Simultaneous *R*-matrix Analysis of ^{16}O Compound Nucleus Reactions

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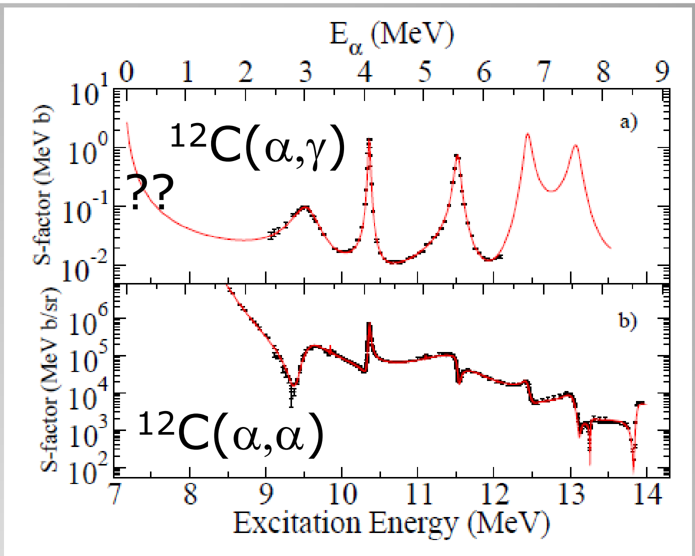
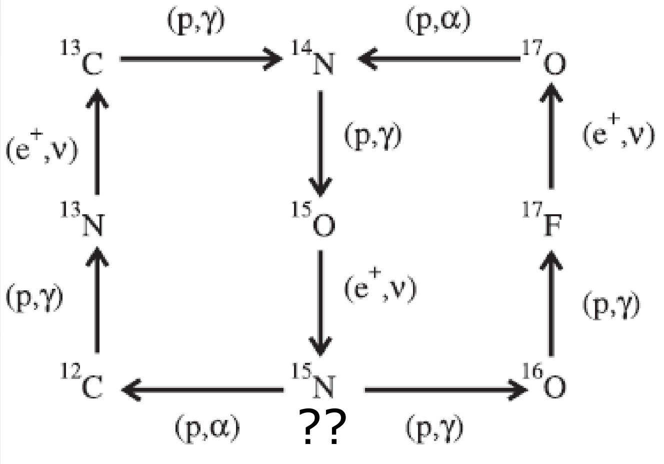
Motivation

- Nuclear Astrophysics
  - $^{12}C(\alpha,\gamma)^{16}O$
    - Main energy producing reaction during helium burning
    - "Holy Grail" of nuclear astrophysics
  - **$^{15}N(p,\gamma)^{16}O$** & $^{15}N(p,\alpha)^{12}C$
    - Branch point for the CNO bi-cycle during stellar hydrogen burning



Schürmann *et al.* (2005), (α,γ)
Tischhauser *et al.* (2009), (α,α)



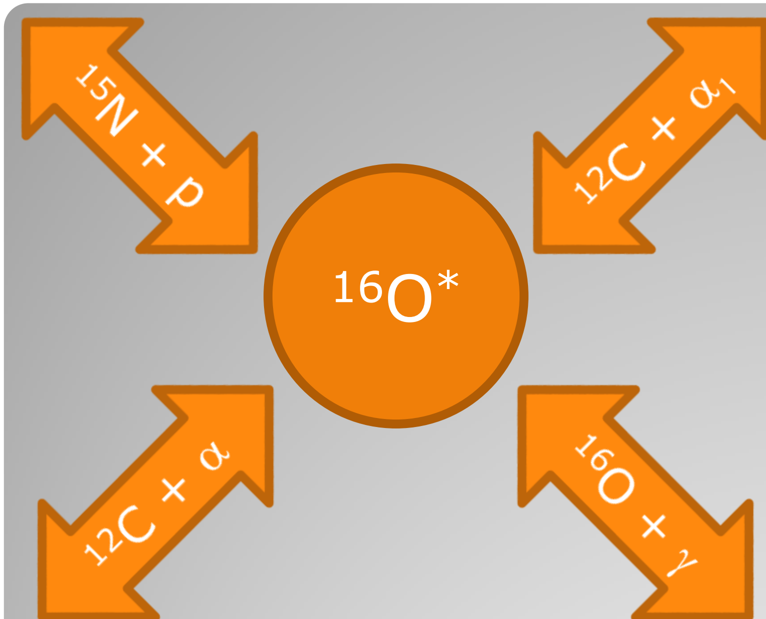
LeBlanc *et al.* (2010)

- AZURE updates
  - Rewritten in C++ (E. Uberseder)
  - Multiple entrance channels
  - Multi-core processing using MINUIT2
  - New GUI interface (QT)
  - Dynamic memory allocation = more data
  - Alternative R-matrix parameterization of (Brune 2002), on-resonance parameters only
  - NOT yet available for public release, coming soon!
  - FORTRAN version also under further development (Dick Azuma)

AZURE: An *R*-matrix code for nuclear astrophysics (Azuma *et al.*, PRC 81, 045805, 2010)

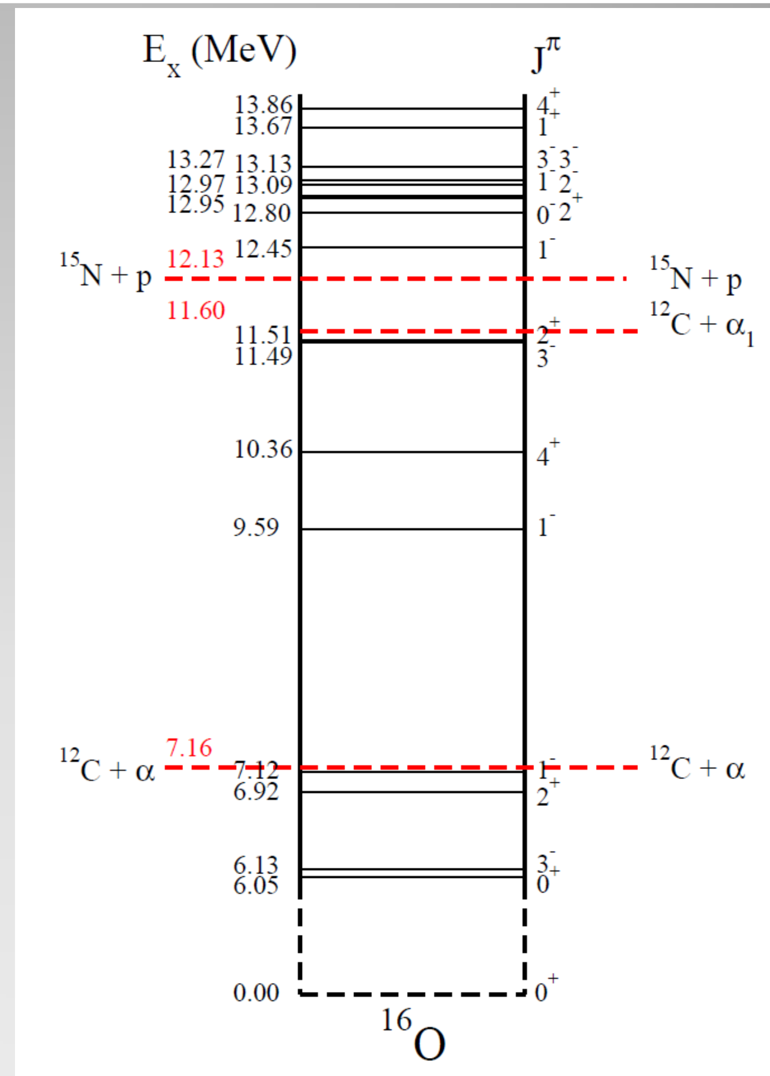
JINA

Structure of ^{16}O



$^{15}N(p,\gamma)^{16}O$

$^{12}C(\alpha,\alpha_0)^{12}C$, $^{12}C(\alpha,\alpha_1)^{12}C$, $^{12}C(\alpha,p)^{15}N$, $^{12}C(\alpha,\gamma)^{16}O$, $^{15}N(p,p)^{15}N$, $^{15}N(p,\alpha_0)^{12}C$, $^{15}N(p,\alpha_1)^{12}C$

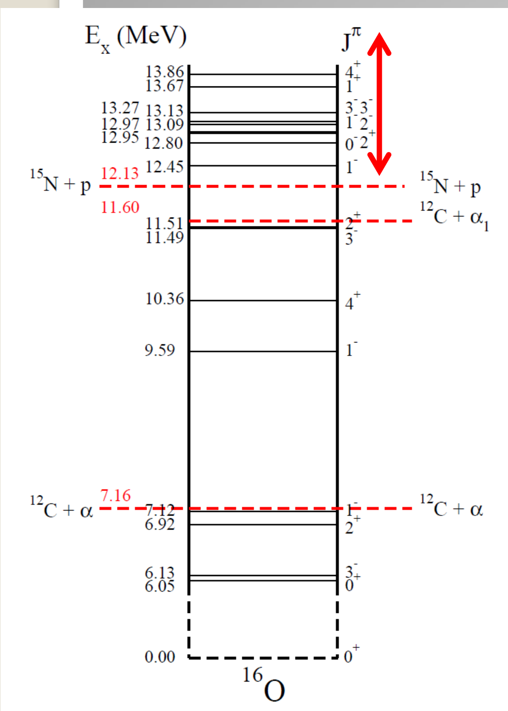


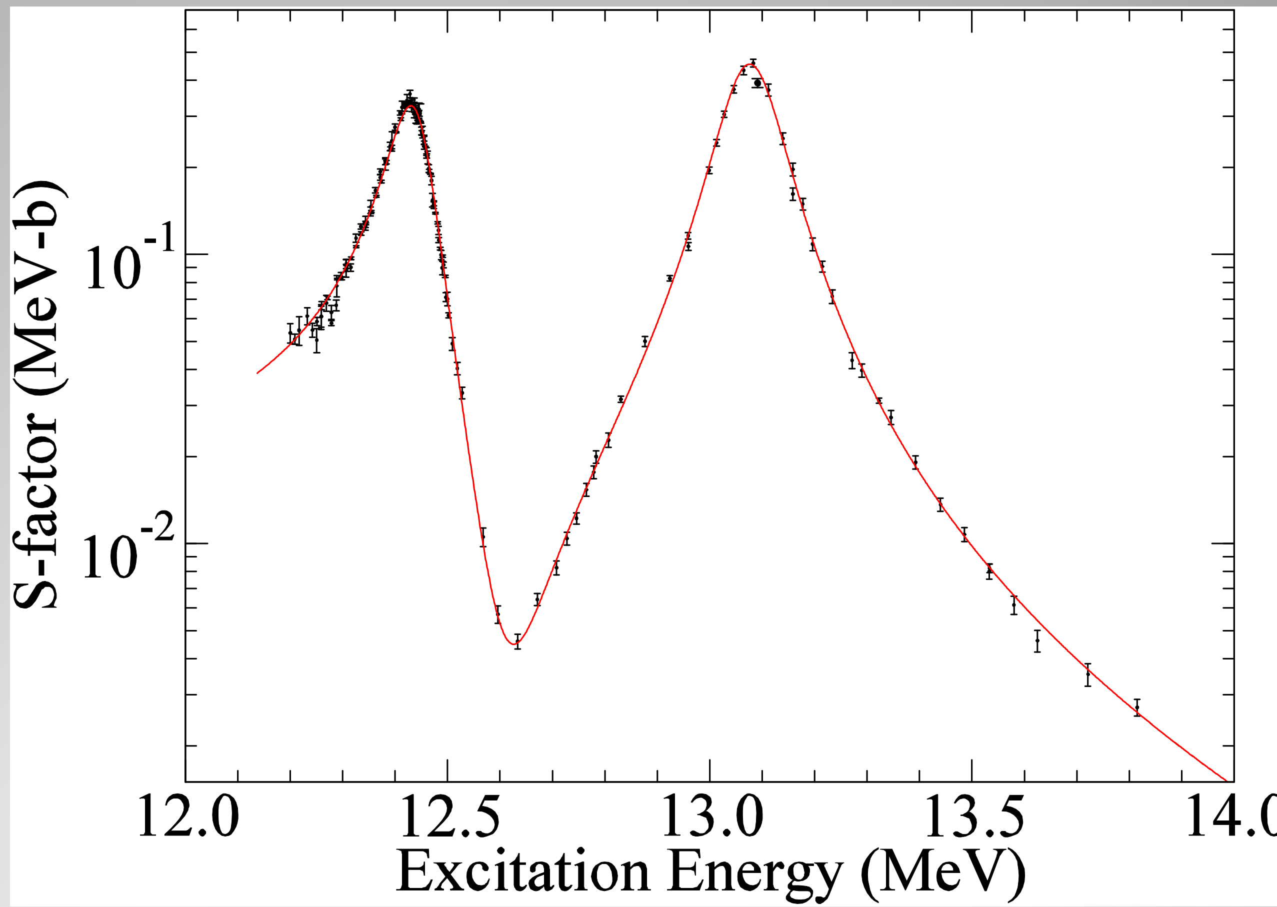
Same energies and partial widths

TABLE I: Summary of references and associated reactions used in the ^{16}O R-matrix analysis.

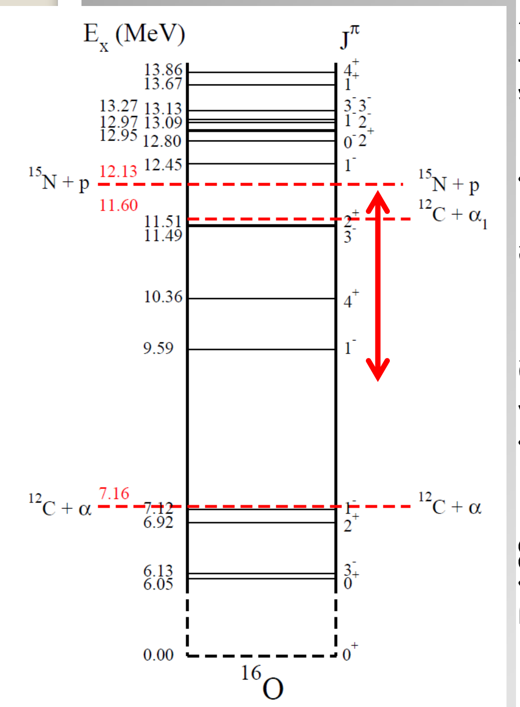
Ref.	Reaction(s)
Schardt et al. [15] (1952)	(p, α_0)
Hagedorn [16] (1957)	(p, p)
Hagedorn and Marion [17] (1957)	(p, α_0)
Bashkin et al. [18] (1959)	(p, p), (p, α_0), (p, α_1)
Hebbard [7] (1960)	(p, γ_0)
Larson and Spear [19] (1964)	(α, γ_0)
Mitchell and Ophel [20] (1965)	(α, α_1), (α, p)
Morris et al. [21] (1968)	(α, α_0)
Kernel et al. [22] (1971)	(α, γ_0)
Brochard et al. [23] (1973)	(p, α_0), (p, γ_0)
Rolfs and Rodney [8] (1974)	(p, γ_0)
D'Agostino Bruno et al. [24] (1975)	(α, α_0)
Ophel et al. [25] (1976)	(α, γ_0)
Bray et al. [26] (1977)	(p, α_0)
Zyskind and Parker [27] (1979)	(p, α_0)
Redder et al. [28] (1982)	(p, α_0)
Feng et al. [29] (1994)	(α, α_0)
Schürmann et al. [13] (2005)	(α, γ)
Tischhauser et al. [14] (2009)	(α, α_0), (α, α_1), (α, p)
Bemmerer et al. [30] (2009)	(p, γ_0)
LeBlanc et al. [4] (2010)	(p, γ_0)
Caciolli et al. [31] (2011)	(p, γ_0)
LeBlanc et al. (2012)	(p, p), (p, α_0)

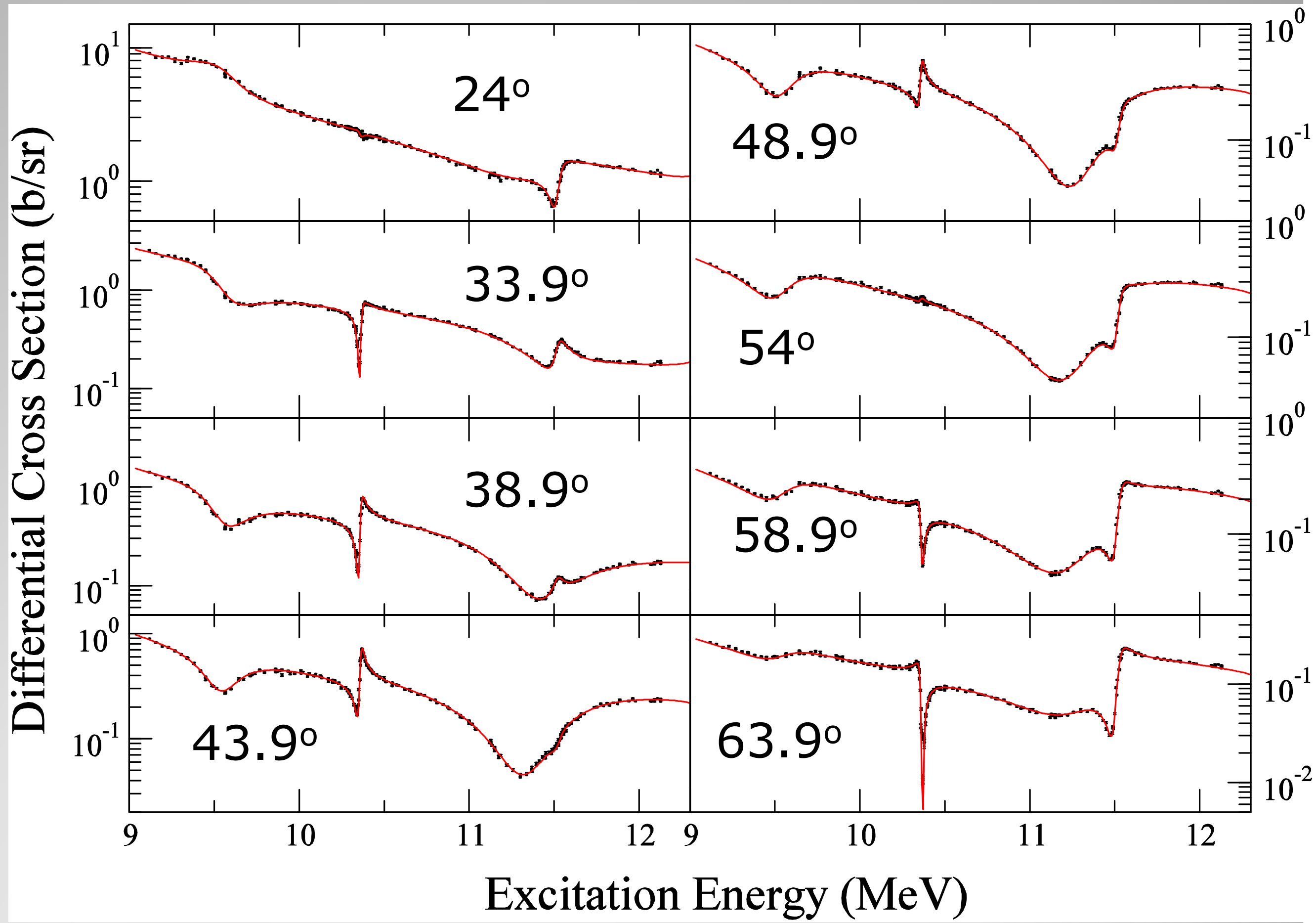
Published Data





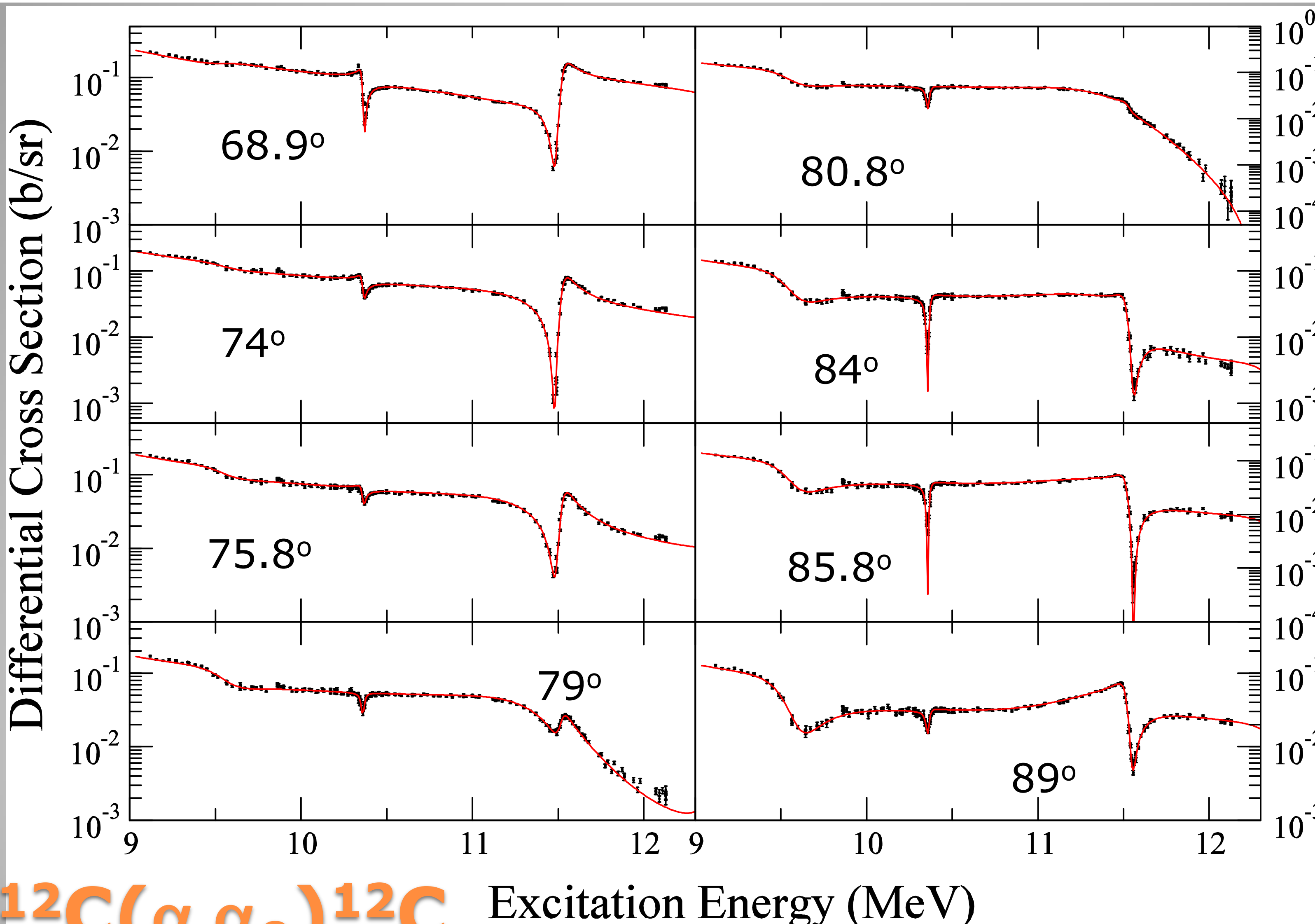
$^{15}N(p,\gamma_0)$ LeBlanc *et al.* (2010) and Caciolli *et al.* (2011)





