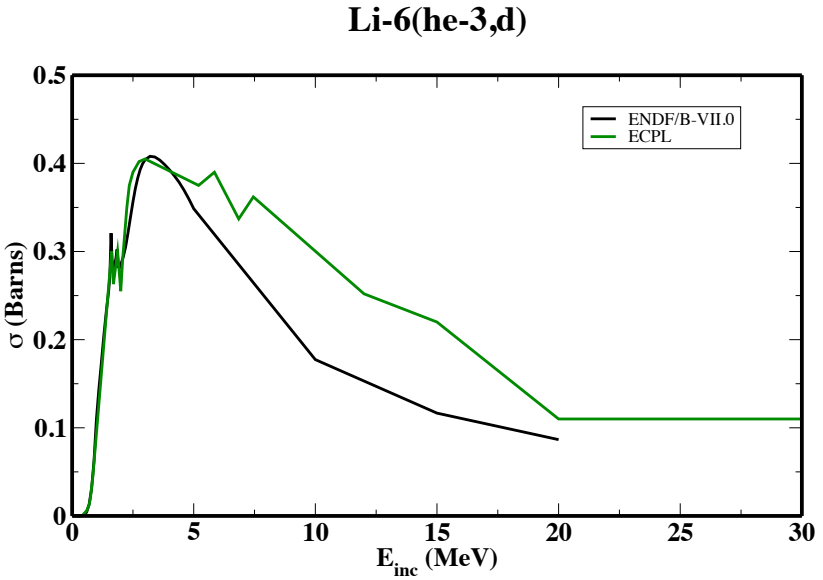
[4] C. Angulo et al. (NACRE Collaboration), Nucl. Phys. A656 (1999)3-187

[5] The LUNA Collaboration, M. Junker, et al., The cross section of 3He(3He,2p)4He measured at solar energies, Nuclear Physics B - Proceedings Supplements, Volume 70, Issues 1-3, Proceedings of the Fifth International Workshop on topics in Astroparticle and Underground Physics, January 1999, Pages 382-385, ISSN 0920-5632.

He3+Li6 evaluation

- ENDF/B-VII.0 (Hale 2002)
  - (He3,el), (He3,pa), (He3,d_0)
- ECPL
  - (He3,el), (He3,pa), (He3,d)





Translation from ENDL to ENDF

- New LLNL evaluations developed using ENDL format from variety of sources
  - Why can we not just simply translate back to ENDF?
- When translating from ENDF into ENDL, information is lost
  - Reformatted ENDF parameterized forms to pointwise data for ENDL
    - such as phase space representation
  - Need to rebuild evaluations in ENDF format using actual ENDF distributions
    - can use GND/fudge to do this now
- Legendre distributions from ECPL stored in different format than ENDF
- Will be first evaluations built using new fudge/GND
  - Develop framework in fudge for cut/paste evaluations from different sources
- Evaluations based on ENDF/B-VII.0
  - Need to include updates to some evaluations for ENDF/B-VII.1
- Documentation needs to be re-written for all evaluations
  - Currently too much ENDL speak