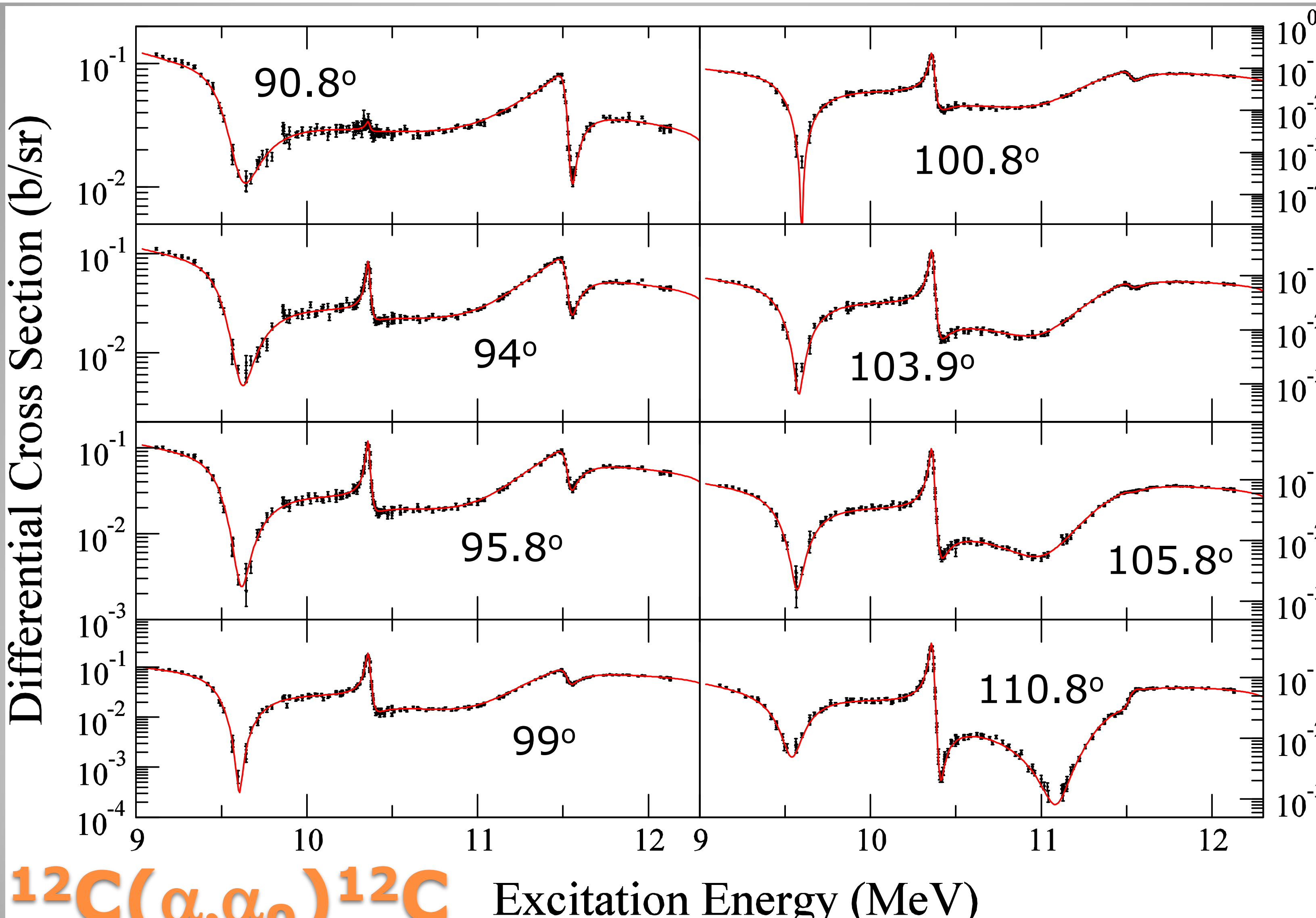
$^{12}C(\alpha,\alpha_0)^{12}C$

Tischhauser *et al.* (2009)



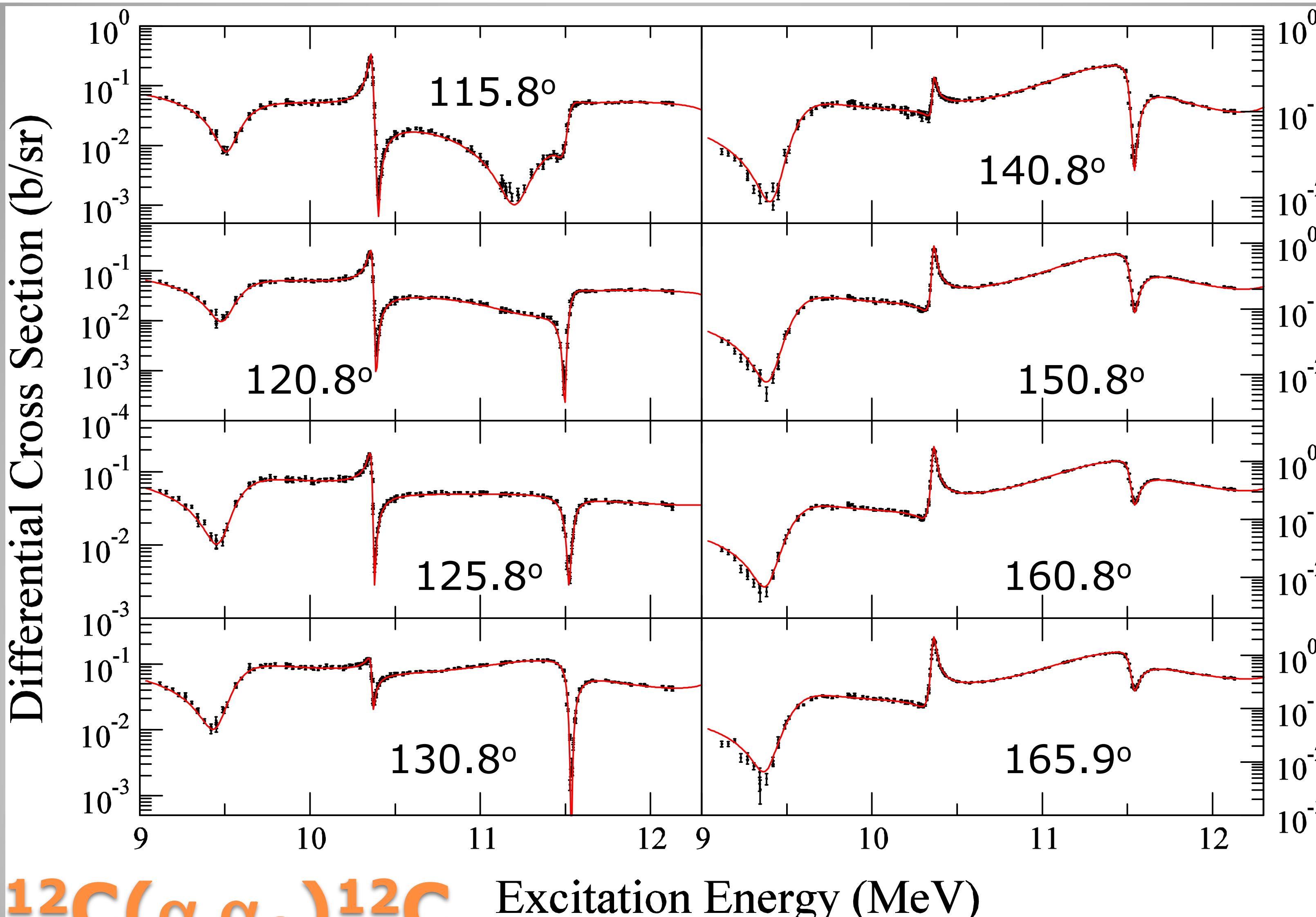
$^{12}C(\alpha,\alpha_0)^{12}C$

Tischhauser *et al.* (2009)



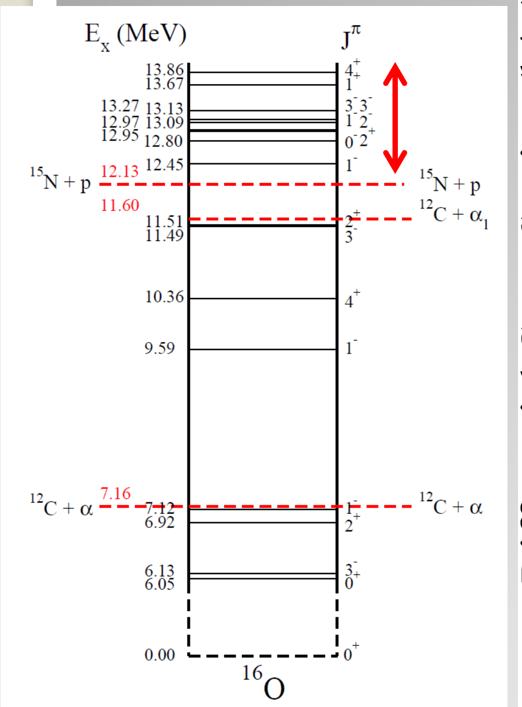
$^{12}C(\alpha,\alpha_0)^{12}C$

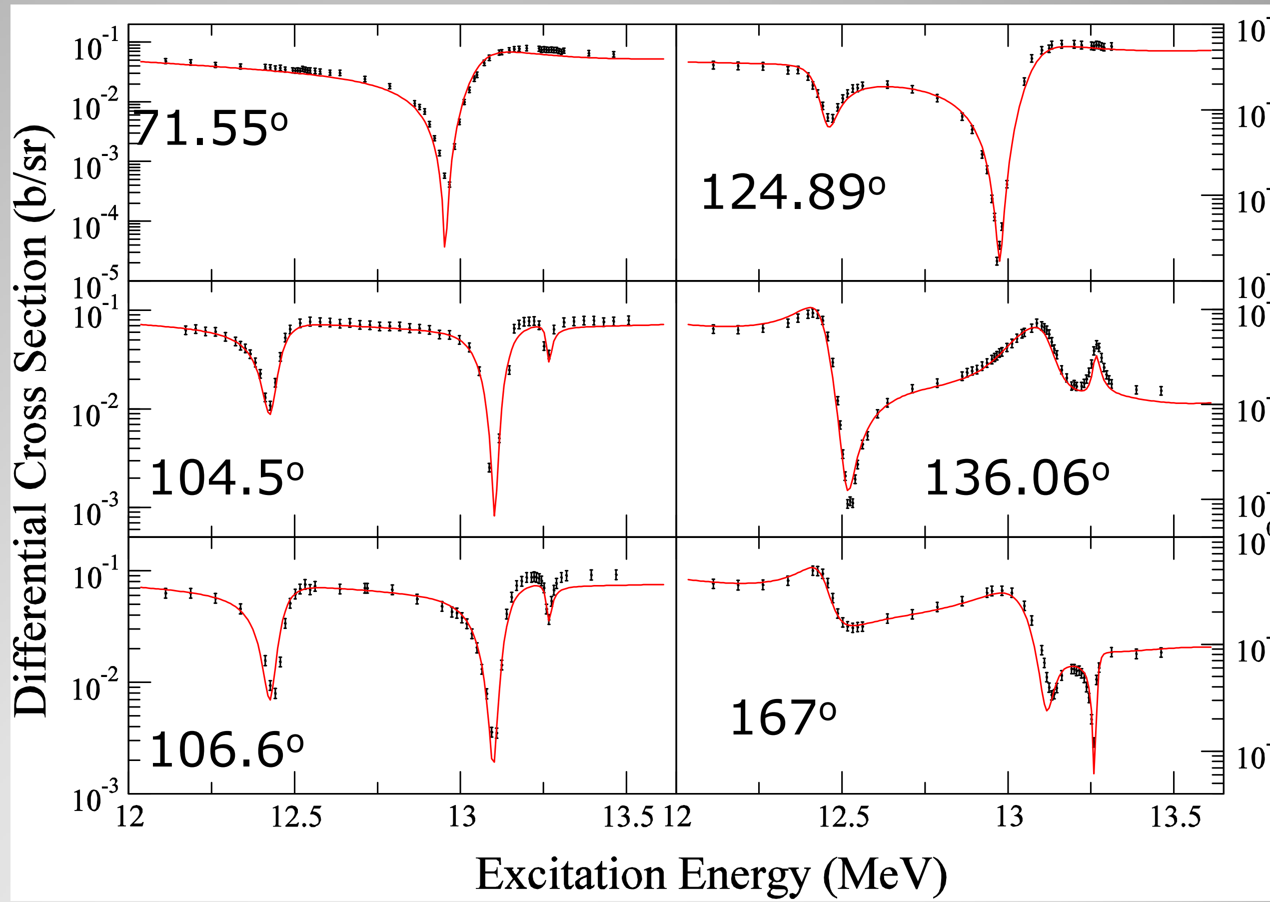
Tischhauser *et al.* (2009)



$^{12}C(\alpha,\alpha_0)^{12}C$

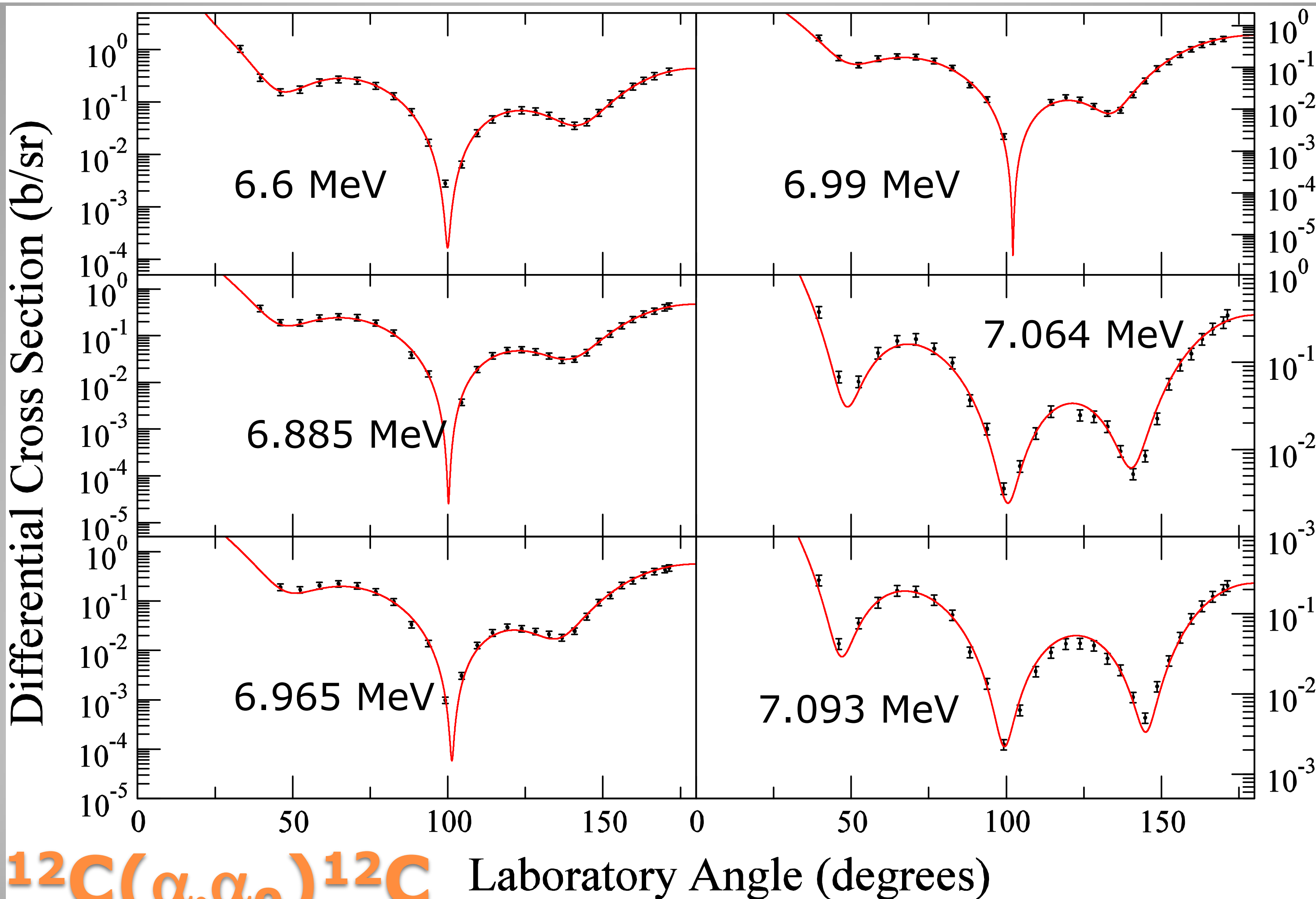
Tischhauser *et al.* (2009)





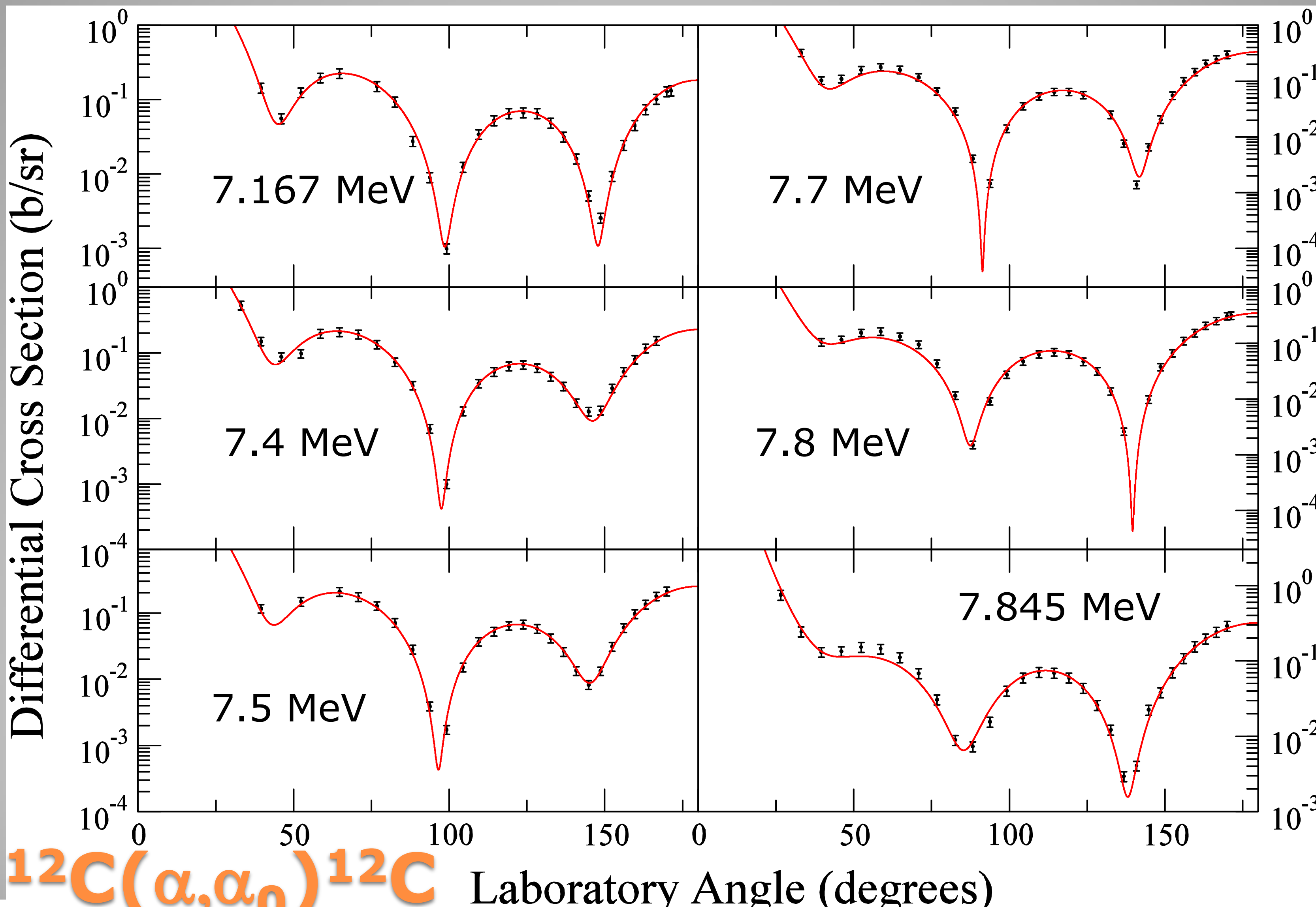
$^{12}C(\alpha,\alpha_0)^{12}C$

Morris *et al.* (1968)



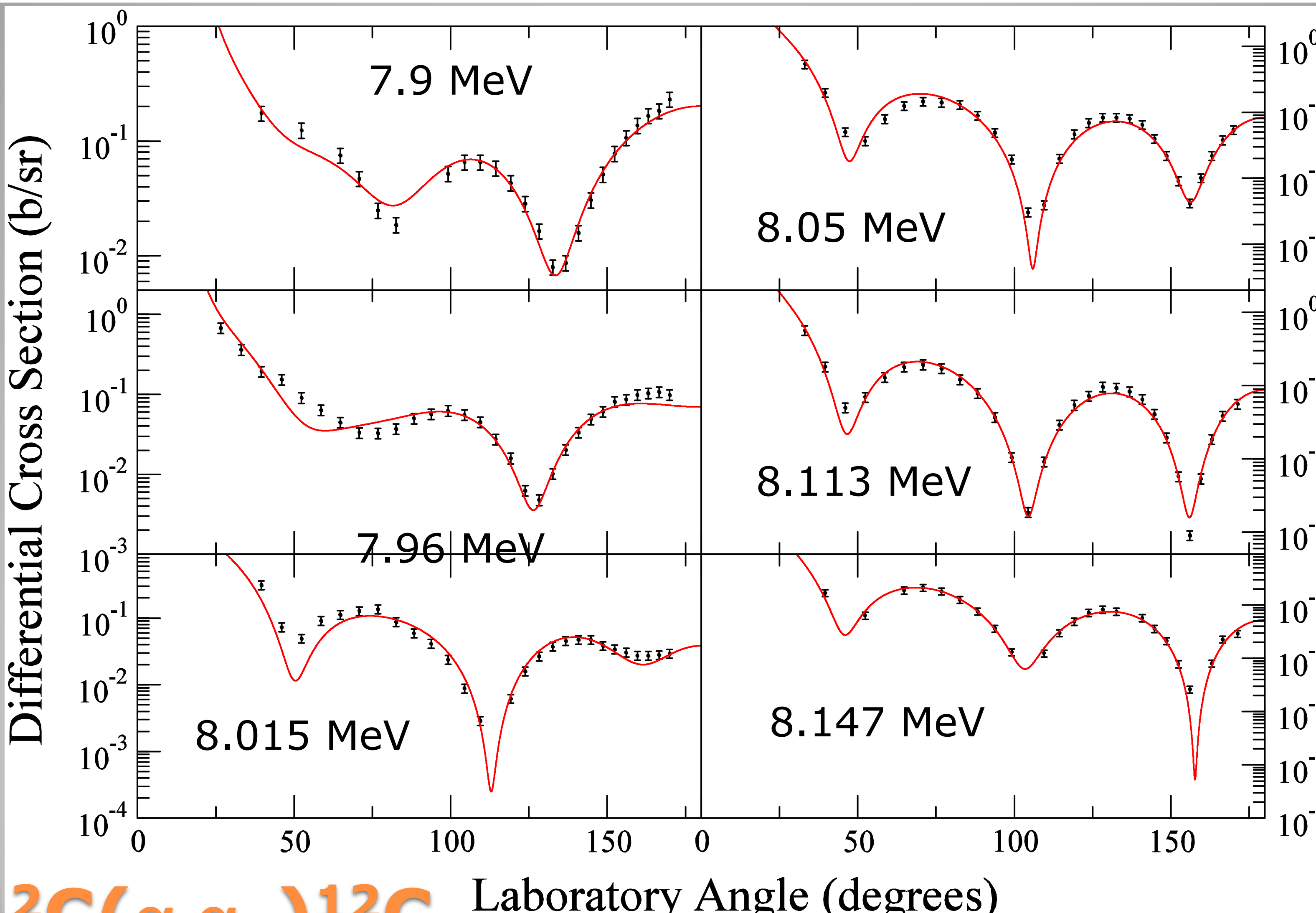
$^{12}C(\alpha,\alpha_0)^{12}C$

Morris *et al.* (1968)



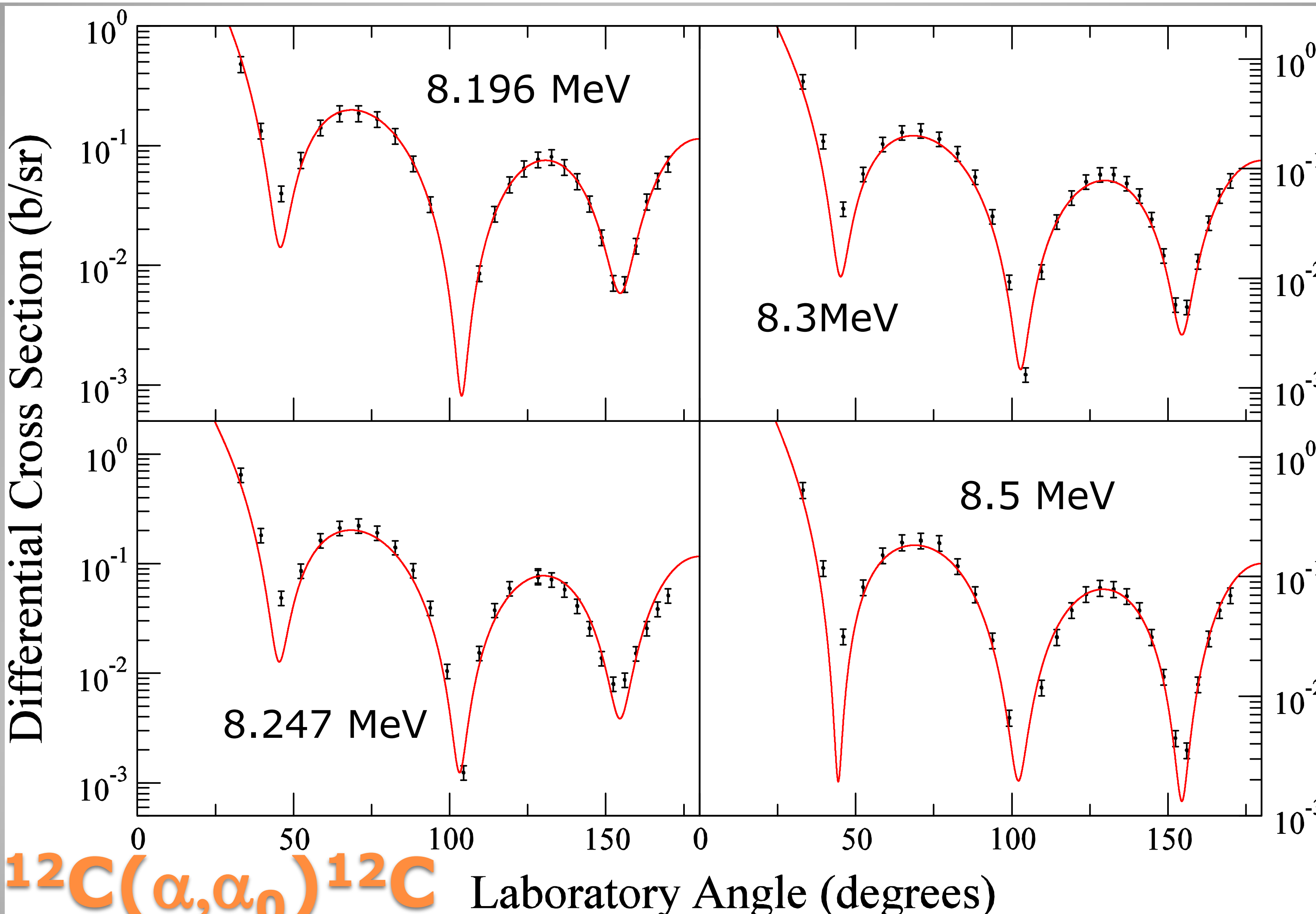
$^{12}C(\alpha,\alpha_0)^{12}C$

Morris *et al.* (1968)



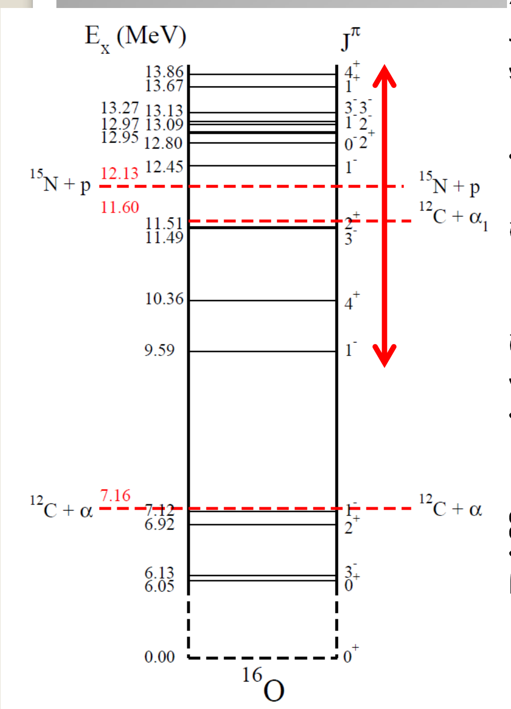
$^{12}C(\alpha,\alpha_0)^{12}C$

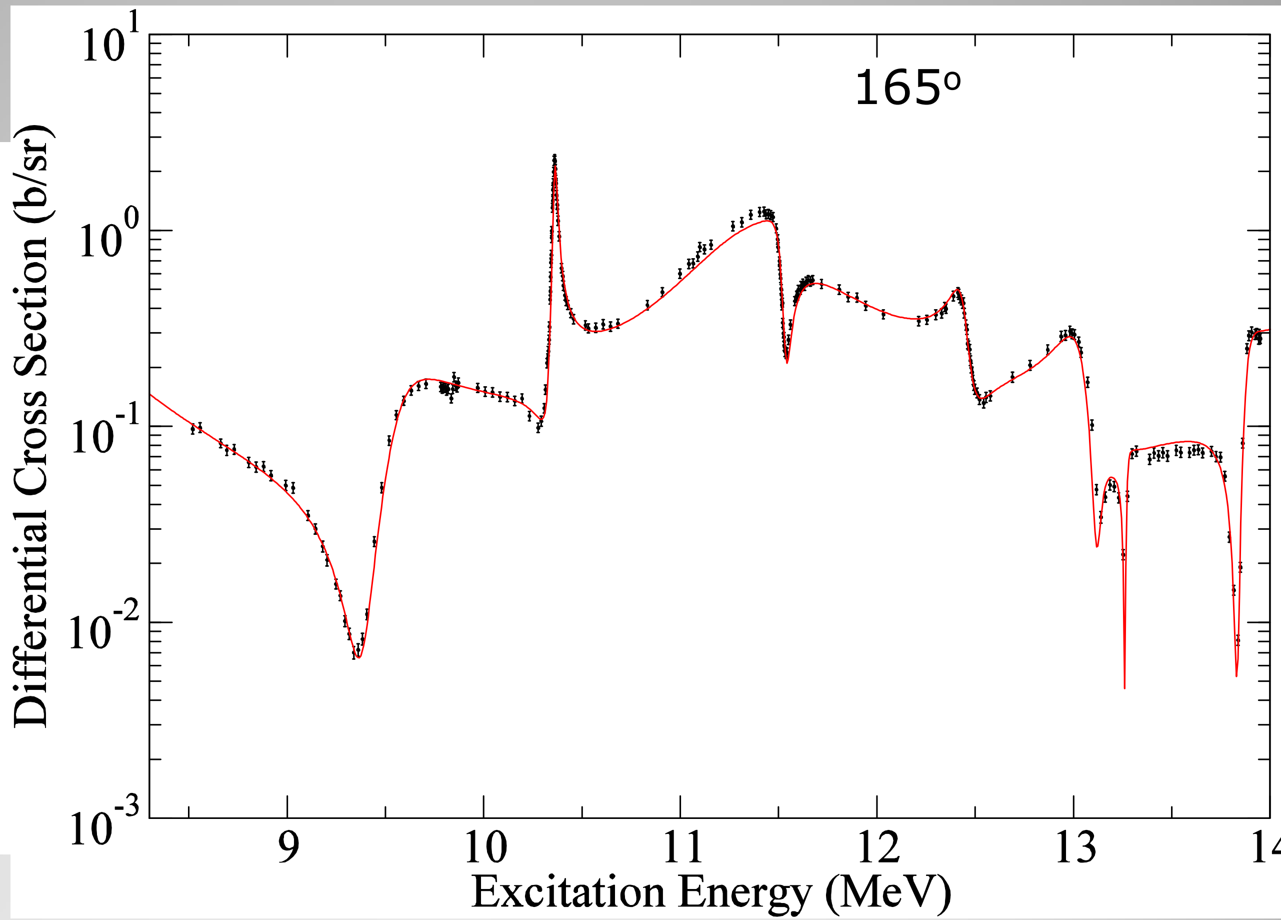
Morris *et al.* (1968)



$^{12}C(\alpha,\alpha_0)^{12}C$

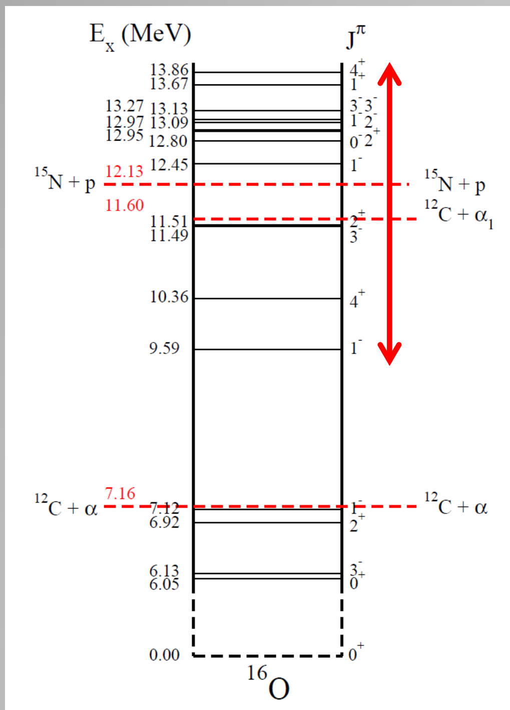
Morris *et al.* (1968)

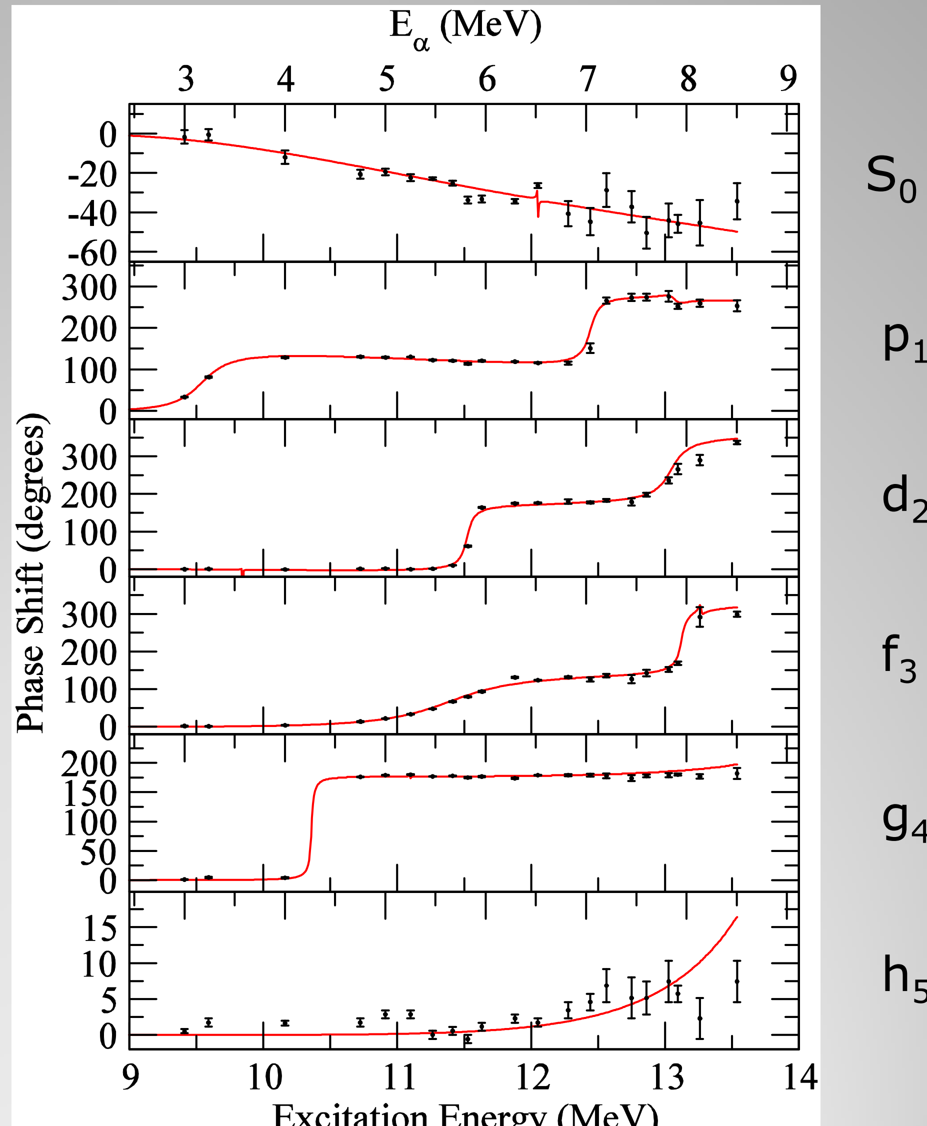




$^{12}C(\alpha,\alpha_0)^{12}C$

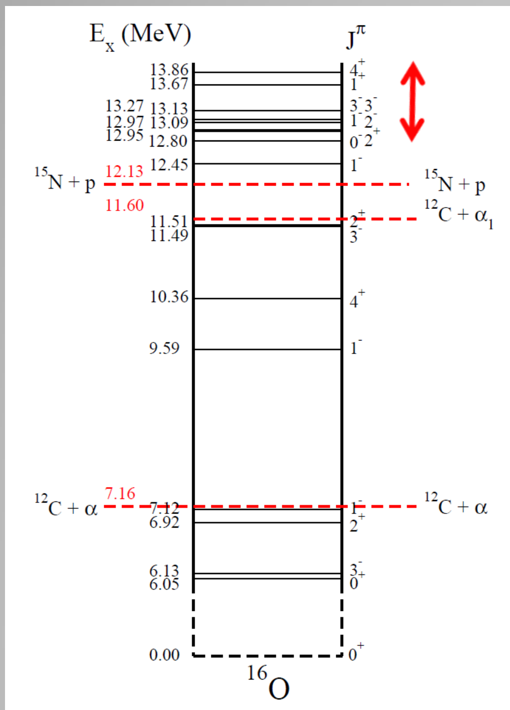
Feng *et al.* (1994)

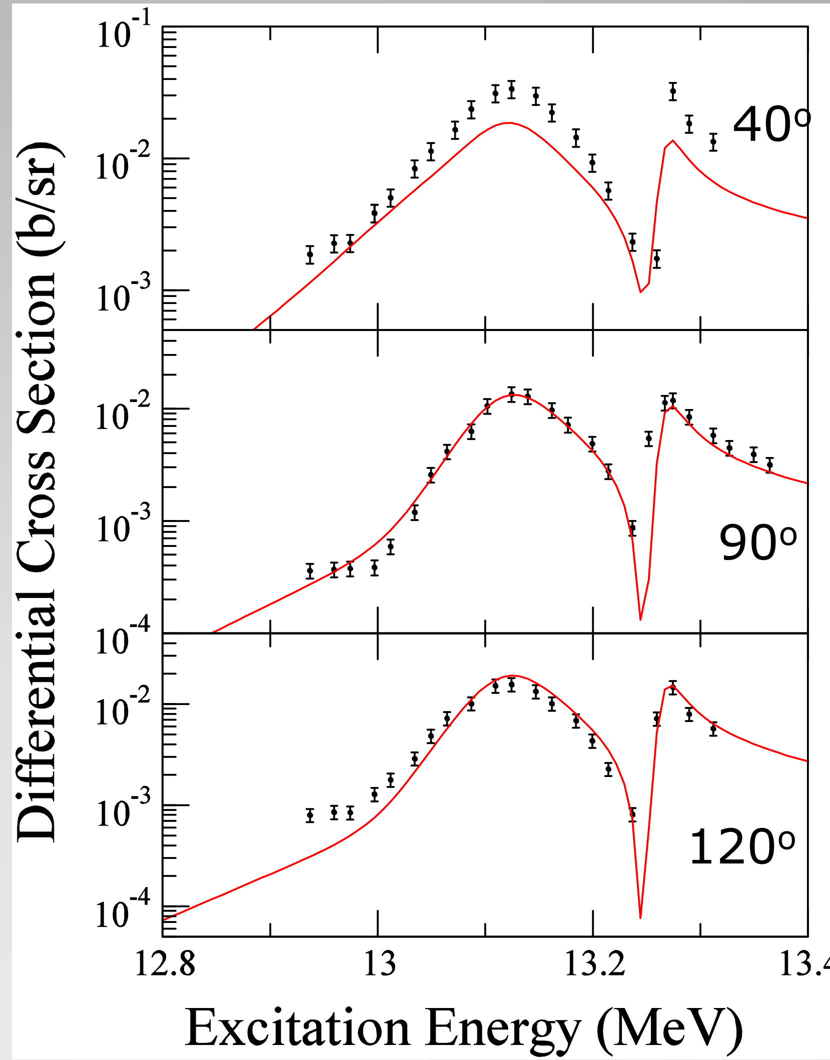




$^{12}C(\alpha,\alpha_0)^{12}C$

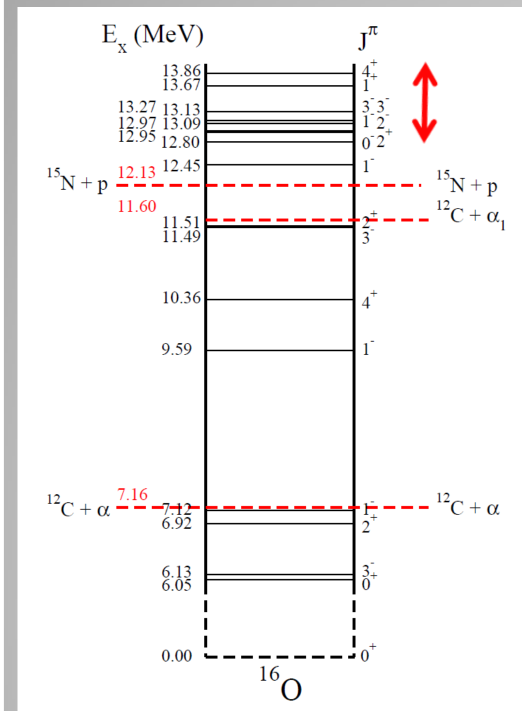
D'Agostino Bruno *et al.* (1975)

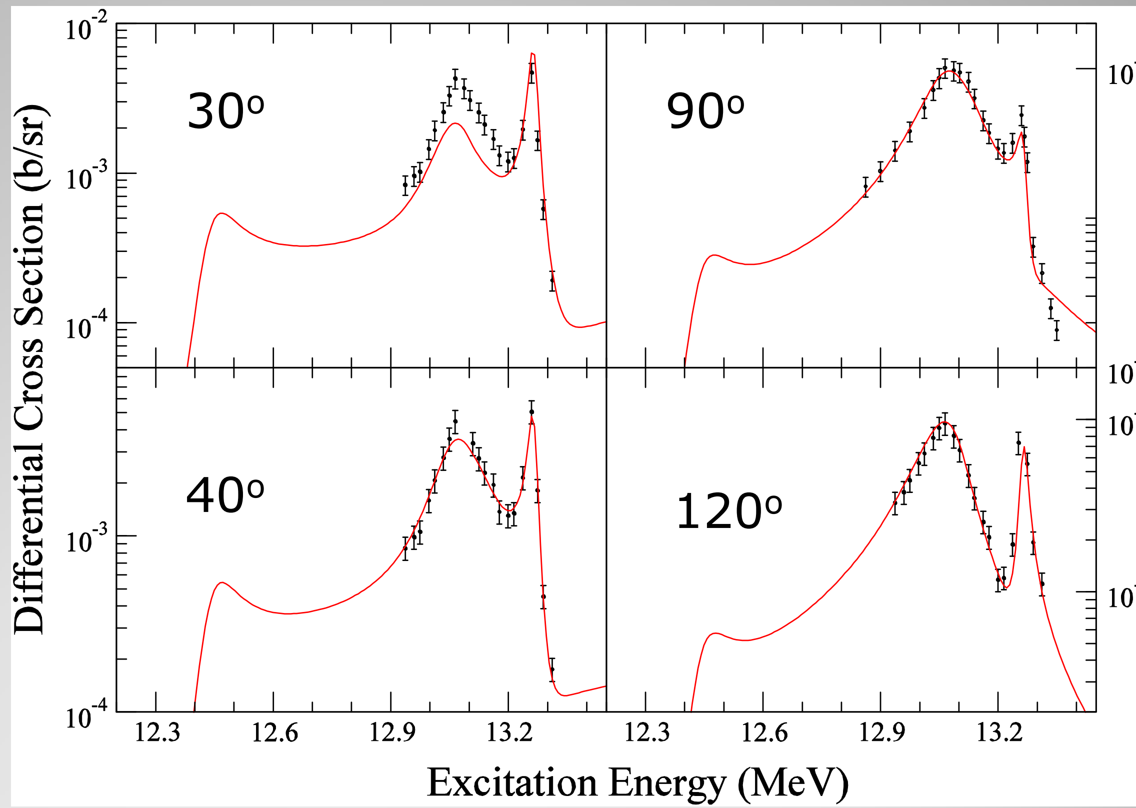




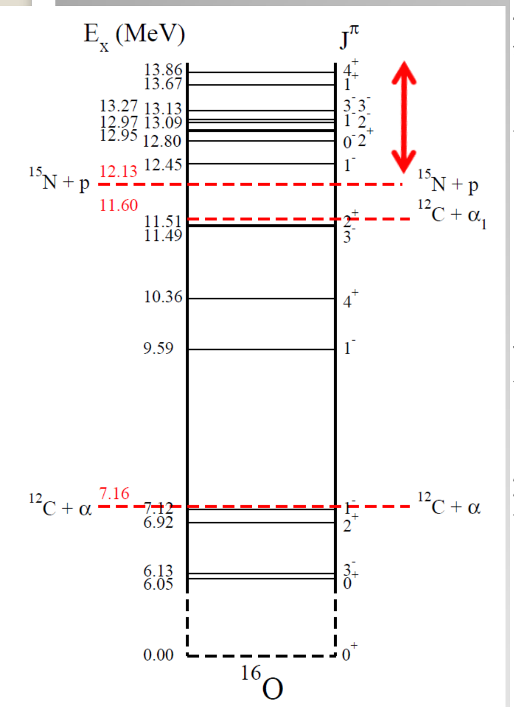
$^{12}C(\alpha,\alpha_1)^{12}C$

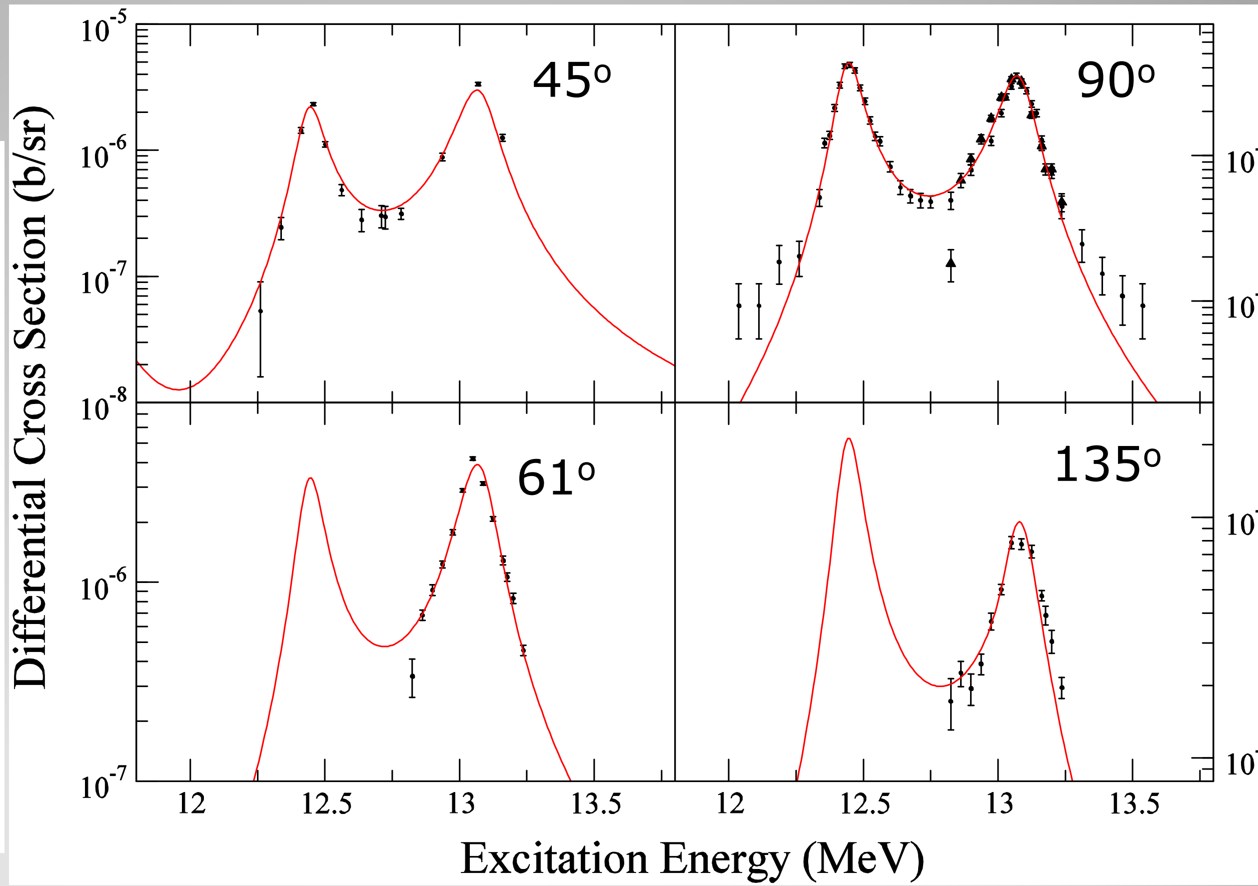
Mitchell and Ophel (1965)





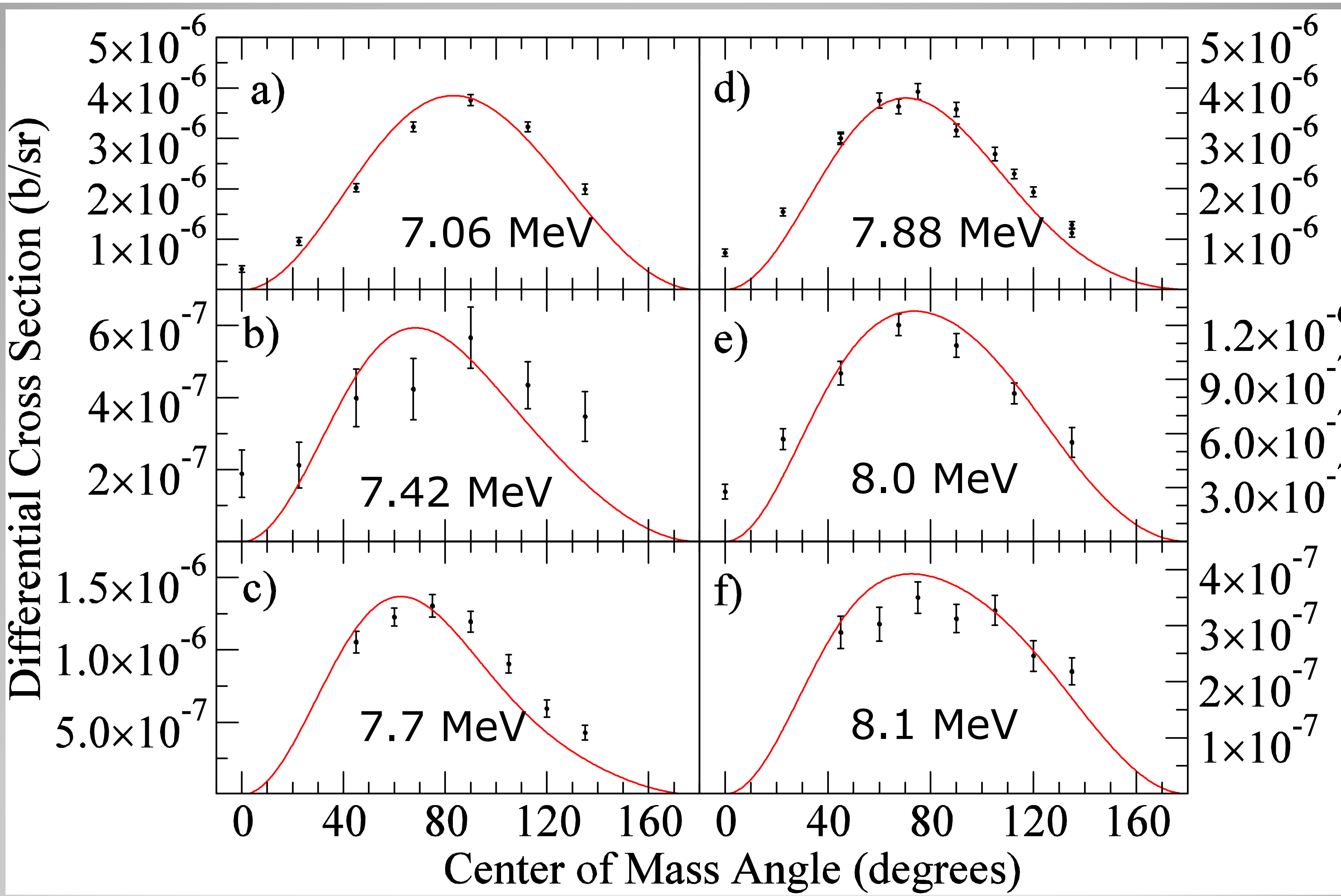
$^{12}C(\alpha,p)^{15}N$
Mitchell and Ophel (1965)





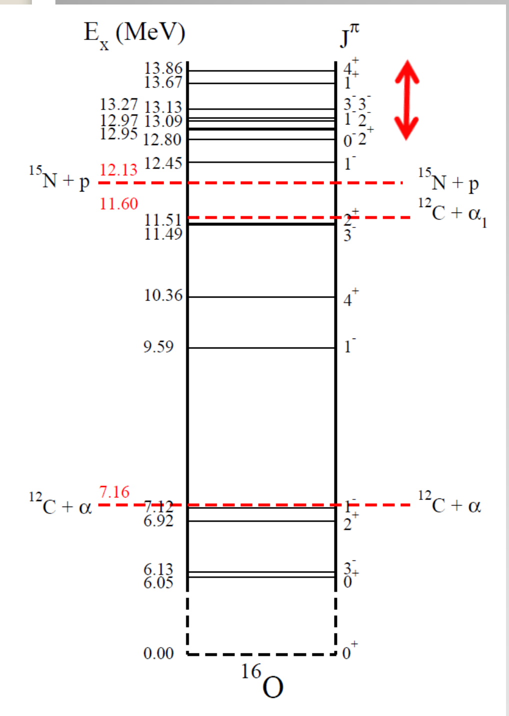
$^{12}C(\alpha,\gamma_0)^{16}O$

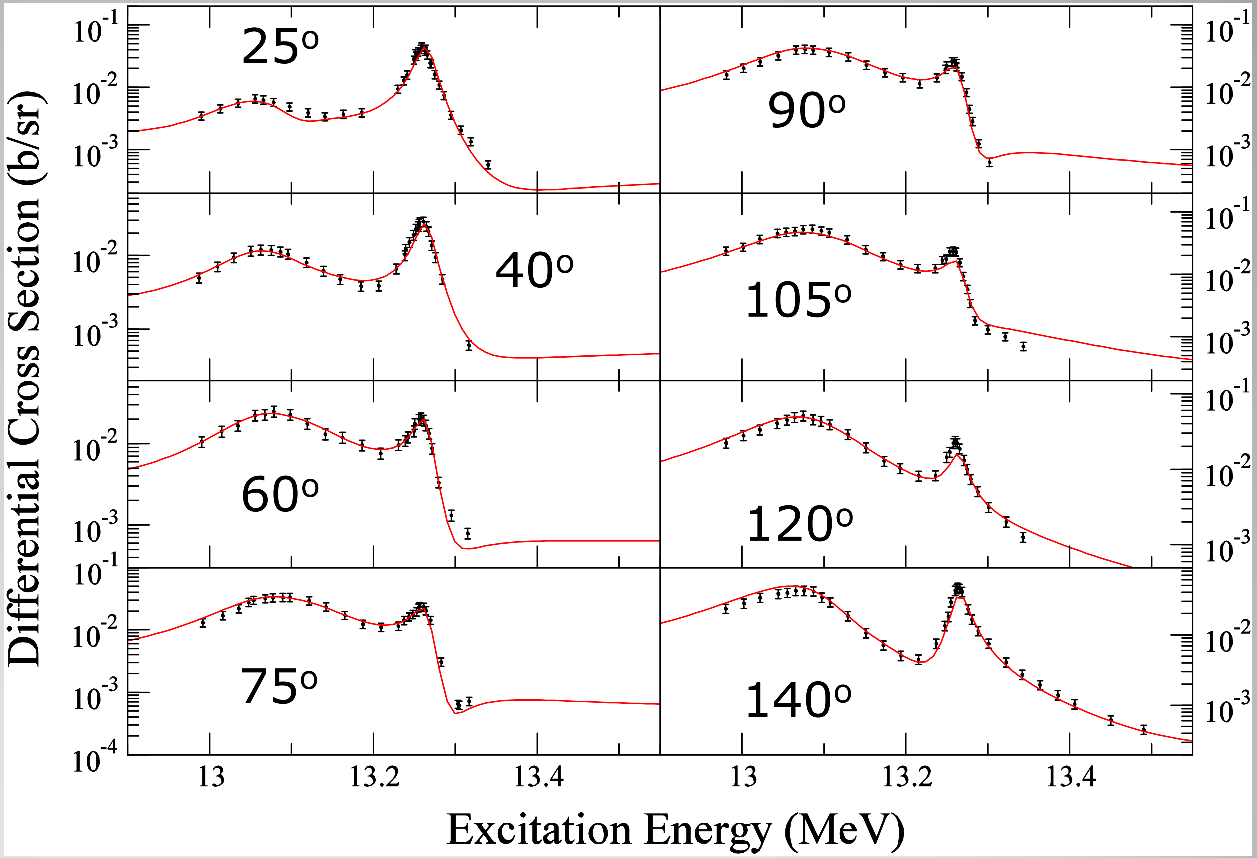
Ophel *et al.* (1976), Larson and Spear (1964), and Kernel *et al.* (1971)



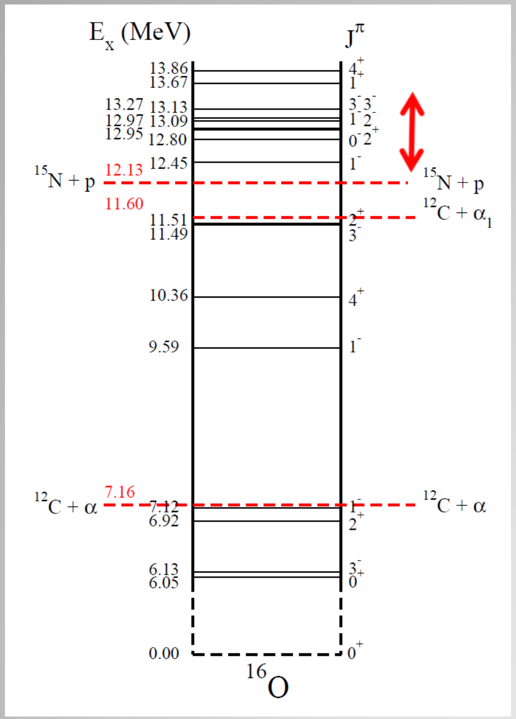
$^{12}C(\alpha,\gamma_0)^{12}C$

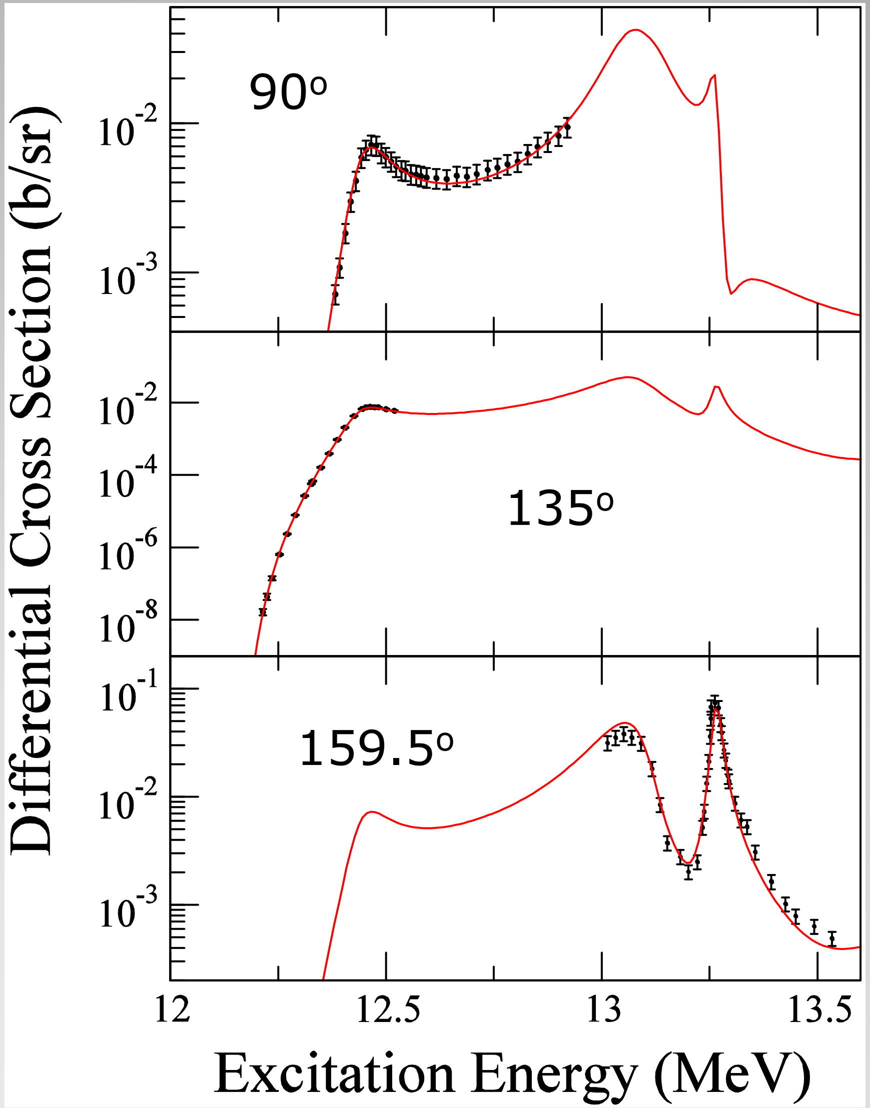
Larson and Spear (1964) and Kernel *et al.* (1971)





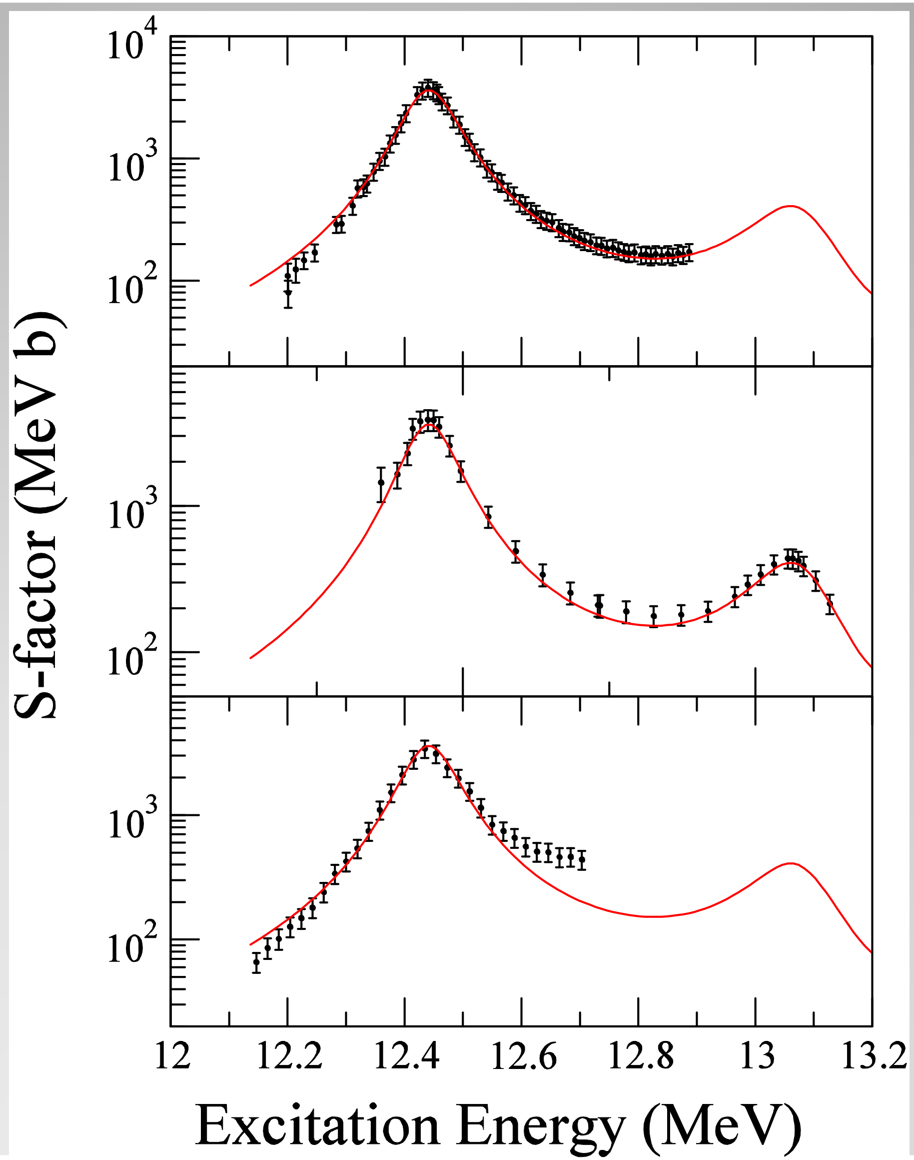
$^{15}N(p,\alpha_0)^{12}C$
Hagedorn and Marion (1957)





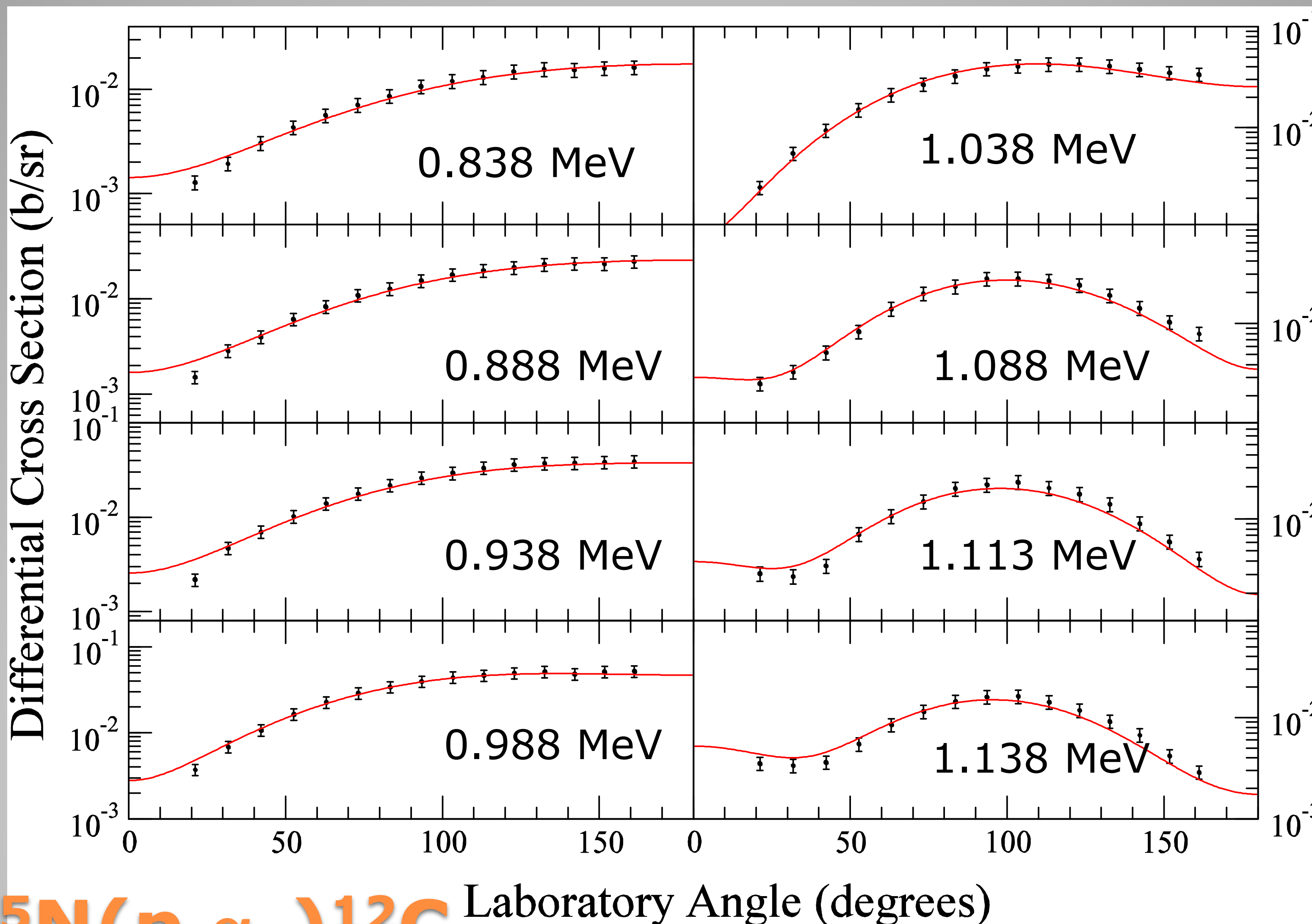
$^{15}N(p,\alpha_0)^{12}C$

Bashkin *et al.* (1959), Zyskind and Parker (1979), and Schardt *et al.* (1952)



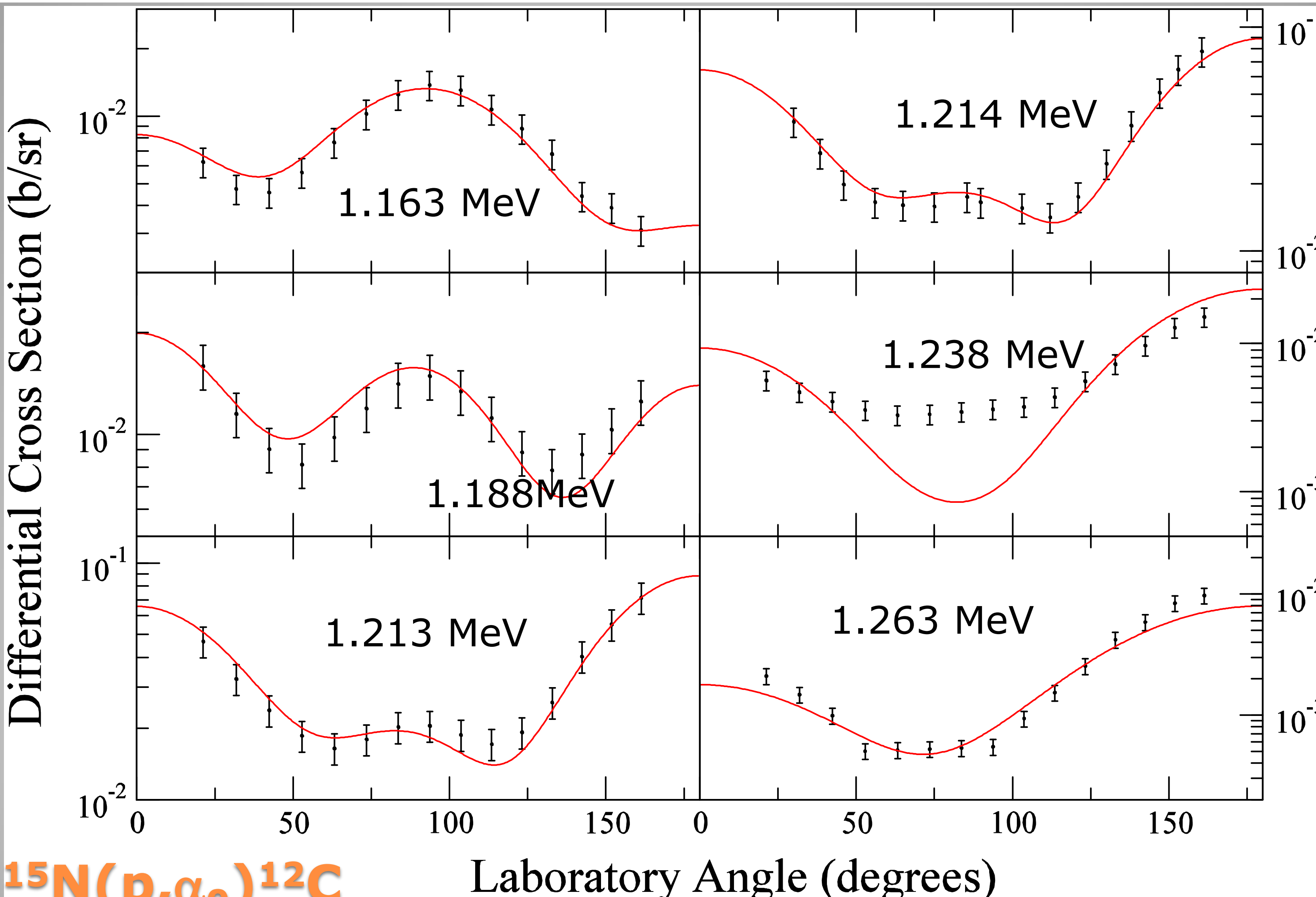
$^{15}N(p,\alpha_0)^{12}C$

Redder et al. (1982), Brochard et al. (1973), and La Cognata et al. (2009)



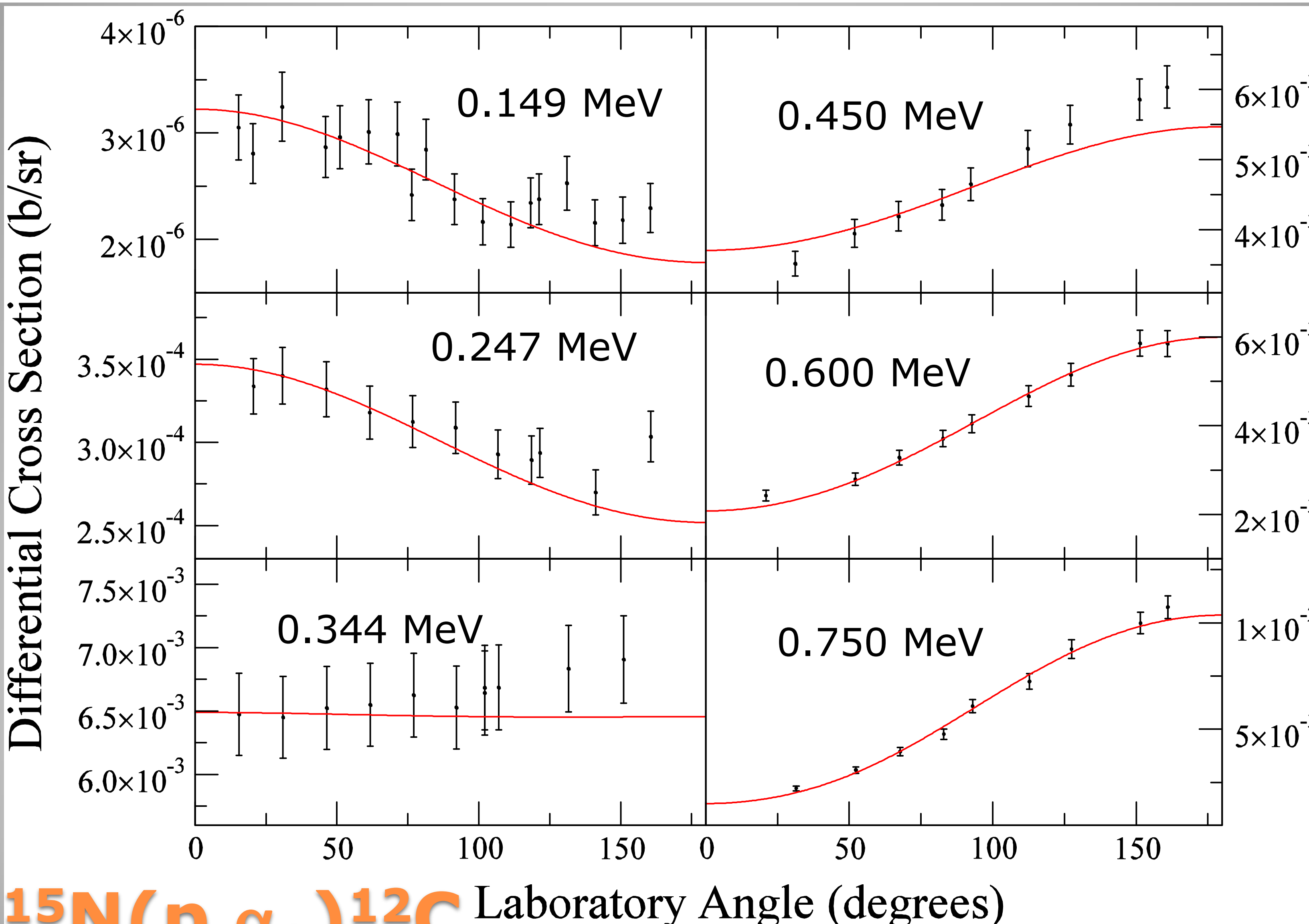
$^{15}N(p,\alpha_0)^{12}C$

Bray *et al.* (1977)



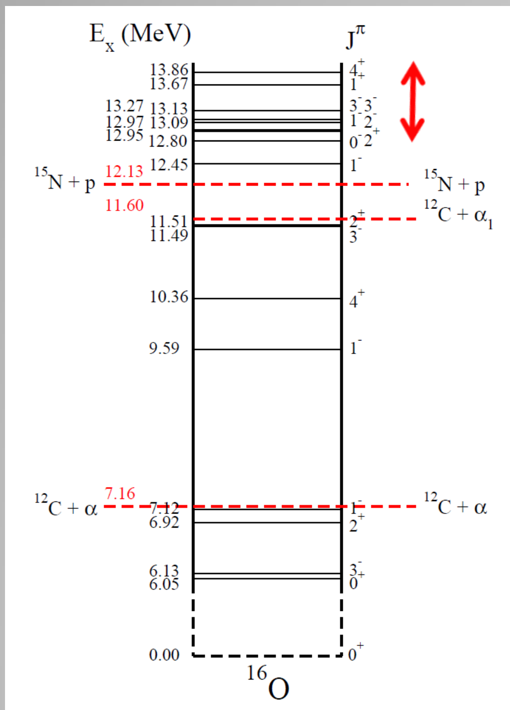
$^{15}N(p,\alpha_0)^{12}C$

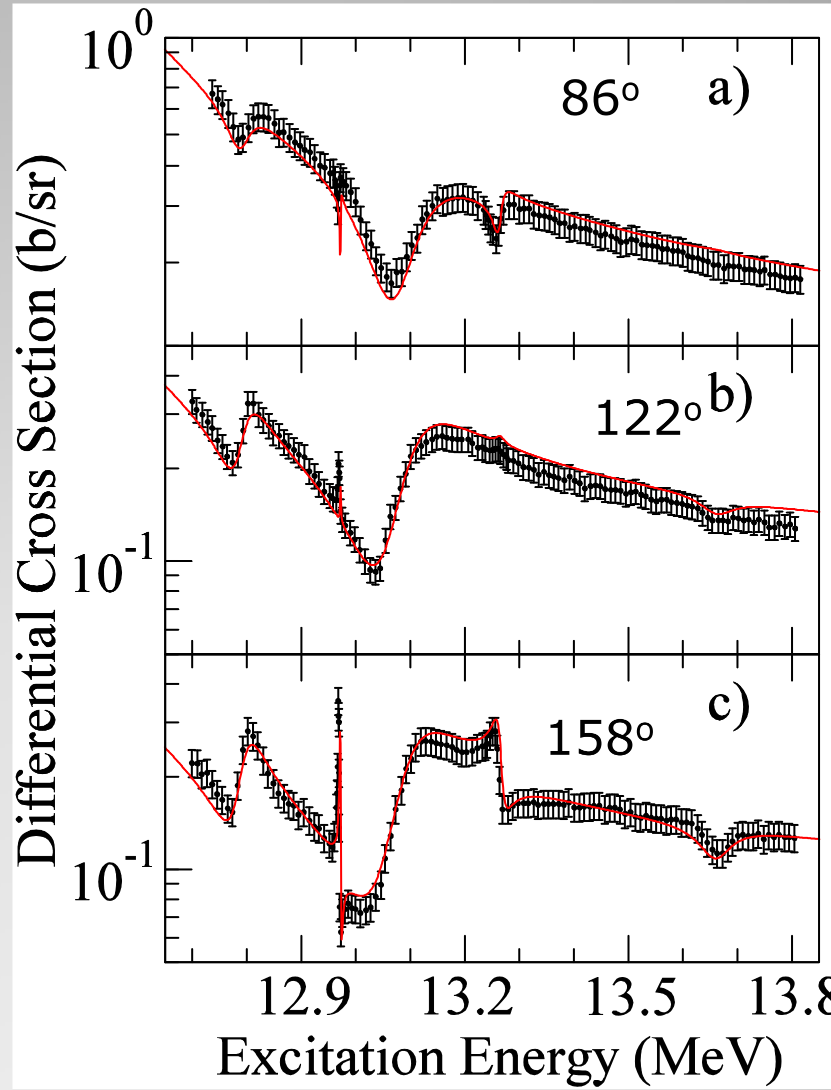
Bray *et al.* (1977) and Bashkin *et al.* (1959)



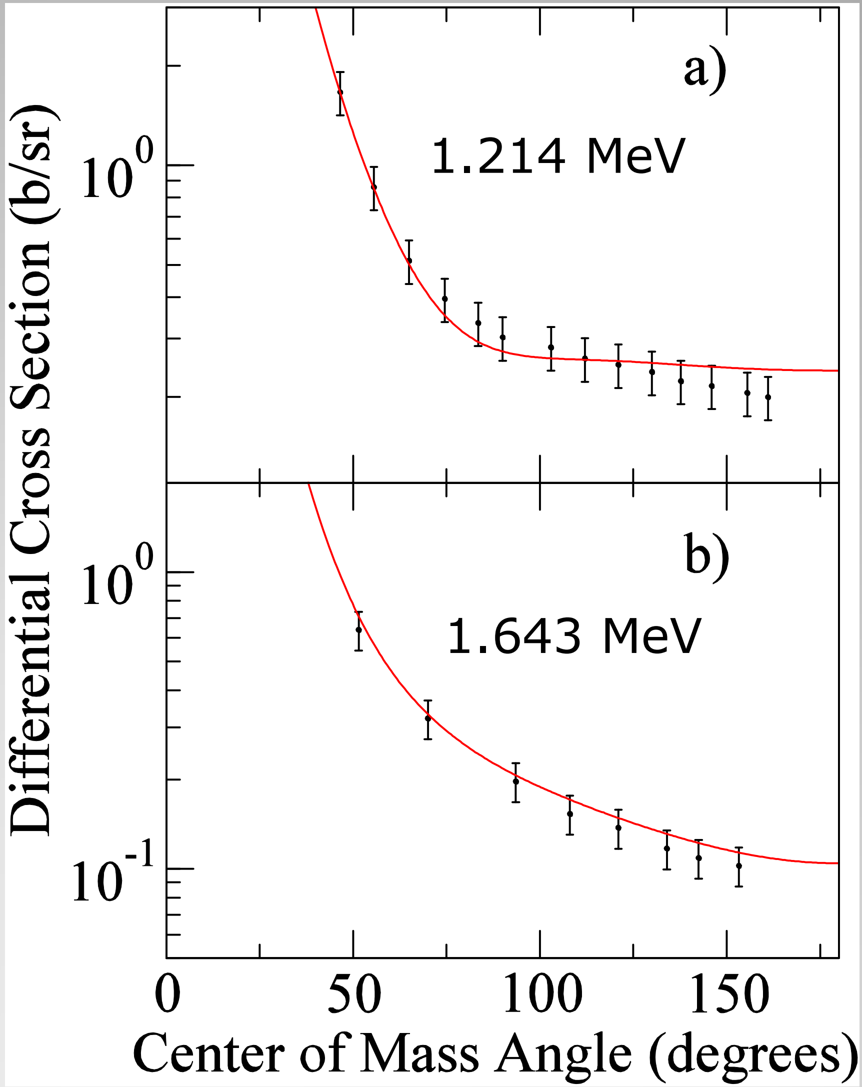
$^{15}N(p,\alpha_0)^{12}C$

Redder *et al.* (1982)

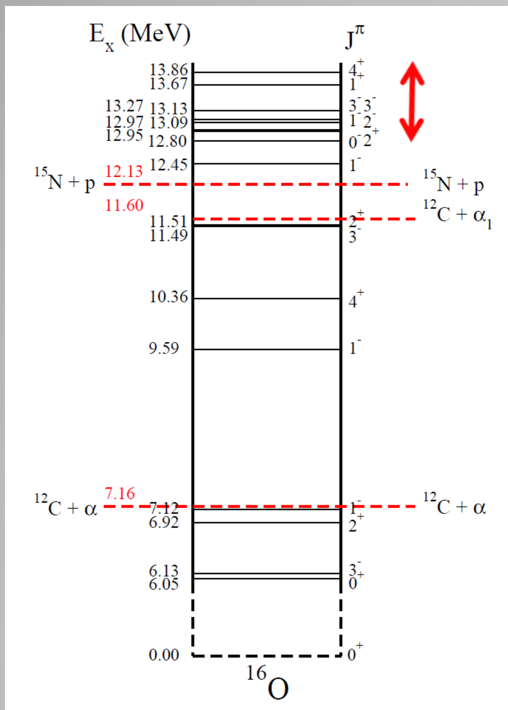


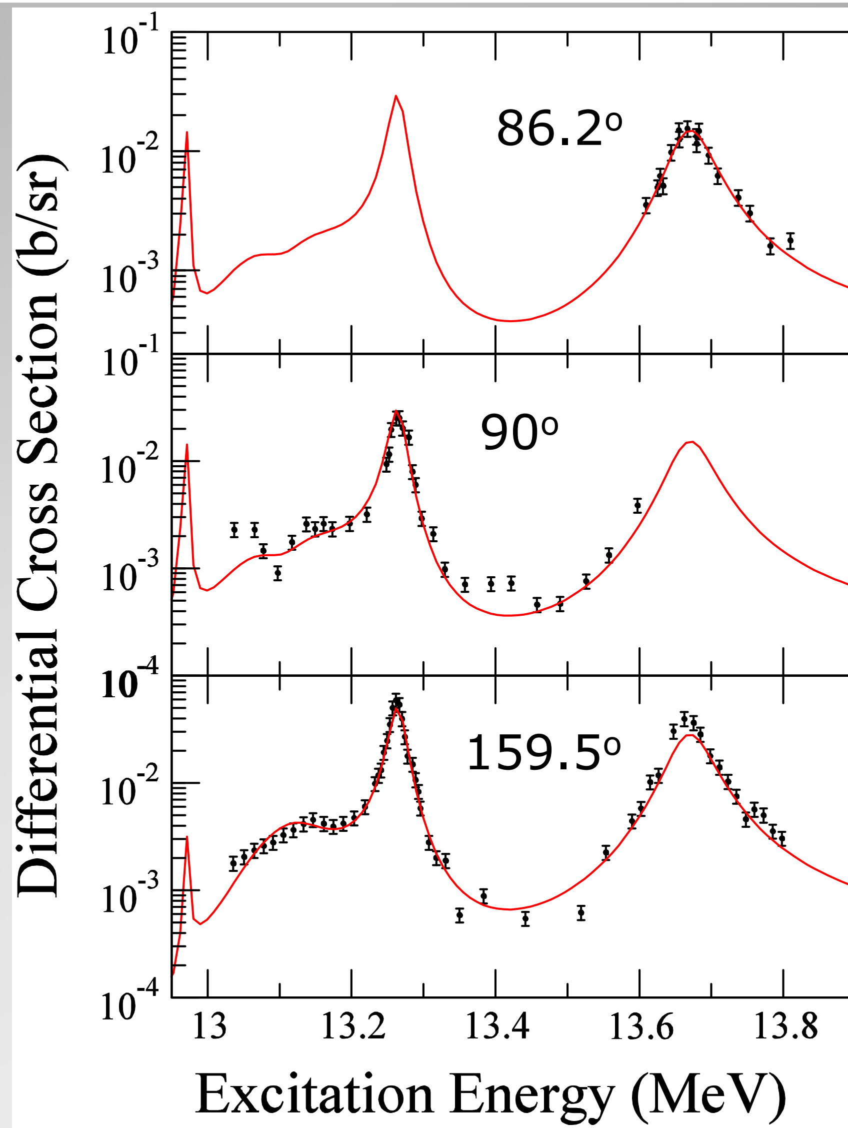


$^{15}N(p,p)^{15}N$ Hagedorn (1957)



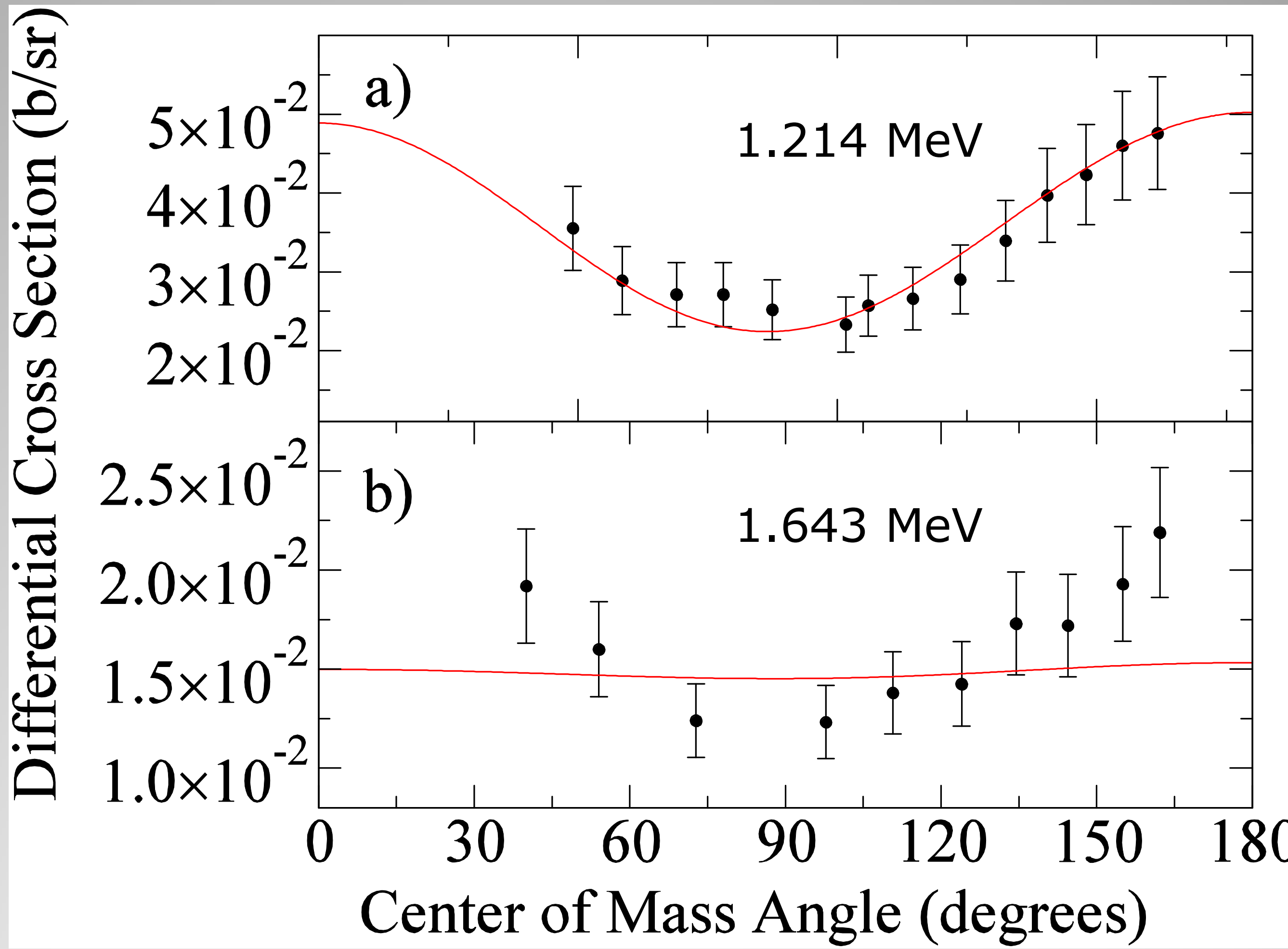
$^{15}N(p,p)^{15}N$ Bashkin *et al.* (1959)





$^{15}N(p,\alpha_1)^{12}C$

Bashkin *et al.* (1959)

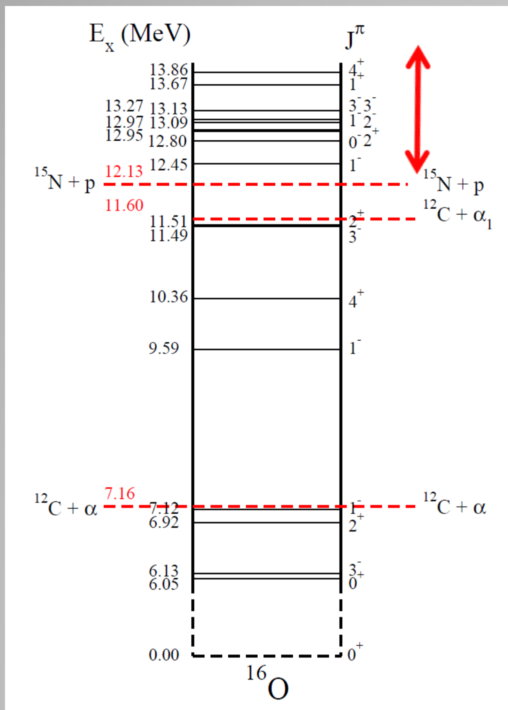


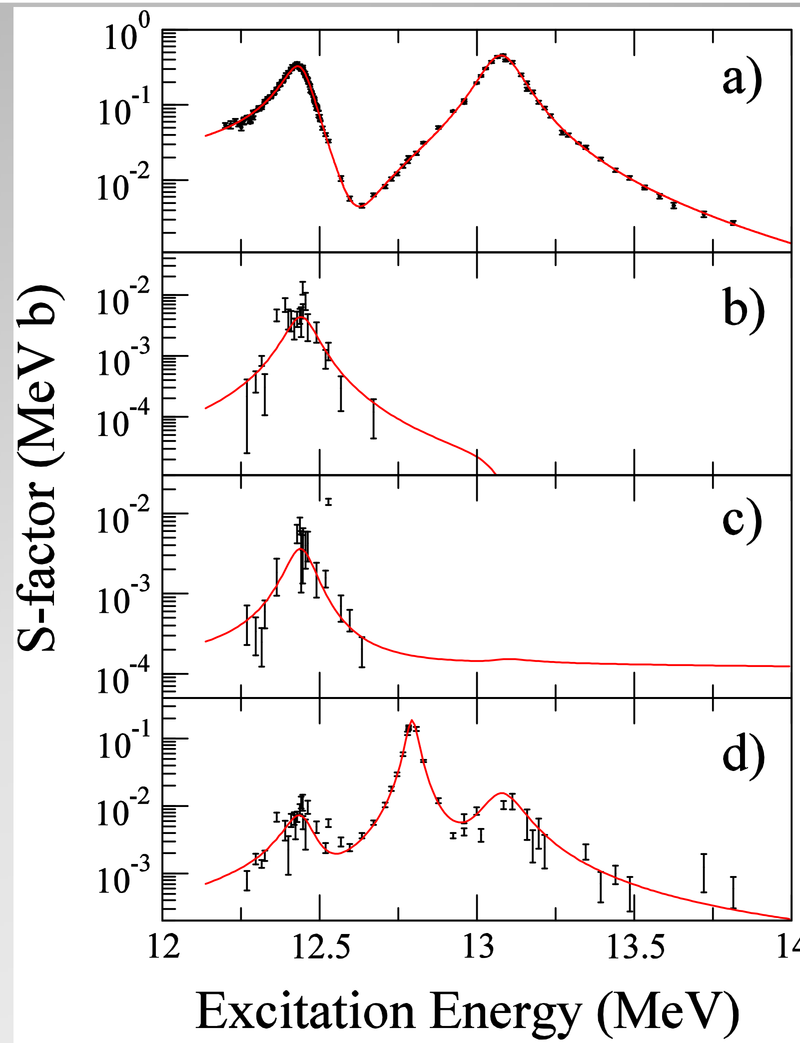
$^{15}N(p,\alpha_1)^{12}C$

Bashkin *et al.* (1959)

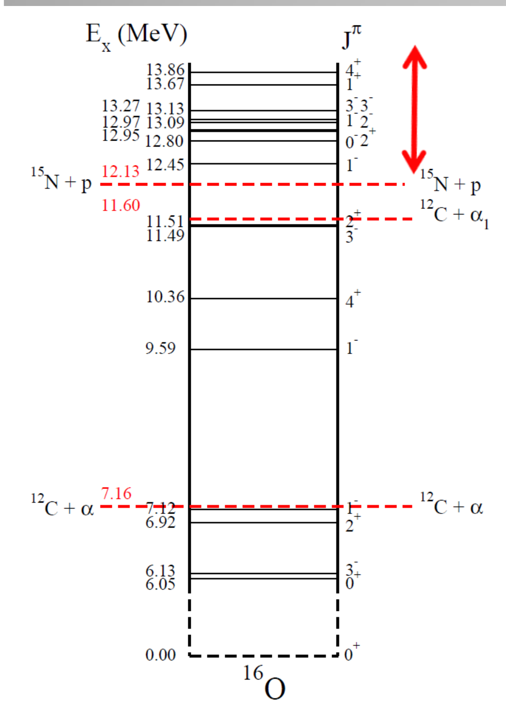
- Global fit now provides a very useful analysis framework for new data

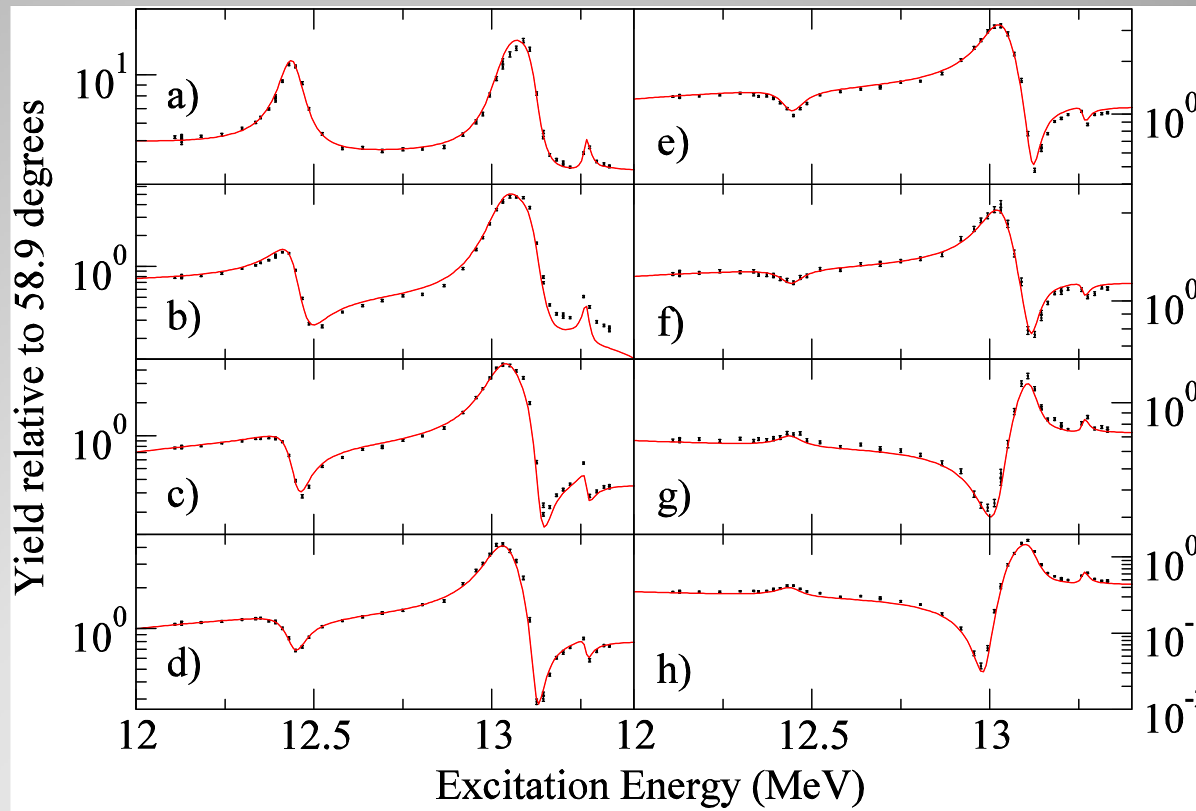
Unpublished Data



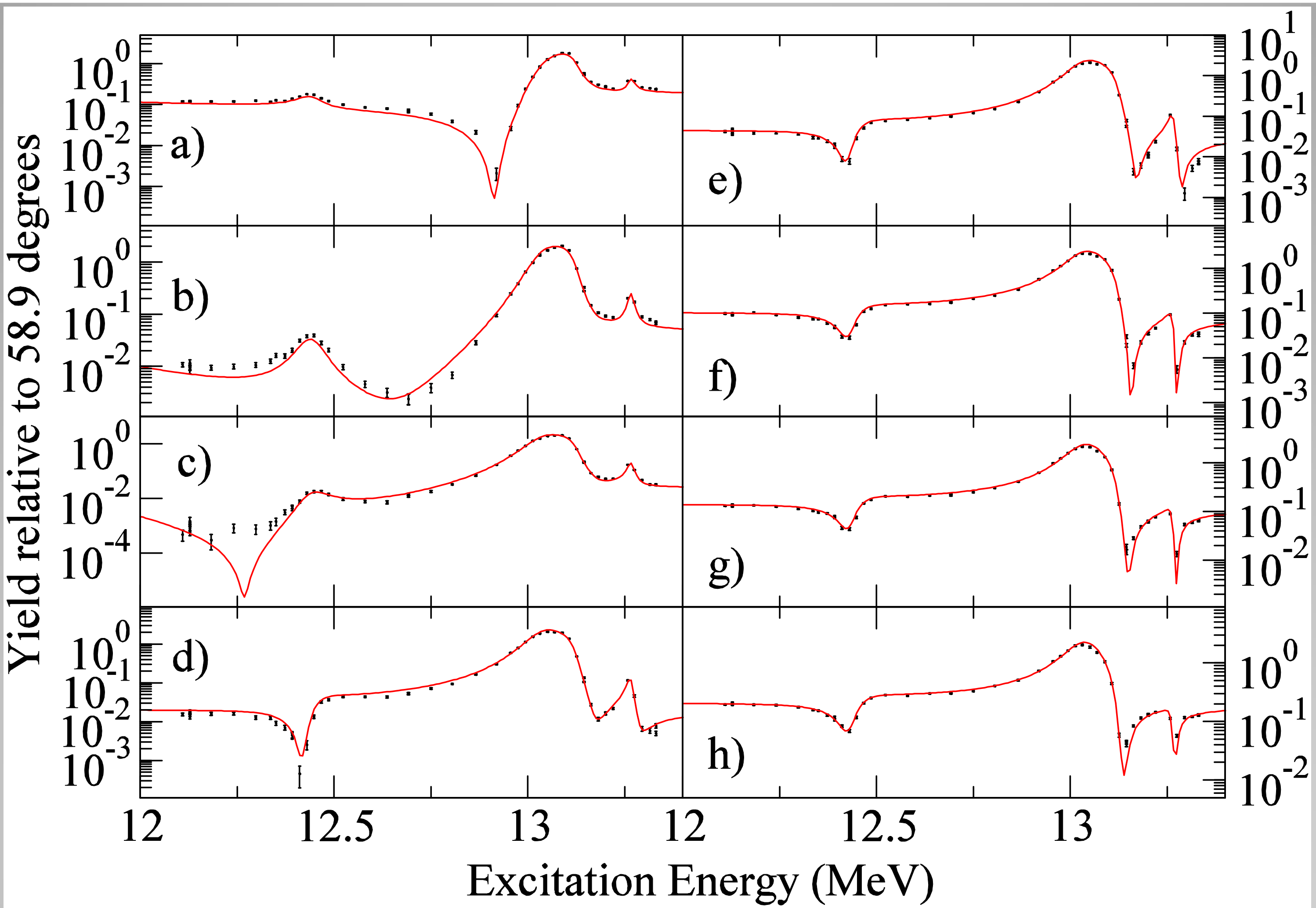


$^{15}N(p,\gamma)$ ground state, 6.05, 6.13, and 7.12 MeV transitions, LeBlanc *et al.* (2010) unpublished

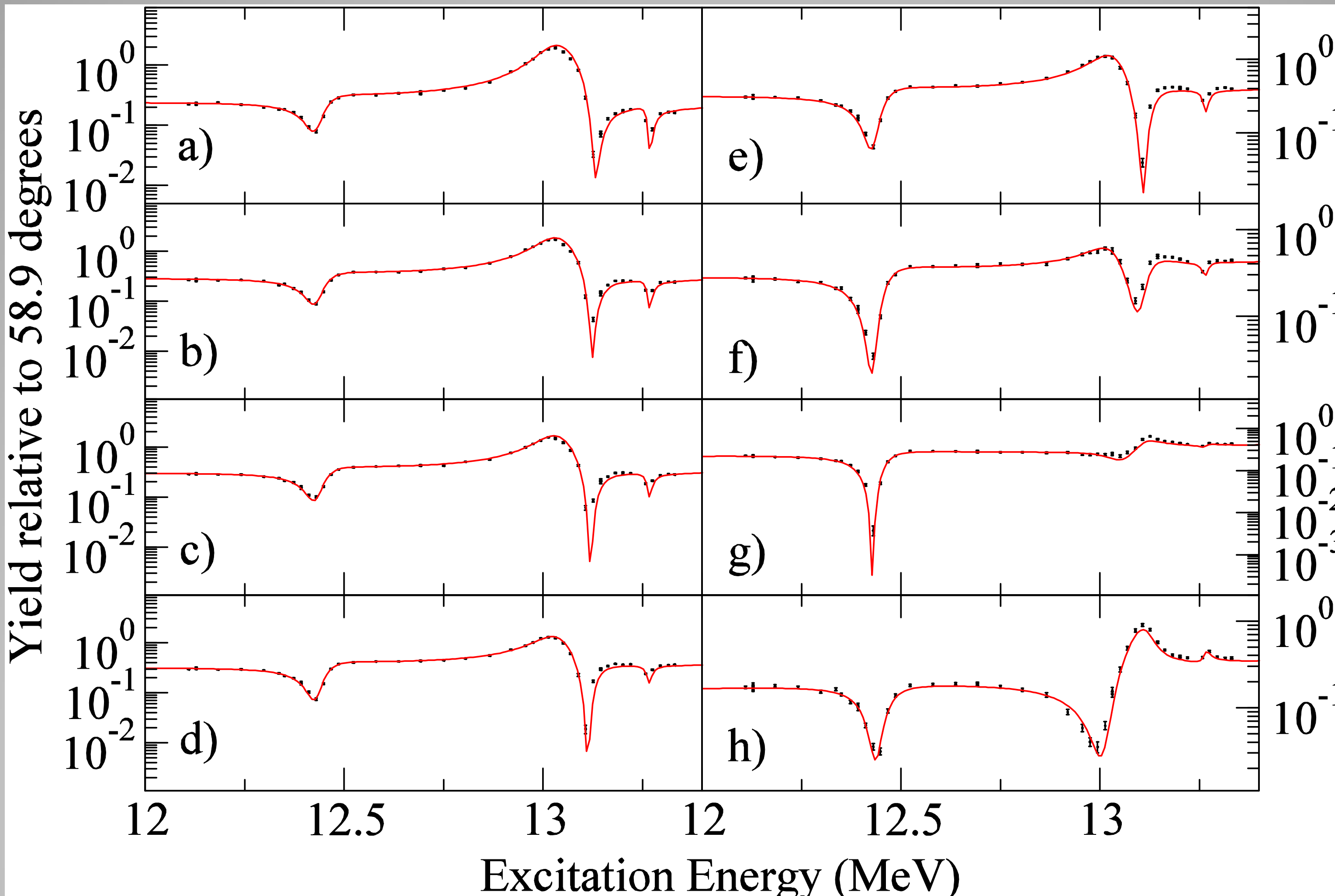




Tischhauser *et al.* (2009) unpublished high energy data at 24, 33.9, 38.9, 43.9, 48.9, 54, 63.9, and 68.9 degrees

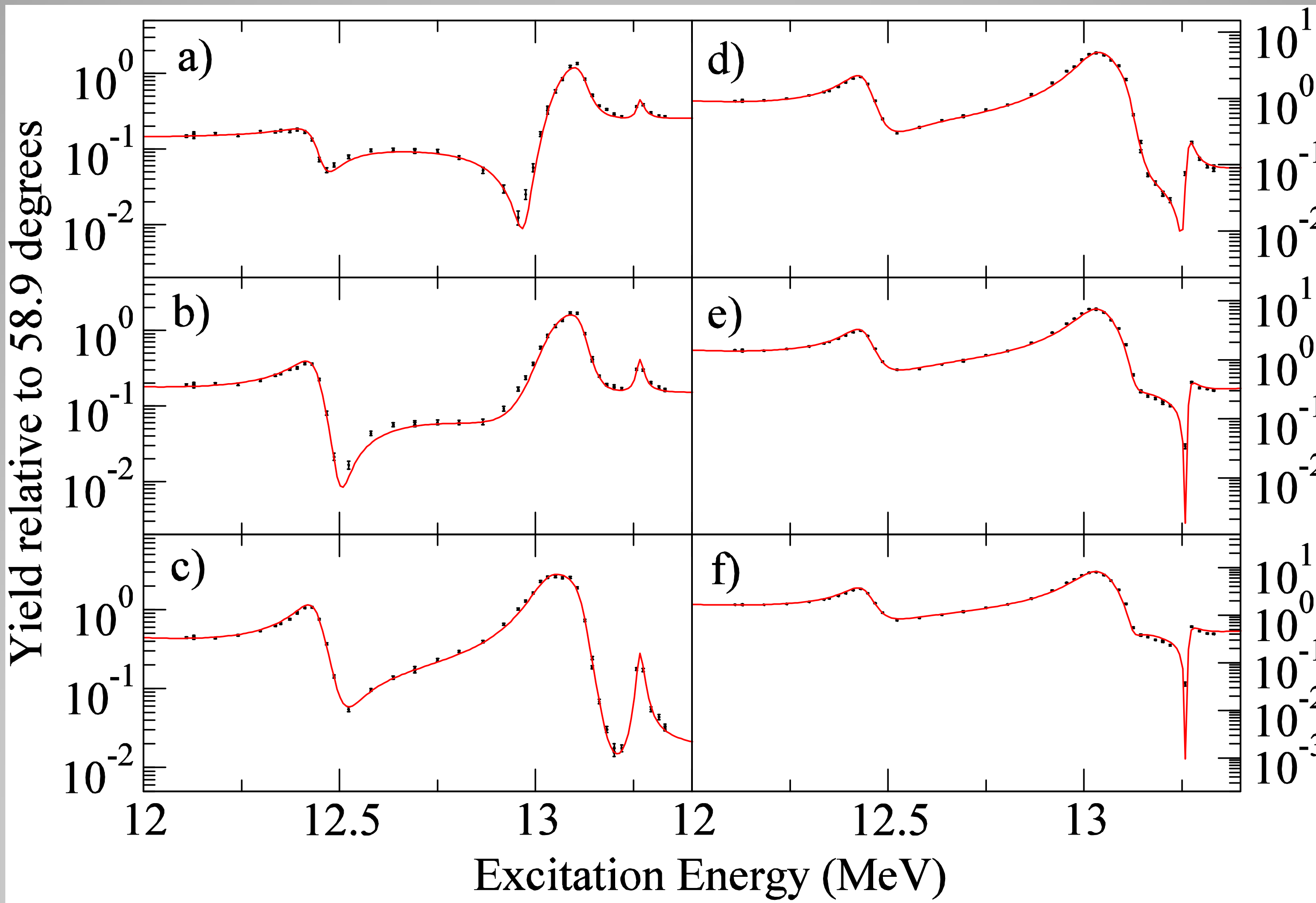


Tischhauser *et al.* (2009) unpublished high energy data at 74, 75.8, 80.8, 84, 85.8, 89, 90.8, and 94 degrees

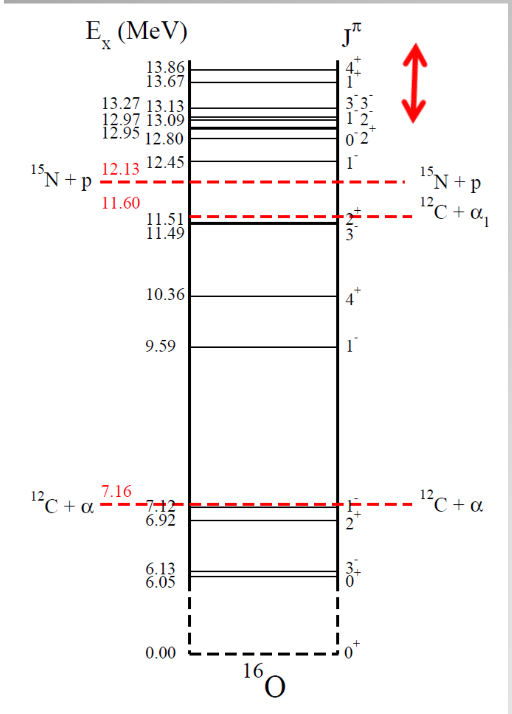


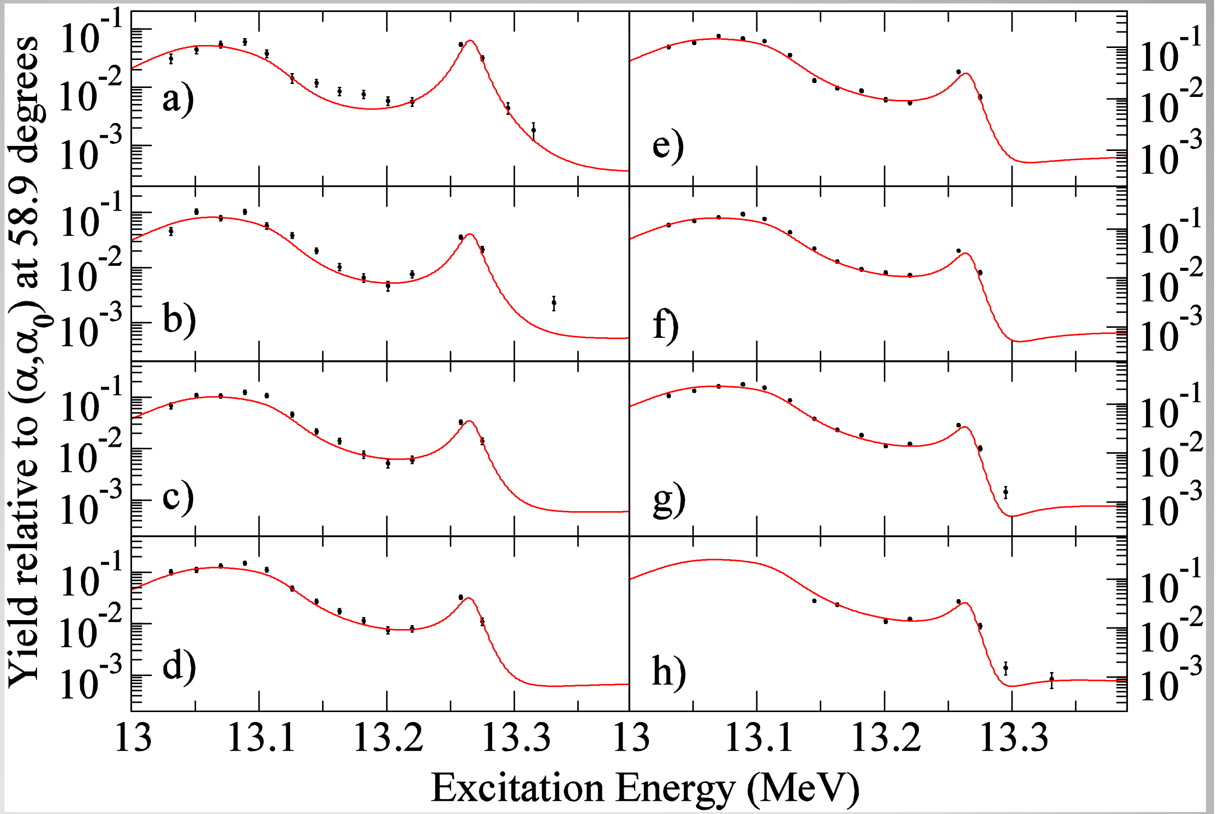
Tischhauser *et al.* (2009)

unpublished high energy data at 95.8, 99, 100.8, 103.9, 105.8, 110.8, 115.8, and 120.8 degrees

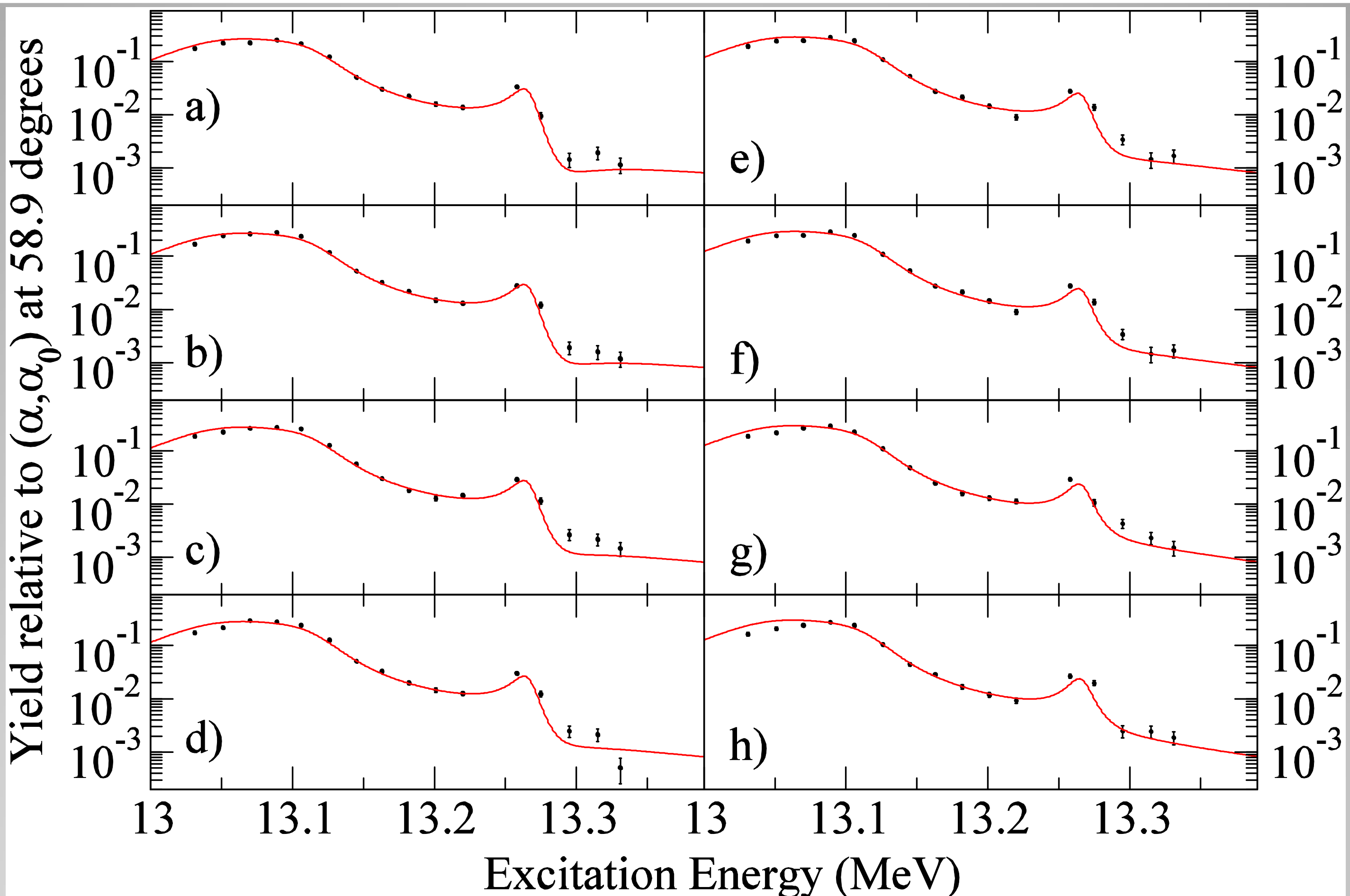


Tischhauser *et al.* (2009)
unpublished high energy data at 125.8, 130.8, 140.8, 150.8, 160.8, and 165.9 degrees

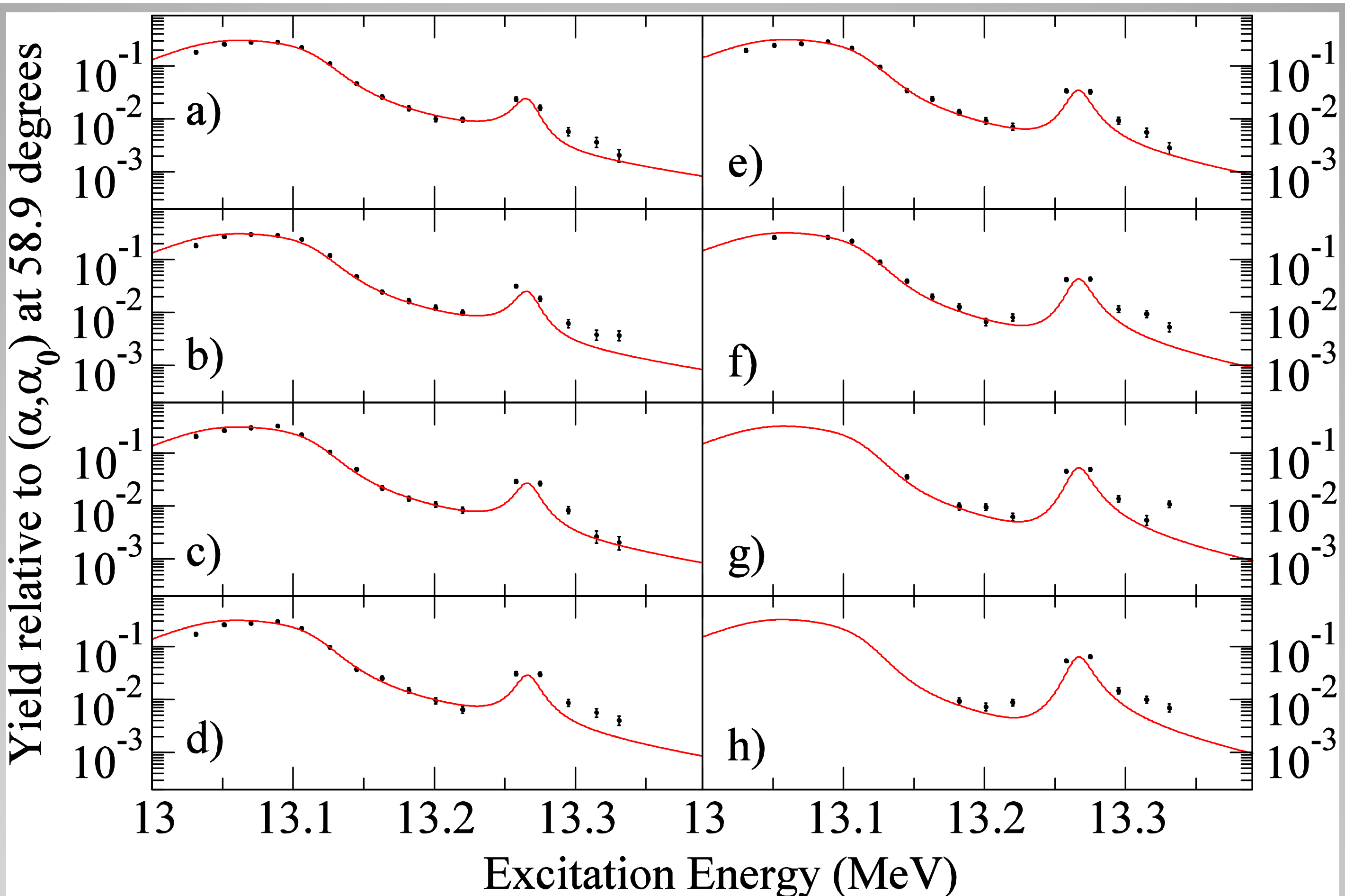




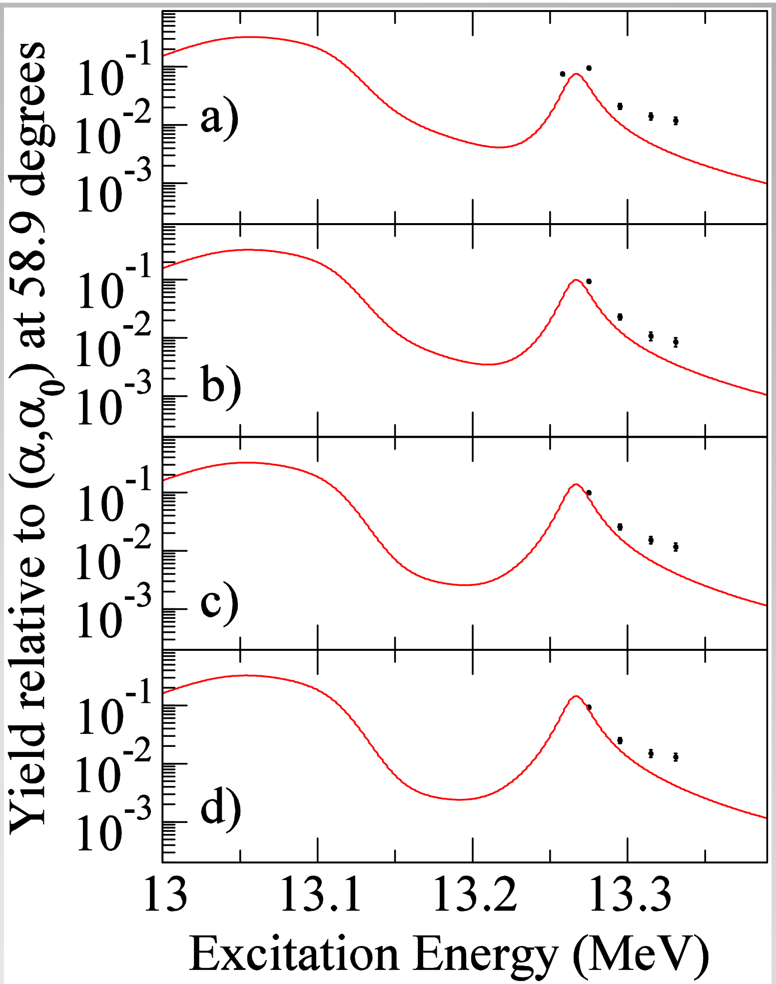
Tischhauser *et al.* (2009) unpublished high energy $^{12}C(\alpha,p)$ data at 24, 33.9, 38.9, 43.9, 48.9, 54, 68.9 and 74 degrees



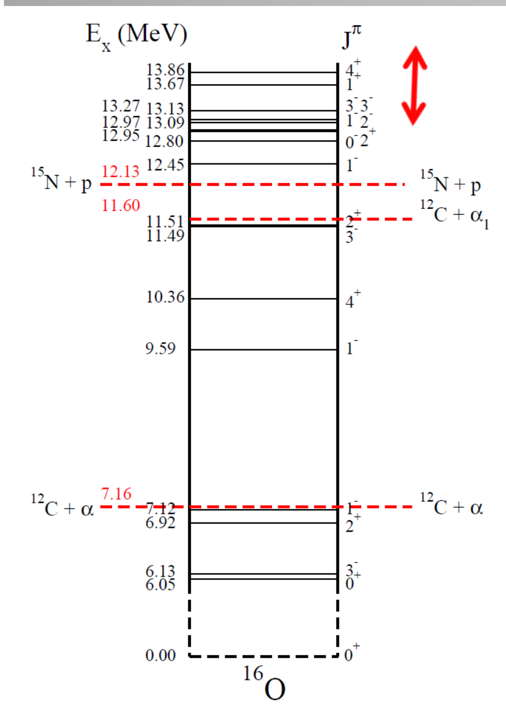
Tischhauser *et al.* (2009) unpublished high energy $^{12}C(\alpha,p)$ data at 79, 80.8, 84, 85.8, 89, 90.8, 94, and 95.8 degrees

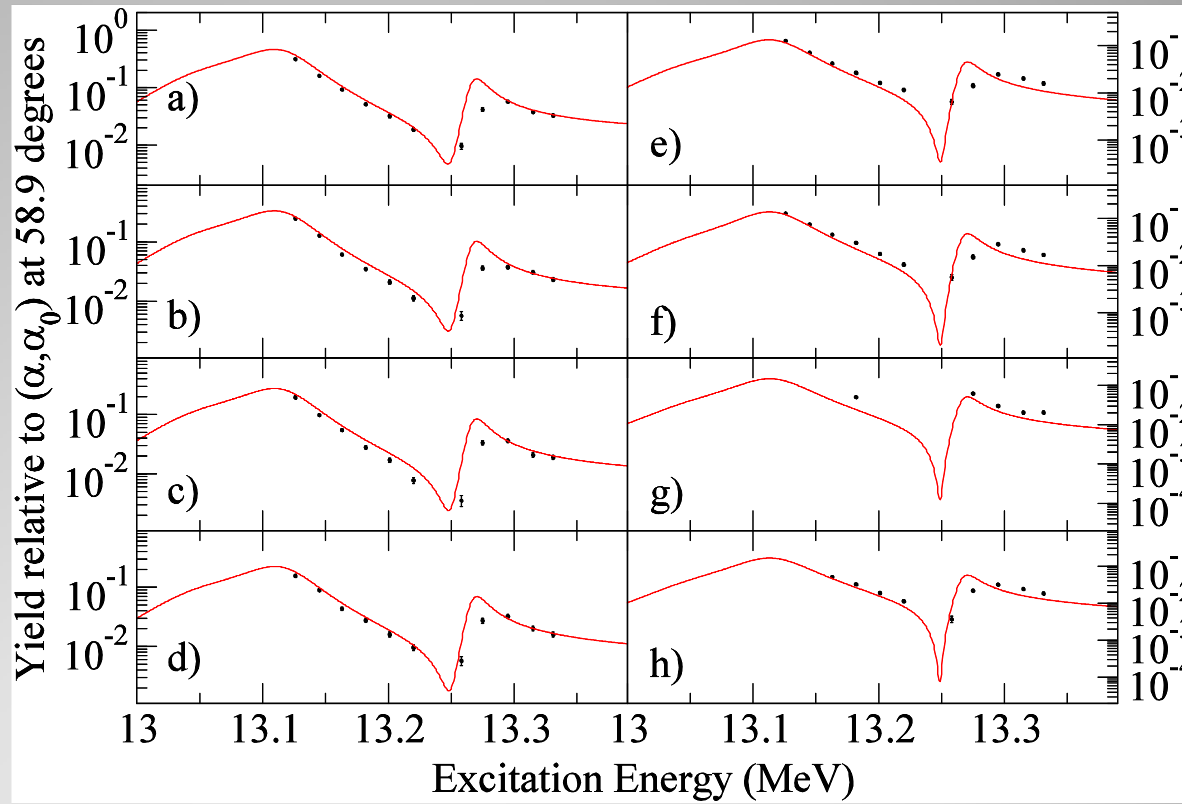


Tischhauser *et al.* (2009) unpublished high energy $^{12}C(\alpha,p)$ data at 99, 100.8, 103.9, 105.8, 110.8, 115.8, 120.8, and 125.8 degrees

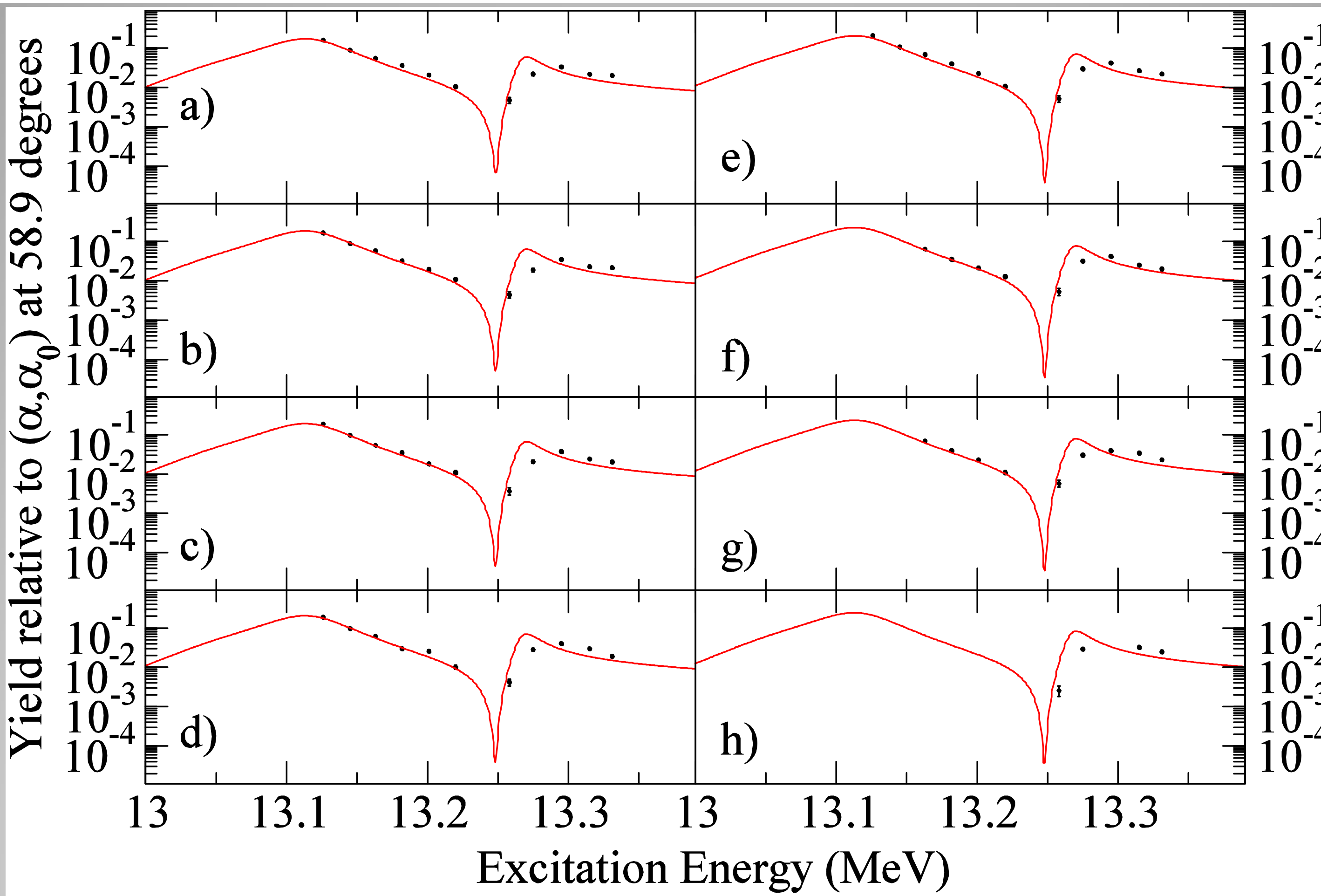


Tischhauser *et al.* (2009)
unpublished high energy $^{12}C(\alpha,p)$ data
at 130.8, 140.8, 150.8, and 160.8 degrees

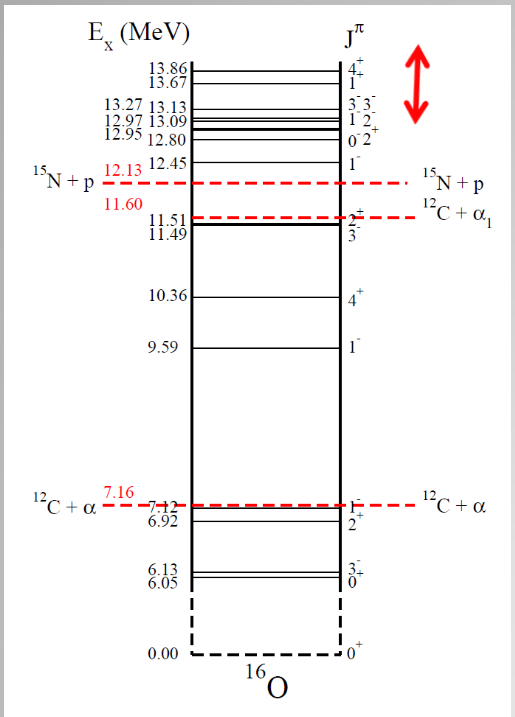


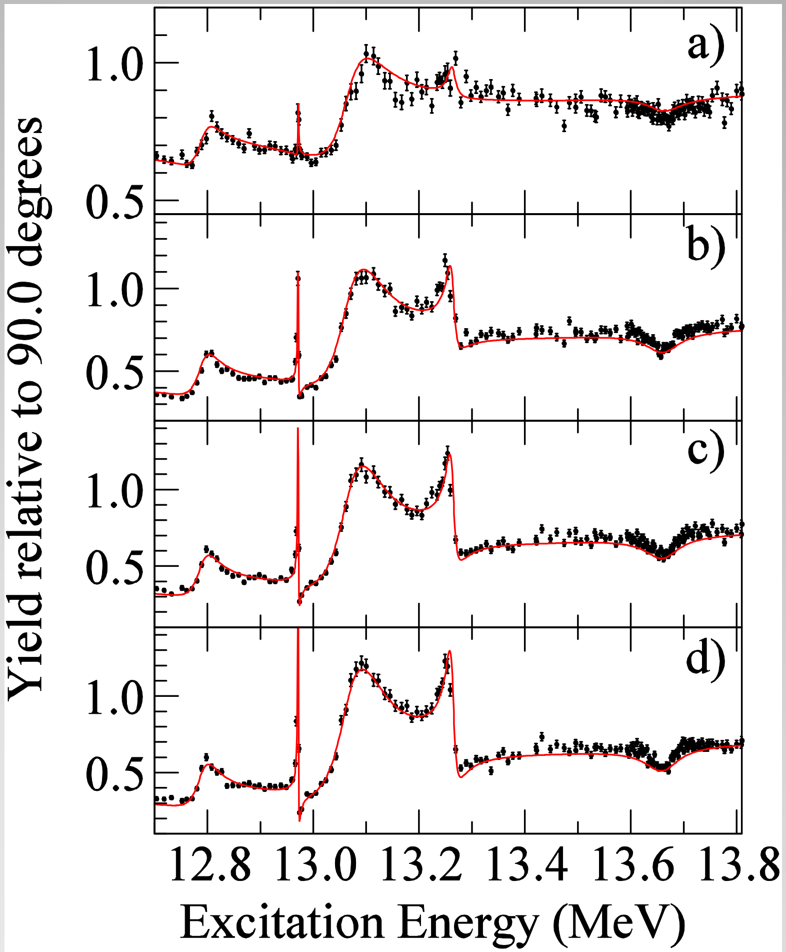


Tischhauser *et al.* (2009) unpublished high energy $^{12}C(\alpha,\alpha_1)$ data at 24, 33.9, 38.9, 43.9, 63.9, 68.9, 74, and 79 degrees

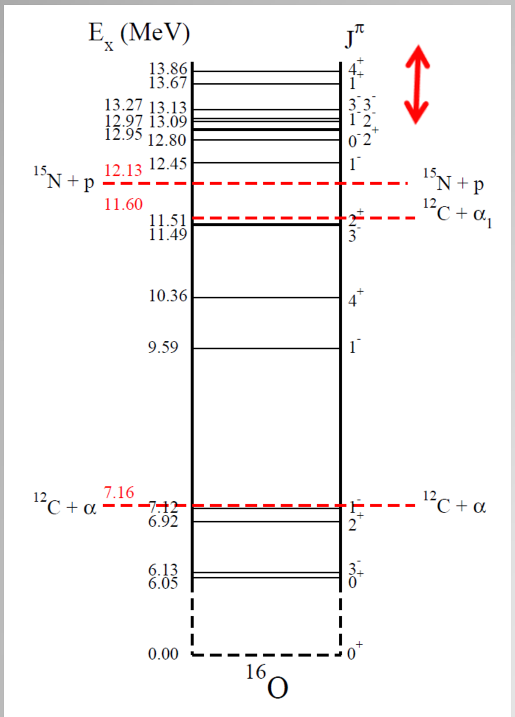


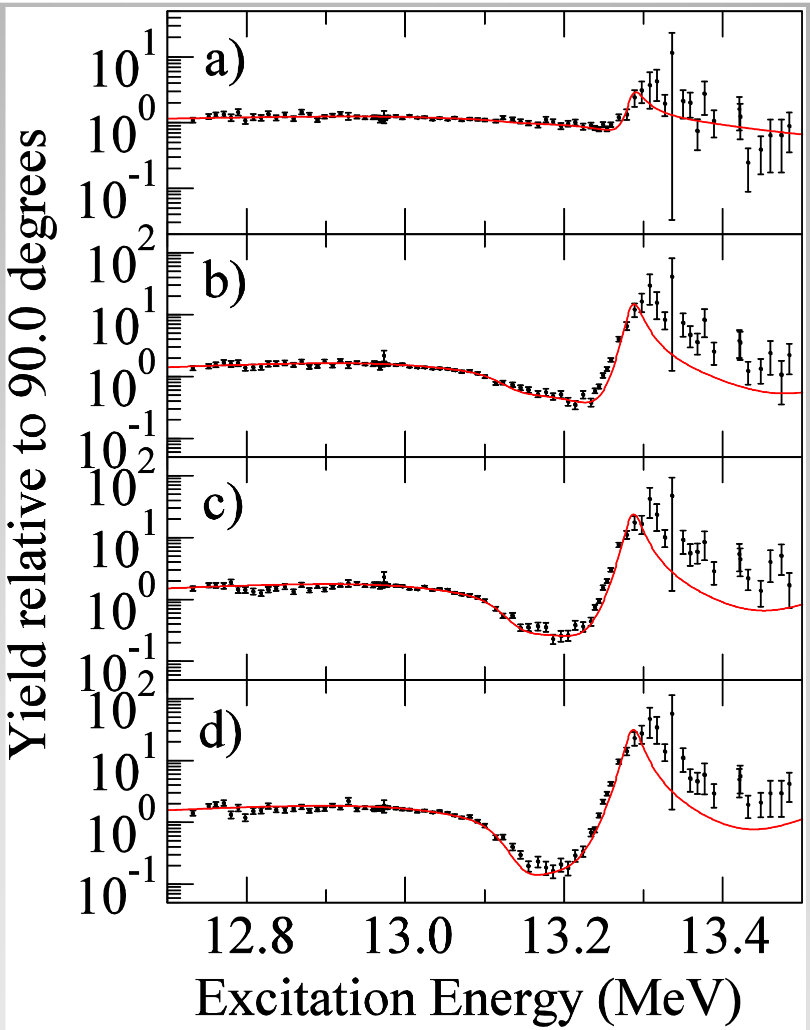
Tischhauser *et al.* (2009) unpublished high energy $^{12}C(\alpha,\alpha_1)$ data at 80.8, 84, 85.8, 89, 90.8, 94, 95.8, and 99 degrees



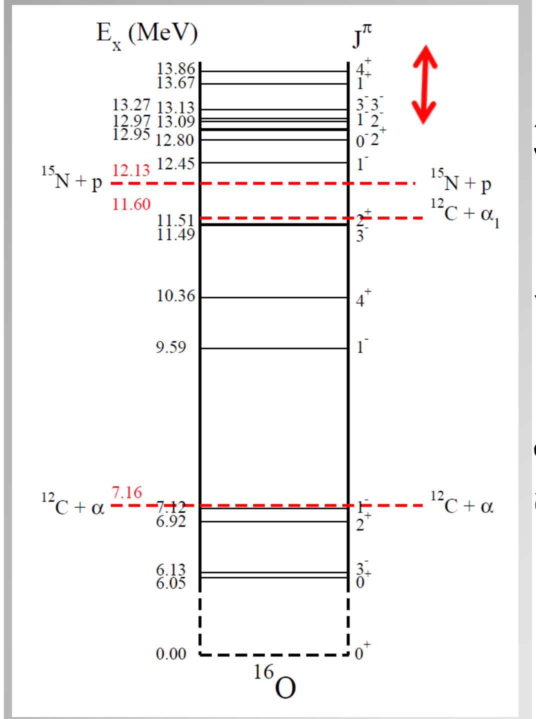


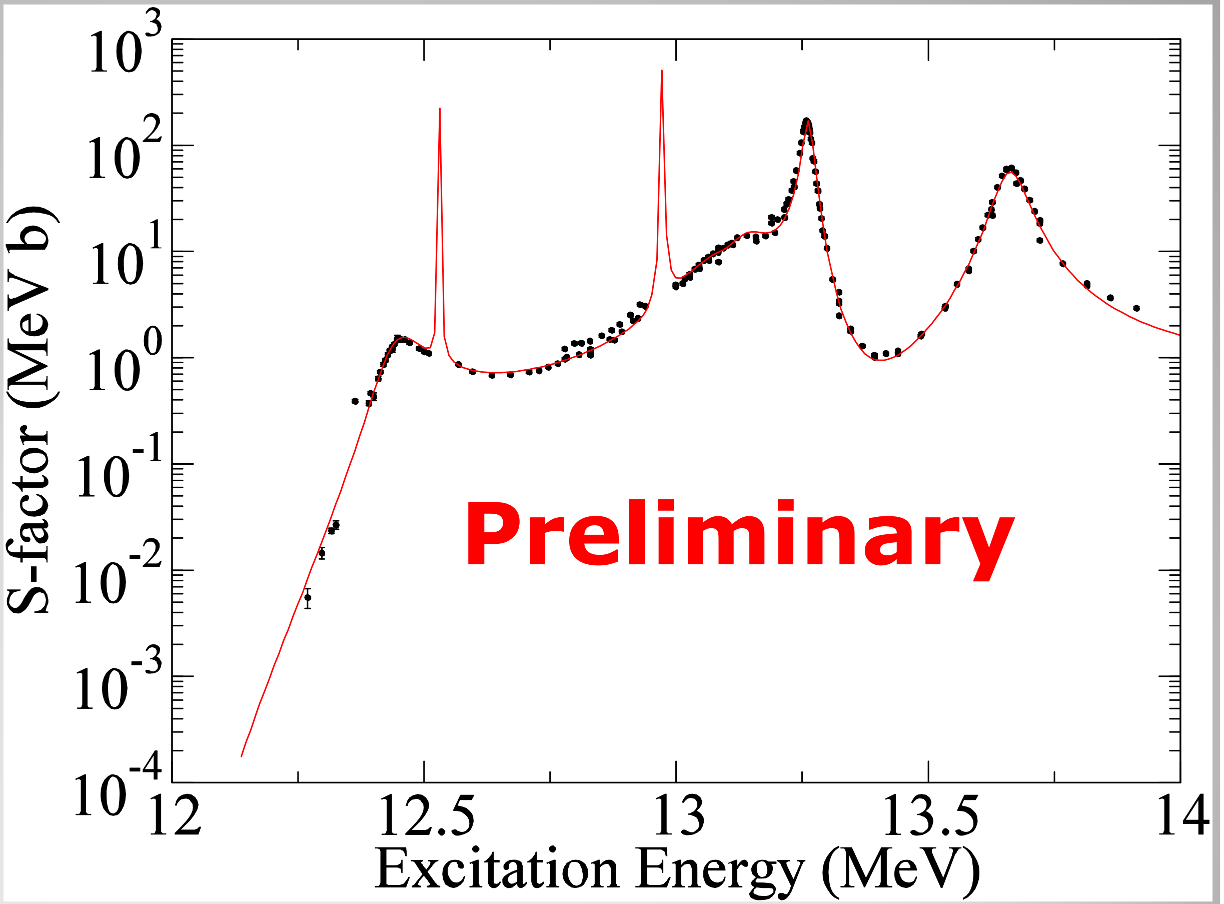
^{15}N(p,p) yield ratio to 90 degrees 105, 135, 150, and 165 degrees, LeBlanc *et al.* (2012)



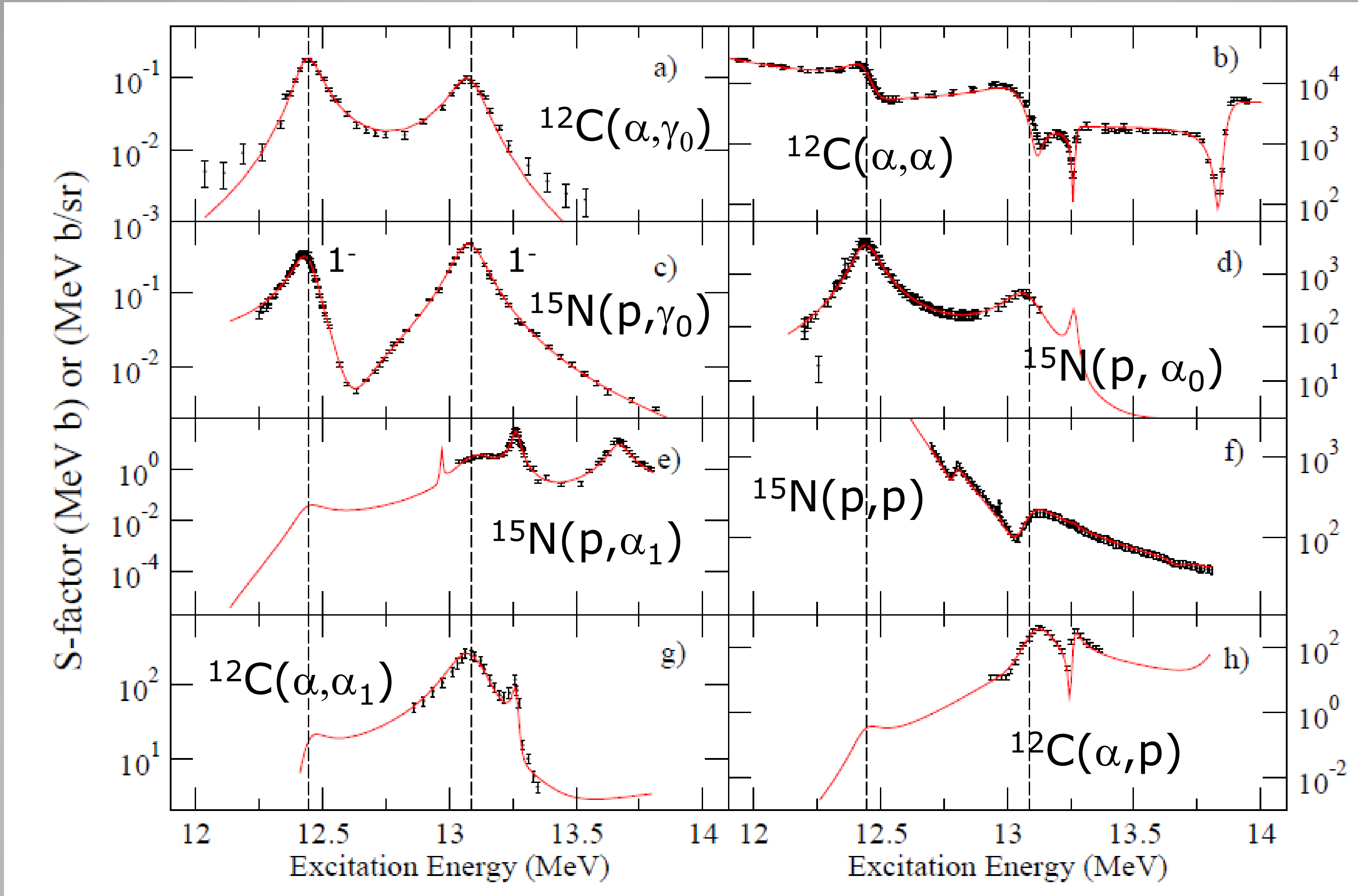


$^{15}N(p,\alpha_0)$ yield ratio to 90 degrees, 105, 135, 150, and 165 degrees, LeBlanc *et al.* (2012)





$^{15}N(p,\alpha_1\gamma)$ data from Leblanc *et al.* (2010) unpublished



Simultaneous
Multiple Entrance/Exit Channel
R-matrix Analysis

$^{15}N(p,\gamma_0)$ Results

- Physically constrained partial widths in *all* channels
- LeBlanc *et al.* (2010) and Caciolli *et al.* (2011)
- Ground state proton ANC fixed at 13.9(1.9) $fm^{-1/2}$
- S(10 keV) = 39.0(3.6) keV b (10%)
- Uncertainty in S(0) improved from 15% to < 10%
- BGP is largest source of uncertainty

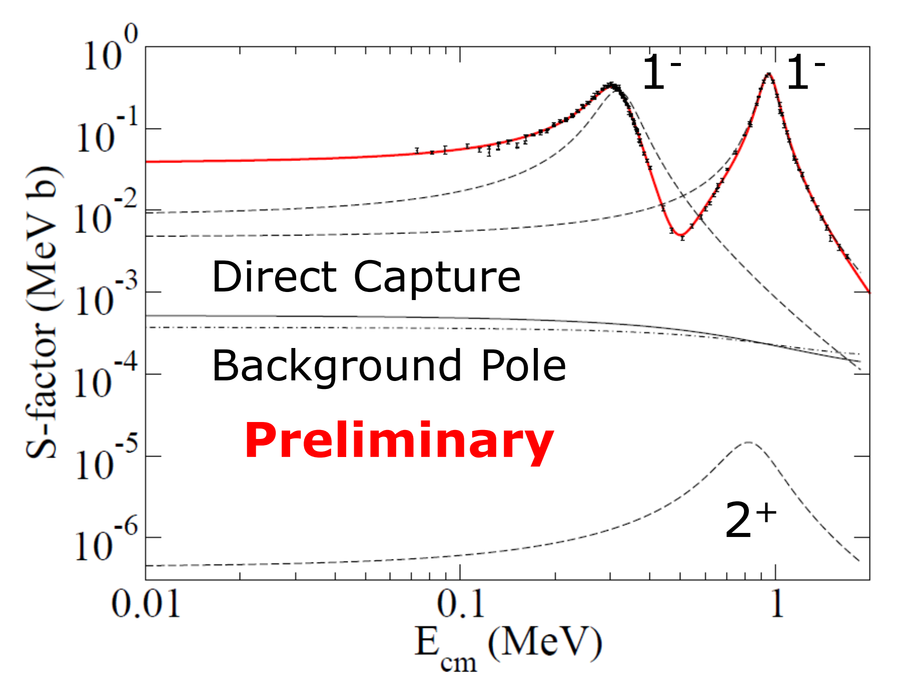


TABLE III. Summary of previous results for extrapolated $S(0)$ values.

Analysis	$S(0)_\gamma$ (keV b)
Hebbard [13]	32
Rolfs and Rodney [12]	64 ± 6
Barker (RR) [16]	≈50–55
Barker (HH) [16]	≈35
Mukhamedzhanov *et al.* [15]	36.0 ± 6.0
LeBlanc *et al.*	39.6 ± 2.6

LeBlanc et al. (2010)

- Multiple (**entrance**/exit) channel *R*-matrix analysis is a very powerful data analysis tool
  - Check of consistency between different reaction channels, reaction data base
  - Improved constraint on level parameters
- Demonstrated on ^{16}O compound nucleus reactions
  - Simultaneous fit of **all** available compound nucleus reaction data (E_x < 13.5 MeV)
  - Improved determination of S(0) for the reaction $^{15}N(p,\gamma)$, uncertainty < 10%

Conclusion

Thank You! azure.nd.edu

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